



# CMS: Latest Results and Prospects

SILAFAE2021: XIII Latin American Symposium on High Energy Physics, 8-12 Nov 2021

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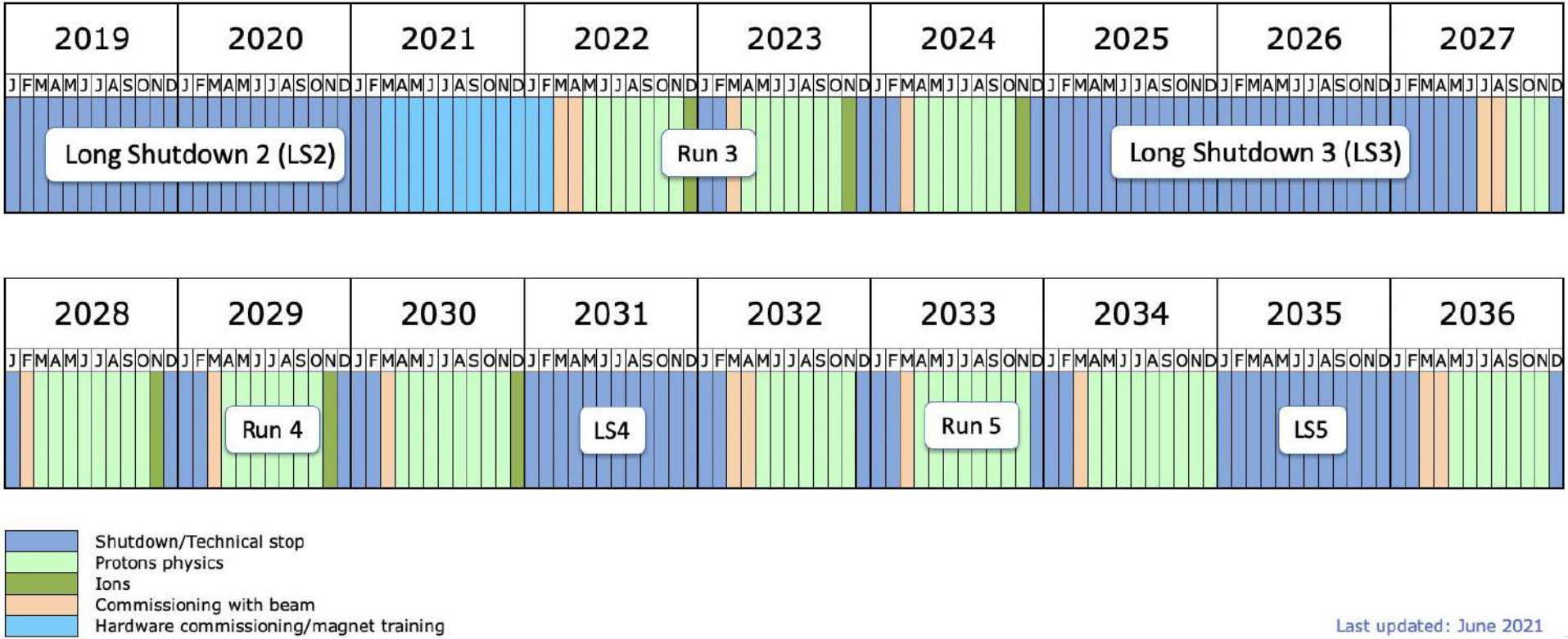
# Outline

- Introduction
- Standard Model Results
  - Standard Model Physics
  - B Physics
  - Heavy-Ion Physics
  - Higgs Physics
  - Top Quark Physics
- Beyond the Standard Model Results
  - Beyond 2 Generations
  - Exotica
  - Super Symmetry
- Future Prospects
- Summary and Conclusions

# Large Hadron Collider (LHC)

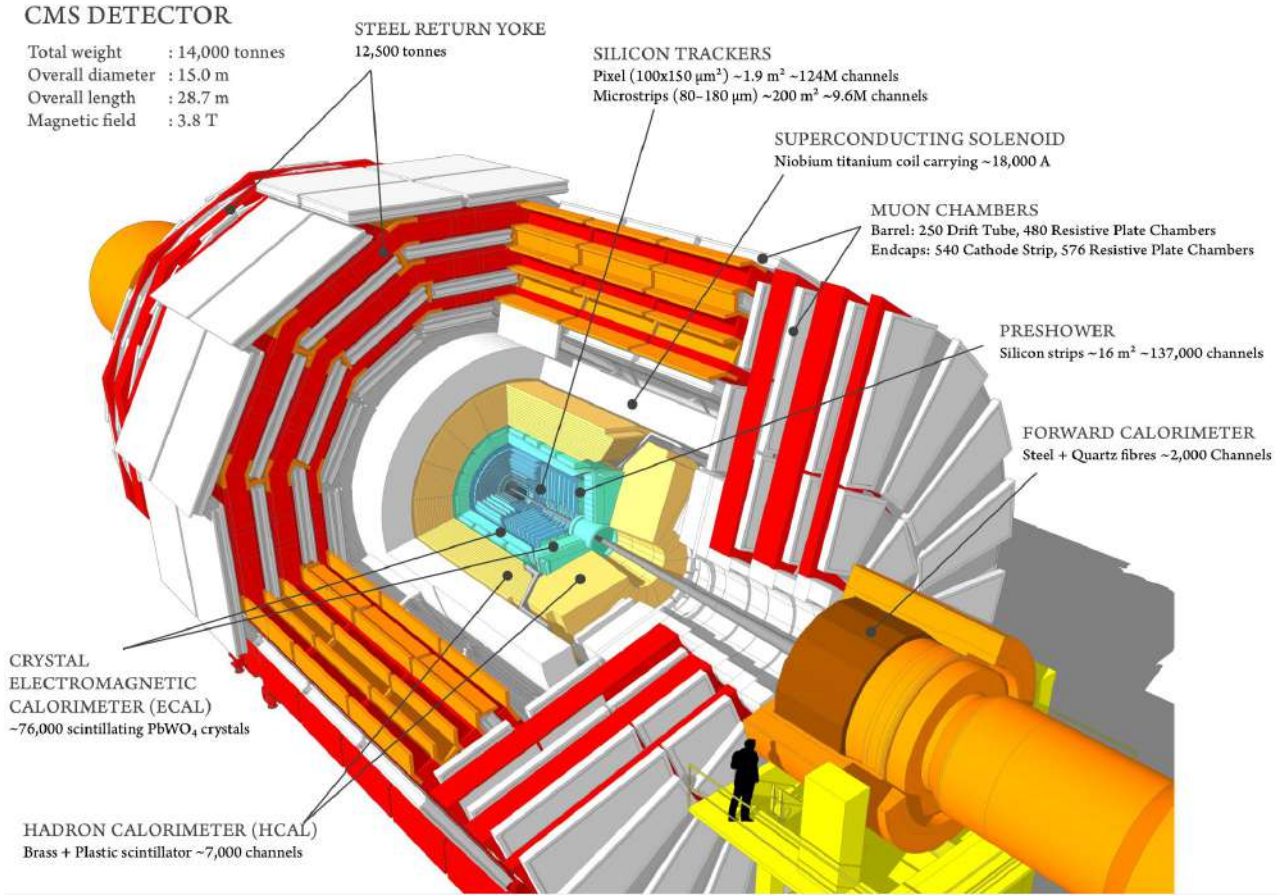
- Largest and highest-energy particle collider
  - At CERN, beneath the France-Switzerland border near Geneva
- Proton and heavy-ion collision programs
  - Record-setting center-of-mass energies and luminosities

# LHC Schedule



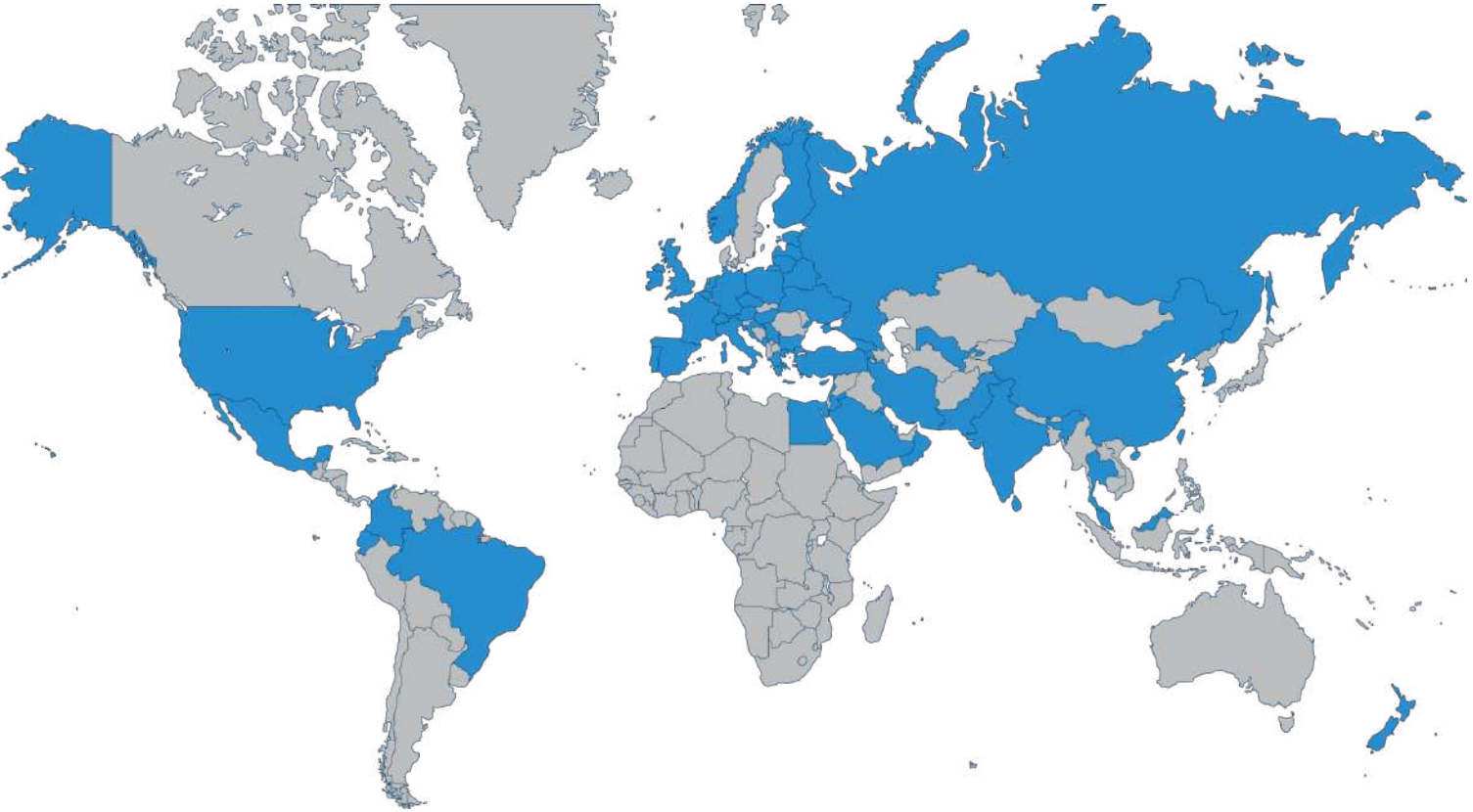

[Longer term LHC schedule]

# Compact Muon Solenoid (CMS)




SketchUpCMS

# CMS Collaboration



~5500
ACTIVE PEOPLE

~3000
PHYSICISTS
(~1000 STUDENTS)

~1000
ENGINEERS

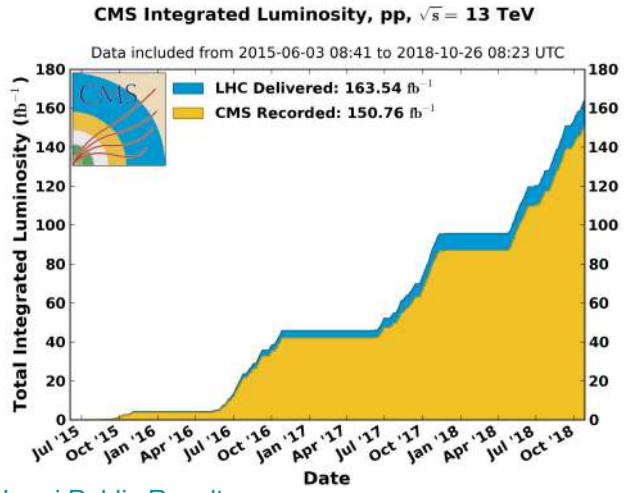
229
INSTITUTES

51
COUNTRIES & REGIONS

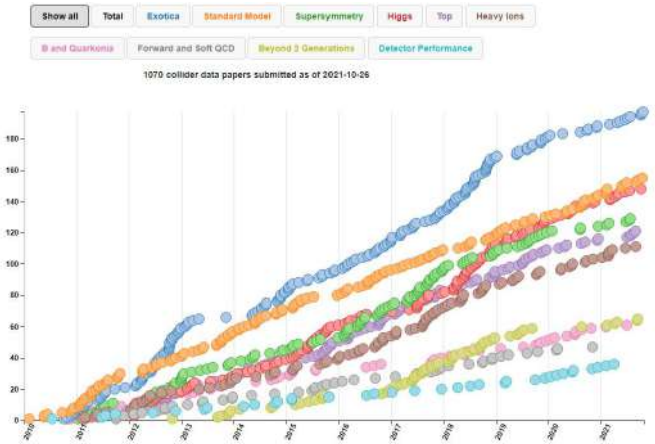
People Statistics

# CMS Run 2 Overview

- Excellent LHC performance
  - Peak Luminosity ~2 × $10^{34}$ Hz/cm$^2$ (2x design value)
  - ~160 fb$^{-1}$ of proton-proton collisions at 13 TeV
- Excellent CMS performance
  - Data-taking efficiency > 92%
  - CMS papers submitted > 1070
  - ~137 fb$^{-1}$ of pp data “good for physics”
  - Upgraded detector in preparation for Run 3
  - Long-term upgrades underway for High-Luminosity LHC

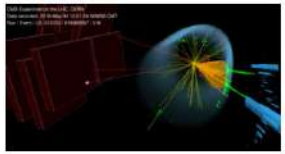



Lumi Public Results




CMS Publications versus Time

# CMS Public Results



TWICE THE HIGGS, TWICE THE FUN!

01 NOV 2021

The Higgs boson, once the sought-after holy grail of particle physics, has now been with us for almost a decade. By now physicists are able to use the Higgs boson itself as a tool for the next discovery beyond the standard model. Interestingly,...

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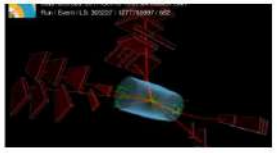

TRIO OF J/Ψ PARTICLES IN ONE GO

28 OCT 2021

High-energy particle accelerators are unique tools to study the structure of matter at the shortest distances. The most powerful accelerator today is the CERN Large Hadron Collider (LHC) that has so far collided beams of protons up to center-of-mass...

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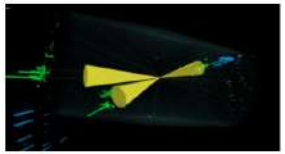

WWW.TRIBOSON.CMS 29 OCT 2021

Apart from the "World Wide Web," three Ws may also have a different interpretation in the LHC era. The standard model of particle physics is a mathematical construct that connects three of the four fundamental forces of nature and classifies all...

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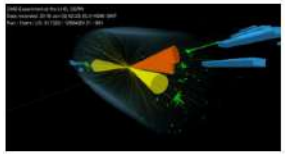

DOES THE BEHAVIOUR OF THE HIGGS BOSON MATCH THE EXPECTATIONS?

13 OCT 2021

The standard model of particle physics is our current best theory to describe the most basic building blocks of the universe, the elementary particles, and the interactions among them. At the heart of the standard model is a hypothesis describing...

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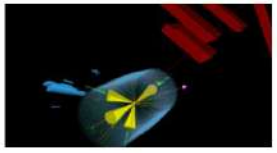

LHC AS THE VECTOR BOSON COLLIDER

13 SEP 2021

After the Higgs boson discovery in the year 2012, the standard model of particle physics offers a complete and consistent description of elementary particle interactions that, despite the many attempts, has not been falsified by experimental...

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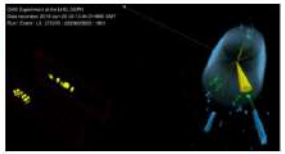

A NEW WINDOW INTO THE SHADOW WORLD: EXOTIC PARTICLE DECAYS IN THE MUON DETECTORS

27 AUG 2021

As physicists seek the elusive particles that may reveal a new understanding of the universe's inner workings, one intriguing possibility is the conceivable existence of new particles that live in a shadow universe, called the "dark sector." The...

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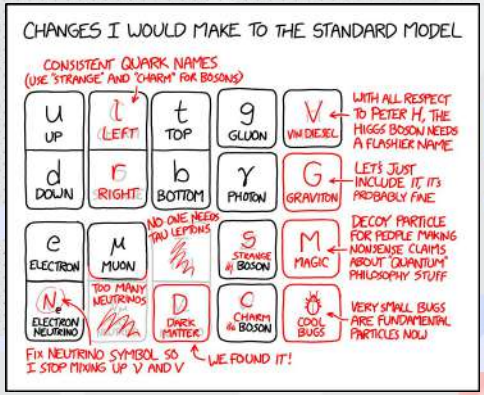
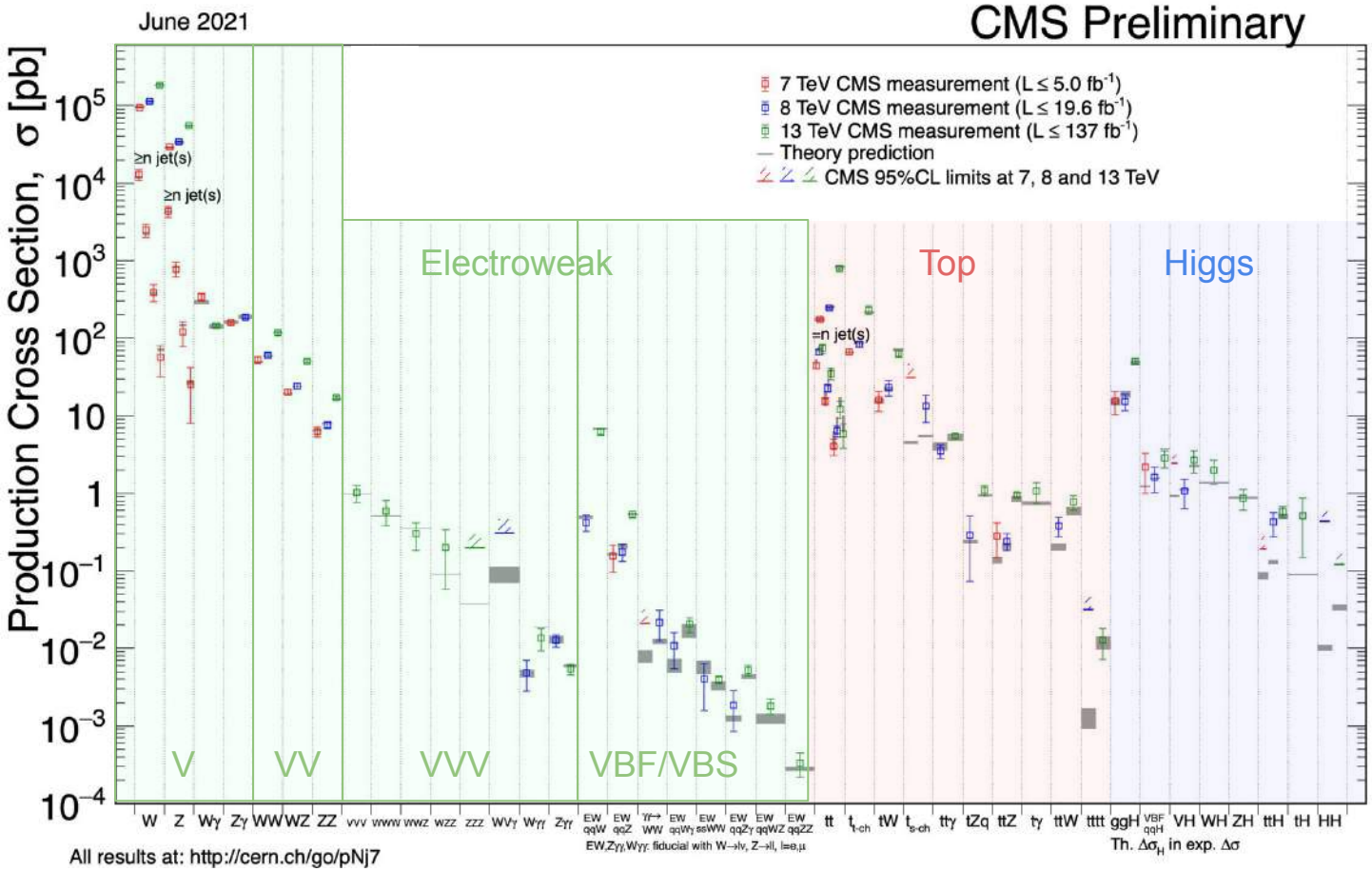
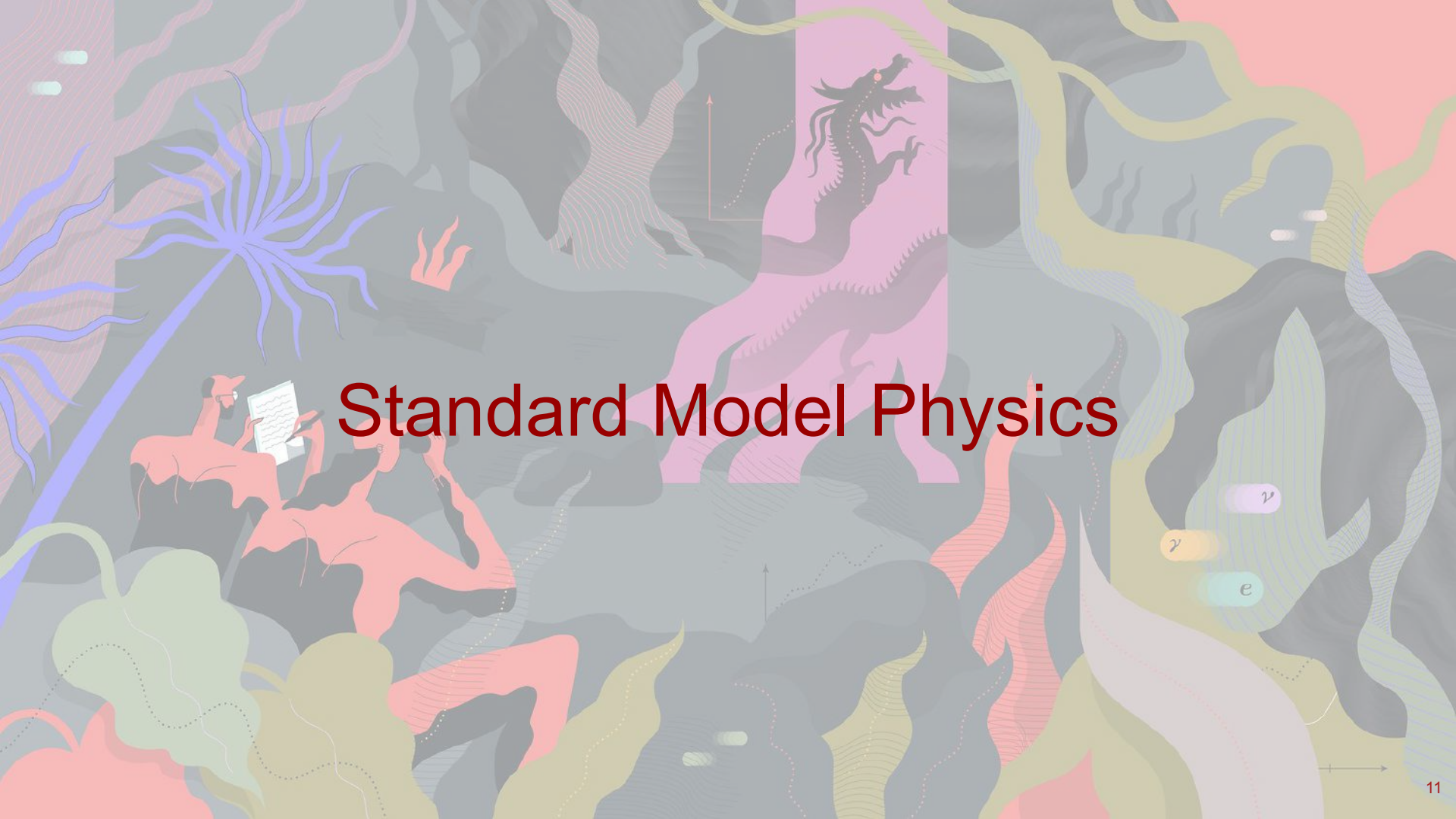



# Standard Model Results

# Standard Model Results

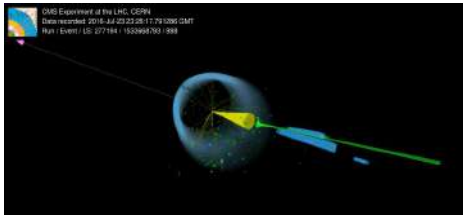


# Standard Model Physics

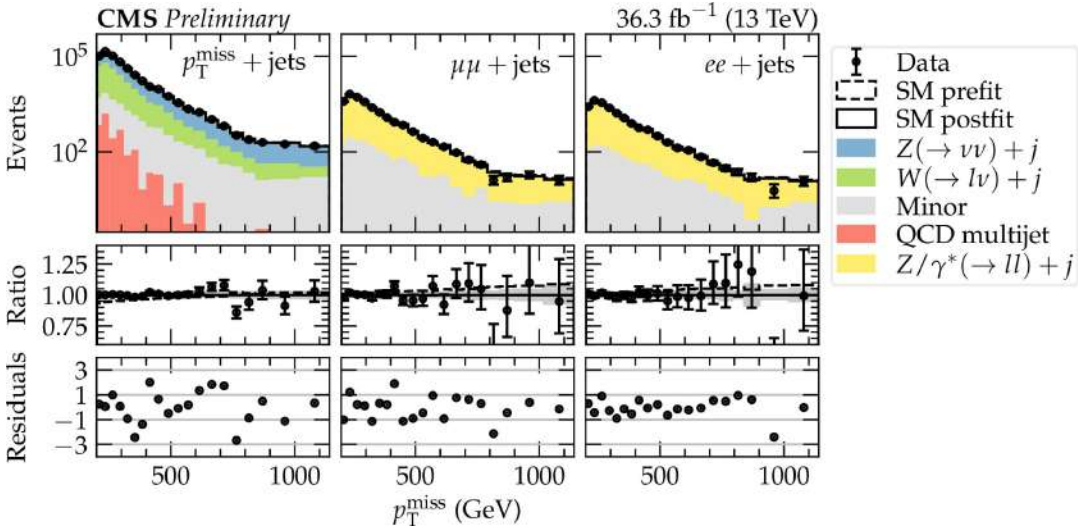


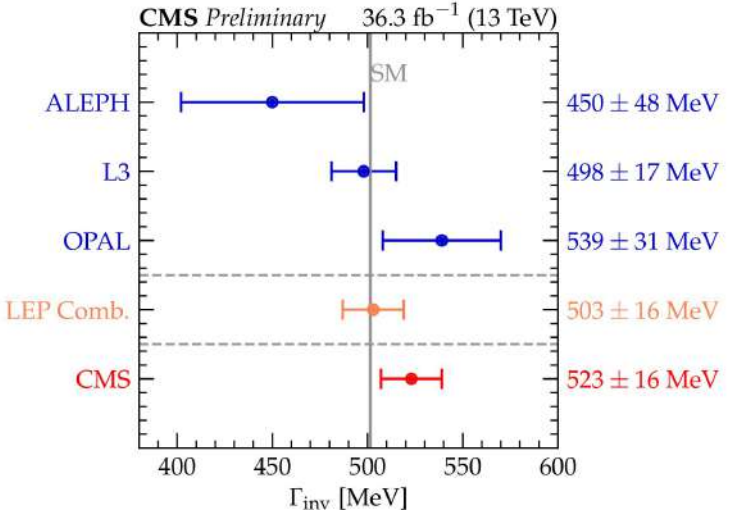
# Z invisible width

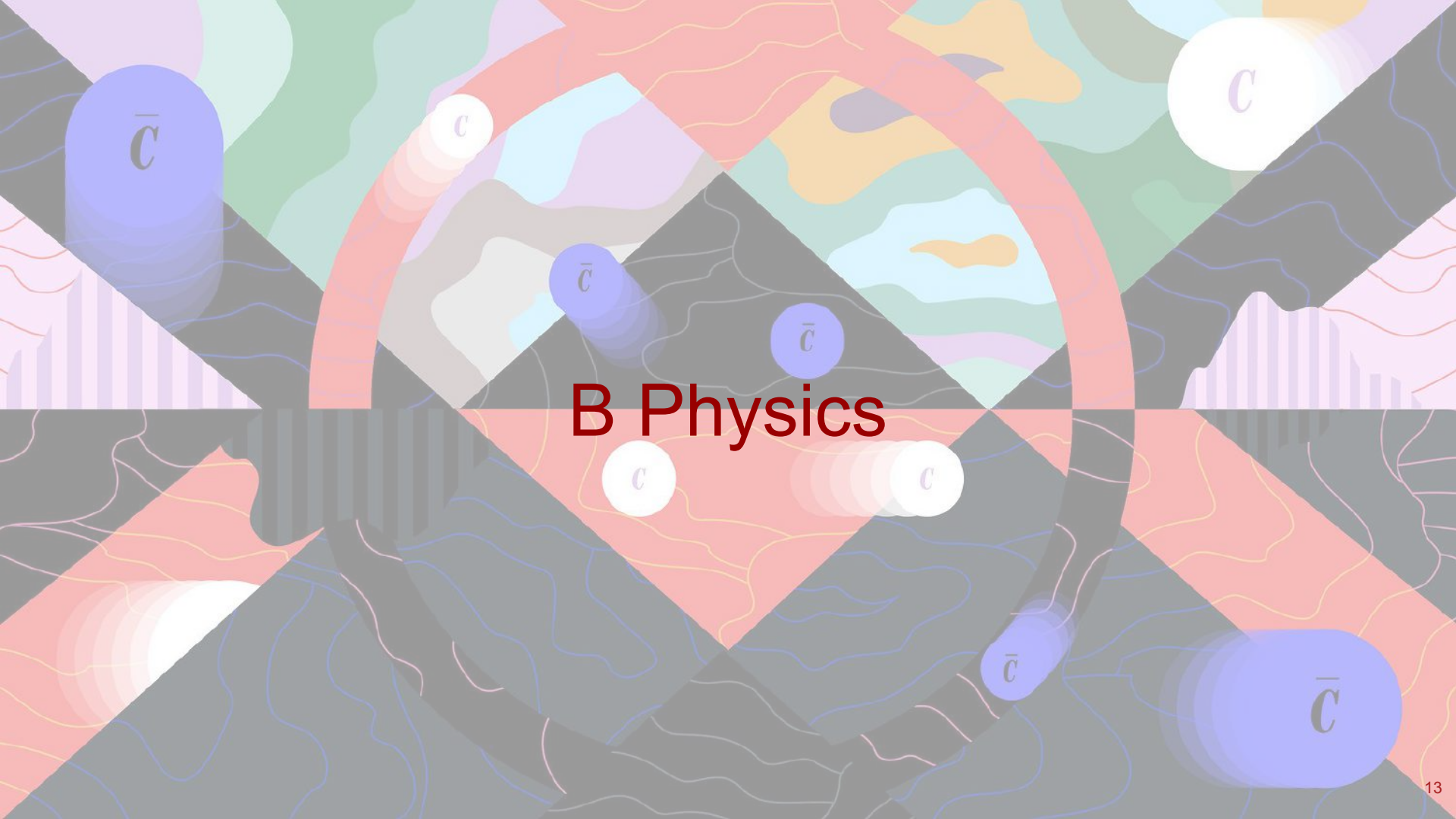
[SMP-18-014]



- First measurement of Z invisible width at a hadron collider
- Most precise direct measurement of the Z invisible width $\Gamma_{inv}$
  - Competitive with the combined direct measurement from LEP
- Simultaneous fit to data regions containing Z→invisible and Z→ee/$\mu\mu$
- $\Gamma_{inv}$ = 523 ± 3 (stat) ± 16 (syst) MeV



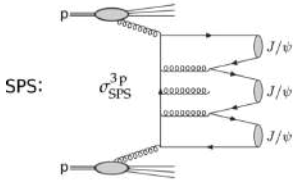



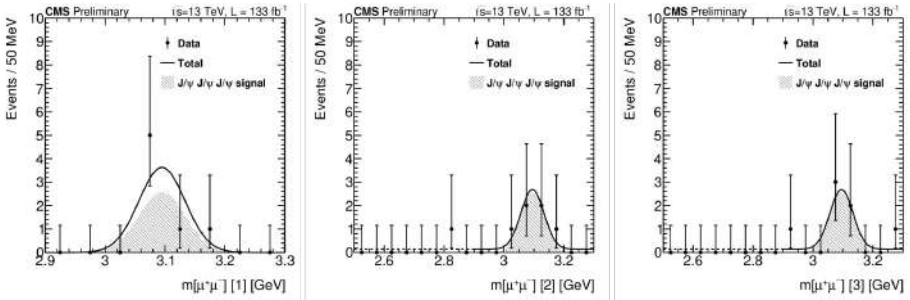

B Physics

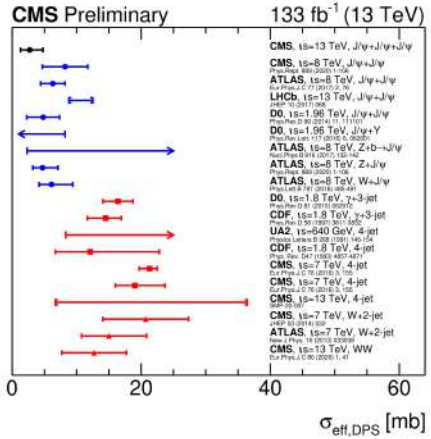
# Observation of triple J/$\psi$ production

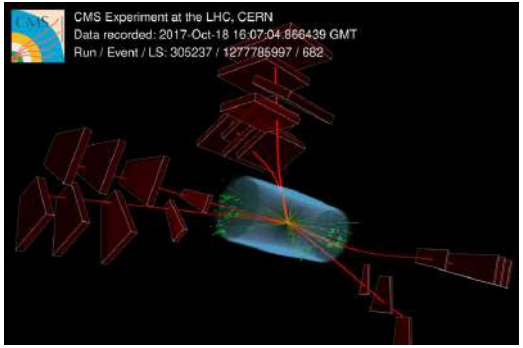
[BPH-21-004]

- First observation of triple J/$\psi$ production
  - Significance in excess of five standard deviations
- Contributions from single-, double-, and triple-parton scattering
  - Final states with three muon pairs
- $\sigma(\mathrm{pp} \to \mathrm{J}\psi\,\mathrm{J}\psi\,\mathrm{J}\psi\,\mathrm{X}) = 272^{+141}_{-104}\ (\mathrm{stat}) \pm 17\ (\mathrm{syst})\ \mathrm{fb}$
  - Measured final state is found to be dominated by DPS and TPS contributions



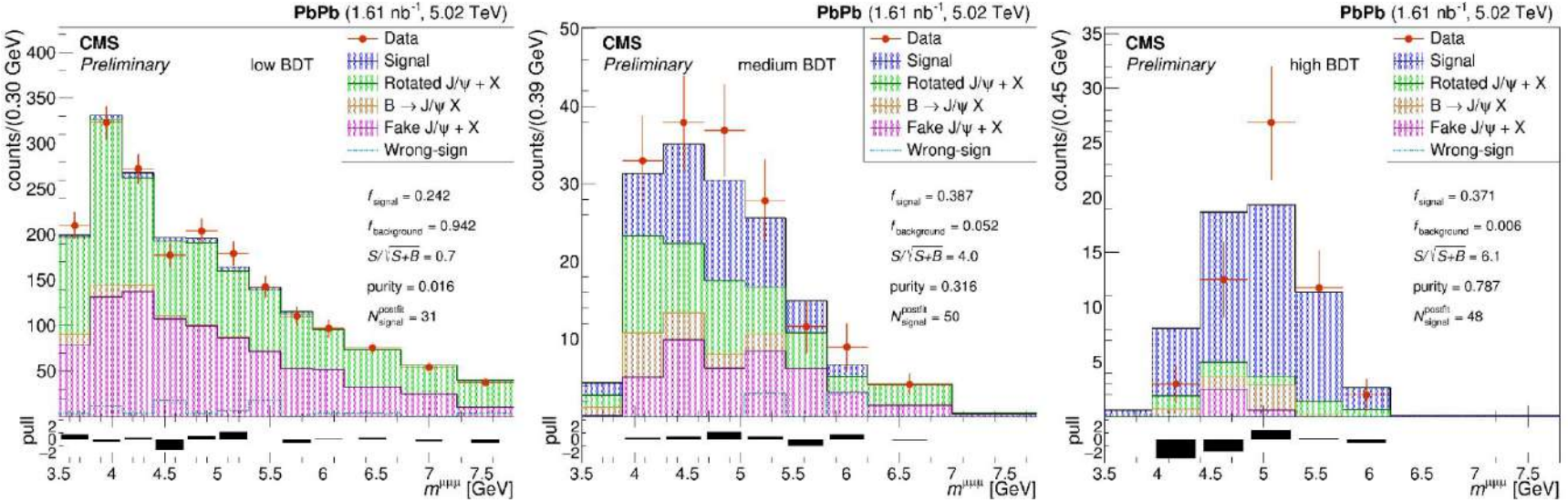

$\sigma_{\mathrm{eff,DPS}}$ for **J/$\psi$+J/$\psi$+J/$\psi$**, **J/$\psi$+J/$\psi$**, **V+J/$\psi$**, **$\gamma$+jets**, **W+jets**, **WW** final states

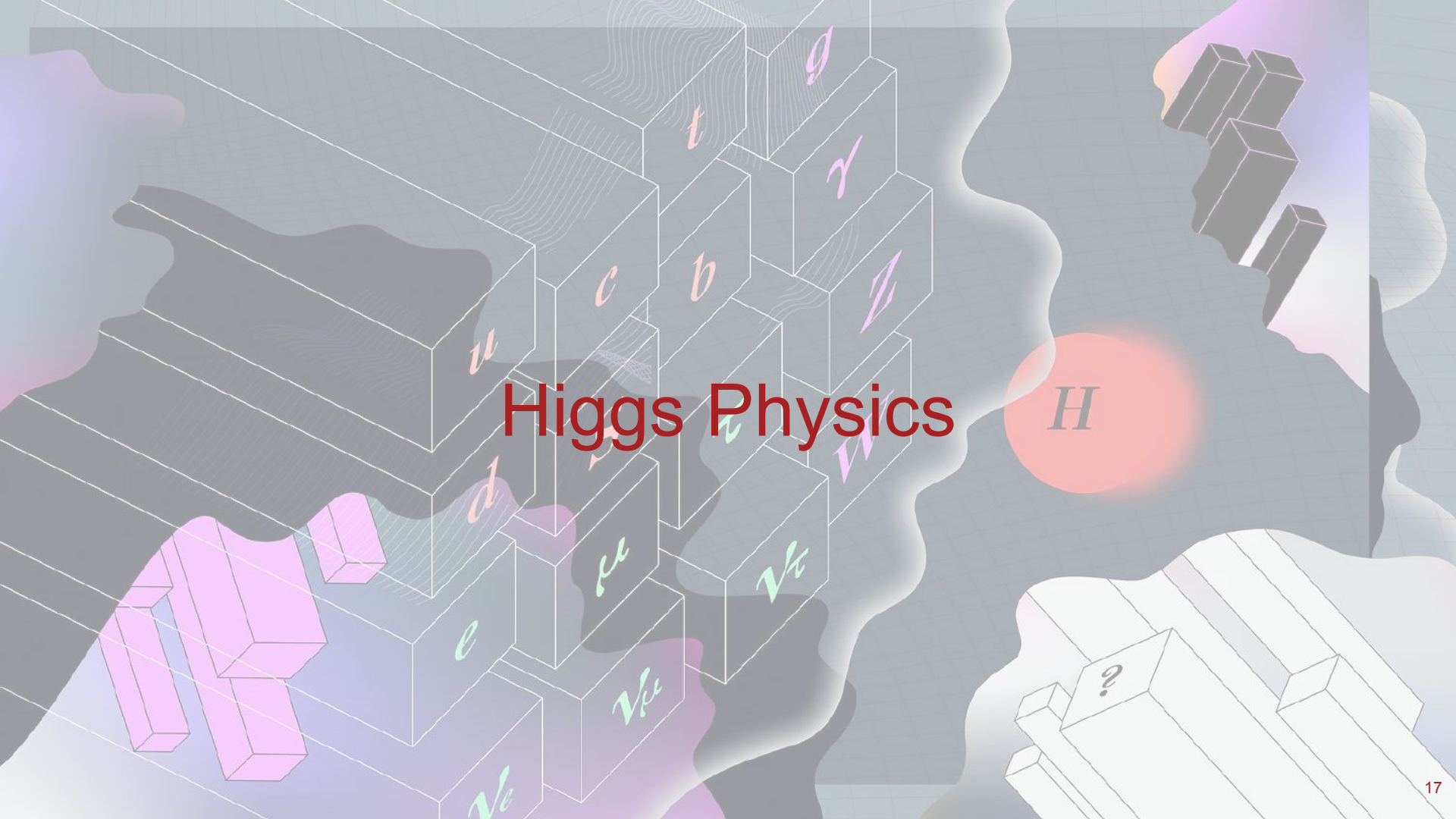
# Heavy-Ion Physics

# First observation of $B_c^+$ meson in Pb Pb collisions

[HIN-20-004]

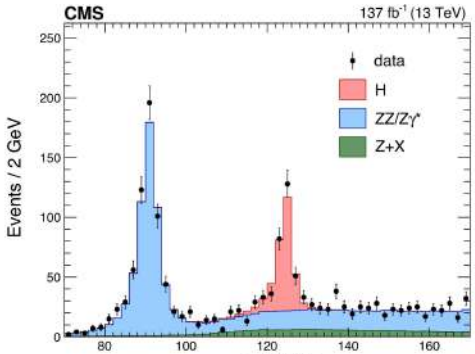
- Decay channel: $B_c^+ \to (J/\psi \to \mu\mu)\mu\nu$
- Only meson containing two different flavored heavy quarks
  - Provides unique bridge between charmonia, bottomonia, and open heavy mesons
- Insight into interplay between suppression and enhancement mechanisms



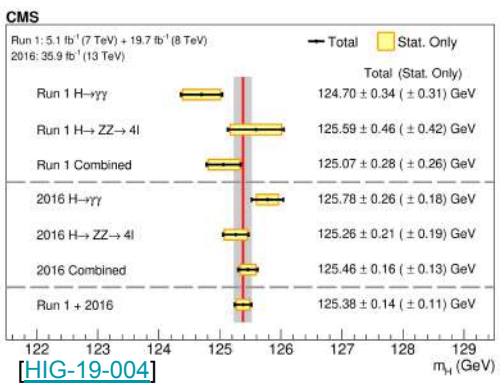

Higgs Physics
H
?

# Higgs Highlights

- Run 1
  - Higgs discovery!
  - Consistent with spin 0
  - Mass measurement at 0.2% level
  - Couplings consistent with SM predictions
- Run 2
  - Observation of all main production mechanisms (ggF, ttH, VBF, VH)
  - Observation of decays to bosons and third-generation fermions
  - Excellent mass measurement [125.38 ± 0.14 GeV]
- All measurements consistent with Standard Model predictions thus far




[HIG-19-009]
[*Phys. Rev. D 104 (2021) 052004*]

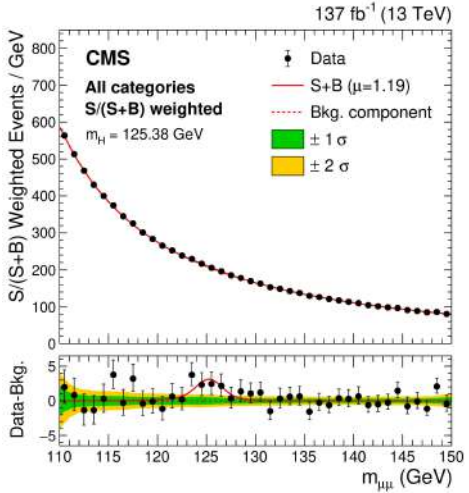


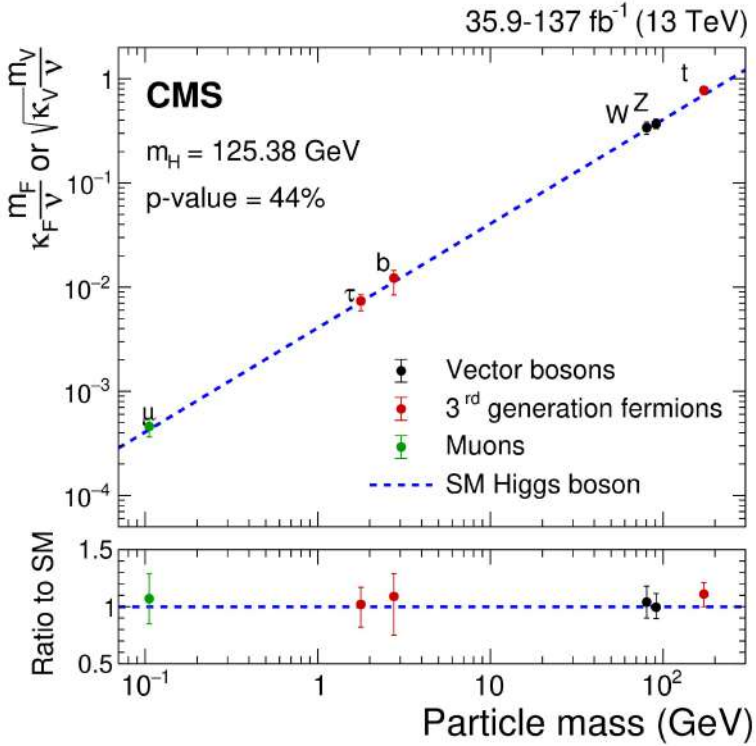

[HIG-19-004]
[*Phys. Lett. B 805 (2020) 135425*]

# Evidence for Higgs boson decay to a pair of muons

[HIG-19-006] [JHEP 01 (2021) 148]

- First evidence of Higgs coupling with 2nd generation fermions
  - Observed (expected) significance 3.0σ (2.5σ)
- Rare decay (branching fraction ~$2\times10^{-4}$)
- Large irreducible bkg from $Z\to\mu\mu$
- ggH, VBF, VH, ttH categories
- $\mu = 1.19^{+0.41}_{-0.39}\,(\text{stat})\,^{+0.17}_{-0.16}\,(\text{syst})$

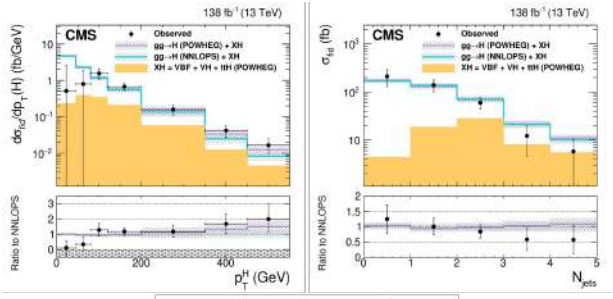


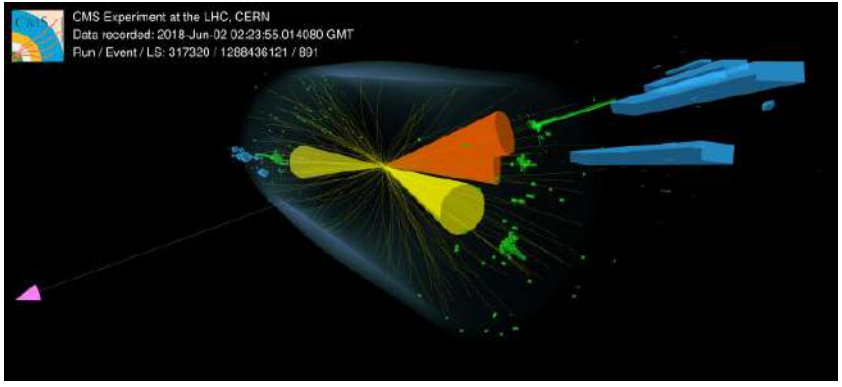



# Inclusive and differential H→$\tau\tau$ cross sections

[HIG-20-015] [*Submitted to Phys. Rev. Lett.*]

- First differential measurements of H→$\tau\tau$ cross section
- Integrates over production modes (ggF, VBF, VH, ttH)
- Measured as functions of $p_T$(H), $N_{Jets}$, $p_T$(leading jet)
- Significant improvement over measurements in other final states
  - Events with a large jet multiplicity or with a Lorentz-boosted Higgs boson

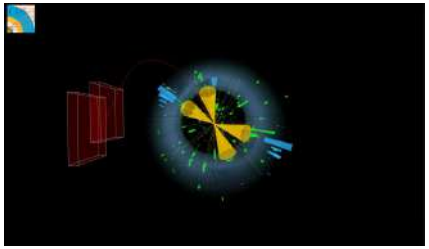


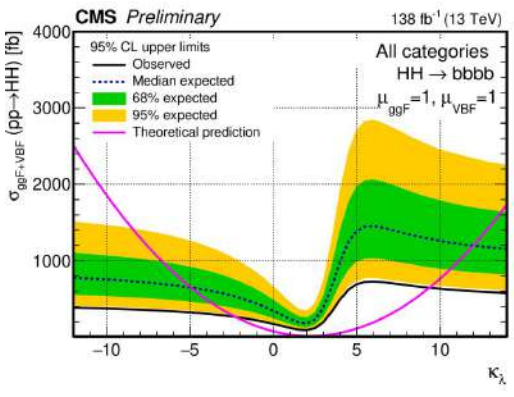



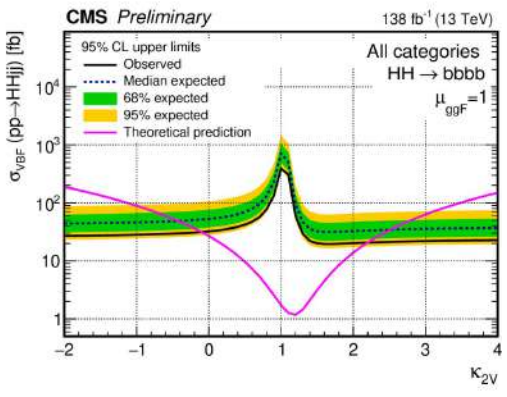
# Search for H(bb)H(bb)

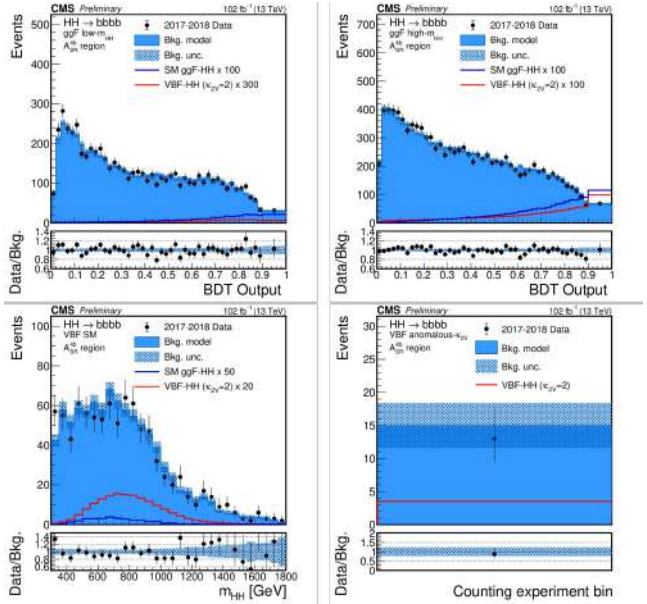
[HIG-20-005]

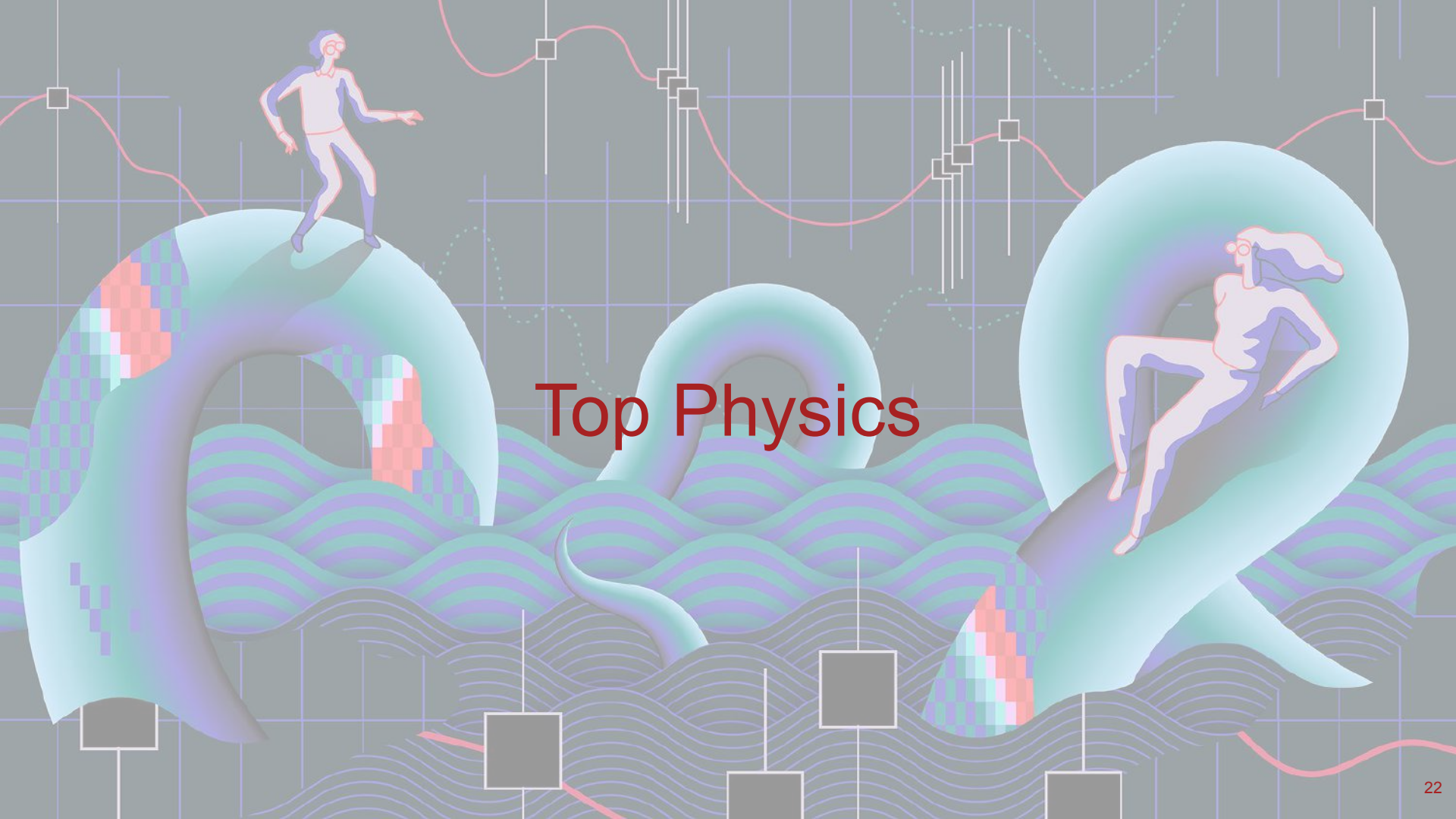
- Di-Higgs production exploring several couplings: HHH, HVV, HHVV
  - Dedicated HLT triggers with 3 b-jet
  - Targets both ggF and VBF production
- New multivariate analysis strategy
  - New background estimation from multiple control regions
- B-tagging improvements
  - Phase-1 pixel detector upgrade
  - Latest tagger from BTV (DeepFlavour)





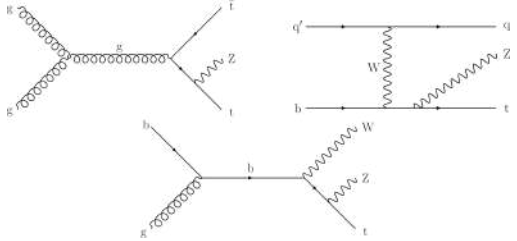



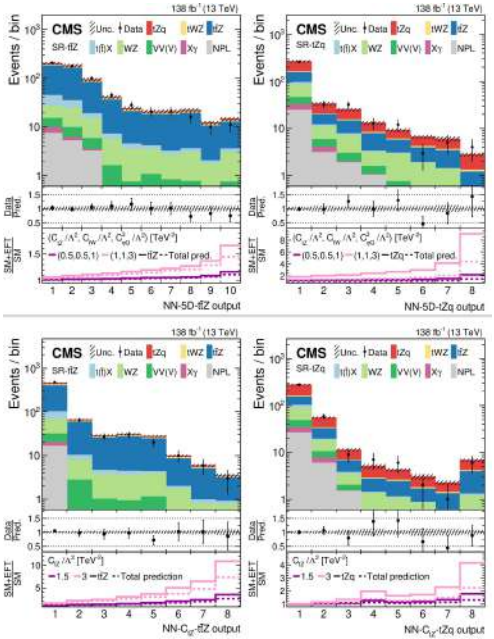

Top Physics

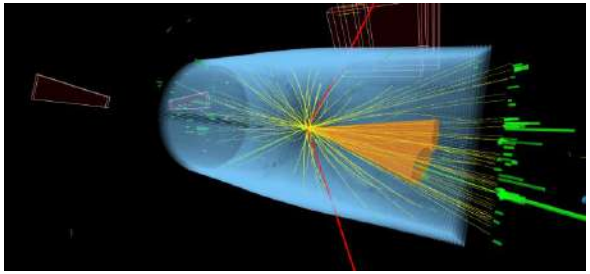
# Probing effective field theory (EFT) with ttZ

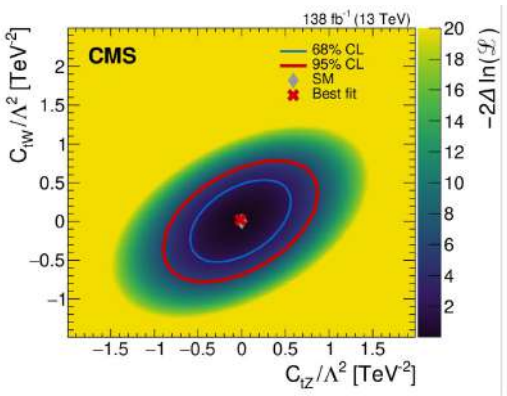
[TOP-21-001] [*Submitted to J. High Energy Phys.*]

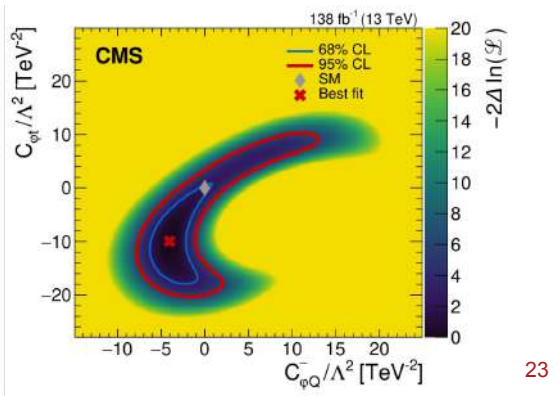


- Search for new EFT top quark interactions
  - Associated production of 1 or 2 top quarks with a Z boson in multilepton final states
  - Events with 3 or 4 light leptons, divided into signal and control (WZ/ZZ) regions
  - Dimension-6 EFT operators and relative Wilson coefficients considered
  - Machine learning optimizes sensitivity to each EFT parameter



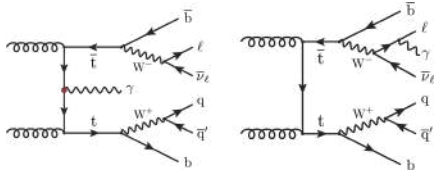





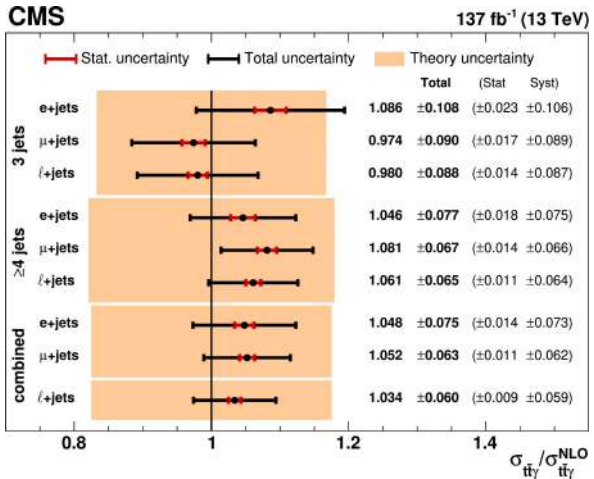



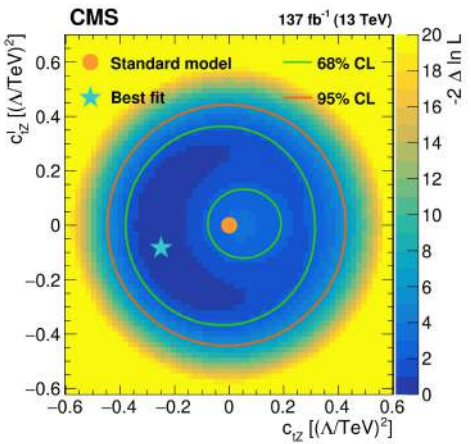
# Measurement of tt$\gamma$ cross section

[TOP-18-010] [Submitted to J. High Energy Phys.]



- Associated ttX production provides direct probe into top quark couplings
  - Can be modified in BSM models
- Measurement of top quark pair and associated photon cross section
  - One highly energetic e/$\mu$, one isolated photon, and ≥ 3 jets (≥1 b-tagged)
  - $\sigma_{tt\gamma}^{fid.}$ = 800 ± 7 (stat) ± 46 (syst) fb
    - Good agreement with Standard Model prediction
  - Differential cross sections in $p_T(\gamma)$, $|\eta(\gamma)|$, $\Delta R(l,\gamma)$ are measured and interpreted with SMEFT
    - Most stringent direct limits on anomalous EM dipole moment interactions

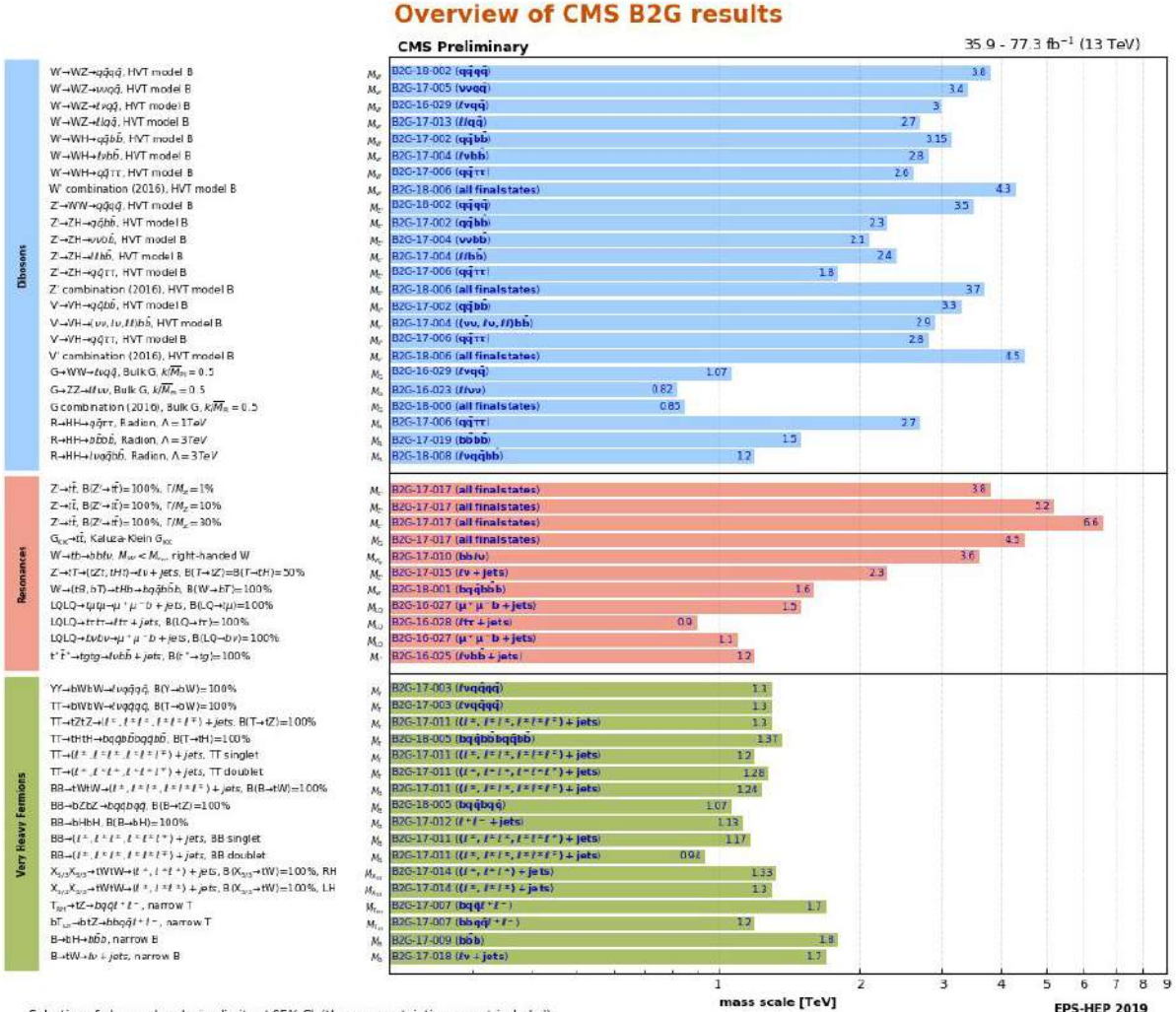


# Beyond the Standard Model Results

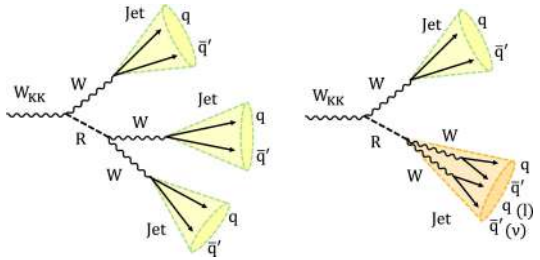
# Beyond 2 Generations

# B2G Results

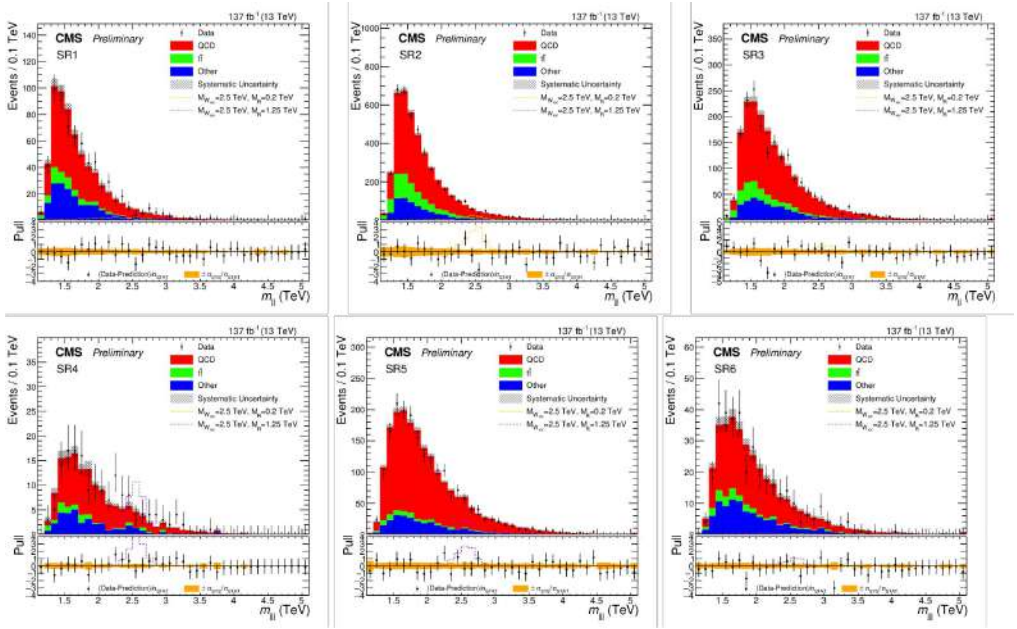

Overview of CMS B2G results
CMS Preliminary
35.9 - 77.3 fb$^{-1}$ (13 TeV)
Dibosons
Resonances
Very Heavy Fermions
B2G-18-002 (qq̄qq̄) 3.6
B2G-17-005 (ννqq̄) 3.4
B2G-16-029 (ℓνqq̄) 3
B2G-17-013 (ℓℓqq̄) 2.7
B2G-17-002 (qq̄bb̄) 3.15
B2G-17-004 (ννbb̄) 2.8
B2G-17-004 (ℓℓbb̄) 2.8
B2G-17-006 (qq̄ττ) 2.6
B2G-18-006 (all finalstates) 4.3
B2G-18-002 (qq̄qq̄) 3.5
B2G-17-002 (qq̄bb̄) 2.3
B2G-17-004 (ννbb̄) 2.1
B2G-17-004 (ℓℓbb̄) 2.4
B2G-17-006 (qq̄ττ) 1.8
B2G-18-006 (all finalstates) 3.7
B2G-17-002 (qq̄bb̄) 3.3
B2G-17-004 ((νν, ℓν, ℓℓ)bb̄) 2.9
B2G-17-006 (qq̄ττ) 2.8
B2G-18-006 (all finalstates) 4.5
B2G-16-029 (ℓνqq̄) 1.07
B2G-16-023 (ℓℓνν) 0.82
B2G-18-000 (all finalstates) 0.85
B2G-17-006 (qq̄ττ) 2.7
B2G-17-019 (b̄b̄bb̄) 1.5
B2G-18-008 (ℓνqq̄bb̄) 1.2
B2G-17-017 (all finalstates) 3.8
B2G-17-017 (all finalstates) 5.2
B2G-17-017 (all finalstates) 6.6
B2G-17-017 (all finalstates) 4.5
B2G-17-010 (bb̄ℓν) 3.6
B2G-17-015 (ℓν + jets) 2.3
B2G-18-001 (bqq̄bb̄) 1.6
B2G-16-027 (μ⁺μ⁻b + jets) 1.5
B2G-16-028 (ℓτℓτ + jets) 0.9
B2G-16-027 (μ⁺μ⁻b + jets) 1.3
B2G-16-025 (ℓνbb̄ + jets) 1.2
B2G-17-003 (ℓνqq̄qq̄) 1.3
B2G-17-003 (ℓνqq̄qq̄) 1.3
B2G-17-011 ((ℓ⁺ℓ⁻, ℓ⁺ℓ⁻ℓ⁺ℓ⁻) + jets) 1.1
B2G-18-005 (bqq̄b̄bqq̄b̄) 1.37
B2G-17-011 ((ℓ⁺ℓ⁻, ℓ⁺ℓ⁻ℓ⁺ℓ⁻) + jets) 1.2
B2G-17-011 ((ℓ⁺ℓ⁻, ℓ⁺ℓ⁻ℓ⁺ℓ⁻) + jets) 1.28
B2G-17-011 ((ℓ⁺, ℓ⁺ℓ⁻, ℓ⁺ℓ⁻ℓ⁺) + jets) 1.24
B2G-18-005 (bqq̄bqq̄) 1.07
B2G-17-012 (ℓ⁺ℓ⁻ + jets) 1.13
B2G-17-011 ((ℓ⁺, ℓ⁺ℓ⁻, ℓ⁺ℓ⁻ℓ⁺) + jets) 1.17
B2G-17-011 ((ℓ⁺, ℓ⁺ℓ⁻, ℓ⁺ℓ⁻ℓ⁺) + jets) 0.94
B2G-17-014 ((ℓ⁺, ℓ⁺ℓ⁻) + jets) 1.33
B2G-17-014 ((ℓ⁺, ℓ⁺ℓ⁻) + jets) 1.3
B2G-17-007 (bqq̄ℓ⁺ℓ⁻) 1.7
B2G-17-007 (bb̄qq̄ℓ⁺ℓ⁻) 1.2
B2G-17-009 (bb̄b) 1.8
B2G-17-018 (ℓν + jets) 1.7
W′→WZ→qq̄q̄, HVT model B
W′→WZ→ννqq̄, HVT model B
W′→WZ→ℓνqq̄, HVT model B
W′→WZ→ℓℓqq̄, HVT model B
W′→WH→qq̄bb̄, HVT model B
W′→WH→ℓνbb̄, HVT model B
W′→WH→qq̄ττ, HVT model B
W′ combination (2016), HVT model B
Z′→WW→qq̄q̄q̄, HVT model B
Z′→ZH→qq̄bb̄, HVT model B
Z′→ZH→ννbb̄, HVT model B
Z′→ZH→ℓℓbb̄, HVT model B
Z′→ZH→qq̄ττ, HVT model B
Z′ combination (2016), HVT model B
V′→VH→qq̄bb̄, HVT model B
V′→VH→ℓ(νν, ℓν, ℓℓ)bb̄, HVT model B
V′→VH→qq̄ττ, HVT model B
V′ combination (2016), HVT model B
G→WW→ℓνqq̄, Bulk G, $k/\overline{M}_{Pl}=0.5$
G→ZZ→ℓℓνν, Bulk G, $k/\overline{M}_{Pl}=0.5$
G combination (2016), Bulk G, $k/\overline{M}_{Pl}=0.5$
R→HH→qq̄ττ, Radion, Λ = 3TeV
R→HH→bb̄bb̄, Radion, Λ = 3TeV
R→HH→ℓνqq̄bb̄, Radion, Λ = 3TeV
Z′→tt̄, B(Z′→tt̄)=100%, $\Gamma/M_Z=1\%$
Z′→tt̄, B(Z′→tt̄)=100%, $\Gamma/M_Z=10\%$
Z′→tt̄, B(Z′→tt̄)=100%, $\Gamma/M_Z=30\%$
$G_{KK}$→tt̄, Kaluza-Klein $G_{KK}$
W′→tb→bbℓν, $M_{W'} \ll M_{\nu_R}$, right-handed W
Z′→tT→(tZ/t, tH/t)+ℓν + jets, B(T→tZ)=B(T→tH)=50%
W′→(tb̄, bT)→tHb→bqb̄bb̄, B(W′→bT)=100%
LQLQ→tμ/tμ−μ⁺μ⁻b + jets, B(LQ→tμ)=100%
LQLQ→tτ/tτ−→ℓτ + jets, B(LQ→tτ)=100%
LQLQ→tνb/νν−μ⁺μ⁻b + jets, B(LQ→bν)=100%
t*t̄*→tg/tg→ℓνbb̄ + jets, B(t*→tg)=100%
Y′→bWbW→ℓνqq̄qq̄, B(Y→bW)=100%
T′→bWbW→ℓνqq̄qq̄, B(T→bW)=100%
T′→tZtZ→ℓ⁺ℓ⁻, ℓ⁺ℓ⁻ℓ⁺ℓ⁻, ℓ⁺ℓ⁻ℓ⁺ℓ⁻ + jets, B(T→tZ)=100%
T′→tHtH→bqq̄bb̄bqq̄bb̄, B(T→tH)=100%
T′→(ℓ⁺, ℓ⁺ℓ⁻, ℓ⁺ℓ⁻ℓ⁺ℓ⁻) + jets, TT singlet
T′→(ℓ⁺, ℓ⁺ℓ⁻, ℓ⁺ℓ⁻ℓ⁺ℓ⁻) + jets, TT doublet
BB→tWbW→(ℓ⁺, ℓ⁺ℓ⁻, ℓ⁺ℓ⁻ℓ⁺ℓ⁻) + jets, B(B→tW)=100%
BB→bZbZ→bqq̄bqq̄, B(B→tZ)=100%
BB→bHbH, B(B→bH)=100%
BB→(ℓ⁺, ℓ⁺ℓ⁻, ℓ⁺ℓ⁻ℓ⁺ℓ⁻) + jets, BB singlet
BB→(ℓ⁺, ℓ⁺ℓ⁻, ℓ⁺ℓ⁻ℓ⁺ℓ⁻) + jets, BB doublet
$X_{5/3}X_{5/3}$→(tW)(tW)→(ℓ⁺, ℓ⁻ℓ⁺) + jets, B($X_{5/3}$→tW)=100%, RH
$X_{5/3}X_{5/3}$→(tW)(tW)→(ℓ⁺, ℓ⁺ℓ⁻) + jets, B($X_{5/3}$→tW)=100%, LH
$T_{5/3}$→tZ→bqq̄ℓ⁺ℓ⁻, narrow T
bT$_{-1/3}$→btZ→bbqq̄ℓ⁺ℓ⁻, narrow T
B→bH→bb̄b, narrow B
B→tW→bν + jets, narrow B
$M_{W'}$
$M_{Z'}$
$M_{V'}$
$M_{G}$
$M_{R}$
$M_{t'}$
$M_{Y'}$
$M_{T'}$
$M_{B}$
$M_{X_{5/3}}$
$M_{T_{5/3}}$
$M_{T_{-1/3}}$
1
2
3
4
5
6
7
8
9
mass scale [TeV]
EPS-HEP 2019
Selection of observed exclusion limits at 95% CL (theory uncertainties are not included).

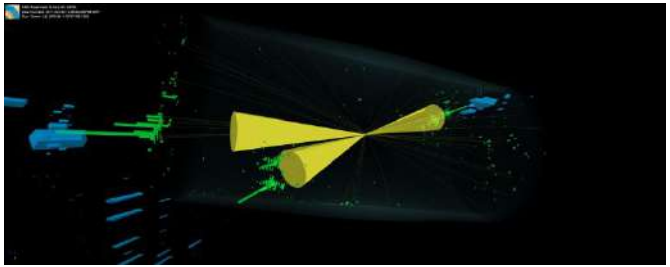
# Search for resonances into WWW

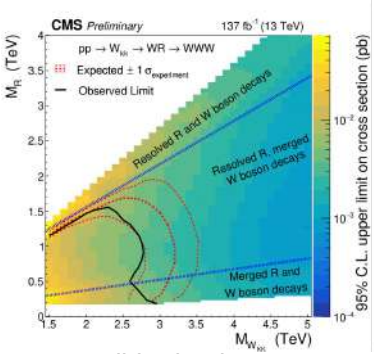
[B2G-21-002]



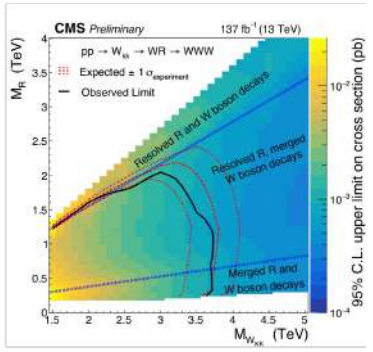

- Search for decays via a scalar radion (R)
  - X → WR → WWW (hadronic decays)
  - Two or three massive, Lorentz-boosted jets
- Results combined with complementary search in the $l$+jets final state





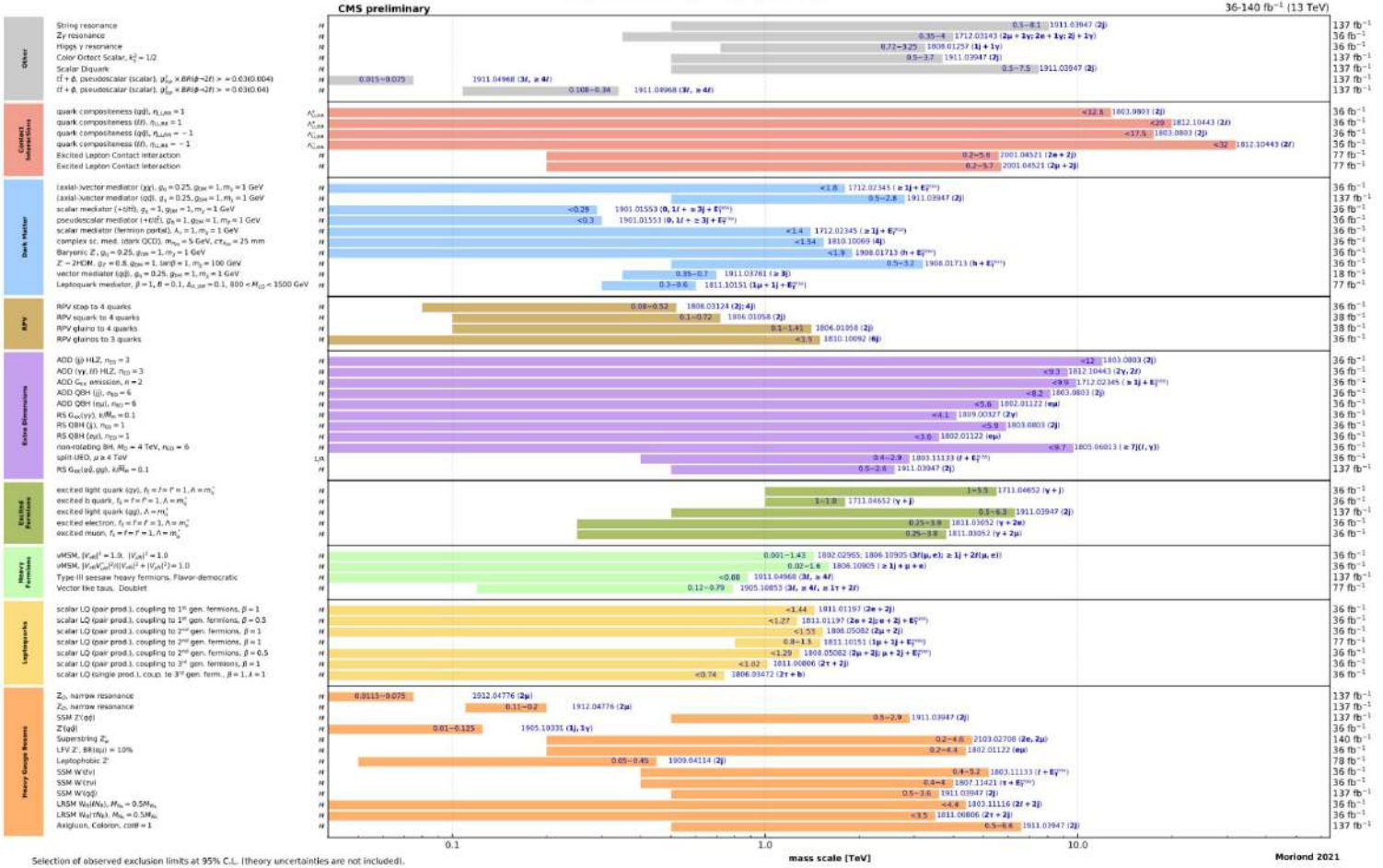

all-hadronic




all-hadronic + single-lepton

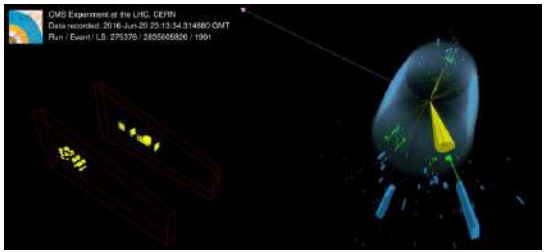

Exotica

# Exotica Results

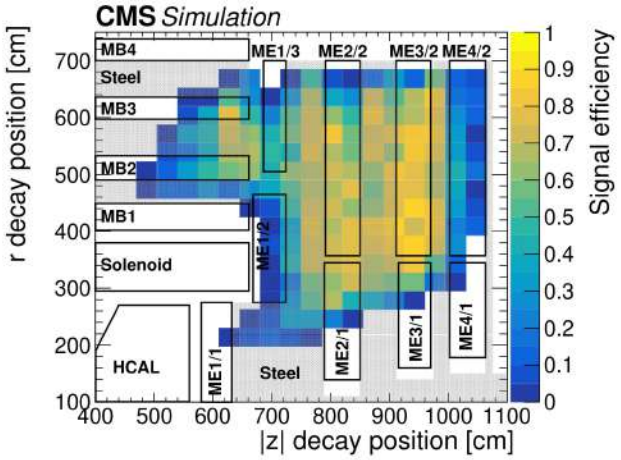


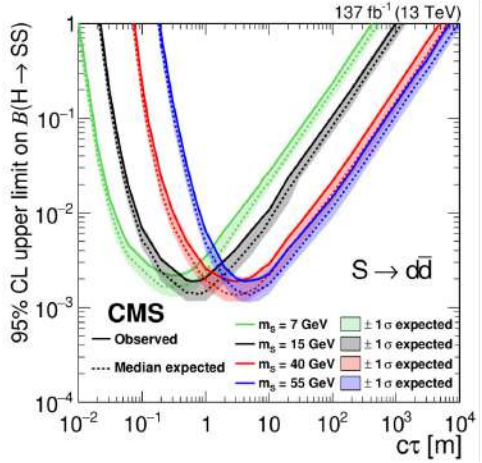
# Search for long-lived particles decaying in CMS Muon Endcap

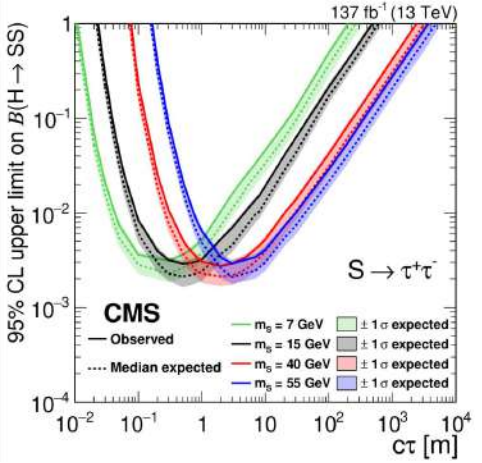
[EXO-20-015] [*Accepted for publication in Phys. Rev. Lett.*]



- Higgs decaying to two neutral long lived scalars
  - Each decaying to a pair of b-quarks, d-quarks or tau leptons
  - Most stringent limits to date on BR(Higgs→SS→uu/dd/$\tau\tau$)
- Novel reconstruction technique: CMS endcap muon detectors as calorimeter
  - Hits in the CSC are clustered using the DBScan algorithm
  - Method validated using Z events where one muon undergoes bremsstrahlung in the Endcap Muon Detector and the photon produces an EM shower



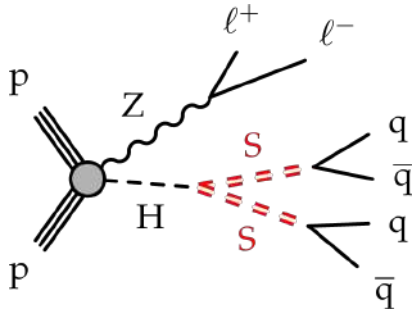



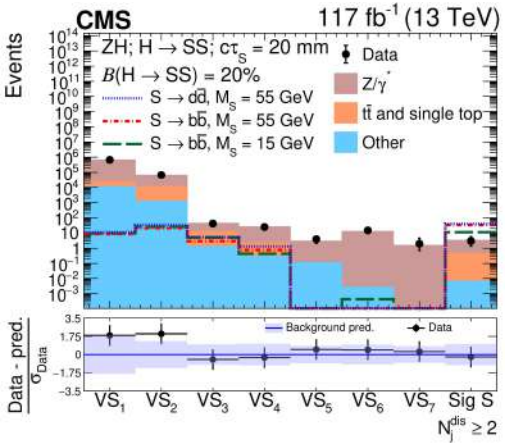



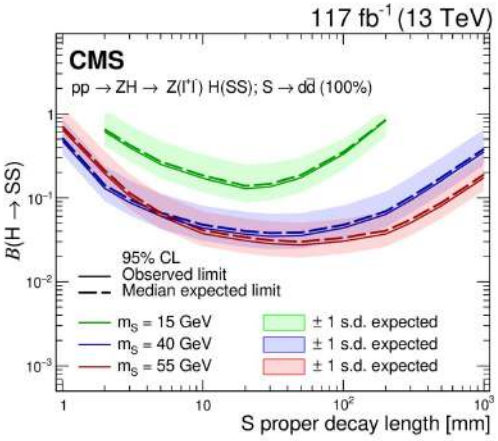
# Search for H→long-lived particles in associated Z boson production

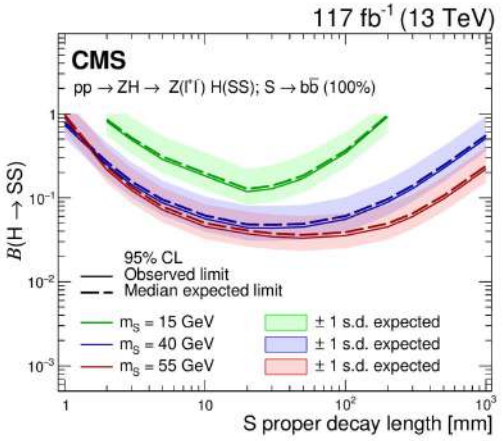
[EXO-20-003] [*Submitted to J. High Energy Phys.*]

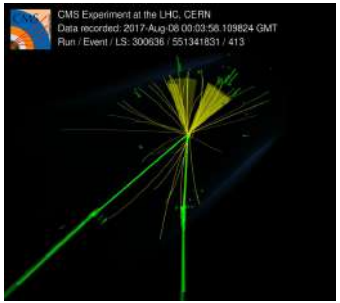
- Search for long-lived particles (LLP) pairs decaying into jets, with associated Z production
  - At least two displaced jets (3 tracking-based displacement variables)
  - Both light (d) and heavy (b) jets are considered
- Benchmark model: Higgs decay to a pair of scalar LLPs
  - Probing decay lengths from 1 mm to 1 m

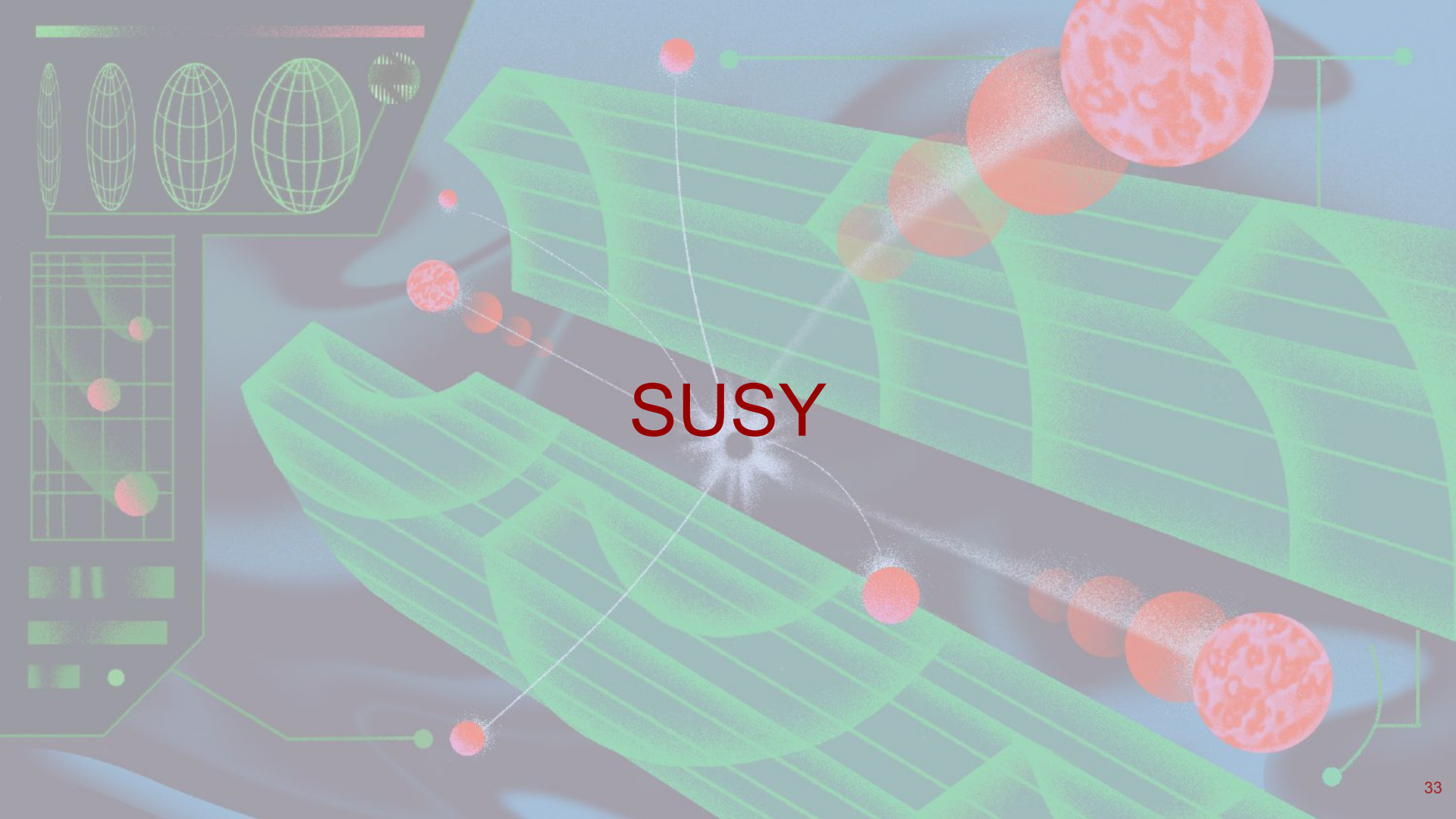


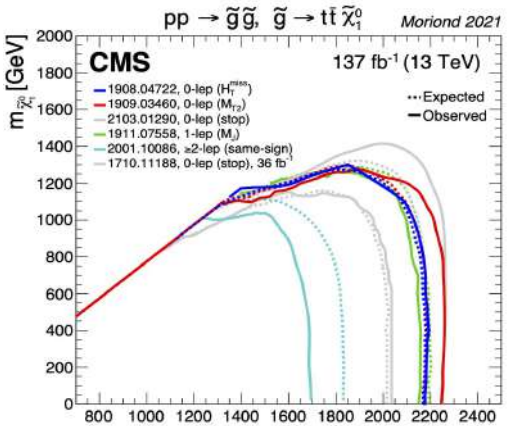



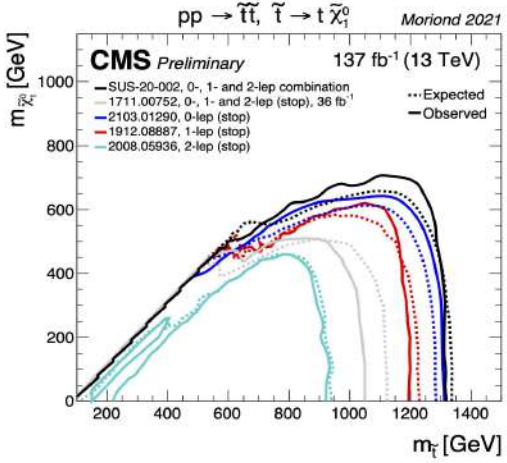



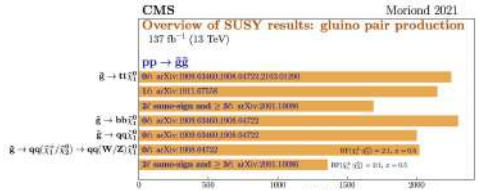



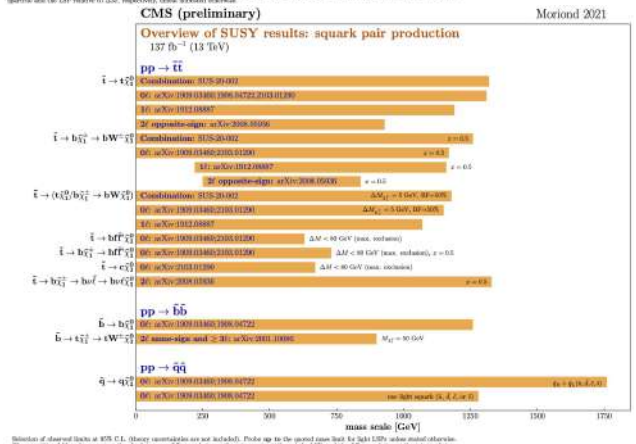

SUSY

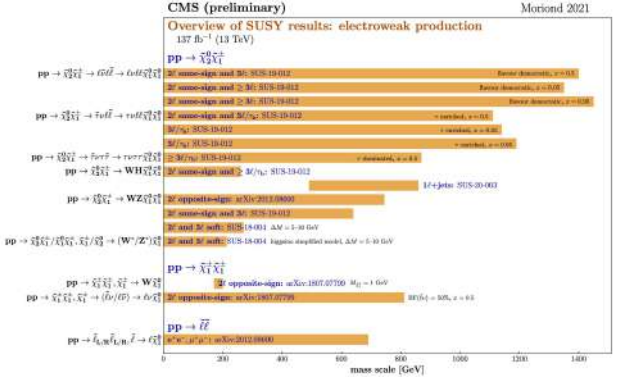
# SUSY Results

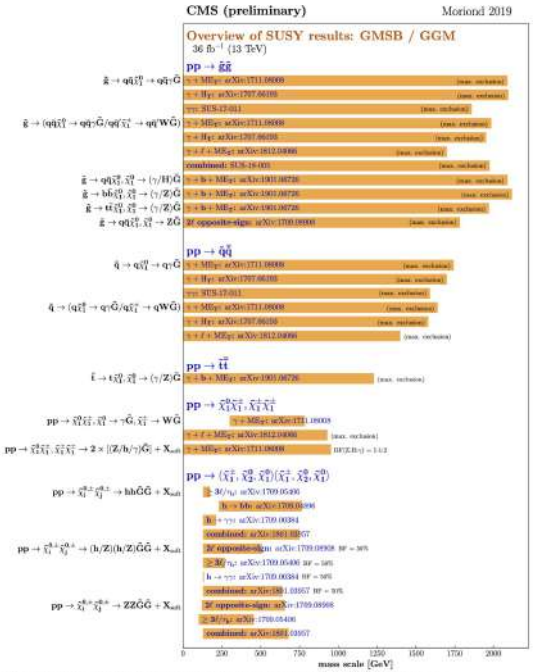


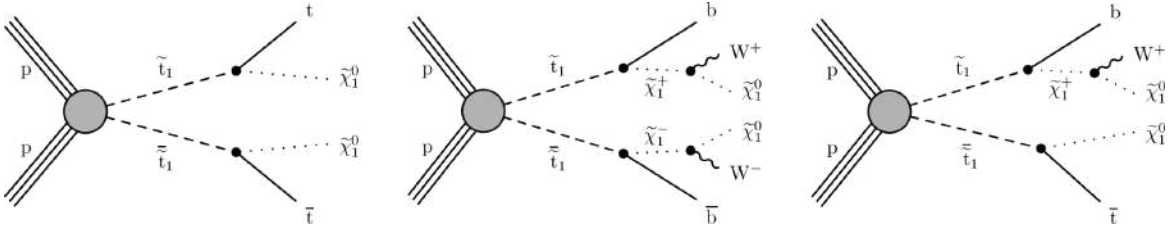



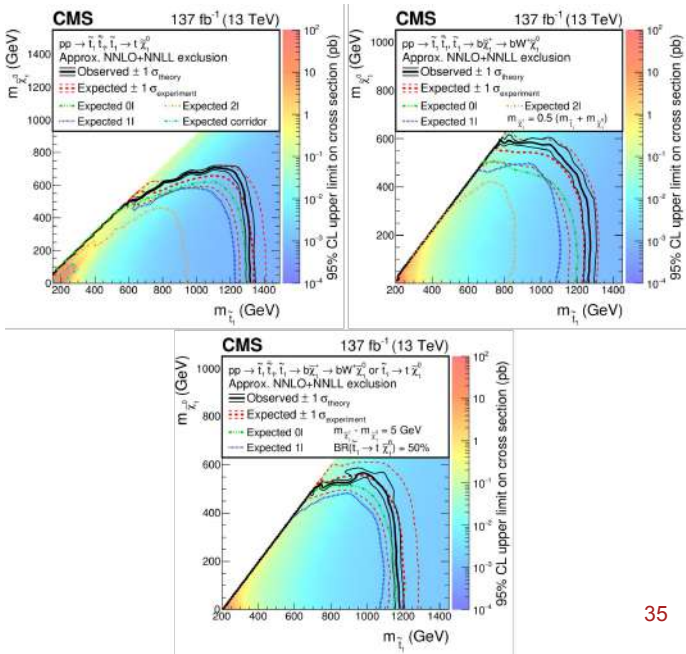



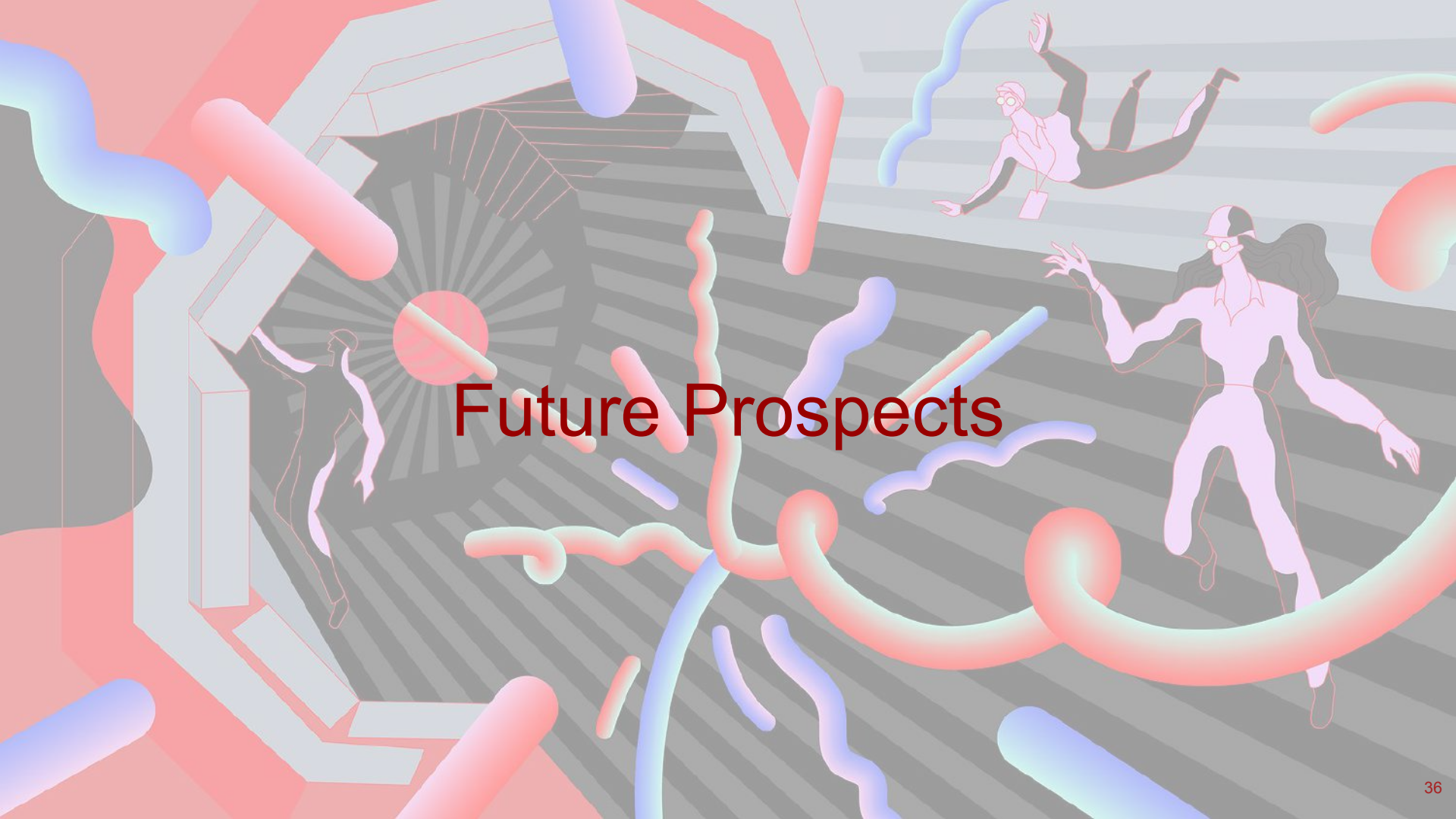
# Top Squark in Compressed Spectra

[SUS-20-002] [*Accepted for publication in Eur. Phys. J. C*]

- Compressed spectra where SUSY mass differences are small (~GeV)
- Signatures with ≥ 2 jets and large $E^{T}_{miss}$
  - Categorized into events with 0, 1, 2 leptons
- Deep neural network algorithm used to separate signal from background
- Includes dark matter interpretation
  - Via a spin-0 mediator in association top pair

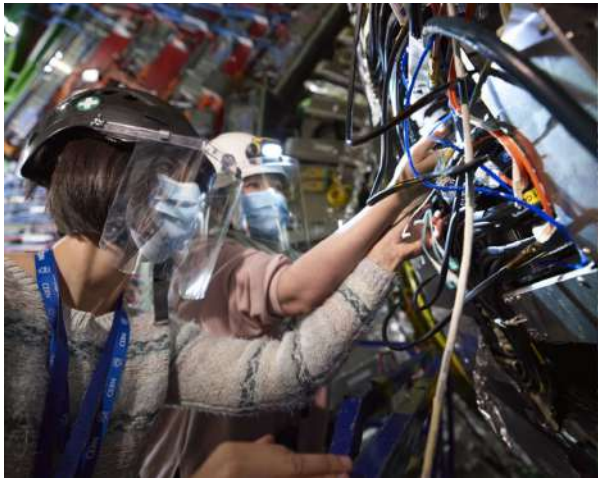



Future Prospects

# CMS LS2 activities

- New beam pipe installed (Phase-2 design)
- Phase-1 pixel re-installed (new layer 1 and DCDC)
- Rebuilt BRIL luminosity sub-detectors installed
- HCAL Phase-1 readout upgrade completed
- New GEM subsystem (GE1/1 chambers installed)

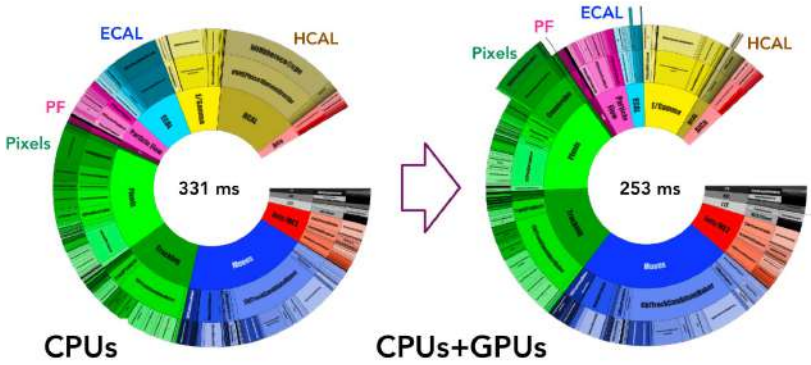


# Run 3 preparation

- LHC test/pilot beams program just completed
  - Full detector, including Run 3 upgrades, exercised during stable beams
- DAQ/Trigger/HLT upgrades
  - Heterogeneous architecture (CPU/GPU) in High Level Trigger
    - New possibilities for trigger algorithms leveraging GPUs
    - Testbed for HL-LHC Computing and triggering
  - Increase in data scouting and data parking
  - Dedicated and improved long-lived particle triggers

| Mode | GPDs | LHCb | ALICE |
|---|---|---|---|
| p-p | 160/fb | 25-30/fb (~50/fb by LS4) | 200/pb |
| Pb-Pb | 6/nb (13/nb by LS4) | 1/nb (2/nb by LS4) | 6/nb (13/nb by LS4) |
| p-Pb | 0.5/pb (~1.2/pb by LS4) | 0.1/pb (~0.6/pb by LS4) | 0.25/pb (~0.6/pb by LS4) |
| O-O | 0.5/nb | 0.5/nb | 0.5/nb |
| p-O | LHCf 1.5/nb | 0.1/pb | |

Run 3 Luminosity Targets

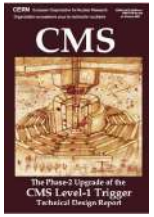


# High Luminosity LHC (HL-LHC)


[High Luminosity LHC Project]

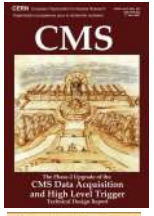
# CMS Phase-2 Upgrades

[CMS TDRs]



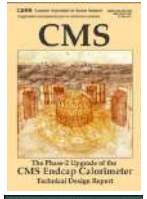

## L1-Trigger

* Tracks in L1-Trigger at 40 MHz
* PFlow selection 750 kHz L1 output



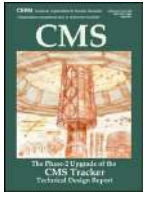

## DAQ/HLT

* HLT output: 7.5 kHz
* 40 MHz data scouting



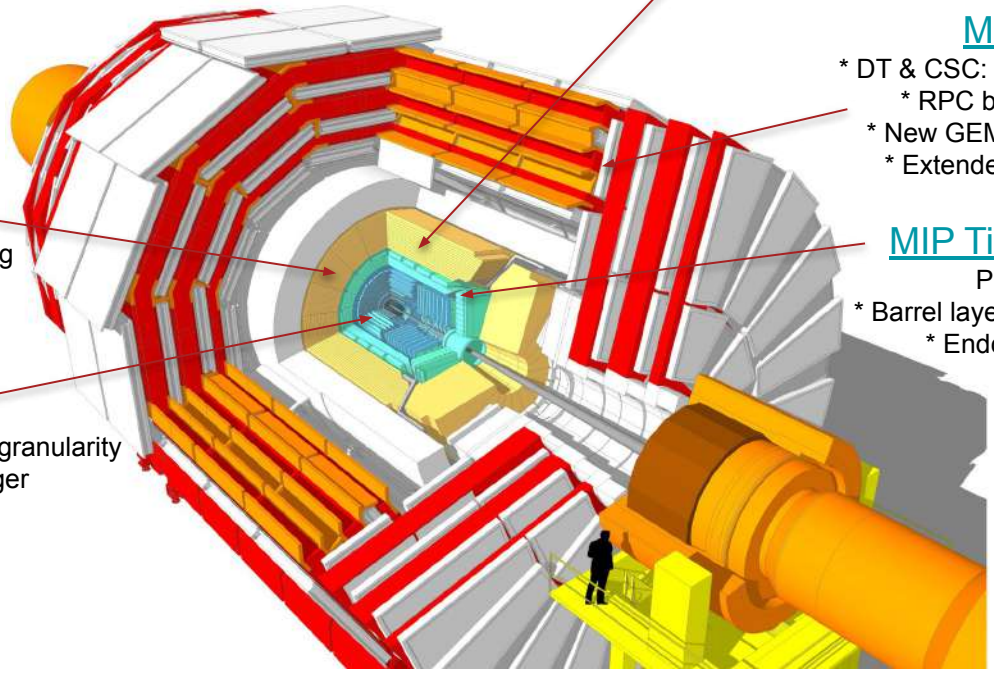

## Endcap Calorimeter

* 3D showers and precise timing
* Si, Scint+SiPM in Pb/W-SS



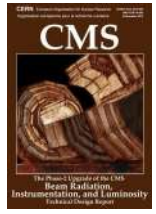

## Tracker

* Si-Strip and Pixels increased granularity
* Design for tracking in L1-Trigger
* Extended coverage to η ≈ 3.8



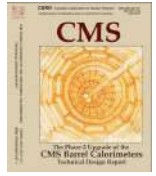
## Beam Radiation Instr. and Luminosity

* Bunch-by-bunch luminosity measurement:
  1% offline
  2% online



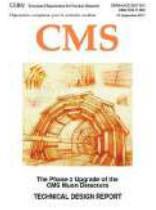

## Barrel Calorimeters

* ECAL crystal granularity readout at 40 MHz with precise timing for e/$\gamma$ at 30 GeV
* ECAL and HCAL new Back-End boards



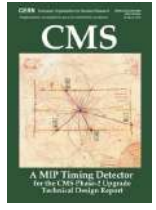

## Muon Detectors

* DT & CSC: new FE/BE readout
* RPC back-end electronics
* New GEM/RPC 1.6 < η < 2.4
* Extended coverage to η ≈ 3




## MIP Timing Detector

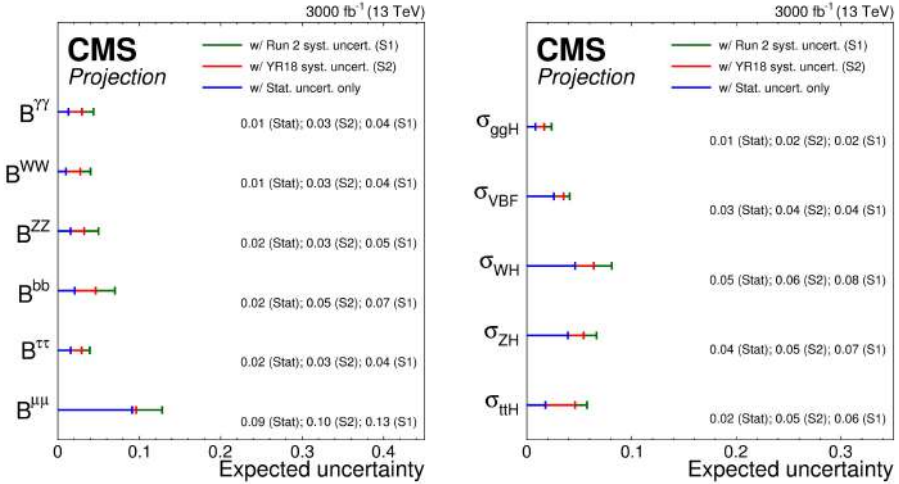
Precision timing with:
* Barrel layer: Crystals + SiPMs
* Endcap layer: Low Gain Avalanche Diodes



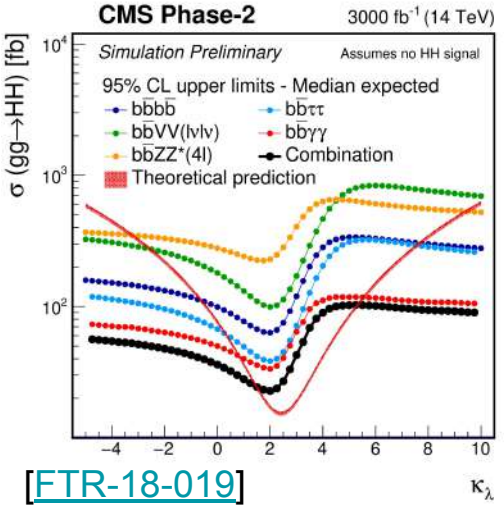
# Higgs Prospects at HL-LHC

[FTR-18-011] [FTR-18-019]

- HL-LHC facilitates precision Higgs coupling measurements
  - Couplings (except rarest) constrained to <10% level
  - Direct access to Higgs potential shape and $\kappa_\lambda$ sensitive to BSM physics
- Observing di-Higgs production is a flagship measurement
  - Expect to achieve 3σ observation significance from combination of channels
  - Expected ~10% improvement in b-tagging efficiency from new tracker



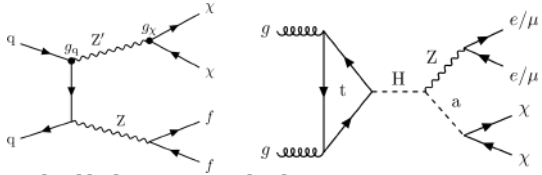

[FTR-18-011]



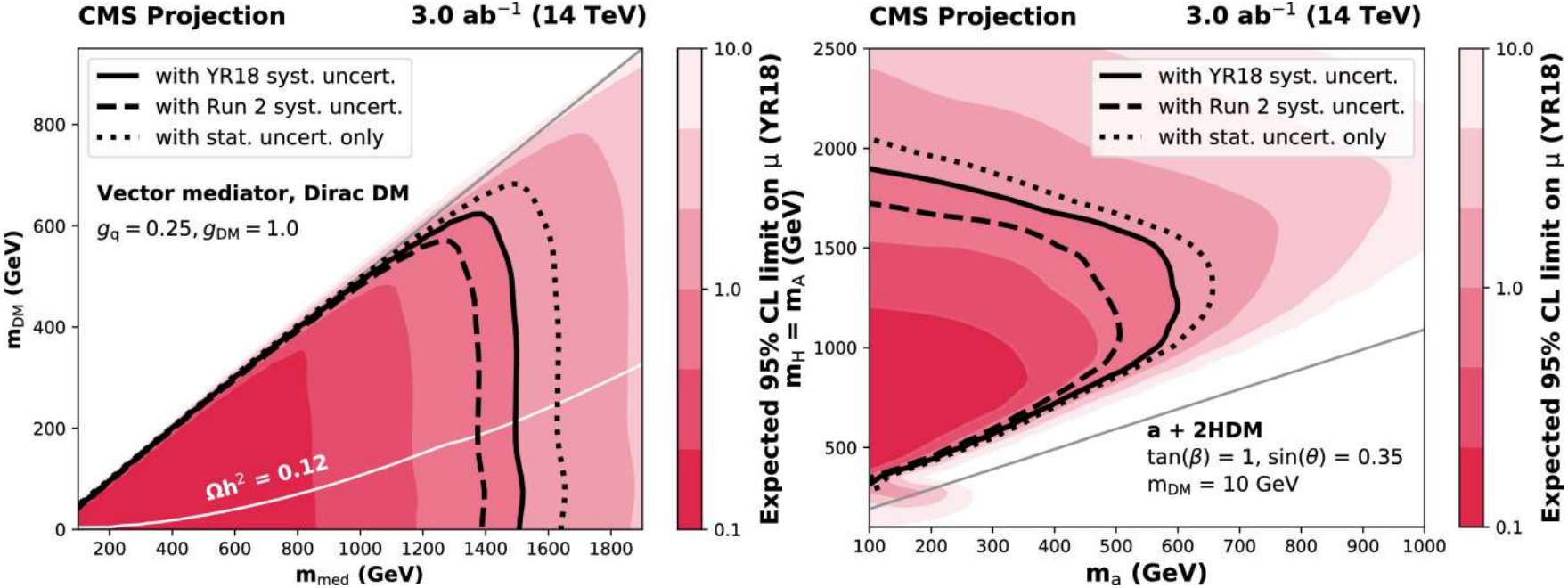

[FTR-18-019]

# Mono-Z search for dark matter at HL-LHC

[FTR-18-007]



- Expected sensitivity and exclusion in searches for new invisible particles
  - Push sensitivity to large DM mass and push down in couplings
  - Extends sensitivity of mediator masses by ~ factor of 2 relative to current LHC results



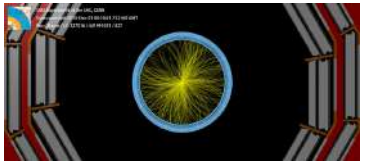
# Summary and Conclusions

- LHC and CMS performing very well and preparing for Run 3 & beyond
- Wealth of results from Run 2 dataset
  - Higgs consistent with Standard Model predictions
  - No signs of new physics yet
- Run 3 upgrades installed and tested
  - Ready for data-taking in 2022
- The High-Luminosity LHC era will provide an unprecedented dataset
  - All CMS Technical Design Reports prepared
  - Further characterize the SM and expand the search for new particles and interactions

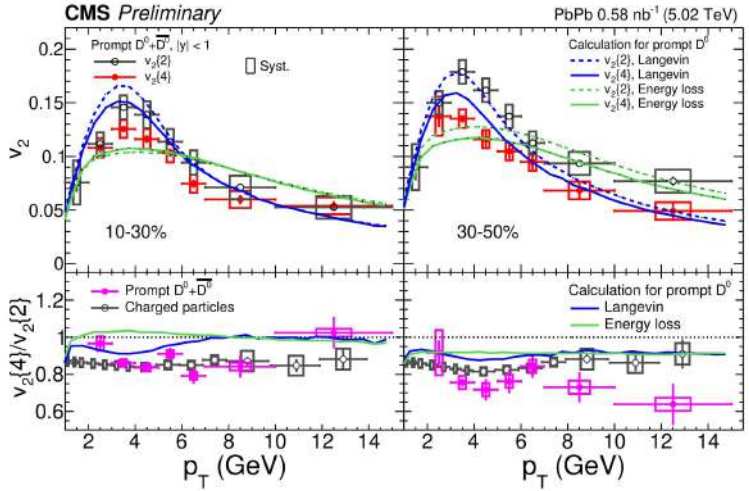
# Backup

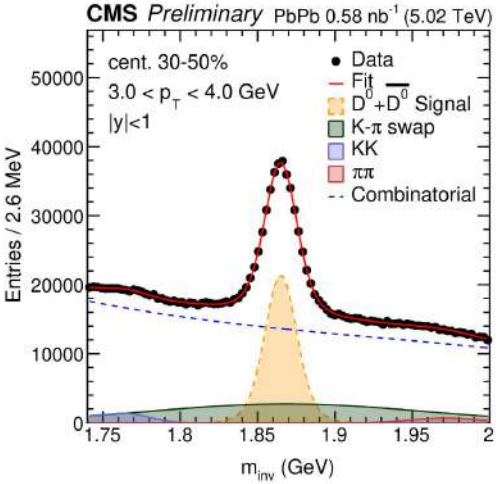
# Probing charm dynamics in 5.02 TeV PbPb

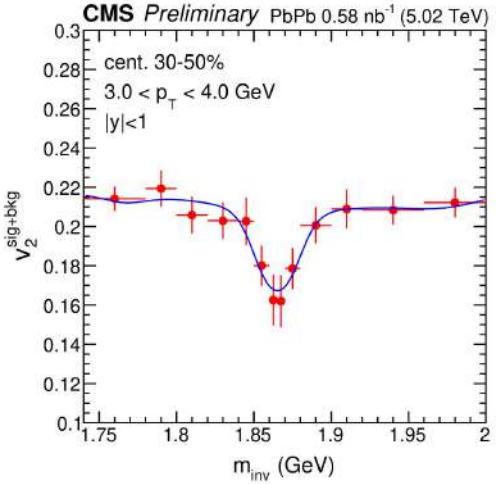
[HIN-20-001]



- Measure multiparticle (4) azimuthal correlations of prompt $D^0$ mesons
  - Elliptic flow of $D^0$ mesons extracted using a four-particle cumulant method, as a function of $D^0$ transverse momentum and centrality
  - The prompt $D^0$ meson *v2* ratios using four- and previous two-particle cumulant methods are below unity and comparable to those of charged particles



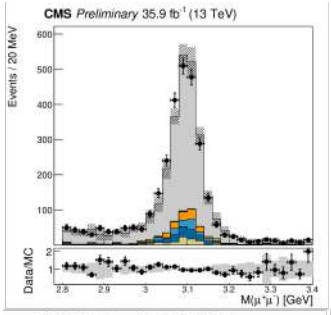



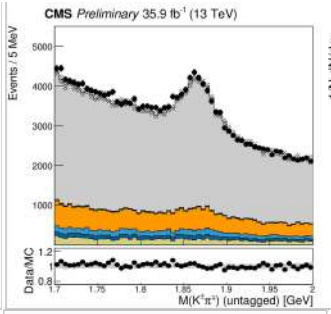



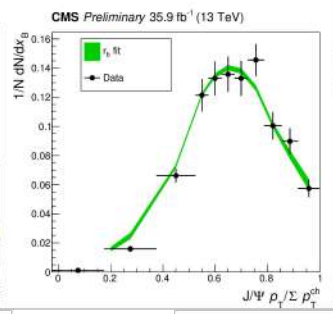
# Measurement of b quark fragmentation using charmed mesons

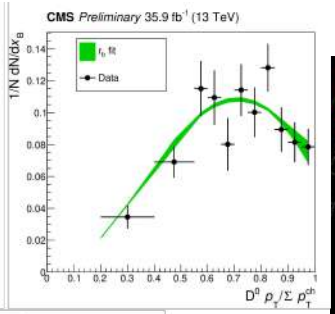
[TOP-18-012]

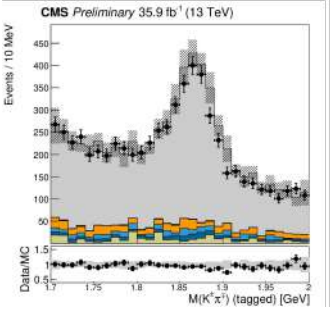
- First measurement of b quark fragmentation function in ttbar events at LHC
- Charm mesons produced inside b jets from tt pairs
  - Used to determine the shape parameter of the Lund-Bowler fragmentation function
- Significantly improves experimental constraints on shape of the function

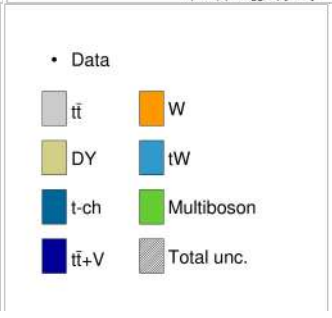


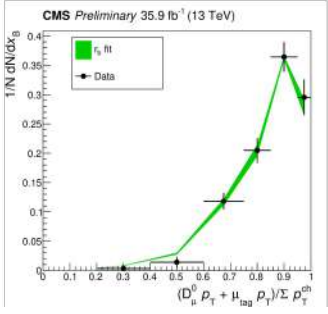



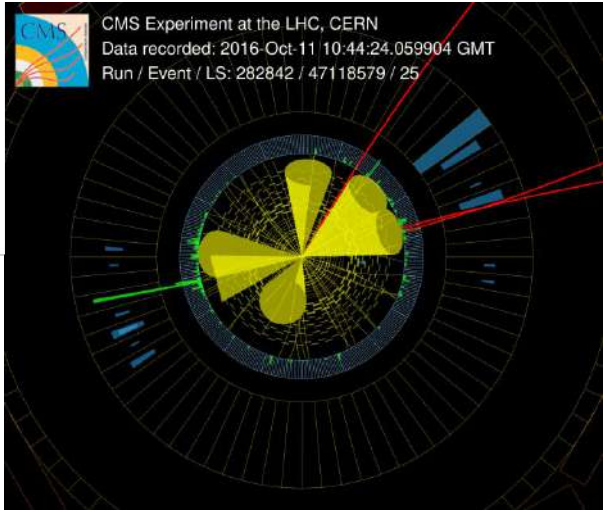



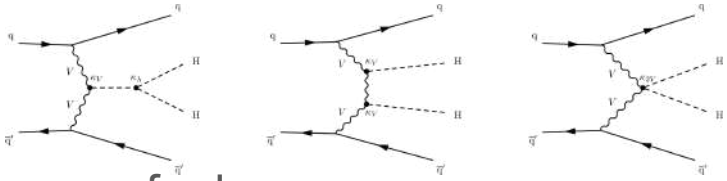



# VBF HH→4b boosted

[B2G-21-001]



- BSM VBF HH cross section can dramatically increase for large $m_{HH}$
- First test of the VVHH coupling in boosted topology
  - Multivariate GNN classifier (ParticleNet) applied to identify H→b-jet decays
- Limits set for for a range of signal hypotheses of different $\kappa_{2V}$ and $\kappa_V$ couplings
  - $0.6 < \kappa_{2V} < 1.4$ (for $\kappa_V = \kappa_\lambda = 1$)