

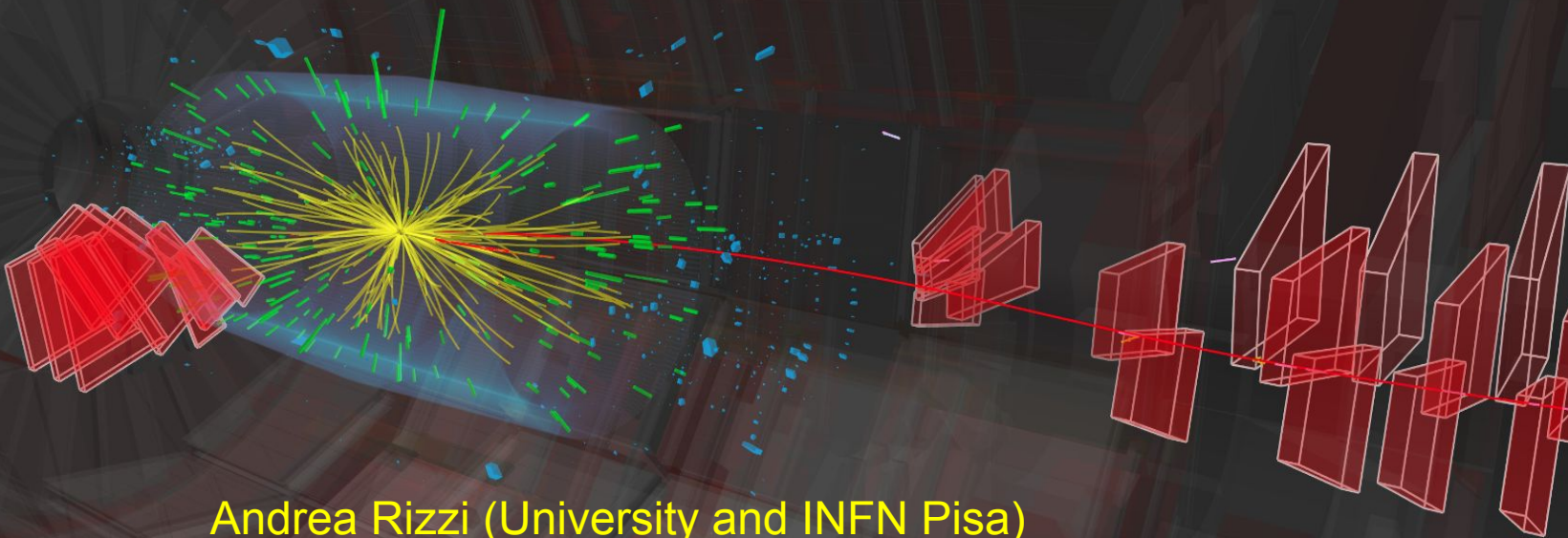


CMS Experiment at the LHC, CERN

Data recorded: 2022-Jul-05 14:48:56.743936 GMT

Run / Event / LS: 355100 / 51596902 / 53

CMS Highlights



Andrea Rizzi (University and INFN Pisa)
on behalf of the CMS Collaboration

CMS@ICHEP

85 parallel talks
28 posters

ICHEP, Bologna, July 11th, 2022



Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI PISA

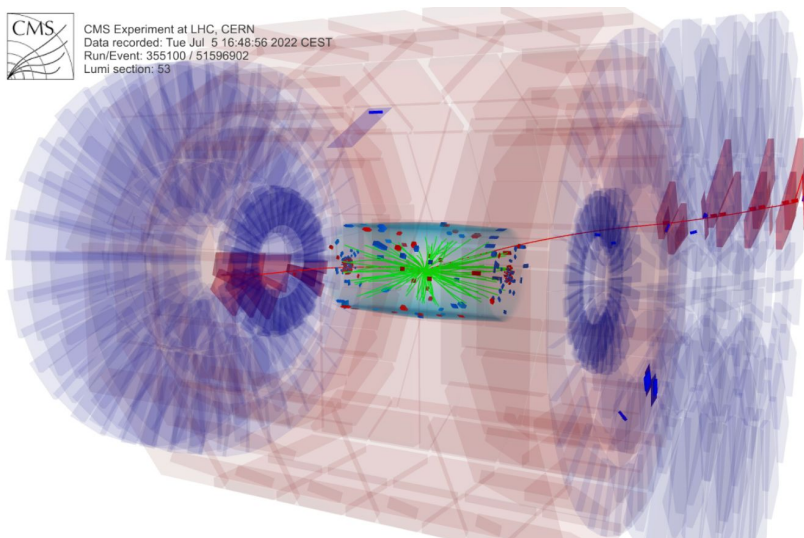
Outline



- CMS Status and Run-3 startup
- Highlights from recent physics results
- Future prospects

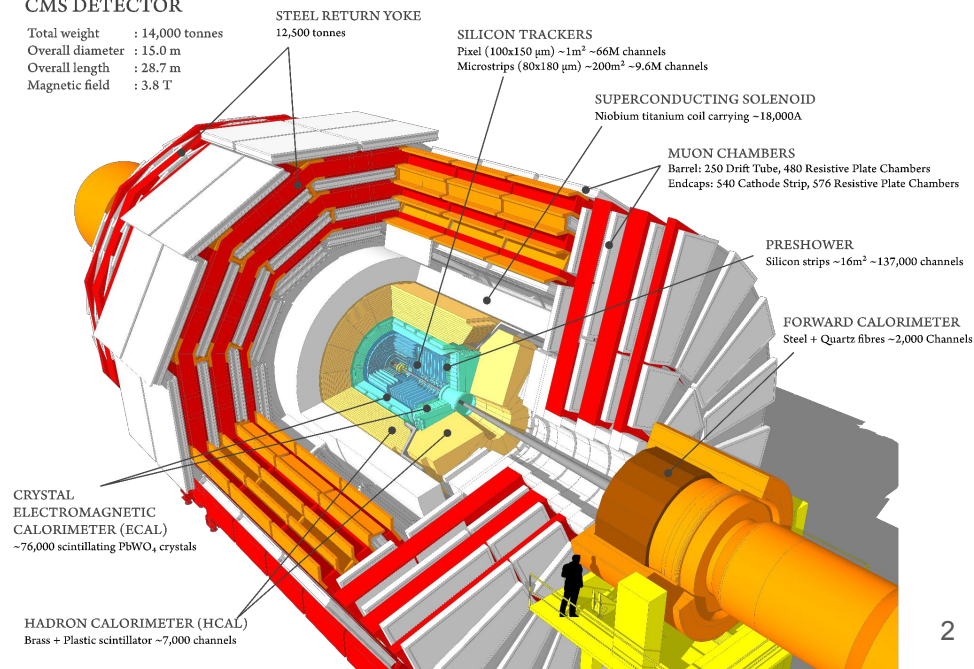


CMS Experiment at LHC, CERN
Data recorded: Tue Jul 5 16:48:56 2022 CEST
Run/Event: 355100 / 51596902
Lumi section: 53



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



What's new since Run-2



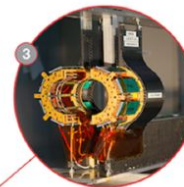
BEAM PIPE

Replaced with an entirely new one compatible with the future tracker upgrade for HL-LHC, improving the vacuum and reducing activation.



PIXEL TRACKER

All-new innermost barrel pixel layer, in addition to maintenance and repair work and other upgrades.



BRIL

New generation of detectors for monitoring LHC beam conditions and luminosity.



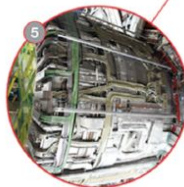
CATHODE STRIP CHAMBERS (CSC)

Read-out electronics upgraded on all the 180 CSC muon chambers allowing performance to be maintained in HL-LHC conditions.



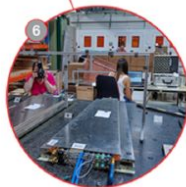
HADRON CALORIMETER

New on-detector electronics installed to reduce noise and improve energy measurement in the calorimeter.



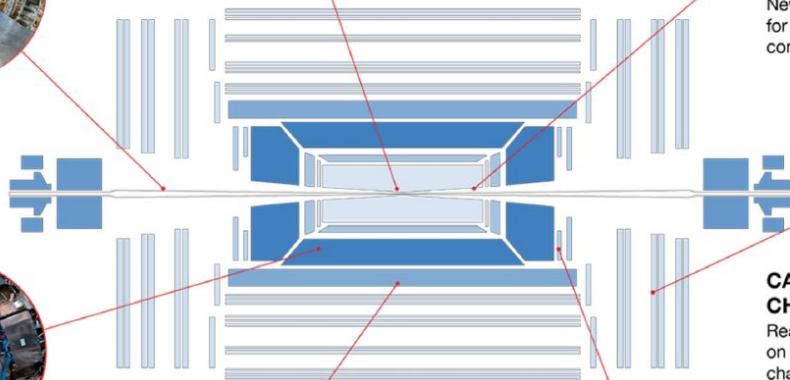
SOLENOID MAGNET

New powering system to prevent full power cycles in the event of powering problems, saving valuable time for physics during collisions and extending the magnet lifetime.

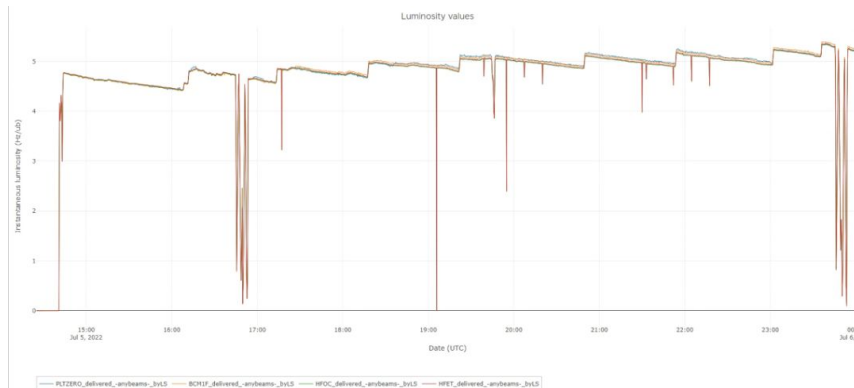
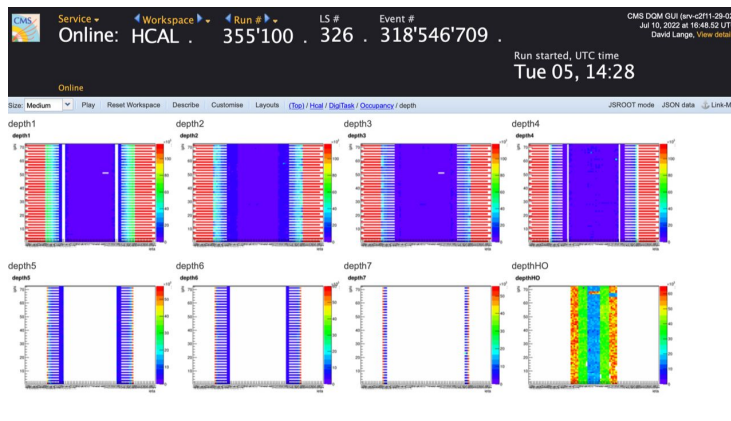
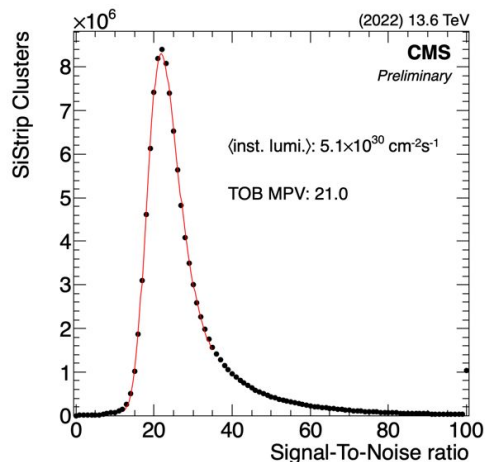
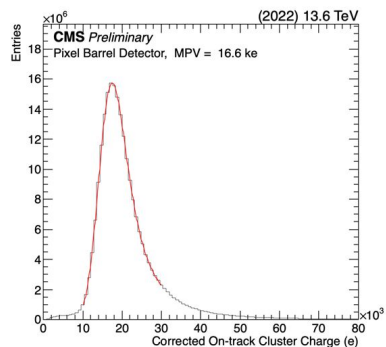


GAS ELECTRON MULTIPLIER (GEM) DETECTORS

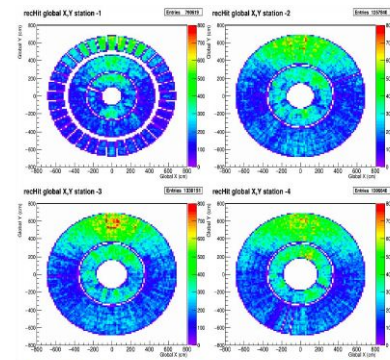
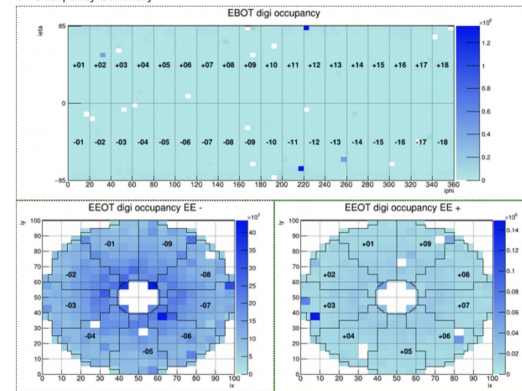
An entire new station of detectors installed in the endcap-muon system to provide precise muon tracking despite higher particle rates of HL-LHC.



Run-3: all systems go

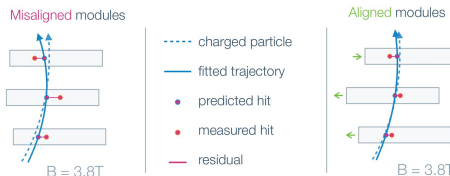
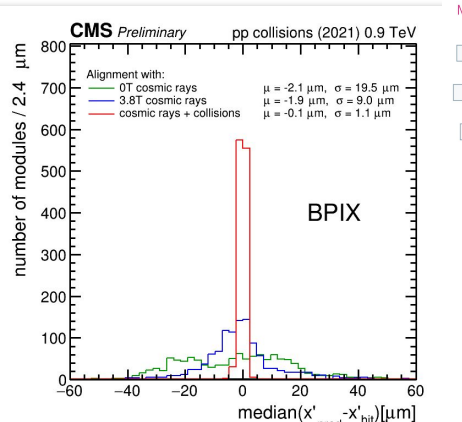
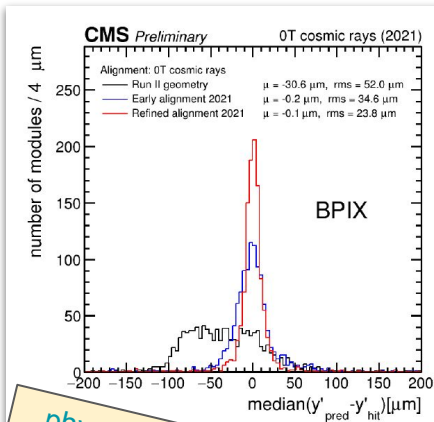


01 Occupancy Summary



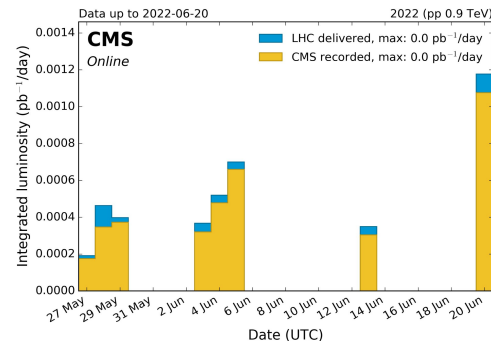
Cathode Strip Chamber (CSC)
rechit occupancy

Run 3: first beams, first physics

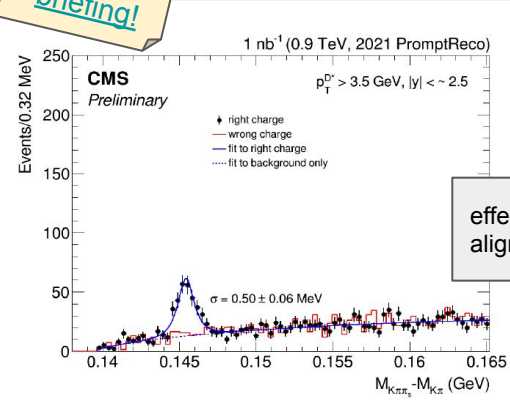


Detector alignment with
cosmics and early 900
GeV collisions

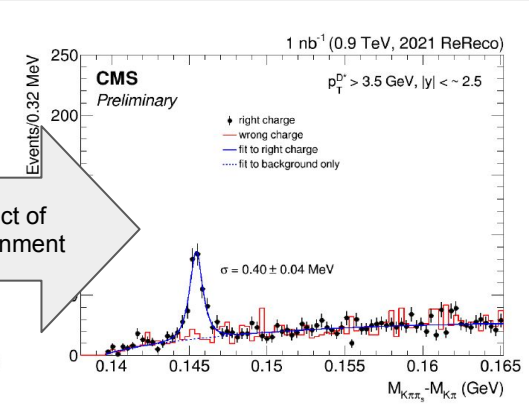
Run3 luminosity
measurement



physics
briefing!



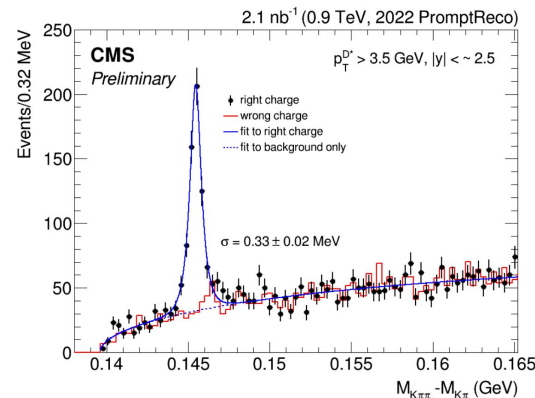
effect of
alignment



Reconstruction
of D^* peak in

$$D^* \rightarrow D^0 \pi_s$$

$$\downarrow K\pi$$

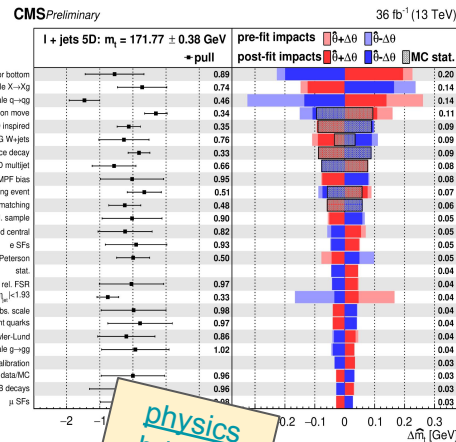
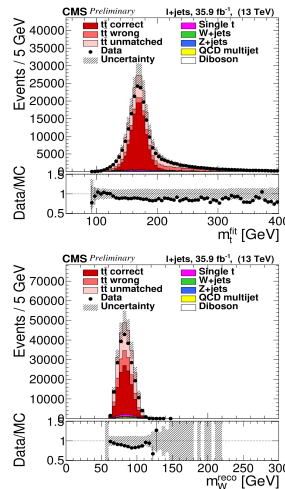


Physics Highlights (from Run-2)

Precisely measuring “all” top masses

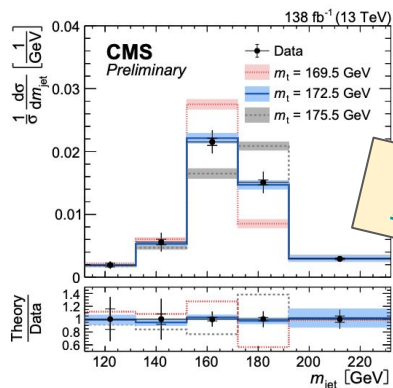


- Direct measurement with **5D fit** constraining jet uncertainty from **W peak**
 - $m_t = 171.77 \pm 0.38 \text{ GeV}$
- Measurement from **tt+jet cross section**
 - $m_t^{\text{pole}} = 172.94 \pm 1.37 \text{ GeV}$
- Measurement of **mass distribution** and m_t in hadronic decay to **boosted jets**
 - $m_t = 172.76 \pm 0.81 \text{ GeV}$



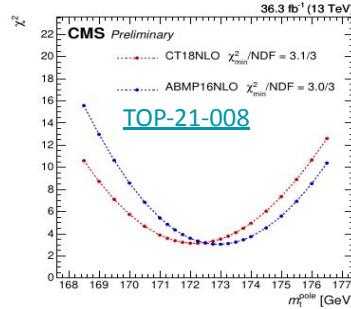
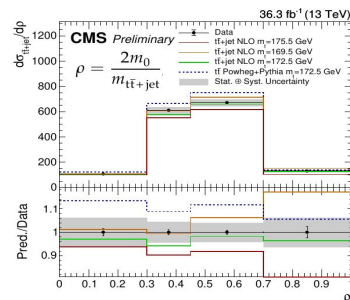
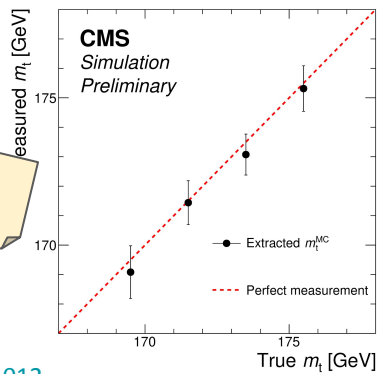
TOP-20-008

physics briefing!



physics briefing!

TOP-21-012



Ten years since Higgs boson discovery



nature

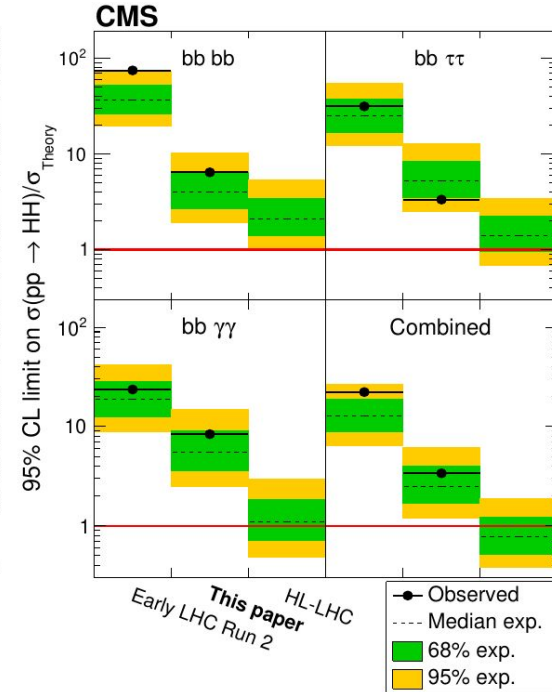
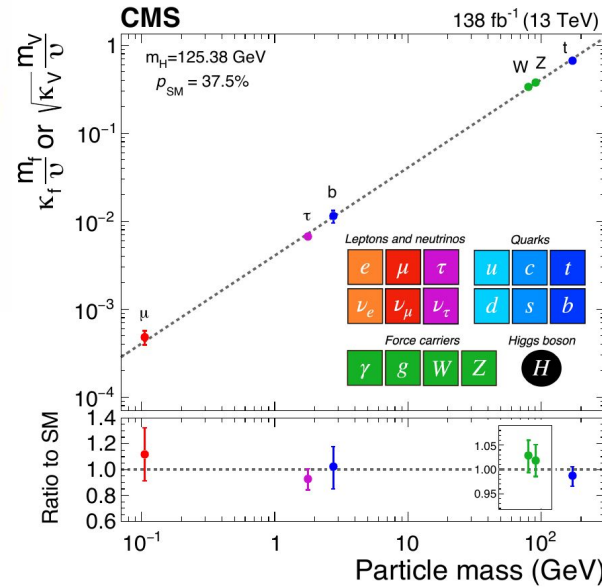
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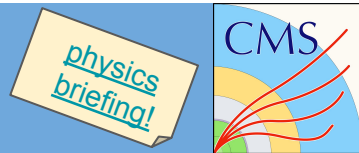
A portrait of the Higgs boson by the CMS experiment ten years after the discovery

The CMS Collaboration

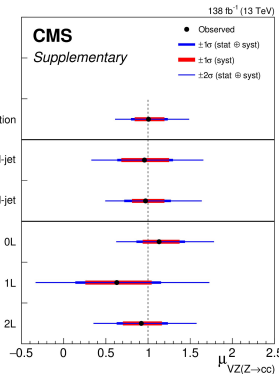
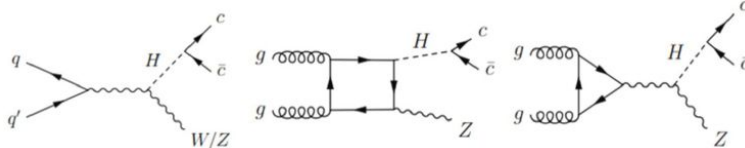
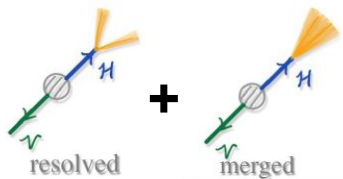


- Combination of multiple results fitting for *coupling modifiers*
- **Combination of HH** results for the three most sensitive channels (4b, 2b2 τ , 2b2 γ)
 - Reaching ~3x SM sensitivity, expect SM sensitivity with HL-LHC
- See our Nature paper for more details and **Chiara's talk tomorrow**

Higgs coupling to charm



- Coupling to charm is **extremely challenging** to be measured at SM value
- CMS developed **new charm tagging techniques** for resolved and boosted jets
- current analyses (**VH** and boosted-**ggH**) sensitive to NP that would increase the coupling to charm (**$\sim 10\times$ SM sensitivity**)
- Calibration candle is the **$Z \rightarrow c\bar{c}$** decay

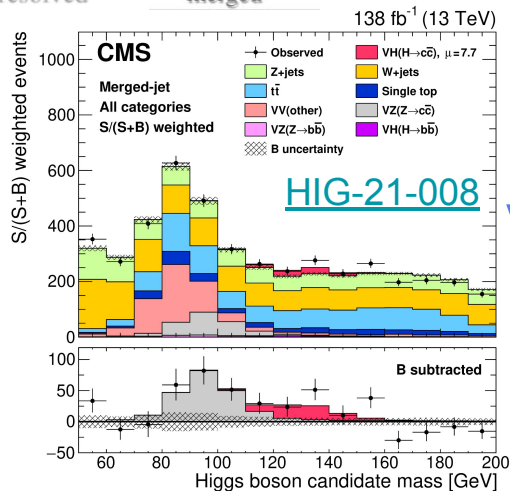


Bonus:

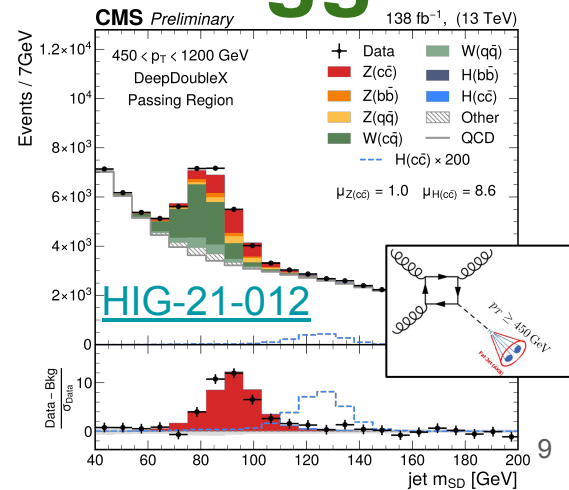
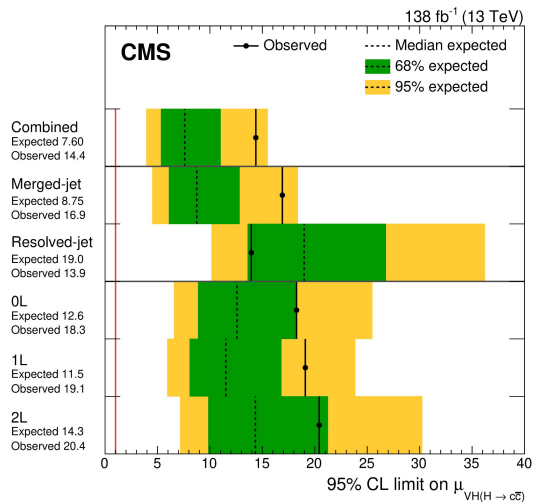
Both analyses observed the $Z \rightarrow c\bar{c}$ decay with $> 5\sigma$

gg→gZ(cc):
 $\mu_Z = 0.91^{+0.18}_{-0.15}$ (exp.) ± 0.7 (th.) ± 0.05 (stat.)

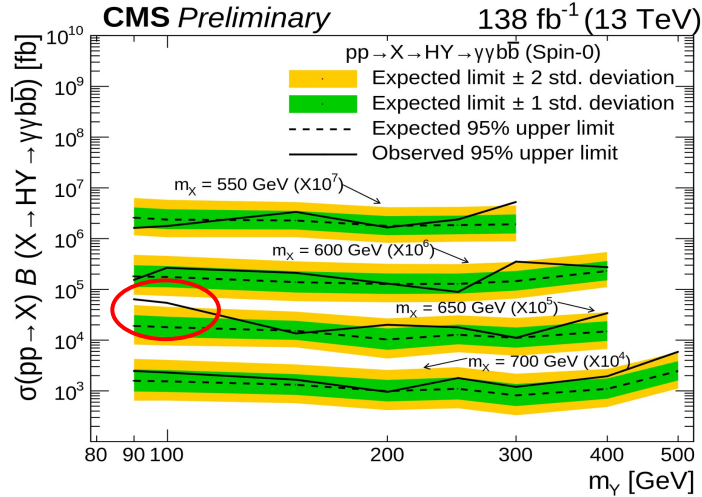
ggH



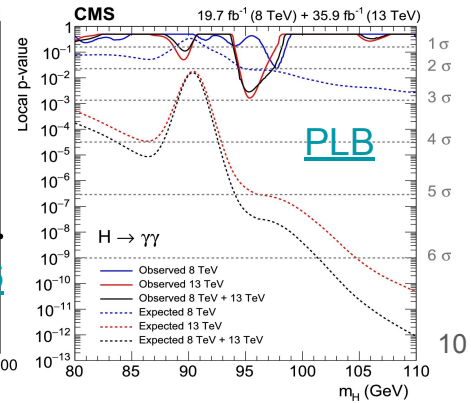
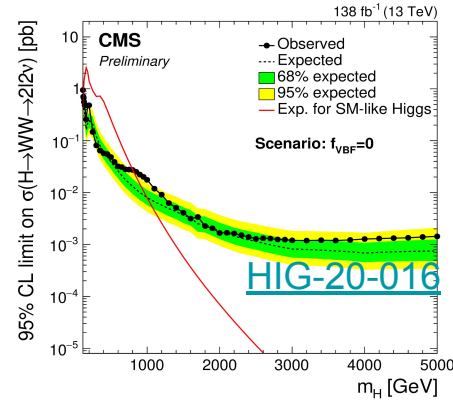
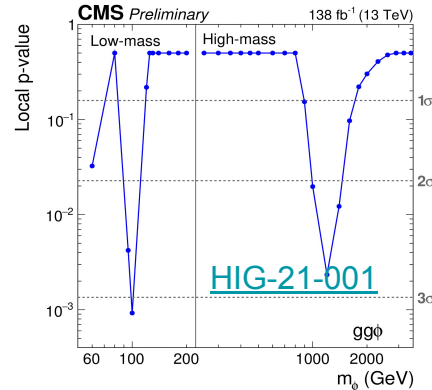
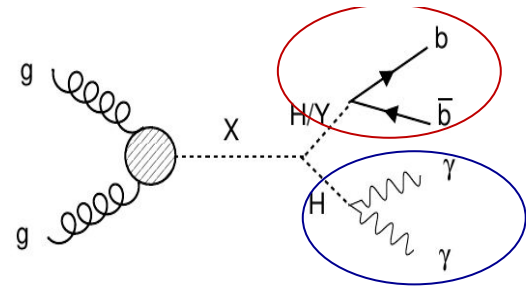
VH



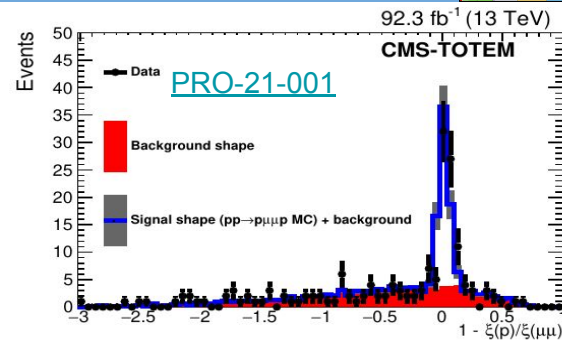
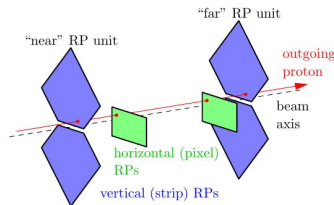
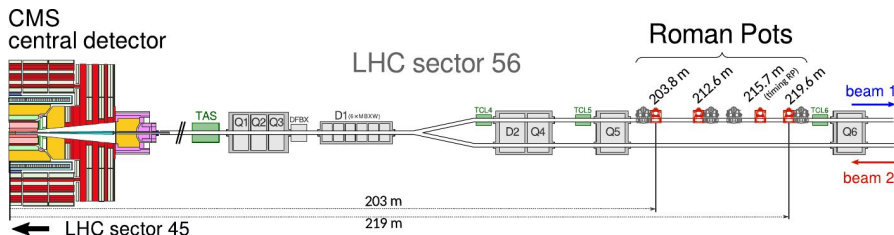
New physics searches with Higgs



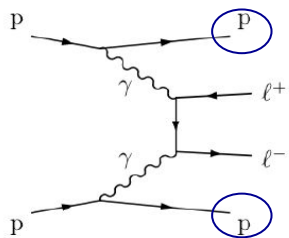
- Search for resonances (X) decaying to $H/Y(bb)H(\gamma\gamma)$
- Excess at (125,90) with 650 GeV heavy resonance mass**
 - 3.8 σ local, 2.8 σ global
- Interesting pair of numbers (caveat: cherry picking here, do not attempt back of the envelope combinations)
 - $H \rightarrow \tau\tau$ 90-100 GeV excess: 3.1 σ local, 2.7 σ global
 - $H \rightarrow WW$ 650 GeV excess: 3.8 σ local, 2.6 σ global
 - $H \rightarrow \gamma\gamma$ 95 GeV excess: 2.8 σ local, 1.3 σ global
- Stay tuned for more Run-2 and Run-3 analyses



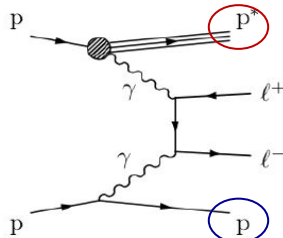
Exploiting the Precision Proton Spectrometer



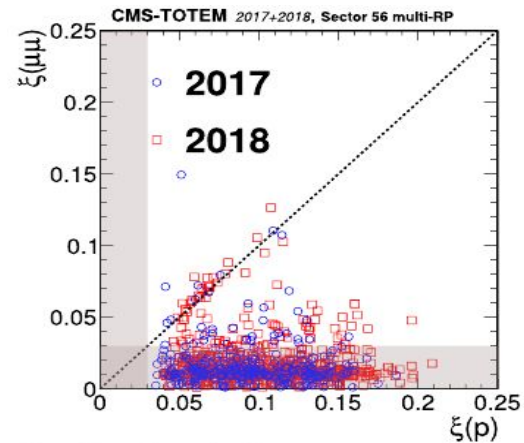
- One or both protons can survive intact after an LHC interaction
- Deviation from LHC orbit allows to measurement momentum loss
- Knowing proton momentum allows to close the event kinematics
- Paper on calibration of the PPS (timing and alignment) recently published by CMS and TOTEM collaborations
- Physics calibration comparing di-lepton events independent reconstruction via PPS and in the central CMS detector



Both protons remaining intact

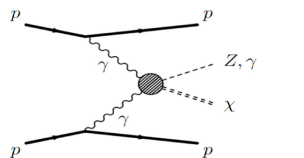


only one proton remaining intact

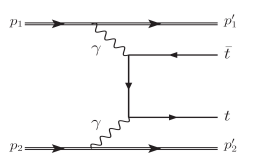
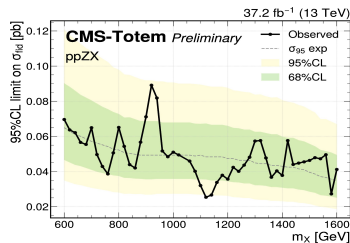


$$\tilde{\xi} = (p_{\text{nom}} - p) / p_{\text{nom}}$$

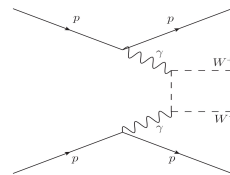
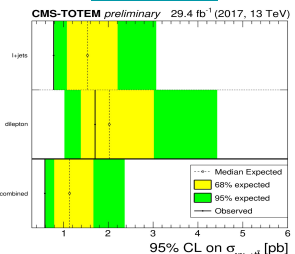
LHC: the Large pHoton Collider



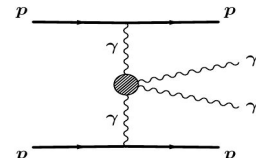
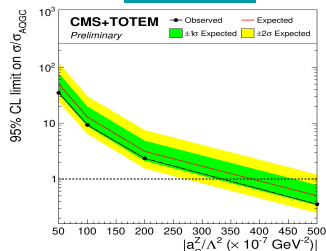
EXO-19-009



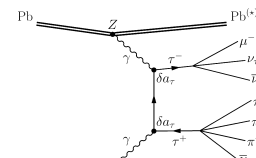
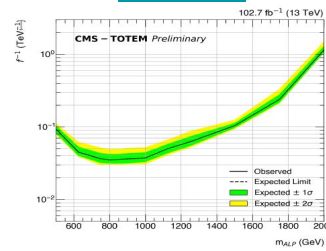
TOP-21-007



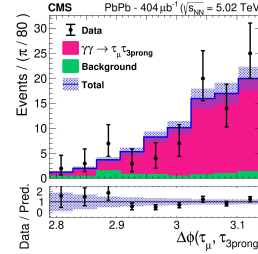
SMP-21-014



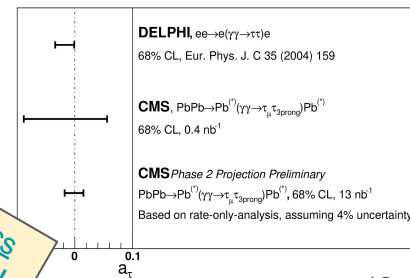
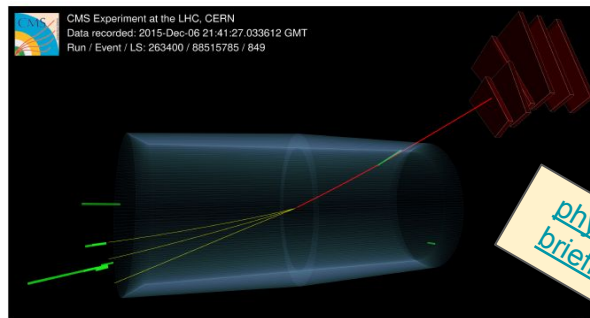
EXO-21-007



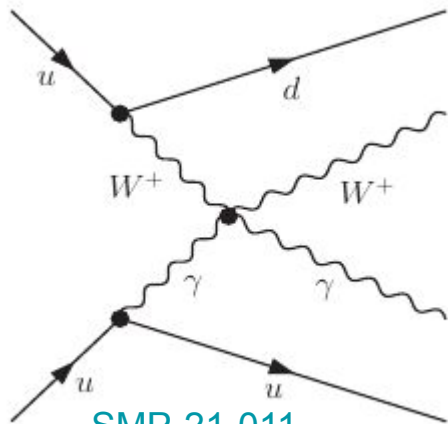
HIN-21-009



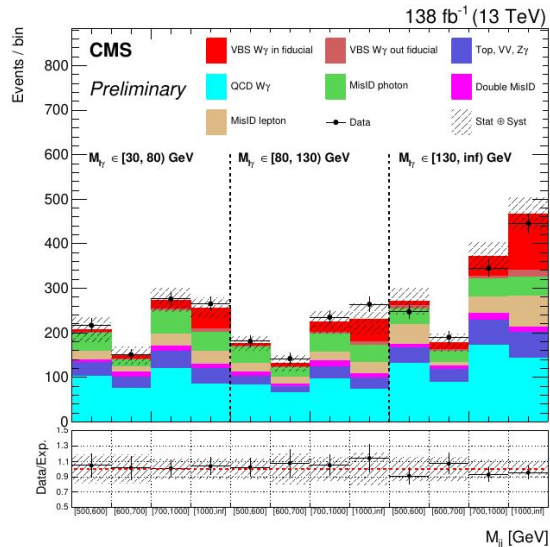
- Exploiting PPS or Heavy Ion runs we can use LHC as a **photon-photon collider**!
- Multiple results from direct search for new physics to limits on anomalous couplings obtained with this techniques in the past months



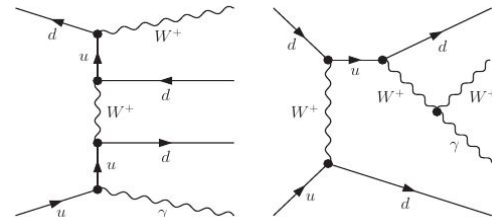
LHC: the Large gauge Bosons Collider



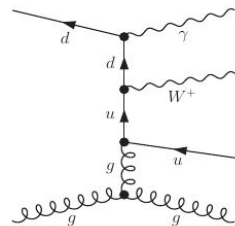
[SMP-21-011](#)



Other EWK processes



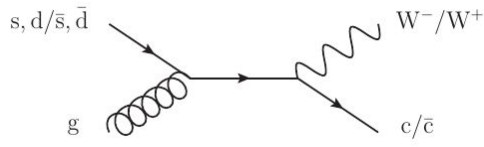
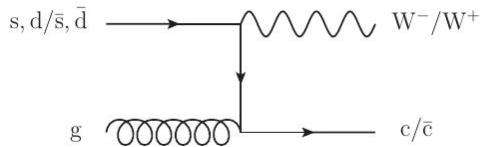
QCD production of $W\gamma + 2\text{jets}$



- LHC can also be used as a **gauge bosons** collider to study Vector Boson Scattering/Fusion processes
 - CMS reports **observation** of $W + \gamma$ EW production
- Pure electroweak processes
- Characteristic signature of 2 jets with large m_{jj} and rapidity gap
- Access to anomalous tri/quadrilinear couplings

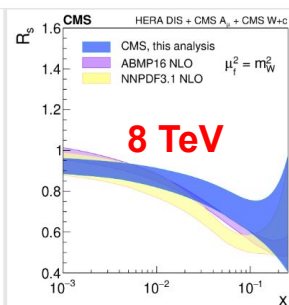
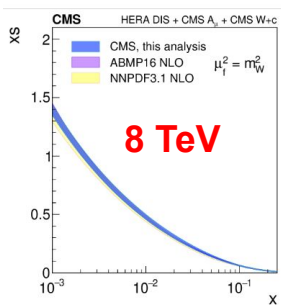
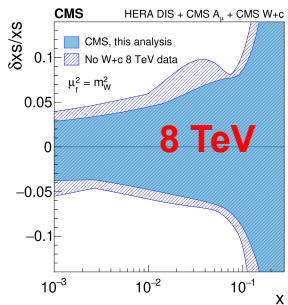
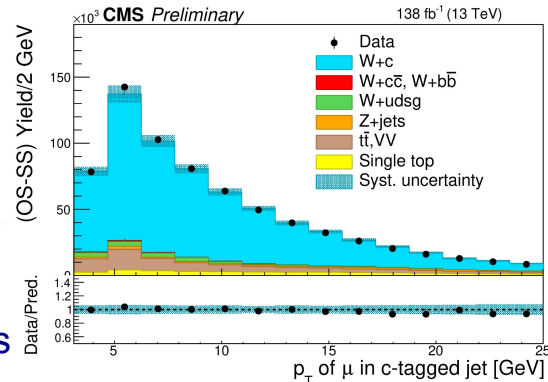
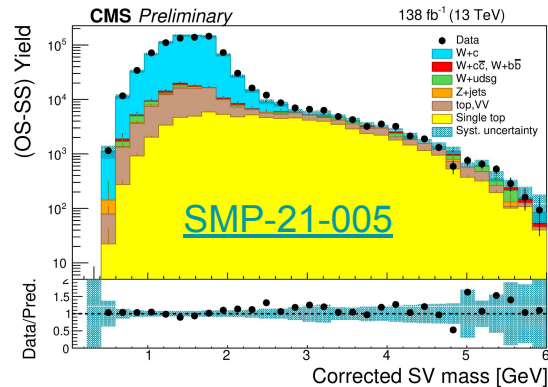
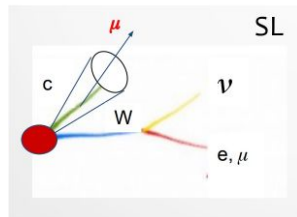
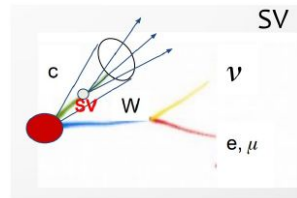
Expected. limit	Observed. limit	U_{bound}
$-5.1 < f_{M0}/\Lambda^4 < 5.1$	$-5.6 < f_{M0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M1}/\Lambda^4 < 7.4$	$-7.8 < f_{M1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M2}/\Lambda^4 < 1.8$	$-1.9 < f_{M2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M3}/\Lambda^4 < 2.5$	$-2.7 < f_{M3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M4}/\Lambda^4 < 3.3$	$-3.7 < f_{M4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M5}/\Lambda^4 < 3.6$	$-3.9 < f_{M5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T0}/\Lambda^4 < 0.51$	$-0.47 < f_{T0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T1}/\Lambda^4 < 0.31$	$-0.31 < f_{T1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T2}/\Lambda^4 < 0.92$	$-0.85 < f_{T2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T5}/\Lambda^4 < 0.31$	$-0.31 < f_{T5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T6}/\Lambda^4 < 0.25$	$-0.25 < f_{T6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T7}/\Lambda^4 < 0.68$	$-0.67 < f_{T7}/\Lambda^4 < 0.73$	3.1

Measurement of W+charm production



- Final state with leptonic decay of W
- Tagging charm jet with secondary vertex or muon in jet
- This new measurements will allow to strongly constrained the s quark PDF

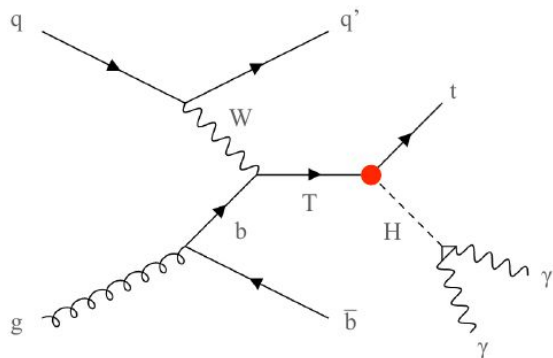
Channel	$N_{\text{sel}}(1 - f_{\text{bkg}})$	$C(\%)$	$\sigma(W+c)$ [pb]
$W \rightarrow e\nu, \text{SL}$	$341\,316 \pm 1294$	$1.419 \pm 0.025 \pm 0.066$	$175.3 \pm 0.7 \pm 9.1$
$W \rightarrow \mu\nu, \text{SL}$	$194\,299 \pm 934$	$0.856 \pm 0.019 \pm 0.033$	$165.4 \pm 0.8 \pm 8.8$
$W \rightarrow e\nu, \text{SV}$	$276\,167 \pm 1717$	$1.261 \pm 0.024 \pm 0.062$	$159.6 \pm 1.0 \pm 8.6$
$W \rightarrow \mu\nu, \text{SV}$	$397\,555 \pm 1876$	$1.786 \pm 0.028 \pm 0.081$	$162.3 \pm 0.8 \pm 8.2$



Most precise analysis of W+c production Expect significant improvements with respect to 8 TeV analysis

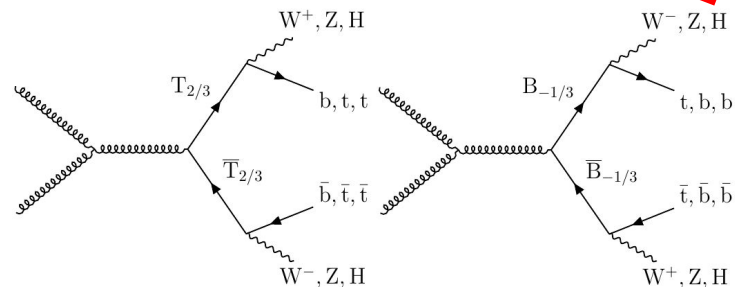
Direct search for new physics: Vector-like quarks

CMS
New@ICHEP

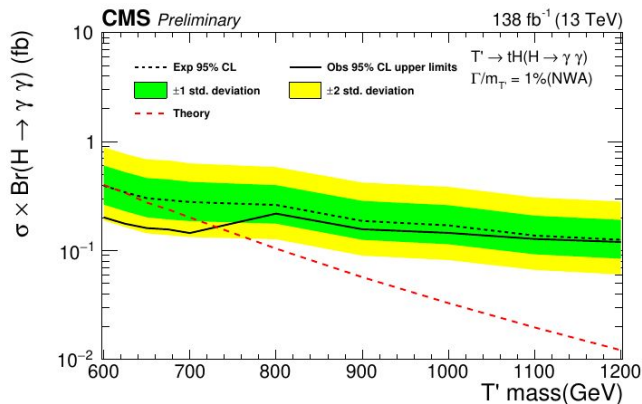


Resonances of b/t quarks with vector bosons

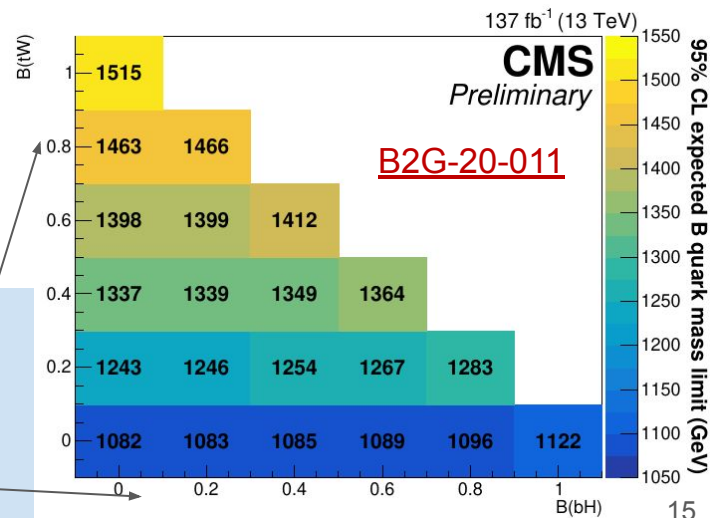
Recent results in both **single** production and **pair** production



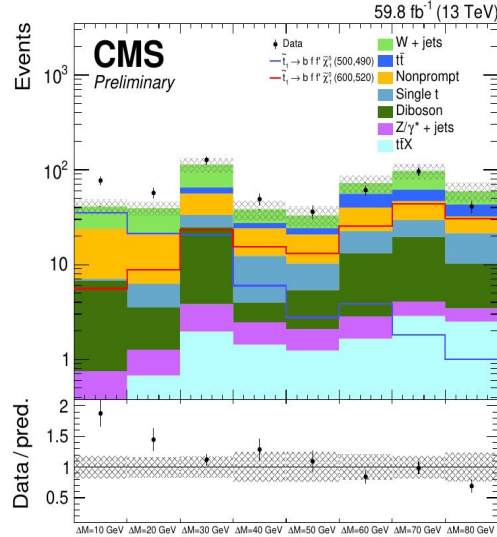
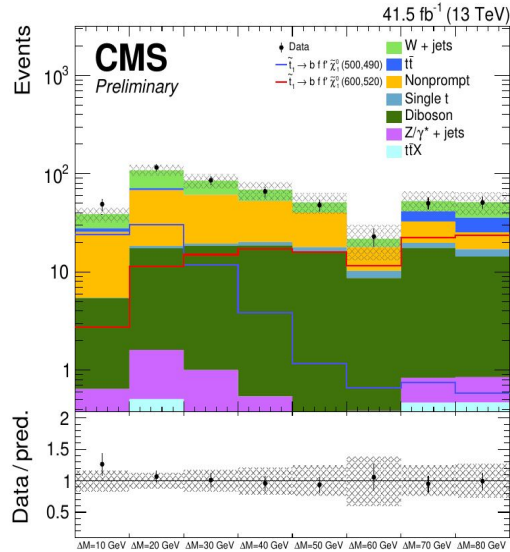
[B2G-21-007](#)



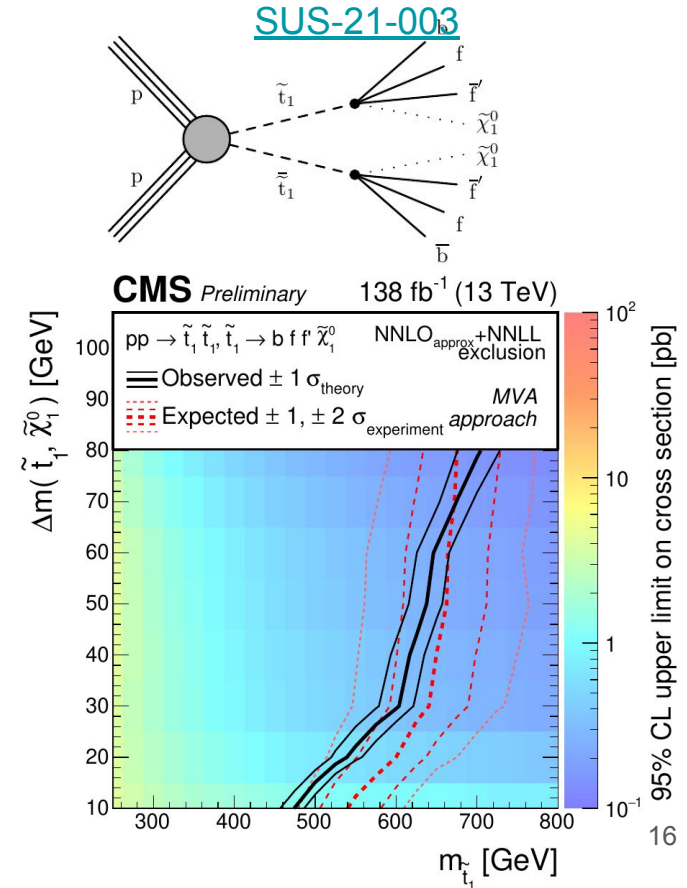
Exclusion limits computed as a function of the branching fractions rather than for fixed values in order to be less model dependent



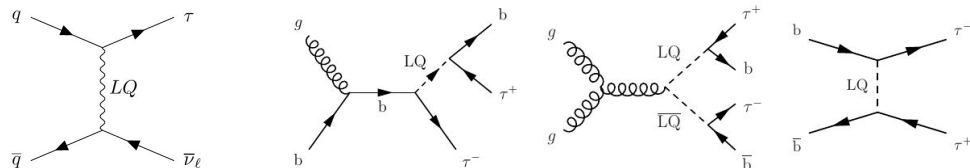
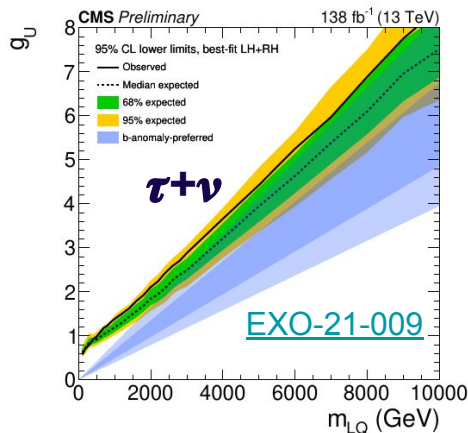
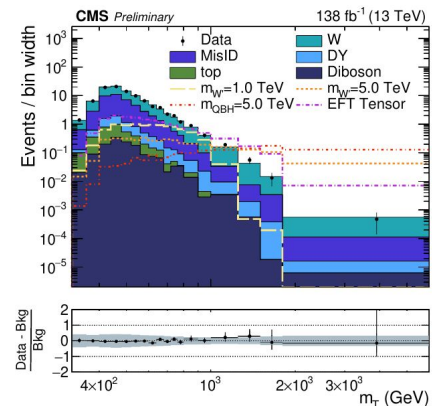
SUSY: compressed stop decays



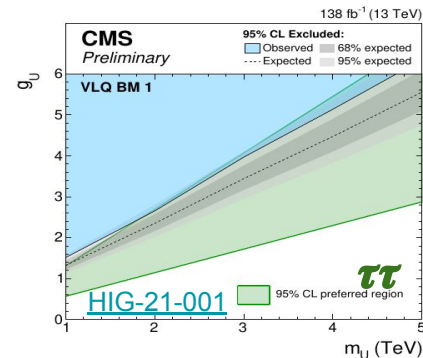
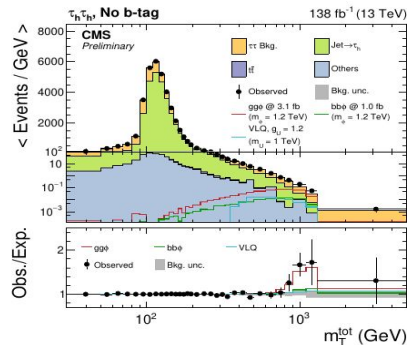
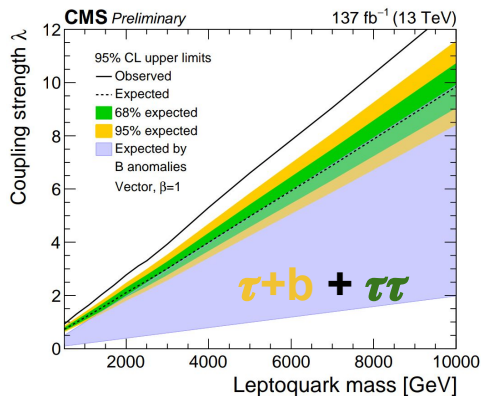
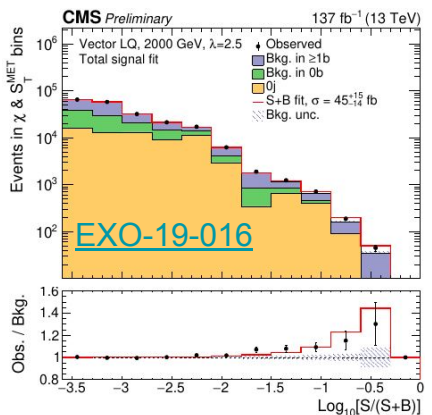
- $\Delta m < m_W \Rightarrow$ four body decay allowed
 - Jet + missing energy + soft leptons
- Trained BDT for different Δm hypotheses
- Slight excess (2.5 σ local) at low Δm



Searches related to b-anomalies with τ



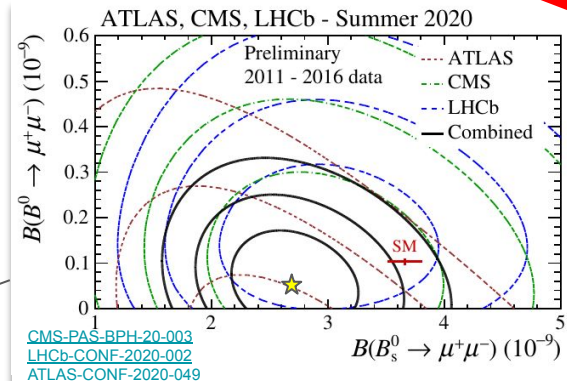
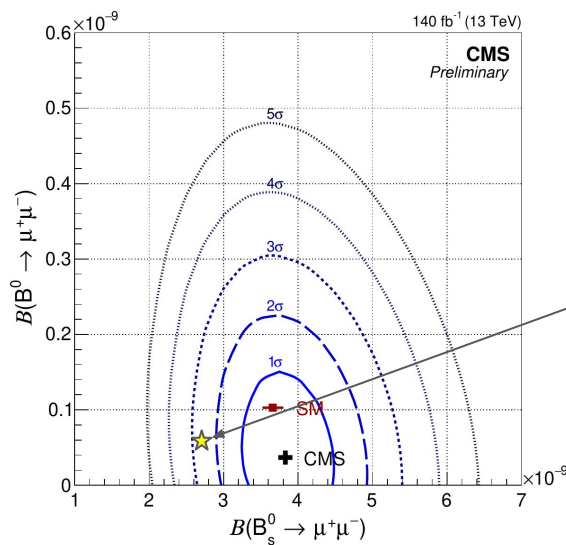
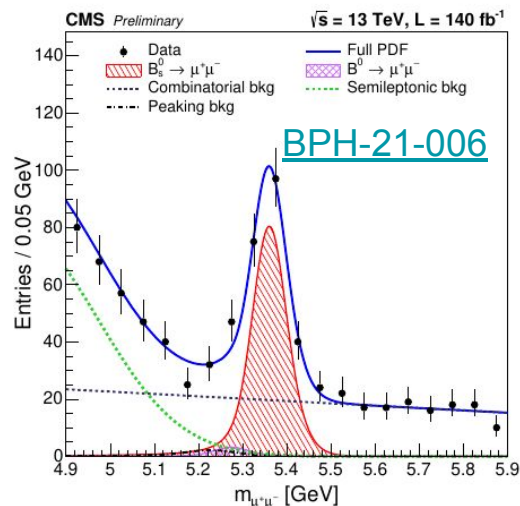
- Final states with $\tau+\nu$, $\tau+b$ and $\tau\tau$ are investigated
- Good probe of models related to b-anomalies (e.g. leptoquark)
- Sensitivity approaching the “preferred” region from b-anomalies in some LQ models
- Some sizeable excess in non-resonant $\tau\tau$ final state (seen by two different analyses)



Full Run 2 result on $B_s \rightarrow \mu\mu$

physics
briefing!

CMS
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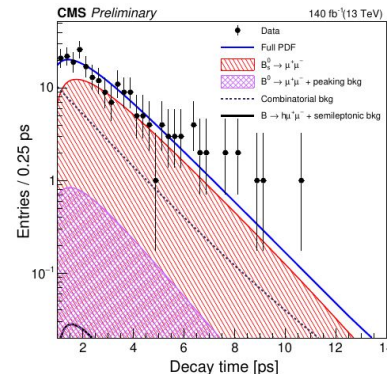
$$\tau_{B_s^0 \rightarrow \mu^+\mu^-} = 1.91^{+0.37}_{-0.35} \text{ ps}$$

$$\tau = 1.83^{+0.23}_{-0.20} (\text{stat})^{+0.03}_{-0.03} (\text{syst}) \text{ ps.}$$

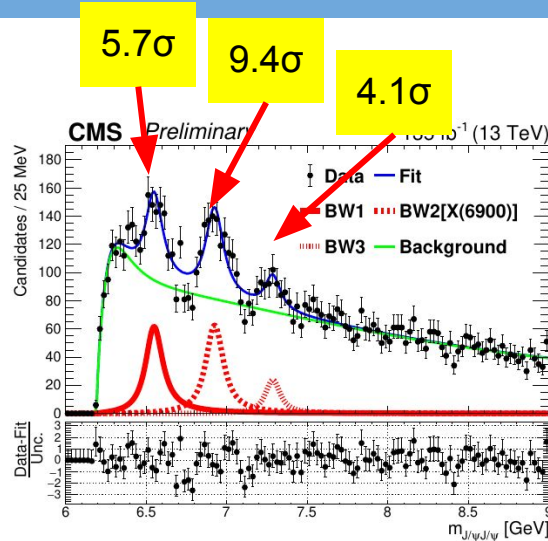
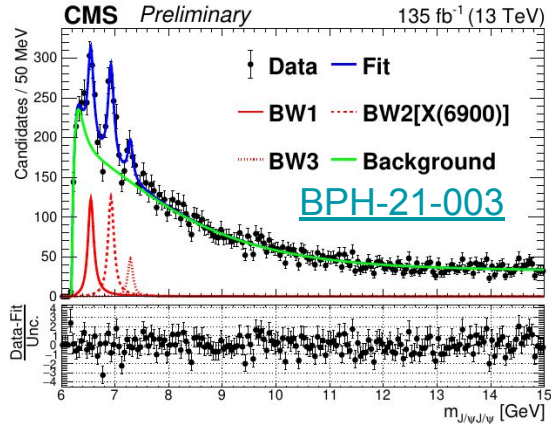
$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = [3.95^{+0.39}_{-0.37} (\text{stat})^{+0.29}_{-0.24} (\text{syst})] \times 10^{-9}$$

- Updated results with **full Run-2 luminosity**
- Most precise single experiment measurement to date
 - Highly compatible with SM prediction
- Most precise measurement of lifetime

..if you missed the parallel
Dedicated CERN
Seminar on July 26th



J/ψ J/ψ resonances



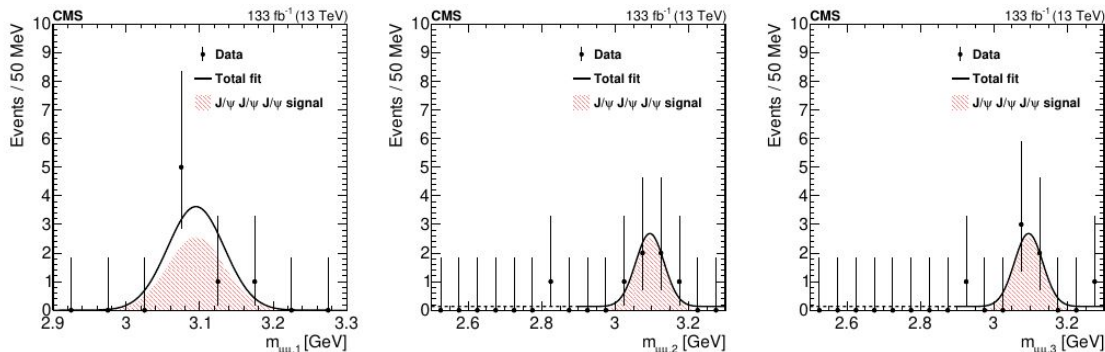
- Study spectrum of J/psi pairs mass
- Three clear peaks visible
- Central one compatible with [LHCb X\(6900\)](#)
- Fit model including interference to be finalized
- The three resonances are compatible with some recent predictions of tetraquarks states around the X(6900)

	BW1	BW2	BW3
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
Γ	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
N	474 ± 113	492 ± 75	156 ± 56

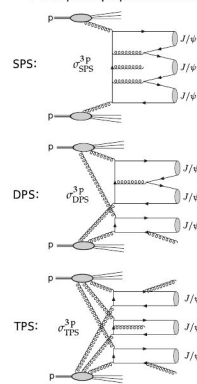
Triple J/ψ and WW Double Parton Scattering



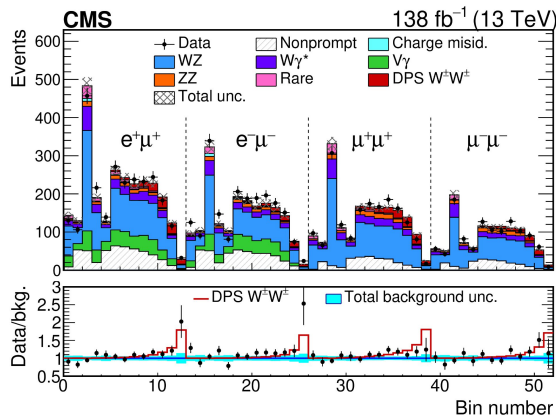
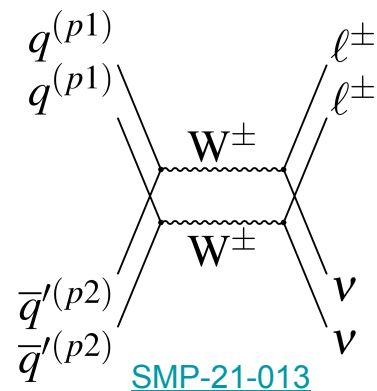
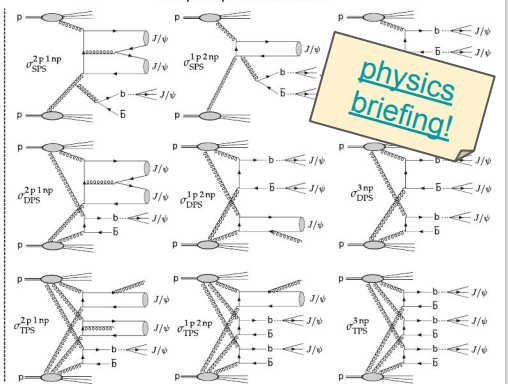
BPH-21-004



Pure prompt production:

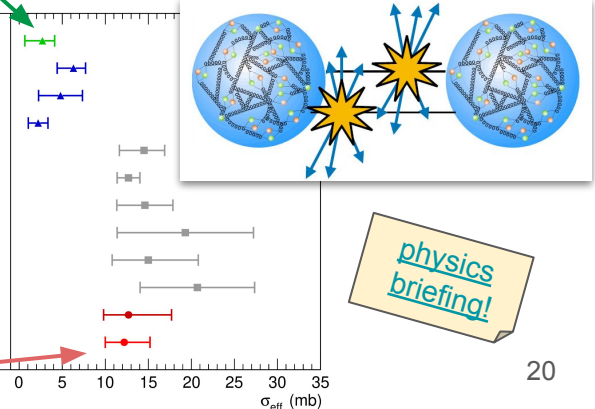


Nonprompt contributions:



CMS Supplementary

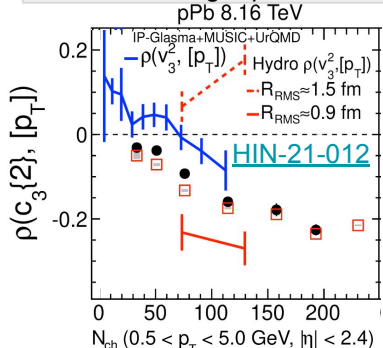
CMS J/ψ+J/ψ+J/ψ (13 TeV)
arXiv:2111.05370
ATLAS J/ψ+J/ψ (8 TeV)
Eur. Phys. J. C 77 (2017) 76
D0 J/ψ+J/ψ (1.96 TeV)
Phys. Rev. D 90 (2014) 111101
D0 J/ψ+Y (1.96 TeV)
Phys. Rev. Lett. 116 (2016) 082002
CDF γ+3jets (1.8 TeV)
Phys. Rev. Lett. 79 (1997) 584
D0 γ+3jets (1.96 TeV)
Phys. Rev. D 69 (2014) 072006
D0 γ+b/c+2jets (1.96 TeV)
Phys. Rev. D 93 (2016) 052008
ATLAS W+2jets (7 TeV)
New J. P. 15 (2013) 033638
CMS W+2jets (7 TeV)
JHEP 03 (2014) 032
CMS WW (13 TeV, 77.4 fb⁻¹)
Eur. Phys. J. C 80 (2020) 41
CMS WW (13 TeV, 138.0 fb⁻¹)
CMS-PAS-SMP-21-013



Pinning down the Standard Model of Heavy Ion collisions

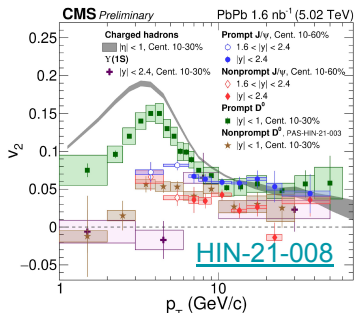
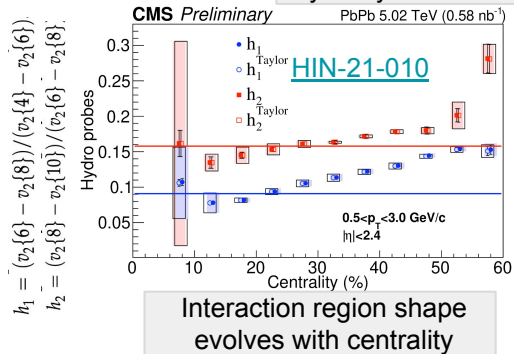


Correlator using 2-particle cumulant



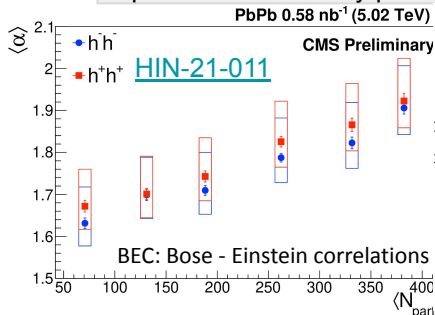
Initial state & flow with higher-order cumulants

Hydrodynamic evolution

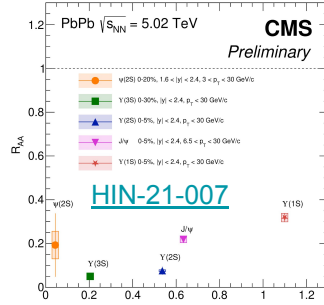


Azimuthal anisotropy: improved heavy flavor v_2

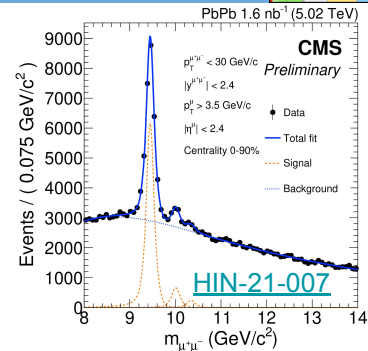
2-particle BEC & Levy parameters



Nuclear modification factor

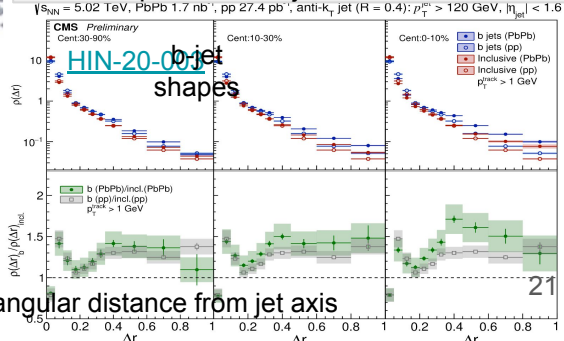


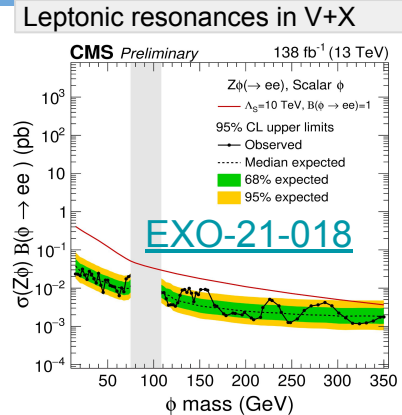
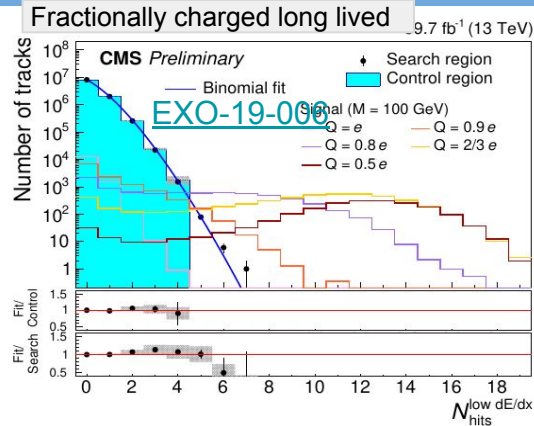
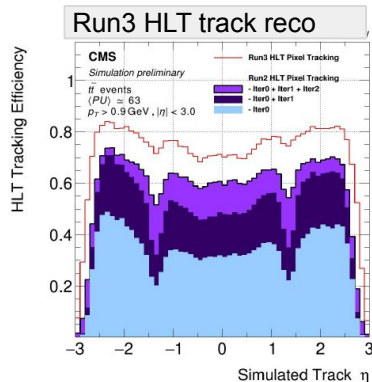
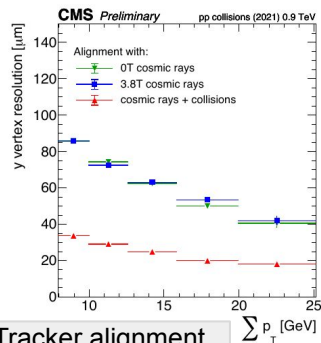
Sequential suppression



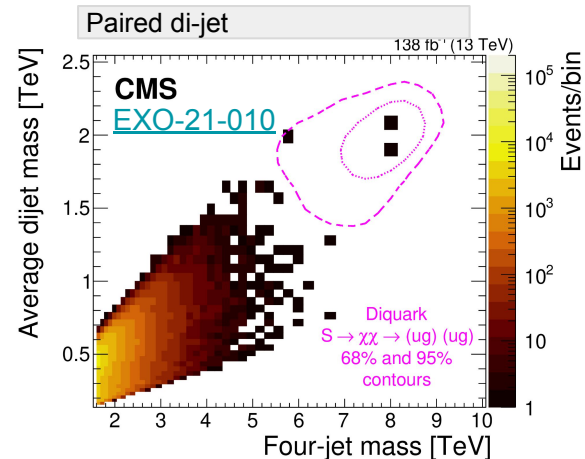
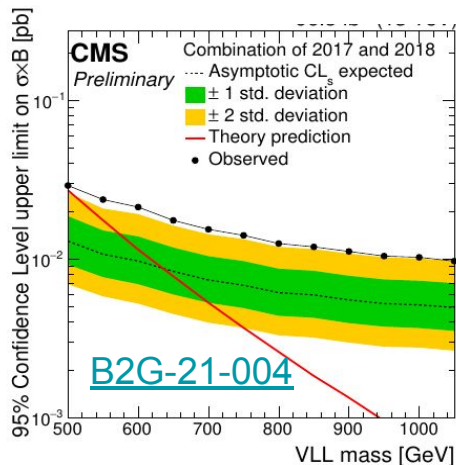
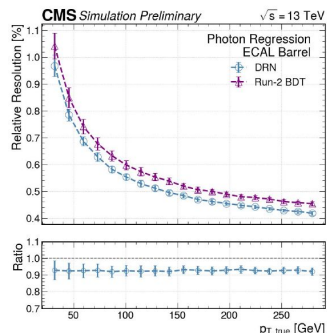
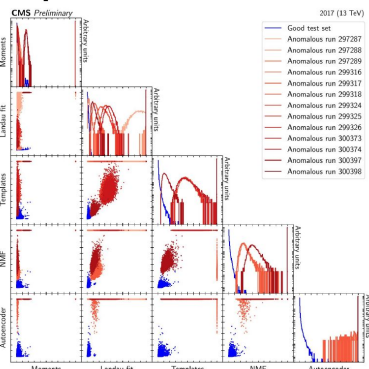
First observation of Y(3S) in PbPb

Flavor dependence of jet-medium interactions





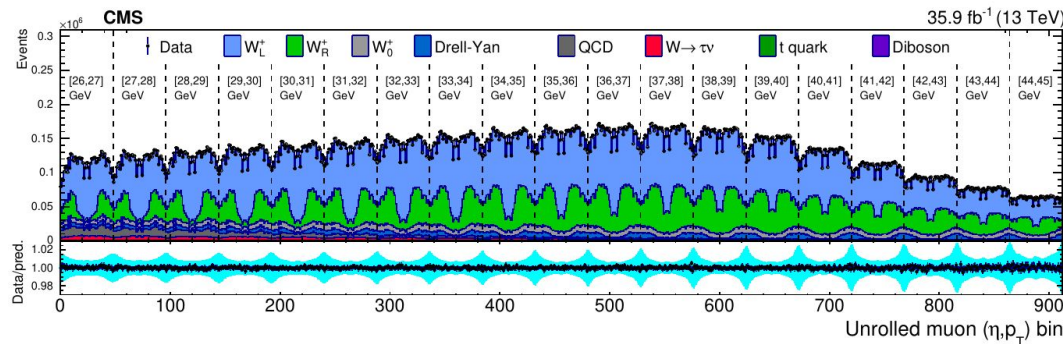
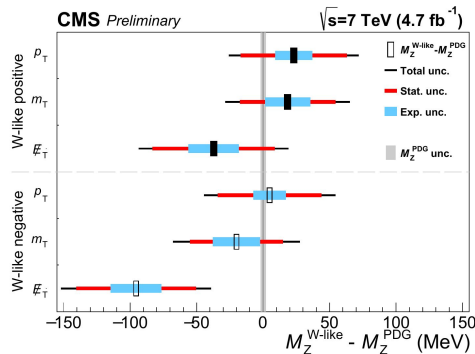
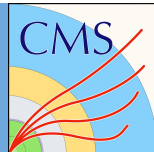
Computer assisted DQM



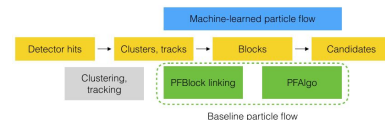
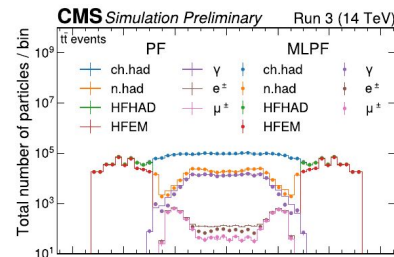
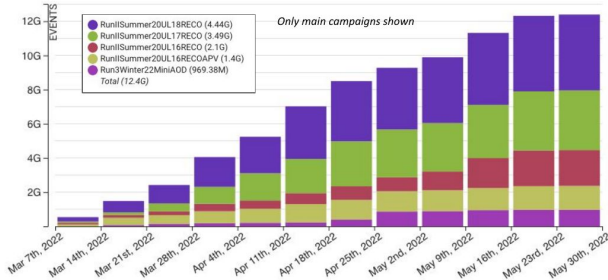
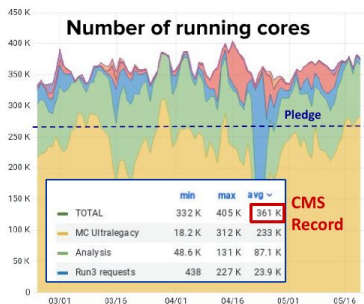
Vector-like leptons

Future prospects

Short term future



- **(secret revealed) we are working on a W mass analysis:** W-like Z mass at end of Run-1, W-helicity paper in Run-2, ...
- Run-2 data analysis is not over (not just W mass!)
- Exciting new things with Run-3 data: **new triggers deployed**, **scouting** (high rate trigger-objects analysis) and **parking** (opportunistic reco)
- Pushing the limits of scientific computing: > 1 billion **fully-simulated (GEN to RECO)** events produced every week, ubiquitous Machine Learning applications, streamlining the analysis process, heterogeneous computing (GPU in use at HLT for Run-3)



Longer term future

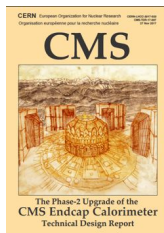


L1-Trigger HLT/DAQ

<https://cds.cern.ch/record/2714892>

<https://cds.cern.ch/record/2759072>

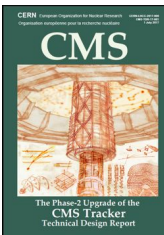
- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting



Calorimeter Endcap

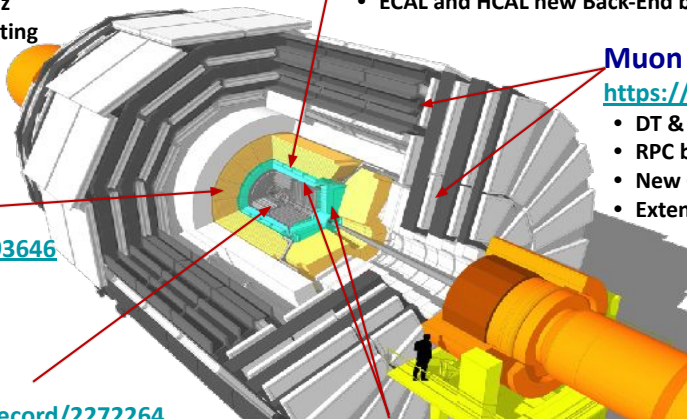
<https://cds.cern.ch/record/2293646>

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



Tracker <https://cds.cern.ch/record/2272264>

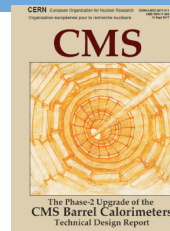
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \approx 3.8$



Barrel Calorimeters

<https://cds.cern.ch/record/2283187>

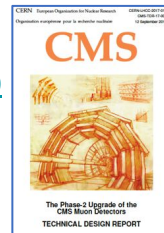
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards



Muon systems

<https://cds.cern.ch/record/2283189>

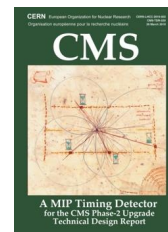
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \approx 3$



Beam Radiation Instr. and Luminosity

<http://cds.cern.ch/record/2759074>

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



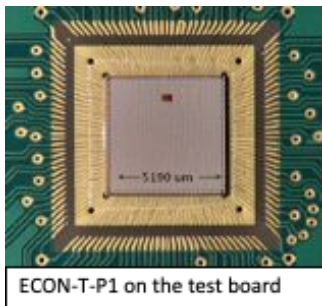
MIP Timing Detector

<https://cds.cern.ch/record/2667167>

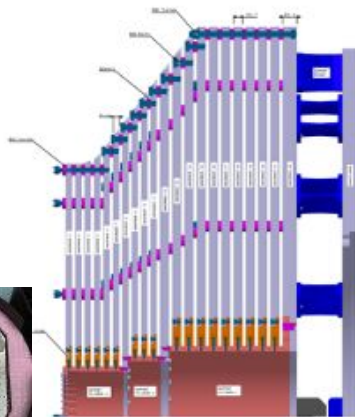
Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Phase 2 Upgrade in a few pictures



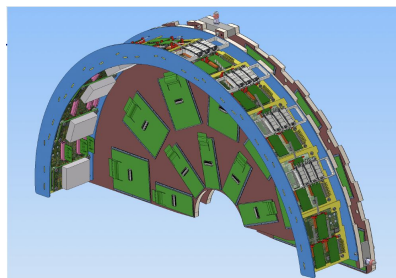
ECON-T-P1 on the test board



CE-H absorber structure, support wedges, and back-flange



HGCAL partial sensors



TFPX dee with the 10-portcards revised cartridge



Detector module (two arrays)

BTL



SiPM and LYSO array

TECs

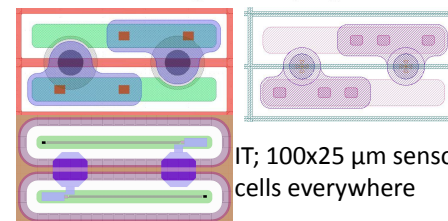


SiPM array backside

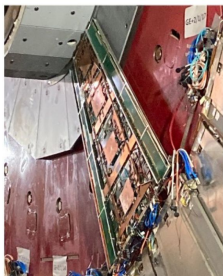
TRACKER INTEGRATION & SERVICES: BTST



Full size 1m long BTST finished prototype at Purdue

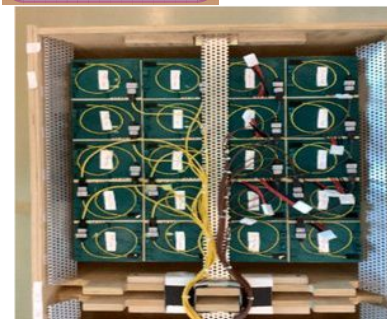
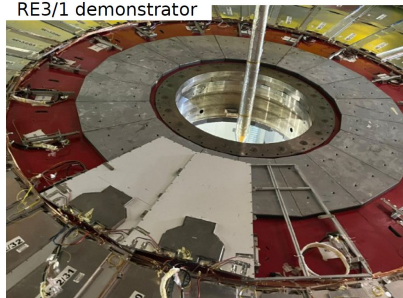


IT; 100x25 μm sensor cells everywhere



GE2/1 demonstrator

RE3/1 demonstrator



Conclusions



- CMS is ready to take Run-3 data
- Run-2 is a fantastic dataset many analyses still ongoing, CMS keep publishing ~80 analysis per year
- *“If at the end of Run-2 you will see no 3 sigma deviations, you will never discover anything new, until at least HL-LHC” (anonymous)*
 - => multiple 2-3 sigma tensions, it will be fun understanding what they are (Bad background models? Statistical fluctuations? New physics?)
- Direct access to models explaining b-anomalies
- Ten years after discovery, Higgs physics still very interesting (including some of the tensions)
- Preparing for HL-LHC: a lot of new detectors to finalize, prototype, build and test

