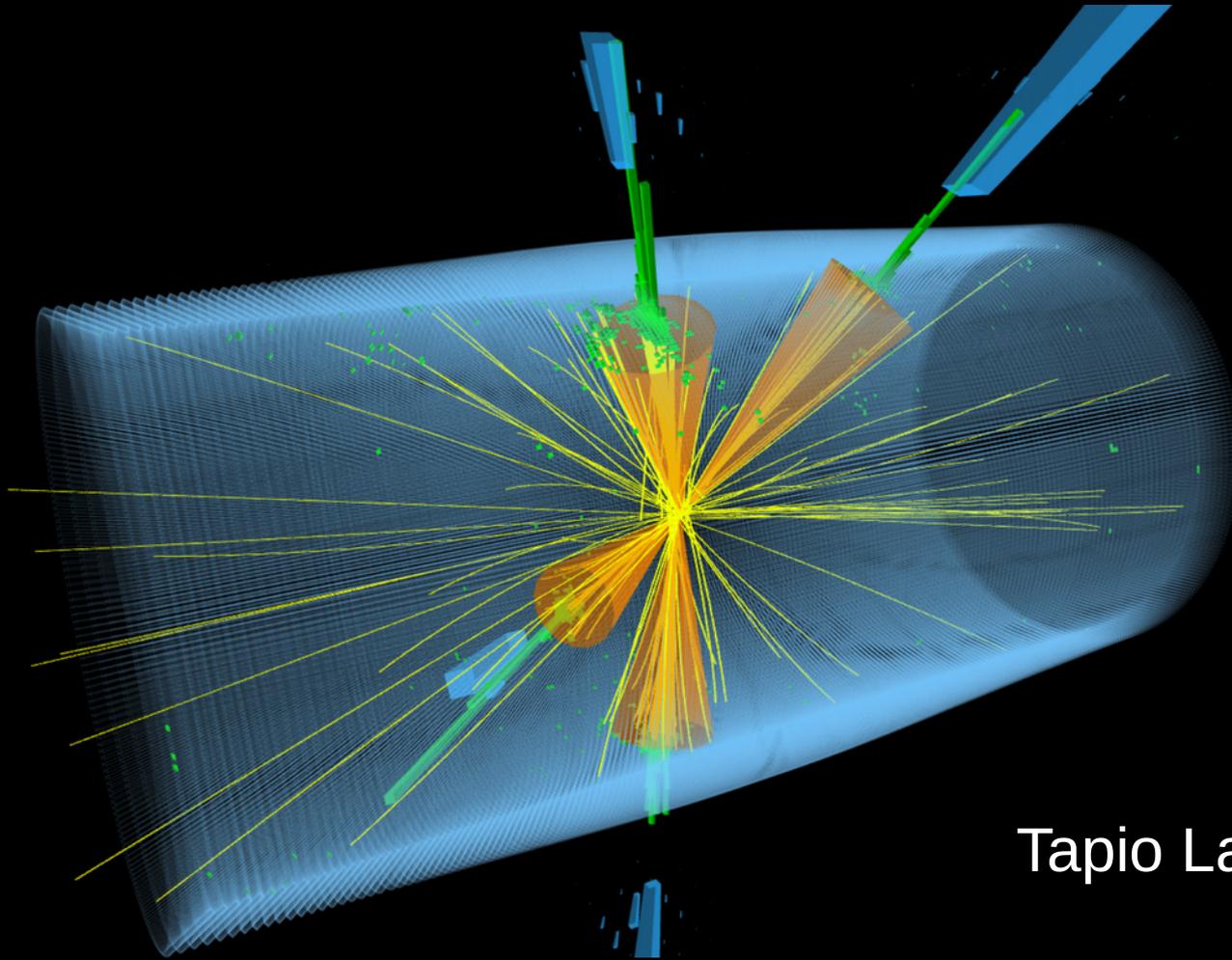


CMS + TOTEM

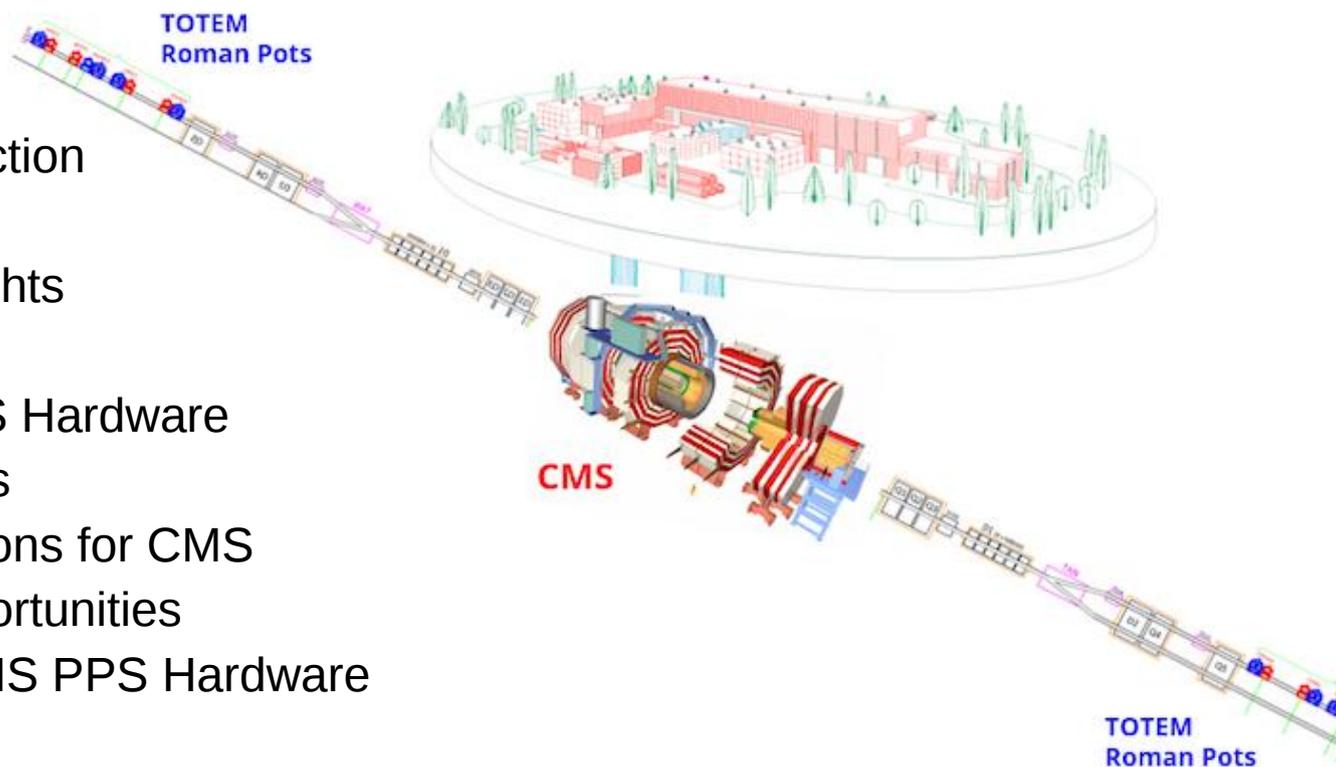
Run 2 results and Run 3 start



Tapio Lampén (HIP)

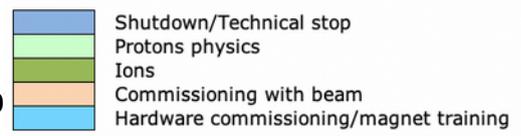
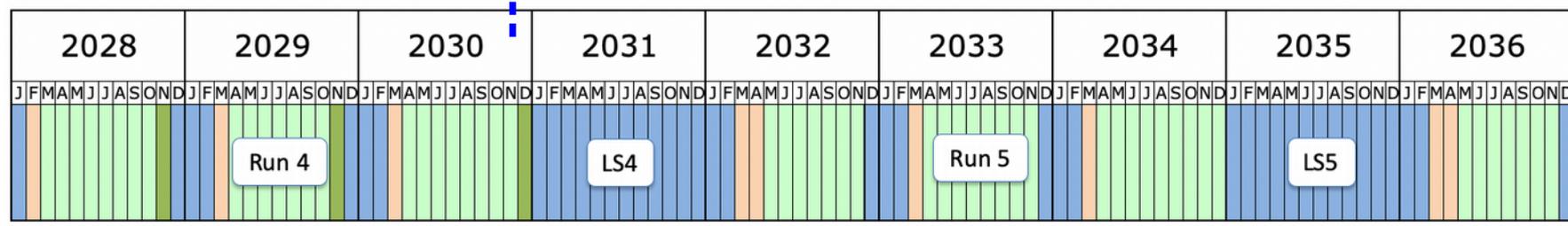
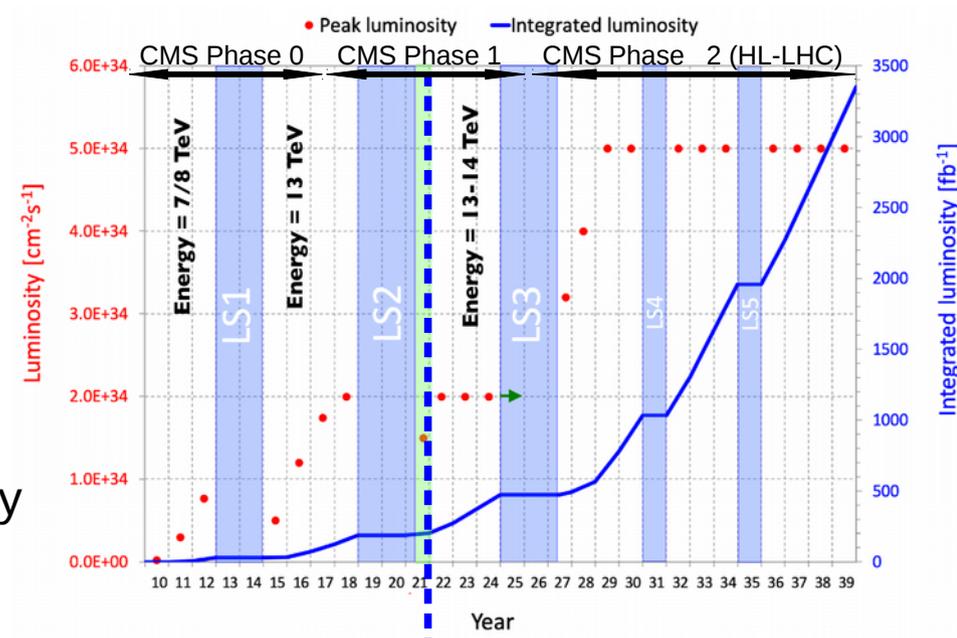
Particle Physics Day 2021
16.11.2021 Jyväskylä

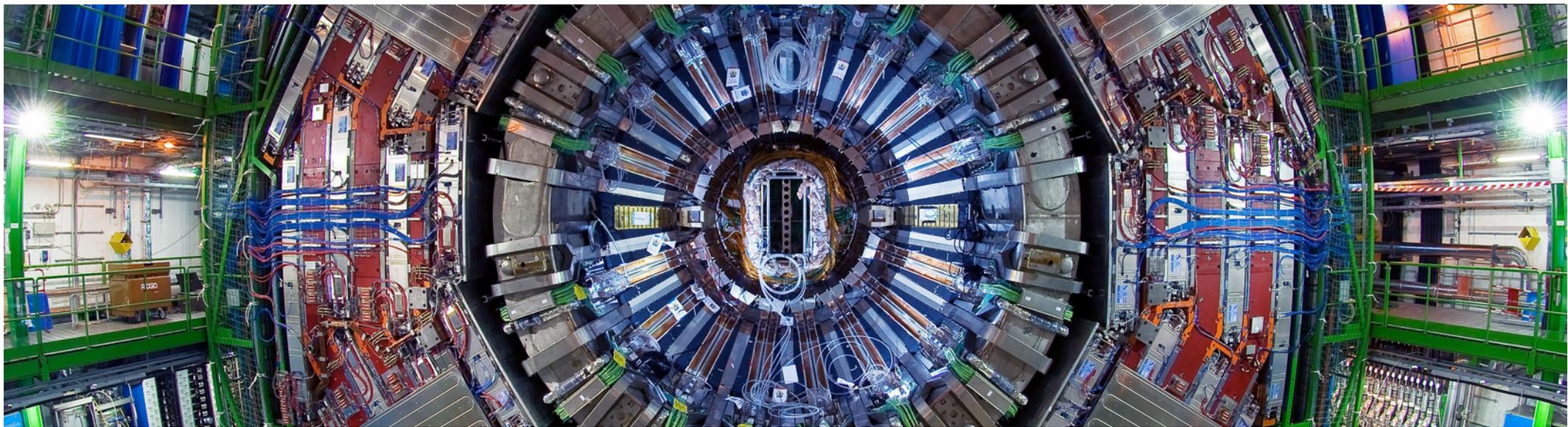
- Introduction: LHC Run 2, Run 3, HL-LHC
- Run 2, CMS:
 - Recorded data
 - Publications
 - Legacy Reconstruction
 - Highlights
- Run 2, TOTEM: Highlights
- Run 3:
 - New/Updated CMS Hardware
 - New CMS Methods
 - Improved Calibrations for CMS
 - CMS Physics Opportunities
 - New TOTEM & CMS PPS Hardware
- CMS Open Data
- Summary



LHC: Run 2, Run 3, HL-LHC

- Large Hadron Collider Run 3:
 - starting now after Long Shutdown 2 (LS2), Stable Beams expected in May -22
 - doubles integrated luminosity in 2022-2024
 - collision energy 13->13.6TeV (14TeV being discussed)
- new era of luminosity in 2027 with High-Luminosity LHC (HL-LHC), aiming to 3000-4000 fb⁻¹





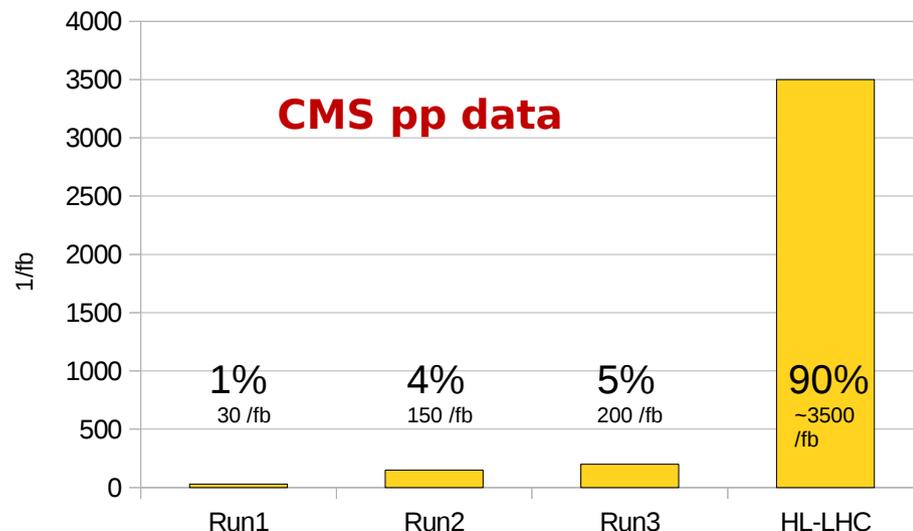
Run 2

Data / Publications / On-going Studies / Selected results

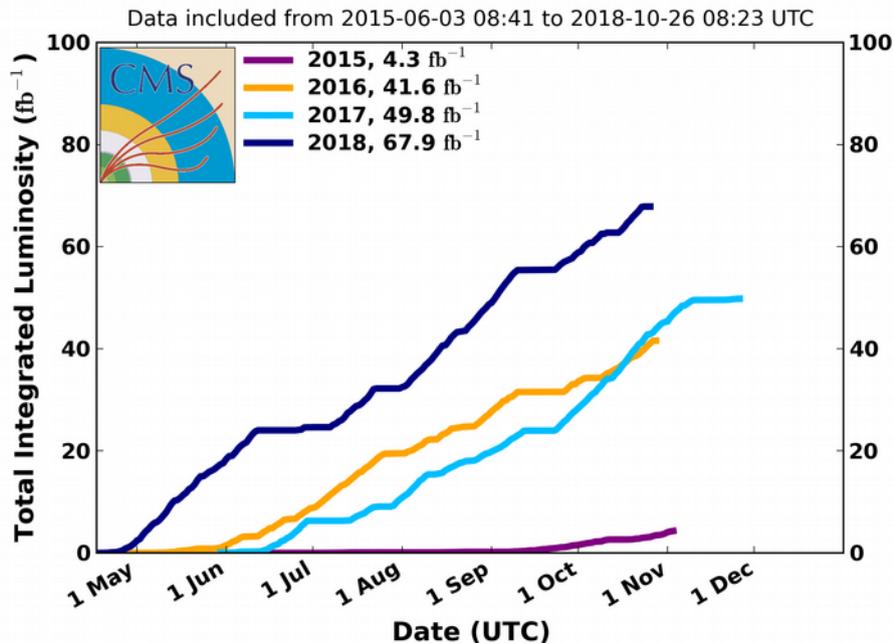


CMS Data Recorded during Run 2

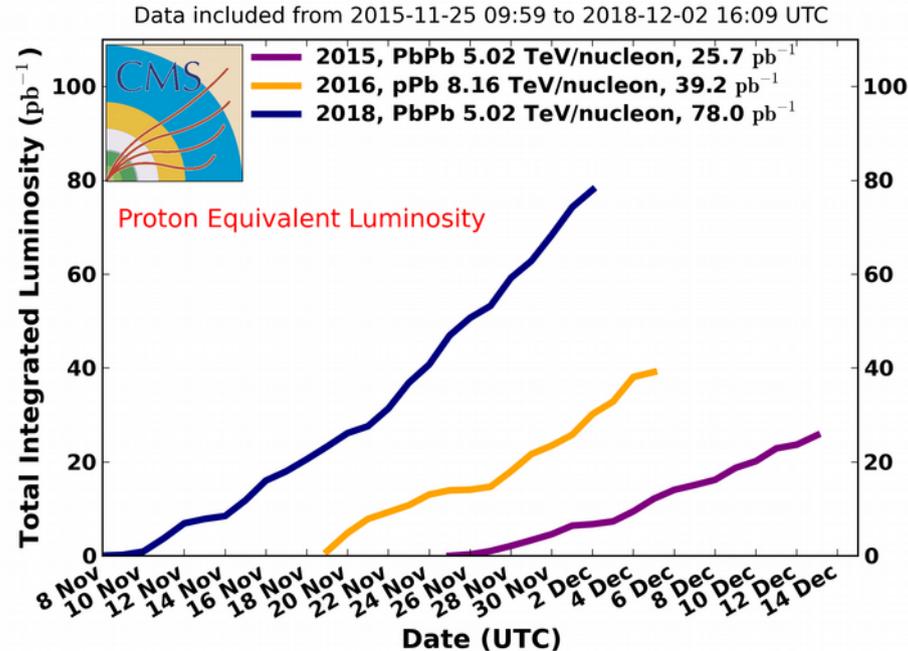
- in Run 2 CMS collected about 150fb⁻¹ data (~4% of all data to be collected by LHC)
- Heavy Ion data (mostly PbPb & pPb):
2015: 590ub⁻¹
2018: 1800ub⁻¹



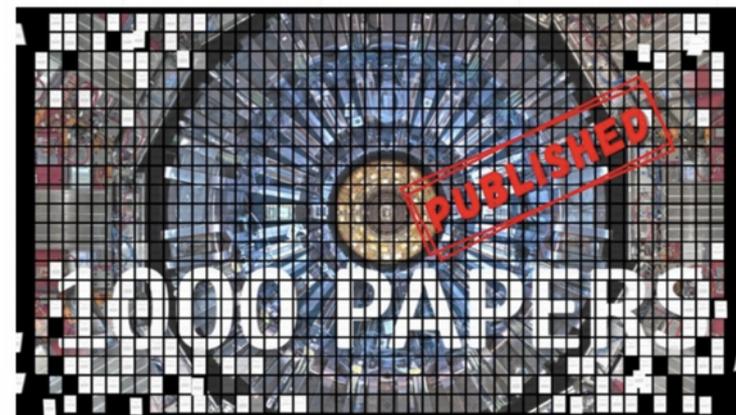
CMS Integrated Luminosity Delivered, pp, $\sqrt{s} = 13$ TeV



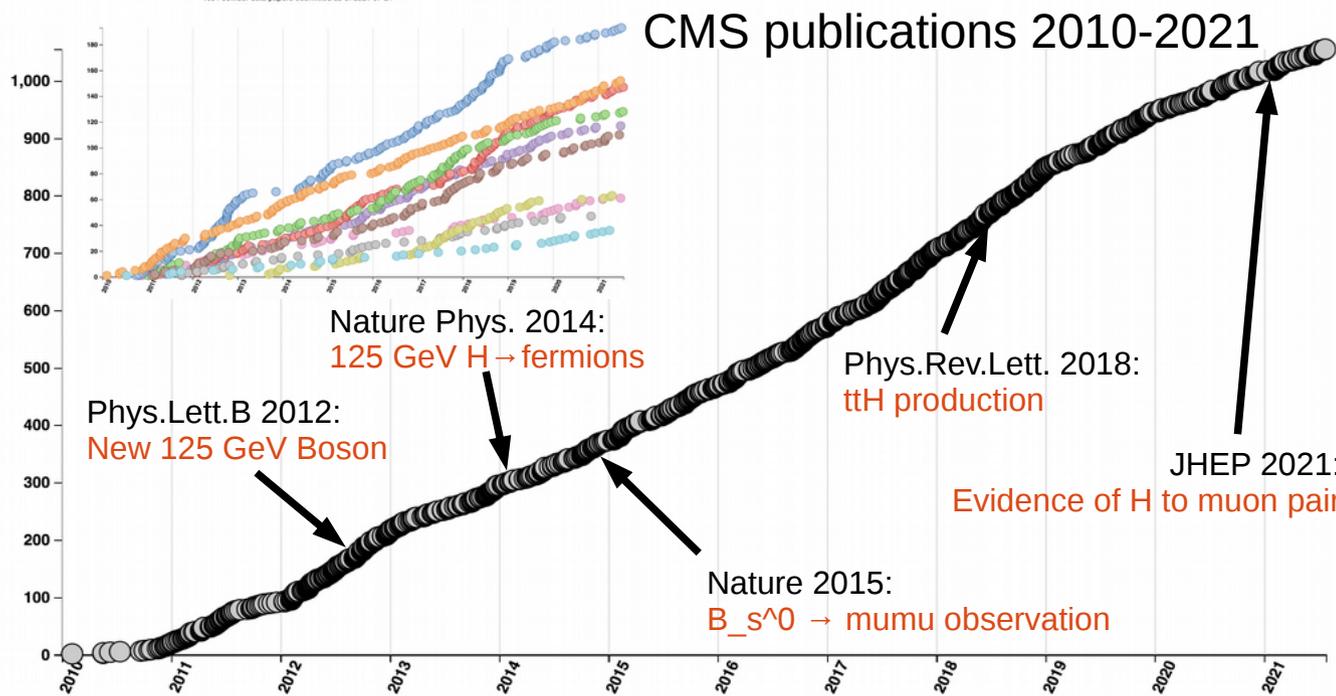
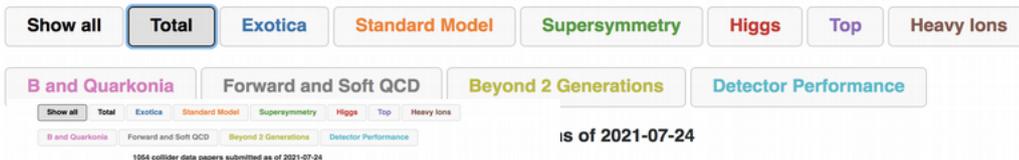
CMS Integrated Luminosity Delivered, PbPb+pPb



- **1075 publications** (last week)
574 based on Run 1 data
501 based on Run 2 data (so far)
- Most cited one
"Observation of a New Boson at a Mass of 125 GeV.." in *Phys.Lett.B* from 2012 (>10k citations)



Video published for 1000th CMS paper (19 Jul 2020)



Strong HIP contribution in high-impact CMS papers (after 3 Higgs papers and 2 TDRs):

- Jet Energy Correction paper (#6, 1300 citations, 2011)
- Particle-flow algorithm paper (#8, 1100 citations, 2017)
- Jet energy scale & resolution (#19, 760 citations, 2017)

- Quality of data significantly improved in Legacy recalibration campaign for 2016-2018 data (97.5% of Run 2 data)
- About 140 CMS analyses progressing towards publication, 300 analyses in publication plan for next 6 months (also carried out in HIP, e.g. just pre-approved $H^+ \rightarrow WH$)
- Output from Run 2 physics program output continues strongly for the next few years ([link](#) to recent CMS results)

[JINST 16 \(2021\) P05014](#)

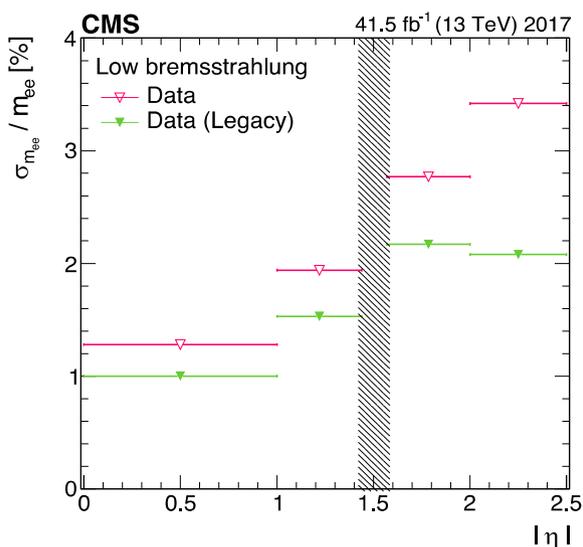
[CMS-DP-2020-012](#)

[DP Note in Preparation](#)

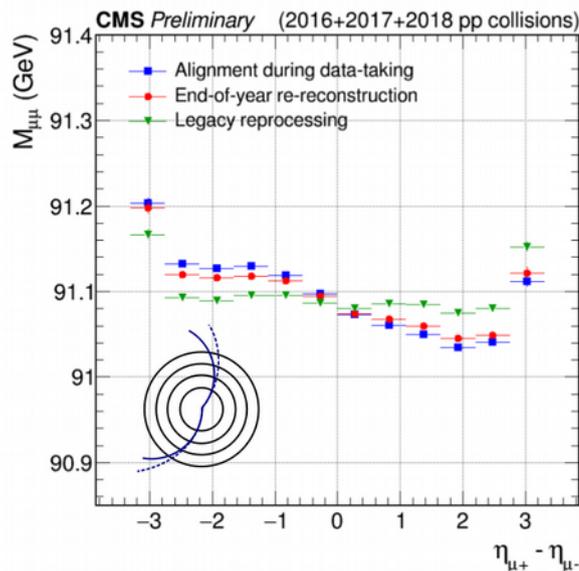
Comparison of Z mass resolution Before and after final calibration Included in Legacy Run 2 rereco

Z- \rightarrow mumu mass wrt. eta of muons; Tracker alignment data-taking / EOY / Legacy

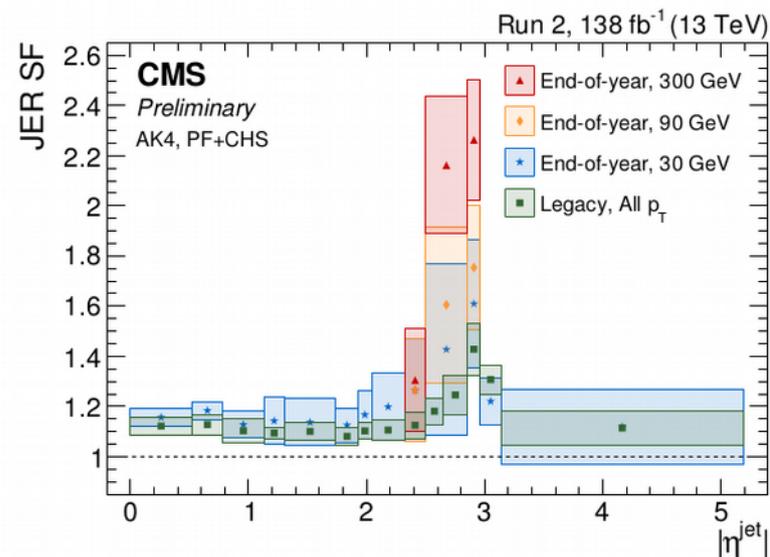
Jet Energy Resolution (JER) Calibration: scale factor improvement EOY- \rightarrow Legacy



16 Nov 2021



PPD 2021 Jyväskylä

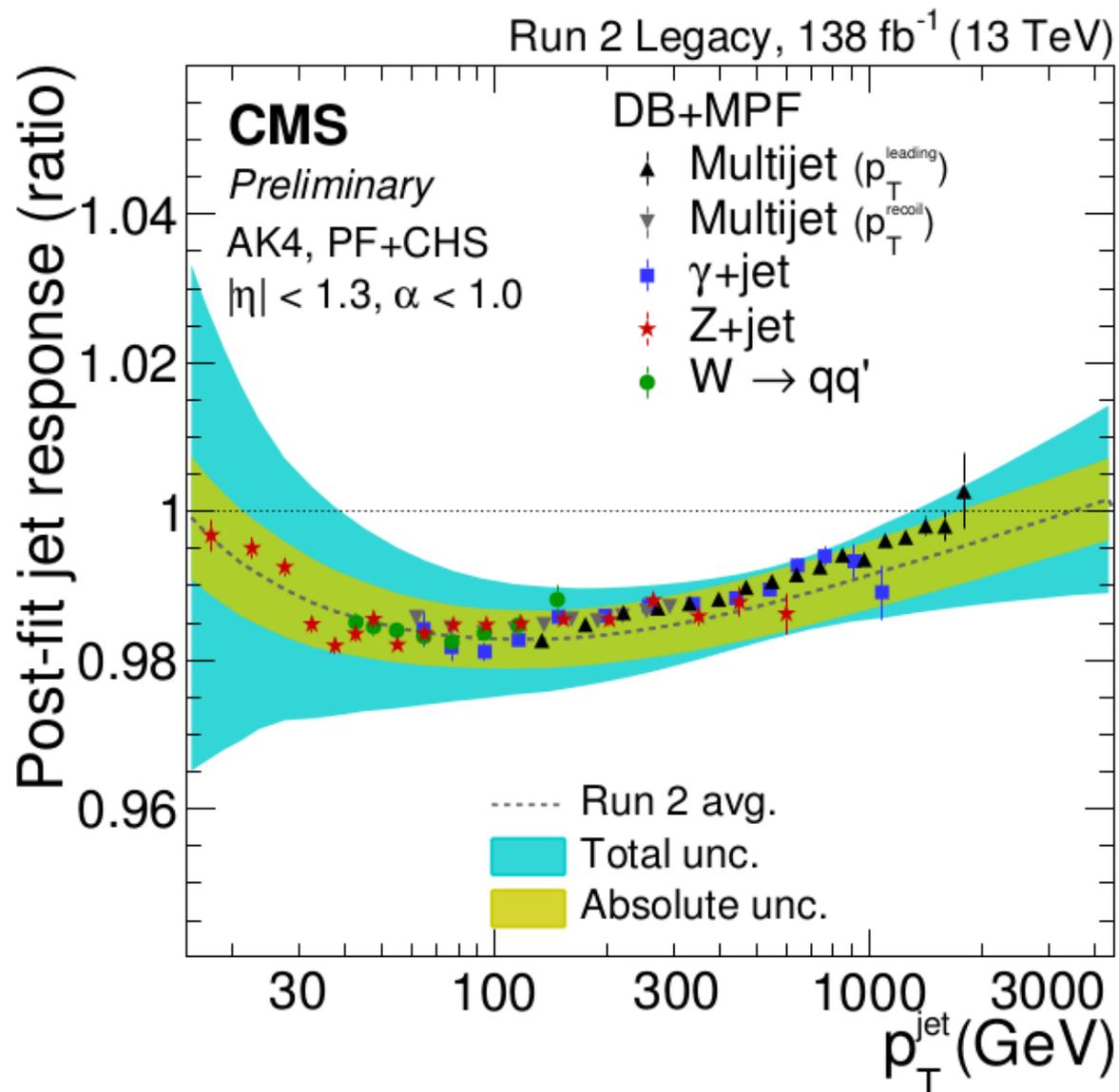


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Jet Energy Correction (JER) Calibration: absolute p_T -dependent residual correction

[DP Note in Preparation](#)

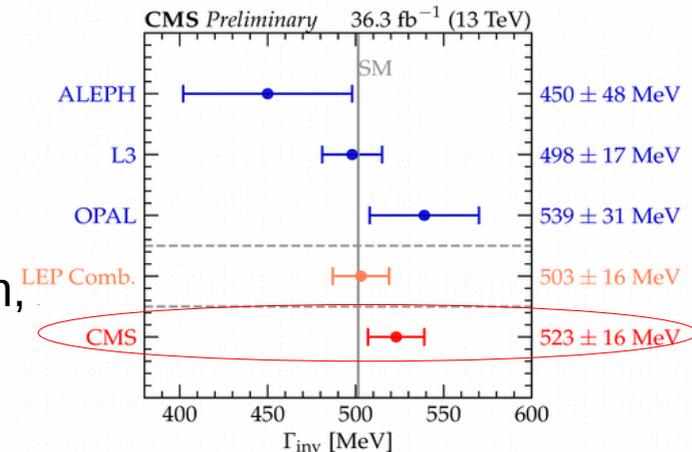
- Calibration expected to exceed Run 1 precision soon with
 - more channels
 - more data
 - more consistency
 - more insight
- All input channels and their global fit covered by HIP!



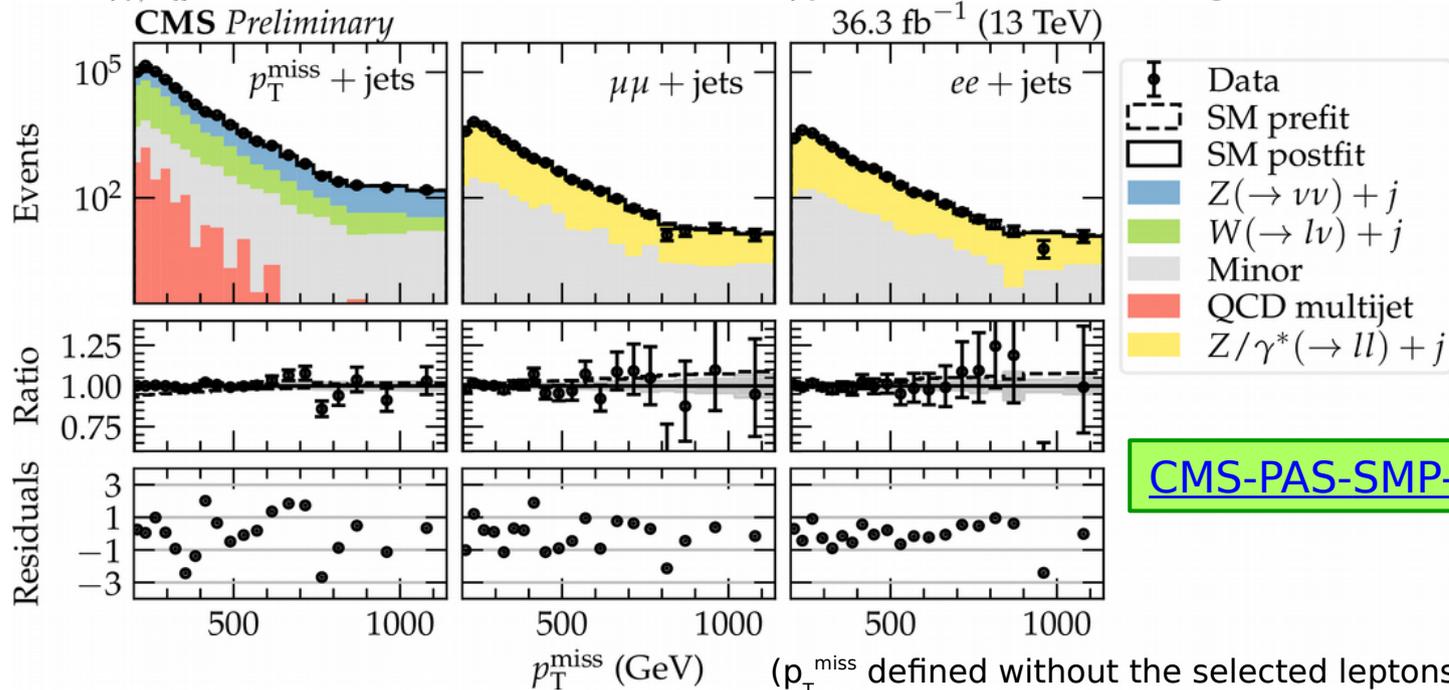
CMS Highlight: Z invisible width

- **Precision measurement** with 2016 13TeV data: Z invisible width (decay to invisible particles, related to # of ν species coupling to Z)
- 523 ± 3 (stat) ± 16 (syst) MeV , first time measured at hadron collider and with 13 TeV!
- most precise direct single measurement of the Z invisible width, competitive with the **combined** direct measurement from LEP experiments
- independent, complementary test of SM at higher energy

$$\Gamma(Z \rightarrow \nu\bar{\nu}) = \frac{\sigma(Z + \text{jets})\mathcal{B}(Z \rightarrow \nu\bar{\nu})}{\sigma(Z + \text{jets})\mathcal{B}(Z \rightarrow \ell\bar{\ell})} \Gamma(Z \rightarrow \ell\bar{\ell})$$



Ratio of $\Gamma_{\nu\nu}/\Gamma_{ll}$ from a simultaneous fit of $Z \rightarrow \nu\nu, Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ enriched categories

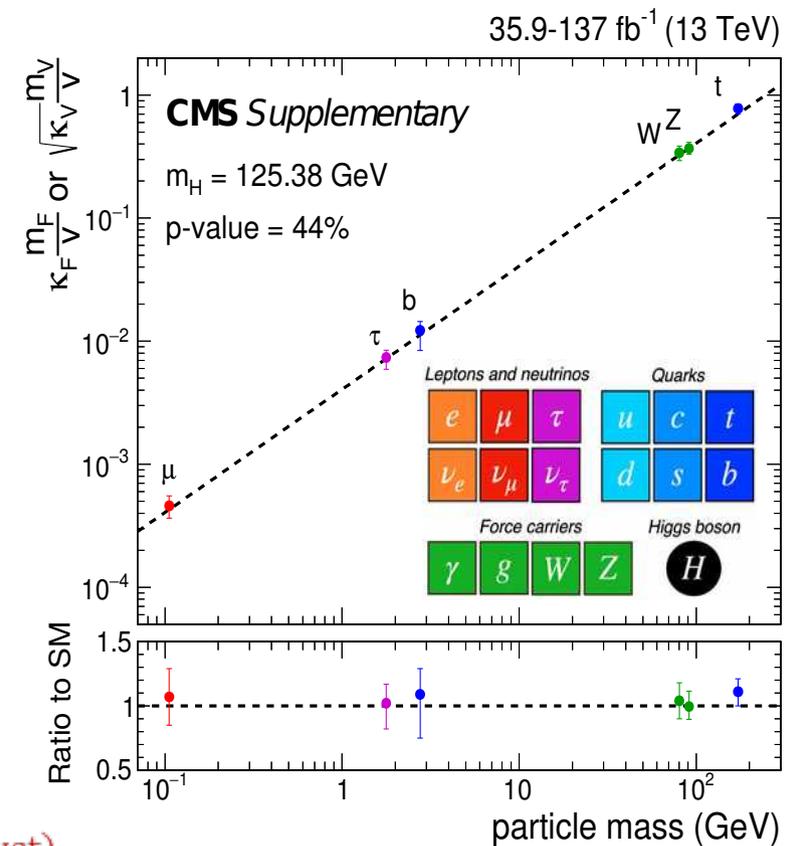
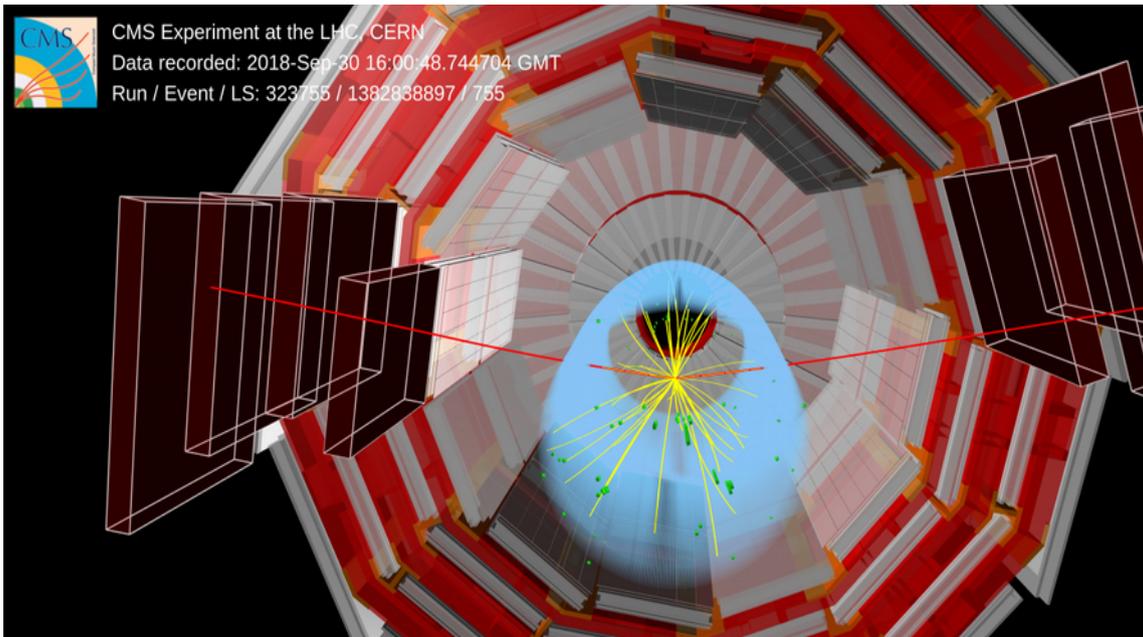


CMS-PAS-SMP-18-014

CMS Highlight: $H \rightarrow \mu\mu$

- Most precise measurement and **First evidence** of coupling of Higgs boson with muons (second generation fermions) JHEP 01 (2021) 148
- Note: $H \rightarrow c\bar{c}$, coupling of H with second generation quarks, will be a long-term goal for HL-LHC

$H \rightarrow \mu\mu$ candidate in gluon fusion channel Mass = 125.46 ± 1.13 GeV

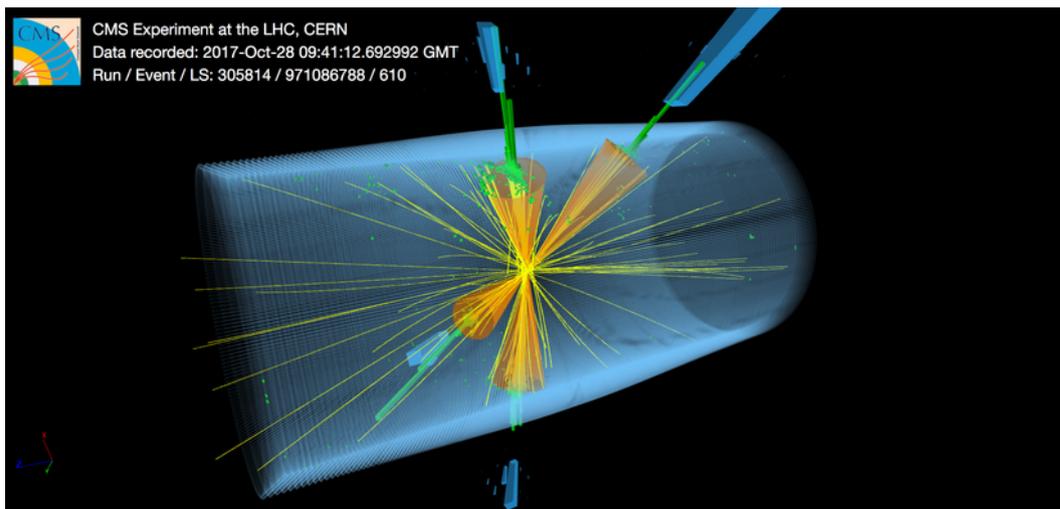
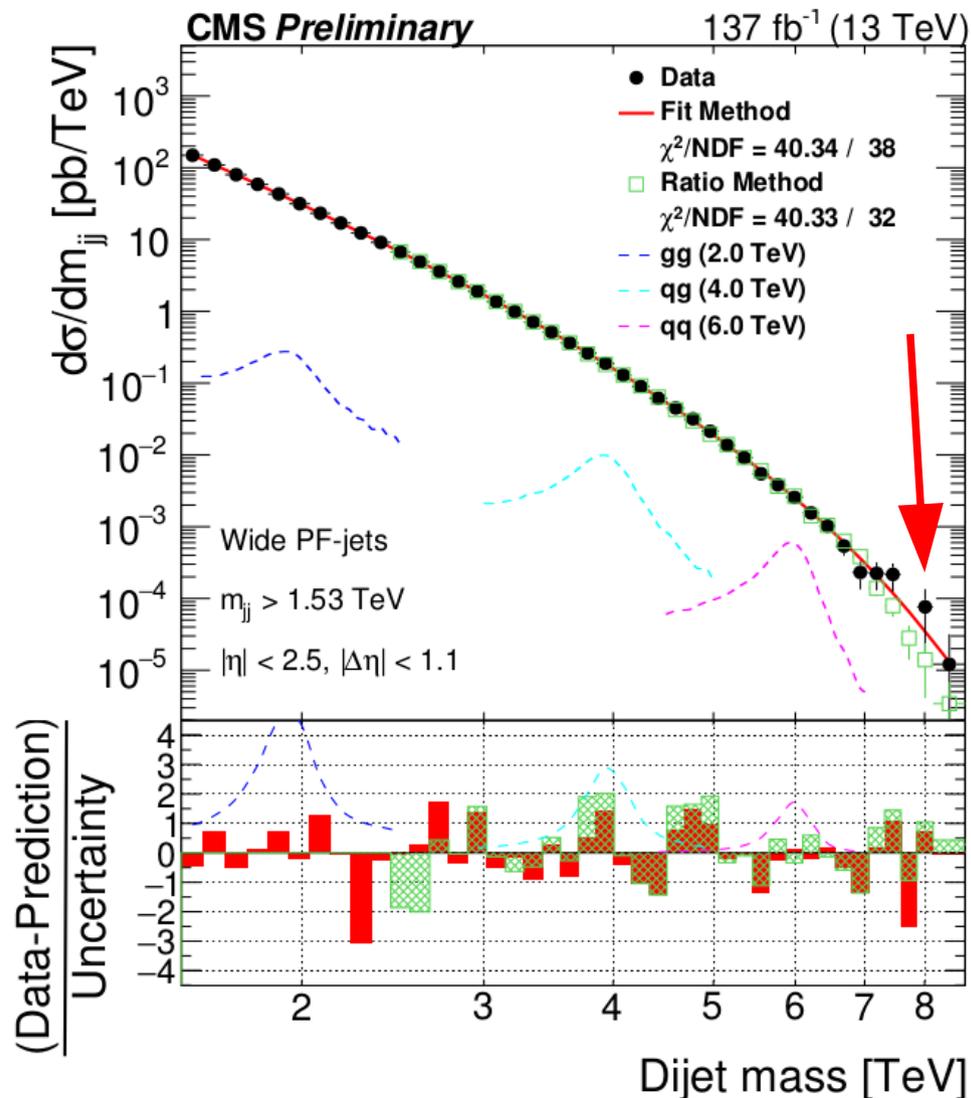


- Signal strength, relative to the SM prediction $\mu = 1.19_{-0.39}^{+0.40}$ (stat) $_{-0.14}^{+0.15}$ (syst)
- Obs. (exp.) significance 3.0σ (2.5σ)

CMS Highlight: Search for high mass dijet resonances

JHEP (05) 2020, 033

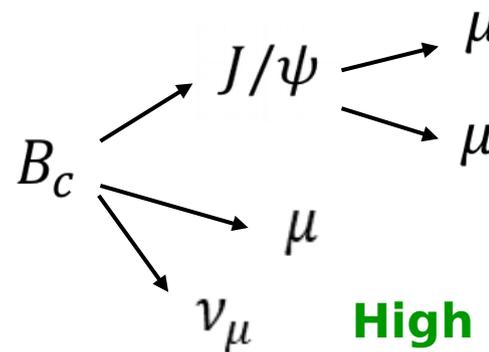
- Search for resonances with $m > 1.8$ TeV decaying to jets
- One four-jet topology event found at high mass
- No significant evidence (yet) for production of new particles, **high prospects for Run 3!**
- Exclusion at 95% C.L. of a dark matter mediator ($m = 1.8 - 4.8$ TeV)



Heavy Ion results: first observation of B_c^+ in PbPb

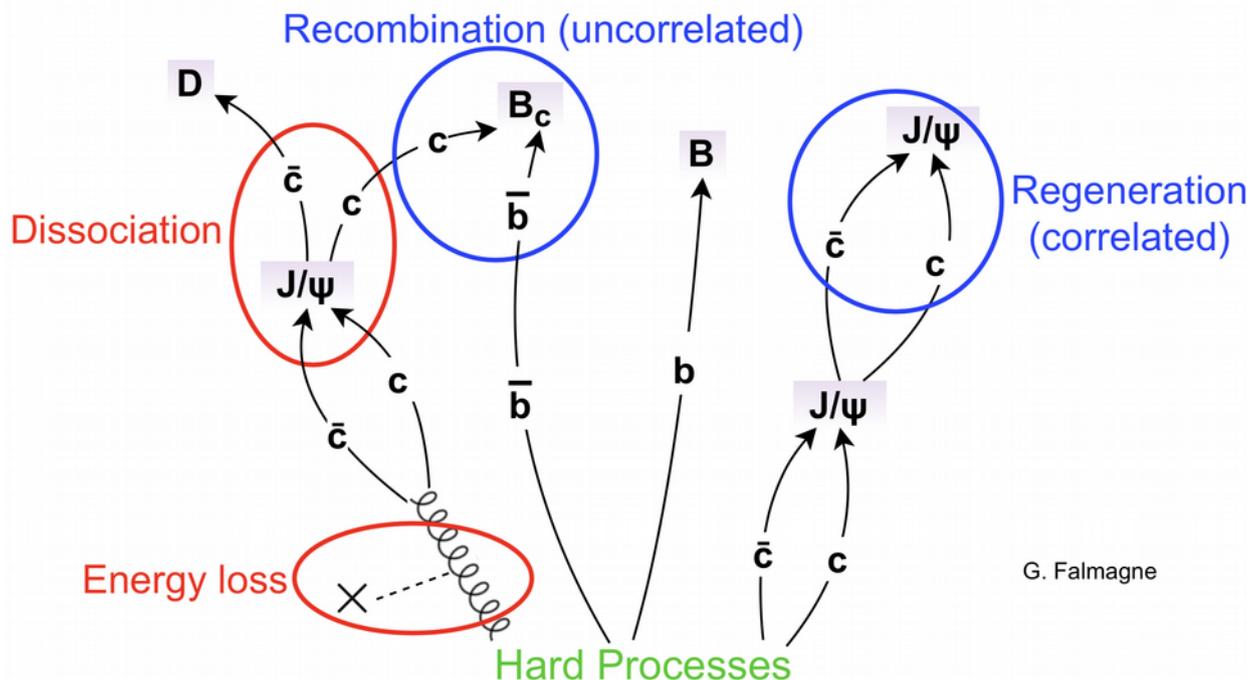
CMS-PAS-HIN-20-004

- B_c contains both b and c quark: **bridge** between bottom and charm mesons, and quarkonia
- provides unique insight into interplay between suppression and recombination (at low p_T)
- signal is three displaced muons (2 opposite-sign muon from J/Psi)

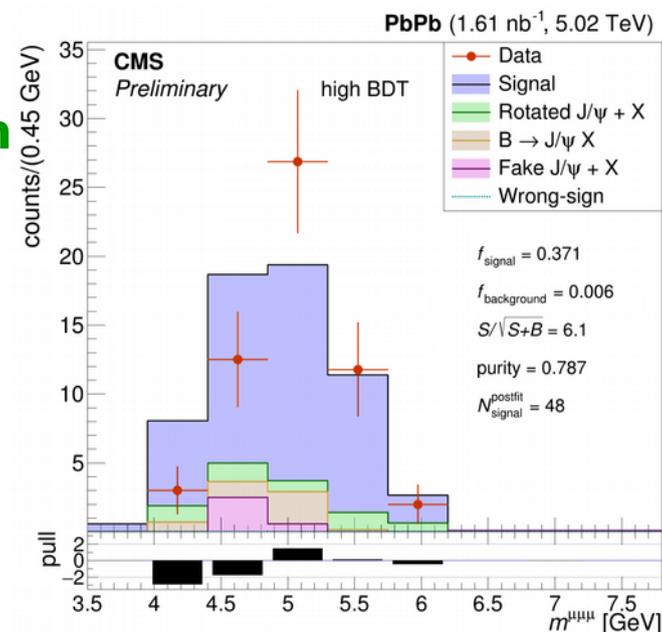


High BDT category

Interplay of several processes in B_c^+ production



G. Falmagne



First observation of B_c in PbPb collisions, significance > 5sigma



TOTEM highlights: odderon discovery

Slide by K. Österberg, [more information](#)

t-channel exchange of an odderon in elastic scattering at TeV energies predicts:

- **rapidly increasing total cross section & decreasing ρ parameter** in pp scattering

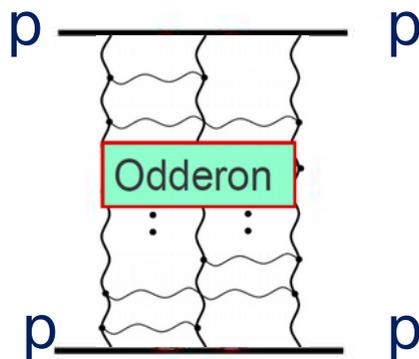
TOTEM collaboration, Eur. Phys. J. C 79 (2019) 785

- **significant difference between pp & $p\bar{p}$ elastic $d\sigma/dt$** in region of diffractive minimum & secondary maximum of the pp elastic $d\sigma/dt$

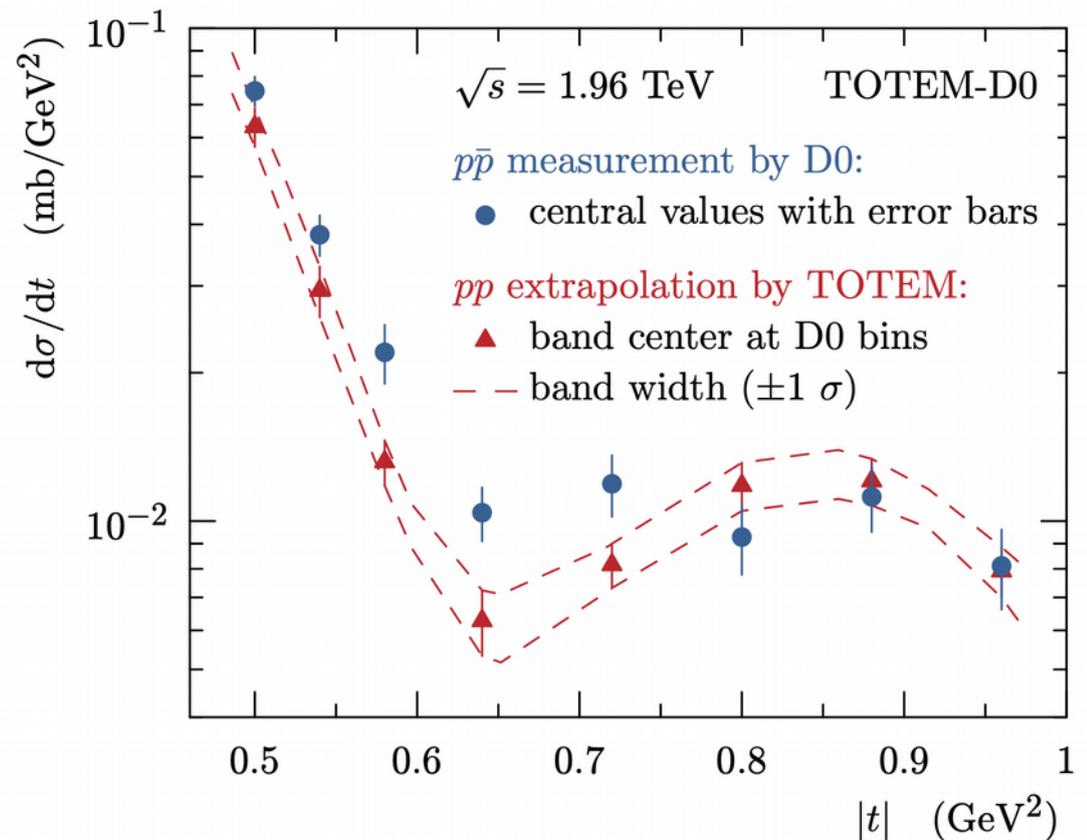
D0 and TOTEM collaborations, Phys. Rev. Lett. 127 (2021) 062003

Combining the 2 separate indications excludes models without t-channel exchange of odderon @ $5.2-5.7\sigma \Rightarrow$

observation of a colourless C-odd gluonic exchange, an odderon



odderon exchange:
compounds of 3 (or odd
number of) gluons
exchanged between
protons



CMS-TOTEM highlights: exclusive diphoton search

CMS and TOTEM collaborations, arXiv:2110.05916, submitted to Phys. Rev. Lett.

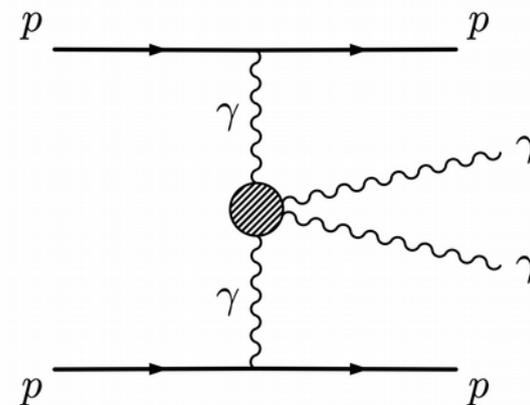
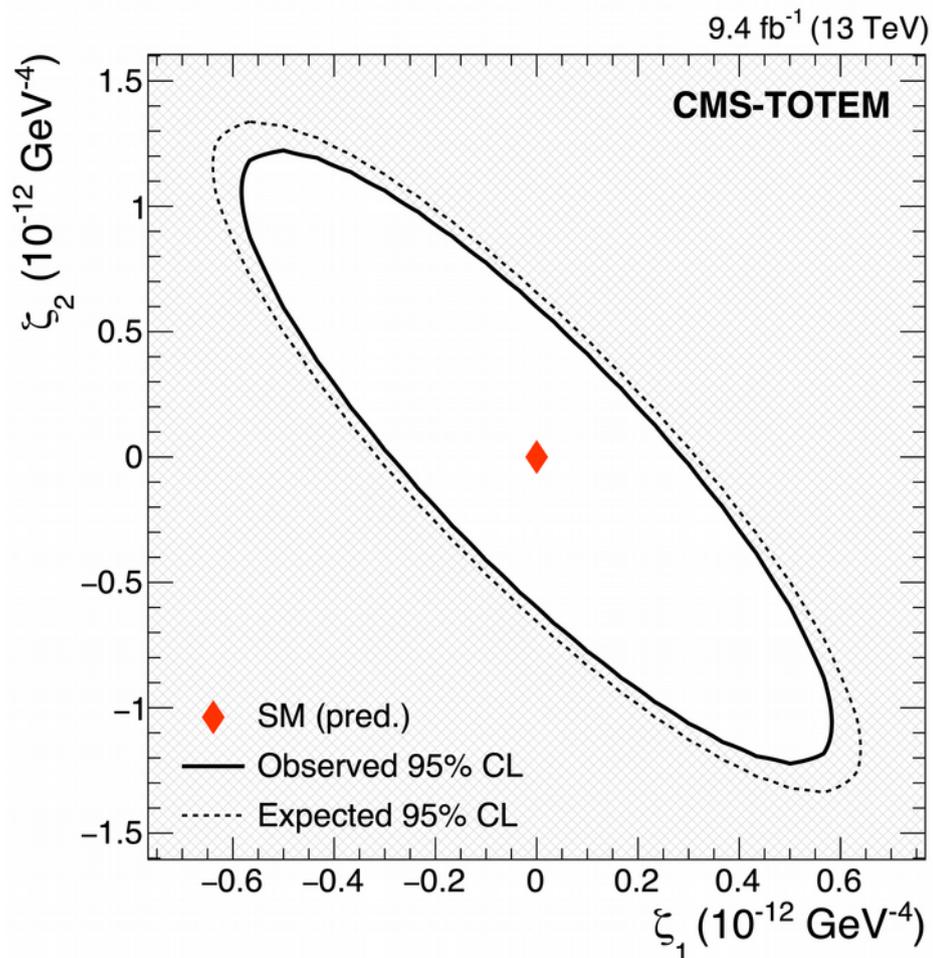
Slide by K. Österberg

High mass (> 800 GeV) exclusive diphoton search using 2016 CMS-TOTEM PPS data

Sensitive to anomalous 4-photon coupling & high mass axion like particles

Background significantly reduced
by rapidity & mass matching:

$$y_{\gamma\gamma} = y_{pp} \text{ \& } m_{\gamma\gamma} = m_{pp}$$

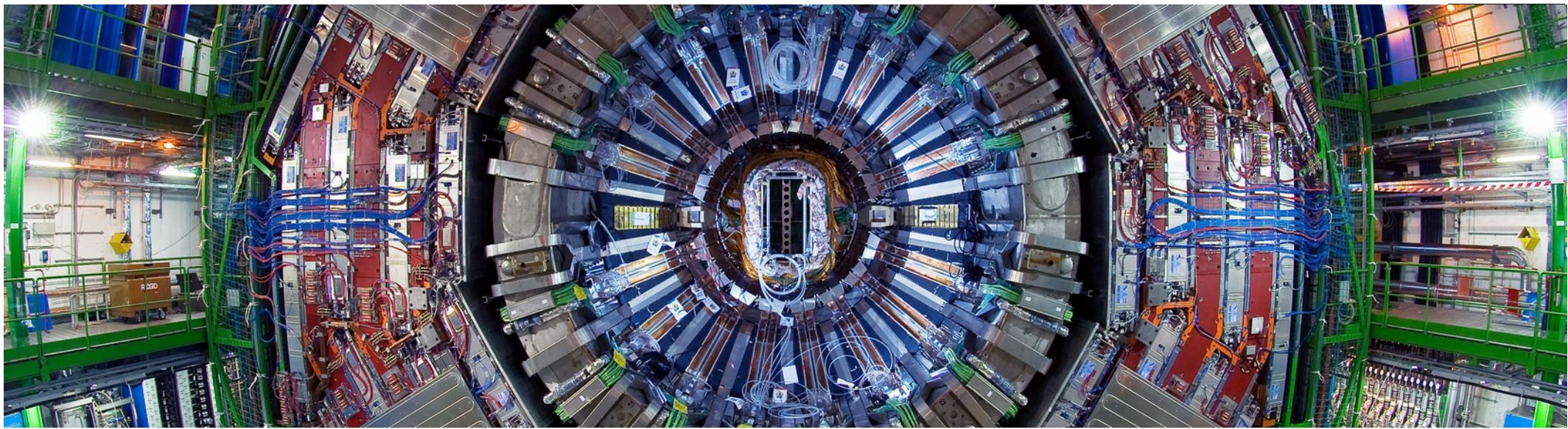


$$|\zeta_1| < 2.88 \times 10^{-13} \text{ GeV}^{-4} (\zeta_2 = 0)$$

$$|\zeta_2| < 6.02 \times 10^{-13} \text{ GeV}^{-4} (\zeta_1 = 0),$$

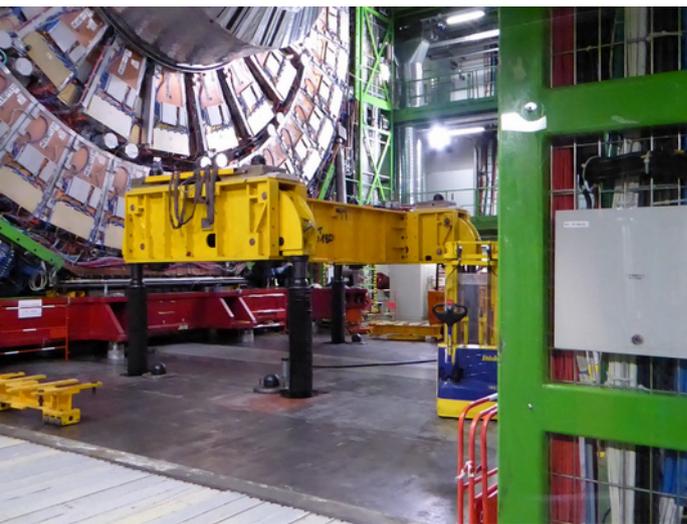
where $\zeta_{1,2} = a_{1,2}^{\gamma\gamma} / \Lambda^4$

First limits on the
4-photon coupling
parameters ζ_1 & ζ_2



Run 3

New Hardware & Methods / Physics Opportunities



16 Nov 2021



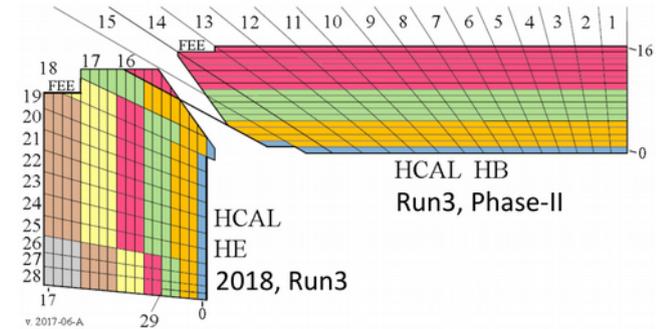
PPD 2021 Jyväskylä

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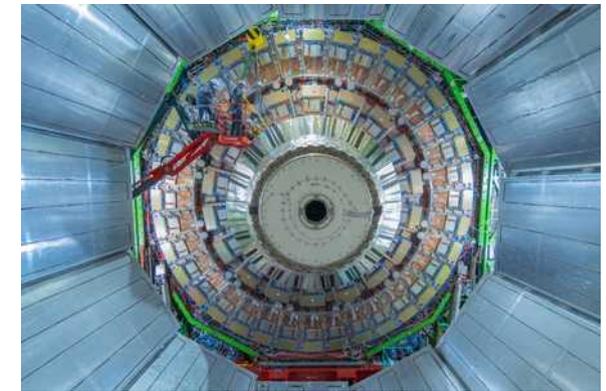
CMS New/Updated Hardware for Run 3

- Updates/refurbishment during LS2
- Successful Pilot Beam Test last month, CMS operated smoothly with full 3.8T magnetic field (pp @ 2x450 GeV)
- After a few relatively-minor LS2 interventions, CMS expected to be fully closed by annual Lab closure 2021 => **ready in time for start of Run 3**

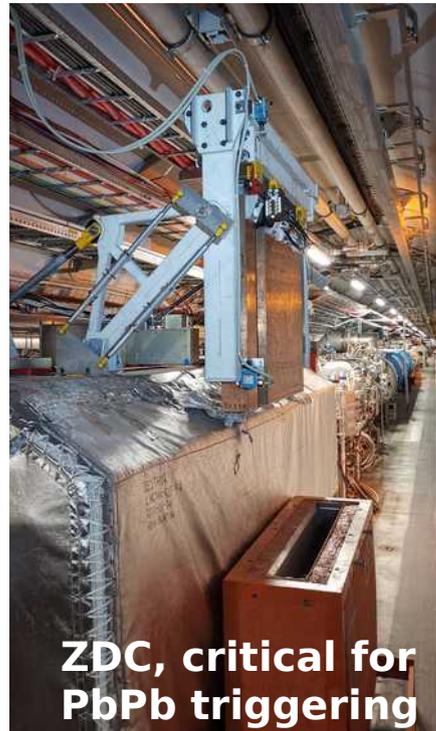
HCAL readout upgrade



GEM detector first station (GE1/1) (first Phase II upgrade)



New beam pipe installed



ZDC, critical for PbPb triggering

New Barrel Pixel L1 installed

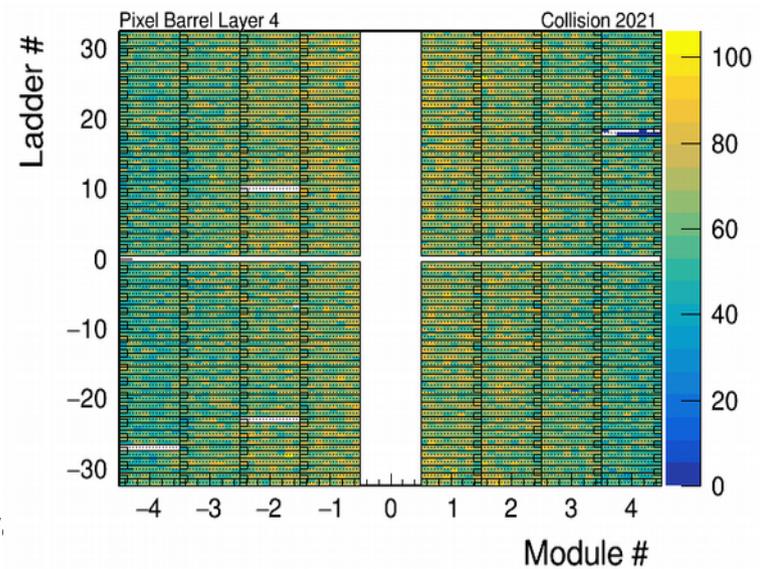
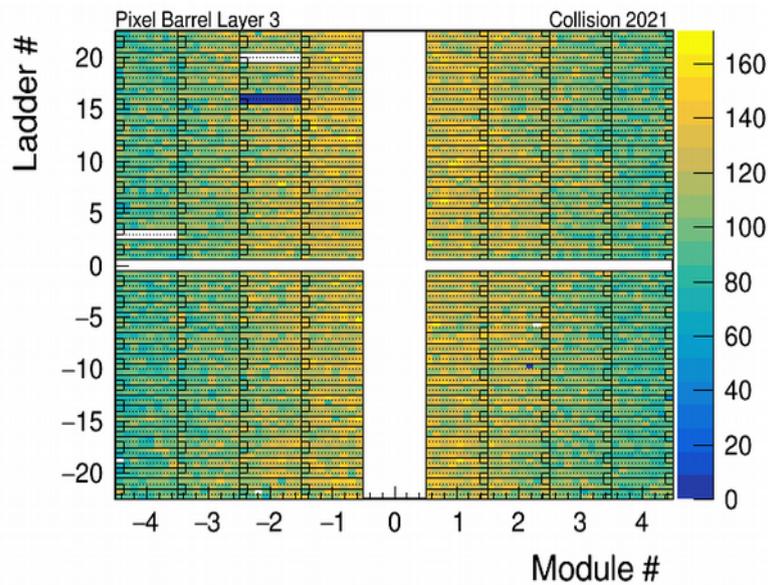
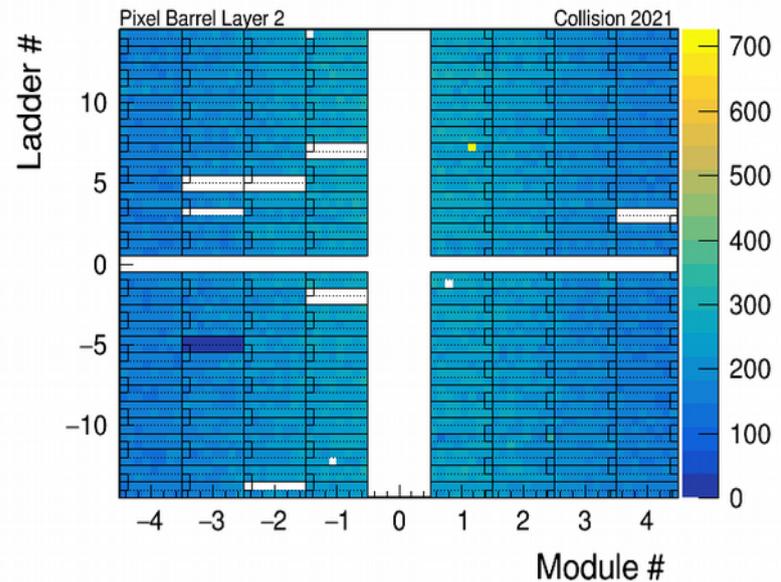
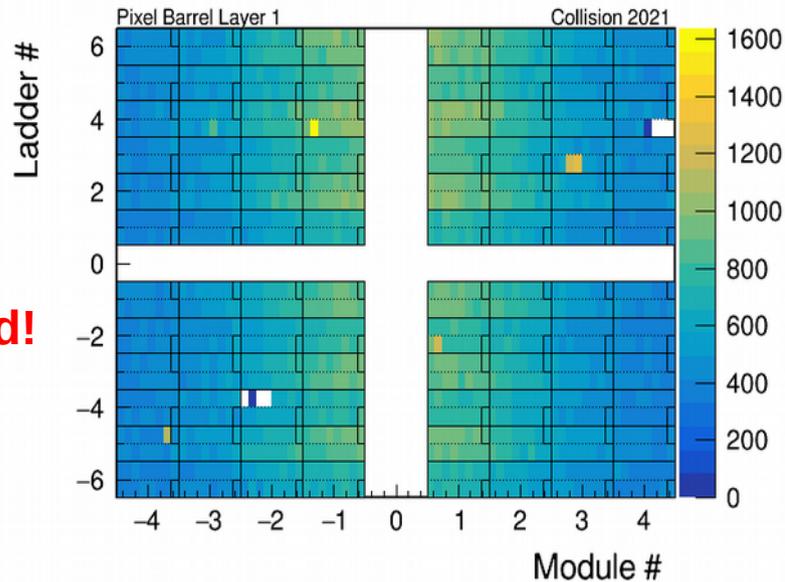


CMS New Pixel Layer for Run 3

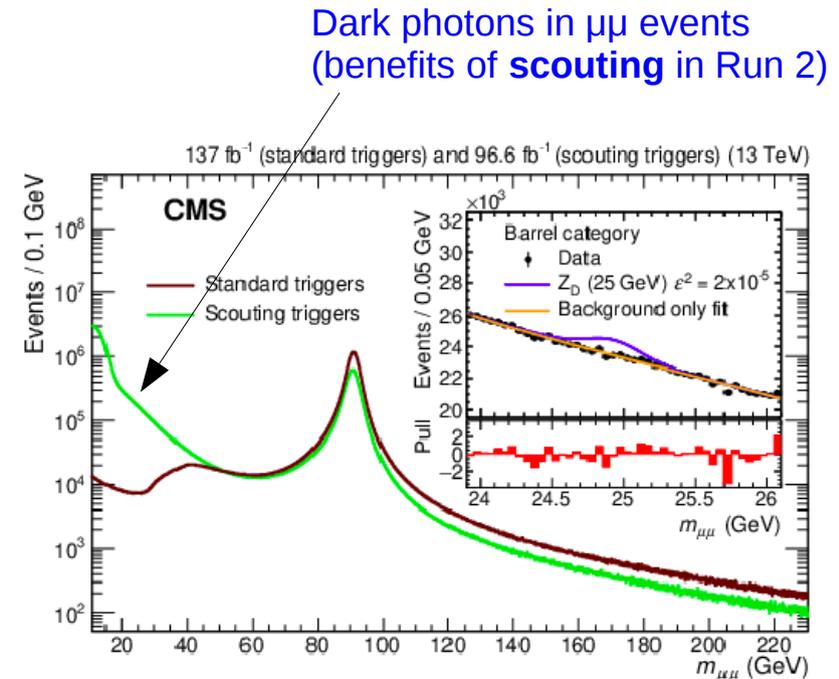
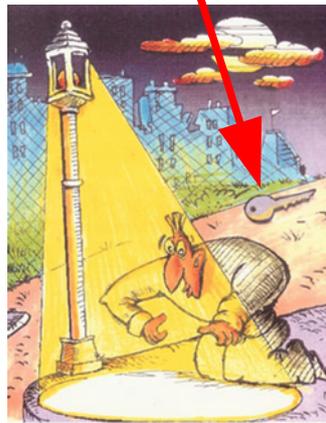
- Active fraction of new Pixel Layer 1 is 99.5%
(Barrel Pixel and Forward Pixel around 99% and 98%)

Cluster occupancy during collisions of 2021

**Layer 1
Renewed!**



- smart improvements in trigger and non-conventional data taking methods, e.g.
 - **Scouting** (trigger-level analysis):
 - online reconstruction at HLT farm with reduced data format
 - new phase space, increase of kinematic reach
 - e.g. low p_T , MET
 - **Parking:**
 - full raw data saved for later reconstruction
 - unbiased B decays collected with low p_T displaced triggers, to study e.g. LFU violation
 - **Long-lived particles (LLP)** improvements in L1 trigger
 - e.g. increase efficiency for signatures (displ. muons, out-of-time ECAL/HCAL, trigger with hadronic showers)



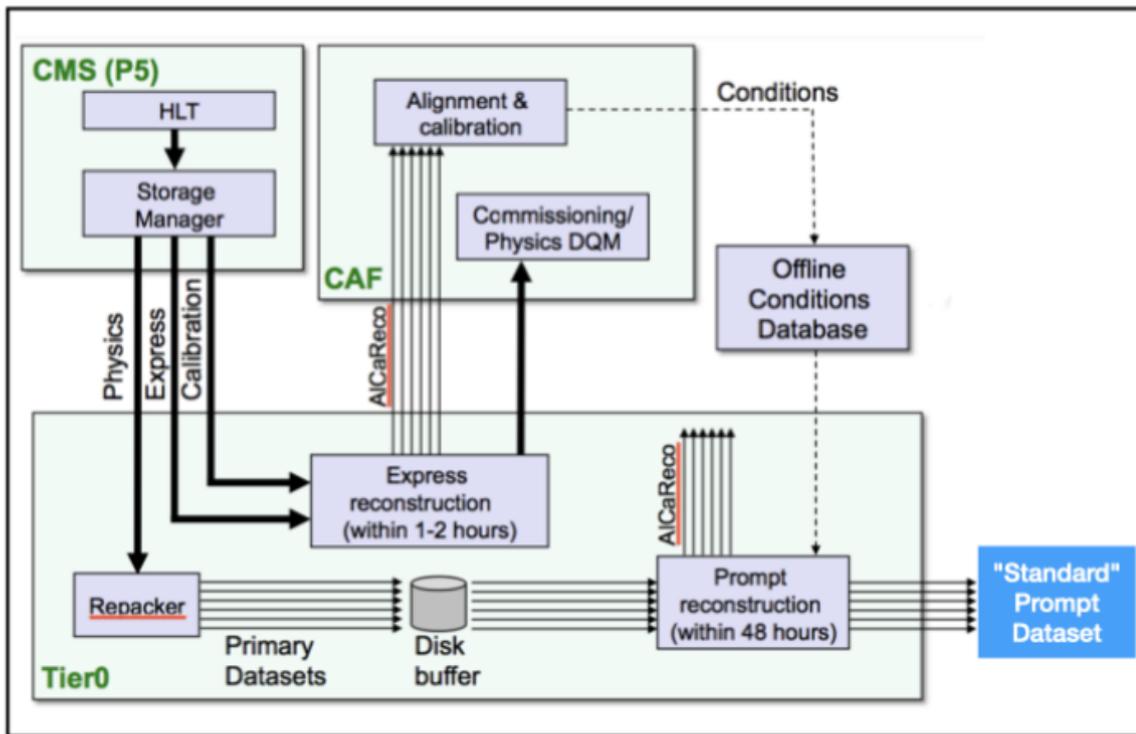
Faster Processing at HLT with Heterogeneous event reconstruction (CPU + GPU Nvidia T4)

- Improvement of 5-6x demonstrated
- ECAL & HCAL local reconstruction, pixel reconstruction and tracking.
- Current baseline for Run 3 HLT farm

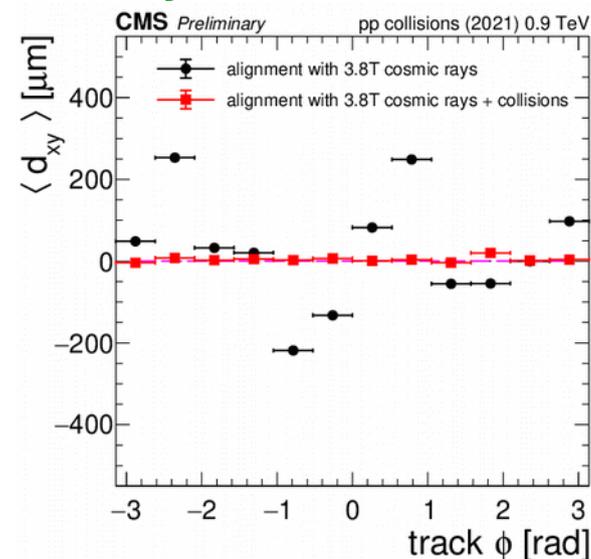
- Calibration workflows:
 - expertise from Legacy recalibration campaign
 - natural continuation: **automatization**, can improve significantly data quality right after data taking
 - framework for quick calibration **Prompt Calibration Loop (PCL)** exists, new calibrations are being implemented

- Current PCL Workflows:
- Beam-spot calibration
 - SiStrip bad-channel calibration
 - SiStrip Gains calibration
 - SiPixel Large structure alignment
 - SiPixel Lorentz angle calibration
 - ECAL pedestal calibration
 - PPS timing calibration

Prompt Calibration Loop (PCL) providing calibrations for reconstruction in 48h



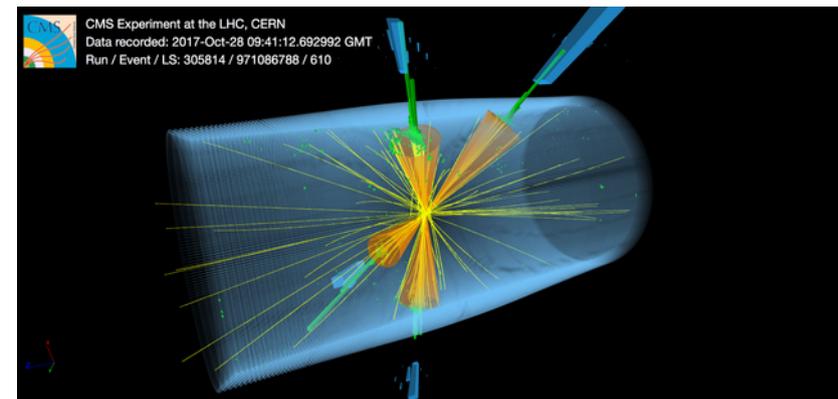
Run 3 Calibration already started Tracker detectors realigned with cosmic ray and Pilot beam data



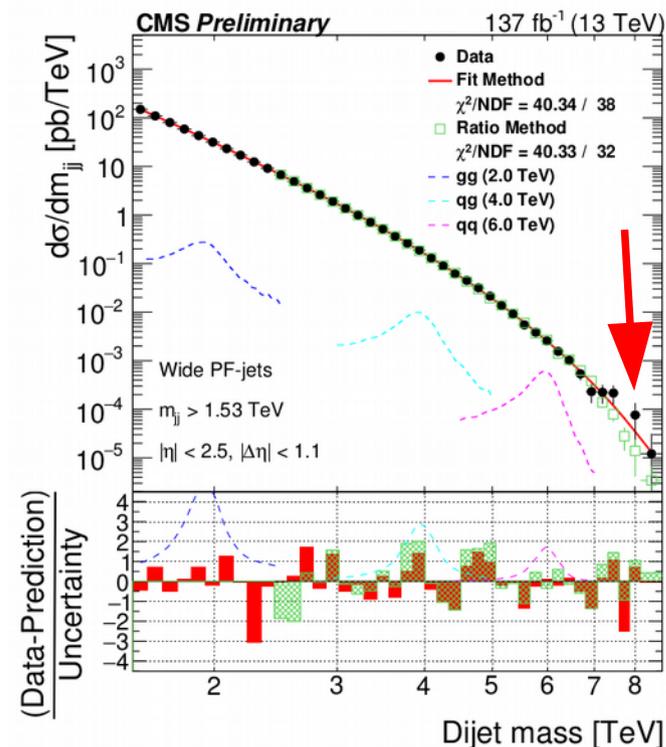
Average track impact parameter in the transverse plane showing no bias

JHEP (05) 2020, 033

- **Repetition** of all analyses with:
 - 1-2x integrated luminosity, **13->13.6 TeV**
 - improved **sensitivity** (e.g. new calibrations, ML techniques, trigger improvements)
 - new trigger methods can 10x data in dedicated samples
- Particularly interesting analyses:
 - High p_T / mass channels (small increase of collision energy can multiply cross section) → Search for high mass dijet resonances
 - Higgs boson pair production and self-coupling (CMS-PAS-HIG-20-005)
- Much more than 2x integrated luminosity!
- Remaining mysteries include: vacuum stability, SUSY WIMP, dark matter, jet quenching, #Higgs bosons
- In addition: have to prepare novel experimental methods for challenges of HL-LHC



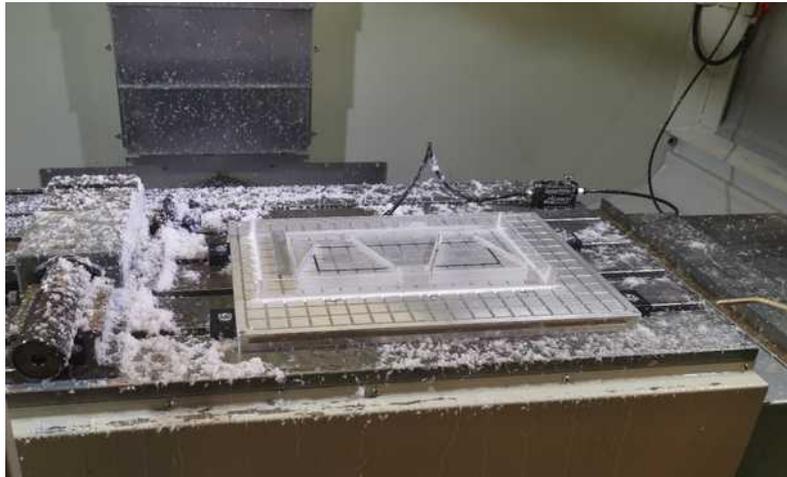
Search for high mass dijet resonances



TOTEM nT2 detector

- **New scintillator-based T2 detector ("nT2")** for measuring the inelastic rate in a 13.6 TeV (?) total cross section measurement run towards the end of 2022
- HIP contribution: scintillators, fibers and photo detectors.
- nT2 tile prototyping completed successfully & mass production on-going

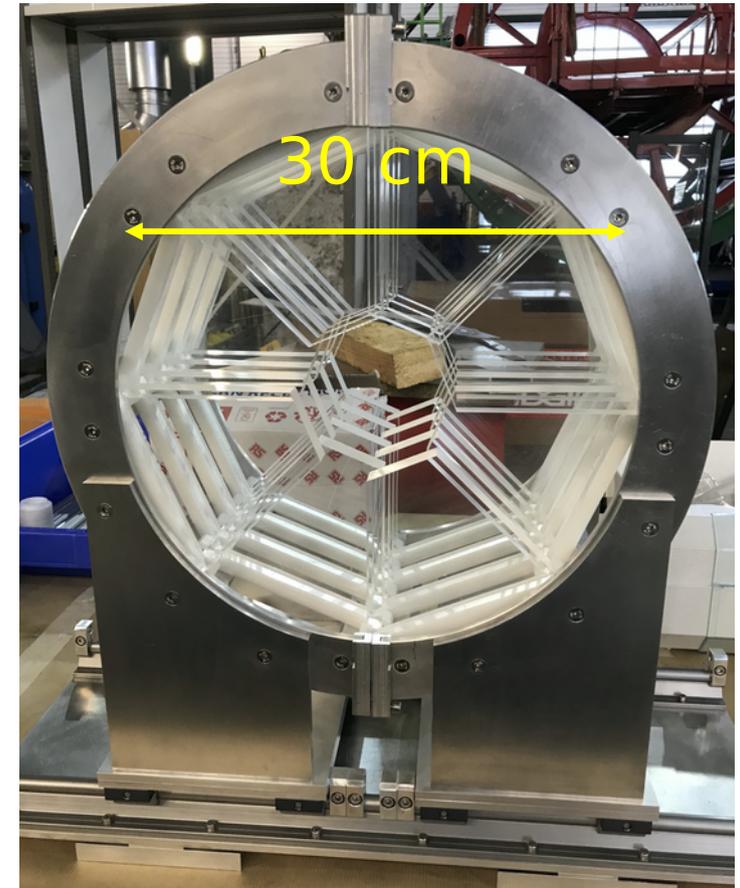
Tile cutting
with CNC
machine in
Physicum
workshop



Packaged scintillator tiles for first quarter

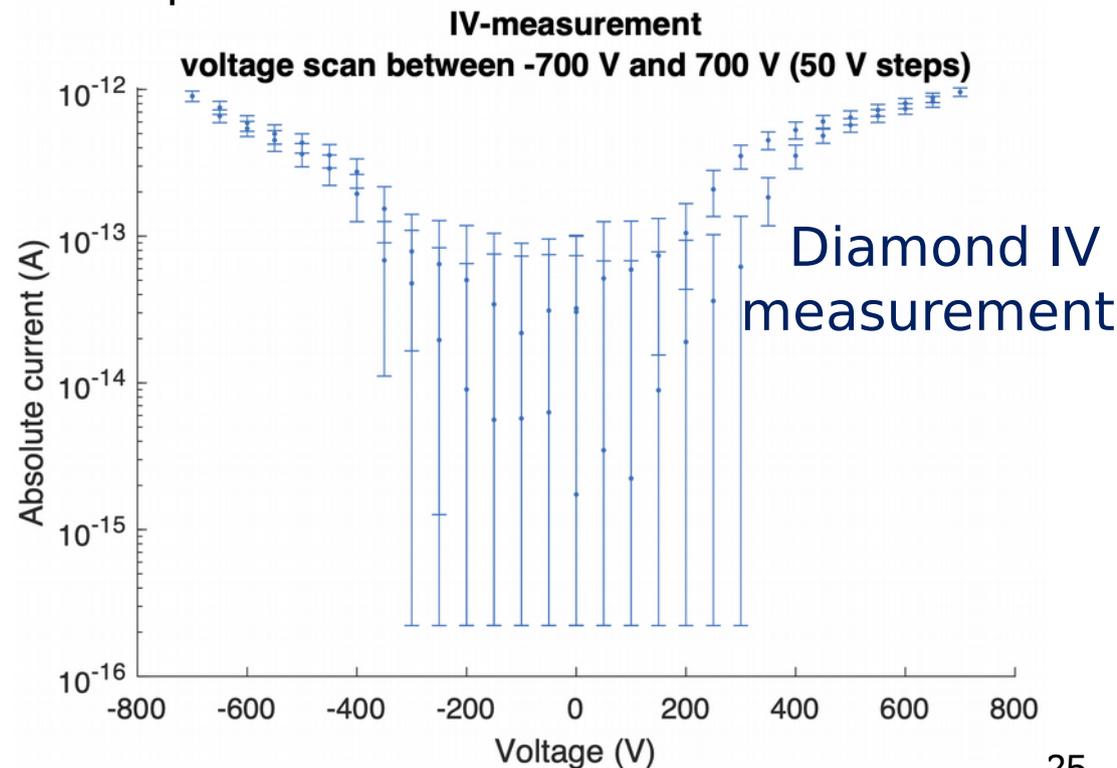
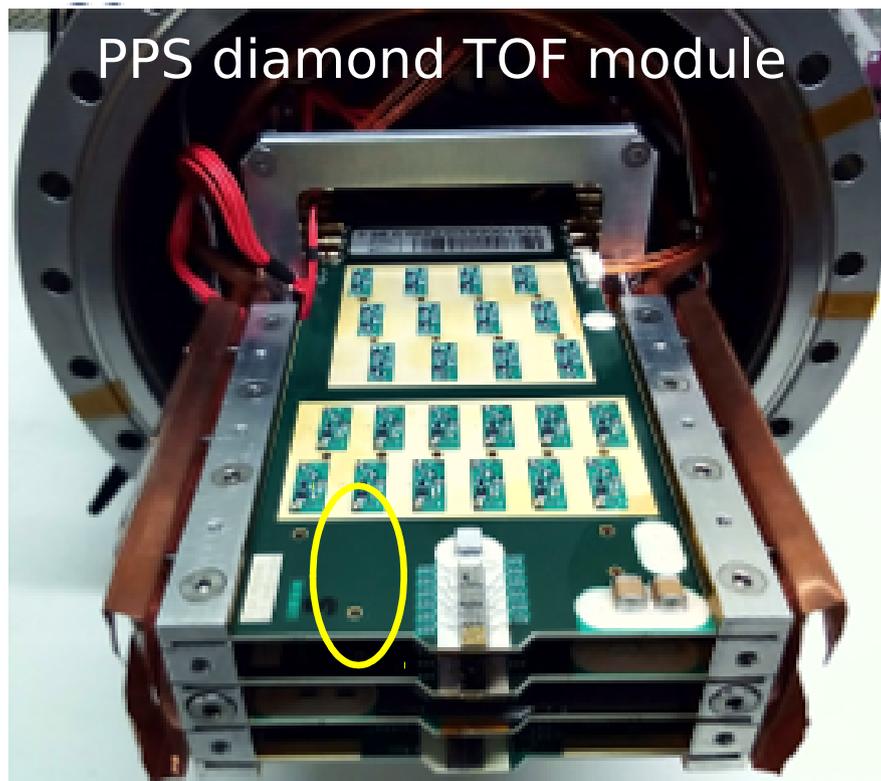


Half nT2 mockup

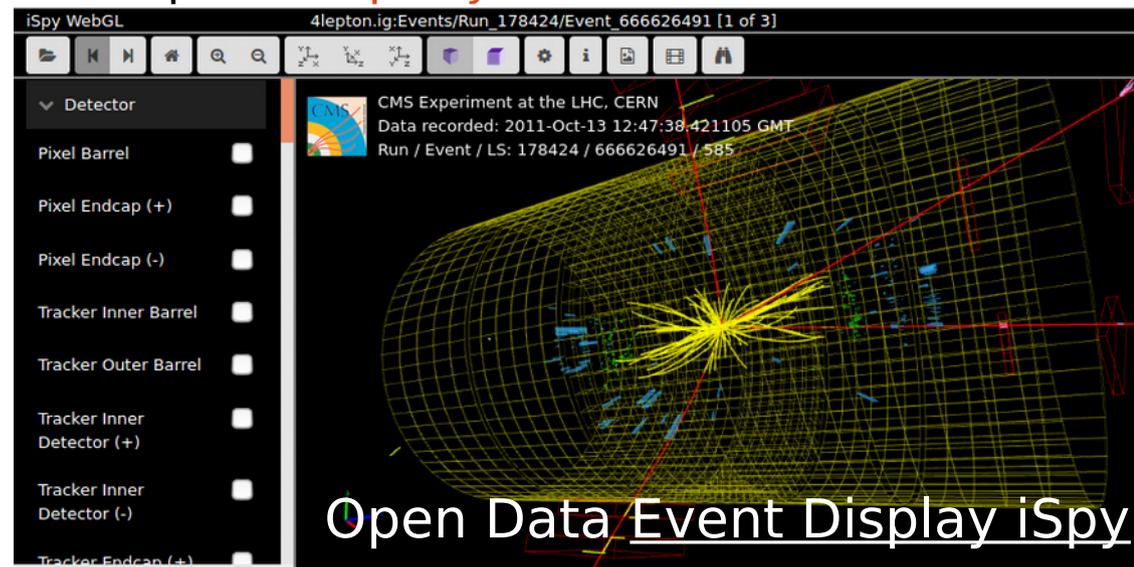


CMS PPS TOF detector upgrade

- **CMS Proton Precision Spectrometer (PPS):** study high mass exclusive processes ($pp \rightarrow p + X + p$) using proton detection in standard LHC high luminosity runs
- Time-of-flight (TOF) detector to match proton z vertex with z of central system X
- Run 3 upgrade: a second set of double-layered diamond TOF sensors for two additional timing RPs (1 RP/side of CMS) => **improve TOF precision to 30 ps**
- HIP contribution: diamond purchase, metallisation and QA
- Current plan: install diamonds in 2 timing RPs in Jan -22, then in 2 remaining RPs during short LHC technical stops in 2022



- Annual Univ. of Helsinki Open Science Award to Kati Lassila-Perini in facilitating the use of CMS open data of particle physics in research and education
- CMS has already released 100% of pp data from 2010-2011
- Release of first batches of HI data from 2010-2011 in Dec 2020 together with corresponding reference pp data
- Plans for CMS **Open Data**:
 - release of first batch of Run 2 pp data from 2015 by the end 2021 (data first time in slimmer - and easier-to-use - MiniAOD format)
 - 2022: releases of Run 2 pp data from 2016 ; remaining data from 2012 according to release timeline of CMS open data **policy**.
 - the CMS open data team facilitates use of these data
 - two **workshops** organized for CMS open data users, the next one in summer 2022
 - **user feedback and requests** are collected



- LHC entering Run 3 for 3 years, then era of HL-LHC starts in 2027
- Run 2 analyses going strong:
 - CMS has published many great results already, many more coming in next few years with fine-tuned Legacy data from 2016-2018
 - Odderon discory of TOTEM strongly suggests existence of gluonic particles; TOTEM also continues analysing Run 2 data
- Run 3 Outlook
 - TOTEM will install new nT2 detectors , CMS PPS will upgrade TOF detector
 - CMS: new/updated hardware, new methods and improvements in calibration, ==> better detector, better physics results (energy increase 13->13.6TeV can multiply cross section in high pT / mass channels!)
 - Essential preparation for HL-LHC (10x integrated luminosity)



Thank you!

Remark: Visit HIP blog: <https://blog.hip.fi/>