Flavour Physics at CMS

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భారతీయ సాంకేతిక విజ్ఞాన సంస్థ హైదరాబాద్
भारतीय प्रौद्योगिकी संस्थान हैदराबाद
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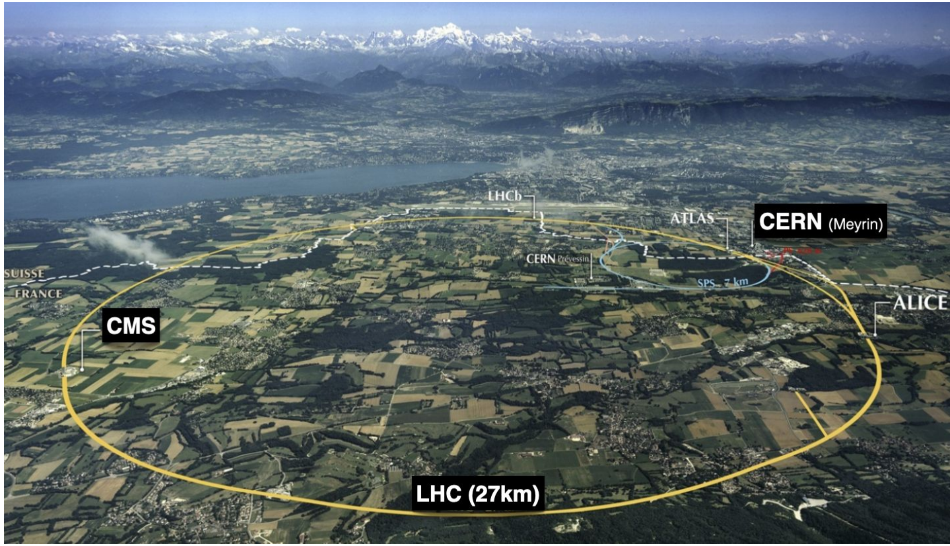
LHC & CMS

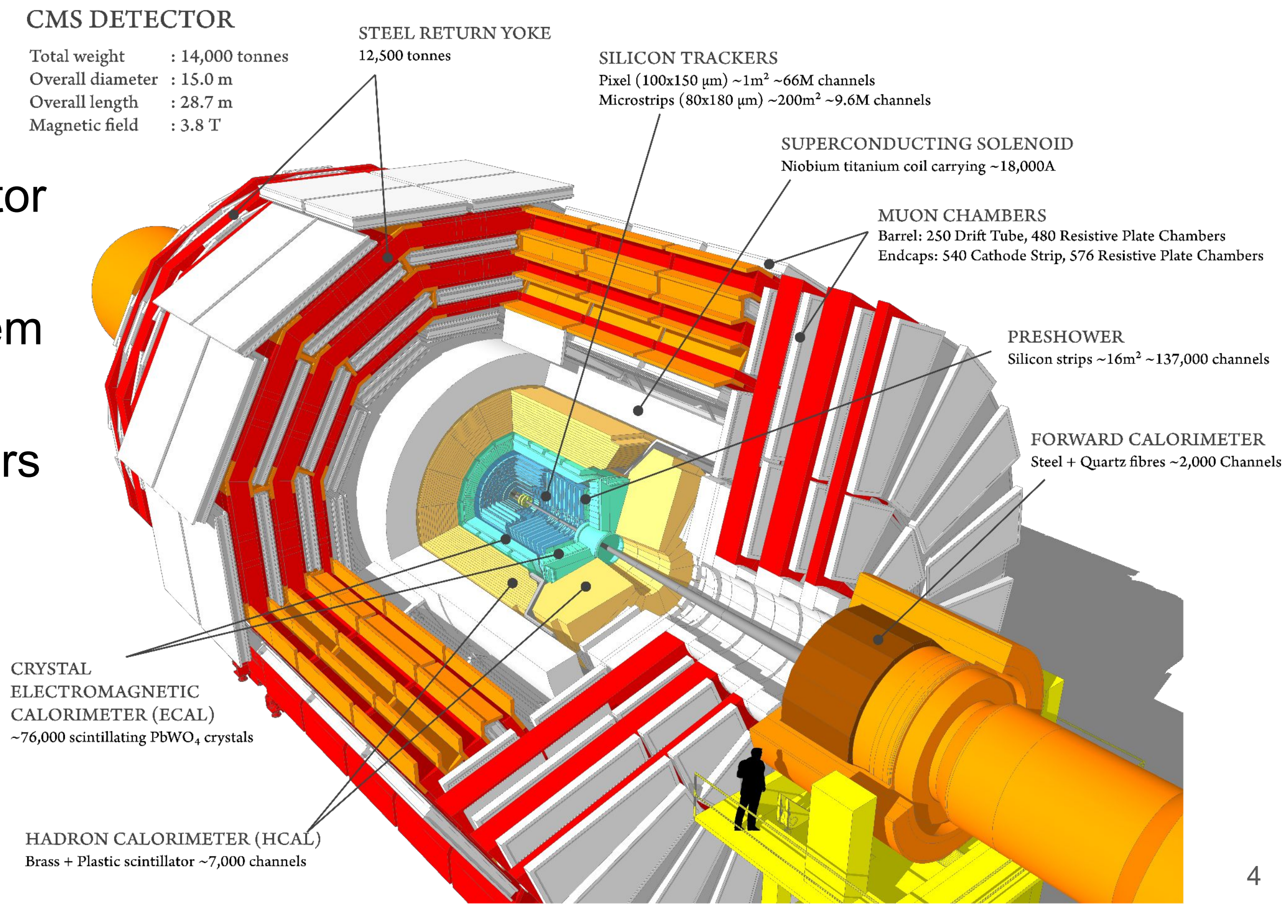
Large Hadron Collider (LHC)

- LHC is the world's largest and most powerful particle accelerator.
- Based at CERN, on the Franco-Swiss border near Geneva
- Designed to collide protons at com energy of 14TeV with instantaneous luminosity of $10^{34}/(cm^2 \cdot s)$
- Currently operating at 13.6 TeV
- 4 major experiments
- Leads the "Energy Frontier"

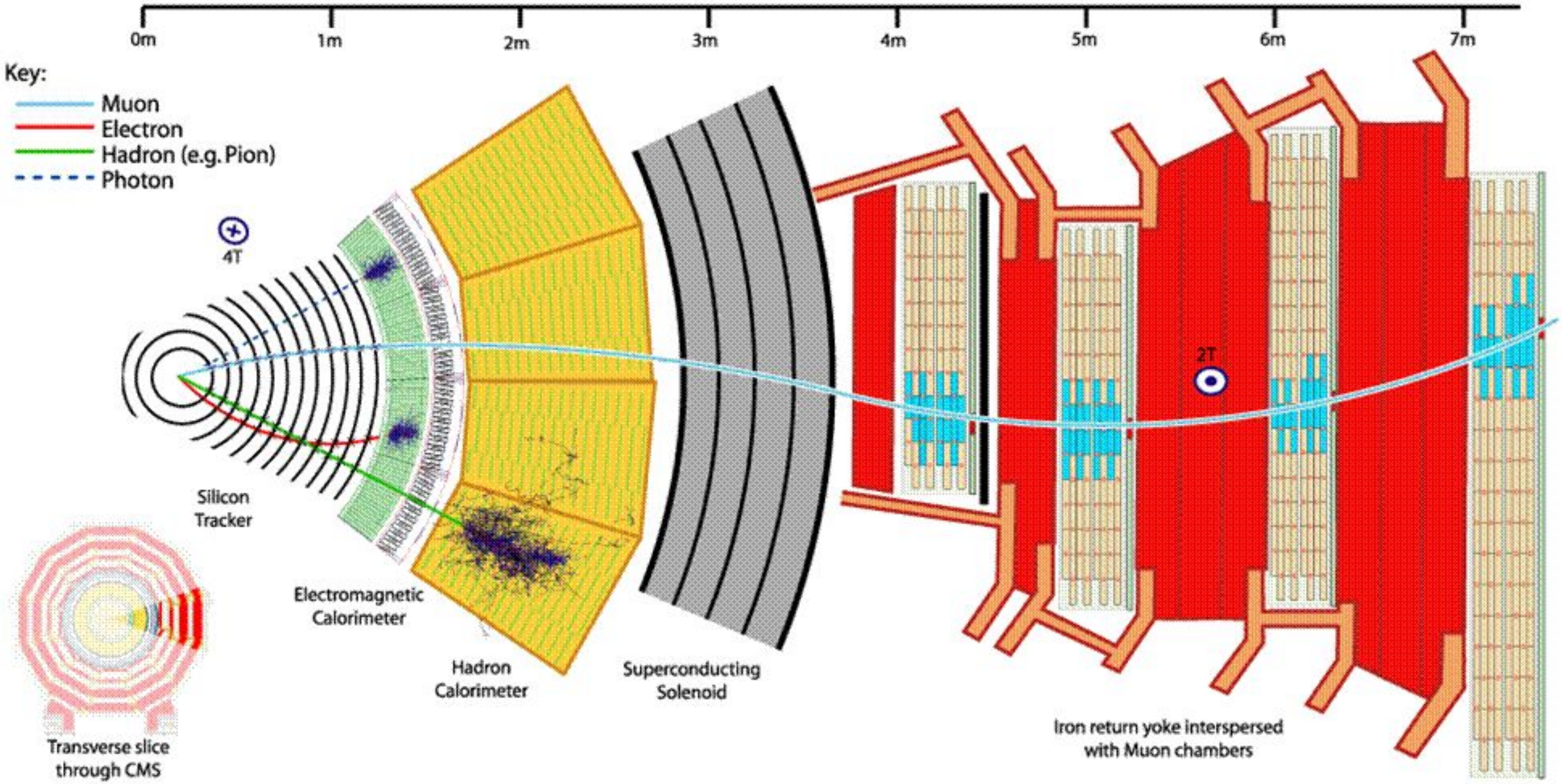


Compact Muon Solenoid (CMS) Detector

- General purpose detector
- Excellent tracking system
- Excellent muon detectors

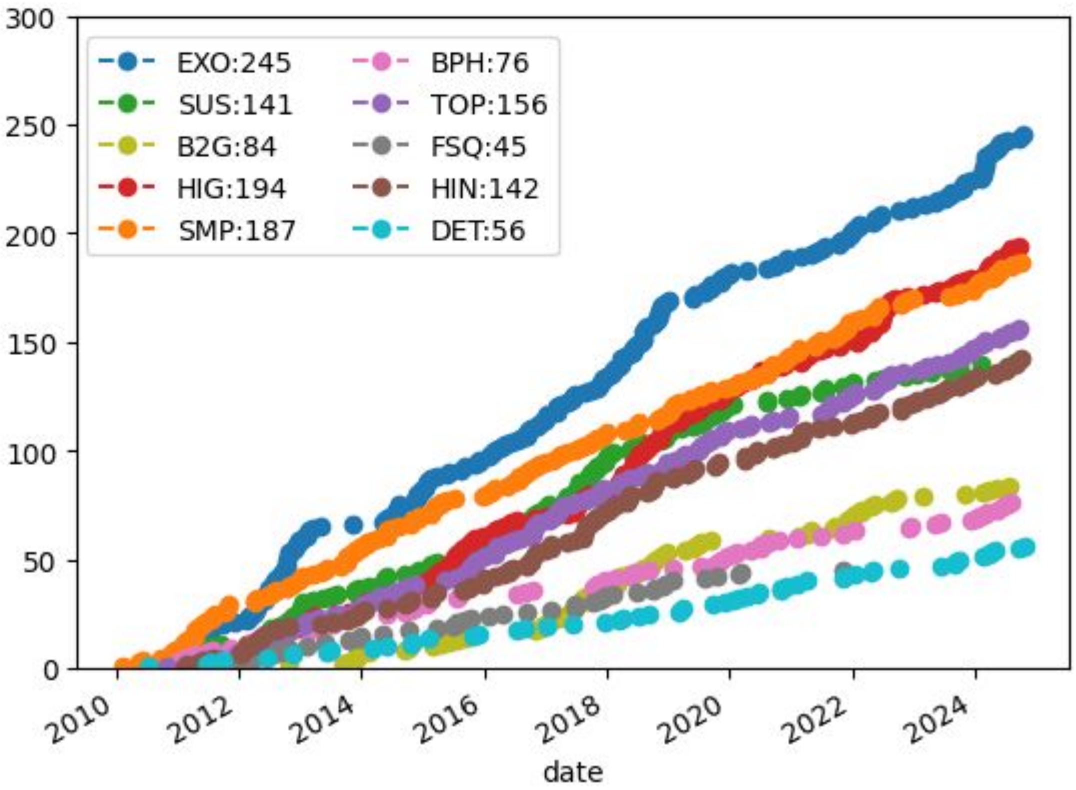


Particle reconstruction at CMS



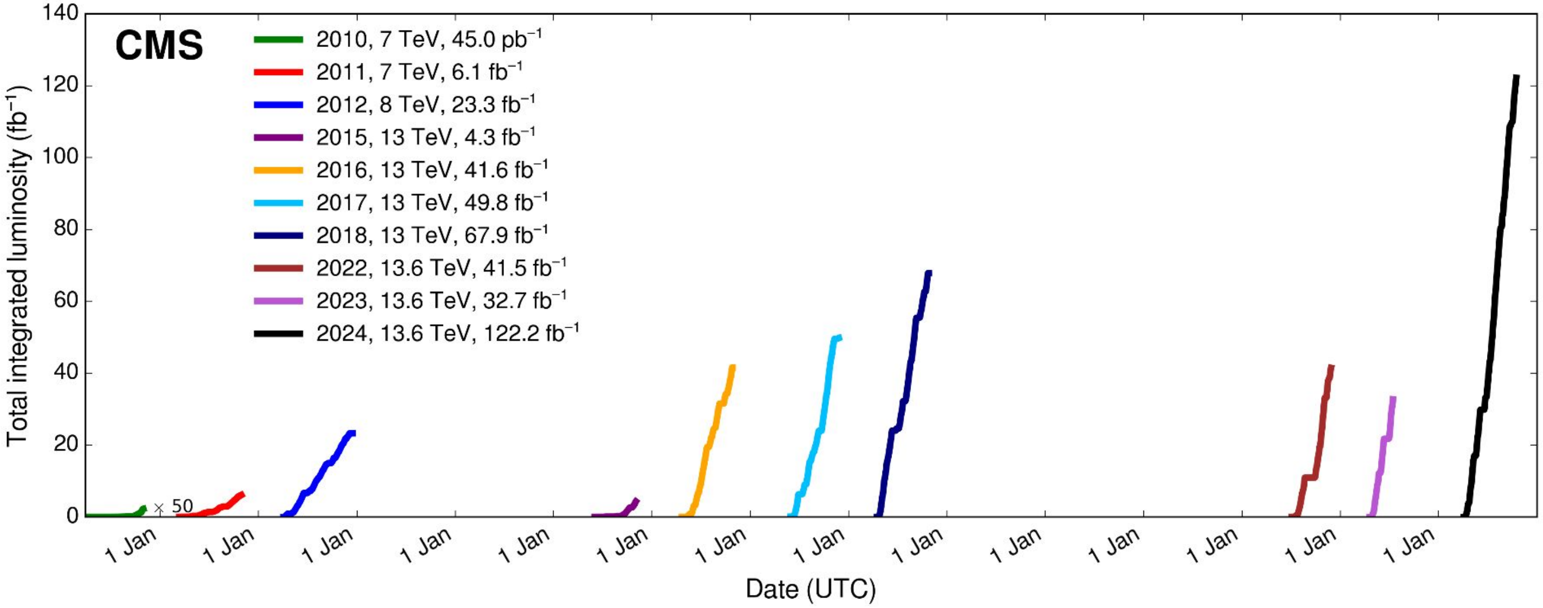
Physics at CMS

- CMS has a wide ranging physics program
  - Higgs studies
  - Standard Model measurements
  - BSM searches
  - Top quark physics
  - Flavour physics
  - Heavy ion physics
  - etc.



Luminosity

- Integrated Luminosity Recorded by CMS during proton collisons



Luminosity

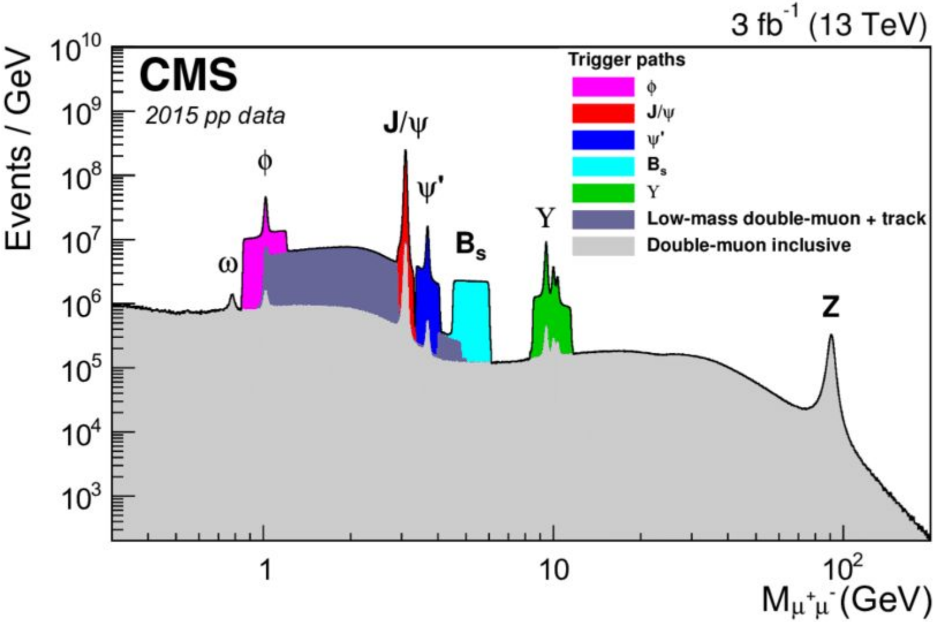
- Comparison with LHCb:

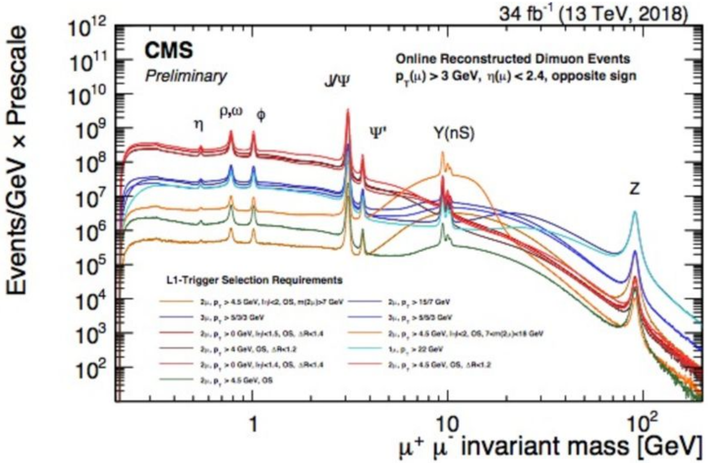
	LHC era			HL-LHC era	
	Run 1 7, 8 TeV (2010-12)	Run 2 13 TeV (2015-18)	Run 3 ~14 TeV	Run 4 ~14 TeV	Run 5+ ~14 TeV
ATLAS, CMS	25 fb	100 fb	300 fb	→	3000 fb
LHCb	3 fb	8 fb	23 fb	46 fb	100 fb

- Significantly higher luminosity recorded by CMS compared to LHCb

Trigger

- Main challenge for Falvour physics is the triggering
    - And low momenta object reconstruction
- Dimuon triggers are most useful





Flavour at CMS

Rare decays

nature

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nature › letters › article

Letter | Open access | Published: 13 May 2015

Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

CMS Collaboration & LHCb Collaboration

Nature **522**, 68–72 (2015) | Cite this article

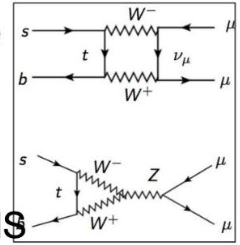
Rare decays: $B^0_{(s)} \rightarrow \mu^+\mu^-$

cds.cern.ch/record/2815334

$B^0_{(s)} \rightarrow \mu^+\mu^-$
the physics case

motivations

- $B^0_{(s)} \rightarrow \mu^+\mu^-$ strongly suppressed in the SM (FCNC and helicity)
- connected to $b \rightarrow s l^+ l^-$ transitions via the EFT operators can help understand $b \rightarrow s$ anomalies doi.org/10.1140/epjc/s10052-021-09725-1
- probe SM though lifetime measurements
- clear final state and experimental signature at CMS



result

- pp @ 13 TeV Run2 data (2016-2018) 140 /fb
  - updates the published result on 2016 data (30 /fb)
- 12.5 sigma observation of the $B^0_{(s)} \rightarrow \mu^+\mu^-$ decay, upper limit on the $B(B^0 \rightarrow \mu^+\mu^-)$ and life time measurement of $B^0_{(s)} \rightarrow \mu^+\mu^-$

Rare decays: $B^0_{(s)} \to \mu^+\mu^-$: New results

$B^0_{(s)} \to \mu^+\mu^-$ results

$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 3.83^{+0.38}_{-0.36}(stat)^{+0.14}_{-0.13}(syst)\ ^{+0.14}_{-0.13}(fs/fu)$

x 10^{-9} (from $J/\Psi\ K^+$)

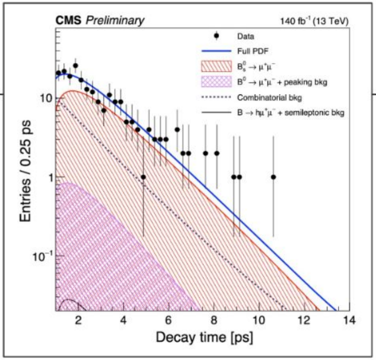
$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 3.95^{+0.39}_{-0.37}(stat)^{+0.27}_{-0.22}(syst)\ ^{+0.21}_{-0.19}(BF)$

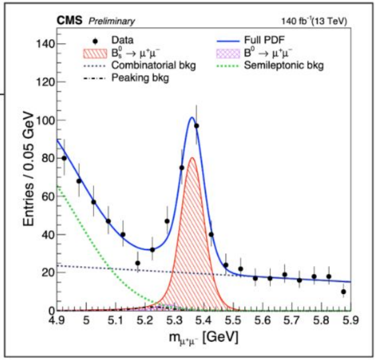
x 10^{-9} (from $J/\Psi\phi$)

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.5 \times 10^{-10}$ @ 90% CL

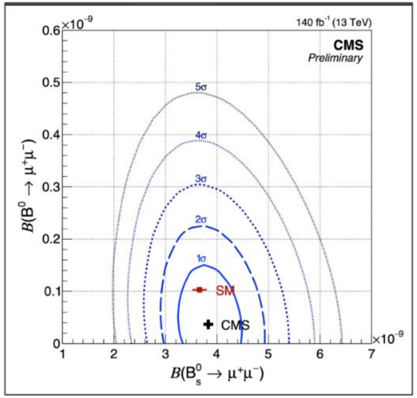
$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10}$ @ 95% CL

$\tau(B^0_s) = 1.83^{+0.23}_{-0.20}(stat)^{+0.04}_{-0.04}\ (syst)$ ps





- All UML fit results are compatible with the SM prediction within 1 sigma
- most precise measurement of $B^0_s \to \mu^+\mu^-$ branching fraction and lifetime to date



Rare decays

doi.org/10.48550/arXiv.2305.04904

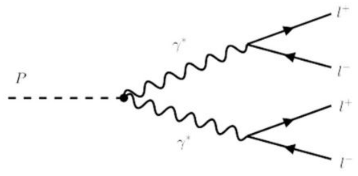
$\eta \to 4\mu$

motivation

- $\eta \to 4\mu$ decay predicted with a very low branching fraction (3.9×10^{-9})
  - never observed so far: precision test of the Standard Model (SM)
  - sensible to new physics scenarios doi.org/10.1016/j.physrep.2021.11.001

result

- first observation of the rare $\eta \to 4\mu$ decay



data scouting

- trigger thresholds limited by the computing power and bandwidth of the experiment
- reduce event size and fasten data acquisition
  - limit the amount of information to muon tracks
  - save HLT reconstruction and skip *prompt* event processing
  - event size reduced to ~kB (from ~MB)

→ can use looser muon thresholds → allow for low transverse momentum (pT) rare decays searches

Heavy flavor spectroscopy : Recent results

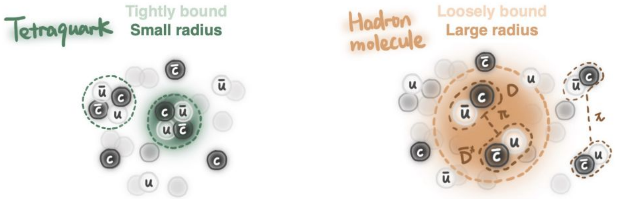
- X(3872) studies
  - Measurement of X(3872) to $J/\psi\pi^+\pi^-$ (2013)
  - Observation of $B_s^0 \to X(3872)\phi$ (2020)
  - Evidence of X(3872) in PbPb collisions (2022)

- Observations of new exotic hadrons
  - Observation of X(4140) in $J/\psi\phi$ from $B^\pm \to J/\psi\phi K^\pm$ (2014)
  - Observation of new structure in $J/\psi\, J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (2023)

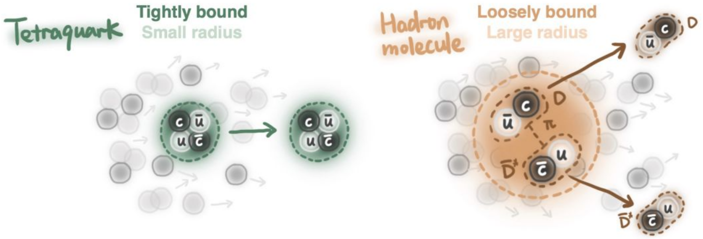
- Observations of new decay channels (after 2022 only)
  - Observation of $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ (2022)
  - Observation of $\Lambda_b^0 \to J/\psi\,\Xi^- K^+$ (2024)
  - Observation of $\Xi_b^- \to \psi(2S)\Xi^-$ (2024)

Heavy flavor spectroscopy : X(3872) in HI collisions

- Coalescence with particles in QGP ➜ Enhance X(3872)



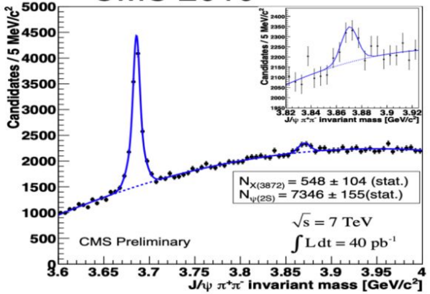
- Breakup by co-moving particles ➜ Suppress X(3872)

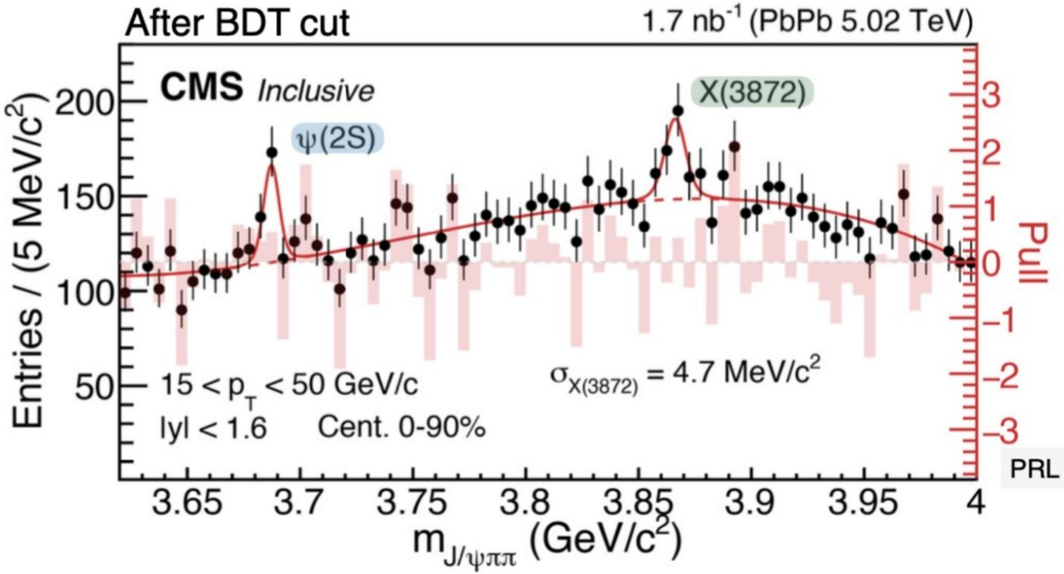


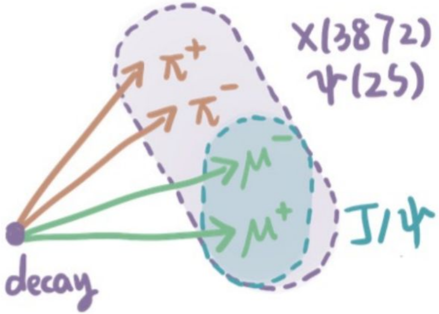
Heavy flavor spectroscopy : X(3872) in HI collisions

- First evidence of X(3872) production in HI
- Statistical significance ~ 4.2 σ

CMS 2010



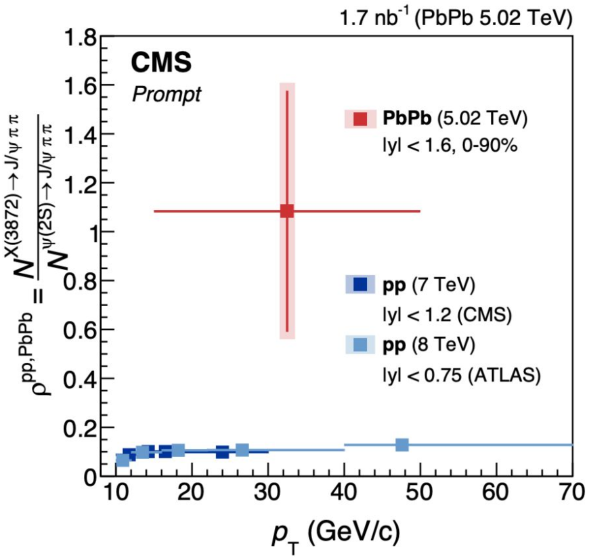




PRL 128 (2022) 032001

Heavy flavor spectroscopy : X(3872) in HI collisions

X(3872)/ψ(2S) Ratio in PbPb



PRL 128 (2022) 032001

- X(3872) to ψ(2S) ratio
  ρ_{PbPb} = 1.08 ± 0.49 (stat.) ± 0.52 (syst.)
- Indication of ρ enhancement in PbPb w.r.t to pp
- Better precision needed to draw conclusion

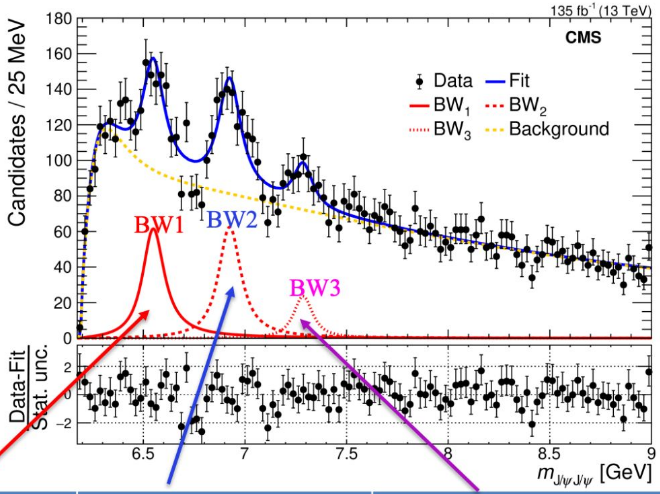
Heavy flavor spectroscopy : J/ψJ/ψ -> 4 muons

PRL 132 (2024), 111901

χ^2 Prob. = 1%

[6.2,7.8] GeV

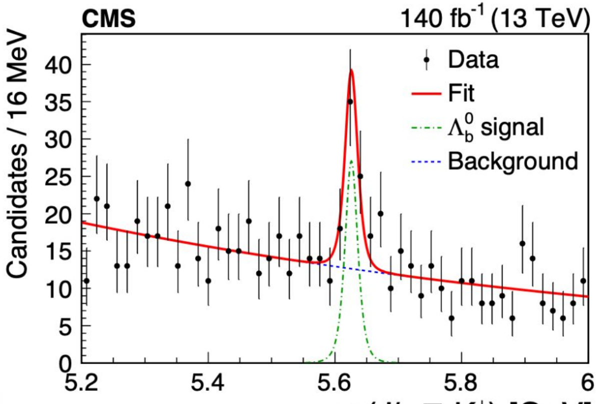
Statistical significance based on:
$2\ln(L_0/L_{max})$

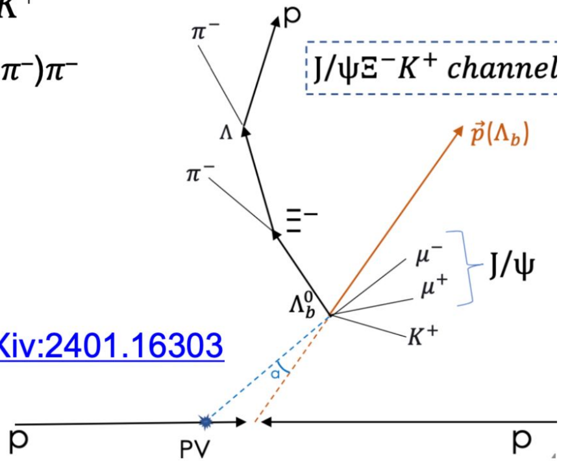


	BW1 (MeV)	BW2 (MeV)	BW3 (MeV)
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
Γ	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}
σ(stat.)	6.5	9.4	4.1
σ(stat. + syst.)	5.7	9.4	4.1
	Observation	Confirmation of X(6900) from LHCb	Evidence

Heavy flavor spectroscopy：Observation of new decay channels

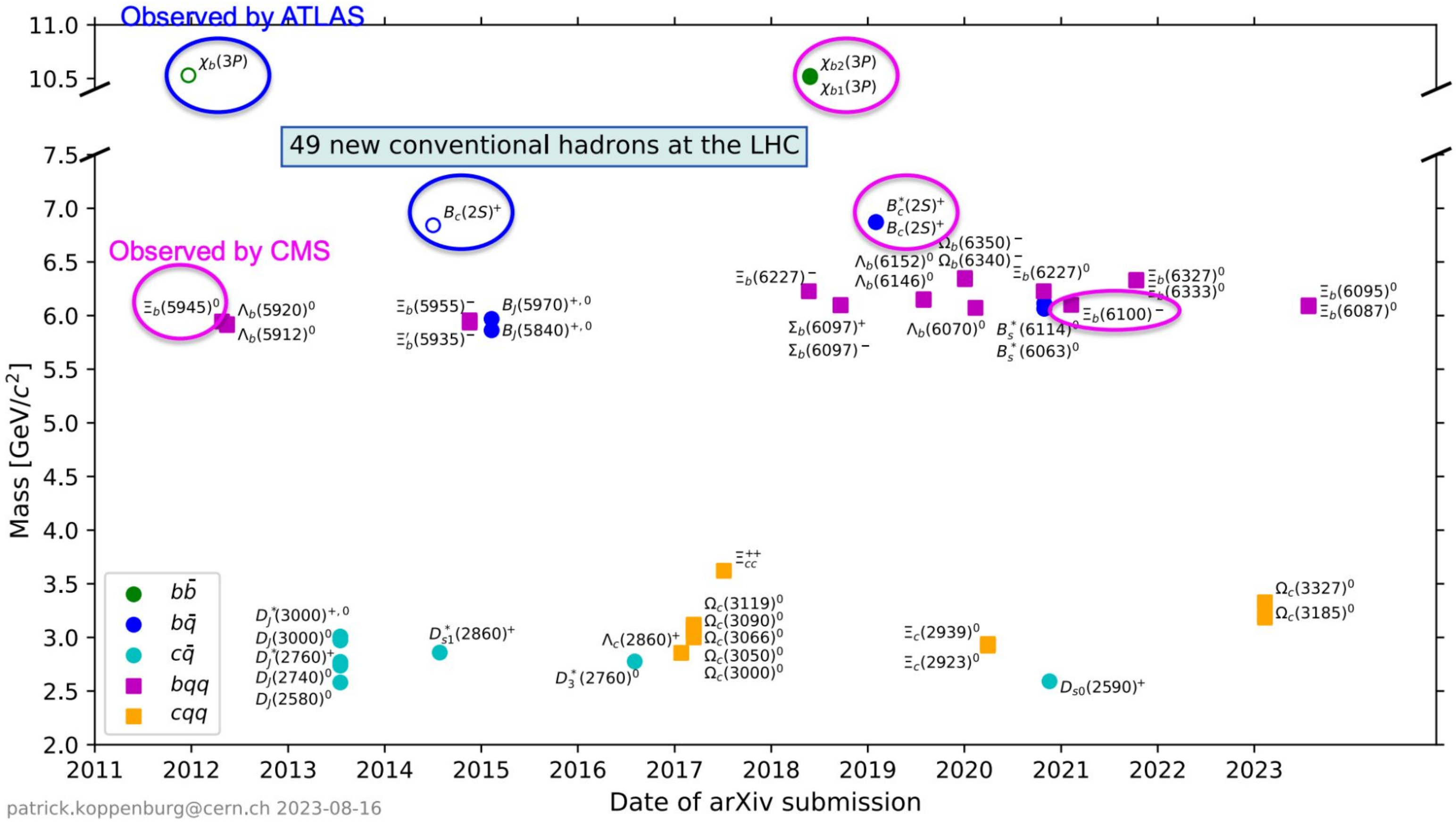
- Multi-body decays of b-hadrons may proceed through exotic intermediate resonances
  - E. g. pentaquark $J/\psi\, p$ structure in $\Lambda_b \to J/\psi\, p\, K^-$ observed by LHCb
  - $\Lambda_b \to J/\psi\, \Xi^- K^+$ final state can unveil yet-unobserved (e. g. doubly-strange) pentaquarks
- First-time observation of $\Lambda_b \to J/\psi\, \Xi^- K^+$
  - In final states with $J/\psi \to \mu\mu$, $\Xi^- \to \Lambda(\to p\pi^-)\pi^-$
  - $\mathbf{5.8\,\sigma}$ significance





arXiv:2401.16303

New conventional hadrons at the LHC



https://www.nikhef.nl/~pkoppenb/particles.html

Lepton Flavour Universality studies

Tests of LFU in the Heavy Flavor sector

$b \to s\ell\ell$

$$R(H_s) = \frac{\mathcal{B}(H_b \to H_s\mu\mu)}{\mathcal{B}(H_b \to H_s ee)}$$

- Small BR (loop level)
- Precise theoretical predictions
- Neutrino-less

$$R_K = \frac{BF(B \to \mu\mu K)}{BF(B \to eeK)}$$

SM: 1.00 ± 0.01

$b \to c\ell\nu_\ell$

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c\tau\nu_\tau)}{\mathcal{B}(H_b \to H_c\mu\nu_\mu)}$$

- Large BR (tree level)
- Theory and syst. uncertainties
- Neutrinos in the final state

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$

SM: 0.2582 ± 0.0038
PRL 125, 222003 (2018)

Lepton Flavour Universality studies

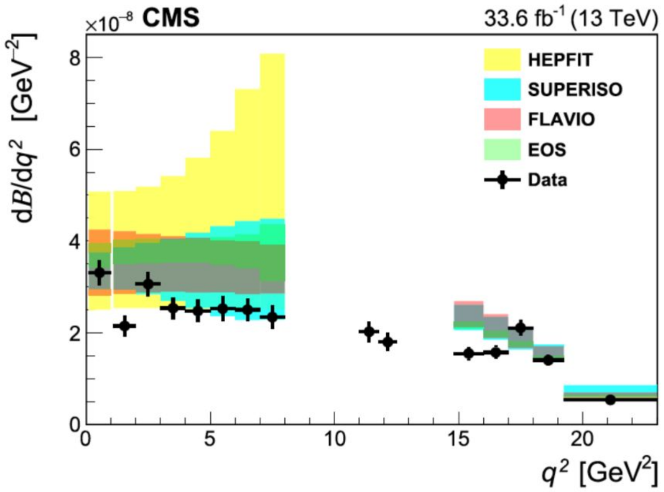
Rep. Prog. Phys. 87 077802

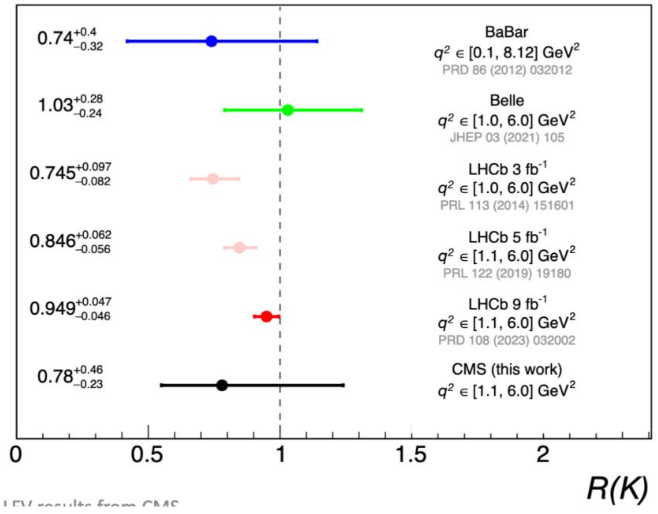
R(K): test of LFU in $B^{\pm} \to K^{\pm}\ell^{+}\ell^{-}$ decays

Results: compatible with the SM
R(K) in $q^2 \in [1.1; 6.0]$ GeV² in agreement with the world-average, with **unc. reduced by 40%**

$$= 0.78^{+0.46}_{-0.23}\,(stat)^{+0.09}_{-0.05}(syst)$$

Limited by small stat. in the electron channel. Main syst: background description, trigger turn-on





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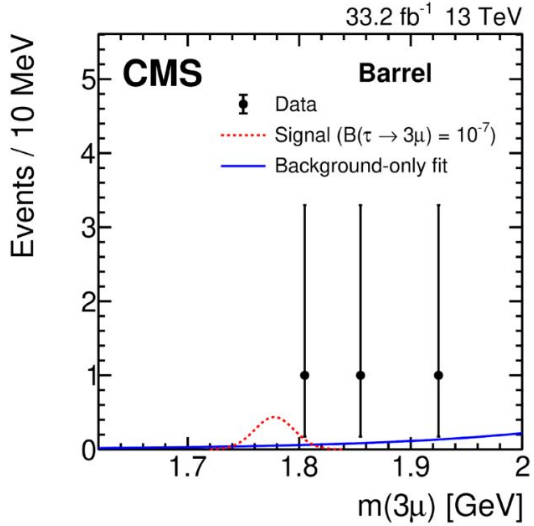
Lepton Flavour Violation studies

$\tau^+ \to \mu^+\mu^+\mu^-$

- $\tau \to 3\mu$ excellent candidate for new physics searches
  - LFV process, strongly suppressed in the SM ($\sim 10^{-55}$), but predicted at the level of $10^{-8} - 10^{-10}$ by some BSM models   Bordone et al. 10.1007/JHEP10(2018)148
  - clear final state signature
  - fairly abundant in pp collisions (per /fb)

- CMS targets τ leptons produced via D/B mesons and via W bosons
- analysis on 2016 pp data @ 13 TeV (30 /fb)
- select three-muon events and reduce the background contamination via BDT
- observed (expected) UL from three-muon invariant mass distribution
  - $B^{HF}(\tau \to 3\mu) < 9.2\ (10.0) \times 10^{-8}$ @ 90% CL
  - $B^{W}(\tau \to 3\mu) < 20.0\ (13.0) \times 10^{-8}$ @ 90% CL
  - **$B(\tau \to 3\mu) < 8.0\ (6.9) \times 10^{-8}$ @ 90% CL**



Lepton Flavour Violation studies

arXiv:2312.03199v1 submitted to PRD

Search for cLFV in the top quark sector: $\mu e t q$

Probe $\mu e t q$ coupling in EFT in t production and decay, where q=u/c

Signal signature:

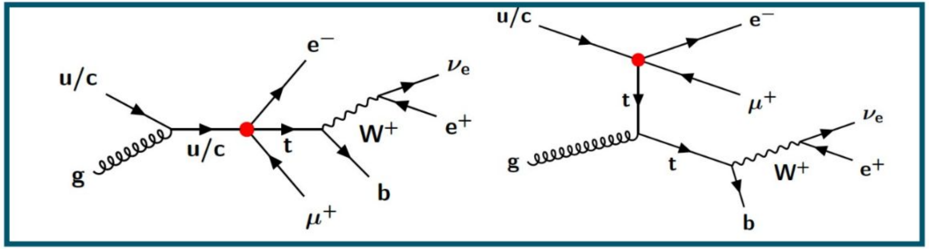
- OS eμ pair
- Leptonic top quark decay → additional lepton + one b-jet
- one/zero light jet (u/c)

Background:

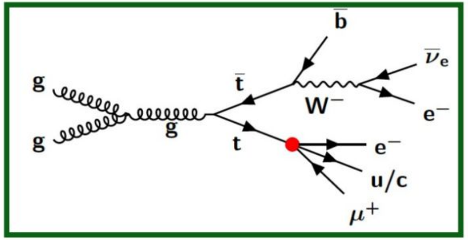
- Prompt (WZ, multiboson, $t(\bar{t})$ +X(X)) from simulation
- Non-prompt data-driven estimation

Statistically dominated, main systematics: lepton reco. and iso, jet modelling, non-prompt leptons

Two Signal regions defined:



CFLV in single top production



$t\bar{t}$ production + CLFV in top decay

SR + $m(e\mu) < 150$ GeV: top quark decay enriched,
SR + $m(e\mu) > 150$ GeV: top quark production enriched.

Many more studies…

CMS B Physics results:
https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH/BPH.html

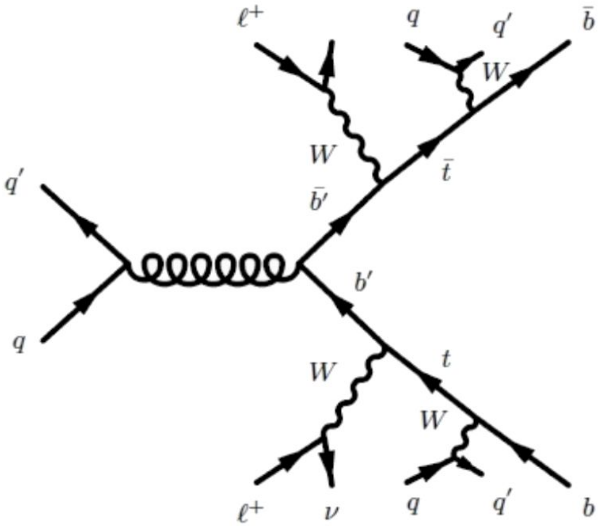
Beyond the Standard Model: Direct Searches

Fourth Generation Searches

- Certain BSM models predict fourth generation of fermions

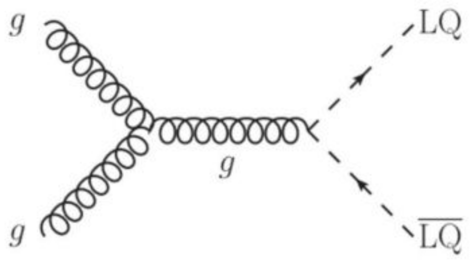
- Analyses look at:
  - b’ → t + W
  - t’ → t + Z
  - t’ → b + W

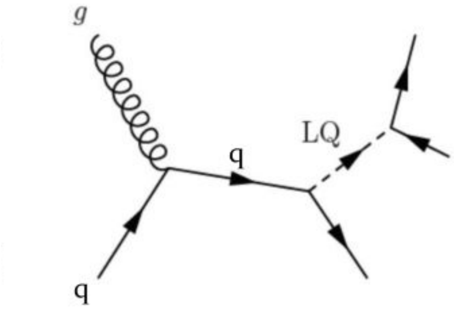
- No discoveries yet, efforts continue



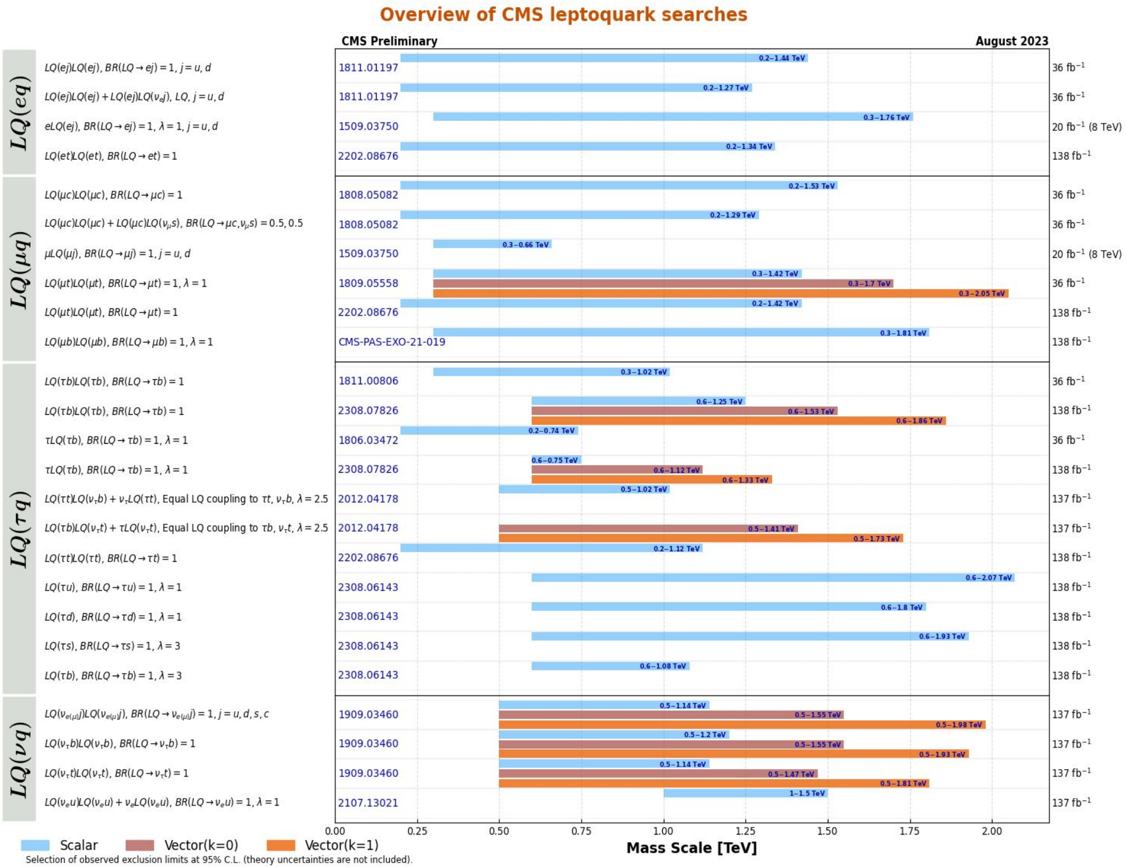
Leptoquarks

- “leptoquarks” (LQ) are hypothetical particles that carry both lepton and baryon number.
- Predicted in many BSM models such as GUT theories, composite models, R parity violating SUSY etc.
- LQ have fractional electric charge
- LQ can have spin 0 (scalar LQ) or 1 (vector LQ)
- At hadron colliders, they can be produced mainly in a pair or singly, in association with a lepton
- CMS has several LQ searches based on final states





Leptoquarks

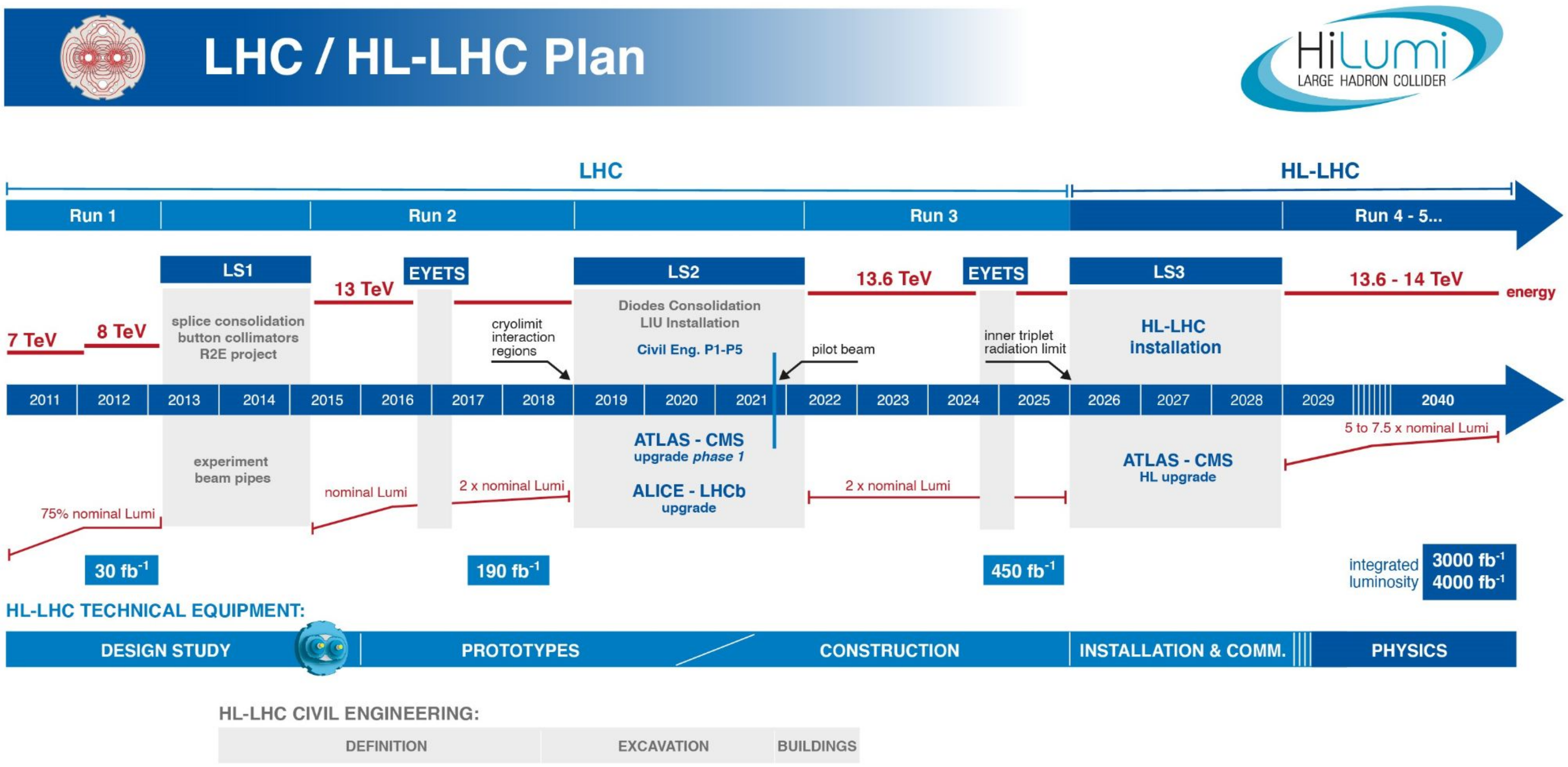


And many more (including VLQ, RHN, etc.)

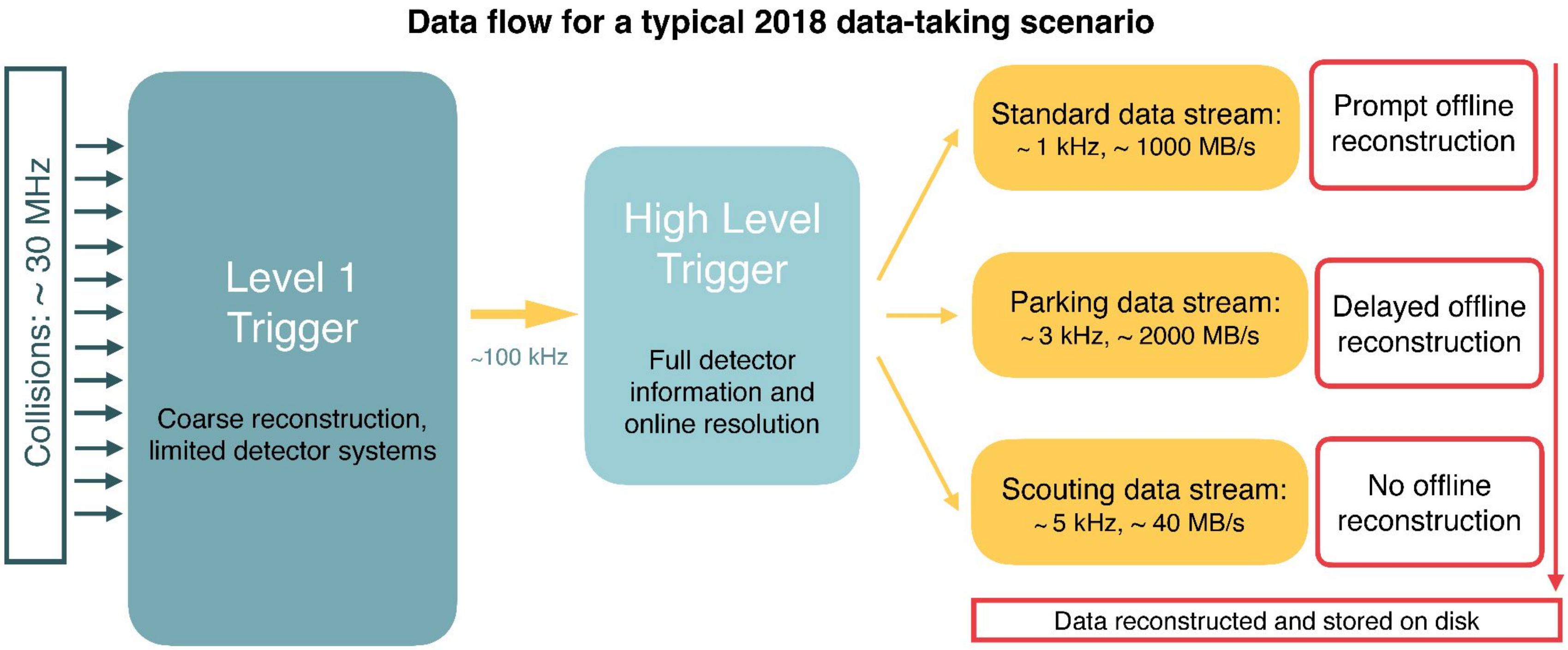
CMS scientific results:
https://cms.cern/org/cms-scientific-results

Future prospects

Plan of the LHC and the High-Luminosity LHC



Scouting & B-Parking



Future prospects

- Long scope ahead with HL-LHC
- New triggers, new reconstruction techniques being worked on
- Expect several new Flavour physics results from CMS in the future

Thank you!