Flavour Physics

CMS @ HL-LHC & beyond

N.Leonardo, LIP & IST

on behalf of LIP | CMS | HF team

Portuguese Discussion European Strategy Particle Physics, 20/1/2025

European Strategy Update

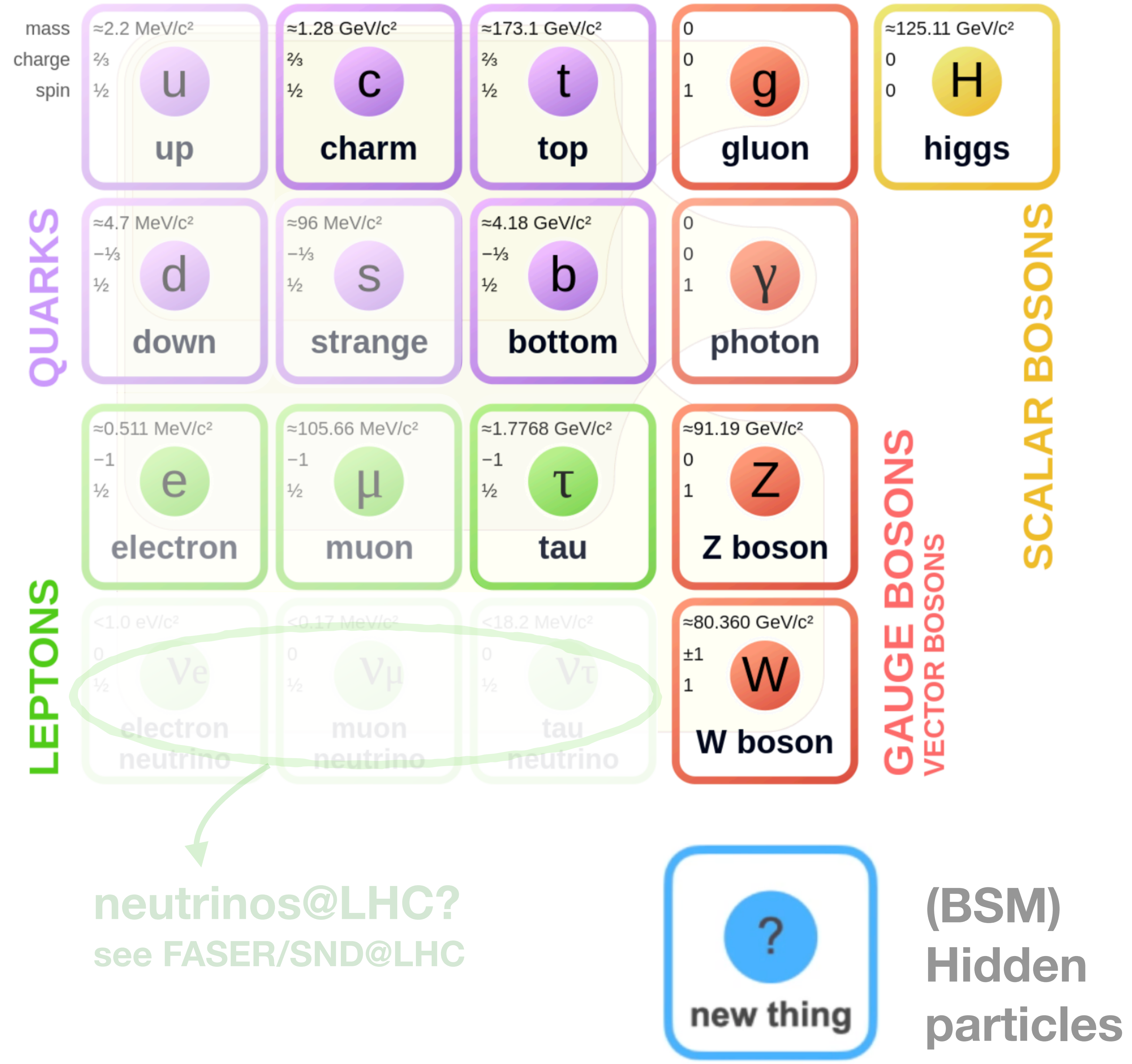
LIP
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

CERN

CMS

fct Fundação para a Ciência e a Tecnologia

CMS — general-purpose experiment at (HL-)LHC



(HL-)LHC facilitates widest scope of particle physics research

It will *remain* the **Energy Frontier** (now & over next several decades!)
Scrutinize **SM**: Electroweak/Higgs, Heavy Flavour, QCD/Heavy Ions
Offers highest potential for ground-breaking discovery **beyond SM**
Extend scope: photon collider, collider neutrinos, lifetime frontier

HL-LHC upgraded detectors

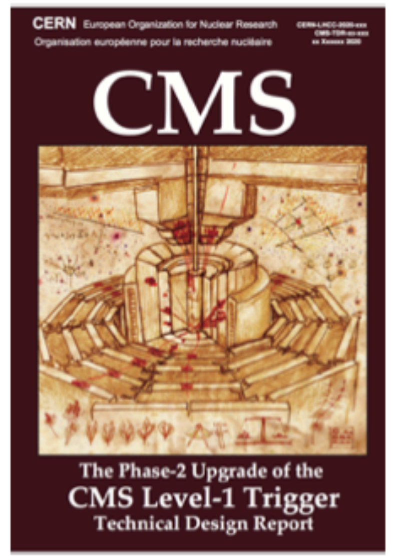
ATLAS/CMS general-purpose detectors with enhanced capability will reach unique SM precision and BSM sensitivity; further complemented by dedicated apparatuses

CMS Upgrade — HL-LHC

Precision Proton Spectrometer

https://cds.cern.ch/record/2750358

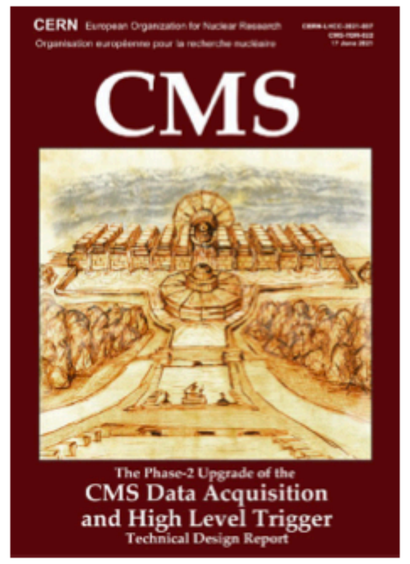
- improved detector with larger mass acceptance
- locations at 196, 220, 234, 420m from IP



L1-Trigger

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

- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



DAQ & High-Level Trigger

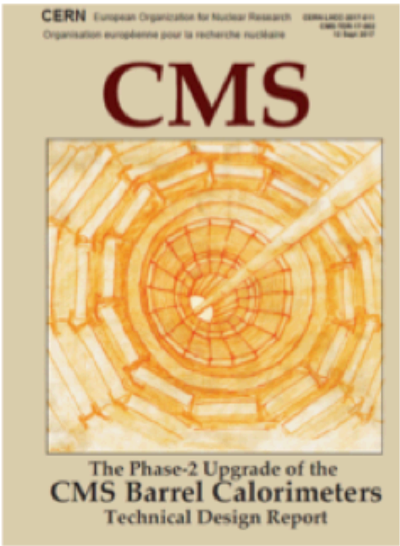
https://cds.cern.ch/record/2759072

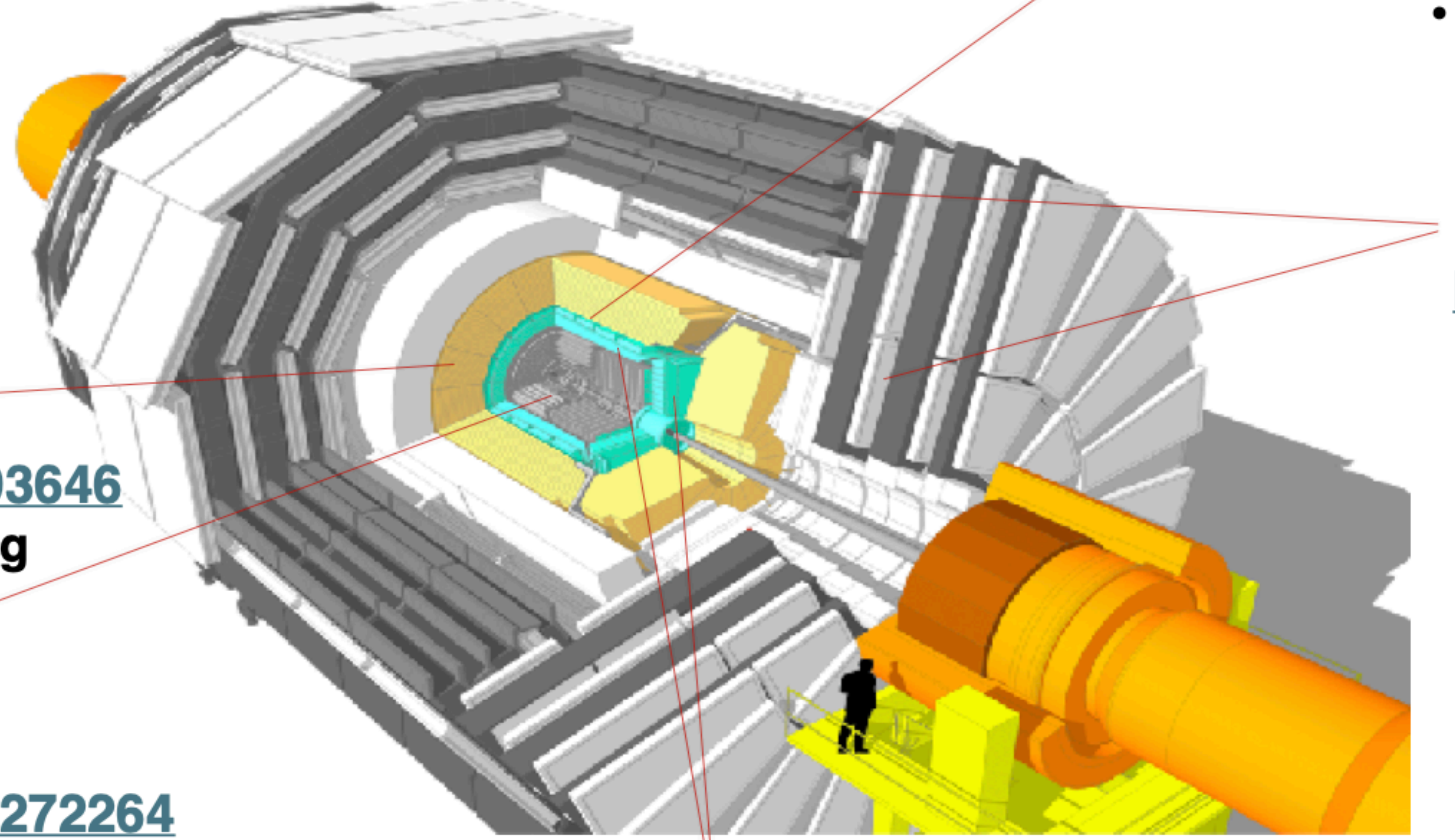
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

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

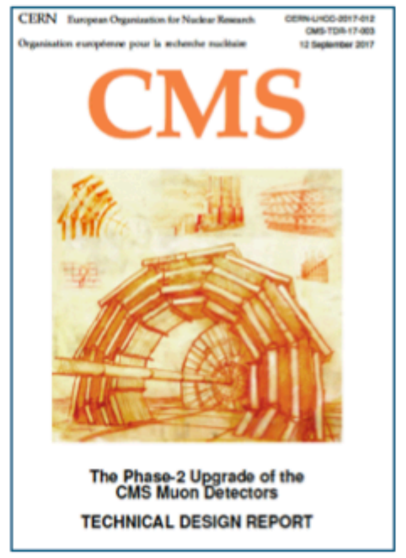


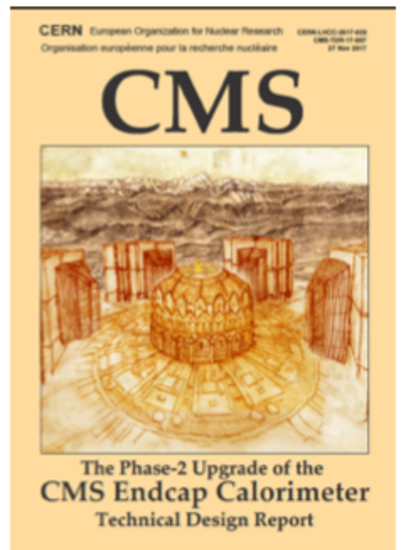


Muon systems

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

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

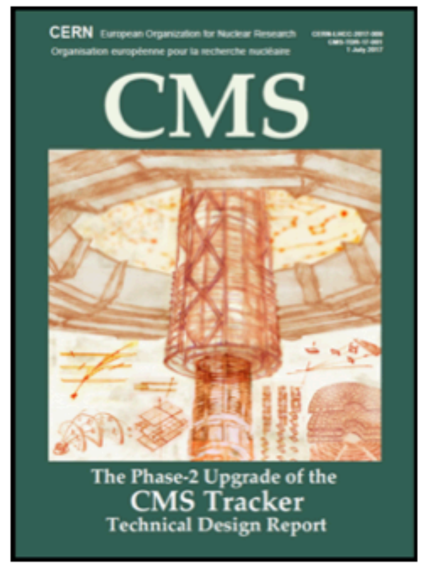




Calorimeter Endcap

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

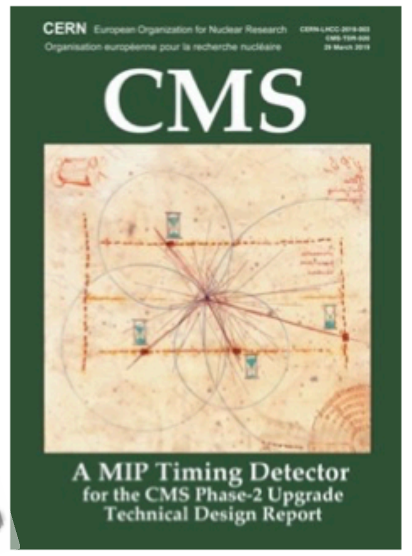
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS



Tracker

https://cds.cern.ch/record/2272264

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



MIP Timing Detector

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

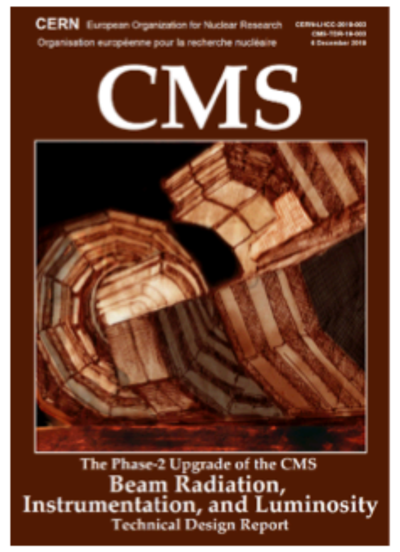
Precision timing with:

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

Beam Radiation Instr. and Luminosity

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

- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors



Operation and physics analyses at the CMS experiment at the CERN LHC

LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

Mariana Araújo[1] Cristóvão Beirão[1] Alessio Boletti[1] Tiziano Camporesi[1] Daniela Cardoso[1] Giacomo da Molin[1] Madalena Ferreira[1] Michele Gallinaro[1] Jonathan Hollar[1,2] Henrique Legoinha[1] Nuno Leonardo[1] Giovanni Marozzo[1] Matteo Pisano[1] João Varela[1] João Seixas[1] Johan Wulff[1]

[1]LIP Lisbon [2]CERN

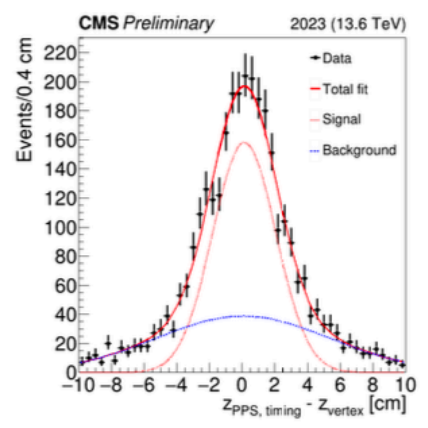
LIP-CMS group activities

LIP is a member of the CMS experiment since its creation in 1992. Activities include:

- **Physics analyses:** Electroweak, Top, Higgs, BSM, B-physics, Quarkonia, Heavy-ions;
- **Experiment operation & maintenance:** PPS, physics objects (taus, protons), computing.

The group is involved in different analyses at the frontier of particle physics.

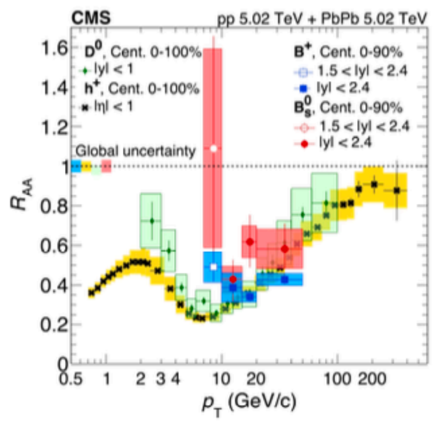
Maintenance and Operation



The group participates in the detector maintenance and operation.

- Precision Proton Spectrometer (PPS): project manager
- Other coordination positions: B-Physics Data Analysis, Standard Model PAG MC contact, MTD/BTL electronics systems, LHC HF WG
- Tagged Protons Physics Object Group
- Tau lepton identification and proton timing calibration [CMS-DP-2024-009, 2024]
- Group members are regularly asked to participate in Analysis Review Committees (ARC) and Detector Review Committees
- The group provides central shifts and EPR work according to the rules of the CMS collaboration

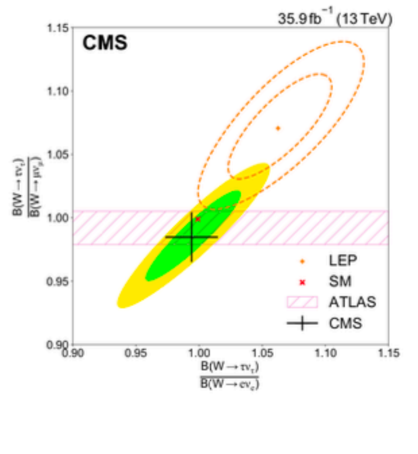
Probing the primordial fluid



We explore **heavy flavour** as probes of the Quark-Gluon Plasma (**QGP**)

- B mesons reconstructed for **first time** in nuclear collisions [PLB, 829:137062, 2022]
- Measured **relative production** of B mesons in pp and PbPb (R_{AA}) [arXiv:2409.07258]
- Probing QGP medium-induced effects on heavy quark **hadronization**
- **Strangeness enhancement** evidence in the beauty sector in QGP
- Investigating the nature of **exotic hadron** $X(3872)$ using PbPb [PRL, 128(3), 2022]

Lepton Flavour Universality (LFU)

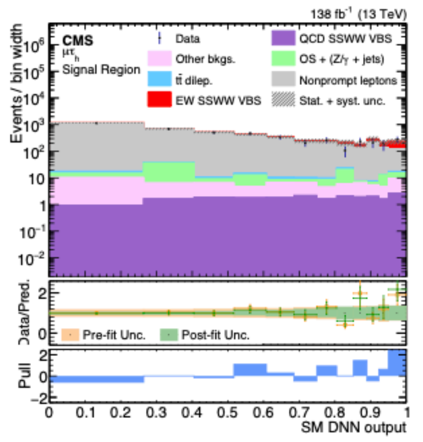


We perform a precision study of the lepton couplings to the W bosons in $t\bar{t}$ events.

- Measured $t\bar{t}$ cross section in dilepton events containing a τ lepton [JHEP, 02:191, 2020]
- Different behaviour of the leptons (**LFU violation**) would be a clear signal of new physics
- Study **top quark** decays to obtain a pure sample of W-bosons in final states with all lepton families
- Observables carefully crafted to minimise effects of leading systematics
- **Machine Learning** tools employed at different levels in the analysis
- Extracting a high precision measurement to test the predictions on the **Weak Nuclear interactions** competitive with the state-of-the-art [PRD, 105:072008, 2022].

Multiboson production

We study **multiboson production** in final states with **hadronically decaying tau** leptons. Studies are ongoing on Vector Boson Scattering (VBS) as well as inclusive production.



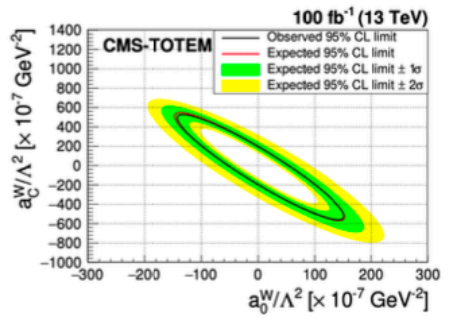
Motivation:

- Insight into the EW and Higgs sectors can be achieved through measurements of VBS processes [Rev. Phys., 8:100071, 2022]
- Tau leptons provide **unexplored** final states, which can increase our sensitivity to **rare processes** [arXiv:2410.04210]
- Tau leptons have strong **couplings** to **new particles** in many bSM models
- Tau leptons carry **polarization** information through their **decay**

Challenges:

- Rejection of hadronic **jets misidentified** as taus
- Careful **modelling** of non-prompt **backgrounds**

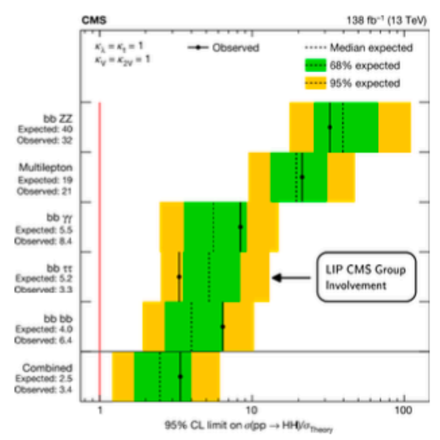
Exclusive processes



We search for exclusive process production in proton-proton collisions using intact forward protons reconstructed in near-beam detectors.

- Observation of proton-tagged central exclusive production of high-mass lepton pairs [JHEP, 07:153, 2018]
- Exclusive $t\bar{t}$ production [JHEP, 06:187, 2024]
- Search for high-mass $\gamma\gamma \to WW/ZZ$; No excess above the SM background prediction is observed, and upper limits are set on anomalous quartic gauge couplings (aQGCs) [JHEP, 07:229, 2023]
- Search for exclusive τ lepton pair production (in progress).

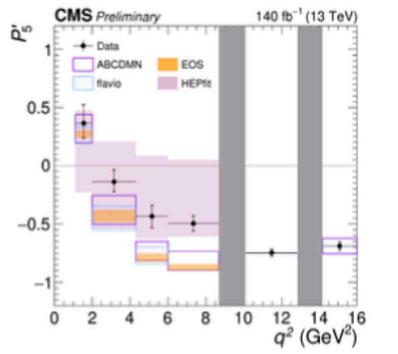
Higgs Pair Production



We explore the Higgs boson properties, studying the $HH \to bb\tau\tau$ process, the second most sensitive to the trilinear H self coupling λ_{HHH}. The cross section for HH production in the SM is extremely small, thus escaping detection at the LHC so far.

- The structure of the Higgs scalar field potential and the strength of the H self-coupling are precisely predicted in the SM [Nature, 607(7917):60, 2022]
- Observed (expected) upper limit on the HH production cross section corresponding to 3.3 (5.2) times the SM predictions [Phys. Lett. B, 842:137531, 2023]
- Contributions to the non-resonant analysis in the development of the DNN signal discriminant
- Search for resonant HH($bb\tau\tau$) pair production (in progress)

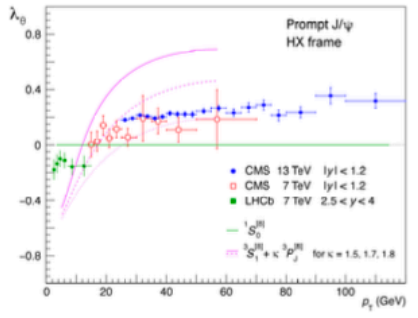
Rare decays in B-physics



We study the full **angular distribution** of the $B^0 \to K^{*0}(K^+\pi)\mu\mu$ process [CMS-PAS-BPH-21-002].

- This rare decay is strongly suppressed in the SM and sensitive to contributions from BSM physics
- Fit of the angular variables and B^0-candidate mass to access eight physics observables
- Results are among the most precise measurements of these observables, and present **evidence of tension with SM predictions**, the so-called *Flavor Anomalies*

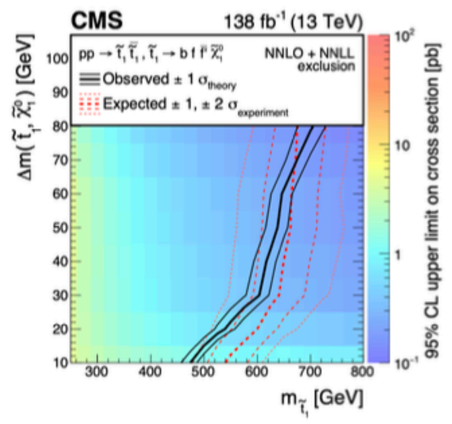
Quarkonium production



We study quarkonium polarization.

- Quarkonium production is a benchmark to understand quark binding into hadrons
- **Polarization** measurements highlight features that may hide behind inclusive measurements
- Particle Polarization in HEP; An introduction on vector particle production at the LHC: [Lecture Notes in Physics 1002 (2023)]
- Polarization measurements of prompt χ_{c1} and χ_{c2} [PRL 124 (2020) 162002], and of J/ψ and $\psi(2S)$ [PLB 858 (2024) 139044]

Supersymmetry (SUSY) and the Dark Sector



We search for SUSY and dark matter at unprecedented collision energies [arXiv:2405.13778]

- The SM explains only 5% of the Universe and is not able to answer other outstanding questions. It cannot account for the invisible "dark matter".
- We search for SUSY in events with at least one soft lepton, low jet multiplicity, and missing transverse momentum in pp collisions at 13 TeV
- We explored a compressed mass spectrum where the mass difference between the produced stop and the lightest SUSY particle (LSP) is smaller than the W boson mass
- No significant excess is observed above the expectation from SM processes. Set limits on top squark masses up to 480 and 700 GeV [JHEP, 06:060, 2023]

Acknowledgements

We acknowledge support from: CERN/FIS-INS/0029/2021 (FCT), CERN/FIS-PAR/0005/2021 (FCT), PTDC/FIS-PAR/1214/2021 (FCT), AMUSE - EU MSCA-RISE-2020 101006726, MuCol - EU HORIZON-INFRA-2022-DEV-01-01 101094300

Horizon 2020 European Union Funding for Research & Innovation

Collaboration in the Phase-2 Upgrades of the CMS experiment

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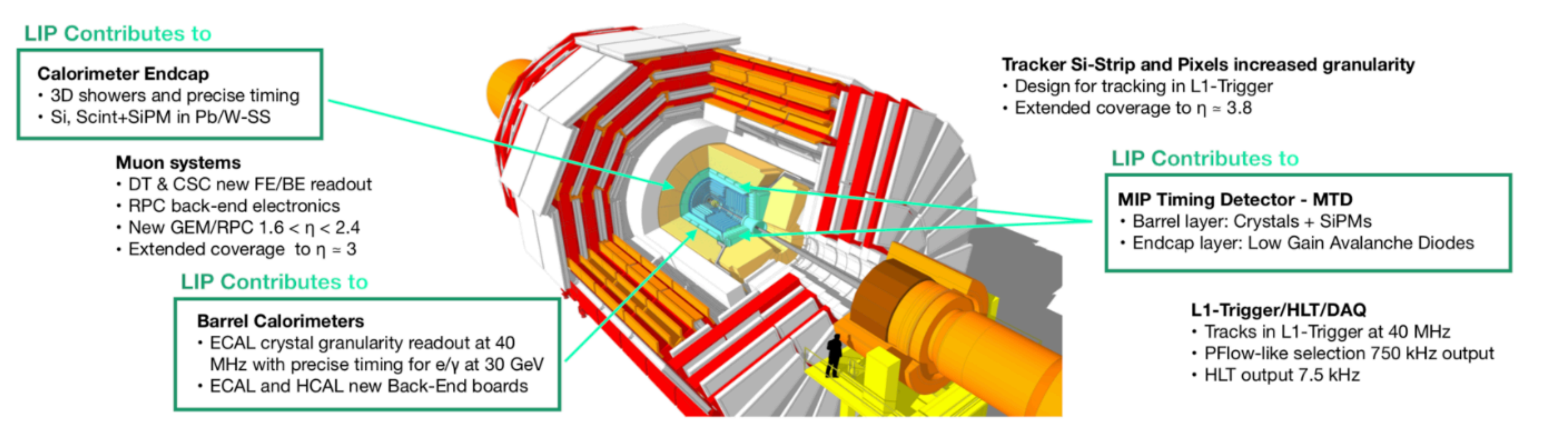

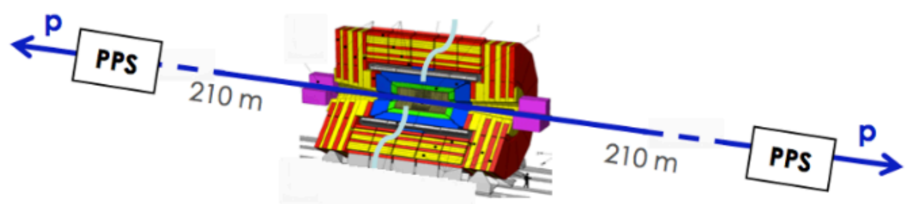

LIP contributes to

Precision Proton Spectrometer

- Detector design and physics prospects

High Granularity Calorimeter (HGCAL)

HGCAL is a new high-granularity sampling calorimeter replacing the endcap calorimeters. LIP collaborated with industry supplying a high-current low voltage regulator ASIC resistant to radiation for the HGCAL front-end system. The group participated in test beam at CERN to evaluate the performance of the first prototypes.

Precision Proton Spectrometer (PPS)

The new near-beam proton spectrometer will include timing and tracking detectors. For the detector technology, synergies with the ongoing developments for the Phase-2 upgrades of central pixel system and MTD are considered.

The LIP group is pursuing R&D studies of LGAD silicon sensors and associated electronics for the timing measurements.

- Submitted LoI and CERN approved for HL-LHC [arXiv:2103.02752]
- R&D for the PPS timing detectors: Develop LGAD sensors and associated electronics for use as timing detectors, resistant to highly non-uniform radiation and with good (40-50 ps per plane) time resolution
- Simulation studies to optimize geometry and radiation resilience of final design
- ETROC ASIC being developed for the CMS Endcap Timing Layer (ETL). The group is closely collaborating with Fermilab team for **characterization of ETROC+LGAD**
- Functionality tests of the latest version of the ETROC2 performed at Fermilab
- **Time resolution of 35 ps** measured in test beam for ETROC2+LGAD system
- **Characterization of the full 16x16 channels** ETROC2 bonded to the LGAD sensors performed with cosmic rays and later with particle beams
- Characterization of LGAD sensors were performed before and after **irradiation**

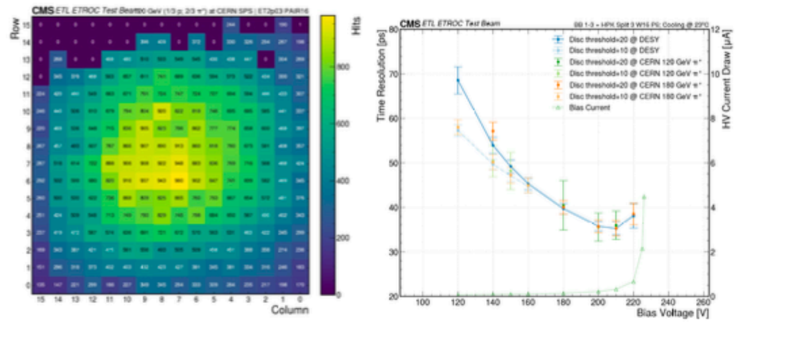

Figure 1. 16 × 16 channel ETROC2 exposed to beam (left); ETROC2 time resolution (right).

Electromagnetic Calorimeter (ECAL)

Full replacement of the barrel Electromagnetic Calorimeter (ECAL) electronics is required to meet the new trigger requirements, to minimize the impact of event pileup and provide a precise time measurement of e.m. showers. In collaboration with industry, LIP provided a high-performance ADC ASIC for the ECAL front-end electronics resistant to radiation.

MIP Timing Detector (MTD)

The MTD [CERN-LHCC-2019-003] will **precisely measure the arrival time** of charged particles. It consists of barrel (BTL) and endcap (ETL) using different technologies, i.e. LYSO+SiPM and LGAD silicon sensors, respectively. It will improve the rejection of particles from simultaneous collisions, and allow particle identification.

The LIP group leads the design, production, and validation of the BTL front-end electronics with the development of a **high-performance ASIC, TOFHiR2**, for sensor readout.

- TOFHiR2, a 32-channel ASIC, was produced and tested successfully [JINST 19 (2024) 05, P05048]. Front-end electronics is fully produced and being validated

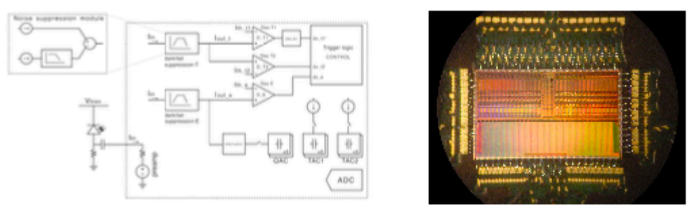

Figure 2. Block diagram of the TOFHIR2 channel (left); TOFHiR2 ASIC (right).

- Performance of BTL module prototypes studied in beams. A MIP time resolution of 28 ps measured for unirradiated devices [JINST 16 (2021) 07, P07023]
- Timing performance measured in beam test campaigns for prototypes with different construction and operation parameters [arXiv:2410.08738]

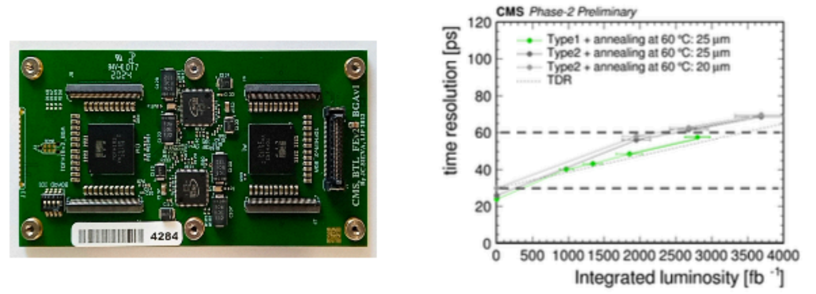

Figure 3. BTL front-end board (left); BTL time resolution vs integrated luminosity (right).

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Horizon 2020 European Union Funding for Research & Innovation

LIP-CMS Physics

N. Leonardo for the LIP-CMS group

LIP Research Line Strategy Discussion

LHC Experiments and Phenomenology

March 25, 2021

Research Line Strategy Discussion #1: LHC Experiments and Phenomenology

Thursday 25 Mar 2021, 09:30 → 13:00 Europe/Lisbon

LIP-CMS: Upgrades and Technology

J. Hollar for the LIP-CMS group

CMS phase-2 upgrade for High-Luminosity LHC

Alessio Boletti for the LIP CMS group

Jornadas 2024, Braga

Cristóvão B. da Cruz e Silva for the LIP-CMS Group

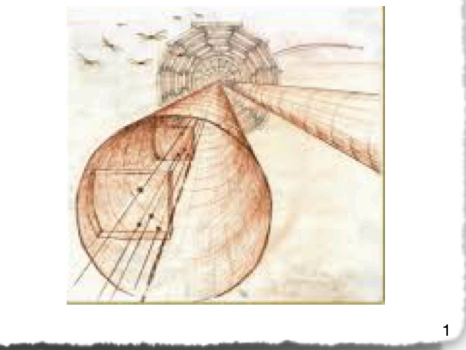
Jornadas - LIP 2024

17 Oct 2024, 18:00 → 19 Oct 2024, 17:00 Europe/Lisbon

The CMS Precision Proton Spectrometer (PPS) Past, Present, and Future

Jonathan Hollar (LIP)

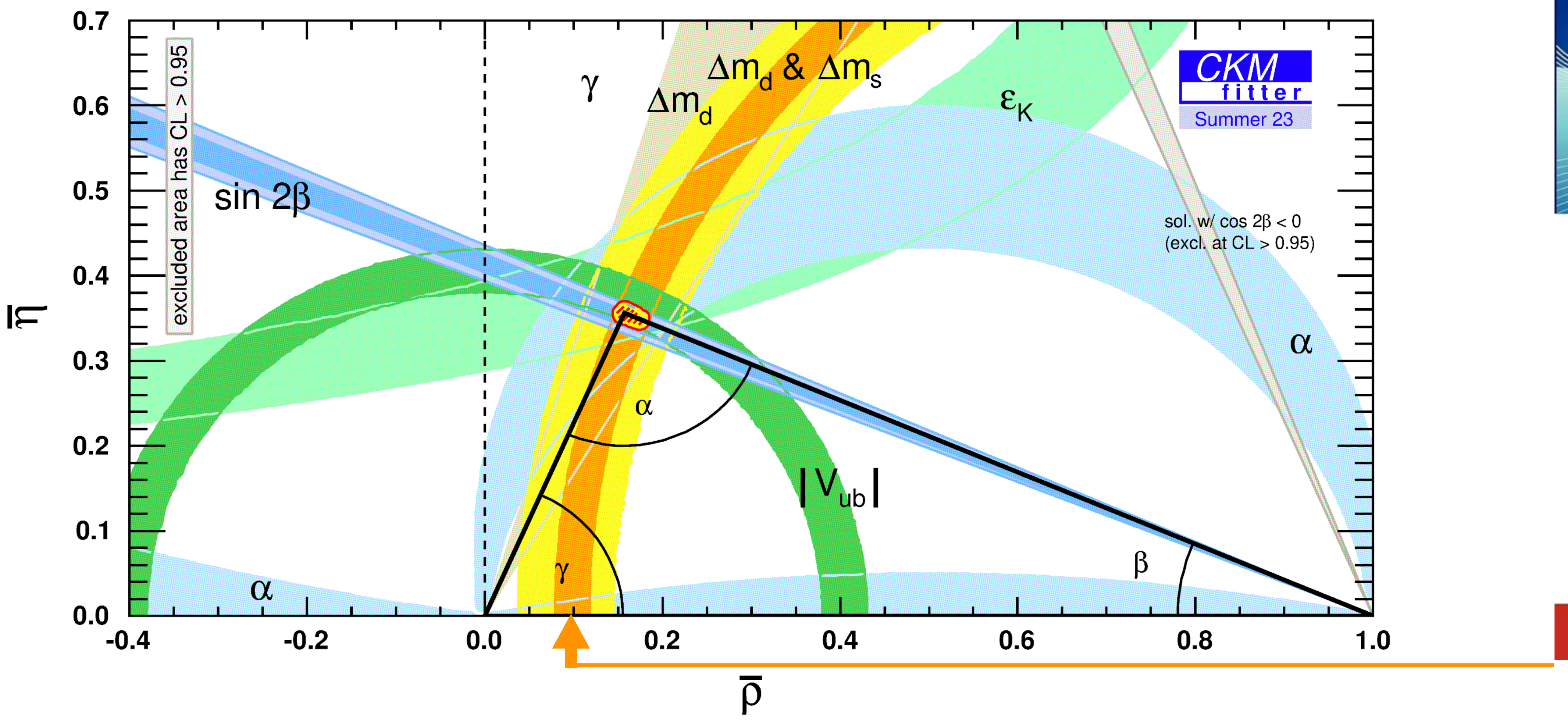
LIP Seminar, Jan. 21, 2021

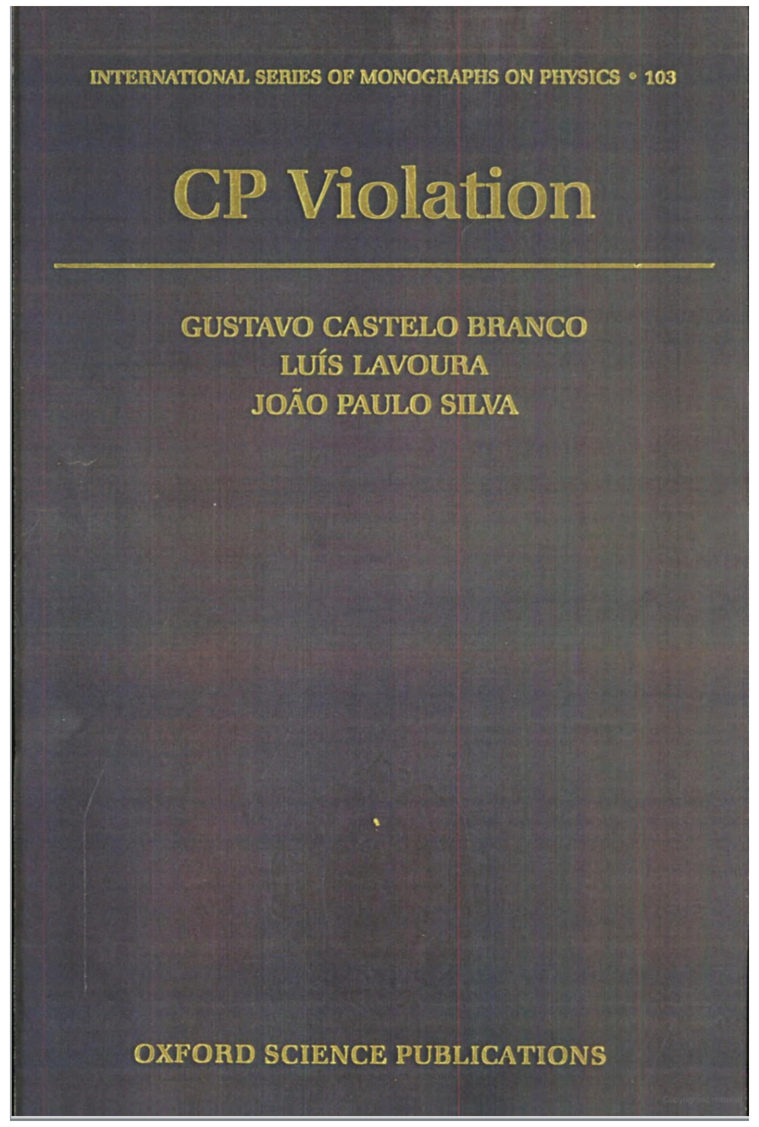


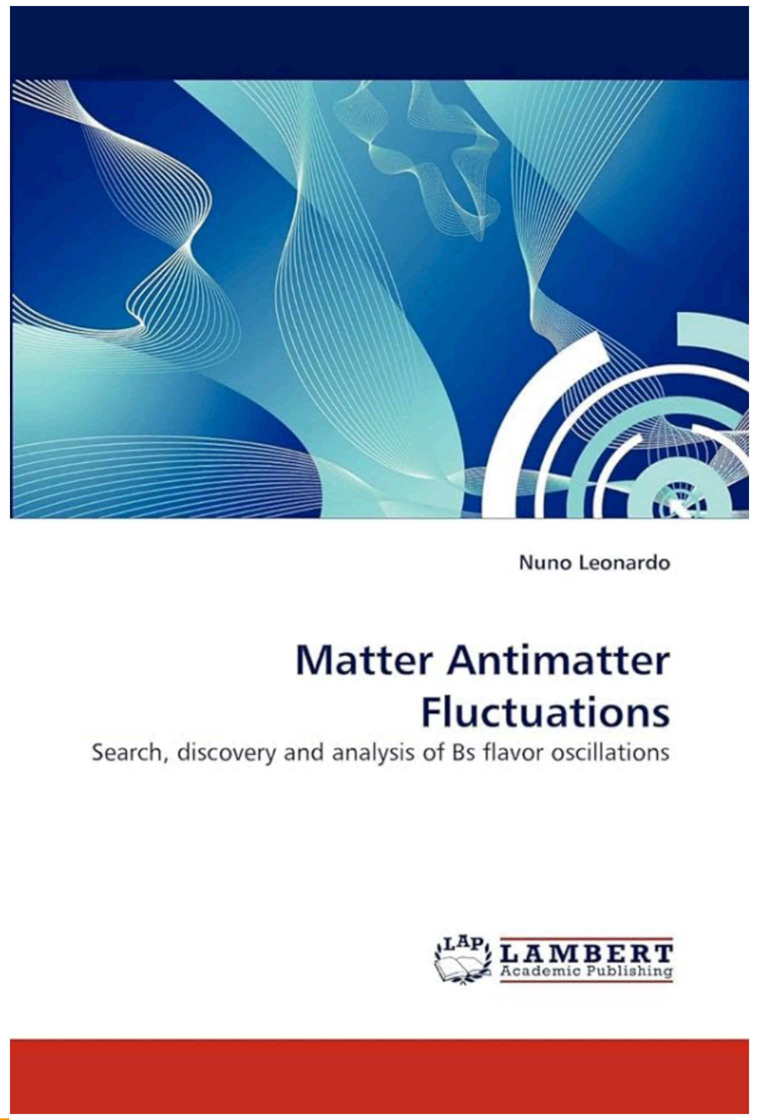
Flavour Physics @ PT

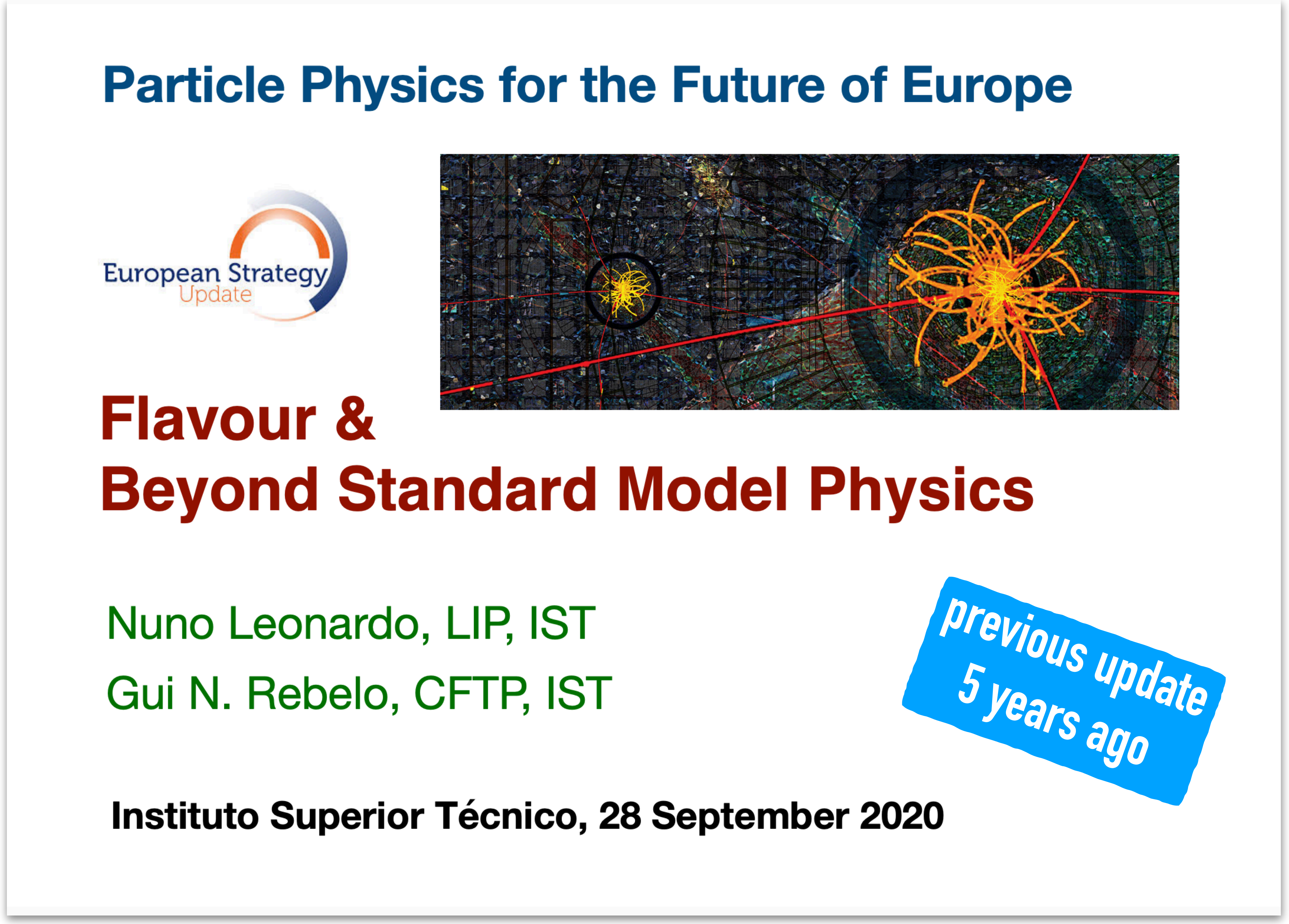
Portugal has **long-standing** involvement in flavor physics — theory & experiment

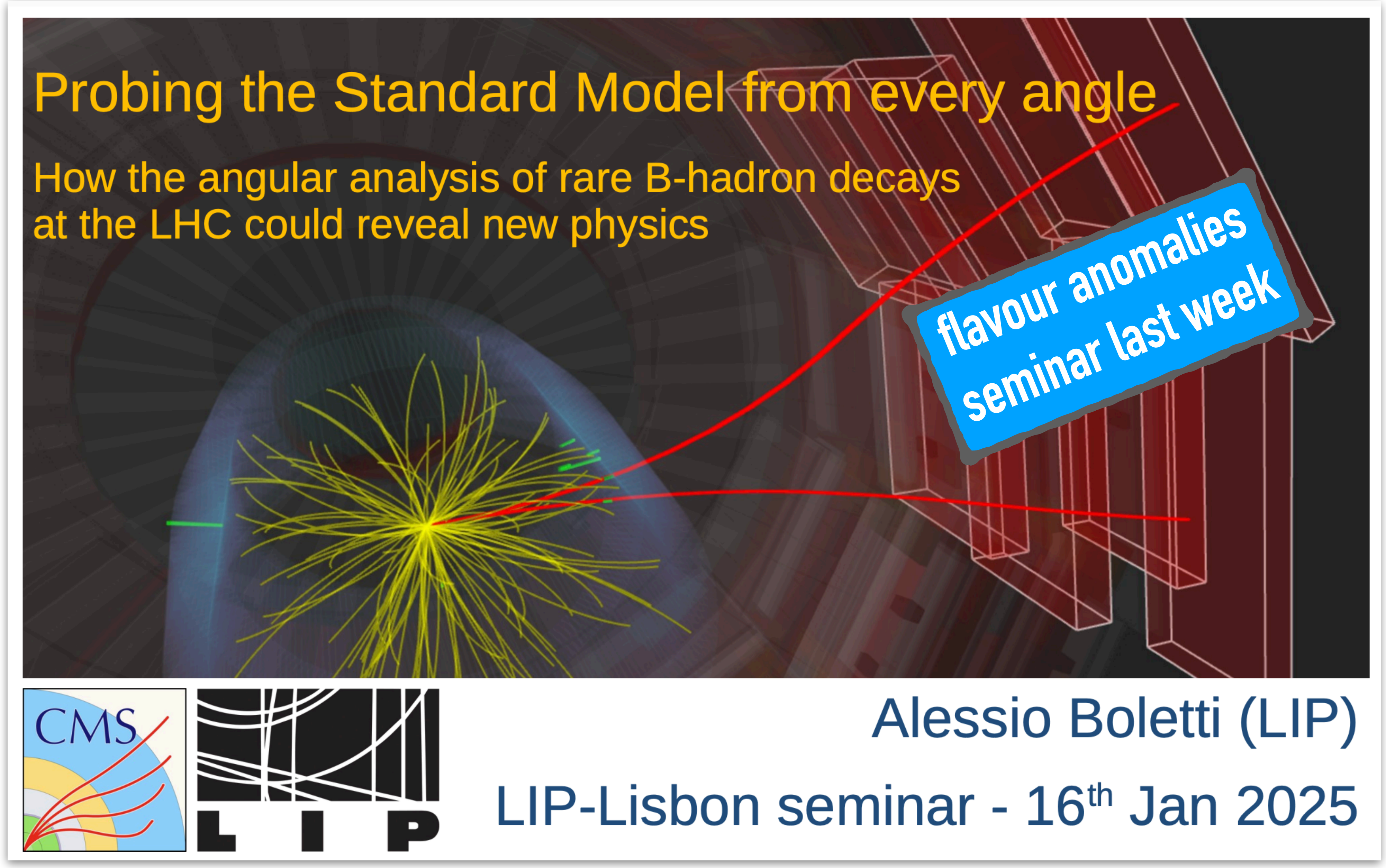
- **theory** :: see dedicated contributions
- **experiment**
  - expertise from Tevatron exploited at LHC
  - contributed multiple flagship results
  - held multiple coordination roles: production, properties, CP violation, rare decays, trigger, analysis tools, CMS wide (CMS B PAG) and LHC wide (LHC HF WG) convenerships







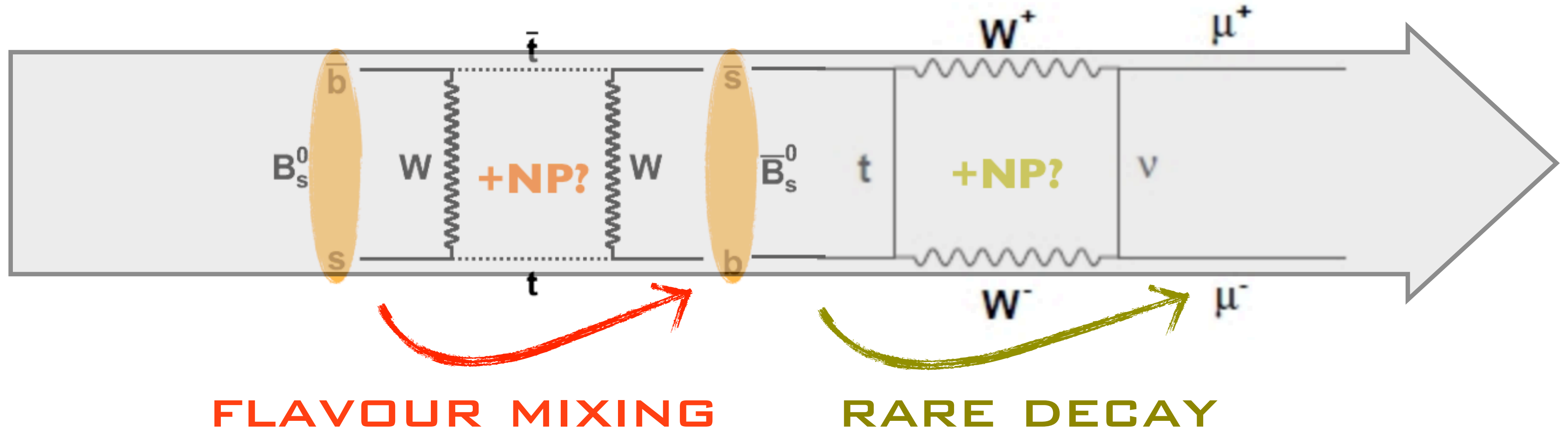




Flavour towards BSM

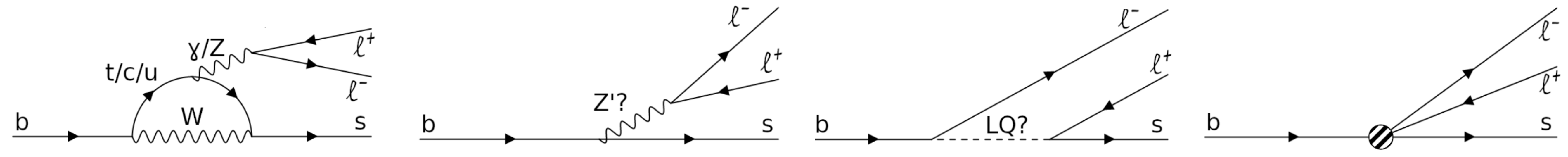
European Strategy Update

B

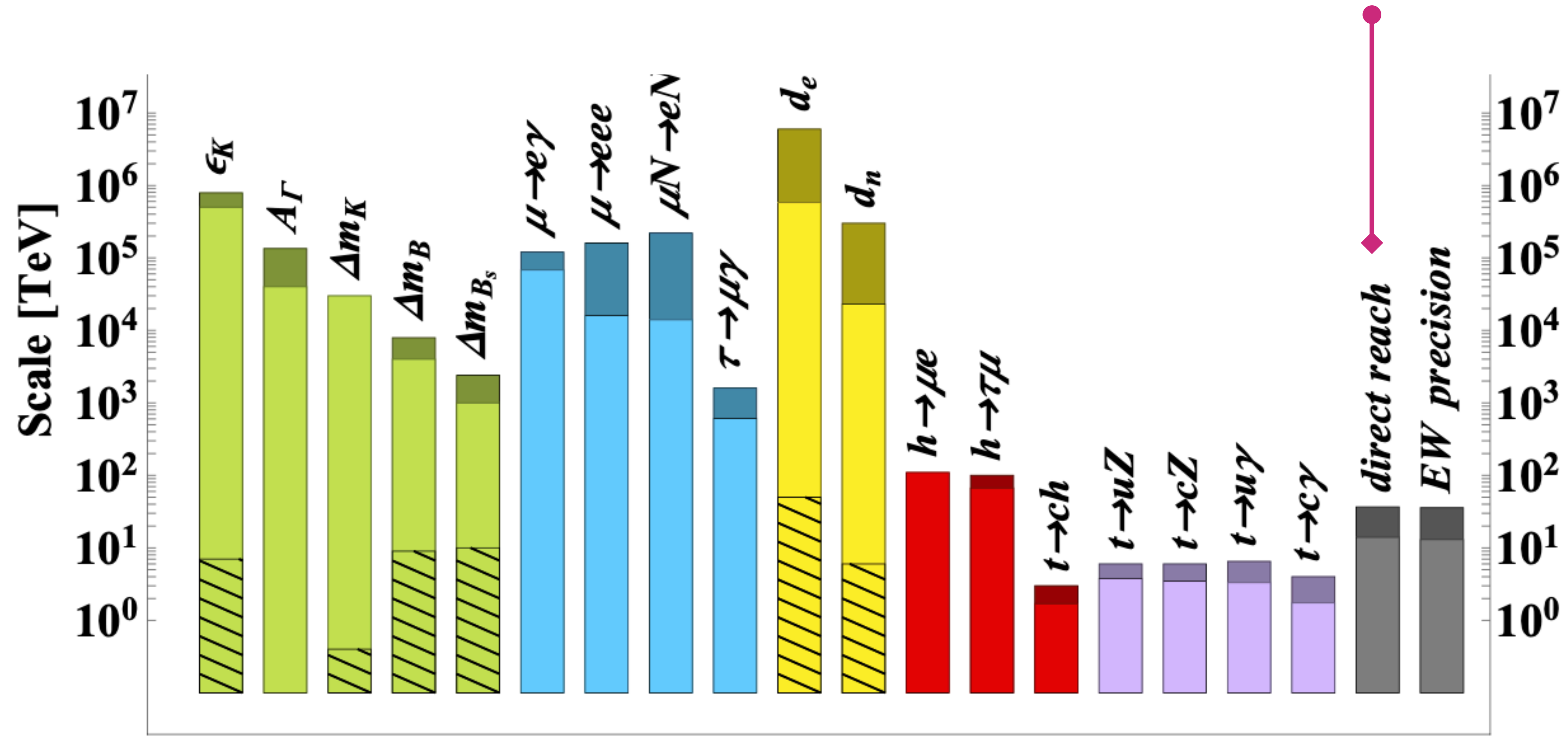


μμ

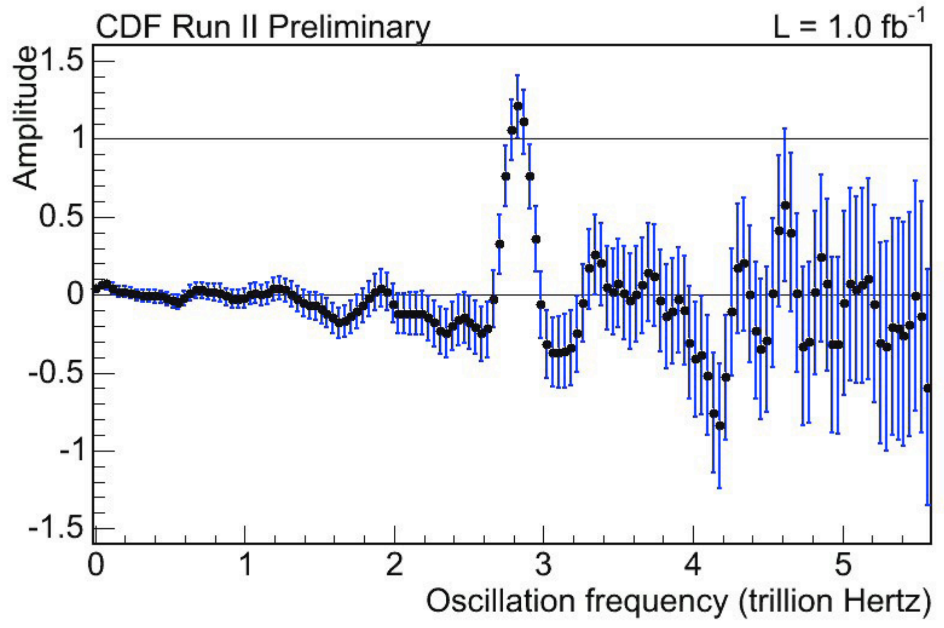
FCNC BSM BSM EFT



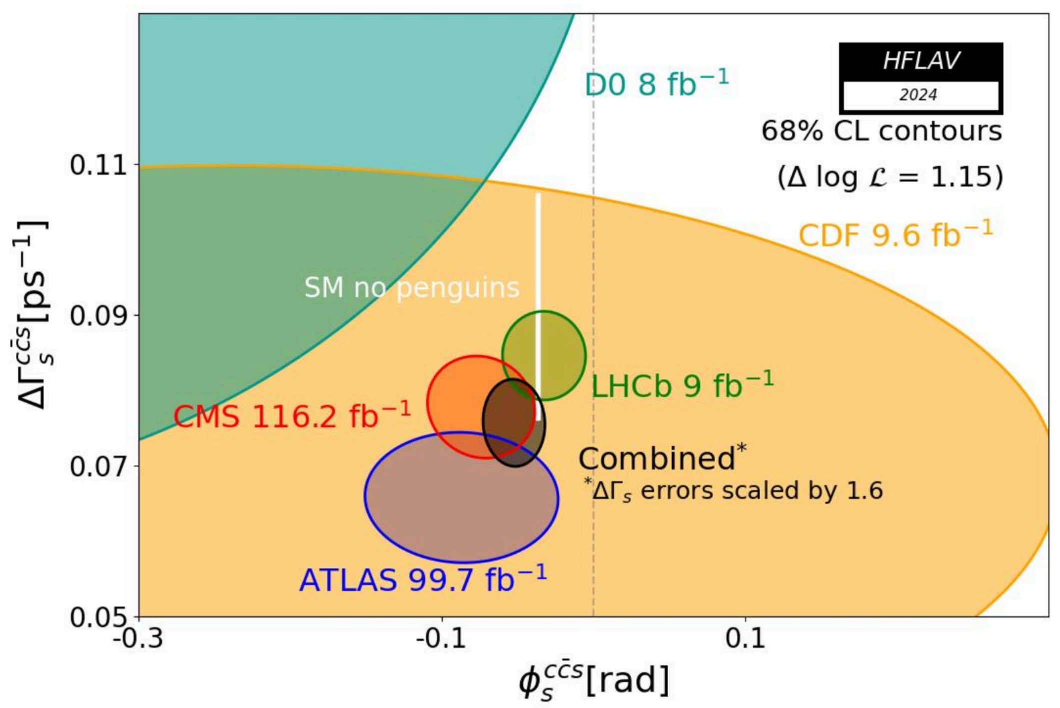
probing beyond √s reach



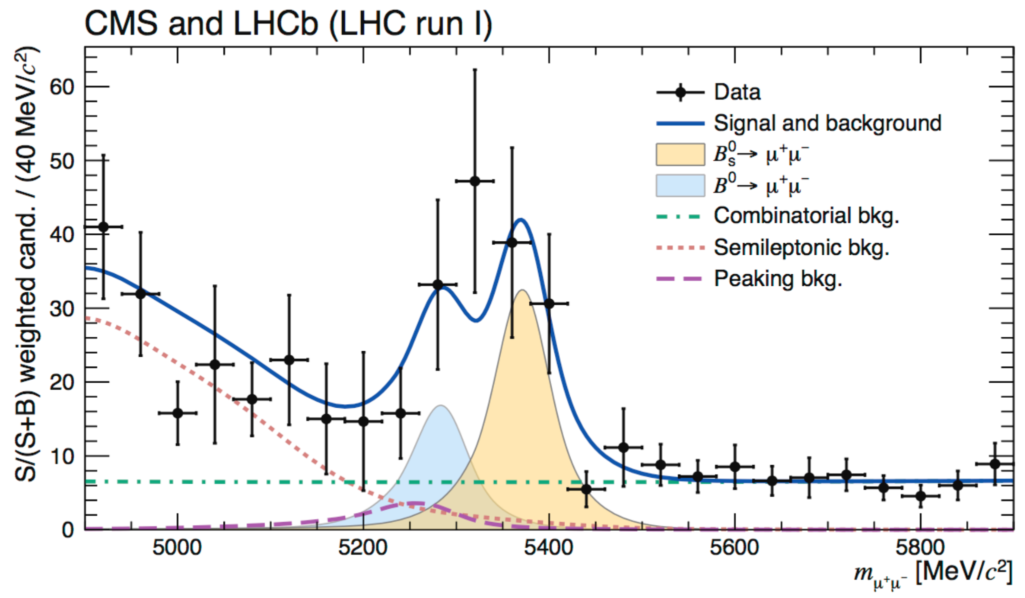
b→b flavour mixing



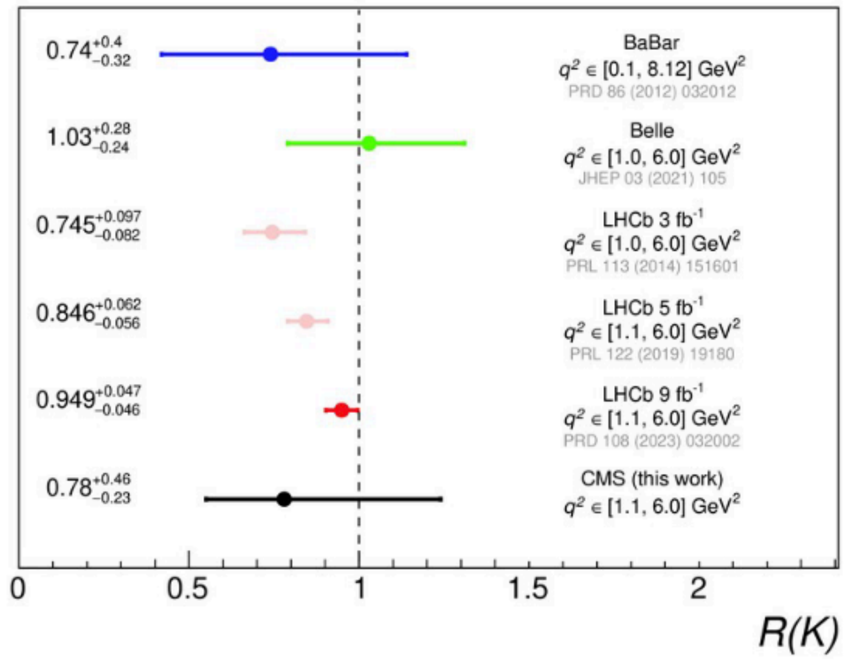
mix+decay: CP violation



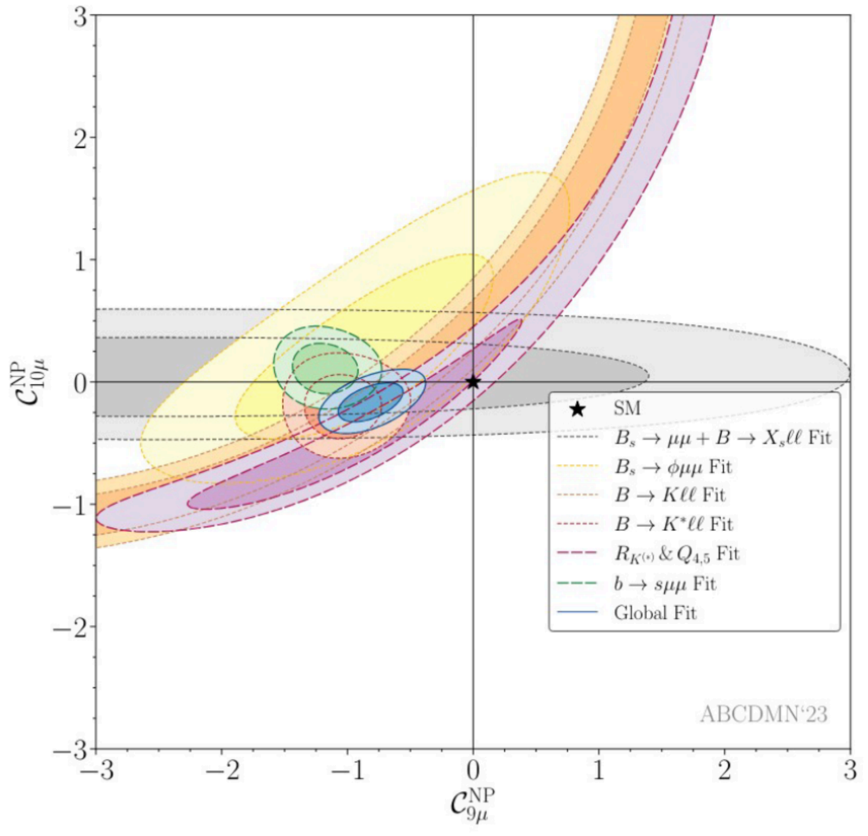
b→sll rare decay



b→sll: LFV, LFUV



B anomalies



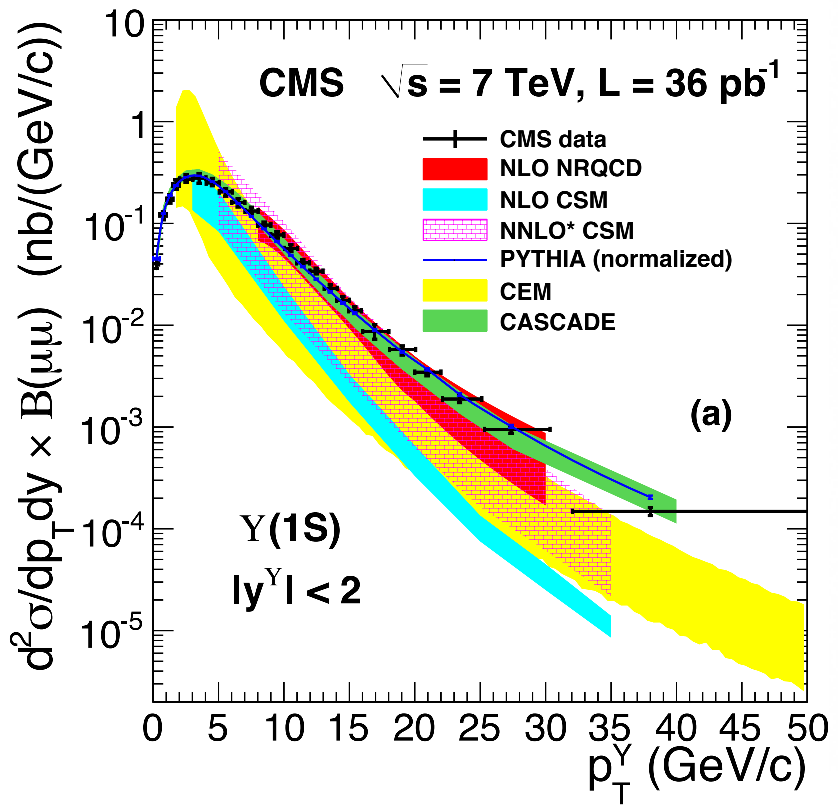
Favour probes of QCD, QGP, Higgs

Hidden flavour

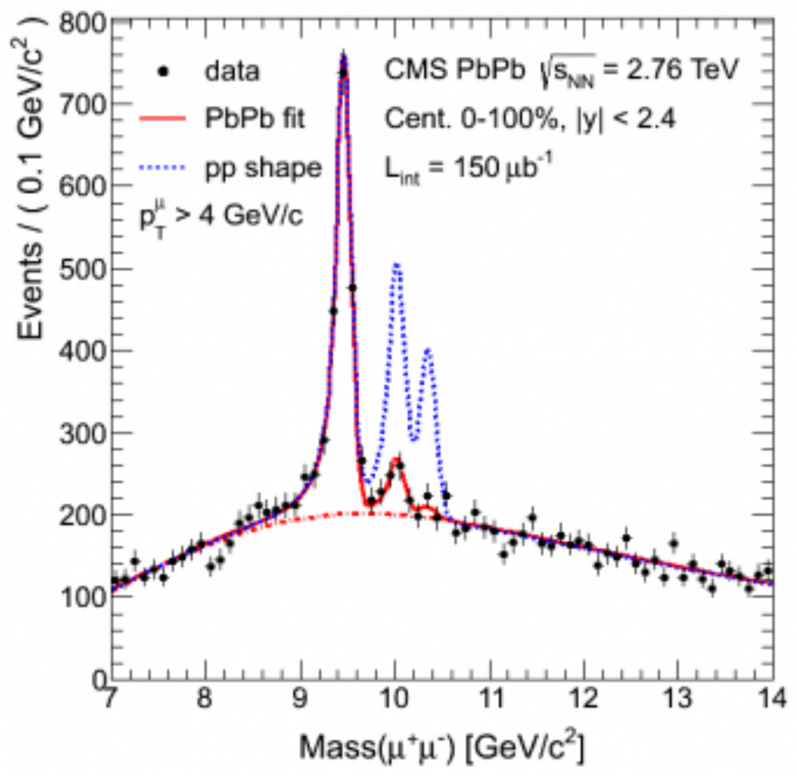
Open flavour

Exotica

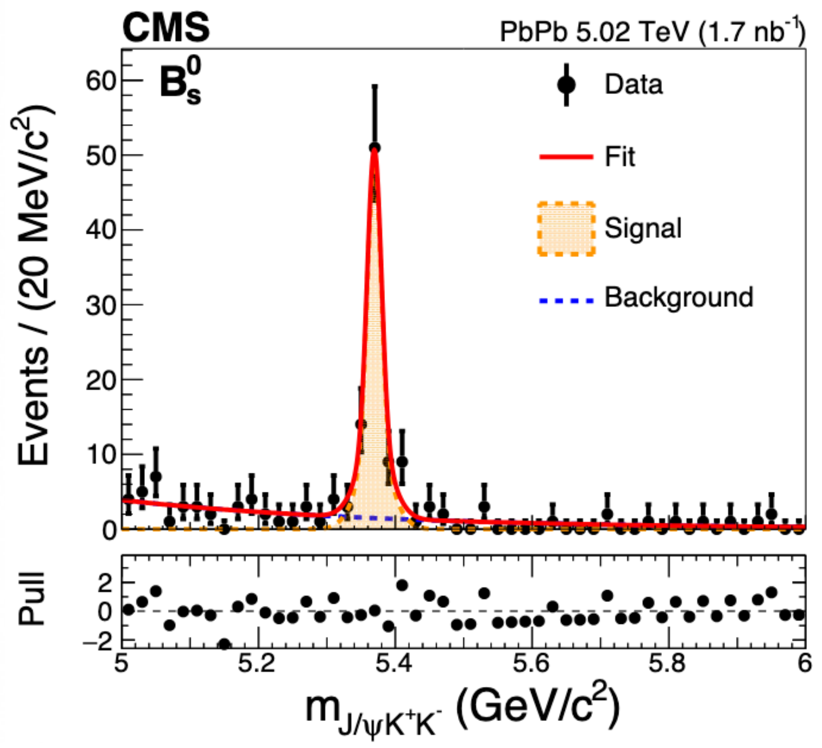
Y production

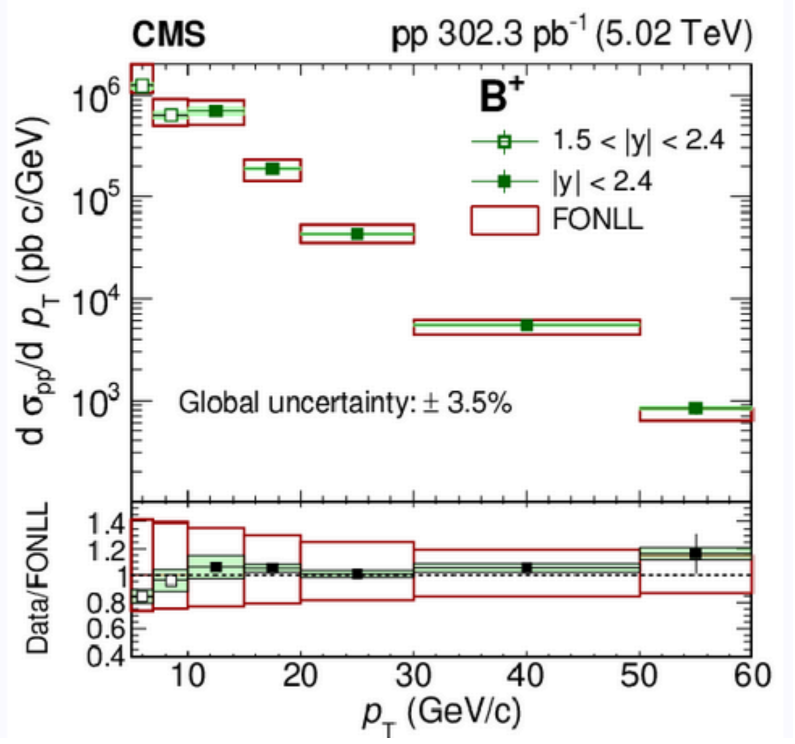


onia melting

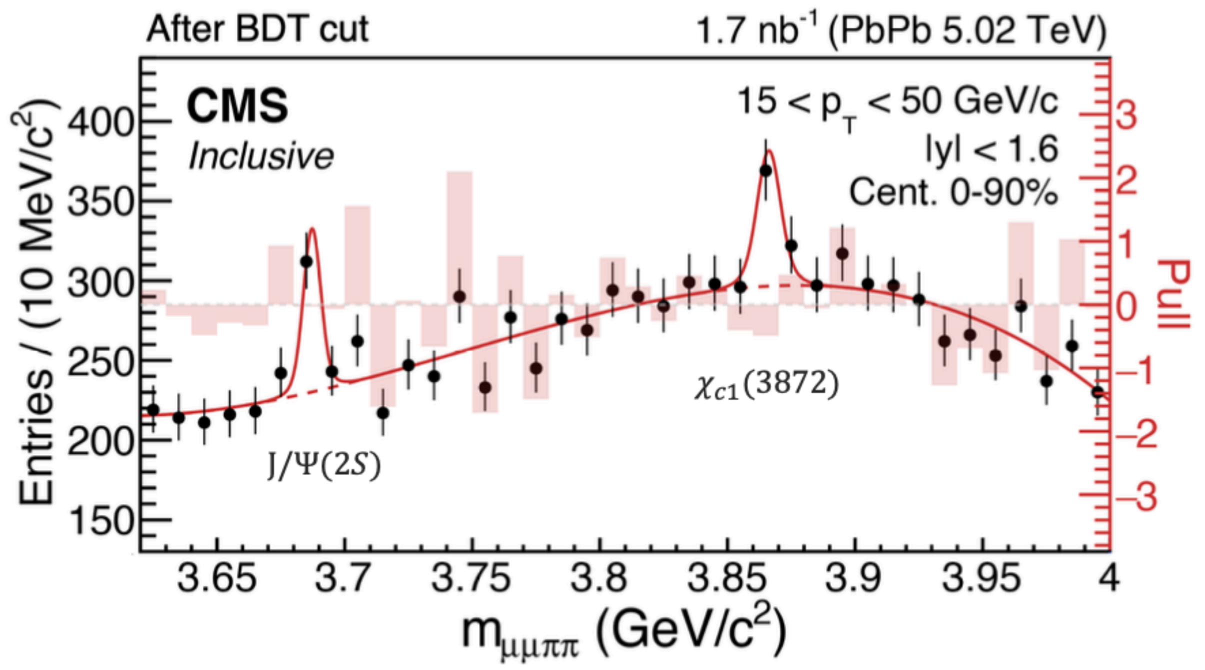


B production

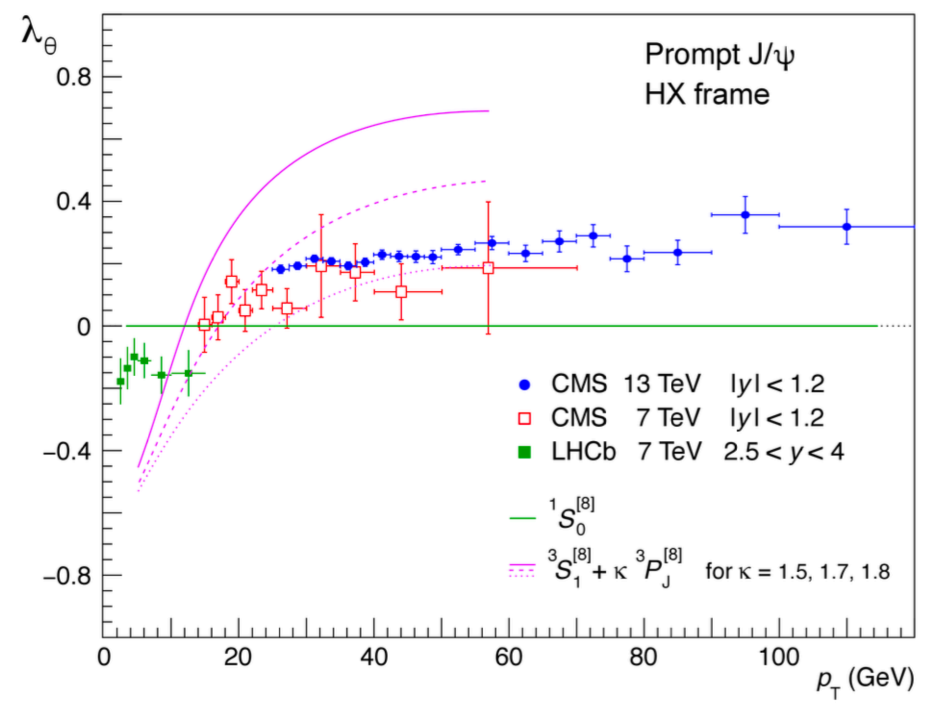


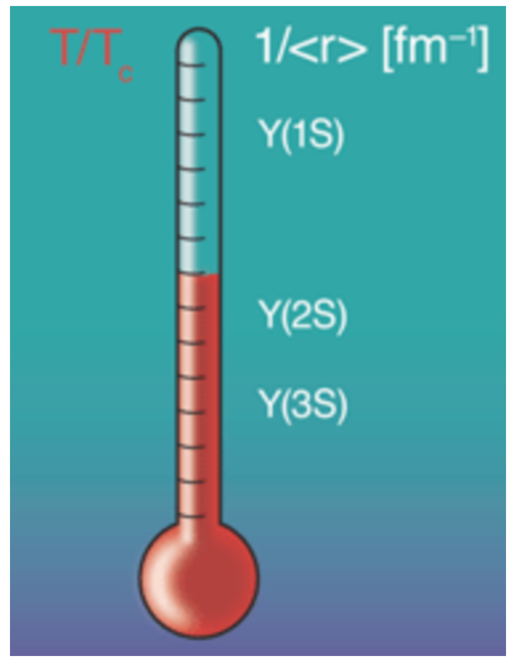


X(3872) in hot medium

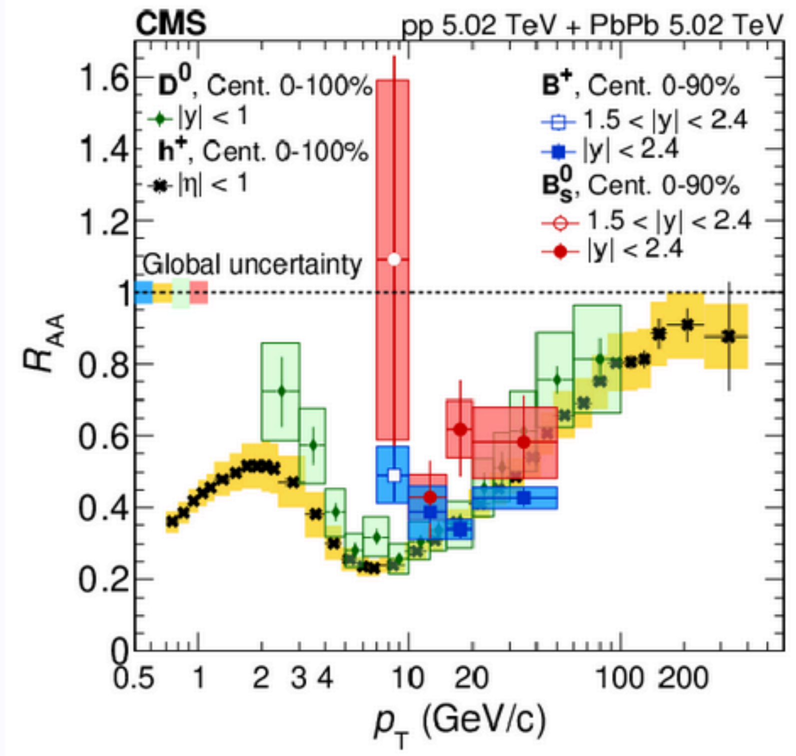


ψ polarisation

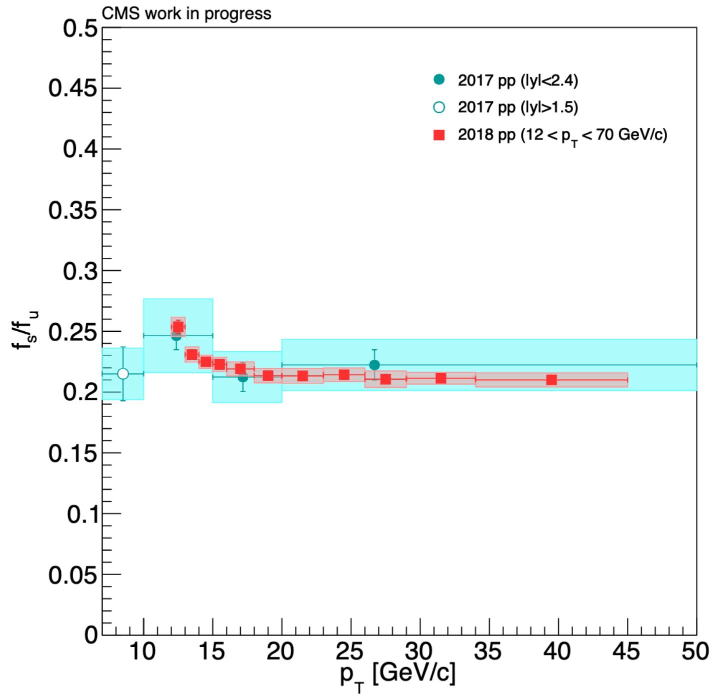




B suppression

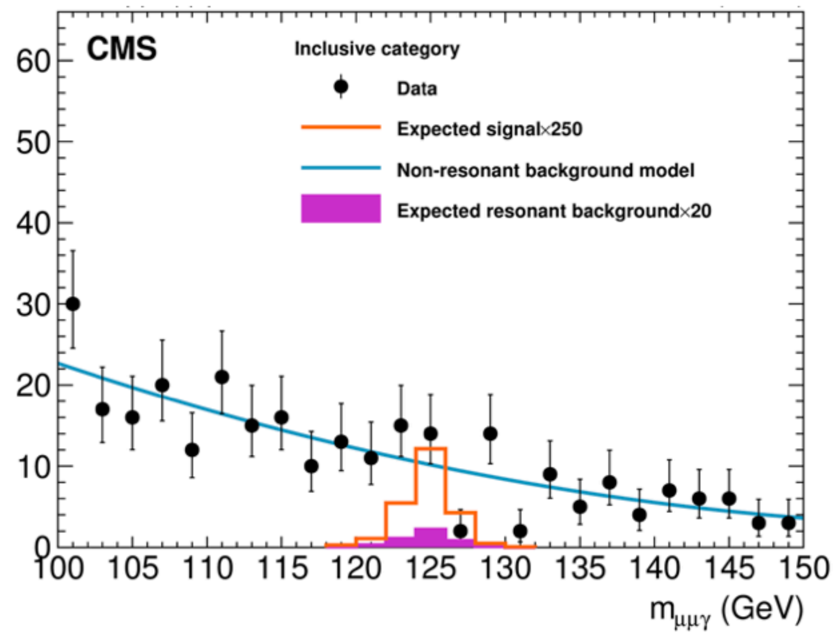


b fragmentation



Higgs

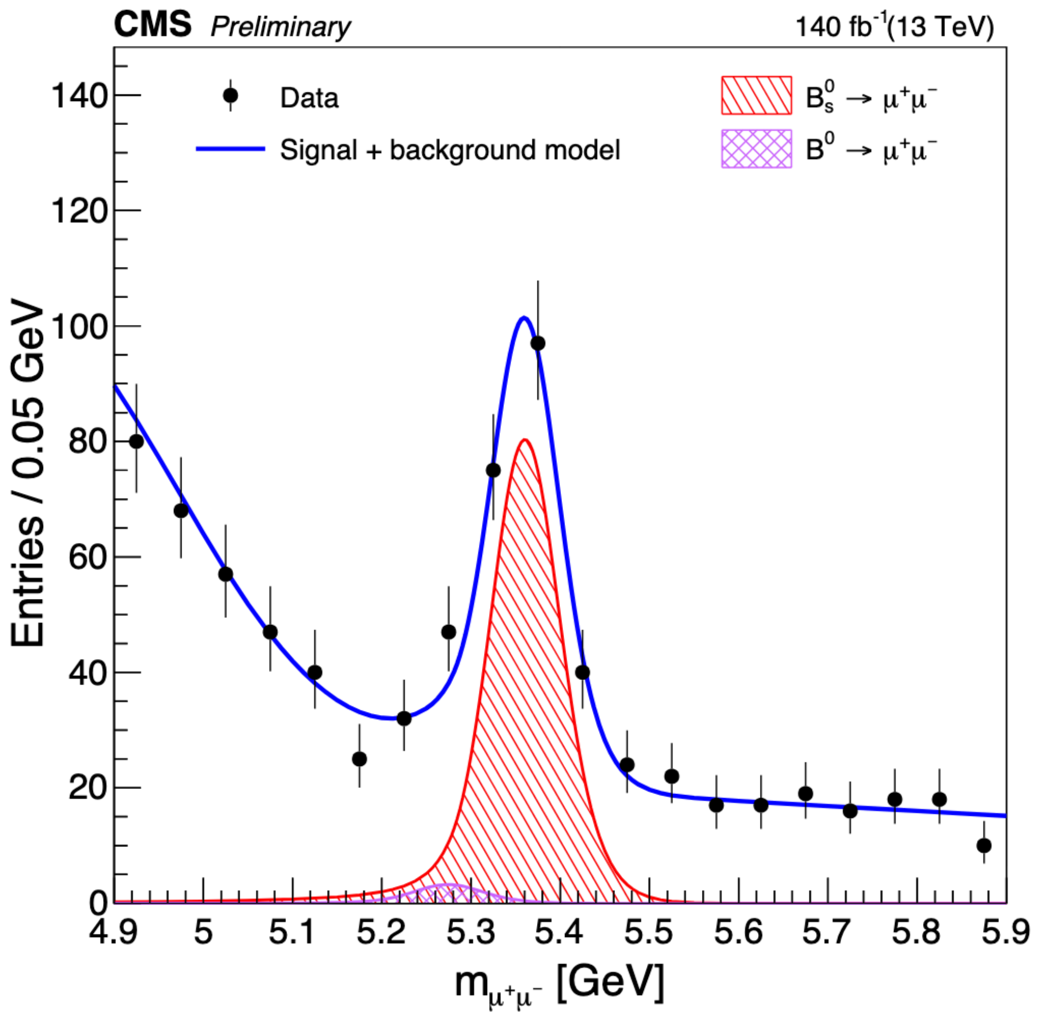
H→Qγ



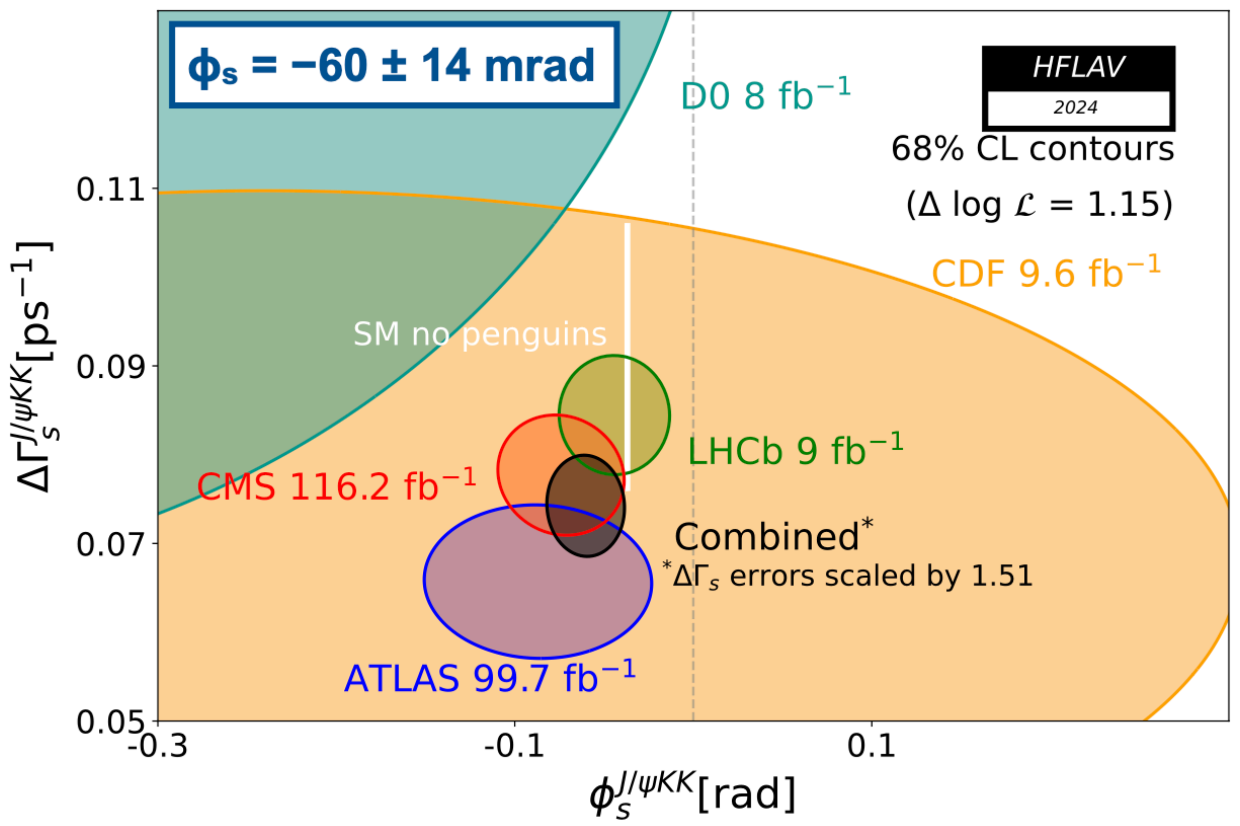
Flavour benchmark channels @ HL-LHC

Now

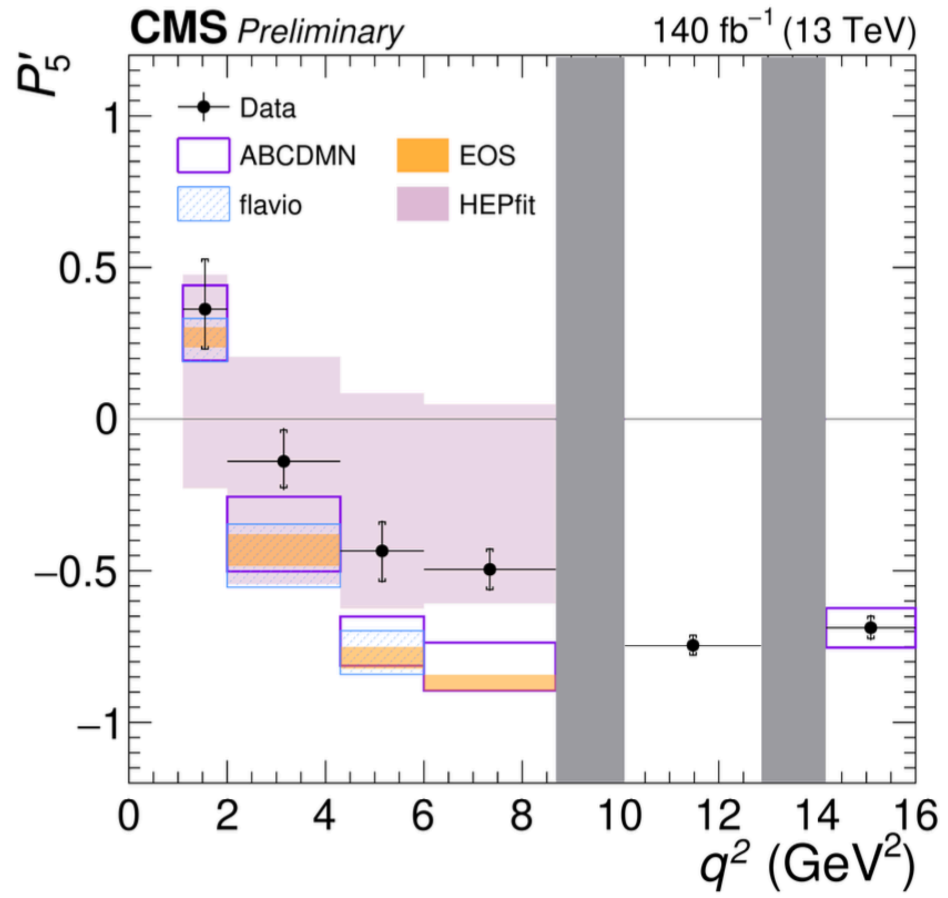
B→μμ



B→ψφ



B→K*μμ

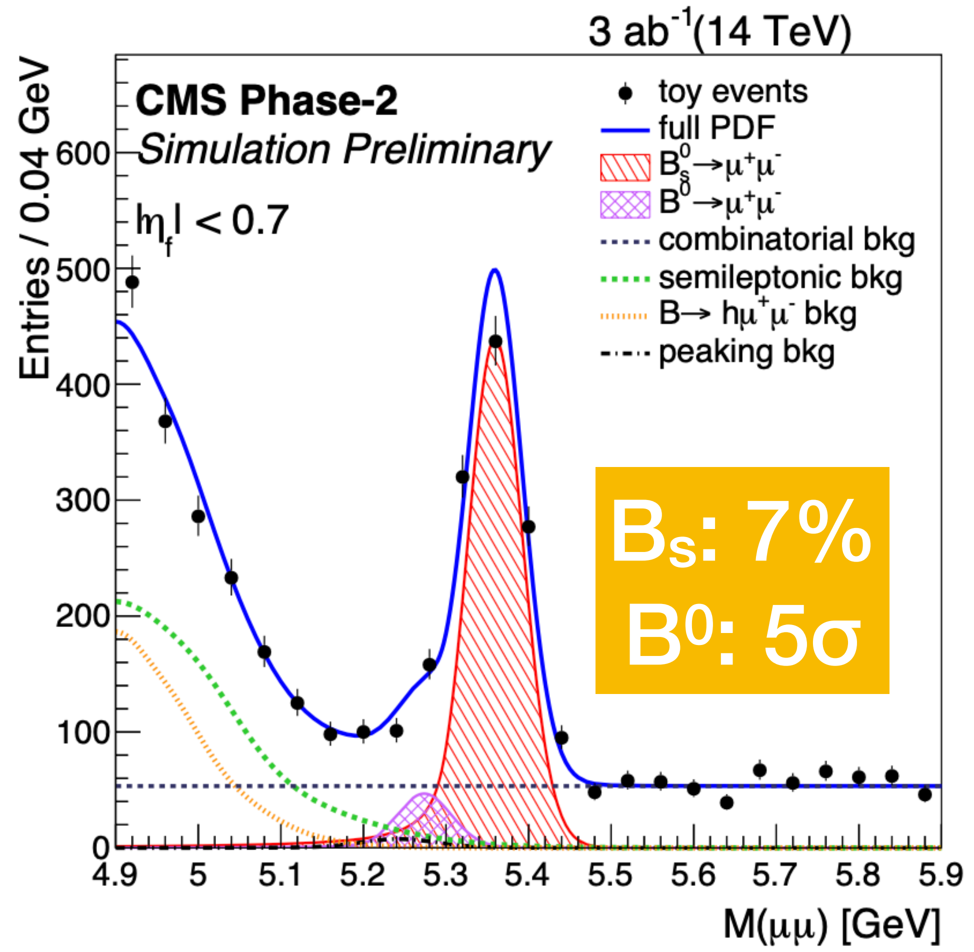


τ→μμμ

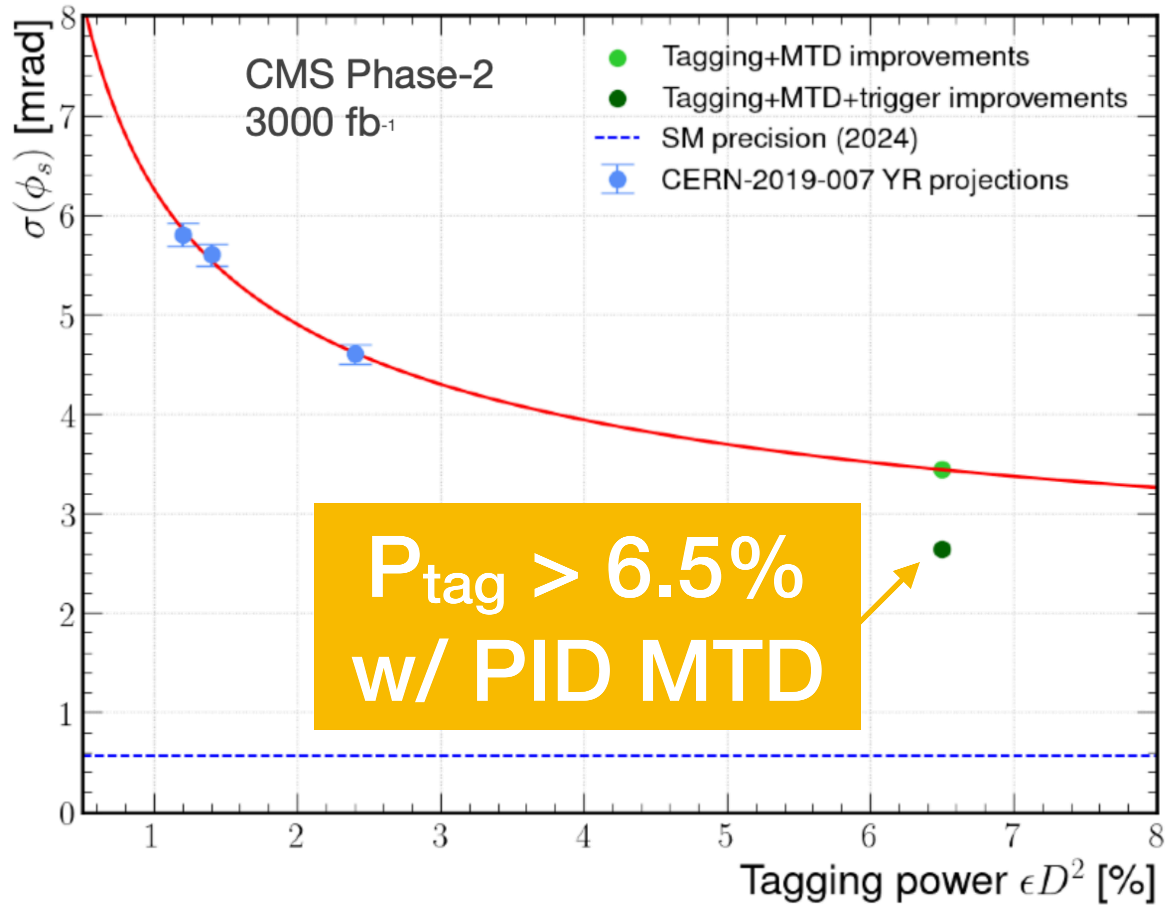
Year	Collab.	Production	Data	Exp*	Obs*
2010	Belle	Y	782 fb^{-1}	-	2.1
2010	BaBar	Y	468 fb^{-1}	4.0	3.3
2014	LHCb	HF	3.0 fb^{-1} (7-8 TeV)	5.0	4.6
2016	ATLAS	W	20.3 fb^{-1} (8 TeV)	39	38
2023	CMS	HF & W	131 fb^{-1} (13 TeV)	2.4	2.9
2024	Belle II	Y	424 fb^{-1}	-	**1.9**

[*] x 10^{-8} @90% CL

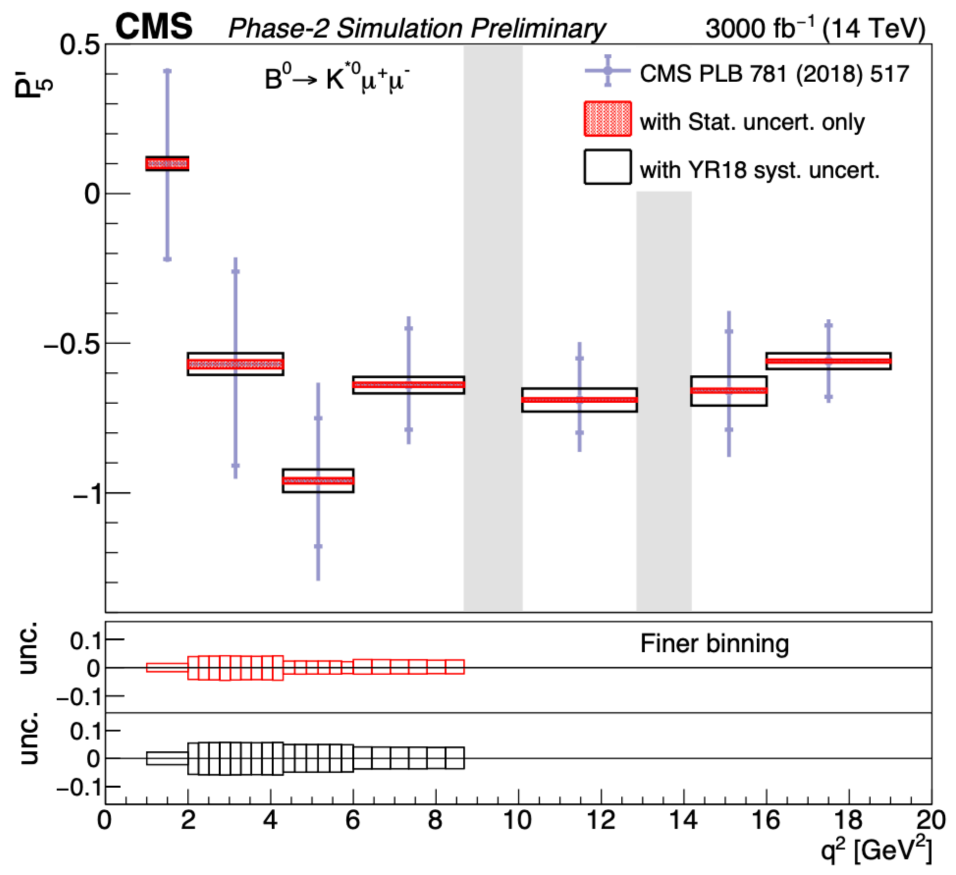
HL-LHC



Bs: 7%
B0: 5σ



P_{tag} > 6.5%
w/ PID MTD



proj. being updated, D & W channels

$B(\tau \to 3\mu)$ 90%C.L. limit	3.7×10^{-9}
$B(\tau \to 3\mu)$ for 3σ-evidence	6.7×10^{-9}
$B(\tau \to 3\mu)$ for 5σ-observation	1.1×10^{-8}

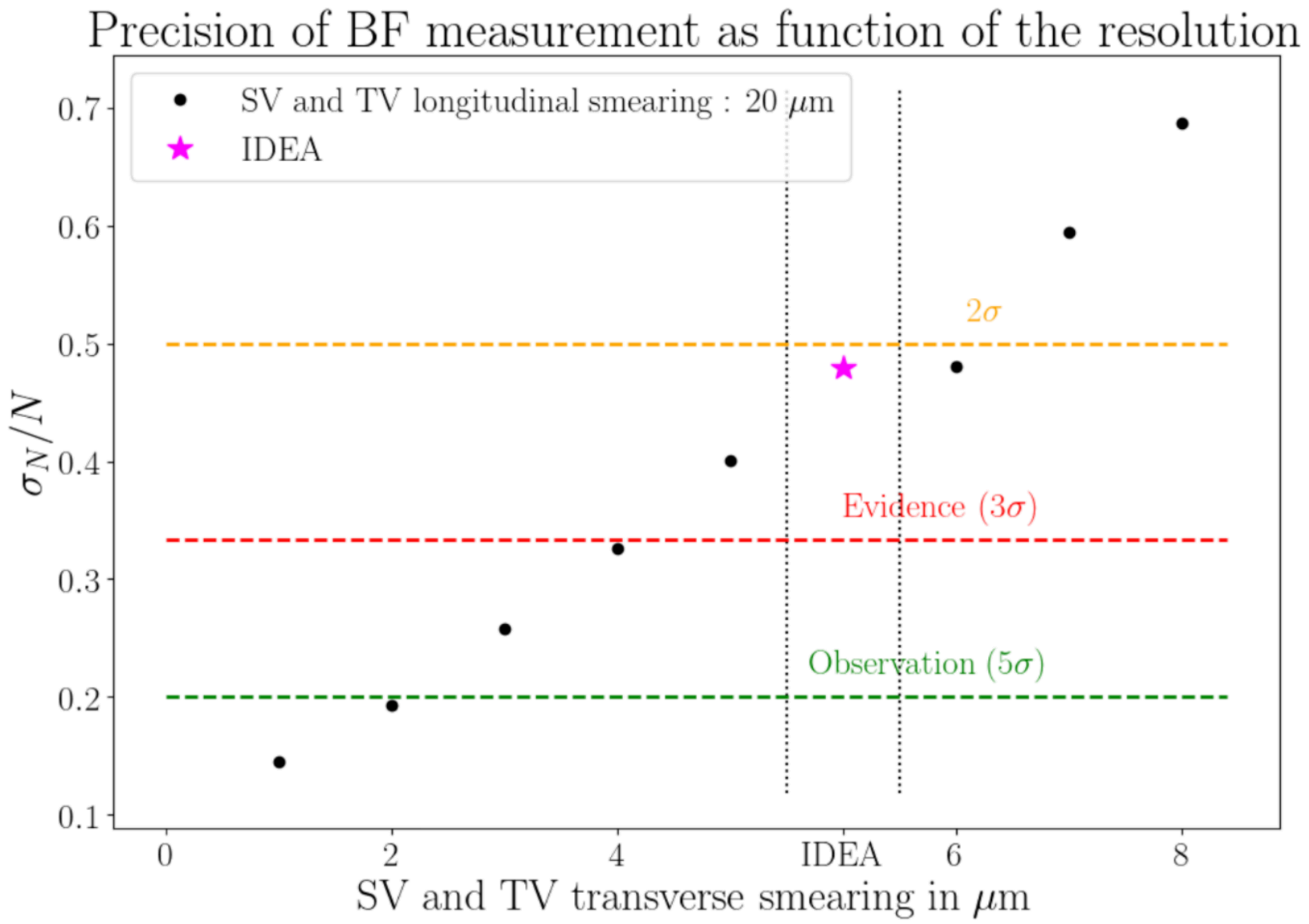
extended acceptance |η|<2.8

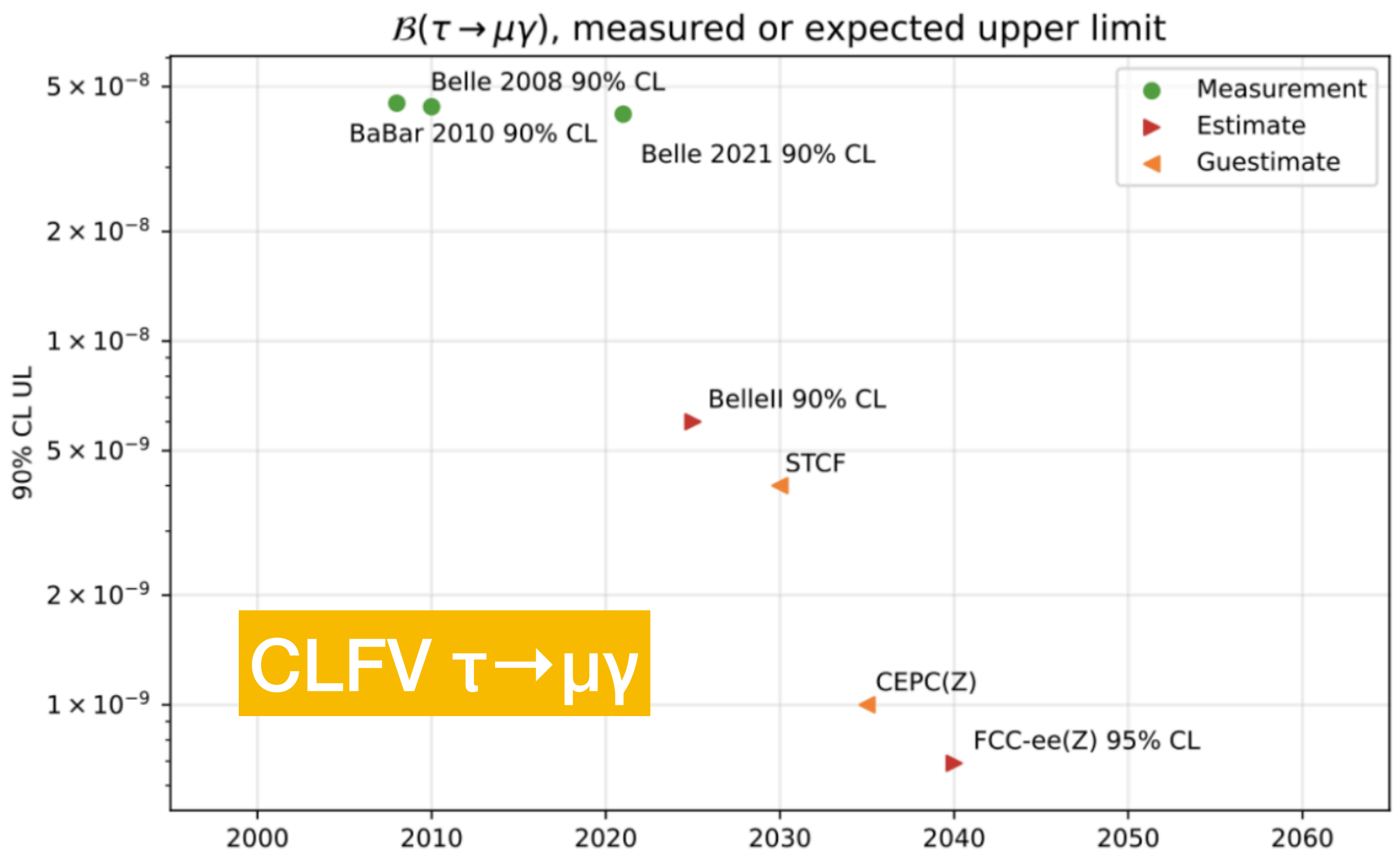
Flavour @ Future Colliders

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

$B \to K^* \tau\tau$

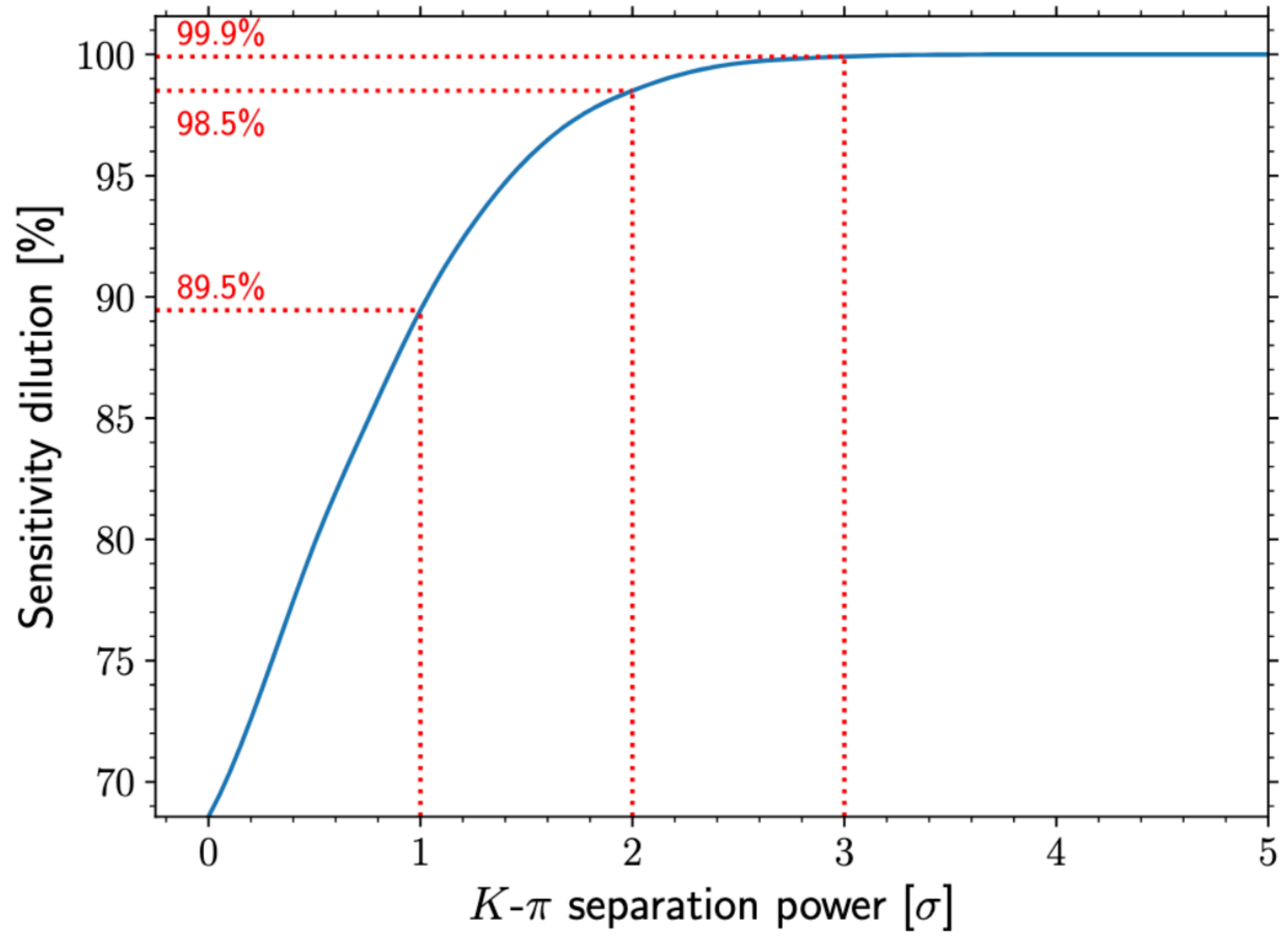
- yet to be observed
- SM BF ~10^{-7}
- NP ⟶ 3^{rd} generation
- IDEA ➥ 3.5σ





$B \to K^* \nu\nu$

- yet to be observed
- not possible at LHC
- theoretically cleaner than $b \to s l^+ l^-$
- novel probes of CPV



Strategy Input

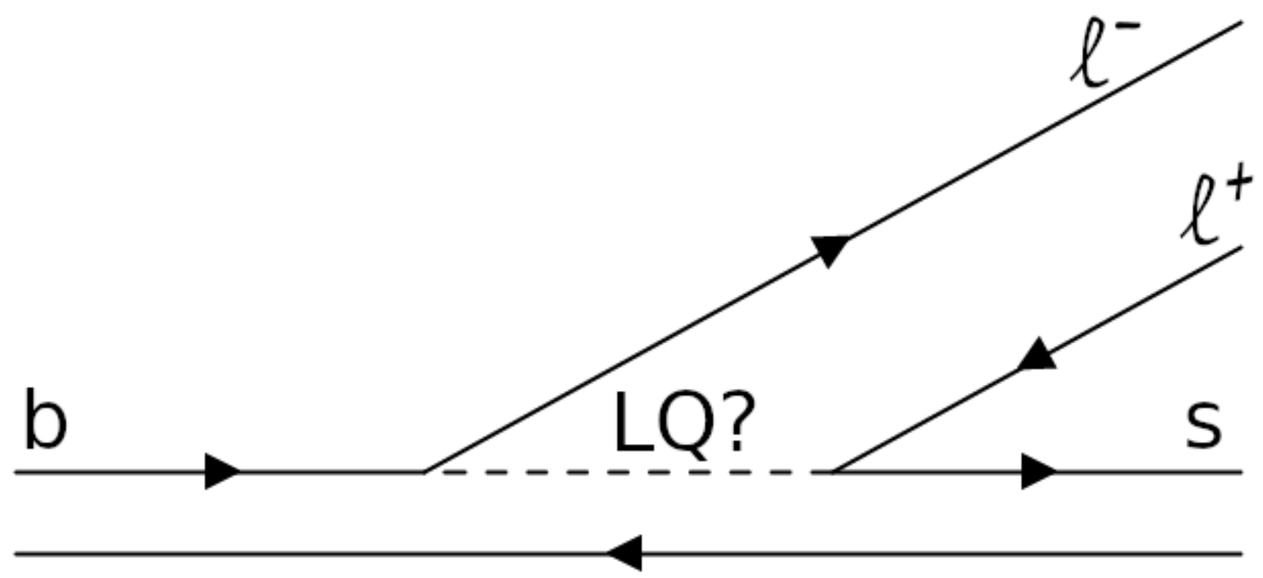
- Re-state the **HL-LHC as the leading priority** for the field
  - support the construction of the general-purpose ATLAS/CMS upgraded detectors
  - support the upgrades of dedicated detectors (LHCb, SND@LHC)
  - support projects extending the physics scope and discovery opportunity
  - support the continued exploration of both pp collisions and ion collisions
  - support the operation during 2030-2041 to reach $3ab^{-1}$ and execution of full physics program

- Advance feasibility and sensitivity studies for a **next collider** and associated detectors
  - support an e^+e^- factory (Z,WW,ZH,tt) such as the FCCee for precision measurements
  - allow to probe (flavour) channels not accessible at hadron colliders

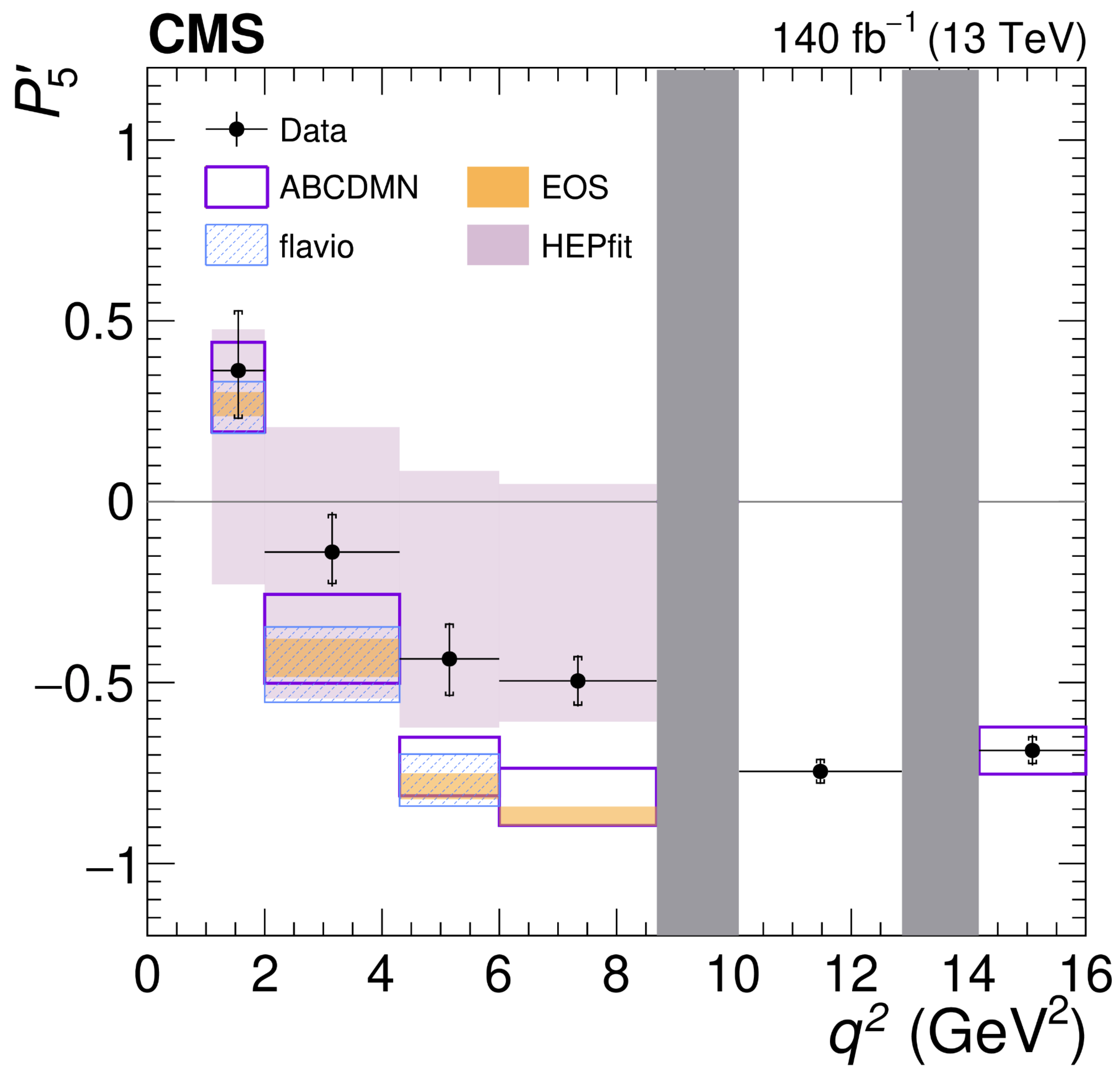
Backup

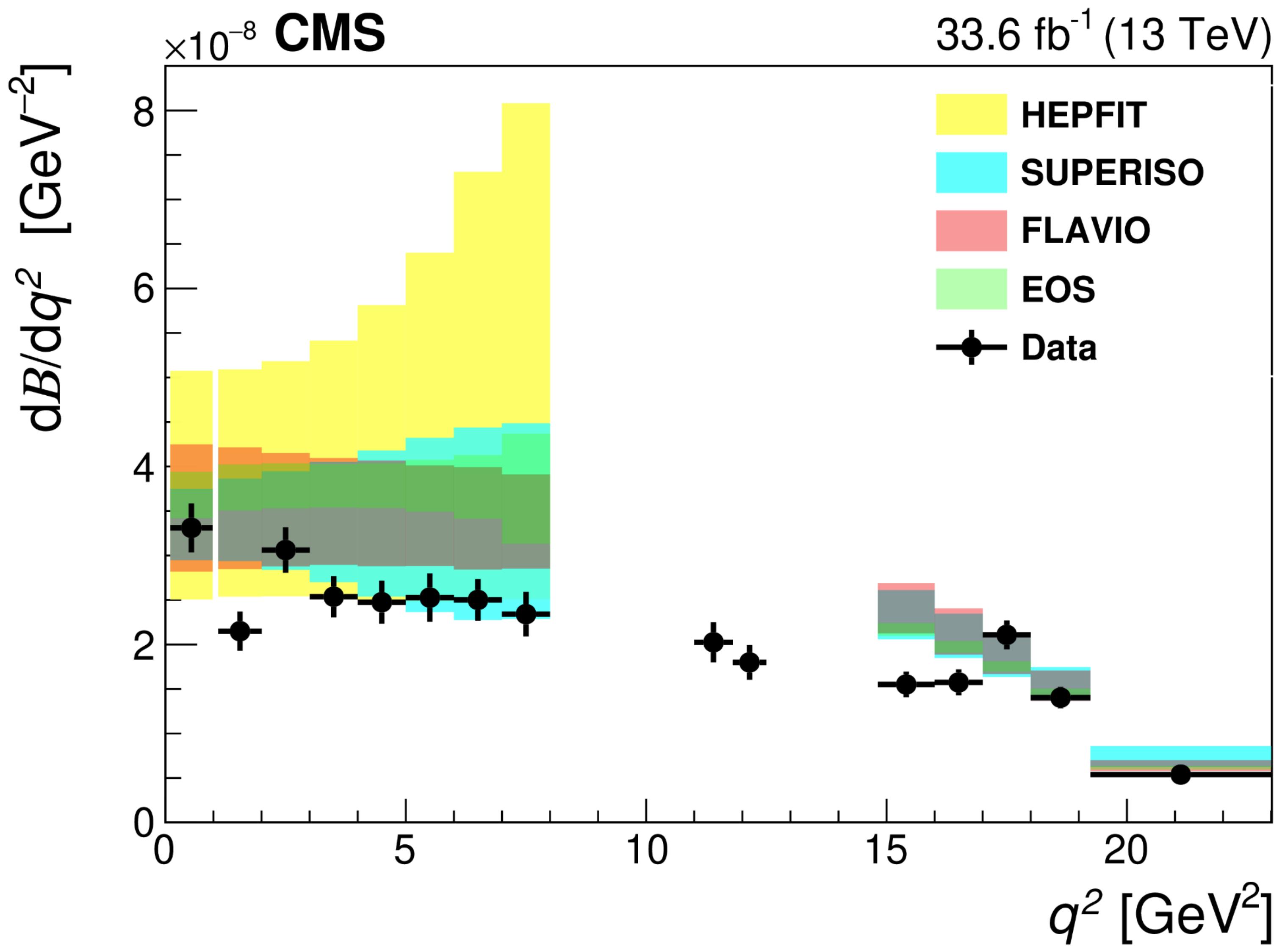
The flavour anomalies

Set of experimental observations in flavour sector revealed discrepancies with SM predictions, in processes sensitive to virtual contribution from new physics

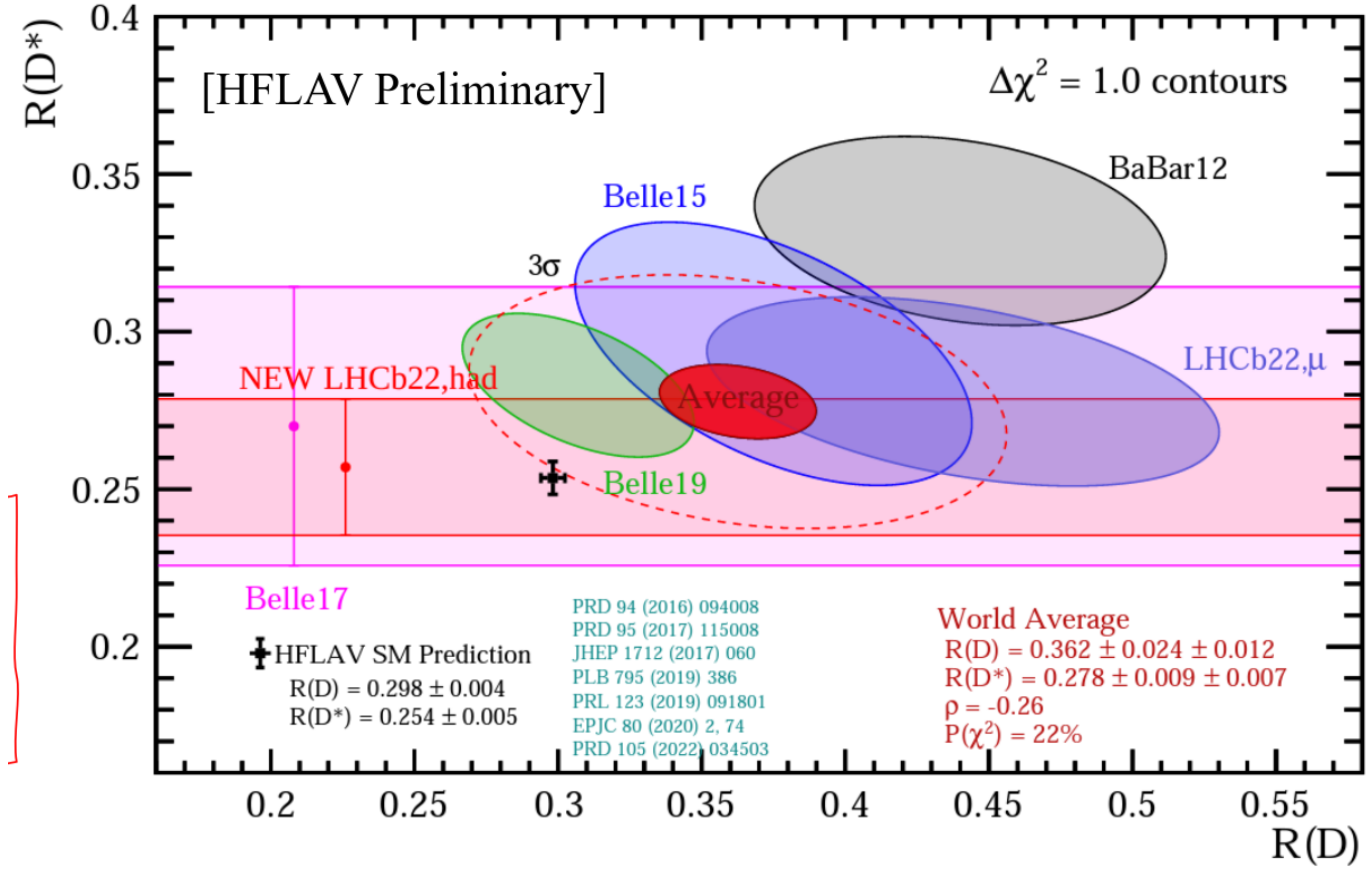


$b \to sll$ decays:
Angular observables and branching fraction





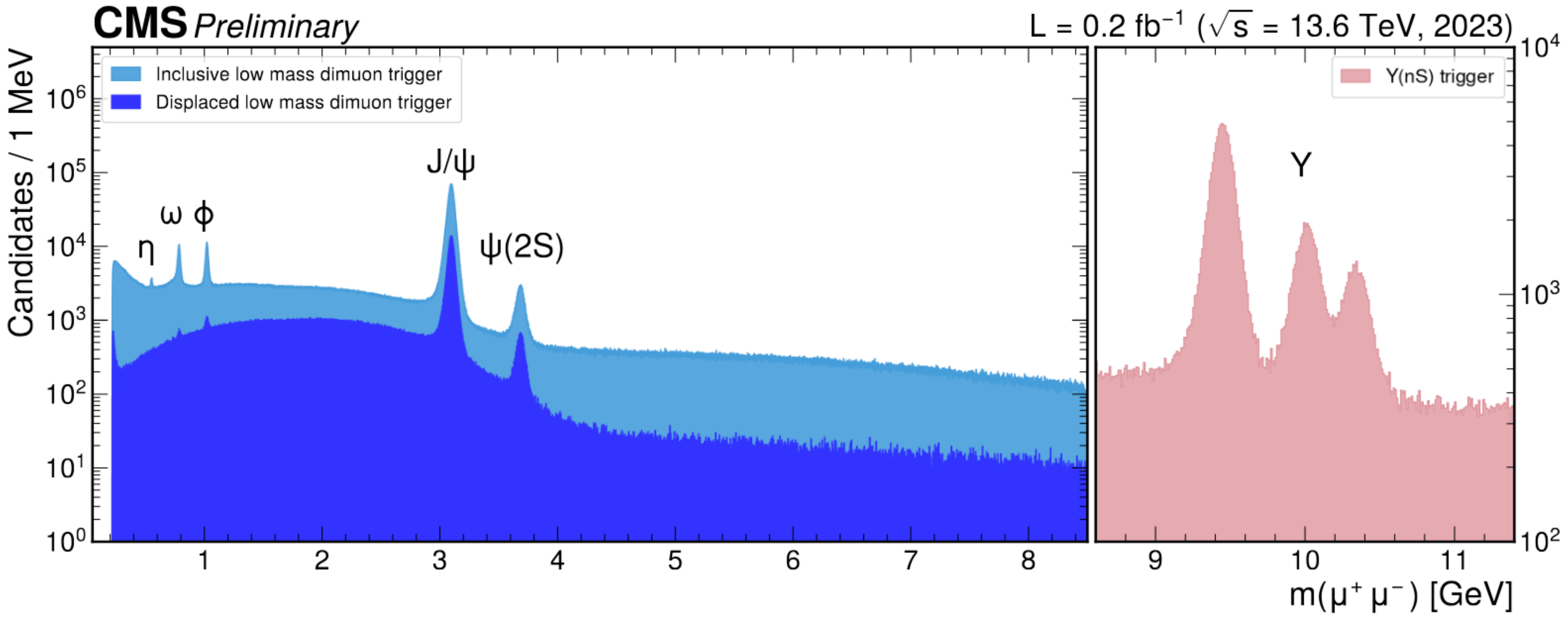
$b \to cl\nu$ decays:
Lepton Flavour Universality tests

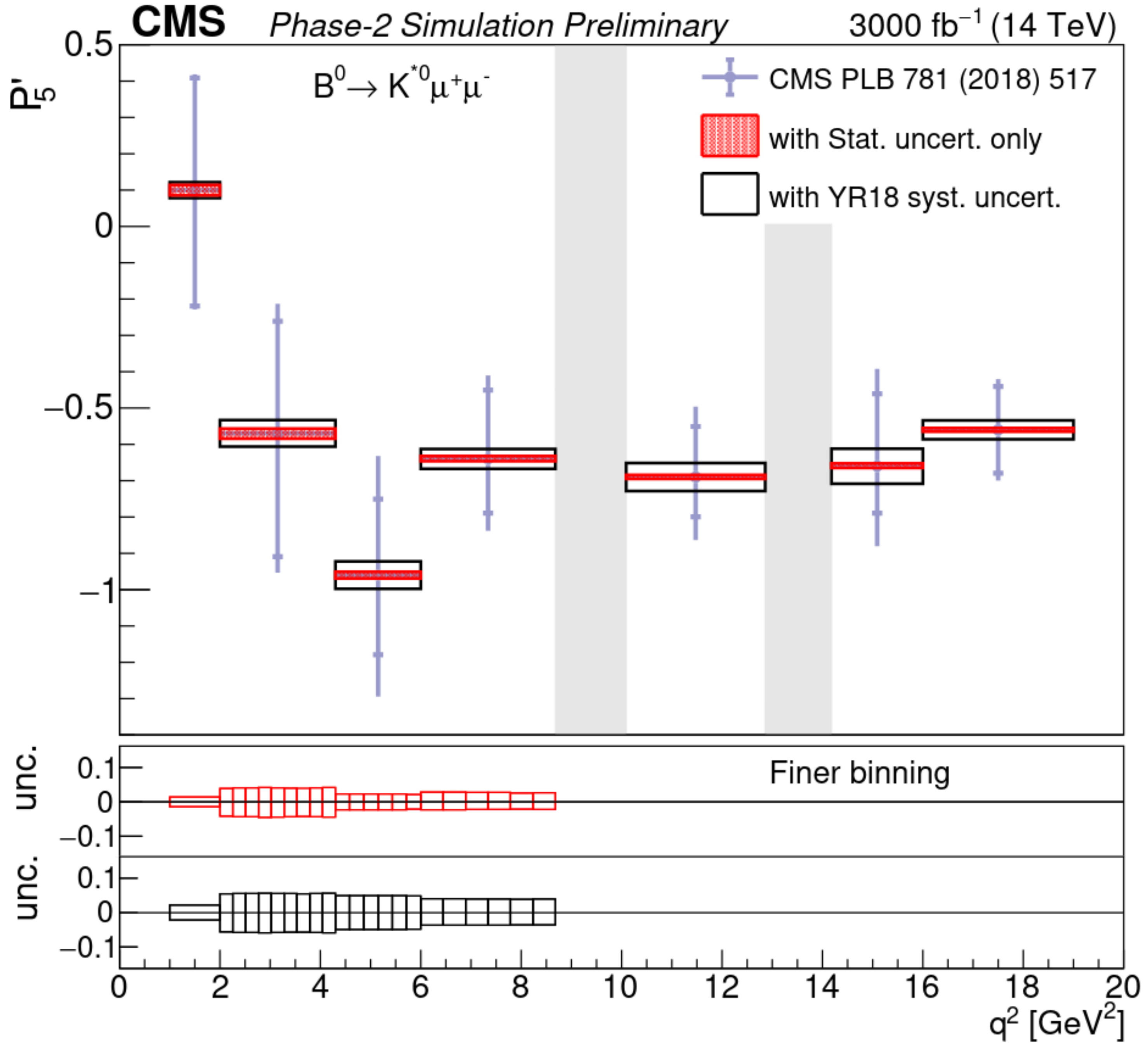


Prospects for b→sμμ studies at CMS

While measurements performed on the LHC Run 2 data showed evidences of tensions with the SM predictions, the data from Run 3 and HL-LHC is critical to achieve to understand the origin of these discrepancies.

Improvements in trigger algorithms deployed in Run 3





Projections of B0->K*0μμ angular analysis with a dataset of 3 ab^{-1} show achieved precision and granularity as a function of the dimuon invariant mass