

OUTLINE

- Introduction
- Motivation
 - Experimental Motivation
 - Theoretical Motivation
- And CMS?
 - Smart ideas
 - Recent Results
 - Future prospects
- Trigger strategy at CMS
- Conclusions



Introduction

Motivation

CMS results

Trigger strategy at CMS

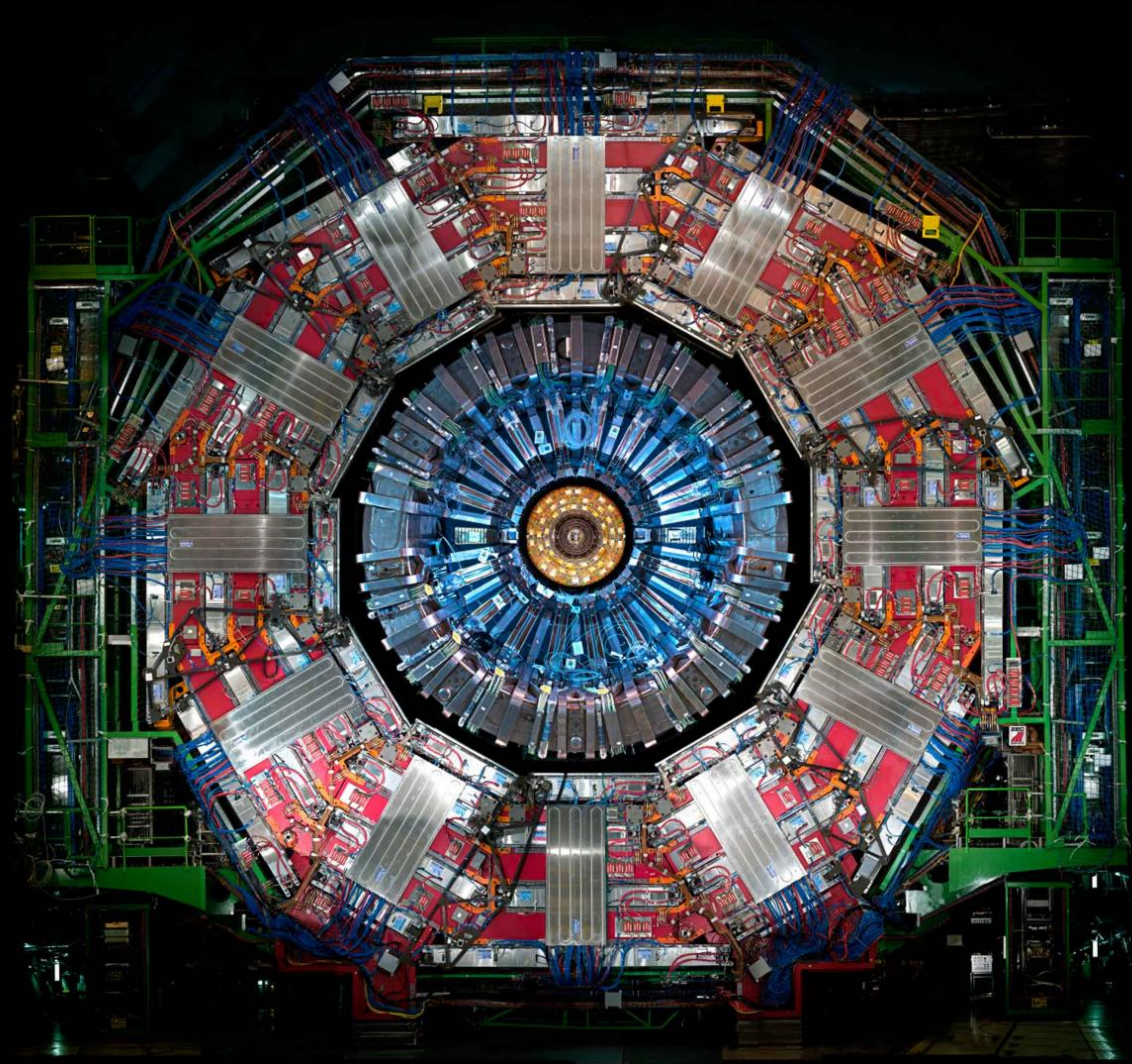
Conclusions





Introduction

- The Large Hadron Collider (*LHC*) is already 16 years old!
 - Energies never reached before
 - Run 3 (2022-2026) at 13.6 TeV
- The Compact Muon Solenoid: one of the four interaction points
 - Multi-purpose detector with broad physics program
 - Many precision physics results and searches for new physics





LHC: Unique data

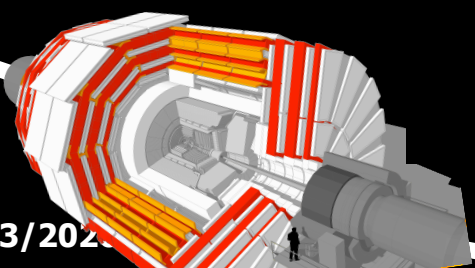
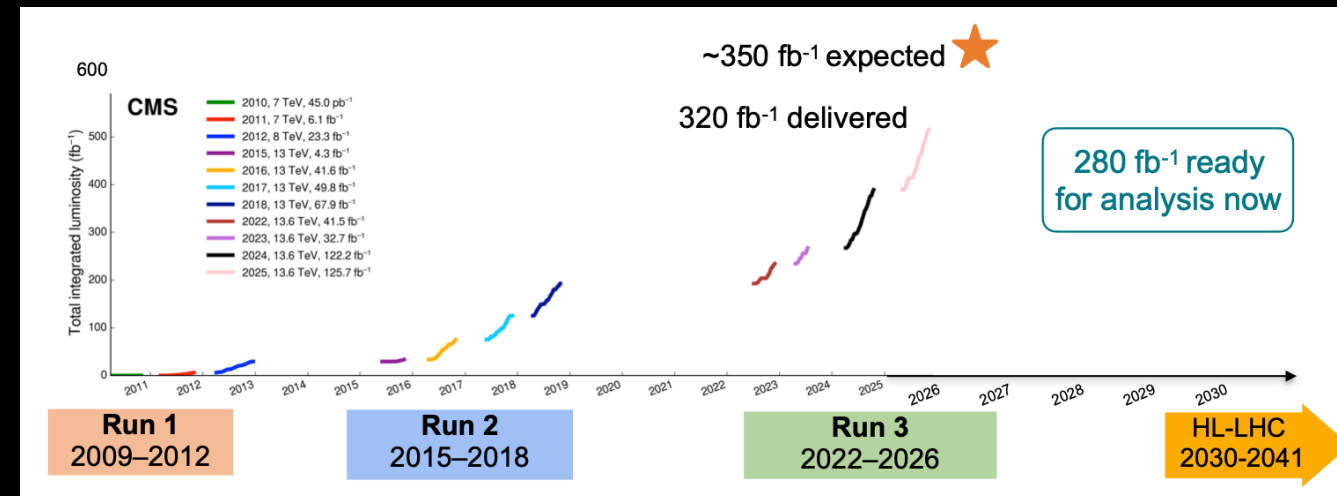
CMS collected 137 fb⁻¹ in Run 2

- Up to 137 fb⁻¹ for the results in this talk

Run 3 more than twice as large as Run 2:

- 2024+2025 alone larger than 2016-2023

280 fb⁻¹(until mid 2025)



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Tracker Upgrade at CMS

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New physics? Where?

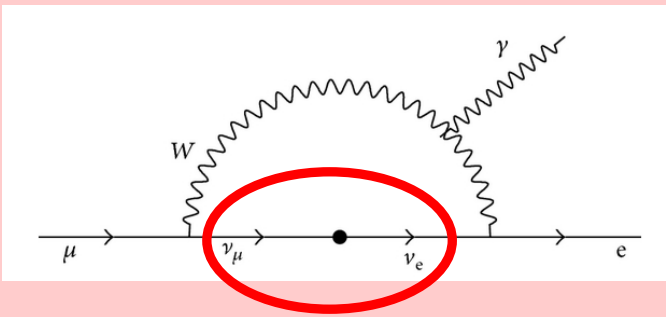
➤ In the SM, **charged leptons** - *electrons, muons and taus*– must have identical electroweak (EW) behaviour: **Lepton Flavour Universality (LFU)**

▪ **NOT a formal symmetry**, but experimentally confirmed

☑ Broken by Higgs-lepton interactions

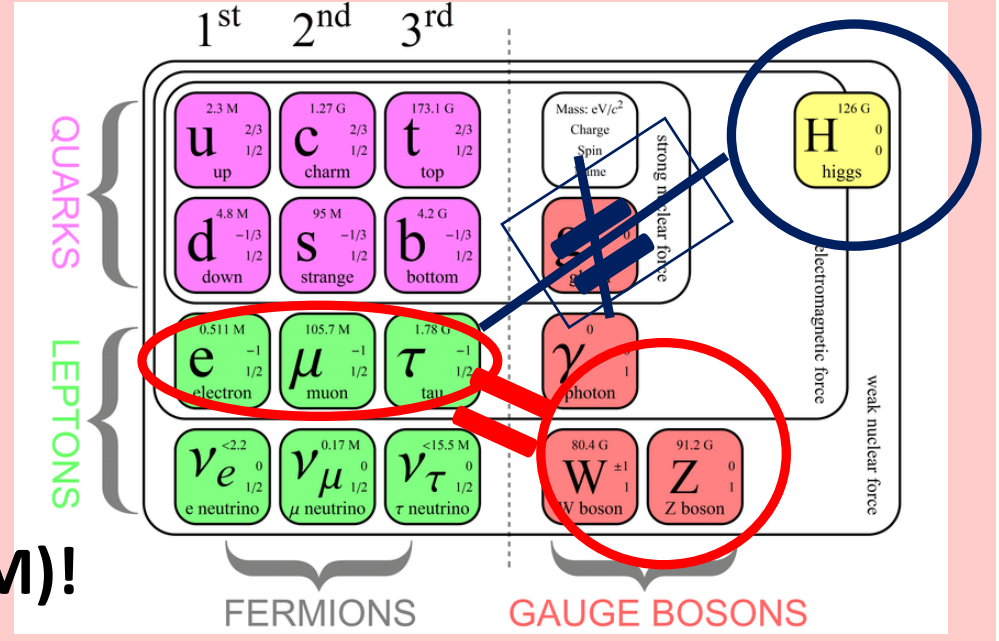
☑ Violation *possible* only via *neutrino mixing*. Very Rare process:

$$B(\mu^+ \rightarrow W^+ \nu(\nu_\mu \rightarrow \nu_e) \rightarrow e^+ \gamma) < 10^{-55}$$



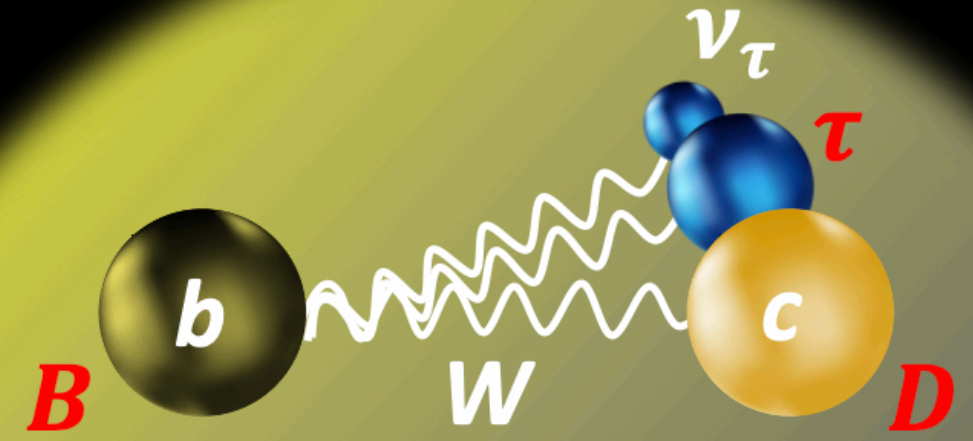
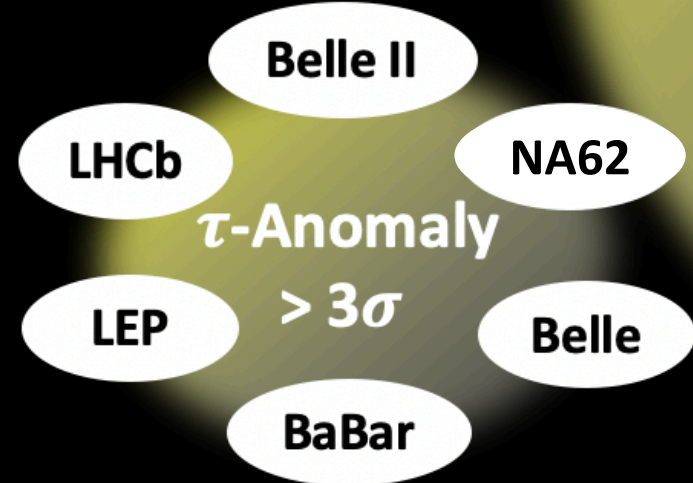
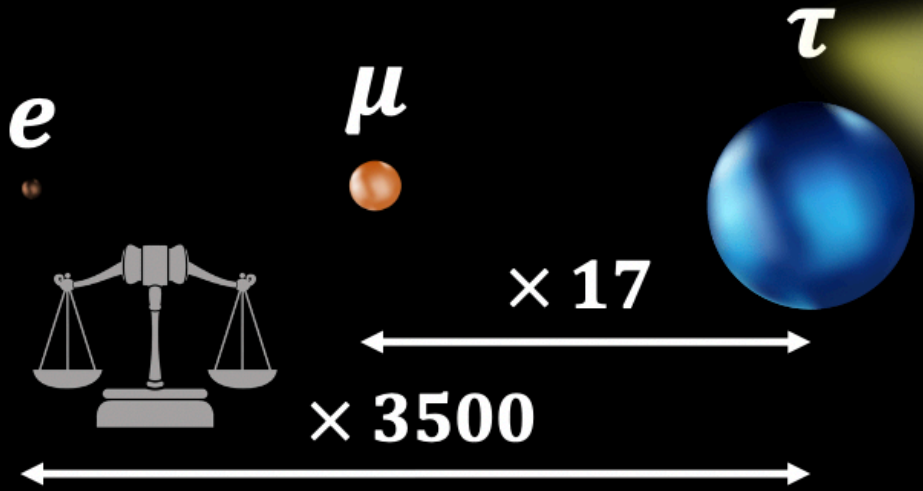
Why should SM EW adhere to LFU?

LFU violation (LFUV) => beyond the SM (BSM)!





LFUV PUZZLE



NEW PHYSICS ?





Hunting for LFUV I

Where?

- From low- p_T to high- p_T ...
Huge phase-space!

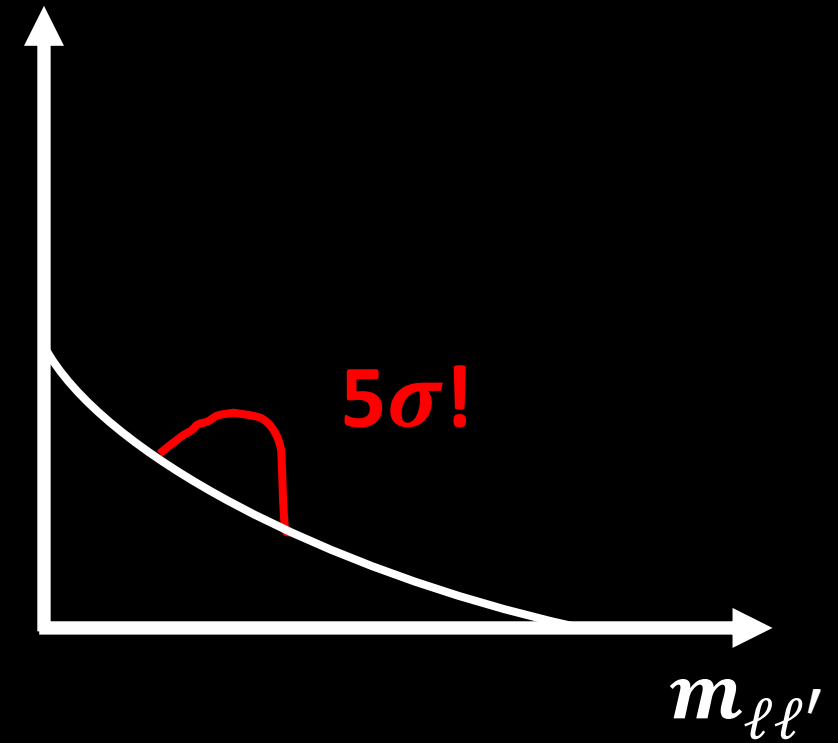




Hunting for LFUV II

How?

- Different approaches:
 - **Classic bump search**





Hunting for LFUV III

How?

- Different approaches:
 - **Infer the impact of additional contributions due to LFUV**

- **Additional LFUV Operators:**

$$\mathcal{L} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda^2} \sum_a C_a^{(6)} O_a^{(6)} + \dots$$

- **Deviation of SM processes looking at clear observables**



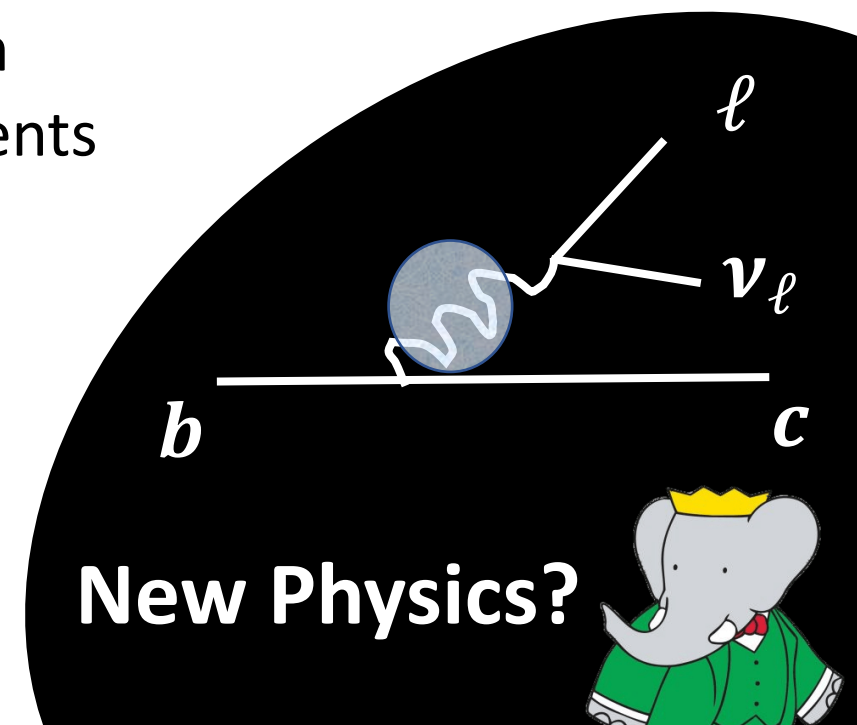
Once upon a ratio ...

Semi-leptonic decays of B mesons as sensitive LFUV probes

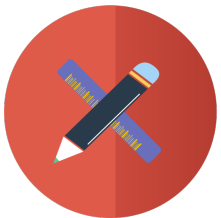
$$\mathcal{R}(H_c) = \frac{\mathcal{B}(H_b \rightarrow H_X \ell \ell)}{\mathcal{B}(H_b \rightarrow H_X \ell \ell)}$$

- Decays to different leptons => test LFU between them
- Common uncertainties cancel out in ratio measurements
- Which decay should we test?
- Large interest for $H_c \Rightarrow b \rightarrow c$ decay
 - Tree-level process in the SM
 - Precise theoretical calculation

A surprisingly result in 2012



New Physics?



$b \rightarrow c$: a west-coast story

Phys. Rev. Lett. 109 (2012) 101802
Belle II Preprint 2024-001
Phys. Rev. Lett. 134 (2025) 061801

➤ LFUV: taus vs muons:

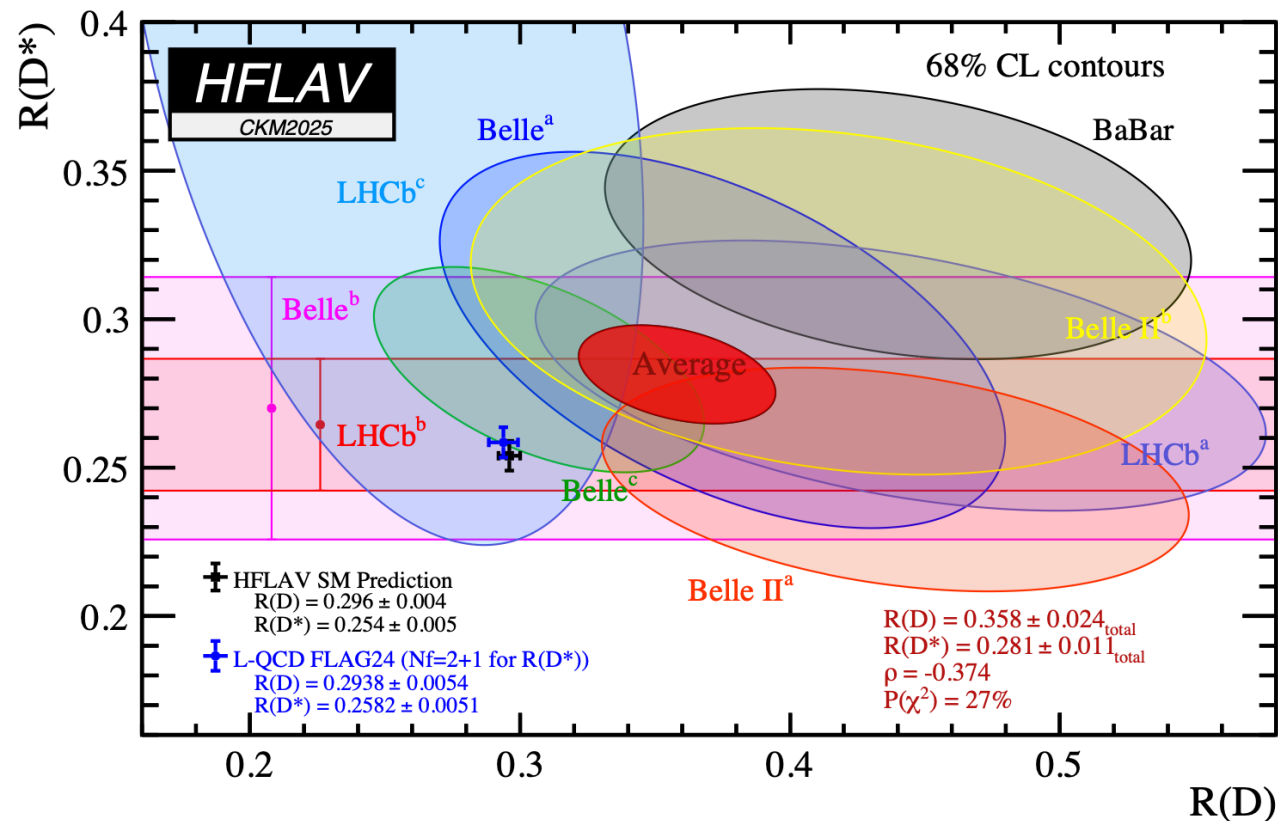
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B^0 \rightarrow D^{(*)-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{(*)-} \mu^+ \nu_\mu)}$$

- BaBar: 3σ -deviation
- Belle and Belle II (Jan 2024)
- LHCb – (2018 and 2025)

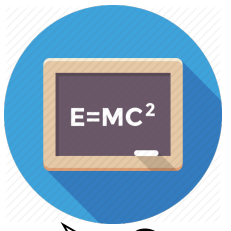
➤ Same LFUV test - $\mathcal{R}(J/\psi)$

- 2σ -deviation by LHCb

3. 8σ -deviation from the SM!

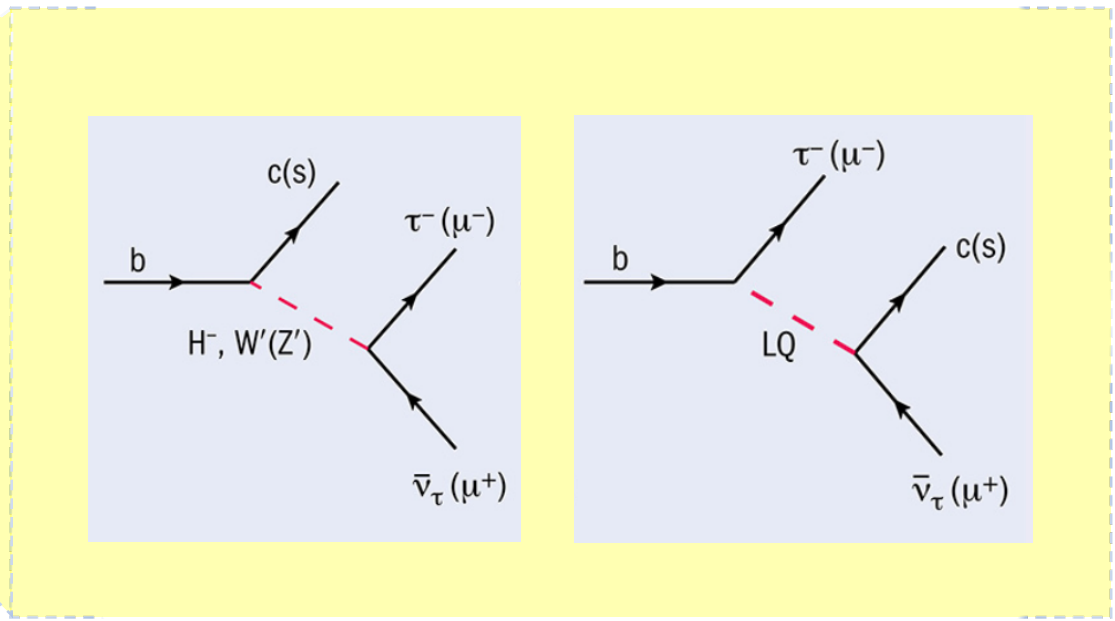
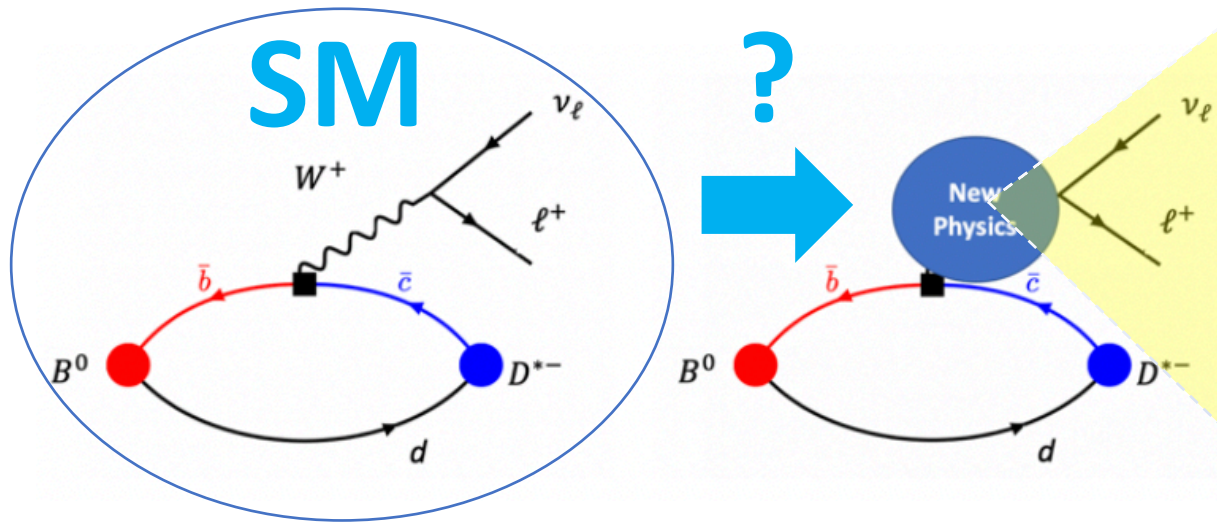


Growing sensitivity puzzling the scientific community ...

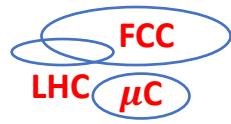


Theoretical motivation

- Several BSM models to explain it:
 - ❑ Extended Higgs or Gauge sector or LeptoQuarks



- **Impact:**
- Which machine after the LHC?
- Which physics program? Clear indication from LFUV!



- Flavour Anomaly Workshop
- >550 scientists at CERN
- "LFUV" in iNSPIRE >1500 contributions appear



$b \rightarrow s$: the elephant in the room



- LFUV: muons vs electrons

$$\mathcal{R}(H_s) = \frac{\mathcal{B}(H_b \rightarrow H_s \mu^+ \mu^-)}{\mathcal{B}(H_b \rightarrow H_s e^+ e^-)}$$

- Some excitement for a 3.1σ -deviation for $\mathcal{R}(K^{(*)})$ by LHCb:

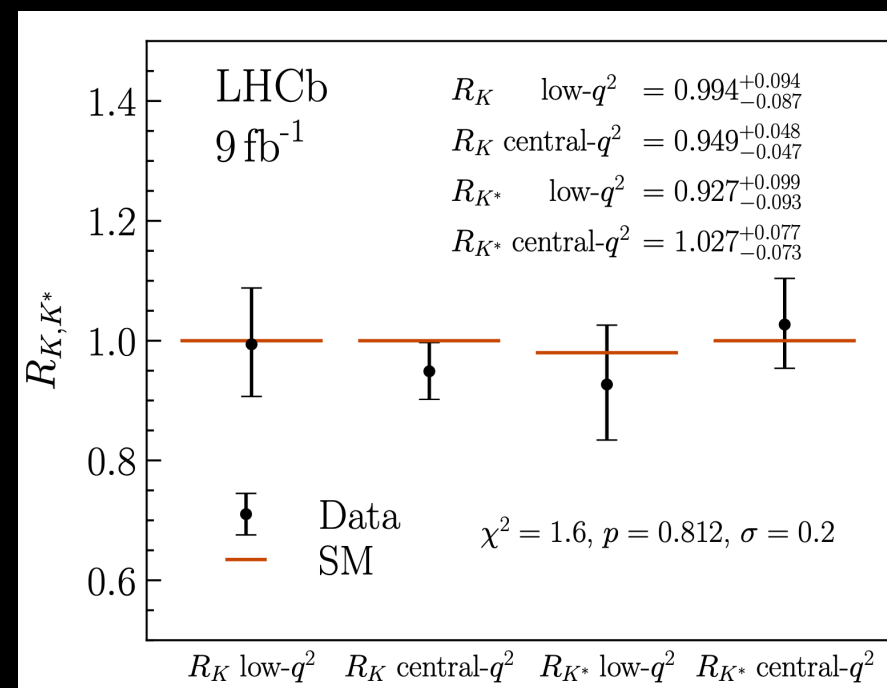
Nature Physics volume 18, pages 277–282 (2022)

- Updated result (Dec 2022):

- [Phys. Rev. D 108 \(2023\) 032002](#)
- [Phys. Rev. Lett. 131 \(2023\) 051803](#)

New Physics?

SM consistent!





Motivation: And now what?

- BSM model: additional LFUV operators to SM
 - >120 operators studied

$$\mathcal{L}_{SM-EFT} = \mathcal{L}_{SM} (= \mathcal{L}_{SM,gauge} + \mathcal{L}_{SM,Higgs}) + \sum_i C_i Q_i$$

New Physics:
flavour asymmetry



? Third-generation

BSM only for 3rd generation

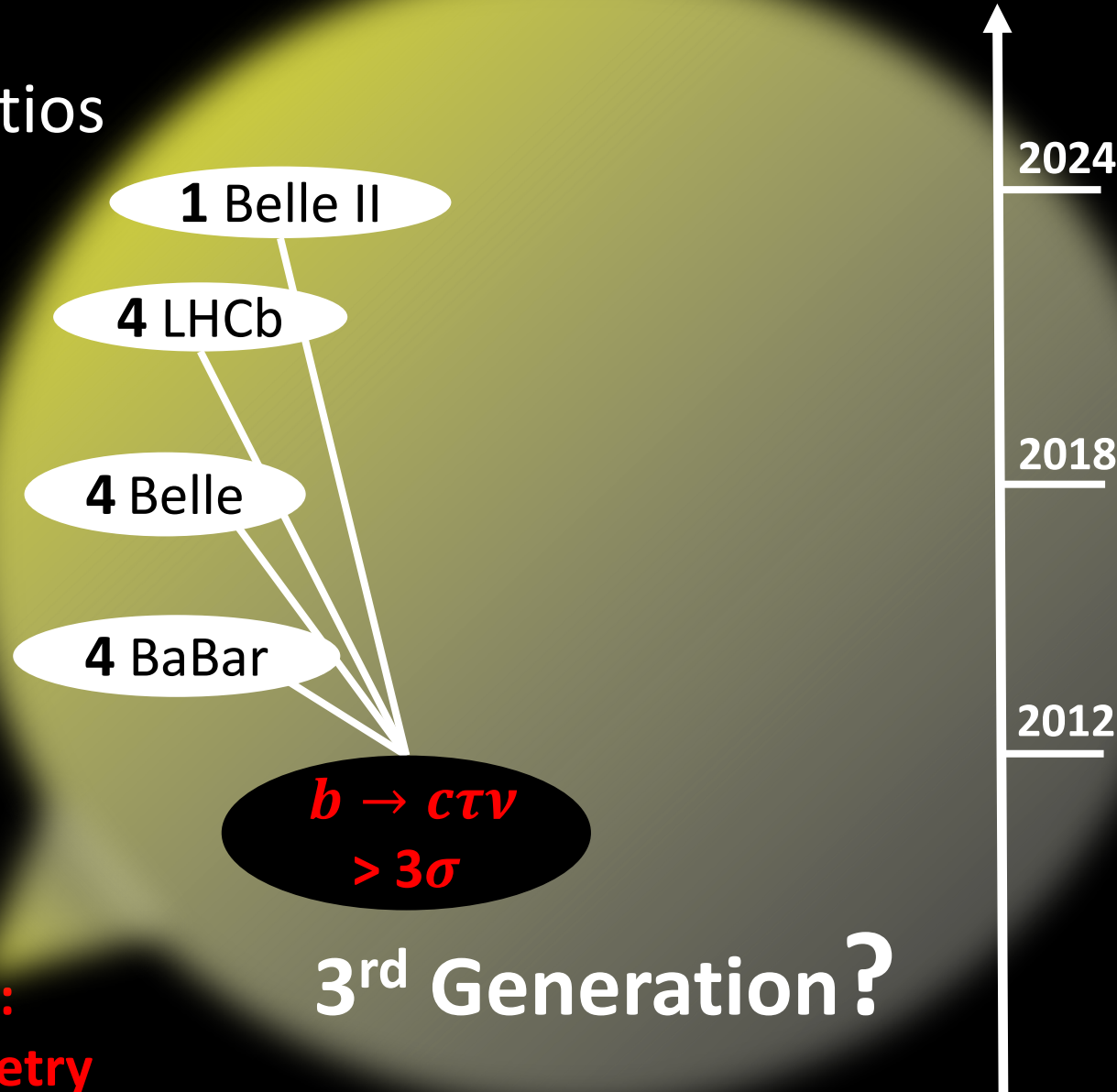
- No place for LFUV $b \rightarrow s\mu\mu$
- Cannot be limited to $\mathcal{R}(D^{(*)})$

[J. High. Energ. Phys. 2024,49 \(2024\)](#)



Theory Vs Experiments

- 13 measurements on the $\mathcal{R}(D^{(*)})$ ratios
 - 4 experiments

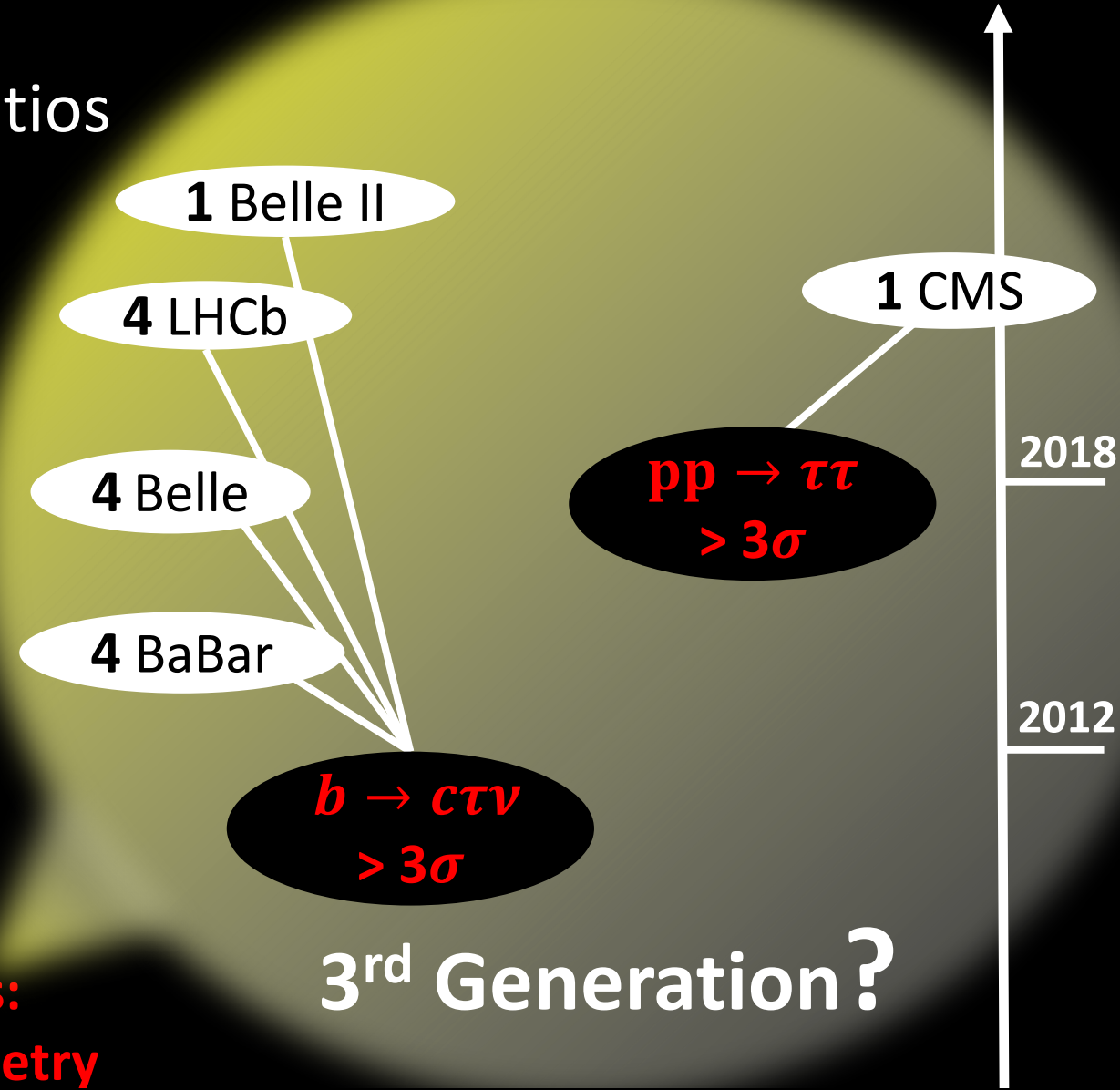


**New Physics:
flavour asymmetry**



Theory Vs Experiments

- 13 measurements on the $\mathcal{R}(D^{(*)})$ ratios
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- Using $\mathcal{R}(D^{(*)})$ results, BSM predicts observable at the current energies:
 1. $pp \rightarrow \tau\tau$ excess (at 95-100 GeV, CMS)
 - Compatible with ATLAS extrapolation



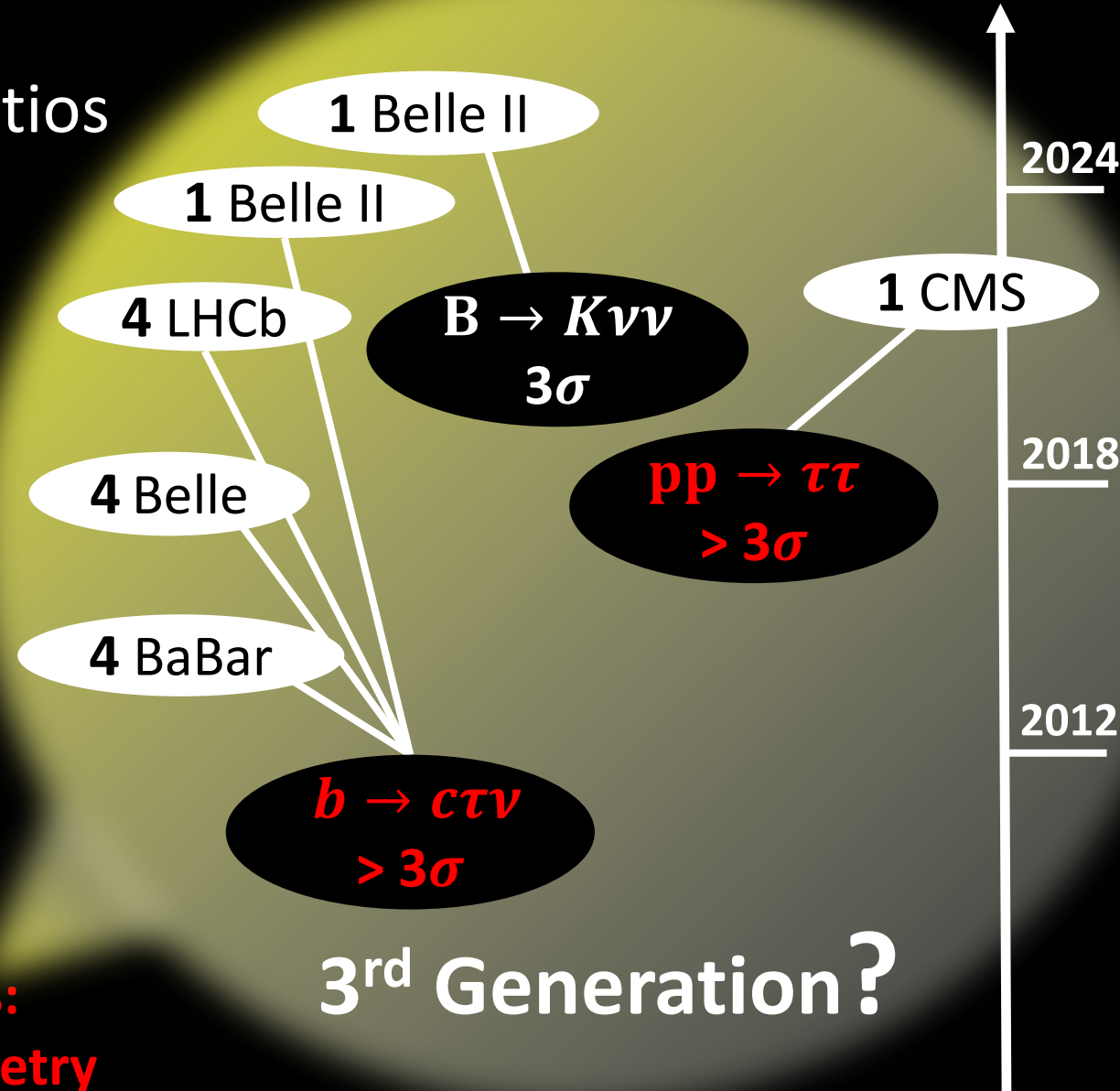
**New Physics:
flavour asymmetry**

3rd Generation?



Theory Vs Experiments

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 - Compatible with ATLAS extrapolation
 2. $B^+ \rightarrow K^+ \nu \bar{\nu}$ 3σ deviation from SM

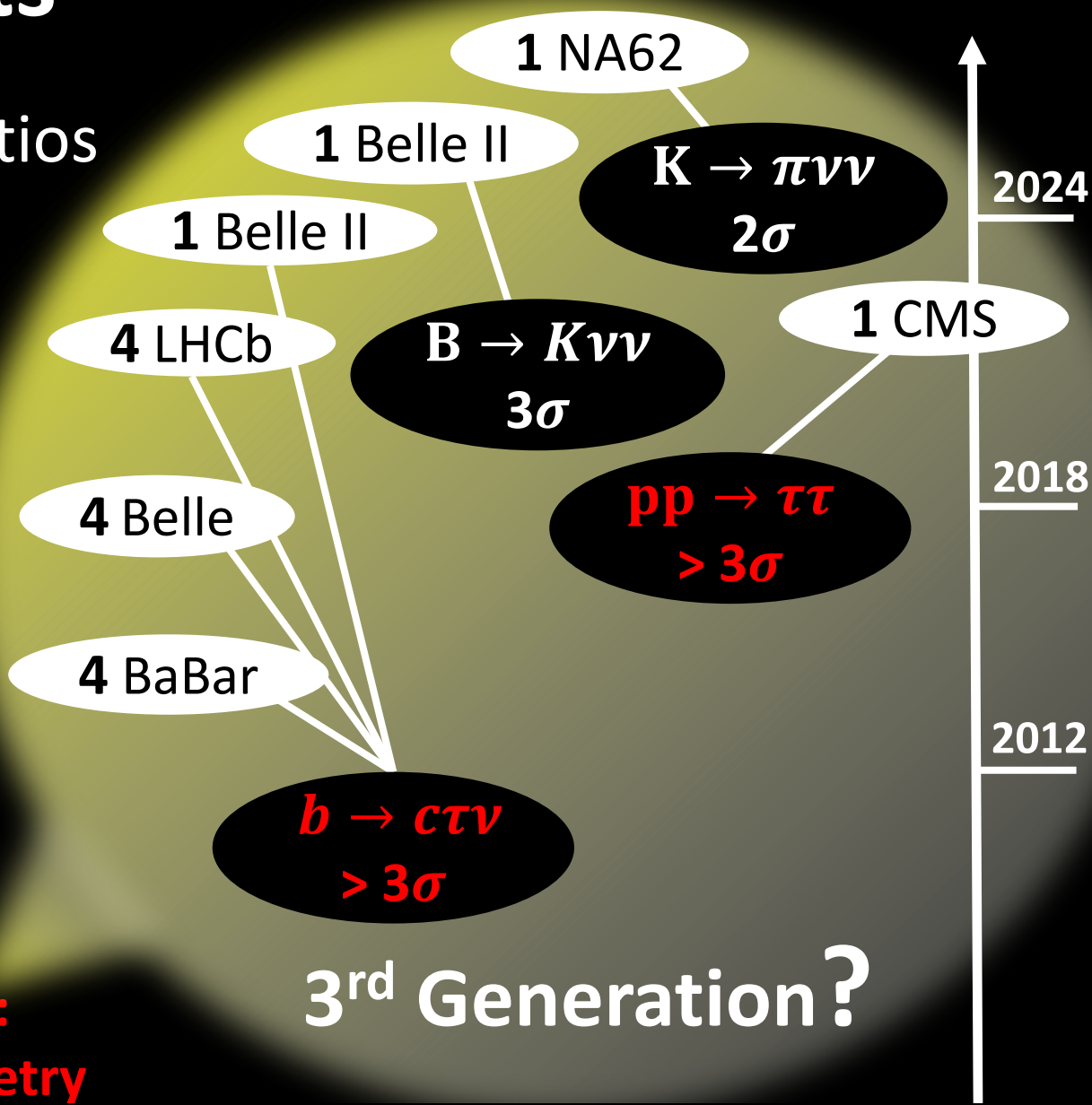


New Physics:
flavour asymmetry



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 3. $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ 2σ deviation from SM



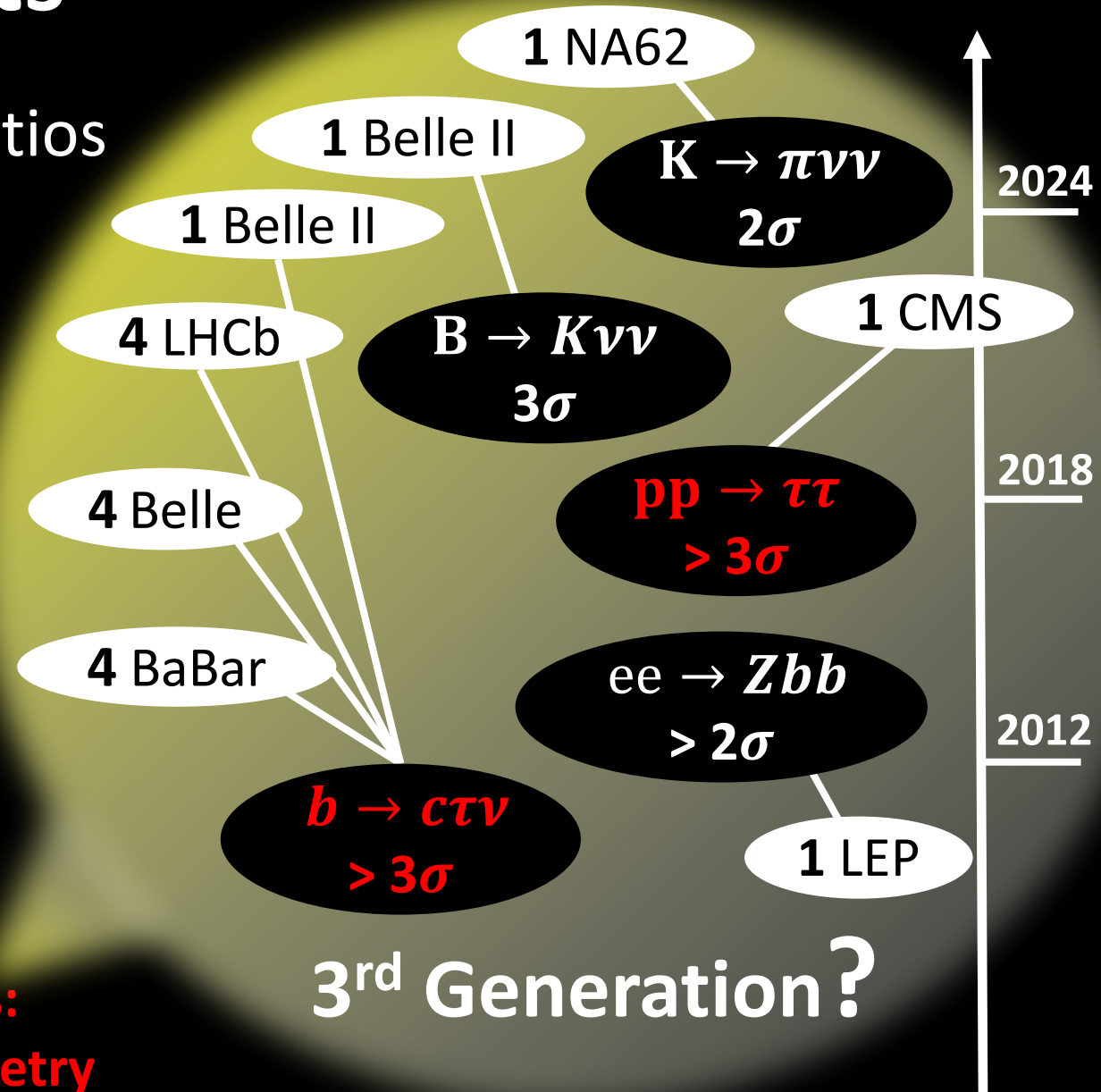
**New Physics:
flavour asymmetry**

3rd Generation?



Theory Vs Experiments

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 - 4 experiments
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 1. $pp \rightarrow \tau\tau$ excess (at 95-100 GeV, CMS)
 - Compatible with ATLAS extrapolation
 2. $B^+ \rightarrow K^+ \nu\bar{\nu}$ 3σ deviation from SM
 3. $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ 2σ deviation from SM
 4. $e^+e^- \rightarrow Zbb > 2\sigma$ excess at 98 GeV (LEP)



New Physics:
flavour asymmetry



Theory Vs Experiments

- 17 measurements from 7 experiments
- Just a matter of time to collect data?

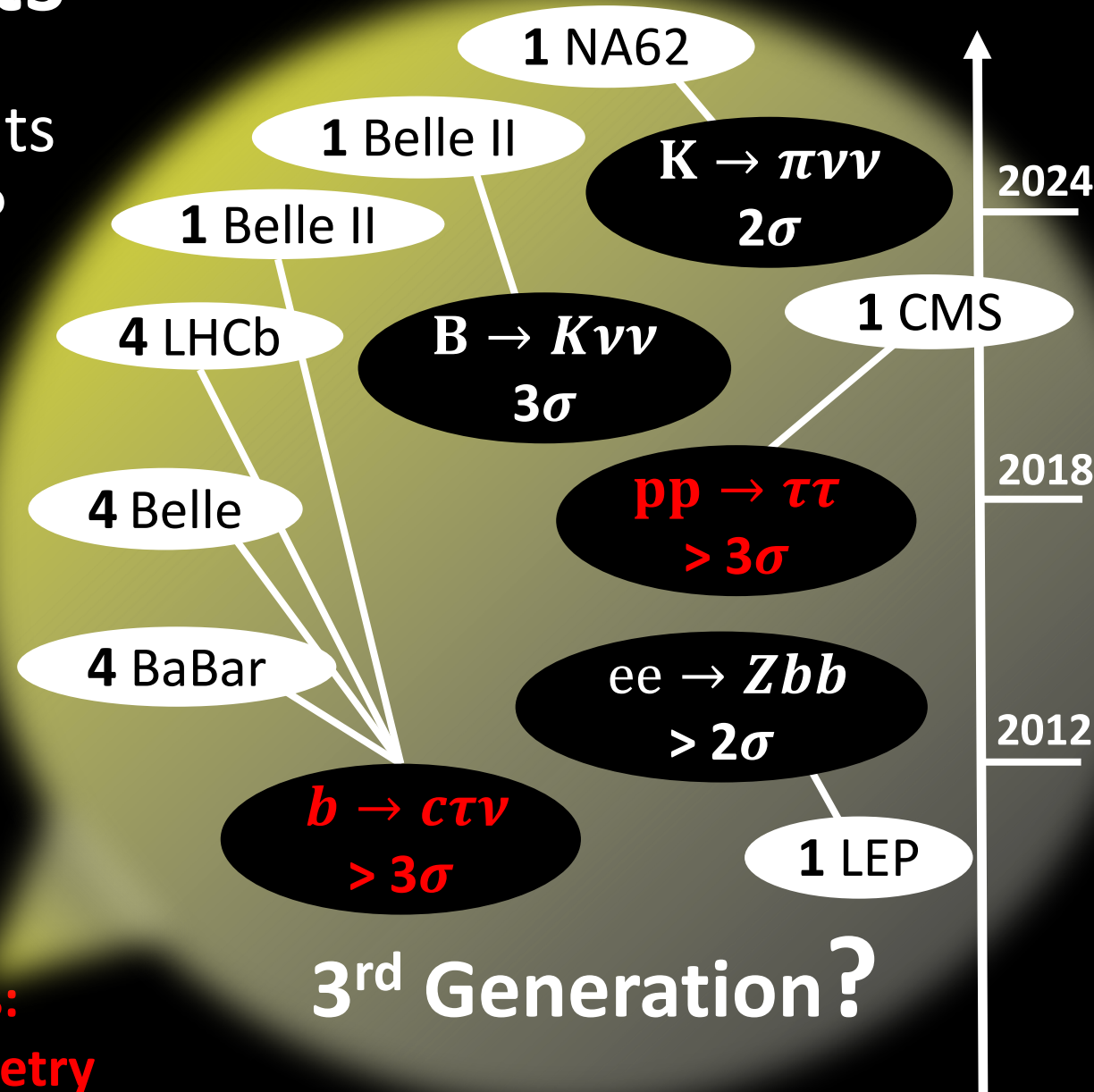
$$\mathcal{L}_{SM-EFT} = \mathcal{L}_{SM,gauge} + \mathcal{L}_{SM,Higgs} + \sum_i C_i Q_i$$

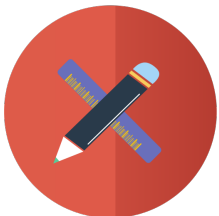
Flavour symmetry

Flavour asymmetry

... and CMS?

New Physics:
flavour asymmetry

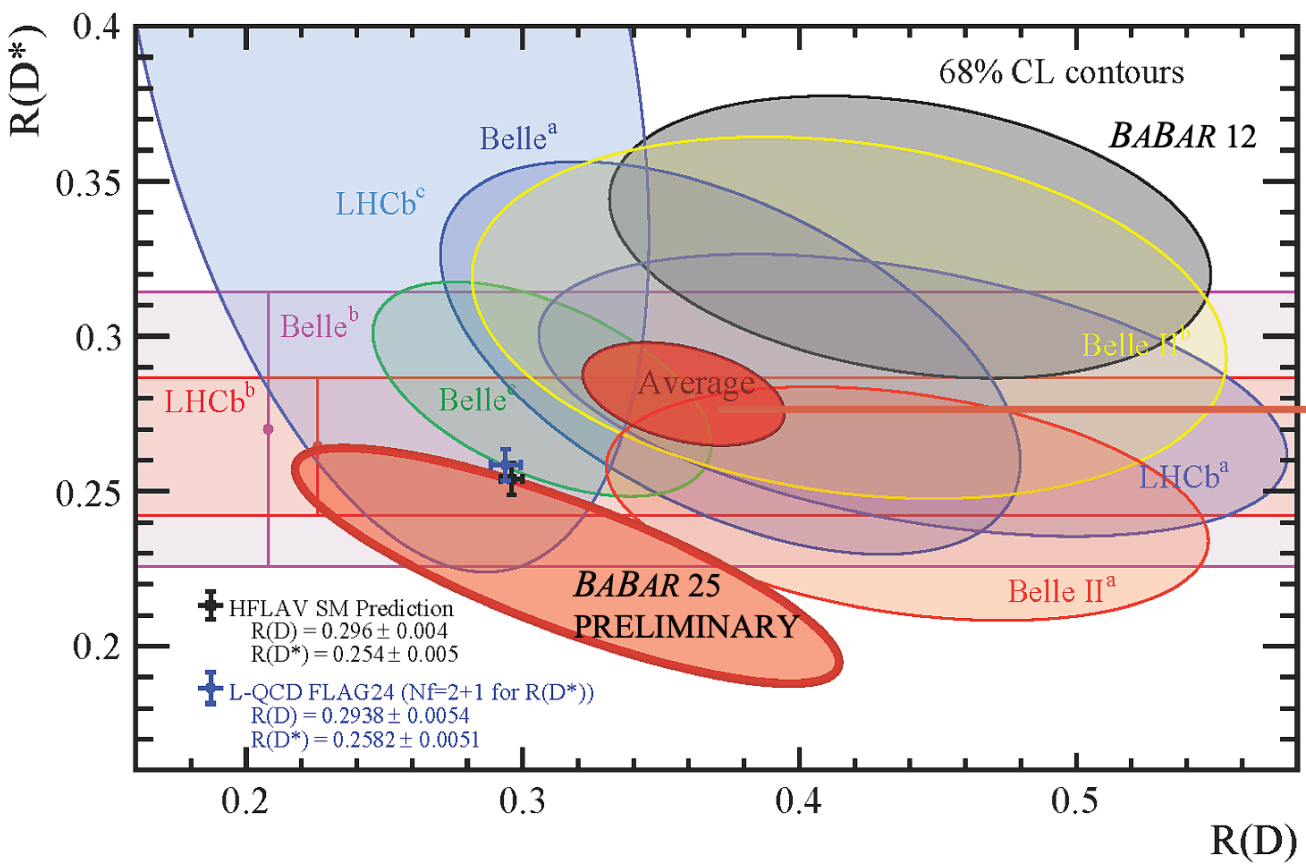




$b \rightarrow c$: a west-coast story + 13 years

➤ After 13 years, new results from BaBar [[talk](#) at VFSB_LPC workshop, Dec 2025]

➤ **Once the paper out, it will be included in the HFLAV average**



This average does not include the BABAR 25 preliminary result



Dec. 15-19, 2025
LHC Physics Center
Fermilab, Batavia, IL

Violation of Fundamental Symmetries

with **B mesons**

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Join us for a VFSB event in Chicago!

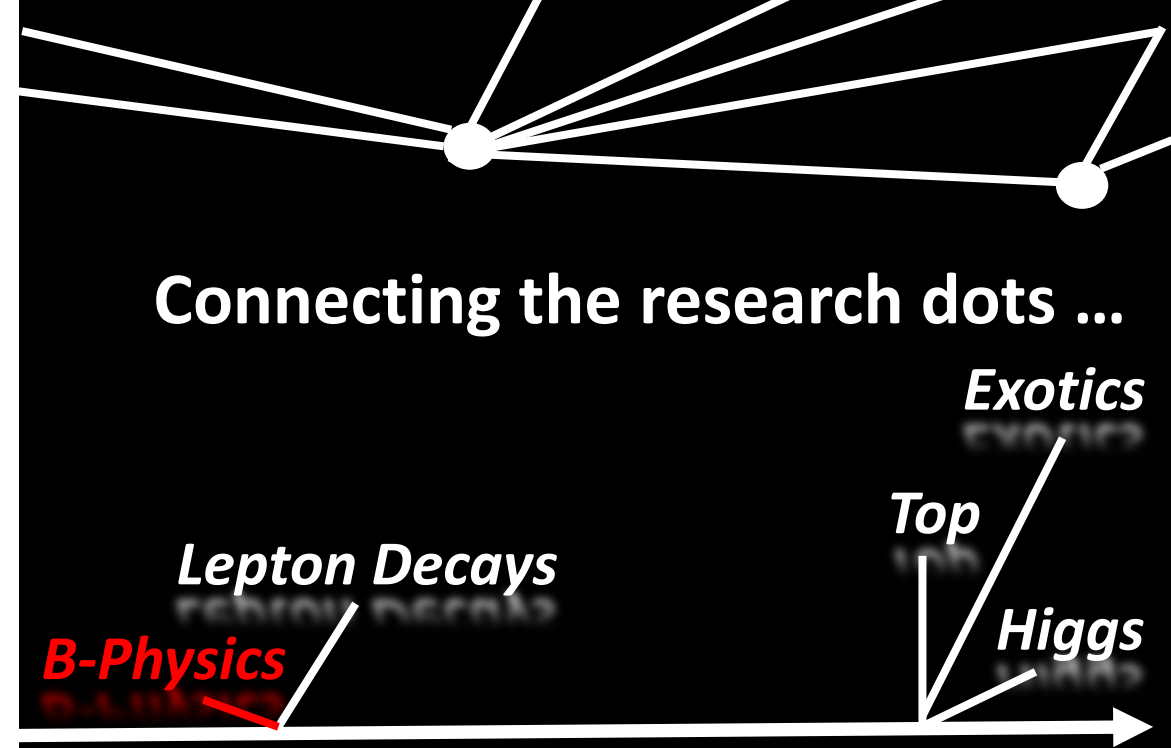
Fermilab



Hunting for LFUV IV

Often you move from

- low- p_T to high- p_T
 - one approach to another
- ... in a complementary mode!



Connecting the research dots ...



- $\mathcal{R}(D^{(*)})$
- $pp \rightarrow \tau\tau$ excess

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Why B_c mesons?

- For $b \rightarrow c$ process, another interesting meson

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

- “Young” mesons (CDF, 1998):

[Phys. Rev. Lett. 81, 2432](#)

- Cannot be produced at Belle II
... **unique opportunity for LHC**

- **Only 1 measurement (LHCb):**
 2σ away from the SM

[Phys. Rev. Lett. 120, 121801 \(2018\)](#)

1



How B_c mesons at CMS?

➤ For $b \rightarrow c$ process, another interesting meson

$$\mathcal{R}(J/\psi)_{lep} = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} = \frac{\mathcal{B}(B_c^+ \rightarrow \mu^+ \mu^- \mu^+ \nu_\mu \bar{\nu}_\tau \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow \mu^+ \mu^- \mu^+ \nu_\mu)}$$

➤ “Young” mesons (CDF, 1998):

[Phys. Rev. Lett. 81, 2432](#)

➤ Cannot be produced at Belle II
... **unique opportunity for LHC**

➤ **Only 1 measurement (LHCb):**
 2σ away from the SM

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1

➤ **Clear $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$ and $J/\psi \rightarrow \mu^+ \mu^-$ decays, only μ and ν**

▪ CMS excellent at muon ID and reconstruction

▪ CMS 4π acceptance to get rid of additional tracks around B_c vertex

Key for precision measurements!

2



How B_c mesons at CMS?

➤ For $b \rightarrow c$ process, another interesting meson

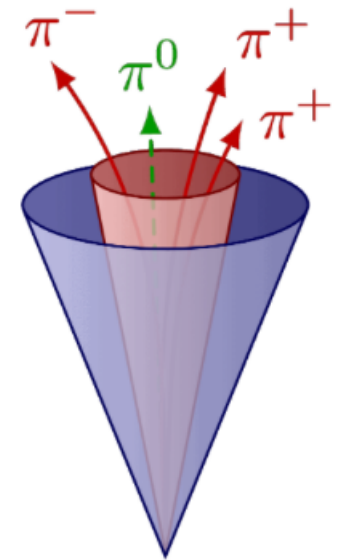
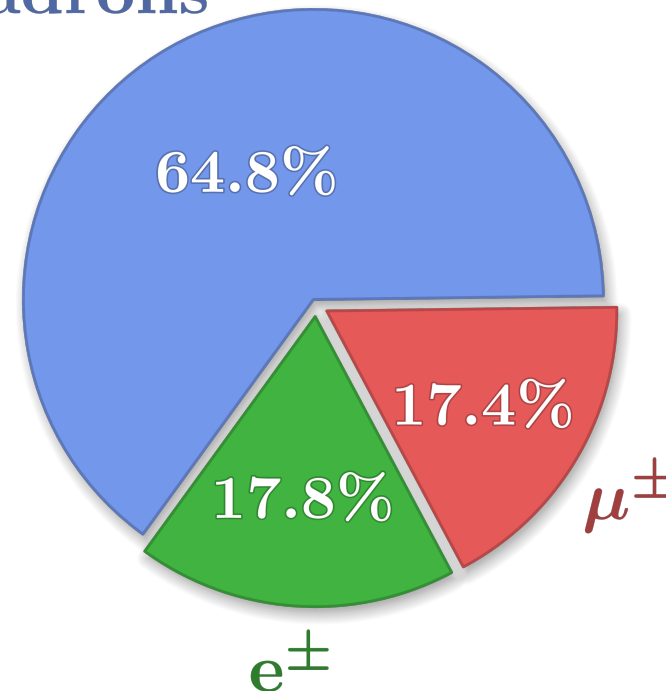
$$\mathcal{R}(J/\psi)_{had} = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} = \frac{\mathcal{B}(B_c^+ \rightarrow \mu^+ \mu^- \pi^+ \pi^- \pi^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow \mu^+ \mu^- \mu^+ \nu_\mu)}$$

➤ Simultaneous fit with the leptonic channel

- Extraction of one denominator
- One signal strength for the numerator in both channels
- Larger dataset (2016-2018)
- Orthogonal samples, less than 0.1% overlap expected

3

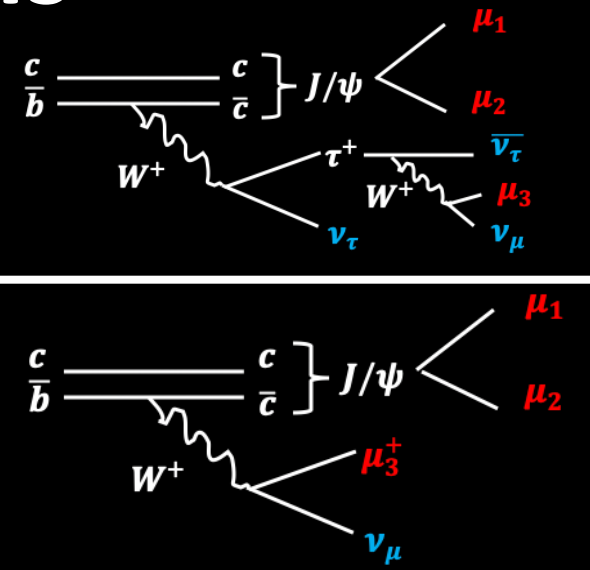
hadrons



**3-prong
decay mode**



Signals



$$\mathcal{R}(J/\psi) = \frac{\text{[Top Diagram]}}{\text{[Bottom Diagram]}}$$

➤ Similar final states



Similar reconstruction and Simultaneous fit



Due to neutrinos, **COLLINEAR APPROXIMATION** to reconstruct

key kinematics: $p_{B_c} = \frac{m_{B_c}}{m_{3\mu}^{vis}} \cdot p_{3\mu}^{vis}$



Backgrounds

➤ Muon Fakes

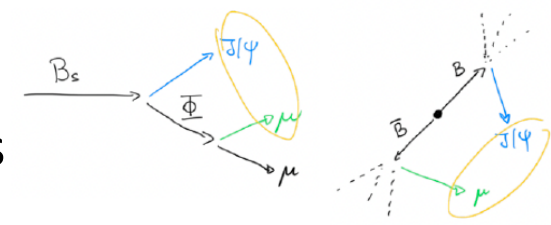
- J/ψ + misidentified muons (pions or kaons)

➤ B_c background

- Feeddowns: excited $c\bar{c} \rightarrow J/\psi$
- Other $B_c^+ \rightarrow J/\psi H_c^+ X$ decays

➤ H_b background

- $H_b \rightarrow J/\psi + \mu$ decays



➤ Combinatorial Dimuon + μ^+

- Unrelated muons, which reconstruct the J/ψ invariant mass

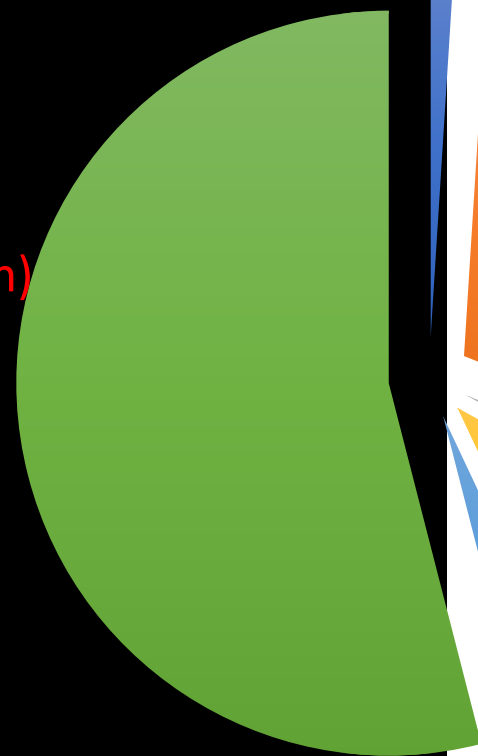
Signals

➤ Separation between signals

- lepton mass difference
- neutrino contribution
- ✓ $q^2 = (p_{B_c^+} - p_{J/\psi})^2$
- ✓ $\frac{IP_{3D}}{\sigma_{IP_{3D}}}$ (impact parameter)
- ✓ $\frac{L_{xy}}{\sigma_{L_{xy}}}$ (transverse decay length)

54%* :
 $J/\psi\mu^+\nu_\mu$

3% :
 $J/\psi\tau^+\nu_\mu$



* Numbers are based on the analysis inclusive category



Backgrounds

➤ Separation Signal Vs Background (Muon Fakes)

- Isolation (ISO) of the third muon

30% : Muon Fakes
Data driven

2% : B_c background MC based

10% : H_b background MC based

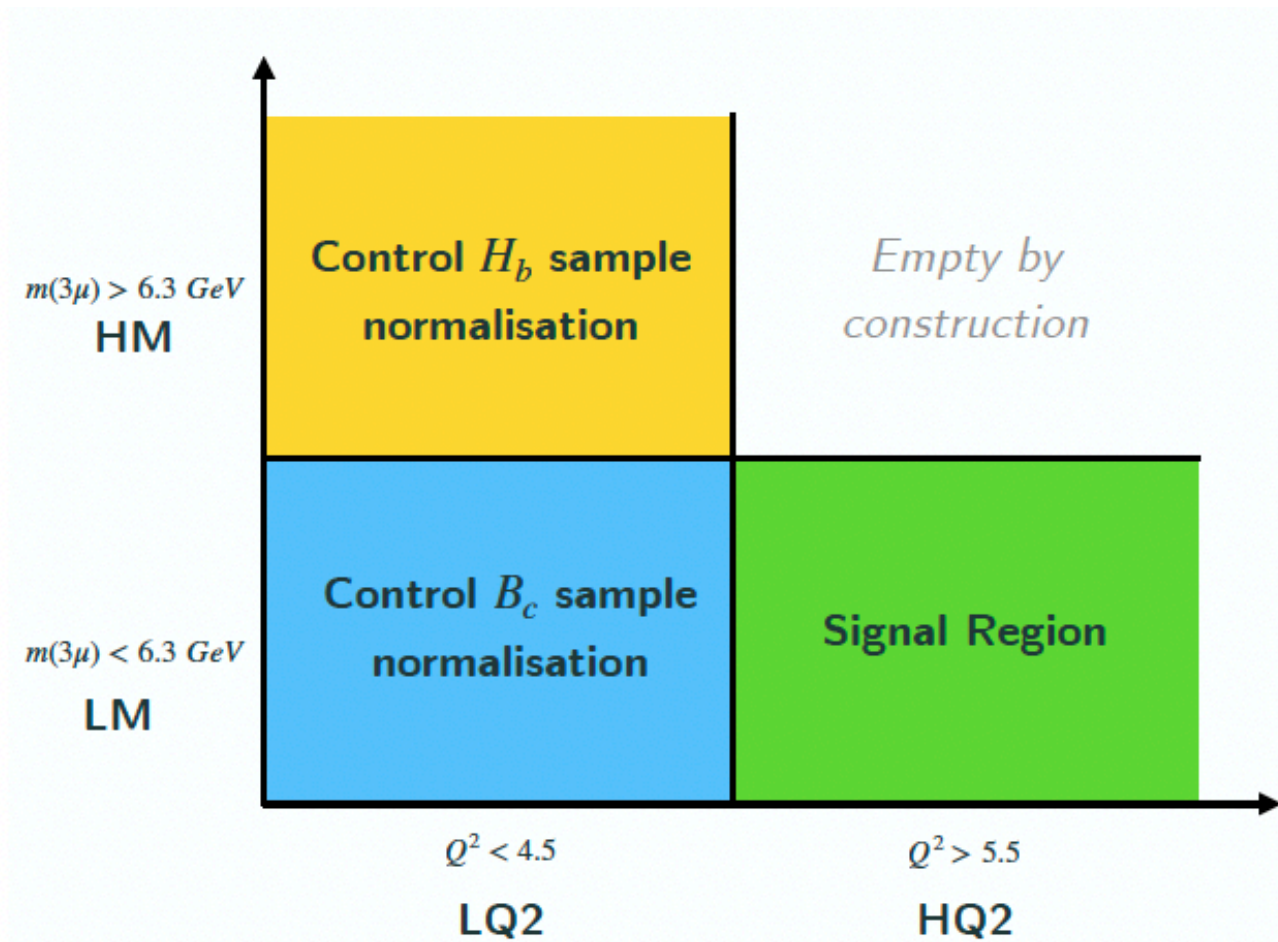
1% : Comb. Dimuon + μ^+ Data driven





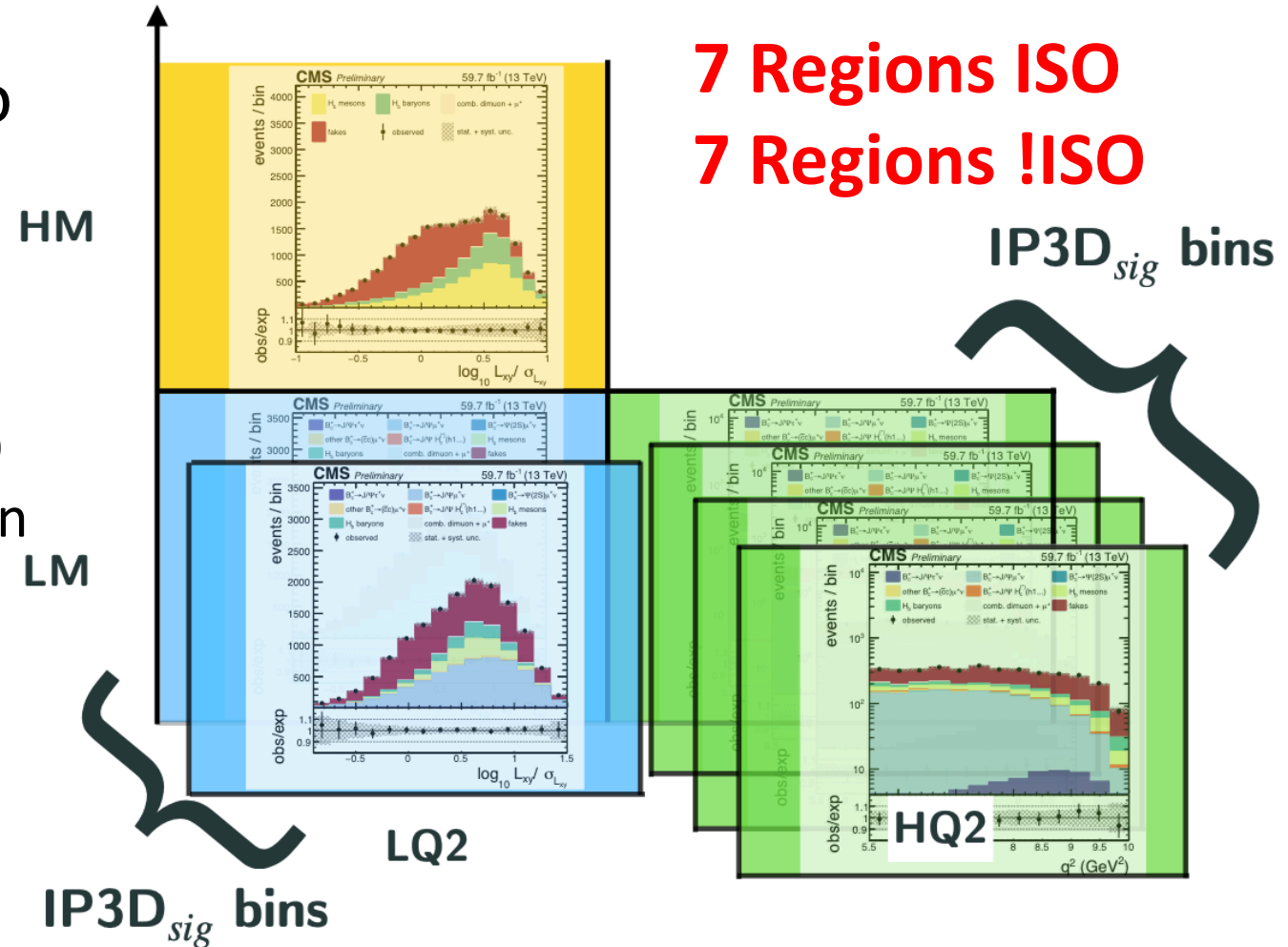
Analysis Strategy I

- Binned maximum likelihood fit to q^2 and $L_{xy}/\sigma_{L_{xy}}$ distributions
- Free floating parameters: B_c and H_b normalizations
- Parameter-Of-Interest (POI) : $\mathcal{R}(J/\psi)$
- **Blind strategy:** POI scaled by unknown random number



Analysis Strategy II

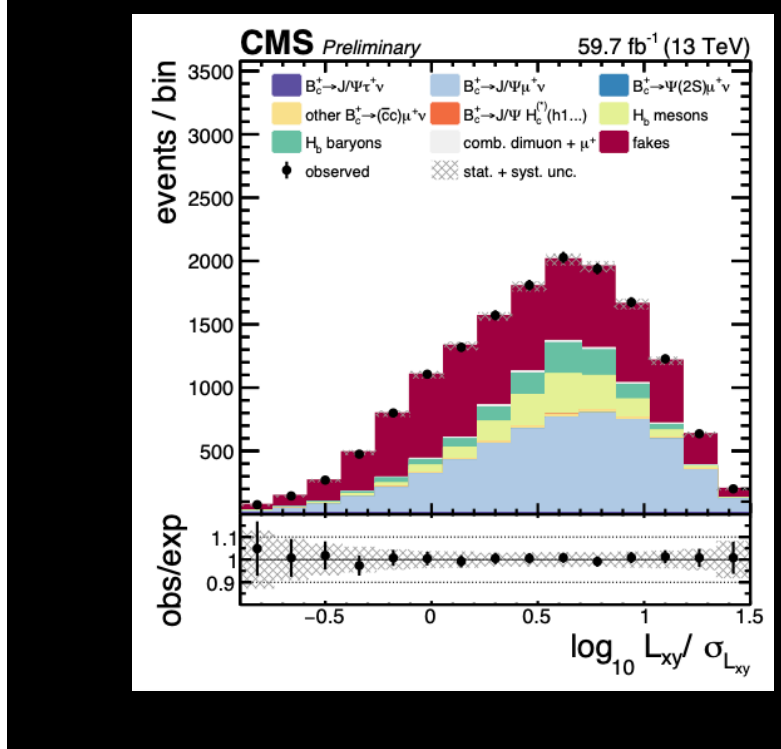
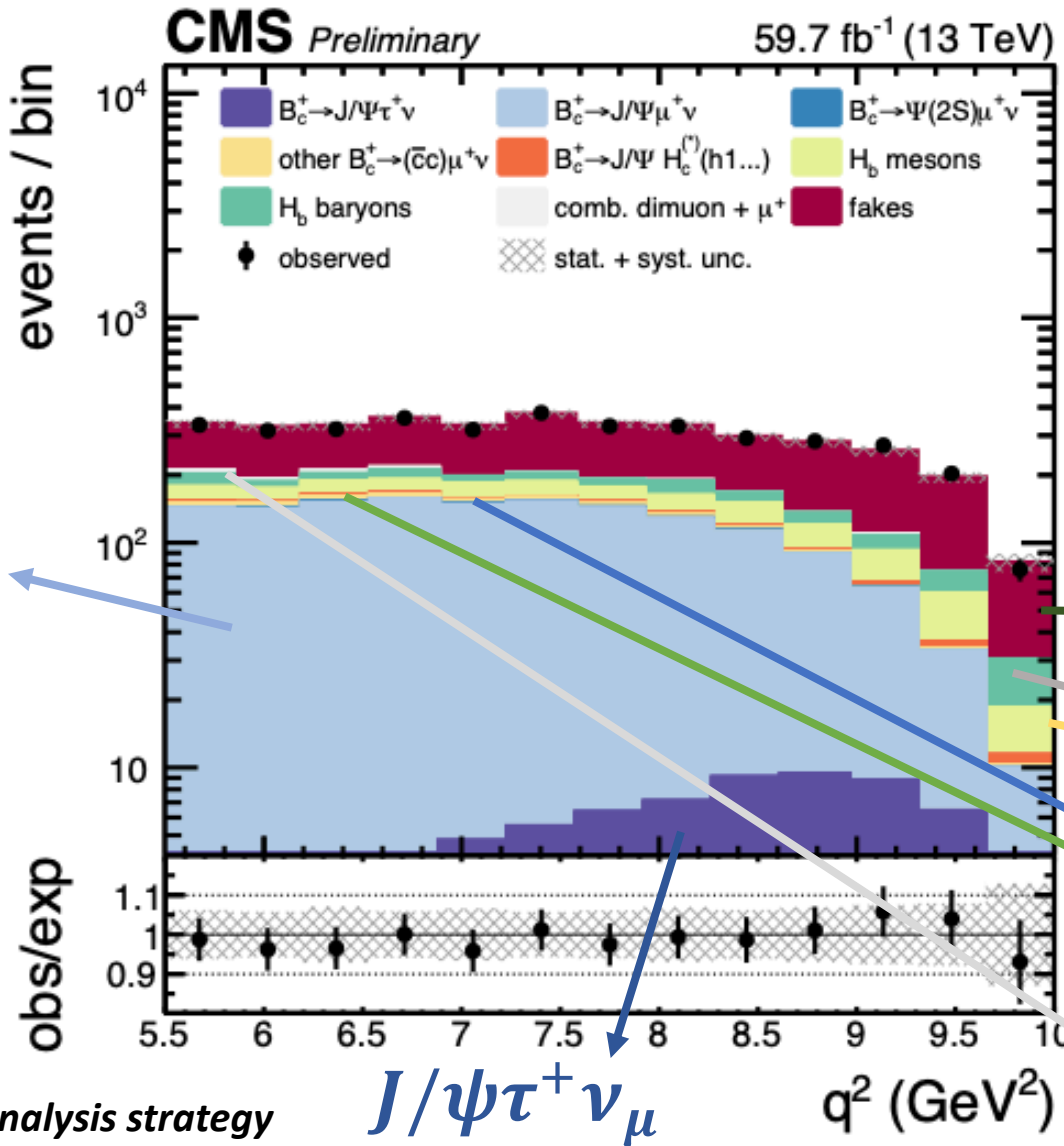
- Binned maximum likelihood fit to q^2 and $L_{xy}/\sigma_{L_{xy}}$ distributions
- Free floating parameters: B_c and H_b normalizations
- Parameter-Of-Interest (POI) : $\mathcal{R}(J/\psi)$
- **Blind strategy**: POI scaled by unknown random number
- **14 categories to optimize S/B and control background contributions**





Discriminants

LEP



$J/\psi \mu^+ \nu_\mu$

Muon Fakes

H_b background

B_c background

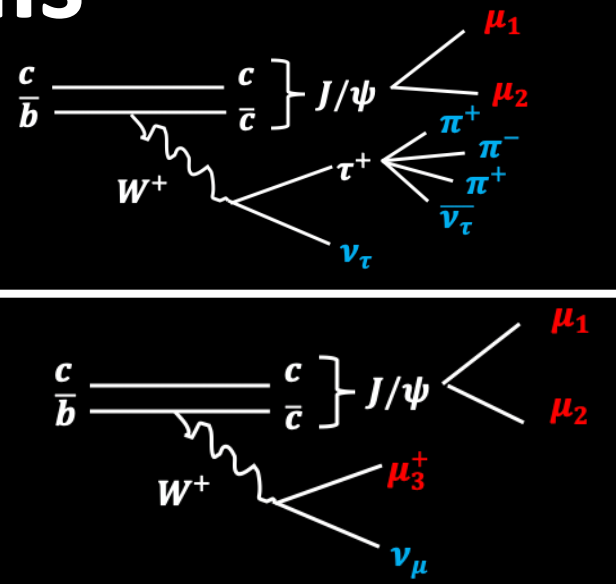
Comb. Dimuon + μ^+

* Projections after the analysis strategy

$J/\psi \tau^+ \nu_\mu$



Signals



$$\mathcal{R}(J/\psi) = \frac{\text{[Top Diagram]}}{\text{[Bottom Diagram]}}$$



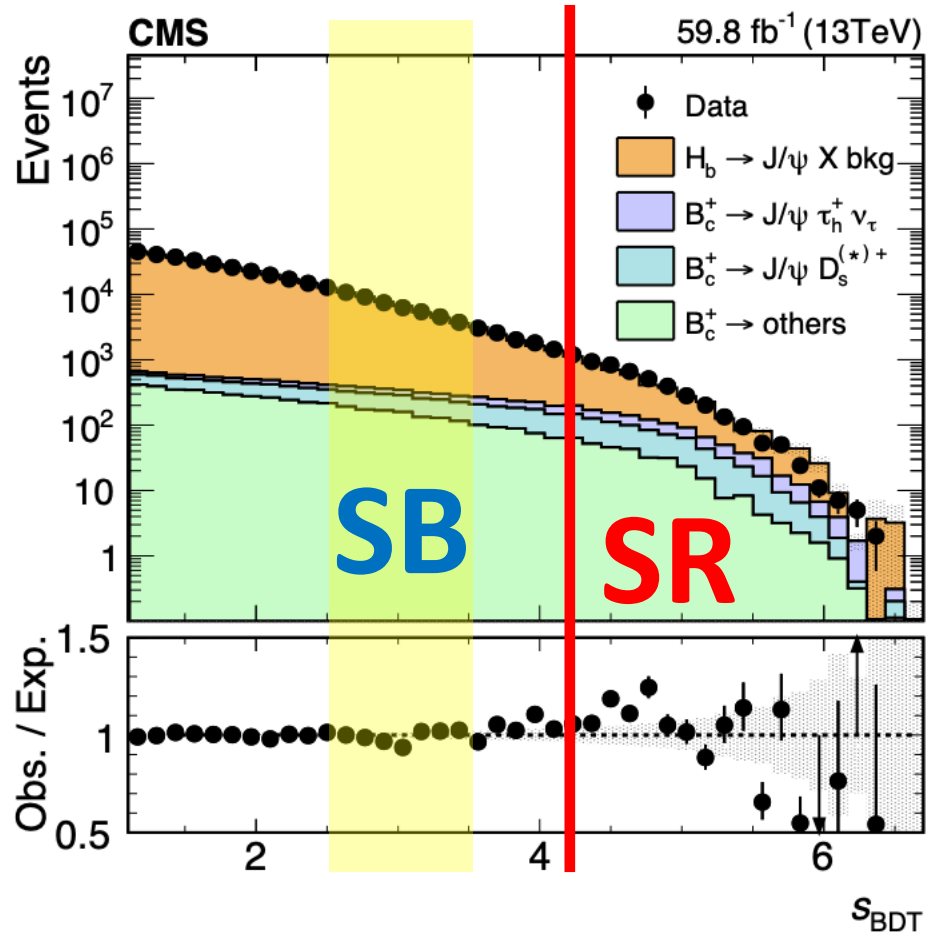
Backgrounds

- **H_b background: dominant**
 - $H_b \rightarrow J/\psi + X$ decays
- **B_c backgrounds: $B_c^+ \rightarrow J/\psi D_{(s)}^{(*)+} X$**
 - Leading $B_c^+ \rightarrow J/\psi D_s^{(*)+}$

➤ Background suppression



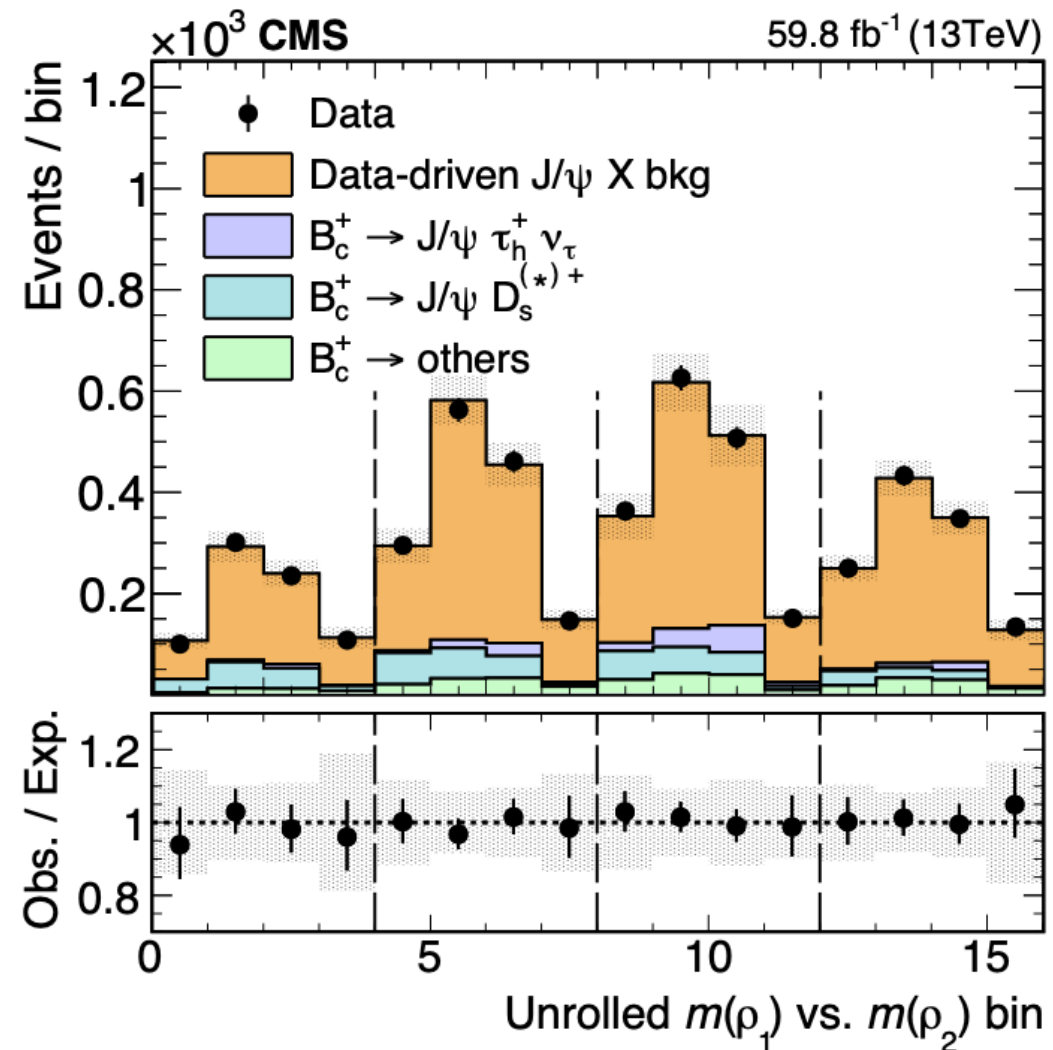
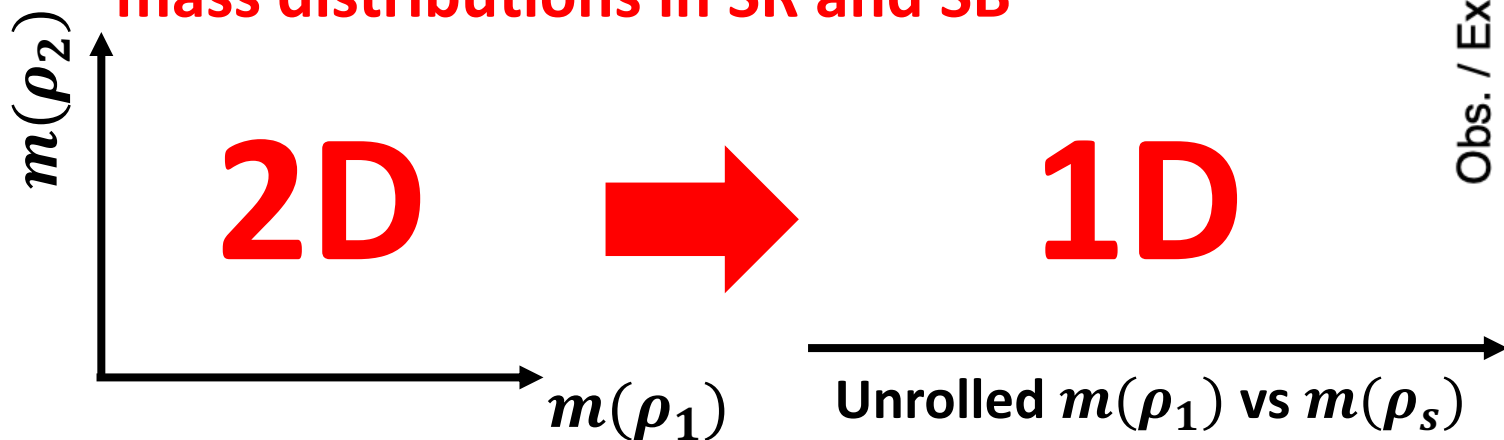
BDT discrimination based on key variables: τ flight length, particles multiplicity, isolation, ID requirements





Analysis Strategy

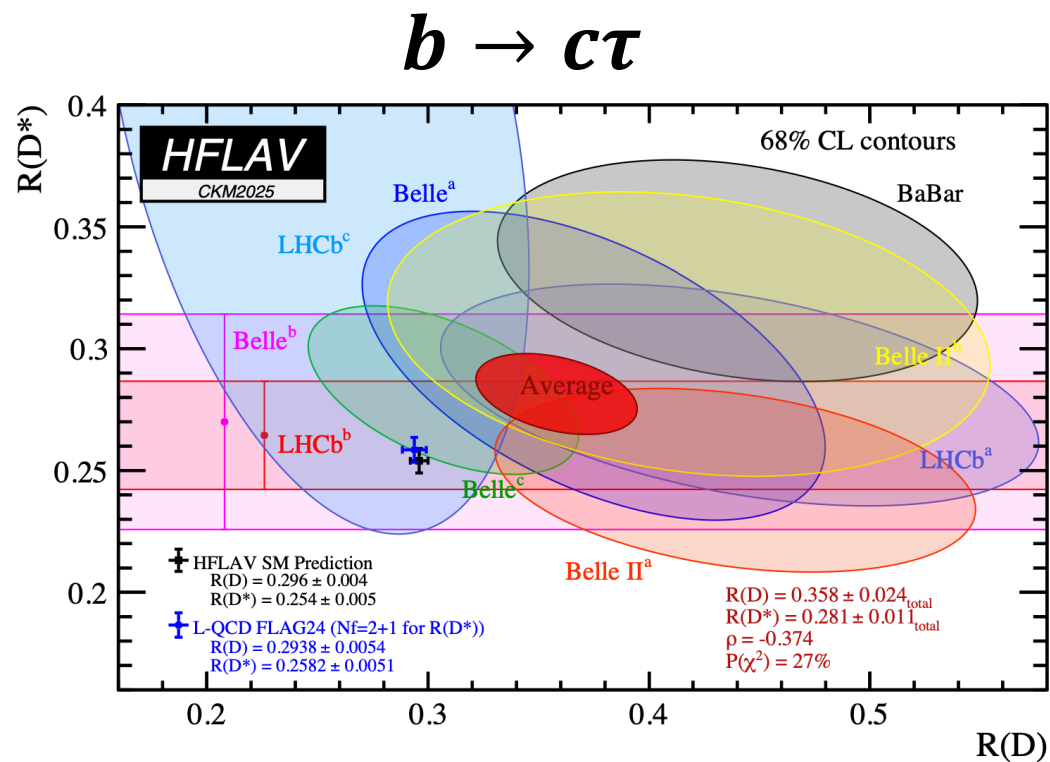
- 3-prong τ decays likely to occur through an intermediate resonance
 $\tau^+ \rightarrow a_1(\rightarrow \rho^0(\rightarrow \pi^+\pi^-)\pi^+\nu_\tau)$
 - Two possible ρ^0 combinations (ρ_1, ρ_2) depending on the triplet pions selected
 - Pions ordered in p_T
- **Simultaneous fit to the unrolled (ρ_1, ρ_2) mass distributions in SR and SB**





Results

- First CMS result for the tau-anomaly
- First result compatible with the SM ($<1\sigma$)
- CMS can compete on LFUV with LHCb



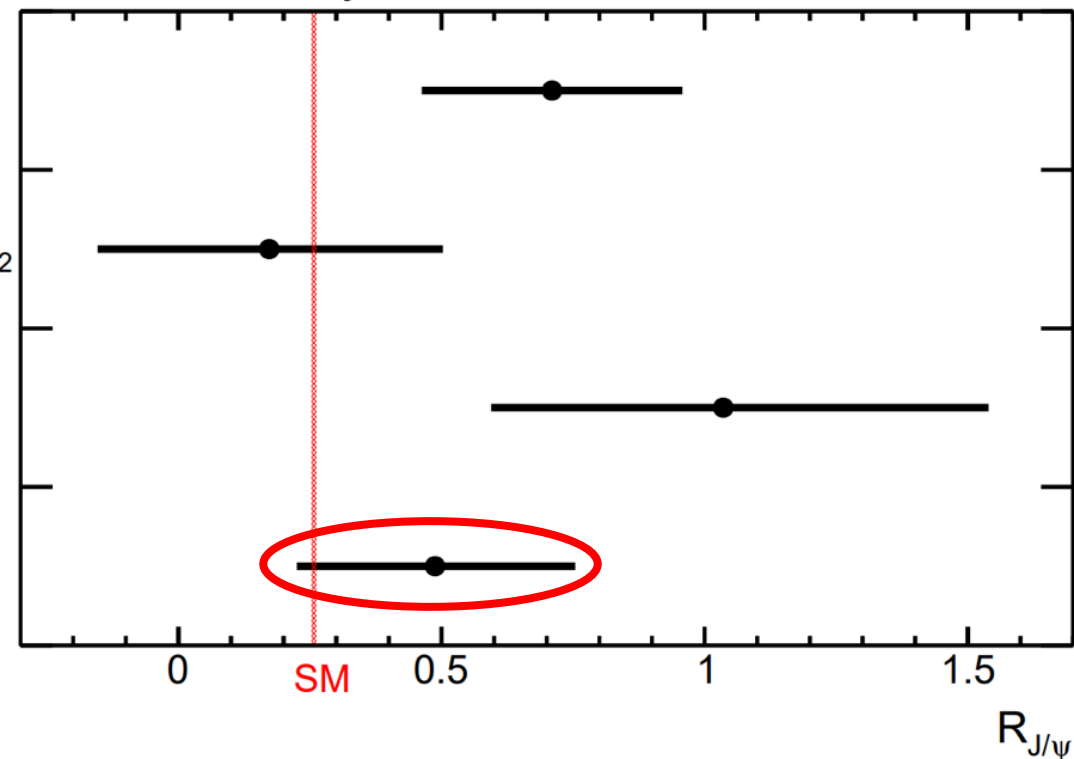
LHCb, Run1, τ_μ
Phys. Rev. Lett.
120 (2018) 121801

CMS, 2018, τ_μ
CMS-PAS-BPH-22-012

CMS, Run2, $\tau_{3\pi}$

CMS
Combination

CMS Preliminary





Future Prospects: How

- CMS first B -anomaly result
 - CMS can do it!
- Can we do better?
 - ☐ Improve the sensitivity for $\mathcal{R}(J/\psi)$
 - ✓ More data than Run 2 data
 - ✓ Dedicated trigger strategy



Future Prospects: How

- CMS first B -anomaly result
 - CMS can do it!
- Can we do better?
 - ❑ Improve the sensitivity for $\mathcal{R}(J/\psi)$
 - ❑ Additional mesons and ratios

$$\checkmark \mathcal{R}(X) = \frac{\mathcal{B}(H_b \rightarrow H_c \tau^+ \nu_\tau)}{\mathcal{B}(H_b \rightarrow H_c \mu^+ \nu_\mu)}$$

$B_s \Rightarrow \mathcal{R}(D_s)$

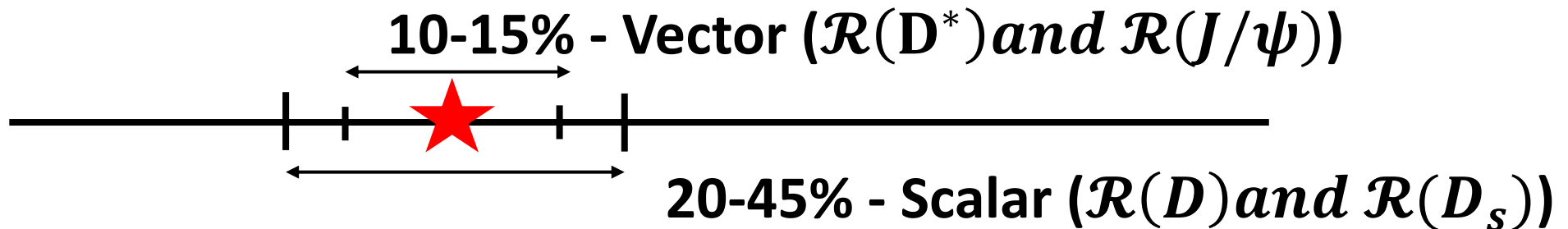
$B^0 \Rightarrow \mathcal{R}(D^{(*)})$

Only at LHC!



Future Prospects: D_s

- Theoretically, same motivation as for D^{*-} , D^- mesons
- Coherent picture for expected deviations in the $b \rightarrow c$ quark-transition to be explained with the same new physics
- What deviation?



CMS: measurement at 3-9%
Most precise single-experiment

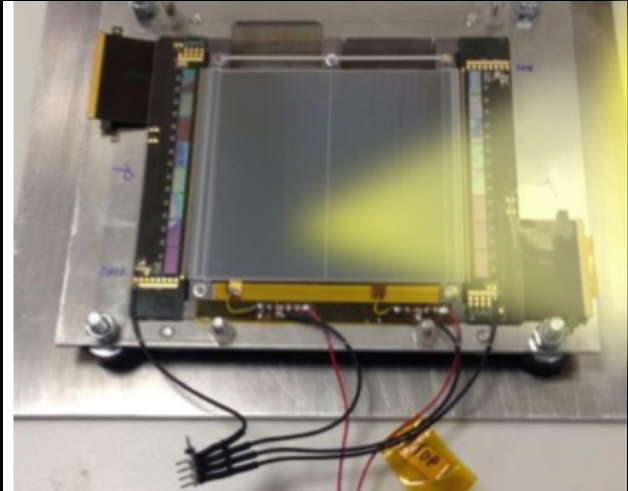
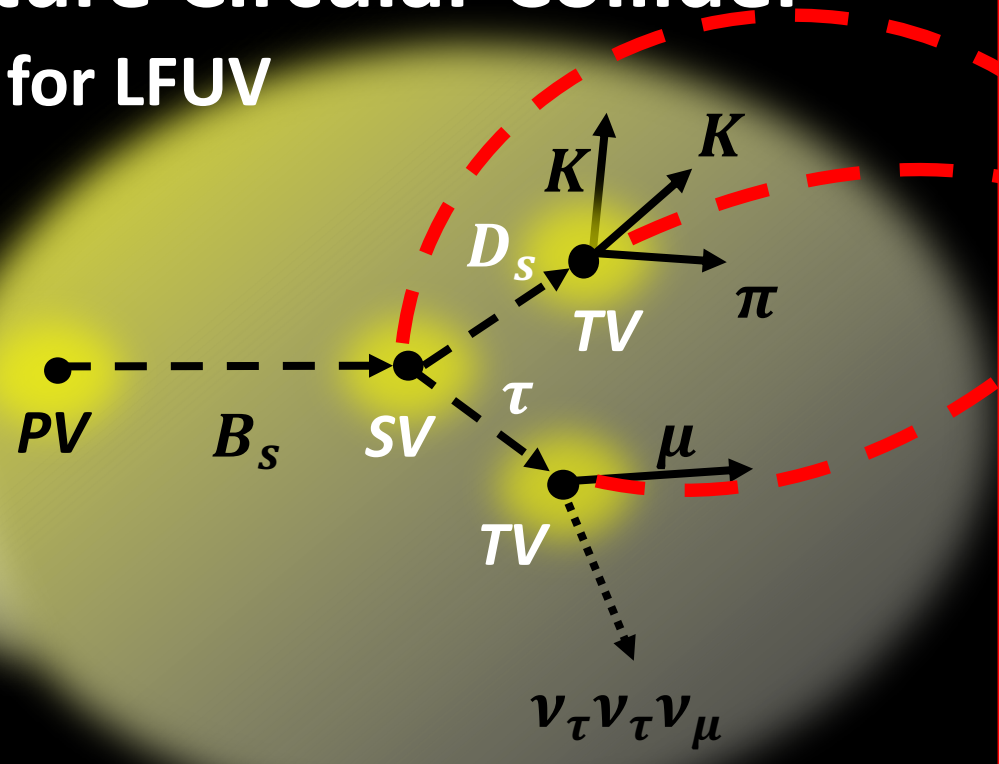
First measurement of $\mathcal{R}(D_s)$
=> scalar contribution
... where less is known!

Next-generation machines?



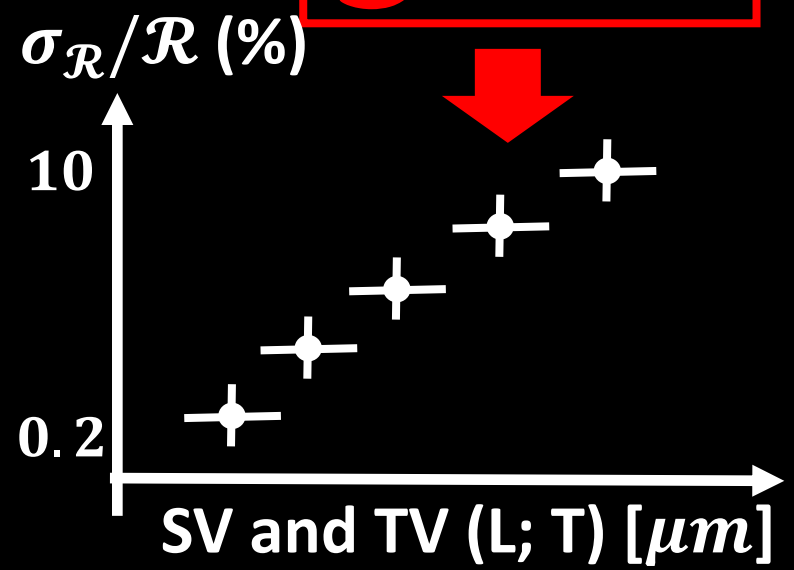
Goals for Future Circular Collider

- Best FCC-ee tracker for LFUV
 - Better than 3-9%?
 - Better than 1%?



CMOS-Monolithic-Active-Pixel Sensor

- 1** (5; 1) μm
- 2** (20; 3) μm
- 3** (30; 8) μm



HOW? Longitudinal-Transverse (L; T) resolution of SV, TV



THE CMS TRIGGER





The CMS Trigger



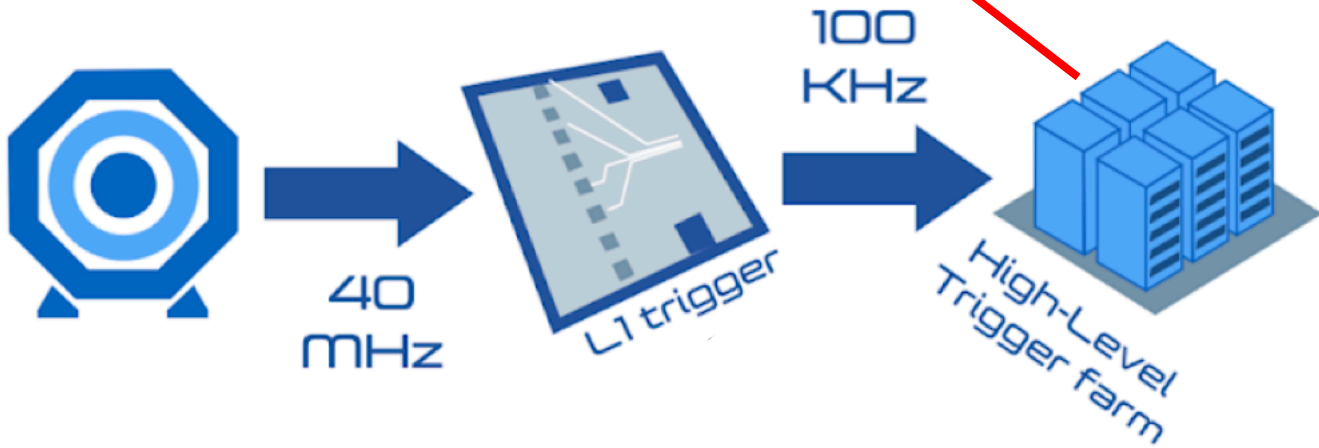


CMS Trigger Strategy

1 STANDARD STREAM

- Core of CMS Physics Program
- Stable over years
- About 2.5 kHz*
- About 1.5 MB/evt
- Processed in Real Time (within 48 hours)

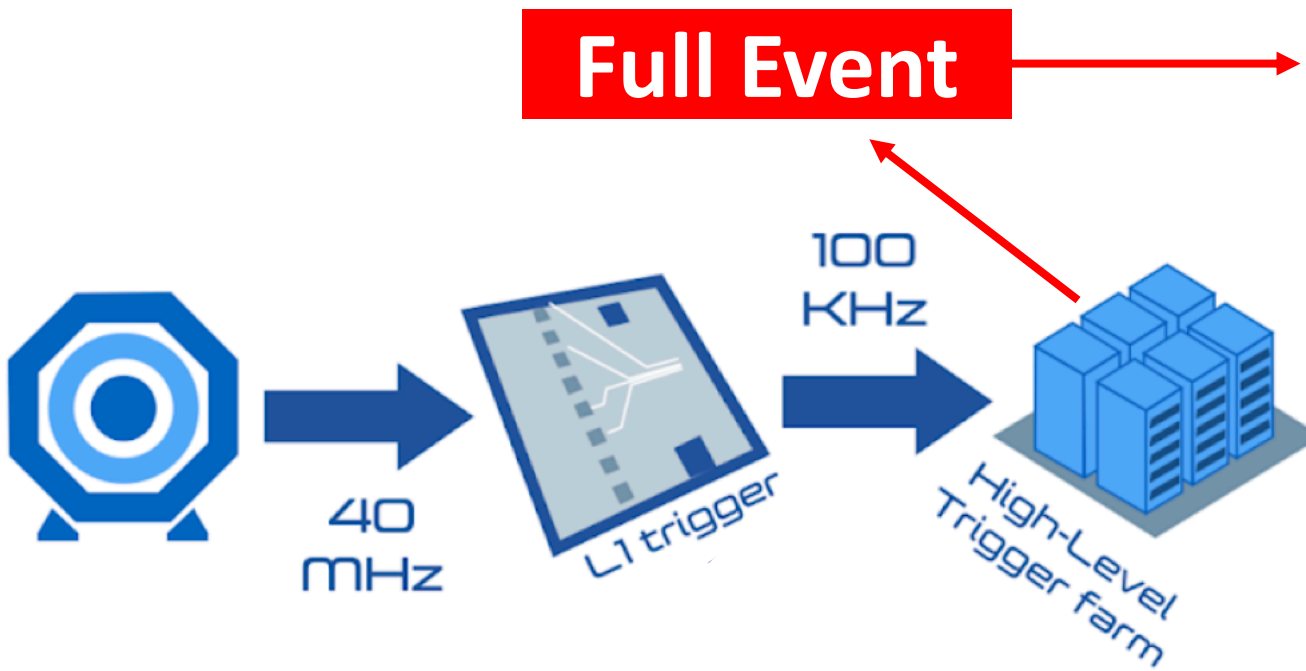
Full Event



*The Luminosity Reference is 2E34 (Run 3 at 13.6 TeV)



CMS Trigger Strategy



1 STANDARD STREAM

- Core of CMS Physics Program
- Stable over years
- About 2.5 kHz*
- About 1.5 MB/evt
- Processed in Real Time (within 48 hours)

2 PARKING STREAM

- Specific CMS Physics Program
- Variable over years
- About 3 kHz*
- About 1.5 MB/evt
- Stored on tape and reconstructed when resources available . **So far prompt Reco!**

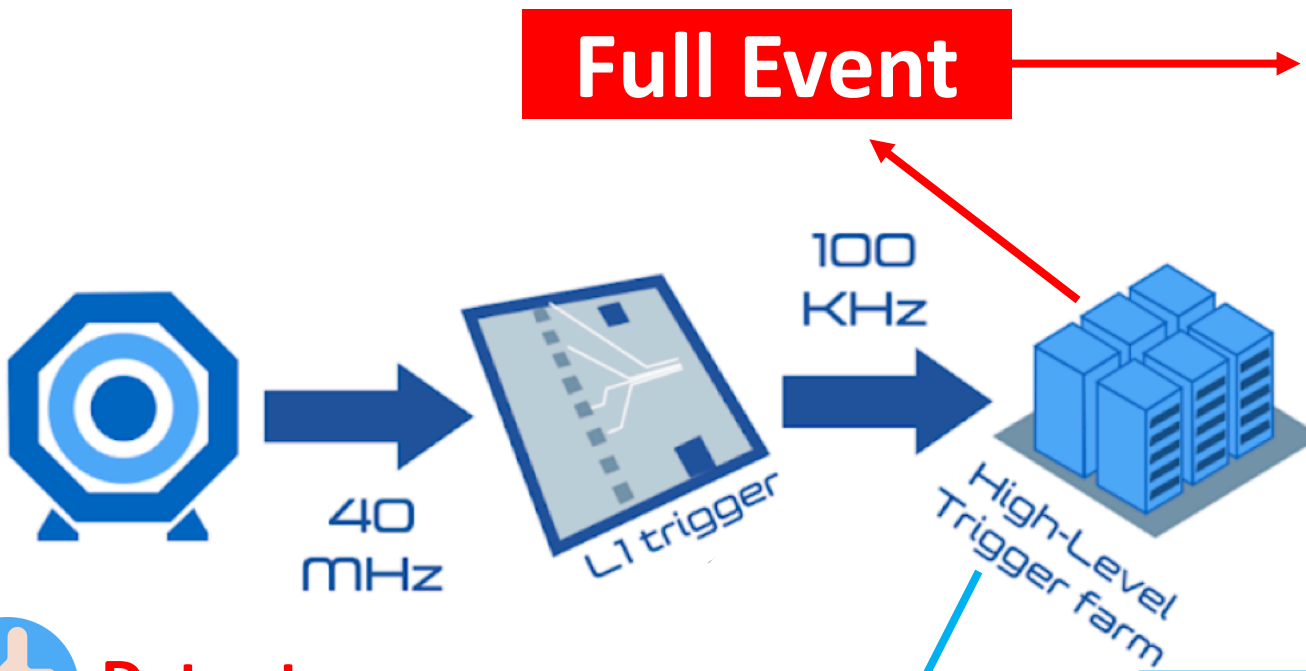


Prompt reconstruction

*The Luminosity Reference is 2E34 (Run 3 at 13.6 TeV)



CMS Trigger Strategy



Full Event

Reduced Data Format

1 STANDARD STREAM

- Core of CMS Physics Program
- Stable over years
- About 2.5 kHz*
- About 1.5 MB/evt
- Processed in Real Time (within 48 hours)

2 PARKING STREAM

- Specific CMS Physics Program
- Variable over years
- About 3 kHz*
- About 1.5 MB/evt
- Stored on tape and reconstructed when resources available . **So far prompt Reco!**

3 (HLT) SCOUTING STREAM

- Extend CMS Physics Program on high-rate searches
- About 25 kHz*
- Event size: Standard stream/100
- HLT Reco Objects stored in analysis-friendly format

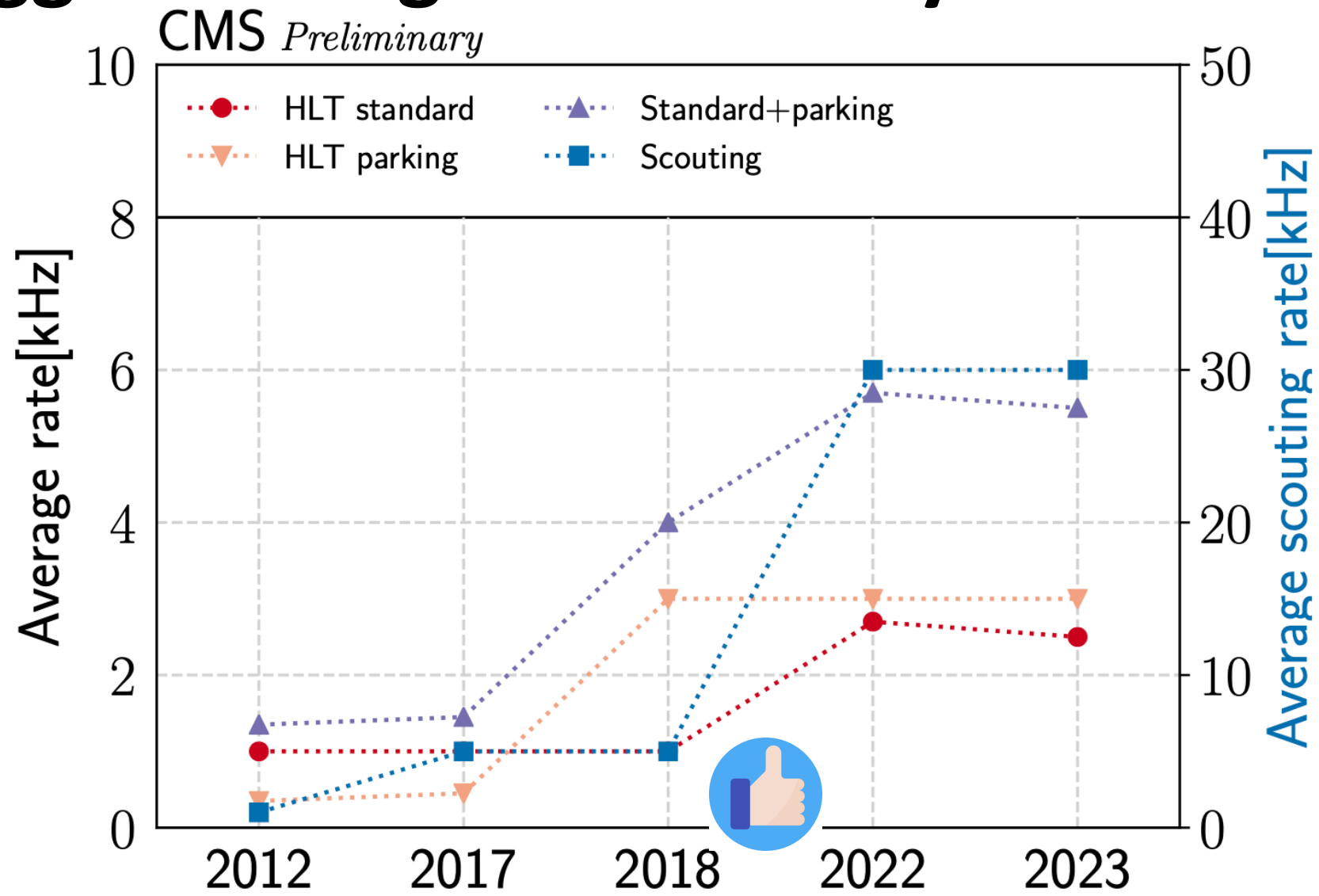
Data storage

*The Luminosity Reference is 2E34 (Run 3 at 13.6 TeV)




Trigger strategies over the years

[arXiv:2403.16134](https://arxiv.org/abs/2403.16134)





Parking strategies over the years

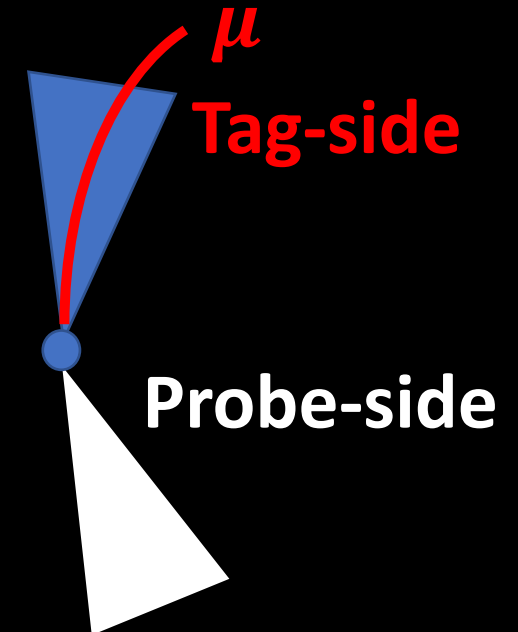
- Introduced in 2012 mostly to limit trigger impact on multijet analyses
 - all-jet+MET, SUSY searches, VBF Trigger, Higgs ...
 - Reintroduced *opportunistically* in 2018
 - Aimed at Lepton Flavour Universality anomalies
 - Set of displaced-muon L1 triggers
 - Established as part of *standard* CMS operations in 2022
 - More sophisticated Parking campaign evolving year after year
 - New machine configurations with $\mathcal{L}_{inst} \approx 2.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
-  Total HLT Parking budget of \approx **3 kHz** in 2023
Pushing the L1 rate beyond the limit of 100 kHz ... **110 kHz!**



B-Parking

- Can we maximize the CMS potential and sensitivity for $\mathcal{R}(H_c)$?
 - Study of the quark transition $b \rightarrow c\ell\nu$
 - Trigger logic for displaced muons $b(\rightarrow c) \rightarrow \mu X$
 - **Before 2018 CMS could not perform low- p_T displaced-single-muon measurements**

- Trigger goal: accumulation of large sample of $b\bar{b}$ pairs
 - Tag side: search for displaced muon with p_T in 7-12 GeV
 - **About 1/3 of B-meson decays into a single muon**
 - Probe side: unbiased set of B-mesons with minimal kinematic bias
 - **Rare decays $\mathcal{O}(10^{-7})$ can become accessible to CMS**





B-Parking: Physics potential

$$N_{b\bar{b}} = t_{LHC} \mathcal{R} P_{b\bar{b}} \approx \mathcal{O}(10^{10})$$

- t_{LHC} : LHC Operational running time of 6×10^6 s for 6 months (140 days)
- \mathcal{R} : trigger rate of about 2 kHz throughout the LHC fill
- $P_{b\bar{b}}$: purity of data stream of about 80%

➤ Tag side ideal for $\mathcal{R}(D^*)$, $\mathcal{R}(J/\psi)$

- $\mathcal{O}(10^4)$ of $B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$ and $\mathcal{O}(10^6)$ of $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$

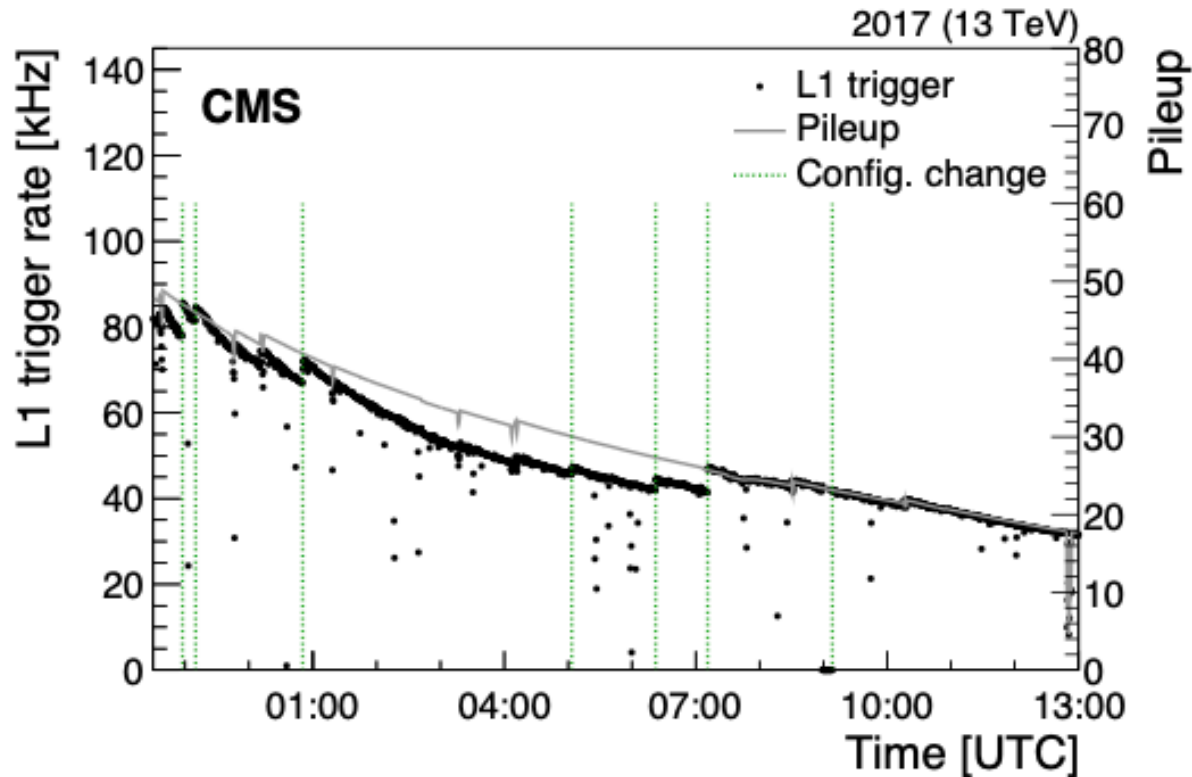
➤ Probe side ideal for $\mathcal{R}(K^{(*)})$

- $N_{B^+ \rightarrow K^+ e^+ e^-} \approx N_{b\bar{b}} f_{B^+} \mathcal{B} \mathcal{A} \approx \mathcal{O}(10^3)$ of $B^+ \rightarrow K^+ e^+ e^-$

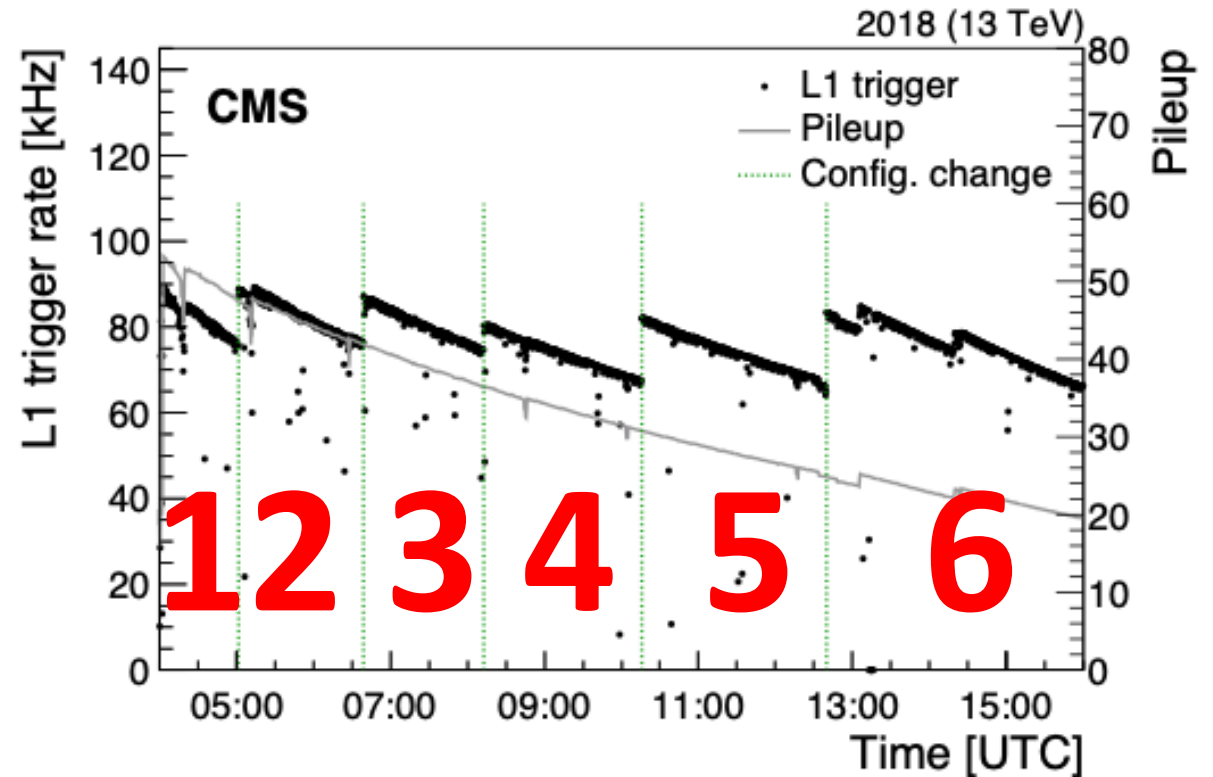


B-Parking: HOW?

Without B-Parking



With B-Parking





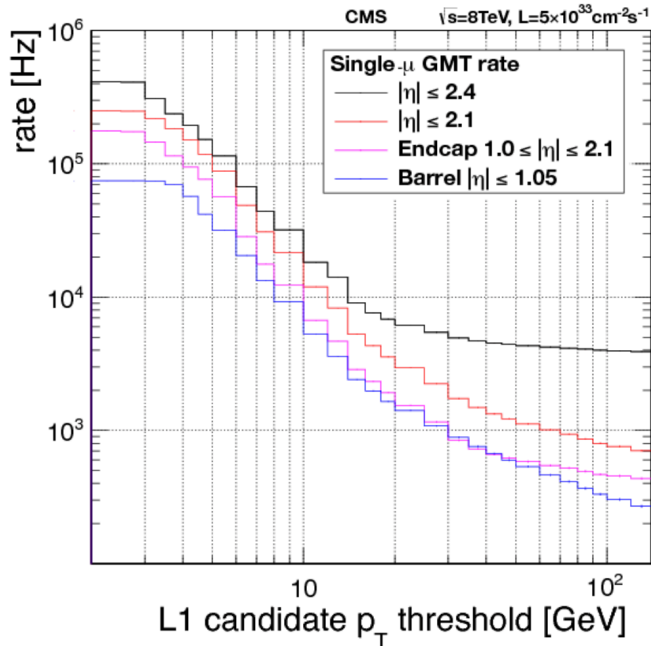
B-Parking: HOW?

$\mathcal{L}_{\text{inst}}$ [$10^{34}\text{cm}^{-2}\text{s}^{-1}$]	Pileup	L1 μp_T [GeV]	HLT μp_T [GeV]	HLT μ IP _{sig}	Peak L1 rate [kHz]	Peak HLT rate [kHz]	Purity [%]
2.0	54.0	—	—	—	—	—	—
1.7	45.9	12	12	6	20	1.5	92 ± 5
1.5	42.8	10	9	6	30	2.8	87 ± 4
1.3	35.1	9	9	5	32	3.0	86 ± 4
1.1	29.7	8	8	5	43	3.7	83 ± 4
0.9	24.3	7	7	4	53	5.4	59 ± 3

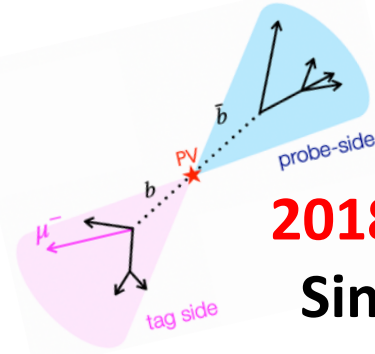
CMS BPH: GROWING RESOURCES

➤ Throughout the years, CMS BPH has evolved significantly ... new resources

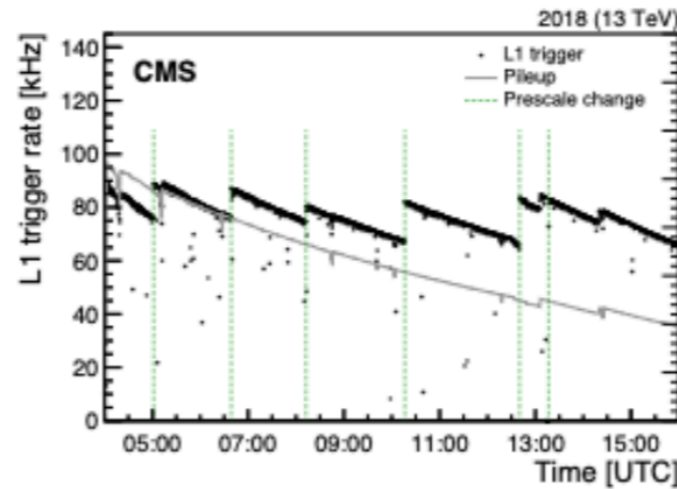
2012 Standard Trigger



Run 1

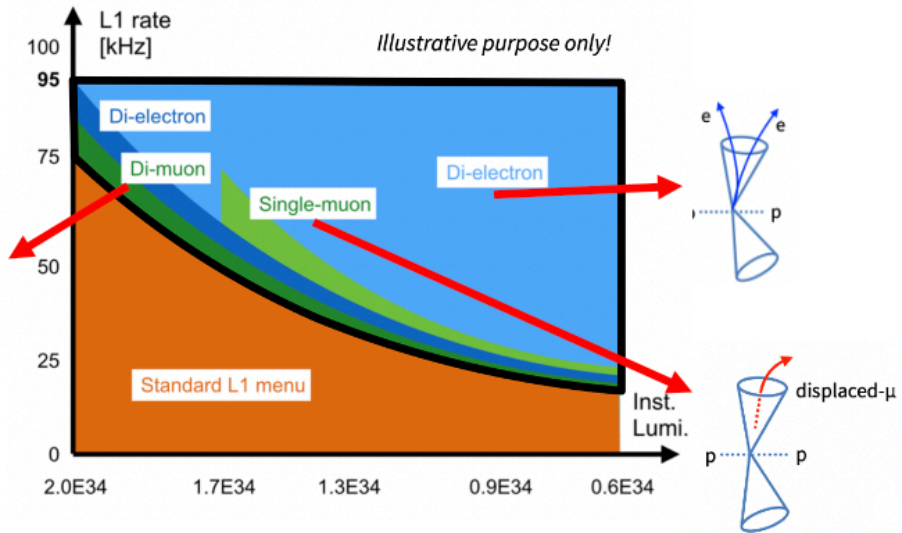


2018 BParking SingleMuon



Run 2

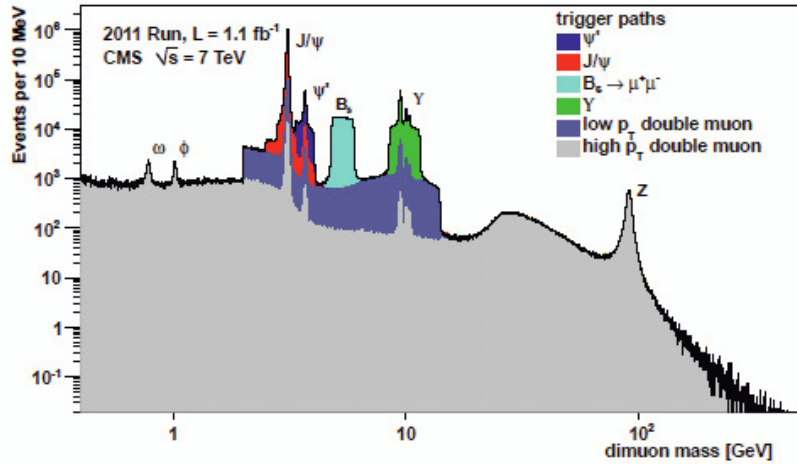
2022-2026 BParking: DoubleMuon, DoubleElectron SingleMuon,



Run 3

CMS BPH: GROWING RESOURCES

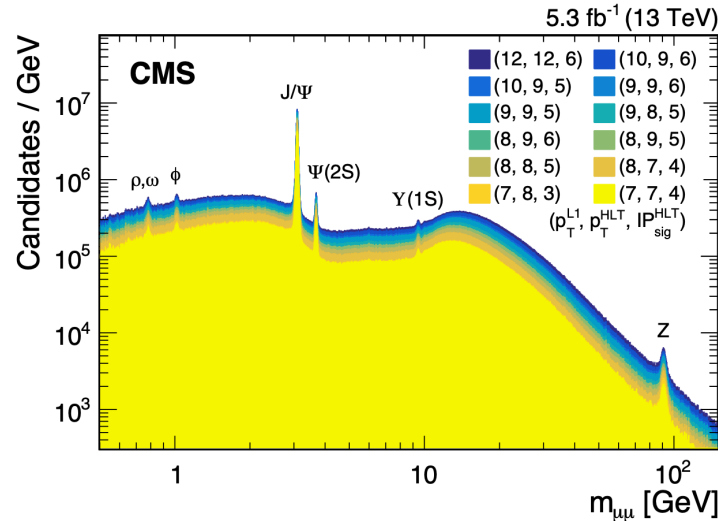
➤ Throughout the years, CMS BPH has evolved significantly ... more spectra



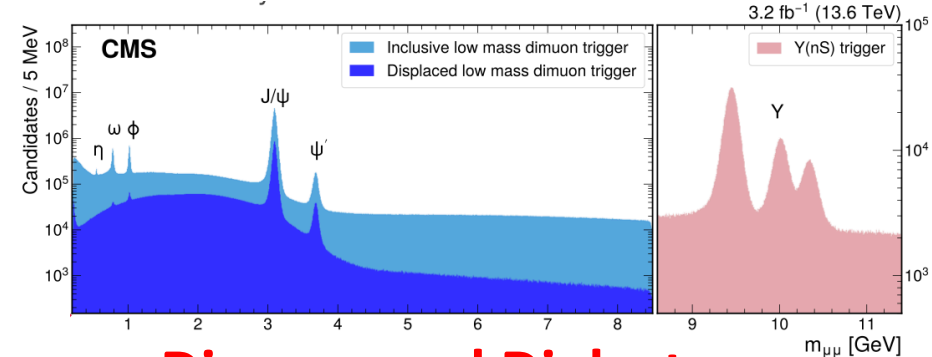
Dimuon spectrum: collection of exclusive triggers

Run 1

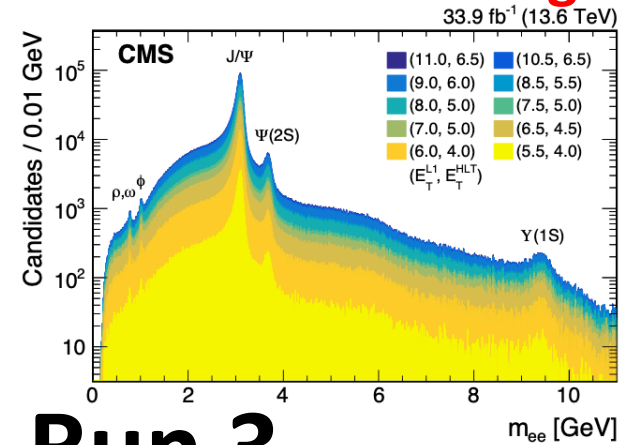
Dimuon spectrum from 2018 BParking



Run 2



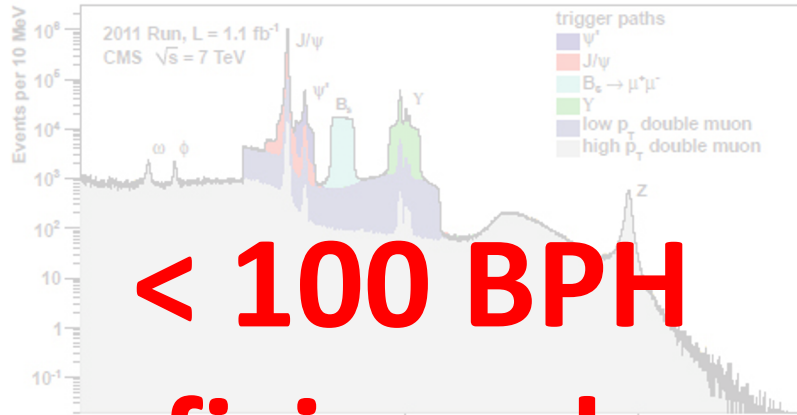
Dimuon and Dielectron spectrum from 2022-23 Parking



Run 3

CMS BPH: GROWING PAG

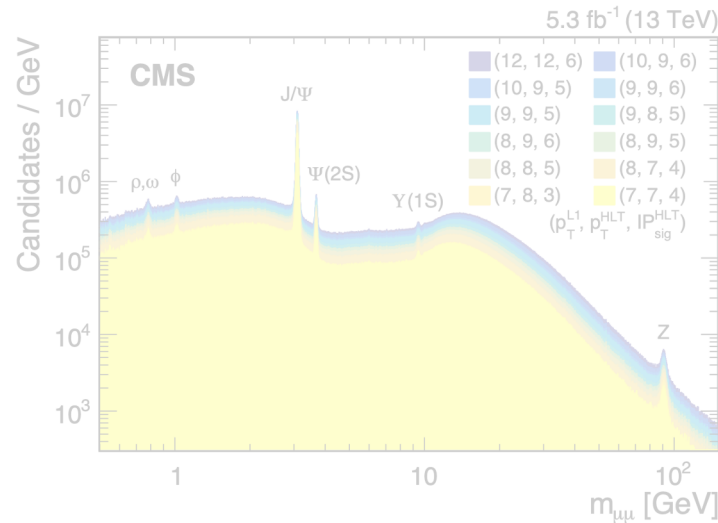
➤ Throughout the years, CMS BPH has evolved significantly ... more people



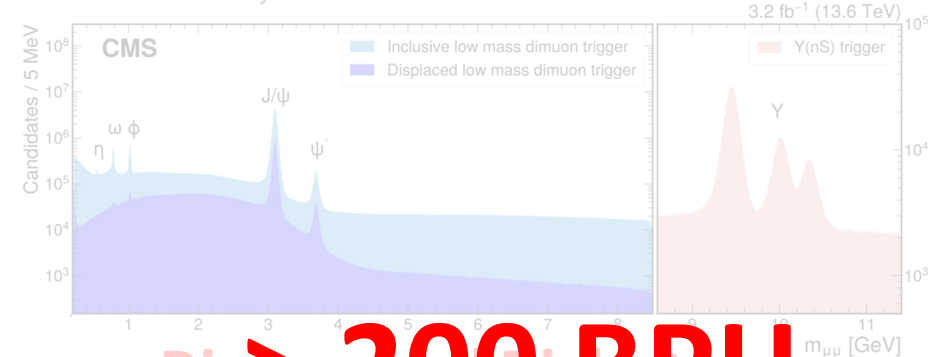
Dimuon spectrum: collection of exclusive triggers

Run 1

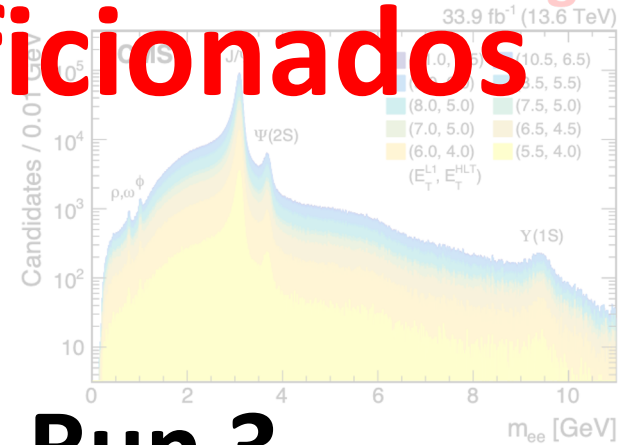
Dimuon spectrum from 2018 BParking



Run 2



Dimuon spectrum from 2022-23 BParking



Run 3



How $\mathcal{R}(K)$ at CMS?

➤ CMS focuses on the ratio:

$$\mathcal{R}(K) = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}$$

Theoretical clear: SM value of 1 ± 0.01





How $\mathcal{R}(K)$ at CMS?



➤ CMS focuses on the ratio:

$$\mathcal{R}(K) = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}$$

Theoretical clear: SM value of 1.00 ± 0.01

$$= \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow J/\psi(\rightarrow \mu^+ \mu^-)K^+)} / \frac{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{\mathcal{B}(B^+ \rightarrow J/\psi(\rightarrow e^+ e^-)K^+)}$$



Signals

- Introduction of $B^+ \rightarrow J/\psi K^+$ channel
 - Numerator and denominator measured to be consistent with 1% precision
 - Cancellation of systematic uncertainties



Backgrounds

- Combinatorial and misidentified electrons
- Partially reconstructed $B^{0/+} \rightarrow K^{*0} \ell \ell$
- Resonant leakage: final-state photons
- **Suppression using BDT and dedicated low- p_T electron reconstruction and ID**

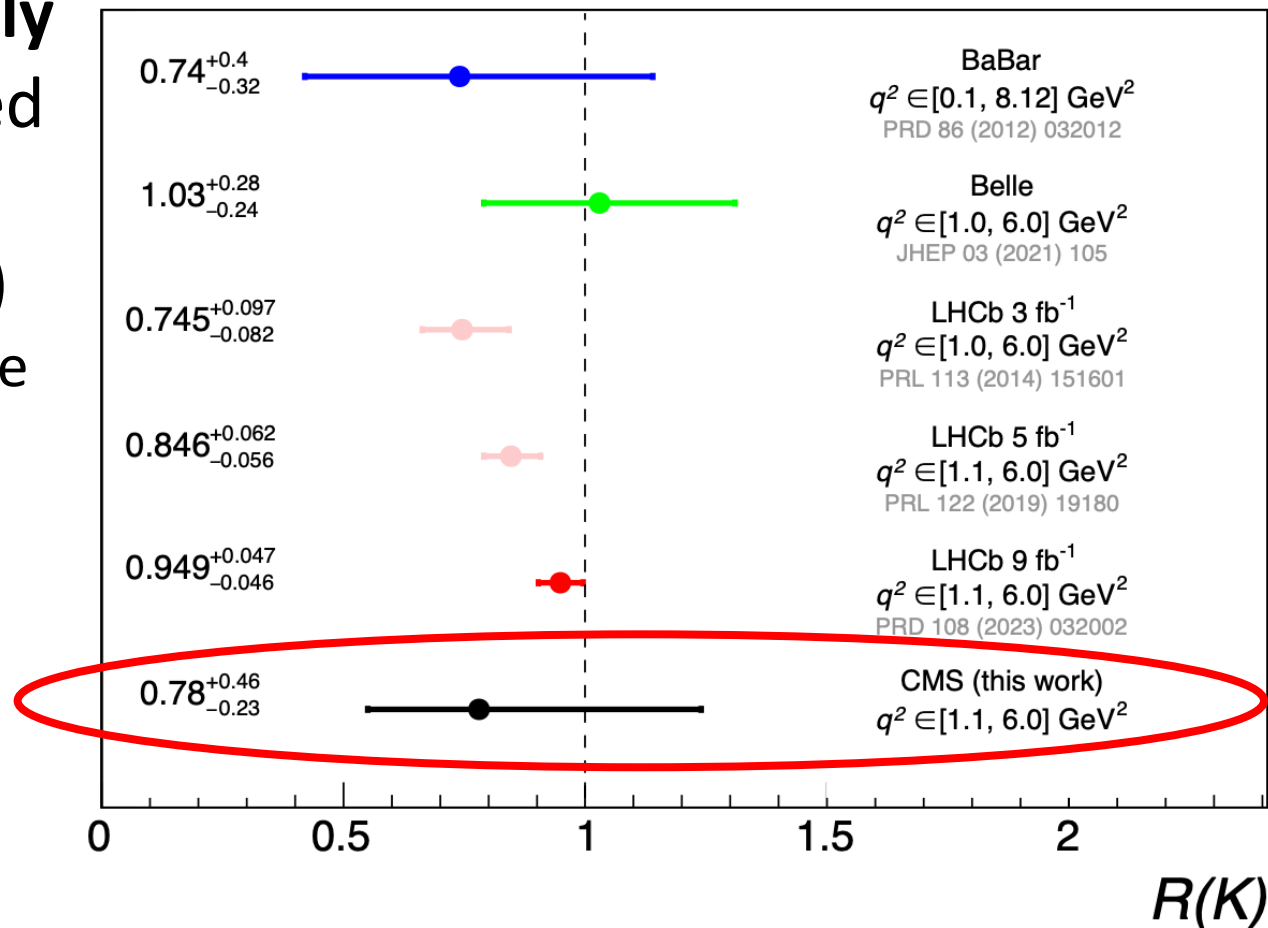


Results



$$b \rightarrow s\ell\ell$$

- **First CMS result on the muon anomaly**
- **First result based on the data collected with the CMS BParking trigger**
- **Result compatible with the SM ($<1\sigma$)**
 - Precision limited by small statistics of the electron channel
 - Leading systematic uncertainties from background description and trigger turnon
- **New measurement with more statistics (Run 3 + Run 2) ongoing**
 - **Aiming for the LHCb precision**



OUTLINE

- Introduction
- Motivation
 - Experimental Motivation
 - Theoretical Motivation
- And CMS?
 - Smart ideas
 - Recent Results
 - Future prospects
- Trigger strategy at CMS
- Conclusions



Introduction

Motivation

CMS results

Trigger strategy at CMS

Conclusions



CONCLUSIONS

- LFUV interesting research area to look for new physics
- Some experimental indications puzzling the scientific community
- CMS recently released a result based on B_c mesons
 - **First CMS result for the $b \rightarrow c$ quark transition**
 - Result agrees with the SM, but still compatible with some BSM models
- A diversified trigger strategy has been and will be vital to expand the CMS physics potential for this and other precision measurements
 - **First CMS result for the $b \rightarrow s\ell\ell$ quark transition**

... STAY TUNED!

HF Physics in the USA



BACK-UP



Introduction

Motivation

CMS results

Tracker Upgrade at CMS

Conclusions

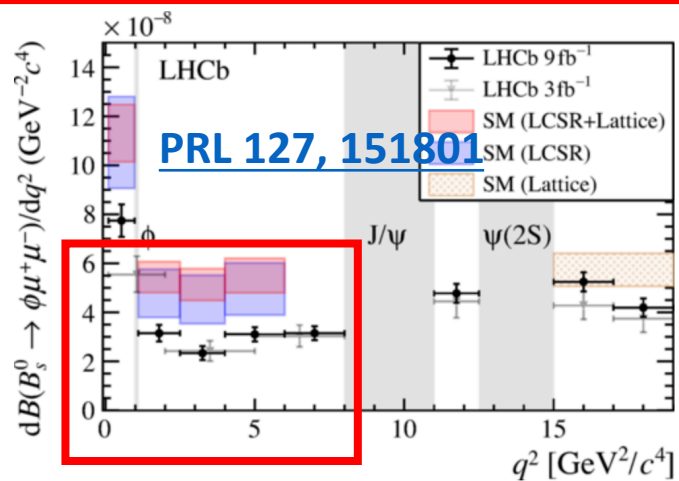
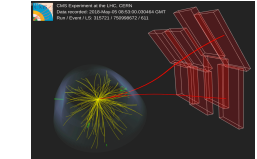


Ratio strategy for LFUV

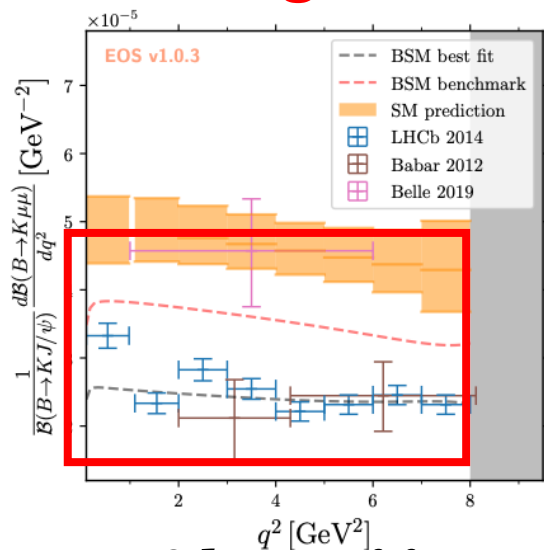
$$\frac{d\Gamma}{dq^2}(B \rightarrow D^* \ell \nu) = \eta_{ew}^2 g_l^2 g_q^2 |V_{cb}|^2 F(q^2),$$

$$\mathcal{R}(D^*) = \frac{g_\tau^2 \int_\tau F_\tau(q^2)}{g_\mu^2 \int_\mu F_\mu(q^2)},$$

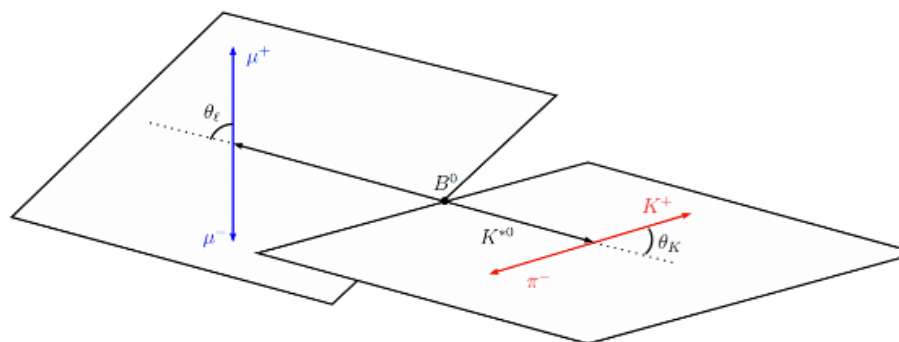
Rare Decays: $b \rightarrow s\ell\ell$ deviations



Branching Fraction

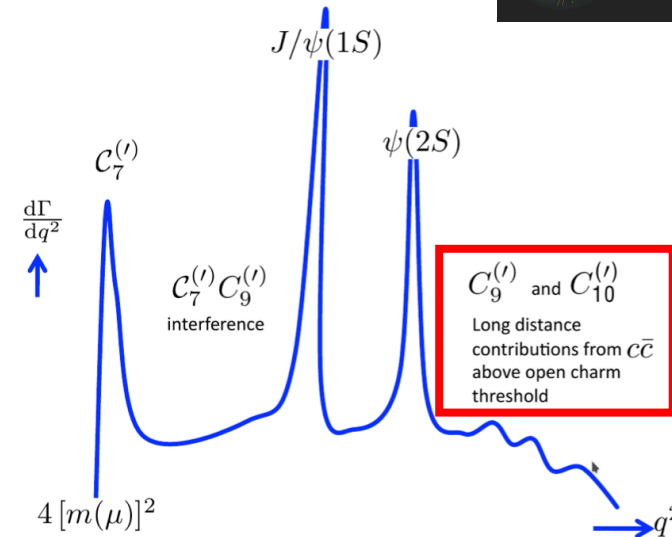
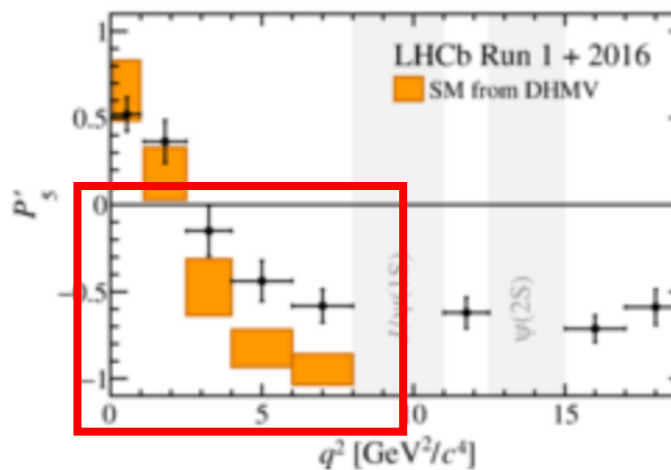


Years of $b \rightarrow s\ell\ell$ results in possible disagreement with SM!



Angular Analysis

Parametrization with q^2 and 3 angles



EFT Interpretation

Effective couplings in $b \rightarrow s\ell^+\ell^-$ transitions		
Wilson coefficient	Operator	
γ -penguin	$C_7^{(l)}$	$\frac{e}{g^2} m_b (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
ew. penguin	$C_9^{(l)}$	$\frac{e^2}{g^2} (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\mu} \gamma^\mu \mu)$
	$C_{10}^{(l)}$	$\frac{e^2}{g^2} (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\mu} \gamma^\mu \gamma_5 \mu)$
scalar	$C_S^{(l)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b) (\bar{\mu} \mu)$
pseudoscalar	$C_P^{(l)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b) (\bar{\mu} \gamma_5 \mu)$

Bright Future, Part II

- Recent projections for key HFP
Input to the EPPSU (May 2025)
- Prospects don't include CMS upgrades for HL-LHC, conservative estimates
 - The **Track Trigger + tracker coverage** will be key for fully hadronic final states (CPV), $\tau \rightarrow 3\mu$, HF cross sections ...
- **Some measurements** are missing (β , CPV etc.): **“+” in table**
- **Sensitivity leaders in more HF measurements of relevance**

Experiment Assumed data sample	ATLAS 20.3-99.7 fb ⁻¹	CMS 116-140 fb ⁻¹	LHCb 2-9 fb ⁻¹	Belle II 364-1075 fb ⁻¹
CKM angles				
β	—	+1	0.57° [15]	1.2° [16]
α	—	—	—	6.6° [17]
γ	—	—	2.8° [18]	13° [17]
ϕ_s [mrad]	42 [19]	23 [20]	20 [21]	—
CP violation in loop-dominated decays				
$S(B^0 \rightarrow \eta' K_S^0)$	—	—	—	0.087 [17]
$\phi_s(B_s^0 \rightarrow \phi\phi)$ [mrad]	—	—	69 [22]	—
$\phi_s(B_s^0 \rightarrow K^{*0}\bar{K}^{*0})$ [mrad]	—	—	130 [23]	—
CP violation in $B_{(s)}^0$-$\bar{B}_{(s)}^0$ mixing				
a_{sl}^s [10 ⁻⁴]	—	—	33 [24]	—
a_{sl}^d [10 ⁻⁴]	—	—	36 [25]	40 [26]
CP violation in the charm sector				
ΔA_{CP} [10 ⁻⁵]	—	—	29 [27]	630 [16]
$A_{CP}(D^{+0} \rightarrow \pi^{+0}\pi^0)$ [10 ⁻⁵]	—	+2	900 [28], —	870, 750
$A_{\Gamma}(KK, \pi\pi)$ [10 ⁻⁵]	—	—	11 [29]	—
$\Delta x(D^0 \rightarrow K_S^0\pi^+\pi^-)$ [10 ⁻⁵]	—	—	18 [30]	140 [31]
Semileptonic B decays				
$ V_{ub} $	—	—	6% [32]	6.3% [33]
$ V_{cb} $	—	+1	—	1.7% [34]
$R(D), R(D^*)$	—	—	14% [35], 6% [36]	12%, 7% [17]
Leptonic B decays				
$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$ [10 ⁻⁹]	$^{+0.8}_{-0.7}$ [37]	0.45 [38]	0.48 [39]	—
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$ [10 ⁻¹⁰]	< 2.1* [37]	< 1.5 [38]	0.79 [39]	—
$\tau_{\text{eff}}(B_s^0 \rightarrow \mu^+\mu^-)$ [ps]	$^{+0.45}_{-0.18}$ [40]	0.23 [38]	0.29 [39]	—
$S(B_s^0 \rightarrow \mu^+\mu^-)$	—	—	—	—
$\mathcal{B}(B^+ \rightarrow \tau^+\nu_\tau)$	—	—	—	34% [17]
$\mathcal{B}(B^+ \rightarrow \mu^+\nu_\mu)$	—	—	—	41% [17]
Flavour-changing neutral current $b \rightarrow sll$ decays				
$P_5'(B^0 \rightarrow K^{*0}\mu^+\mu^-)$ [10 ⁻³] †	390 [41]	100 [42]	111 [43]	—
$\mathcal{B}(B^{+0} \rightarrow K^{+*0}\nu\bar{\nu})$	—	—	—	57%, 110% [17]
$\mathcal{B}(B^{+0} \rightarrow K^{+*0}\tau^+\tau^-)$ [10 ⁻⁴]	—	—	—	< 10, < 18 [44]
Flavour-changing neutral current $b \rightarrow s\gamma$ decays				
$\mathcal{B}(B \rightarrow X_s\gamma; E_\gamma > 1.6 \text{ GeV})$	—	+1	—	(16 – 18)% [17]
$S(B^0 \rightarrow K_S^0\pi^0\gamma)$	—	—	—	0.27 [45]
$S(B_s^0 \rightarrow \phi\gamma)$	—	—	0.32 [46]	—
$A_{\Gamma}^{(2)}(B^0 \rightarrow K^{*0}e^+e^-; \text{very low } q^2)$	—	—	0.10 [47]	0.76 [48]
$\alpha_\gamma(A_b^0 \rightarrow A^0\gamma)$	—	—	0.26 [49]	—
Lepton flavour violation in τ decays				
$\mathcal{B}(\tau^+ \rightarrow \mu^+\gamma)$ [10 ⁻⁸]	—	—	—	< 7.5 [16]
$\mathcal{B}(\tau^+ \rightarrow \mu^+\mu^+\mu^-)$ [10 ⁻⁸]	< 37.6 [50]	< 2.9 [51]	< 4.6 [52]	< 1.8 [53]

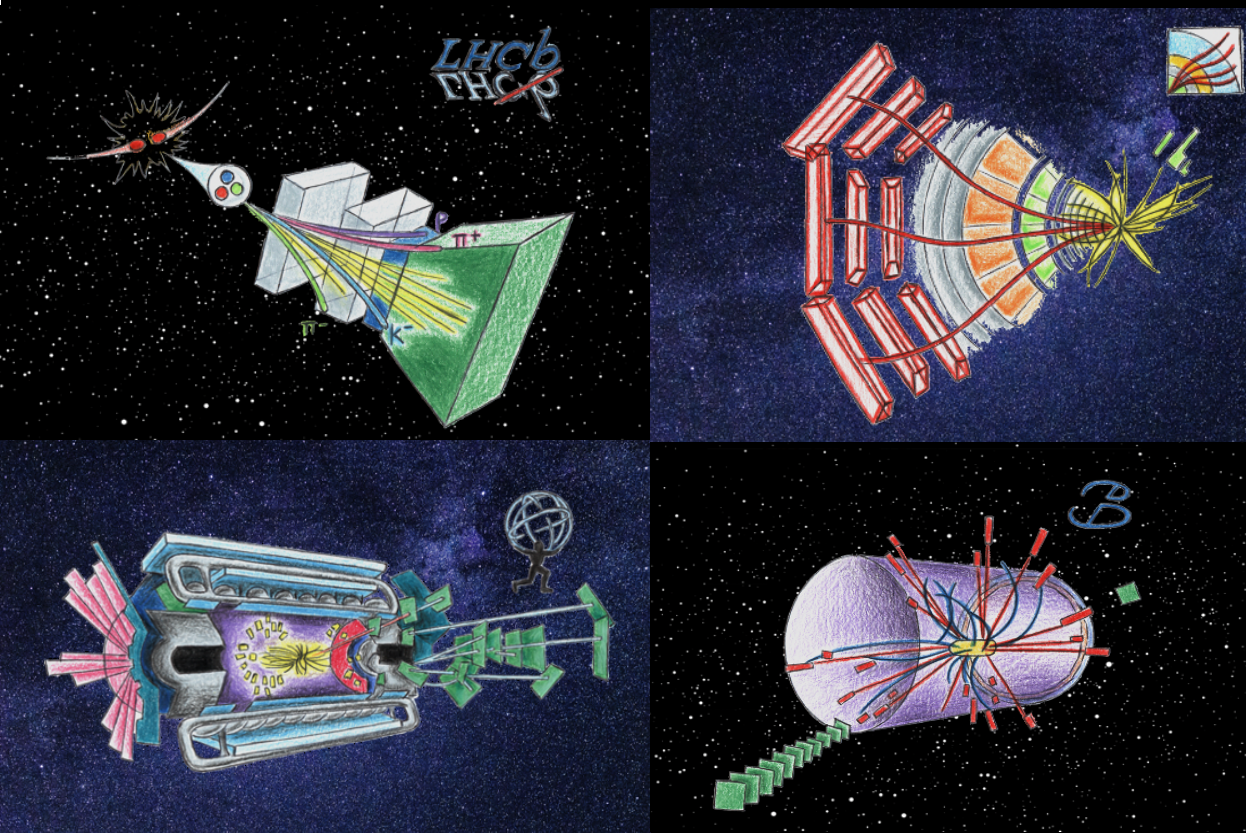
arXiv:2503.24346

HF Physics in the USA



HF and LFUV at CMS

EVEN IN THE OUTREACH PART



Event displays/collisions by Marta Tornago (CMS)



Future Prospects: Why D_s ?

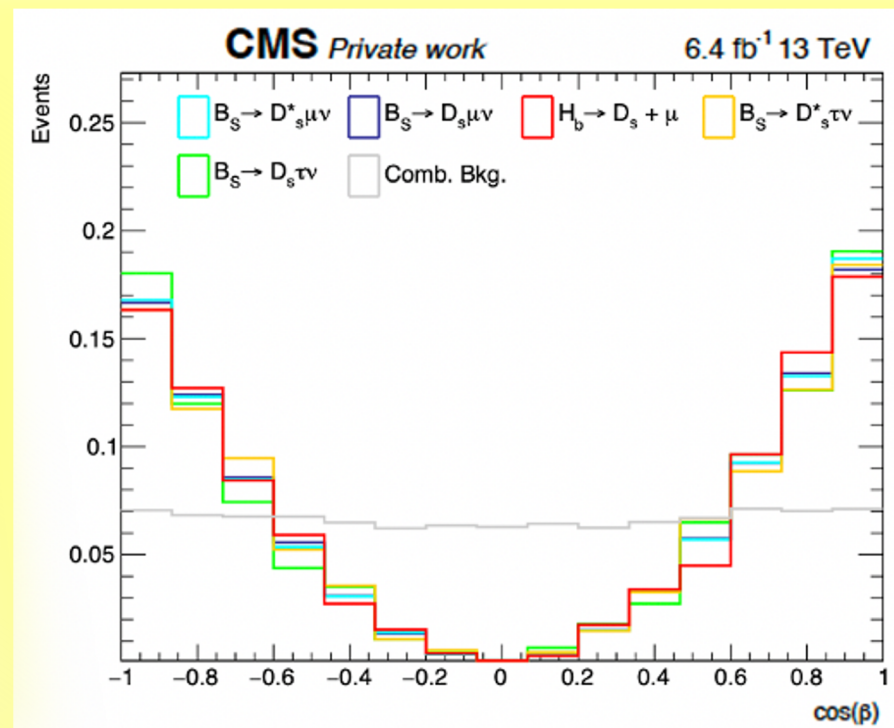
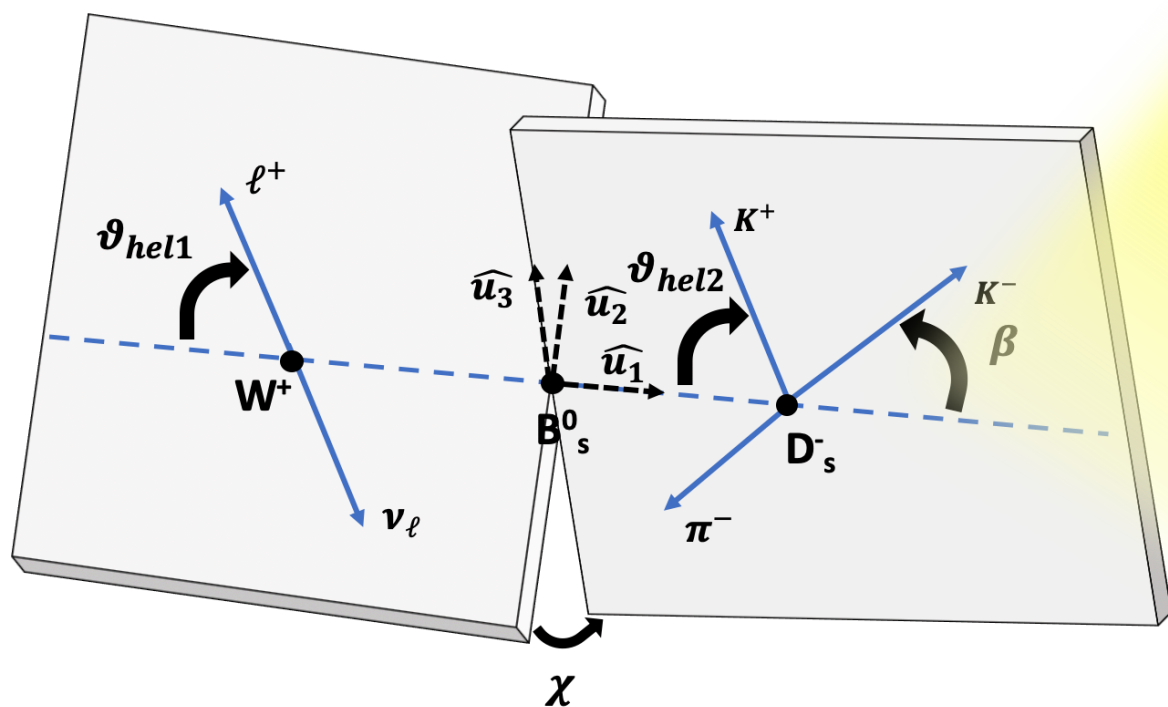
$$\mathcal{R}(D_s) = \frac{\mathcal{B}(B_s \rightarrow D_s^- \tau^+ \nu_\tau)}{\mathcal{B}(B_s \rightarrow D_s^- \mu^+ \nu_\mu)}$$

➤ Experimentally, great potential:

- Spin properties $D_s^- \rightarrow \phi(\rightarrow K^+ K^-)\pi^-$ lead to useful helicity variables to separate signal from background
- $J^P(D_s) = 0^-$, $J^P(\phi) = 1^-$ and $J^P(\pi) = 0^-$, the distribution of $\cos \vartheta_{hel2}$ must follow a $\cos^2 \vartheta_{hel2}$ for signal and uniform distribution for the combinatorial background
- Important for a precision measurement



Future Prospects: Why D_s ?

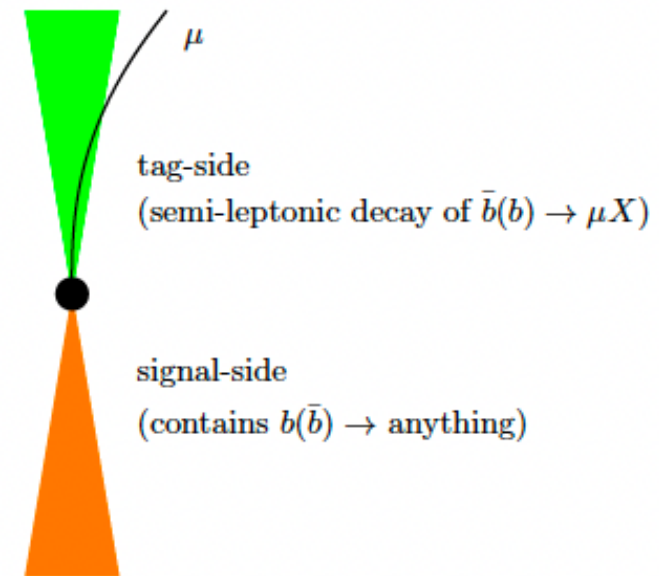
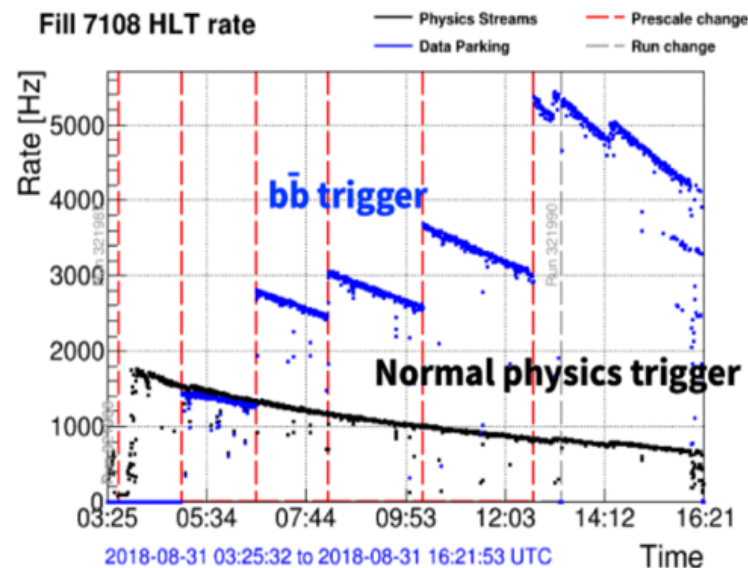
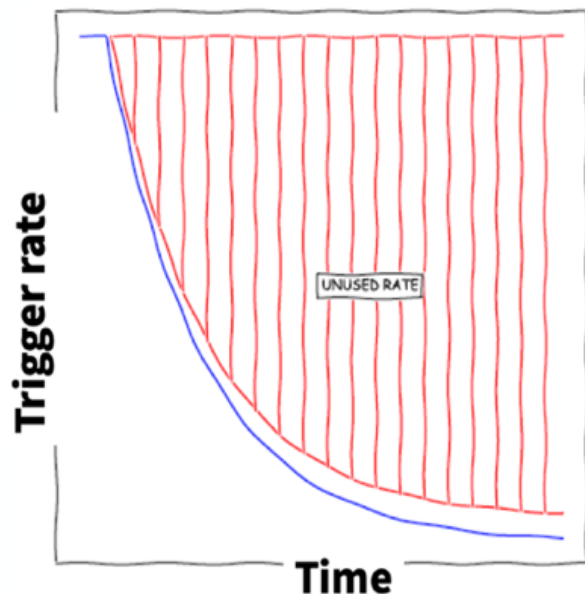


Feasibility study with Master Thesis I supervised! Successful!

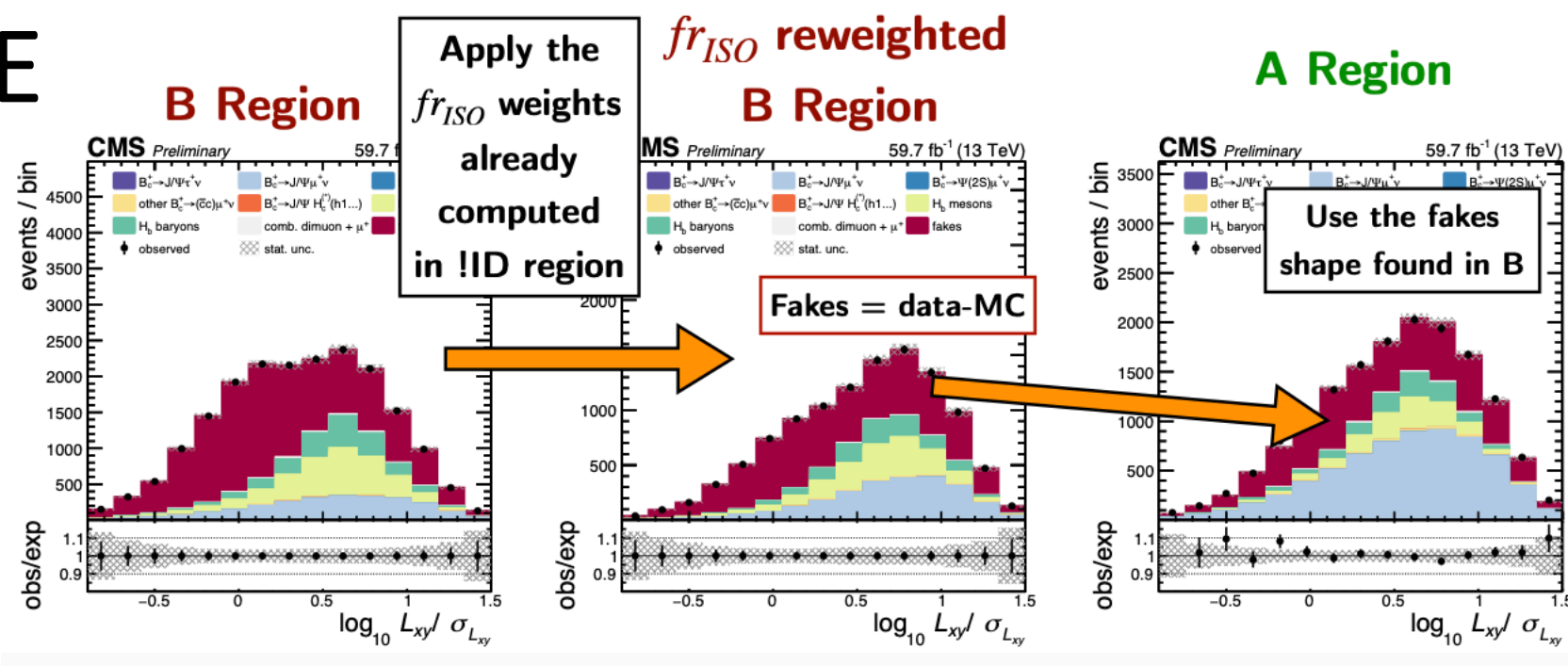
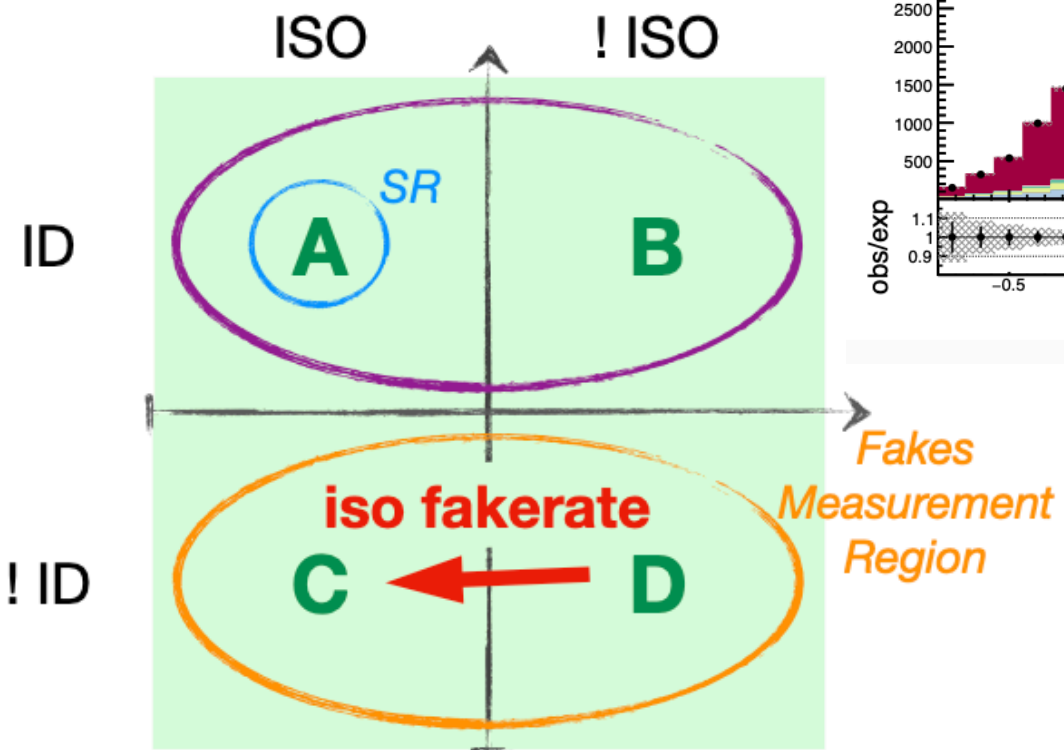


CMS Trigger for B-physics

- Exploit the luminosity drop during the fill
 - No impact on CMS main program
 - $\downarrow \mathcal{L} \Rightarrow$ relax HLT thresholds to reach B-physics phase space
- Trigger tag logic $b \rightarrow \mu X \Rightarrow$ unbiased 10 billion bb events
- To be designed in Run 3 and potentially HL-LHC



FAKES ESTIMATE



$$Fakes(SR) = fr_{iso} \cdot Data(B) - fr_{iso} \cdot MC(B)$$

SYSTEMATIC UNCERTAINTIES

Contribution	Unc. type	$\Delta R(J/\psi) \cdot 10^{-2}$
Theory	S	19
fakes stat.		
non closure	S (bin-by-bin)	13
fakes	N	8
fakes	S	7
finite MC size	S (bin-by-bin)	9
IP3D/ σ_{IP3D} , $L_{xy}/\sigma_{L_{xy}}$ corr.	S	9
muon ID, iso, trigger	N	6
H_b sample	N	0.8
B_c^+ bkg. BRs	N	0.6
J/ψ comb. norm.	N	0.1
Other	N	< 0.1
Total systematic uncertainty		28

Theoretical picture

The first complete, non-redundant basis for the SMEFT at $d = 6$ has been presented in [20]: it consists of 59 independent gauge-invariant structures, which reduce to 53 if we exclude CP-odd terms. This relatively small number of terms gives rise to a large proliferation of independent operators (1350 in the CP-conserving limit) once flavor indices are incorporated. Flavor symmetries therefore play a key role in both restricting and organizing this otherwise large basis [18, 21]. As anticipated, in this work we focus on $U(2)^5$ -invariant operators.

The $U(2)^5 = U(2)_q \times U(2)_u \times U(2)_d \times U(2)_\ell \times U(2)_e$ symmetry is a global symmetry acting on each of the five SM fermion species with independent gauge quantum numbers (q, u, d, ℓ, e) . Within each of these species, the two lightest generations transform as a

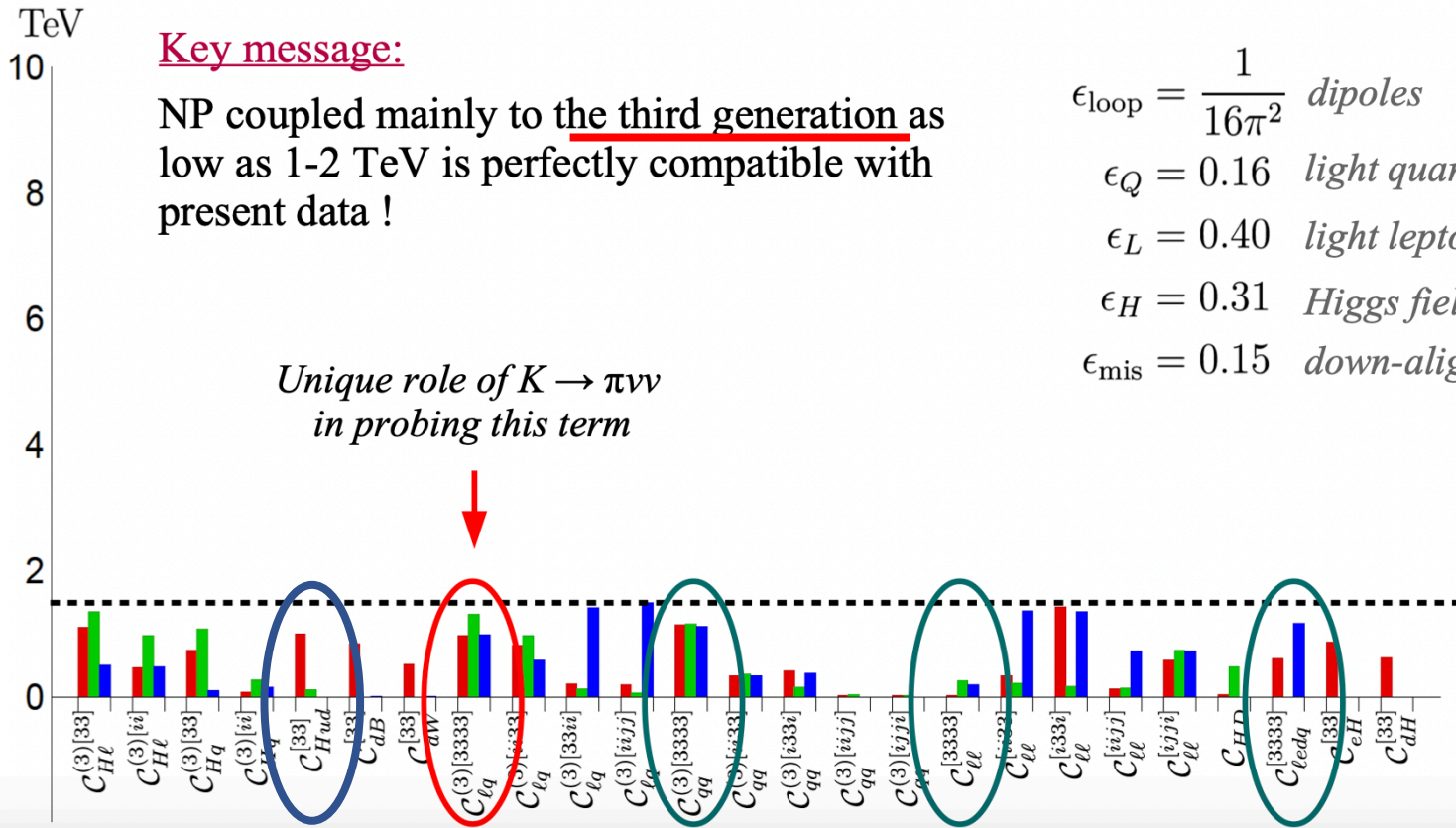
Theoretical picture

G. Isidori – *The BSM potential of rare kaon decays*

Kaons @ CERN – Sept. 2023

► Flavor non-universal interactions

■ flavor ■ EW ■ collider



Bounds on SMEFT coeff. in the $U(2)^5$ limit

Allwicher, Cornella, GI, Stefaneck, to appear.

$$\epsilon_{\text{loop}} = \frac{1}{16\pi^2} \text{ dipoles}$$

$$\epsilon_Q = 0.16 \text{ light quarks}$$

$$\epsilon_L = 0.40 \text{ light leptons}$$

$$\epsilon_H = 0.31 \text{ Higgs fields}$$

$$\epsilon_{\text{mis}} = 0.15 \text{ down-align.}$$

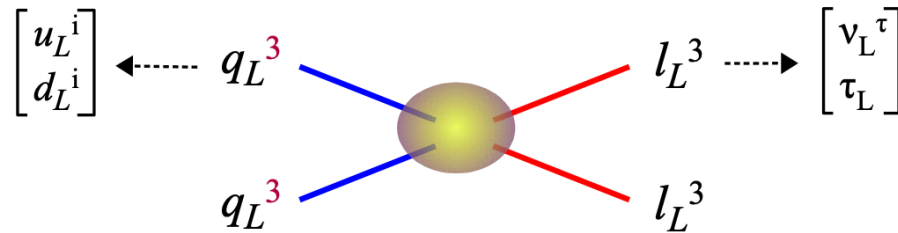
<https://arxiv.org/pdf/2311.00020.pdf>

Theoretical picture

G. Isidori – The BSM potential of rare kaon decays

Kaons @ CERN – Sept. 2023

► Effective-theory approach

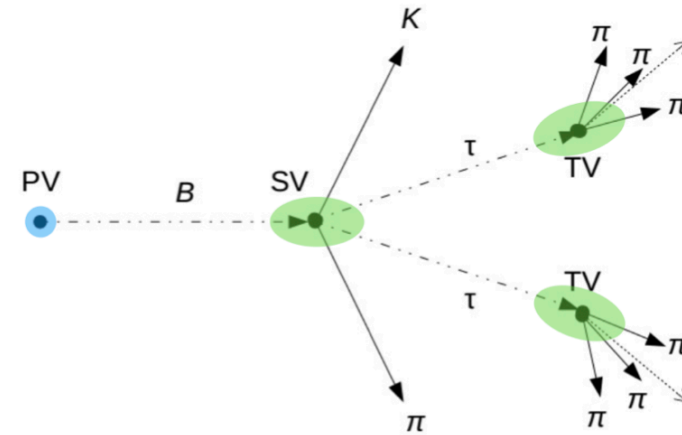


$C \times V_{ts} V_{td} $	$C \times V_{ts} $	$C \times V_{cb} $	C	$C \times V_{ub} V_{td} $
$B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	$B(B^+ \rightarrow K^+ \nu \bar{\nu})$	$R[D^{(*)}]$	$\sigma(pp \rightarrow \tau \tau)$	$\sigma(\nu^\tau N \rightarrow N' \tau)$
Now [NA62]: $\Lambda > 1.7 \text{ TeV}$ $\delta B = 5\%$ [HIKE]: $\Lambda > 4.7 \text{ TeV}$	Now [Belle-II]: $\Lambda > 1.3 \text{ TeV}$ 50 ab^{-1} [Belle-II]: $\Lambda > 3.6 \text{ TeV}$	Now [HFLAV]: $\Lambda > 0.6 \text{ TeV}$ 50 ab^{-1} [Belle-II]: $\Lambda > 1.2 \text{ TeV}$	Now [ATLAS]: $\Lambda > 1.2 \text{ TeV}$ 3 ab^{-1} [HL-LHC]: $\Lambda > 1.7 \text{ TeV}$	Now: – $\delta \sigma = 5\%$ [future ?]: –

LFUV at FCC-ee (IDEA)

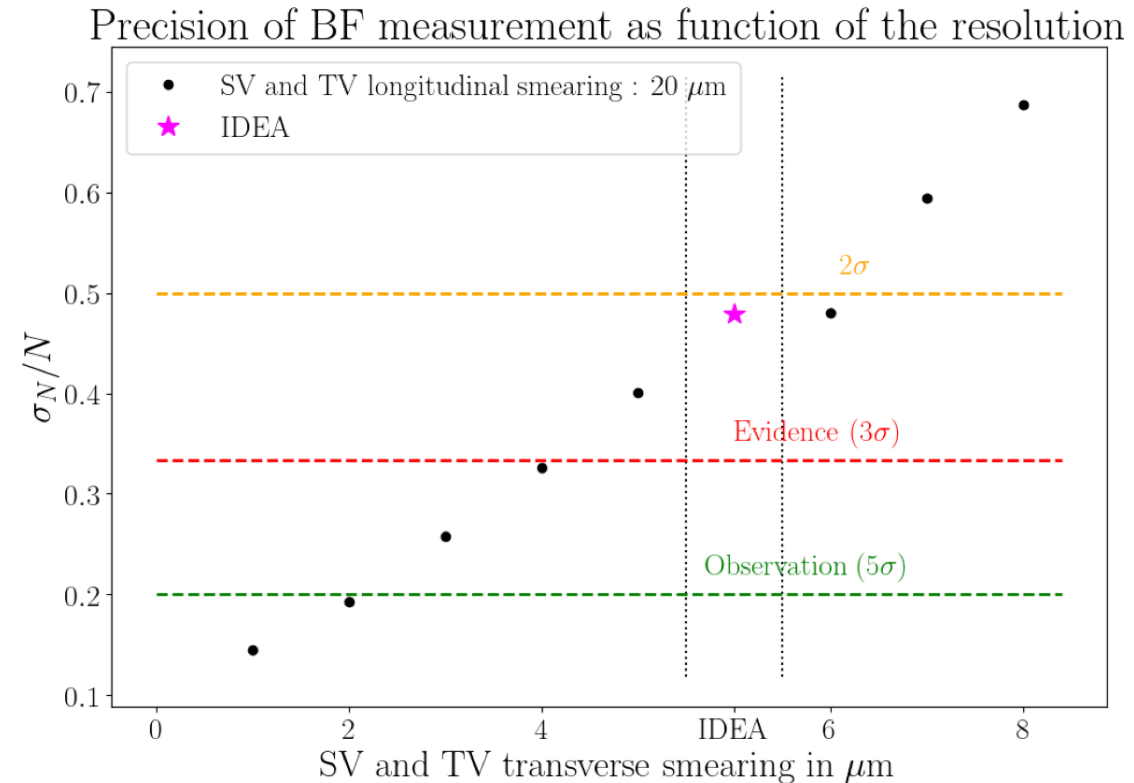
https://indico.cern.ch/event/1202105/contributions/5396842/attachments/2661513/4610846/Talk_FCC_London.pdf

- PV : 3D normal law including Beam Spot Constraints.
- SV & TV \rightarrow ellipsoidal (decaying particle direction as reference) :
 - longitudinal,
 - transverse.
- Several working points examined (Longitudinal-Transverse configuration denoted as L-T in the following) :
 - 5 μm to 20 μm longitudinal,
 - 1 μm to 8 μm transverse.
- 20-3 (L-T) smearing used as reference in the following.
- Experimental vertexing efficiency is conservatively taken as 80% for the time beingⁱ.



LFUV at FCC-ee (IDEA)

https://indico.cern.ch/event/1202105/contributions/5396842/attachments/2661513/4610846/Talk_FCC_London.pdf



Emulation of the vertex resolution performances in order to look for the feasibility of the search of $B^0 \rightarrow K^{*0} \tau\tau$ at FCC-ee :

- we can't make that mode with the state-of-the-art vertex^x detector,
- **we are not that far neither.**