

Flavour physics at CMS

Flavourful Opportunities in Semileptonic B Decays:
Connecting Theory and Experiment

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CP-violation

meas. of ϕ_s in $B_s \rightarrow J/\Psi \phi$

meas. of β in $B^0 \rightarrow J/\Psi K_s$

A_{CP} in $D^0 \rightarrow K_s K_s$

Exotic hadrons and spectroscopy

search for tetraquarks

measurement of tetraquark properties

baryon decays

Production and properties

differential cross sections

associated V + HF production

fragmentation fractions

lifetimes

Public results
[searchable database](#)
[legacy webpage](#)

Flavour Physics at CMS

Lepton flavour (non-) universality

$R(K), R(J/\Psi)$

Lepton flavour violation

$\tau \rightarrow 3\mu$

Rare decays

FCNC $b \rightarrow s \ell \ell$

measurement of “golden” $B_s \rightarrow \mu\mu$

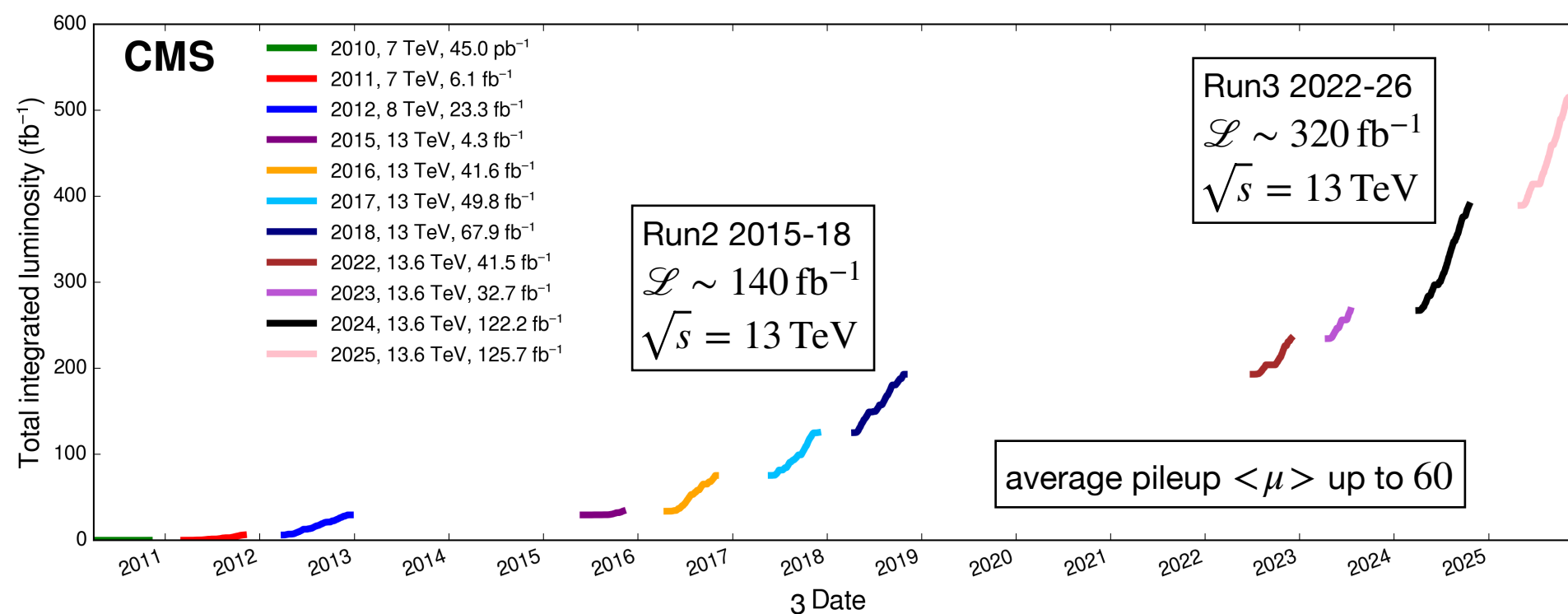
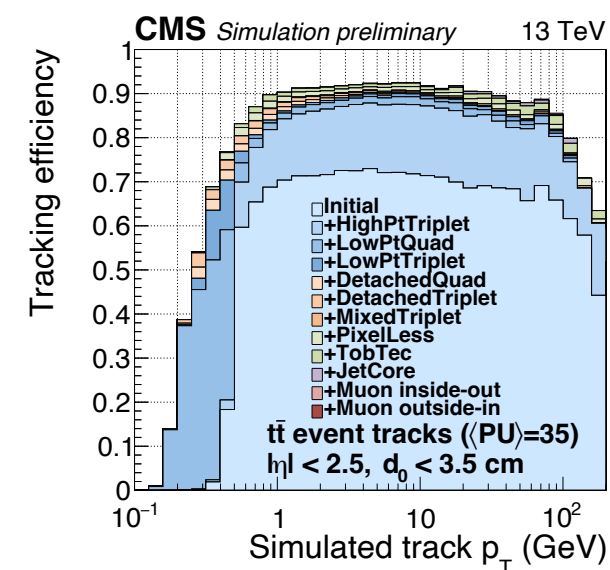
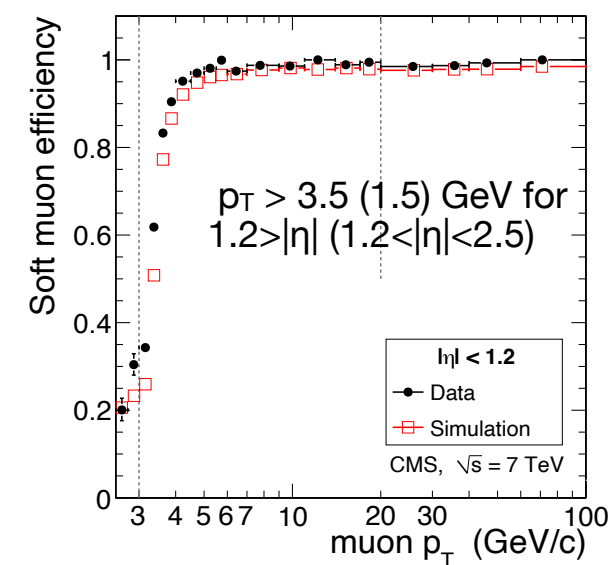
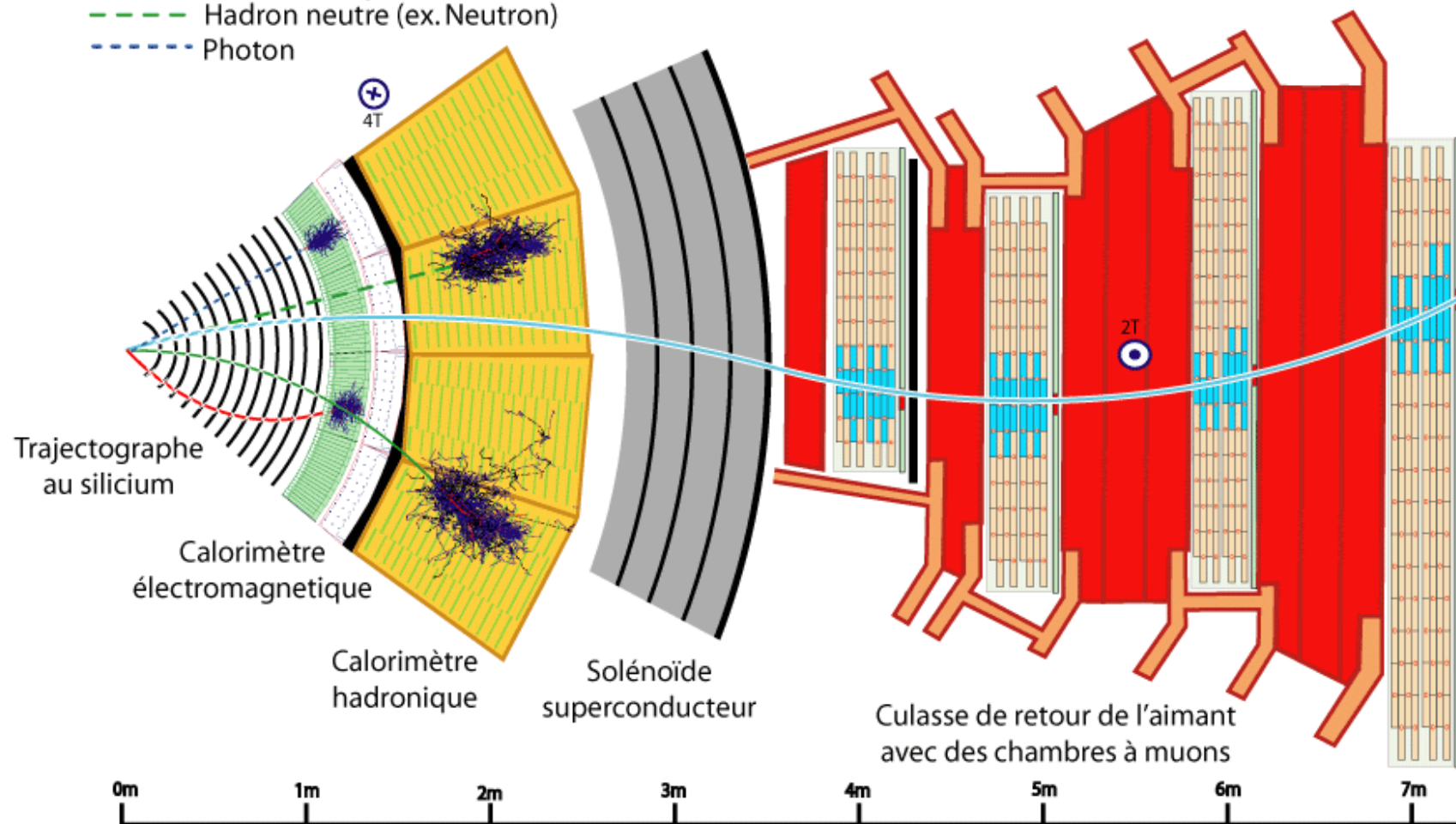
search for rare $D^0 \rightarrow \mu\mu$

angular analyses $B^0 \rightarrow K^{*0} \mu\mu, B_s \rightarrow \phi \mu\mu$

$d\mathcal{B}(H_b \rightarrow H_s \mu\mu)/dq^2$

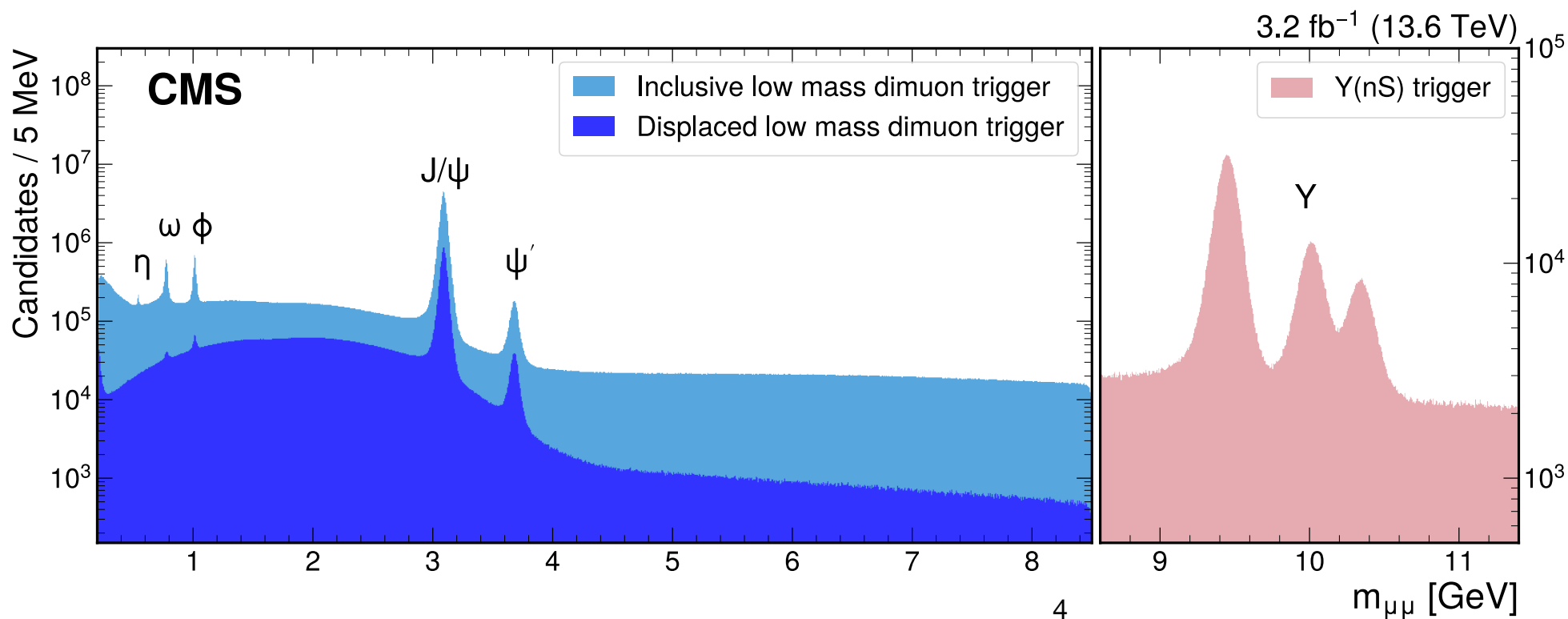
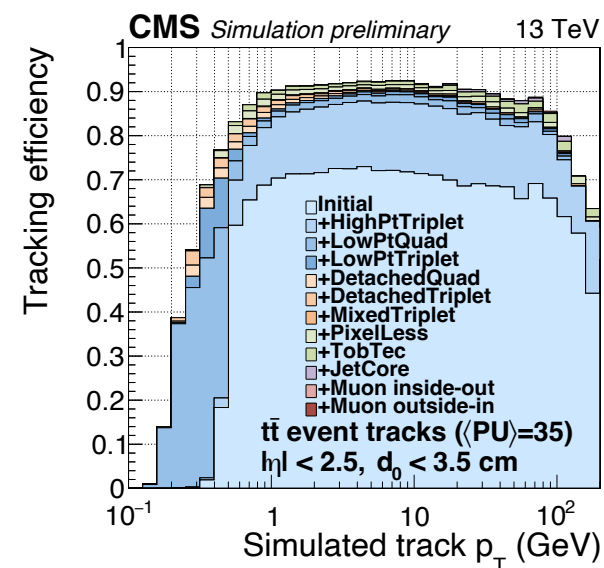
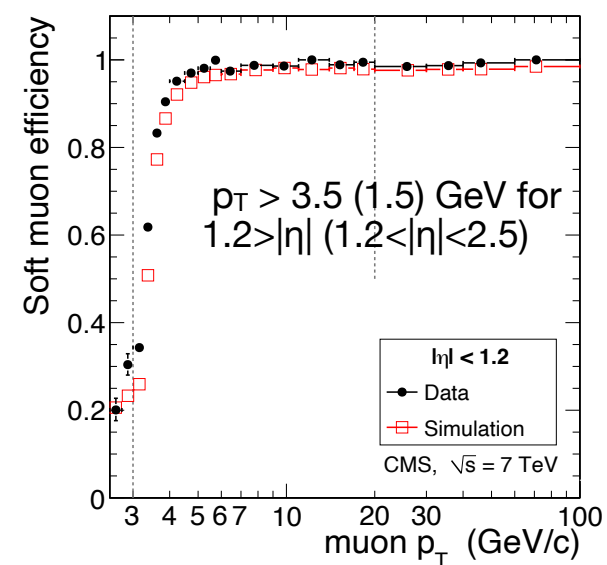
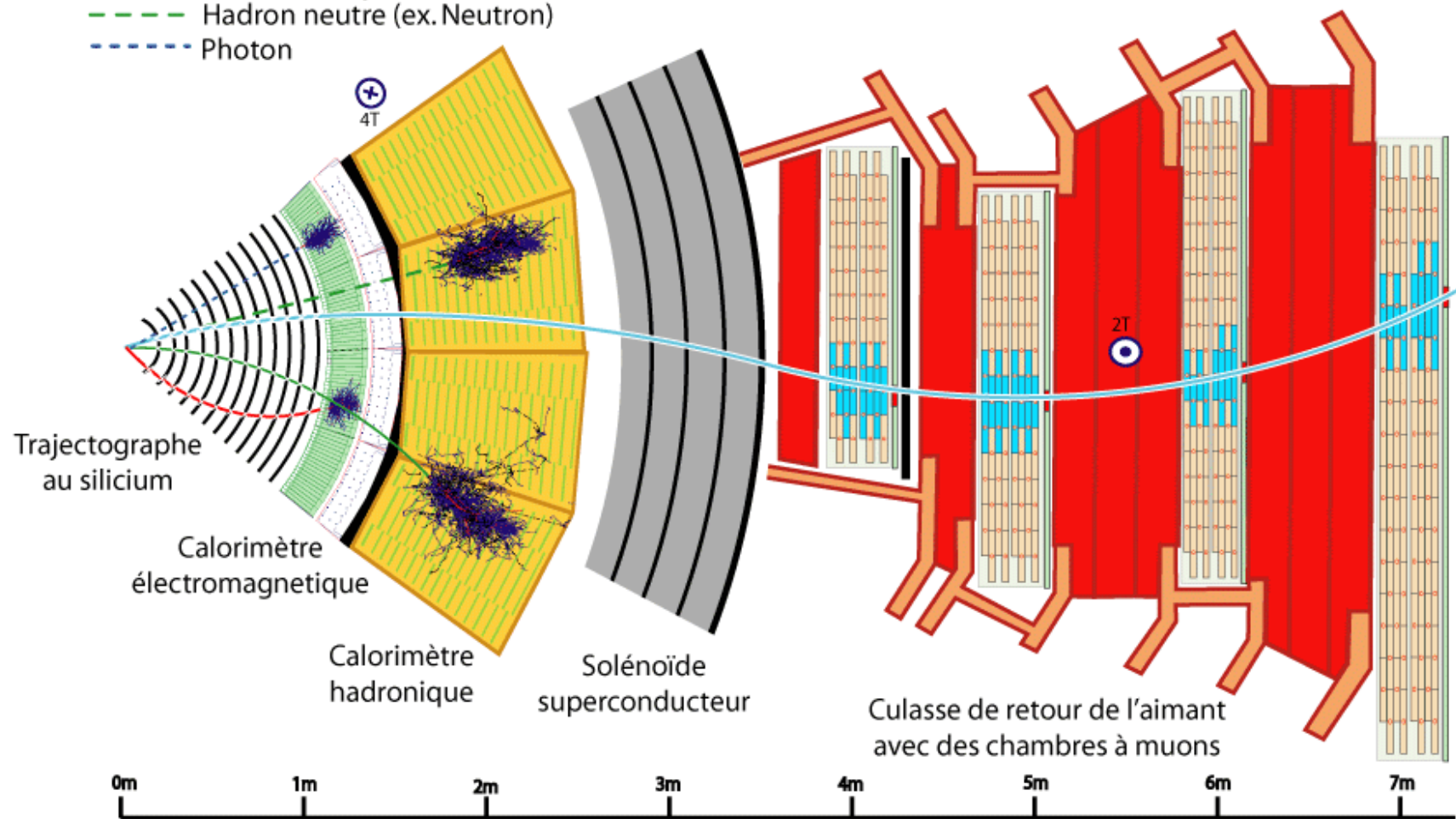
Légende:

- Muon
- Électron
- Hadron chargé (ex. Pion)
- Hadron neutre (ex. Neutron)
- Photon



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- Muon
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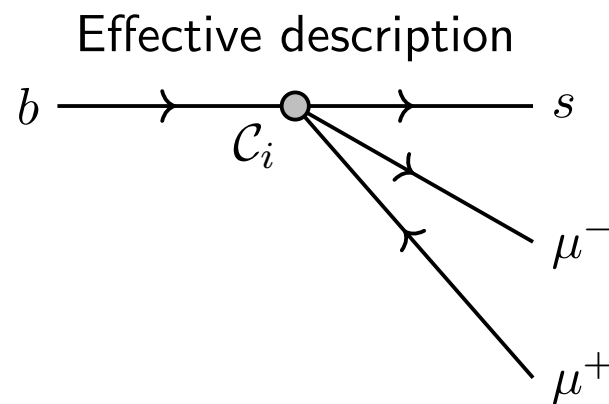


Run 3

inclusive di-muon trigger
 $m_{\mu\mu} < 8 \text{ GeV}$ $p_T > 3,4 \text{ GeV}$,
 ~full η coverage

$b \rightarrow s \ell \ell$ decays

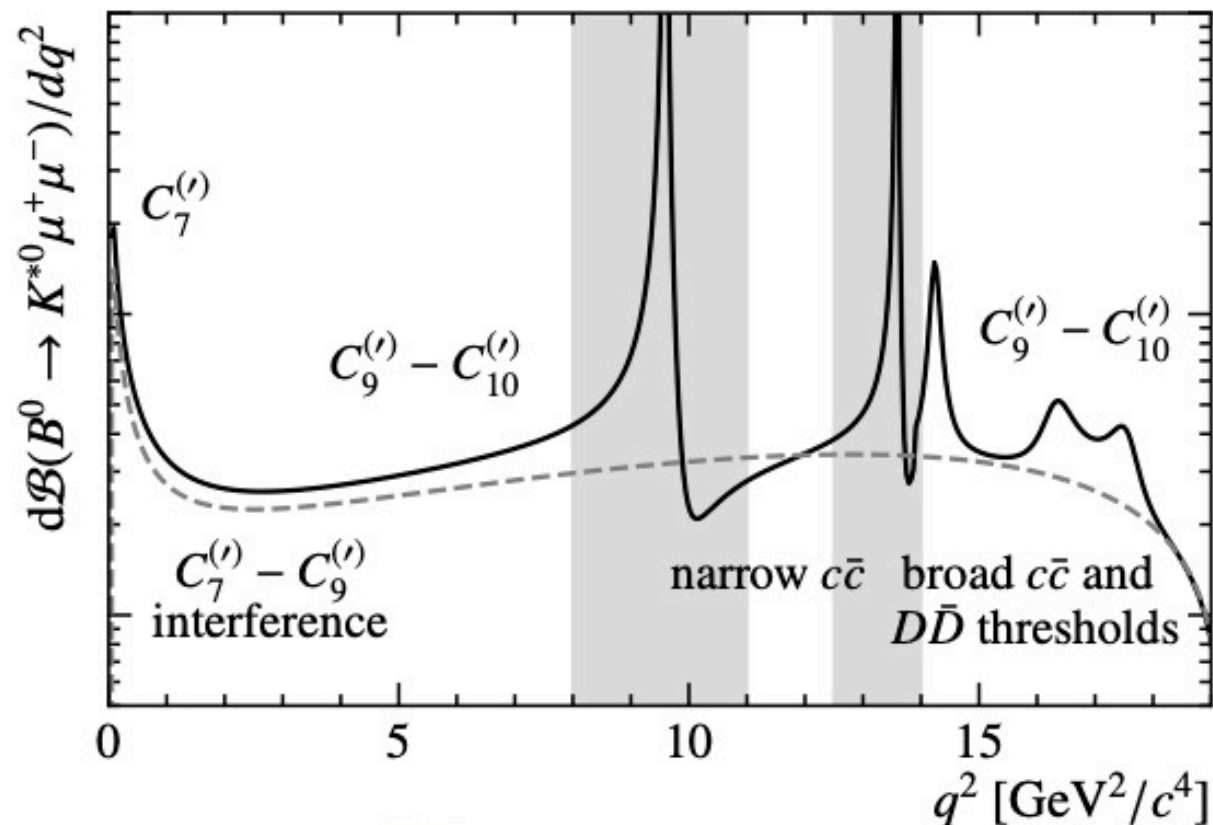
EFT for $b \rightarrow s \ell \ell$ decays



$$\mathcal{H}_{\text{eff}} \propto V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

local operators

Wilson coefficients



NP could modify the Wilson Coefficients,
or enable new operators

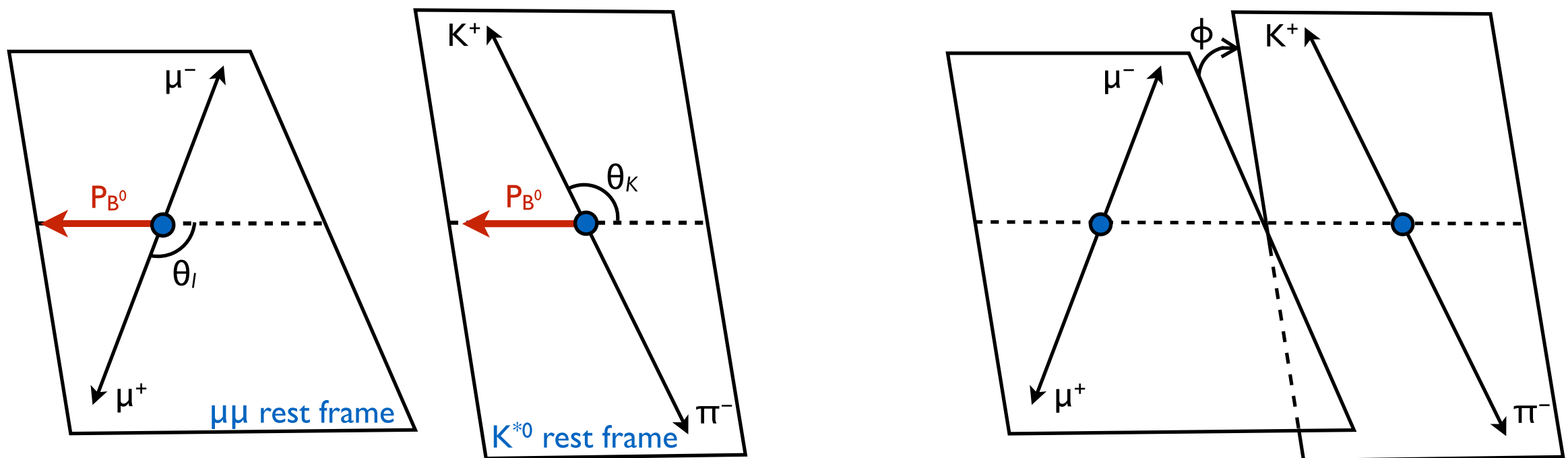
different dimuon mass squared (q^2) ranges
sensitive to different operators

NP contribution to C_9 expected to
be constant vs q^2 (2401.18007)

$B^0 \rightarrow K^*(\rightarrow K\pi)\mu\mu$ angular decay rate

The differential $B^0 \rightarrow K^*(\rightarrow K\pi)\mu\mu$ decay rate is written as a function of the angular variables $(\cos \theta_K, \cos \theta_l, \Phi)$

- expressed in terms of the set of clean (reduced impact of form factor uncertainties) observables $P_i^{(\prime)}$ which are related to the Wilson coefficients as in [JHEP 01 \(2013\) 048](#)



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$$\frac{d^4\Gamma_{P\text{-wave}}}{dq^2 d^3\Omega} = \frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{dq^2 d\cos\theta_l d\cos\theta_K d\phi} = \frac{9}{32\pi} \left[\frac{3}{4} F_T \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\ \left. + \left(\frac{1}{4} F_T \sin^2 \theta_K - F_L \cos^2 \theta_K \right) \cos 2\theta_l + \frac{1}{2} P_1 F_T \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \right. \\ \left. + \sqrt{F_T F_L} \left(\frac{1}{2} P'_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + P'_5 \sin 2\theta_K \sin \theta_l \cos \phi \right) \right. \\ \left. - \sqrt{F_T F_L} \left(P'_6 \sin 2\theta_K \sin \theta_l \sin \phi - \frac{1}{2} P'_8 \sin 2\theta_K \sin 2\theta_l \sin \phi \right) \right. \\ \left. + 2P_2 F_T \sin^2 \theta_K \cos \theta_l - P_3 F_T \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]$$

F_L is the fraction of longitudinally polarised K^* (and $F_T = 1 - F_L$)

P_2 is related to A_{FB} , the muon forward backward asymmetry

$P_i^{(\prime)}$ is the base of optimised observables

$B^0 \rightarrow K^*(\rightarrow K\pi) \mu\mu$ angular decay rate

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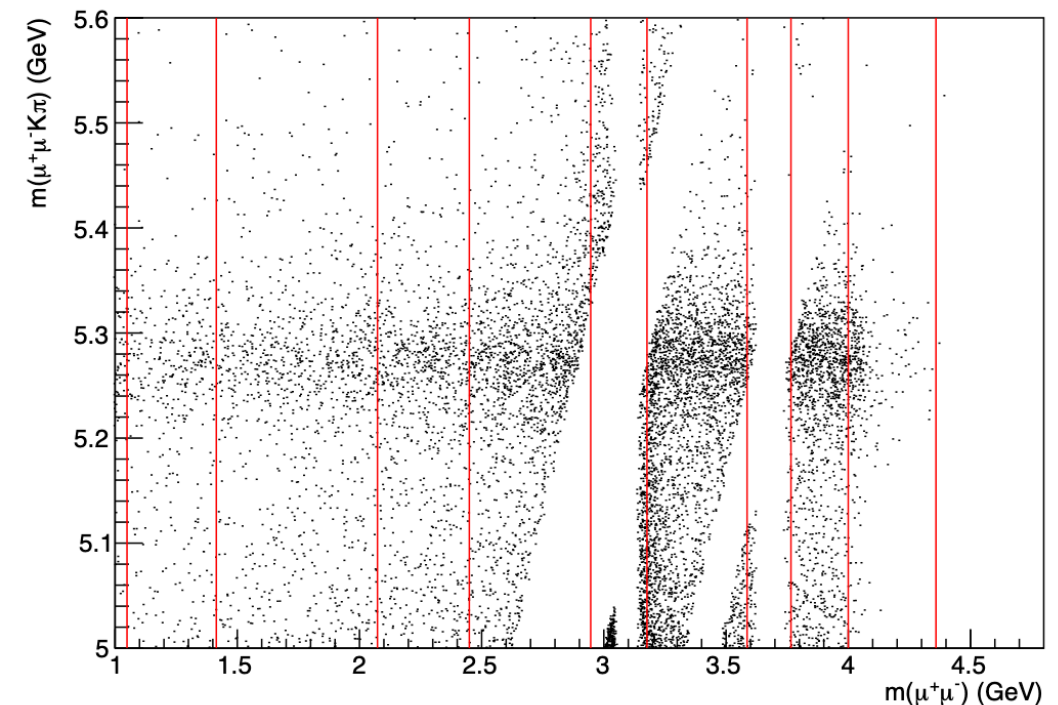
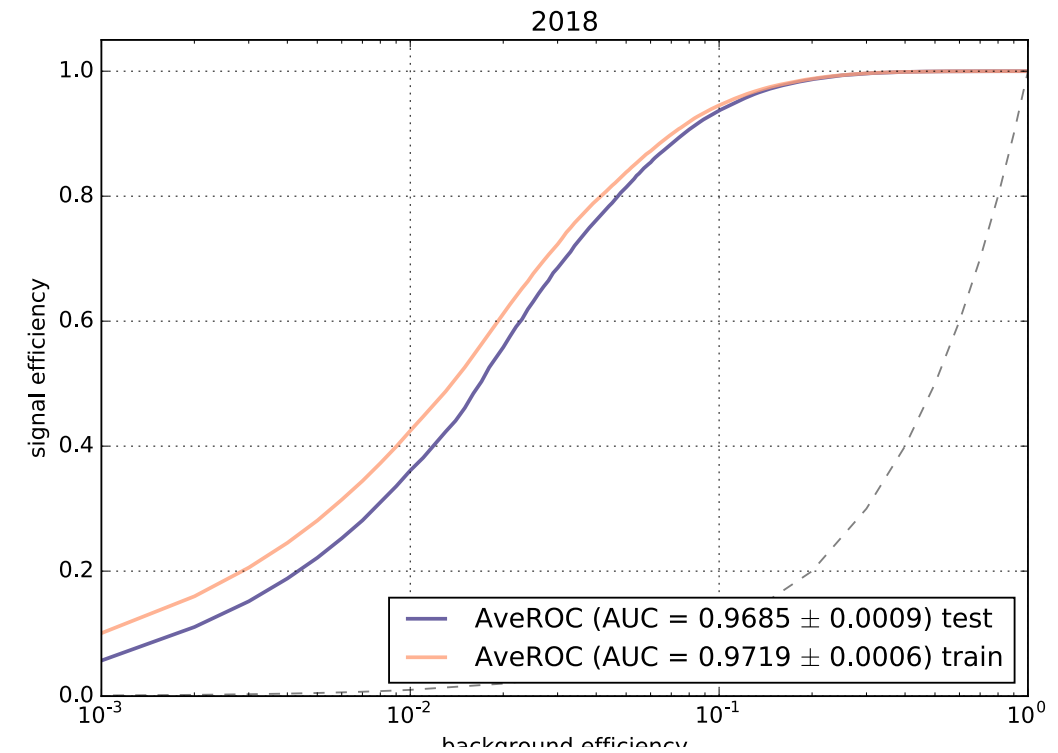
The $K\pi$ system can also be in S-wave configuration, modifying angular distribution as

$$\frac{d^4\Gamma_{total}}{dq^2 d^3\Omega} = (1 - F_S) \frac{d^4\Gamma_{P\text{-wave}}}{dq^2 d^3\Omega} + F_S \frac{d^4\Gamma_{S/SP\text{-wave}}}{dq^2 d^3\Omega}$$

we treat S-wave
pars as nuisance

$B^0 \rightarrow K^*(\rightarrow K\pi) \mu\mu$ analysis in a nutshell

- **Run2 dataset (2016-2018), $L = 140 \text{ fb}^{-1}$**
- trigger: 2 mu + a track, fitted to a common displaced vertex
- resonant J/Ψ and $\Psi(2S)$ modes standard candles, validation etc...
- **background from mass sidebands**
- BDT for background reduction
- **$K\pi$ disambiguation based on mass assigned $\rightarrow$ pick hypothesis with mass closest to $K^{*0}(892)$**
 - 13% mistag rate
- “diagonal” q^2 vs $m(K\pi\mu\mu)$ cut to eliminate leakage from resonant modes



Fit model

4D unbinned ML fit to $(\cos \theta_K, \cos \theta_l, \Phi, m_{K\pi\mu\mu})$ in each q^2 bin

$$\text{pdf}(m, \cos \theta_K, \cos \theta_l, \phi) = Y_S \left[S^C(m) S^a(\cos \theta_K, \cos \theta_l, \phi) \epsilon^C(\cos \theta_K, \cos \theta_l, \phi) \right. \\ \left. + R \cdot S^M(m) S^a(-\cos \theta_K, -\cos \theta_l, -\phi) \epsilon^M(\cos \theta_K, \cos \theta_l, \phi) \right] \\ + Y_B B^m(m) B^a(\cos \theta_K, \cos \theta_l, \phi)$$

signal component

signal yield

R = ratio of average mistag fraction on data and on MC

bkg yield

background component

mistagged signal ~13%

S^a is the decay rate formula shown earlier

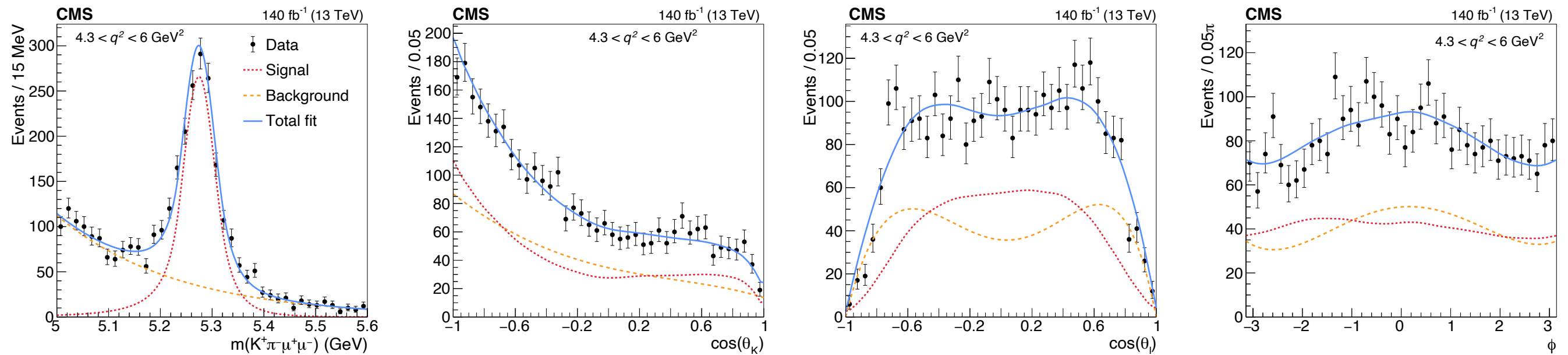
ingredients:

- mass shapes (signal and background) $S^C(m), S^M(m), B^m(m)$
- signal efficiency ϵ^C, ϵ^M from simulation
- angular distributions of the background $B^a(\cos \theta_K, \cos \theta_l, \Phi)$ from data sidebands

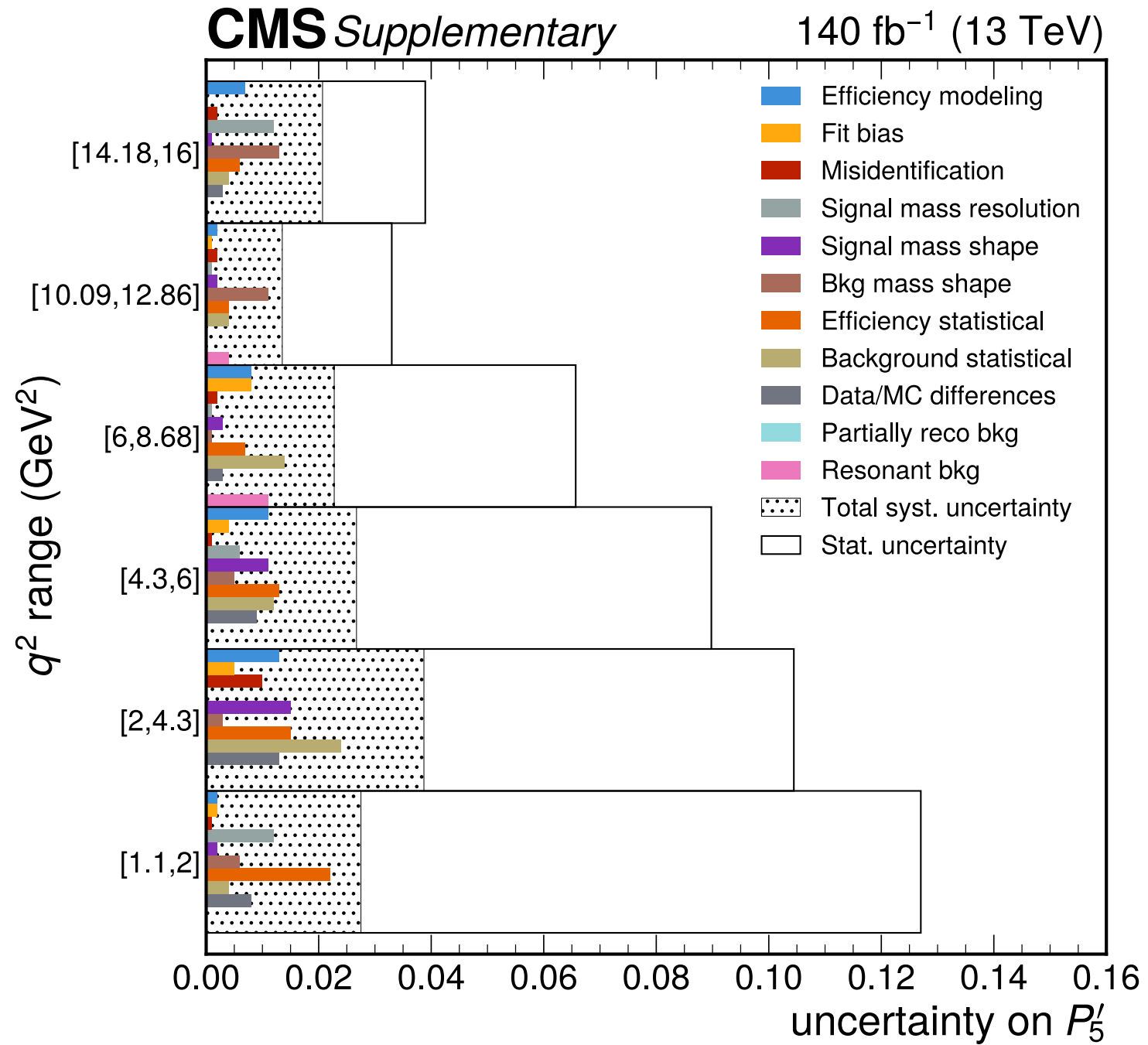
Fit projections

Bin index	q^2 range [GeV ²]	Yield
0	1.1 - 2	792 ± 34
1	2 - 4.3	1903 ± 55
2	4.3 - 6	1572 ± 51
3	6 - 8.68	2693 ± 69
4 (J/ψ)	J/ψ : 8.68 - 10.09	2655410 ± 3047
5	10.09 - 12.86	4967 ± 91
6 ($\psi(2S)$)	$\psi(2S)$: 12.86 - 14.18	179671 ± 562
7	14.18 - 16	3330 ± 67

* trigger problem $\rightarrow$ too few events in bin 8 $16 < q^2 < 23.04$ GeV², not considered

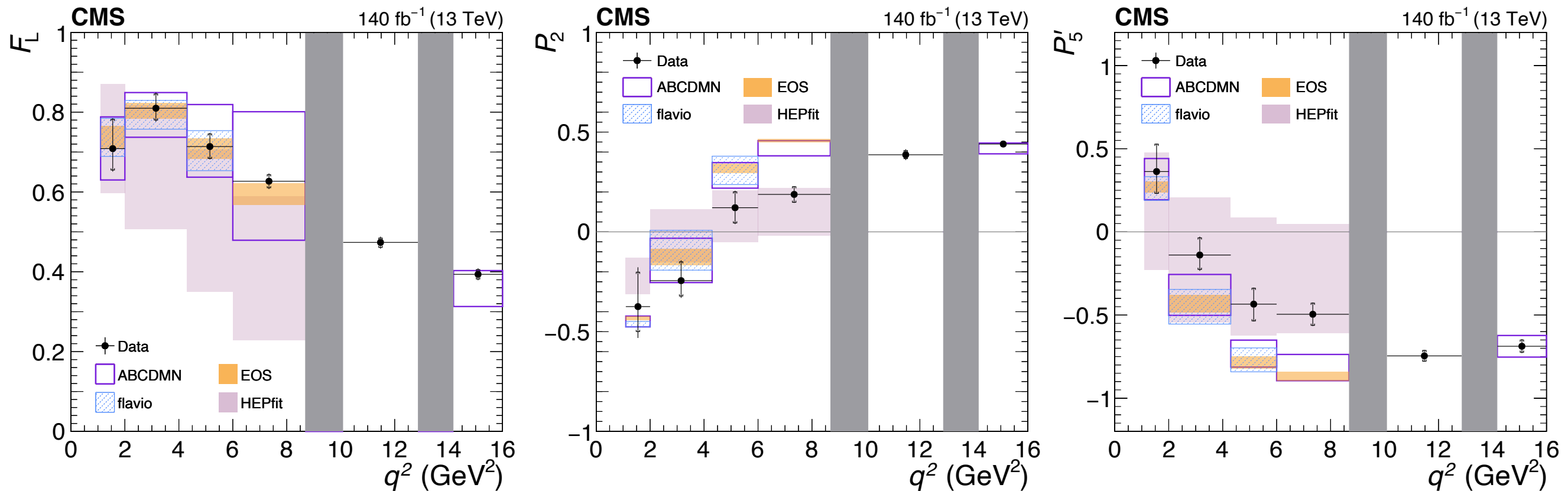


Systematic uncertainties



statistically limited

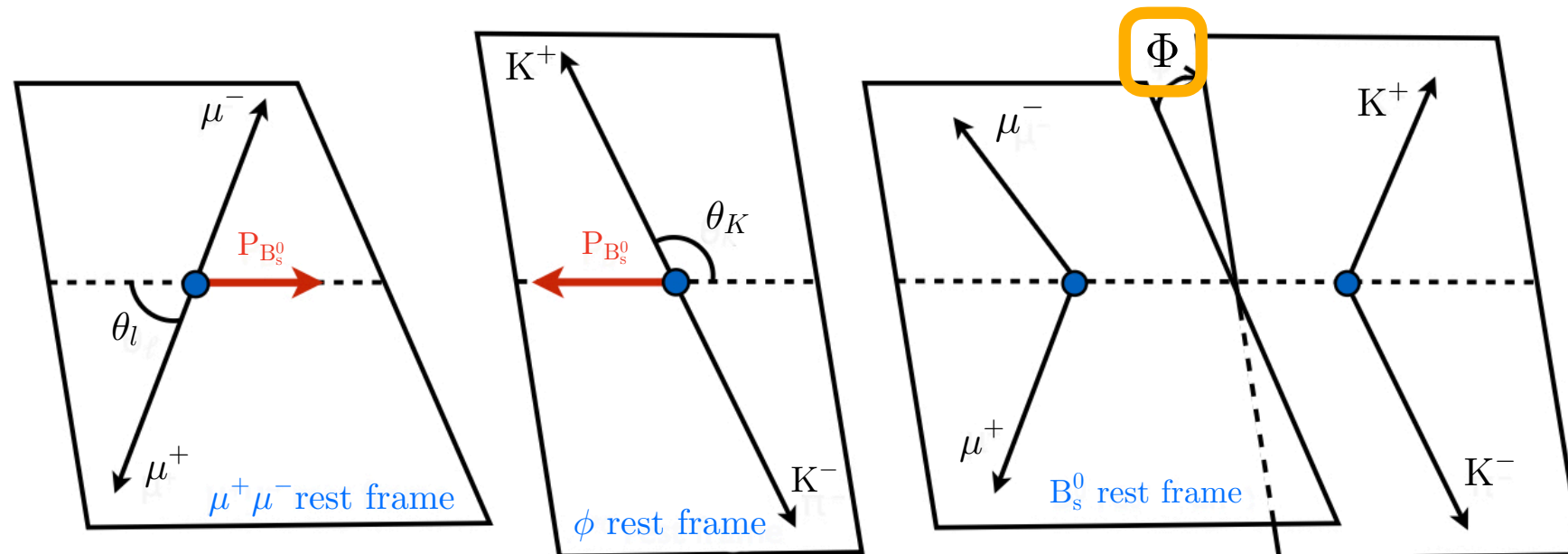
Results



- [FLAVIO](#): local form-factors from Lattice QCD and Light-Cone Sum Rule, QCDF for non-local form-factors
[EOS](#): local form-factors derived from combination of LQCD and LCSR, novel parametrisation of non-local form-factors ([JHEP 09 \(2022\) 133](#))
- good compatibility with the SM predictions for most parameters, some tensions in the q^2 region below the J/ψ for the P_5' and P_2 parameters
- competitive precision, observed trends remarkably similar to LHCb's

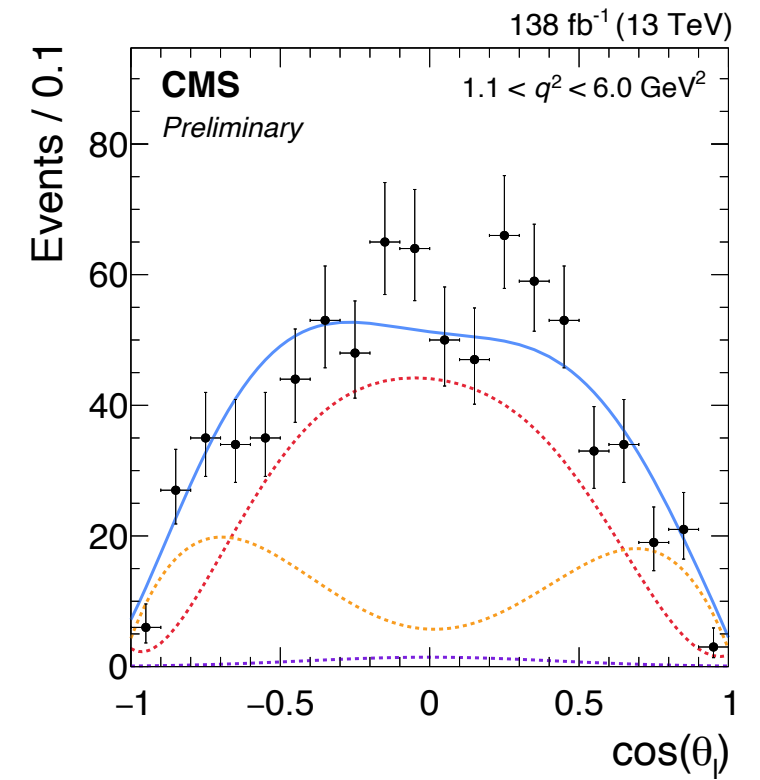
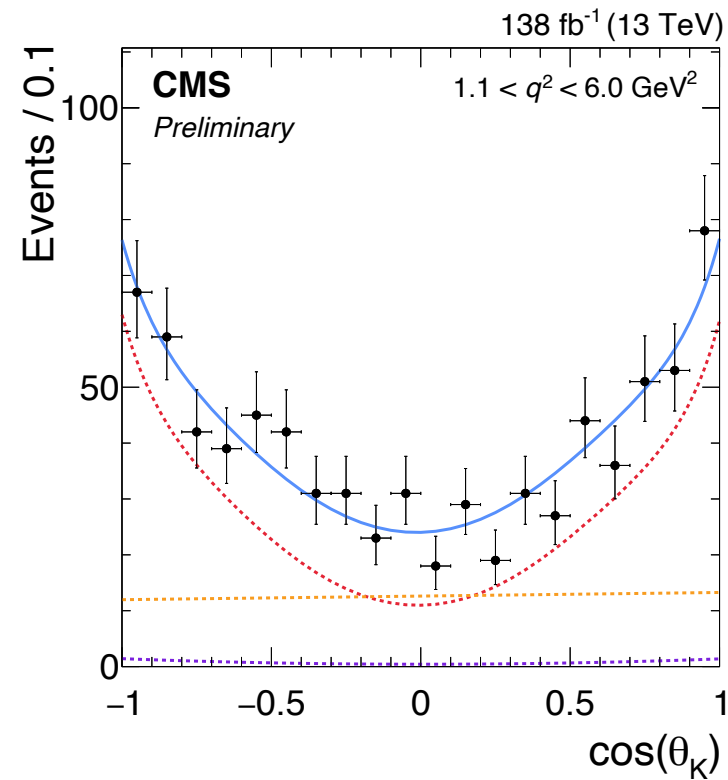
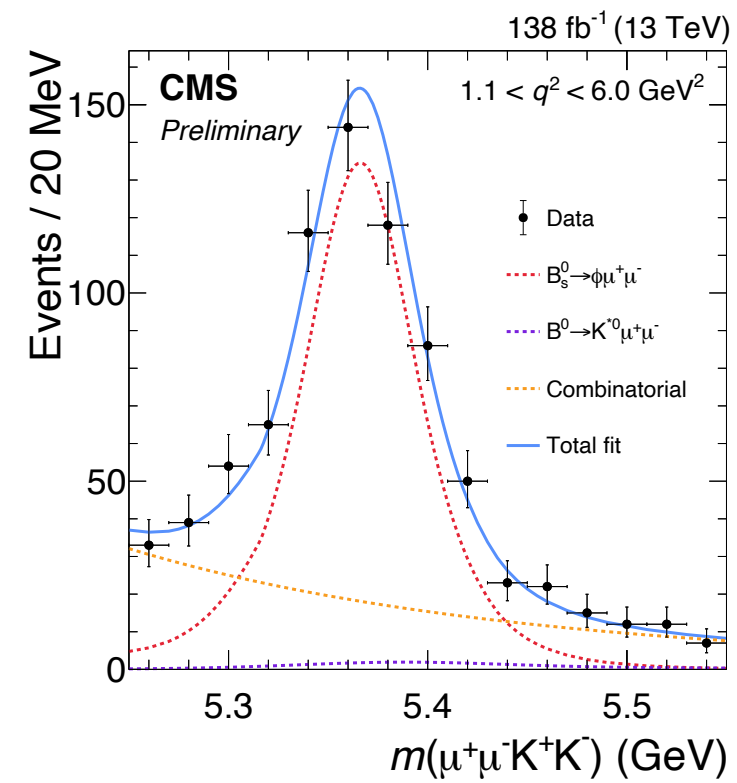
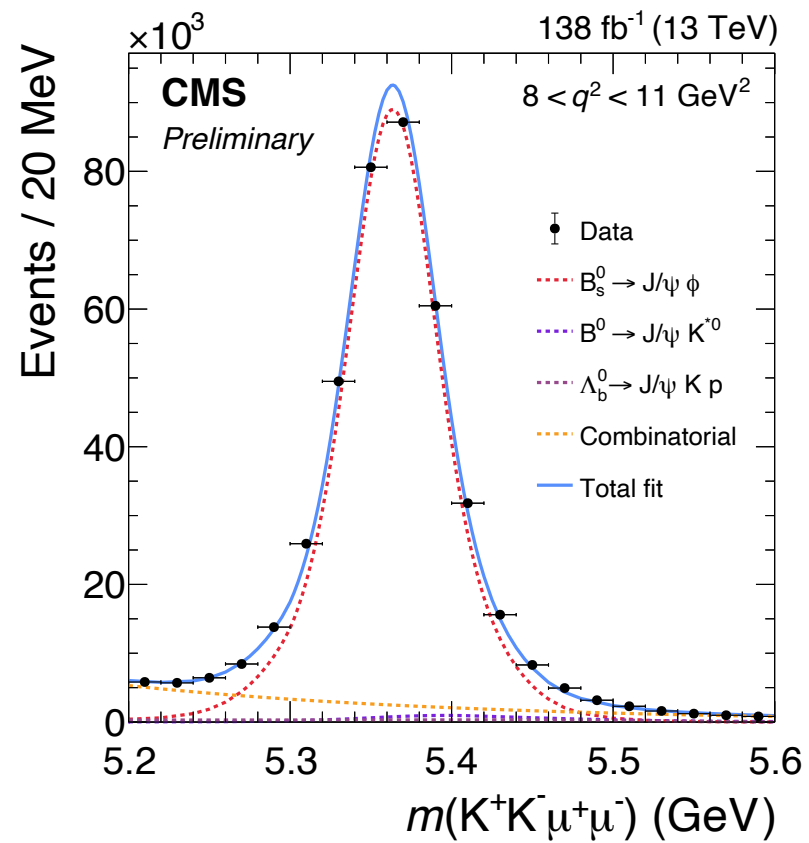
$$B_s \rightarrow \phi(KK)\mu\mu$$

- full Run2, 138 fb⁻¹
- selections and analysis philosophy similar to $B^0 \rightarrow K^*\mu\mu$
 - BDT selection, anti radiation “diagonal” cut
 - combinatorial bkg from sidebands, $B^0 \rightarrow K^{*0}\mu\mu$ from MC with f_s/f_d input
 - 3D fit to mass, and two angles θ_l and θ_K
- **measure both $d\mathcal{B}(B_s \rightarrow \phi\mu\mu)/dq^2$ and reduced set of angular observables F_L and A_6**
 - decision driven by limited statistics, angle Φ integrated out
- **normalization to reference $\mathcal{B}(B_s \rightarrow J/\psi\phi)$ carries overall 3.9% uncertainty**

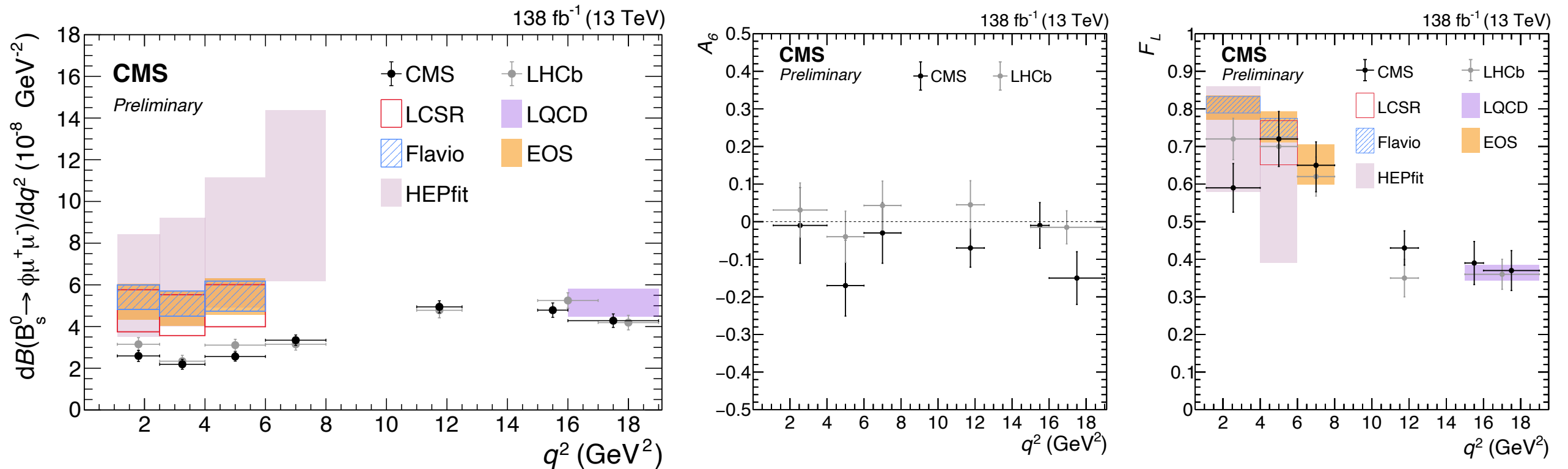


Fit projections

resonant mode



Results

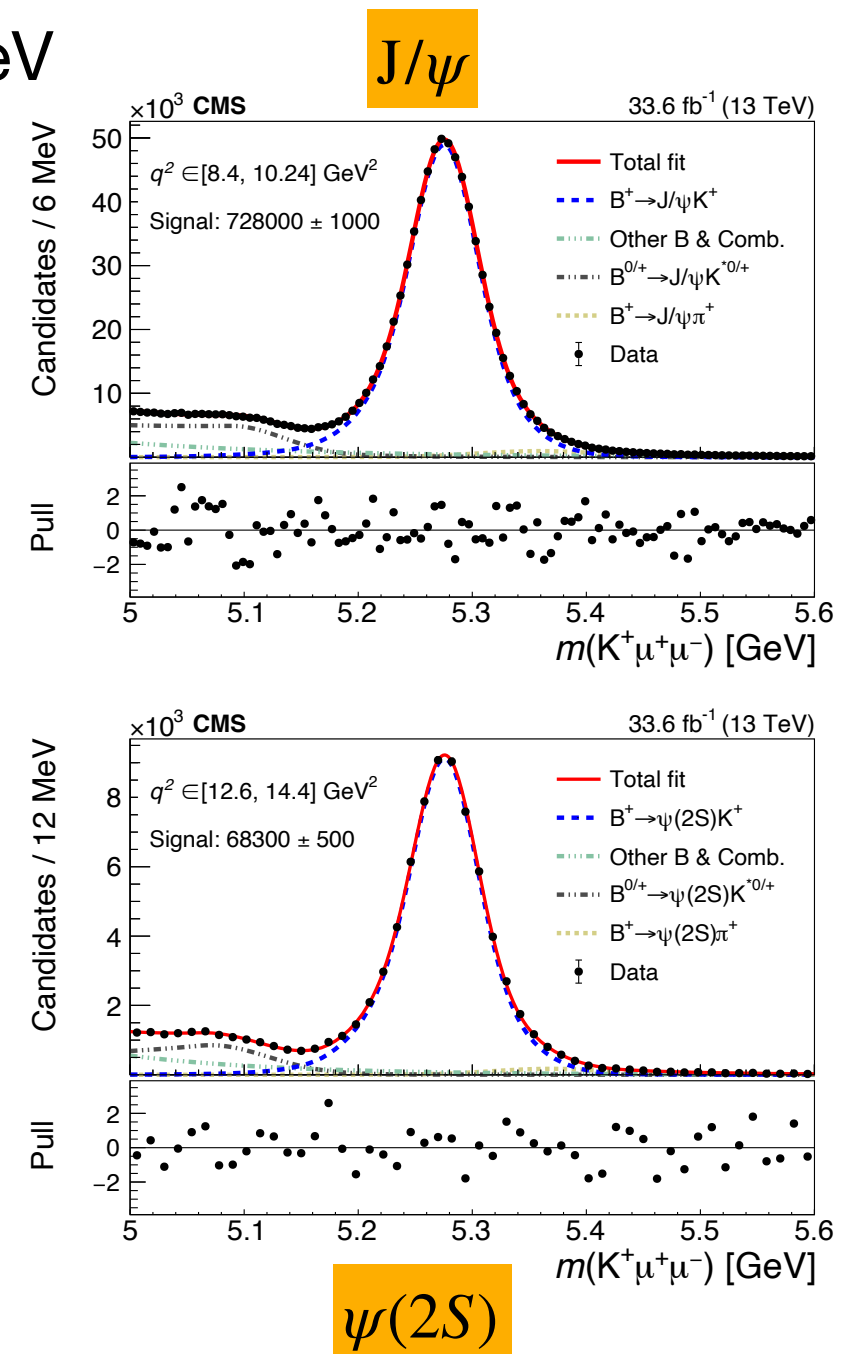


- **angular observables consistent with SM expectations and LHCb**
 - statistical error dominates
- **differential branching fraction below various expectations across all q^2 bins**
 - confirms trend observed by LHCb, undershot in bins 1 and 3

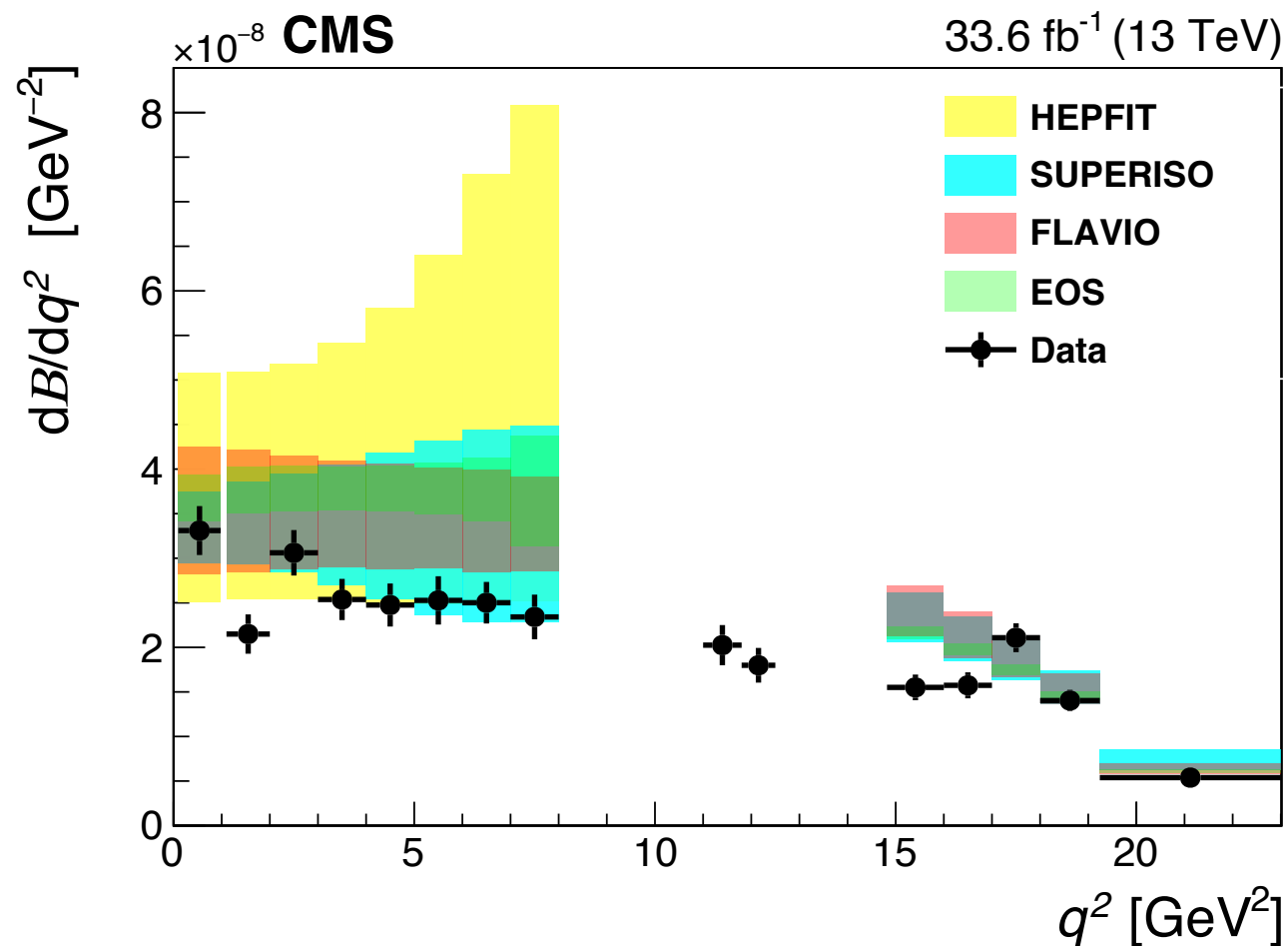
Measurement of $d\mathcal{B}(B^\pm \rightarrow K^\pm \mu^+ \mu^-)/dq^2$

analysis overview

- performed in conjunction with $R(K)$
 - uses BParking dataset, tag side (backup), μ $p_T > 9$ GeV
 - $L = 33.6 \text{ fb}^{-1}$, only a fraction of Run2 stats
- BDT to reduce backgrounds**
- simultaneous fit to several q^2 bin**
 - bkg composition varies in different bins
 - as opposed to before no “diagonal cut” applied
“leakage” noticeable
 - normalize to resonant J/ψ mode
- ratio $\mathcal{B}(\psi(2S))/\mathcal{B}(J/\psi)$ for validation, control of $A \times \epsilon$



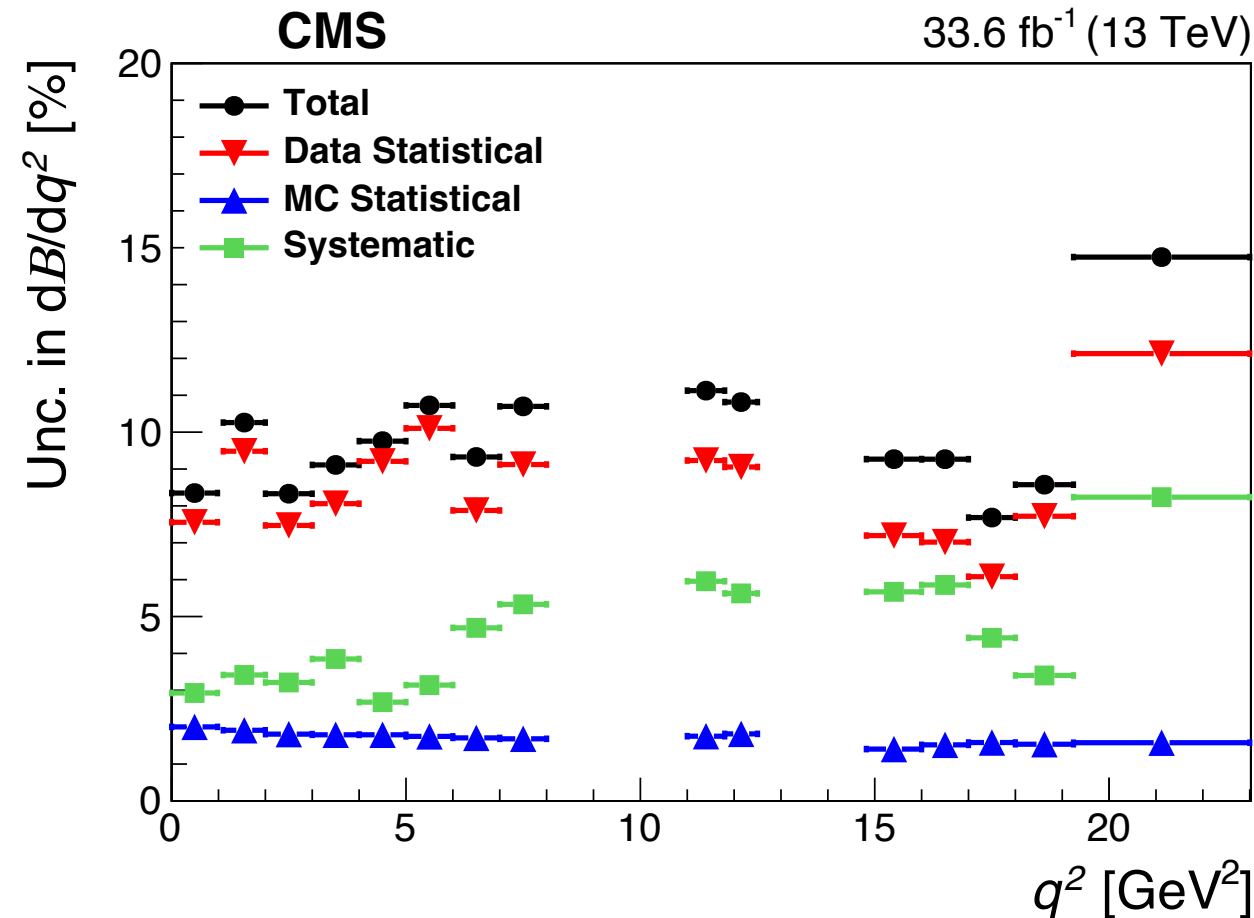
Results



q^2 range [GeV ²]	Signal yield	Branching fraction [10 ⁻⁸]
0.1–0.98	260 ± 20	2.91 ± 0.24
1.1–2.0	197 ± 19	1.93 ± 0.20
2.0–3.0	306 ± 23	3.06 ± 0.25
3.0–4.0	260 ± 21	2.54 ± 0.23
4.0–5.0	251 ± 23	2.47 ± 0.24
5.0–6.0	264 ± 27	2.53 ± 0.27
6.0–7.0	267 ± 21	2.50 ± 0.23
7.0–8.0	256 ± 23	2.34 ± 0.25
11.0–11.8	207 ± 19	1.62 ± 0.18
11.8–12.5	172 ± 16	1.26 ± 0.14
14.82–16.0	272 ± 20	1.83 ± 0.17
16.0–17.0	246 ± 17	1.57 ± 0.15
17.0–18.0	317 ± 19	2.11 ± 0.16
18.0–19.24	242 ± 19	1.74 ± 0.15
19.24–22.9	158 ± 19	2.02 ± 0.30

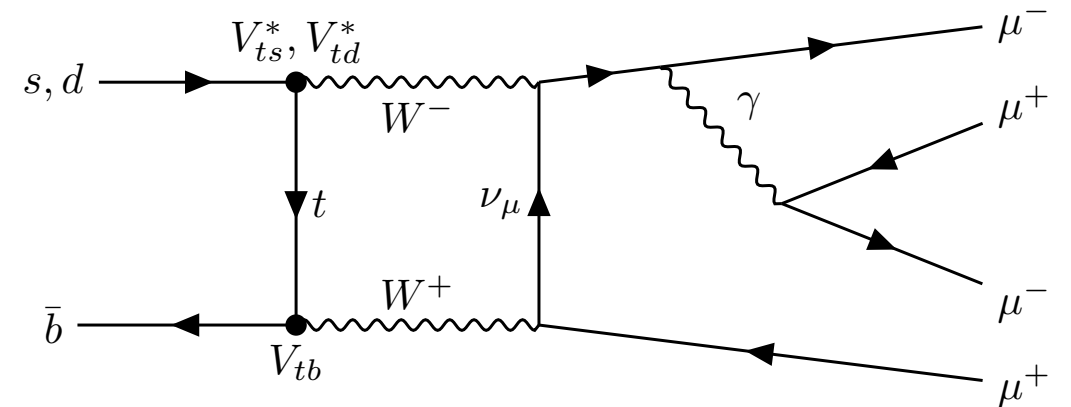
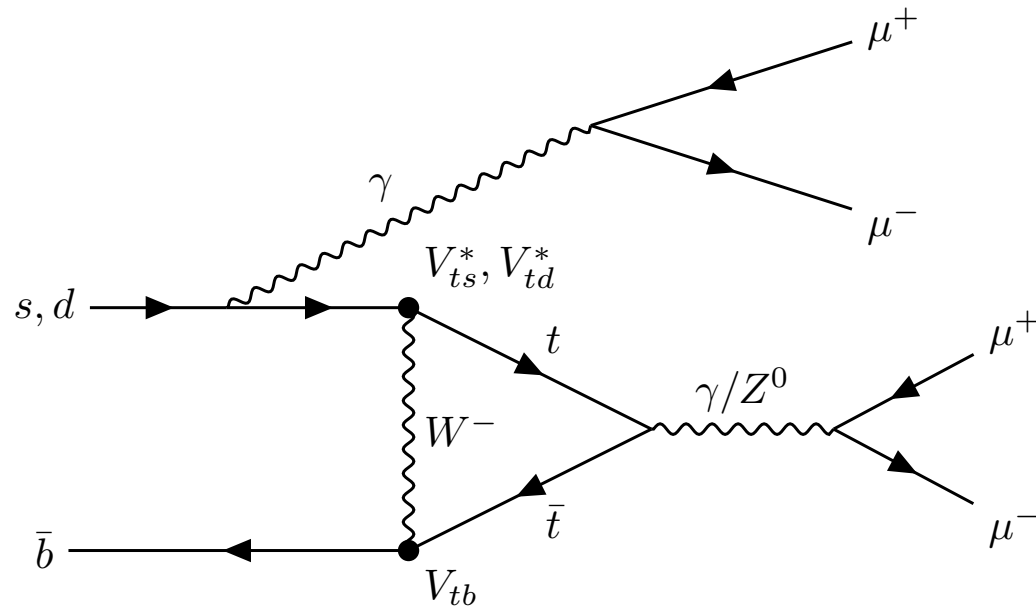
- data sit at the lower edge or below theory predictions
- similar to LHCb,
- competitive uncertainty

Uncertainties



- **as before, this measurement is statistically limited**
 - only 33.6 fb⁻¹, Run2 + Run3 > 300 fb⁻¹ already

Search for $B_s(B^0) \rightarrow 4\mu$



- Highly suppressed FCNC, CKM**

in the SM: $\mathcal{B}(B^0 \rightarrow 4\mu) = (0.4 - 4.0) \times 10^{-12}$
 $\mathcal{B}(B_s^0 \rightarrow 4\mu) = (0.9 - 1.0) \times 10^{-10}$
 $\rightarrow$ sensitive new physics

$$\mathcal{H}_{\text{eff}}(b \rightarrow s \ell^+ \ell^-) \propto V_{ts}^* V_{tb} \sum_{j=7,9,10} C_j \mathcal{O}_j,$$

- In EFT, contributions from $\mathcal{O}_7, \mathcal{O}_9, \mathcal{O}_{10}$**
 currently, significant anomaly observed
 in $\mathcal{O}_9$ from angular analyses [[2508.09986](#)]

$$\mathcal{O}_7^{(\prime)} = \frac{m_b}{e} (\bar{s} \sigma_{\mu\nu} P_{L(R)} b) F^{\mu\nu},$$

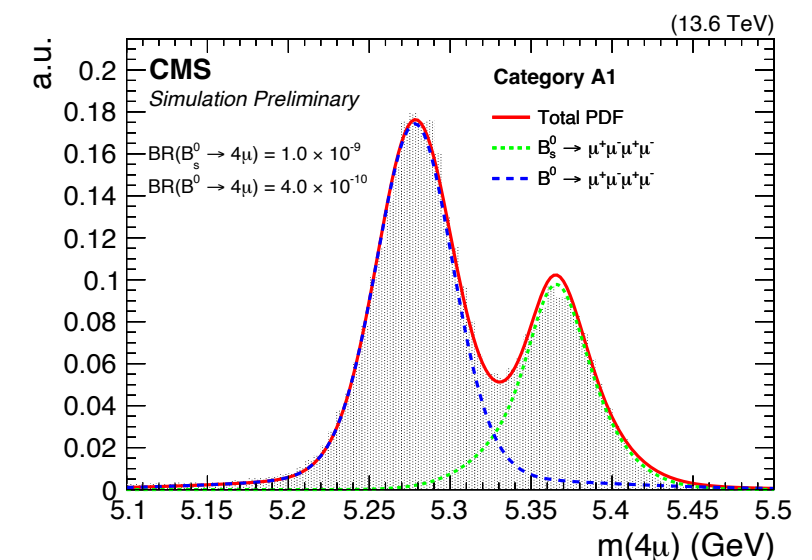
$$\mathcal{O}_9^{(\prime)} = (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{l} \gamma^\mu l),$$

$$\mathcal{O}_{10}^{(\prime)} = (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{l} \gamma^\mu \gamma_5 l),$$

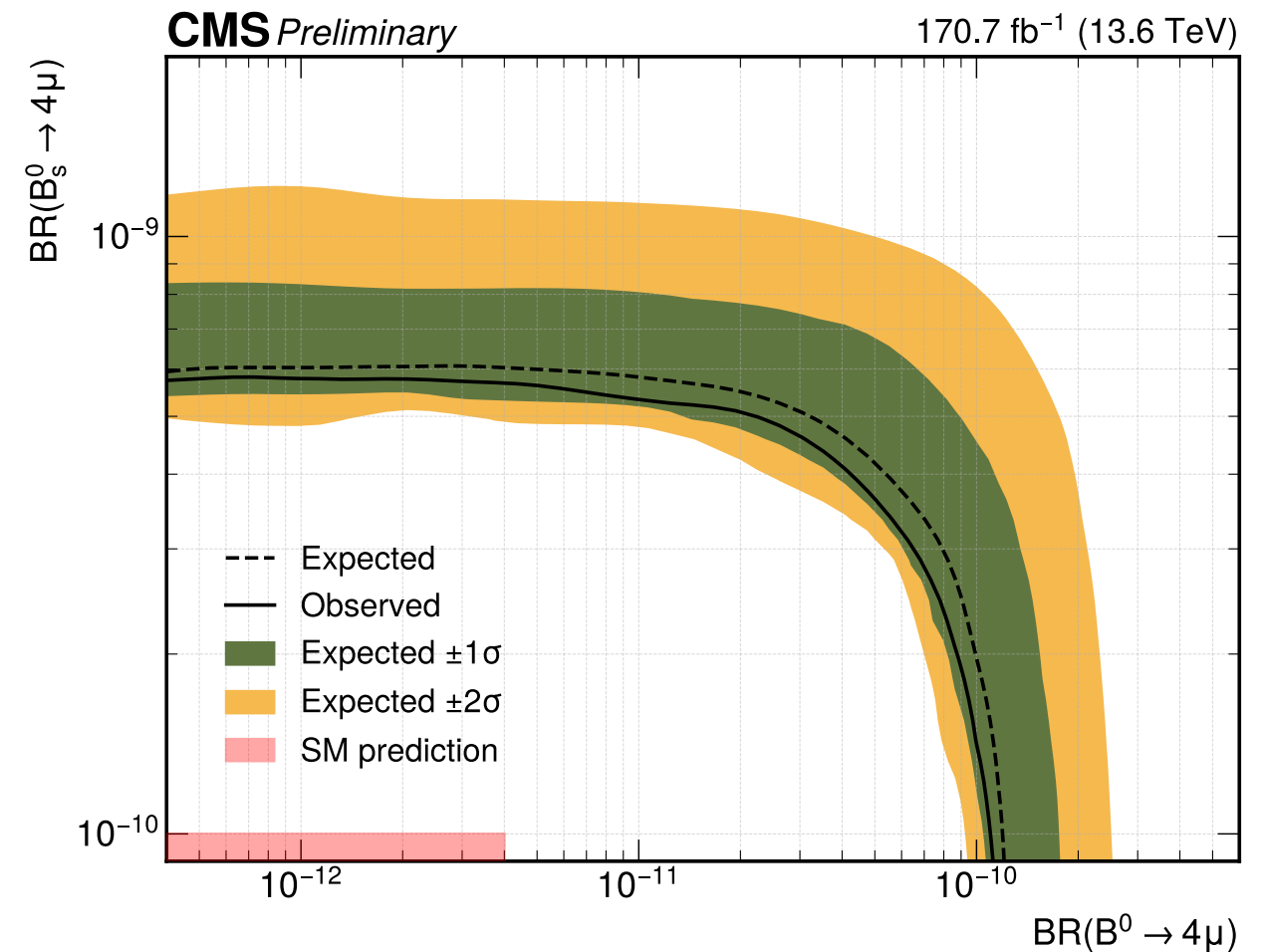
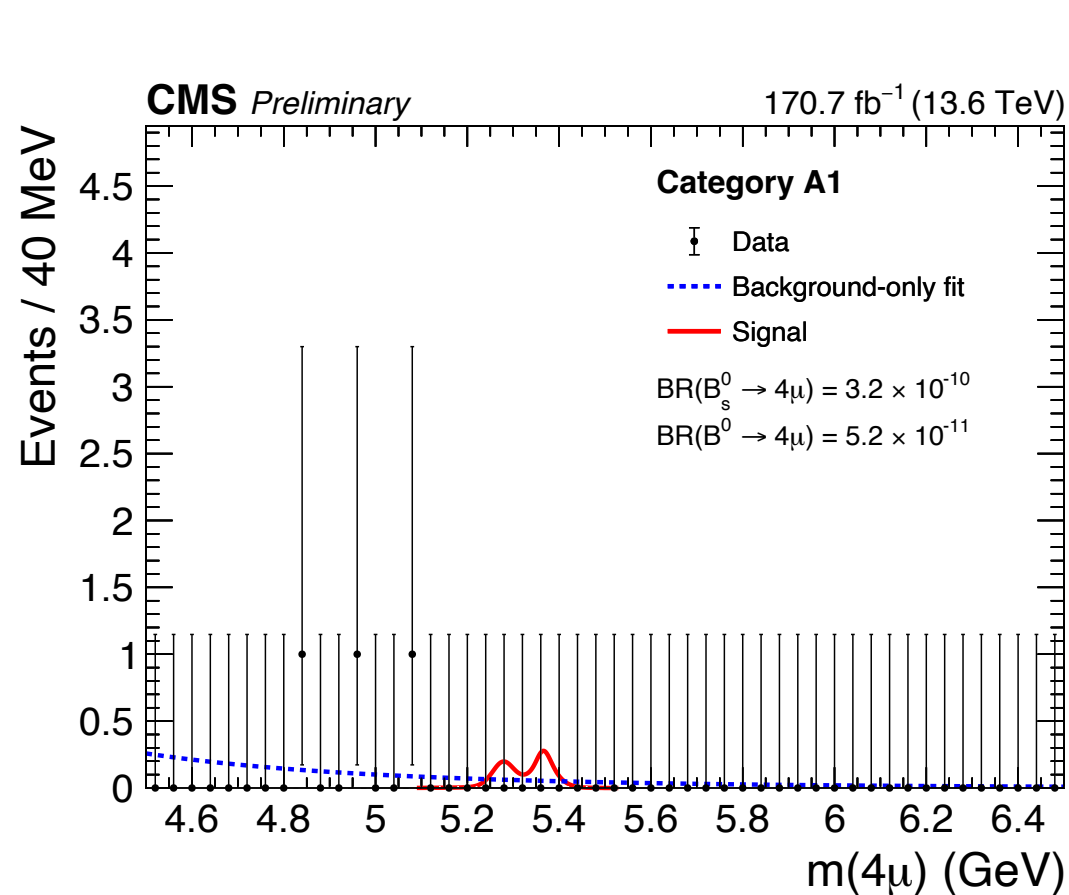
- best limit by [LHCb](#)** $\mathcal{B}(B^0 \rightarrow 4\mu) = 1.8 \times 10^{-10}$, $\mathcal{B}(B_s^0 \rightarrow 4\mu) = 8.6 \times 10^{-10}$
 considered only one signal at a time

Analysis design

- **ParkingDoubleMuonLowMass - HLT_DoubleMu4_3_LowMass**
2022 + 2023 + 2024 → **L = 171fb⁻¹**
 - per-year dataset lumped together
 - per-year MC samples added with weights corresponding to relative integrated luminosities
- **“bump hunt” (double) peak on smooth background**
 - consider *a/so* both B_s^0 and B^0 signals simultaneously
 - background from data sidebands (or wrong sign)
- **object-level selection + BDT**
- **data-driven normalization using $B_s^0 \rightarrow J/\psi(\mu\mu)\phi(\mu\mu)$**
 - maximal cancellation of systematics
- **data/MC validation and corrections using $B_s^0 \rightarrow J/\psi(\mu\mu)\phi(KK)$**
 - very similar distributions between signals, control and normalization processes
- **events categorized in 6 classes, based on 4μ mass resolution and BDT score**
 - BDT WP optimization on independent dataset to avoid bias
- **95% CL upper limits obtained from fitting the 4μ mass distributions in 6 categories**



Results



- observed (expected) 95% upper limits**

$$\mathcal{B}(B^0 \rightarrow 4\mu) < 1.3 \text{ (1.4)} \times 10^{-10}$$

$$\mathcal{B}(B_s^0 \rightarrow 4\mu) < 5.7 \text{ (6.0)} \times 10^{-10}$$

- 30% improvement over previous best, by LHCb**

- 2D limits obtained for the first time**

- more realistic scenario, possible NP likely to influence both processes
- correlation comes from both mass resolution and from sideband background estimation

- analysis is almost background free**

- scale faster than $\sqrt{\mathcal{L}}$

Discussion

- **update/extend meas. of $d\mathcal{B}(H_b \rightarrow H_s \mu\mu)/dq^2$ of**
 $B^+ \rightarrow K^+ \mu\mu$ $B^+ \rightarrow K^{*+} \mu\mu$ $B^0 \rightarrow K_s \mu\mu,$
 $B^0 \rightarrow K^{*0} \mu\mu$ $B_s \rightarrow \phi \mu\mu$ $\Lambda_b^0 \rightarrow \Lambda^0 \mu\mu$
- **of the above, update angular analyses (including full angular), add new channels**
- potentially, can do the same with electrons, at least in some channels. For sure much less precise. Is it worth it?
- **update $B_s \rightarrow \mu\mu$ with full Run3 statistics**
- **first attempts at $b \rightarrow s\tau\tau$ ongoing**
- besides $B_s(B^0) \rightarrow 4\mu$, can do $B_s(B^0) \rightarrow 2\mu 2e$ and $B^+ \rightarrow 2\mu e \nu_e$

Lepton Flavour (Universality) Violation

Lepton flavour universality (LFU)

accidental symmetry,
identical couplings
of leptons to W, Z

- broken by Higgs Yukawa
- **LFUV $\rightarrow$ NP**

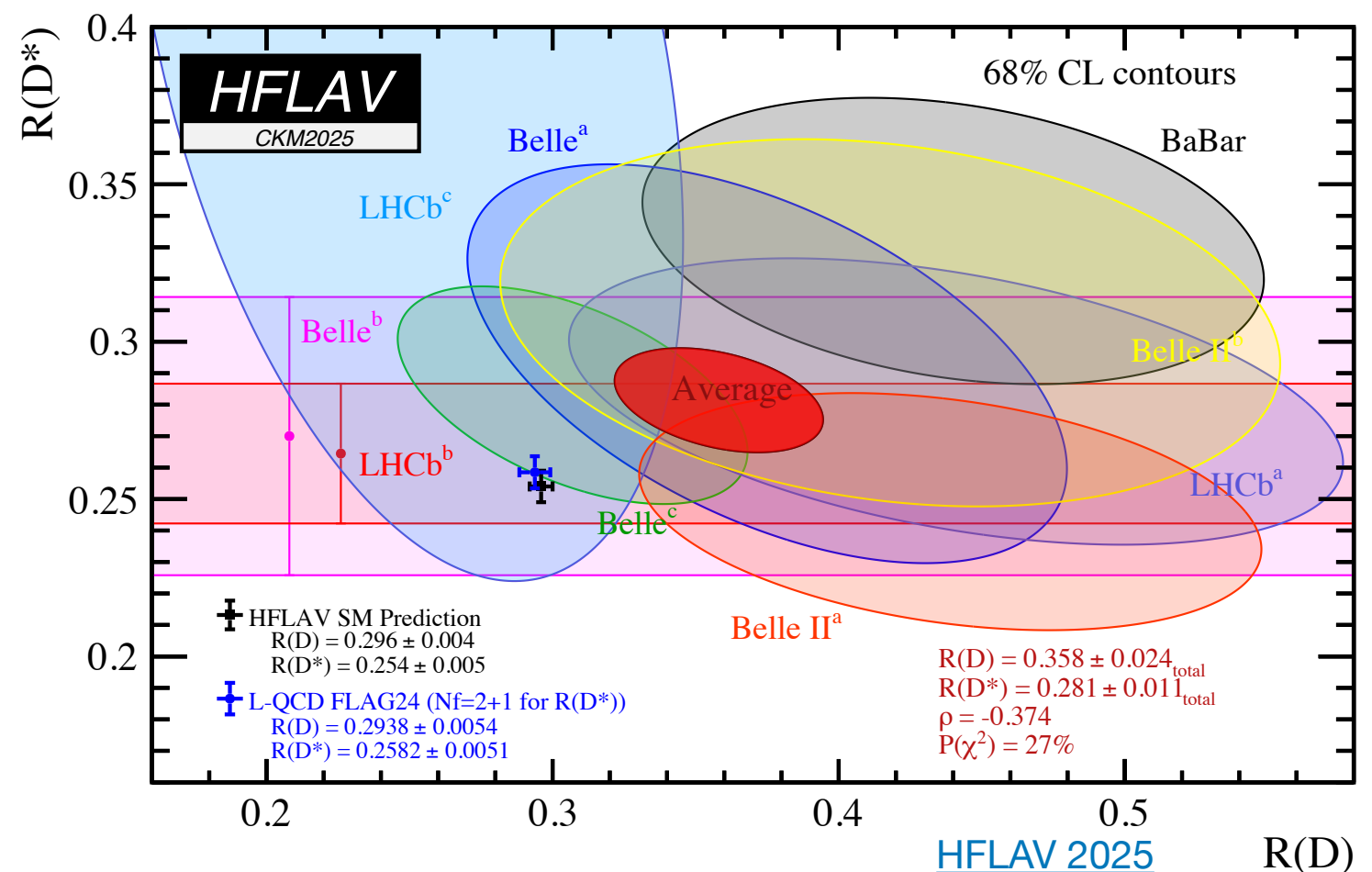
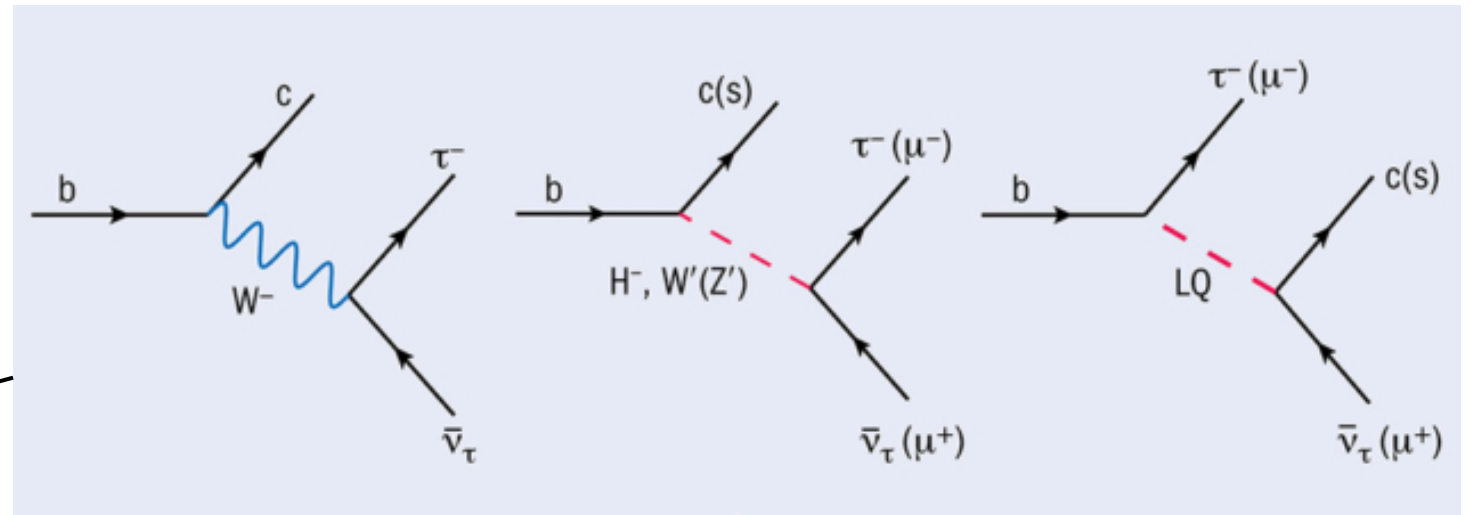
$$\mathcal{M}(H_b \rightarrow H_c \ell \nu) \propto V_{cb} L_\mu H^\mu$$

H^μ parametrized by Form Factors

measure ratios

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

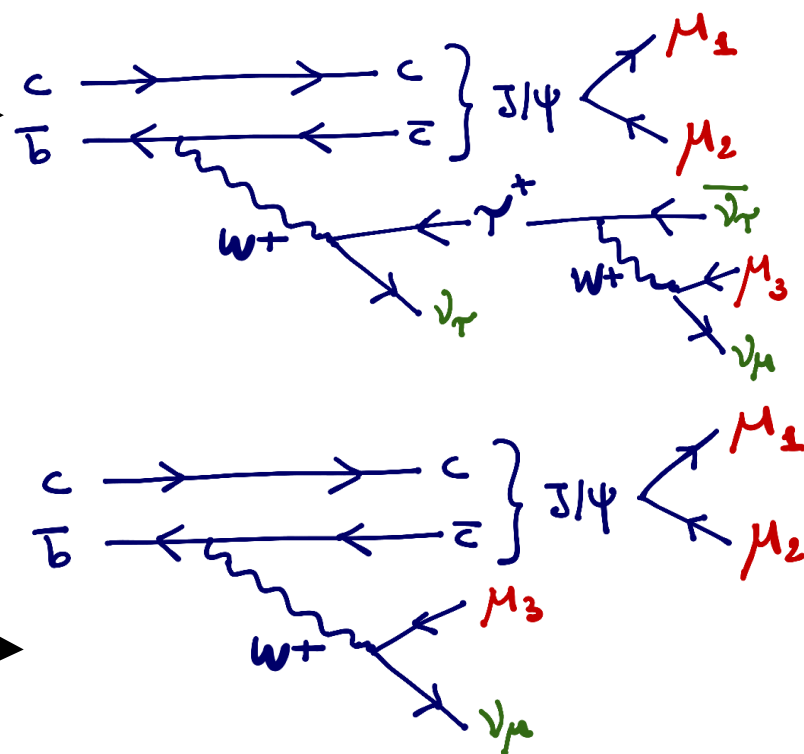
- ratios cancel V_{cb} , partially cancel FF
- precise theory calculations



$> 3\sigma$ tension in $R(D^{(*)})$

LFUV test: measurement of $R(J/\psi)$

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

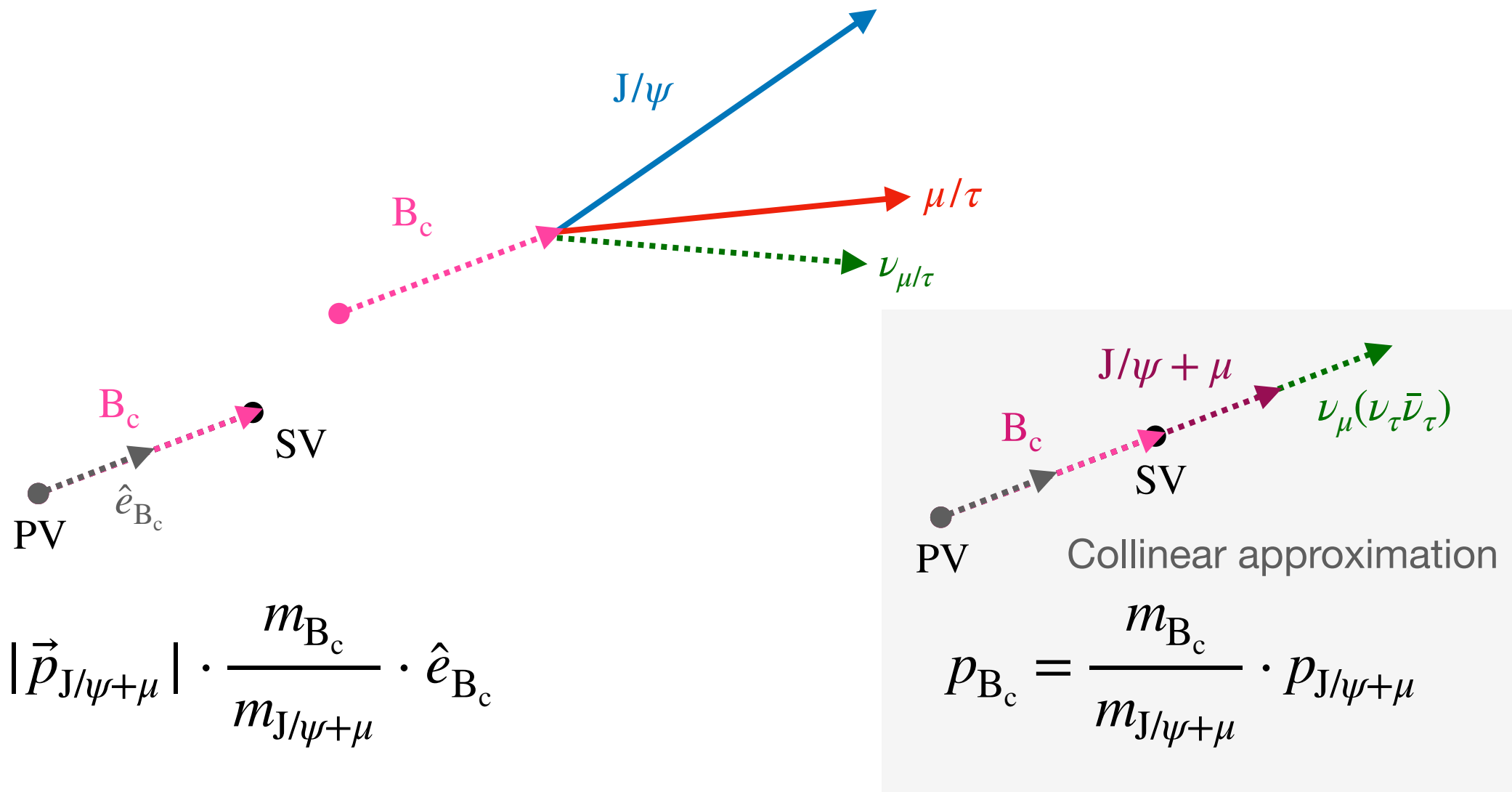


- B_c only accessible at LHC, $R(J/\psi)$ **complementary to $R(D^{(*)})$**
- **SM prediction** $R(J/\psi) = 0.26$ Phys. Rev. Lett. 125, 222003
- **recently updated LHCb**
 $R(J/\psi) = 0.51 \pm 0.12$ (stat.) ± 0.08 (syst.) seminar
 2σ deviation
- **three muon final state, $J/\psi \rightarrow \mu\mu$ and $\tau \rightarrow \mu \nu_\mu \nu_\tau$**

Analysis at a glance

- **2018 dataset** $\mathcal{L} = 59.7 \text{ fb}^{-1}$
- **same $3\mu + 1(3)\nu$ final state for numerator τ (denominator μ)**
undetected neutrino(s) $\rightarrow$ missing momentum
- **simultaneous ML binned template fit**
parameter of interest $R(J/\psi)$
- ***collinear approximation* to infer full B_c momentum**
$$p_{B_c} = m_{B_c}^{\text{PDG}} / m_{3\mu}^{\text{vis}} \cdot p_{3\mu}^{\text{vis}}$$
- **distinguish 1 ν vs. 3 ν via kinematic variables e.g.**
 $q^2 = (p_{B_c} - p_{J/\psi})^2$ mass of the leptonic system
- **$J/\Psi + \mu$ trigger, basic kinematic/ID selections on 3μ candidate**
 μ_3 also required to be isolated

B_c momentum reconstruction



- **two options considered, opted for collinear approximation**
 - better tau/mu discrimination
- p_{B_c} four momentum crucial to define key kinematic observables e.g.

$$q^2 = (p_{\tau/\mu} + p_{\nu_\tau/\nu_\mu})^2$$

Signal and background processes

- signals

$$B_c \rightarrow J/\psi \tau \nu \text{ (num)}$$

$$B_c \rightarrow J/\psi \mu \nu \text{ (den)}$$

- fake muon background**

J/ψ + misID had

- H_b background**

J/ψ from b-hadron + μ
(98% combinatorial)

- $B_c \rightarrow J/\psi + D_{(s)}^{(*)}, B_c \rightarrow (c\bar{c})\mu\nu,$
 $B_c \rightarrow \psi(2S)\mu\nu$

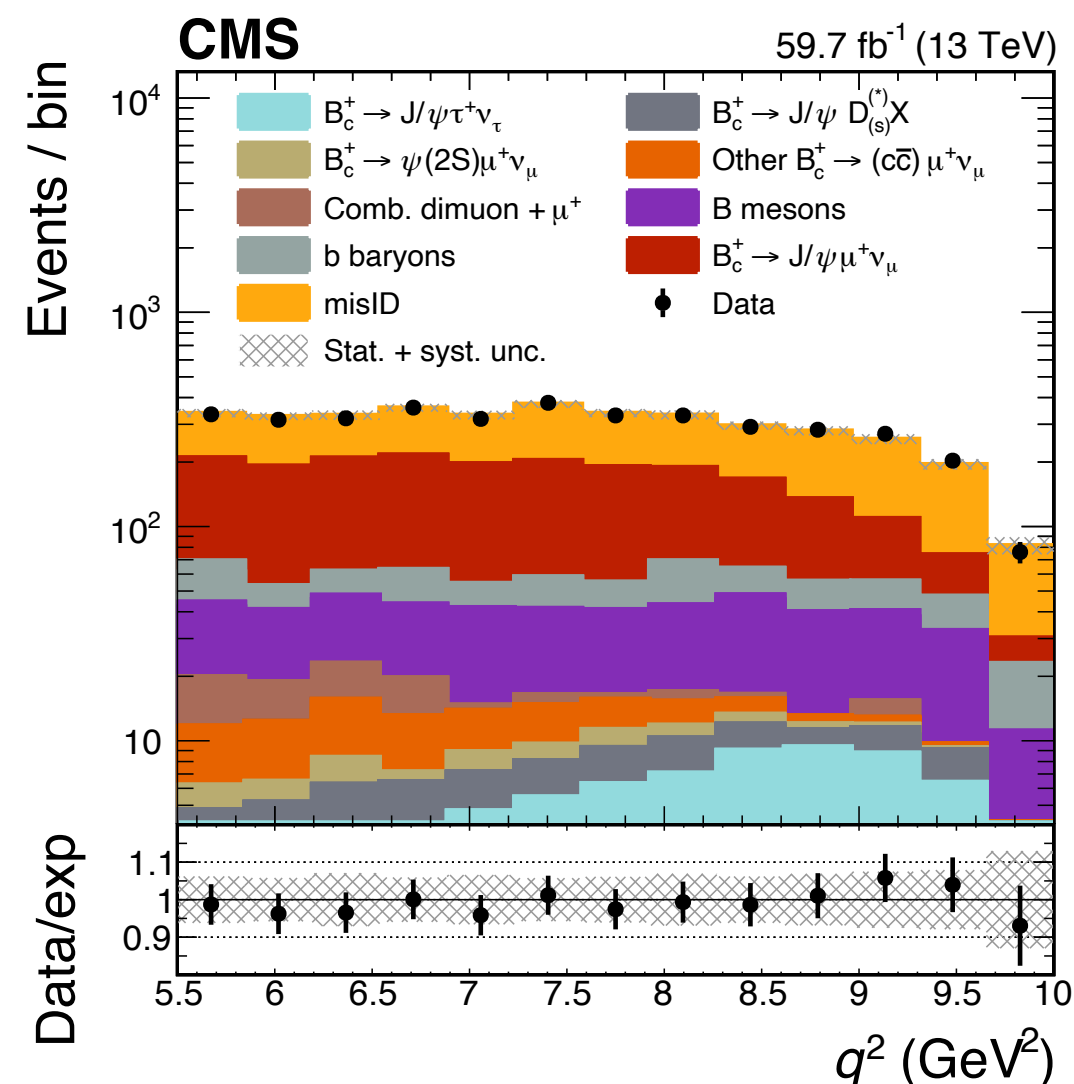
- combinatorial dimuon + X**

data driven

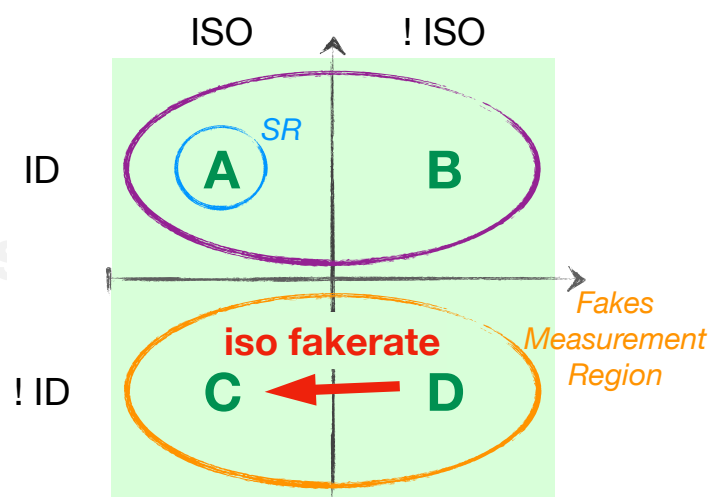
simulation
+
control region

simulation

data driven



Signal and background processes



- **fake muon background**

J/ψ + misID had

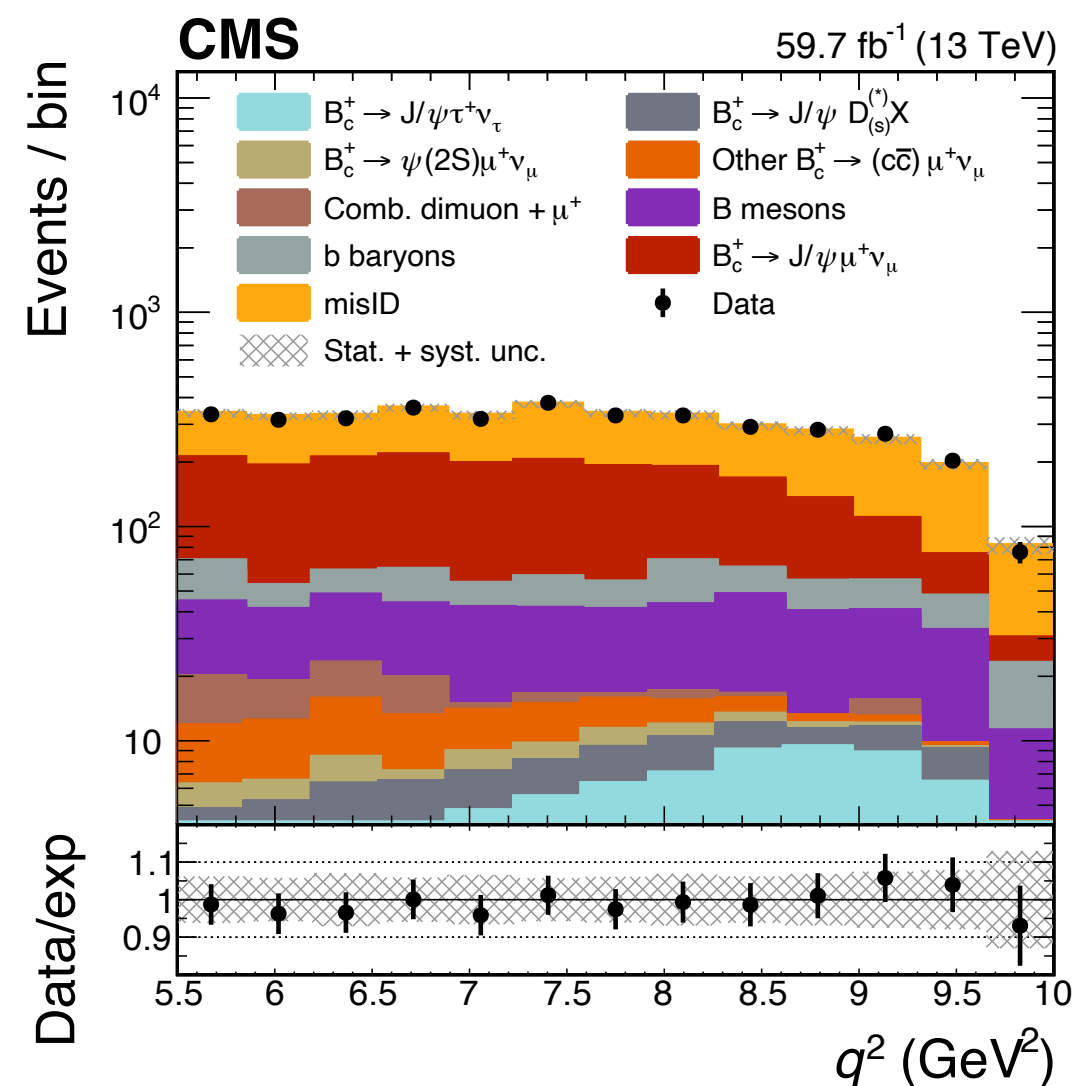
data driven

- fr_{ISO} measured in region adjacent to signal region (inverted μ_3 ID)

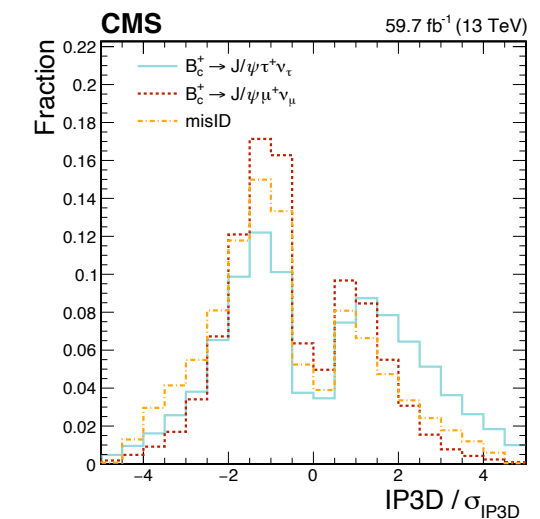
- fr_{ISO} fitted using NN classifiers to model multidimensional dependencies (kinematics, topology...)

- combinatorial dimuon + X

data driven



- constrain H_b**



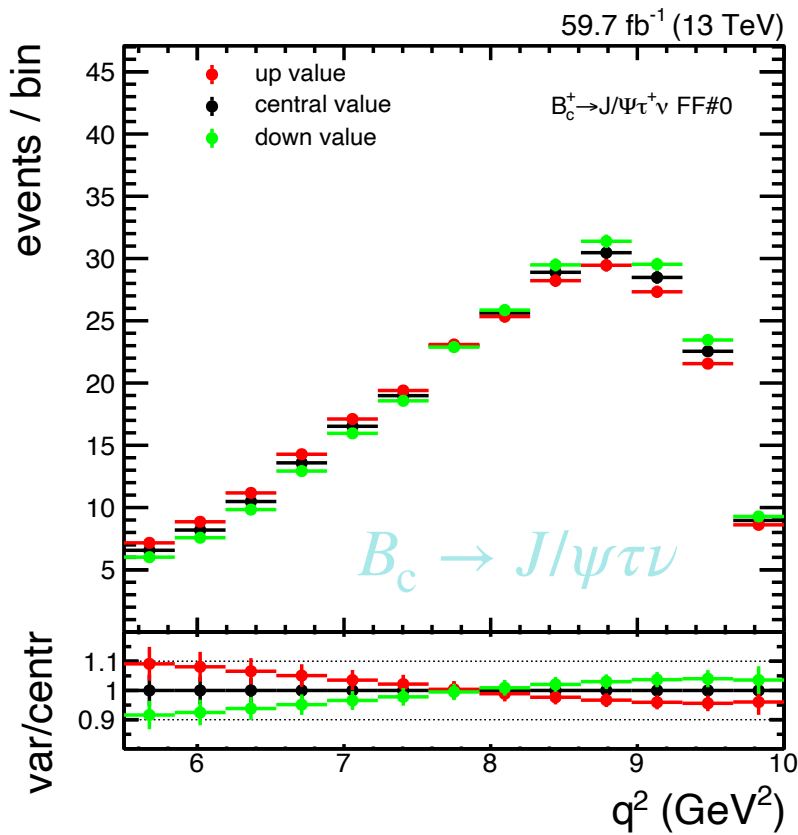
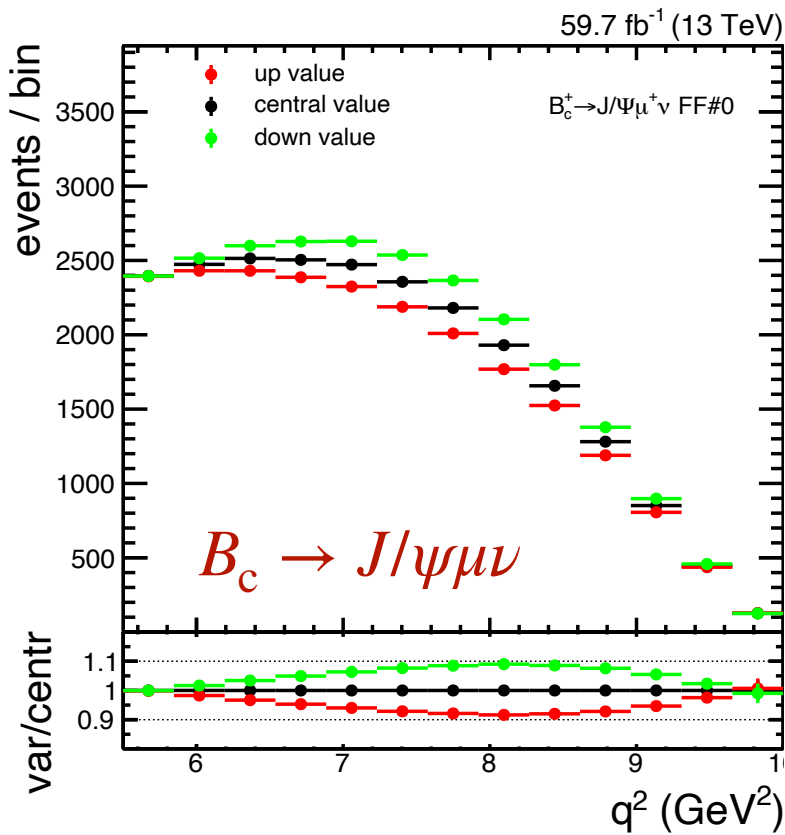
signal enriched

constrain
 $B_c \rightarrow J/\psi \mu \nu$
and fakes

Uncertainties

uncertainties incorporated in ML fit
as nuisance parameters, profiled
 H_b and B_c norm. free floating,
constrained in control regions

Contribution	Type	Unc. (10^{-2})
Form factor (theory)	S	19
misID statistical	S (bin-by-bin)	13
misID systematic	N, S	8, 0.7
Finite MC size	S (bin-by-bin)	9
Topological	S	9
Efficiencies	N	6
Total systematic uncertainty		28



dispersive BLG form factors
[\[Cohen, et al. 2019\]](#)
implemented with
[\[Hammer\]](#)
dominant uncertainty
large impact on key kinematic
observable q^2
recent LQCD FF 10x more
accurate [\[Harrison 2025\]](#)

Results

$$R(J/\psi) = 0.17^{+0.18}_{-0.17} (\text{stat.})^{+0.19}_{-0.19} (\text{theo.})^{+0.21}_{-0.22} (\text{syst.})$$

$$R(J/\psi) = 0.17 \pm 0.33$$

- **first LFUV result in $b \rightarrow c\ell\nu$ transitions at CMS**
on partial Run2 dataset
- in agreement with both SM 0.26
and LHCb $0.51 \pm 0.12 \pm 0.08$ within less than 1σ
- **sensitivity expected to significantly improve in coming iterations**

Leptonic $R(J/\psi)$ prospects

$$R(J/\psi) = 0.17^{+0.18}_{-0.17} (\text{stat.})^{+0.19}_{-0.19} (\text{theo.})^{+0.21}_{-0.22} (\text{syst.})$$

current result statistically and systematically limited
where to go from here?

- **statistical uncertainty**

320 fb⁻¹ collected in Run3, 80 fb⁻¹ still not analyzed from Run2 →
potentially up to 10x data for full Run2 + Run3
(trigger, acceptance, efficiency vary year by year)

- **systematic uncertainty**

fake background estimate uncertainties *extremely* conservative
several systematic uncertainties scale with stats

- **theory uncertainty (form factors)**

we used [Phys. Rev. D 100, 094503](#), more recent LQCD FF available now
(LHCb uses Harrison [2503.15090](#))

Leptonic $R(J/\psi)$ prospects - segue

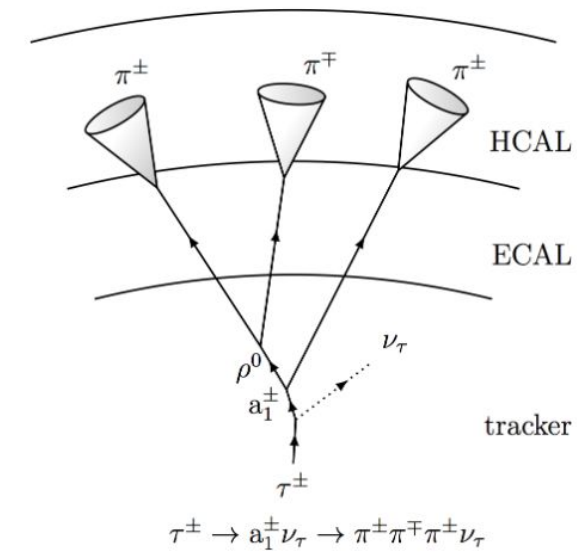
$$R(J/\psi) = 0.17^{+0.18}_{-0.17} (\text{stat.})^{+0.19}_{-0.19} (\text{theo.})^{+0.21}_{-0.22} (\text{syst.})$$

- **collinear approximation for B_c momentum reconstruction**
pros: chosen because of higher B_c boost in CMS and better μ/τ separation in q^2
cons: all B_c kinematic variables, e.g. q^2 , m_{miss}^2 , E_μ^* , ...
100% correlated, no gain in combining them / multidim fit
- **simultaneous fit of pass/fail μ_3 isolation region**
pros: in situ estimate, let data constrain fakes, robust and reliable
cons: too much leeway, penalises performance
introduces strong correlations between uncertainties

Hadronic $R(J/\psi)$

$$R(J/\psi) = \frac{\mathcal{B}(B_c \rightarrow J/\psi \tau_{\text{had}} \bar{\nu})}{\mathcal{B}(B_c \rightarrow J/\psi \mu \bar{\nu})} = \frac{\mathcal{B}(B_c \rightarrow J/\psi \pi \pi \pi (+\pi^0) \bar{\nu})}{\mathcal{B}(B_c \rightarrow J/\psi \mu \bar{\nu})}$$

Decay mode	Meson resonance (MeV)	$\mathcal{B}[\%]$
$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \rightarrow h^- \nu_\tau$		11.5
$\tau^- \rightarrow h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \rightarrow h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \rightarrow h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \rightarrow h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other hadronic decays		3.2
All hadronic decays		64.8



- **focus on $\tau^+ \rightarrow \pi^+ \pi^+ \pi^- (\pi^0)$ hadronic tau decays**
- **combine with leptonic analysis, common denominator**
- **in this analysis, full Run2 dataset $\sim 137 \text{ fb}^{-1}$**

Hadronic $R(J/\psi)$ prospects

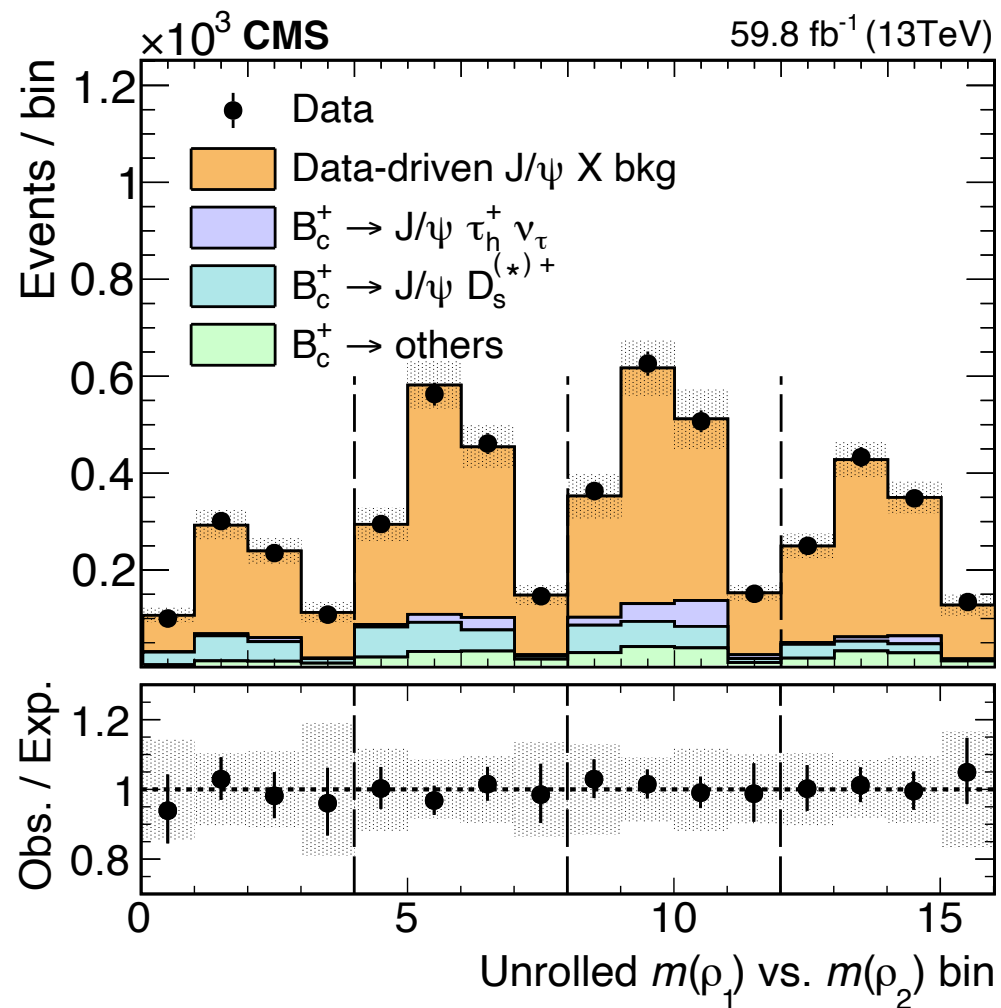
- **statistical uncertainty**
 - 320 fb⁻¹ collected in Run3
 - ***trigger breakthrough***, dropped extra track overtaxing condition
 - this demands a profound revision of the analysis strategy
 - potential is hard to quantify precisely, but certainly major boost
- **theory uncertainty (form factors)**

the same considerations made for the leptonic channel hold here.
In addition, the hadronic channel is much less sensitive to FF

Analysis strategy

- **dedicated low p_T tau reconstruction**
- BDT to suppress backgrounds, mostly J/Ψ from B decay plus combinatorial 3 tracks
- $J/\Psi + X$ background estimated from data
- $B_c \rightarrow J/\psi + D_{(s)}^{(*)}$ background from simulation
- dominant decay $\tau \rightarrow a_1(1260) \rightarrow \rho^0(\rightarrow \pi^+\pi^-)\pi^+$
- **signal extraction from binned ML fit to “unrolled” 2D $m(\rho_1) \times m(\rho_2) = m(\pi_1^+\pi^-) \times m(\pi_2^+\pi^-)$ distribution**

Results

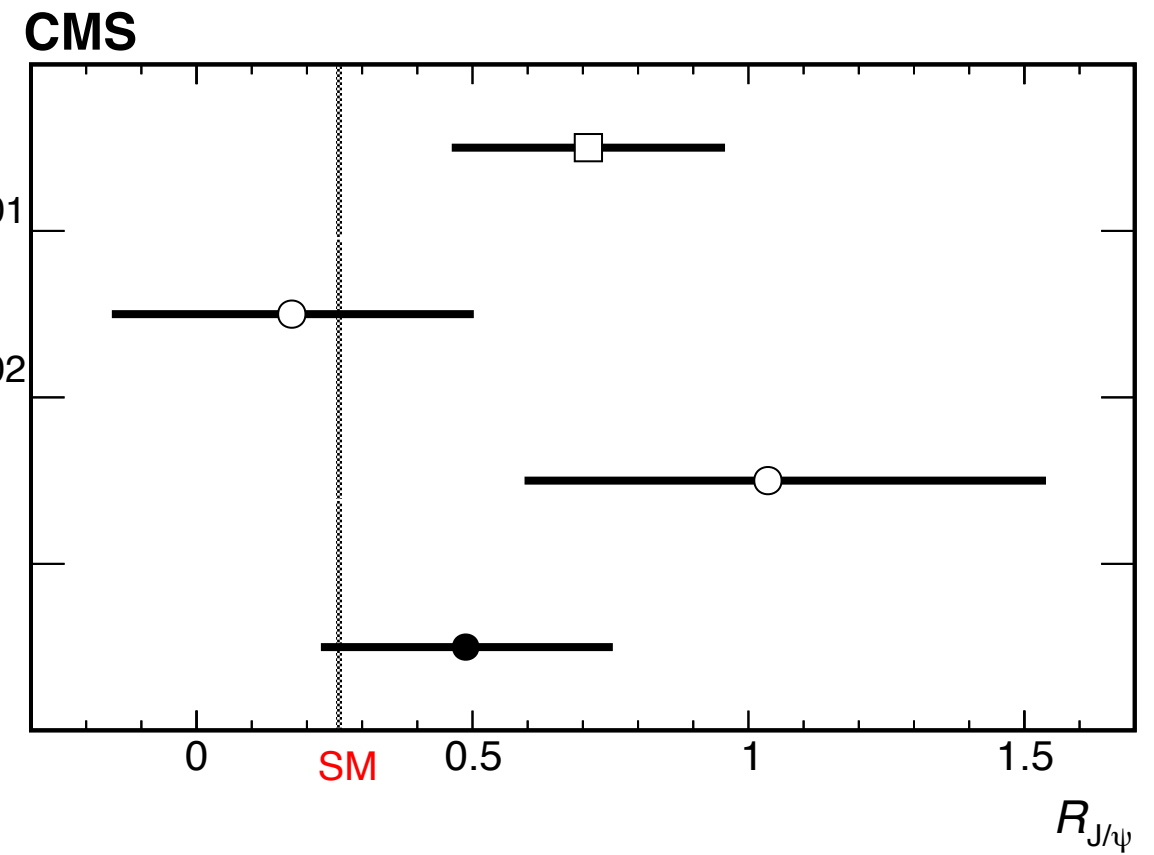


LHCb, Run 1, τ_μ
Phys. Rev. Lett.
120 (2018) 121801

CMS, 2018, τ_μ
Phys. Rev. D
111 (2025) 051102

CMS, Run 2, $\tau_{3\pi}$

CMS
Combination



combined

$$R(J/\psi) = 0.49 \pm 0.09 \text{ (stat.)} \pm 0.25 \text{ (syst.)}$$

Hadronic $R(J/\psi)$ prospects

- **significantly better triggers in Run3**
inclusive dimuon, as opposed to dimuon plus track with vertex conditions (works against tau decay being displaced)
- **in light of the above, increase in statistics much larger than Run3 / Run2 luminosity ratio of about 2**
- **less sensitive to form factors**
- ... but large combinatorial bkg challenging

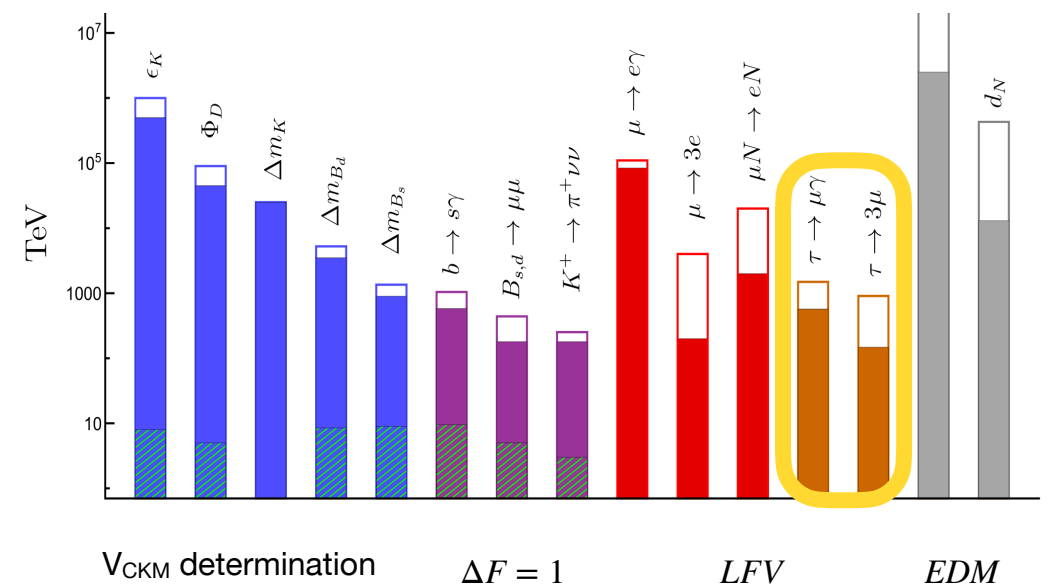
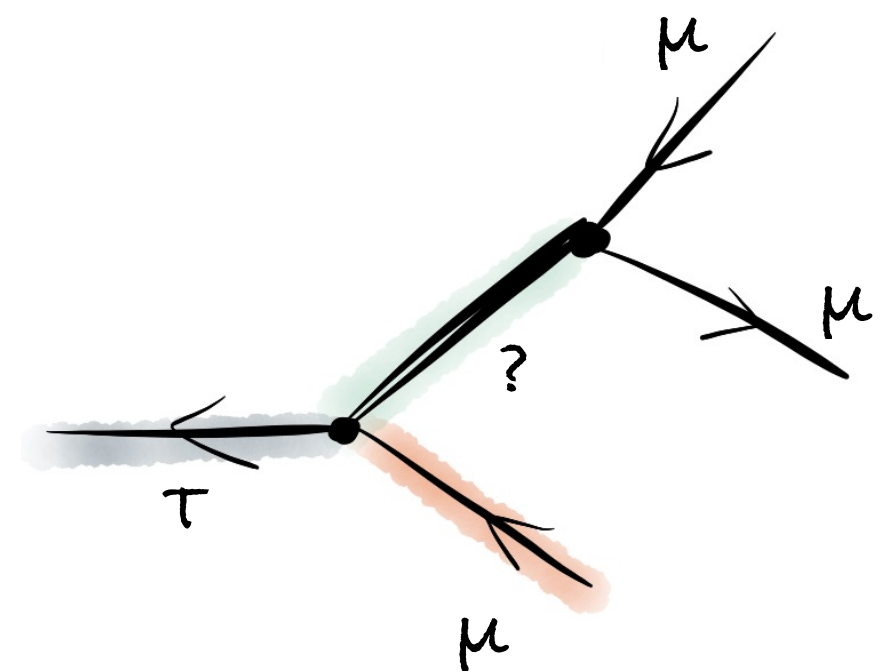
LFV in $\tau \rightarrow 3\mu$

Lepton Flavour Violating (LFV)

decays strongly suppressed in the SM

- allowed by **neutrino oscillations**
at lowest BR (SM BR ($\tau \rightarrow 3\mu$) $\sim 10^{-55}$ [1])
- **New Physics**
some NP model predict BR $\sim 10^{-9}$ [2,3]
- strong indirect bounds on NP scale

- [1] [10.1140/epjc/s10052-020-8059-7](https://arxiv.org/abs/10.1140/epjc/s10052-020-8059-7)
 [2] [10.1393/ncr/i2018-10144-0](https://arxiv.org/abs/10.1393/ncr/i2018-10144-0)
 [3] [10.1007/JHEP10\(2018\)148](https://arxiv.org/abs/10.1007/JHEP10(2018)148)

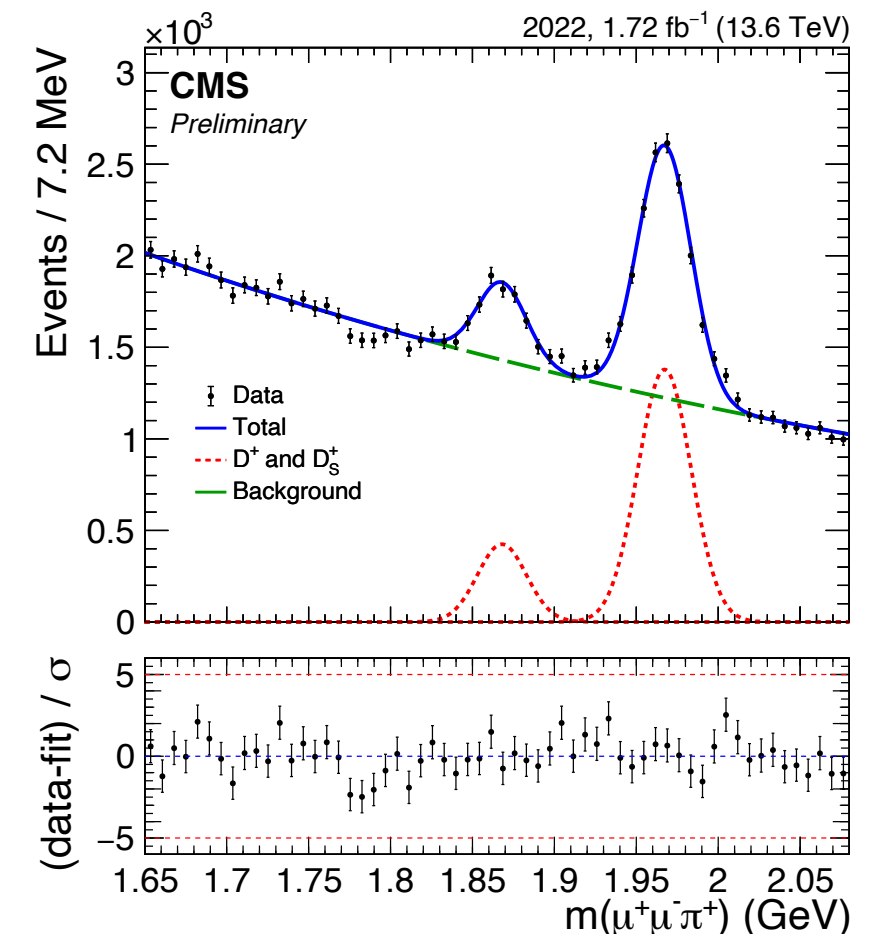
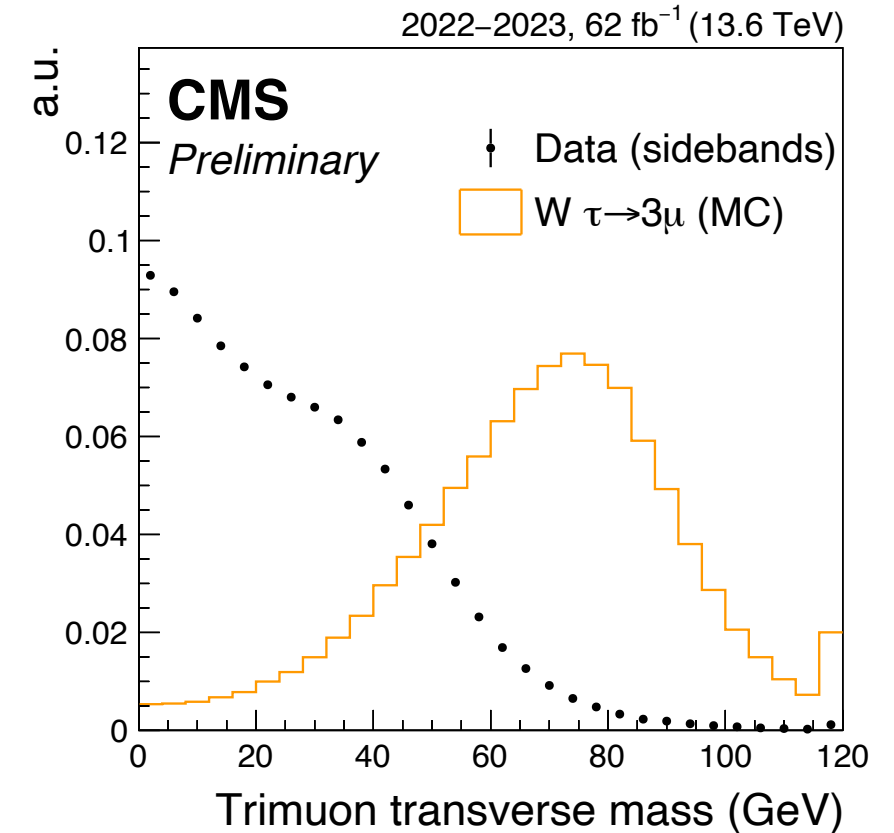


Observed upper limits on $\mathcal{B}(\tau \rightarrow 3\mu)$ ($\times 10^{-8}$ 90% CL)

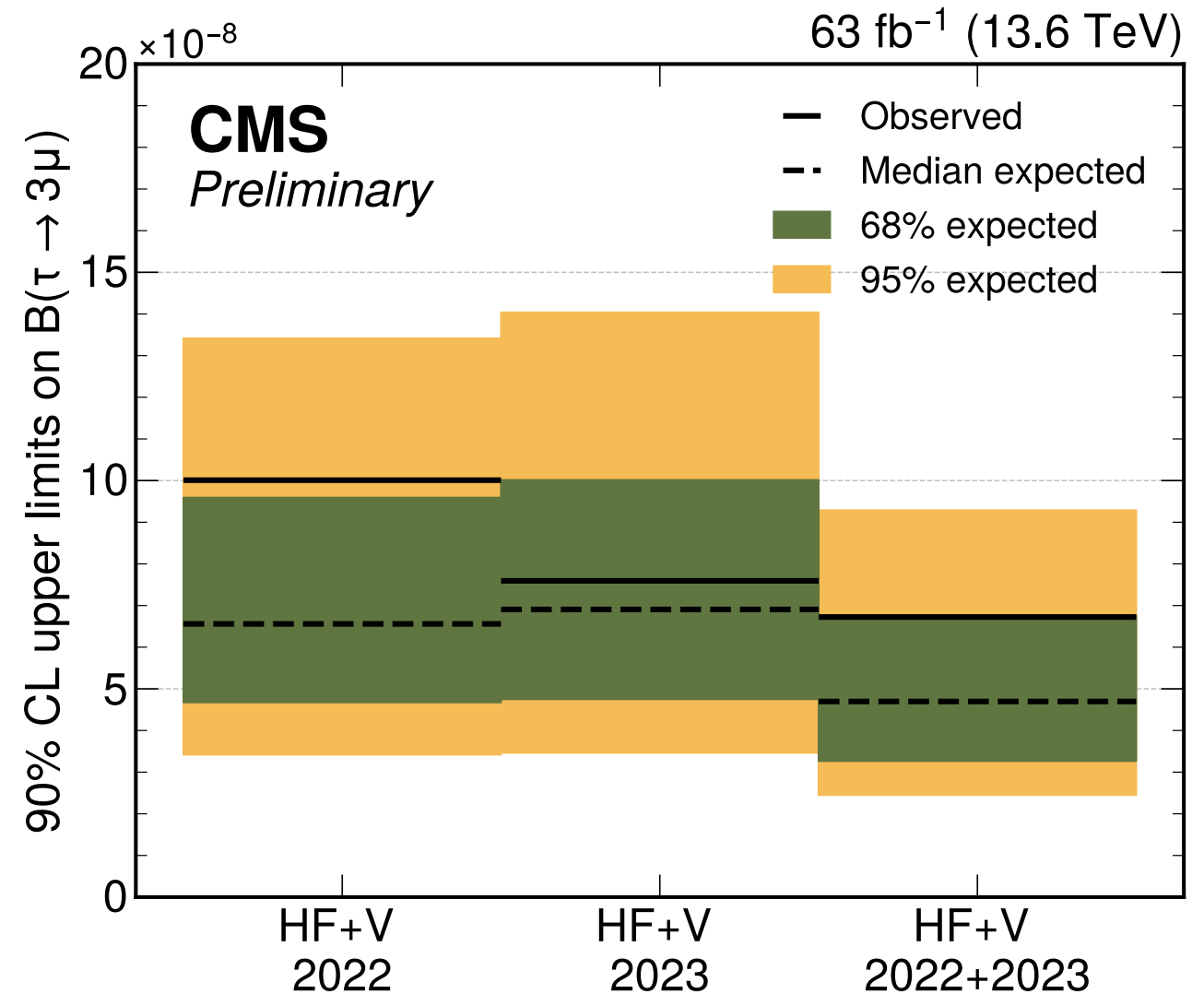
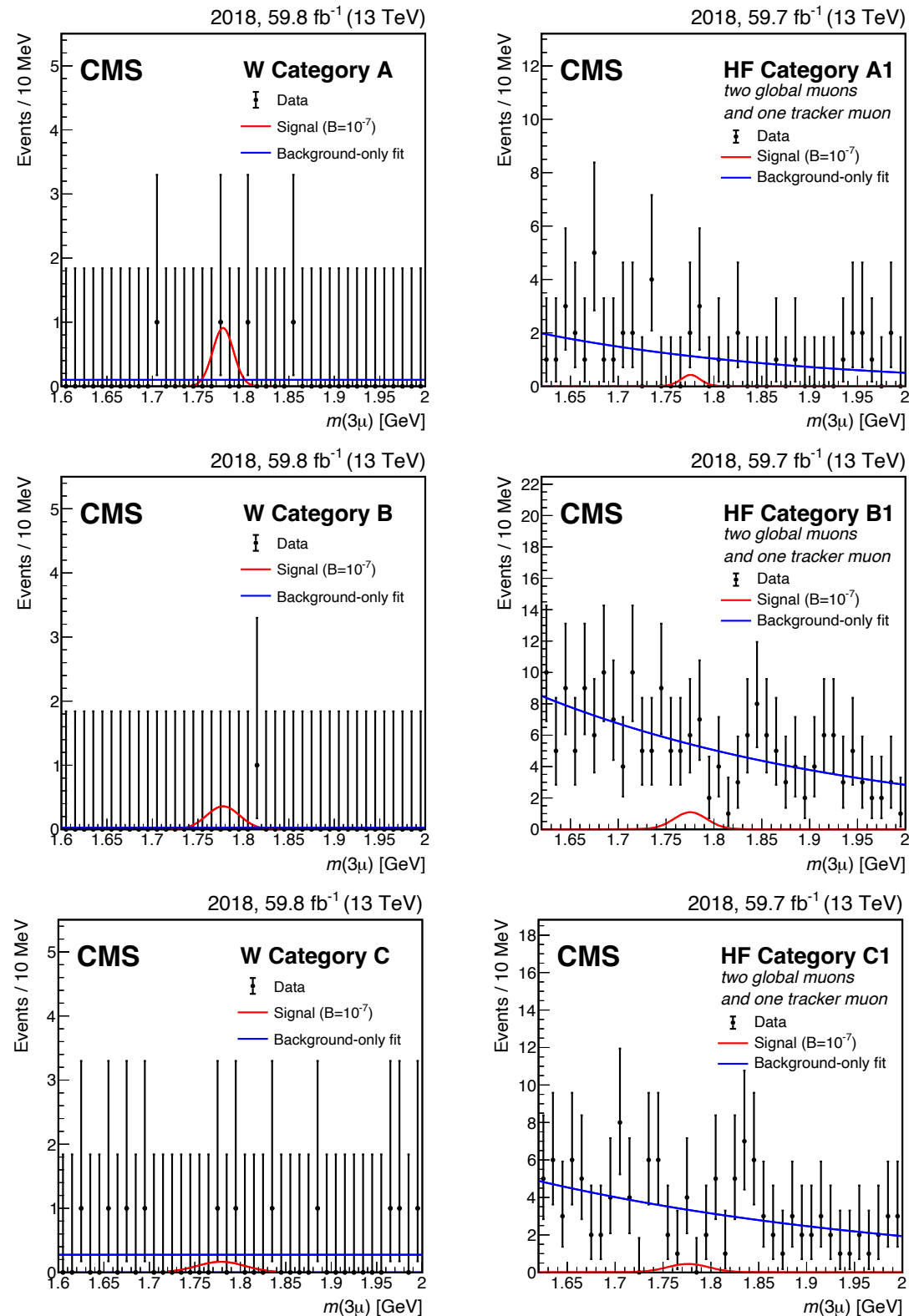
- | | | | |
|--------------|---------|---------------------------|---|
| • Belle II | < 1.9 | $ee \rightarrow \tau\tau$ | 10.1007/JHEP09(2024)062 |
| • Belle | < 2.1 | $ee \rightarrow \tau\tau$ | 10.1016/j.physletb.2010.03.037 |
| • BaBar | < 3.3 | $ee \rightarrow \tau\tau$ | 10.1103/PhysRevD.81.111101 |
| • LHCb Run2 | < 1.9 | $HF \rightarrow \tau X$ | 2601.20785 |
| • ATLAS Run1 | < 38 | $W \rightarrow \tau \nu$ | 10.1140/epjc/s10052-016-4041-9 |

Analysis strategy

- **CMS 2022-2023 Run3 analysis (63 fb⁻¹) follows full Run2 analysis (~137 fb⁻¹)**
- **“bump hunt”**
resonant signal at known mass,
smooth and non resonant backgrounds from data
sideband
- **two production modes**
 - $W \rightarrow \tau\nu, Z \rightarrow \tau\tau$
high momentum, very low background
 - $HF \rightarrow \tau X$, where HF comprises primarily $D_s \rightarrow \tau\nu$,
 $D \rightarrow \tau\nu$,
and direct as well as cascade B decays
softer, more backgrounds, larger cross section
- $W \rightarrow \tau\nu$ **normalized by $\sigma \cdot \mathcal{L}$,**
 $HF \rightarrow \tau X$ **normalized in data using $D_s \rightarrow \phi(\mu\mu)\pi$**
- BDT for background suppression

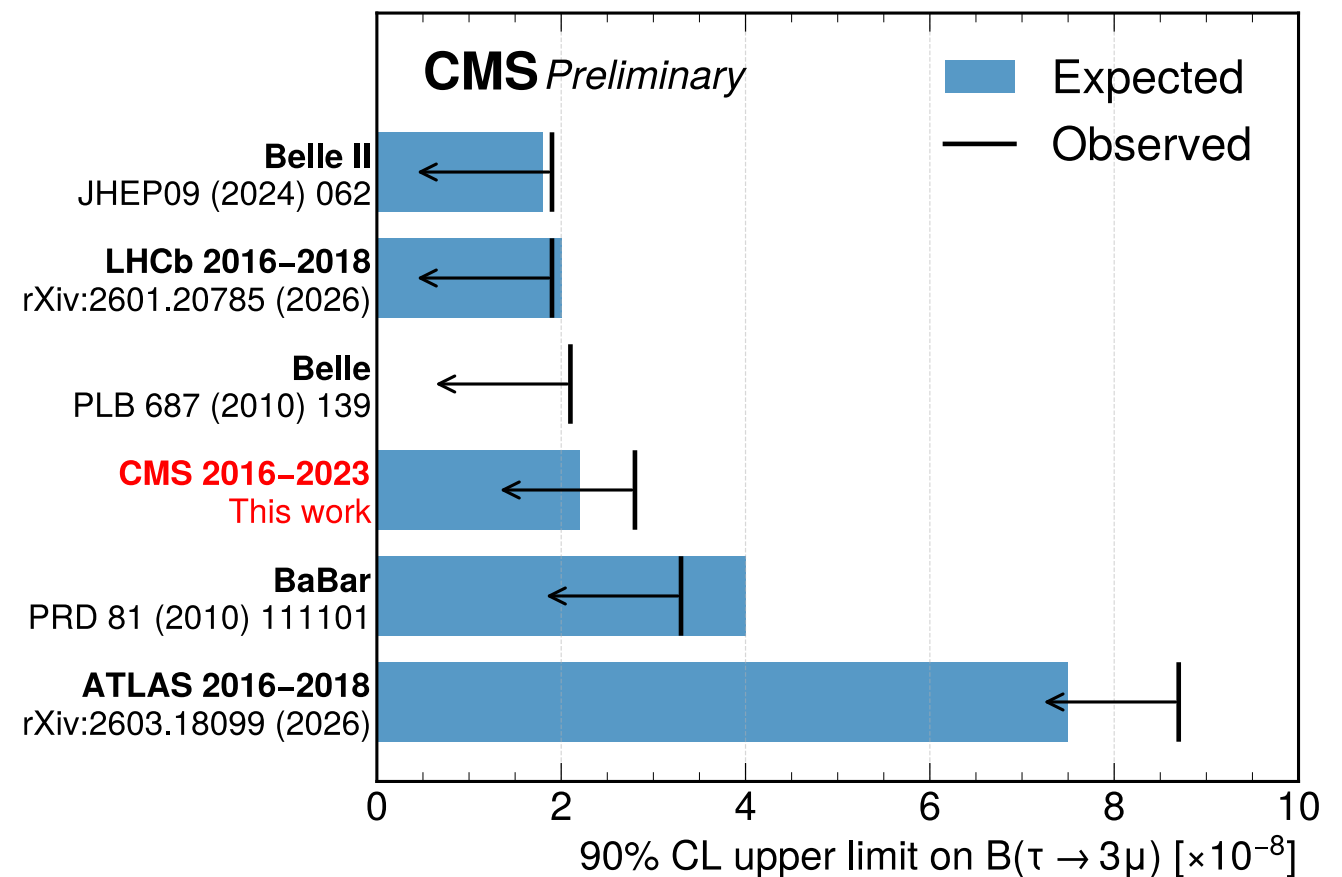
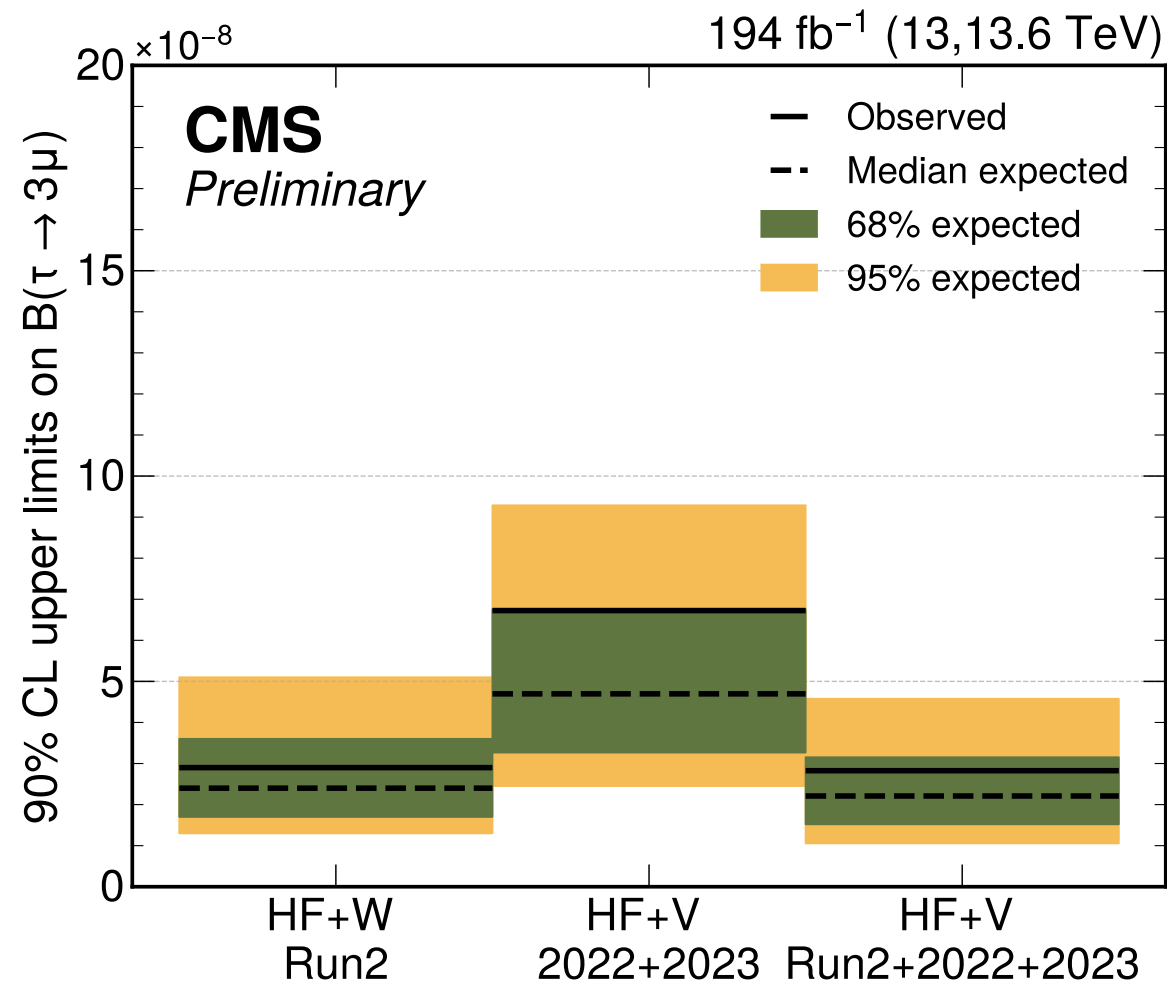


Results



$Br(\tau \rightarrow 3\mu) < 6.7 (4.7) \times 10^{-8}$ @ 90% CL (HF+V)

Run2 + partial Run3 combination



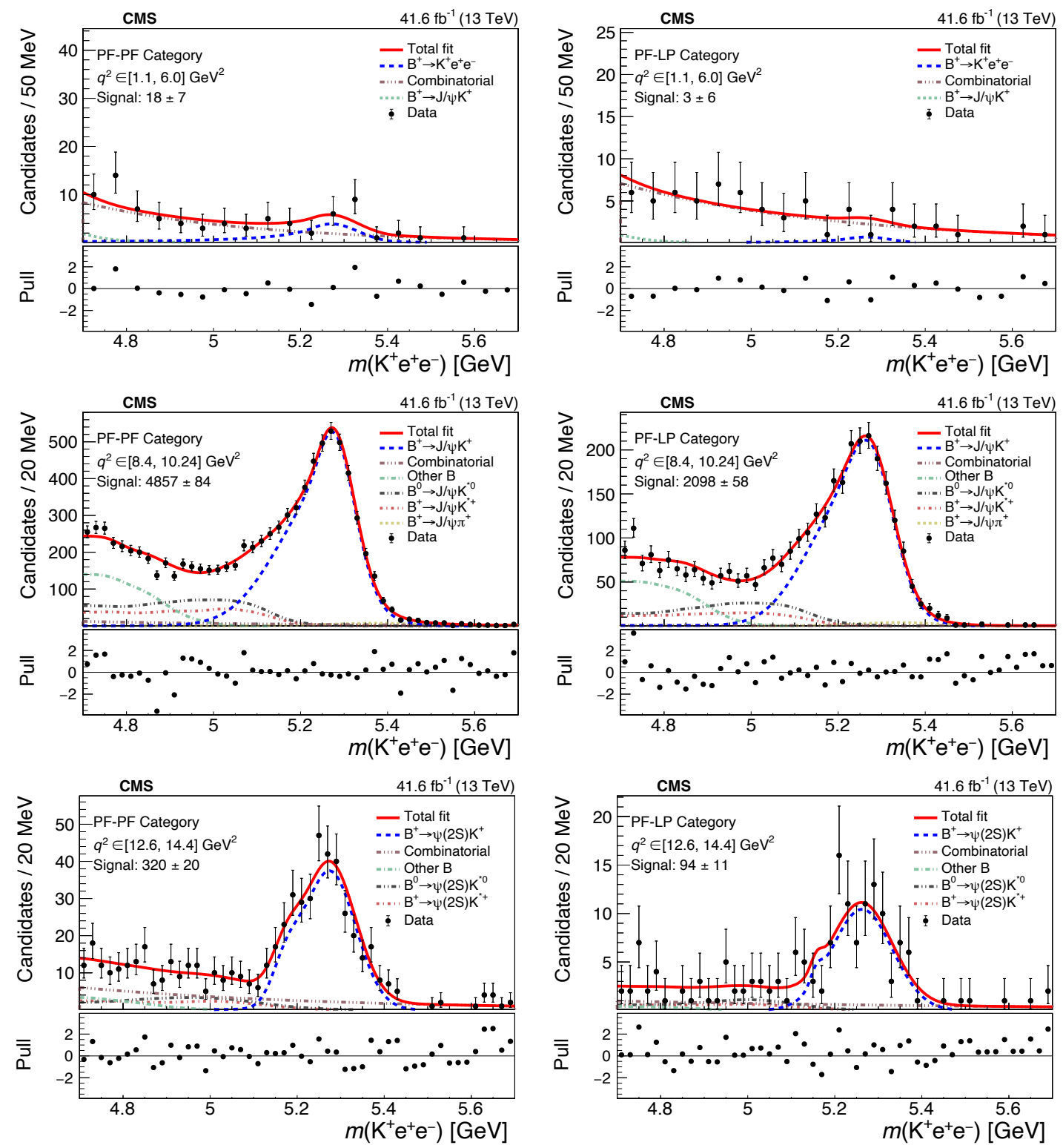
CMS limit at 90% CL $\mathcal{B}(\tau \rightarrow 3\mu) = 2.8(2.2) \times 10^{-8}$ obs.(exp.)
 expect to reach below 2×10^{-8} that with full Run3 statistics

FLUV using the $R(K)$ ratio

$$R(K)(q^2)[q_{\min}^2, q_{\max}^2] = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)[q_{\min}^2, q_{\max}^2]}{\mathcal{B}(B^+ \rightarrow J/\psi(\mu^+ \mu^-)K^+)} \bigg/ \frac{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)[q_{\min}^2, q_{\max}^2]}{\mathcal{B}(B^+ \rightarrow J/\psi(e^+ e^-)K^+)}$$

- **double ratio relative $\rightarrow$ substantial cancellation of systematics**
- **BParking dataset electron (muon) channel from probe (tag) side**
 - primary vertex determined by trigger muon
- **electron channel split in two categories depending on ID quality**
- **BDT discriminator(s) for background rejection**
- $D^0 \rightarrow K\pi$ veto: reject events if the mass of the kaon and its opposite sign lepton is < 2 GeV, when the kaon/pion mass is assigned to the potentially misidentified particle
- **simultaneous UML fit to $m(K\ell\ell)$ in bins of q^2 to extract $R^{-1}(K)$**
 - combinatorial, partial reco, leakage PDFs modelled from sidebands / MC

Mass fits in electron channel



Process	$B^+ \rightarrow K^+ e^+ e^-$	$B^+ \rightarrow J/\psi(e^+ e^-) K^+$	$B^+ \rightarrow \psi(2S)(e^+ e^-) K^+$
Signal	DCB function	CB + Gaussian	CB + Gaussian
Comb. background	Exponential	Exponential	Exponential
$B^+ \rightarrow K^*(892)^{0/+} X$	—	KDE template	KDE template
$B^+ \rightarrow \pi^+ X$	—	CB function	—
$B^+ \rightarrow J/\psi(e^+ e^-) K^+$	KDE template	—	—
Other b decays	—	KDE template	KDE template

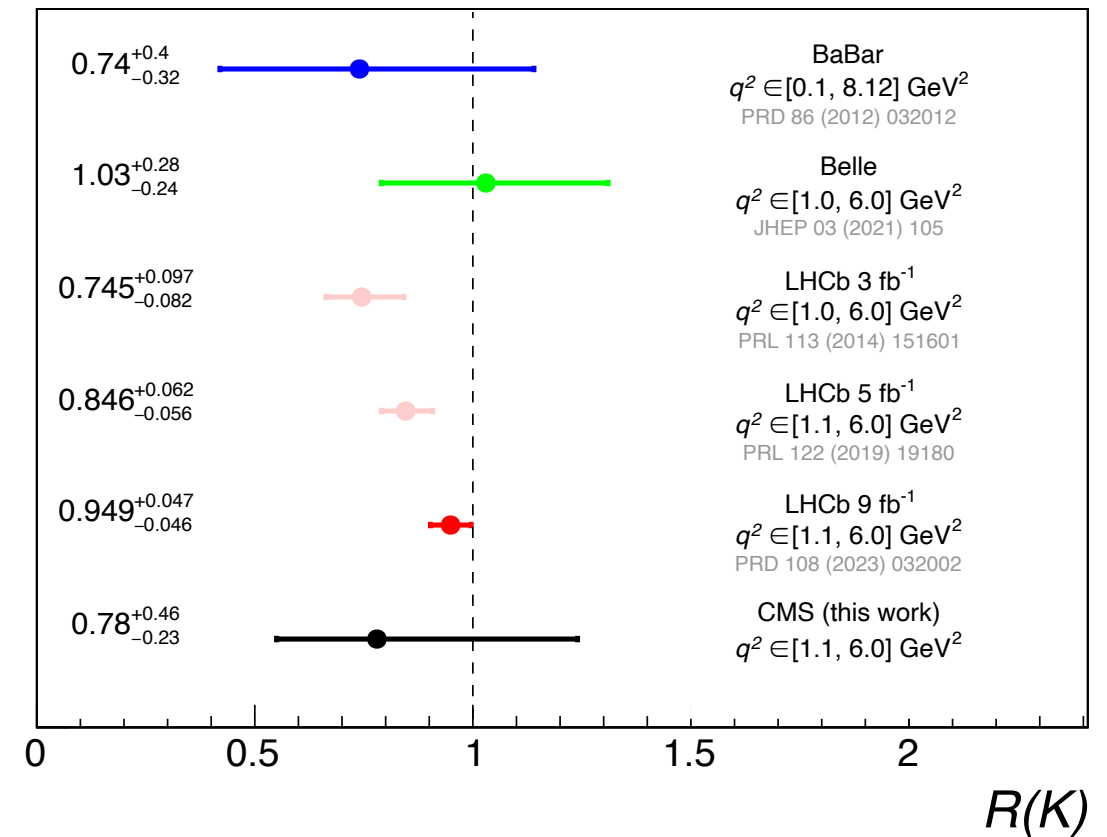
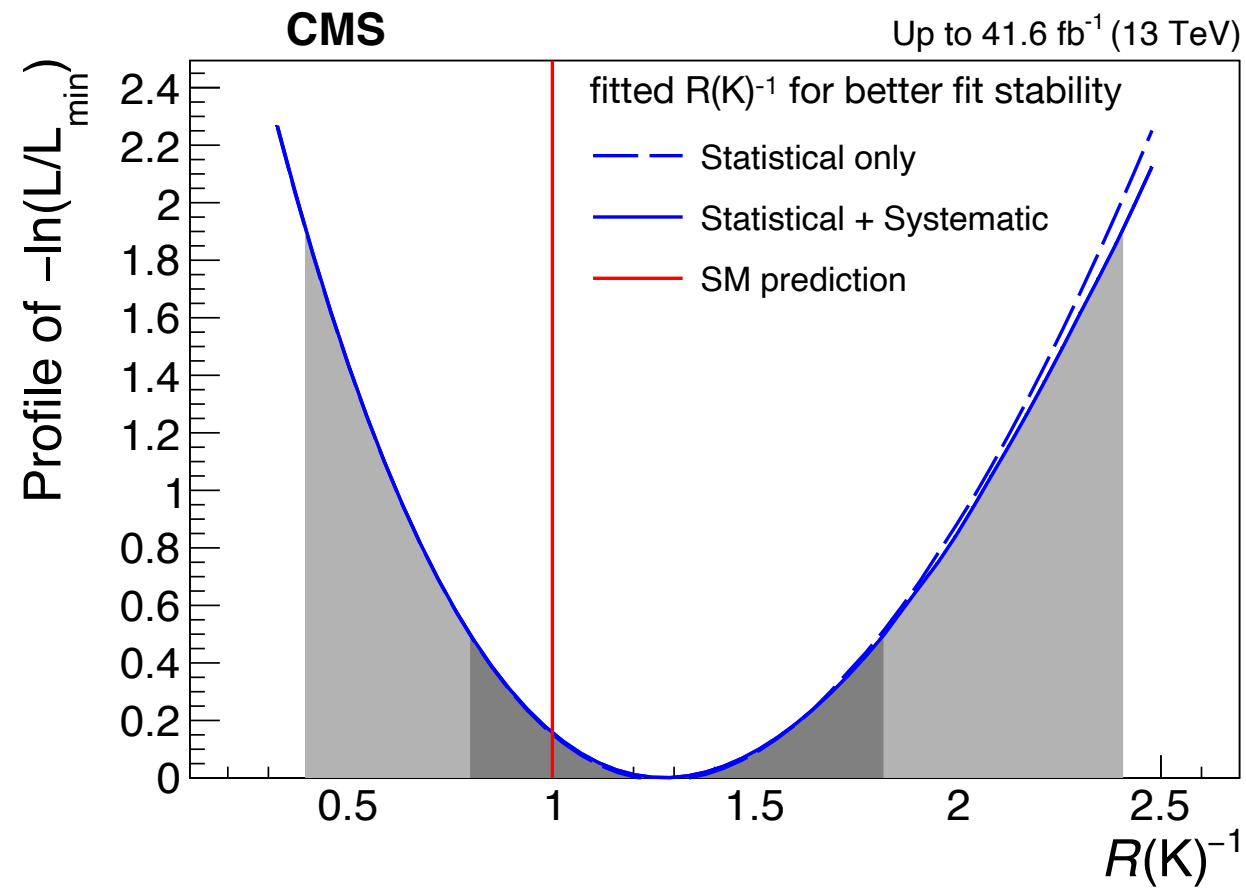
Channel	q^2 range [GeV ²]	PF-PF yield	PF-LP yield
$B^+ \rightarrow K^+ e^+ e^-$	1.1–6.0	17.9 ± 7.2	3.0 ± 5.9
$B^+ \rightarrow J/\psi(e^+ e^-) K^+$	8.41–10.24	4857 ± 84	2098 ± 58
$B^+ \rightarrow \psi(2S)(e^+ e^-) K^+$	12.60–14.44	320 ± 20	94 ± 11

- **resonant channels show good mass resolution FWHM < 5%**
 - using standard CMS electron energy calibration
 - comparable to LHCb
- **reasonably small radiative tail**
 - better than LHCb
- **decent S/B but low stats**
- **negligible contamination (O(%)) from peaking background / double electron fakes**
 - measured using $D^0 \rightarrow K\pi$

e ID: **PF-PF**

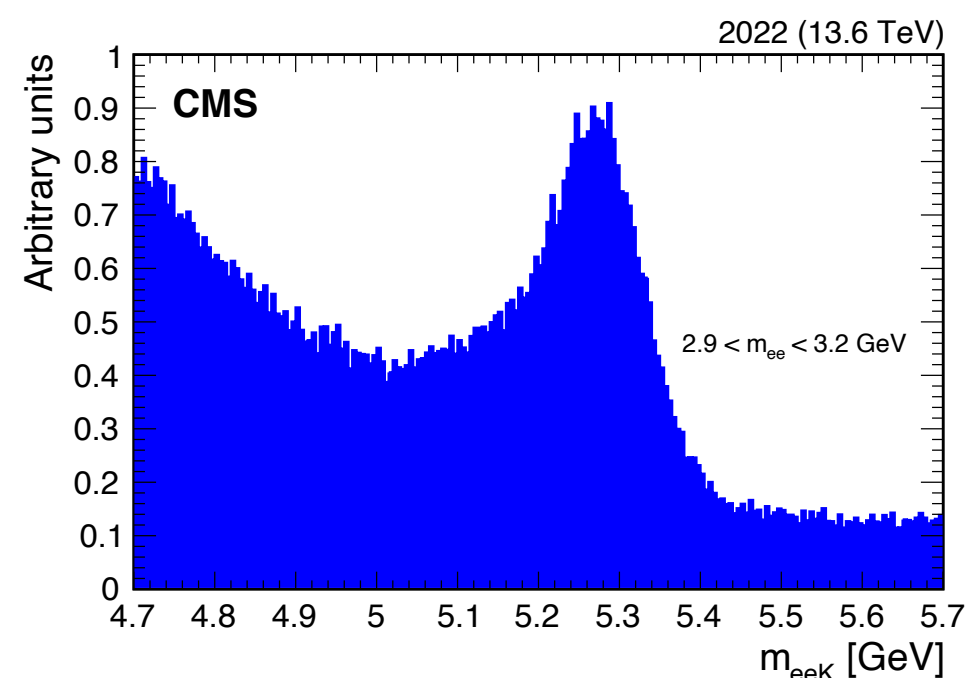
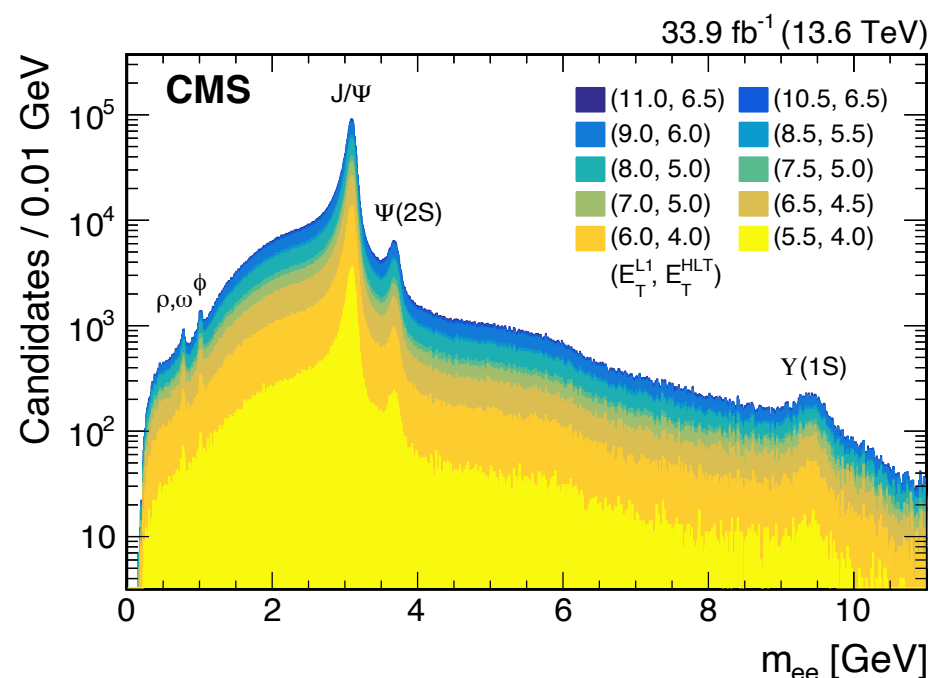
PF-low p_T

R(K) measurement



$$R(K) = 0.78^{+0.46}_{-0.23}$$

$R(K)$ prospects



- **di-electron triggers in Run3**
 - significantly larger statistics, orders of magnitude leap
- **but... is it still interesting after the anomaly disappeared?**
 - see Olcyr Sumensary's [talk](#) at BEAUTY 2026

Discussion

LFV

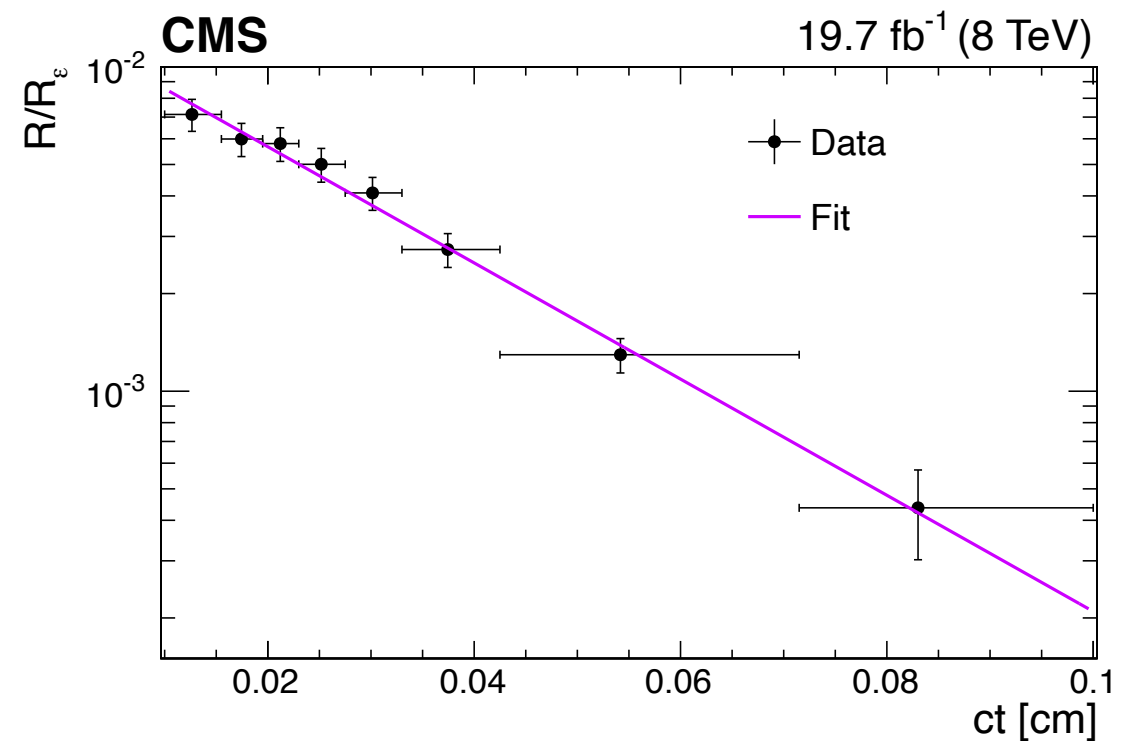
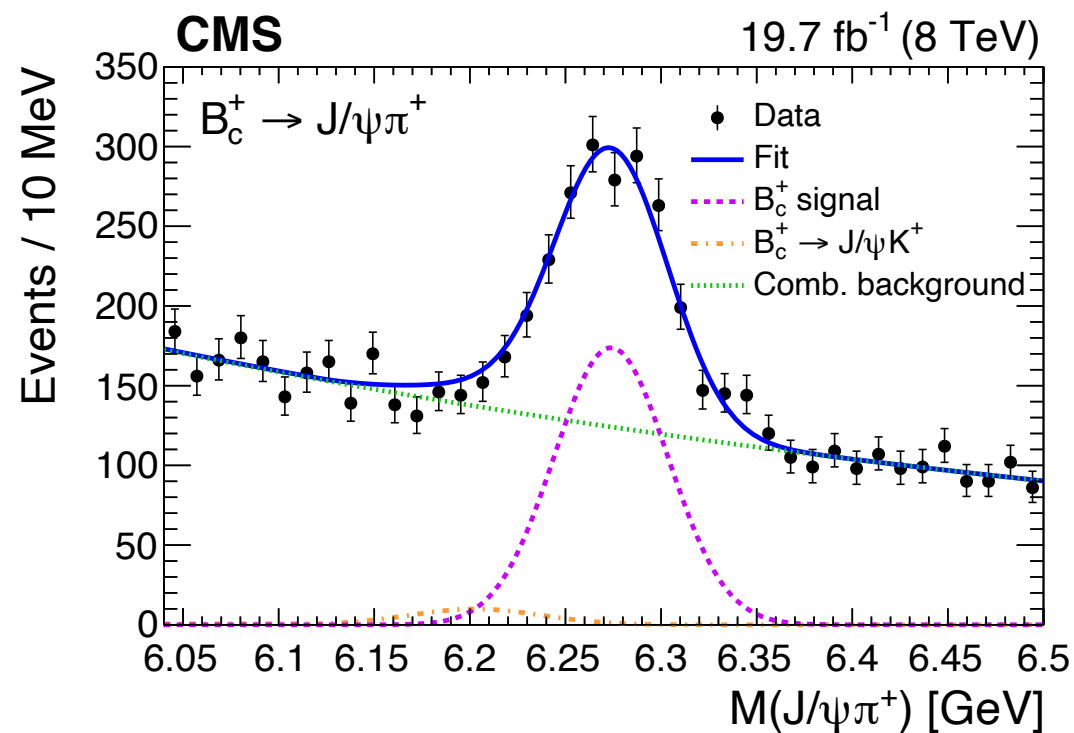
- $\tau \rightarrow 3\mu$ **will be updated to full Run3 statistics**
 - besides experimental advancements, should we refine the aim?
e.g. intermediate resonances?
 - LHC-wide combination
- ongoing work on other LFV channels, e.g. $X \rightarrow Ye\mu$

LFUV

- **lessons learnt, gained experience with first analyses in Run2**
- ongoing update of $R(K)$
- **update $R(J/\psi)$ with full Run3 statistics**
- **potential measurements**
 - V_{cb} [see [LHCb's](#)] other $R(H_c)$ angular $B \rightarrow D\mu\nu$ fit FF
 - other semileptonic e.g. $\Lambda_b \rightarrow \Lambda_c^{(*)}\mu\nu, \Xi_b \rightarrow \Xi_c^{(*)}\mu\nu$

Lifetimes

B_c lifetime



- CMS (and LHCb) most precise measurements from Run2
- **CMS Run3 statistics 15x, cross section 2x**
 - potential breakthrough
- B_c lifetime complementary constraint of LFUV in $R(D^{(*)})$ [see refs in [Blanke](#)]

B_c^+

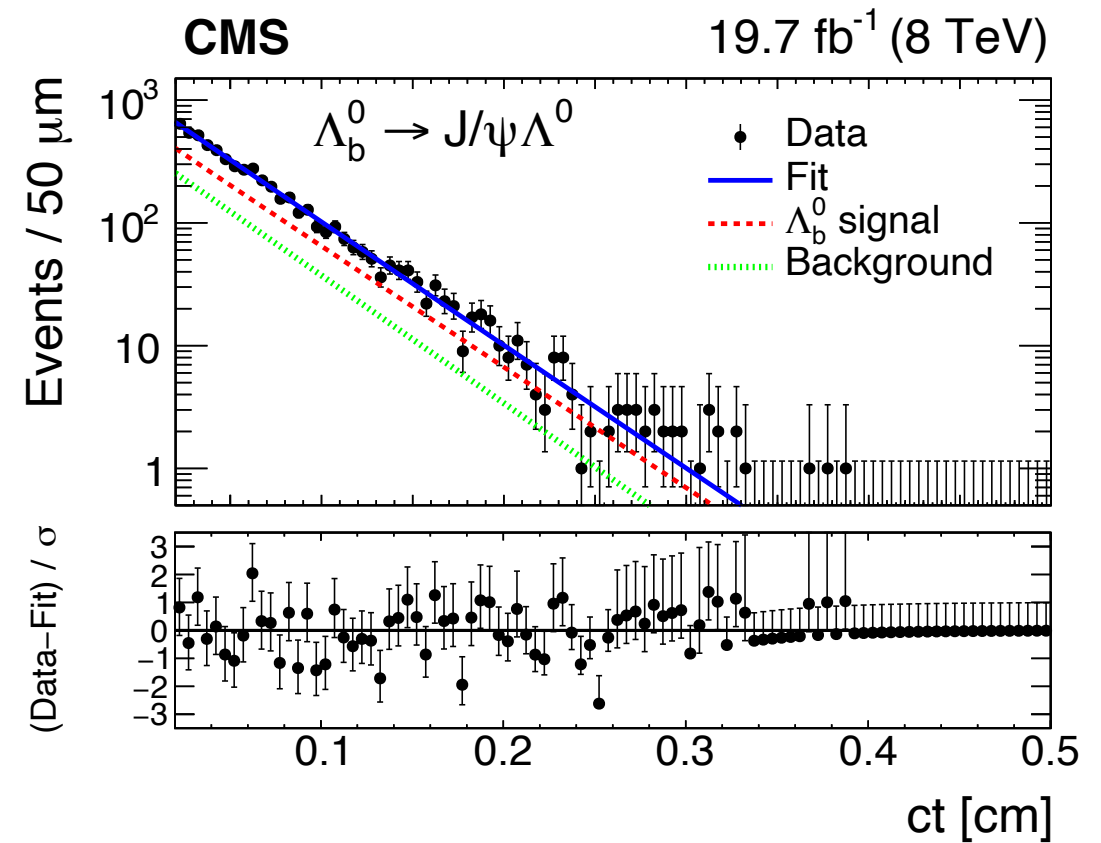
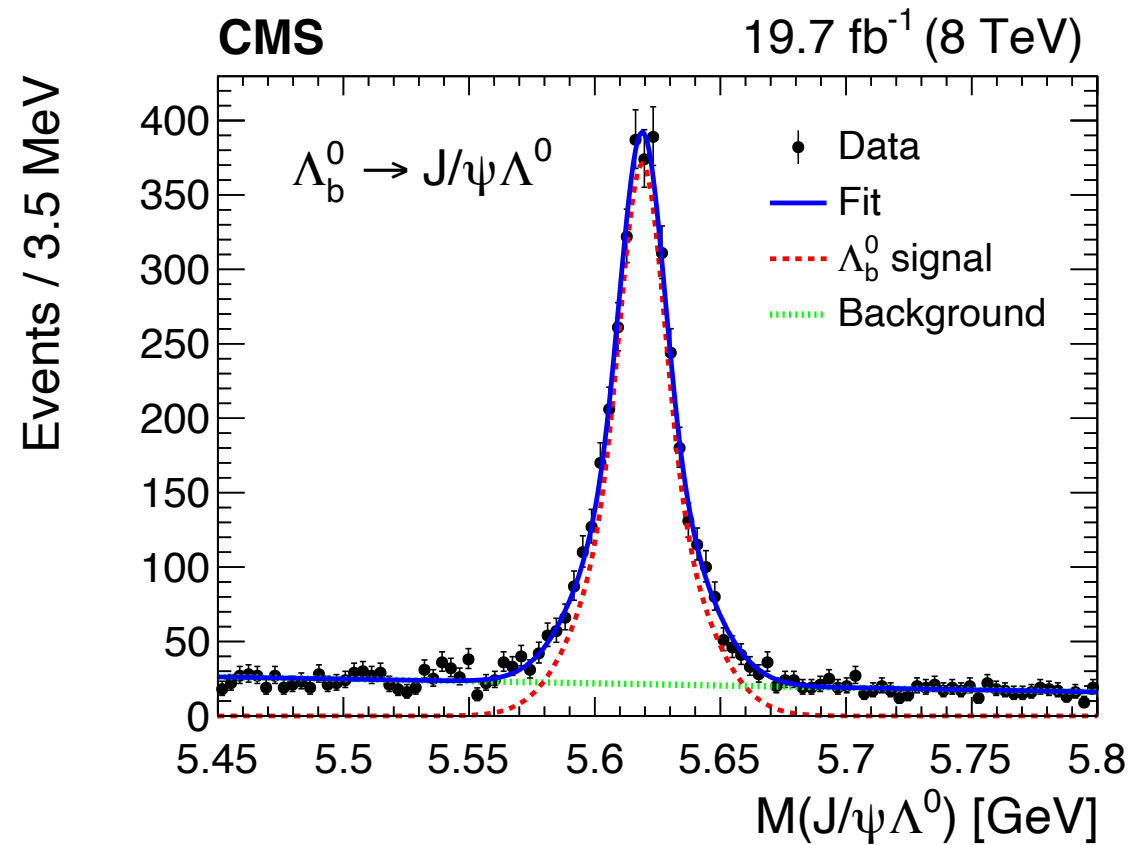
MEAN LIFE

PDGID:S091T

JSON (beta)

VALUE (10^{-12} s)	DOCUMENT ID	TECN	COMMENT
0.510 ± 0.009	OUR EVALUATION (Produced by HFLAV)		
0.510 ± 0.009	OUR AVERAGE		
0.541 ± 0.026 ± 0.014	¹ SIRUNYAN 2018BY Q	CMS	<i>pp</i> at 8 TeV
0.5134 ± 0.0110 ± 0.0057	^{2, 3} AAJ 2015G Q	LHCB	<i>pp</i> at 7, 8 TeV
0.509 ± 0.008 ± 0.012	⁴ AAJ 2014G Q	LHCB	<i>pp</i> at 8 TeV

Λ_b lifetime



- CMS (and LHCb) most precise measurements from Run2
- CMS Run3 statistics 15x, cross section 2x
- potential breakthrough

Λ_b^0 MEAN LIFE

PDGID:S040T

See b -baryon Admixture section for data on b -baryon mean life average over species of b -baryon

VALUE (10^{-12} s)	EVTS	DOCUMENT ID	TECN	COMMENT
1.468 $\pm$ 0.009	OUR EVALUATION	(Produced by HFLAV)		
1.477 $\pm$ 0.027 $\pm$ 0.009	¹	SIRUNYAN 2018BY Q	CMS	pp at 8 TeV
1.415 $\pm$ 0.027 $\pm$ 0.006	²	AAIJ 2014E Q	LHCB	pp at 7 TeV
1.479 $\pm$ 0.009 $\pm$ 0.010	³	AAIJ 2014U Q	LHCB	pp at 7, 8 TeV

$B_s^0 \rightarrow J/\psi K_s^0$ **effective lifetime**

B_s^0 mesons produced in strong eigenstates $B_s^0/\bar{B}_s^0$ but propagate as heavy/light mass eigenstate $B_{s,L}^0/B_{s,H}^0$ with different lifetimes
 $\Delta\Gamma, \Delta\tau = (1.624 - 1.431) \text{ ps}$

Effective lifetime

$$\tau^{\text{eff}} \equiv \frac{\tau_{B_s}}{1 - y^2} \left[\frac{1 + 2yA_{\Delta\Gamma} + y^2}{1 + yA_{\Delta\Gamma}} \right] = \frac{\int t [\Gamma(B_s) + \Gamma(\bar{B}_s)] dt}{\int \Gamma(B_s) + \Gamma(\bar{B}_s) dt}$$

$$\text{where } A_{\Delta\Gamma} = \frac{\Gamma(B_{s,H}) - \Gamma(B_{s,L})}{\Gamma(B_{s,H}) + \Gamma(B_{s,L})} \text{ and } y = \tau_{B_s} \Delta\Gamma/2$$

τ^{eff} **sensitive to BSM physics**
 complementary to, e.g., $\mathcal{B}(B_s^0 \rightarrow \mu\mu)$

$B_s^0 \rightarrow \mu\mu$ **exactly CP-odd**

$$\tau_{\mu\mu}^{\text{SM}} = (1.624 \pm 0.009) \text{ ps} \equiv \tau_{B_{s,H}^0}$$

$B_s^0 \rightarrow J/\psi K_s^0$ **quasi CP-odd**

$$\tau_{J/\psi K_s}^{\text{SM}} = (1.62 \pm 0.02) \text{ ps} \simeq \tau_{B_{s,H}^0}$$

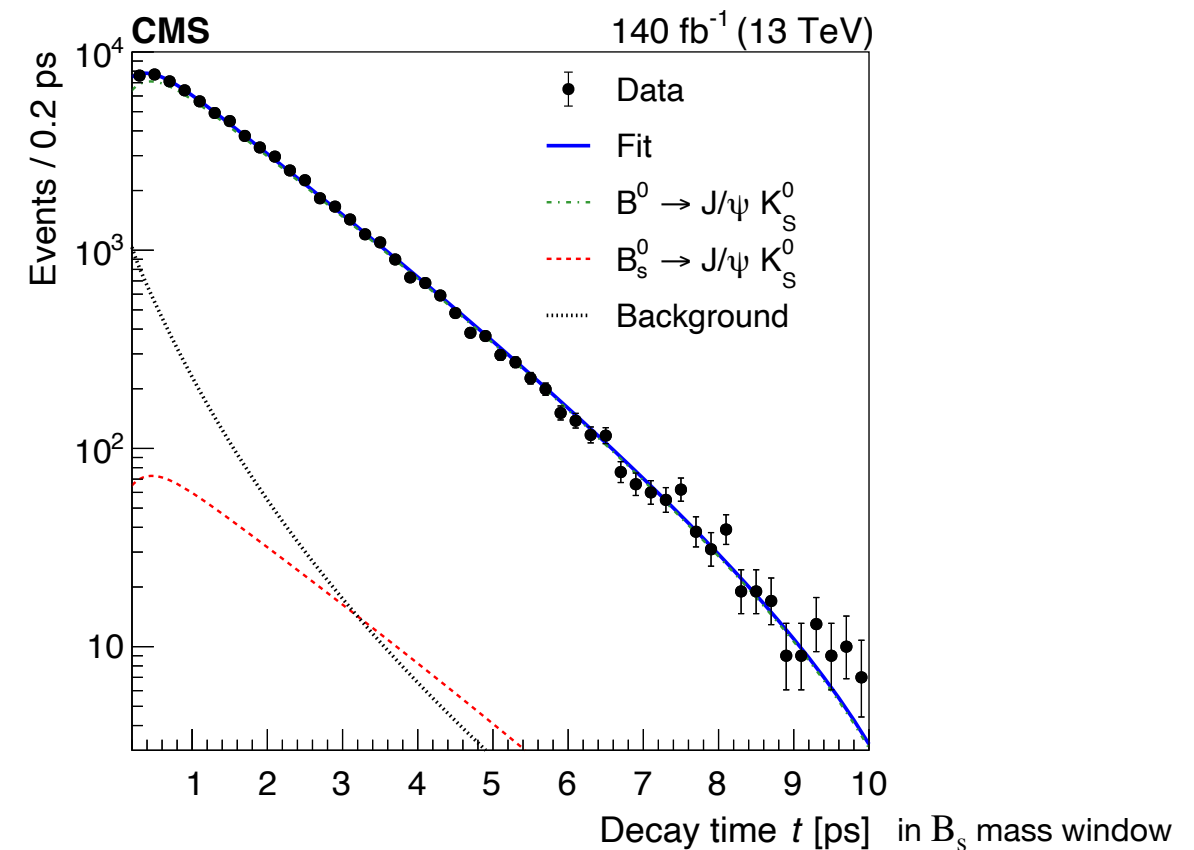
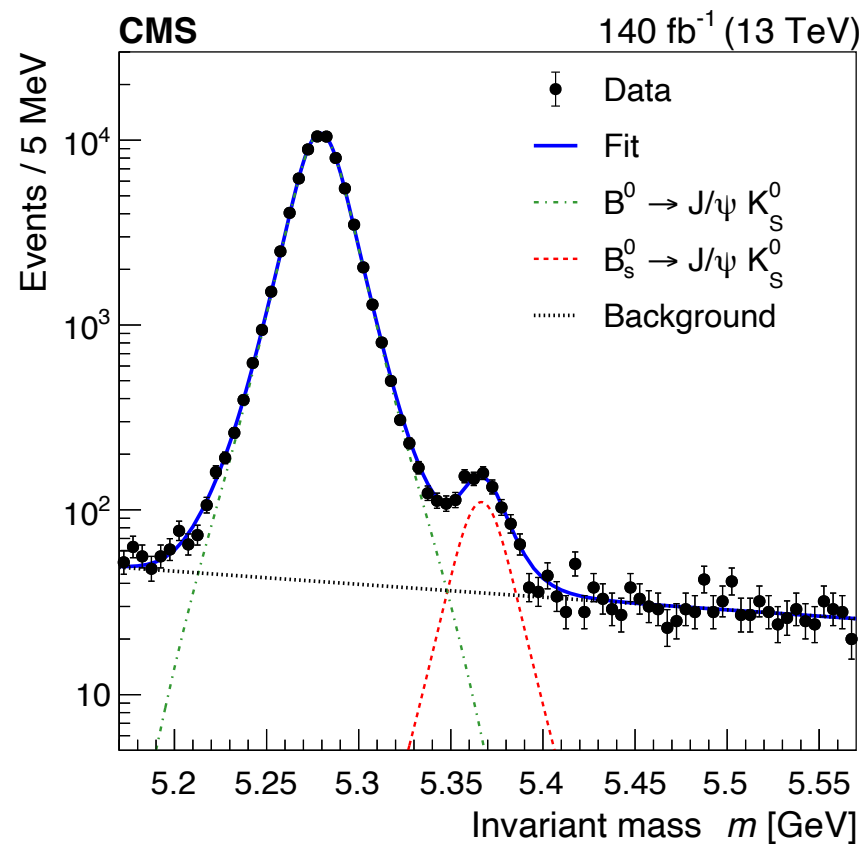
$B_s^0 \rightarrow J/\psi K_s^0$ effective lifetime

>20x larger stats in Run3

see $J/\psi K_s$, 16k vs 727

total uncertainty becomes comparable to SM

- **Full Run2 dataset at 13 TeV, 140 fb⁻¹**
 - using $J/\psi \rightarrow \mu\mu$ high p_T trigger, $K_s^0 \rightarrow \pi\pi$, 727 (68k) $B_s(B_d) \rightarrow J/\psi K_s^0$ events
- 2D UML fit to mass and decay length



$$\tau_{J/\psi K_s}^{\text{obs}} = 1.59 \pm 0.07 \text{ (stat)} \pm 0.03 \text{ (syst)} \text{ ps}$$

in agreement with SM 1.62 ± 0.02 ps
improved accuracy relative to world best from [LHCb](#)

**Some sort of
conclusions**

CMS Flavour in Run3

what to expect

- **all the flagship measurements/searches will be updated**
 $B_s \rightarrow \mu\mu$, angular $P5'$, $\tau \rightarrow 3\mu$, $B_s \rightarrow J/\psi\phi$
 - these are mostly statistically limited, will improve significantly
- **competitive FCNC $b \rightarrow s\ell\ell$ program**
 - angular analyses and differential $d\mathcal{B}/dq^2$ in various channels
- **expand CPV program / CKM metrology beyond $B_s \rightarrow J/\psi\phi$, including CPV in charm**
- **systematic coverage of rare decays in $\geq 2\mu$**

CMS Flavour in Run3

what to expect

- **more LFUV tests in $b \rightarrow c\ell\nu$ transitions, and update $R(K)$**
- **expand LFV searches beyond $\tau \rightarrow 3\mu$**
 - several LFV decays accessible thanks to new triggers, what to prioritize?
- **exotic hadron / spectroscopy very lively and on a growth trajectory**
 - enriching the search for associated production with DPS/TPS interpretation
- **opportunities in cross section and lifetimes measurements, currently only partially covered**

Backup

architecture of the CMS Trigger

Trigger System

- reduce the number of events from the **LHC collision rate (40 MHz)** to the data rate that can be stored, reconstructed and analysed **Offline (~~~1 kHz~~) O(few kHz)**
- maximising the physics reach of the experiment

L1 Trigger

- coarse readout of the Calorimeters and Muon detectors
- implemented in custom electronics, ASICs and FPGAs
- **3 event types, 128 “physics” bits + 64 “technical” bits**
- output rate limited to **~~100 kHz~~** by the readout electronics
>100 kHz in Run3

High Level Trigger

- readout of the whole detector with full granularity
- based on the CMSSW software, running on **O(15k) Xeon cores**
- organised in **O(2500) modules, O(400) trigger paths, O(10) streams**
- output rate limited to an average of **~~~1 kHz~~** by the Offline resources

O(few kHz)

LHC

40 MHz

L1 Trigger

full readout

100 kHz

High Level Trigger

Offline

~~~1 kHz~~

O(few kHz)



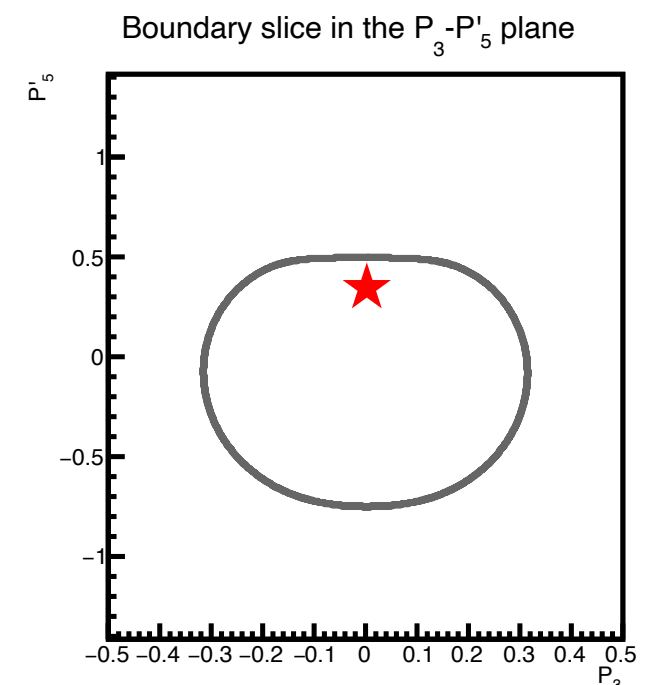
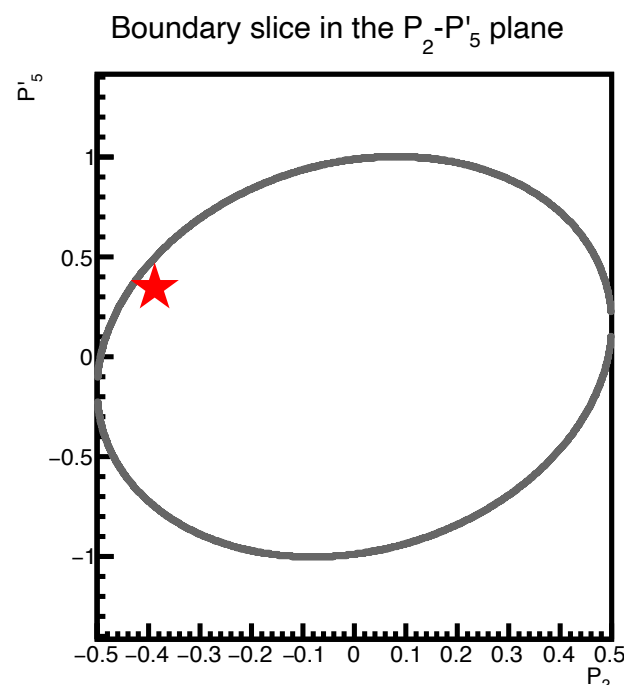
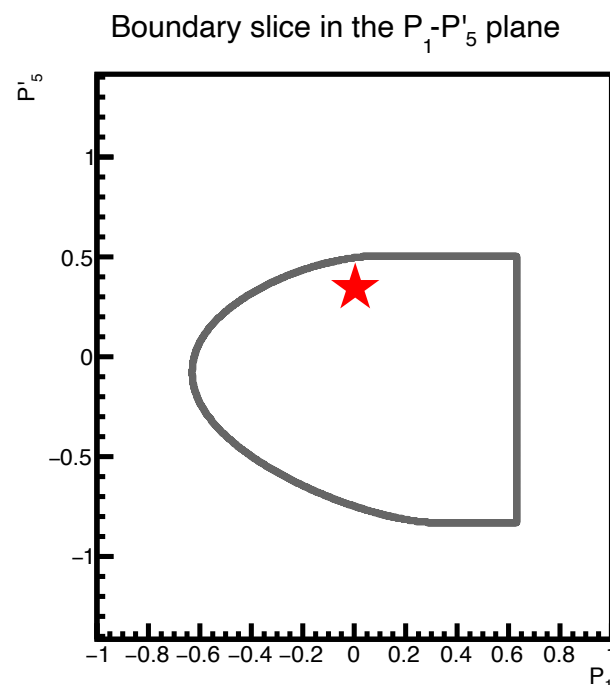
trigger often the bottleneck for “soft” physics at CMS

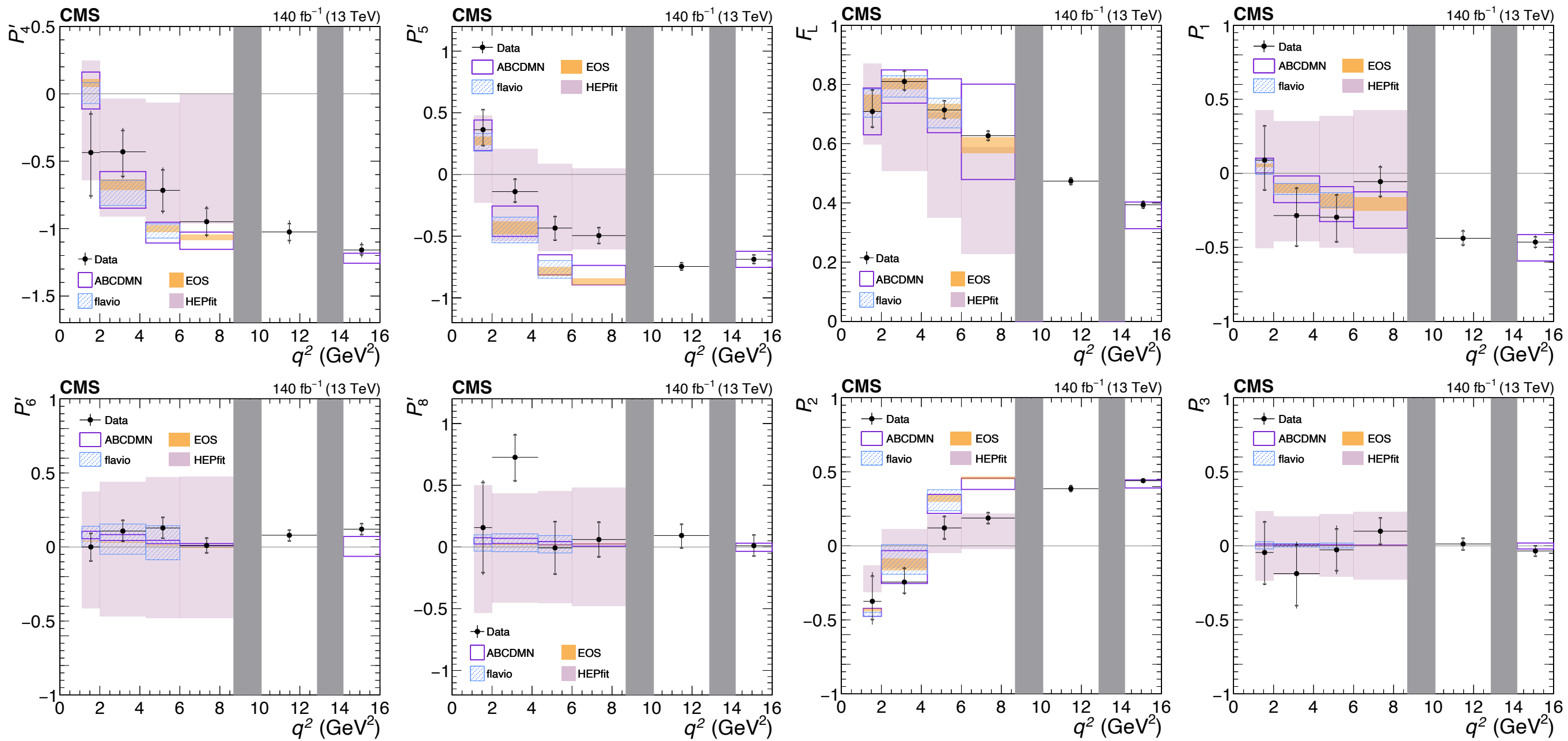
Physical boundaries of $P_i^{(\prime)}$ and F_L

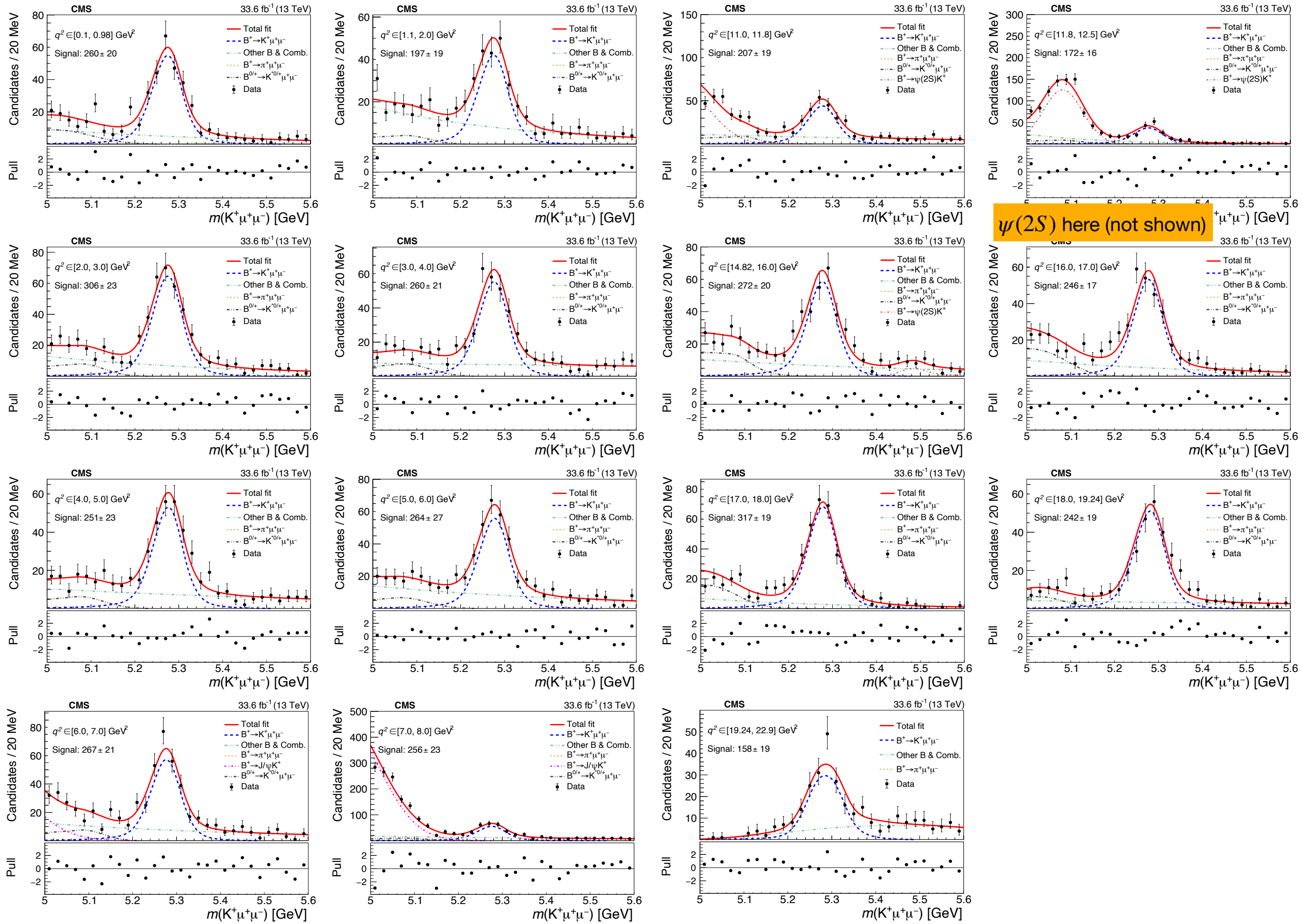
- decay rate be positive definite implies conditions on $P_i^{(\prime)}$ and F_L parameters

$$\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{dq^2 d\cos\theta_l d\cos\theta_K d\phi} \geq 0 \quad \forall(\cos\theta_l, \cos\theta_K, \phi)$$

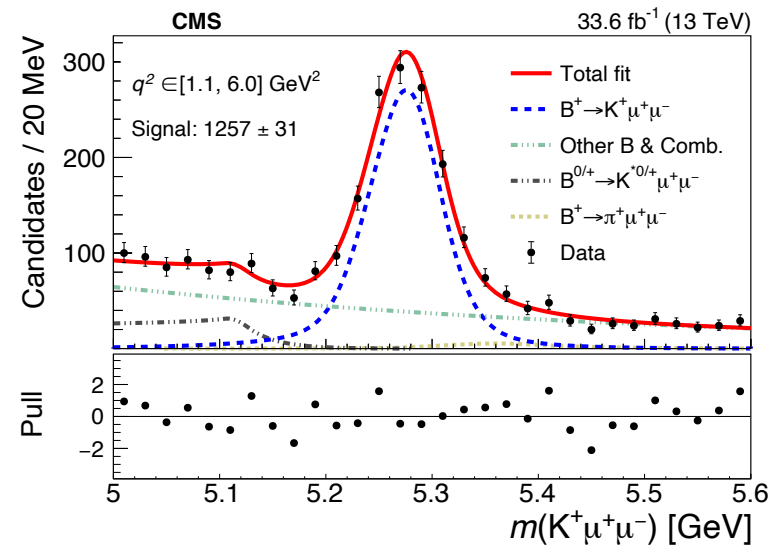
- not analytically solvable, ultimately obtained from numerical scan
- boundaries implemented as penalty terms in the likelihood





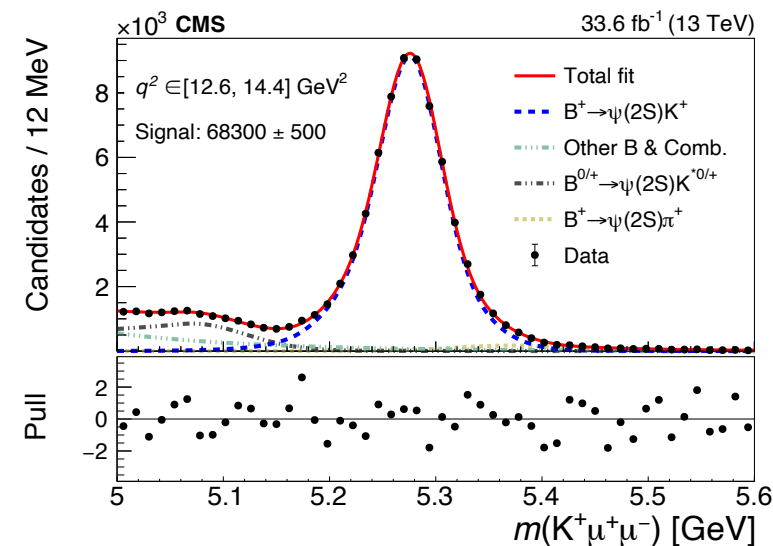
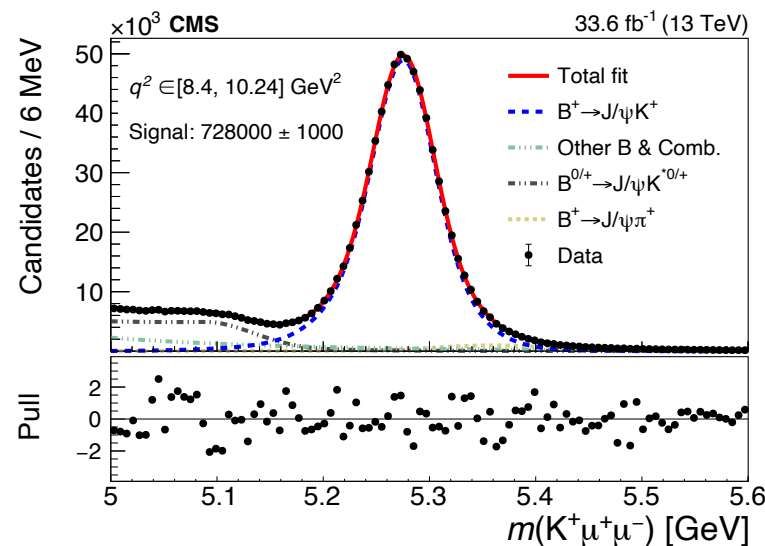


Mass fits in muon channel



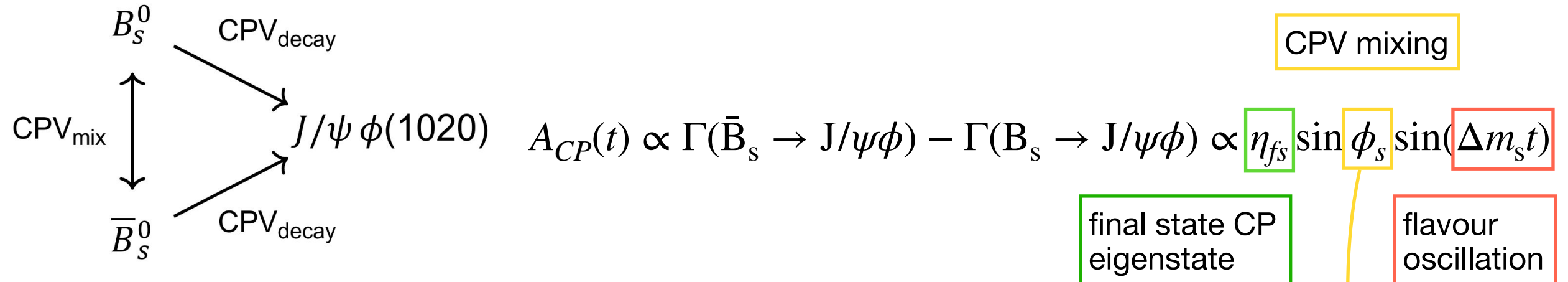
much larger statistics

excellent S/B and resolution

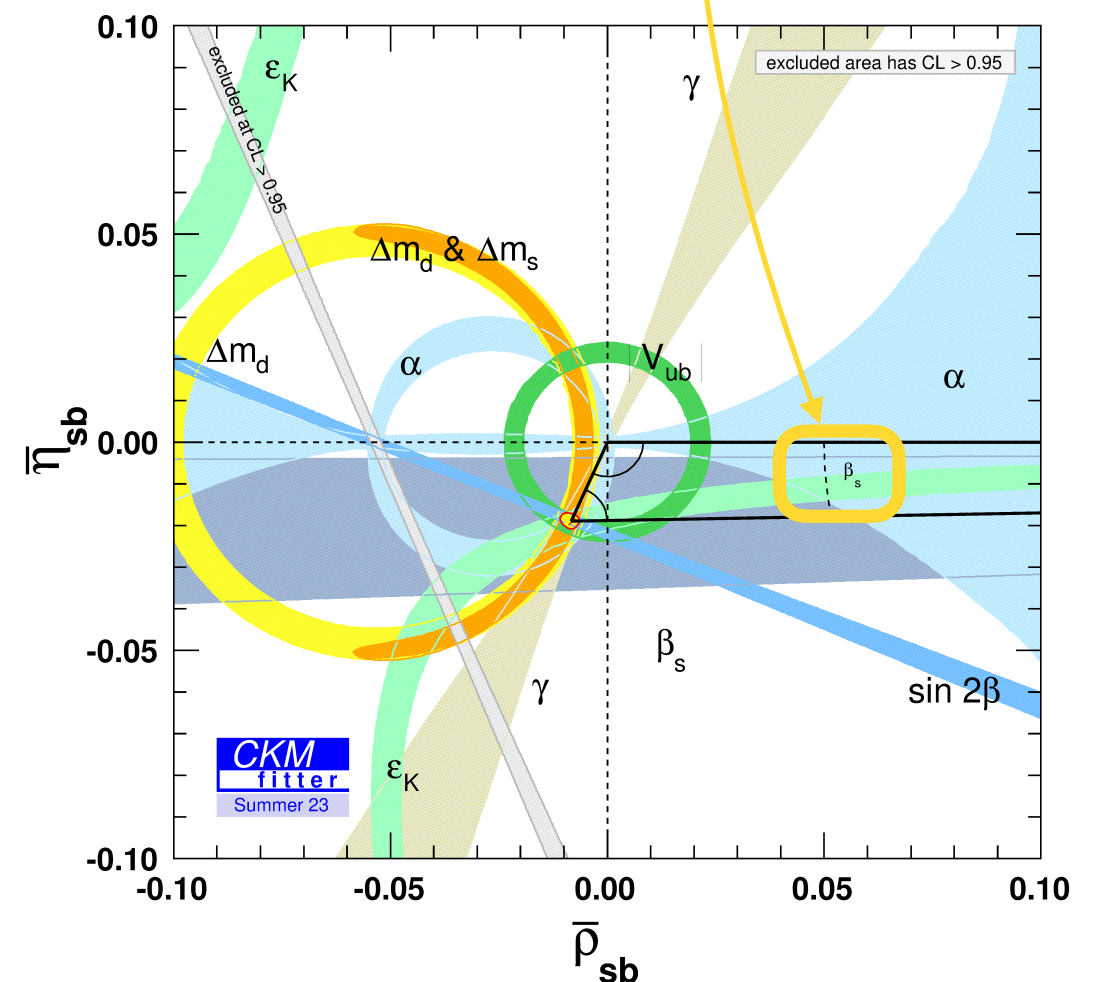


Process	$B^+ \rightarrow K^+ \mu^+ \mu^-$	$B^+ \rightarrow J/\psi(\mu^+ \mu^-) K^+$	$B^+ \rightarrow \psi(2S)(\mu^+ \mu^-) K^+$
Signal	DCB + Gaussian	Sum of 3 Gaussians	DCB + Gaussian
Comb. & other b bkg.	Exponential [†]	Exponential	Exponential
$B^+ \rightarrow K^*(892)^{0/+} X$	DCB (+ expon.)	DCB + exponential	DCB + exponential
$B^+ \rightarrow \pi^+ X$	DCB	DCB	DCB
$B^+ \rightarrow J/\psi(\mu^+ \mu^-) K^+$	DCB (nearby q^2)	—	—
$B^+ \rightarrow \psi(2S)(\mu^+ \mu^-) K^+$	DCB (nearby q^2)	—	—

Mixing-induced CPV in $B_S^0 \rightarrow J/\psi(\mu\mu)\phi(KK)$



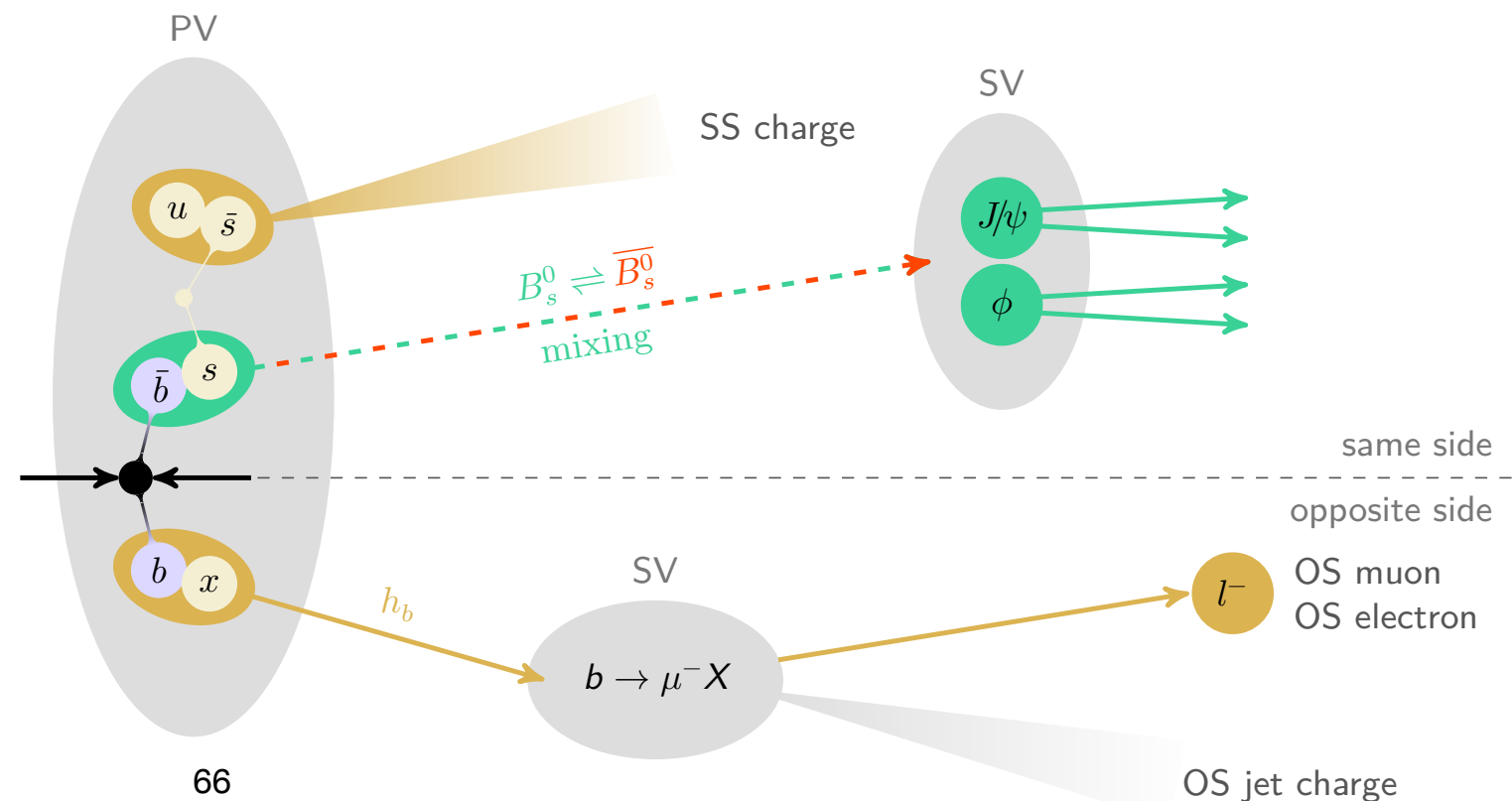
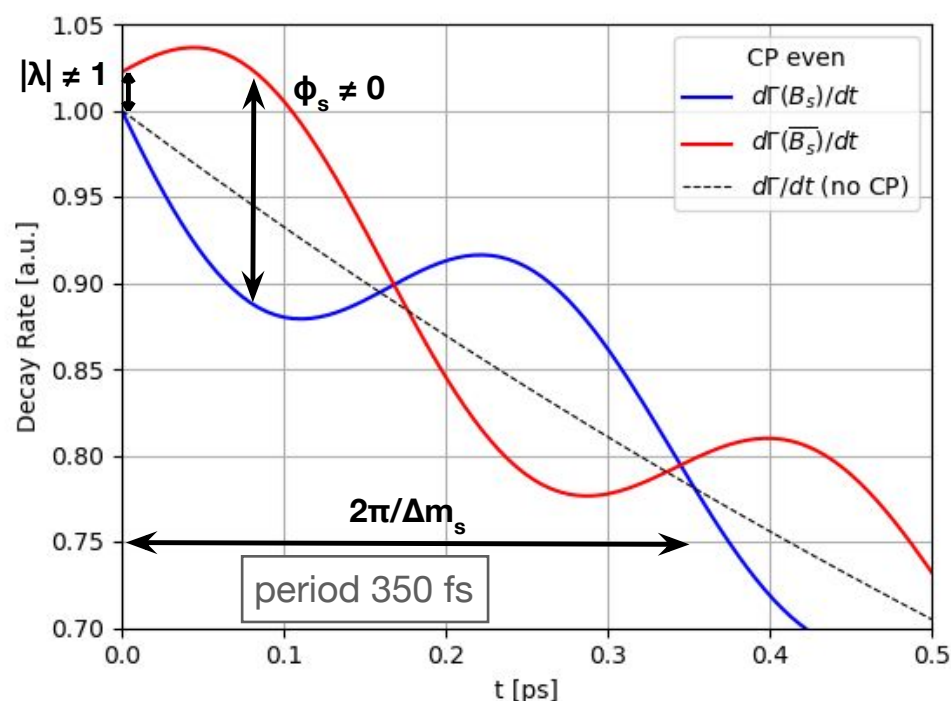
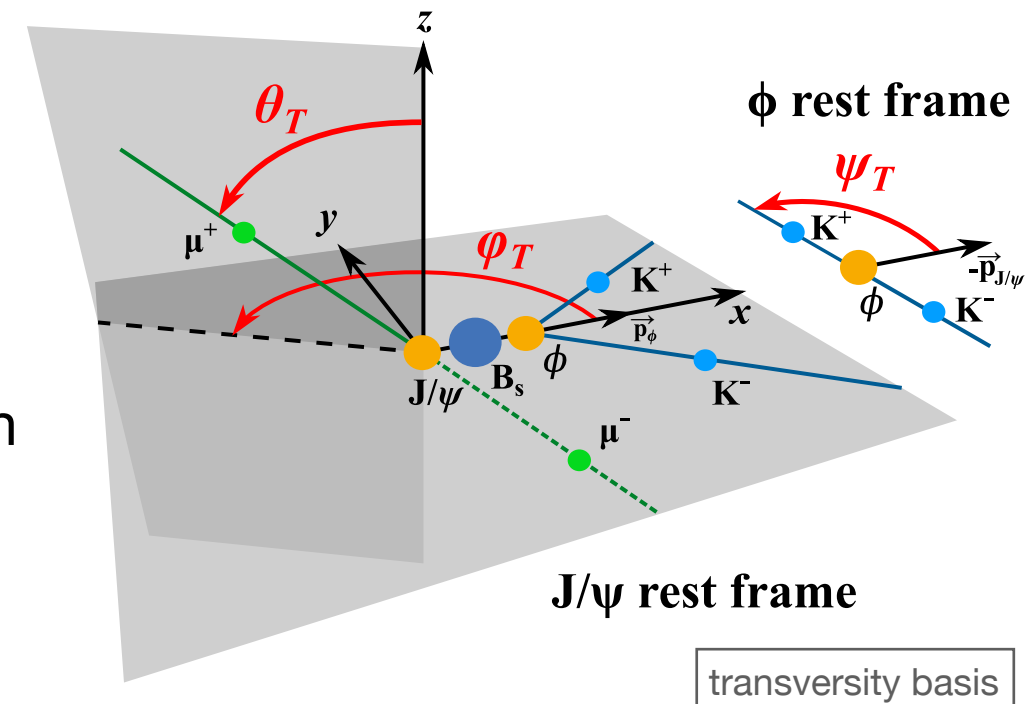
- **measure mixing-induced CPV phase**
 $\phi_s \approx -2\beta_s = -2 \arg(-V_{ts} V_{tb}^* / V_{cs} V_{cb}^*)$
in the B_S^0 system and several other parameters
- **accurate theoretical predictions** [CKMfitter](#), [UTfit](#)
 $\phi_s = -37 \pm 1 \text{ mrad}$
 - sensitive to deviations induced by new physics
 $\beta_{exp} = \beta_{SM,tree} + \Delta\beta_{penguin} + \Delta\beta_{NP}$
- **CMS uses 2017 + 2018 dataset, 13 TeV, 96.5 fb⁻¹**
 - $J/\psi + \mu$ & $J/\psi + \phi(KK)$ triggers



Mixing-induced CPV in $B_s^0 \rightarrow J/\psi(\mu\mu)\phi(KK)$

time-and flavour-dependent angular analysis,
7D UML fit $m, ct, \sigma_{ct}, \omega_{tag}, \cos \theta_T, \cos \psi_T, \varphi_T$

- angular analysis**: to separate CP eigenstates
angular efficiencies
- flavour tagging**: to infer $B_s^0/\bar{B}_s^0$ flavour at production
tagging decision and mistag probability
- time analysis**: to model flavour oscillations
time efficiency and resolution



Mixing-induced CPV in $B_s^0 \rightarrow J/\psi(\mu\mu)\phi(KK)$

Flavour tagging

- 4 separate DNN-based taggers: 3 opposite side (e, μ , jet), 1 same side (first at exp w/o PID)

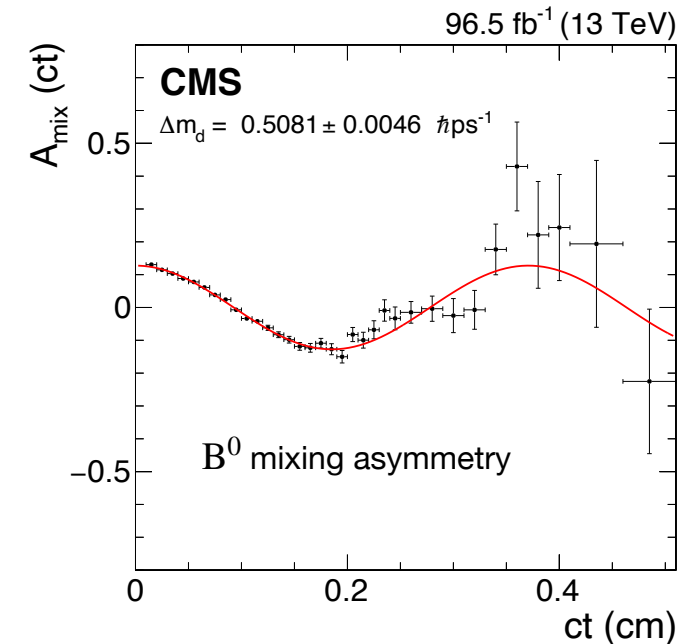
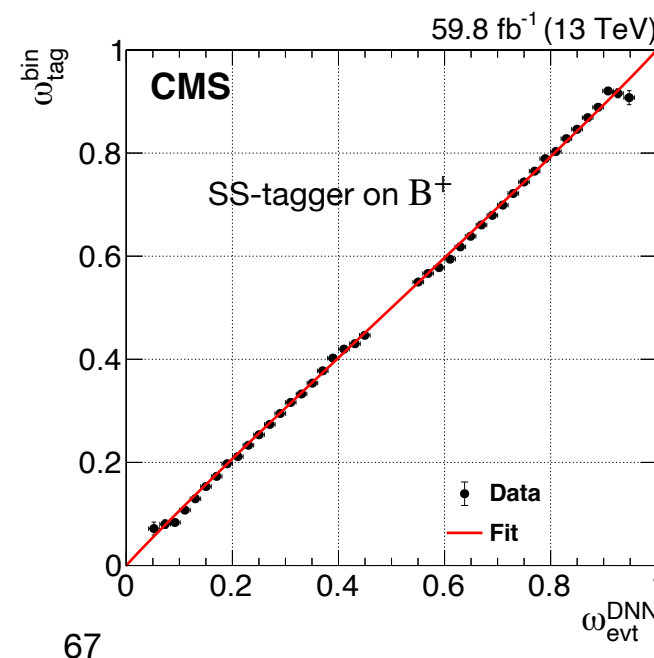
- decision ξ_{tag} : B_s^0 , $\bar{B}_s^0$ or untagged
- designed to be flavour invariant

- **(mis-)tagging efficiency $(\omega_{tag})\epsilon_{tag}$ determine effective statistics**

- tagging power $P_{tag} = \epsilon_{tag}(1 - \omega_{tag})^2 = 5.59\%$
- 491k signal events $\rightarrow$ 28k effective

Category	$\epsilon_{tag} [\%]$	$(1 - \omega_{tag})^2 \mathcal{D}_{eff}^2$	$P_{tag} [\%]$
Only OS muon	6.07 ± 0.05	0.212	1.29 ± 0.07
Only OS electron	2.72 ± 0.02	0.079	0.214 ± 0.004
Only OS jet	5.16 ± 0.03	0.045	0.235 ± 0.003
Only SS	33.12 ± 0.07	0.080	2.64 ± 0.01
SS + OS muon	0.62 ± 0.01	0.202	0.125 ± 0.003
SS + OS electron	2.77 ± 0.02	0.150	0.416 ± 0.005
SS + OS jet	5.40 ± 0.03	0.124	0.671 ± 0.006
Total	55.9 ± 0.1	0.100	5.59 ± 0.02

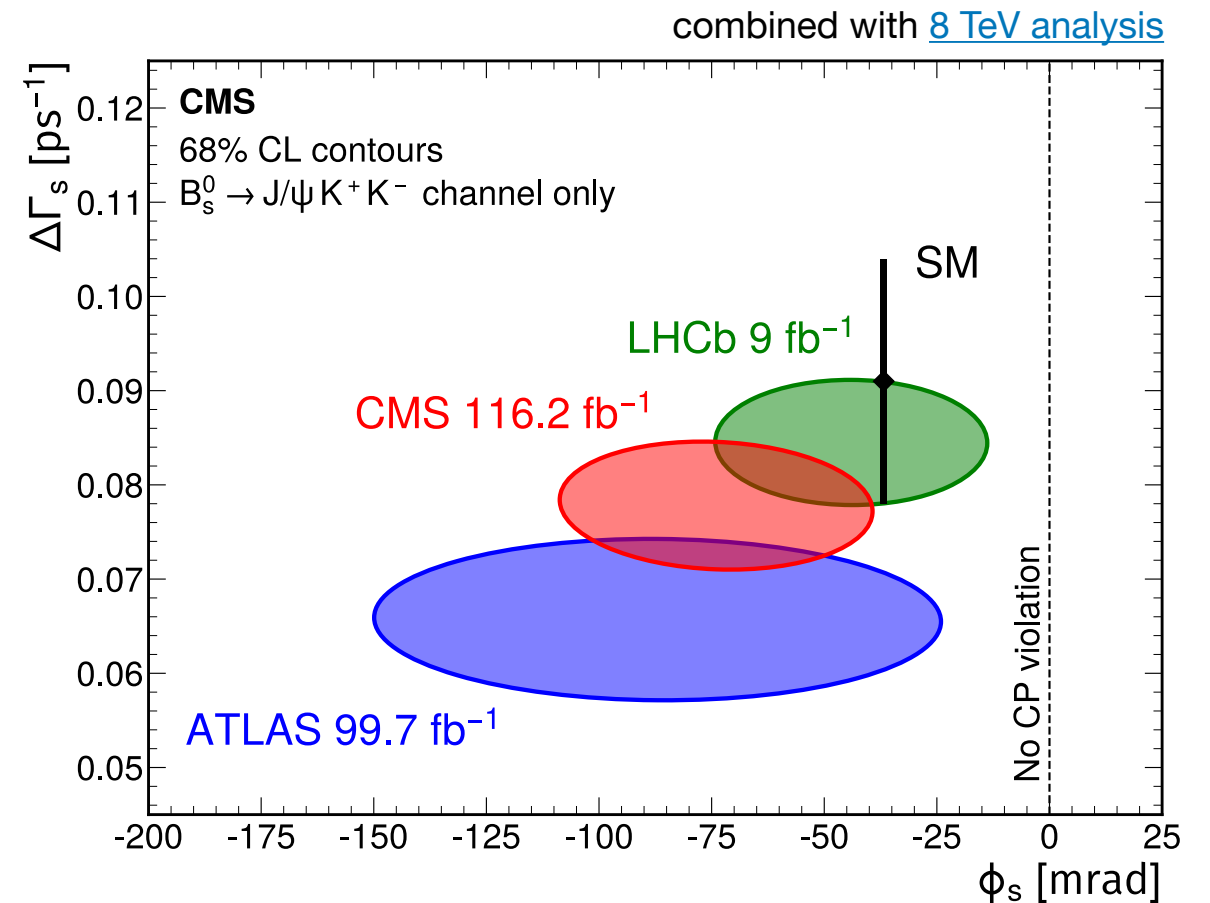
- **calibration:** on self tagging $B^+ \rightarrow J/\psi K^+$
- **validation:** measure B^0 meson oscillations, 4 different CPV analyses, one per tagger, ...



Mixing-induced CPV in $B_s^0 \rightarrow J/\psi(\mu\mu)\phi(KK)$

Results

Parameter	Value	Uncertainty
ϕ_s [mrad]	-74	± 23
$\Delta\Gamma_s$ [ps^{-1}]	0.0780	± 0.0045
Γ_s [ps^{-1}]	0.6633	± 0.0029
Δm_s [$\hbar \text{ps}^{-1}$]	17.759	± 0.038
$ \lambda $	1.011	± 0.019
$ A_0 ^2$	0.5273	± 0.0044
$ A_\perp ^2$	0.2417	± 0.0036
$ A_S ^2$	0.0072	± 0.0032
$\delta_\parallel$ [rad]	3.152	± 0.077
$\delta_\perp$ [rad]	2.940	± 0.098
$\delta_{S\perp}$ [rad]	0.45	± 0.14



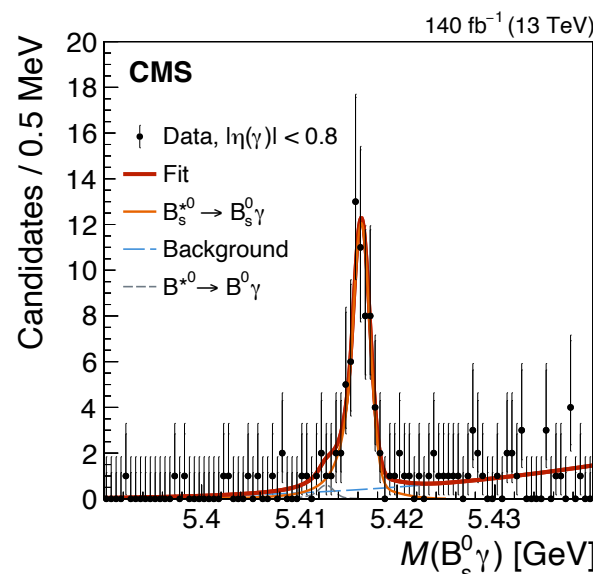
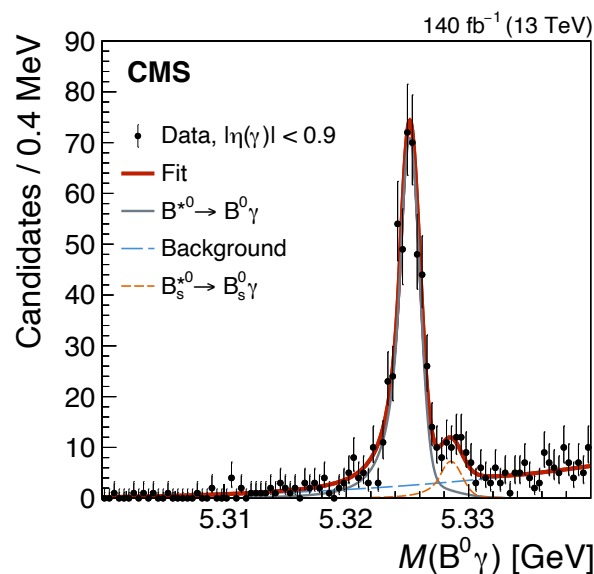
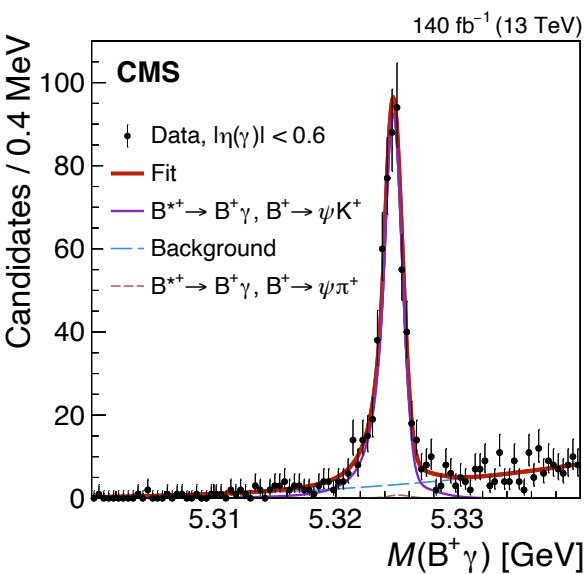
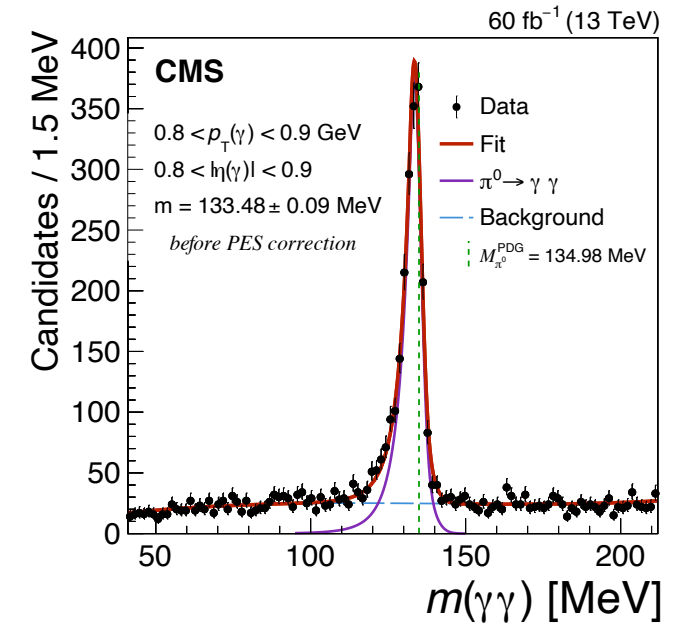
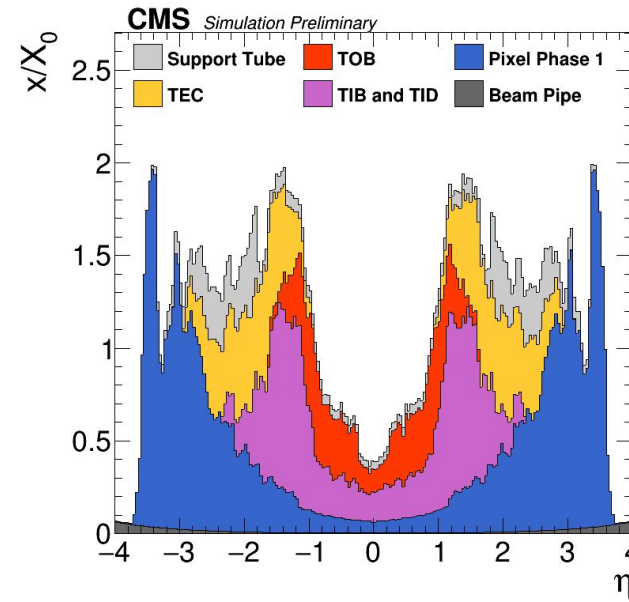
**3.2 σ evidence of $\phi_s \neq 0$
in $B_s^0 \rightarrow J/\psi\phi$ decays**

results in agreement with SM and other
experiments

still statistically limited,
competitive with other measurements

Exclusive reco of excited B^* and mass measurement

- first full reconstruction of the vector mesons B^{*+} , B^{*0} , B_s^*
 - using $\gamma^* \rightarrow e^+e^-$ conversion in material
 - lower acceptance, but cleaner signature than low energy photons
 - energy calibration with $\pi^0 \rightarrow \gamma\gamma$ in rapidity/momentum bins
 - previously: at LEP b-jet + converted γ
at LHCb $B_{s2}^*(5840)^0$ mass diff
- precise measurements of $m(B^*) - m(B)$ 45 – 49 MeV



	Parameter	Value
1	$\Delta m(B^{*+}) \equiv m(B^{*+}) - m(B^+)$	$45.277 \pm 0.039 \pm 0.027 \text{ MeV}$
2	$\Delta m(B^{*0}) \equiv m(B^{*0}) - m(B^0)$	$45.471 \pm 0.056 \pm 0.028 \text{ MeV}$
3	$\Delta m(B_s^{*0}) \equiv m(B_s^{*0}) - m(B_s^0)$	$49.407 \pm 0.132 \pm 0.041 \text{ MeV}$
4	$m(B^{*+})$	$5324.69 \pm 0.04 \pm 0.03 \pm 0.07 \text{ MeV}$
5	$m(B^{*0})$	$5325.19 \pm 0.06 \pm 0.03 \pm 0.08 \text{ MeV}$
6	$m(B_s^{*0})$	$5416.34 \pm 0.13 \pm 0.04 \pm 0.10 \text{ MeV}$
7	$m(B^{*0}) - m(B^{*+})$	$0.50 \pm 0.07 \pm 0.01 \pm 0.05 \text{ MeV}$
8	$m(B_s^{*0}) - m(B^{*+})$	$91.66 \pm 0.14 \pm 0.03 \pm 0.12 \text{ MeV}$
9	$m(B_s^{*0}) - m(B^{*0})$	$91.15 \pm 0.14 \pm 0.03 \pm 0.12 \text{ MeV}$
10	$m(B_s^{*0}) - \frac{1}{2} [m(B^{*0}) + m(B^{*+})]$	$91.40 \pm 0.13 \pm 0.03 \pm 0.12 \text{ MeV}$
11	$\Delta m(B^{*0}) - \Delta m(B^{*+})$	$0.19 \pm 0.07 \pm 0.01 \text{ MeV}$
12	$\Delta m(B_s^{*0}) - \Delta m(B^{*+})$	$4.13 \pm 0.14 \pm 0.03 \text{ MeV}$
13	$\Delta m(B_s^{*0}) - \Delta m(B^{*0})$	$3.94 \pm 0.14 \pm 0.03 \text{ MeV}$
14	$\Delta m(B_s^{*0}) - \frac{1}{2} [\Delta m(B^{*0}) + \Delta m(B^{*+})]$	$4.03 \pm 0.13 \pm 0.03 \text{ MeV}$
15	$\Delta m(B^{*0}) / \Delta m(B^{*+})$	$1.0043 \pm 0.0015 \pm 0.0002$
16	$\Delta m(B_s^{*0}) / \Delta m(B^{*+})$	$1.0912 \pm 0.0031 \pm 0.0007$
17	$\Delta m(B_s^{*0}) / \Delta m(B^{*0})$	$1.0866 \pm 0.0031 \pm 0.0007$
18	$2 \Delta m(B_s^{*0}) / [\Delta m(B^{*+}) + \Delta m(B^{*0})]$	$1.0889 \pm 0.0030 \pm 0.0007$

Flavour at HL-LHC

European strategy report [2503.24346](#) ATLAS + CMS + LHCb + Belle II

- **$L = 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, up to 200 pileup, target lumi up to 4 ab^{-1}**
- **CMS detector upgrades beneficial for flavour physics**
 - tracking at L1 $\rightarrow$ trigger on hadronic signatures
 - $\sim 30\text{ps}$ timing layer $\rightarrow$ enable particle identification
 - pixel, tracker, muon system resolution and coverage
- **only preliminary studies on effect of timing on flavour tag**

**CMS provided four projection studies in the document above,
 $B_s \rightarrow \mu\mu$, $\tau \rightarrow 3\mu$, $B \rightarrow K^*\mu\mu$ and $B_s \rightarrow J/\Psi\phi$**

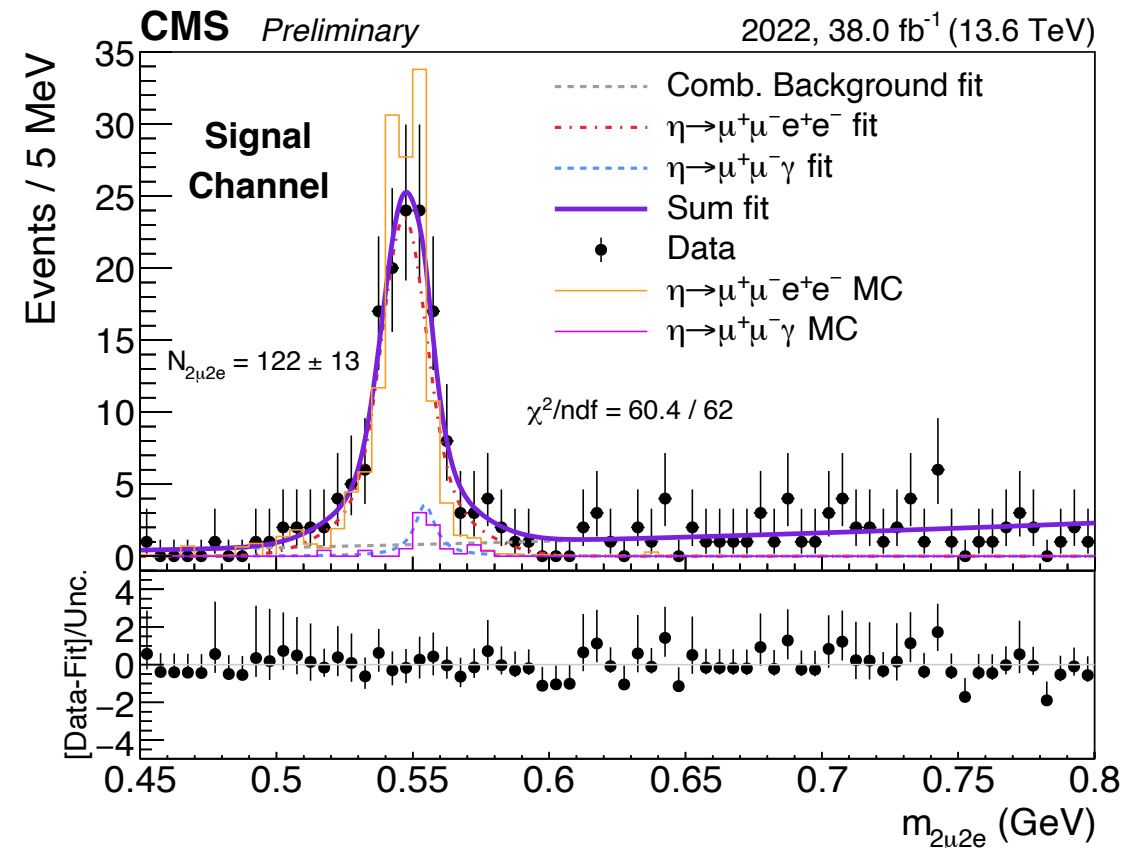
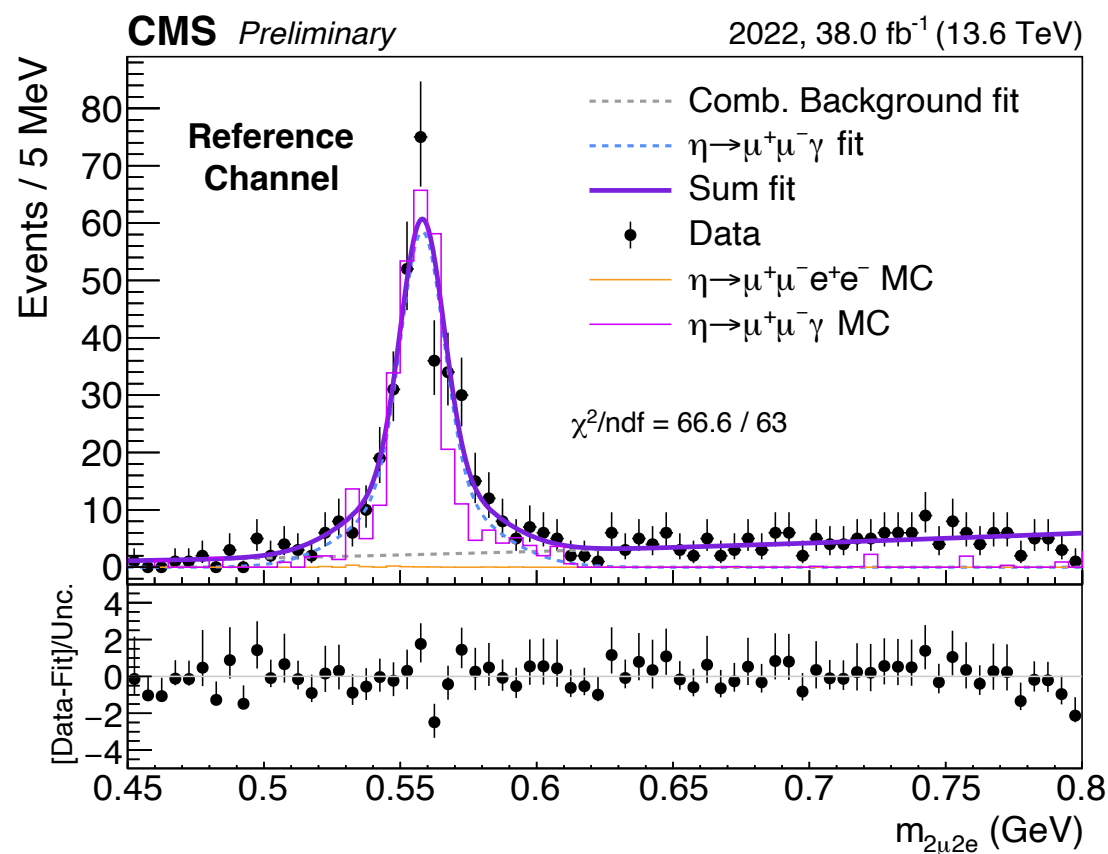
CMS can contribute or is already contributing to several measurements currently marked “—”

Experiment Assumed data sample	ATLAS 3000 fb ⁻¹	CMS 3000 fb ⁻¹	LHCb 300 fb ⁻¹	Belle II 50 ab ⁻¹
CKM angles				
β	—	—	0.08°	0.3°
α	—	—	—	0.6°
γ	—	—	0.3°	1.0°
ϕ_s [mrad]	(4 – 9)	3	3	—
CP violation in loop-dominated decays				
$S(B^0 \rightarrow \eta' K_S^0)$	—	—	—	0.015
$\phi_s(B_s^0 \rightarrow \phi\phi)$ [mrad]	—	—	9	—
$\phi_s(B_s^0 \rightarrow K^{*0} \bar{K}^{*0})$ [mrad]	—	—	8	—
CP violation in $B_{(s)}^0 - \bar{B}_{(s)}^0$ mixing				
a_{sl}^s	—	—	3	—
a_{sl}^d	—	—	2	6.2
CP violation in the charm sector				
ΔA_{CP} [10 ⁻⁵]	—	—	3.3	60
$A_{CP}(D^{+,0} \rightarrow \pi^{+,0} \pi^0)$ [10 ⁻⁵]	—	—	100, —	130, 70
$A_{\Gamma}(KK, \pi\pi)$ [10 ⁻⁵]	—	—	1.2	—
$\Delta x(D^0 \rightarrow K_S^0 \pi^+ \pi^-)$ [10 ⁻⁵]	—	—	1.6	40
Semileptonic B decays				
$ V_{ub} $	—	—	1%	1.2%
$ V_{cb} $	—	—	—	1.0%
$R(D), R(D^*)$	—	—	3.3%, 3.0%	1.4%, 1.0%
Leptonic B decays				
$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$ [10 ⁻⁹]	(0.33 – 0.40)	0.22	0.16	—
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$ [10 ⁻¹⁰]	(0.32 – 0.48)	0.12	0.12	—
$\tau_{\text{eff}}(B_s^0 \rightarrow \mu^+ \mu^-)$ [ps]	^{+(0.07–0.11)} _{–(0.05–0.08)}	0.05	0.05	—
$S(B_s^0 \rightarrow \mu^+ \mu^-)$	—	—	0.2	—
$\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)$	—	—	—	6%
$\mathcal{B}(B^+ \rightarrow \mu^+ \nu_\mu)$	—	—	—	5%
Flavour-changing neutral current $b \rightarrow s \ell \ell$ decays				
$P_5'(B^0 \rightarrow K^{*0} \mu^+ \mu^-)$ [10 ⁻³] [†]	(47 – 82)	23	12	—
$\mathcal{B}(B^{+,0} \rightarrow K^{+,*0} \nu \bar{\nu})$	—	—	—	8%, 23%
$\mathcal{B}(B^{+,0} \rightarrow K^{+,*0} \tau^+ \tau^-)$ [10 ⁻⁴]	—	—	—	< 0.9, < 1.5
Flavour-changing neutral current $b \rightarrow s \gamma$ decays				
$\mathcal{B}(B \rightarrow X_s \gamma; E_\gamma > 1.6 \text{ GeV})$	—	—	—	(4.7 – 8.8)%
$S(B^0 \rightarrow K_S^0 \pi^0 \gamma)$	—	—	—	0.04
$S(B_s^0 \rightarrow \phi \gamma)$	—	—	0.025	—
$A_{\text{T}}^{(2)}(B^0 \rightarrow K^{*0} e^+ e^-; \text{very low } q^2)$	—	—	0.016	0.08
$\alpha_\gamma(\Lambda_b^0 \rightarrow \Lambda^0 \gamma)$	—	—	0.038	—
Lepton flavour violation in τ decays				
$\mathcal{B}(\tau^+ \rightarrow \mu^+ \gamma)$ [10 ⁻⁸]	—	—	—	< 0.7
$\mathcal{B}(\tau^+ \rightarrow \mu^+ \mu^+ \mu^-)$ [10 ⁻⁸]	< (0.13 – 0.64)	< 0.39	< 0.26	< (0.02 – 0.17)

[†] The sensitivity for the P_5' variable is quoted for the range $q^2 \in [4.0, 6.0] \text{ GeV}^2$ for ATLAS and LHCb and $q^2 \in [4.3, 6.0] \text{ GeV}^2$ for CMS.

Observation of $\eta \rightarrow 2e2\mu$

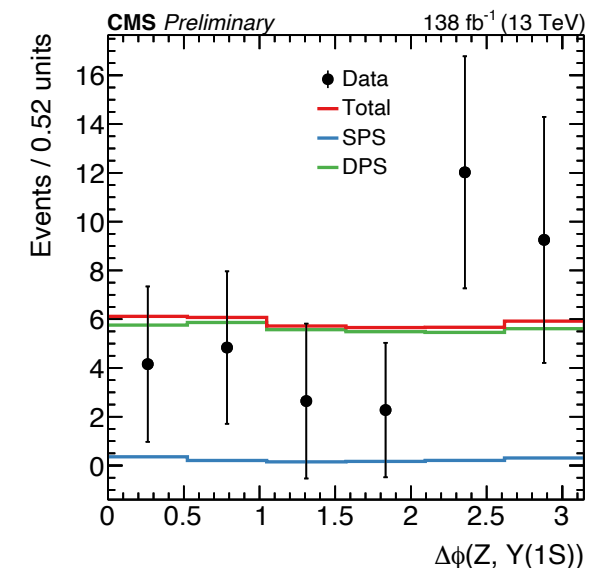
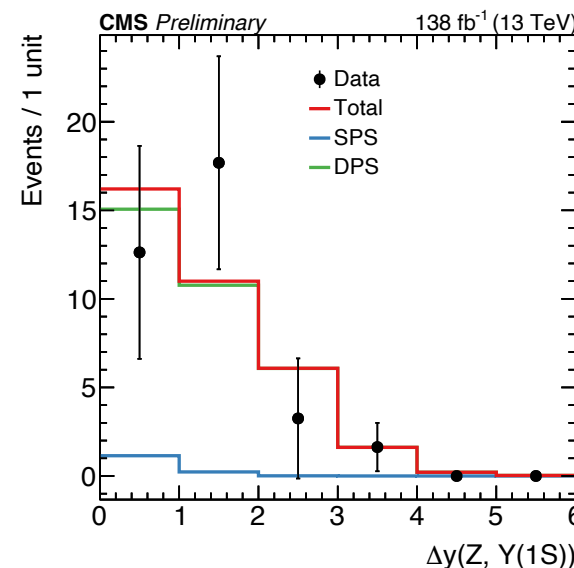
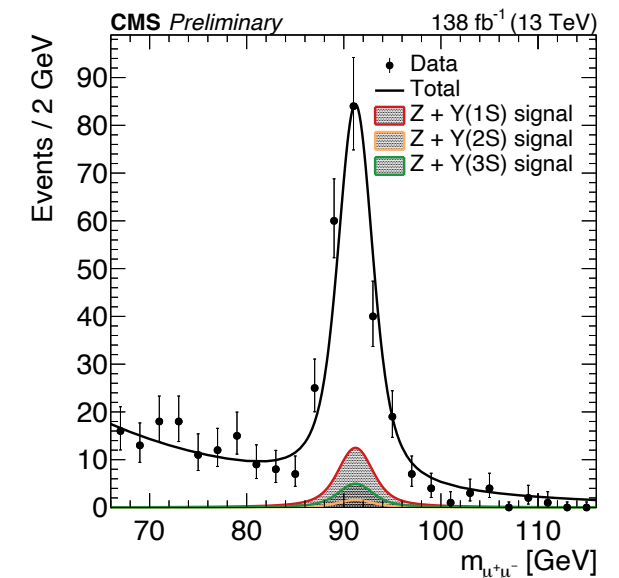
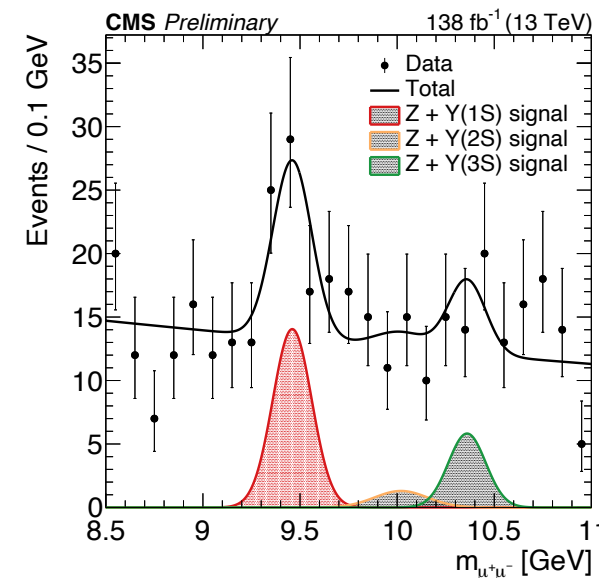
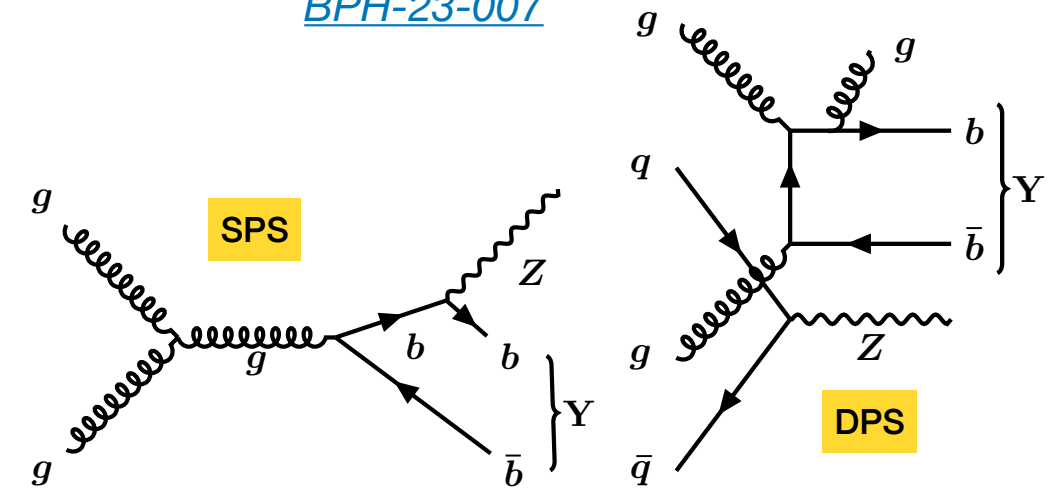
- rare, double Dalitz SM decay
 - q^2 -dependent form factors (same used for μ g-2) cannot be computed exactly
 - experimental input needed
 - prediction $\mathcal{B}(\eta \rightarrow 2e2\mu) = 2.4 \times 10^{-6}$, previous limits 2 order of mag away
- normalized to same final state $\eta \rightarrow 2\mu\gamma(\rightarrow ee)_{\text{conv}}$
 - invert photon conversion veto, di-ele mass veto



observed $\mathcal{B}(\eta \rightarrow 2e2\mu) = (2.2 \pm 0.7) \times 10^{-6}$

Measurement of $\Upsilon(1S) + Z$ production cross section

- produced via single- and double-parton scattering
- exp. input to LDME and NRQCD
- constrain bkg in rare Higgs decays analyses
- Run2 137 fb⁻¹, 4 μ final state, normalized in situ to $Z \rightarrow 4\mu$



- $\Upsilon(1S) + Z$ established at $> 5\sigma$
- DPS fraction $(95 \pm 25) \%$

B meson production fraction ratios in hadronic open-charm decays

- **production fractions (f_d, f_u, f_s) key input for normalization of $B_s \rightarrow \mu\mu$,**
 - uncertainty in f_s/f_u leading systematic
- **(f_d, f_u, f_s) measured at 13 TeV by both [LHCb](#) and [CMS](#)**
 - complementary in p_T and η , observed p_T dependency at low p_T
- **can we measure *absolute* (f_d, f_u, f_s) ratios?**
 - **not** with $B^0 \rightarrow J/\psi K^*$, $B^+ \rightarrow J/\psi K^+$, $B_s \rightarrow J/\psi \phi$ as PF are implicitly included in $\mathcal{B}(B_s \rightarrow J/\psi \phi)$ measured by LHCb [[Phys. Rev. D 104 \(2021\)](#)]
 - but abundant statistics allows to accurately measure trends and dependencies
 - **→ use open charm B decays** $B^0 \rightarrow \pi^+ D^-$, $B^+ \rightarrow \pi^+ \bar{D}^0$, $B_s \rightarrow \pi^+ D_s^-$
 - 2018 B-parking dataset probe side

the master equation

- **Channels:**

- $B^+ \rightarrow \pi^+ \bar{D}^0 (K^+ \pi^-)$
- $B_s^0 \rightarrow \pi^+ D_s^- (\pi^- \varphi (K^+ K^-))$
- $B^0 \rightarrow \pi^+ D^- (K^+ \pi^- \pi^-)$

- **Key Equation:**

$$\begin{aligned}
 \frac{f_s}{f_d} &= \frac{\mathcal{B}(B^0 \rightarrow \pi^+ D^-)}{\mathcal{B}(B_s^0 \rightarrow \pi^+ D_s^-)} \frac{\mathcal{B}(D^- \rightarrow K^+ \pi^- \pi^-)}{\mathcal{B}(D_s^- \rightarrow \pi^- \varphi (K^+ K^-))} \frac{N_{\text{corr}}(B_s^0)}{N_{\text{corr}}(B^0)} \\
 &= \frac{\mathcal{B}(B^0 \rightarrow K^+ D^-)}{\mathcal{B}(B_s^0 \rightarrow \pi^+ D_s^-)} \frac{\mathcal{B}(B^0 \rightarrow \pi^+ D^-)}{\mathcal{B}(B^0 \rightarrow K^+ D^-)} \frac{\mathcal{B}(D^- \rightarrow K^+ \pi^- \pi^-)}{\mathcal{B}(D_s^- \rightarrow \pi^- \varphi (K^+ K^-))} \frac{N_{\text{corr}}(B_s^0)}{N_{\text{corr}}(B^0)} \\
 &= \Phi_{\text{PS}} \left| \frac{V_{us}}{V_{ud}} \right|^2 \left(\frac{f_K}{f_\pi} \right)^2 \frac{\tau_{B^0}}{\tau_{B_s^0}} \frac{1}{N_a N_F} \frac{\mathcal{B}(B^0 \rightarrow \pi^+ D^-)}{\mathcal{B}(B^0 \rightarrow K^+ D^-)} \frac{\mathcal{B}(D^- \rightarrow K^+ \pi^- \pi^-)}{\mathcal{B}(D_s^- \rightarrow \pi^- \varphi (K^+ K^-))} \frac{N_{\text{corr}}(B_s^0)}{N_{\text{corr}}(B^0)}
 \end{aligned}$$

- Prediction of $\mathcal{B}(B^0 \rightarrow K^+ D^-)/\mathcal{B}(B_s^0 \rightarrow \pi^+ D_s^-)$ with external theory inputs

- 1) $\mathcal{B}(B_s^0 \rightarrow \pi^+ D_s^-)$ also dominated by LHCb studies (and dependent on f_s/f_d)
- 2) $\mathcal{B}(B^0 \rightarrow K^+ D^-)$ has a more theoretically clean prediction than $B^0 \rightarrow \pi^+ D^-$, but Cabibbo-suppressed
- 3) $N(B^0 \rightarrow \pi^+ D^-)$ used as a proxy to improve statistics
 - $\mathcal{B}(B^0 \rightarrow K^+ D^-)/\mathcal{B}(B^0 \rightarrow \pi^+ D^-) = 0.0819 \pm 0.0020$, measured with a good precision

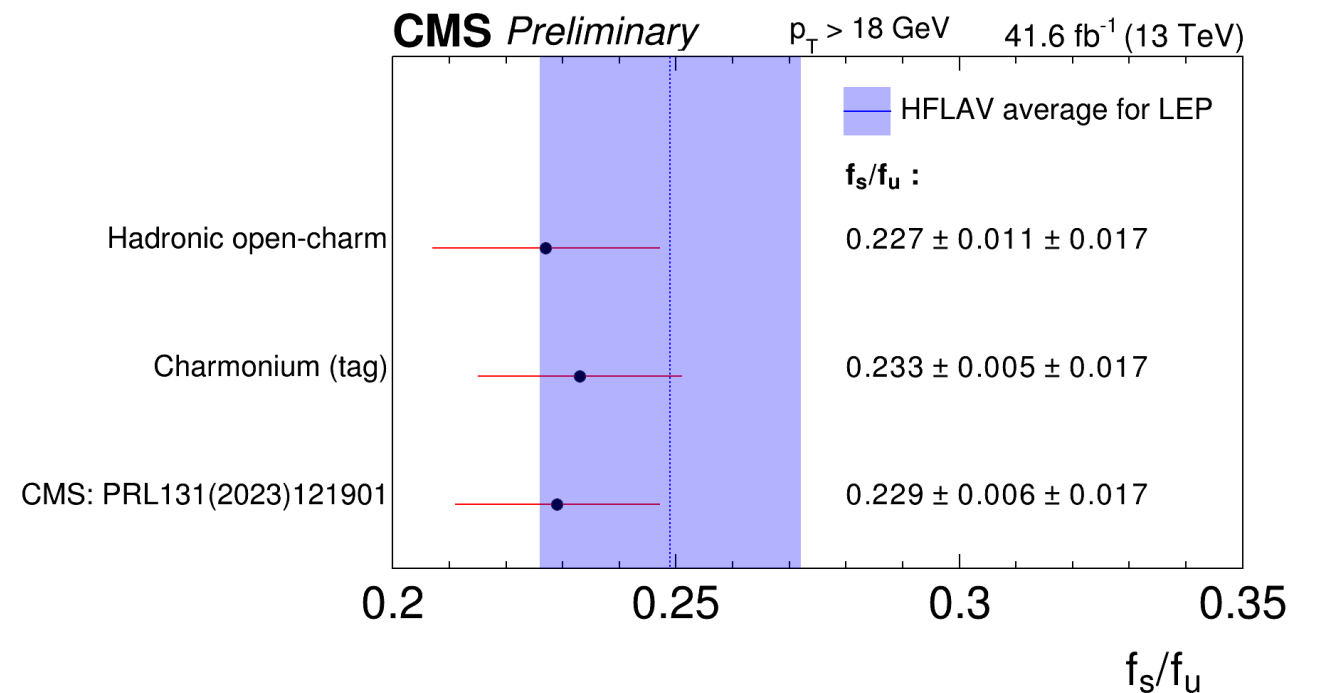
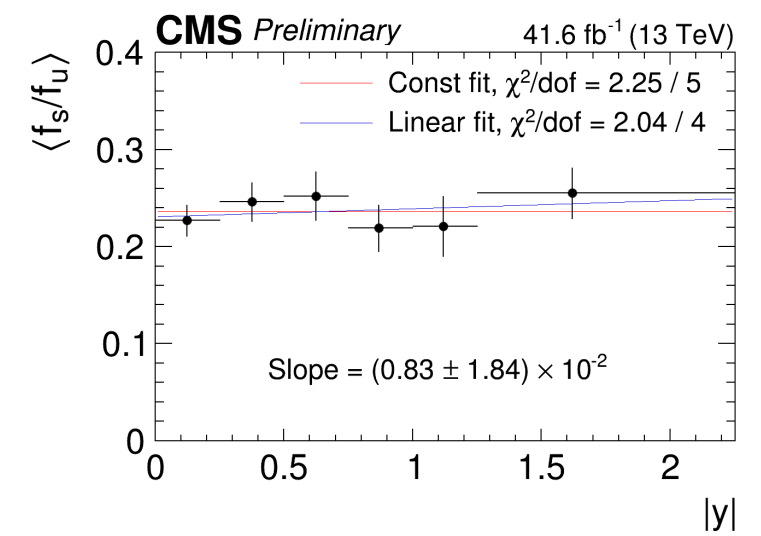
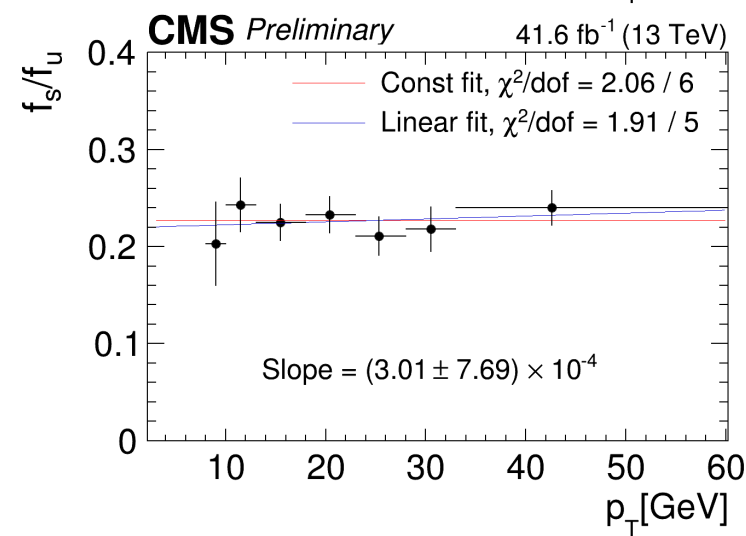
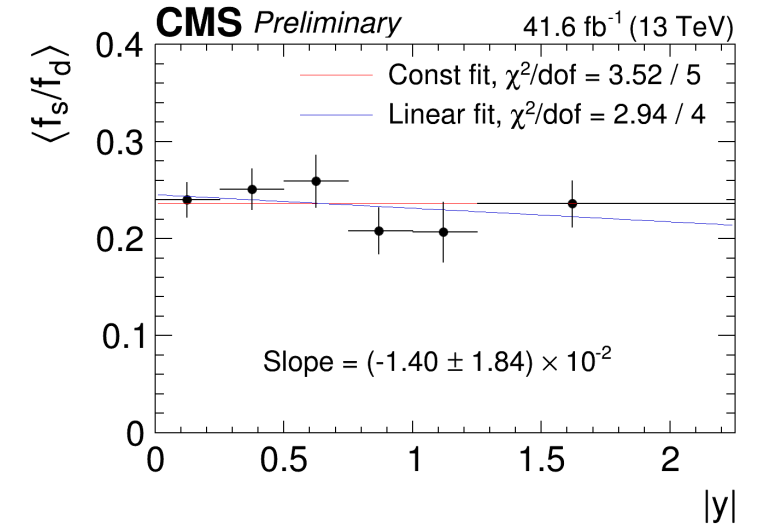
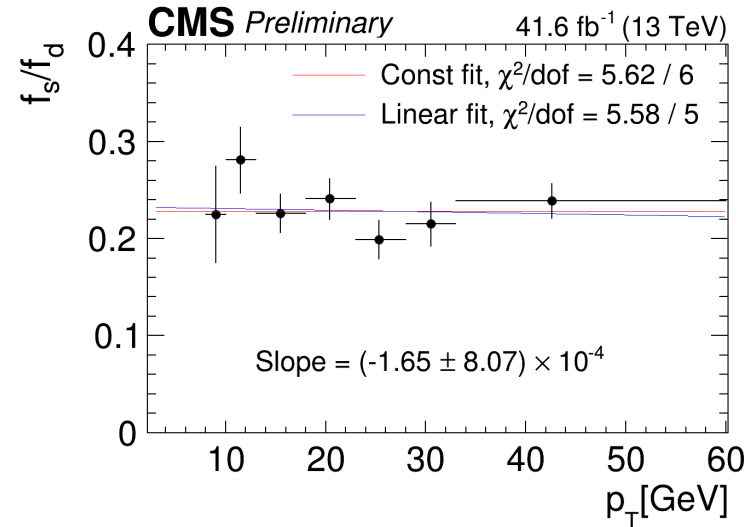
Inputs	Description	Value
Φ_{PS}	The difference in phase space of two channels	1.003 [PDG]
$\frac{ V_{us} f_K}{ V_{ud} f_\pi}$	Product of CKM matrix and decay constant ratios	0.2768 [PRD 100 (2019) 034514]
$\tau_{B_s^0}/\tau_{B^0}$	Lifetime ratio between B^0 and B_s^0	1.002 ± 0.004 [HFLAV]
$1/N_a$	The ratio of correction accounting for non-factorizable effect	$1.0048^{+0.0046}_{-0.0022}$ [EPJC 80 (2020) 347 and 951]
$1/N_F$	The ratio of form factors	1.002 ± 0.042 [EPJC 80 (2020) 347 and 951]

- **absolute f_s/f_d and f_s/f_u are measured**

- no evidence of p_T dependency at high momentum
- confirmed independence vs η

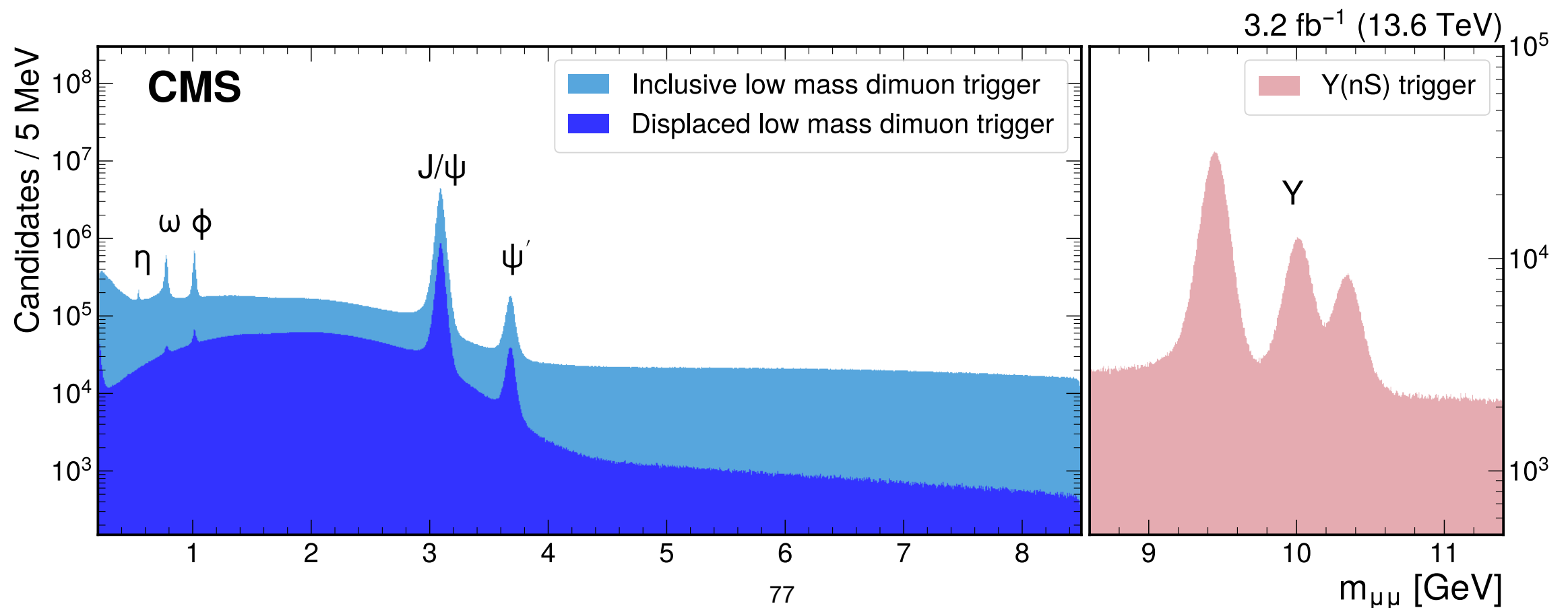
- in addition

- relative ratios measured with charmonium decays
- test of isospin invariance $f_d/f_u = 1?$



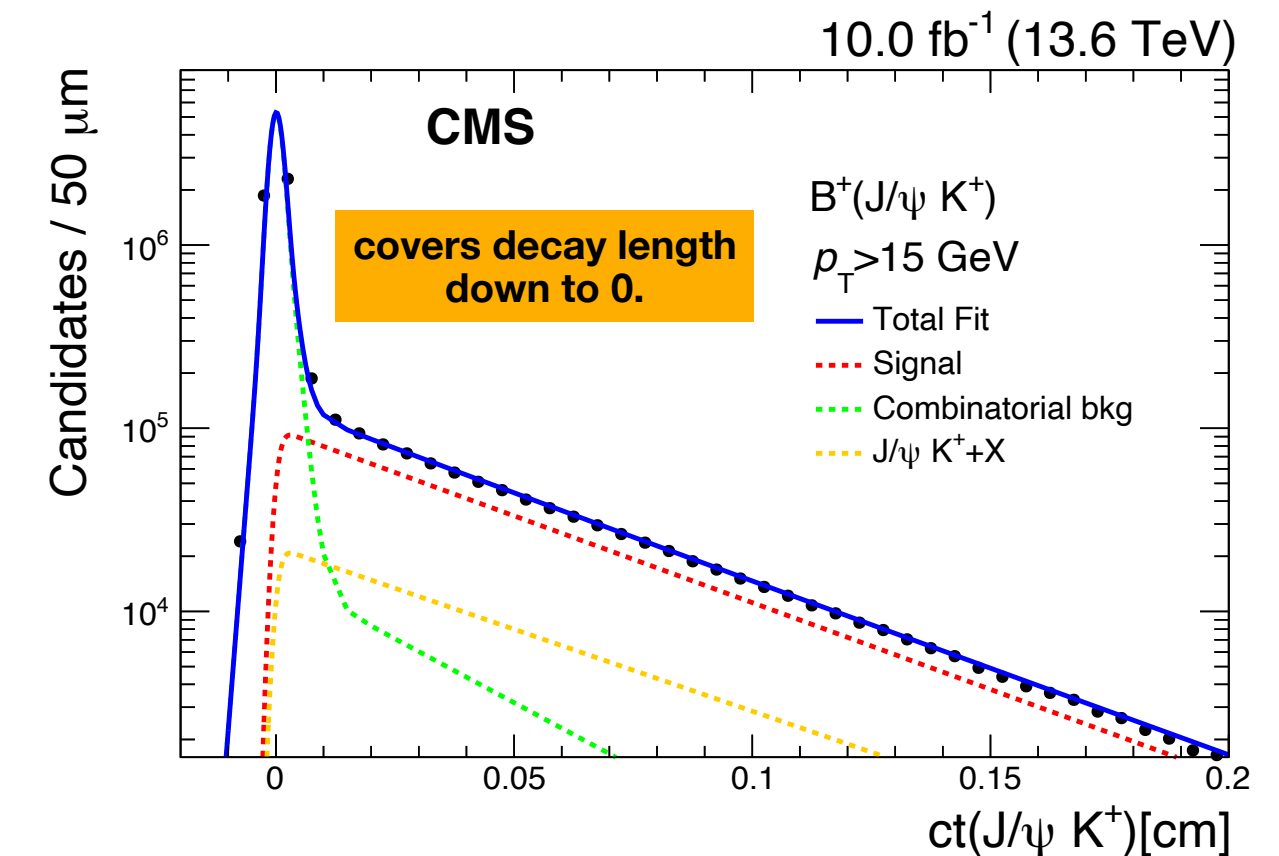
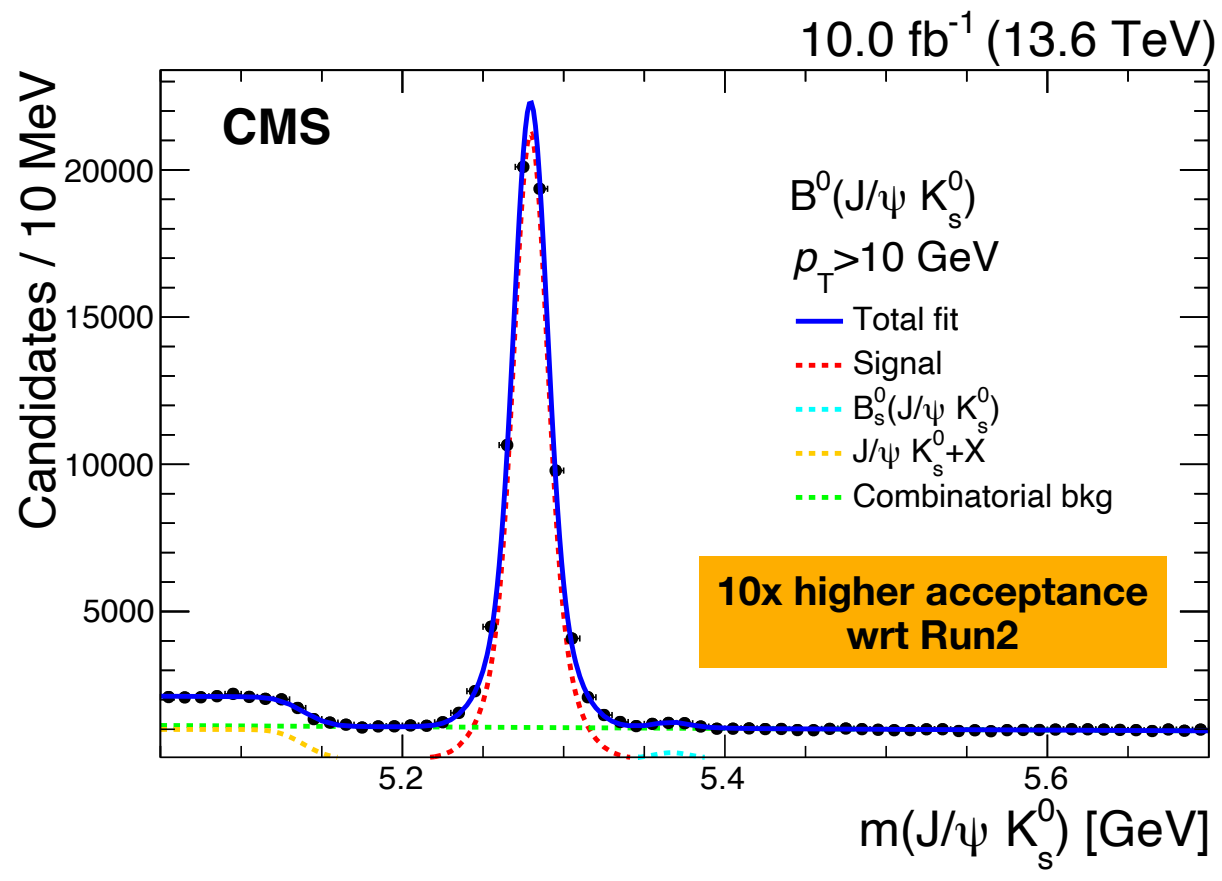
Inclusive dimuon triggers

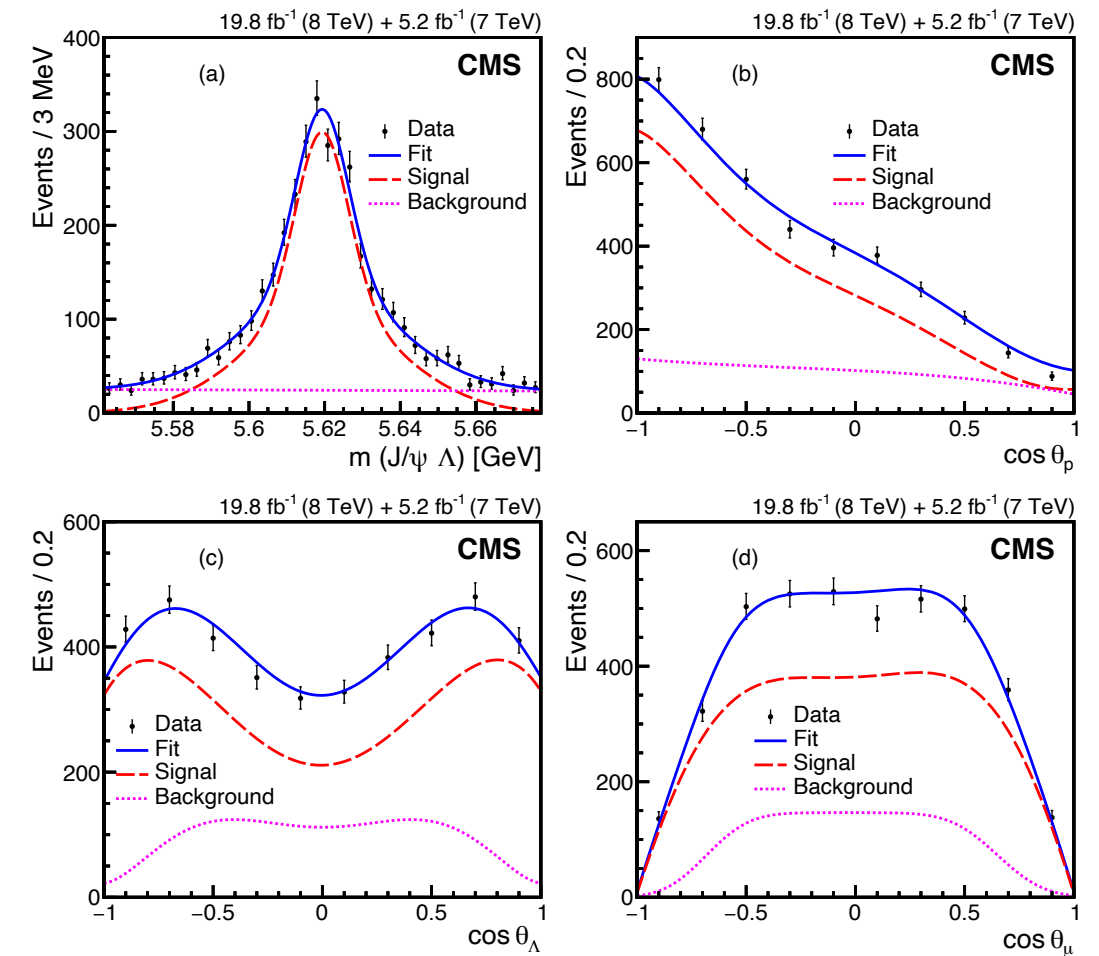
- **inclusive di-muon trigger up to $m_{\mu\mu} < 8 \text{ GeV}$**
 $p_T > 3,4 \text{ GeV}$, ~full pseudorapidity coverage
 - in Run2, either di-mu + track low p_T + displacement, or di-mu inclusive high p_T
 - significant increase in acceptance, (re-)opens new avenues



Inclusive dimuon triggers

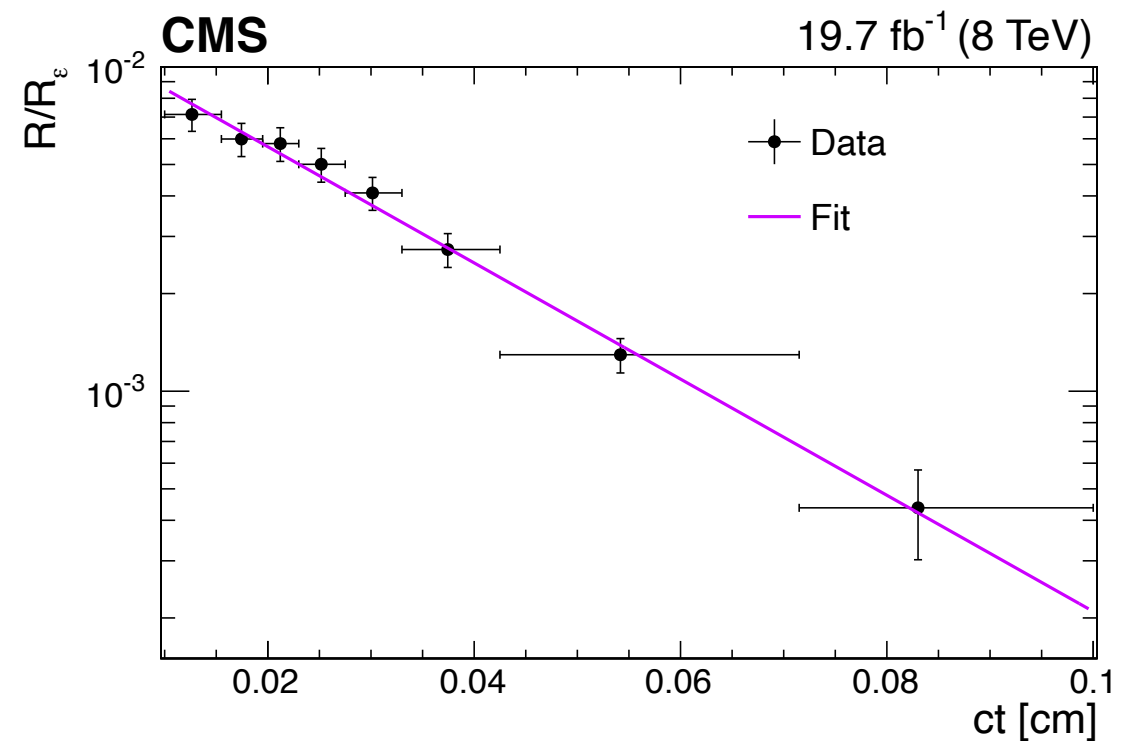
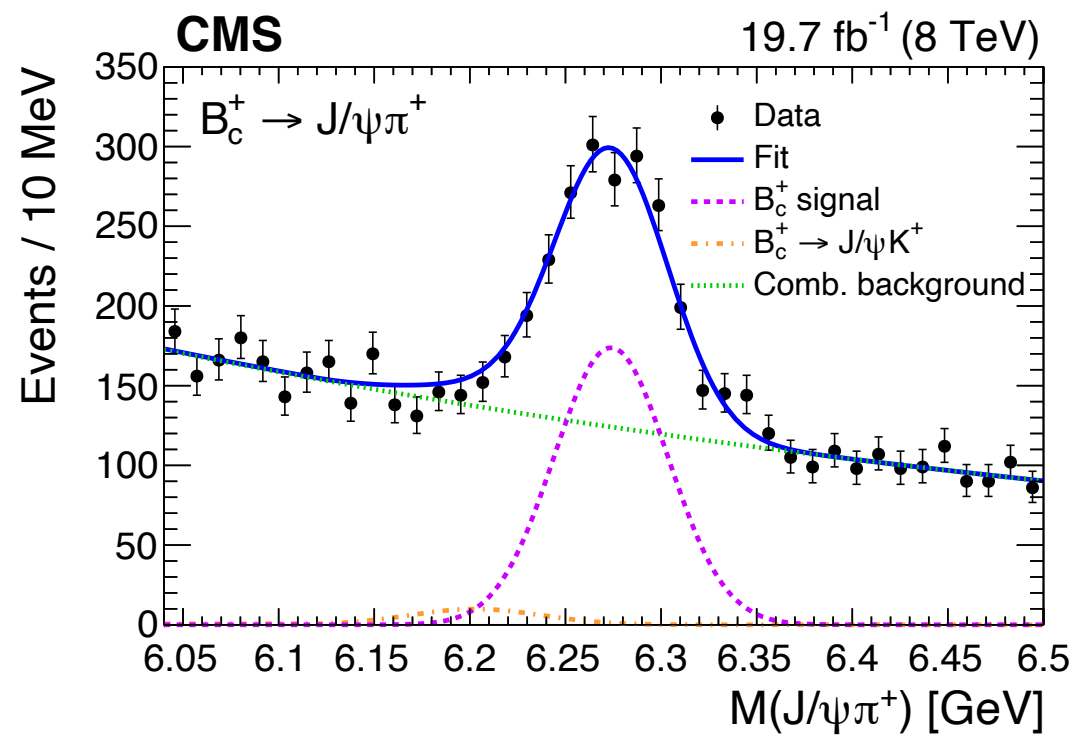
- **inclusive di-muon trigger up to $m_{\mu\mu} < 8 \text{ GeV}$**
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 - significant increase in acceptance, (re-)opens new avenues





- 79

B_c lifetime



- CMS (and LHCb) most precise measurements from Run2
- **CMS Run3 statistics 15x, cross section 2x**
 - potential breakthrough
- B_c lifetime complementary constraint of LFUV in $R(D^{(*)})$ [see refs in [Blanke](#)]

B_c^+

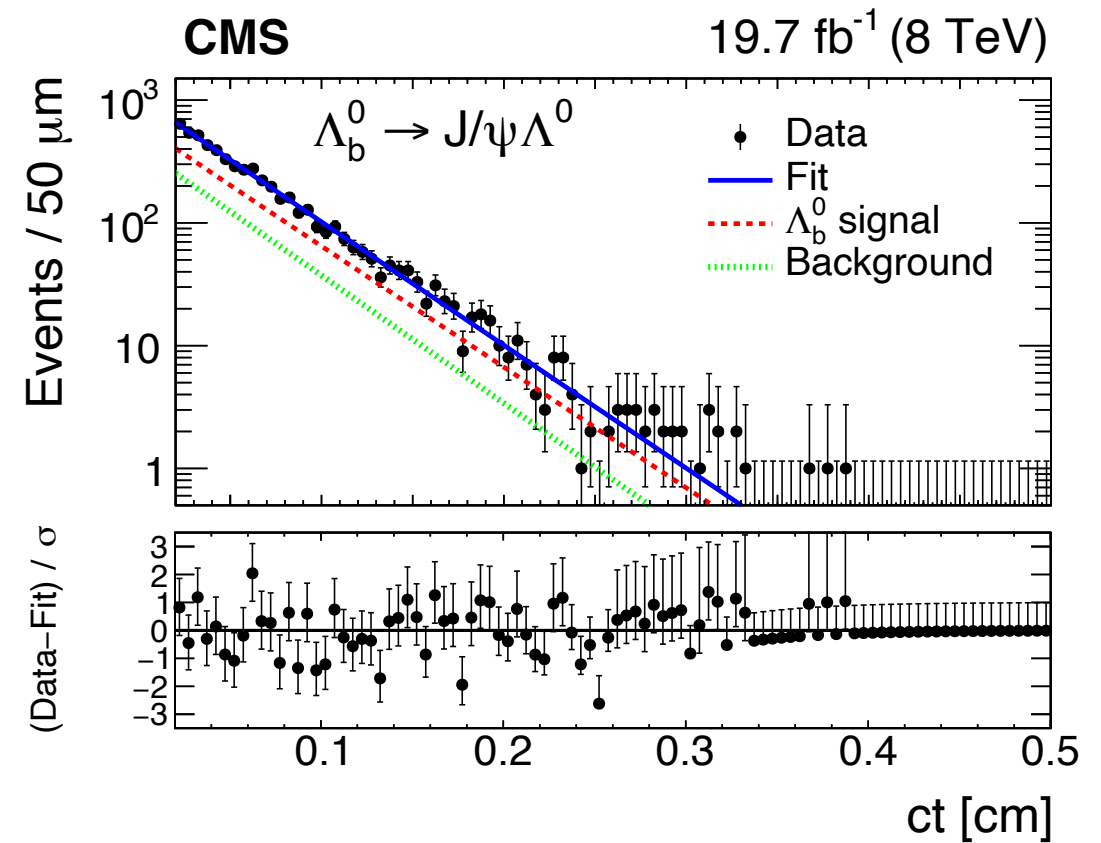
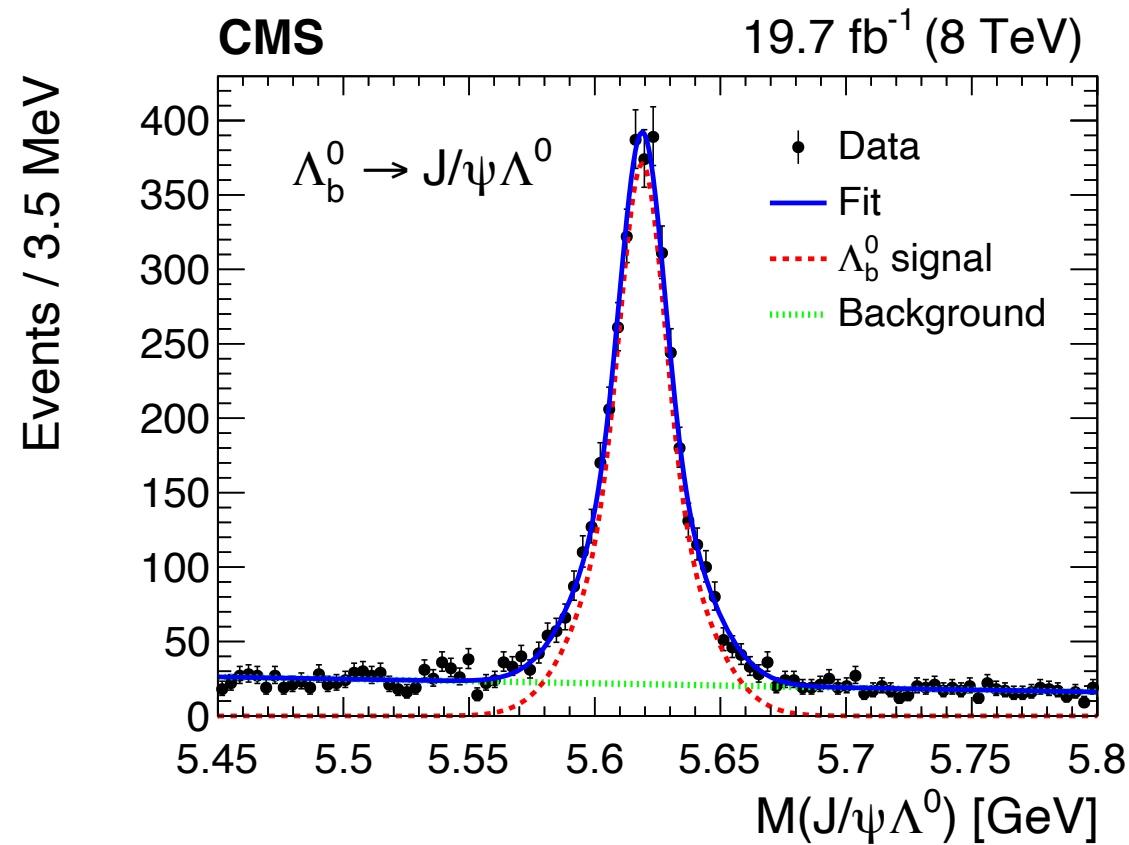
MEAN LIFE

PDGID:S091T

JSON (beta)

VALUE (10^{-12} s)	DOCUMENT ID	TECN	COMMENT
0.510 ± 0.009	OUR EVALUATION (Produced by HFLAV)		
0.510 ± 0.009	OUR AVERAGE		
0.541 ± 0.026 ± 0.014	¹ SIRUNYAN 2018BY 🔍	CMS	<i>pp</i> at 8 TeV
0.5134 ± 0.0110 ± 0.0057	^{2, 3} AAJ 2015G 🔍	LHCB	<i>pp</i> at 7, 8 TeV
0.509 ± 0.008 ± 0.012	⁴ AAJ 2014G 🔍	LHCB	<i>pp</i> at 8 TeV

Λ_b lifetime



- CMS (and LHCb) most precise measurements from Run2
- CMS Run3 statistics 15x, cross section 2x
- potential breakthrough

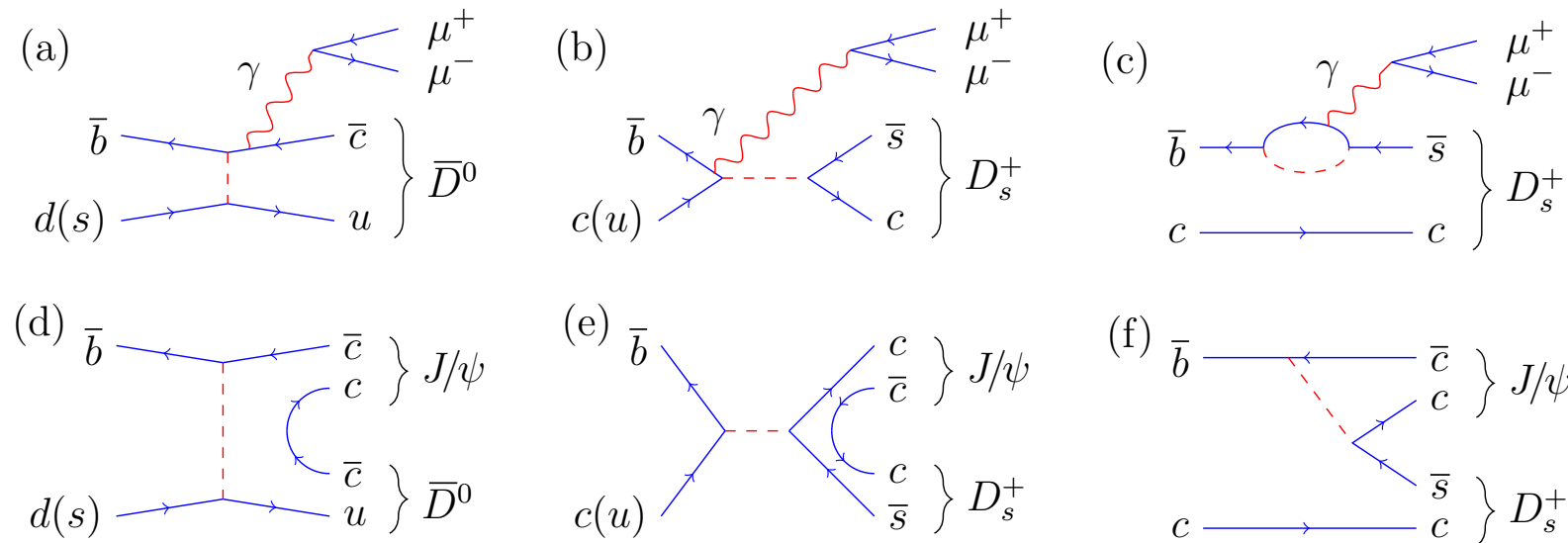
Λ_b^0 MEAN LIFE

PDGID:S040T

See b -baryon Admixture section for data on b -baryon mean life average over species of b -baryon

VALUE (10^{-12} s)	EVTS	DOCUMENT ID	TECN	COMMENT
1.468 $\pm$ 0.009	OUR EVALUATION	(Produced by HFLAV)		
1.477 $\pm$ 0.027 $\pm$ 0.009	¹	SIRUNYAN 2018BY Q	CMS	pp at 8 TeV
1.415 $\pm$ 0.027 $\pm$ 0.006	²	AAIJ 2014E Q	LHCB	pp at 7 TeV
1.479 $\pm$ 0.009 $\pm$ 0.010	³	AAIJ 2014U Q	LHCB	pp at 7, 8 TeV

$b \rightarrow s\ell\ell$ in $B_c \rightarrow D_s\mu\mu$ decays

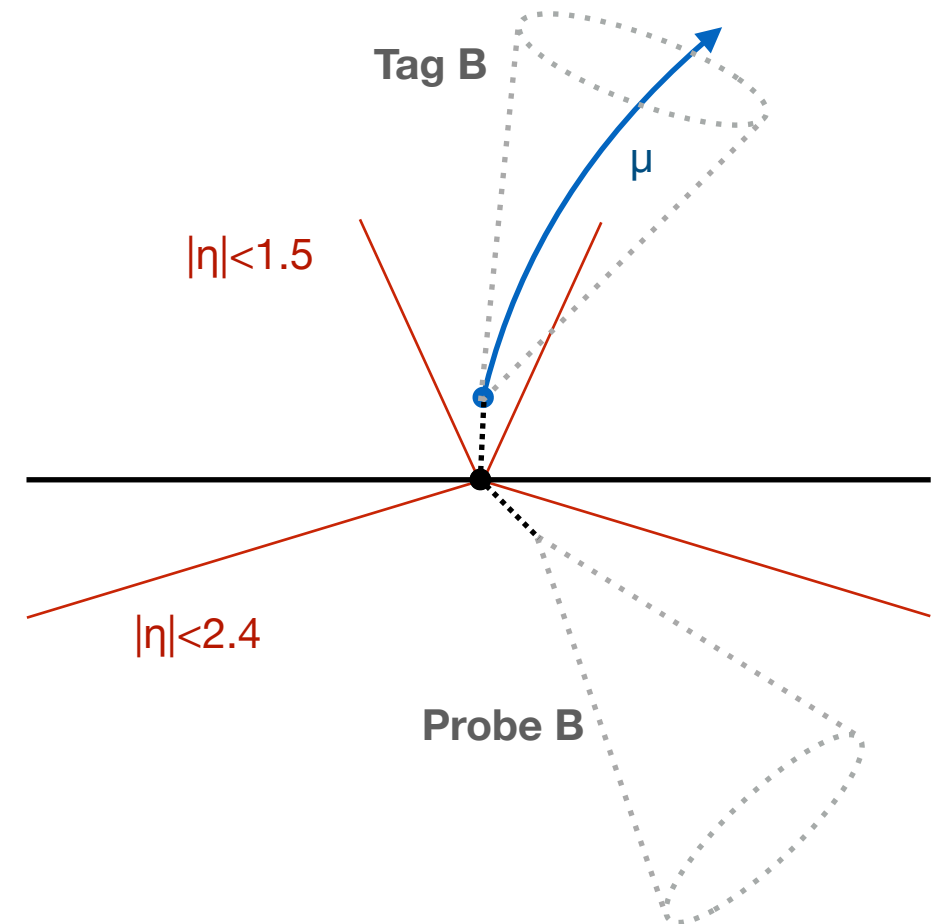


[LHCb
10.1007/JHEP02\(2024\)032](https://arxiv.org/abs/2402.10007)

- cited yesterday by Biplab
- LHCb exclusion already in the 10^{-7} - 10^{-8} range, close to SM exp.
- **with Run 3 data, CMS can access these decays, potentially competitive**

Other semileptonic?

- thanks to single muon triggers, CMS can also access e.g.
 - $\Lambda_b \rightarrow \Lambda_c^{(*)} \mu \nu$
 - $\Xi_b \rightarrow \Xi_c^{(*)} \mu \nu$
 - ...
- time and person power limited

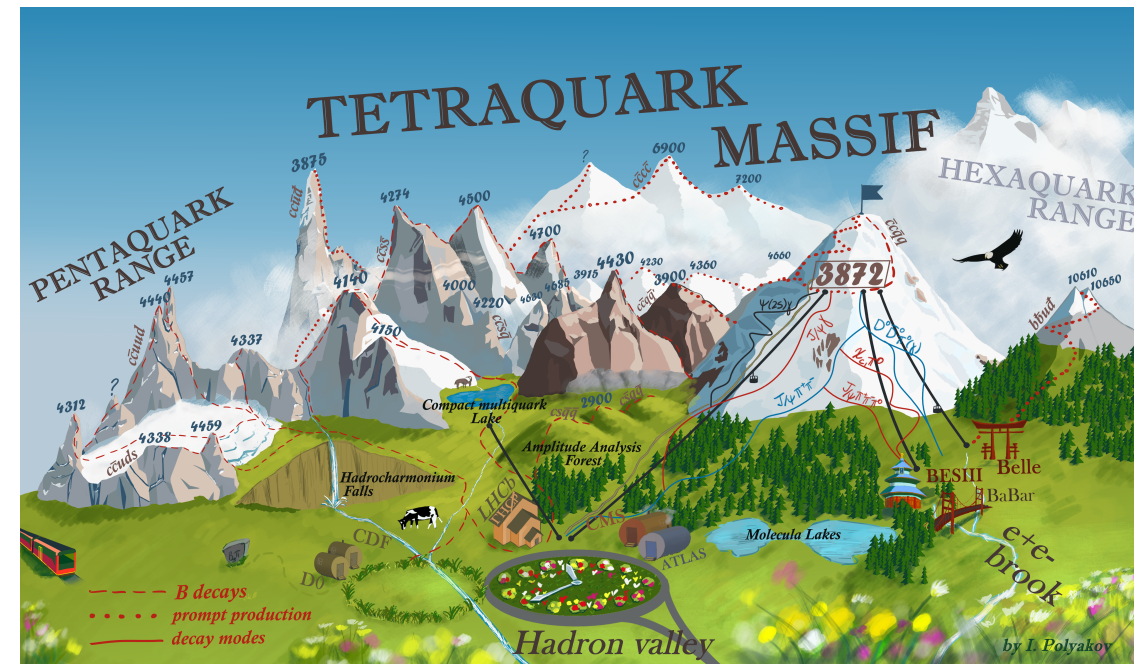


Exotica and spectroscopy

Tetraquarks - motivations

credit [2410.06923](#)

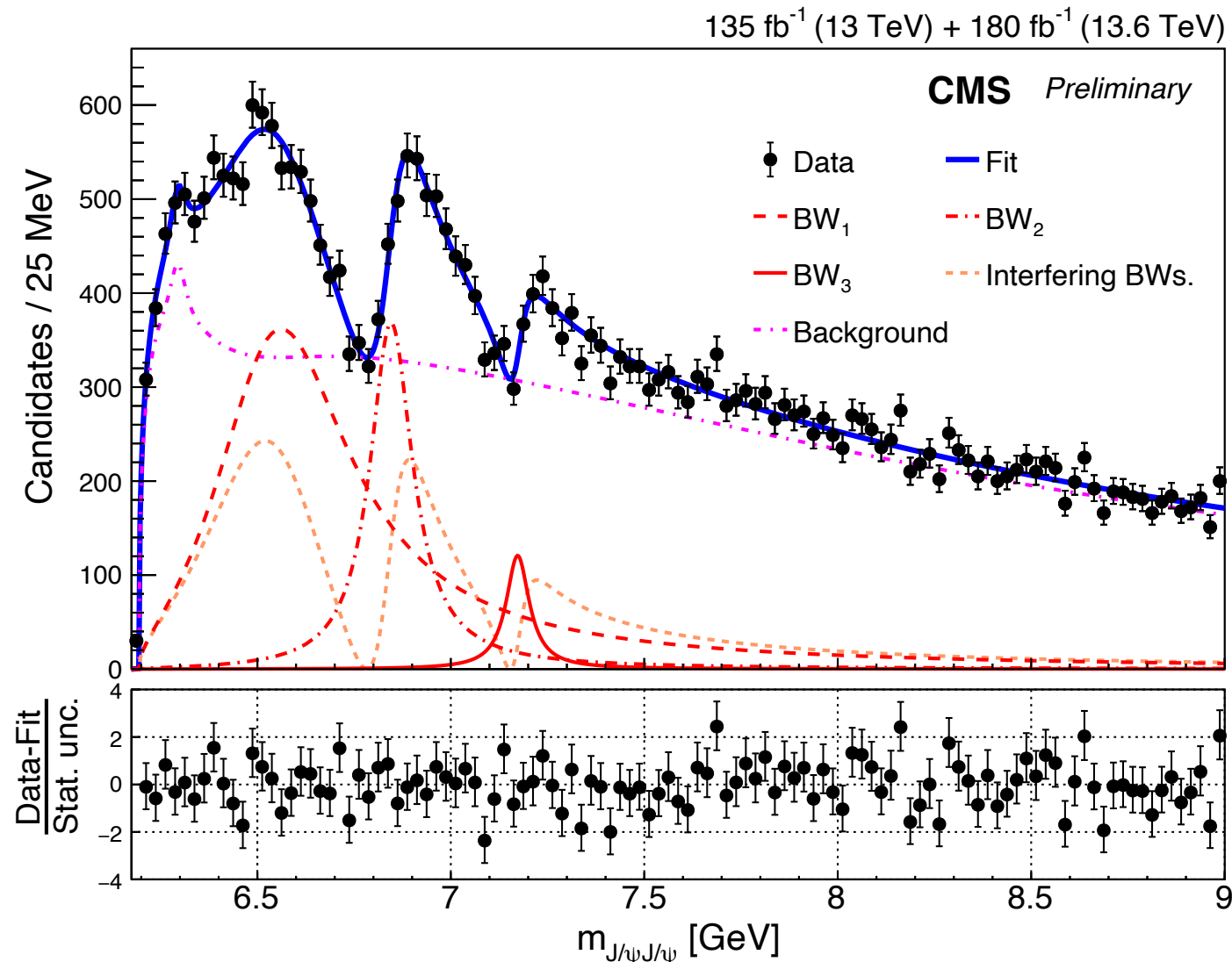
- Gell-Mann and Zweig's (1964) quark model allowed for “exotic” tetra and pentaquarks
 - first confirmed in 2003 discovery of $X(3872) \rightarrow J/\Psi \pi\pi$ [PRL 91 \(2003\)](#)
 - tens more at the LHC (survey by [P. Koppenburg](#))
- tightly-bound states of diquark+diantiquark or loosely-bound meson molecules (or other)?
 - insight into QCD potential, confinement, strong force



Standard Mesons	Exotic Mesons: Tetracharm				Threshold Effects
	Molecule	Diquark	Compact (Amorphous)	Hybrid	e.g. Triangle Singularity
					$\psi(3770) \rightarrow \bar{D} \psi(3770)$ J/ψ

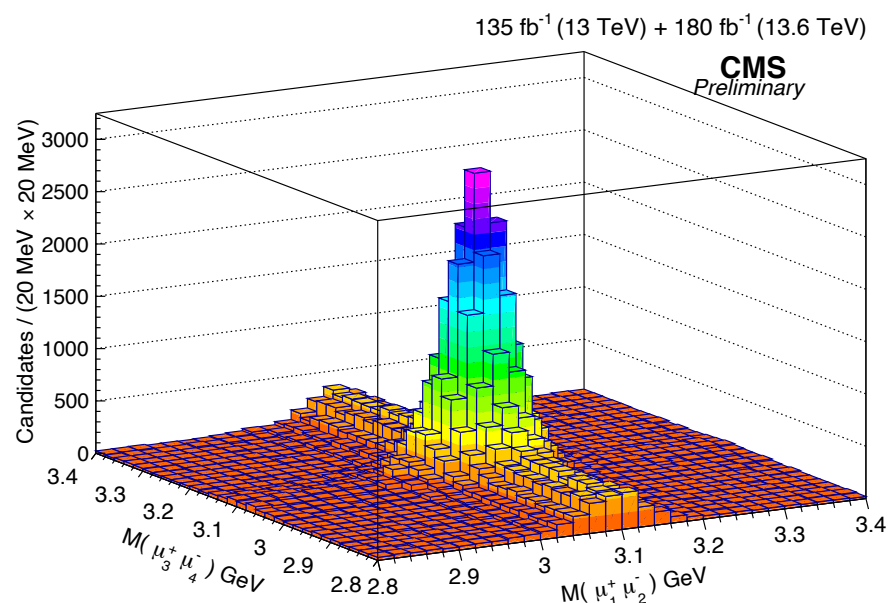
- all-heavy tetra quarks particularly interesting
 - excited hadron in (u, d, s) sector have large widths, overlaps, hard to handle
 - c and b quark resonances more tractable and, in particular, $J/\Psi \rightarrow \mu\mu$ (and possibly $\Upsilon \rightarrow \mu\mu$) are clean experimental signature in CMS

Family of all-charm tetraquarks in $X \rightarrow J/\Psi J/\Psi \rightarrow 4\mu$

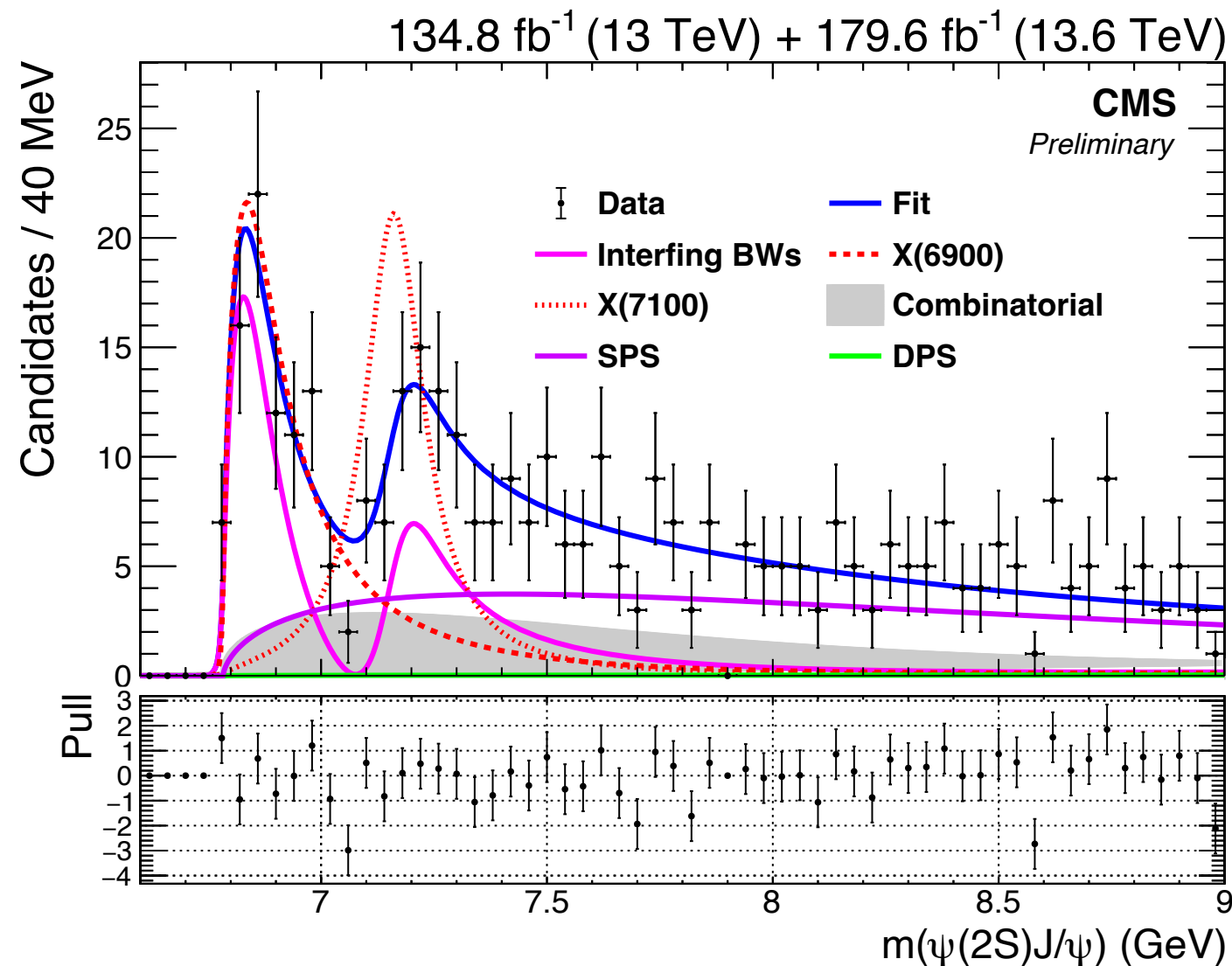


Observation of structures at $X(6600)$, $X(6900)$, and $X(7100)$

- **each confirmed at $\gg 5\sigma$ level**
 - $X(6900)$ observed initially by LHCb and later by ATLAS too
 - other structures seen with lower significances
- **interference between three structures established by CMS at $> 5\sigma$**
 - preferred by other experiments too
- **implies same J^{PC} quantum numbers, family of states with different radial excitation**
 - $m_{X_i}^2$ follow Regge trajectory for radial excitation
- backgrounds include DPS, NRSPS, feed downs, and "empirical" threshold enhancement
- update of Run2 analysis, to include 2022-2024 data, more than double statistics



Family of all-charm tetraquarks in $X \rightarrow J/\Psi \Psi(2S) \rightarrow 4\mu$



Observation of $X(6900)$ at $> 5\sigma$ evidence of $X(7100)$ at 4σ

- near-threshold enhancement in this channel first observed by ATLAS
- **interference assumed** analogous to $J/\Psi J/\Psi \rightarrow 4\mu$
- effect of below-threshold $X(6600)$ as systematic

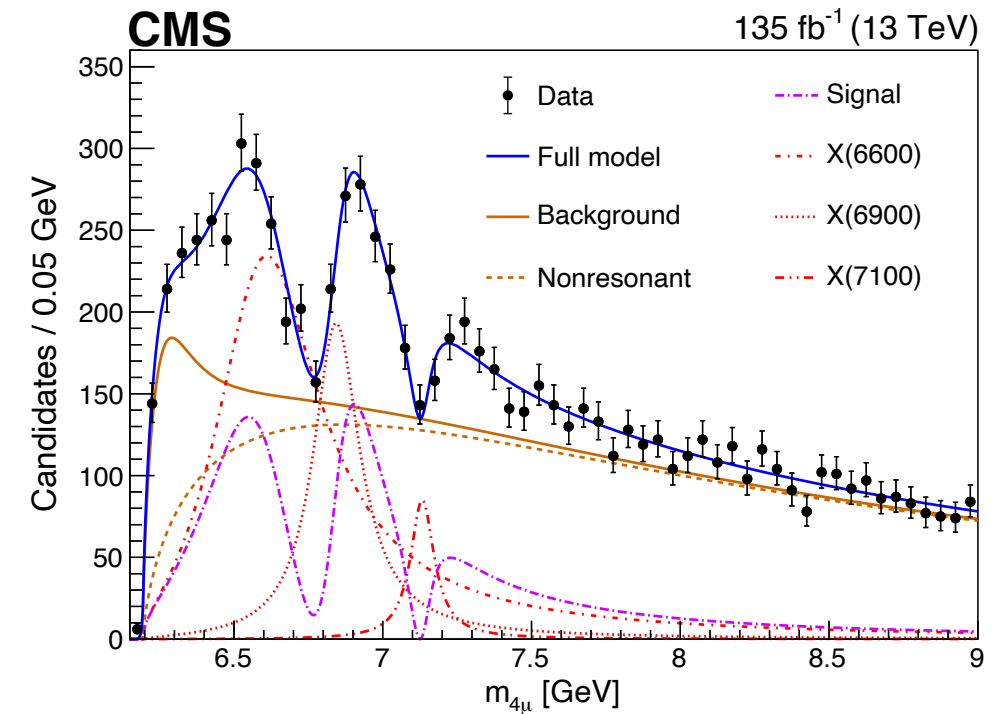
- **masses and widths of $X(6900)$ and $X(7100)$ agree well with those measured in $J/\Psi J/\Psi \rightarrow 4\mu$**

Fit	Sample	Interf.		X(6600)	X(6900)	X(7100)
f_{i23}	$J/\psi\psi(2S)$	BW_2, BW_3	$m :$	—	$6876^{+46+110}_{-29-110}$	7169^{+26+74}_{-52-70}
			$\Gamma :$	—	$253^{+290+120}_{-100-120}$	$154^{+110+140}_{-82-160}$
$f_{JJ} [1]$	$J/\psi J/\psi$	BW_1, BW_2, BW_3	$m :$	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
			$\Gamma :$	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

Determination of J^{PC} of all-charm tetra quarks

measure J and P of the family of three full-charm tetraquarks observed by CMS ($C = +$ from $J/\Psi J/\Psi$ final state)

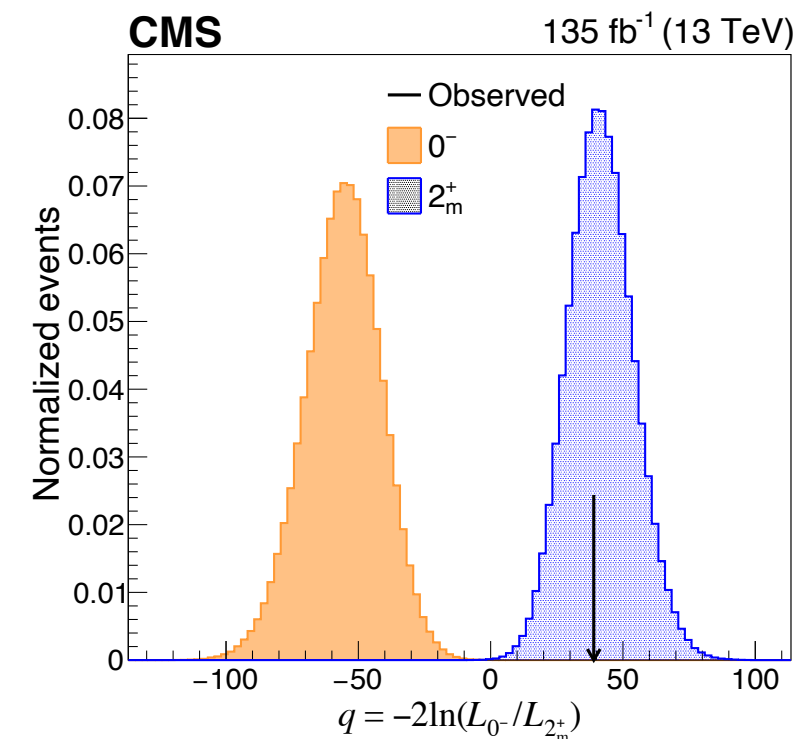
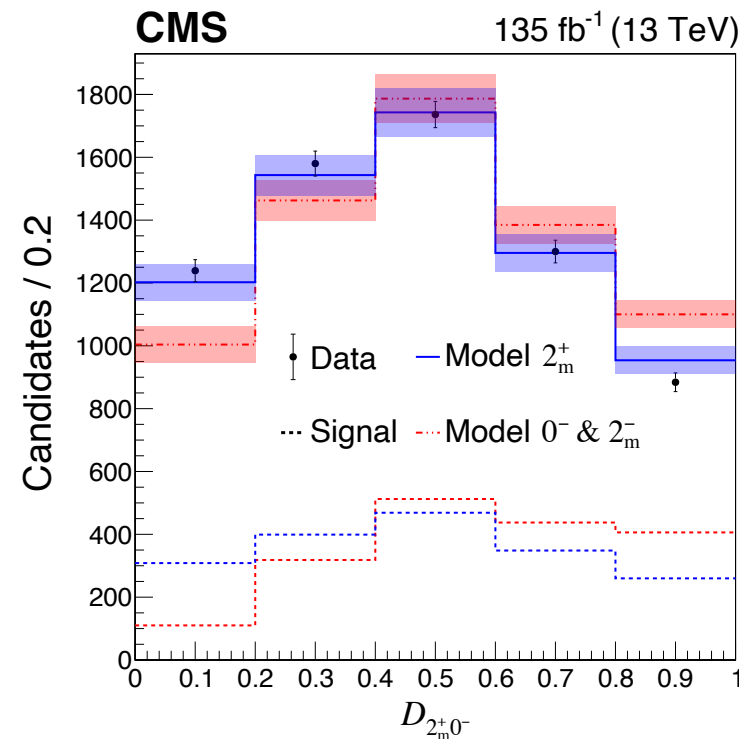
- based on Run2 version of the analysis presented before, $\mathcal{L} = 135 \text{ fb}^{-1}$ [PRL 132 \(2024\) 111901](#)
- build a likelihood ratio discriminant $\mathcal{D}_{ij}$ between two spin-parity hypothesis, using angular variables in the helicity basis
- 2D fit mass and $\mathcal{D}_{ij} \rightarrow$ pairwise hypothesis testing for all considered models



$\vec{\Omega} = (\cos \theta^*, \Phi_1, \Phi, \cos \theta_1, \cos \theta_2)$

$$\mathcal{D}_{ij}(\vec{\Omega} | m_{J/\Psi J/\Psi}) = \frac{\mathcal{P}_i(\vec{\Omega} | m_{J/\Psi J/\Psi})}{\mathcal{P}_i(\vec{\Omega} | m_{J/\Psi J/\Psi}) + \mathcal{P}_j(\vec{\Omega} | m_{J/\Psi J/\Psi})}$$

MELA

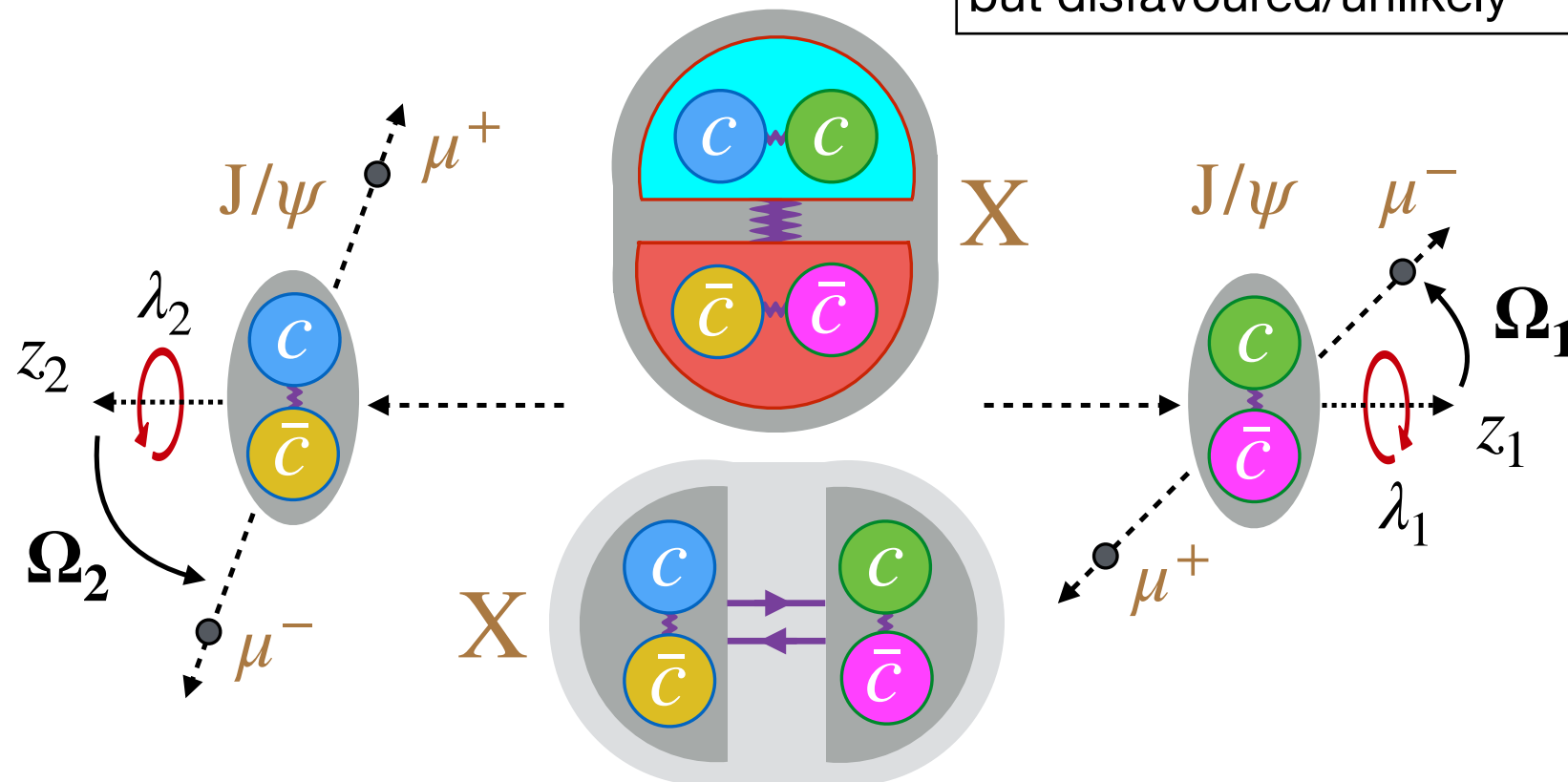


focus on the two more popular tetraquark models to determine which J^{PC} hypothesis to test

“compact” tetraquark
tightly-bound state, color exchange
diquark + diantiquark

(cc) and $(\bar{c}\bar{c})$ have $S = 1$
ground state $L = 0$ most likely
 $L = 0$ (nS), $S = 0, 2 \implies J^P = 0^+, 2^+$

from P and D wave
 $J^P = 0^-, 1^-, 2^-, 1^+, 3^+ \dots$ possible
but disfavoured/unlikely



“molecule” model
loosely-bound state
similar to pion exchange in nucleus,
but much weaker ($m_\pi \ll m_{c\bar{c}}$)

$(c\bar{c})$ not restricted to $S = 1$
more J^P states allowed including
 $J^P = 1^+$, but reasonable to expect
low L preferred

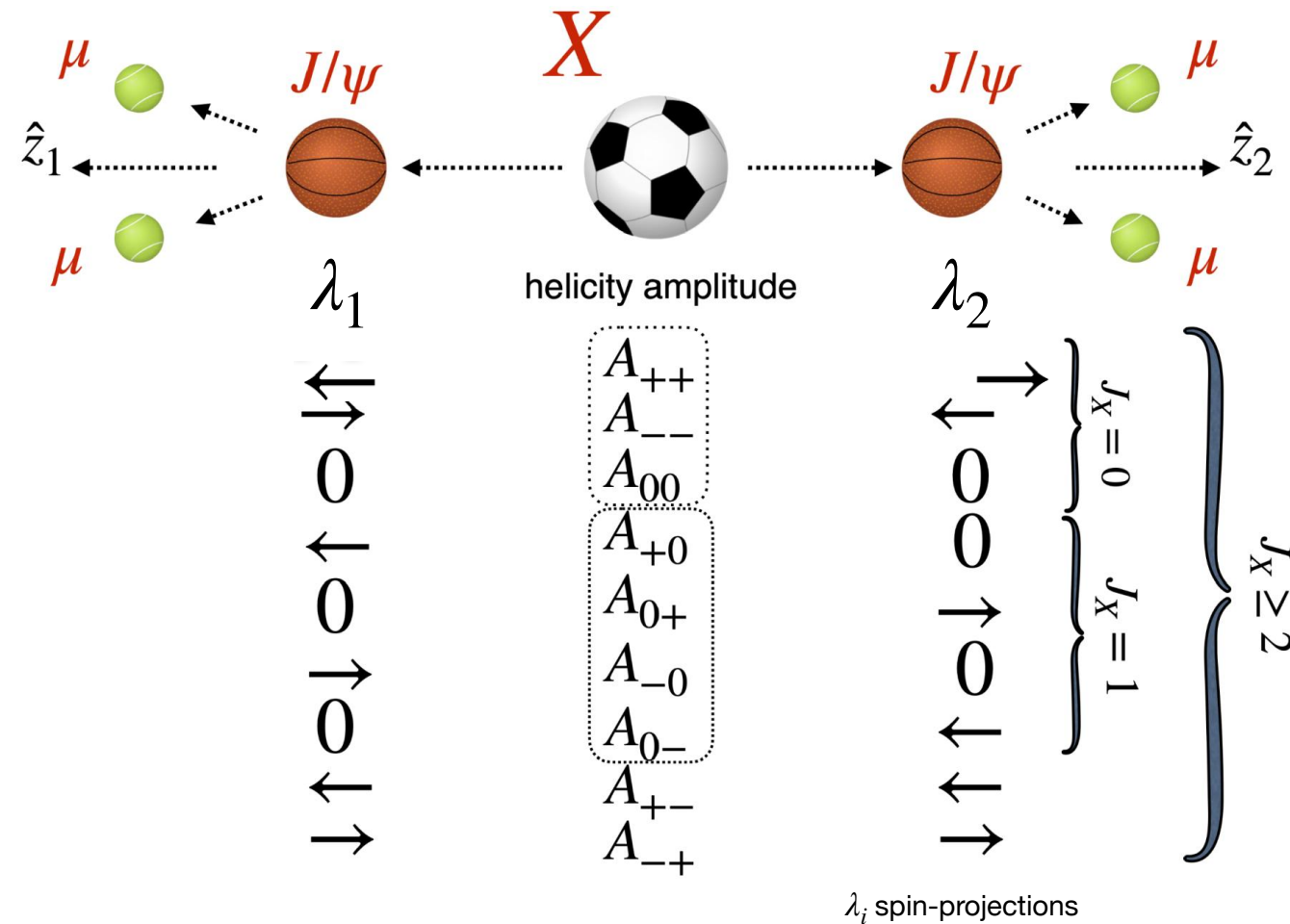
$C = +$ from decay
 C is conserved in QCD

amplitudes are computed analytically $\rightarrow$ can
determine angular distribution from any J^P

symmetry constraints
reduce d.o.f.

S_T	L_T	J_T	J^{PC}
0	0	0	0^{++}
1	0	1	1^{+-}
2	0	2	2^{++}
0	1	1	1^{--}
1	1	2	2^{-+}
1	1	1	1^{-+}
1	1	0	0^{-+}
2	1	3	3^{--}
2	1	2	2^{--}
2	1	1	1^{--}

arXiv:1706.07553v3



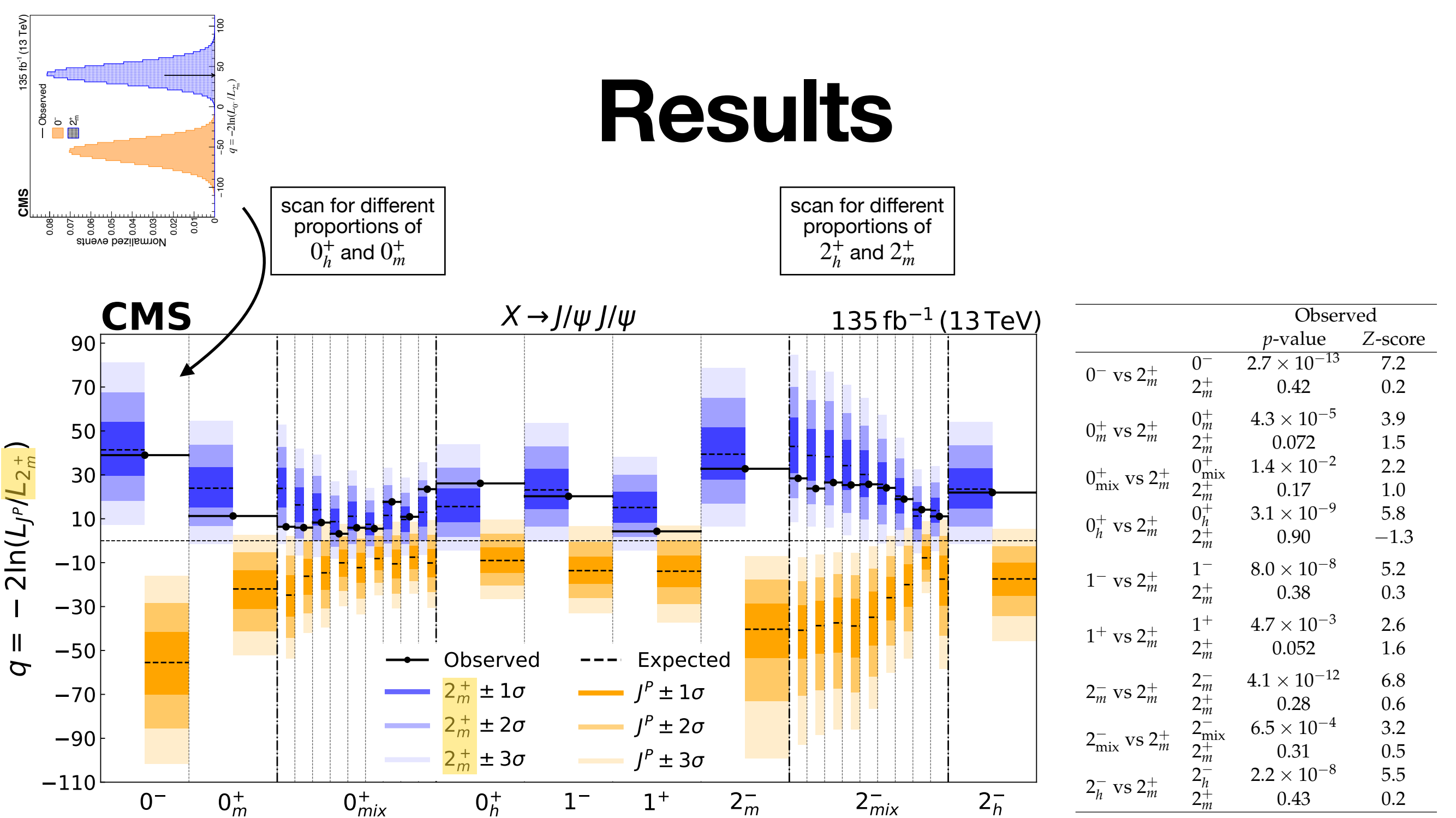
$$A_{\lambda_1 \lambda_2} = (-1)^J A_{\lambda_2 \lambda_1}$$

$$A_{\lambda_1 \lambda_2} = P(-1)^J A_{-\lambda_2 -\lambda_1}$$

J^{PC}	Models J_i^P	Contributing amplitudes	fully determined
0^{-+}	0^-	$A_{++} = -A_{--}$	
0^{++}	0_m^+ and 0_h^+	$A_{++} = A_{--}$ and A_{00}	
1^{-+}	1^-	$A_{+0} = -A_{0+} = A_{-0} = -A_{0-}$	
1^{++}	1^+	$A_{+0} = -A_{0+} = -A_{-0} = A_{0-}$	
2^{-+}	2_m^- and 2_h^-	$A_{++} = -A_{--}$ and $A_{+0} = A_{0+} = -A_{-0} = -A_{0-}$	
2^{++}	2_m^+	$A_{++} = A_{--}, A_{00}, A_{+0} = A_{0+} = A_{-0} = A_{0-},$ and $A_{+-} = A_{-+}$	

remaining d.o.f.
assume model h and m
scan for different proportions

Results



$J^P = 2^+$ strongly favoured

2_m^+ minimal model favoured

$P = +$ established

$J^P = 0^+$ excluded at $> 95\%$ CL

$J^P = 1^+$ excluded at 99% CL

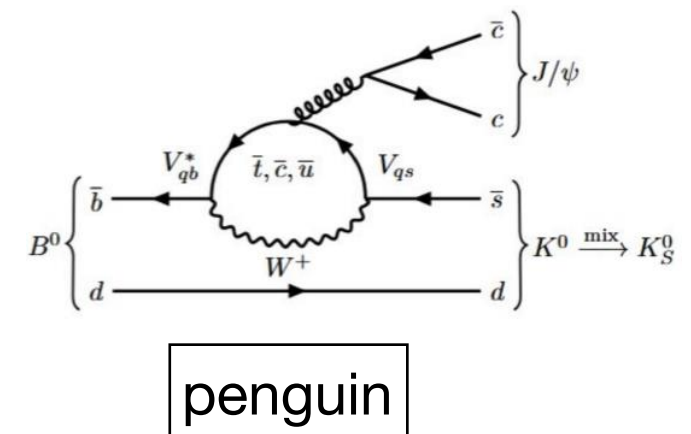
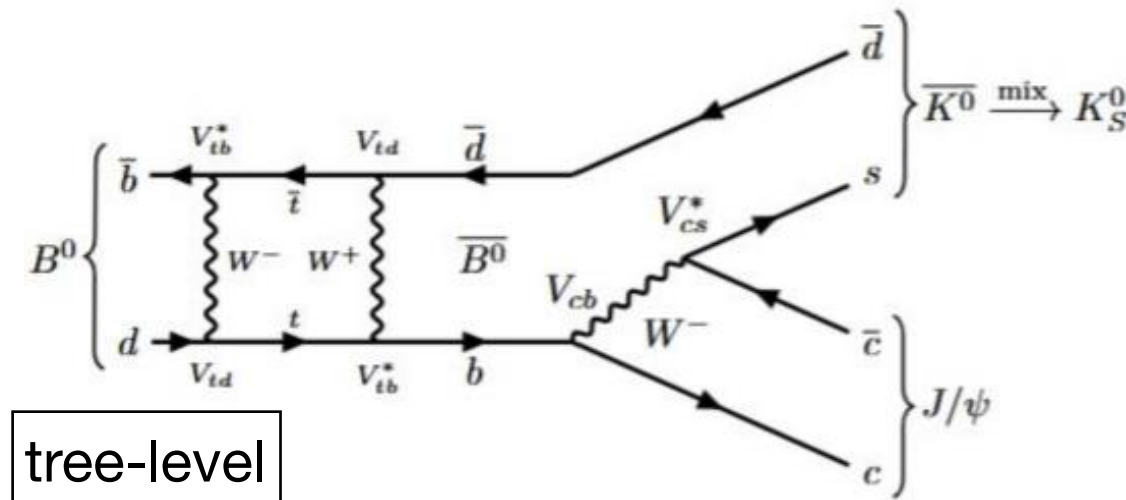
$P = 1$ excludes $L = 1$ in either tetraquark models

molecule model $\rightarrow L = 2$ unlikely, $S = 0, 1$

diquark model $\rightarrow S = 1$ more naturally favours $J = 2$

CPV and CKM metrology

The angle β in $B^0 \rightarrow J/\psi(\mu\mu)K_s(\pi\pi)$



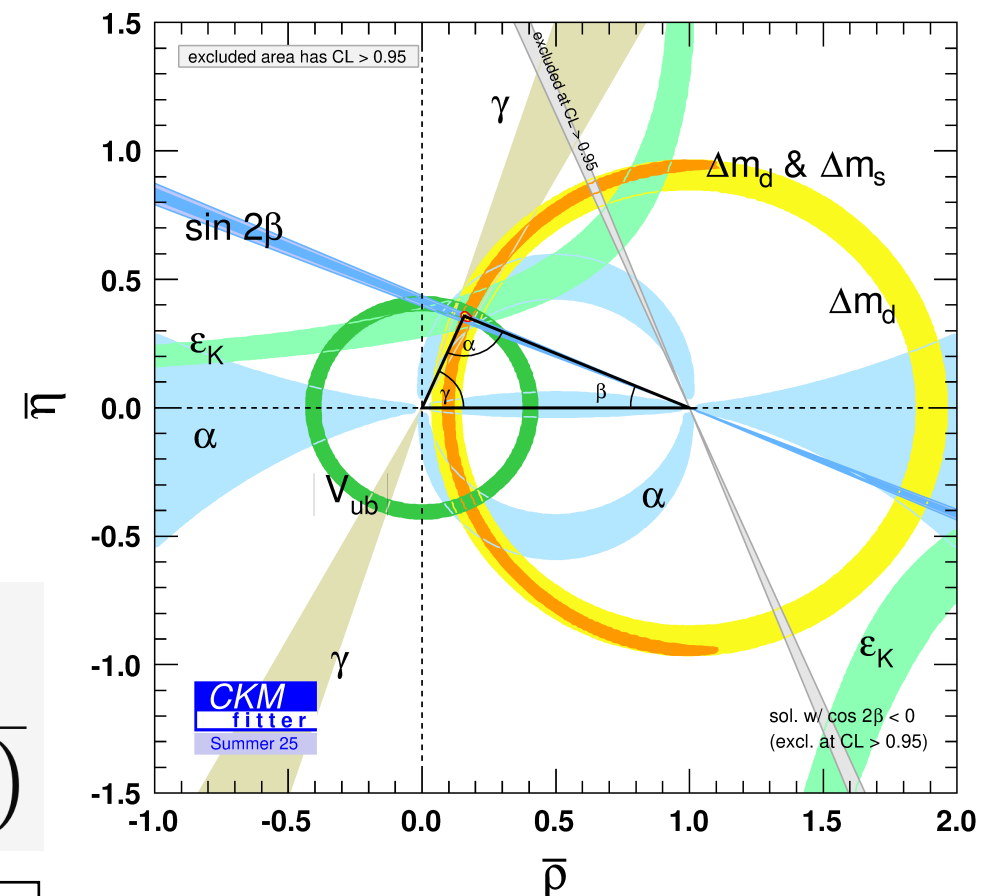
- **large time dependent CPV effect**
 $a_{CP}(t)$, modulated by the slow B^0
flavour oscillations
- BSM contribution estimation limited by penguin pollutions

$$a_{CP}(t) = \frac{S \sin(\Delta m t) - C \cos(\Delta m t)}{\cosh(\Delta \Gamma t/2) - D \sinh(\Delta \Gamma t/2)}$$

S mixing-induced CPV

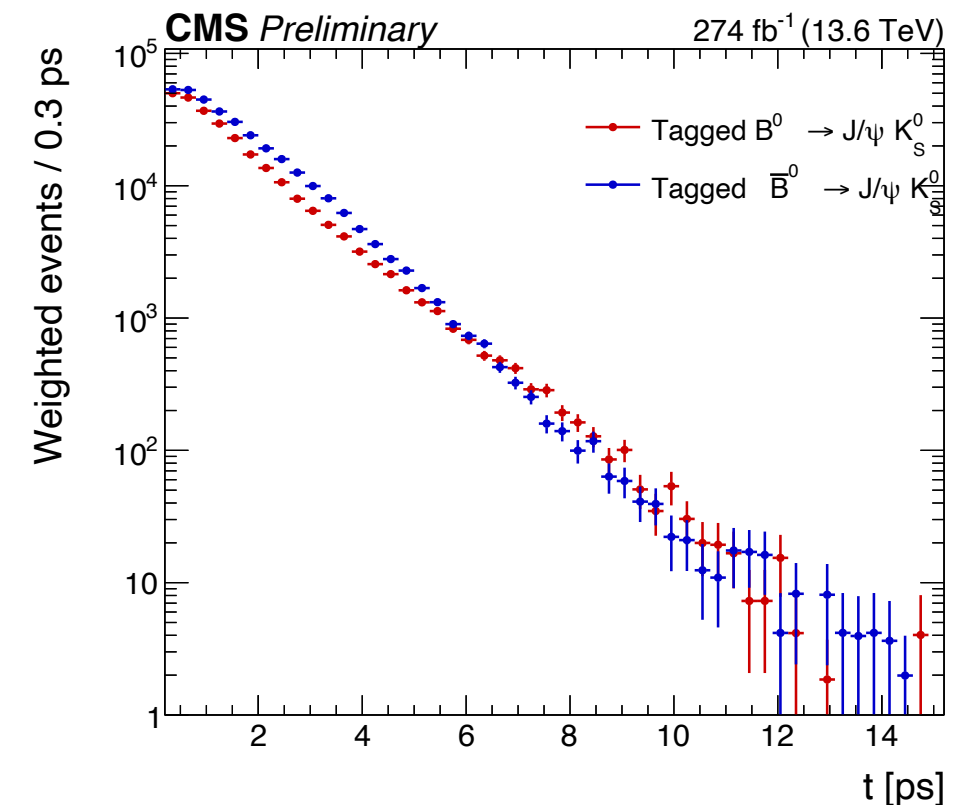
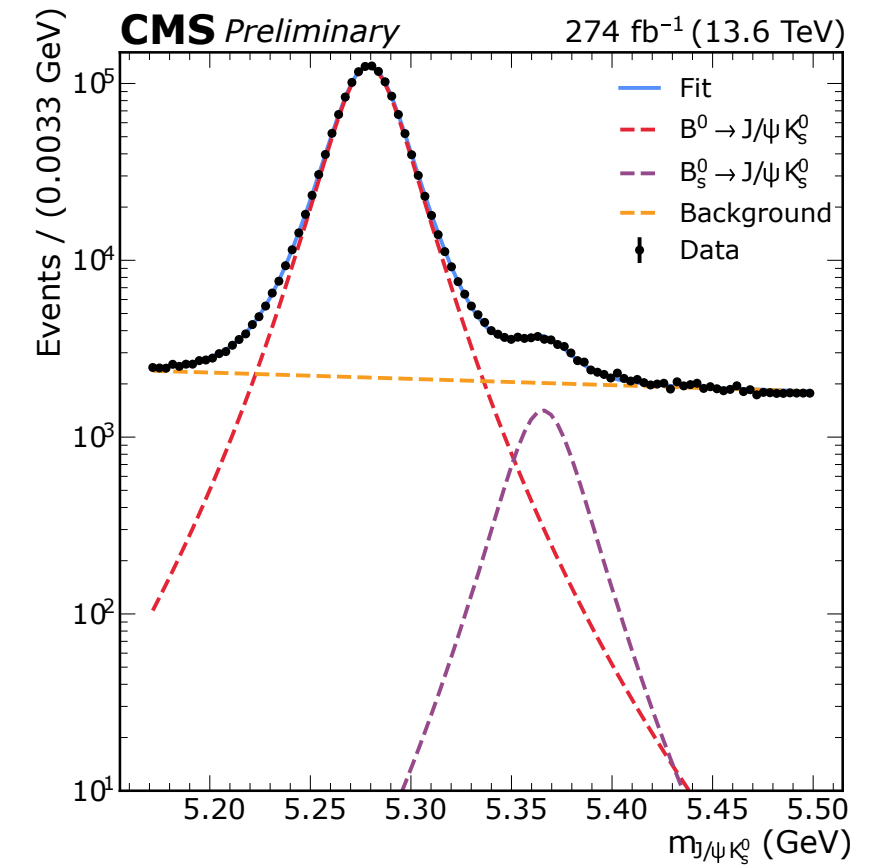
C direct CPV

$$S^2 + C^2 + D^2 = 1$$

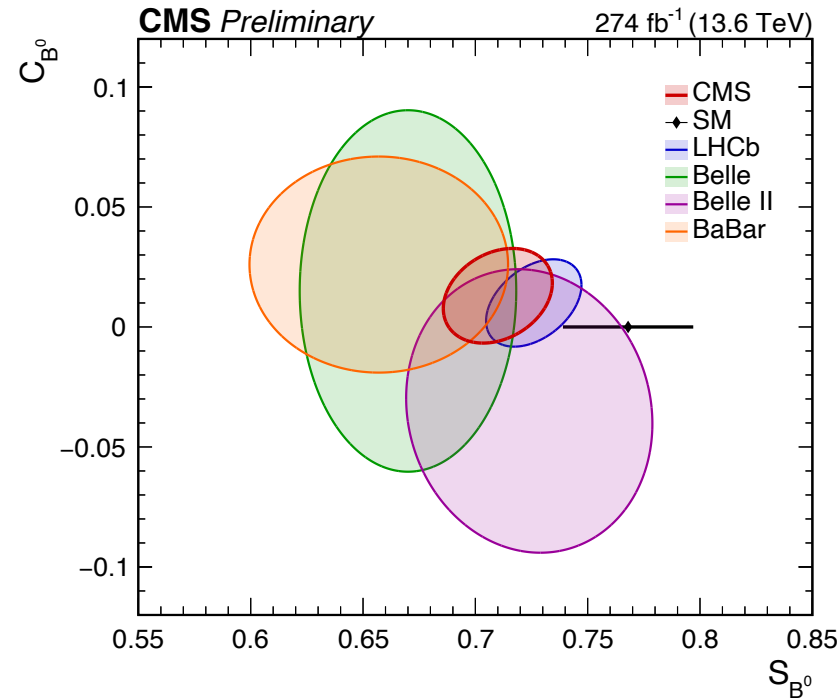
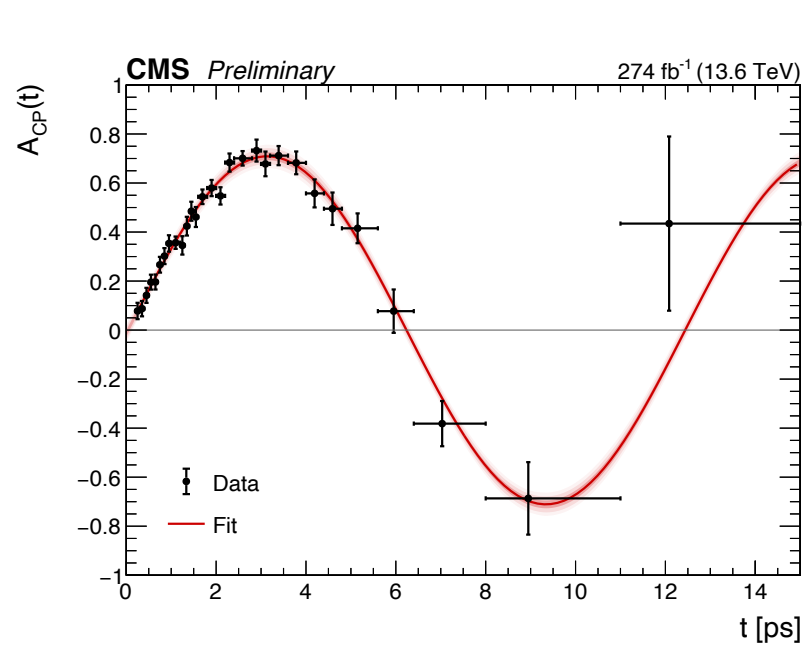


Measurement of β in $B^0 \rightarrow J/\psi(\mu\mu)K_s(\pi\pi)$

- **time-dependent CPV in $B^0 \rightarrow J/\psi K_s$**
- **simultaneous extraction of $\sin 2\beta$ and $\sin 2\beta_s$ from the same final state**
 - B^0 : golden precision channel
 - B_s : penguin control channel
[De Bruyn [2501.09414](#), [talk at BEAUTY2026](#)]
- Run3 2022-2025 (274 fb⁻¹) [2026 (25 fb⁻¹) being added]
1.5M B^0 , 16k B_s candidates
- **Particle Transformer based flavour tagging**, using ℓ and jet both opposite (+ same side for B_s)
 $\mathcal{P}_{tag} = 1.5 - 1.9\%$ for the $B^0 \rightarrow J/\psi K_s$
 $\mathcal{P}_{tag} = 7.5 - 8.2\%$ for the $B_s^0 \rightarrow J/\psi K_s$
- **per-event bkg subtraction via Custom Orthogonal Weight** (generalize sWeight)

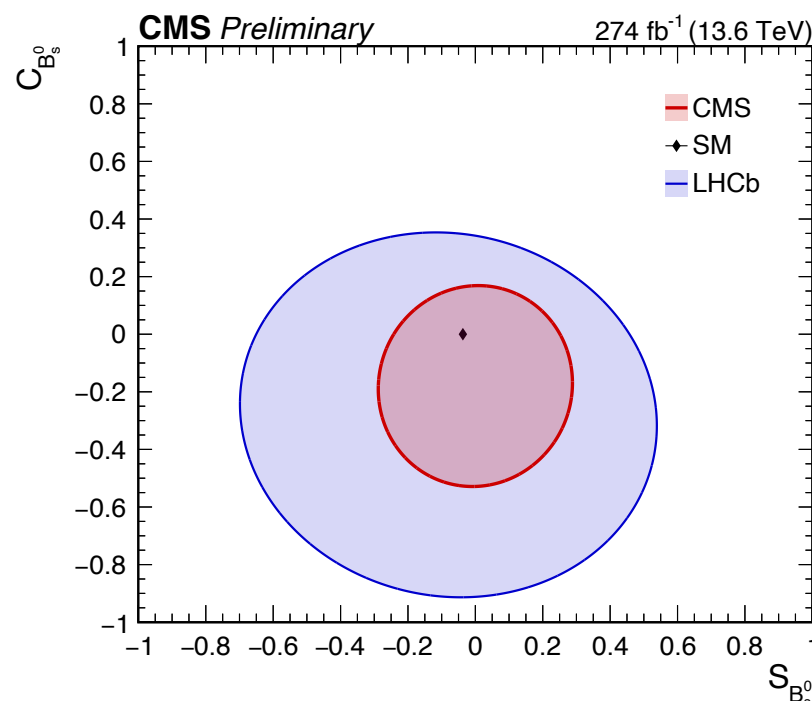
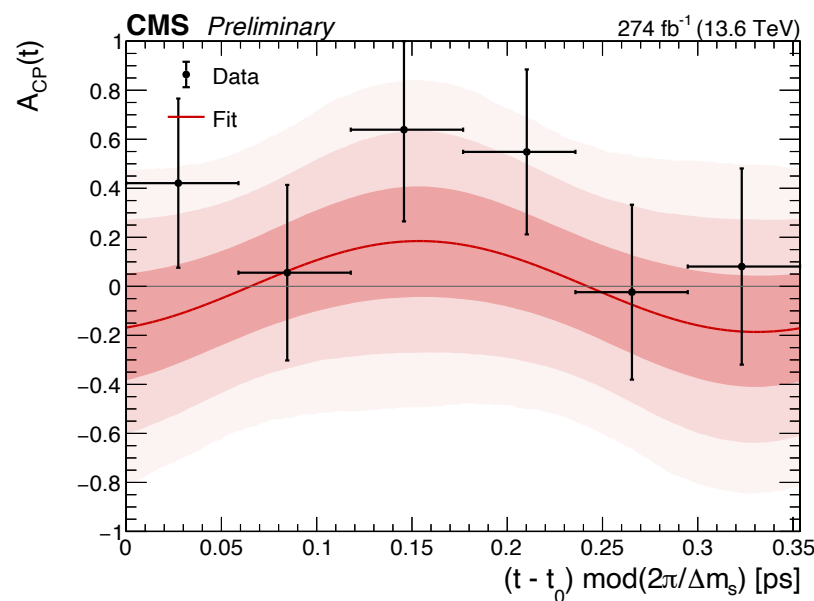


$$\begin{aligned}
S_{B^0} &= 0.710 \pm 0.013 (\text{stat}) \pm 0.009 (\text{syst}), \\
C_{B^0} &= 0.013 \pm 0.011 (\text{stat}) \pm 0.006 (\text{syst}), \\
S_{B_s^0} &= 0.00 \pm 0.19 (\text{stat}) \pm 0.00 (\text{syst}), \\
C_{B_s^0} &= -0.18 \pm 0.23 (\text{stat}) \pm 0.01 (\text{syst}).
\end{aligned}$$



B^0

- comparable to LHCb
- stat. limited with non-negligible systematics
- slightly below SM



B_s^0

- 2x more precise
- sensitive to penguin-induced shifts in $\sin 2\beta$

Search for direct CP violation in $D^0 \rightarrow K_S^0 K_S^0$ decays

CPV in up-quark sector not as well studied as in down-quark

- first observation [LHCb](#)
 $A_{CP}(D^0 \rightarrow KK) - A_{CP}(D^0 \rightarrow \pi\pi) = (-15.4 \pm 2.9) \times 10^{-4}$
- direct CPV in decay $D^0 \rightarrow K_S^0 K_S^0$ [predicted](#) of O(%),
 experimentally accessible and larger than other channels
- previous results:

[Belle](#) $A_{CP}(D^0 \rightarrow K_S^0 K_S^0) = (-0.02 \pm 1.53 \pm 0.02 \pm 0.17) \%$

[LHCb](#) $A_{CP}(D^0 \rightarrow K_S^0 K_S^0) = (-1.86 \pm 1.04 \pm 0.41) \%$

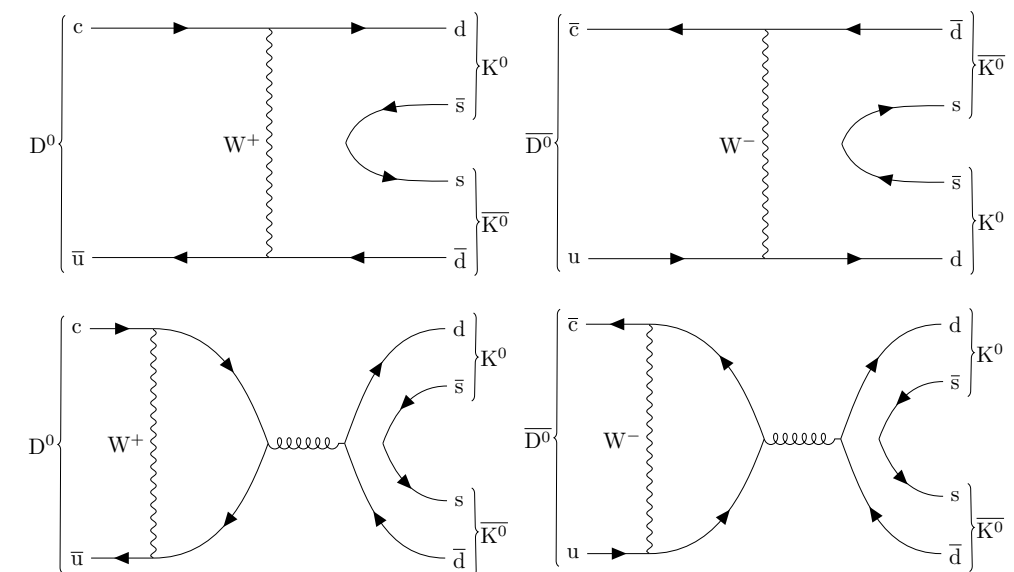
first CPV measurement in charm sector at CMS

2018 data, 41.6 fb⁻¹ BParking dataset [Phys. Rept. 1115 \(2025\) 678](#),
 contains O(10¹⁰) semileptonic B decays, most of type $B \rightarrow D\mu\nu$

use sign of soft pion from $D^* \rightarrow D\pi_s^\pm$ to (self-)tag flavour

time integrated

$$A_{CP} = \frac{\Gamma(D^0 \rightarrow K_S^0 K_S^0) - \Gamma(\bar{D}^0 \rightarrow K_S^0 K_S^0)}{\Gamma(D^0 \rightarrow K_S^0 K_S^0) + \Gamma(\bar{D}^0 \rightarrow K_S^0 K_S^0)}$$



Search for direct **CP** violation in $D^0 \rightarrow K_S^0 K_S^0$ decays

Extraction of A_{CP}

A_{CP} can be broken down into different components:
difference of raw yields, $D^0/\bar{D}^0$ production, detector

$$A_{CP} = A_{CP}^{\text{raw}} - A_{CP}^{\text{pro}} - A_{CP}^{\text{det}}$$

leverage topologically similar, high stats, and *non-CPV* ([CDF](#))
 $D^0 \rightarrow K_S^0 \pi \pi$ channel to cancel A_{CP}^{pro} and A_{CP}^{det}

$$\Delta A_{CP} \equiv A_{CP}(K_S^0 K_S^0) - A_{CP}(K_S^0 \pi^+ \pi^-) = A_{CP}^{\text{raw}}(K_S^0 K_S^0) - A_{CP}^{\text{raw}}(K_S^0 \pi^+ \pi^-)$$

$$A_{CP} = A_{CP}^{\text{raw}}(K_S^0 K_S^0) - A_{CP}^{\text{raw}}(K_S^0 \pi \pi) - A_{CP}(K_S^0 \pi \pi)$$

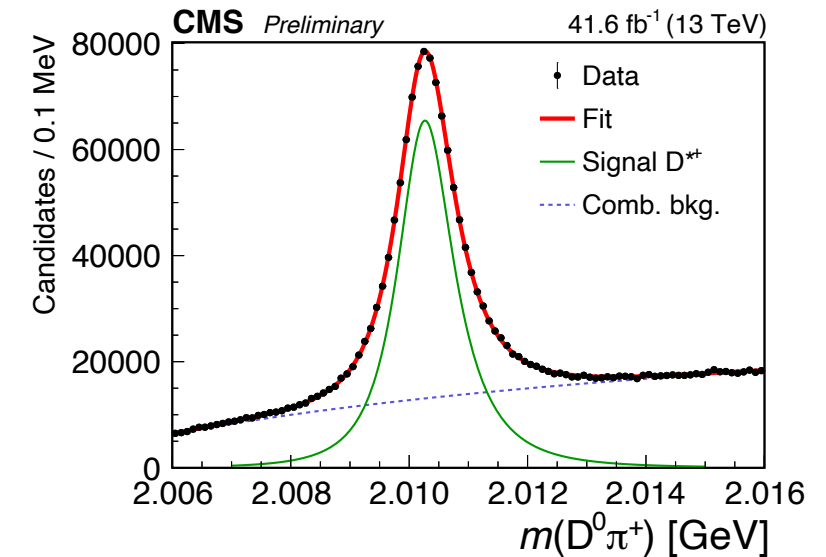
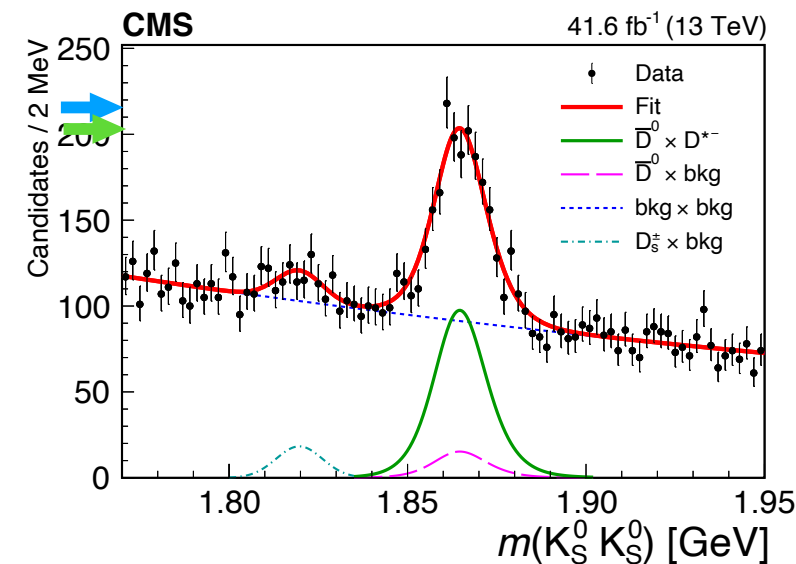
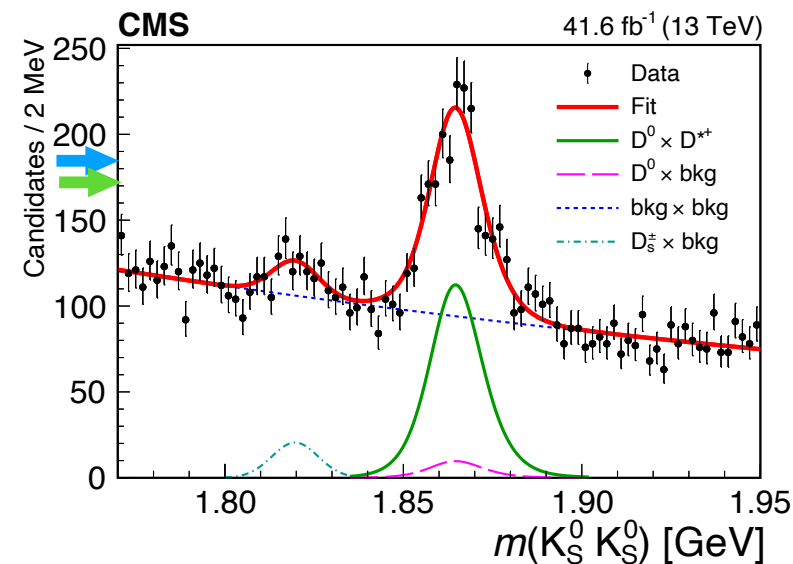
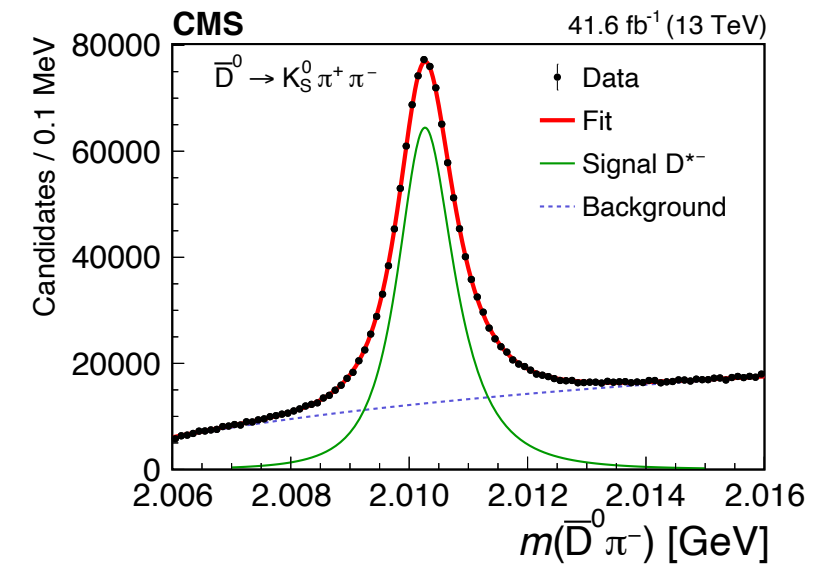
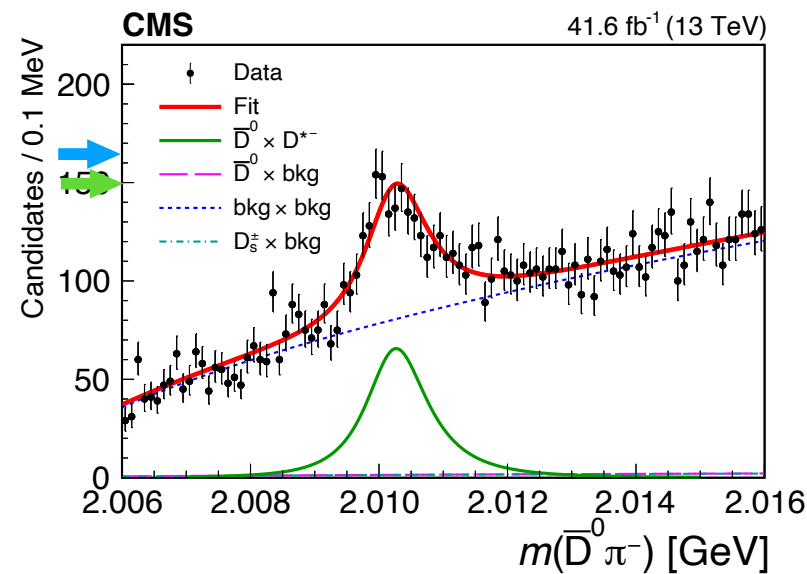
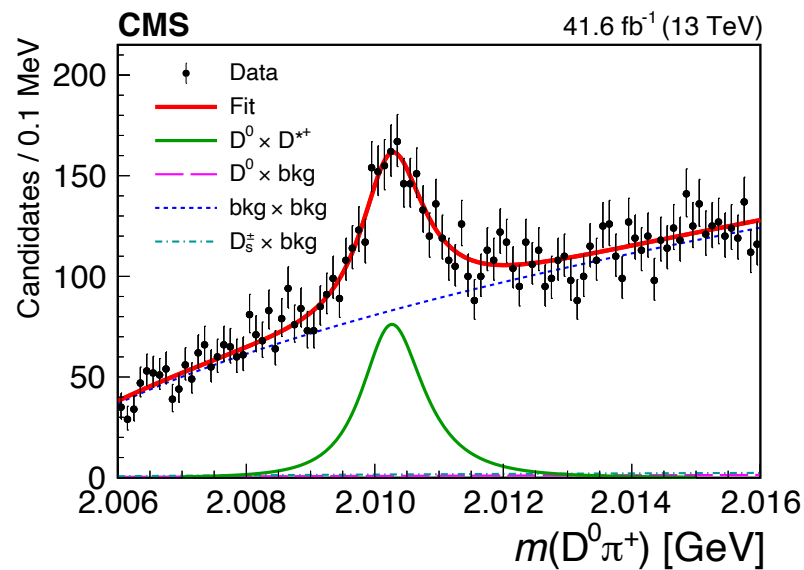
Search for direct CP violation in $D^0 \rightarrow K_S^0 K_S^0$ decays

$$A_{CP}^{\text{raw}}(K_S^0 K_S^0) = (7.1 \pm 3) \%$$

Pion charge	N	χ^2 (x axis)	χ^2 (y axis)
π^+	1095 ± 46	77	90
π^-	951 ± 44	93	62

$$A_{CP}^{\text{raw}}(K_S^0 \pi \pi) = (0.78 \pm 0.10) \%$$

Charge of pion	N	χ^2 with 100 bins
π^+	$944\,800 \pm 3\,500$	78
π^-	$930\,150 \pm 3\,400$	93



notice peak height difference
blue vs green arrows

Search for direct CP violation in $D^0 \rightarrow K_S^0 K_S^0$ decays

Results

$$A_{CP}(K_S^0 K_S^0) = 6.2 \pm 3.0 \text{ (stat)} \pm 0.2 \text{ (syst)} \pm 0.8(A_{CP}(K_S^0 \pi^+ \pi^-)) \%$$

first search for CPV in charm sector at CMS

compatible with no CPV at 2σ , with [LHCb](#) at 2.7σ , with [Belle](#) at 1.8σ

statistically limited, systematics primarily from variations on fit models

paves the way for future and more accurate measurements

Source	Uncertainty, %
$m(D\pi^\pm)$ signal model	0.10
$m(D\pi^\pm)$ background model	0.02
$m(K_S^0 K_S^0)$ signal model	0.04
$m(K_S^0 K_S^0)$ background model	0.02
$m(K_S^0 K_S^0)$ fit range	0.04
Reweighting	0.09
ΔA_{CP} in MC	0.13
Total	0.20