
Sanshirō pond

Flavour physics at CMS

Physics of the two Infinites
Tokyo 17-21.11.2025

Riccardo Manzoni
on behalf of the CMS Collaboration

CP-violation

measurement of ϕ_s in $\mathrm{B_s} \to J/\Psi\phi$

A_{CP} in $\mathrm{D^0} \to \mathrm{K_sK_s}$

...

Exotic hadrons and spectroscopy

search for tetraquarks

measurement of tetraquark properties

baryon decays

...

Production and properties

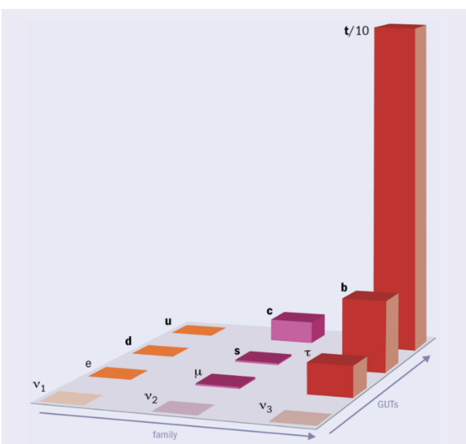
differential cross sections

associated V + HF production

fragmentation fractions

lifetimes

...



Flavour Physics at CMS

(excluding top, see Kai-Feng's talk)

Lepton flavour (non-) universality

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

Lepton flavour violation

$\tau \to 3\mu$, ...

Rare decays

penguin/box FCNC $b \to s\ell\ell$

measurement of "golden" $\mathrm{B_s} \to \mu\mu$

search for very rare $\mathrm{D^0} \to \mu\mu$

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

$d\mathscr{B}(\mathrm{H_b} \to \mathrm{H_s}\mu\mu)/dq^2$

...

all public results here
limited selection in this talk

CP-violation

measurement of ϕ_s in $B_s \to J/\Psi\phi$

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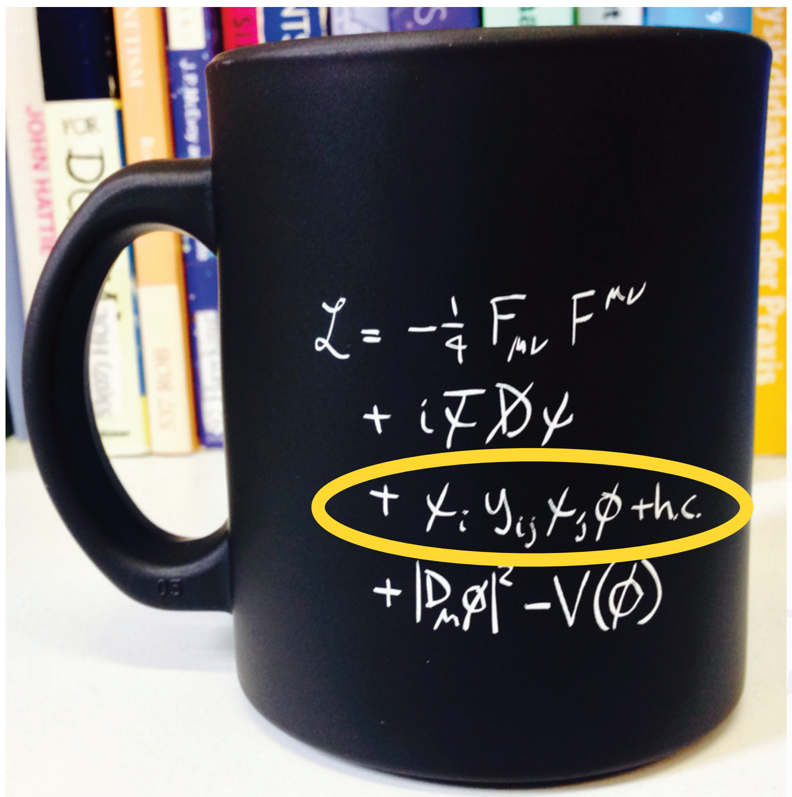
...



- **Sakharov's II condition for baryogengesis C and CP must be violated**
  - crucial to explain matter-antimatter imbalance
- **only source of CP violation in the SM from imaginary phase in Cabibbo-Kobayashi-Maskawa matrix**
  - CKM arises from Higgs Yukawa interaction
    - ***unitary*** transformation between mass and interaction bases
    - measure angles of six ***unitary triangles***
      - over constrained → stress test of SM consistency
- **CKM induced CPV still way too small…**
  - New Physics can significantly modify it

$$V_{\mathrm{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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

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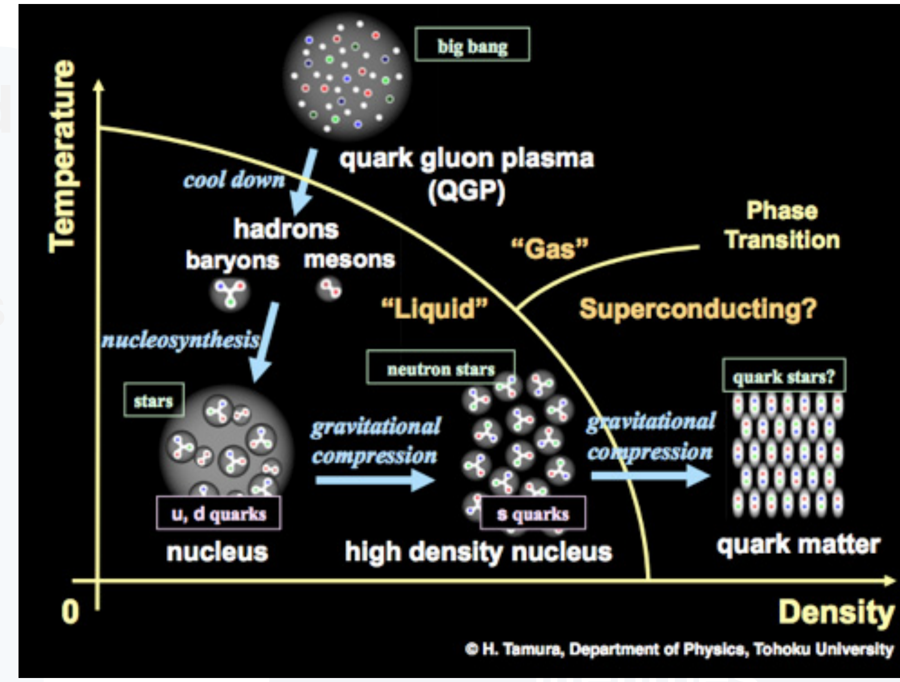
...

the study of exotic hadrons and QCD production processes represent **experimental analogues of the strong-force mediated processes that led to hadron formation in the early Universe**

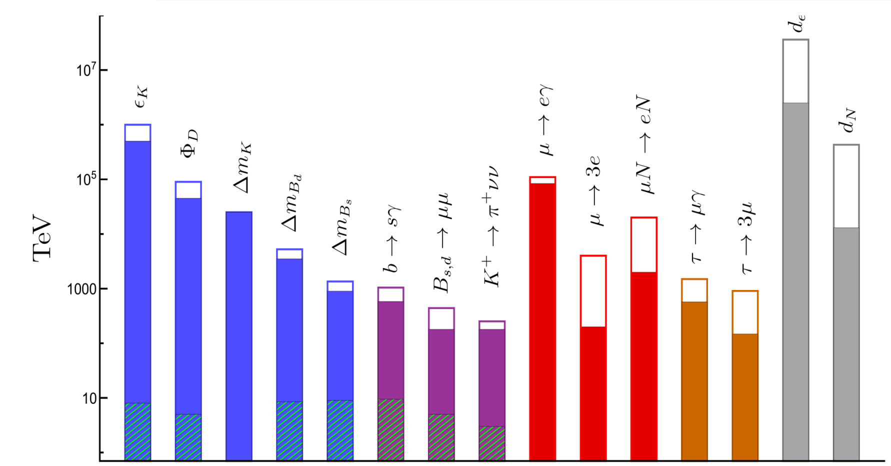
- hot quark-gluon (collision) → hadronisation / cooling
- QCD non perturbative at hadron/nuclei energy → hard from first principles → ***experiments crucial***

- **Sakharov's III condition for baryogengesis:**
  first order phase transition
    - Higgs potential symmetry breaking during cooling would realise for light Higgs $m_{\mathrm{H}} < 70\,\mathrm{GeV}$
    - clearly not fulfilled $m_{\mathrm{H}} = 125\,\mathrm{GeV}$ (see Marumi, Yves' talks), ***"cross-over"***
    - *Beyond the SM particles can modify Higgs potential appropriately and satisfy Sakharov's III condition*



- **dark matter candidates?**

- **precision measurements in Flavour sector**
  → indirect search for New Physics
    - Effective Field Theory: new interactions ⇔ "contact operators"



Lepton flavour (non-) universality

$R(K) = \mathscr{B}(\mathrm{B}^+ \to \mathrm{K}\mu\mu)/\mathscr{B}(\mathrm{B}^+ \to \mathrm{K}ee)$,

$R(J/\Psi) = \mathscr{B}(\mathrm{B_c} \to \mathrm{J/\Psi}\tau\nu)/\mathscr{B}(\mathrm{B_c} \to \mathrm{J/\Psi}\mu\nu)$,

...

Lepton flavour violation

$\tau \to 3\mu$, ...

Rare decays

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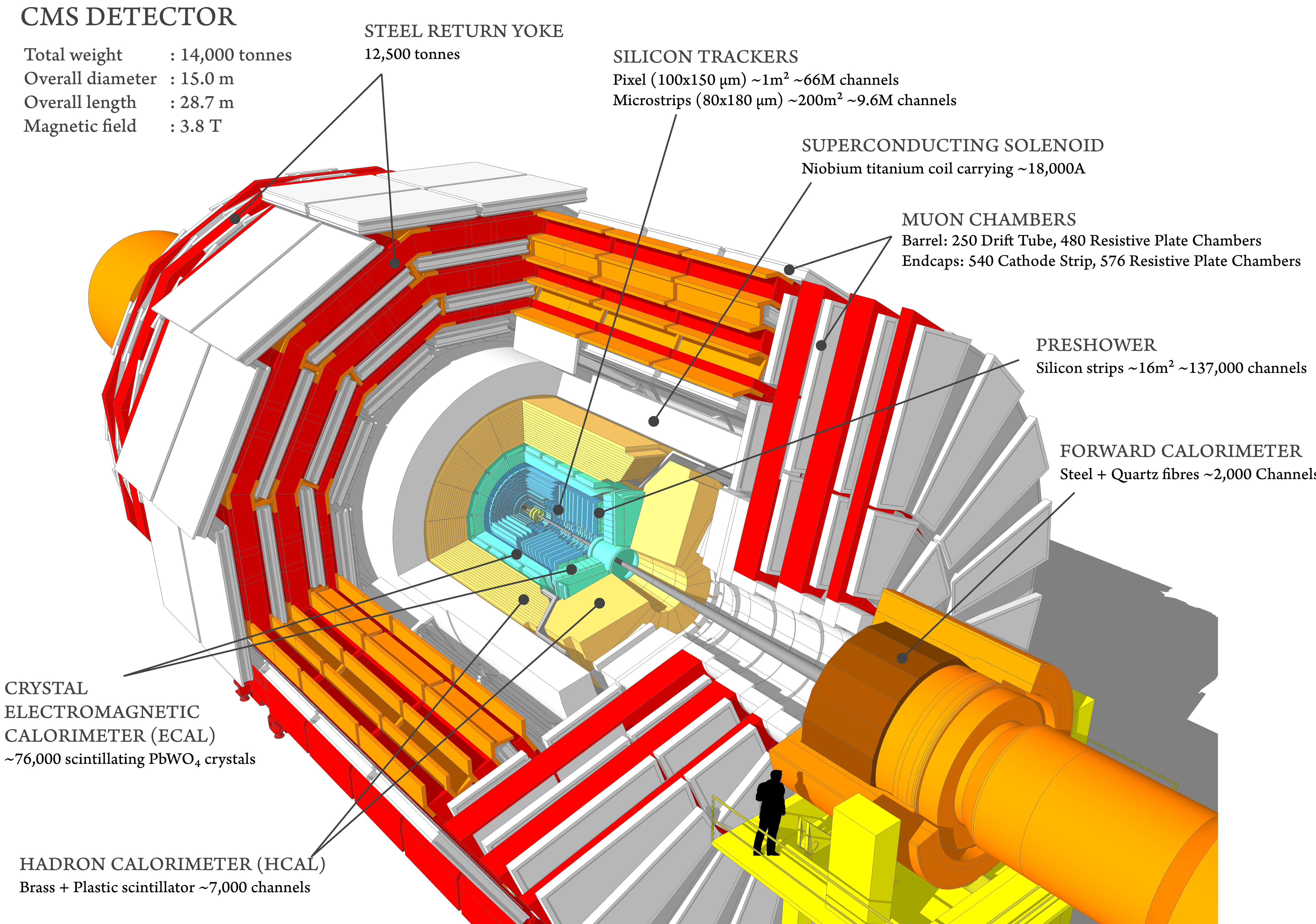
angular analyses $\mathrm{B}^0 \to \mathrm{K}^{*0}\mu\mu$, $\mathrm{B_s} \to \phi\mu\mu$

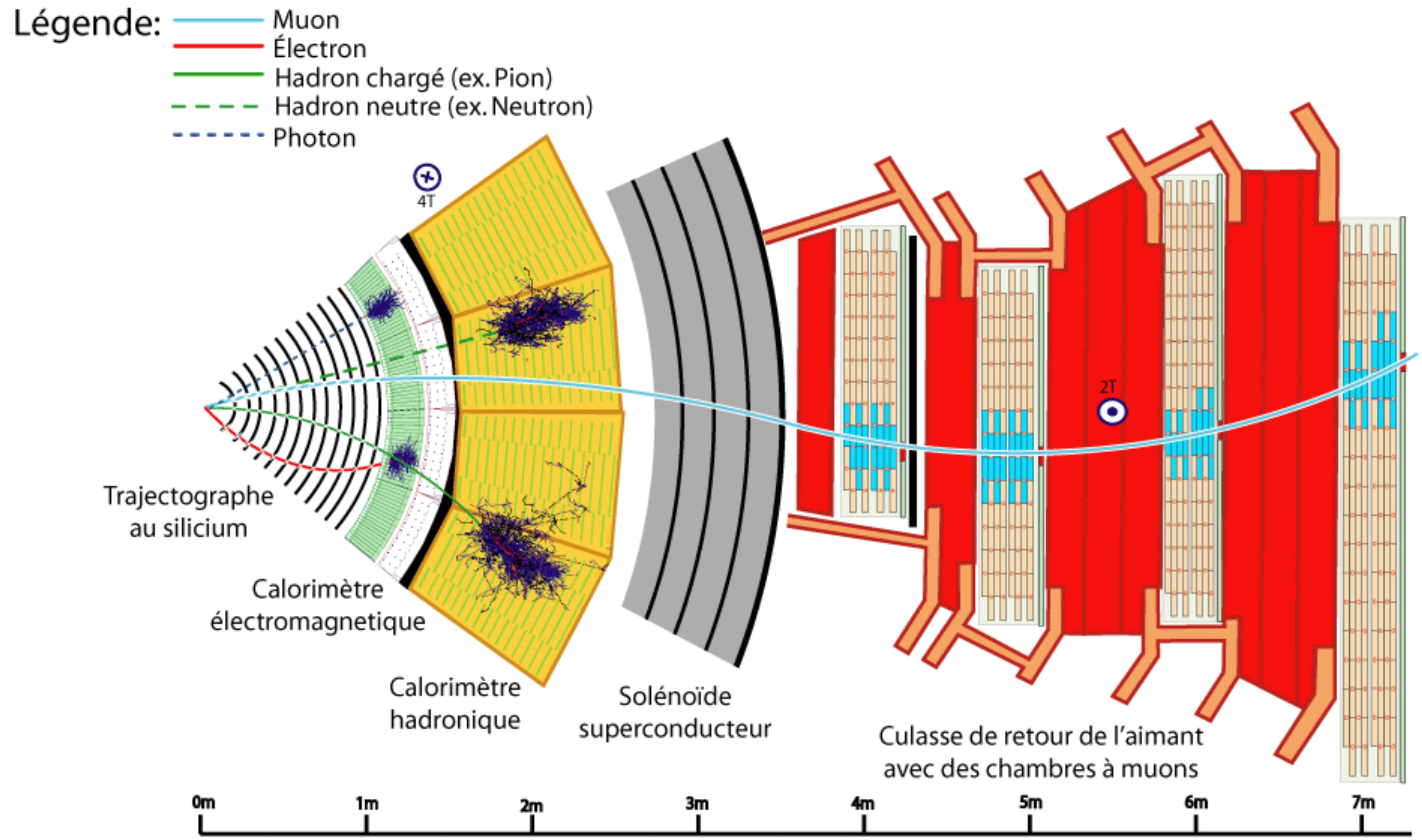
$d\mathscr{B}(\mathrm{H_b} \to \mathrm{H_s}\mu\mu)/dq^2$

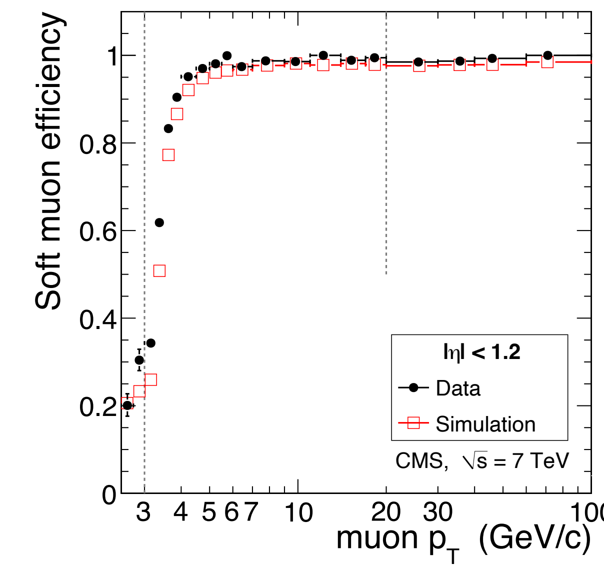
...

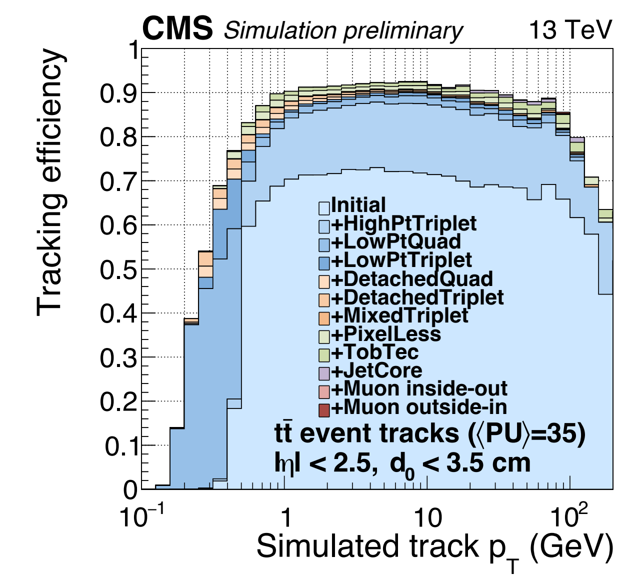


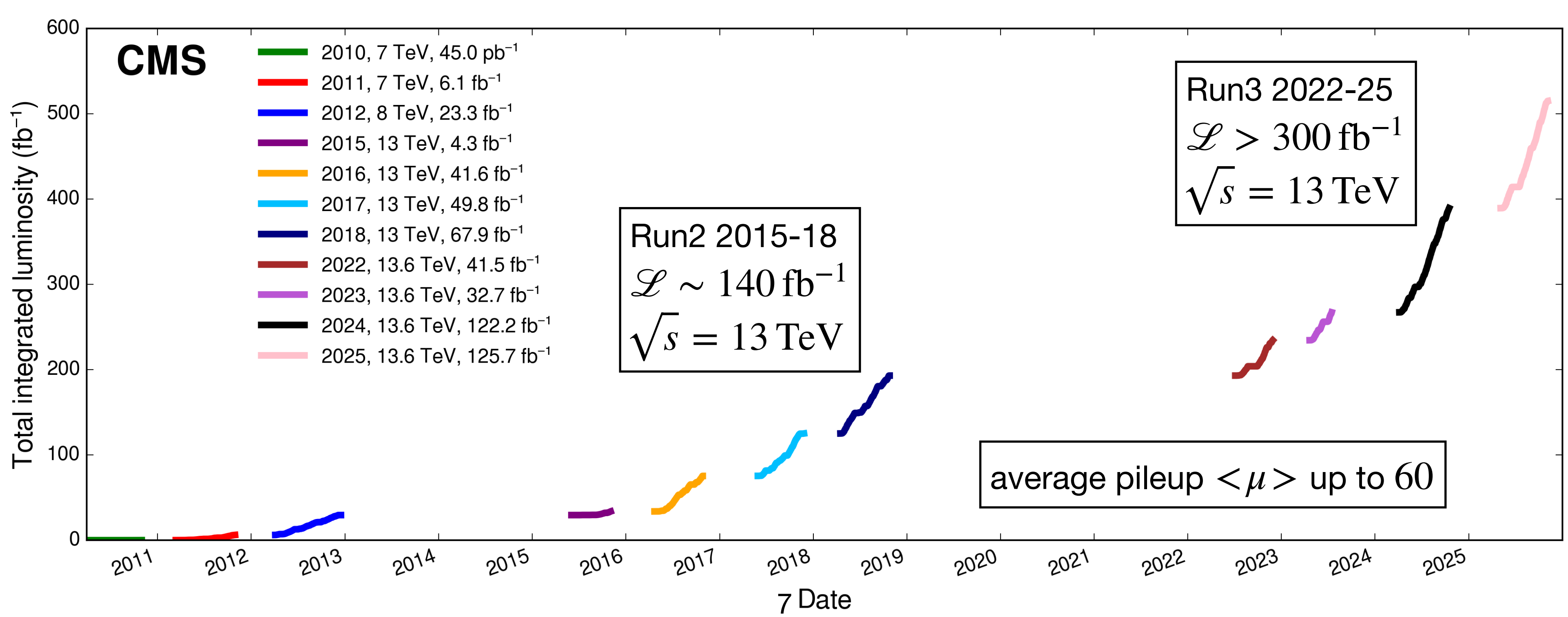
Trigger

LHC → L1 (HW calo & mu) → full readout → HLT (SW) → offline
30 MHz → 100 kHz → few kHz

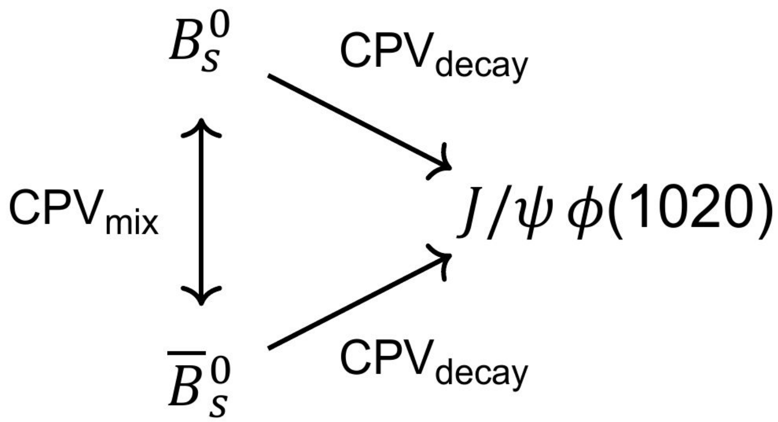

Légende:
Muon
Électron
Hadron chargé (ex. Pion)
Hadron neutre (ex. Neutron)
Photon
4T
2T
Trajectographe
au silicium
Calorimètre
électromagnetique
Calorimètre
hadronique
Solénoïde
superconducteur
Culasse de retour de l'aimant
avec des chambres à muons
0m
1m
2m
3m
4m
5m
6m
7m


Soft muon efficiency
muon p_T (GeV/c)
|η| < 1.2
Data
Simulation
CMS, $\sqrt{s}$ = 7 TeV


CMS Simulation preliminary
13 TeV
Tracking efficiency
Initial
+HighPtTriplet
+LowPtQuad
+LowPtTriplet
+DetachedQuad
+DetachedTriplet
+MixedTriplet
+PixelLess
+TobTec
+JetCore
+Muon inside-out
+Muon outside-in
$t\bar{t}$ event tracks (⟨PU⟩=35)
|η| < 2.5, d_0 < 3.5 cm
Simulated track p_T (GeV)


CMS
Total integrated luminosity (fb^{-1})
2010, 7 TeV, 45.0 pb^{-1}
2011, 7 TeV, 6.1 fb^{-1}
2012, 8 TeV, 23.3 fb^{-1}
2015, 13 TeV, 4.3 fb^{-1}
2016, 13 TeV, 41.6 fb^{-1}
2017, 13 TeV, 49.8 fb^{-1}
2018, 13 TeV, 67.9 fb^{-1}
2022, 13.6 TeV, 41.5 fb^{-1}
2023, 13.6 TeV, 32.7 fb^{-1}
2024, 13.6 TeV, 122.2 fb^{-1}
2025, 13.6 TeV, 125.7 fb^{-1}
Run2 2015-18
$\mathscr{L} \sim 140\ \mathrm{fb}^{-1}$
$\sqrt{s} = 13$ TeV
Run3 2022-25
$\mathscr{L} > 300\ \mathrm{fb}^{-1}$
$\sqrt{s} = 13$ TeV
average pileup $<\mu>$ up to 60
Date

CPV in $B_s^0 \to J/\psi(\mu\mu)\phi(KK)$ decays



CPV mixing

$$A_{CP}(t) \propto \Gamma(\bar{B}_s \to J/\psi\phi) - \Gamma(B_s \to J/\psi\phi) \propto \eta_{fs} \sin\phi_s \sin(\Delta m_s t)$$

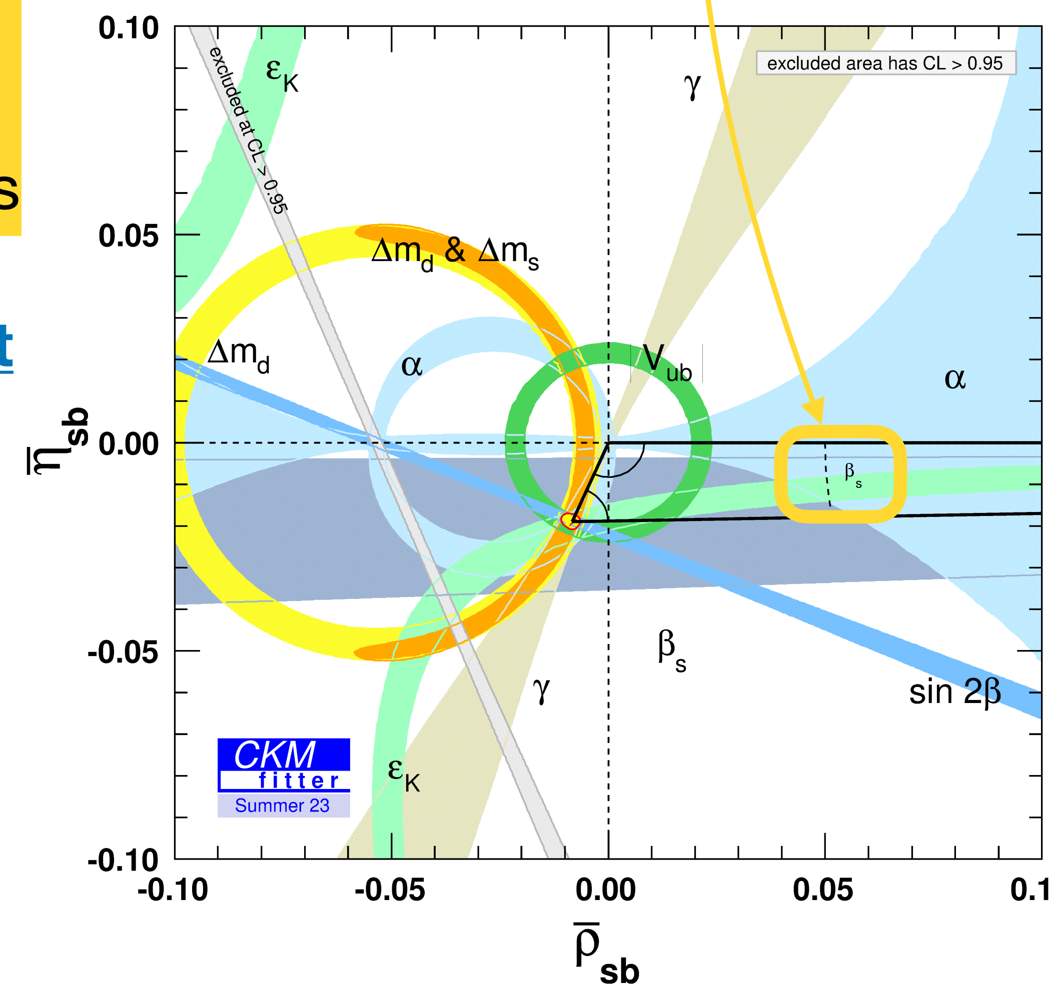
final state CP eigenstate

flavour oscillation

- **measure mixing-induced CPV phase**
  $\phi_s \approx -2\beta_s = -2\arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$
  in the the B_s^0 system and several other parameters

- **accurate theoretical predictions CKMfitter, UTfit**
  $\phi_s = -37 \pm 1$ mrad
  - sensitive to deviations induced by new physics

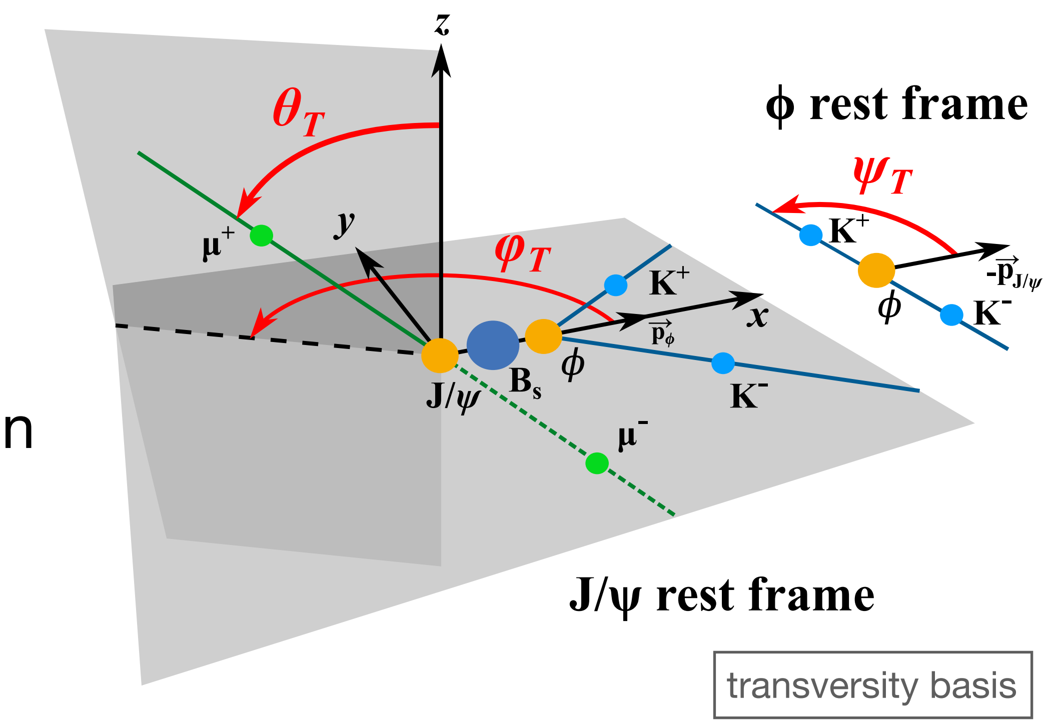
- **CMS uses 2017 + 2018 dataset, 13 TeV, 96.5 fb^{-1}**
  - J/Ψ+μ & J/Ψ+ϕ(KK) triggers

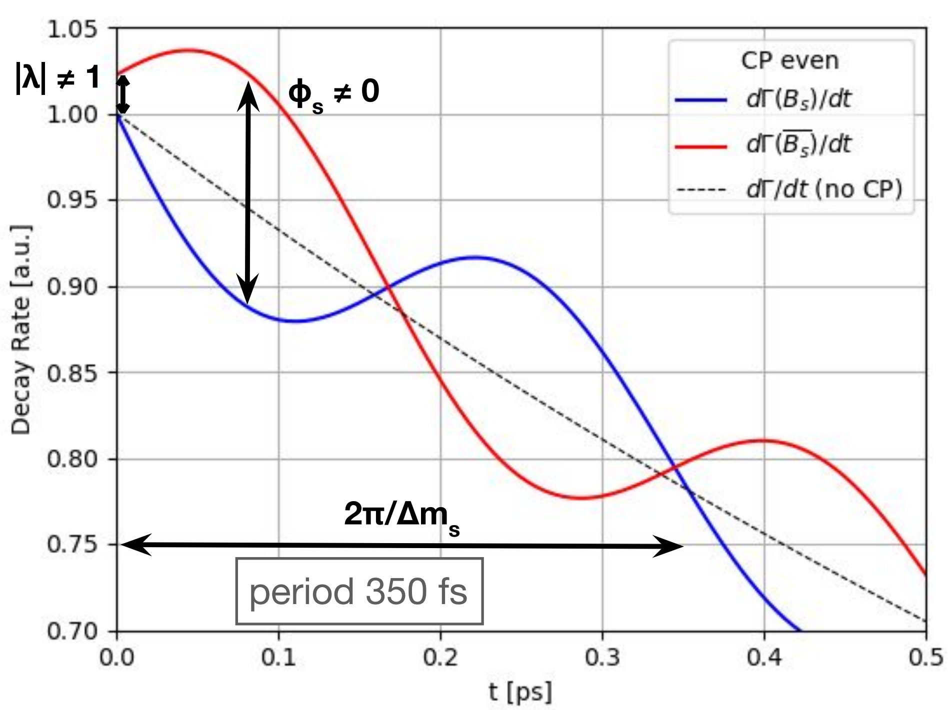


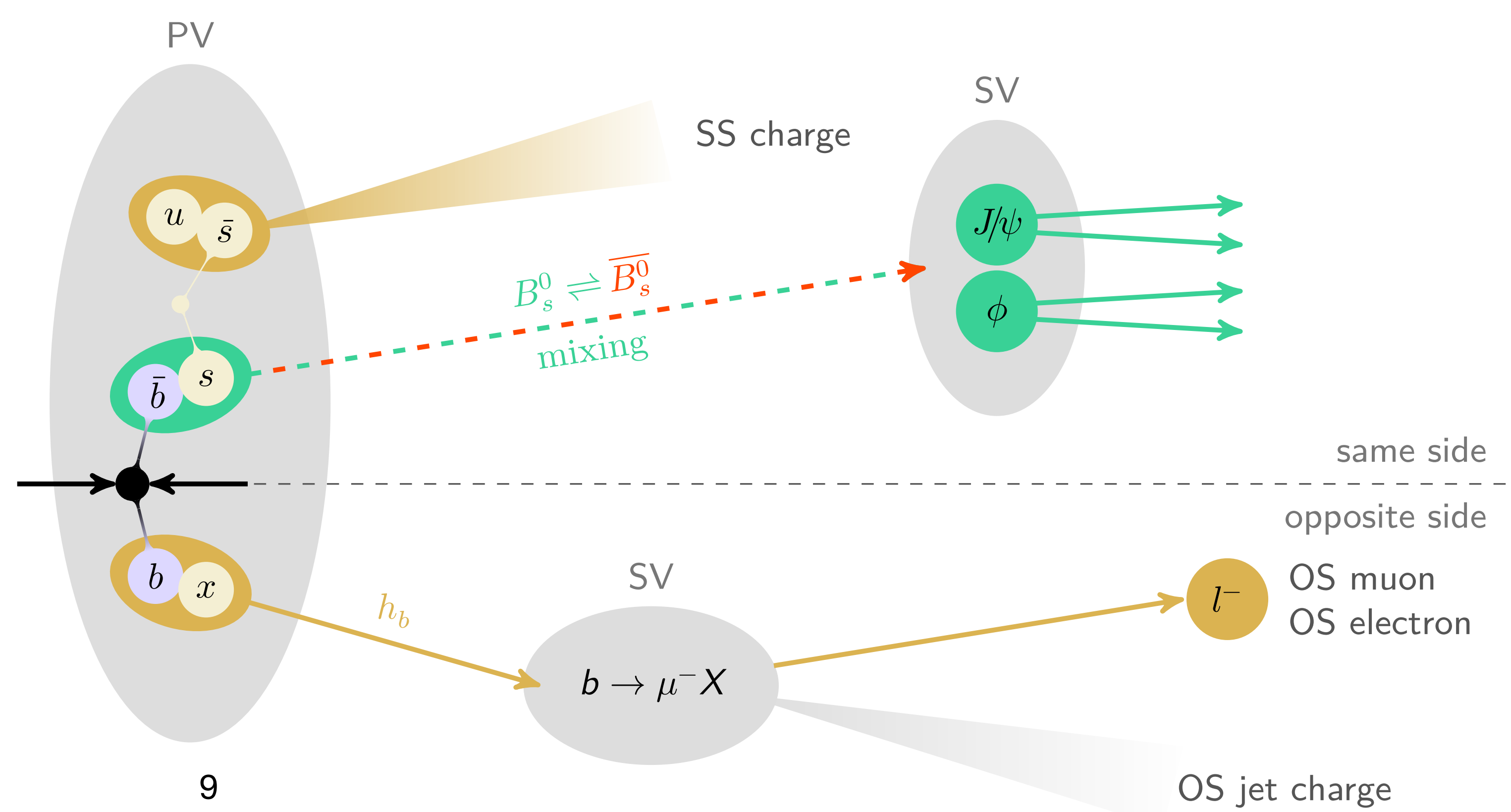
CPV in $B_s^0 \to J/\psi(\mu\mu)\phi(KK)$ decays

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







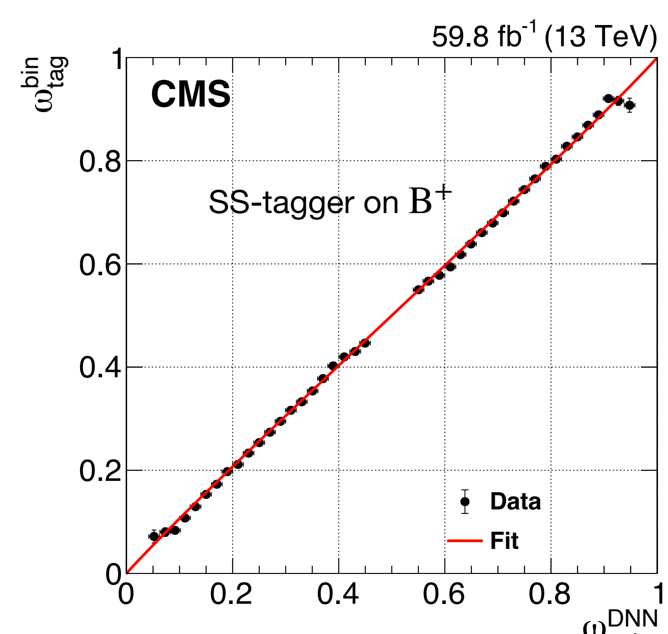
CPV in $B_s^0 \to J/\psi(\mu\mu)\phi(KK)$ decays

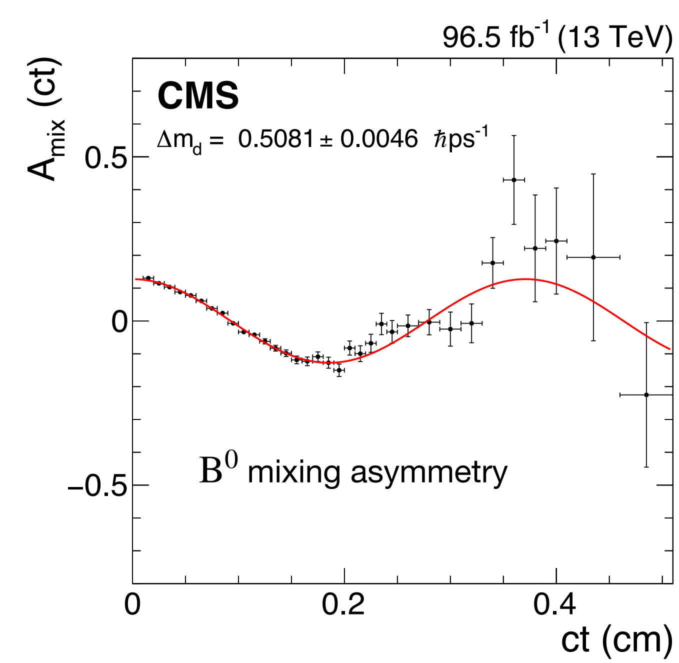
Flavour tagging

- **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 (ω_{tag})ε_{tag} determine effective statistics**
  - tagging power $P_{tag} = \varepsilon_{tag}(1 - \omega_{tag})^2 = 5.59\,\%$
  - 491k signal events → 28k effective

Category	ε_{tag} [%]	$\mathcal{D}^2_{eff}$ $(1-\omega_{tag})^2$	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 $B^+ \to J/\psi K^+$
- **validation:** measure B^0 meson oscillations, 4 different CPV analyses, one per tagger, …



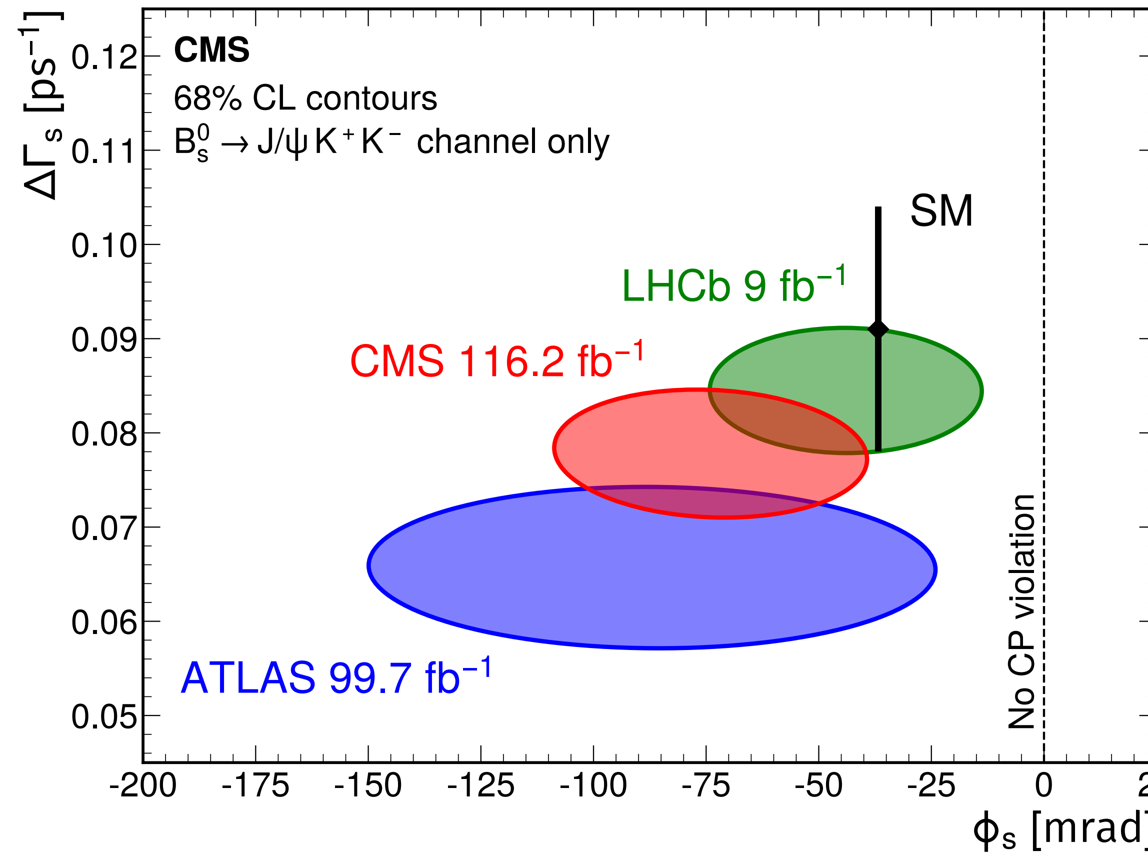


CPV in $B_s^0 \to J/\psi(\mu\mu)\phi(KK)$ decays

Results

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

combined with 8 TeV analysis



3.2 σ evidence of CP violation in $B_s^0 \to J/\psi\phi$ decays

results in agreement with SM and other experiments

still statistically limited, competitive with other measurements

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Search for *CP* violation in $\mathrm{D}^0 \to \mathrm{K}_\mathrm{S}^0\mathrm{K}_\mathrm{S}^0$ decays

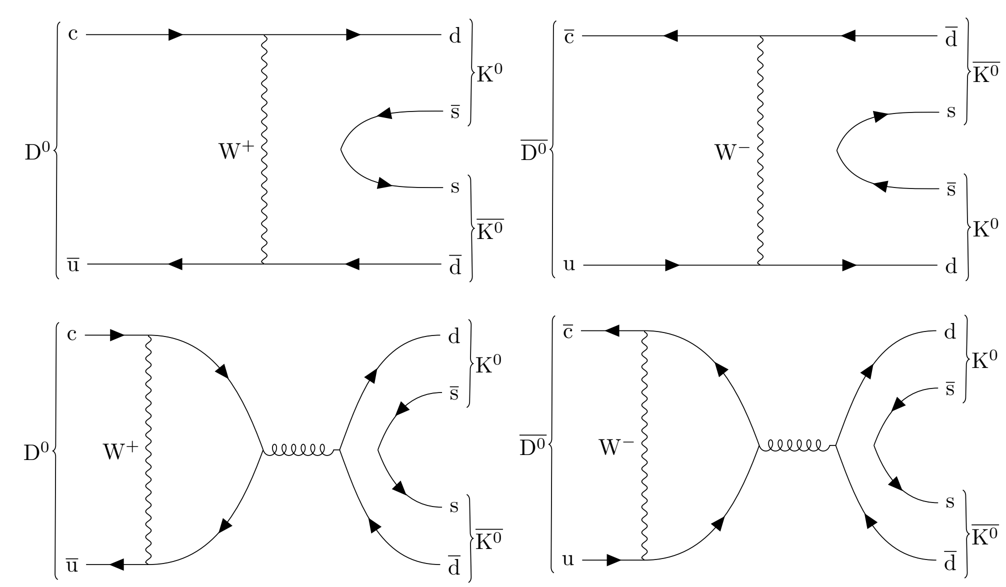
CPV in up-quark sector not as well studied as in down-quark

- only observation LHCb
  $A_{CP}(\mathrm{D}^0 \to \mathrm{KK}) - A_{CP}(\mathrm{D}^0 \to \pi\pi) = (-15.4 \pm 2.9) \times 10^{-4}$
- direct CPV *in decay* $\mathrm{D}^0 \to \mathrm{K}_\mathrm{S}^0\mathrm{K}_\mathrm{S}^0$ predicted of O(%), experimentally accessible and larger than other channels
- previous results:

Belle $A_{CP}(\mathrm{D}^0 \to \mathrm{K}_\mathrm{S}^0\mathrm{K}_\mathrm{S}^0) = (-0.02 \pm 1.53 \pm 0.02 \pm 0.17)\,\%$

LHCb $A_{CP}(\mathrm{D}^0 \to \mathrm{K}_\mathrm{S}^0\mathrm{K}_\mathrm{S}^0) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\,\%$

$$A_{CP} = \frac{\Gamma(\mathrm{D}^0 \to \mathrm{K}_\mathrm{S}^0\mathrm{K}_\mathrm{S}^0) - \Gamma(\bar{\mathrm{D}}^0 \to \mathrm{K}_\mathrm{S}^0\mathrm{K}_\mathrm{S}^0)}{\Gamma(\mathrm{D}^0 \to \mathrm{K}_\mathrm{S}^0\mathrm{K}_\mathrm{S}^0) + \Gamma(\bar{\mathrm{D}}^0 \to \mathrm{K}_\mathrm{S}^0\mathrm{K}_\mathrm{S}^0)}$$



first CPV measurement in charm sector at CMS

2018 data, 41.6 fb^{-1} BParking dataset Phys. Rept. 1115 (2025) 678, contains O(10^{10}) semileptonic B decays, most of type $\mathrm{B} \to \mathrm{D}\mu\nu$

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

time integrated

Search for *CP* violation in $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ decays

Extraction of A_{CP}

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

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

leverage topologically similar, high stats, and *non-CPV* (CDF) $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\pi\pi$ channel to cancel A_{CP}^{pro} and A_{CP}^{det}

$$\Delta A_{CP} \equiv A_{CP}(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) - A_{CP}(\mathrm{K}^0_\mathrm{S}\pi^+\pi^-) = A_{CP}^{\mathrm{raw}}(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) - A_{CP}^{\mathrm{raw}}(\mathrm{K}^0_\mathrm{S}\pi^+\pi^-)$$

$$A_{CP} = A_{CP}^{\mathrm{raw}}(\mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) - A_{CP}^{\mathrm{raw}}(\mathrm{K}^0_\mathrm{S}\pi\pi) - A_{CP}(\mathrm{K}^0_\mathrm{S}\pi\pi)$$

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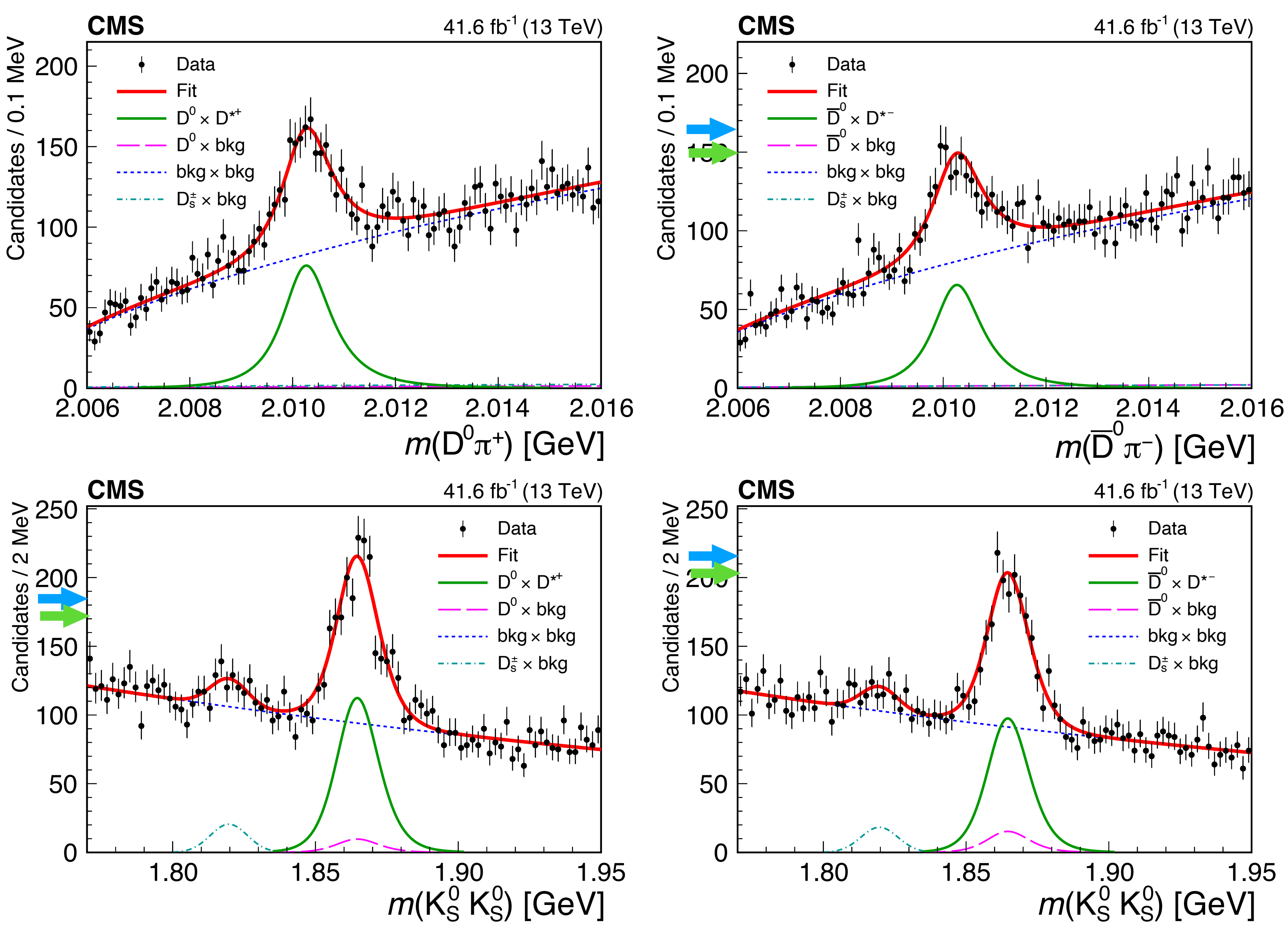
Search for *CP* violation in $\mathrm{D}^0 \to \mathrm{K}^0_S \mathrm{K}^0_S$ decays

$A^{\mathrm{raw}}_{CP}(\mathrm{K}^0_S\mathrm{K}^0_S) = (7.1 \pm 3)\,\%$

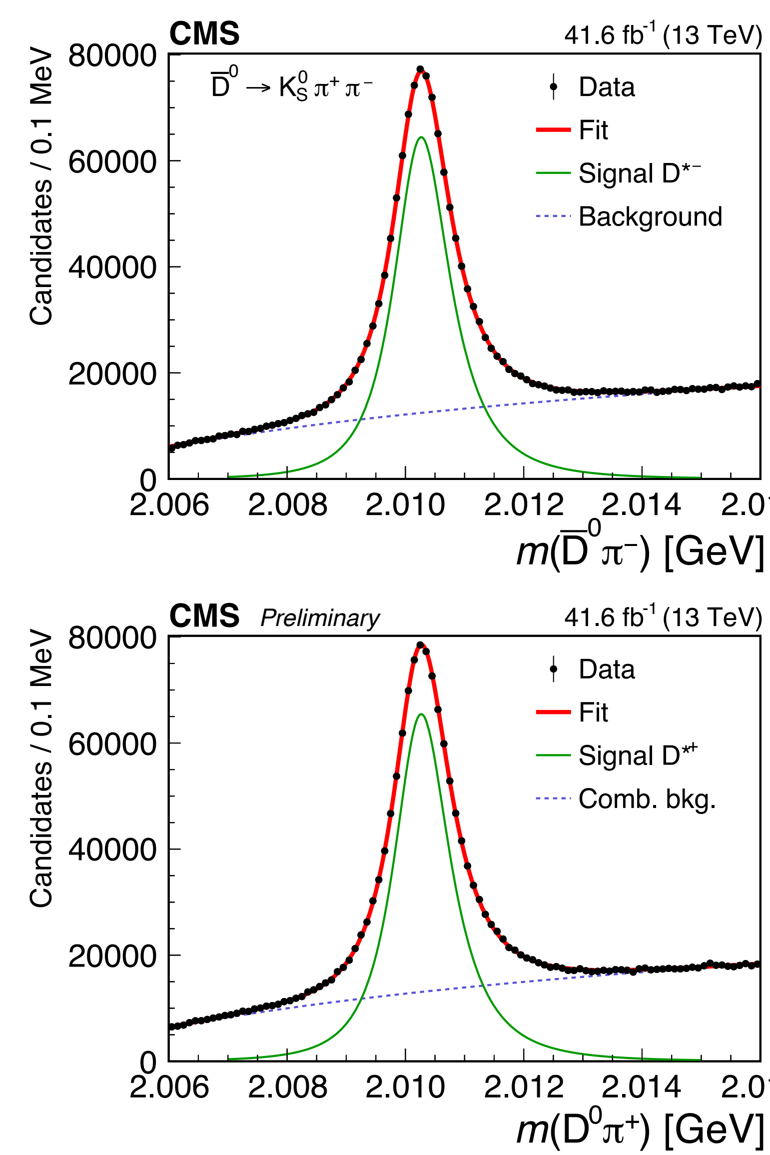
Pion charge	N	χ^2 (x axis)	χ^2 (y axis)
π^+	1095 ± 46	77	90
π^-	951 ± 44	93	62



notice peak height difference
blue vs green arrows

$A^{\mathrm{raw}}_{CP}(\mathrm{K}^0_S\pi\pi) = (0.78 \pm 0.10)\,\%$

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



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Search for *CP* violation in $\mathrm{D}^0 \to \mathrm{K_S^0 K_S^0}$ decays

Results

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

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

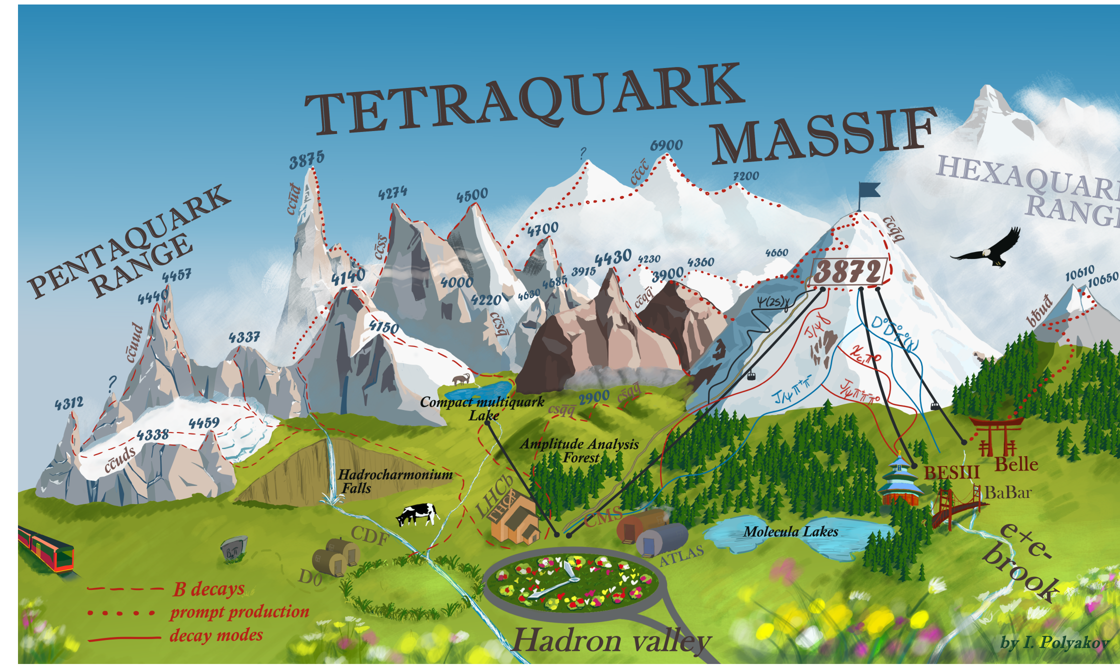
statistically limited, systematics primarily from variations on fit models

paves the way for future and more accurate measurements

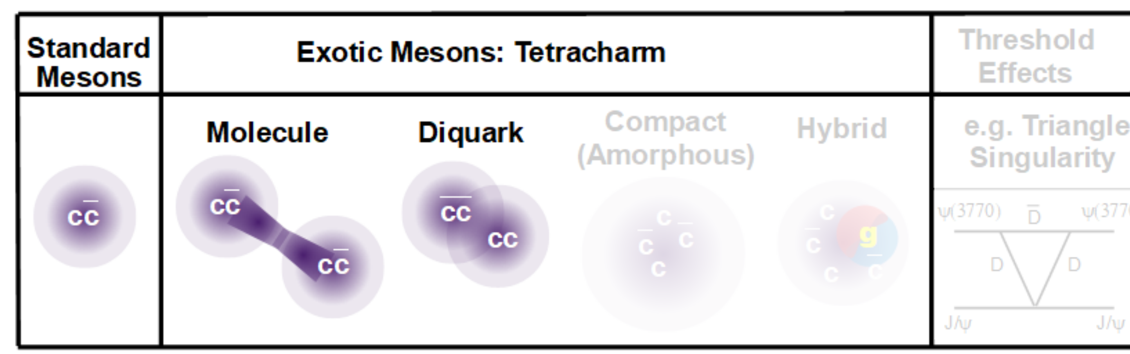
Source	Uncertainty, %
$m(\mathrm{D}\pi^\pm)$ signal model	0.10
$m(\mathrm{D}\pi^\pm)$ background model	0.02
$m(\mathrm{K_S^0 K_S^0})$ signal model	0.04
$m(\mathrm{K_S^0 K_S^0})$ background model	0.02
$m(\mathrm{K_S^0 K_S^0})$ fit range	0.04
Reweighting	0.09
ΔA_{CP} in MC	0.13
Total	0.20

Tetraquarks - motivations

credit 2410.06923



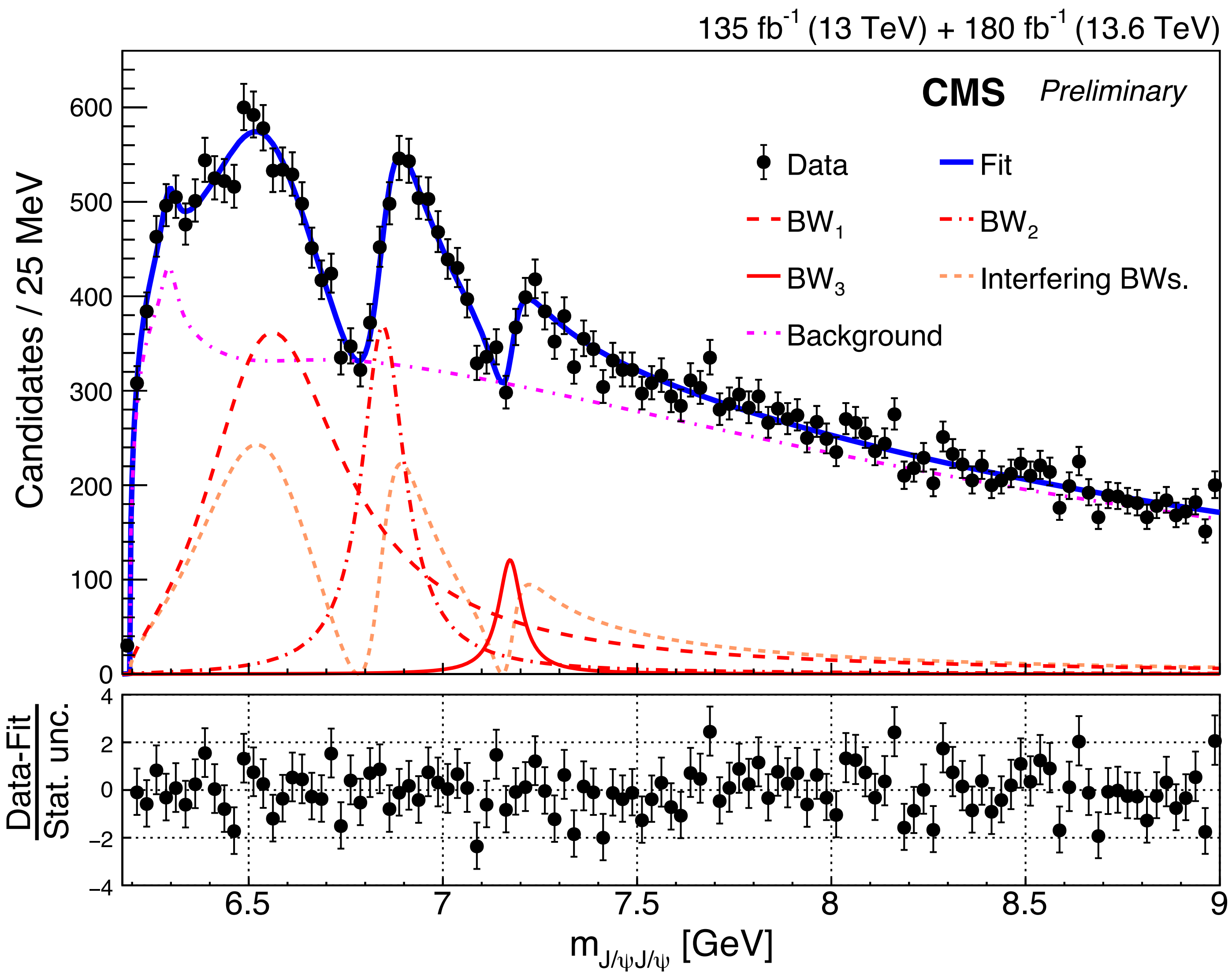
- **Gell-Mann and Zweig's (1964) quark model allowed for "exotic" tetra and pentaquarks**
  - first confirmed in 2003 discovery of $X(3872) \to J/\Psi\, \pi\pi$ PRL 91 (2003)
  - tens more at the LHC (survey by P. Koppenburg)

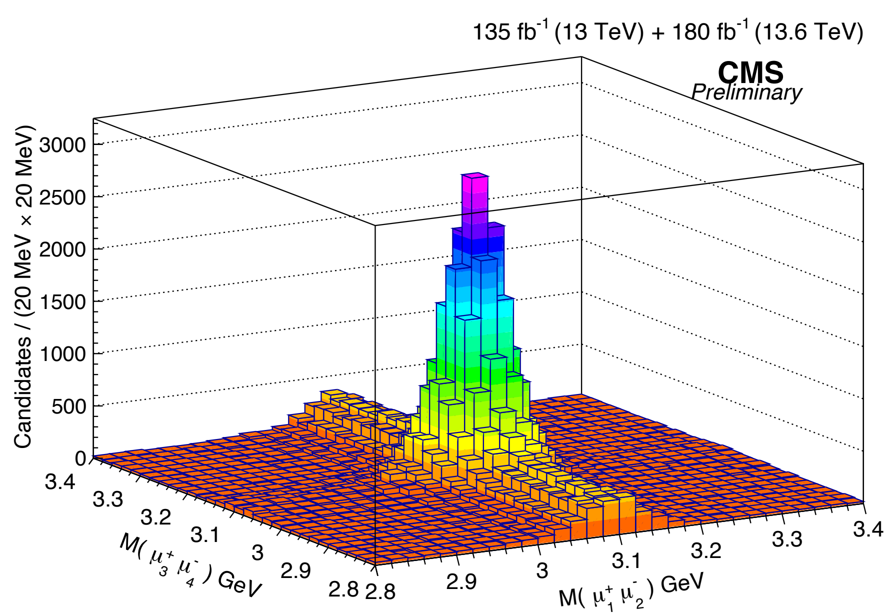


- **tightly-bound states of diquark+diantiquark or loosely-bound meson molecules** (or other)**?**
  - insight into QCD potential, confinement, strong force

- **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, $J/\Psi \to \mu\mu$ (and possibly $\Upsilon \to \mu\mu$) are clean experimental signature in CMS

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

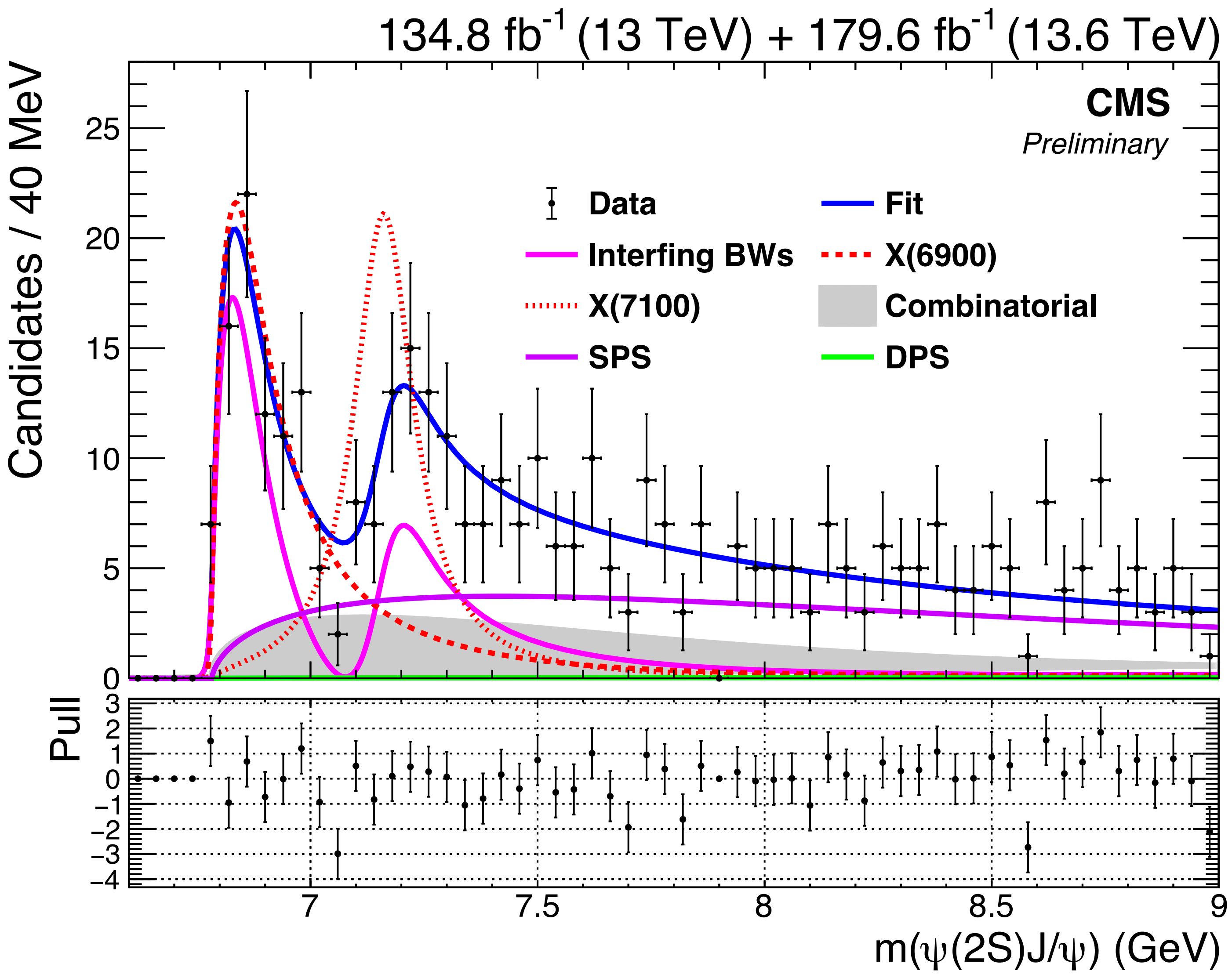




Observation of structures at $X(6600)$, $X(6900)$, and $X(7100)$

- **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**
  - $m^2_{X_i}$ 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 $X \to J/\Psi\, \Psi(2S) \to 4\mu$



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}
			Γ :	—	$253^{+290+120}_{-100-120}$	$154^{+110+140}_{-82-160}$
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}
			Γ :	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

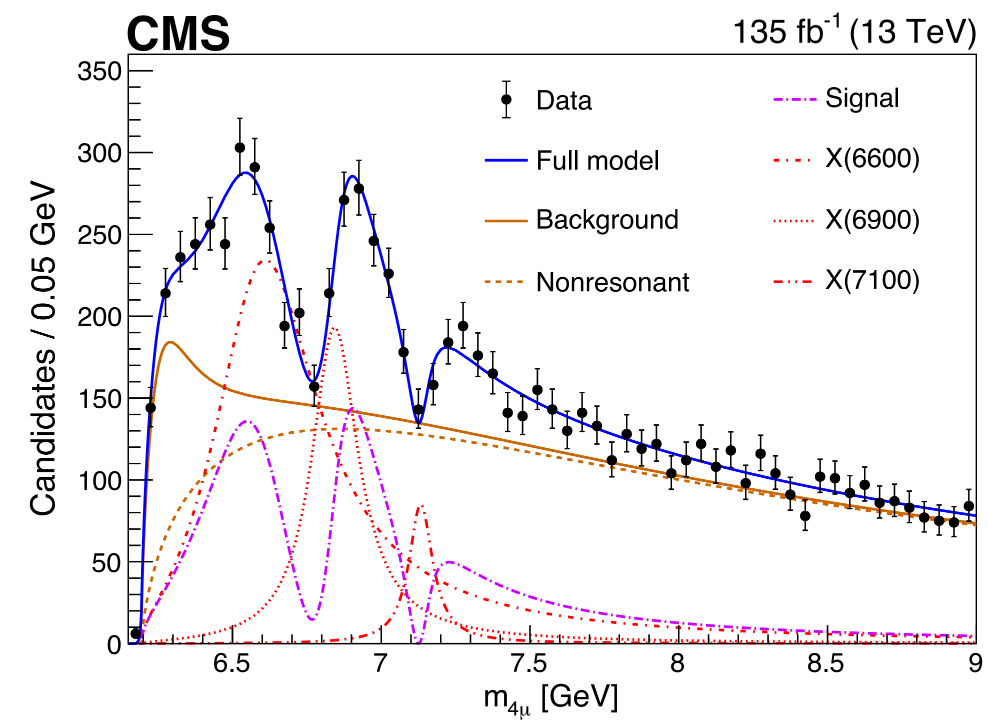
Observation of $X(6900)$ at $> 5\sigma$
evidence of $X(7100)$ at 4σ

- near-threshold enhancement in this channel first observed by ATLAS
- **interference assumed** analogous to $J/\Psi\, J/\Psi \to 4\mu$
- effect of below-threshold $X(6600)$ as systematic
- **masses and widths of $X(6900)$ and $X(7100)$ agree well with those measured in $J/\Psi\, J/\Psi \to 4\mu$**

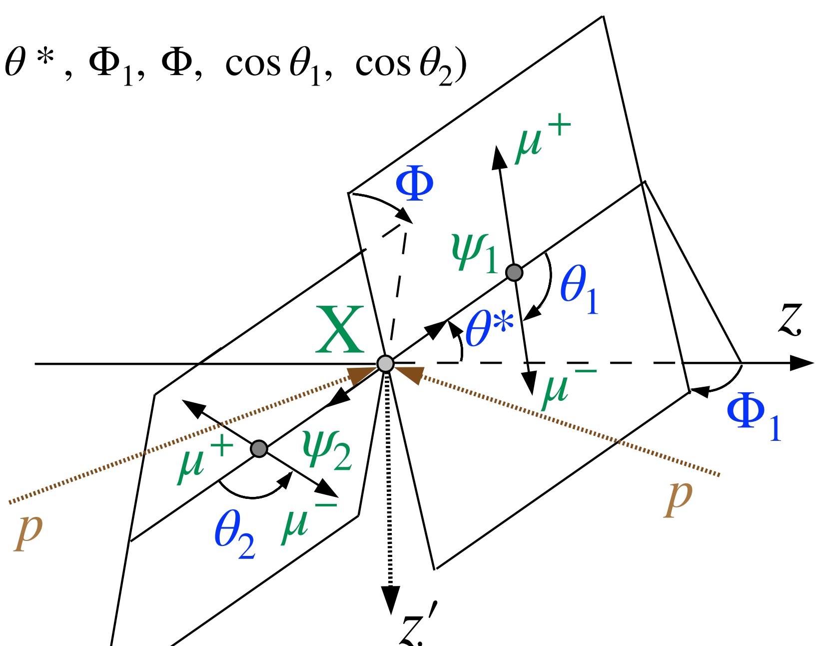
Determination of J^{PC} of all-charm tetra quarks

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, $\mathscr{L} = 135\,\mathrm{fb}^{-1}$ PRL 132 (2024) 111901
- build a likelihood ratio discriminant $\mathscr{D}_{ij}$ between two spin-parity hypothesis, using angular variables in the helicity basis
- 2D fit mass and $\mathscr{D}_{ij}$ → pairwise hypothesis testing for all considered models

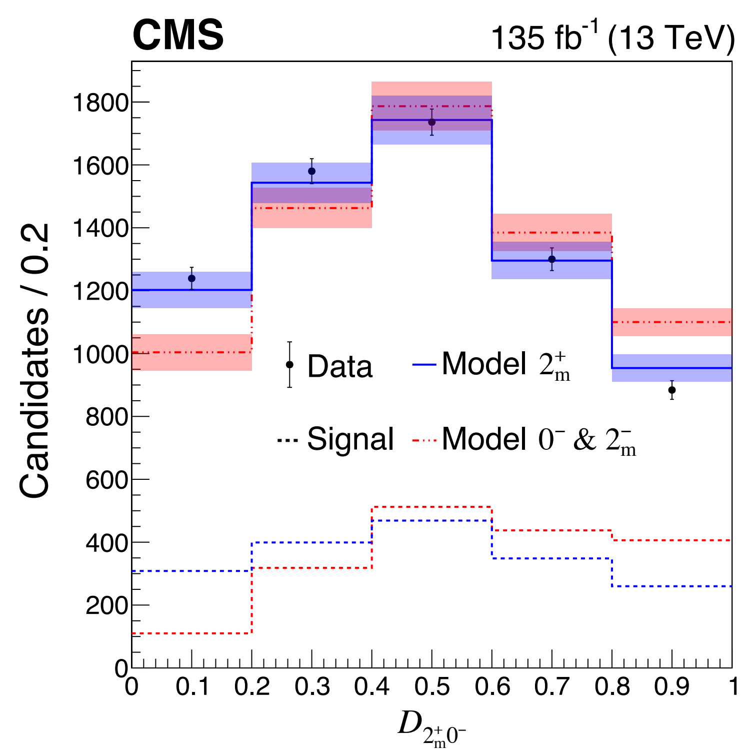


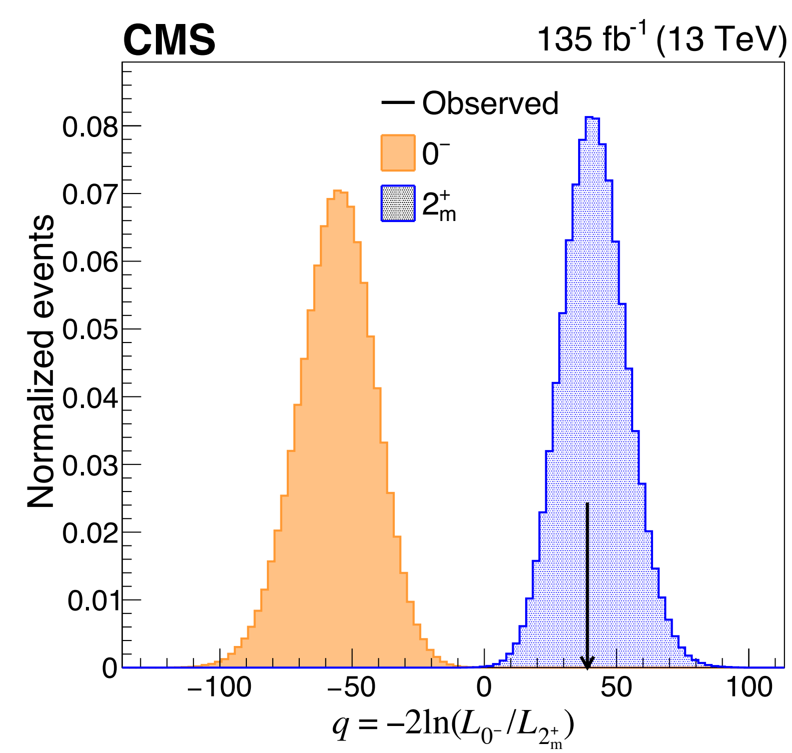
$\vec{\Omega} = (\cos\theta^*,\ \Phi_1,\ \Phi,\ \cos\theta_1,\ \cos\theta_2)$



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

MELA



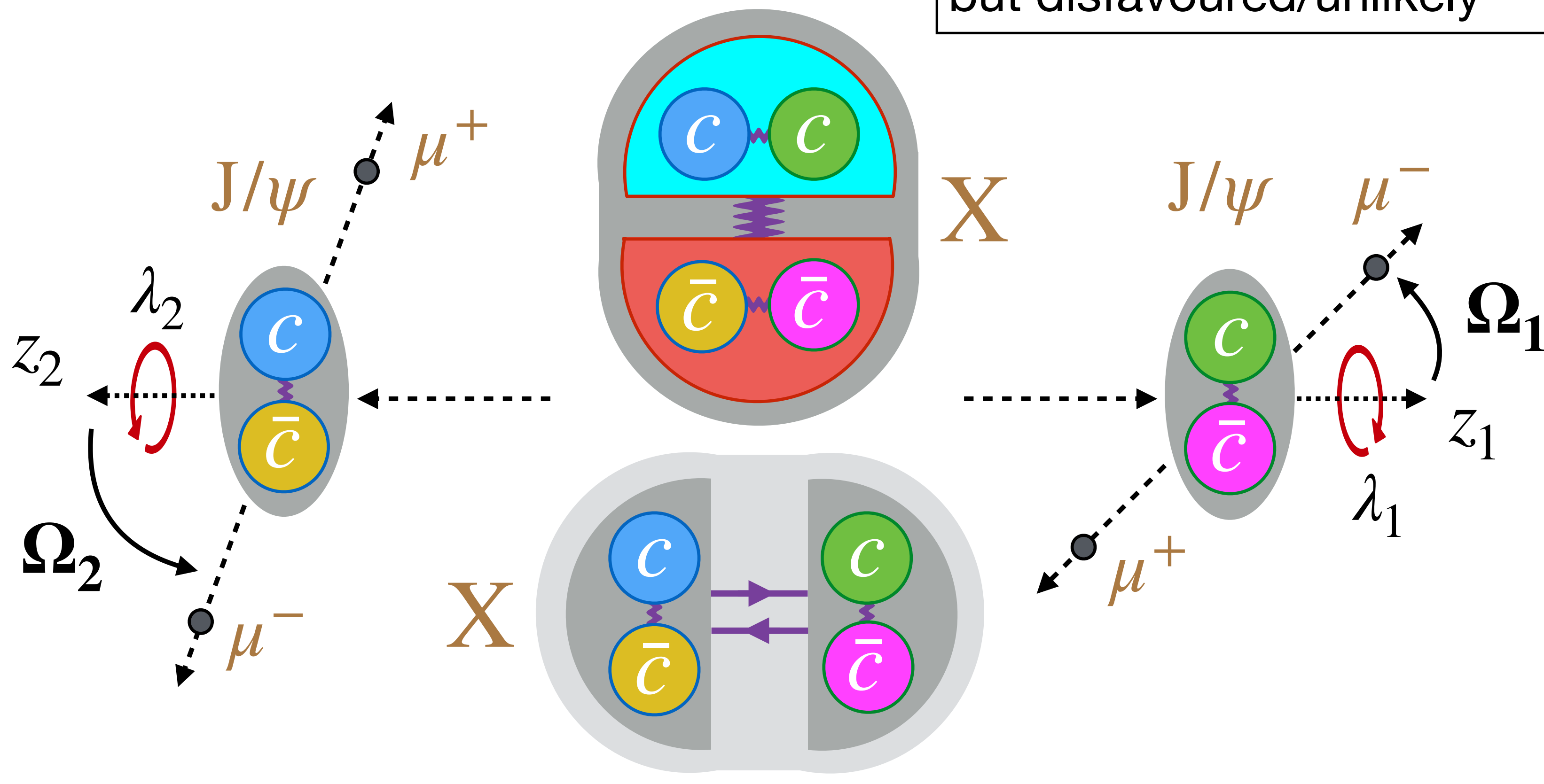


focus on the two more popular tetraquark models to determine which J^{PC} hypothesis to test

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

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

from P and D wave
$J^P=0^-,1^-,2^-,1^+,3^+\ldots$ 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

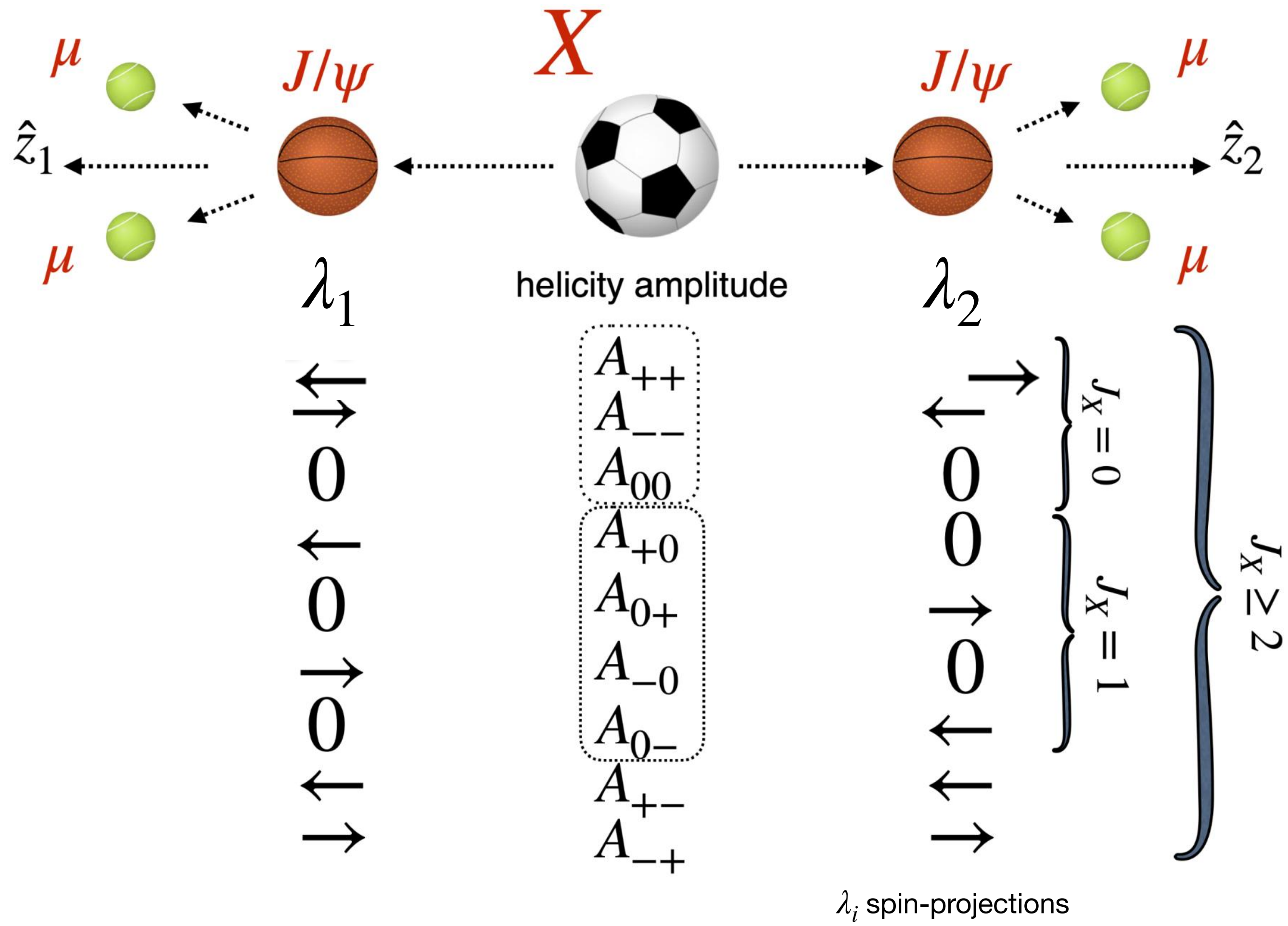
$C = +$ from decay
C is conserved in QCD

amplitudes are computed analytically → 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



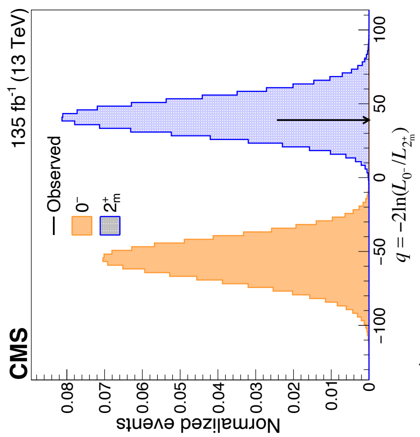
$$A_{\lambda_1\lambda_2} = (-1)^J A_{\lambda_2\lambda_1}$$
$$A_{\lambda_1\lambda_2} = P(-1)^J A_{-\lambda_2-\lambda_1}$$

J^{PC}	Models J_i^P	Contributing amplitudes
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 $A_{+-} = A_{-+}$

fully determined

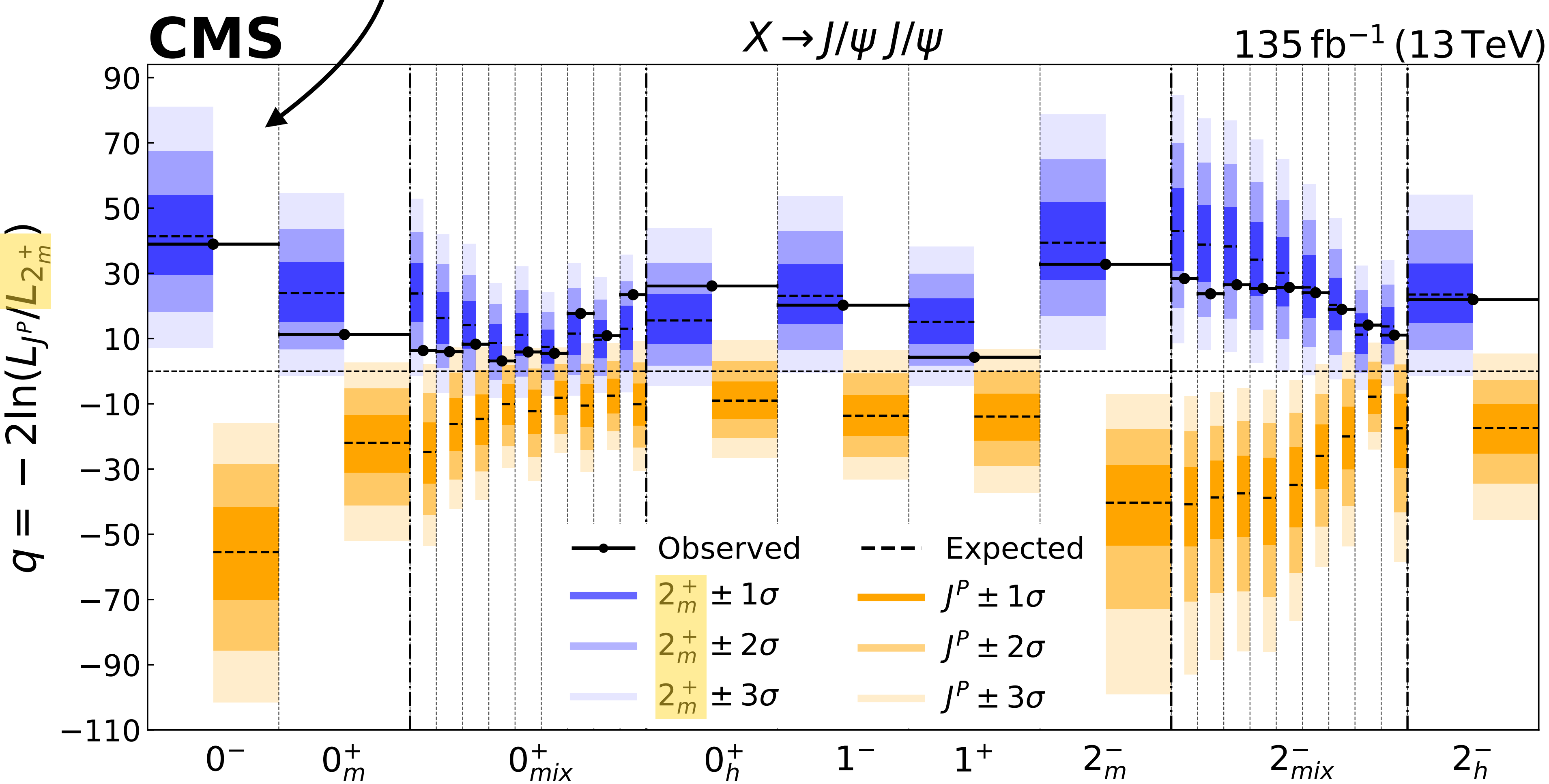
remaining d.o.f.
assume model h and m
scan for different proportions

Results



scan for different proportions of 0^+_h and 0^+_m

scan for different proportions of 2^+_h and 2^+_m



		Observed p-value	Observed Z-score
0^- vs 2^+_m	0^-	2.7×10^{-13}	7.2
	2^+_m	0.42	0.2
0^+_m vs 2^+_m	0^+_m	4.3×10^{-5}	3.9
	2^+_m	0.072	1.5
0^+_{mix} vs 2^+_m	0^+_{mix}	1.4×10^{-2}	2.2
	2^+_m	0.17	1.0
0^+_h vs 2^+_m	0^+_h	3.1×10^{-9}	5.8
	2^+_m	0.90	-1.3
1^- vs 2^+_m	1^-	8.0×10^{-8}	5.2
	2^+_m	0.38	0.3
1^+ vs 2^+_m	1^+	4.7×10^{-3}	2.6
	2^+_m	0.052	1.6
2^-_m vs 2^+_m	2^-_m	4.1×10^{-12}	6.8
	2^+_m	0.28	0.6
2^-_{mix} vs 2^+_m	2^-_{mix}	6.5×10^{-4}	3.2
	2^+_m	0.31	0.5
2^-_h vs 2^+_m	2^-_h	2.2×10^{-8}	5.5
	2^+_m	0.43	0.2

$J^P = 2^+$ strongly favoured

2^+_m minimal model favoured

$P = +$ established

$J^P = 0^+$ excluded at $> 95\,\%$ CL
$J^P = 1^+$ excluded at $99\,\%$ CL

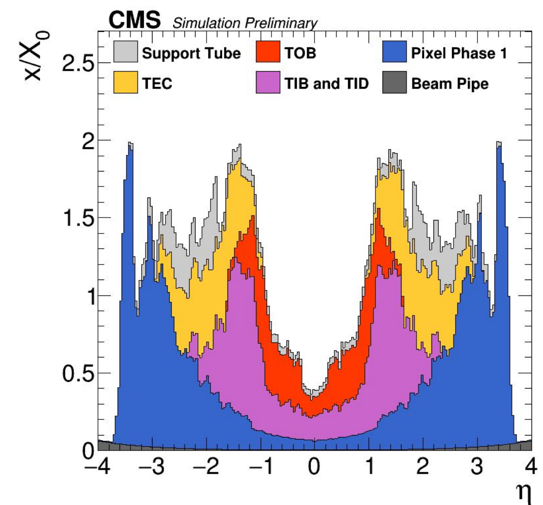
$P = 1$ excludes $L = 1$ in either tetraquark models

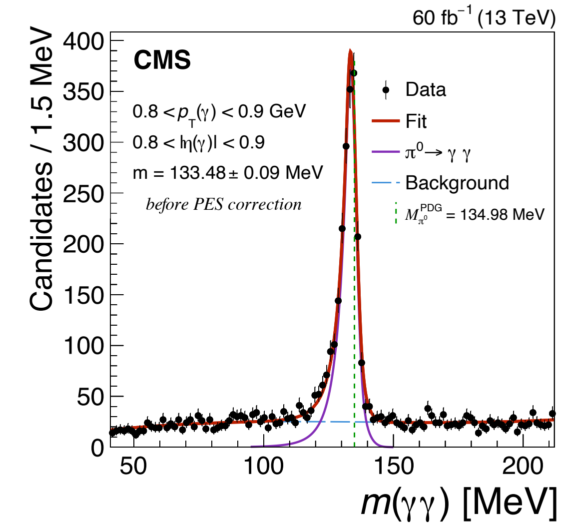
molecule model → $L = 2$ unlikely, $S = 0, 1$

diquark model → $S = 1$ more naturally favours $J = 2$

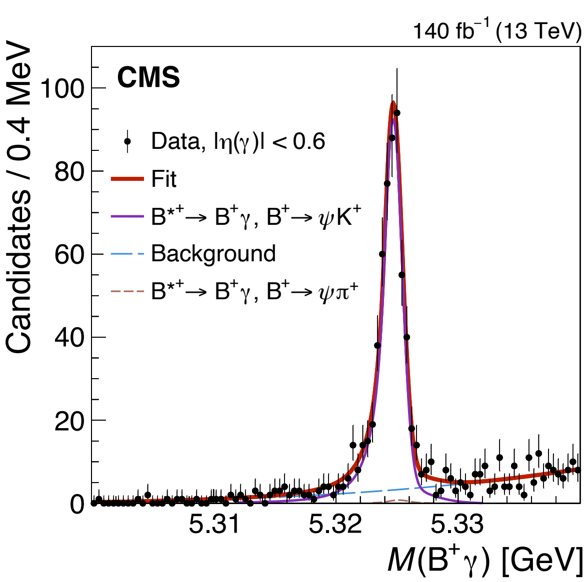
Exclusive reco of excited B^* and mass measurement

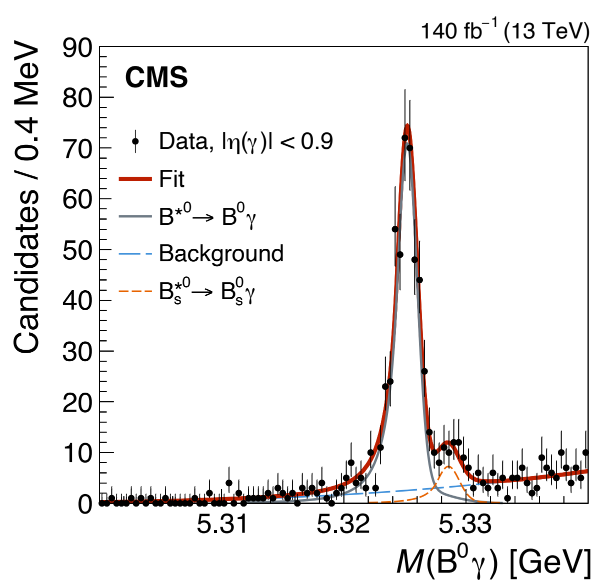
- **first full reconstruction of the vector mesons B^{*+}, B^{*0}, B^*_s**
  - using $\gamma^* \to e^+e^-$ conversion in material
    - lower acceptance, but cleaner signature than low energy photons
    - energy calibration with $\pi^0 \to \gamma\gamma$ in rapidity/momentum bins

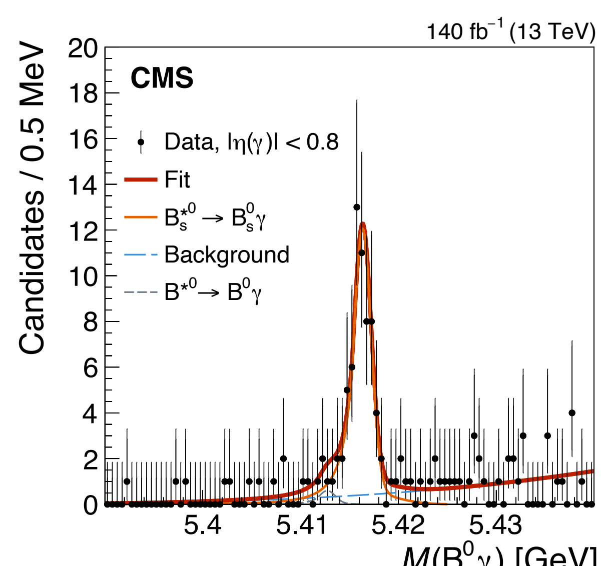




- **precise measurements of $m(\mathrm{B}^*) - m(\mathrm{B})$ $45 - 49\,\mathrm{MeV}$**







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

Summary

Flavour physics is deeply connected to the evolution of early universe and the matter-antimatter asymmetry

CMS carries out an expansive flavour physics programme

study of QCD in production, exotic hadrons, …

CP violation

indirect searches for new physics through precision measurements of rare decays

lepton flavour (universality) violation

using a variety of analysis techniques and tools

angular analysis, multidim fits, machine learning, …

limited selection of recent results in this talk
see here for the full picture

happy to discuss over coffee / tea