Recent Heavy Flavour Physics results by the CMS experiment

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on behalf of the CMS Collaboration

EPS-HEP – 7th July 2025 – Marseille

Outline

- Search for rare $D^0 \to \mu\mu$ decay

[arXiv:2506.06152]
submitted to PRL

- First full reconstruction of B* mesons

[CMS-BPH-24-011]

- Follow other CMS results:
  - Lepton flavor (universality) violation studies with heavy flavor at CMS

    by Chiara Basile, today 3 PM
  - Observation of a family of all-charm tetraquarks with spin-2 and positive parity at CMS

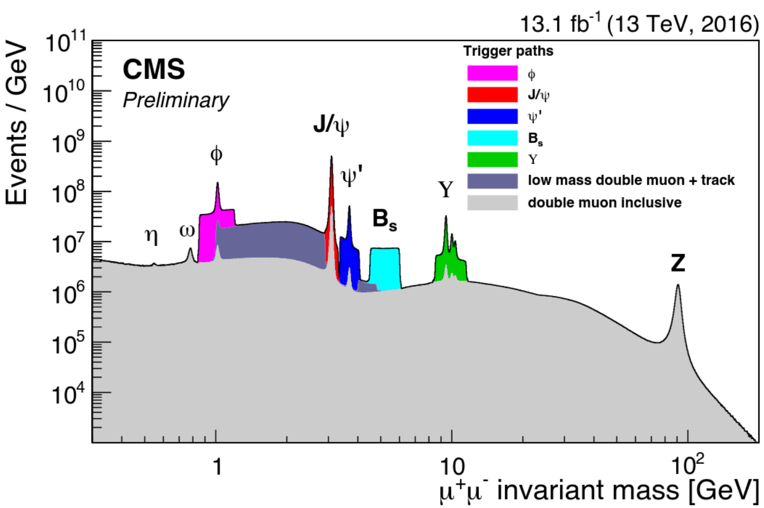
    by Xining Wang, tomorrow 4:30 PM QCD & hadron physics track
  - Production of Heavy Flavours at CMS

    by Marco Buonsante, Wed 5 PM

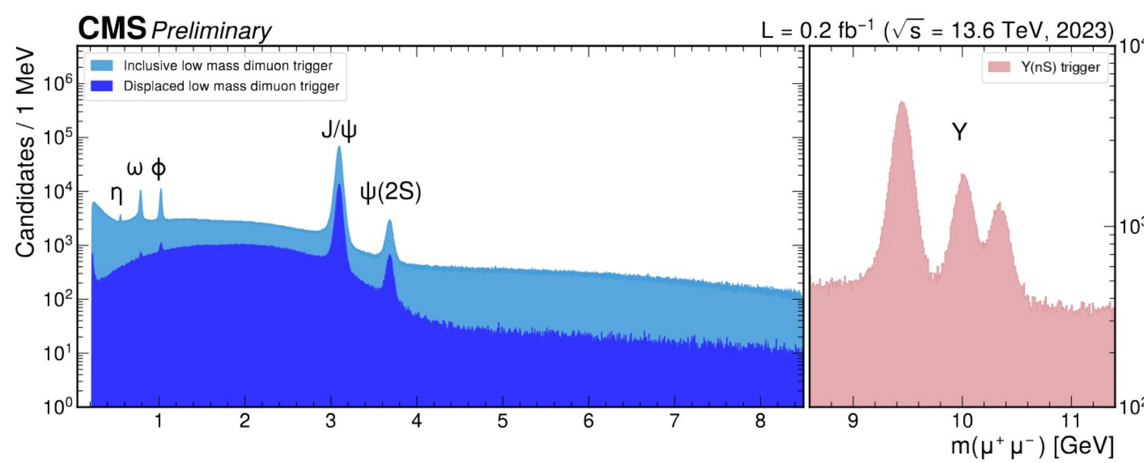
CMS triggers for heavy-flavor physics

Many heavy-flavor analyses in CMS rely on dimuon triggers

Run2: set of triggers dedicated to specific dimuon mass regions or topologies
Run3: inclusive dimuon trigger with loose requirements on the momenta



[CMS-DP-2016-059]



[CMS-NOTE-2023-007]

Search for rare $D^0 \to \mu\mu$ decay

[arXiv:2506.06152]
submitted to PRL

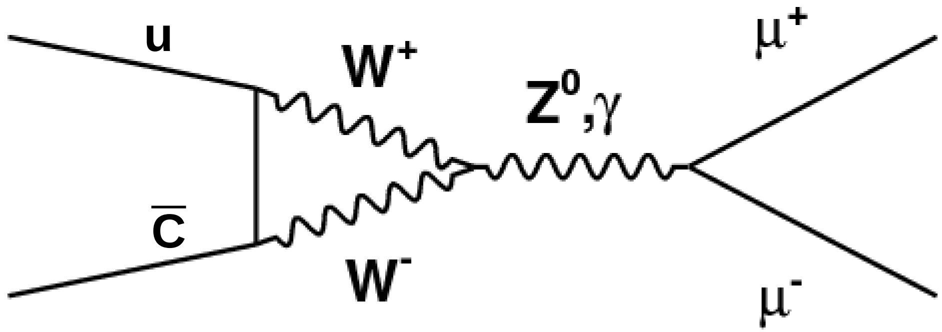
Search for $D^0 \rightarrow \mu\mu$ decay

[arXiv:2506.06152]

Flavour changing neutral currents gained a lot of attention in the last decades

- $bs\ell\ell$ transitions under heavy scrutiny
  ex. $B_s \rightarrow \mu\mu$ and $b \rightarrow s\mu\mu$ analyses

- $cu\ell\ell$ transitions less studied



$D^0 \rightarrow \mu\mu$ decay heavily suppressed in the SM (loop diagram + helicity):
- BR prediction ~ 10^{-13}
- High sensitivity to new-physics phenomena

Former most sensitive analysis by LHCb posed a limit at: $BR(D^0 \rightarrow \mu\mu) < 3.5\ 10^{-9}$ (95% CL)

This analysis uses 2022+2023 CMS data, and first one using new low-p_T dimuon trigger

Search for $D^0 \rightarrow \mu\mu$ decay

[arXiv:2506.06152]

Analysis uses D^0 from cascade decays: $D^{*+} \rightarrow D^0\pi^+$

- Exploits mass difference $\Delta m = m(D^{*+}) - m(D^0)$ to strongly suppress combinatorial
- D^{*+} produced promptly or from B-hadron decays
- Final state: two opposite charged muons + track

$D^0 \rightarrow \pi^+\pi^-$ used as normalization channel:

$$\mathcal{B}(\mathrm{D}^0 \to \mu^+\mu^-) = \mathcal{B}(\mathrm{D}^0 \to \pi^+\pi^-)\frac{N_{\mathrm{D}^0\to\mu\mu}}{N_{\mathrm{D}^0\to\pi\pi}}\frac{\varepsilon_{\mathrm{D}^0\to\pi\pi}}{\varepsilon_{\mathrm{D}^0\to\mu\mu}}$$

Sources of background:

- Combinatorial: suppressed via BDT, exploiting topological and kinematic features
- Peaking backgrounds for signal (w/ misID pions):
  - $D^{*+} \rightarrow D^0(\pi\pi)\pi$
  - $D^{*+} \rightarrow D^0(\pi\mu\nu)\pi$
- Peaking background for normalization channel:
  - D^{*+}->$D^0(K\pi)\pi$

Search for $D^0 \to \mu\mu$ decay - results

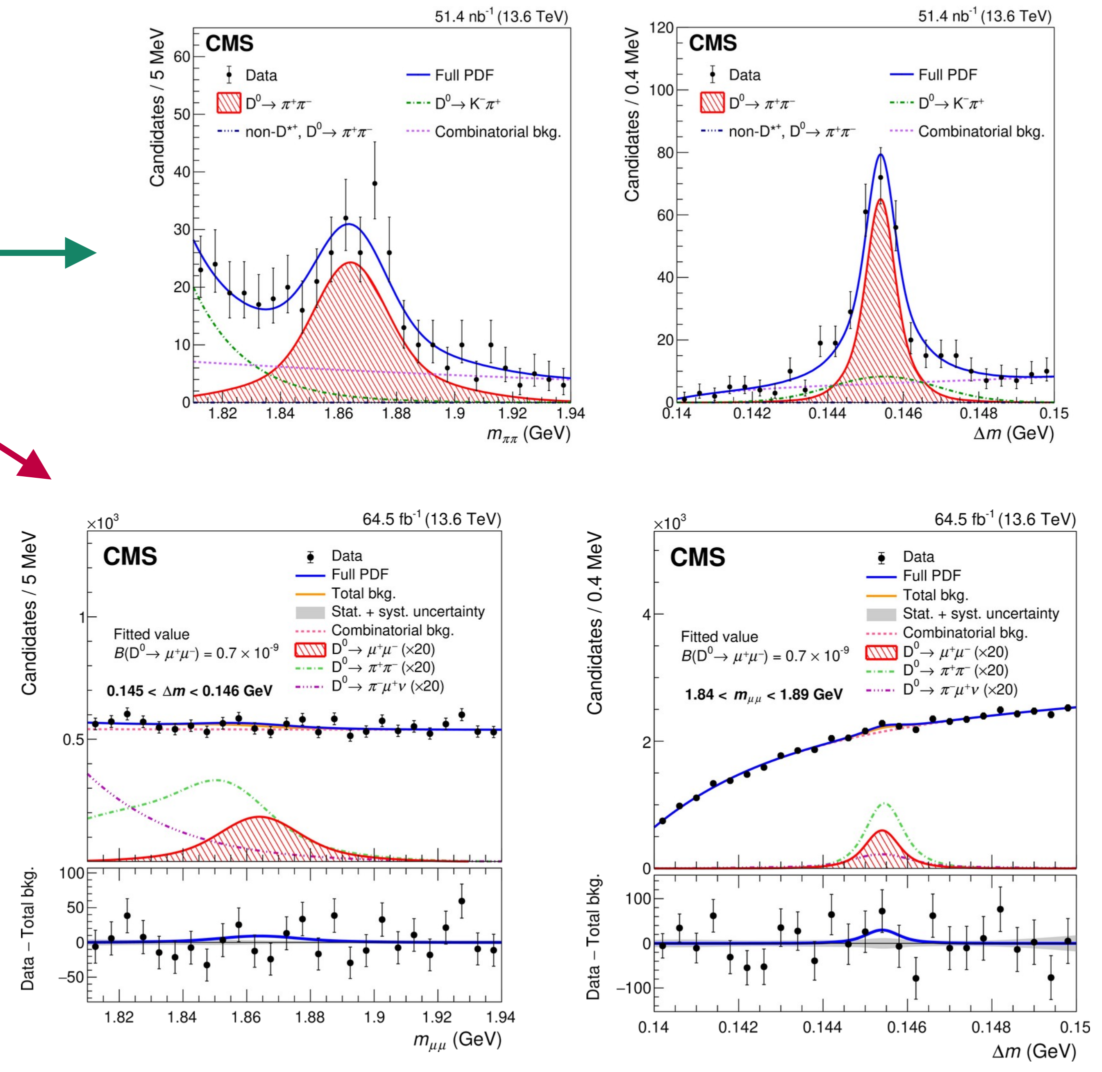
[arXiv:2506.06152]

2D UML fits:
- to [m(ππ), Δm] in normalization sample
- to [m(μμ), Δm] in signal sample

No significant signal excess

Resulting limit:

$BR(D^0 \to \mu\mu) < 2.4\ 10^{-9}$ at 95% CL



Fullly exclusive reconstruction of B^{*+}, B^{*0}, B_s^{*0} radiative decays

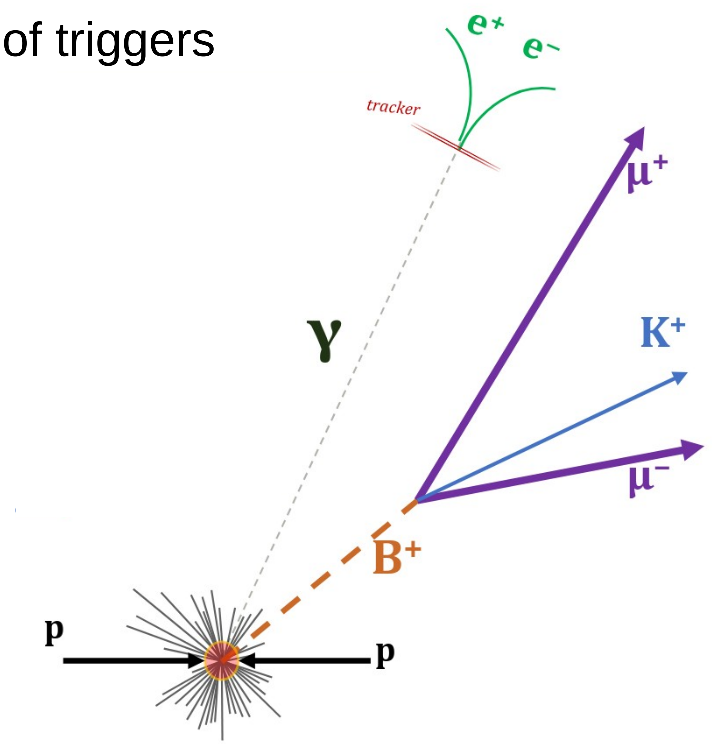
[CMS-BPH-24-011]

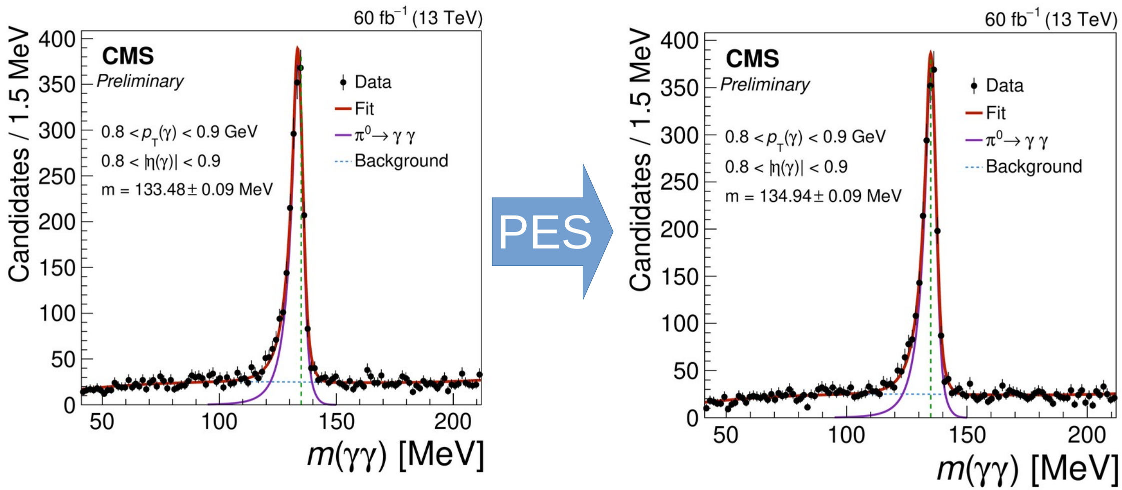
$B^* \to B\gamma$ full reconstruction

[CMS-BPH-24-011]

- CMS analysis on Run-2 heavy-flavor datasets, with mixture of triggers

- Exploits charmonium decays of B mesons
  - $B^+ \to \psi K^+$
  - $B^0 \to \psi K^*(892)^0$ $(\to K^+\pi^-)$
  - $B_s \to \psi\phi$ $(\to K^+K^-)$
  - J/ψ or $\psi(2S) \to \mu\mu$
- Photon conversion reconstruction in e^+e^-
- Refit of electron tracks and $B\gamma$ vertex (including other tracks from PV activity) to improve mass resolution

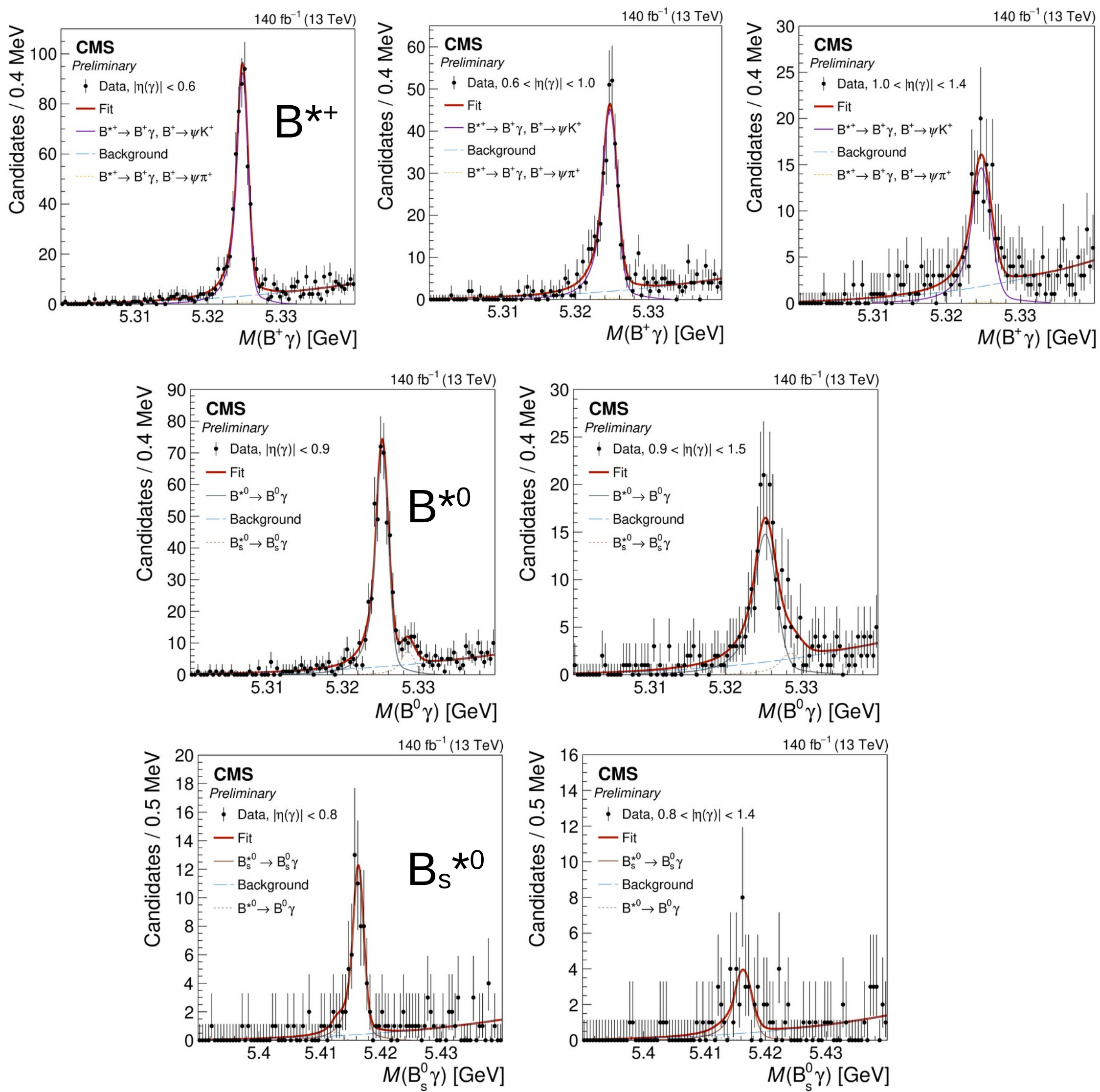




Dedicated photon energy correction:
- $\pi^0 \to \gamma\gamma$ with double conversion used in bins of p_T and η
- Successful in correcting energy underestimation

B* full reconstruction

[CMS-BPH-24-011]



Simultaneous fit in 7 categories of $M(X\gamma) = m(X\gamma)-m(X)+M_{PDG}(X)$

Categories defined by flavor and η ranges with common mass parameters within each flavor

Models include: Signal, Combinatorial bkg,
Peaking bkg: $B^+ \to \psi\pi^+$ and $B^{*0} \leftrightarrow B_s{}^{*0}$ cross-feed

Three states reconstructed fully exclusively for the first time!!

B* mass results

[CMS-BPH-24-011]

	Parameter	Value
1	$\Delta m(\mathrm{B}^{*+}) \equiv m(\mathrm{B}^{*+}) - m(\mathrm{B}^{+})$	$45.277 \pm 0.039 \pm 0.021$ MeV
2	$\Delta m(\mathrm{B}^{*0}) \equiv m(\mathrm{B}^{*0}) - m(\mathrm{B}^{0})$	$45.471 \pm 0.056 \pm 0.024$ MeV
3	$\Delta m(\mathrm{B}_s^{*0}) \equiv m(\mathrm{B}_s^{*0}) - m(\mathrm{B}_s^{0})$	$49.407 \pm 0.132 \pm 0.034$ MeV
4	$m(\mathrm{B}^{*+})$	$5324.69 \pm 0.04 \pm 0.02 \pm 0.07$ MeV
5	$m(\mathrm{B}^{*0})$	$5325.19 \pm 0.06 \pm 0.02 \pm 0.08$ MeV
6	$m(\mathrm{B}_s^{*0})$	$5416.34 \pm 0.13 \pm 0.03 \pm 0.10$ MeV
7	$m(\mathrm{B}^{*0}) - m(\mathrm{B}^{*+})$	$0.50 \pm 0.07 \pm 0.01 \pm 0.05$ MeV
8	$m(\mathrm{B}_s^{*0}) - m(\mathrm{B}^{*+})$	$91.66 \pm 0.14 \pm 0.03 \pm 0.12$ MeV
9	$m(\mathrm{B}_s^{*0}) - m(\mathrm{B}^{*0})$	$91.15 \pm 0.14 \pm 0.03 \pm 0.12$ MeV
10	$m(\mathrm{B}_s^{*0}) - \frac{m(\mathrm{B}^{*0})+m(\mathrm{B}^{*+})}{2}$	$91.40 \pm 0.13 \pm 0.03 \pm 0.12$ MeV
11	$\Delta m(\mathrm{B}^{*0}) - \Delta m(\mathrm{B}^{*+})$	$0.19 \pm 0.07 \pm 0.01$ MeV
12	$\Delta m(\mathrm{B}_s^{*0}) - \Delta m(\mathrm{B}^{*+})$	$4.13 \pm 0.14 \pm 0.03$ MeV
13	$\Delta m(\mathrm{B}_s^{*0}) - \Delta m(\mathrm{B}^{*0})$	$3.94 \pm 0.14 \pm 0.03$ MeV
14	$\Delta m(\mathrm{B}_s^{*0}) - \frac{\Delta m(\mathrm{B}^{*0})+\Delta m(\mathrm{B}^{*+})}{2}$	$4.03 \pm 0.13 \pm 0.03$ MeV
15	$\Delta m(\mathrm{B}^{*0}) / \Delta m(\mathrm{B}^{*+})$	$1.0043 \pm 0.0015 \pm 0.0002$
16	$\Delta m(\mathrm{B}_s^{*0}) / \Delta m(\mathrm{B}^{*+})$	$1.0912 \pm 0.0031 \pm 0.0007$
17	$\Delta m(\mathrm{B}_s^{*0}) / \Delta m(\mathrm{B}^{*0})$	$1.0866 \pm 0.0031 \pm 0.0007$
18	$\frac{2 \cdot \Delta m(\mathrm{B}_s^{*0})}{\Delta m(\mathrm{B}^{*+})+\Delta m(\mathrm{B}^{*0})}$	$1.0889 \pm 0.0030 \pm 0.0007$

Hyperfine splitting in B system!

One order of magnitude precision improvement wrt PDG 2024:

45.34 ± 0.20

45.34 ± 0.20

48.5 ± 1.4

New masses to add to PDG

"B* mass" 5324.75±0.20 MeV

B_s^{*0} mass 5415.4±1.4 MeV

In agreement with CMS-BPH-16-003

First measurements

Some systematics cancel in differences and ratios and theory uncertainty also expected to be reduced

B* mass – comparison with theory

[CMS-BPH-24-011]

A few lattice theory papers provide predictions with uncertainties

One paper comments on the ratio of hyperfine splitting

Parameter	Measurement, MeV	Theory, MeV
$\Delta m(\mathrm{B}^{*+})$ $m(\mathrm{B}^{*+}) - m(\mathrm{B}^{+})$	$45.277 \pm 0.039 \pm 0.021$	50 ± 3 [10] 39 ± 2 [24] 41.7 ± 5.3 [25]
$\Delta m(\mathrm{B}^{*0})$ $m(\mathrm{B}^{*0}) - m(\mathrm{B}^{0})$	$45.471 \pm 0.056 \pm 0.024$	
$\Delta m(\mathrm{B}_s^{*0})$ $m(\mathrm{B}_s^{*0}) - m(\mathrm{B}_s^{0})$	$49.407 \pm 0.132 \pm 0.034$	52 ± 3 [10] 38 ± 1 [24] 37.8 ± 6.7 MeV [25]

Parameter	Measurement	theory
$\Delta m(\mathrm{B}^{*0}) / \Delta m(\mathrm{B}^{*+})$ $\frac{m(\mathrm{B}^{*0})-m(\mathrm{B}^{0})}{m(\mathrm{B}^{*+})-m(\mathrm{B}^{+})}$	$1.0043 \pm 0.0015 \pm 0.0002$ —	———
$\Delta m(\mathrm{B}_s^{*0}) / \Delta m(\mathrm{B}^{*+})$ $\frac{m(\mathrm{B}_s^{*0})-m(\mathrm{B}_s^{0})}{m(\mathrm{B}^{*+})-m(\mathrm{B}^{+})}$	$1.0912 \pm 0.0031 \pm 0.0007$	
$\Delta m(\mathrm{B}_s^{*0}) / \Delta m(\mathrm{B}^{*0})$ $\frac{m(\mathrm{B}_s^{*0})-m(\mathrm{B}_s^{0})}{m(\mathrm{B}^{*0})-m(\mathrm{B}^{0})}$	$1.0866 \pm 0.0031 \pm 0.0007$	1.007 ± 0.034 [10]
$\frac{2 \cdot \Delta m(\mathrm{B}_s^{*0})}{\Delta m(\mathrm{B}^{*+}) + \Delta m(\mathrm{B}^{*0})}$	$1.0889 \pm 0.0030 \pm 0.0007$	

[10] Phys.Rev.D 86 (2012) 094510
[24] JHEP 01 (2025) 123
[25] Phys.Rev.D 92 (2015) 5, 054509

Summary and conclusions

- Search for rare $D^0 \rightarrow \mu\mu$ decay
  - Excellent example of application for new CMS soft dimuon triggers
  - New best limit on the branching ratio
  - Still 4 order of magnitude above SM prediction

- First full reconstruction of B* mesons
  - Uses converted photons to exclusively reconstruct the B^{*+}, B^{*0}, B_s^{*0} states
  - Most precise measurement of hyperfine splitting in B system
  - Theory predictions need to be improved!

- As inclusive dimuon and signle-muon triggers keep collecting data, stay tuned for new exiting results to come!

Backup slides

$D^0 \to \mu\mu$ systematic uncertainties

Source	$D^0 \to \mu\mu$	$D^0 \to \pi\pi$	$D^0 \to \pi\mu\nu$
Trigger efficiency	0.7%	0.7%	0.7%
Muon efficiency	2%	—	1%
Tracking efficiency	4.6%	4.6%	4.6%
Pileup	1%	1%	1%
$D^0 \to \pi^+\pi^-$ yield	8.7%	8.7%	8.7%
Efficiency	0.2%	0.6%	12%
d_{MVA} correction	1.2%	2.0%	—
$\mathcal{B}(D^0 \to \pi^+\pi^-)$	1.7%	—	1.7%
$\mathcal{B}(D^0 \to \pi^-\mu^+\nu)$	—	—	4.5%
Fit bias	1%	—	—
Misidentification rate	—	28%	14%

$D^0 \to \mu\mu$ resulting yields

Range	Signal	Comb. bkg.	$D^0 \to \pi^+\pi^-$	$D^0 \to \pi^-\mu^+\nu$	Data
Full range	100 ± 120	$126\,140 \pm 380$	278 ± 51	231 ± 40	$126\,752$
$0.145 < \Delta m < 0.146\,\text{GeV}$	67 ± 81	$14\,037 \pm 42$	179 ± 33	94 ± 16	$14\,412$
$1.84 < m_{\mu\mu} < 1.89\,\text{GeV}$	90 ± 110	$48\,530 \pm 150$	162 ± 30	62 ± 11	$48\,798$

B* history (from Sergey's talk @LHCP)

History of B* meson studies

CMS-PAS-BPH-24-011

LEP experiments L3, DELPHI, OPAL, ALEPH
using $Z \to b\bar{b}$ process, inclusively reconstruct B meson as **b-jet**
combine **b-jet** with a converted photon (calibrated via π^0)

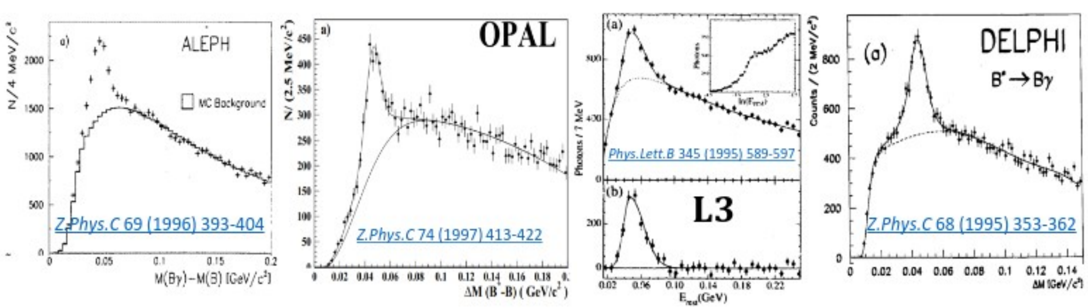
Measure **averaged between B^{*+}, B^{*0}, and B_s^{*0}** mass difference
$m(B^*)-m(B)$

Assumes $\Delta m = m(B^{*0})-m(B^0)=m(B^{*+})-m(B^+)$
for D mesons such Δm are different by 1.5 MeV!

$m_{B^*}-m_B$

VALUE (MeV)		EVTS	DOCUMENT ID		TECN
45.21 ± 0.21	OUR FIT				
45.42 ± 0.26	OUR AVERAGE includes data from $m_{B^*}-m_B$				
46.2 ±0.3 ±0.8			[1] ACKERSTAFF	1997M	OPAL
45.3 ±0.35 ±0.87		4227	[1] BUSKULIC	1996D	ALEP
45.5 ±0.3 ±0.8			[1] ABREU	1995R	DLPH
46.3 ±1.9		1378	[1] ACCIARRI	1995B	L3

28+ year-old measurements!

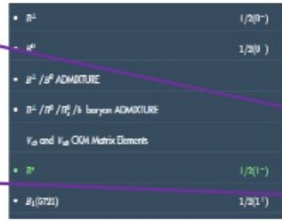


Mass differences also measured via P-wave B_s^0 states

$m(B^{*+})-m(B^+)$ measured by LHCb using the difference between $B^*_{s2}(5840)^0 \to B^{*+}K^-$ and $B^*_{s2}(5840)^0 \to B^+K^-$ peak positions

$m(B^{*+})-m(B^{*0})$ was measured by CMS (BPH-16-003) via the difference between $B_{s1}(5830)^0 \to B^{*0}K^0_S$ and $B_{s1}(5830)^0 \to B^{*+}K^-$ peak positions

PDG still has a single "entry" for B^{*+} and B^{*0}!



B^* MASS	5324.71 ± 0.21 MeV
$m_{B^*}-m_B$	45.21 ± 0.21 MeV
$m_{B^{*+}}-m_{B^+}$	45.37 ± 0.21 MeV
$\lvert(m_{B^{+}}-m_{B^+})-(m_{B^0}-m_{B^0})\rvert$	< 6 MeV CL=95.0%
$m_{B^{*0}}-m_{B^{*+}}$	0.91 ± 0.26 MeV

Main challenge: very low-energy photons emitted in $B^* \to B\gamma$

B* history (from Sergey's talk @LHCP)

B_s^{*0} measurements at B-factories

CMS-PAS-BPH-24-011

B_s^{*0} mass difference w.r.t. B_s^0 was previously measured at B-factories via the energy spectrum of reconstructed B_s^0 mesons assumed to be produced in Y(5S) decays:

- $Y(5S) \to B_s^0 \overline{B}_s^0$
- $Y(5S) \to B_s^{*0} \overline{B}_s^0$
- $Y(5S) \to B_s^0 \overline{B}_s^{*0}$
- $Y(5S) \to B_s^{*0} \overline{B}_s^{*0}$

However, the results were not in a good agreement with each other (PDG scale factor 2.9)

Central value of the mass difference is larger in comparison to B^+ & B^0

$m_{B_s^*} - m_{B_s}$

VALUE (MeV)		DOCUMENT ID		TECN	COMMENT
$48.5^{+1.8}_{-1.5}$	OUR FIT Error includes scale factor of 2.9.				
46.1 ± 1.5	OUR AVERAGE				
$45.7 \pm 1.7 \pm 0.7$		[1] AQUINES	2006	CLEO	$e^+ e^- \to \Upsilon(5S)$
47.0 ± 2.6		[2] LEE-FRANZINI	1990	CSB2	$e^+ e^- \to \Upsilon(5S)$

B_s^* MASS

From mass difference below and the B_s^0 mass.

VALUE (MeV)		DOCUMENT ID		TECN
$5415.4^{+1.8}_{-1.5}$	OUR FIT Error includes scale factor of 2.9.			
5415.8 ± 1.5	OUR AVERAGE Error includes scale factor of 2.6.			
$5416.4 \pm 0.4 \pm 0.5$		LOUVOT	2009	BELL
$5411.7 \pm 1.6 \pm 0.6$		[1] AQUINES	2006	CLEO

Do we have enough data in CMS to exclusively reconstruct B^{*+}, B^{*0}, and B_s^{*0} mesons via J/ψ modes and provide separate measurements of the respective Δm?

B* systematics

Δm uncertainties [keV]

Source	$m(B^{*+}) - m(B^{+})$	$m(B^{*0}) - m(B^{0})$	$m(B_s^{*0}) - m(B_s^{0})$
Signal model	4	8	21
Signal shape parameters	17	18	15
Yield ratios between $\lvert\eta(\gamma)\rvert$ regions	1	2	10
Background shape	2	< 1	7
Cross-feed $B_s^{*0} \leftrightarrow B^{*0}$	< 1	1	10
PES	12	14	16
Total	22	24	34

Δm differences uncertainties [keV]

Source	$\Delta m(B^{*0}) - \Delta m(B^{*+})$	$\Delta m(B_s^{*0}) - \Delta m(B^{*+})$	$\Delta m(B_s^{*0}) - \Delta m(B^{*0})$	$\Delta m(B_s^{*0}) - \frac{\Delta m(B^{*0})+\Delta m(B^{*+})}{2}$
Baseline value	194	4130	3936	4033
Statistical uncertainty	68	138	139	134
Signal model	4	23	23	23
Signal shape parameters	2	7	7	7
Yield ratios between $\lvert\eta(\gamma)\rvert$ regions	3	11	7	9
Background shape	3	9	6	8
$B^+ \to J/\psi\pi^+$ yield	1	1	< 1	< 1
Cross-feed $B_s^{*0} \leftrightarrow B^{*0}$	1	10	12	11
Photon energy scale	4	11	11	11
Total systematic	8	31	31	31

Δm ratio uncertainties

Source	$\Delta m(B^{*0})/\Delta m(B^{*+})$	$\Delta m(B_s^{*0})/\Delta m(B^{*+})$	$\Delta m(B_s^{*0})/\Delta m(B^{*0})$	$\frac{2\cdot\Delta m(B_s^{*0})}{\Delta m(B^{*+})+\Delta m(B^{*0})}$
Baseline value	1.00428	1.09122	1.08656	1.08888
Statistical uncertainty	0.00151	0.00306	0.00309	0.00297
Signal model	0.00009	0.00050	0.00052	0.00052
Signal shape parameters	0.00005	0.00014	0.00016	0.00016
Yield ratios between $\lvert\eta(\gamma)\rvert$ regions	0.00008	0.00023	0.00016	0.00020
Background shape	0.00005	0.00020	0.00014	0.00017
$B^+ \to J/\psi\pi^+$ yield	0.00002	0.00002	0	0.00001
Cross-feed $B_s^{*0} \leftrightarrow B^{*0}$	0.00003	0.00023	0.00025	0.00015
Photon energy scale	0.00009	0.00025	0.00024	0.00024
Total systematic	0.00017	0.00069	0.00068	0.00067