Heavy flavor physics at CMS and D0

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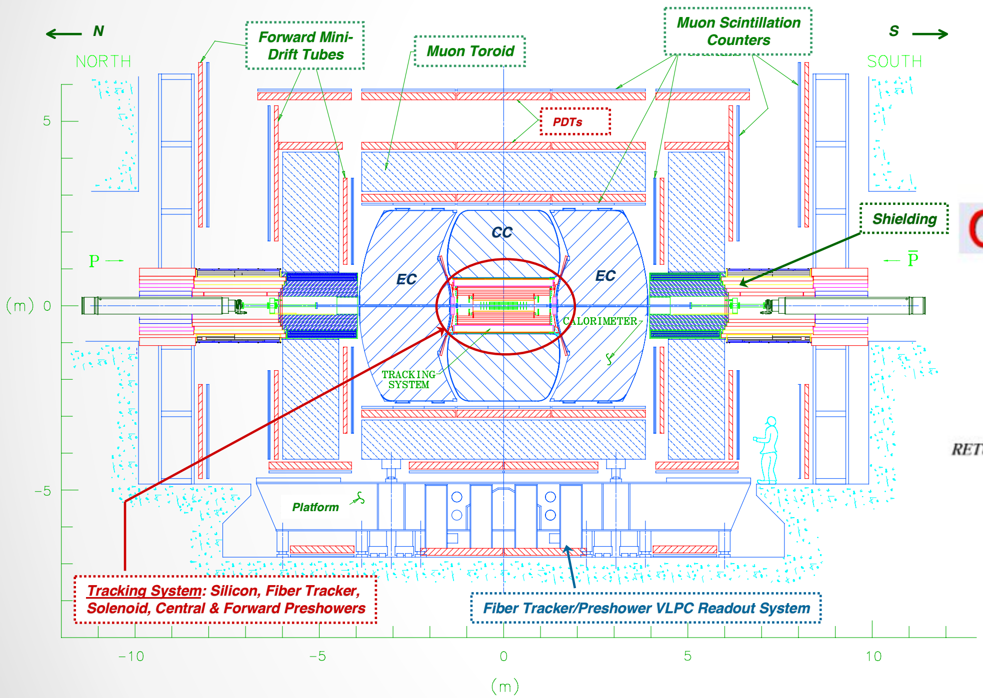
Outline

- Introduction
- D0 & CMS detectors & the B physics program
- CP-Violation in B^0_s.
- B_c meson decays.
- B hadron properties.
- Rare decays as new physics probes.
- Exotic hadrons.
- Summary and outlook

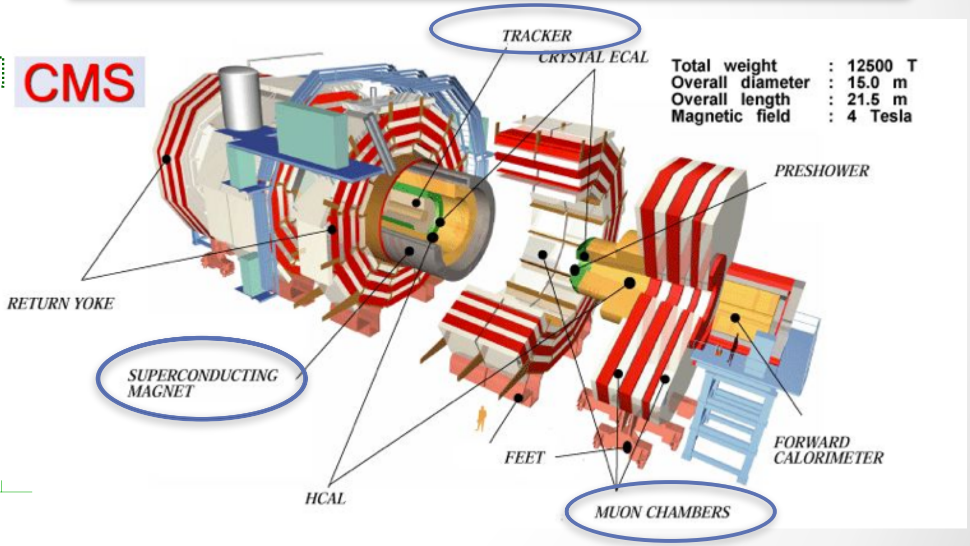
Introduction

- LHC: pp collisions @ 7-8 (Run I) & 13 TeV (Run II) $\Rightarrow$ large B hadron production.
- D0/Tevatron shut down in 2012. B/QCD program still continues.
- Precise measurements of B hadrons properties help to improve or constrain QCD models, and could provide signs of new physics or constrain BSM models.
- CMS is able to provide several measurements of B hadrons properties that are competitive with results from other experiments, such as in:
  - B mesons and baryons: masses, lifetimes, BRs, polarizations, etc.
  - CP-Violation in B mesons.
  - B rare decays: branching ratios, angular parameters.
  - Decays to exotic hadrons.

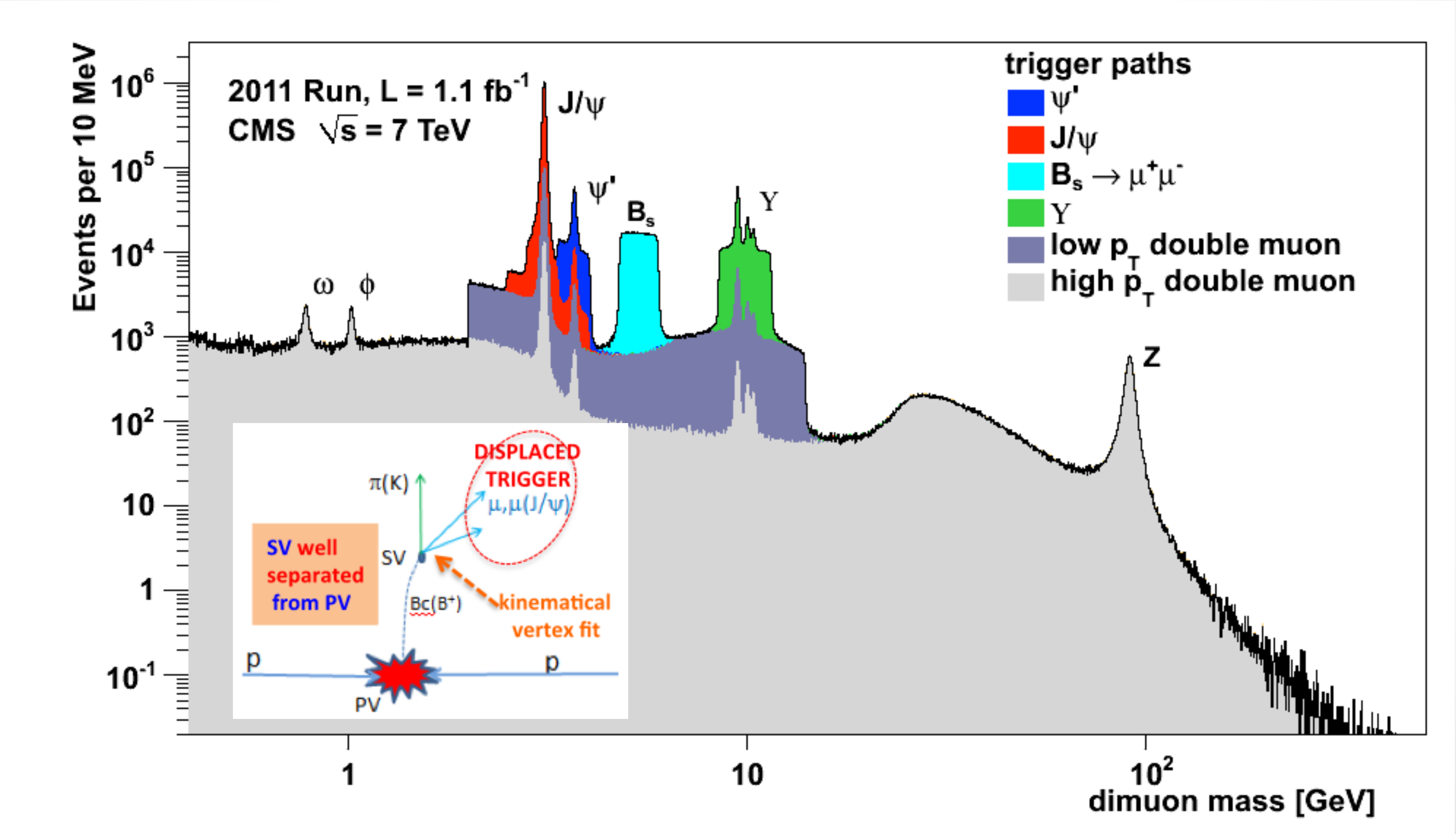
D0 and CMS detectors



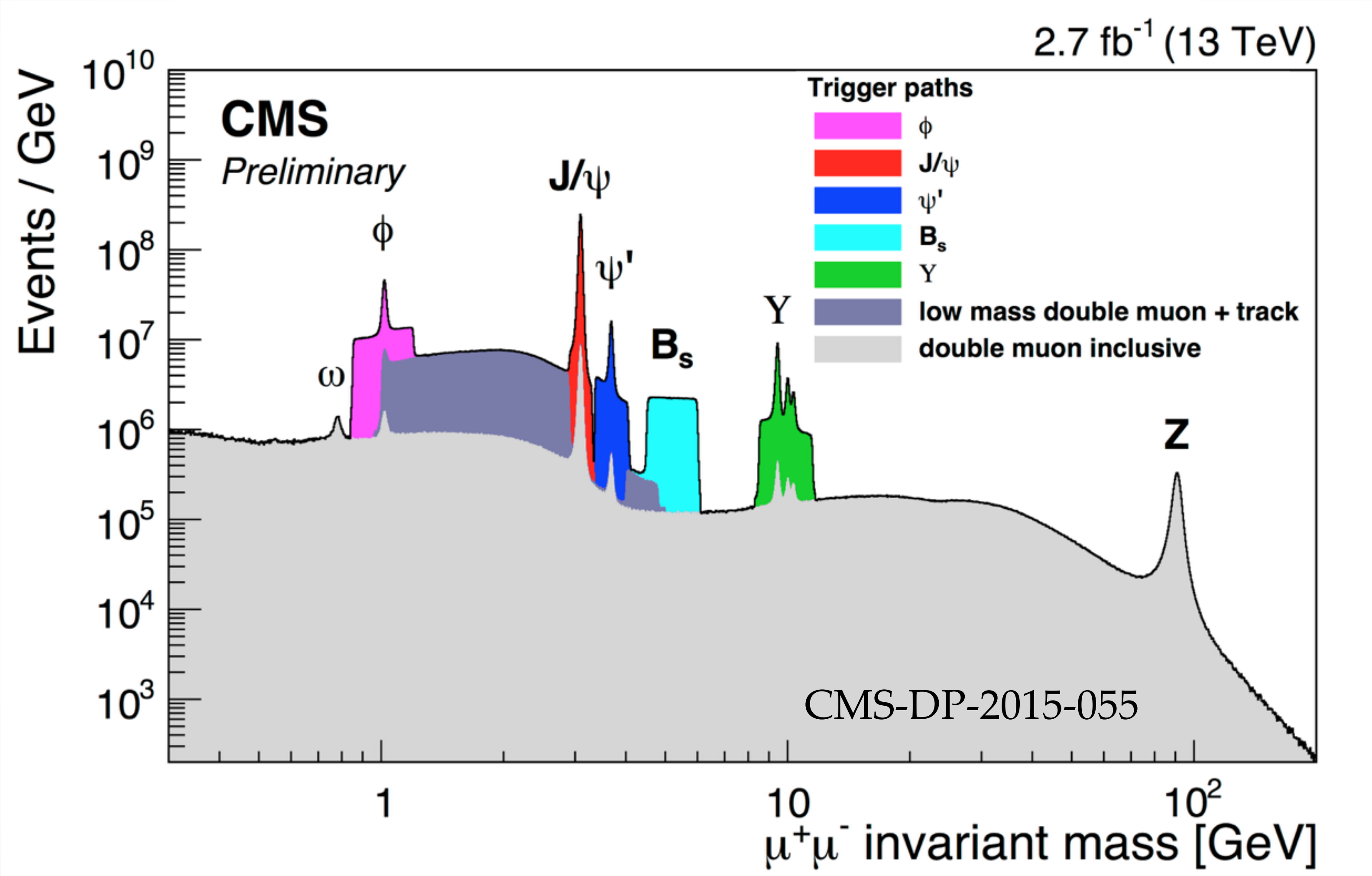
CMS B Physics program ↔ Excellent μ ID + Track and vertex reconstruction



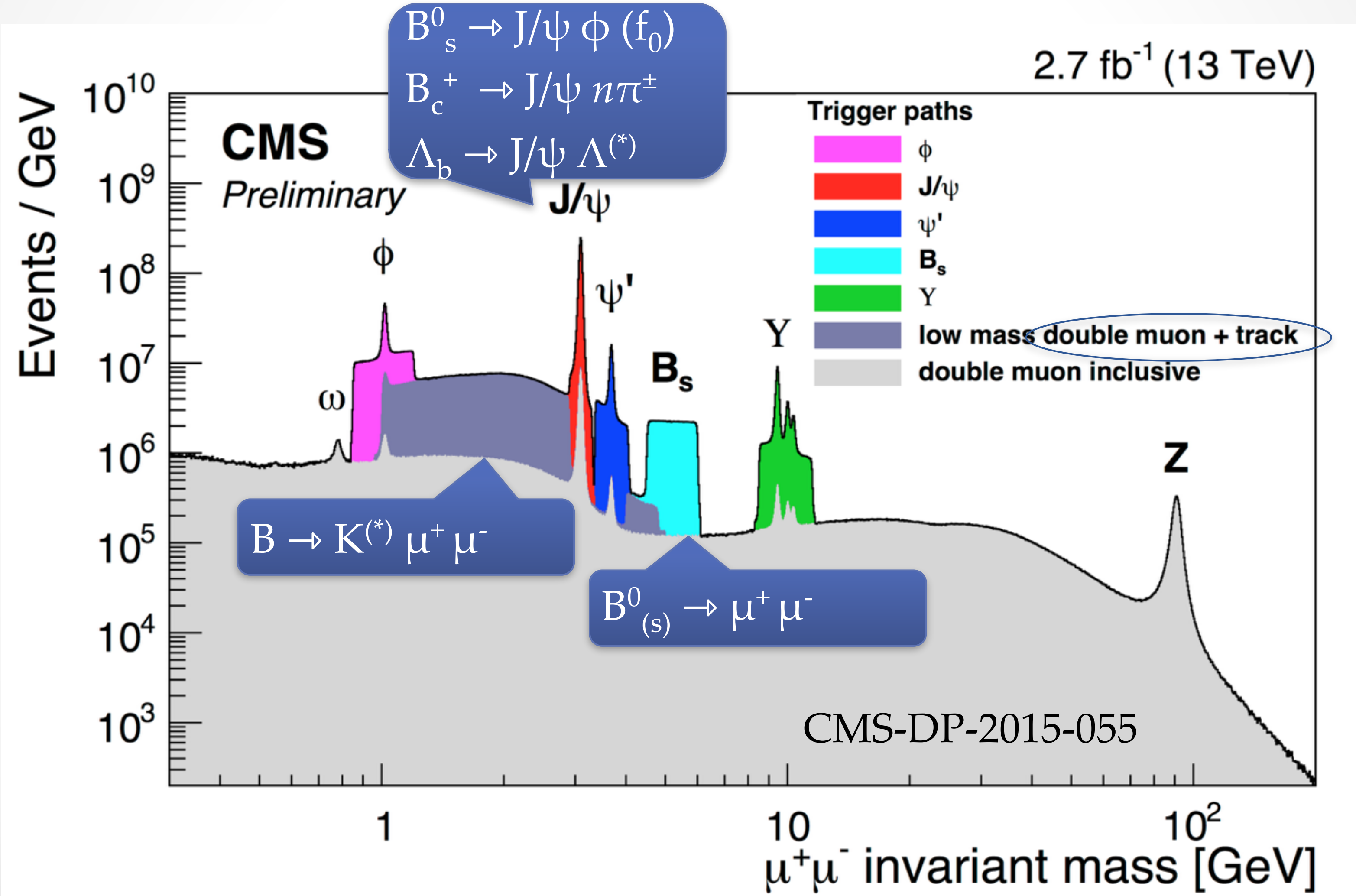
B Physics Triggers (CMS/Run I)

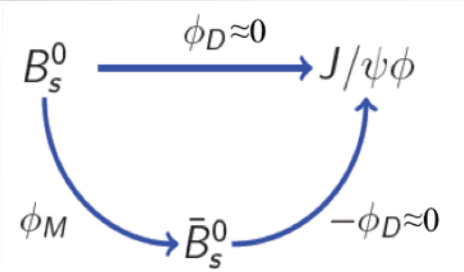


B Physics Triggers (CMS/Run II)

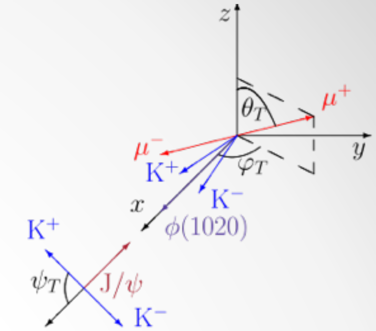


B Physics Triggers (CMS/Run II)



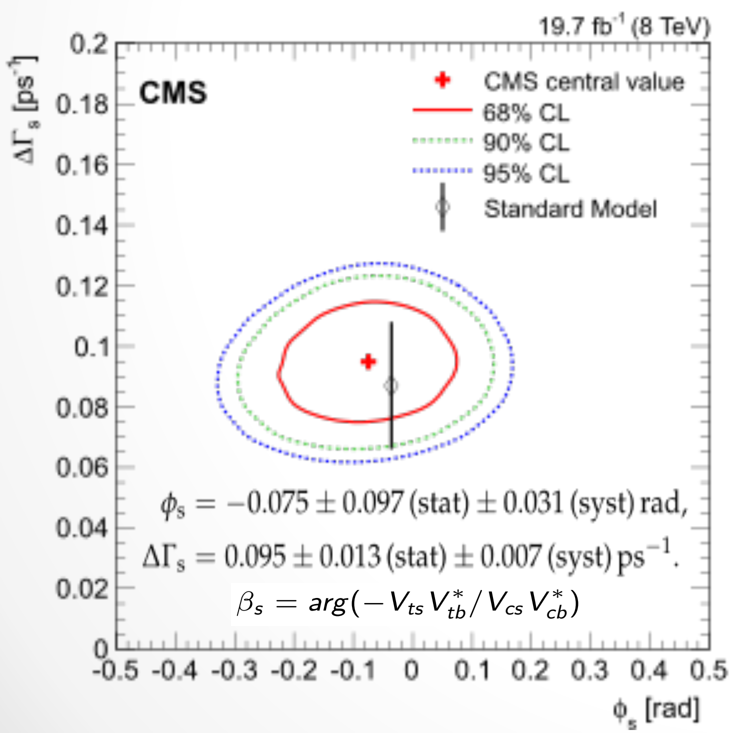


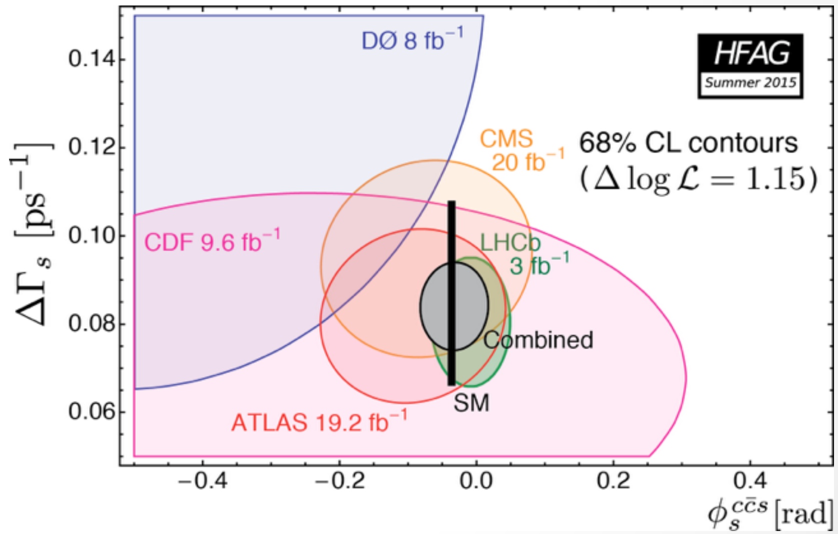
CPV in $B^0_s \to J/\psi\,\phi$



- CPV phase ϕ_s from interference btw direct and through mixing decays.
- Non-standard particles in loops could change the SM prediction of ϕ_s.
- 3+1 angular-time analysis to disentangle CP-odd/even contributions.

CMS, PLB 757 (2016) 97–120





$B^0_s \to J/\psi\,\phi$: ATLAS, CDF, CMS, D0.

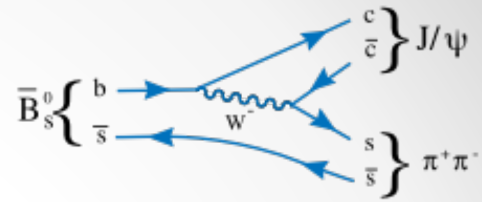
$B^0_s \to J/\psi KK$: LHCb.

$B^0_s \to J/\psi\pi\pi$: LHCb.

$B^0_s \to J/\psi\, D_s D_s$: LHCb.

[http://www.slac.stanford.edu/xorg/hfag/osc/summer_2015/HFAG_phis_inputs.pdf]

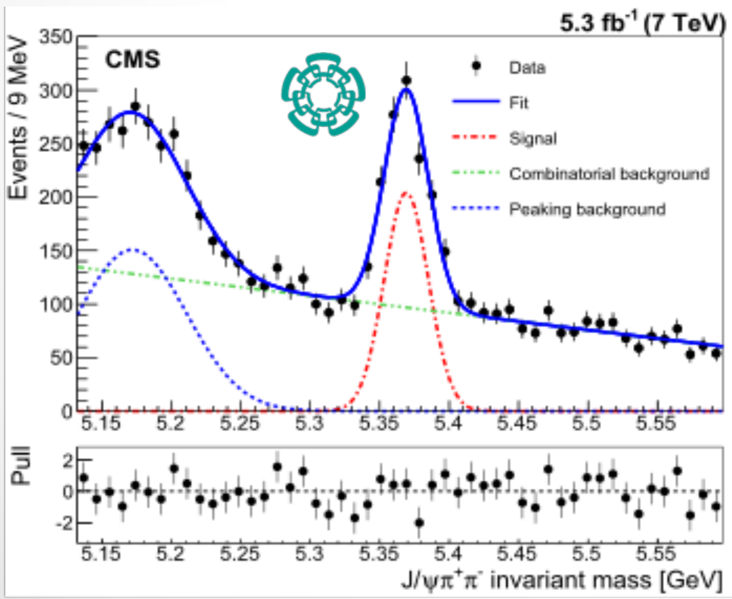
$B^0_s \to J/\psi\, f_0(980)$

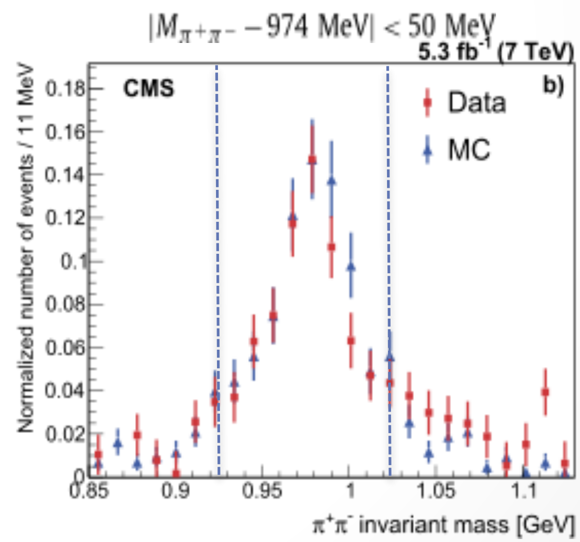


- CMS: CPV analysis is simplified using $B^0_s \to J/\psi\, f_0(\pi^+\pi^-)$ wrt $B^0_s \to J/\psi\phi(K^+K^-)$ decays. It is also a pure CP-odd eigenstate.

$$R_{f_0/\phi} = \frac{\mathcal{B}(B^0_s \to J/\psi f_0)\,\mathcal{B}(f_0 \to \pi^+\pi^-)}{\mathcal{B}(B^0_s \to J/\psi \phi)\,\mathcal{B}(\phi \to K^+K^-)} = \frac{N^{f_0}_{obs}}{N^{\phi}_{obs}}\,\epsilon^{\phi/f_0}_{reco}$$

$$N^{\phi}_{obs} = 8377 \pm 107$$
$$N^{f_0}_{obs} = 873 \pm 49$$



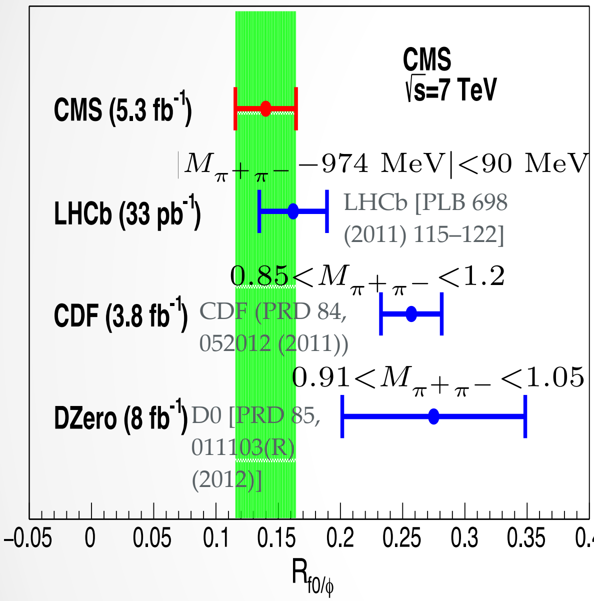


- Region around the $f_0(980)$ can be used to measure $\tau(B^0_s)_{CP\text{-odd}}$ and ϕ_s.

$\mathcal{B}(B^0_s \to \psi f_0(\pi\pi)) / \mathcal{B}(B^0_s \to \psi\phi(KK))$

$$R_{f_0/\phi}\,\big|_{|M_{\pi^+\pi^-} - 974\ \mathrm{MeV}| < 50\ \mathrm{MeV}} = 0.140 \pm 0.008\ (\mathrm{stat})\ \pm 0.023\ (\mathrm{syst})$$

CMS, PLB 756 (2016) 84–112



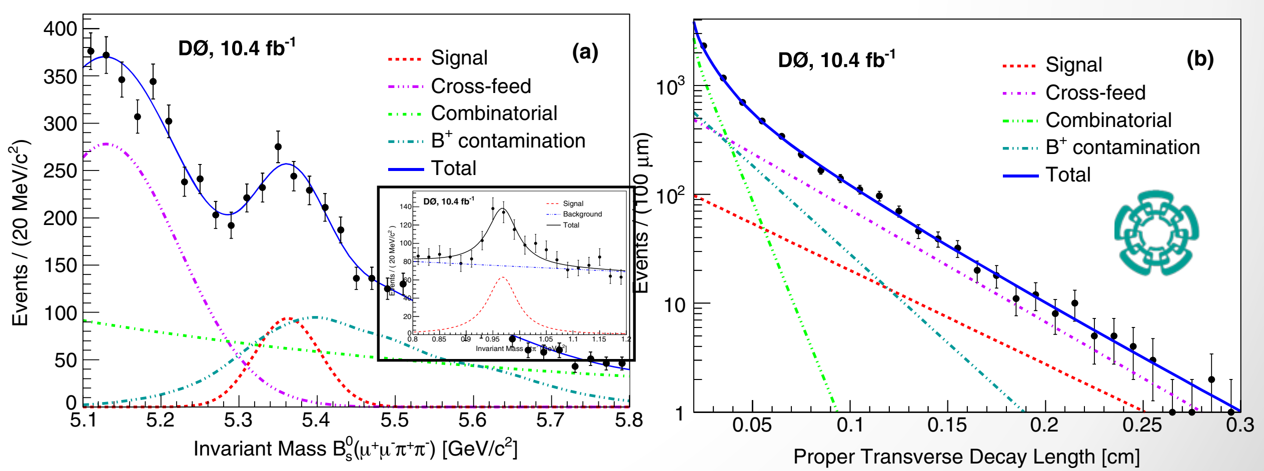
- **Experiments measure R in diff. $M(\pi^+\pi^-)$ ranges.**

$$R_{f_0/\phi}\mathcal{B}(\phi \to K^+K^-) = 0.139 \pm 0.006\ (\mathrm{stat})\ \pm {}^{0.025}_{0.012}\ (\mathrm{syst})$$

LHCb [PRD 86, 052006 (2012)]*

$^*\mathcal{B}(\phi \to K^+K^-) = (48.9 \pm 0.5)\%$

$R_{f0/\phi}$ **≈ 0.2** [Stone & Zhang, PRD 79, 074024 (2009)].



- Next important property is Bs CP-odd lifetime.
- At DØ it was measured: $\tau(B^0_s) = 1.70 \pm 0.14(\mathrm{stat}) \pm 0.05(\mathrm{syst})\ \mathrm{ps}$

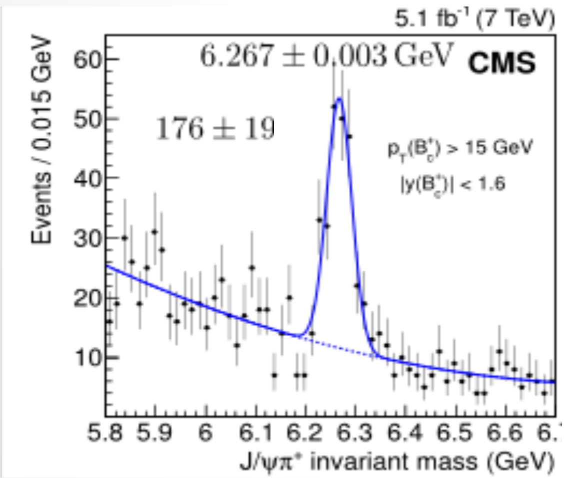
D0, PRD 94, 012001 (2016)

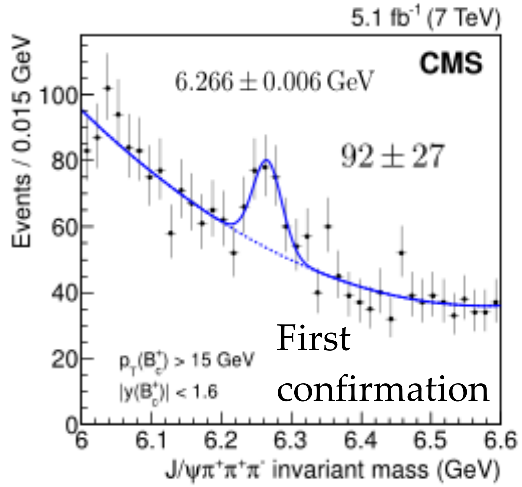
$B_c^+ \to J/\psi\, n\pi^\pm$

- Unique lab to study HQ dynamics.
- b and c quarks competing in decay.
- Measurements in a kin. region complementary to LHCb.

$$R_{c/u} = \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)}$$

$$R_{B_c} = \frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+\pi^+\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$$





- LHCb, $p_T > 4$ GeV, $2.5 < |\eta| < 4.5$, measures $R_{c/u} = 0.68 \pm 0.10 \pm 0.03 \pm 0.05$ [PRL 109 (2012) 232001]. Difference expected since $\langle p_T(B_c^+)\rangle < \langle p_T(B^+)\rangle$ in central region.
- LHCb measures $R_{Bc} = 2.41 \pm 0.30 \pm 0.33$ [PRL 108 (2012) 251802].
- Predictions of R_{Bc}, assuming $B_c \to J/\psi W^{+*}$ and $W^{+*} \to n\pi^+$, btw = 1.5 – 2.3 [PRD 81 (2010) 014005, PRD 81 (2010) 014015].

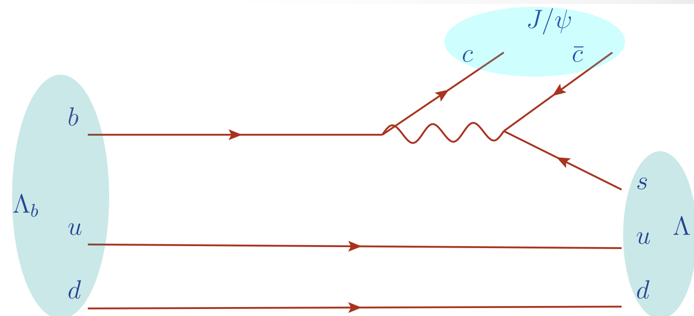
$$R_{c/u} = [0.48 \pm 0.05\,(\text{stat}) \pm 0.03\,(\text{syst}) \pm 0.05\,(\tau_{B_c})]\%$$

$$R_{B_c} = 2.55 \pm 0.80\,(\text{stat}) \pm 0.33\,(\text{syst})\,^{+0.04}_{-0.01}\,(\tau_{B_c})$$

CMS, JHEP 01 (2015) 063

B hadron lifetimes

- B-lifetimes determine importance of non-spectator contributions.
- CMS about to publish precise measurements:



X.X

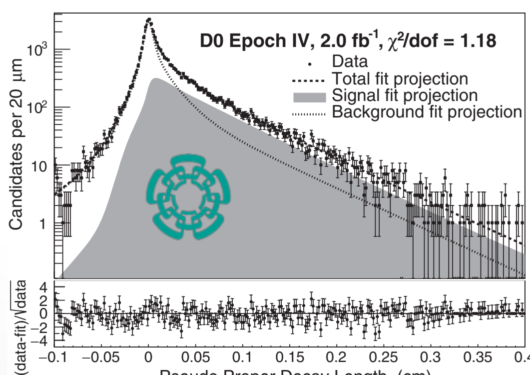
Not approved yet

$$c\tau_{B^+} = 49\ \pm 0.8\,(\text{stat})\ \pm 1.8\,(\text{syst})\ \mu\text{m}$$
$$c\tau_{B^0} = 45\ \pm 1.6\,(\text{stat})\ \pm 2.1\,(\text{syst})\ \mu\text{m}\ (\text{in } J/\psi K^{*0})$$
$$c\tau_{B^0} = 45\ \pm 2.7\,(\text{stat})\ \pm 2.6\,(\text{syst})\ \mu\text{m}\ (\text{in } J/\psi K^0_S)$$
$$c\tau_{B^0_s} = 50\ \pm 10.3\,(\text{stat})\ \pm 3.3\,(\text{syst})\ \mu\text{m}\ (\text{in } J/\psi \pi^+\pi^-)$$
$$c\tau_{B^0_s} = 44\ \pm 2.0\,(\text{stat})\ \pm 2.2\,(\text{syst})\ \mu\text{m}\ (\text{in } J/\psi\phi)$$
$$c\tau_{\Lambda^0_b} = 44\ \pm 8.1\,(\text{stat})\ \pm 2.5\,(\text{syst})\ \mu\text{m}$$
$$c\tau_{B_c^+} = 16\ \pm 7.4(\text{stat}) \pm 3.0\,(\text{syst})\ \mu\text{m}$$

PDG
491.1 ± 1.2
455.4 ± 1.5
455.4 ± 1.5
509.0 ± 12.0
434.9 ± 3.8
443.4 ± 3.6
434.9 ± 3.8
152.0 ± 2.7

- D0: 2nd. most precise $\tau(B_s)$ in flavor-specific $B_s \to D_s^- \mu^+ \nu X$.

D0, PRL 114, 062001 (2015)



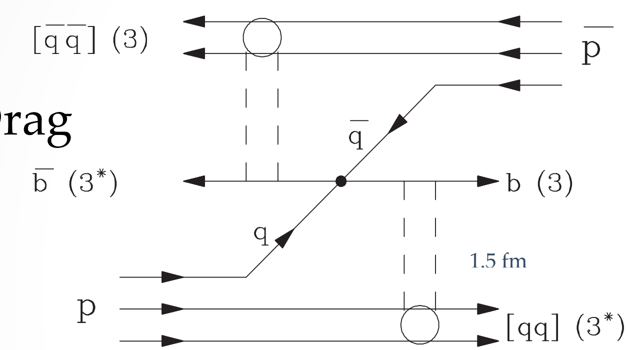
$$\tau_{\text{fs}}(B^0_s) = \frac{1}{\Gamma_s}\frac{1+(\Delta\Gamma_s/2\Gamma_s)^2}{1-(\Delta\Gamma_s/2\Gamma_s)^2}$$
$$= 443.3 \pm 2.9(\text{stat}) \pm 6.3(\text{syst})\ \mu\text{m}.$$

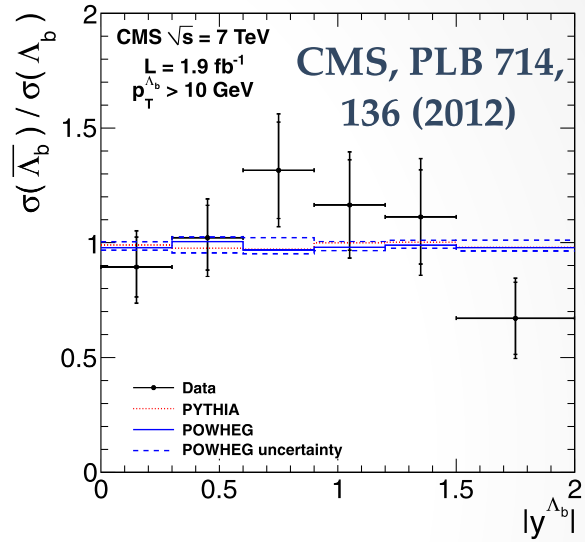
vs. W.A. 453.0 ± 4.2 μm.

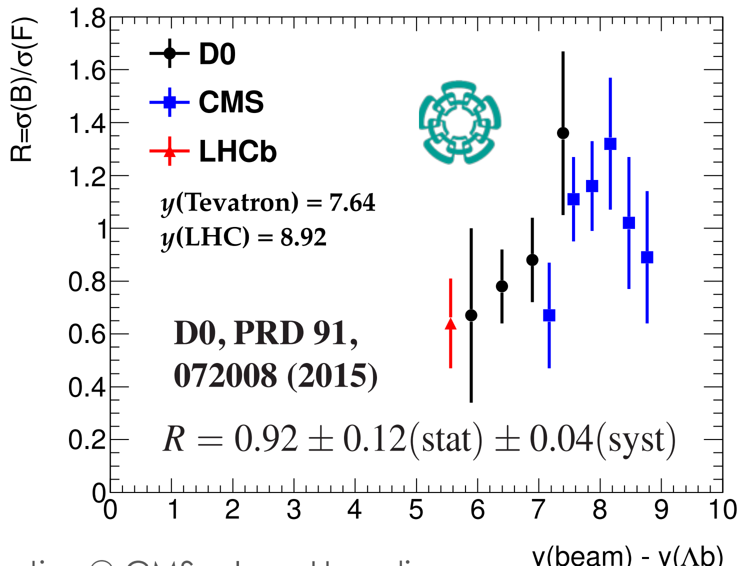
B baryons

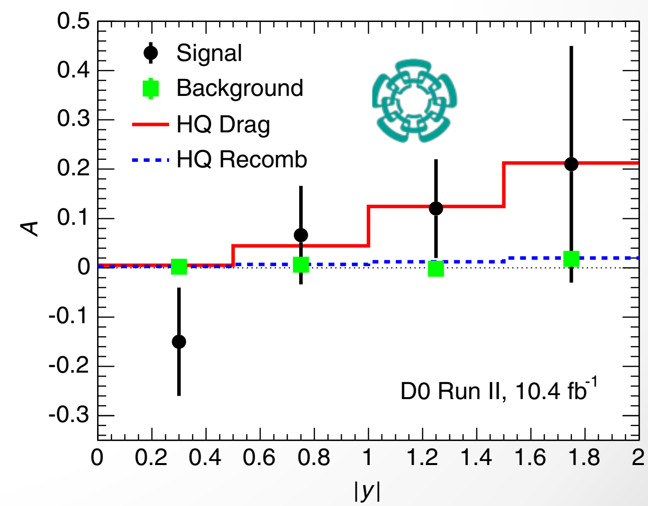
- Apart from lifetime, (hadro-)production measurements.

HQ-Drag





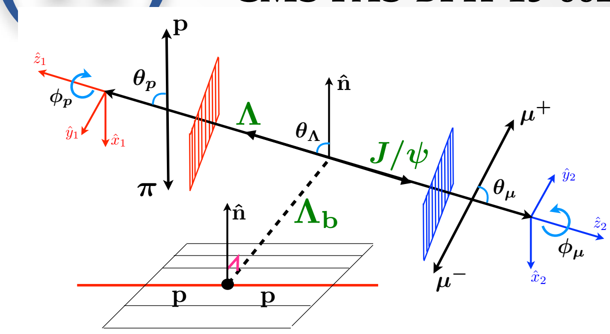




B baryons (II)

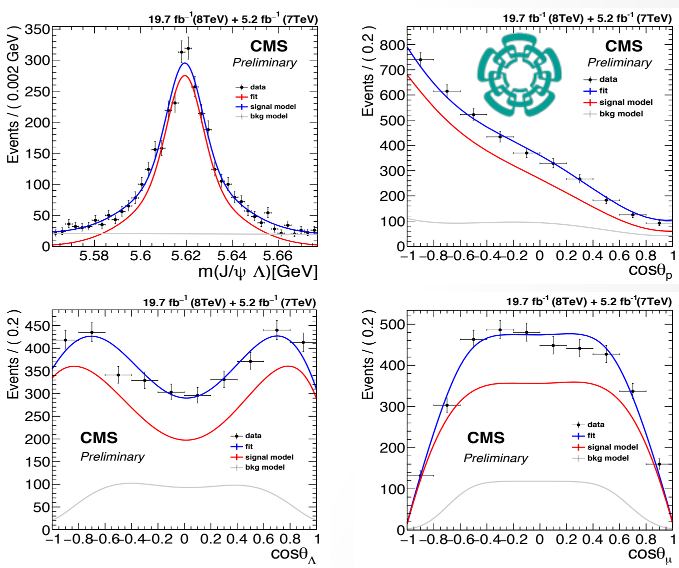
CMS PAS BPH-15-002

- In CMS we measured the Lb polarization and decay parameters of $\Lambda_b \to J/\psi\ \Lambda$.



$$\frac{d\Gamma}{d\Omega_3}(\theta_\Lambda,\theta_p,\theta_\mu) = \int_{-\pi}^{\pi}\int_{-\pi}^{\pi}\frac{d\Gamma}{d\Omega_5}(\theta_\Lambda,\theta_p,\theta_\mu,\phi_p,\phi_\mu)\,d\phi_p d\phi_\mu$$
$$\sim \sum_{i=1}^{8}\eta_i\left(|T_{++}|^2,|T_{+0}|^2,|T_{-0}|^2,|T_{--}|^2\right)c_i\left(P,\alpha_\Lambda\right)f_i\left(\theta_\Lambda,\theta_p,\theta_\mu\right)$$

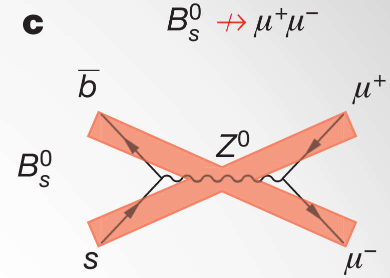
i	η_i	c_i	f_i
1	1	1	1
2	α_2	α_Λ	$\cos\theta_p$
3	$-\alpha_1$	P	$\cos\theta_\Lambda$
4	$-(1+2\gamma_0)/3$	$\alpha_\Lambda P$	$\cos\theta_\Lambda\cos\theta_p$
5	$\gamma_0/2$	1	$(3\cos^2\theta_\mu-1)/2$
6	$(3\alpha_1-\alpha_2)/4$	α_Λ	$\cos\theta_p(3\cos^2\theta_\mu-1)/2$
7	$(\alpha_1-3\alpha_2)/4$	P	$\cos\theta_\Lambda(3\cos^2\theta_\mu-1)/2$
8	$(\gamma_0-4)/6$	$\alpha_\Lambda P$	$\cos\theta_\Lambda\cos\theta_p(3\cos^2\theta_\mu-1)/2$



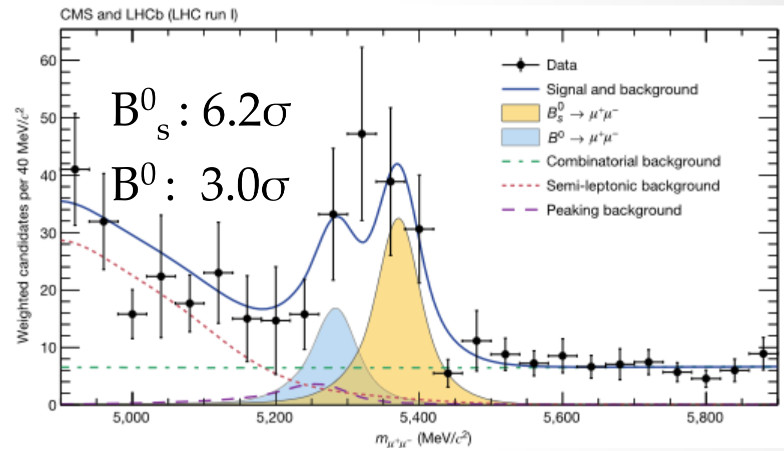
$$P = 0.00 \pm 0.06(stat) \pm 0.02(syst),$$
$$\alpha_1 = 0.12 \pm 0.13(stat) \pm 0.06(syst),$$
$$\alpha_2 = -0.93 \pm 0.04(stat) \pm 0.04(syst),$$
$$\gamma_0 = -0.46 \pm 0.07(stat) \pm 0.04(syst),$$

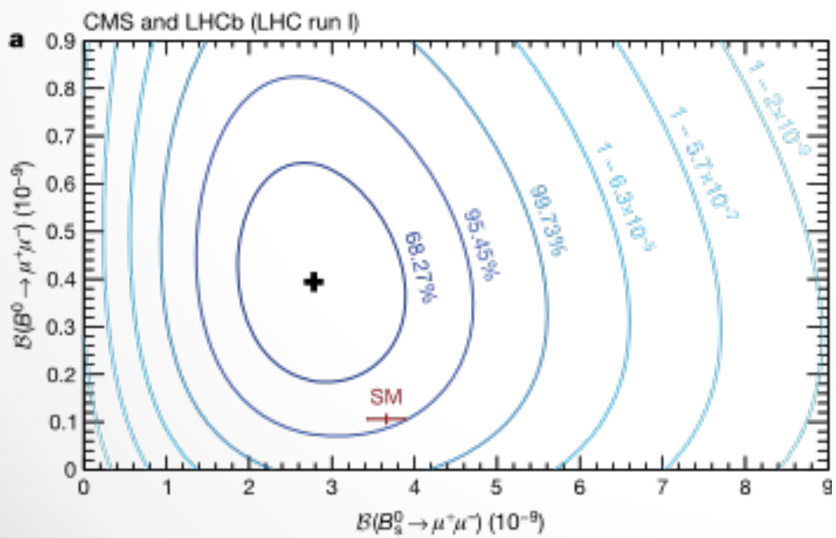
$$|T_{-0}|^2 = 0.51 \pm 0.03(stat) \pm 0.02(syst),$$
$$|T_{+0}|^2 = -0.02 \pm 0.03(stat) \pm 0.02(syst),$$
$$|T_{--}|^2 = 0.46 \pm 0.02(stat) \pm 0.02(syst),$$
$$|T_{++}|^2 = 0.05 \pm 0.04(stat) \pm 0.02(syst).$$

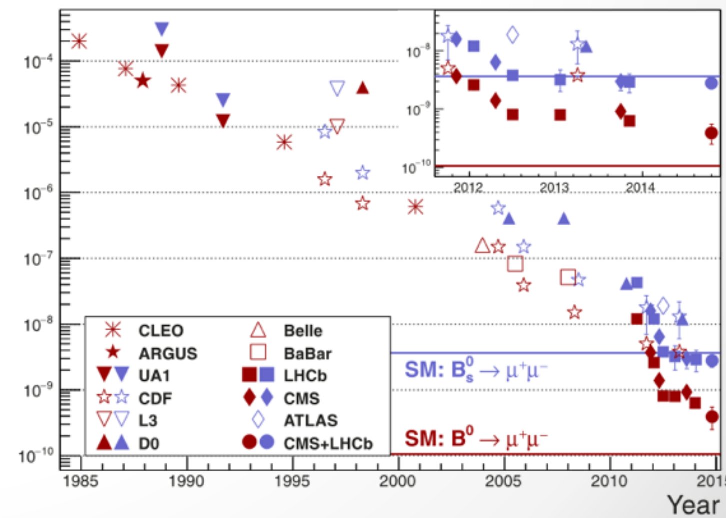
Rare B decays as new physics probes



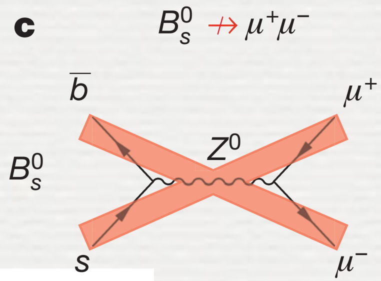
- Rare decays: FCNC decays forbidden @LO. NP (in penguins/boxes) could modify Wilson coefficients.
- Complementary info: S/P-S ($B^0_s \to \mu^+\mu^-$) vs. V/A-V ($B \to K^{(*)}\mu^+\mu^-$) interactions.
- Reliable BR predictions within the SM for $\mathscr{B}(B^0_s \to \mu^+\mu^-)$.

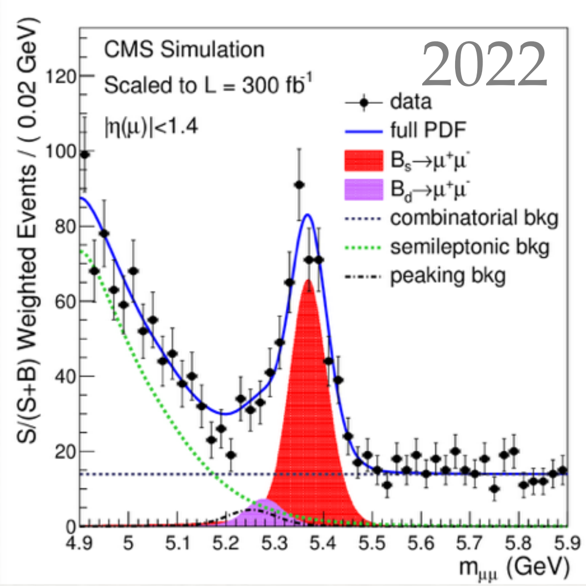


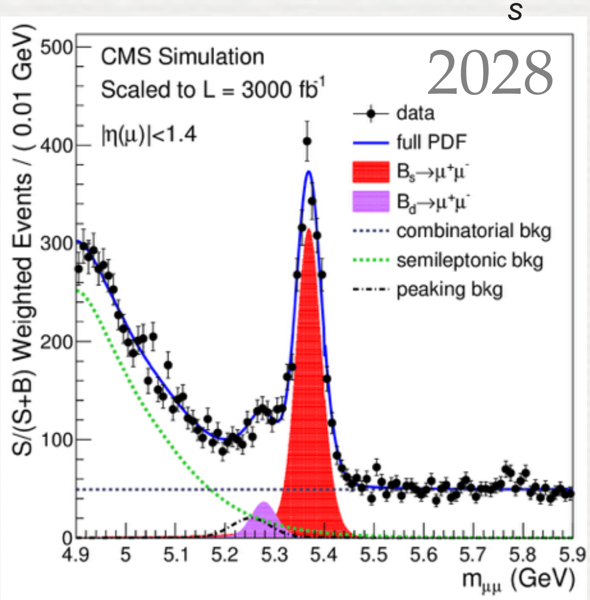




$B^{(0)}_s \to \mu^+\mu^-$: Future



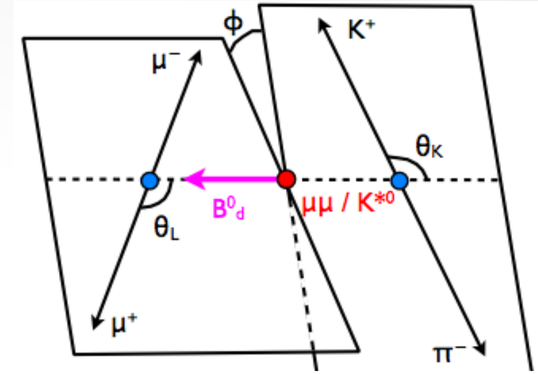




Estimate of analysis sensitivity

$\mathcal{L}(fb^{-1})$	$N(B_s)$	$N(B^0)$	$\delta\mathcal{B}(B_s \to \mu\mu)$	$\delta\mathcal{B}(B^0 \to \mu\mu)$	B^0 sign.	$\delta\frac{\mathcal{B}(B^0 \to \mu\mu)}{\mathcal{B}(B_s \to \mu\mu)}$
20	18.2	2.2	35%	>100%	0.0-1.5 σ	>100%
100	159	19	14%	63%	0.6-2.5 σ	66%
300	478	57	12%	41%	1.5-3.5 σ	43%
300 (barrel)	346	42	13%	48%	1.2-3.3 σ	50%
3000 (barrel)	2250	271	11%	18%	5.6-8.0 σ	21%

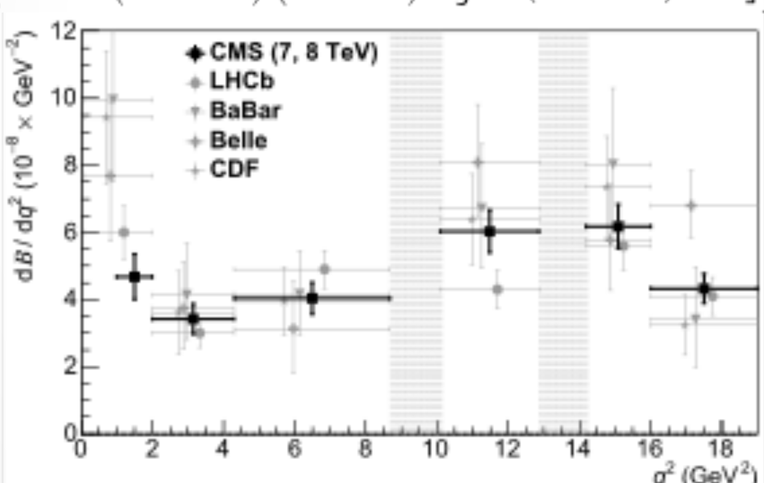
$B^0 \to K^*\mu^+\mu^-$

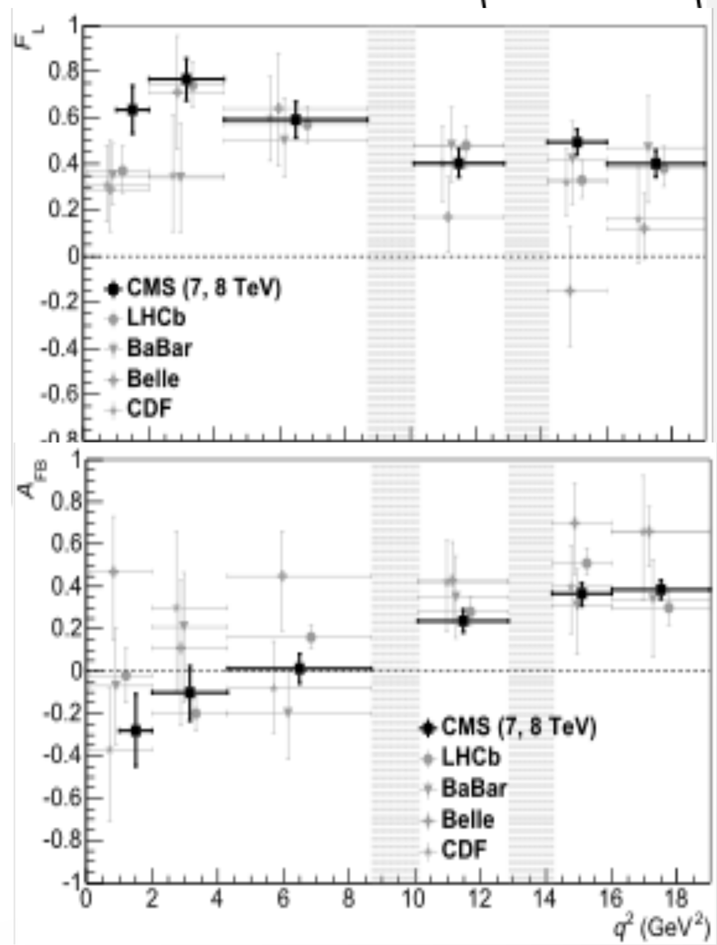


- Search for deviations of BR, F_L (frac. of K* longitudinal. Pol.) and A_{FB} ($\mu^+\mu^-$ F-B asym.) from SM in bins of $q^2 = m^2_{\mu\mu}$.

$$\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_K\, d\cos\theta_l\, dq^2} = \frac{9}{16}\left\{\frac{2}{3}\left[F_S + A_S\cos\theta_K\right]\left(1-\cos^2\theta_l\right) + (1-F_S)\left[2F_L\cos^2\theta_K\left(1-\cos^2\theta_l\right) + \frac{1}{2}(1-F_L)\left(1-\cos^2\theta_K\right)\left(1+\cos^2\theta_l\right) + \frac{4}{3}A_{FB}\left(1-\cos^2\theta_K\right)\cos\theta_l\right]\right\}$$

PLB 753 (2016) 424–448

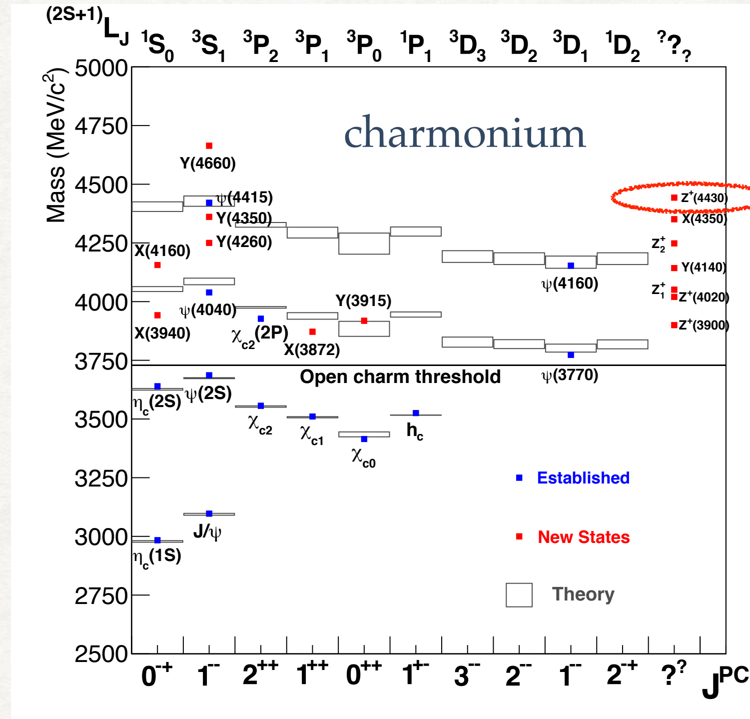


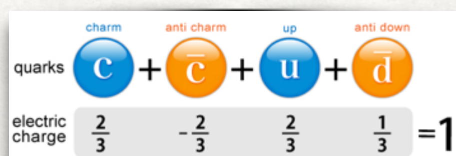


- CMS consistent with other exps. and with predictions of LCSR and Lattice. Ongoing efforts to measure P5'.

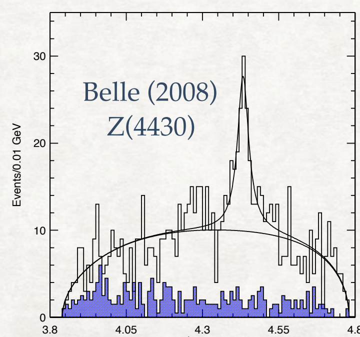
THE XYZ STATES

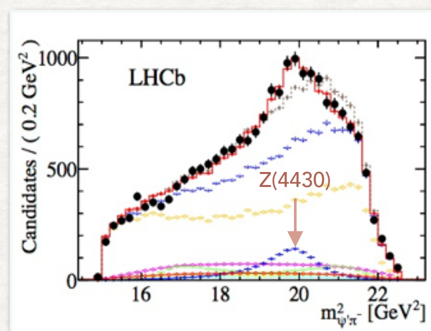
- More than 20 cc-like and bb-like states that do not fit the **$q\bar{q}$** picture discovered in B-fact., Tev., & LHC.
- Most happen to be near a 2-meson threshold.
- Most important: $Z(4430)^{\pm} \to \psi(2S)\pi^{\pm}$ by Belle (2008), confirmed by LHCb (2014) to be a proper BW resonance by Argand diagram.

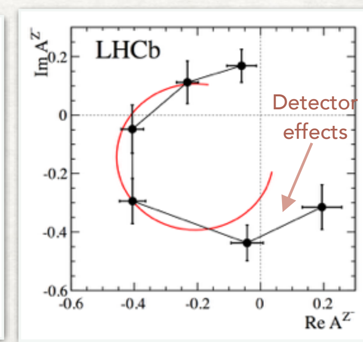




Strong evidence for $q\bar{q}$-like states made of 4 valence quarks.

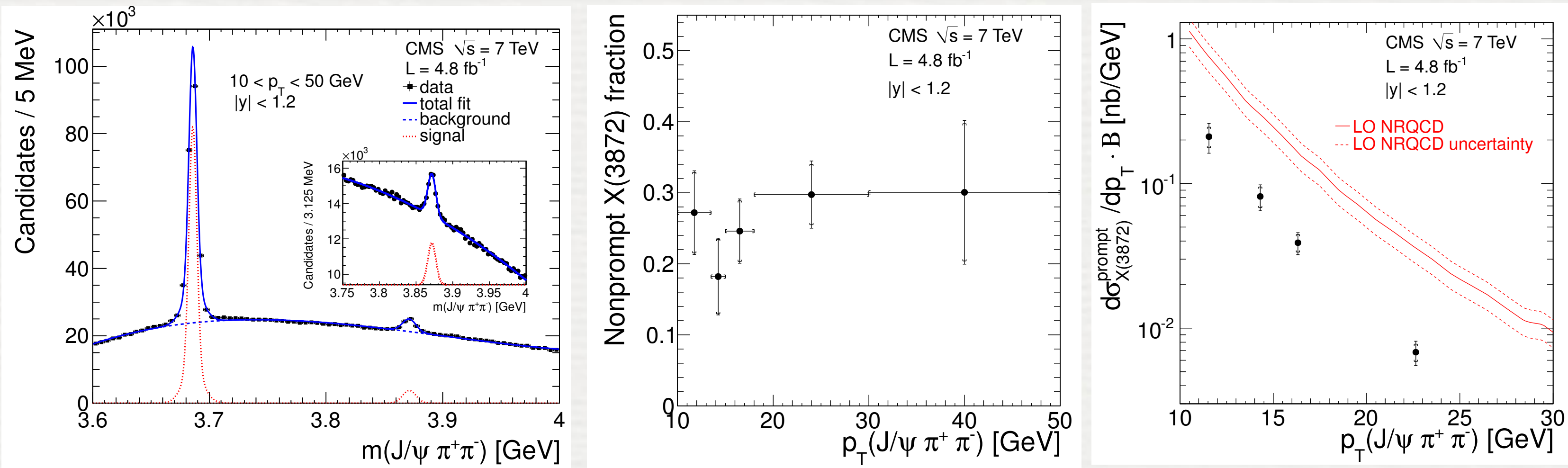






X(3872) PROMPT PRODUCTION IN pp

- Already observed by LHCb, but measured only $\sigma_{inclusive}$ (P+NP).



Results ($\sqrt{s}$ = 7 TeV)

JHEP 04 (2013) 154

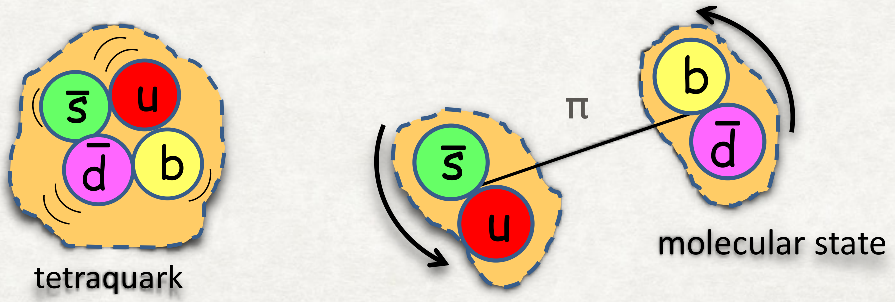
- Unpolarized $J^{PC} = 1^{++}$ state assumed.
- **Fraction of X(3872) coming from b hadrons (NP) is 0.263 ± 0.023 ± 0.016.**
- No p_T dependence of NP (or P) fraction.
- **NRQCD predictions (assuming $c\bar{c}$) for P fraction is evidently off.**
- R = 0.0656 ± 0.0029 ± 0.0065, where

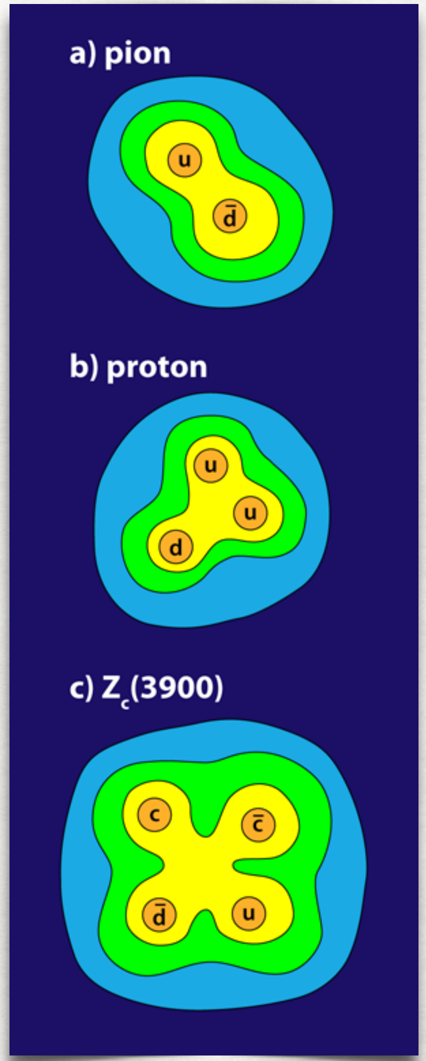
$$R = \frac{\sigma(\mathrm{pp} \to \mathrm{X(3872)} + \mathrm{anything}) \cdot \mathcal{B}(\mathrm{X(3872)} \to \mathrm{J}/\psi\pi^+\pi^-)}{\sigma(\mathrm{pp} \to \psi(2\mathrm{S}) + \mathrm{anything}) \cdot \mathcal{B}(\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^+\pi^-)}$$

$10 < p_\mathrm{T} < 50\,\mathrm{GeV}$ and $|y| < 1.2$

XYZ STATES INTERPRETATION

- PDG names all non-$\mathbf{q\bar{q}}$ candidates **X(mass)**. Theorists/exps. use **Z** for charged states, **Y** for 1^{--} states, and **X** for the rest.
- Two popular interpretations:
  - Meson-meson "molecule": two white states loosely bound by a pion exchange.
  - Compact tetraquark: made of a diquark-antidiquark pair connected by color forces.

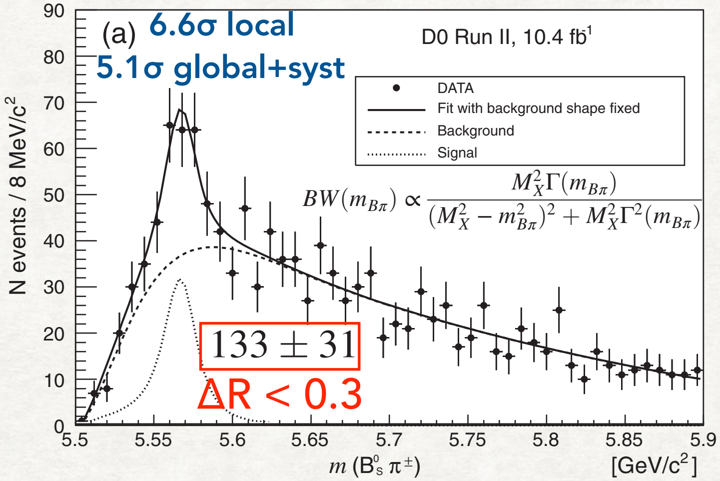




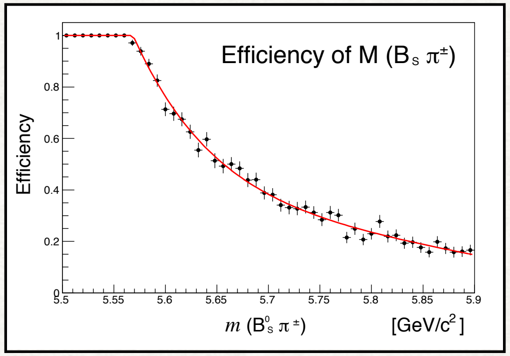
NEW EXOTIC STATE X(5568)

$X(5568) \rightarrow B^0_s \pi^\pm$

PRL **117**, 022003 (2016)



Take into account mass efficiency due to ΔR cut

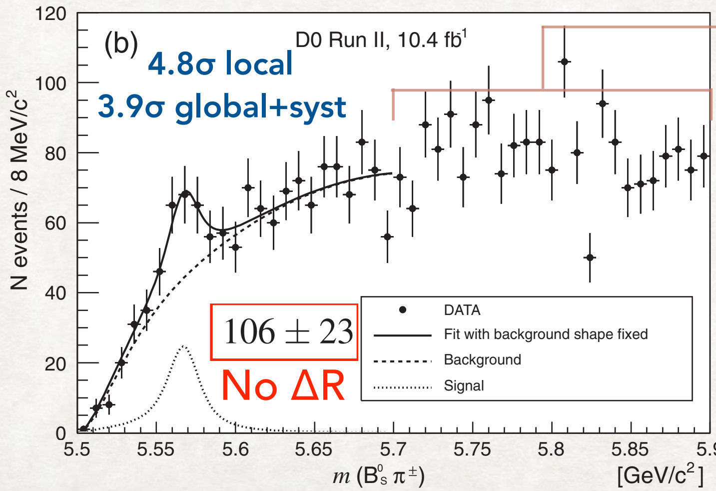


- Mass resolution: $\sigma = 3.9\,\text{MeV}$

$$M_X = 5567.8 \pm 2.9\,^{+0.9}_{-1.9}\,\text{MeV}$$
$$\Gamma_X = 21.9 \pm 6.4\,^{+5.0}_{-2.5}\,\text{MeV}$$

Strong decay!

$$N_X = 133 \pm 31 \pm 15\,\text{cand.}$$



Possible higher-mass B_s^{**} states and/or $B_c \rightarrow B_s n\pi$, miss π^0

(..and yes, we see $B_c^+ \rightarrow B_s \pi^+$ at 6.27 GeV)

X(5568) PRODUCTION RATE

WHAT IS IT?

PRL **117**, 022003 (2016)

- Production rate (for comparisons to others): normalize to B_s^0

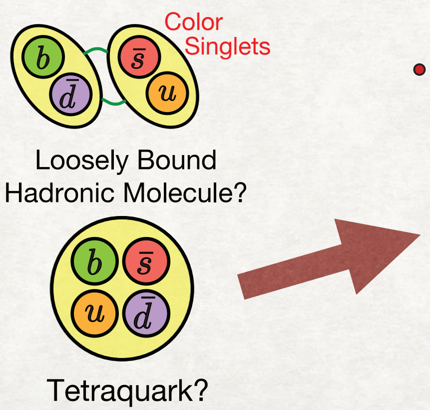
$$R_X = \frac{\sigma(X)\cdot\mathcal{B}(X(5568)\to B_s^0\pi^\pm)}{\sigma(B_s^0)} = (8.6 \pm 1.9 \pm 1.4)\%$$

$10 < p_T(B_s) < 30\,\mathrm{GeV}$

$|\eta| < 2$

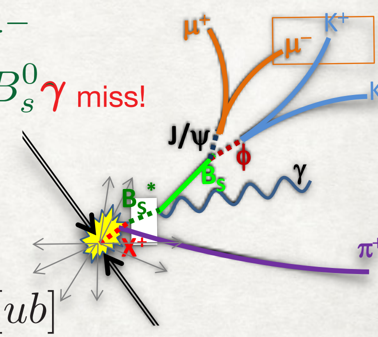
Of all produced B^0_s, about 9% comes from X decaying to B^0_s π$^\pm$. Really?!
A strange charged beauty.

- Unique: only *XYZ* state of four different quarks, mass determination dominated by one heavy quark



- If $X(5568)^- \to B_s^0\pi^-$
  then $J^P = 0^+$
  could be analog of
  $a_0(980)$: $[\bar{s}\bar{d}][us]$
  replace $s \Rightarrow b$: $[\bar{s}\bar{d}][ub]$

- If $X(5617)^- \to B_s^{0*}\pi^-$
  $\hookrightarrow B_s^0\gamma$ miss!
  then $J^P = 1^+$
  could be analog of
  Z_b^+: $[\bar{b}\bar{d}][ub]$
  replace $\bar{b} \Rightarrow \bar{s}$: $[\bar{s}\bar{d}][ub]$



SEARCH OF X(5568) AT CMS

TIE-BREAKER

Available on the CERN CDS information server

CMS PAS BPH-16-002

2016/08/05

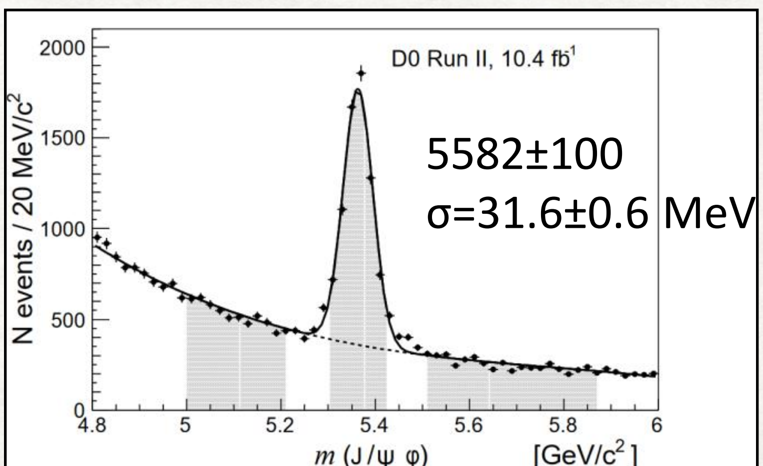
Search for the $X(5568)$ state in $B_s^0\pi^{\pm}$ decays

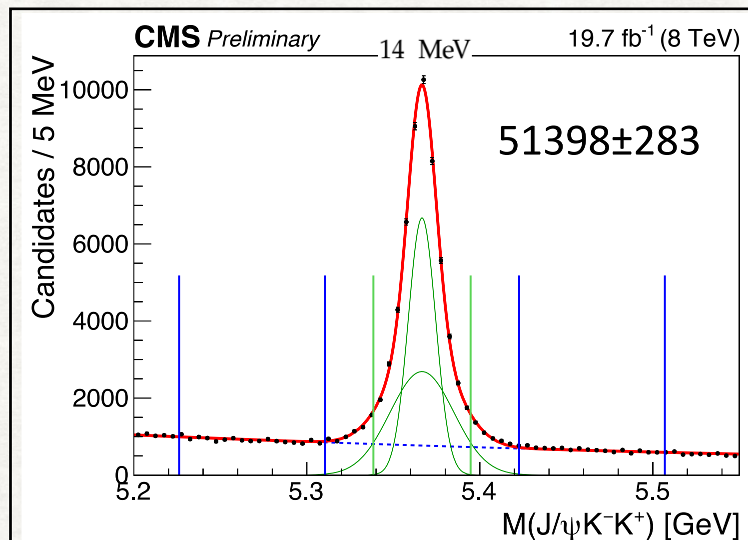
The CMS Collaboration

- Analysis strategy closer to DØ approach:
  - **B^0_s → J/ψ φ**: ~10x more events.
  - Same kinematic region (rapidity & p_T).
  - Better peak(s) resolution (~3x).

B_s^0 yield

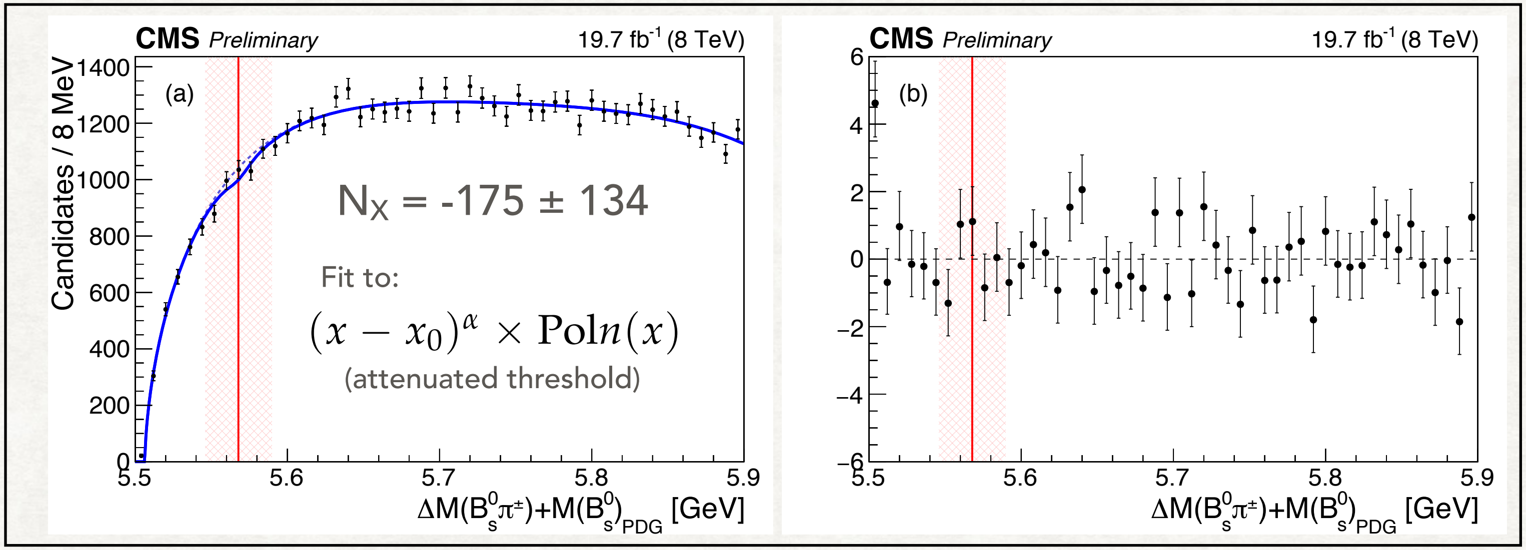
D0	LHCb	CMS
5.6K pT_{Bs}>10GeV	**112K** (pT_{Bs}>5GeV)	**51K** (pT_{Bs}>10GeV)
	44K (pT_{Bs}>10GeV)	





CMS RESULTS

NO X(5568)



No excess is seen

PRELIMINARY CMS RESULTS

CMS PAS BPH-16-002

$\rho_X < 3.9\%$ at 95% CL **CMS**: $p_T(B^0_s) > 10$ GeV & |y| ≲ 2

systematics included

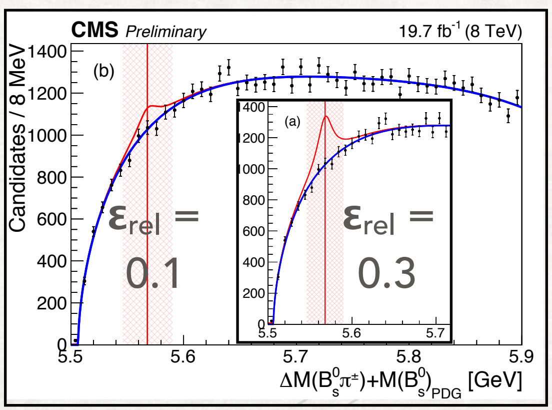
Compare to:

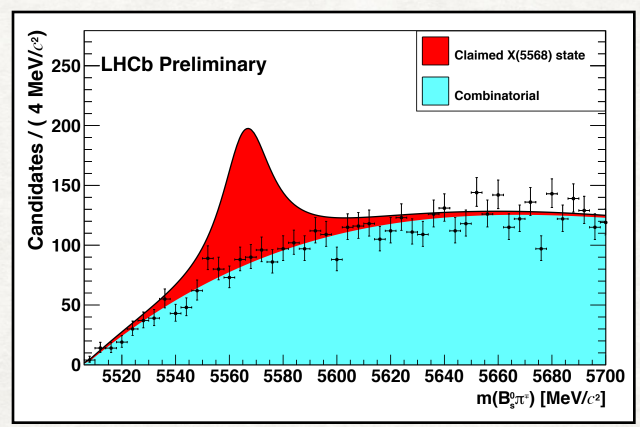
$$\rho_X^{\rm LHCb}[p_T(B^0_s) > 5 \text{ GeV}] < 0.011\,(0.012)$$
$$\rho_X^{\rm LHCb}[p_T(B^0_s) > 10 \text{ GeV}] < 0.021\,(0.024)$$

at $90\,(95)\%$ C.L. **LHCb** 2 < |y| < 4.5

$$\rho = (8.6 \pm 1.9 \pm 1.4)\%.$$

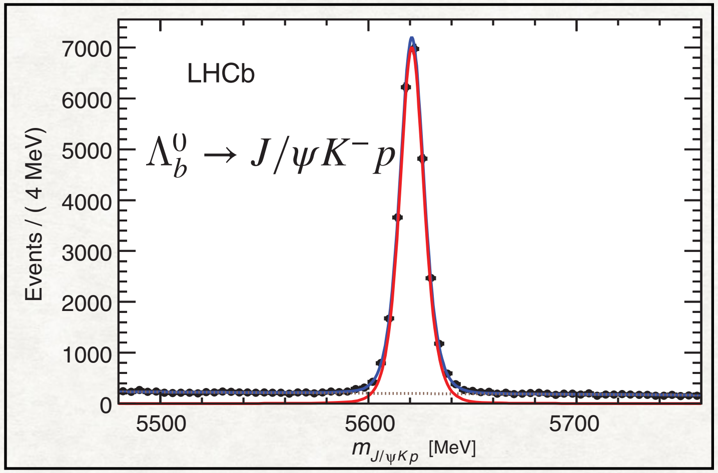
DØ: $p_T(B^0_s) > 10$ GeV & |y| ≲ 2



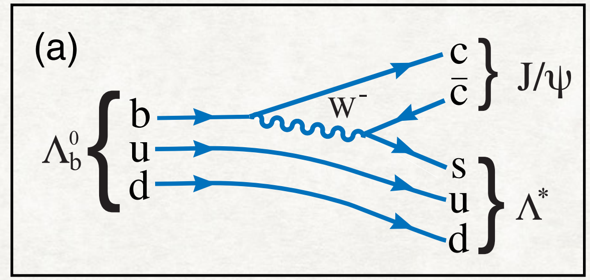


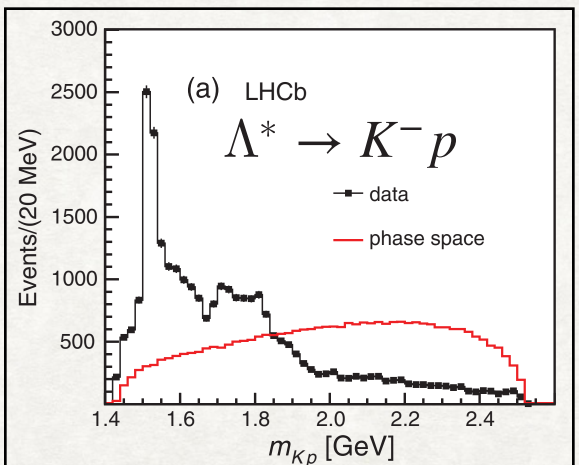
$\epsilon^{\rm rel}(X)$ = 10% (underestimated; real ~30-40%)

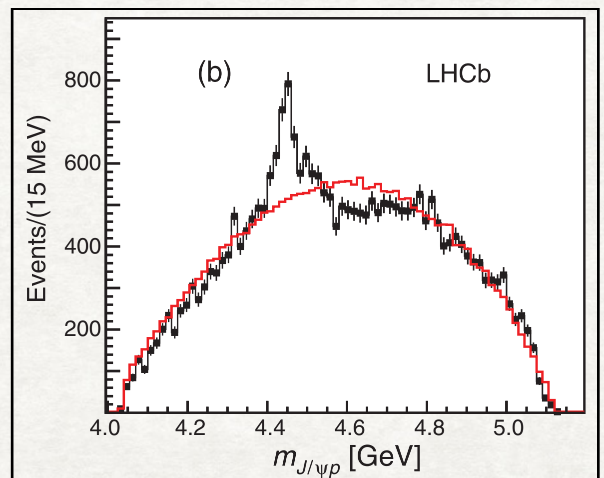
PENTAQUARKS AT LHCb



PRL 115, 072001 (2015)



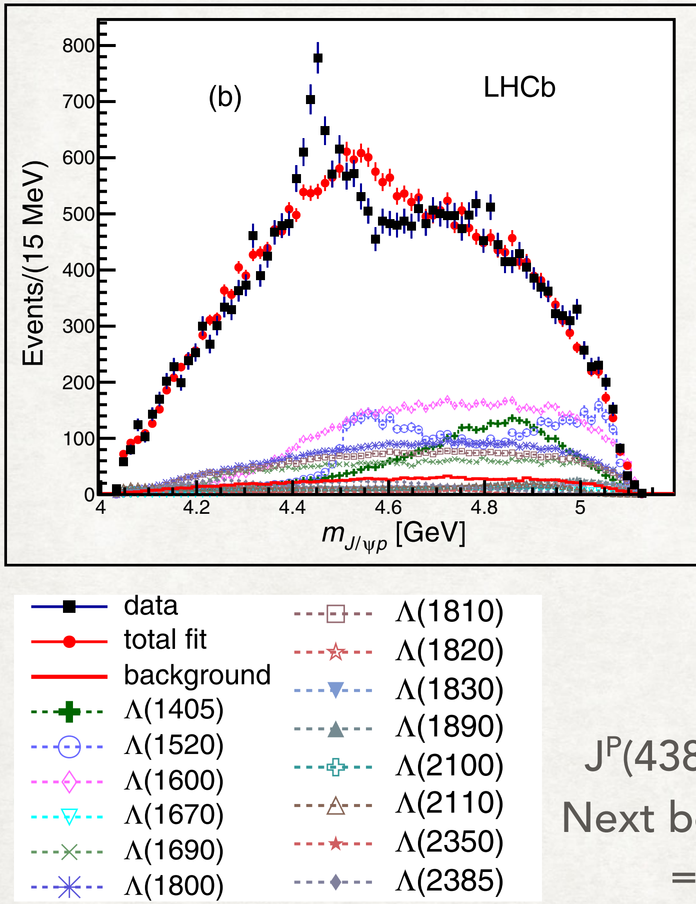


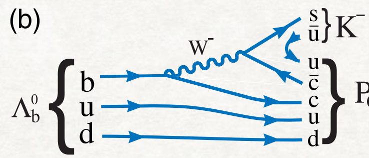


!!!

$\Lambda^* \to$ Kp ACTIVITY IS NOT ENOUGH

BUMPS KEEP THERE!

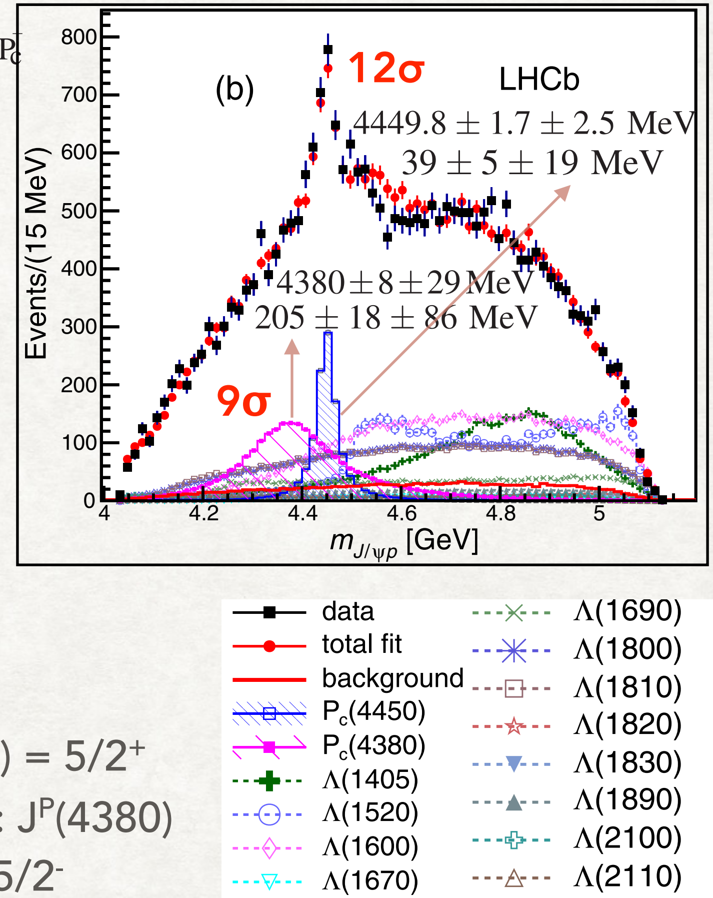




Adding 2 resonances:

$P_c(4450)^+ \to J/\psi\ p$

$P_c(4380)^+ \to J/\psi\ p$



$c\bar{c}uud$

pentaquarks?

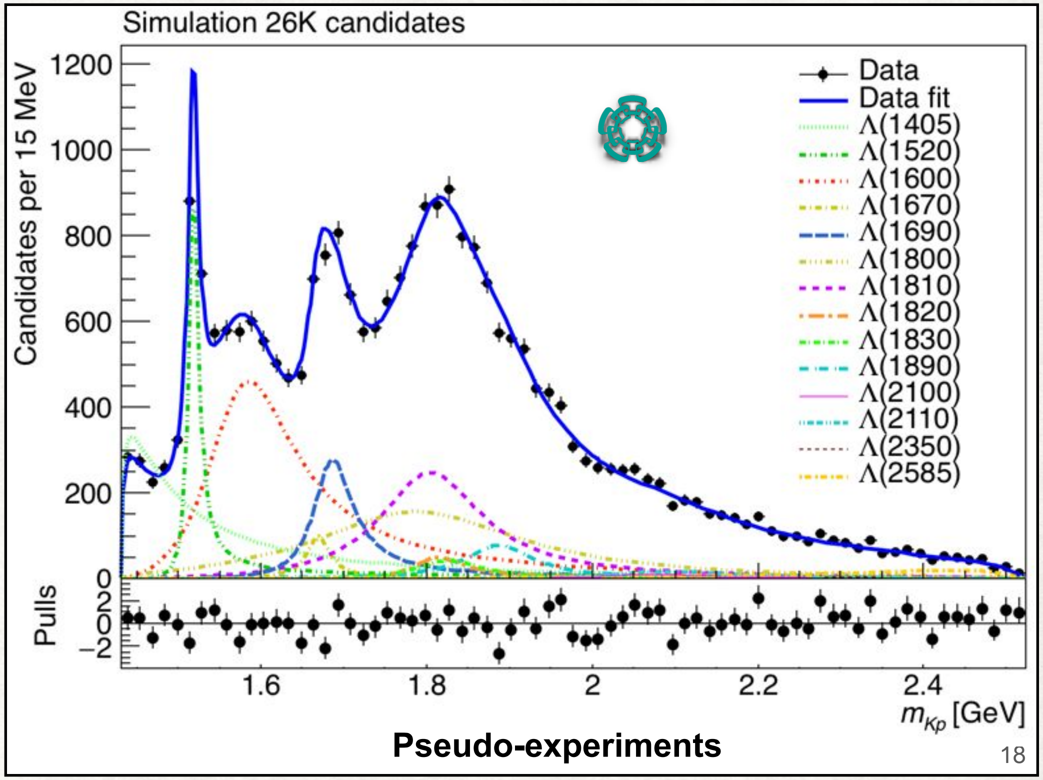
Best fit:

$J^P(4380) = 3/2^-$ & $J^P(4450) = 5/2^+$

Next best fit ($-2\,\Delta\ln\mathscr{L} \approx 1$): $J^P(4380) = 3/2^+$ & $J^P(4450) = 5/2^-$

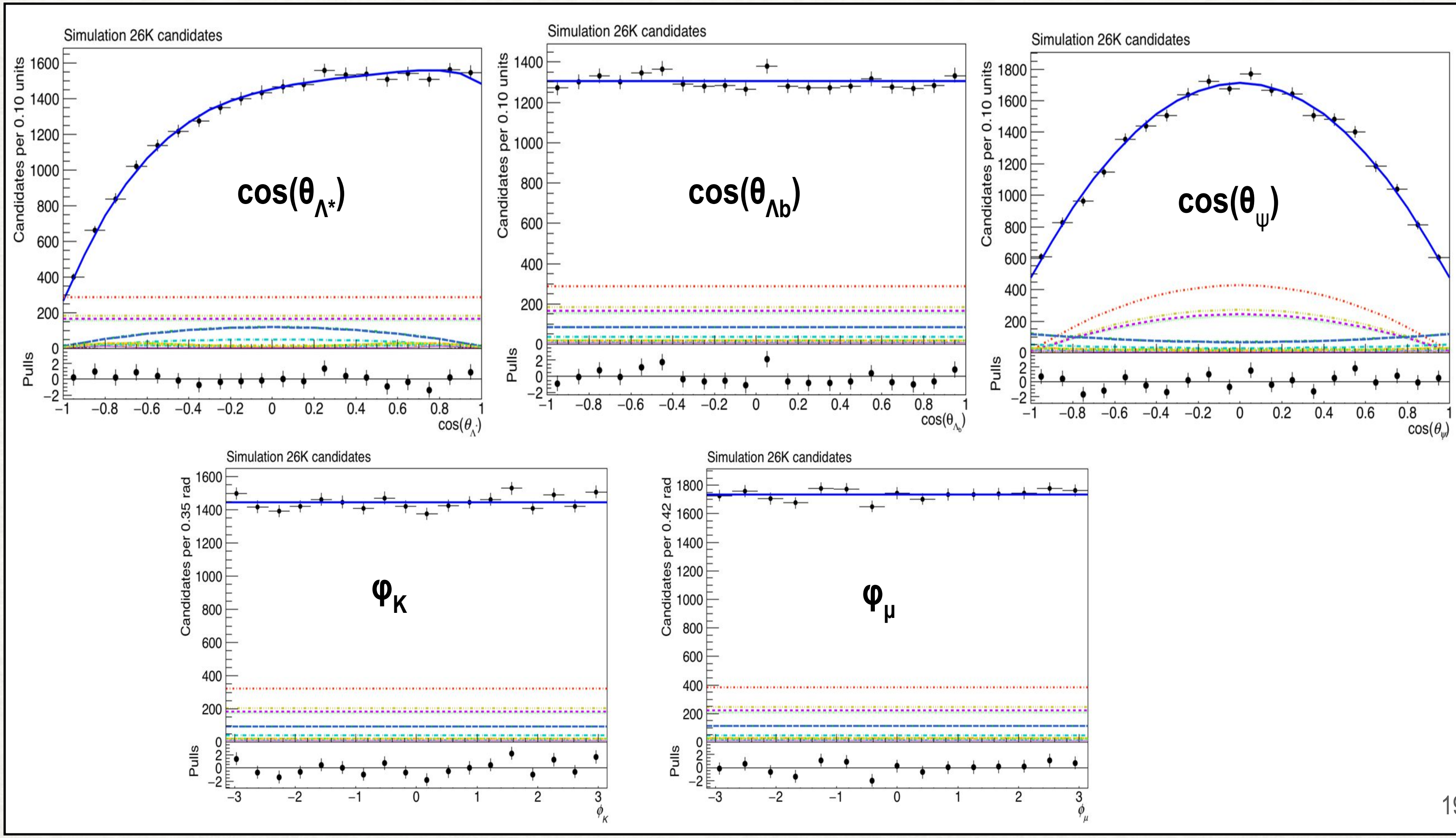
FITTING CODE

- Signal model was ported to RooFit.
- Programming optimized for fast evaluation and negligible precision loss.
- RooFit generates pseudo-experiments.
- RooFit performs 5D integration numerically (or can use "advertised" integrals).
- Fitting tests ongoing in CPUs and CUDA Cores.

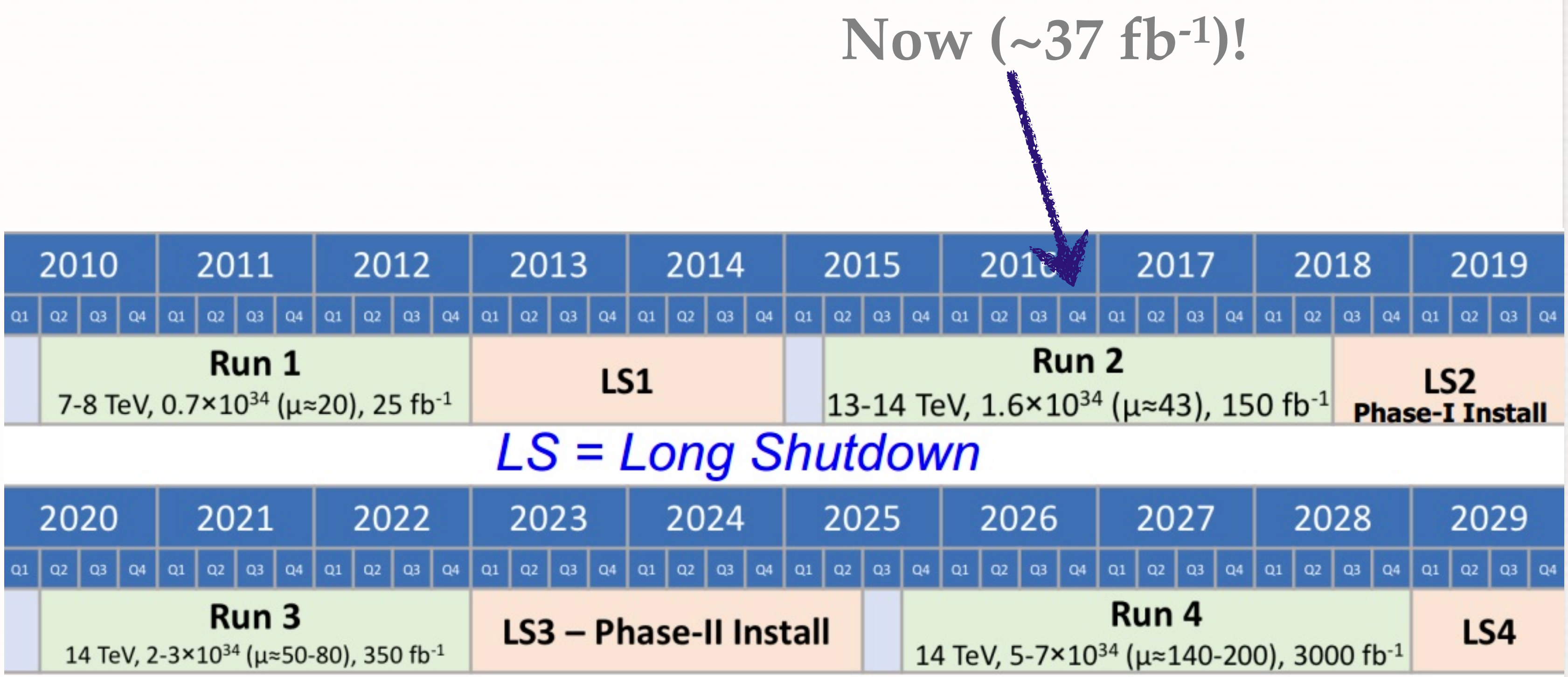


ANGULAR PROJECTIONS

USING ROOFIT



LHC SCHEDULE



- *The HL-LHC running starts in 2025 and continues beyond LS4 until 2035*

Summary

- The CMS experiment has produced several competitive results related to production, branching ratios, CPV, lifetimes, polarizations, and other properties of B hadrons.
- CMS will continue studying the B^0_s system to search for anomalous CPV using decays to $J/\psi K^+K^-$ and $J/\psi\pi^+\pi^-$ with 13 TeV data.
- The B_c, B-baryon, quarkonium and exotic hadrons program will also continue and benefit from the additional data in Run II.
- The observation of $B^0 \to \mu^+\mu^-$ is one of the main long term goals of CMS. Detector upgrades will improve its sensitivity.
- Similarly, $b \to s\ \mu^+\mu^-$ analyses are now within the core of the CMS B physics program. Special trigger paths have been incorporated for their detailed study with 13 TeV data.