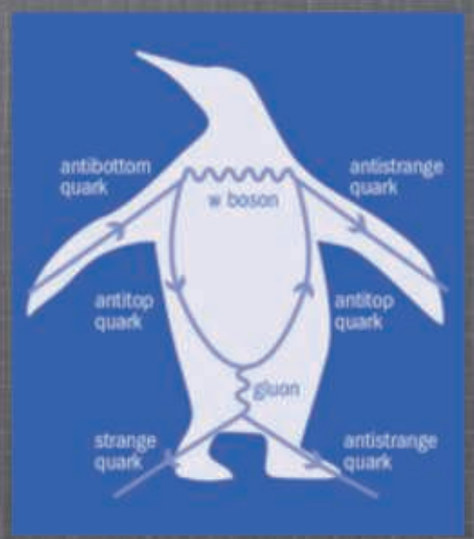
CMS RESULTS ON BOTTOM QUARK PHYSICS



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XXIX Annual Meeting of the DPyC-SMF

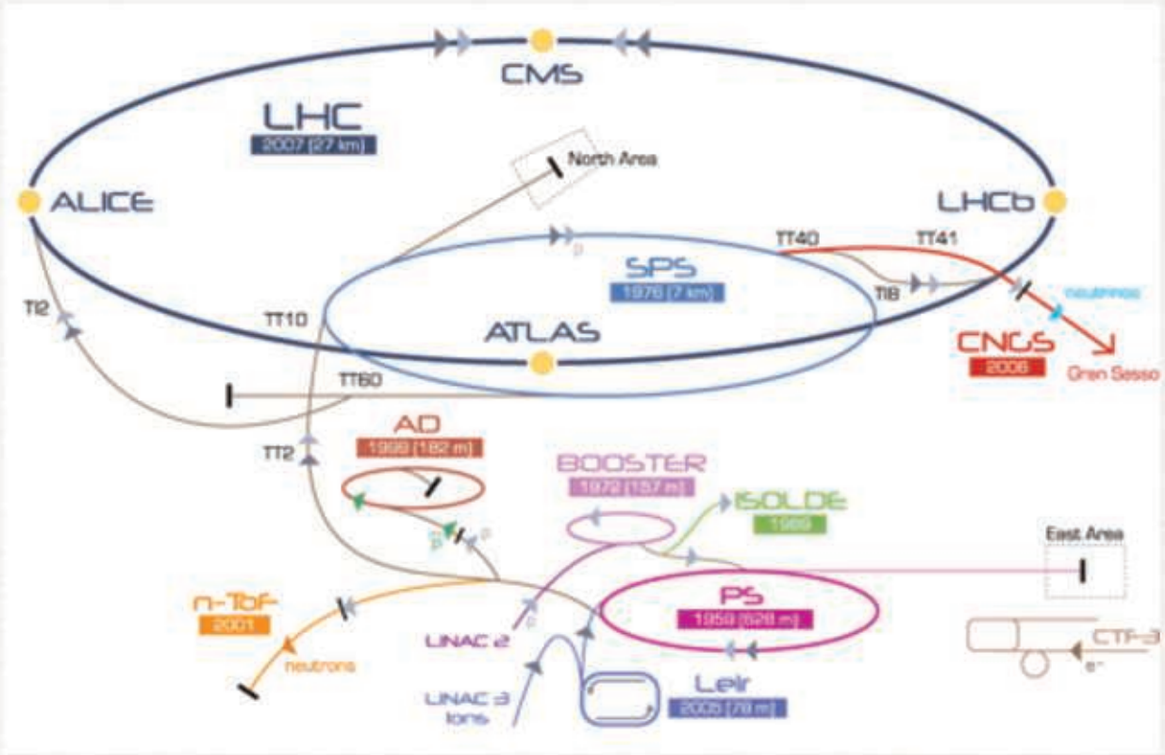
OUTLINE

- The Large Hadron Collider (LHC)
- The Compact Muon Solenoid (CMS) Experiment
- B hadron production & properties using the J/ψ trigger
- A new B baryon
- Strict tests of Standard Model (SM) with rare decays
- Quarkonia
- Exotica: unexpected particles
- Summary


CMS
LHCb
ALICE
ATLAS

LHC

- International: ~10,000 scientists & engineers from ≳ 100 universities and labs.
- 27 km tunnel, ~100 m underground.
- pp collisions @7-8 TeV in Run I (2011-2). Soon 13 TeV (Last night!).
- Bunches of ~10^{11} p crossing every 50 ns. Soon 25 ns.



LHC SCHEDULE

Available data (this talk)

Now!

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4
Run 1 7-8 TeV, 0.7×10^{34} (μ≈20), 25 fb^{-1}			**LS1**		**Run 2** 13-14 TeV, 1.6×10^{34} (μ≈43), 150 fb^{-1}			**LS2** Phase-I Install	

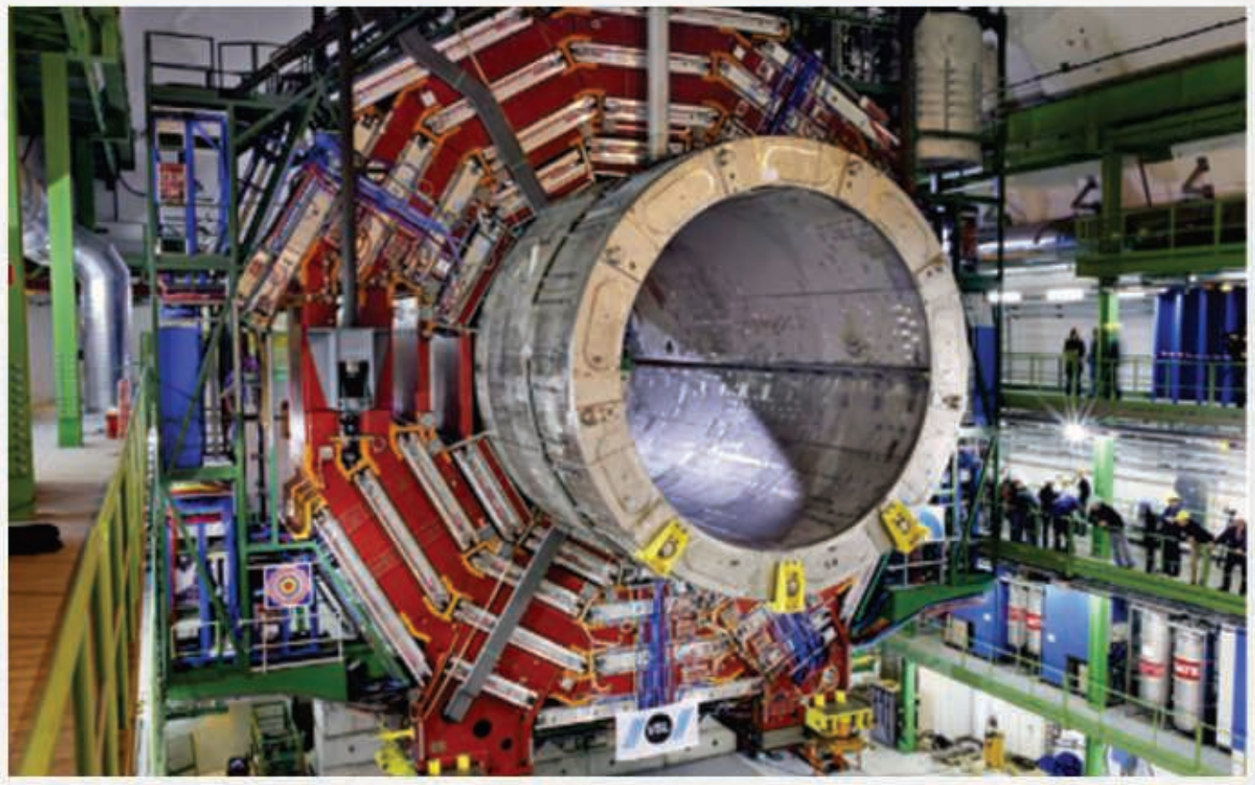
LS = Long Shutdown

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4
Run 3 14 TeV, 2-3×10^{34} (μ≈50-80), 350 fb^{-1}			**LS3 – Phase-II Install**		**Run 4** 14 TeV, 5-7×10^{34} (μ≈140-200), 3000 fb^{-1}			**LS4**	

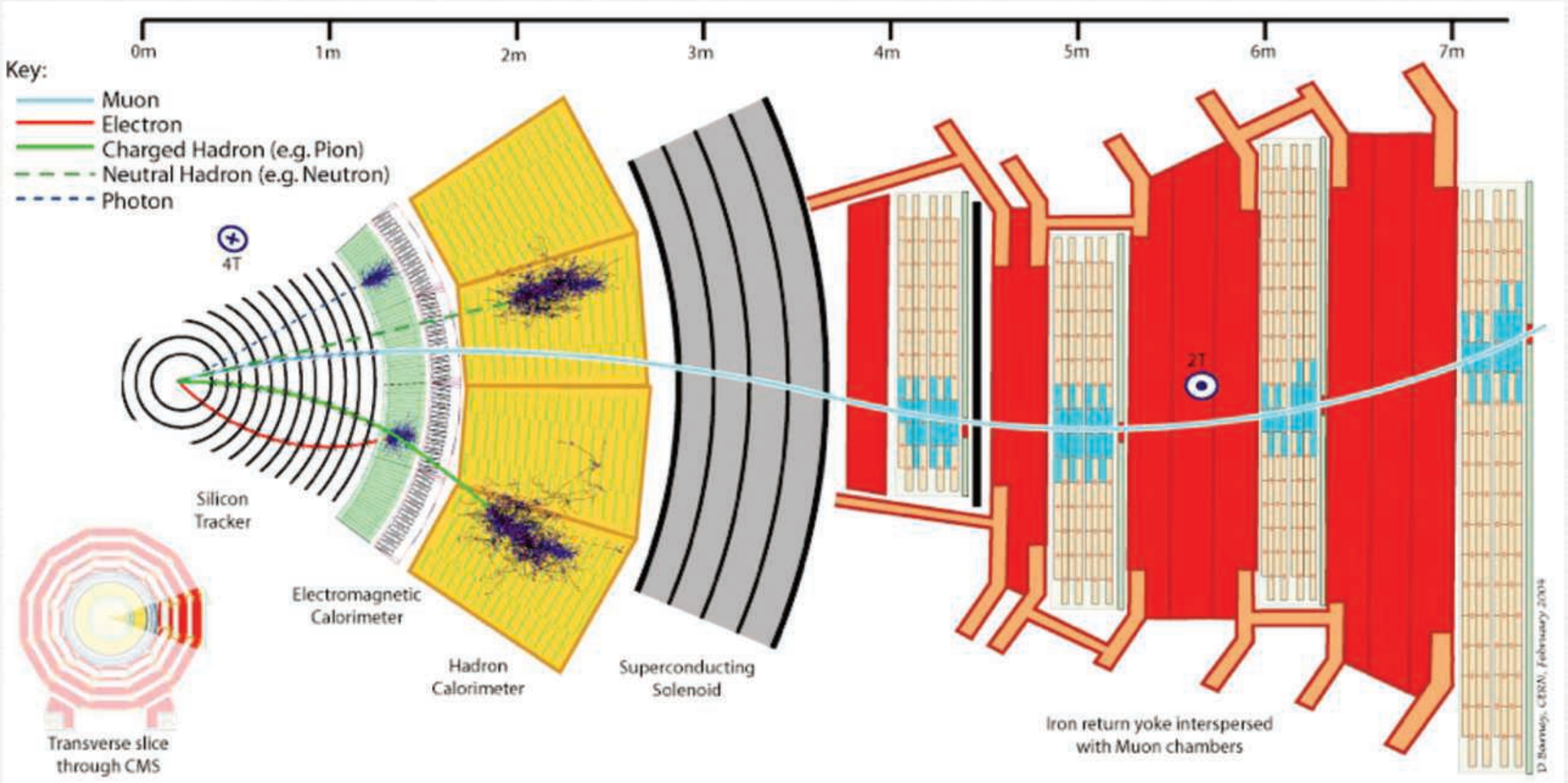
- *The HL-LHC running starts in 2025 and continues beyond LS4 until 2035*

CMS

- In Cessy, France.
- ~3000 collaborators.
- Multipurpose detector:
  - Designed to search and study new particles with masses ~0.1 - 1 TeV.
- New particles would decay to bottom quarks.



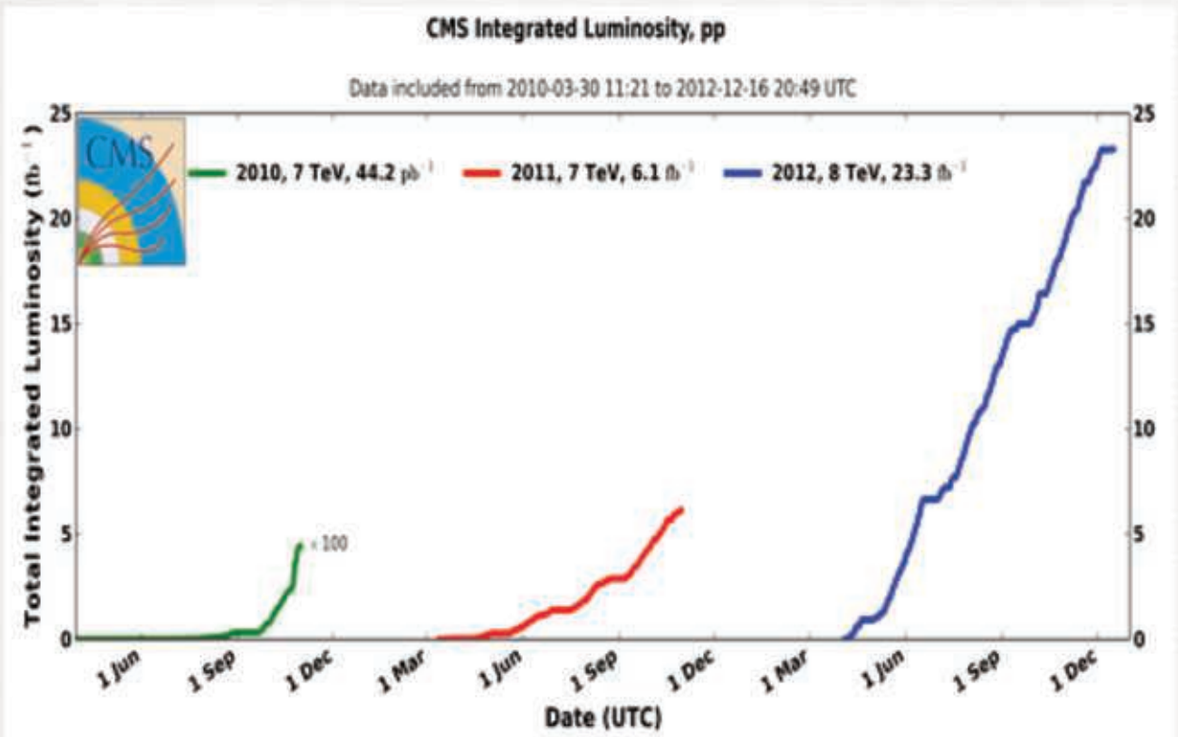
DETECTION

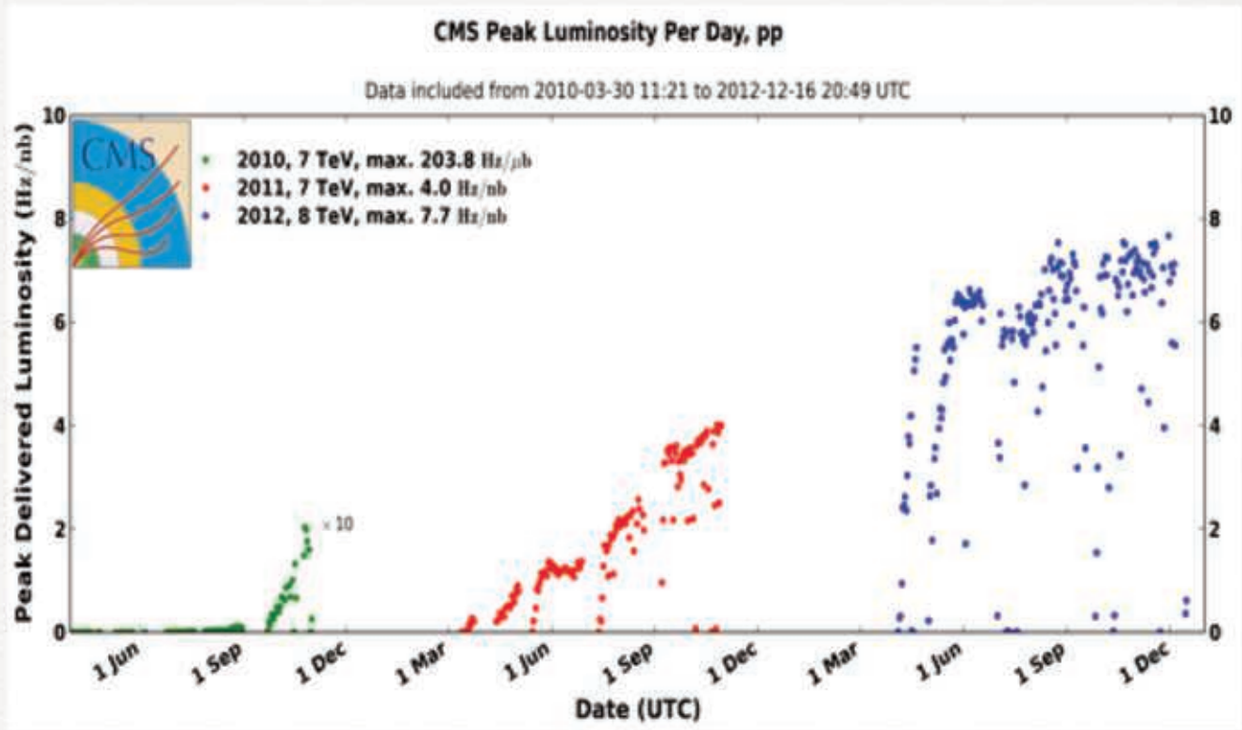


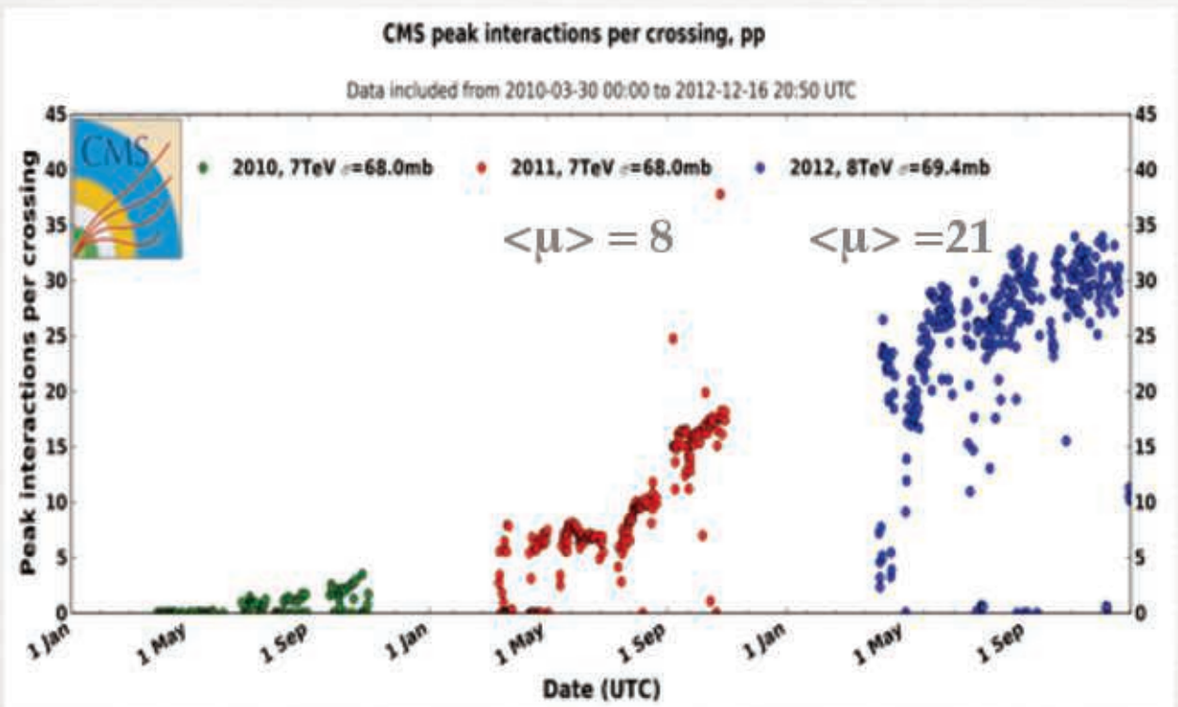
PV (xy) resolution ~ 20 μm

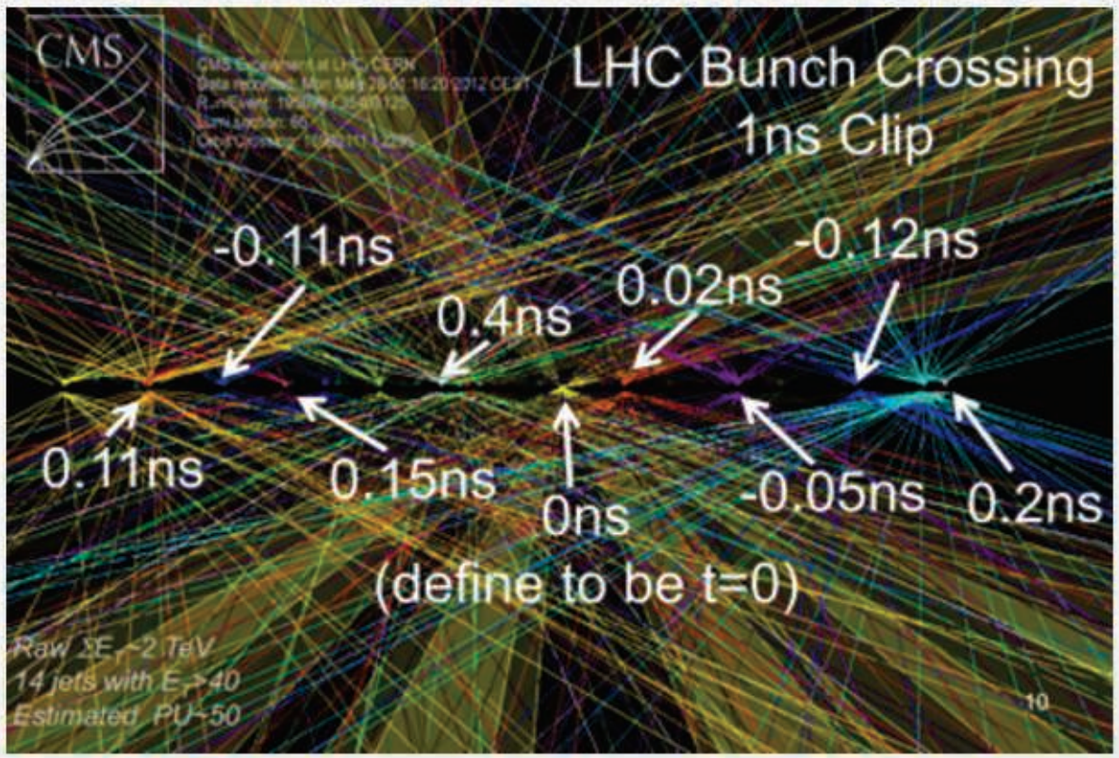
Track & μ p_T resolution ~ 1.5%

DATA, LUMI & PILE-UP

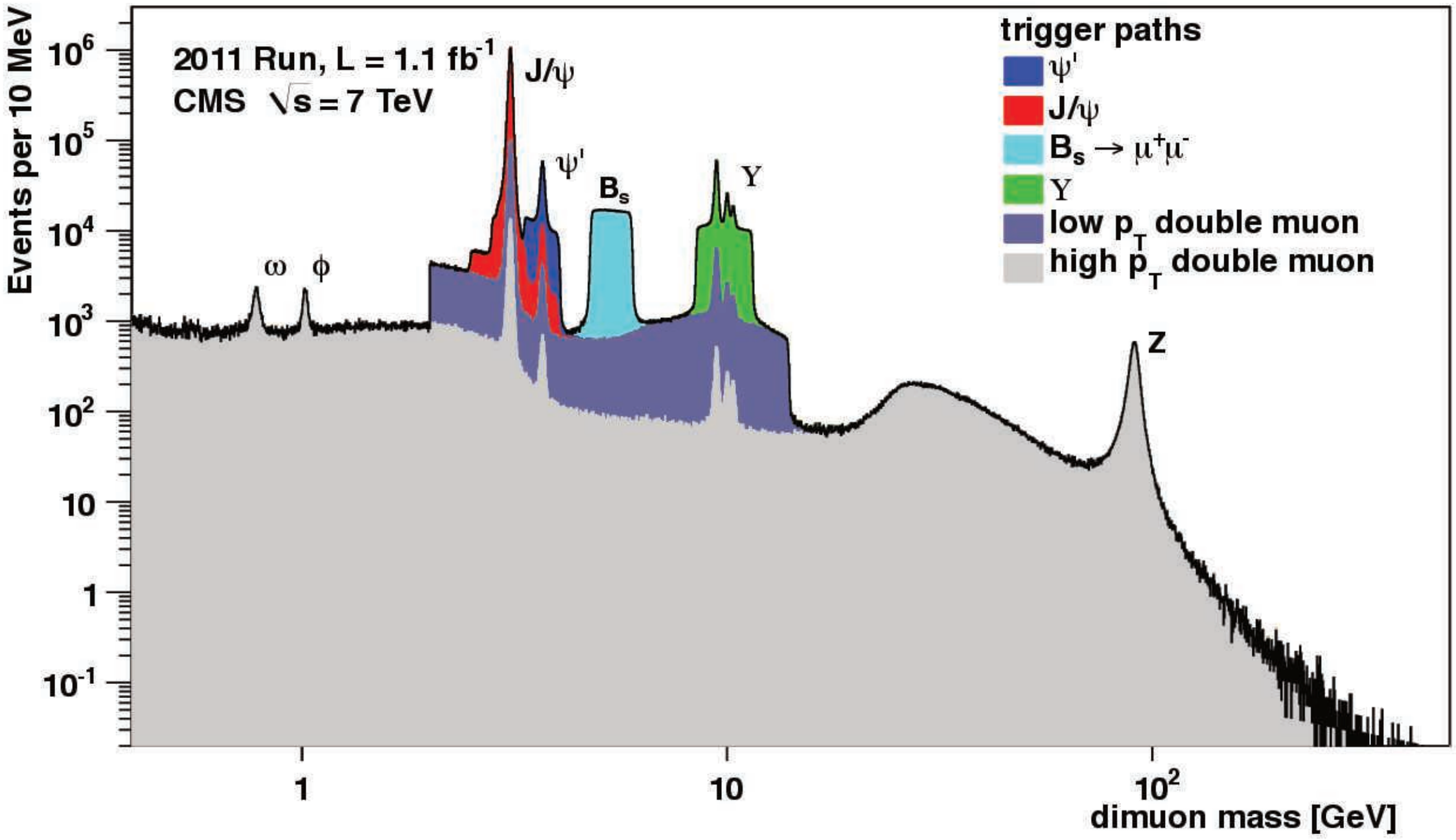


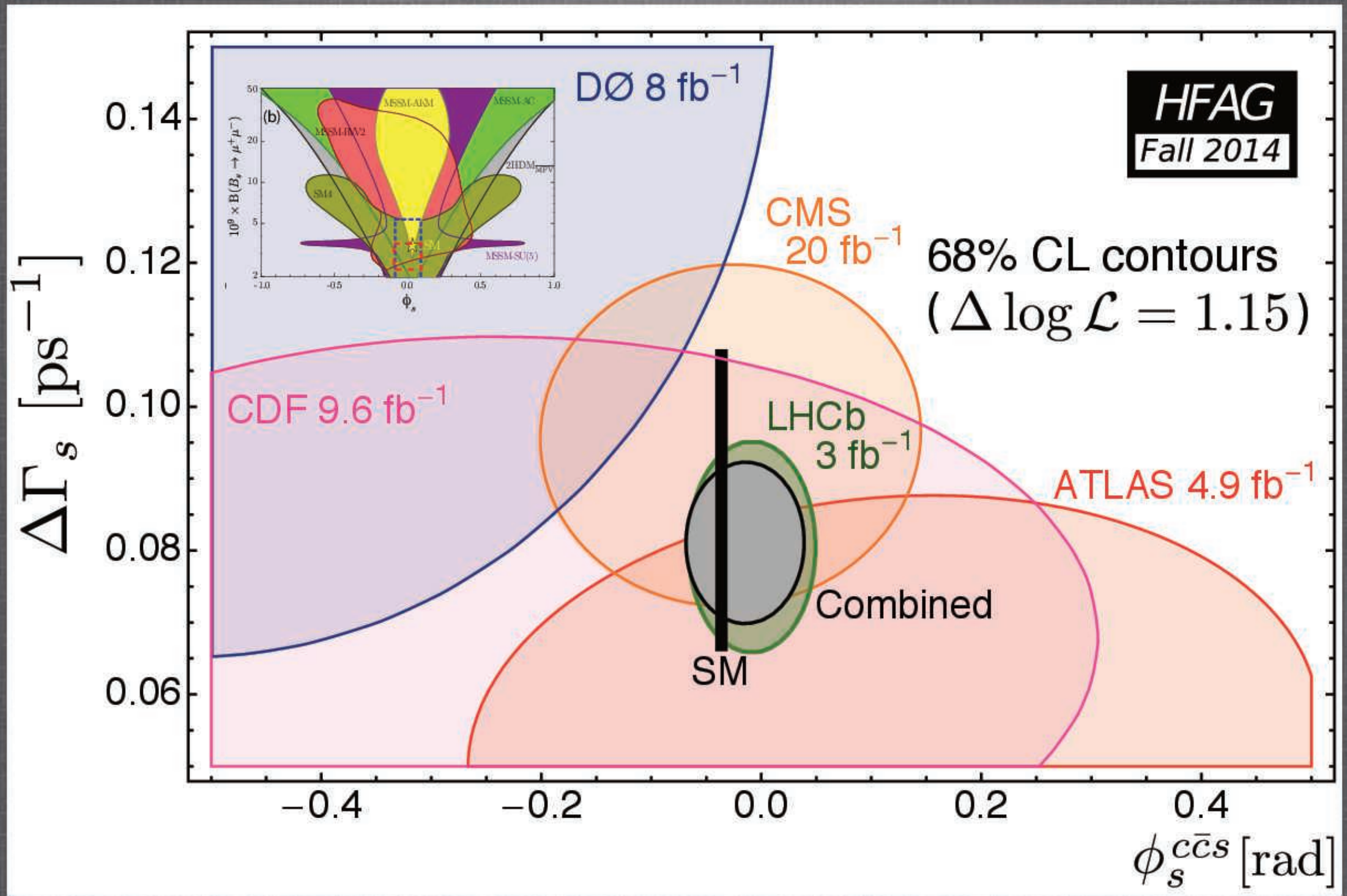






BHP TRIGGERS

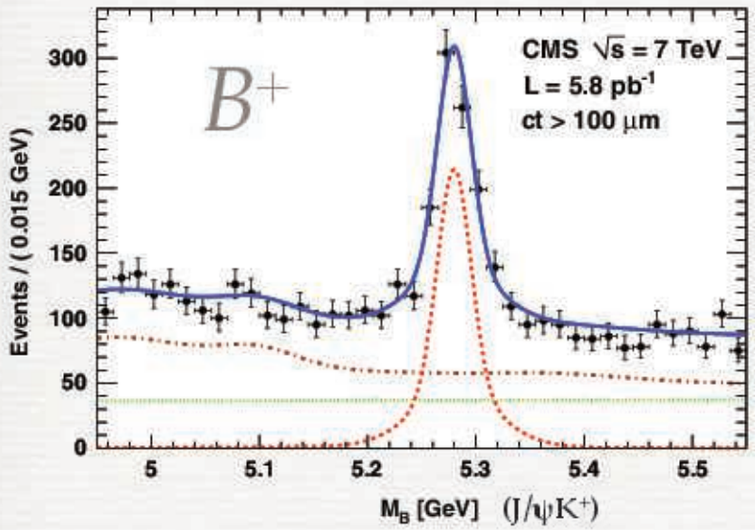


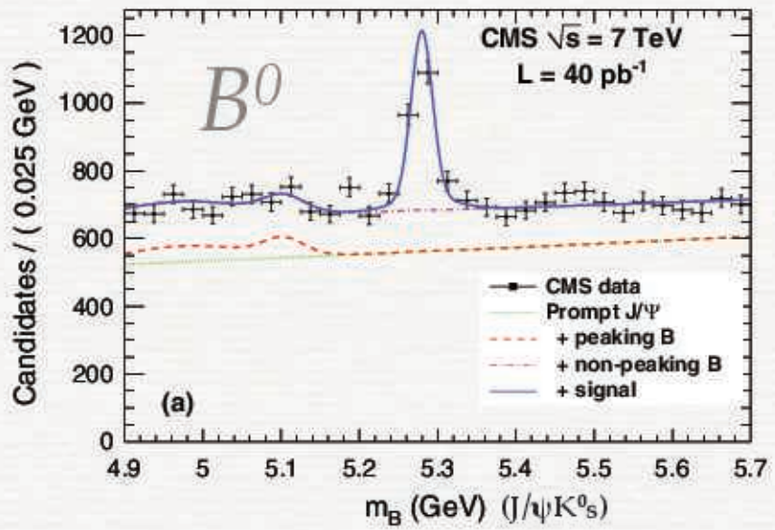


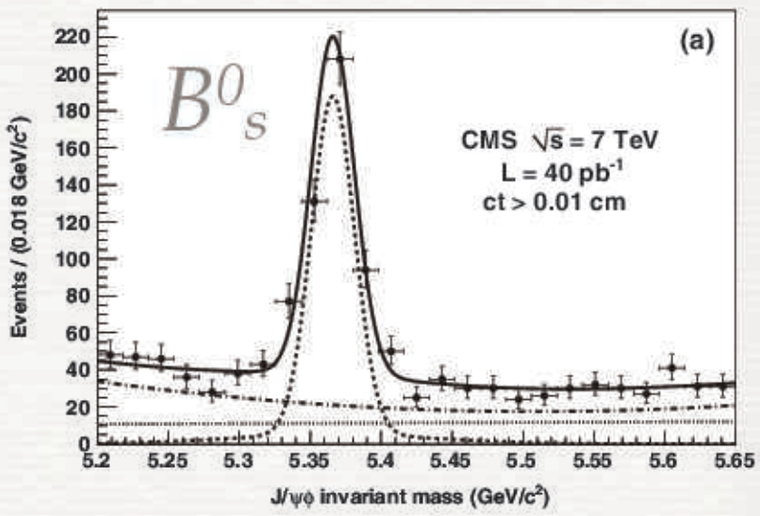
PHYSICS RESULTS

B MESON PRODUCTION

≲40 pb^{-1}







B meson production

$B^+ \to J/\psi K^+$ PRL 106 (2011) 112001

$p_{TB} > 5\text{GeV}$, $|y_B| < 2.4$

$\sigma(pp \to B^+) = (28.1 \pm 2.4 \pm 2.0)\mu\text{b}$

$B^0 \to J/\psi K^0_S$ PRL 106 (2011) 252001

$p_{TB} > 5\text{GeV}$, $|y_B| < 2.2$

$\sigma(pp \to B_0) = (33.2 \pm 2.5 \pm 3.5)\mu\text{b}$

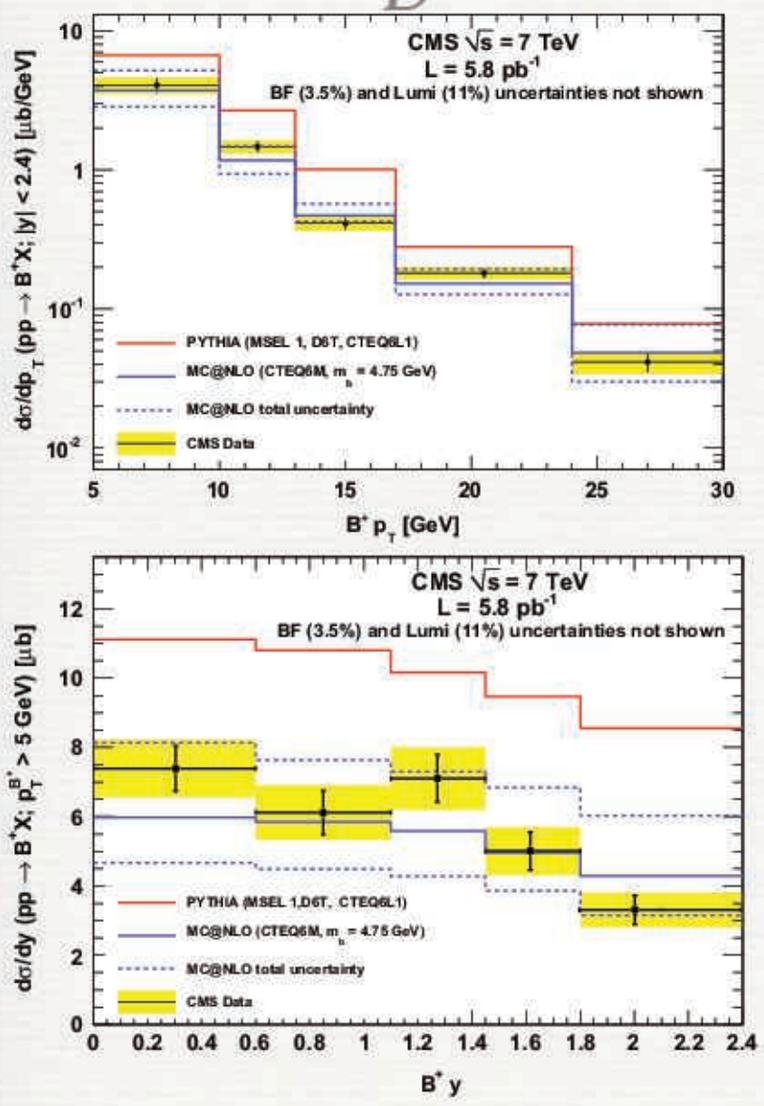
$B_s \to J/\psi\phi$ PRD 84 (2011) 052008

$8 < p_{TB} < 50\text{GeV}$, $|y_B| < 2.4$

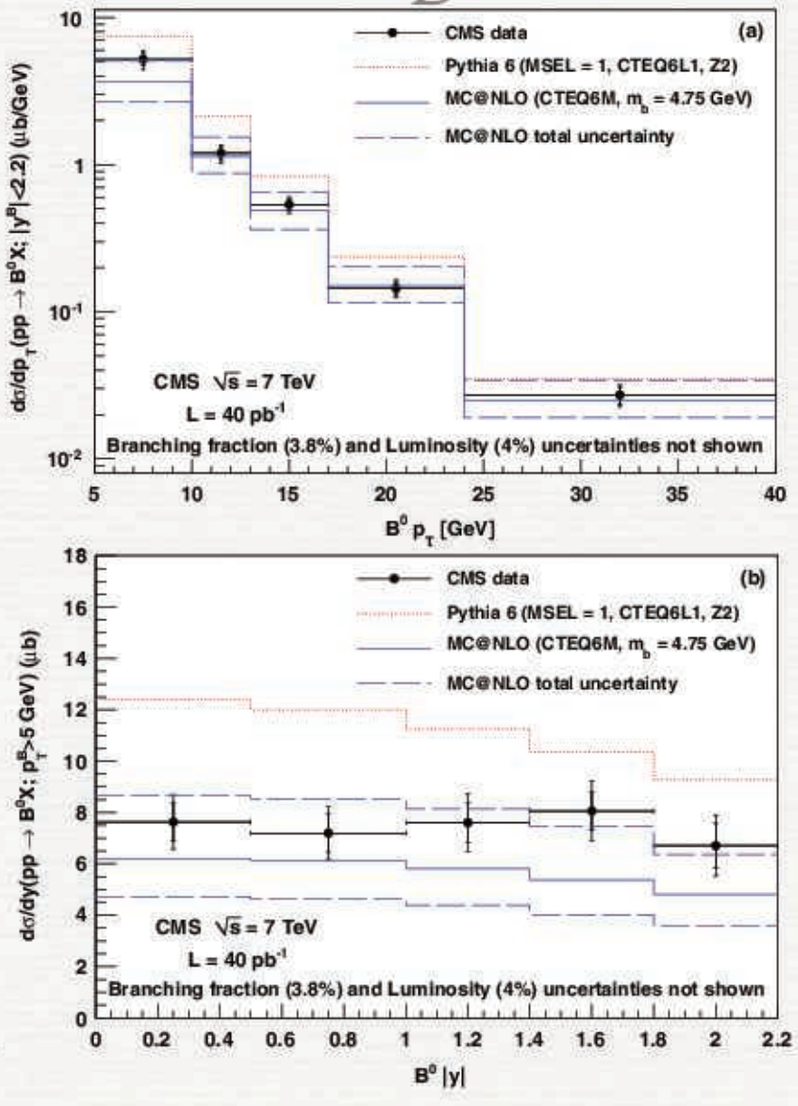
$\sigma(pp \to B_s \to J/\psi\phi) = (6.9 \pm 0.6 \pm 0.6)\text{nb}$

DIFFERENTIAL CROSS-SECTIONS OF B MESONS

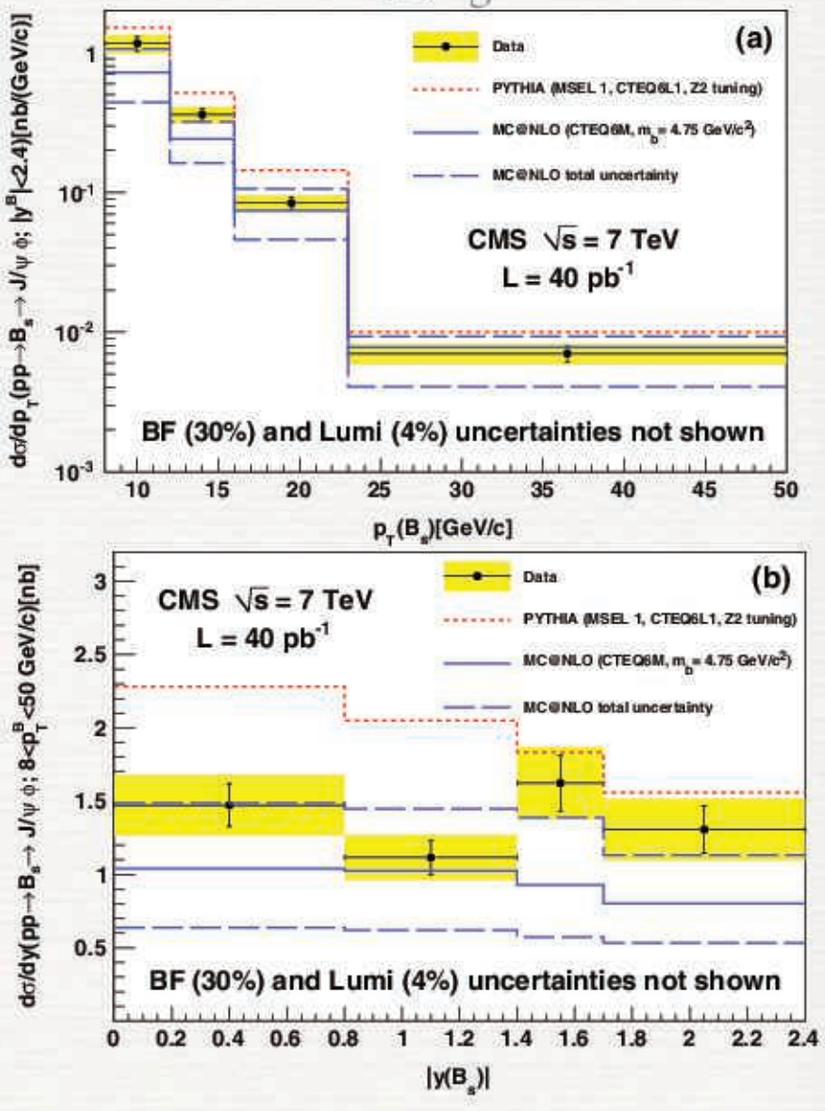
B^+



B^0

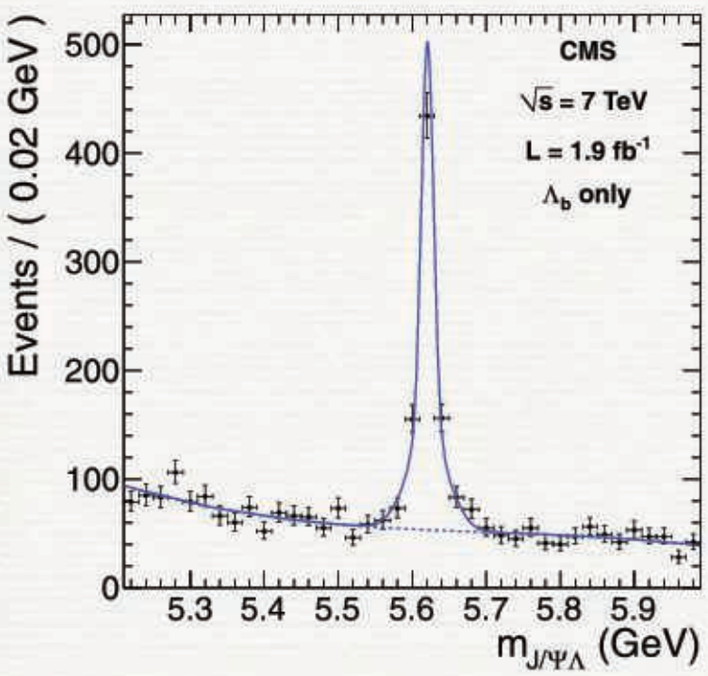


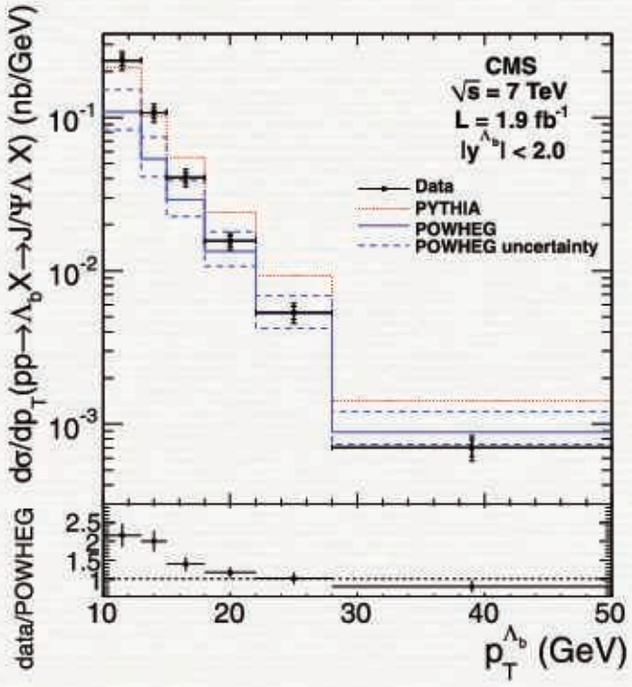
B^0_s

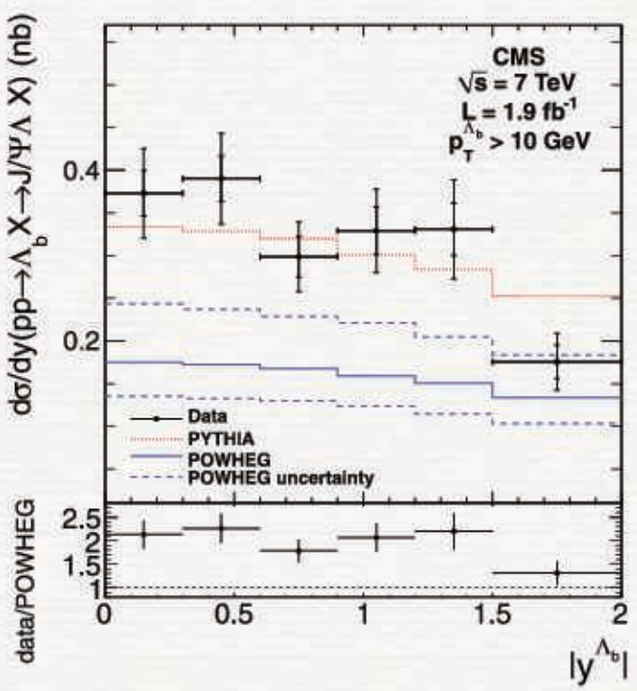


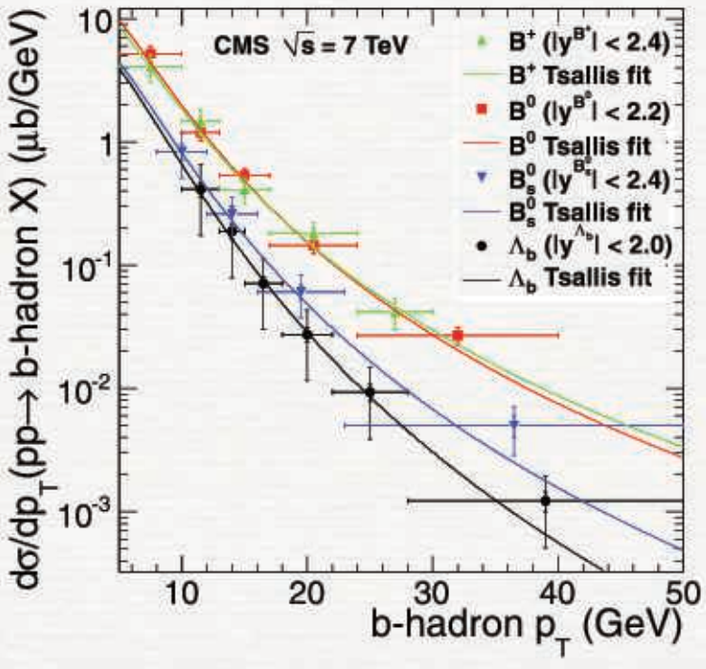
- Quite good agreement with MC@NLO.
- Pythia failing mainly in normalization and wrt. rapidity.

B BARYON PRODUCTION









- Pythia & POWHEG predictions not great.
- Differences in meson vs. baryon: baryon p_T spectrum is softer.

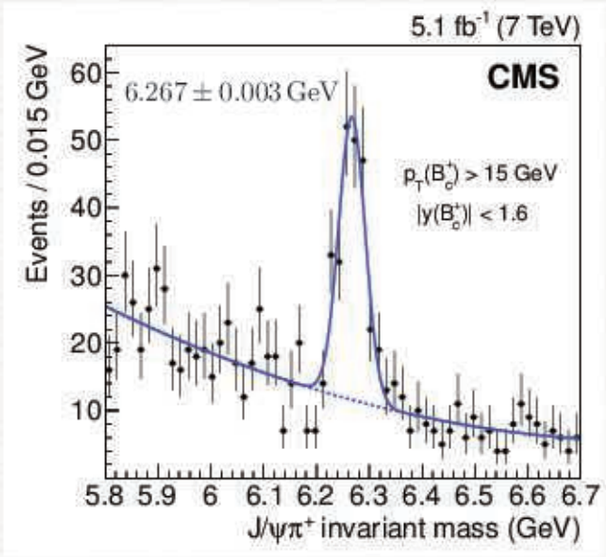
Results ($\sqrt{s} = 7\text{TeV}$, $\mathcal{L} = 1.9\text{fb}^{-1}$) PLB 714 (2012) 136

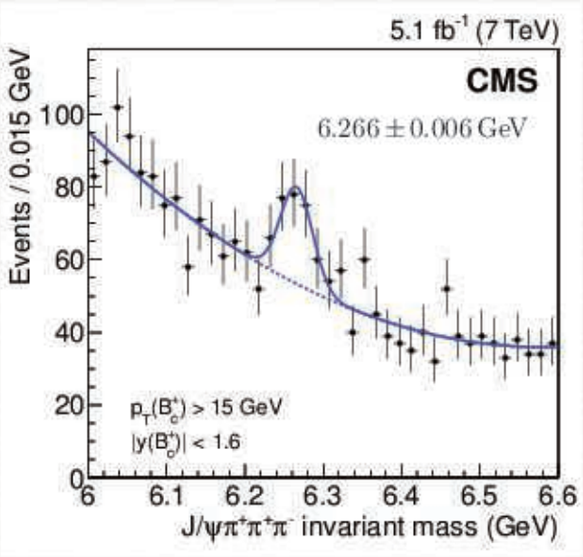
$$\sigma(pp \to \Lambda_b^0 X) \times \mathcal{B}(\Lambda_b^0 \to J/\psi \Lambda^0) = (1.16 \pm 0.06 \pm 0.12)\text{nb}$$

$$\frac{\sigma(pp \to \bar{\Lambda}_b^0 X)}{\sigma(pp \to \Lambda_b^0 X)} = 1.02 \pm 0.07 \pm 0.09$$

B_c^+ MESON

- *b* and *c* heavy quarks competing in decay (decays faster).
- Reconstructed in $J/\psi\pi^+$ and $J/\psi\pi^+\pi^+\pi^-$.
- Low detection efficiency (low p_T π's).
- Cross section measurements could help improve B_c production models.





Results ($\sqrt{s} = 7$ TeV) JHEP 01 (2015) 063

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

$$[0.48 \pm 0.05\,(\text{stat}) \pm 0.03\,(\text{syst}) \pm 0.05\,(\tau_{B_c})]\%$$

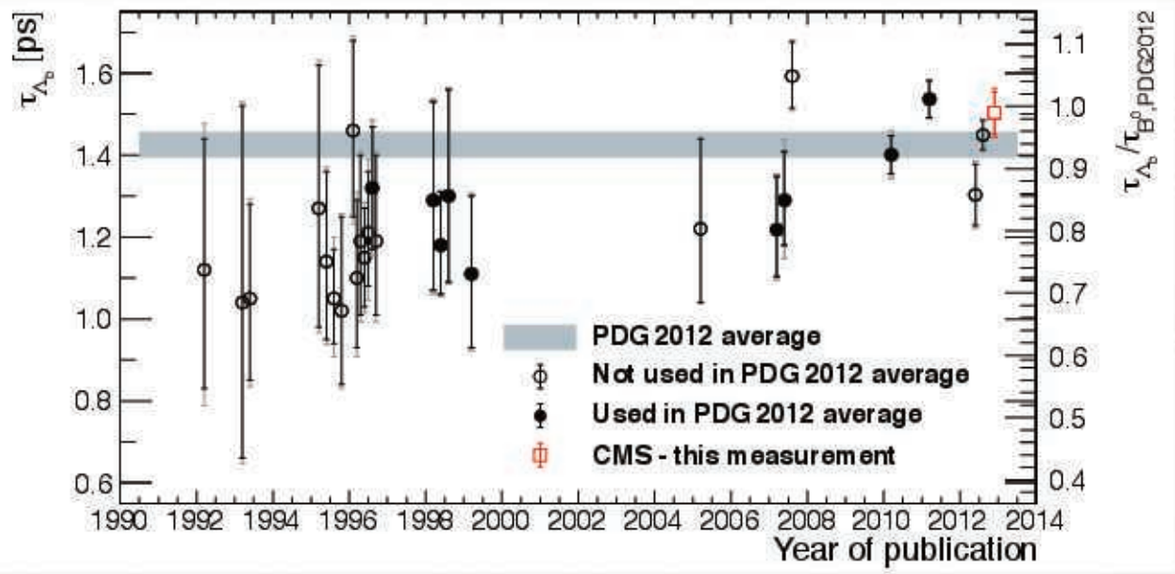
$$\frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+\pi^+\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} =$$

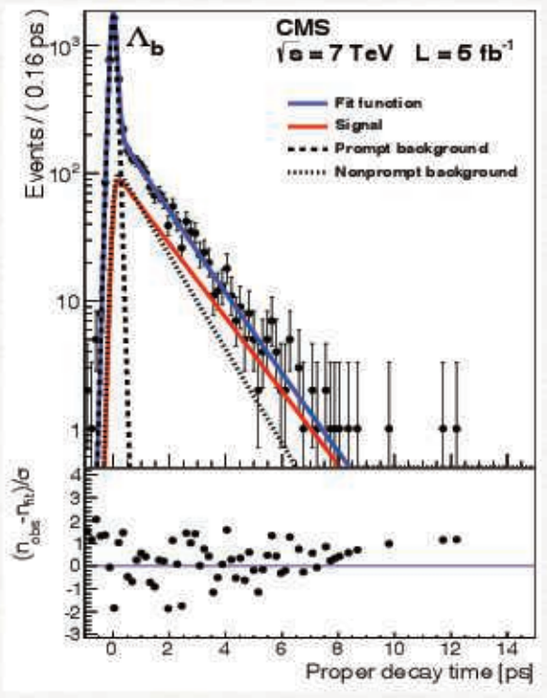
$$2.55 \pm 0.80\,(\text{stat}) \pm 0.33\,(\text{syst})^{+0.04}_{-0.01}\,(\tau_{B_c})$$

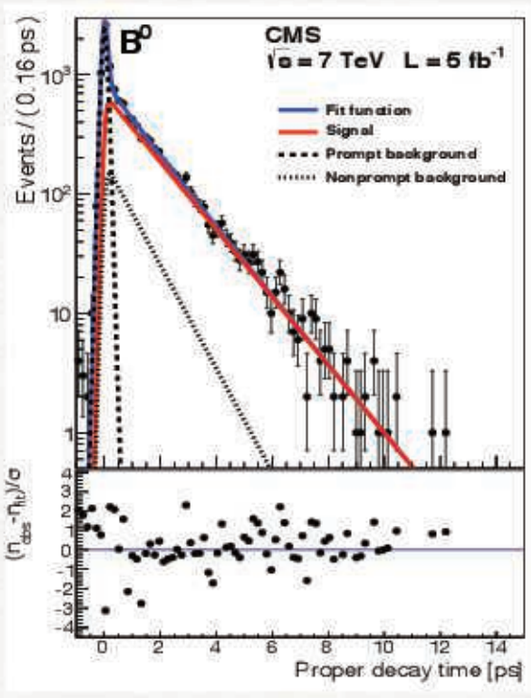
Lifetime measurement coming soon...

Λ_b LIFETIME

- Early predictions too high: $\tau(\Lambda_b)/\tau(B^0) > 0.9$.
- Recent HQE @NLO & $\mathcal{O}(m_b^{-4})$: $\tau(\Lambda_b)/\tau(B^0) \approx 0.88$.
- Simultaneous UL-Fit to mass ($J/\psi\Lambda$) and proper decay time using unbiased (trigger) sample.







Results ($\sqrt{s} = 7$TeV) JHEP 07 (2013) 163

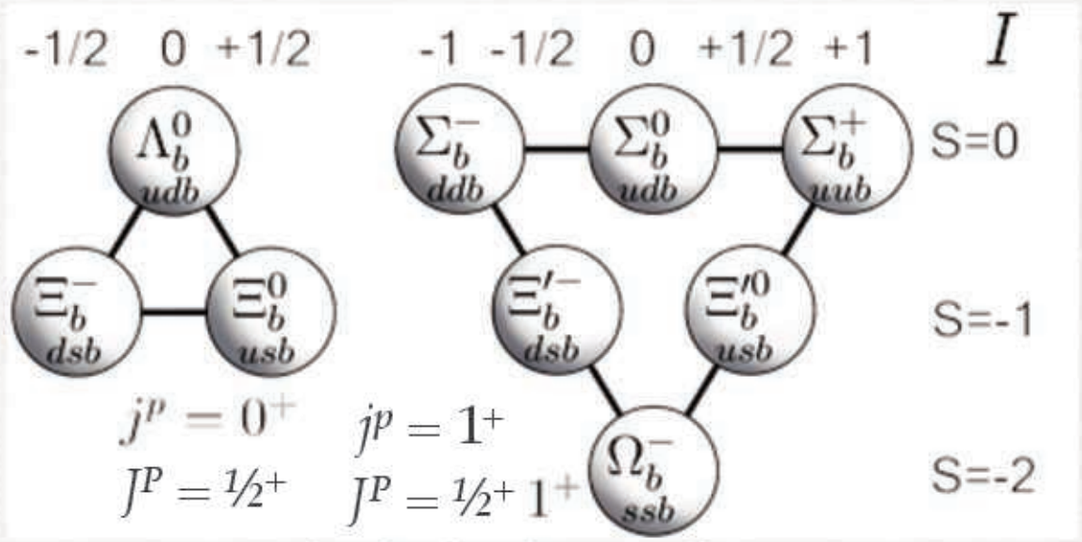
$$\tau_{\Lambda_b^0} = (1.503 \pm 0.052 \pm 0.031)\text{ps}$$

$$\tau(\Lambda_b)/\tau(B^0) = 0.98 \pm 0.04$$

More precise lifetime and polarization measurements coming soon...

SEARCH FOR A NEW *B* BARYON

- Quark model predicts 3 *bsd* (ground) baryon states:
  - Ξ_b (lightest state).
  - Ξ_b'.
  - Ξ_b^* (in $j = 1$, $J^P = 3/2^+$ sextet).
- Ξ_b decays weakly.
- $\Xi_b^{(*)}$ predominately decays strongly to $\Xi_b \pi$, then E.M. to $\Xi_b \gamma$.
- CMS is inefficient to (soft) γ detection.



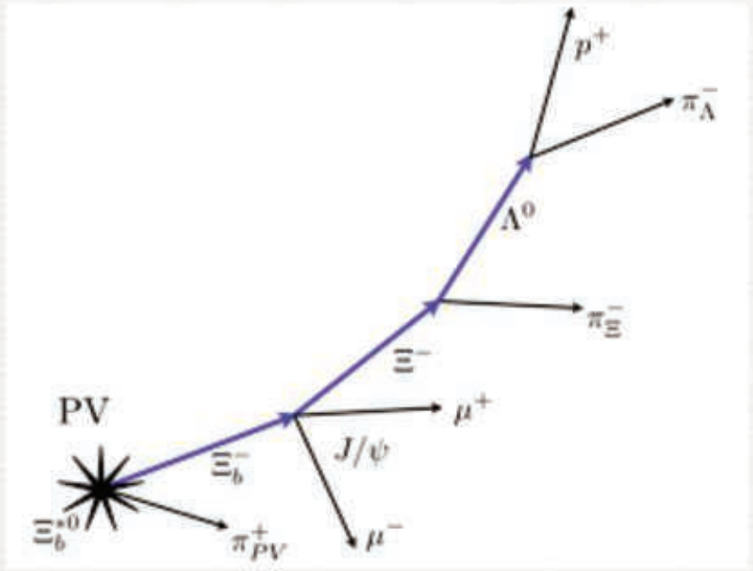
j = light di-quark spin

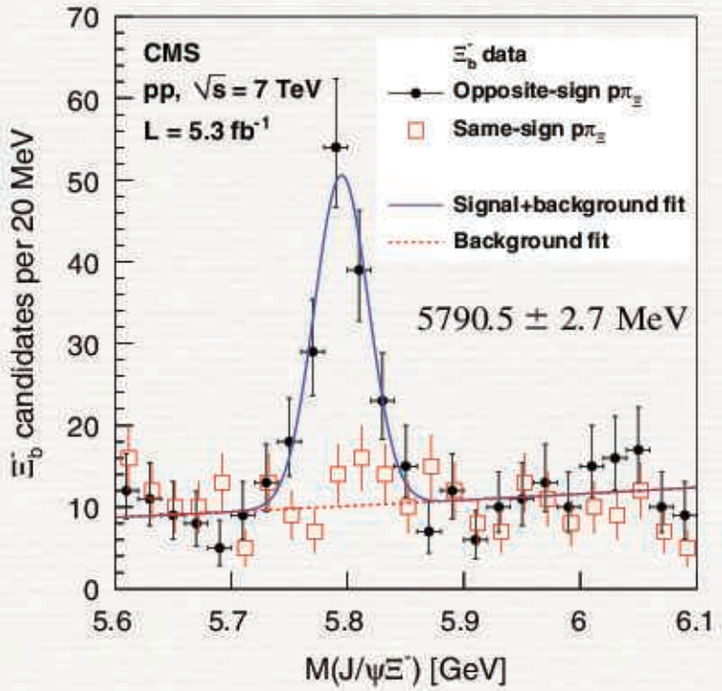
J^P = spin-parity of baryon

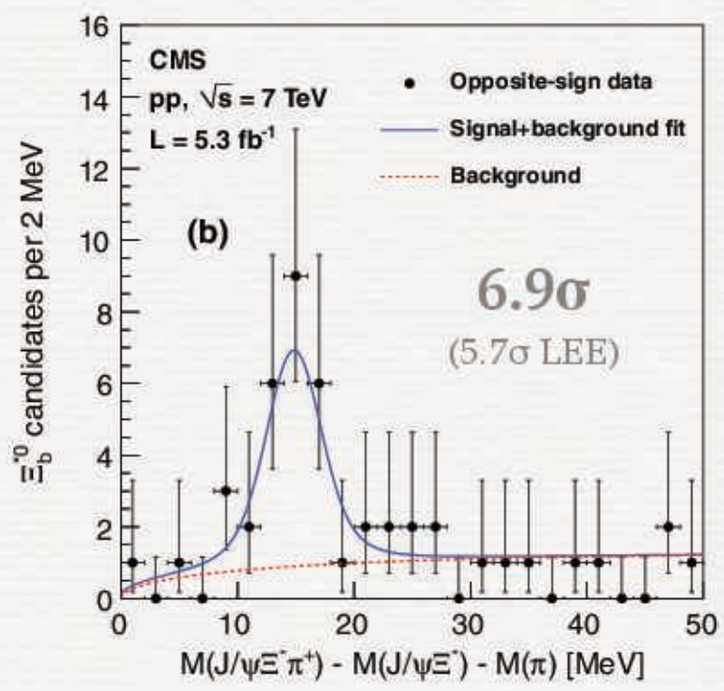
- Theory: $m_{\Xi_b'^0} - m_{\Xi_b^-} < m_\pi$ ⇒ kinematically forbidden.
- Then look for:

$$\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+$$

OBSERVATION OF Ξ_b^{*0}







Mass fit ($\sqrt{s} = 7$TeV) PRL 108 (2012) 252002

$$Q = (14.84 \pm 0.74 \pm 0.28)\text{MeV}$$

$$m_{\Xi_b^{*0}} = 5945.0 \pm 0.7(\text{stat}) \pm 0.3(\text{syst}) \pm 2.7(\text{PDG})\ \text{MeV}$$

$$\Gamma = 2.1 \pm 1.7(\text{stat})\ \text{MeV}$$

$$(\ \Gamma = 0.51 \pm 0.16\ \text{MeV},\ \text{expected})$$

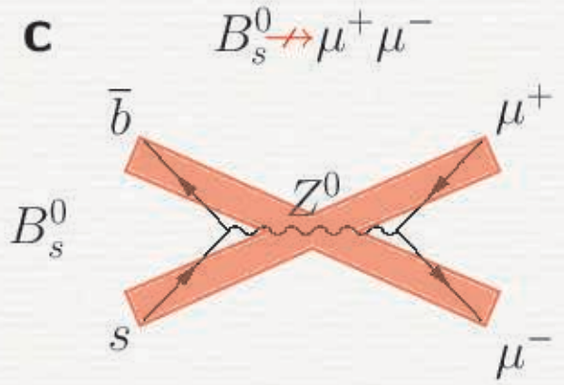
RARE DECAYS
$B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

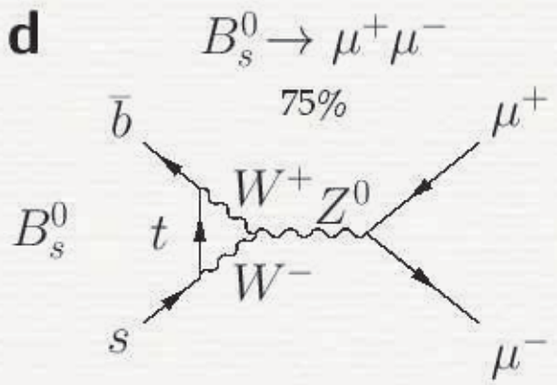
- FCNC decay forbidden @LO.
- Helicity $(m_\mu/m_B)^4$ & CKM suppressed.
- Reliable predictions:

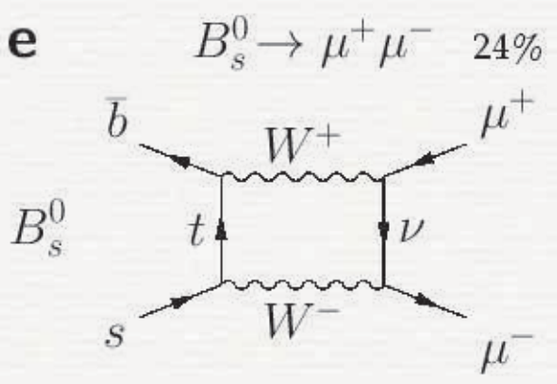
$$\mathcal{B}(B^0_s \to \mu^+\mu^-)_{\rm SM} = (3.66 \pm 0.23) \times 10^{-9}$$

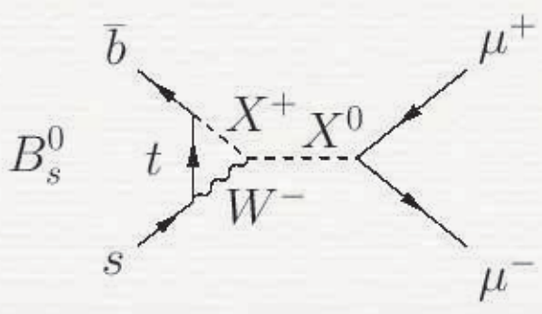
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{\rm SM} = (1.06 \pm 0.09) \times 10^{-10}$$

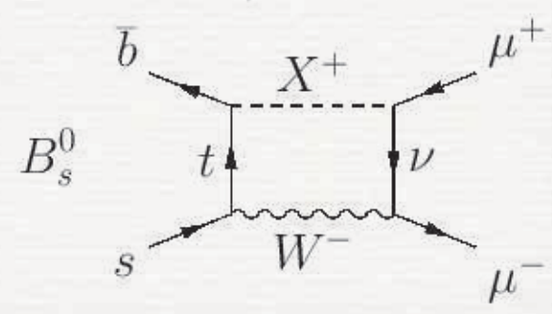
- Sensitive to NP:
  - MSSM ($\tan\beta \gg 0$).
  - 2HDM and M(H^+).
  - Leptoquarks.
  - 4th gen quark, etc.

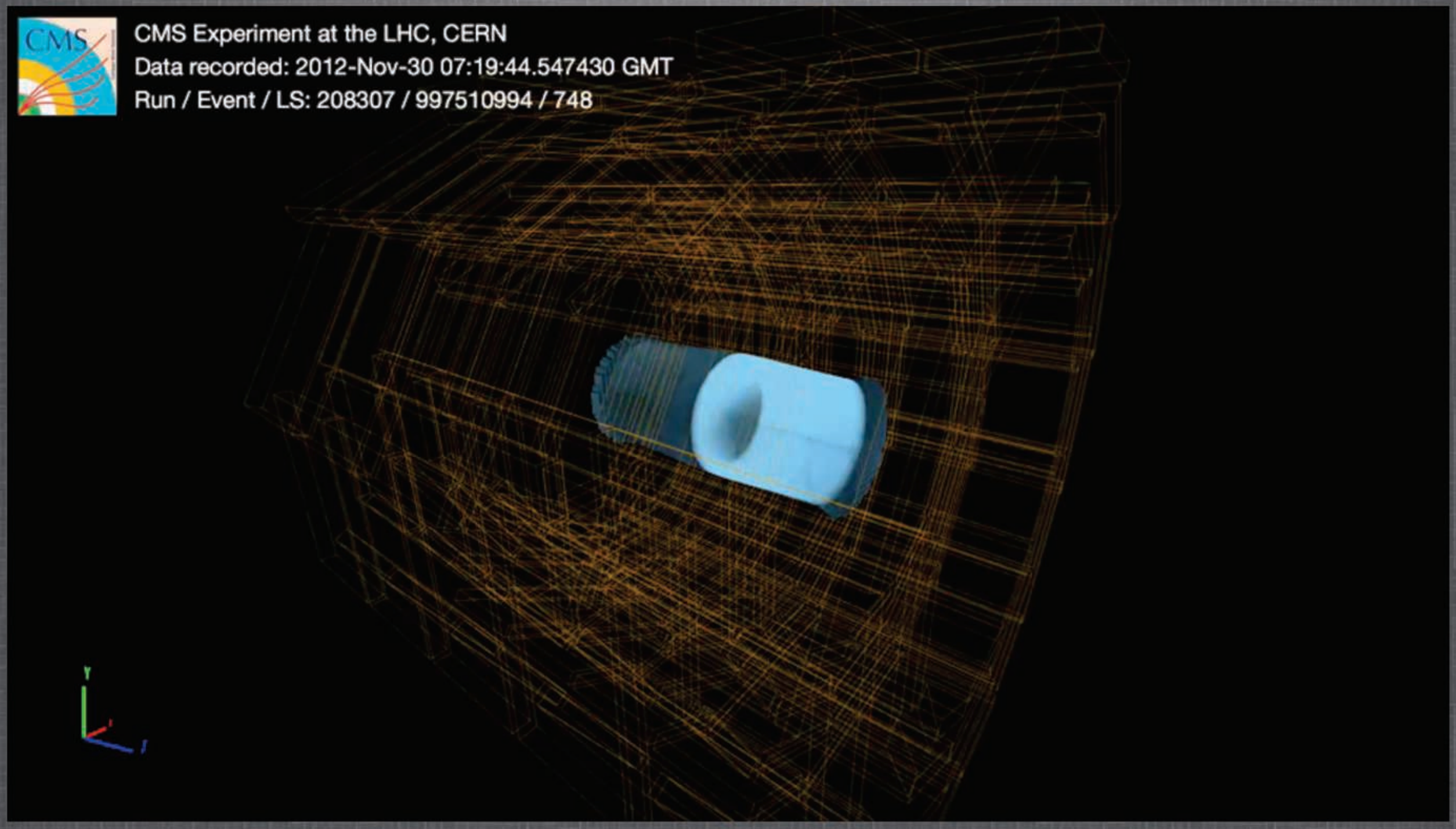












Dimuon trigger + blind analysis

SEARCH FOR $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

- Trained 3 BDT (MC = signal, SB = bkg) to reject bkg.:
  - To train ↔ test ↔ apply (1/3 sample).
  - Divide 2011-12, barrel & endcap ⇒ *12 BDT*!
  - 12 input variables (quality, kinematic, isolation) ⇒ 1 MV.
- Best signal-to-bkg BDT selection used to set BR($B^0 \to \mu^+\mu^-$) limit.
- Use MV to define 12 event categories w/ different purities:
  - Simultaneous fit to all categories to extract BR($B^0_s \to \mu^+\mu^-$).
- Combinatorial bkg. extrapolated from sidebands (SB).
- Semileptonic ($\Lambda_b \to p\mu\nu$) & peaking ($B \to hh'$) bkgs. from MC.
- $B^+ \to J/\psi K^+$ & $B^0_s \to J/\psi\phi$ as normaliz. & control samples.

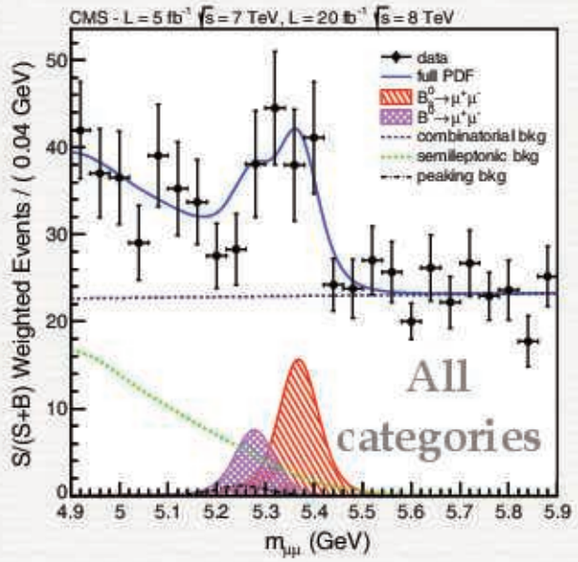
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \frac{N_S}{N_{\rm obs}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{\rm tot}^{B^+}}{\varepsilon_{\rm tot}} \mathcal{B}(B^+)$$

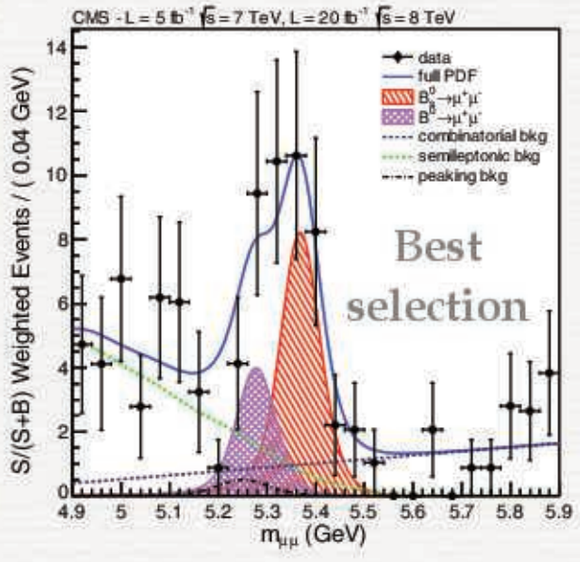
efficiencies from MC

RESULTS

See Alberto's talk

$B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

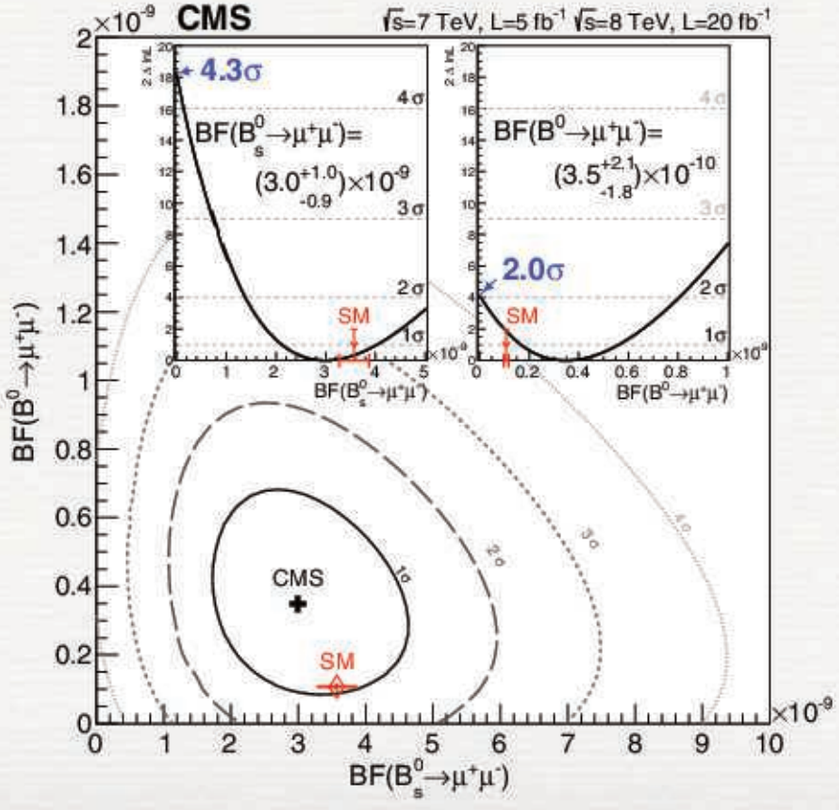


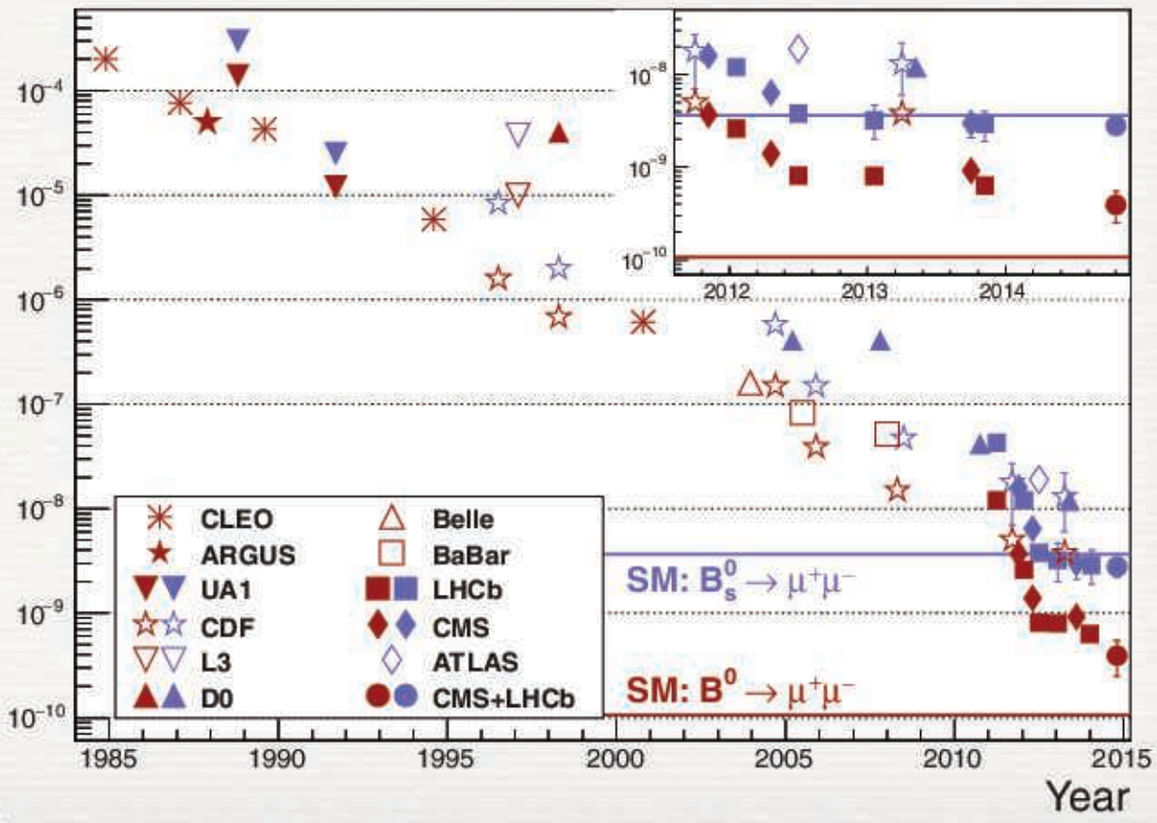


Results (full sample) PRL 111 (2013) 101804

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$
$$\mathcal{B}(B^0_d \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$$
$$\mathcal{B}(B^0_d \to \mu^+\mu^-) < 1.1 \times 10^{-9} \text{ @ 95\% C.L.}$$

Previous CMS results:
PRL 107 (2011) 191802 & JHEP 04 (2012) 033





NATURE 2015: CMS & LHCb

- Combined 20 MVA discriminant categories.
- LHCb included Λ_b component.
- CMS improved Λ_b MC and included ε_{ct}.

$$\mathbf{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \cdot 10^{-9} \text{ (stat+syst)}$$ **(6.2σ significance)**

$$\mathbf{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \cdot 10^{-10} \text{ (stat+syst)}$$ **(3.0σ significance)**

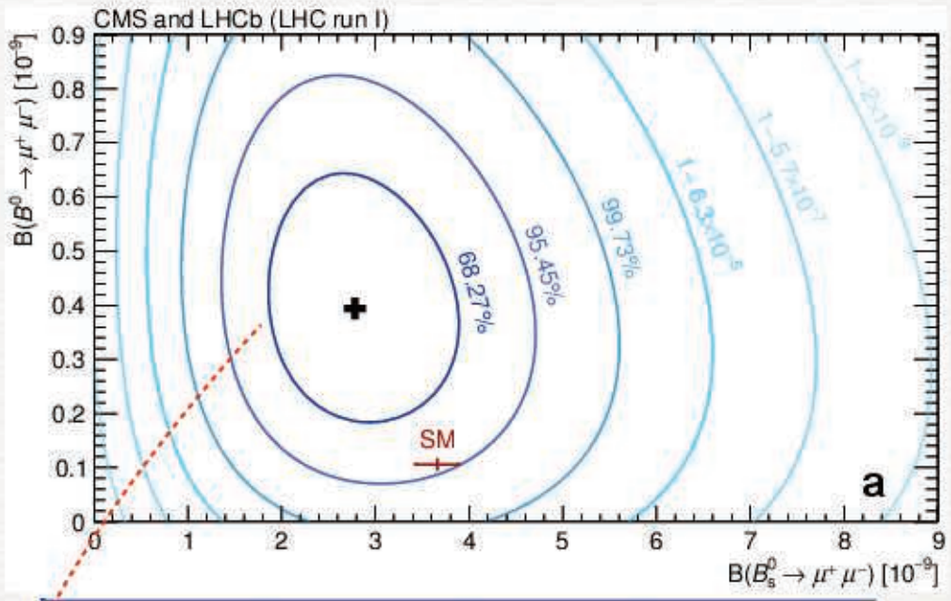
[Feldman-Cousins]

$$\mathcal{S}^{B_s^0}_{\rm SM} = 0.76^{+0.20}_{-0.18} \quad \& \quad \mathcal{S}^{B^0}_{\rm SM} = 3.7^{+1.6}_{-1.4}$$

$$R \equiv \frac{\mathbf{B}(B^0 \to \mu^+\mu^-)}{\mathbf{B}(B_s^0 \to \mu^+\mu^-)} = (0.14^{+0.08}_{-0.06})$$

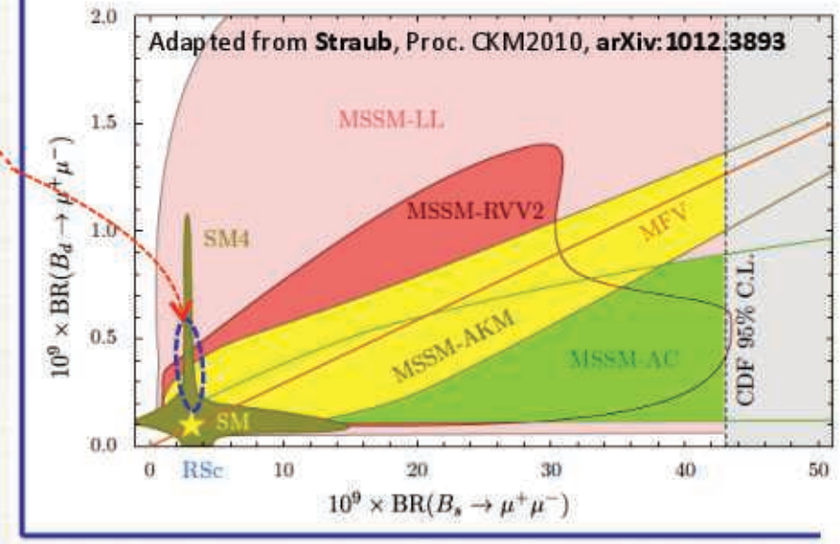
compatible with SM @ 2.3σ level

Very sensitive probe of NP ($R_{\rm SM} = R_{\rm MFV}$)



Compare with SM, MFV & 4 SUSY flavor models

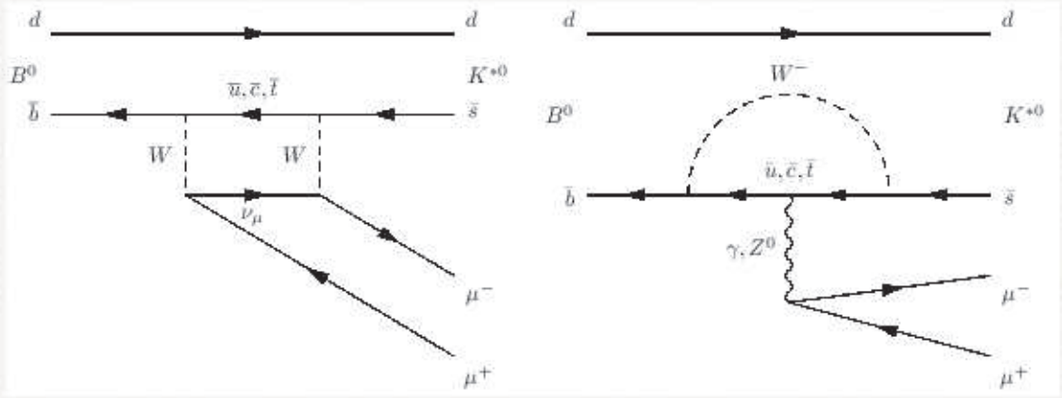
- MFV assumes:
  1) no CPV beyond the CKM phase
  2) flavour independence of Wilson coefficients



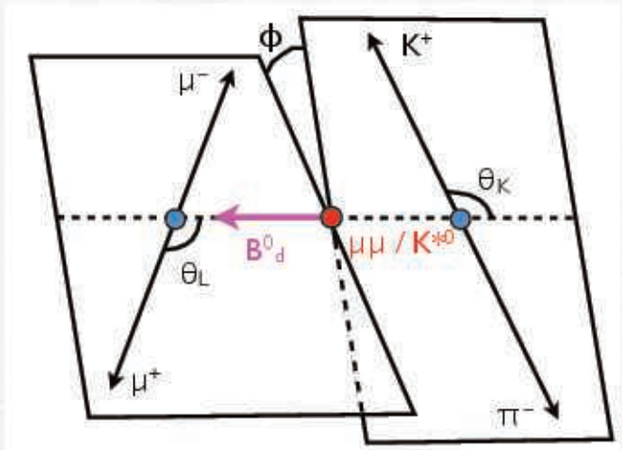
Ready to analyze Run II data!

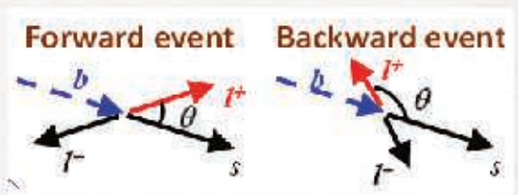
RARE DECAY
$B^0 \to K^*(892)^0 \mu^+ \mu^-$

- Not allowed @LO (BR~10^{-6}).
- Complementary to $B^0_s \to \mu+\mu^-$ (V/A vs. S/P-S interactions).
- Deviations of **BR**, F_L (frac. of K^{*0} long. pol), and A_{FB} (μ's F-B asym.) from SM in q^2-dep. ($q^2 = m_{\mu\mu}^2$) can point to NP:
  - E.g. MSSM-MFV & GMSSM affect $C_7^{(\prime)}$ & C_{10} Wilson coeffs. in OPE.



$$\frac{d\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{dq^2} = \frac{Y_S}{Y_N}\frac{\epsilon_N}{\epsilon_S}\frac{d\mathcal{B}(B^0 \to K^{*0} J/\psi)}{dq^2}$$

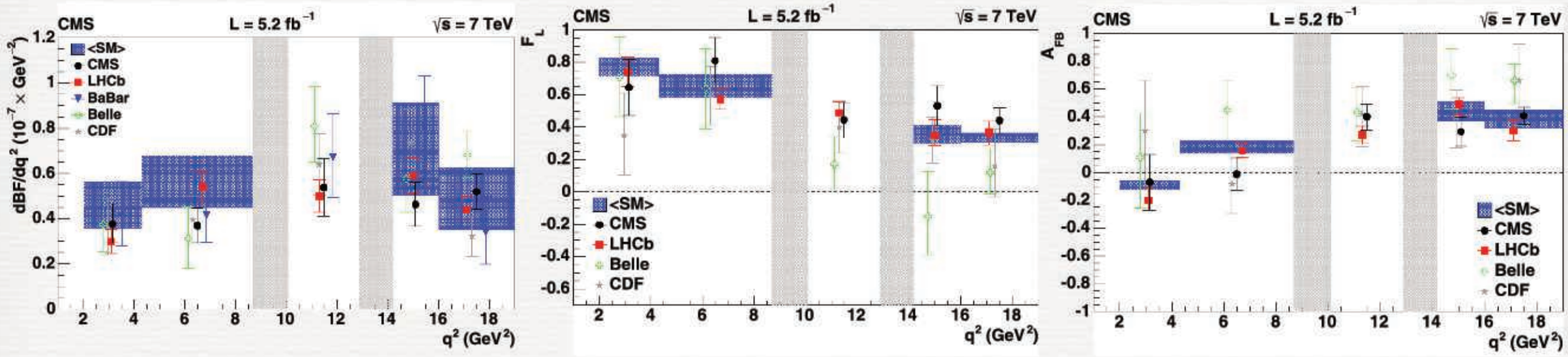




$$\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\vartheta_k\, d\cos\vartheta_l\, dq^2} = \frac{9}{16}\Big\{\Big[\frac{2}{3}F_S + \frac{4}{3}A_S\cos\vartheta_K\Big](1-\cos^2\vartheta_l) + (1-F_S)\Big[2F_L\cos^2\vartheta_K(1-\cos^2\vartheta_l) + \frac{1}{2}(1-F_L)(1-\cos^2\vartheta_K)(1+\cos^2\vartheta_l) + \frac{4}{3}A_{FB}(1-\cos^2\vartheta_K)\cos\vartheta_l\Big]\Big\}$$

ϕ is integrated (flat acceptance)
F_S = Kπ S-wave fraction
A_S = S&P waves interference amplitude

RESULTS OF BR, A_{FB} & F_L FOR $B^0 \to K^{*0}\mu^+\mu^-$ DECAYS



PDF fit ($\sqrt{s} = 7$TeV) PLB 727 (2013) 77

- Events divided in q^2 bins, $B^0 \to K^{*0}(J/\psi\ , \psi')$ regions removed
- Unbinned max-likelihood fit to $K\pi\mu\mu$ mass, ϑ_μ , ϑ_K

- Agreement with SM and consistent with other experiments.

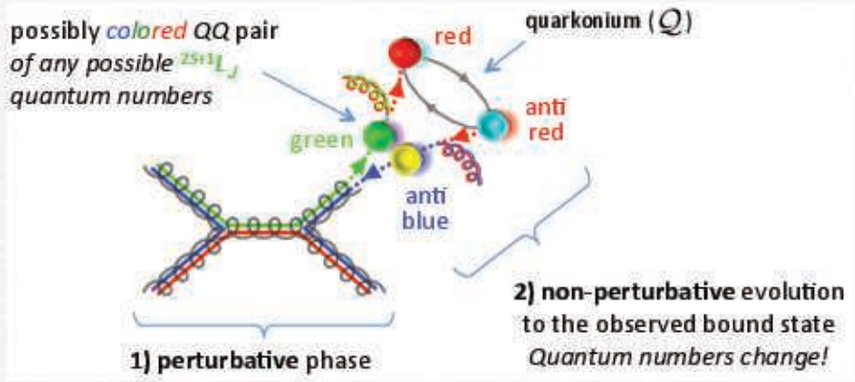
Update to test LHCb P_5' anomaly (BaBar did not confirm) with a full angular analysis and parameters with small form-factor dependence coming soon...

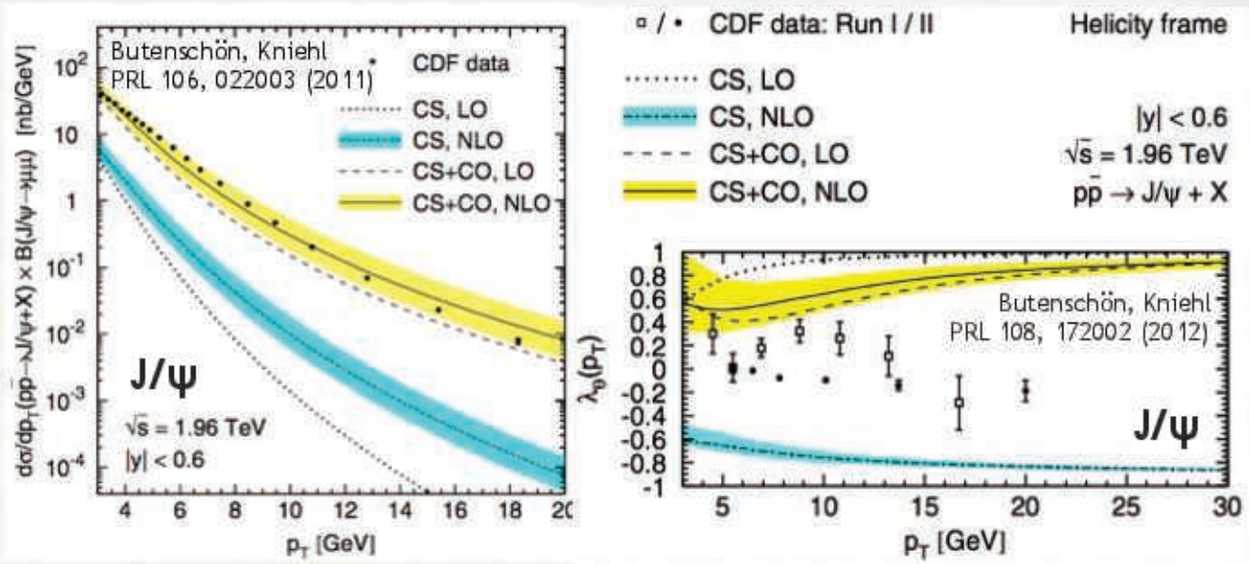
J/ψ, ψ(2S) & Υ(*n*S) POLARIZATIONS

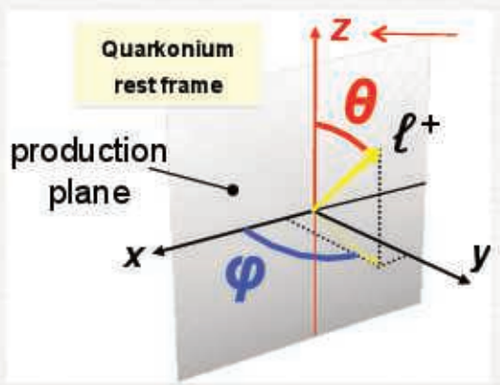
- Quarkonia ($c\bar{c}$ or $b\bar{b}$) ~ non-relativistic systems ⇒ σ's reproduced by NRQCD.
- Large transverse Pol. expected (λ_θ ~1 @ high pT). Not seen by CDF in J/ψ.
- Υ(*n*S) is a better lab for NRQCD than J/ψ or ψ′.
- Angular analysis of $Q \to \mu^+\mu^-$:

$$W(\cos\vartheta, \varphi|\vec{\lambda}) \propto \frac{1}{(3+\lambda_\vartheta)}(1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi)$$

λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$ are the polarization parameters





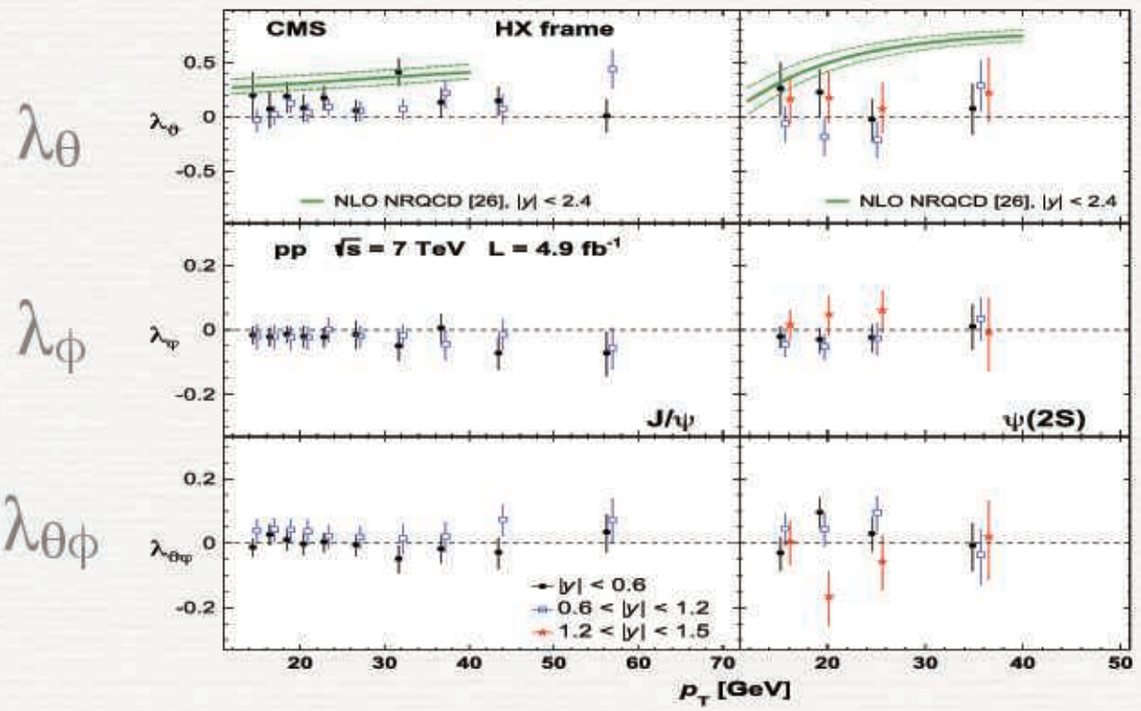


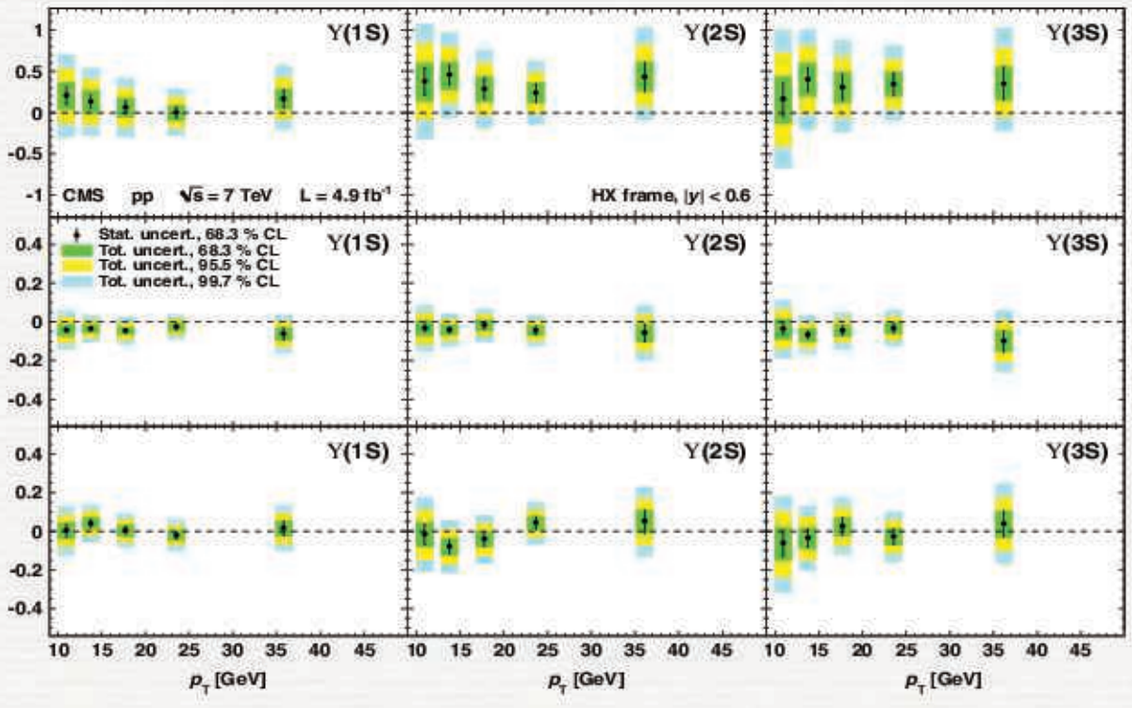
z-direction (frame)

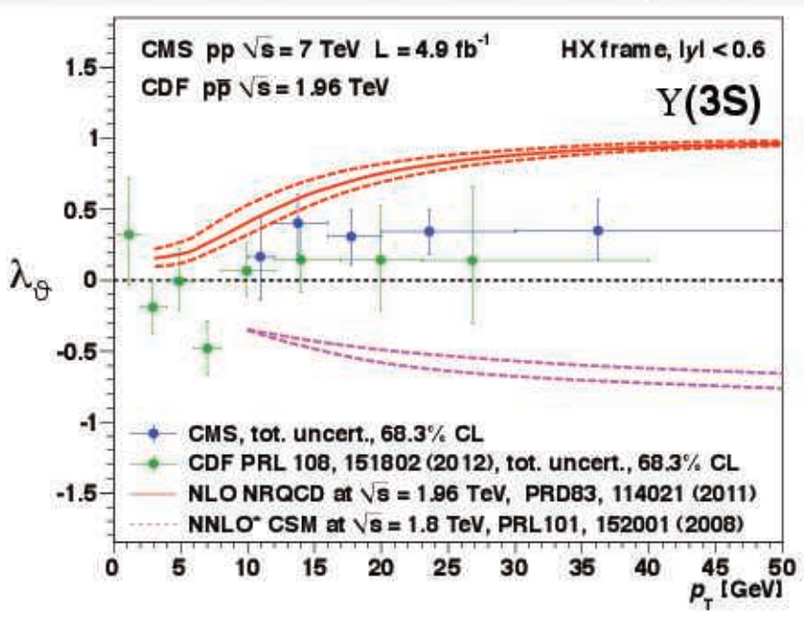
- HX (Helicity): $\mathbf{p}_Q$
- CS (Collins-Soper): $\langle \mathbf{p}_{p1}, \mathbf{p}_{p2} \rangle$
- PX: ⊥CS

RESULTS: J/ψ, ψ(2S) & Υ(*n*S) POLARIZATIONS

J/ψ ψ(2S) Υ(1S) Υ(2S) Υ(3S)





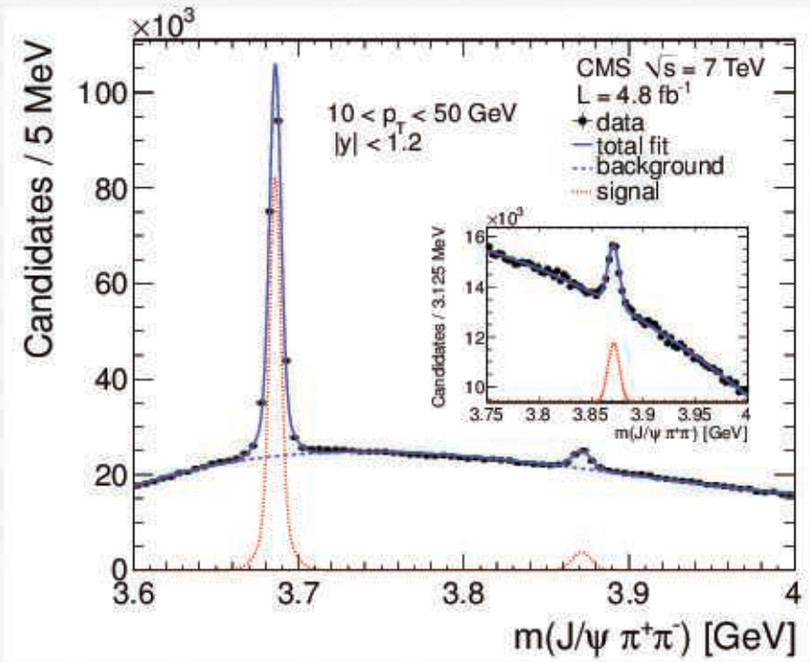


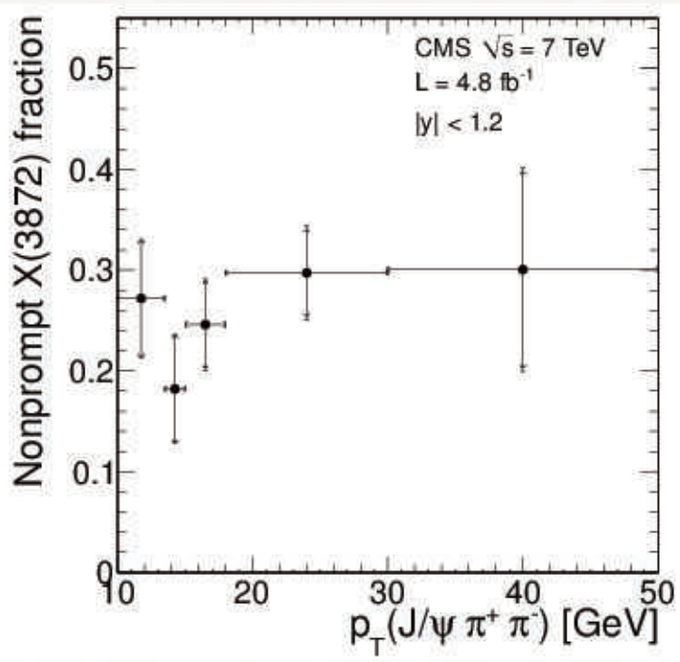
Results ($\sqrt{s} = 7$ TeV) PRL 110 (2013) 081802 & PLB 727 (2013) 381

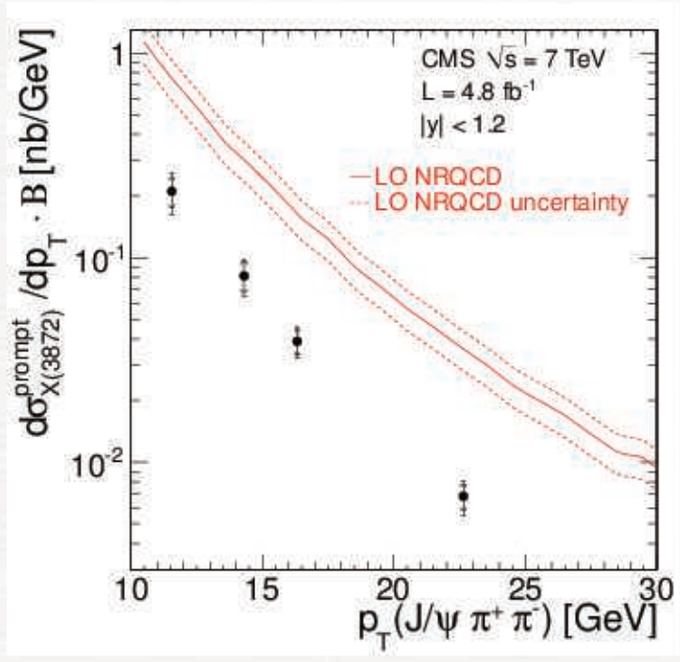
- All polarizations are consistent with zero.
- Excludes large polarizations in the explored kinematical region.
- For λ_θ, in clear disagreement with NRQCD predictions, even for Υ(3S)!

X(3872) PROMPT PRODUCTION IN pp

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







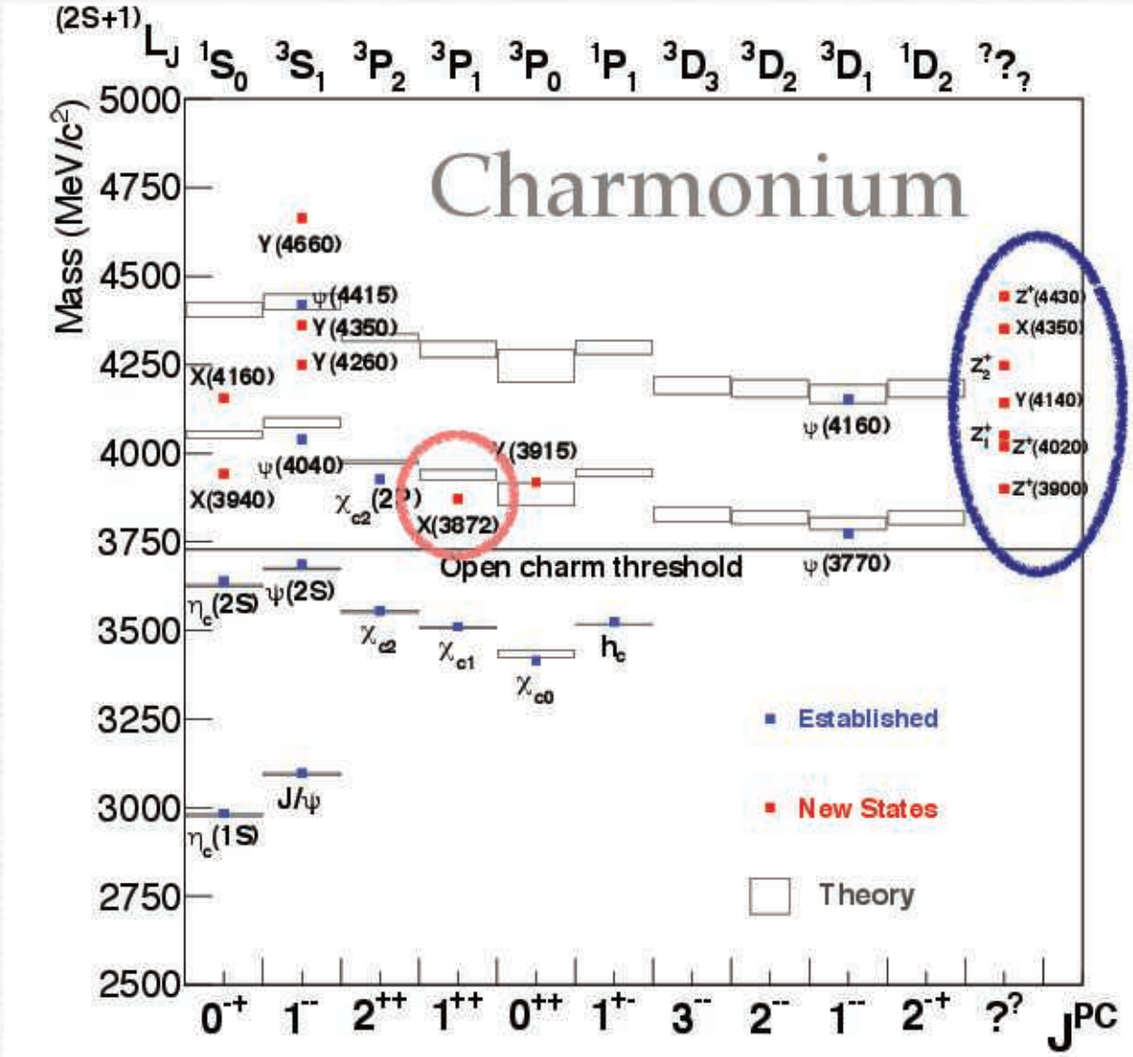
Results ($\sqrt{s} = 7$ TeV)

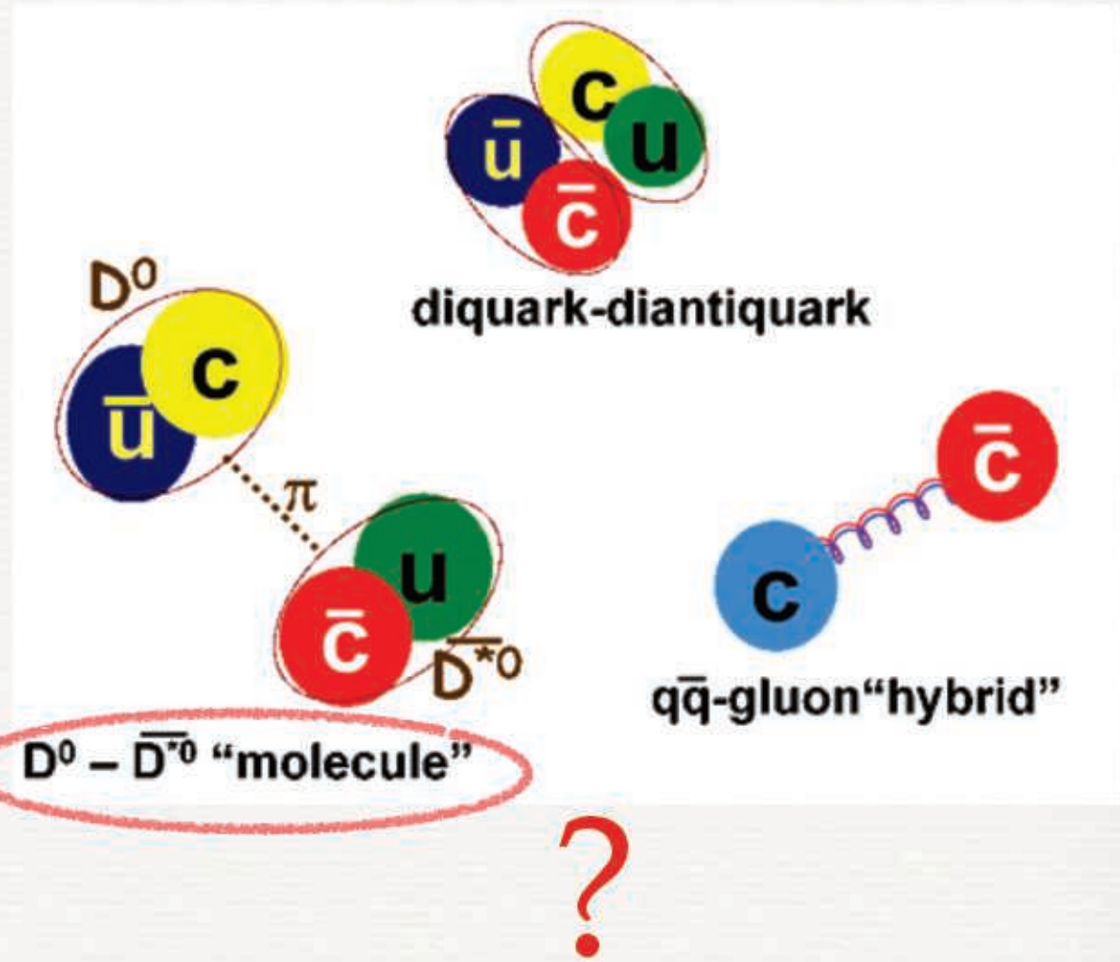
JHEP 04 (2013) 154

- Unpolarized $J^{PC} = 1^{++}$ state assumed.
- **Fraction of X(3872) coming from b hadrons (NP) is $0.263 \pm 0.023 \pm 0.016$.**
- No p_T dependence of NP (or P) fraction.
- **NRQCD predictions (assuming $c\bar{c}$) for P fraction is evidently off.**
- $R = 0.0656 \pm 0.0029 \pm 0.0065$, where $R = \dfrac{\sigma(pp \to X(3872) + \text{anything}) \cdot \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + \text{anything}) \cdot \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}$

$10 < p_T < 50\,\text{GeV}$ and $|y| < 1.2$

WHAT IS THE X(3872) PARTICLE?

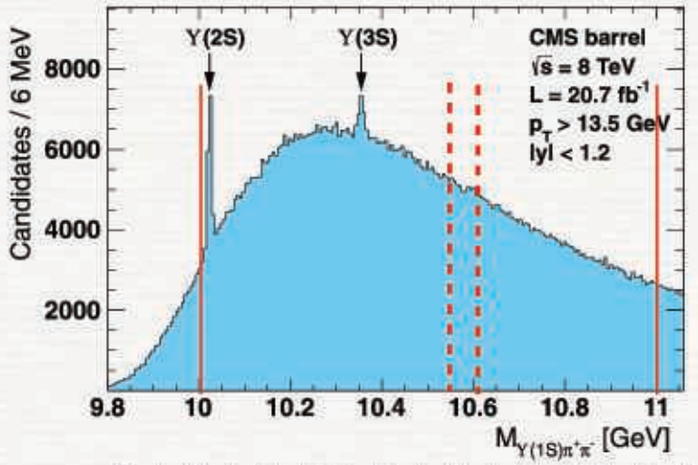


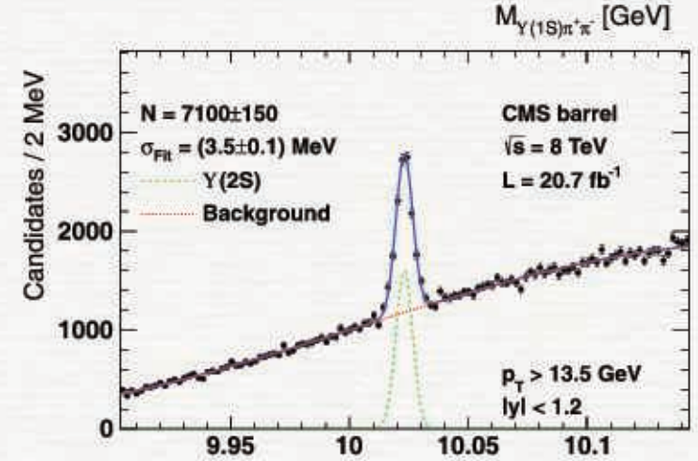


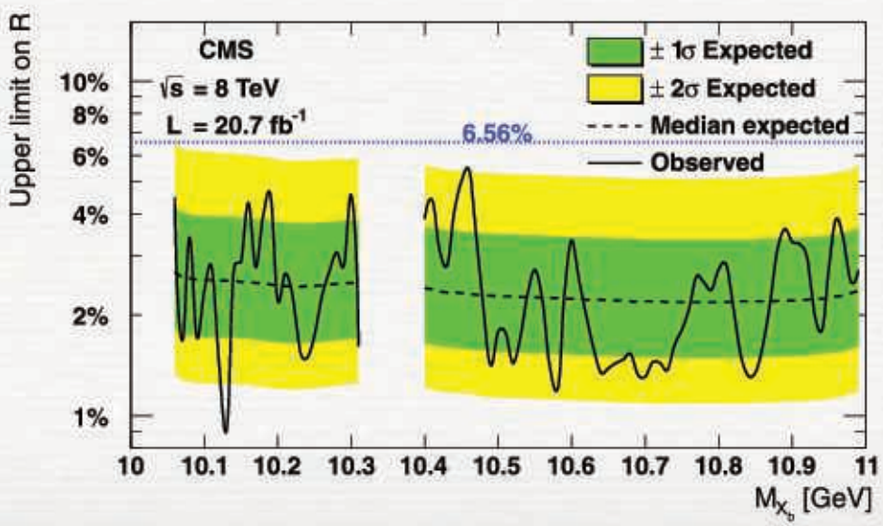
Is there bottonium counterpart of the X(3872) ... let's name it X_b?

SEARCH FOR THE EXOTIC BOTTONIUM X_b

- Assume X_b exists:
  - $X_b \to \Upsilon(1S)\pi^+\pi^-$.
  - $R = R_{X_b/\Upsilon(2S)} \approx 6.5\%$ $(= R_{X/\psi(2S)})$
    $\Rightarrow X_b$ expected $> 5\sigma$.
  - Narrow resonance $\Gamma < 1.2$ MeV.
  - Close to the $B\overline{B}$ or $B\overline{B}^*$ thresholds (10.562-10.604 GeV).
- Υ trigger, optimize Υ(2S) signal.
- Fit every 10 MeV, width fixed to MC.







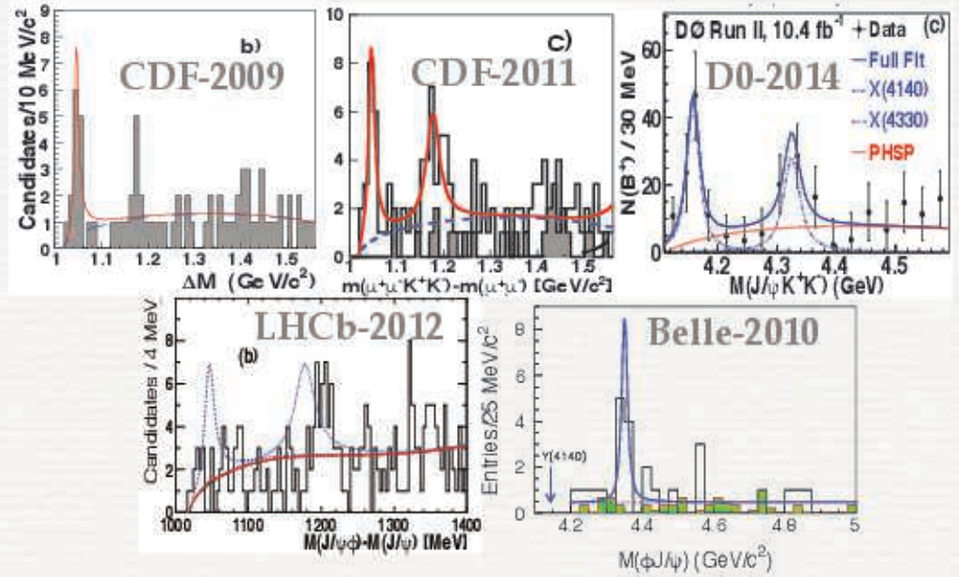
Results($\sqrt{s} = 8$TeV) PLB 727 (2013) 57

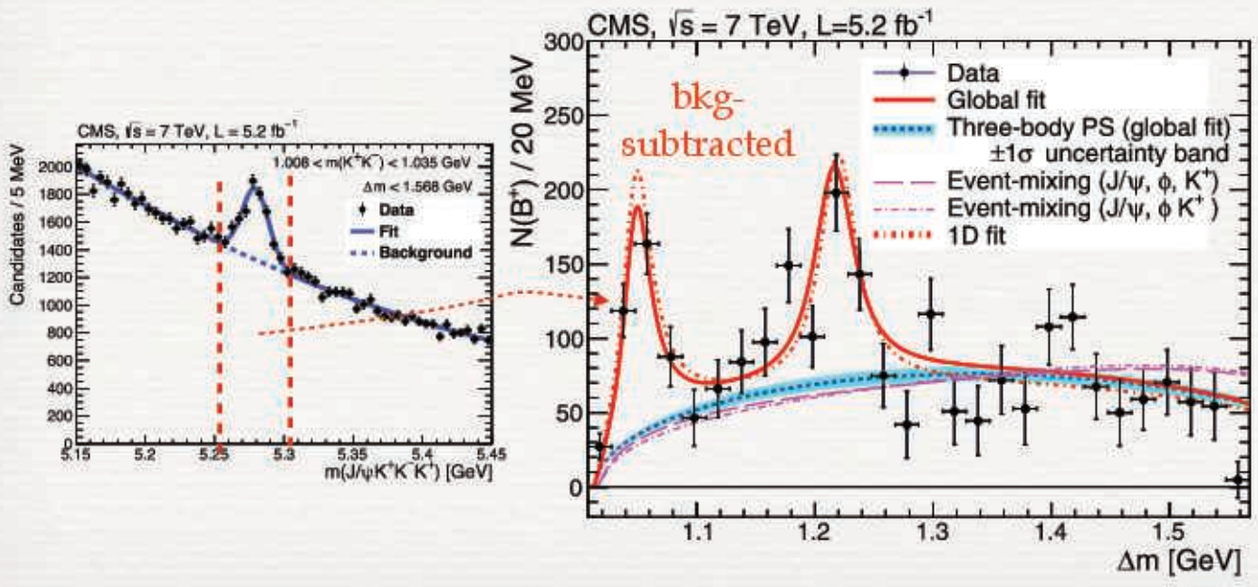
$$\frac{\sigma(pp \to X_b \to \Upsilon(1S)\pi^+\pi-)}{\sigma(pp \to \Upsilon(2S) \to \Upsilon(1S)\pi^+\pi-)} < (0.9 \div 5.4)\%@95\%C.L.$$

OBSERVATION OF THE EXOTIC Y(4140)

- Evidence of a resonance near ψφ thesh. in $B^+ \to \psi\phi K^+$ (CDF/09, D0).
- CDF/11 found ~5σ. D0 ~3σ.
- Not confirmed by Belle & LHCb.
- CMS extracts $B^+ \to \psi(\mu^+\mu^-)\phi(K^+K^-)K^+$ signal in intervals of:

$$\Delta m \equiv m(\mu^+\mu^-\mathrm{K}^+\mathrm{K}^-) - m(\mu^+\mu^-)$$





Results ($\sqrt{s} = 7$ TeV) PLB 734 (2014) 261-281

- $m_1 = m_{Y(4140)} = 4148.0 \pm 2.4 \pm 6.3$ MeV, $\Gamma_1 = 28\ ^{+15}_{-11} \pm 19$ MeV, signif. $> 5\sigma$.
- $R_{YK/\psi\phi K} = (10 + 3)\%$, consistent with CDF (15%) and LHCb (<7%).
- $m_2 = 4313.8 \pm 5.3 \pm 7.3$ MeV, $\Gamma_2 = 38\ ^{+30}_{-15} \pm 16$ MeV, signif. not reported due to possible K_2 contam.

SKIPPED TODAY

Properties:

1. BR($B^0_s \to J/\psi f_0(980)$) (arXiv:1501.06089, 2015) (see Alberto's talk).  See Alberto's talk

Production:

2. Cross section ratio $\sigma(\chi_{b2}(1P))/\sigma(\chi_{b1}(1P))$ (arXiv:1409.5761, 2015).
3. $\Upsilon(nS)$ differential cross sections (arXiv:1501.07750v1, 2015).
4. $\Upsilon(nS)$ cross sections (PRD D 83, 112004 (2011) & PLB 727 (2013) 101–125).

Bottonium

5. Relative prompt production rate of χ_{c2} and χ_{c1} (Eur. Phys. J. C (2012) 72:2251).
6. Prompt J/ψ and $\psi(2S)$ double-differential cross sections (arXiv:1502.04155, 2015).
7. Prompt J/ψ pair production (JHEP09(2014)094).
8. Prompt and non-prompt J/ψ production (Eur. Phys. J. C (2011) 71: 1575).
9. J/ψ and $\psi(2S)$ production (JHEP02(2012)011).

Charmonium

10. Cross section for production of $b\bar{b}X$ decaying to muons (JHEP06(2012)110).
11. Inclusive b-hadron production cross section with muons (JHEP03(2011)090).
12. Inclusive b-jet production (JHEP04(2012)084).
13. $B\bar{B}$ angular correlations (JHEP03(2011)136).

b-quark/ hadron

SUMMARY

- Successful BHP (dimuon) CMS program.
- Three important observations/discoveries.
- CMS tops in some important analyses or is competitive with LHCb.
- Many results using Run I data are in the pipeline and several groups are ready to analyze Run II.
- The *Mexican group* is involved in several BHP analyses which should become ~ 3 papers (exotics/ quarkonium, B lifetimes, B-baryon polarization) by the end of 2015.

THANKS!!!