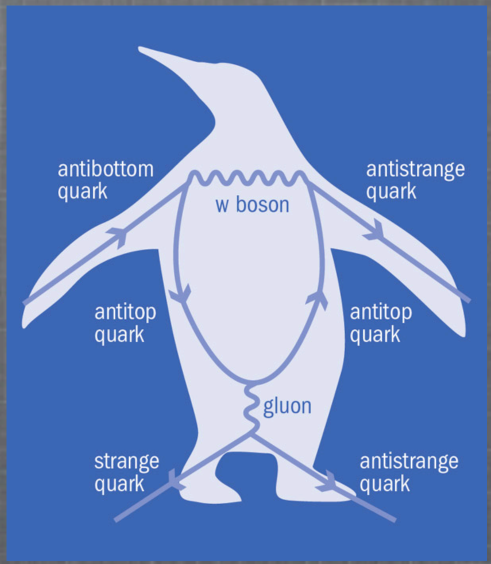
BOTTOM PHYSICS RESULTS FROM CMS



Ivan Heredia de la Cruz
Department of Physics, CINVESTAV & CONACYT

Nov. 5, 2015

MWPF2015, Mazatlan, Mexico

OUTLINE

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- The LHC

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- The CMS Experiment

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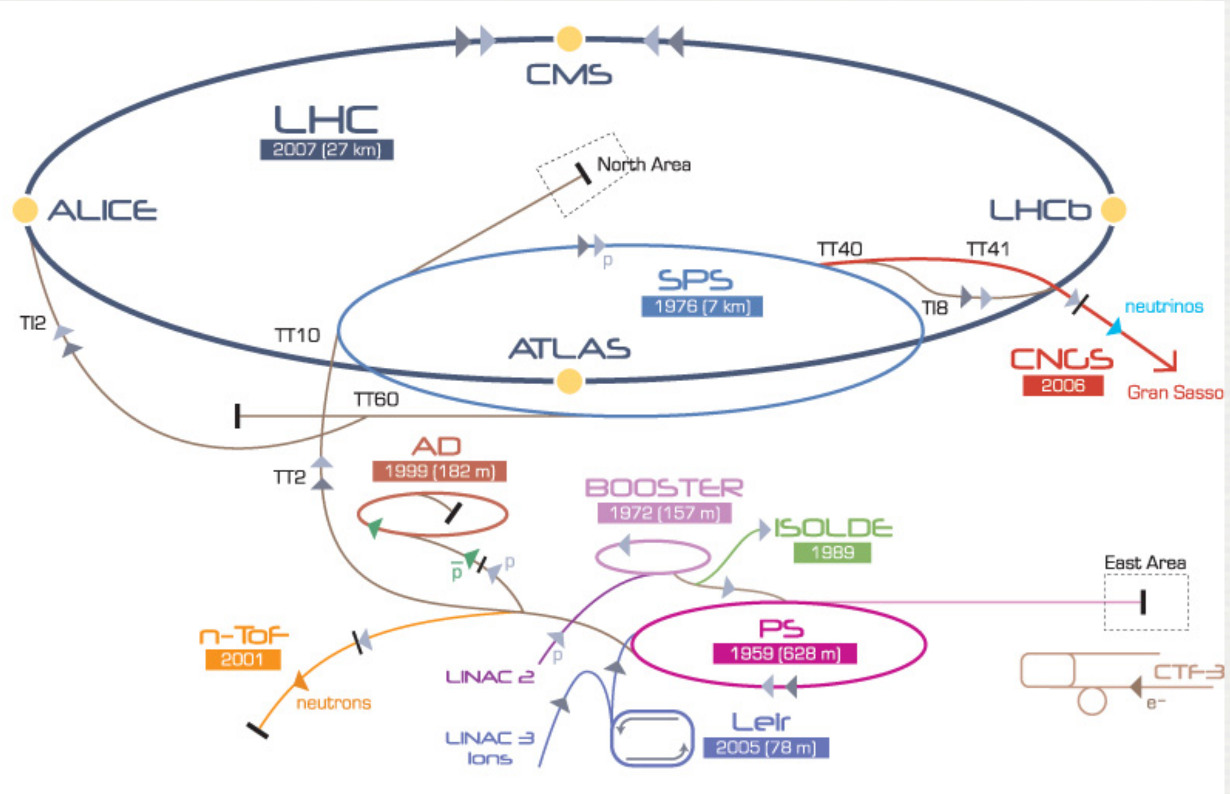
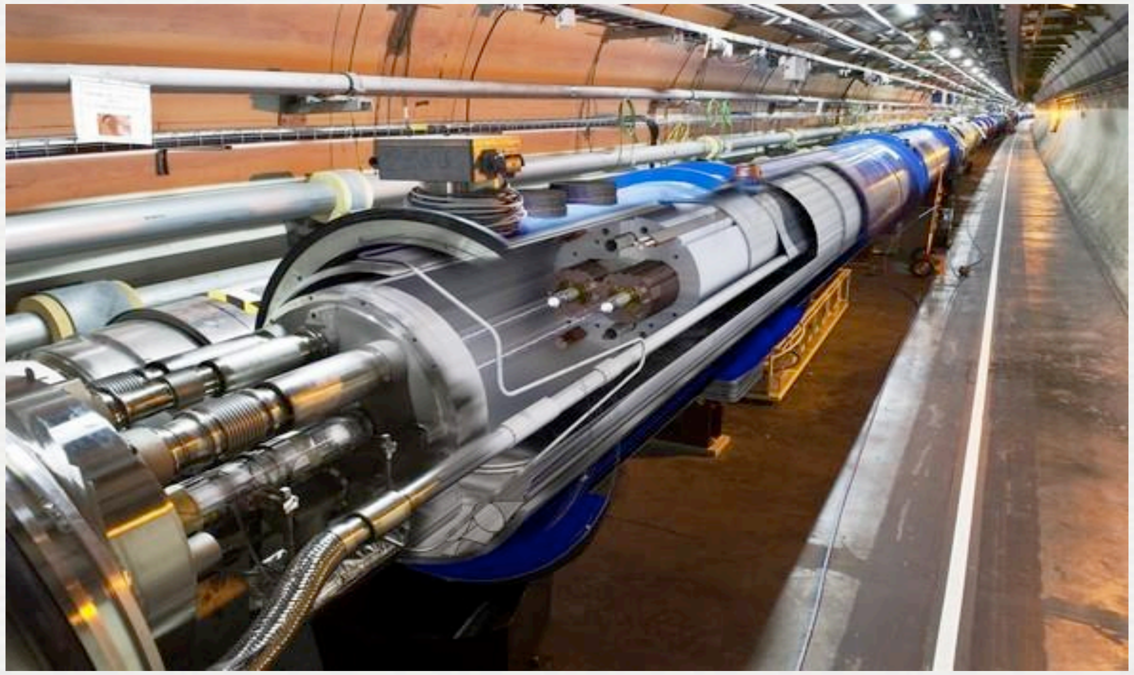
- Exotica: unexpected particles
- Summary


(Cessy, France)
CMS
LHCb
ALICE
ATLAS

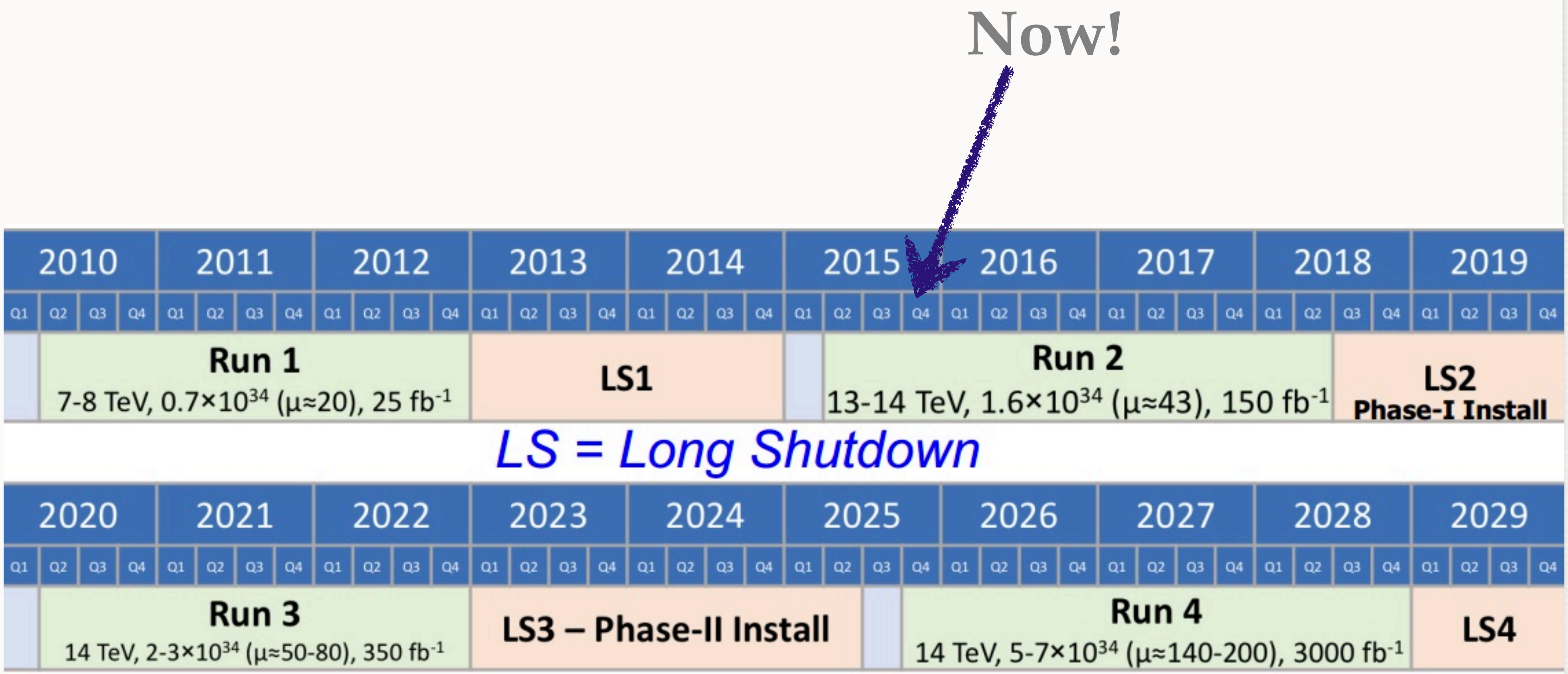
LHC

- 27 km tunnel, ~100 m underground.
- pp collisions @7-8 TeV in Run I (2011-2). Now **13 TeV** (just stopped).
- Bunches of ~10^{11} p crossing every 50 ns → **25 ns.**





LHC SCHEDULE



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

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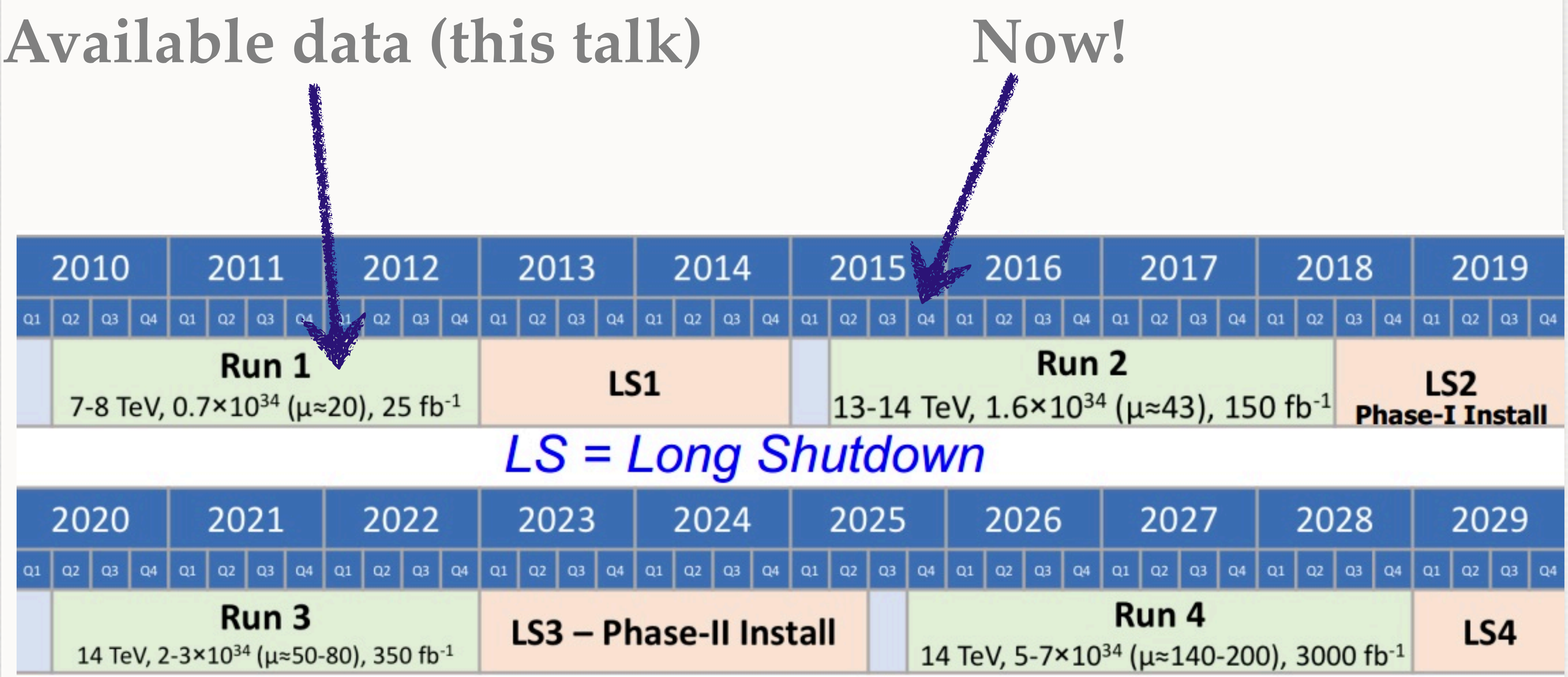


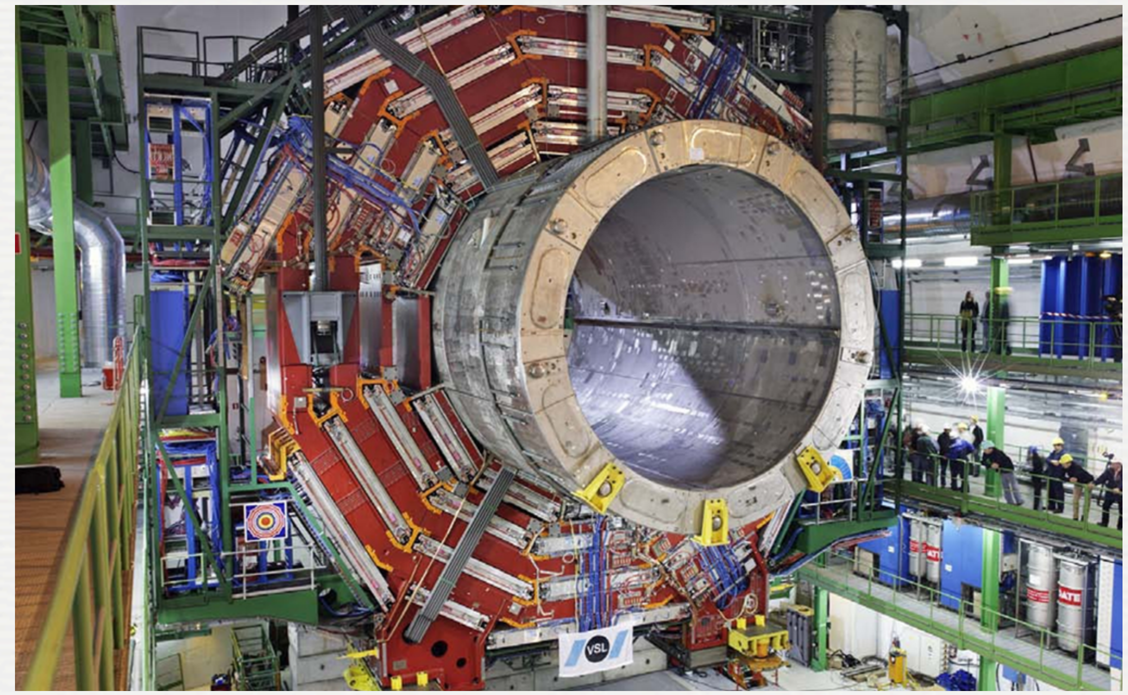
- *The HL-LHC running starts in 2025 and continues beyond LS4 until 2035*

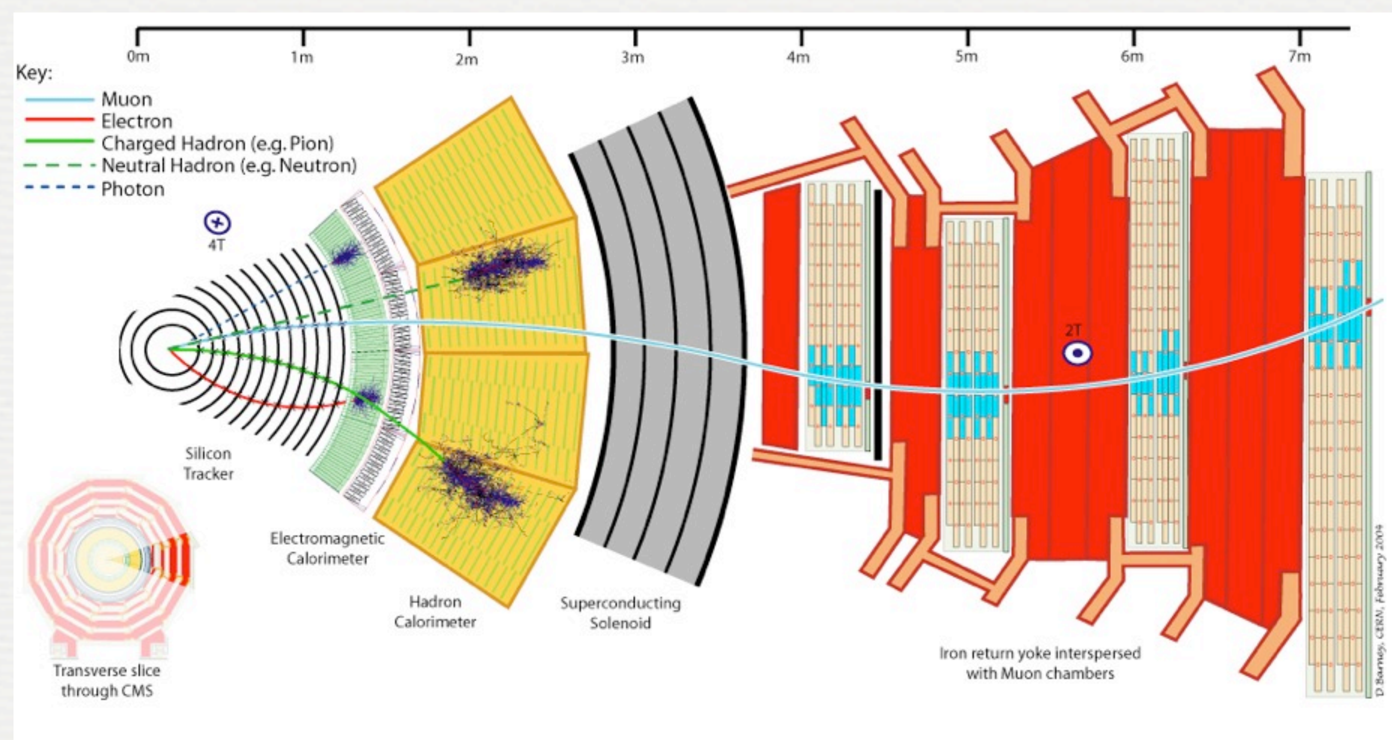
CMS

- Multipurpose detector:
  - Designed to search and study new particles with masses ~0.1 - 1 TeV.
  - New particles would decay to bottom quarks.

PV (xy) resolution ~ 20 μm

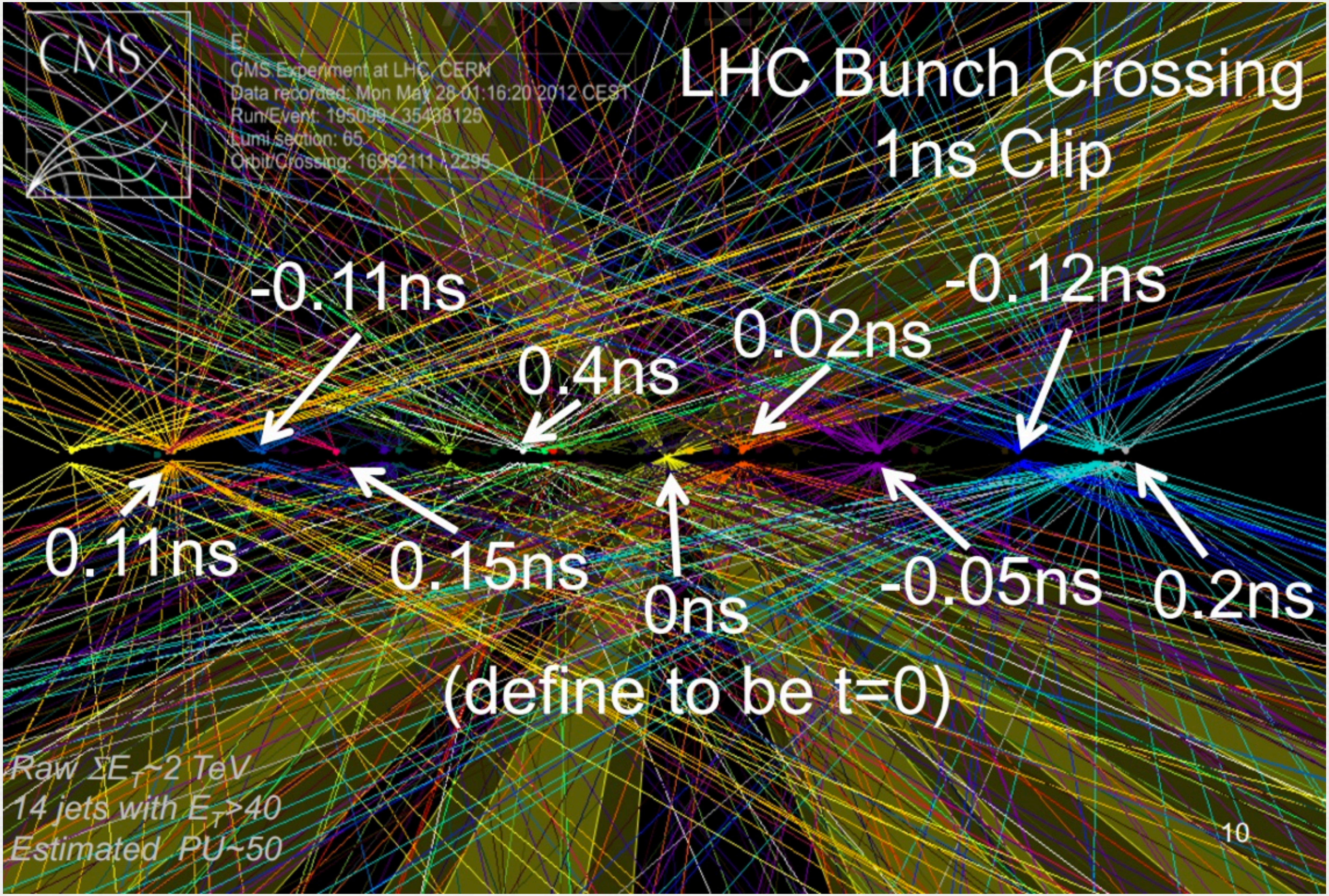
Track & μ p_T resolution ~ 1.5%



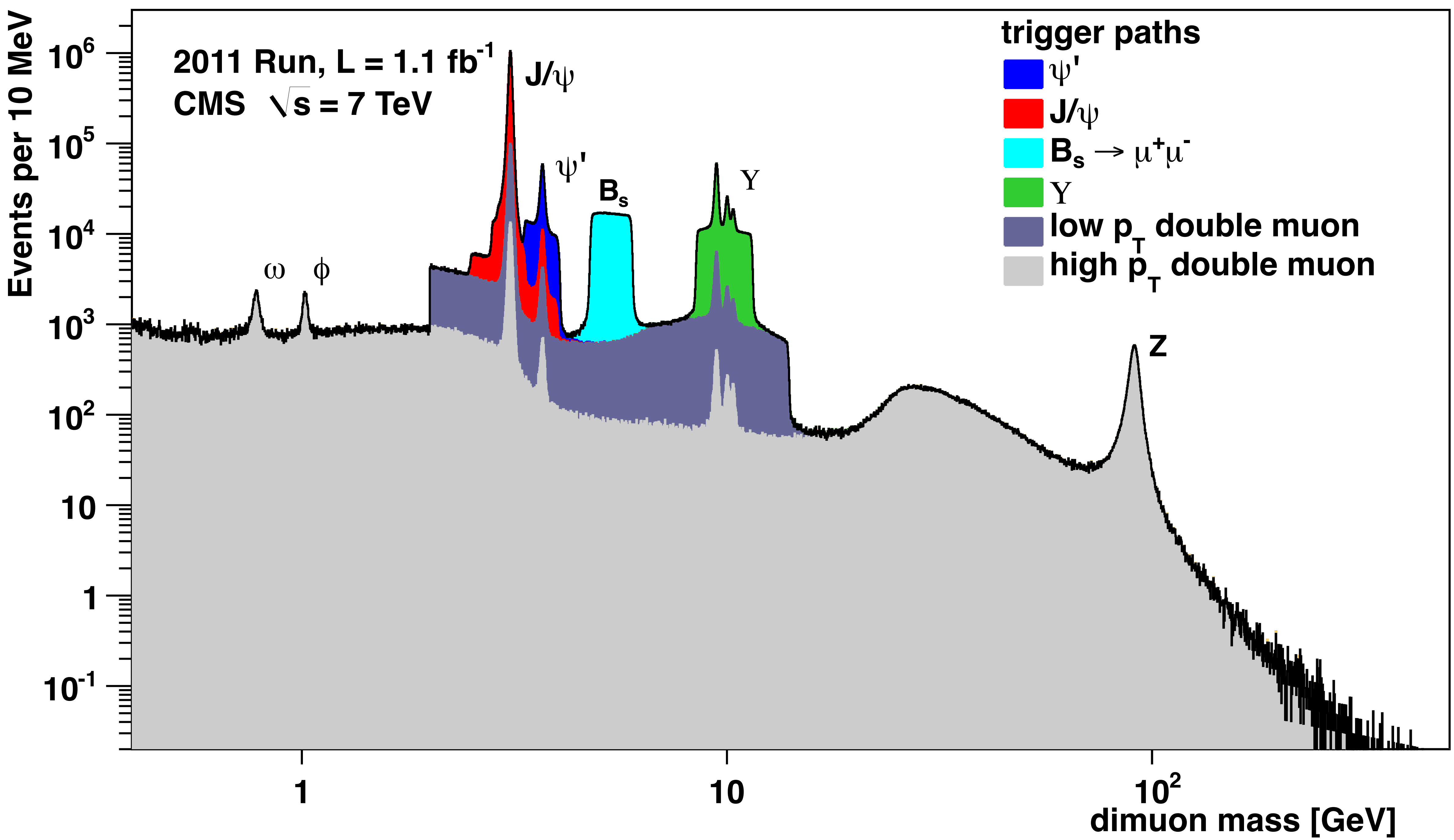


$<\mu>_{2011} = 8$

$<\mu>_{2012} = 21$ $<\mu>_{2015} \sim 40$

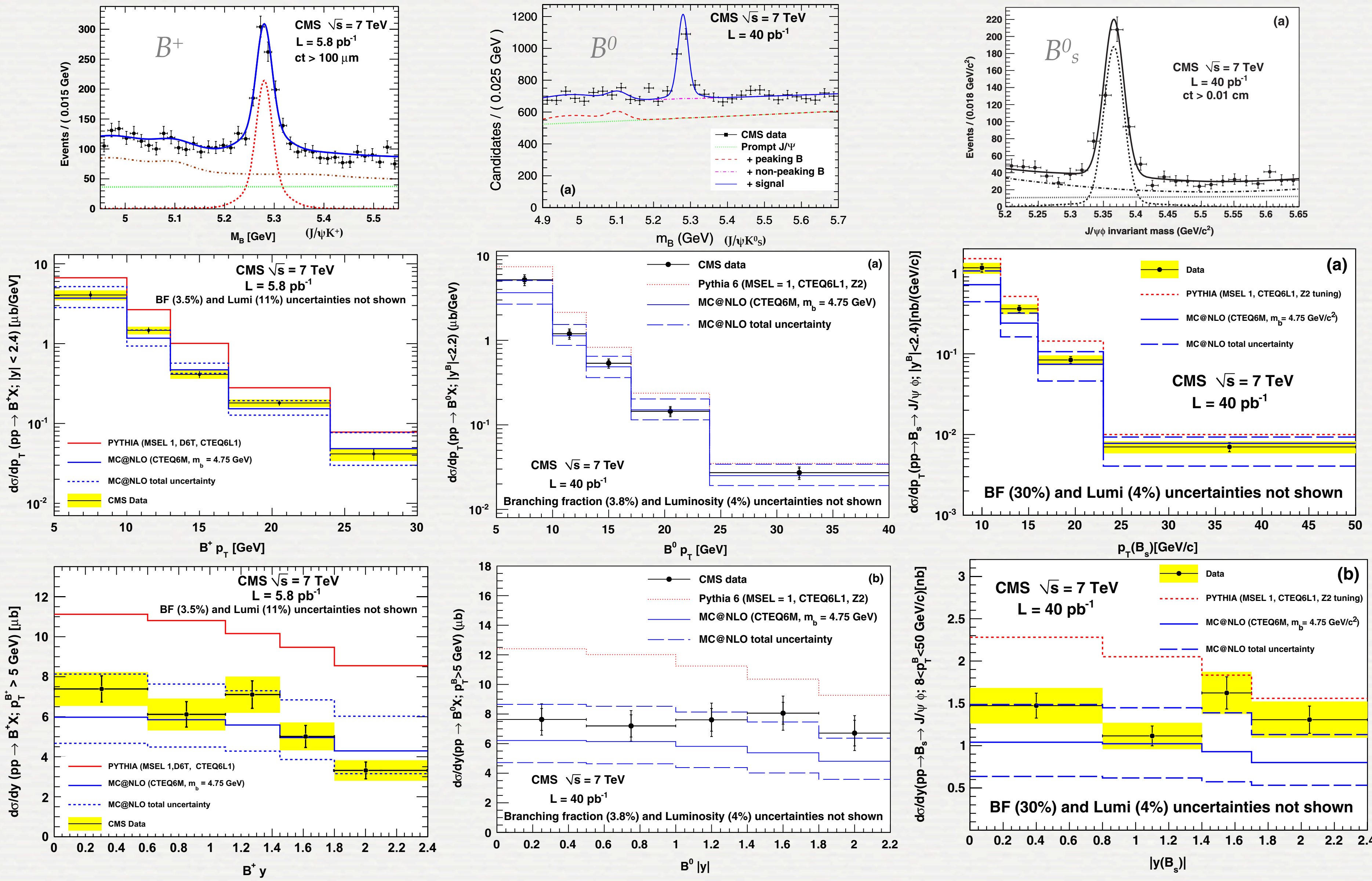


BPH PROGRAM (~10% BANDWIDTH)



Thursday, November 5, 15

B MESON PRODUCTION @ 7 TEV



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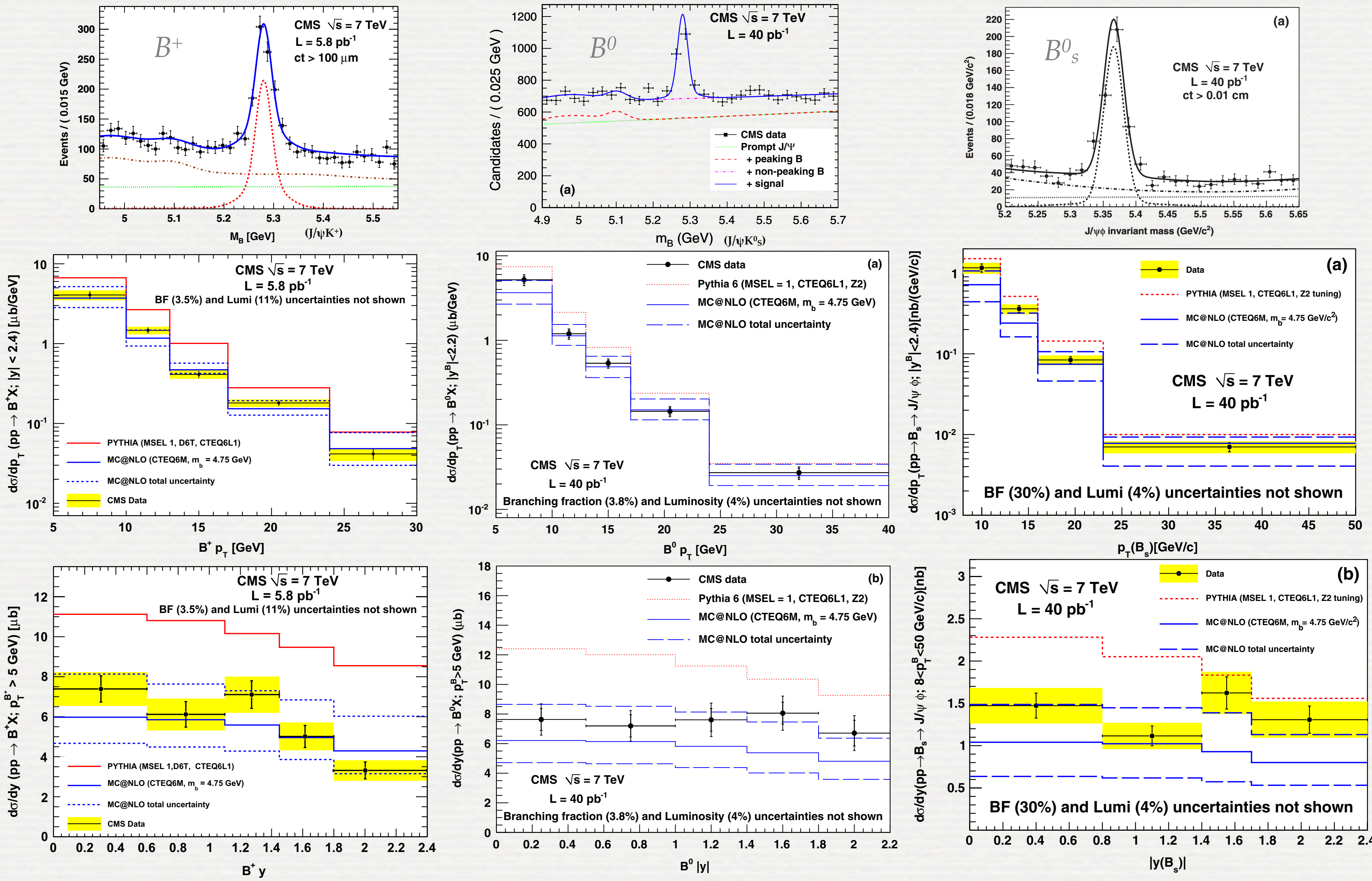

$B_s \to J/\psi\phi$ PRD 84 (2011) 052008

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

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

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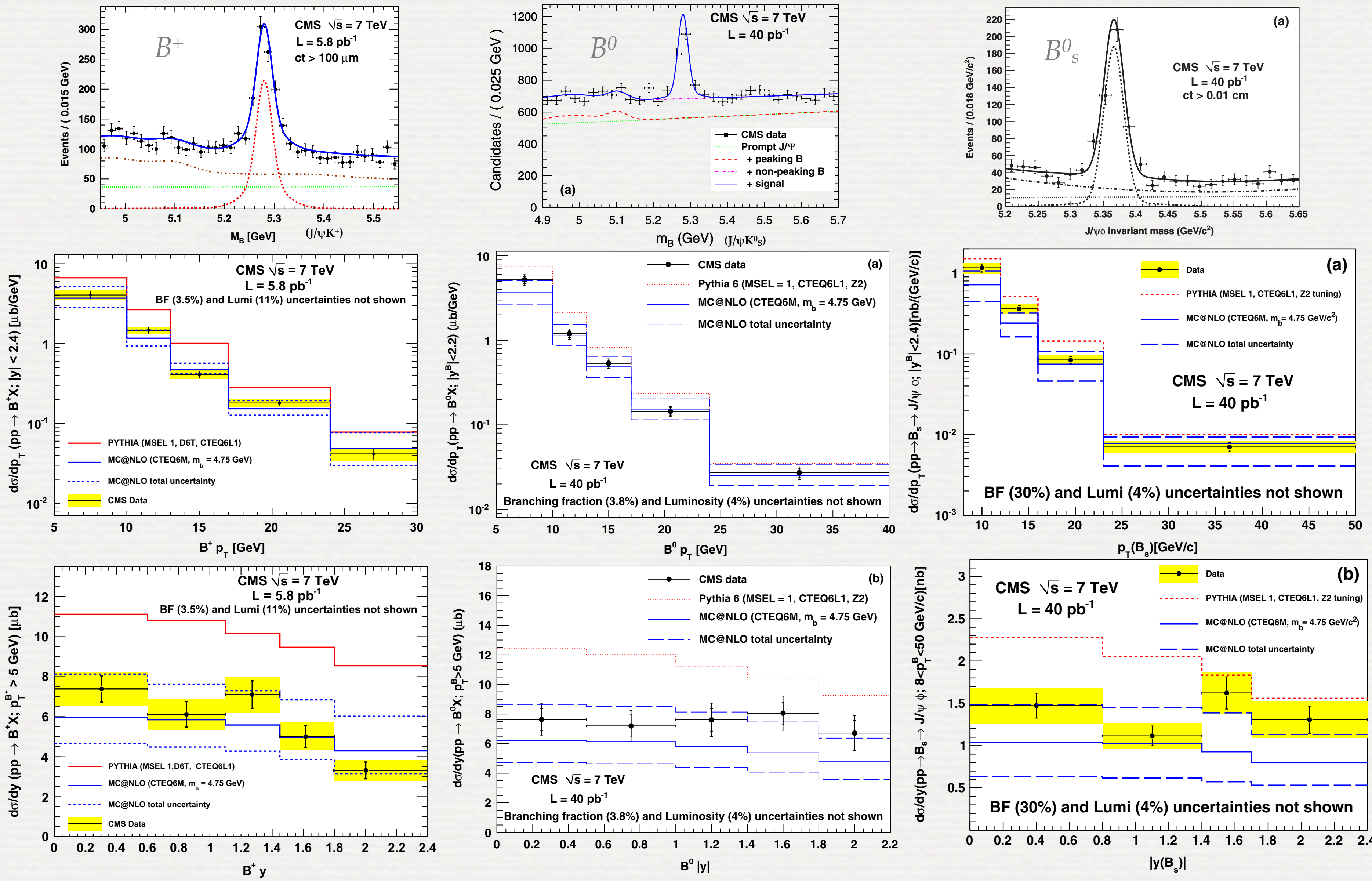

$B^0 \to J/\psi K^0_S$ PRL 106 (2011) 252001

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

$\sigma(pp \to B_0) = (33.2\pm2.5\pm3.5)\mu\text{b}$

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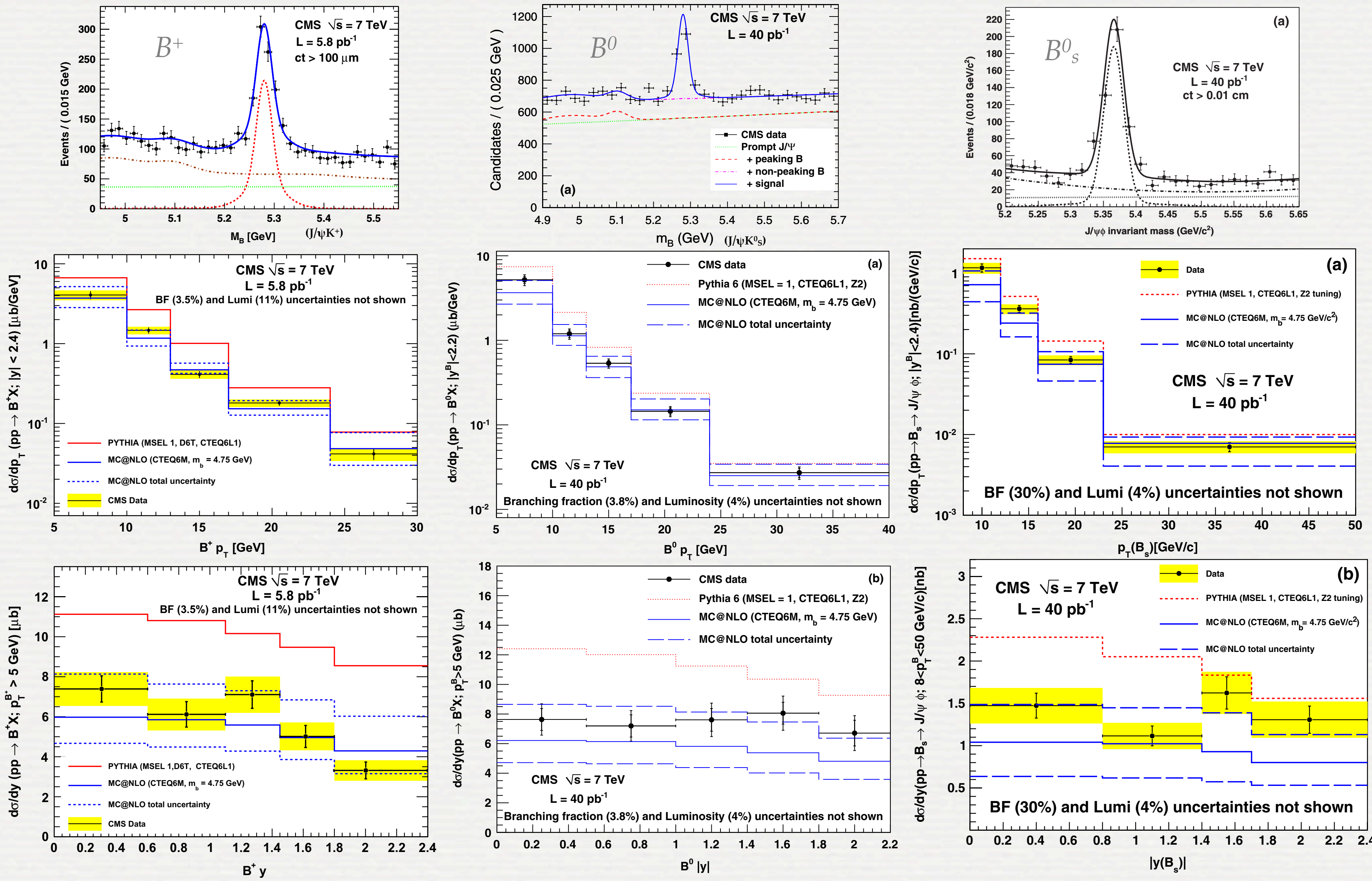

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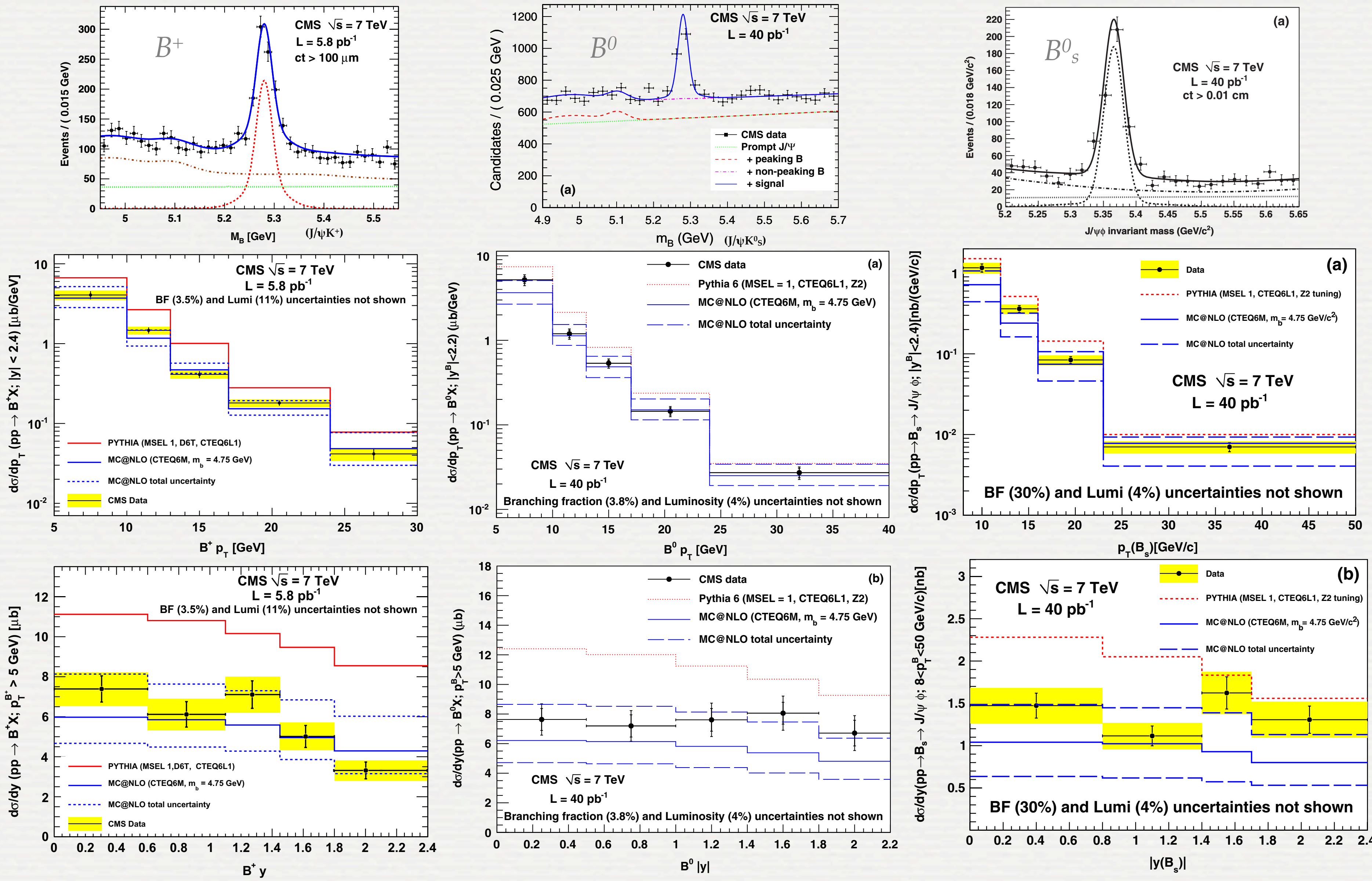

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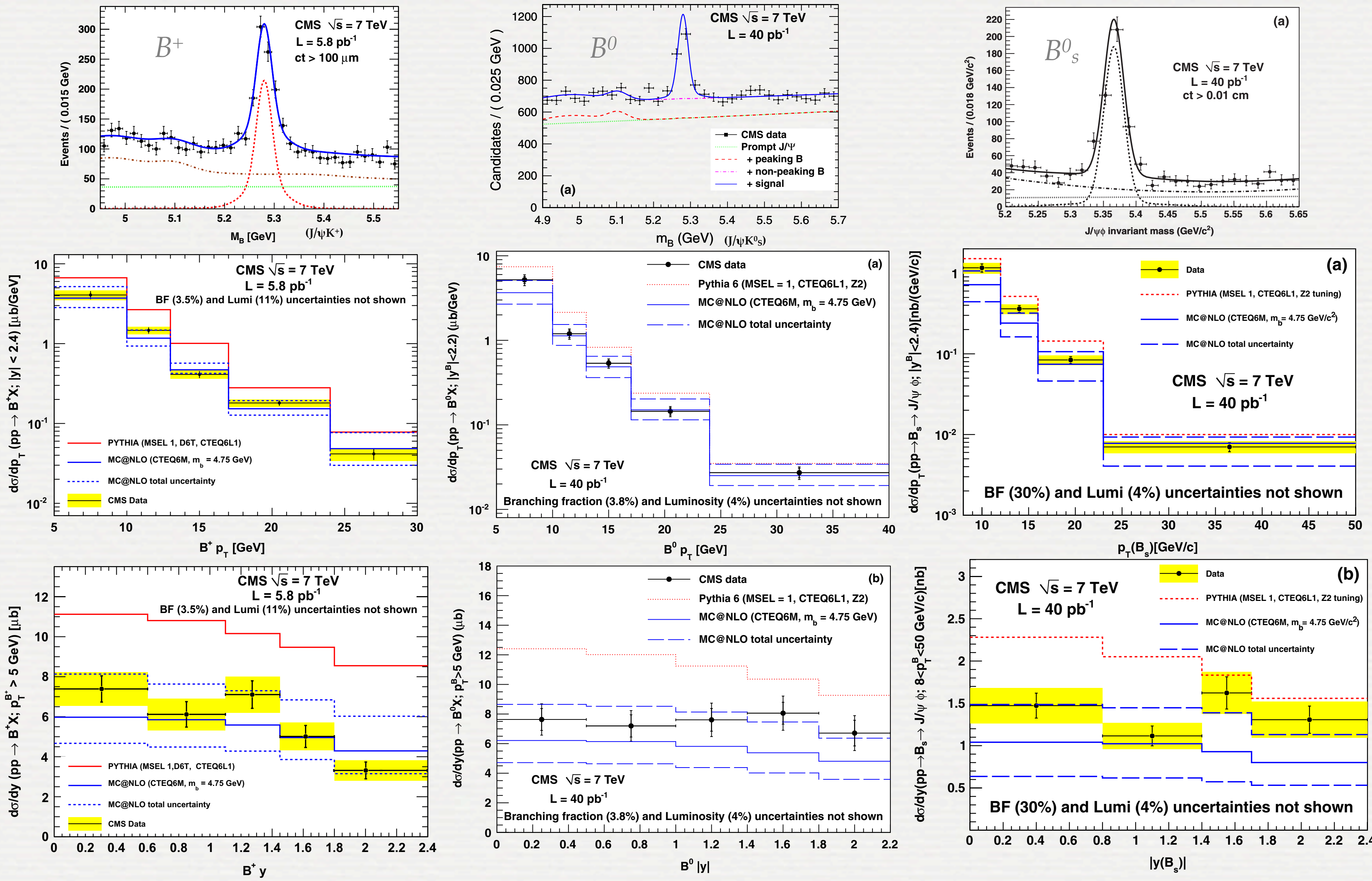

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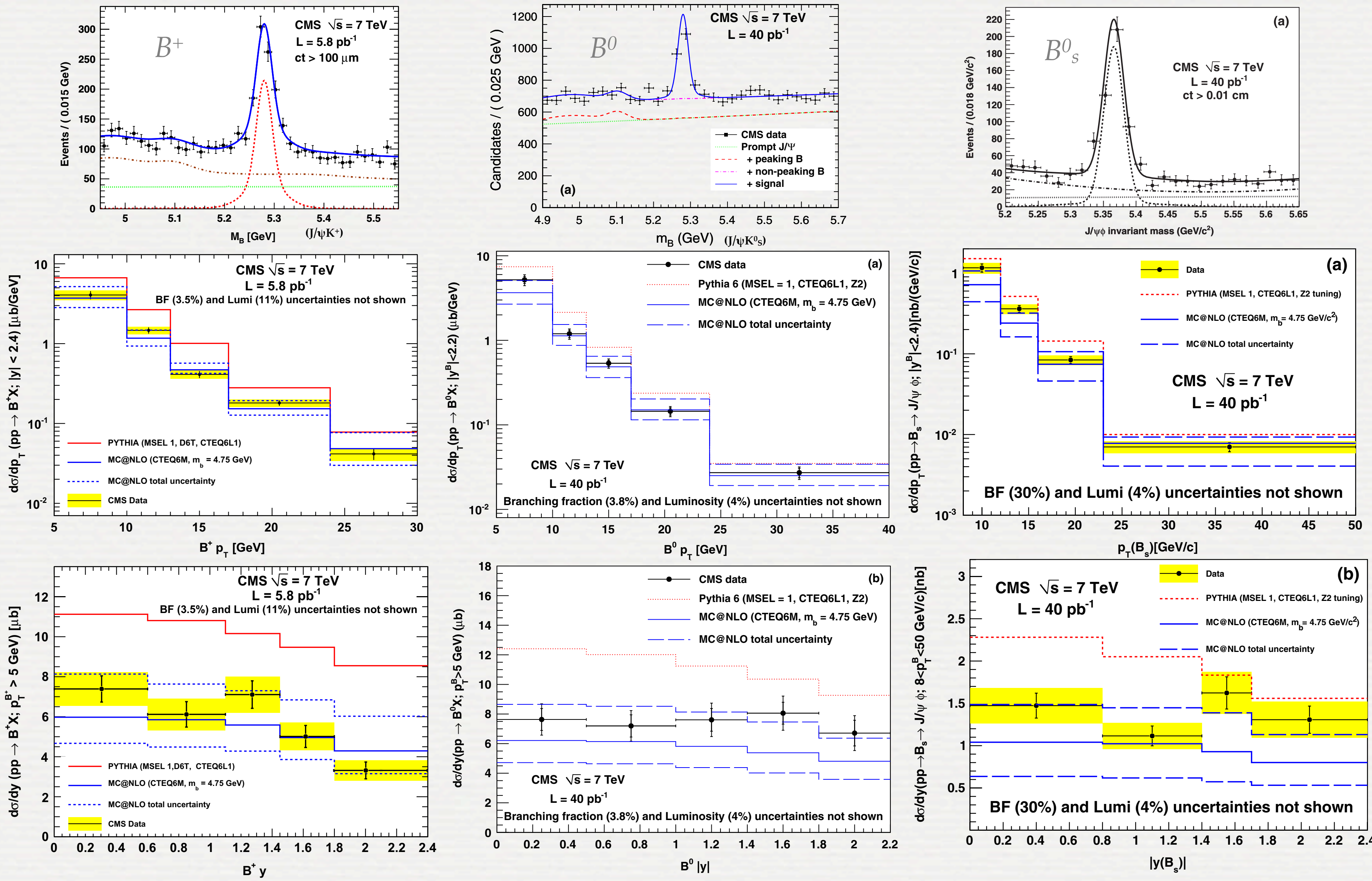

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Measurements @ 13 TeV coming soon...

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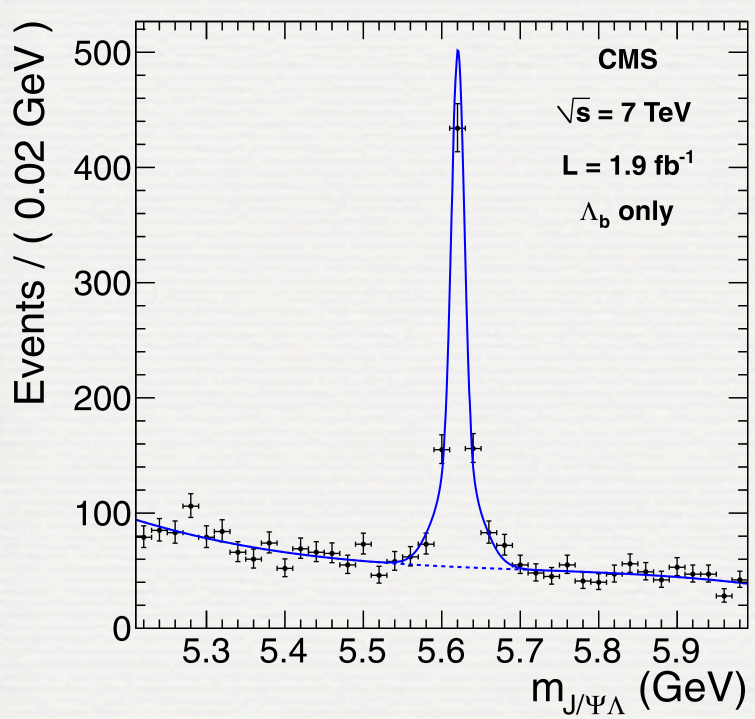

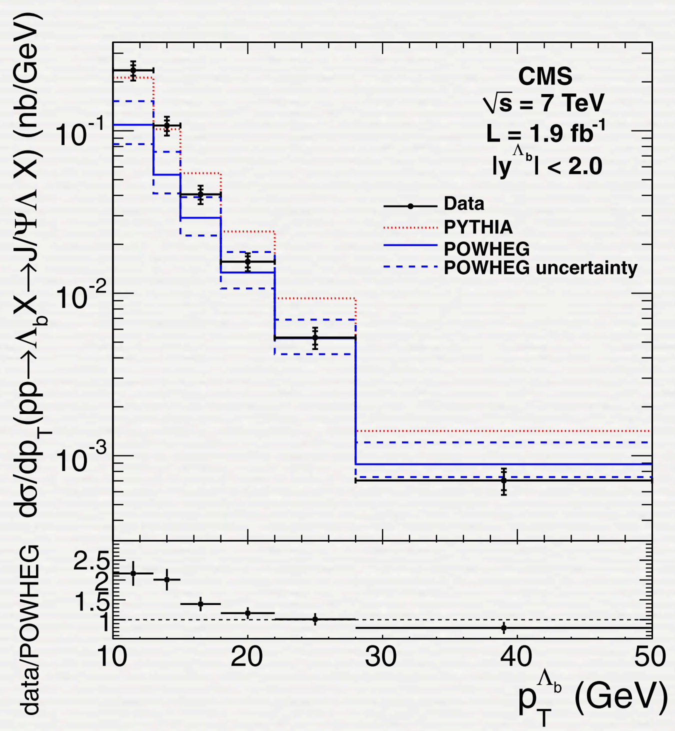

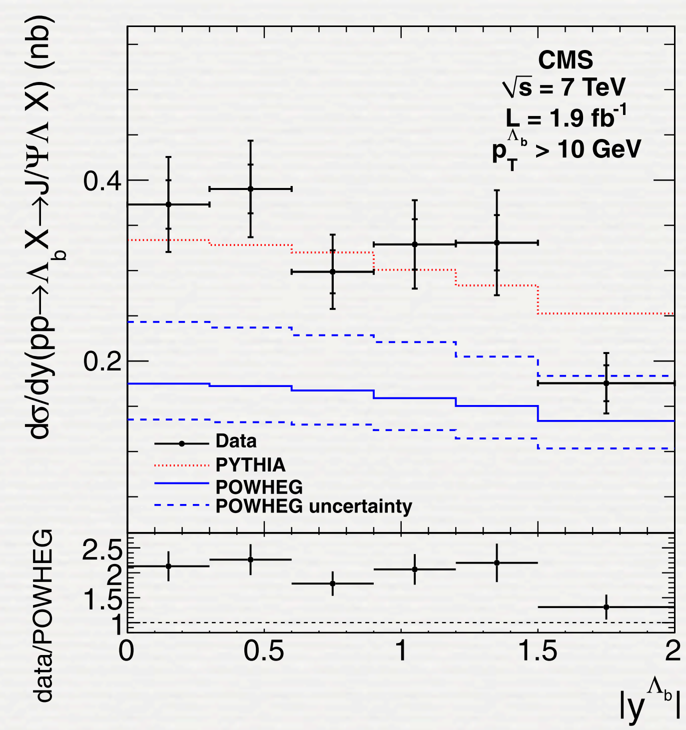

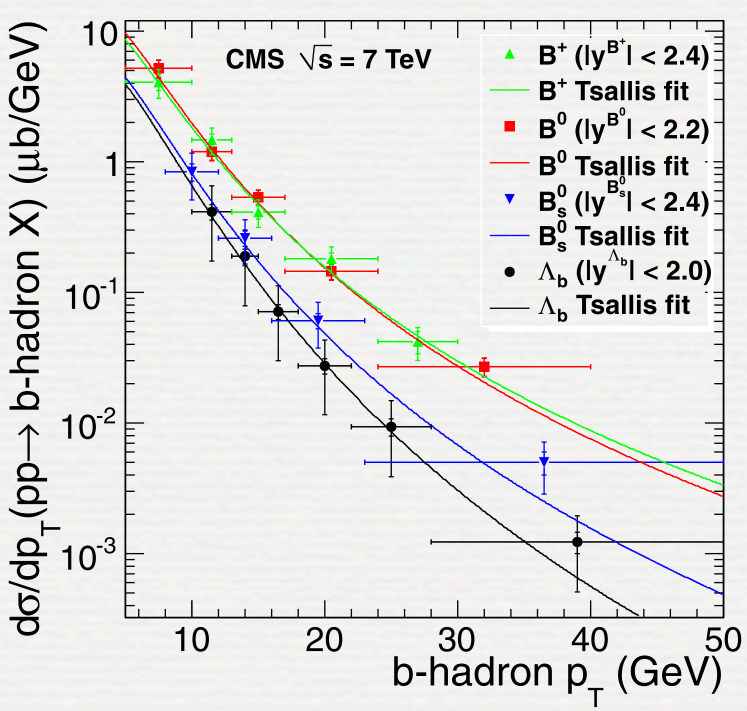

- Pythia & POWHEG predictions not great.
- Baryon p_T spectrum is softer.

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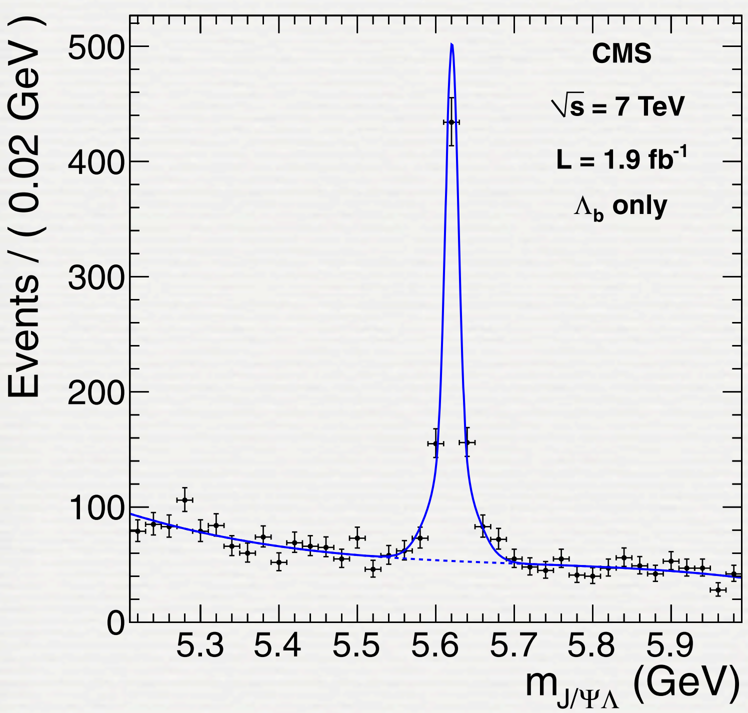

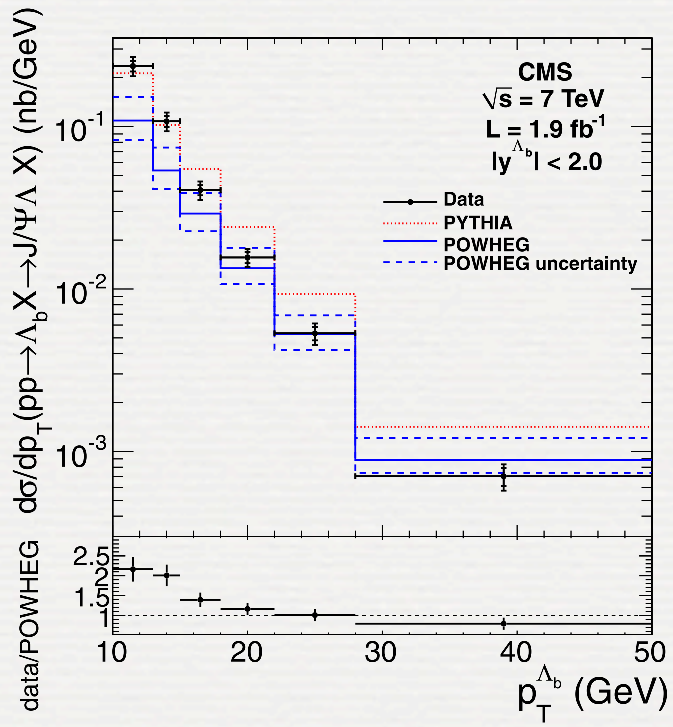

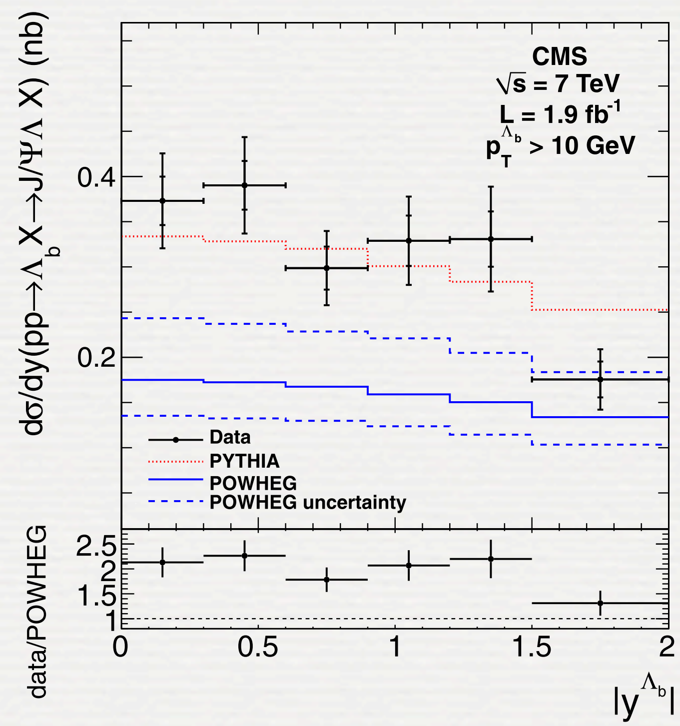

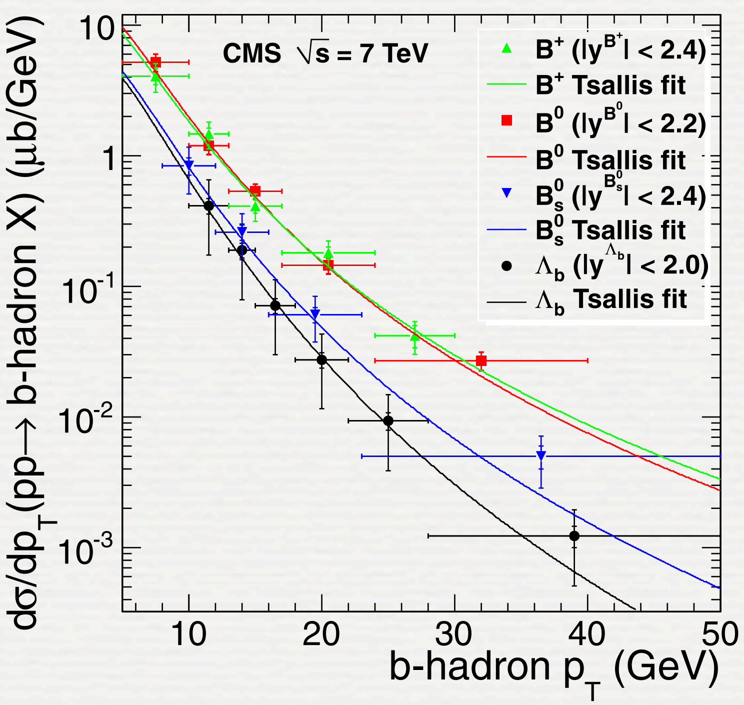

Results ($\sqrt{s} = 7$TeV , $\mathcal{L} = 1.9\text{fb}^{-1}$) PLB 714 (2012) 136

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

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

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Λ_b LIFETIME

- Early predictions too high: $\tau(\Lambda_b)/\tau(B^0) > 0.9$.
- Recent HQE @NLO & $\mathcal{O}(m_b^{-4})$: $\tau(\Lambda_b)/\tau(B^0) \approx 0.88$.
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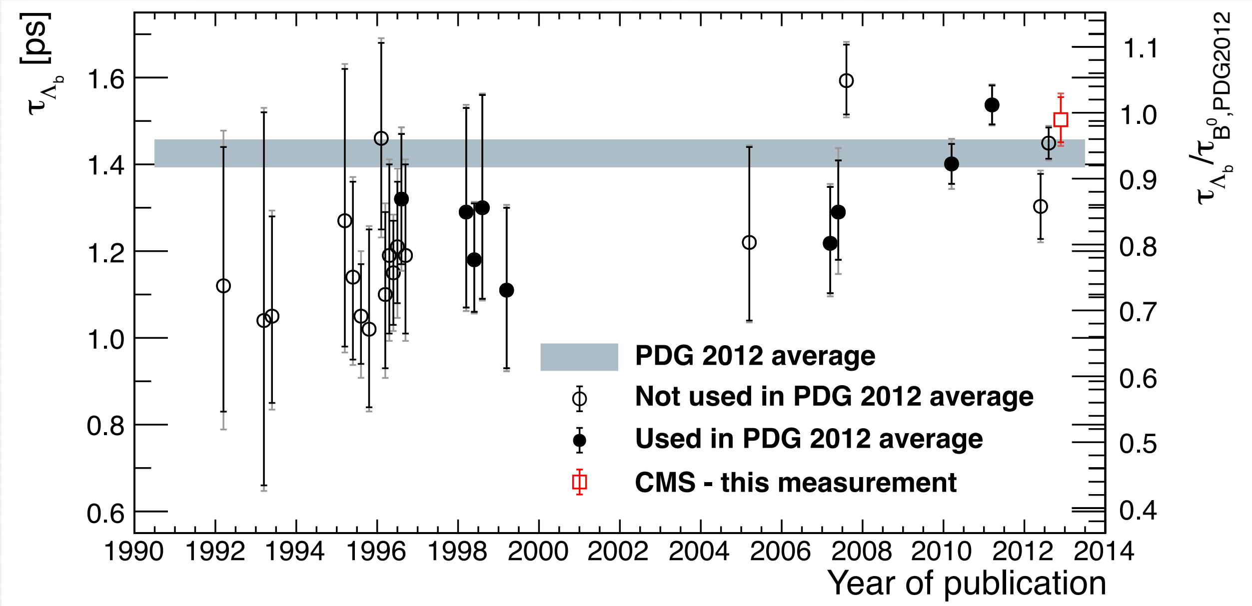

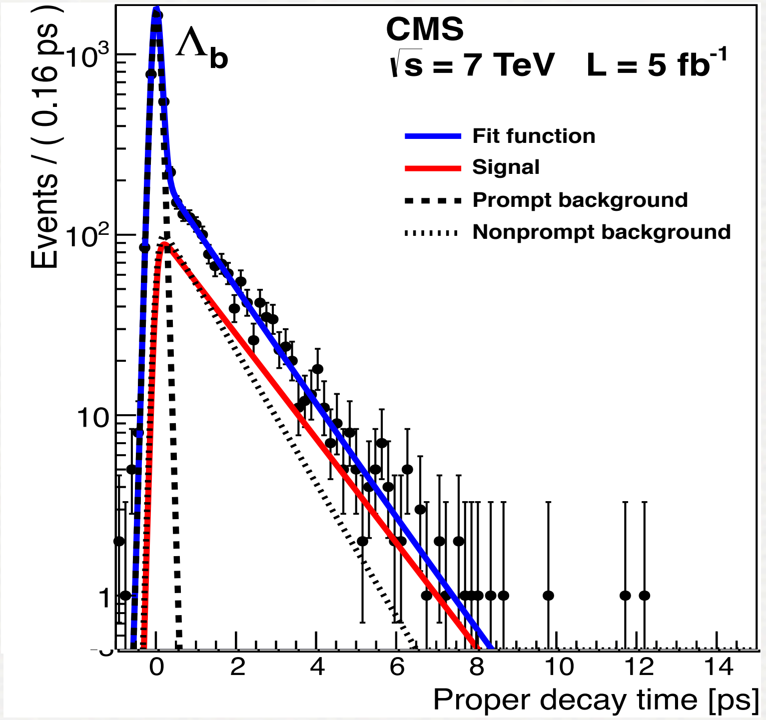

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Results ($\sqrt{s} = 7$TeV) JHEP 07 (2013) 163

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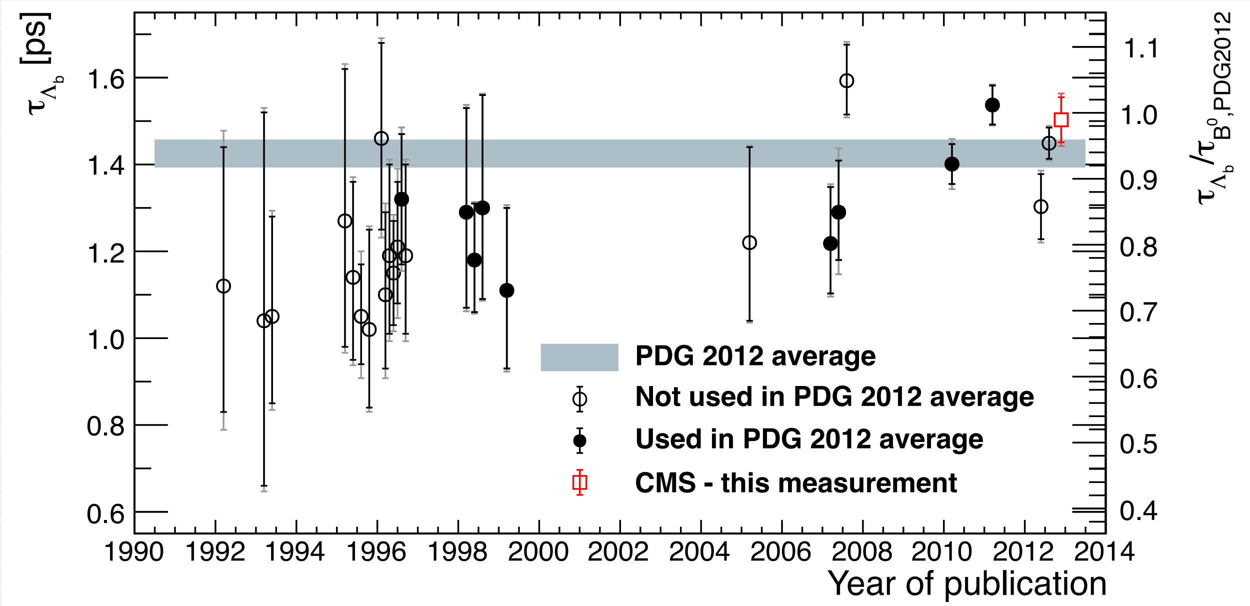
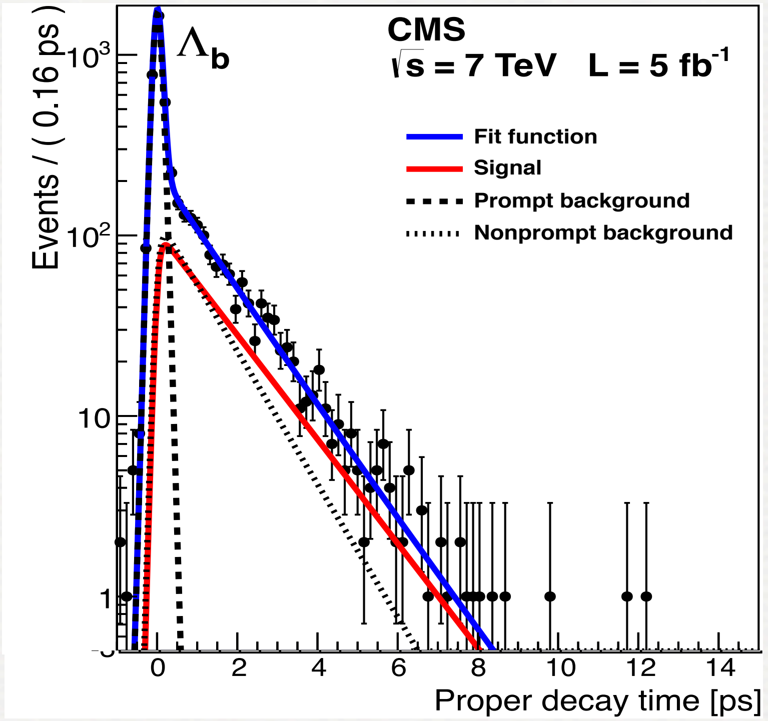
$$\tau(\Lambda_b)/\tau(B^0) = 0.98 \pm 0.04$$





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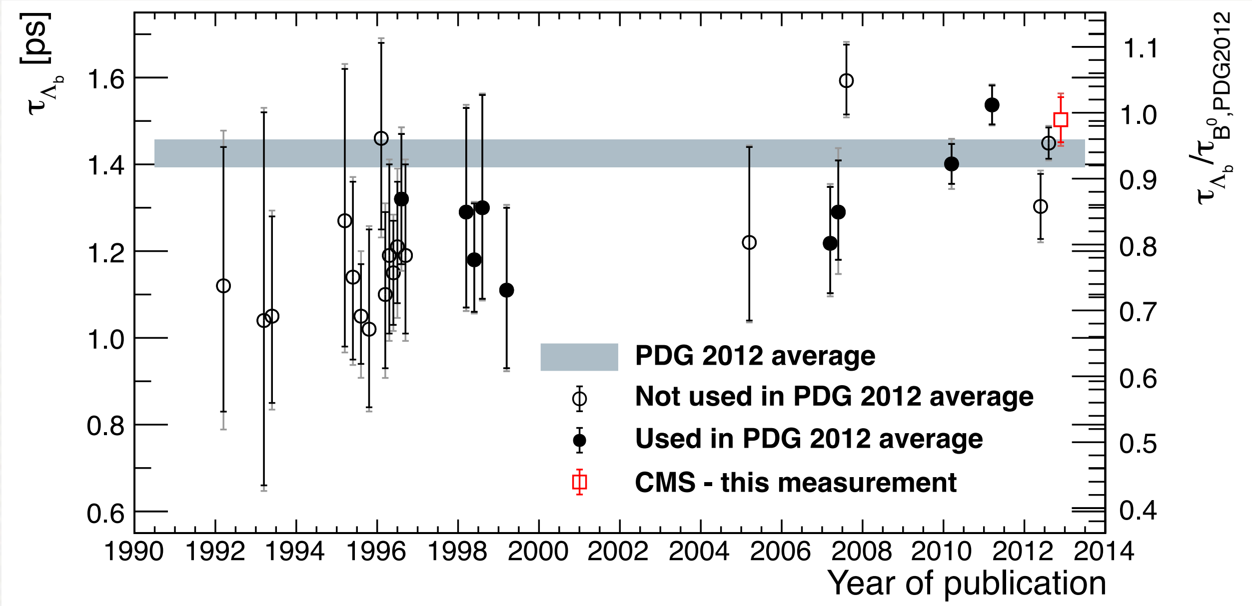

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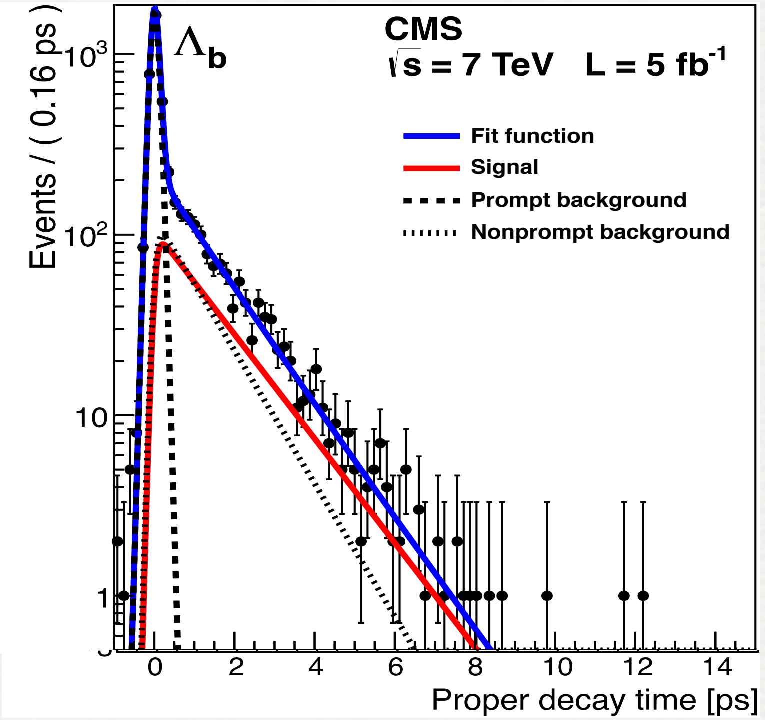
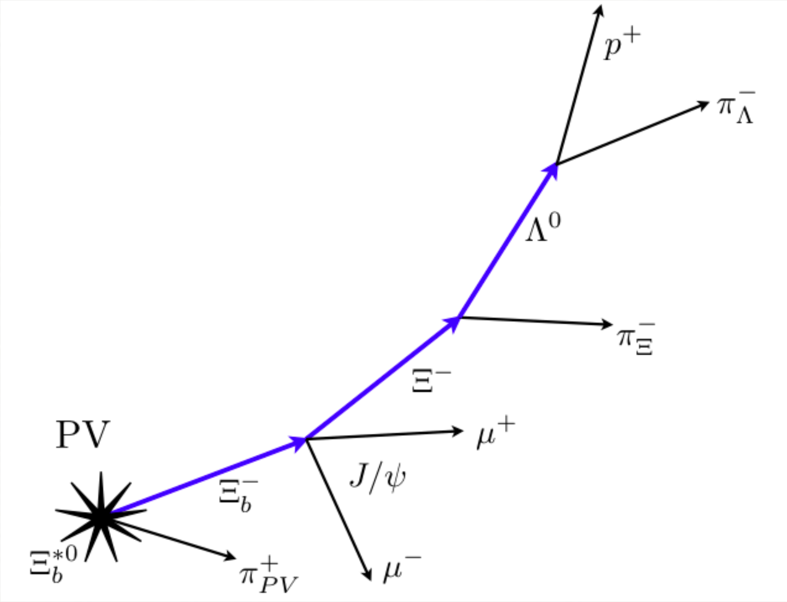


A more precise lifetime measurement, together with B^+, B^0, B_s (effective and CP-odd), Ξ_b lifetimes (legacy paper) and *polarization* measurements coming soon...

OBSERVATION OF A NEW BARYON



Now looking for Ξ_{bb} ...

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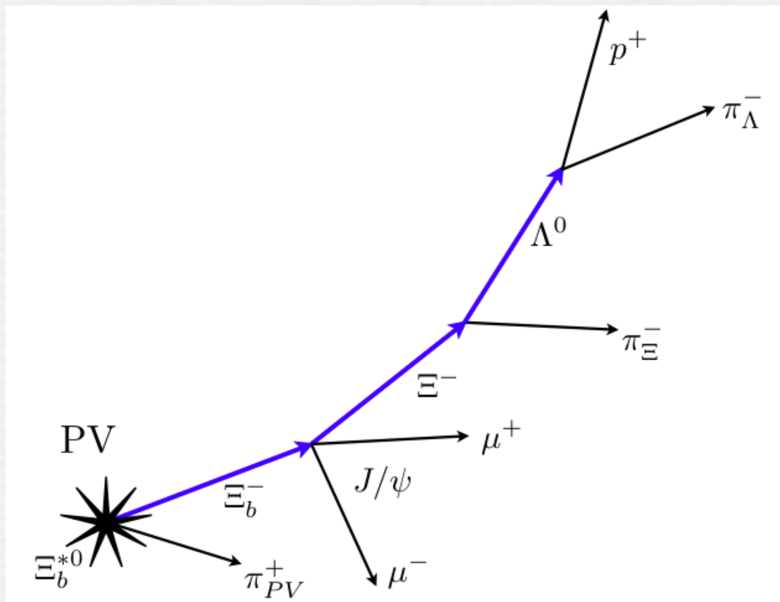

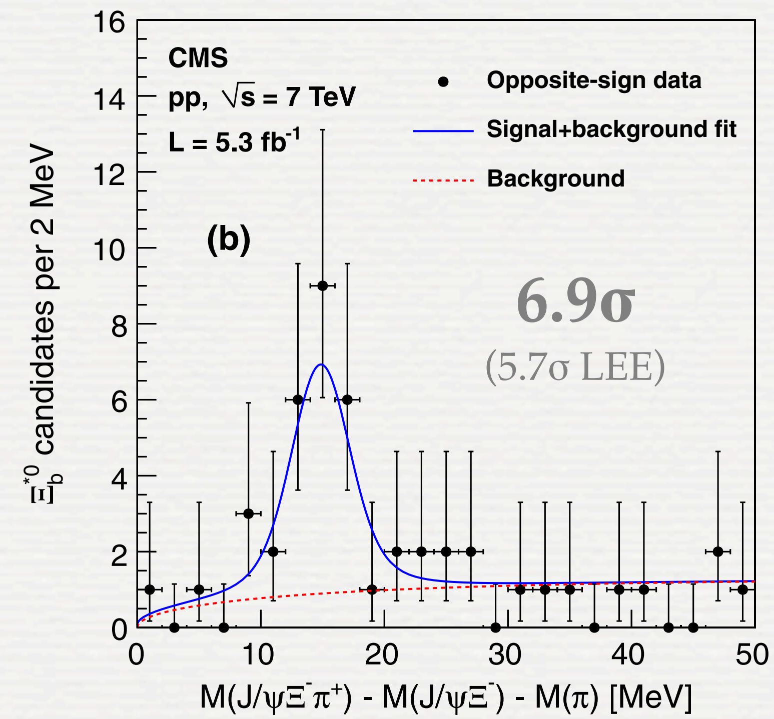

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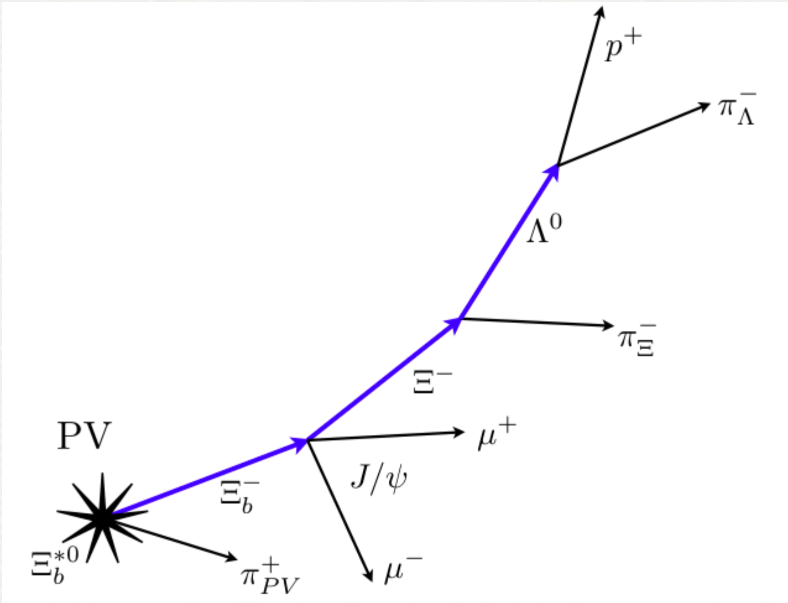
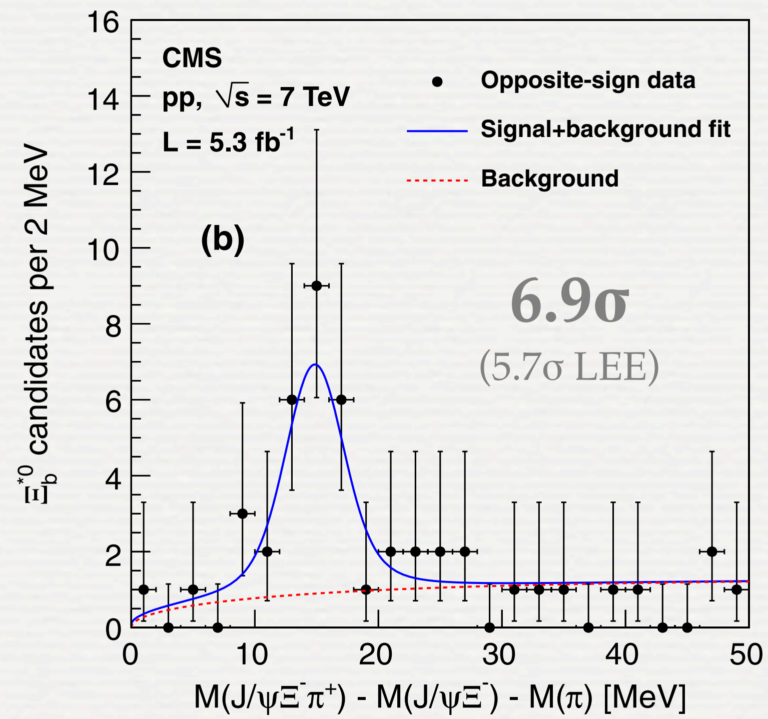




Mass fit ($\sqrt{s} = 7$TeV) PRL 108 (2012) 252002

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

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

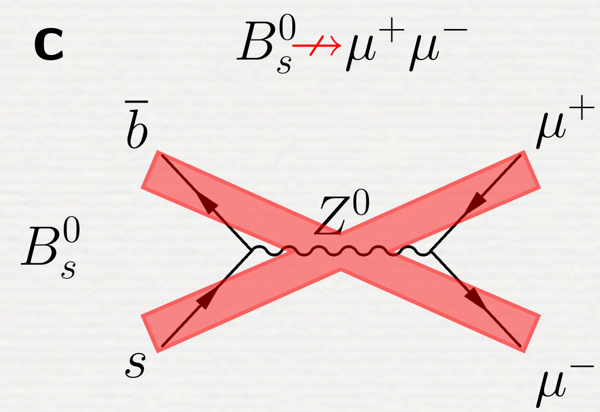
$$\Gamma = 2.1 \pm 1.7(\text{stat})\ \text{MeV}$$

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

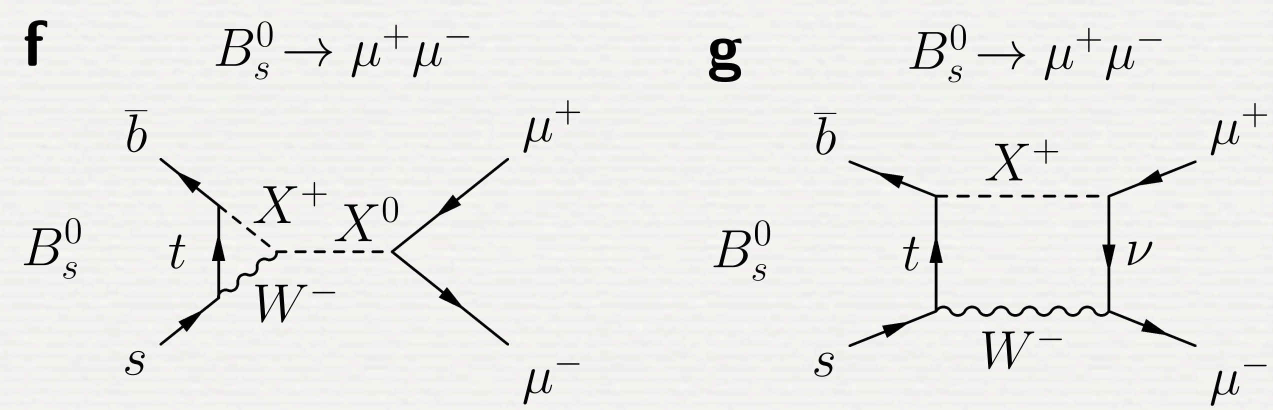
Now looking for Ξ_{bb} ...

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:
- Sensitive to NP:
  - MSSM (tanβ≫0).
  - 2HDM.
  - Leptoquarks.
  - 4th gen quark, etc.



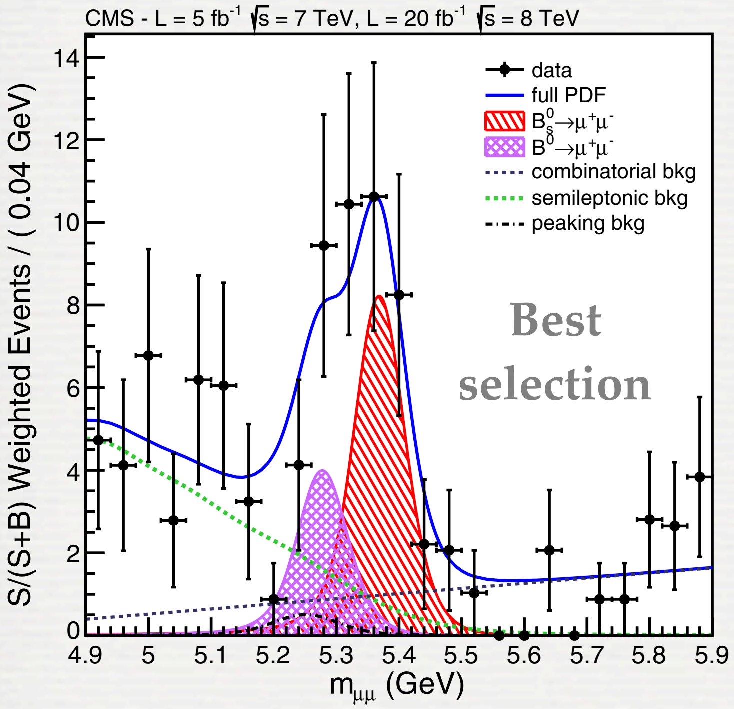
$$\mathcal{B}(B^0_s \to \mu^+\mu^-)_{\text{SM}} = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10}$$



$X^+ = W^+$ in SM

RESULTS

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



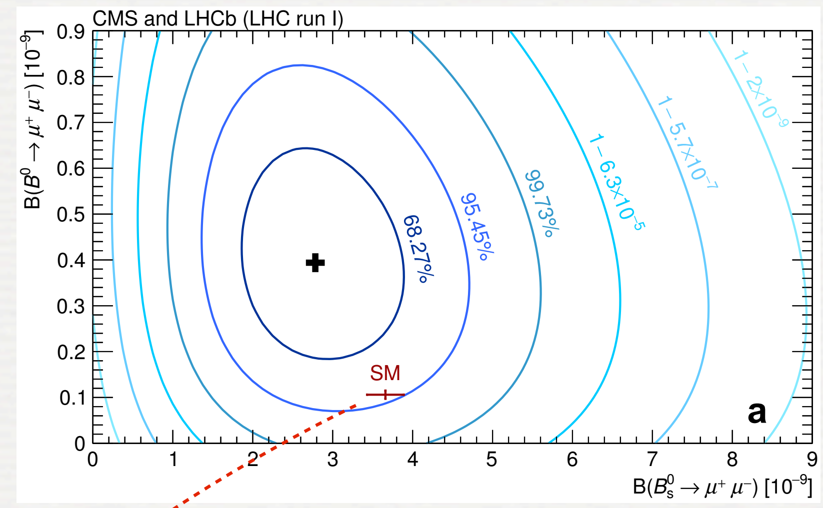
Results (full sample) PRL 111 (2013) 101804

$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$ **4.3σ**

$\mathcal{B}(B^0_d \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$ **2σ**

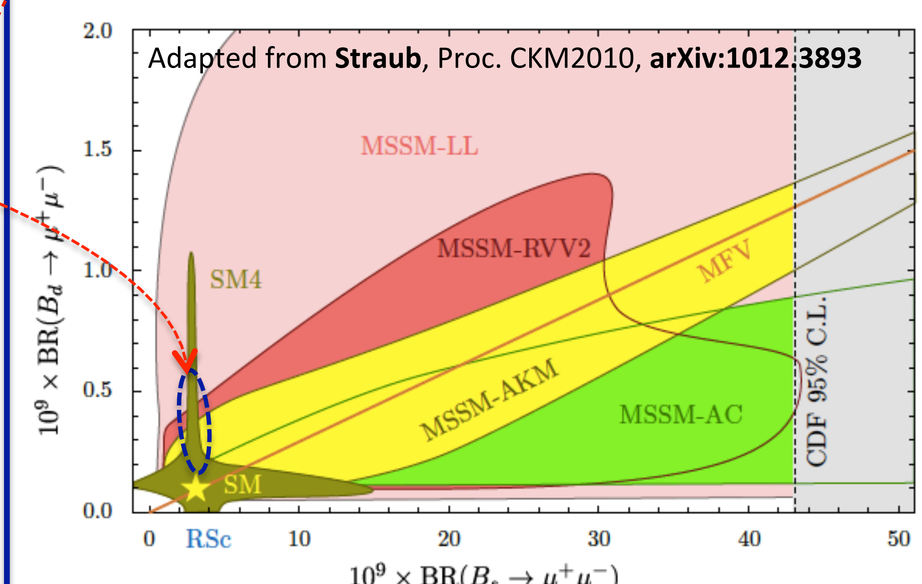
$\mathcal{B}(B^0_d \to \mu^+\mu^-) < 1.1 \times 10^{-9}$ @ 95% C.L.

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



Compare with SM, MFV & 4 SUSY flavor models

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



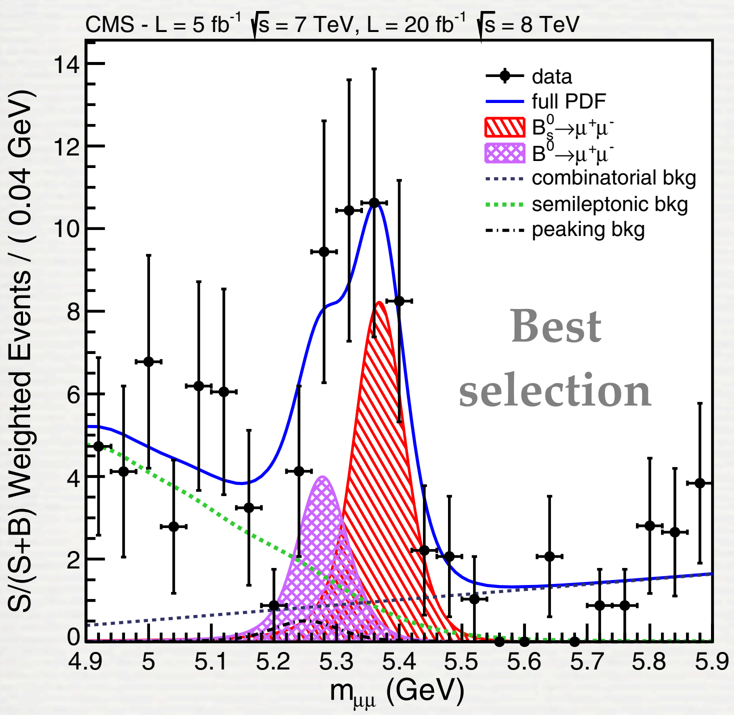
NATURE 2015:
CMS & LHCb combination

$$\mathbf{B}(B^0_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \cdot 10^{-9} \quad \mathbf{6.2\sigma}$$

$$\mathbf{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \cdot 10^{-10} \quad \mathbf{3.0\sigma}$$

RESULTS

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



Best selection

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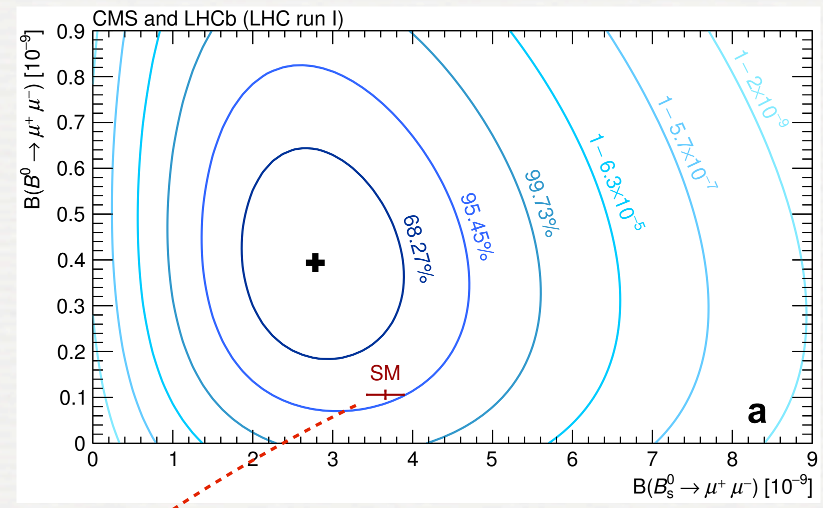

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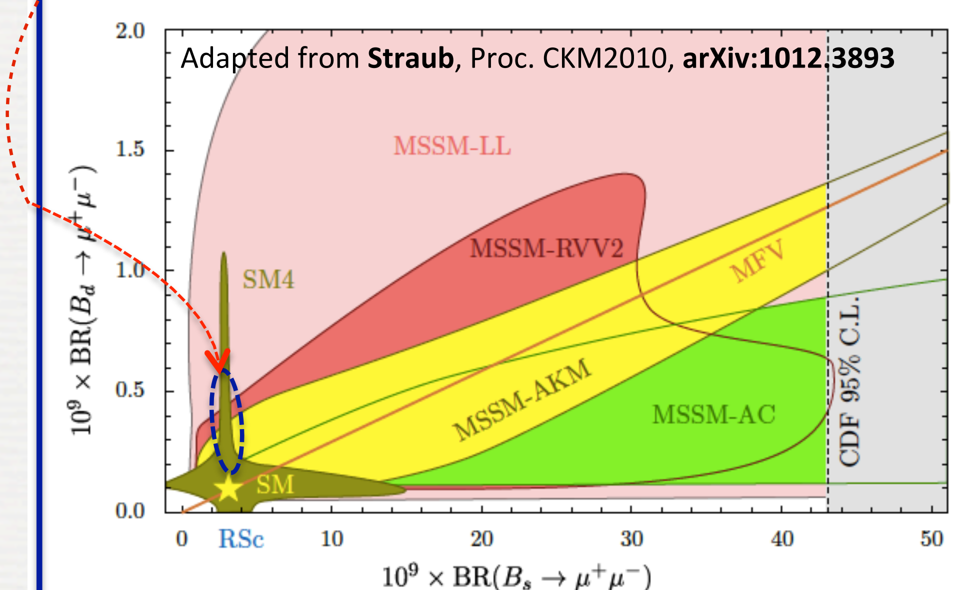


NATURE 2015: CMS & LHCb combination

$$\mathrm{B}(B^0_s \rightarrow \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \cdot 10^{-9} \quad \mathbf{6.2\sigma}$$

$$\mathrm{B}(B^0 \rightarrow \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \cdot 10^{-10} \quad \mathbf{3.0\sigma}$$

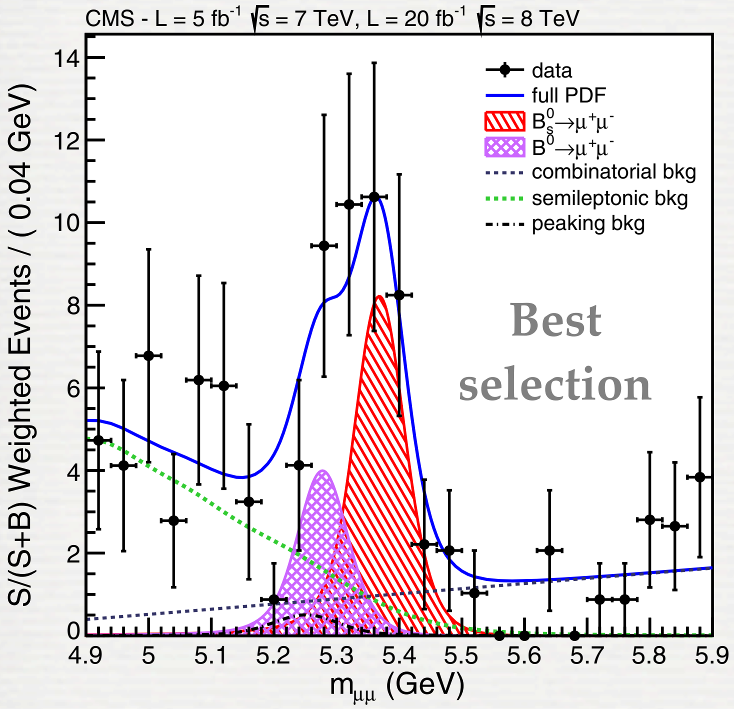
$$R \equiv \frac{\mathrm{B}(B^0 \rightarrow \mu^+\mu^-)}{\mathrm{B}(B^0_s \rightarrow \mu^+\mu^-)} = (0.14^{+0.08}_{-0.06})$$

compatible with SM @ 2.3σ level

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

RESULTS

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



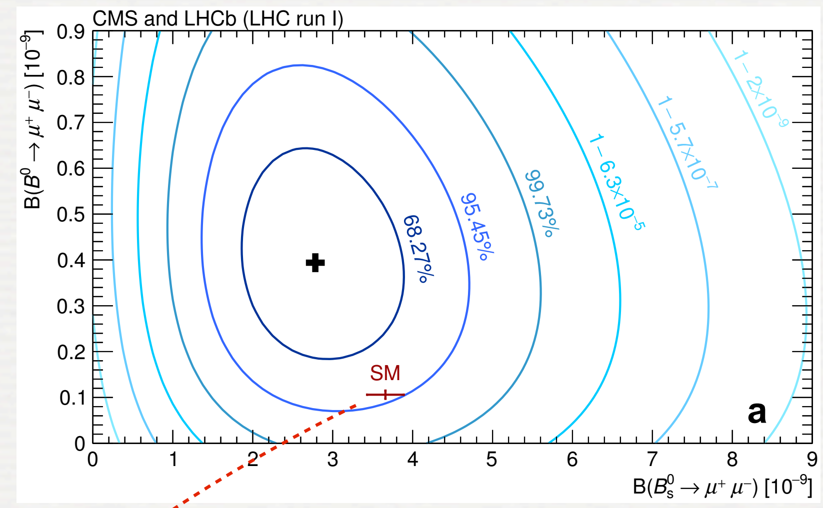
Results (full sample) PRL 111 (2013) 101804

$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$ **4.3σ**

$\mathcal{B}(B^0_d \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$ **2σ**

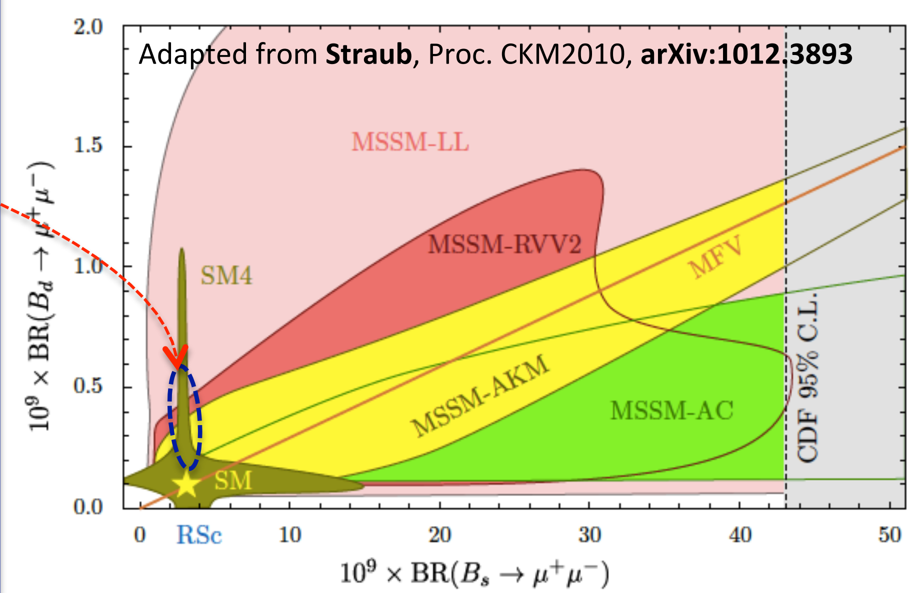
$\mathcal{B}(B^0_d \to \mu^+\mu^-) < 1.1 \times 10^{-9}$ @ 95% C.L.

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



Compare with SM, MFV & 4 SUSY flavor models

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



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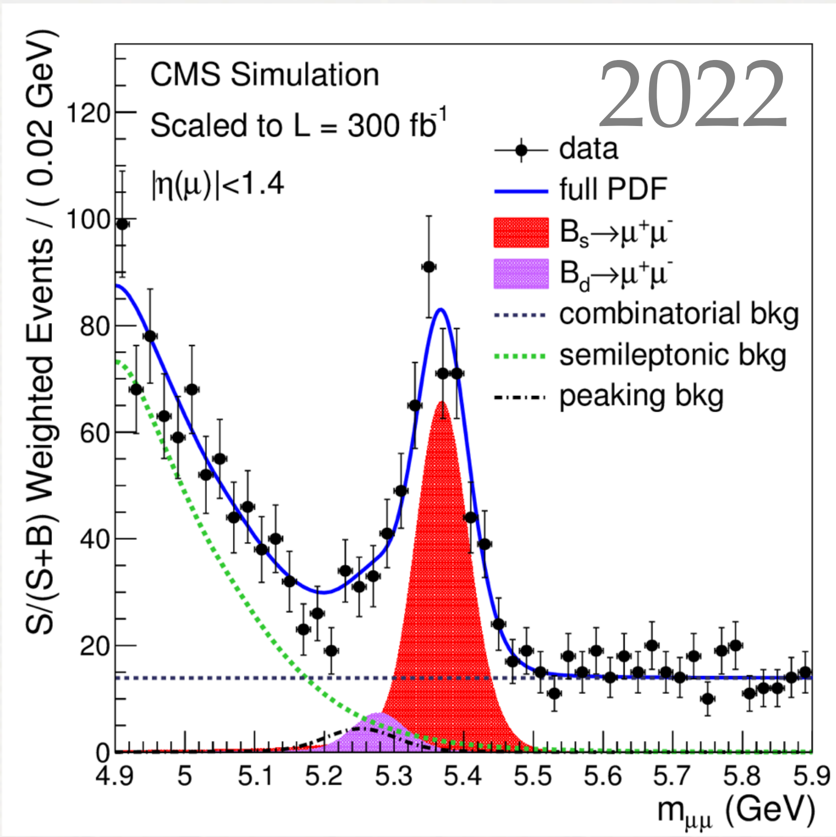
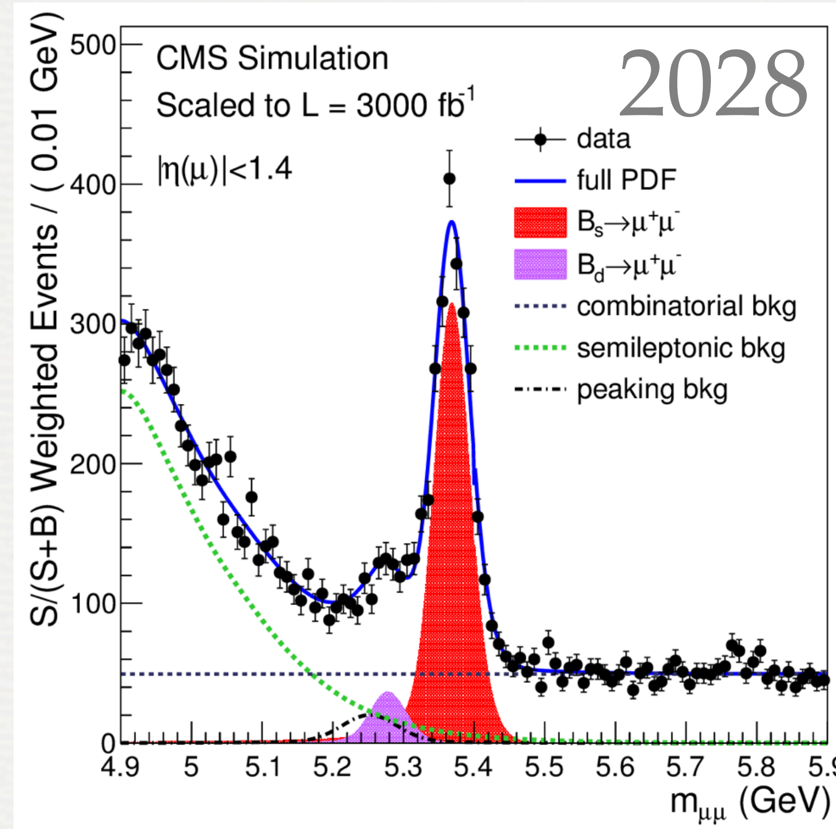
compatible with SM @ 2.3σ level

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

Already analyzing Run II data!

$B^0_s \to \mu^+\mu^-$ & $B^0 \to \mu^+\mu^-$: Future



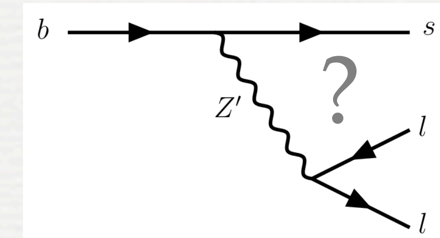


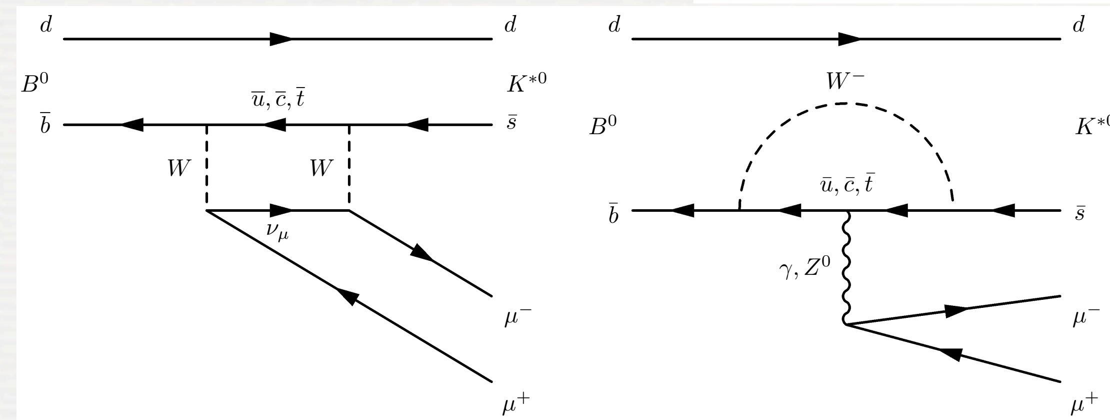
Estimate of analysis sensitivity

$\mathcal{L}(fb^{-1})$	$N(\mathrm{B}_s)$	$N(\mathrm{B}^0)$	$\delta\mathcal{B}(\mathrm{B}_s \to \mu\mu)$	$\delta\mathcal{B}(\mathrm{B}^0 \to \mu\mu)$	B^0 sign.	$\delta\frac{\mathcal{B}(\mathrm{B}^0 \to \mu\mu)}{\mathcal{B}(\mathrm{B}_s \to \mu\mu)}$
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%

RARE DECAY

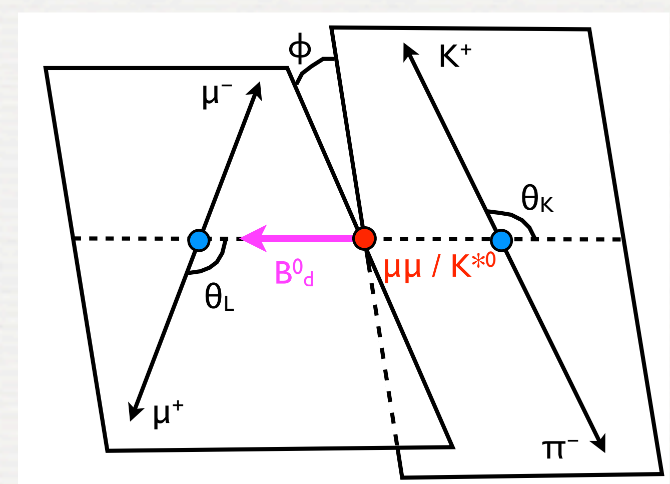
$B^0 \to K^*(892)^0 \mu^+ \mu^-$



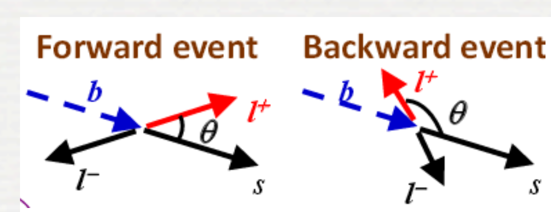


- Not allowed @LO (BR~10^{-6}).
- Complementary to $B^0_s \to \mu^+\mu^-$ (V/A vs. S/P-S interactions).
- Deviations of **BR**, F_L (frac. of K^{*0} long. pol), and A_{FB} (μ's) from SM in $q^2 = m_{\mu\mu}^2$ dep. can point to NP.

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

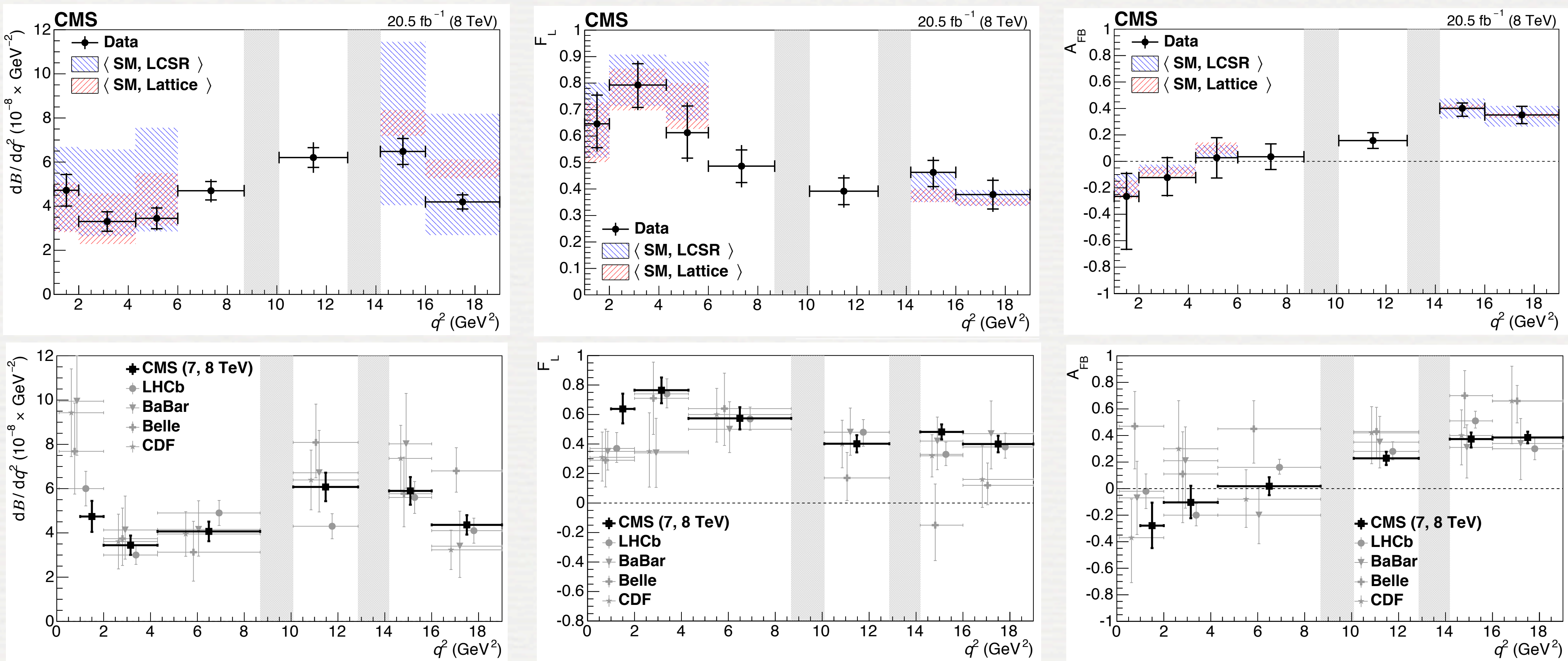


$$\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\vartheta_K d\cos\vartheta_l dq^2} = \frac{9}{16}\Big\{\Big[\frac{2}{3}F_s + \frac{4}{3}A_s\cos\vartheta_K\Big](1-\cos^2\vartheta_l)$$
$$+(1-F_S)\Big[2F_L\cos^2\vartheta_K(1-\cos^2\vartheta_l)$$
$$+\frac{1}{2}(1-F_L)(1-\cos^2\vartheta_K)(1+\cos^2\vartheta_l)$$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



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

RESULTS FOR $B^0 \to K^{*0}\mu^+\mu^-$



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

NEW:

arXiv:1507.08126v1 [hep-ex] 29 Jul 2015

- Agreement with SM and consistent with other experiments.

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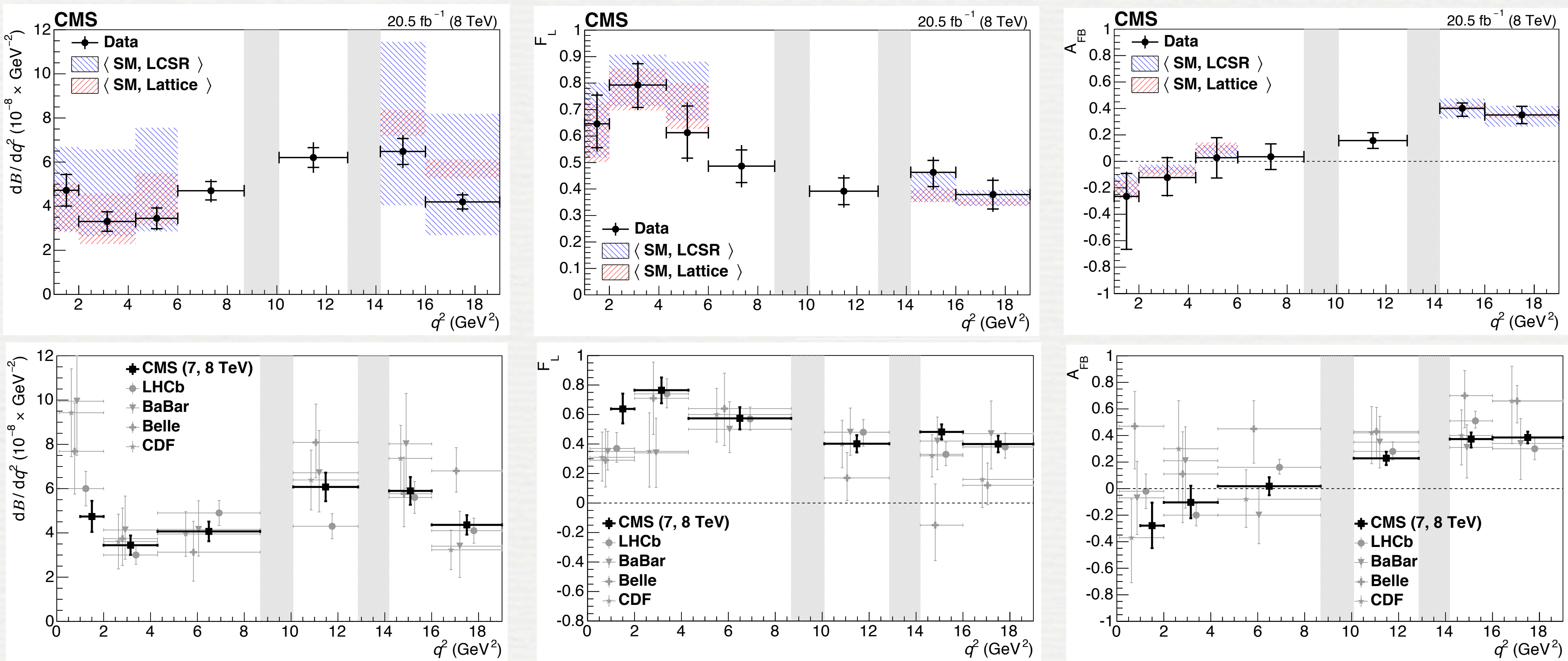

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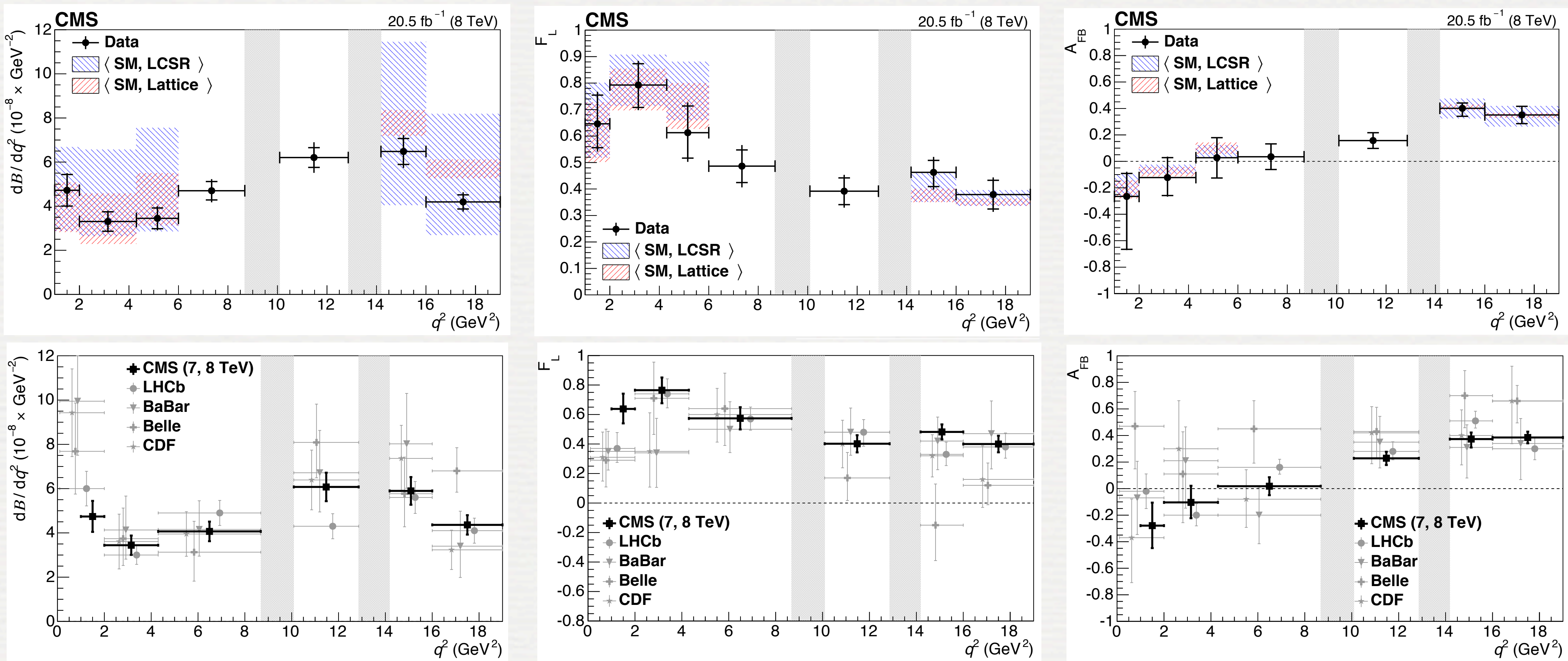

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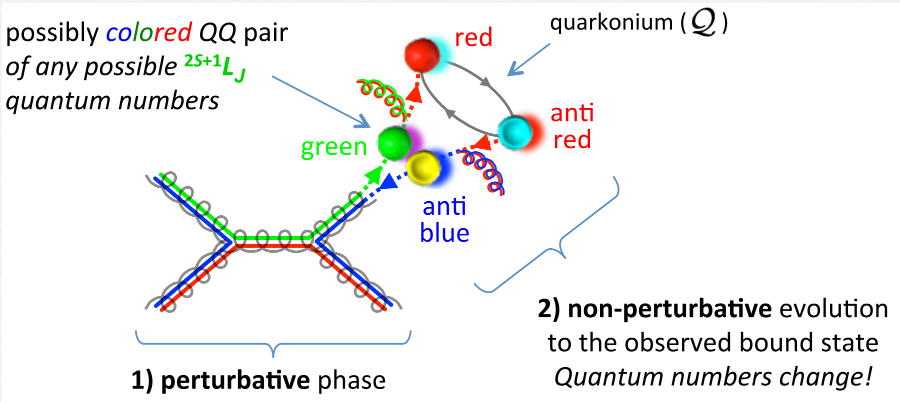
Studying $\Lambda_b \to \mu\mu\Lambda^{(*)}$ (Cecilia talk!)

QUARKONIUM POLARIZATION

- Quarkonia ($c\bar{c}$ or $b\bar{b}$) ~ non-relativistic systems ⇒ σ's reproduced by NRQCD.



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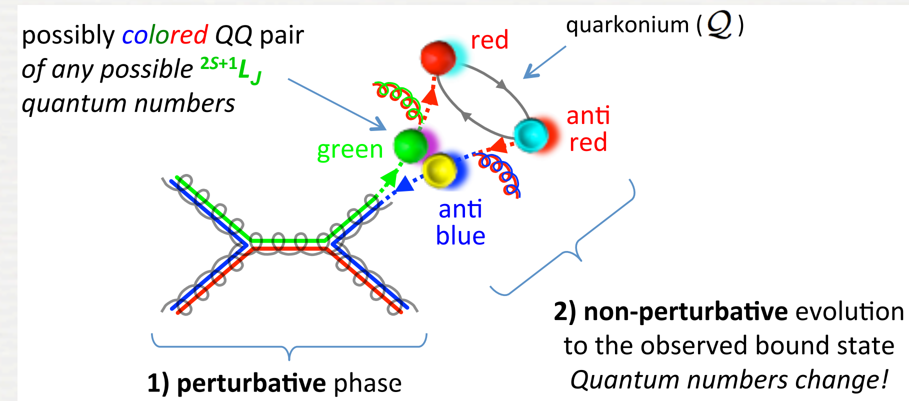

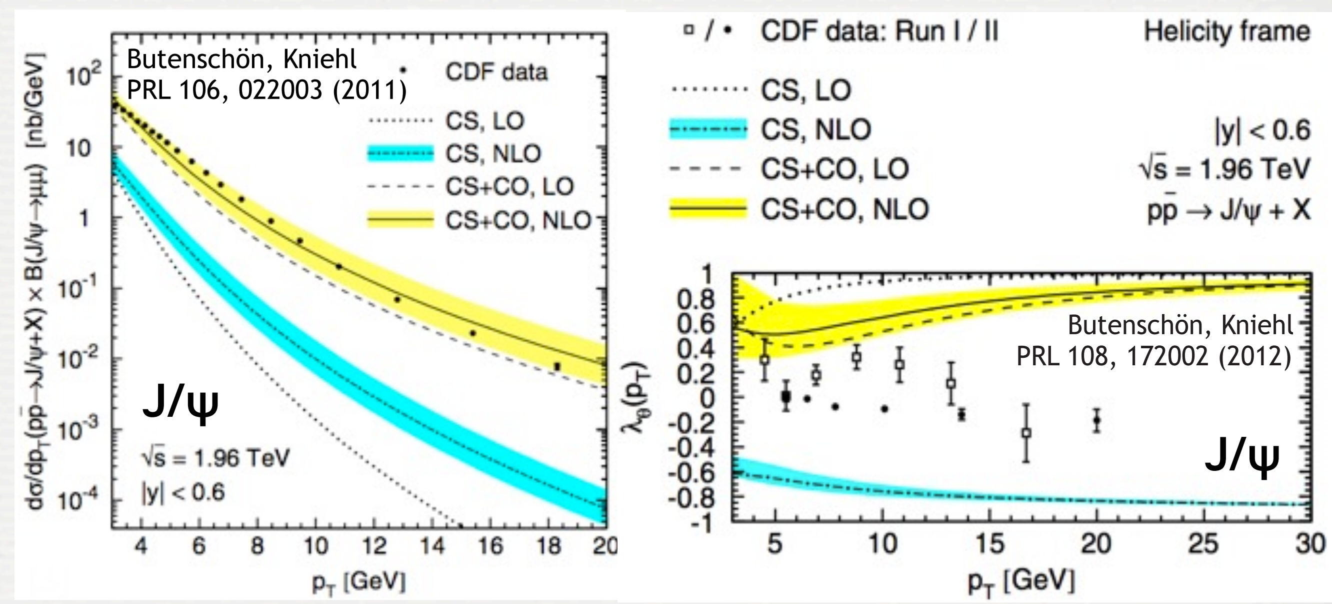

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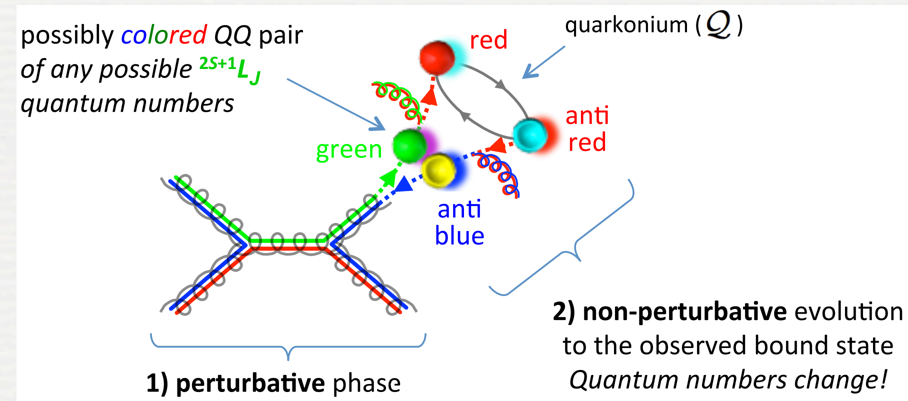
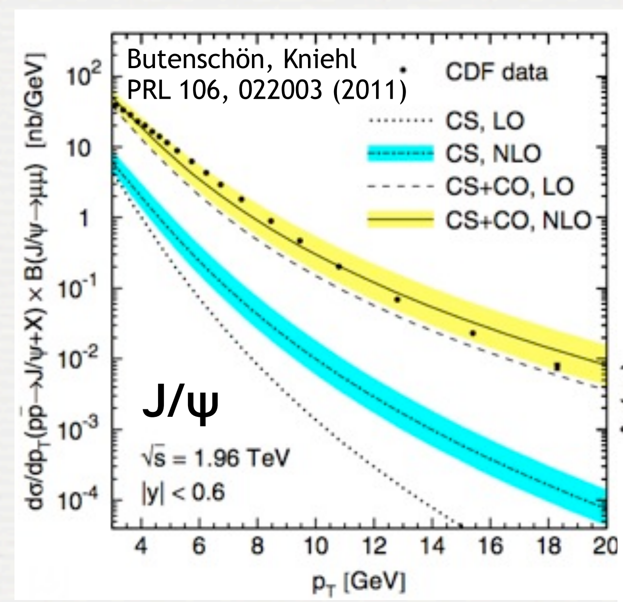
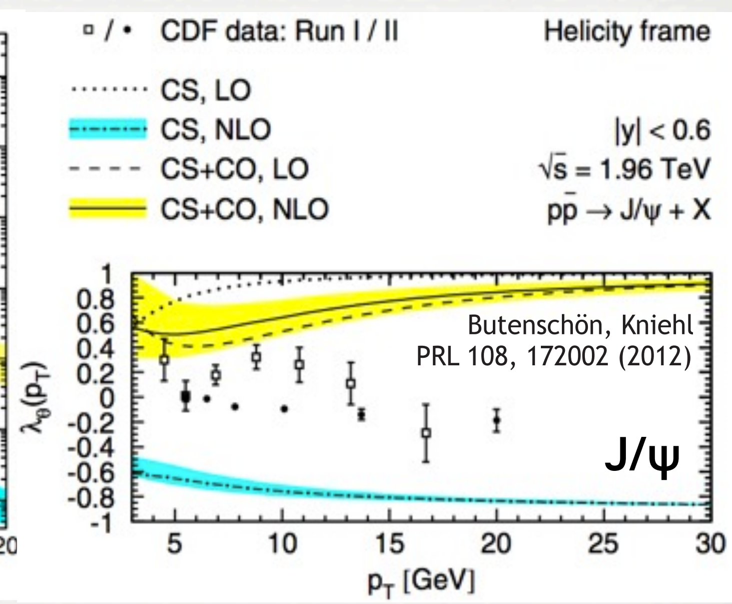
- **Large** transverse **Pol. expected** (λ_θ ~1 @ high pT). **Not seen by CDF in J/ψ.**
- Υ(*n*S) is a better lab for NRQCD than J/ψ or ψ'.
- Angular analysis of $Q \to \mu^+\mu^-$:

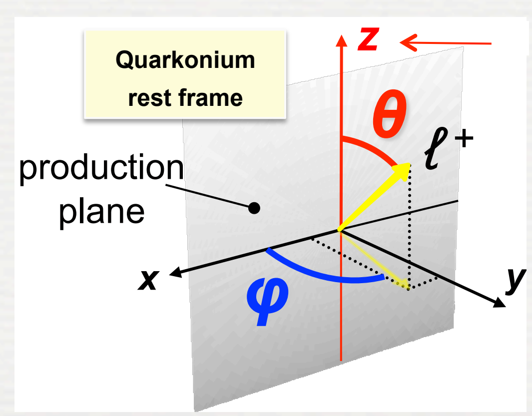
$$W(\cos\vartheta, \varphi|\vec{\lambda}) \propto \frac{1}{(3+\lambda_\vartheta)}(1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi)$$

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







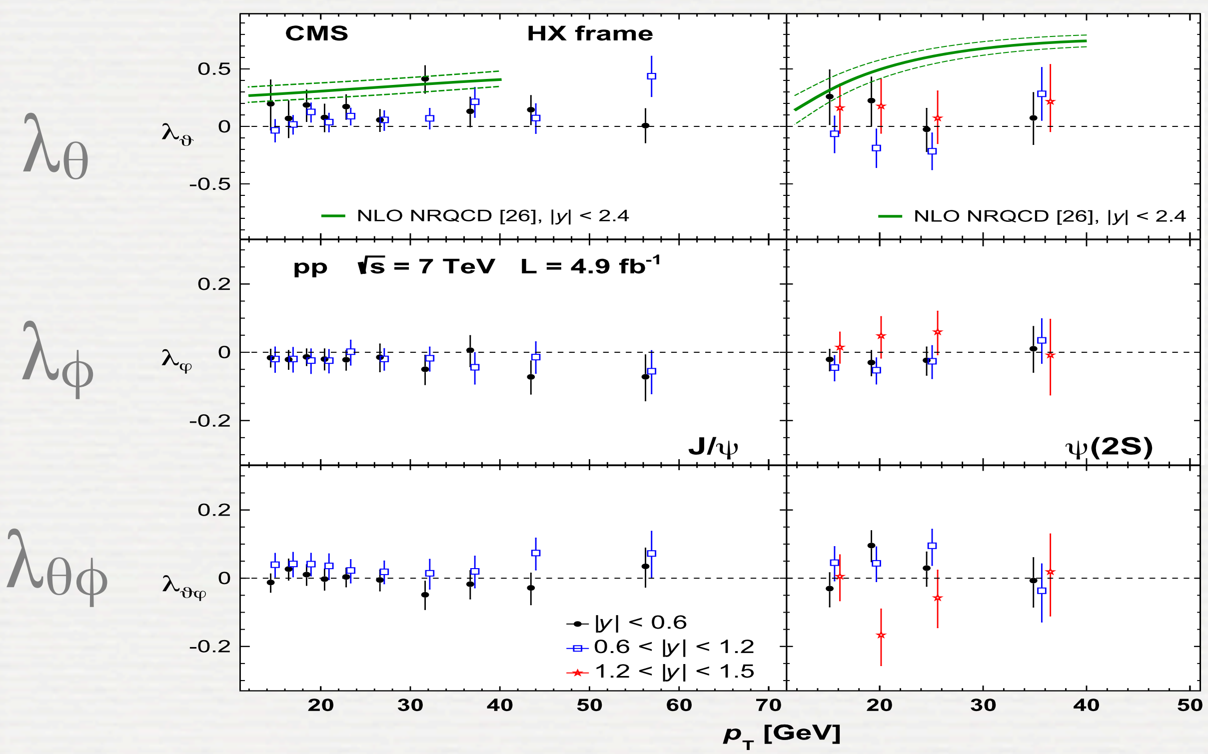


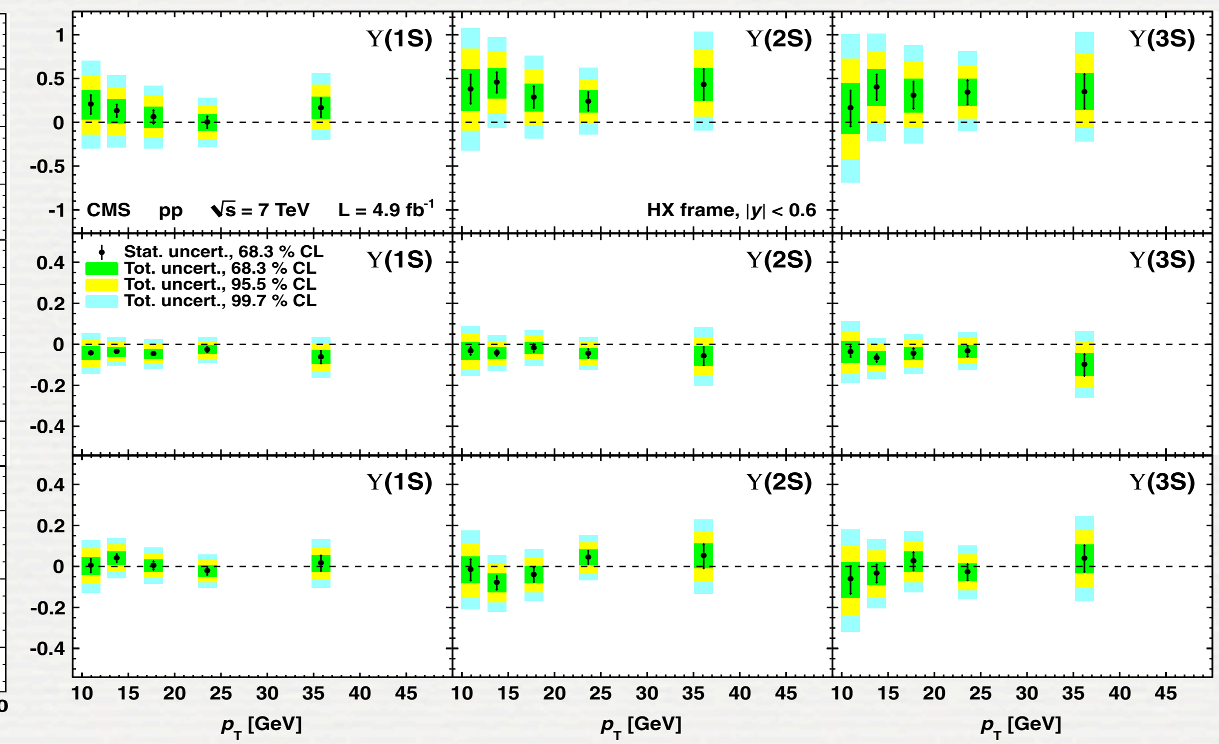
z-direction (frame)

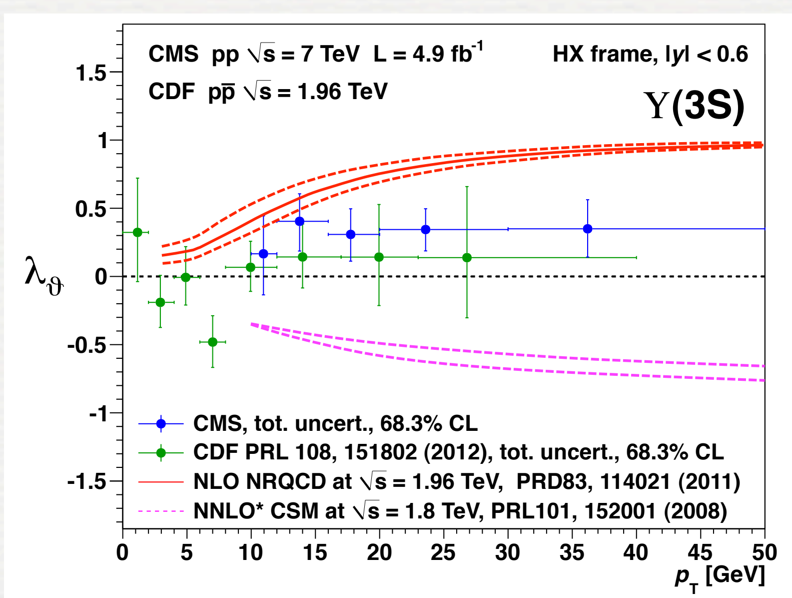
- HX (Helicity): p_Q
- CS (Collins-Soper): $\langle p_{p1}, p_{p2} \rangle$
- PX: ⊥CS

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.
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- For λ_θ, in clear disagreement with NRQCD predictions, even for Υ(3S)!

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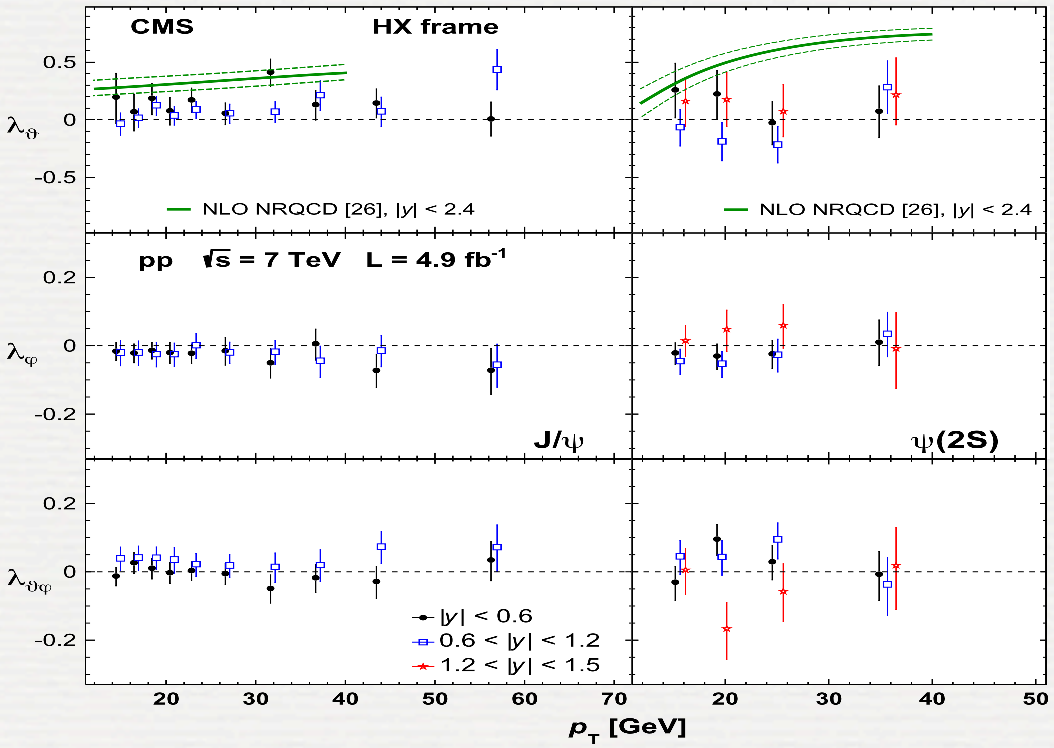
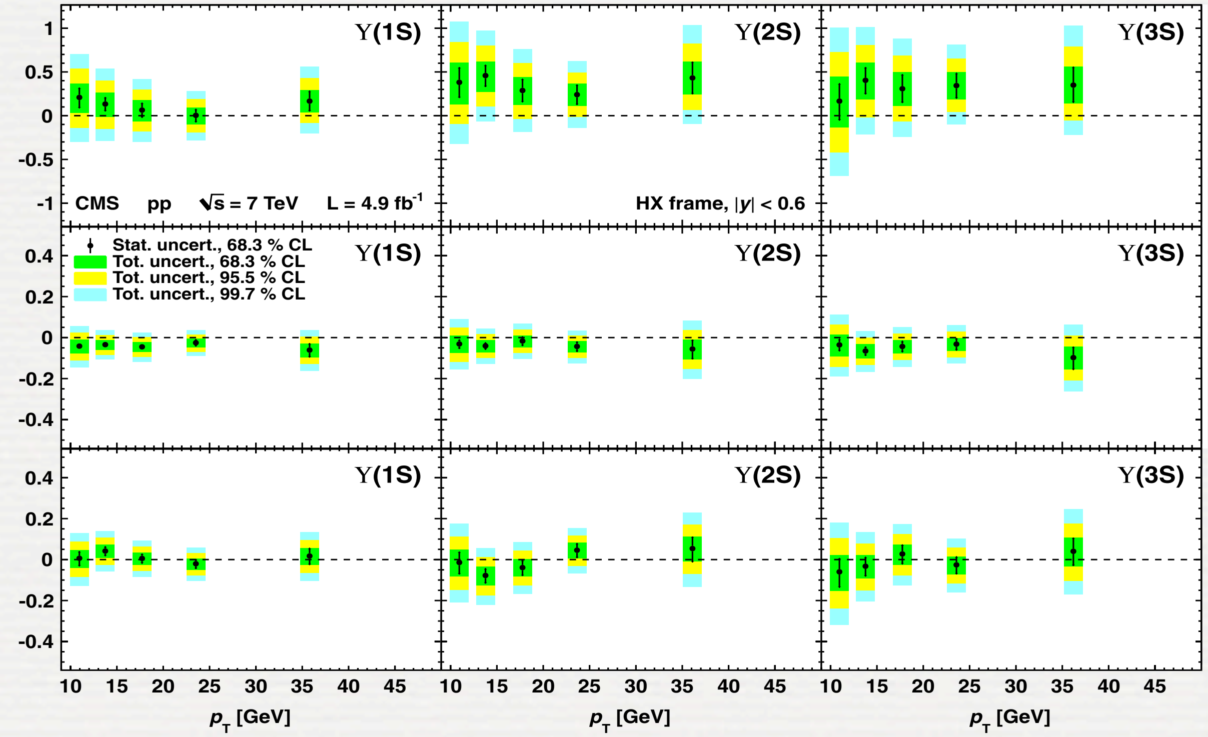
J/ψ ψ(2S) Υ(1S) Υ(2S) Υ(3S)

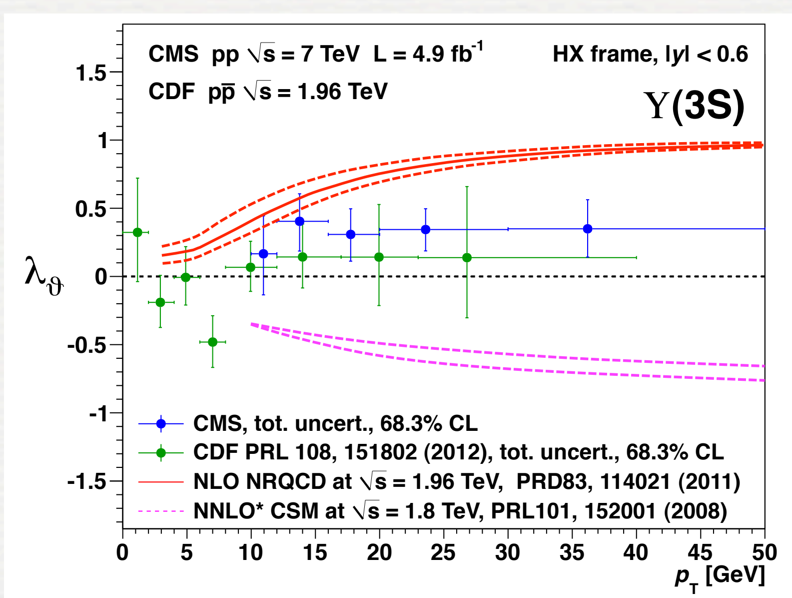
λ_θ

λ_ϕ

$\lambda_{\theta\phi}$







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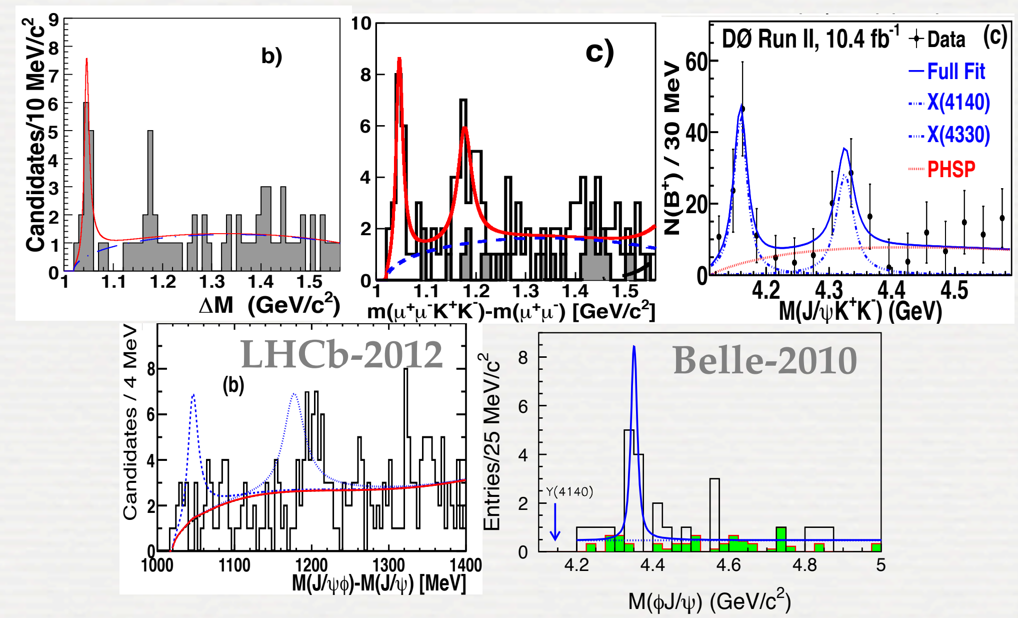
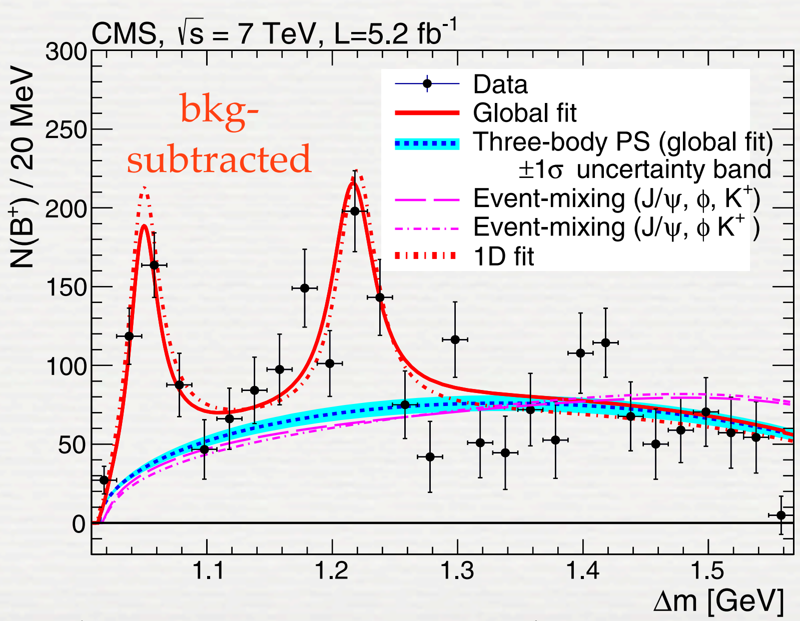
Studies ongoing at 13 TeV.

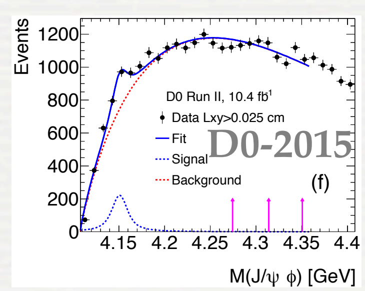
CONFIRMATION OF EXOTIC Y(4140)

- 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:

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







D0/**15** > 5σ

Bottom physics @ CMS, Ivan Heredia, MWPF-2015

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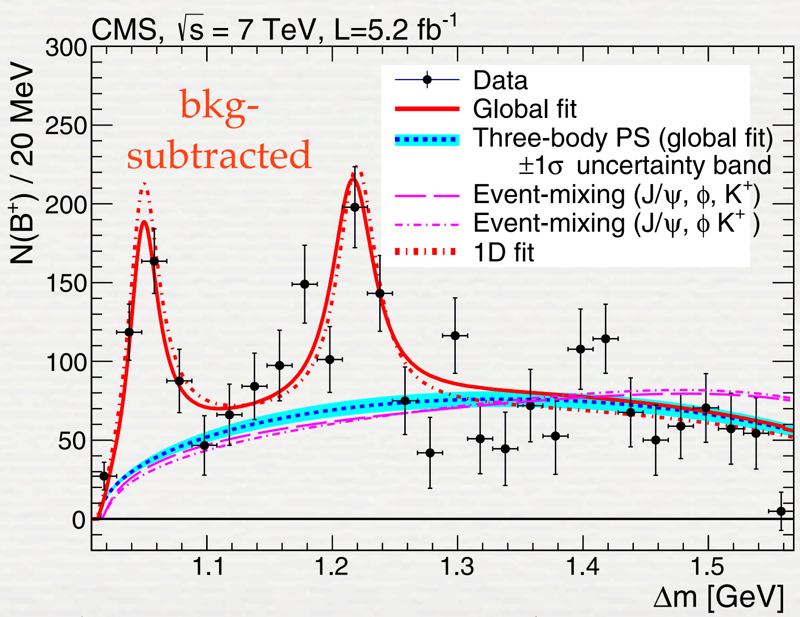

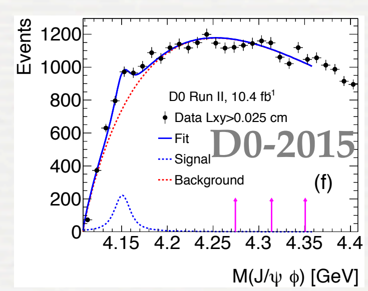

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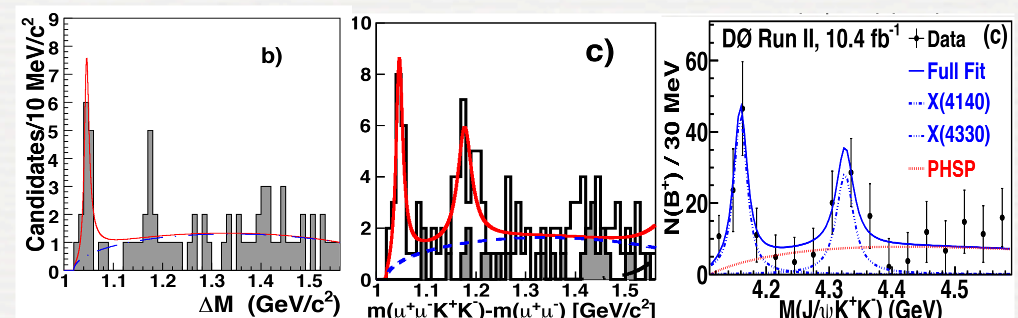

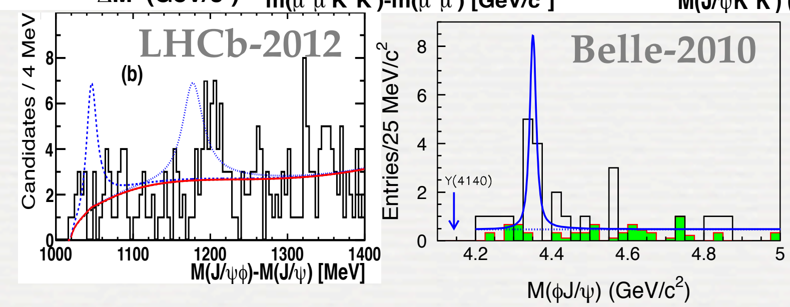

Results (√s = 7 TeV) PLB 734 (2014) 261-281

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

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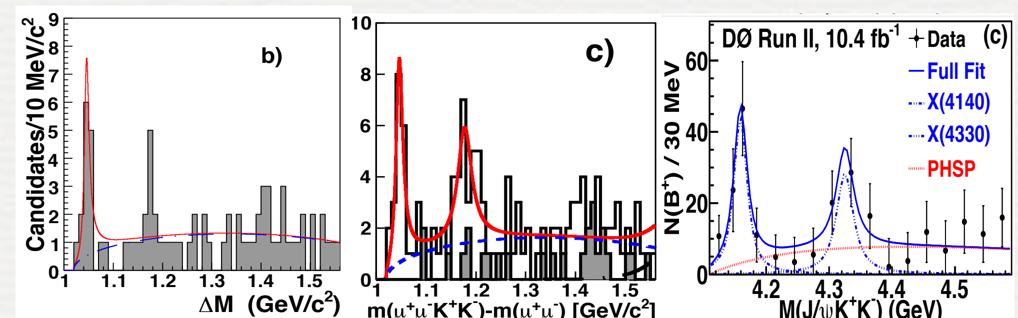

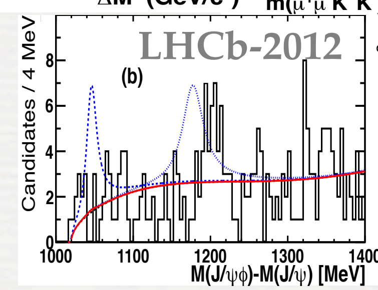

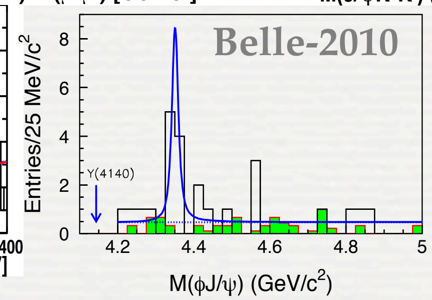

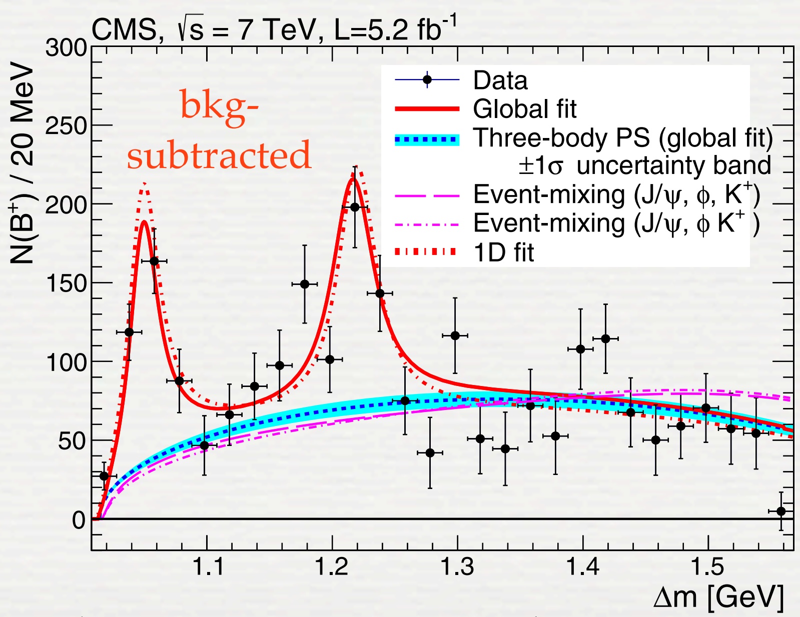

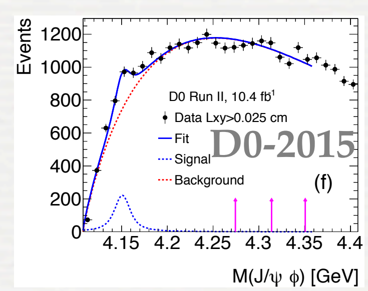

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Now looking LHCb pentaquark!

SKIPPED TODAY

*** Run II early analyses.**

*** Properties:**

1. CP-violating weak phase ϕ_s in $B^0_s \to J/\psi\phi$ (arXiv:1507.07527, 2015).
2. BR($B^0_s \to J/\psi f_0(980)$) (arXiv:1501.06089, 2015).

*** Production @ 7 - 8 TeV:**

Bottonium

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

Charmonium

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

b-quark/ hadron

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

SKIPPED TODAY

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

Bottonium

Charmonium

b-quark/ hadron

Measuring at 13 TeV!

SUMMARY

- Successful BPH (dimuon) CMS program.
- Several important observations/discoveries.
- CMS tops some important analyses or is competitive with LHCb.
- Many results using Run I data are in the pipeline and we are already analyzing Run II.
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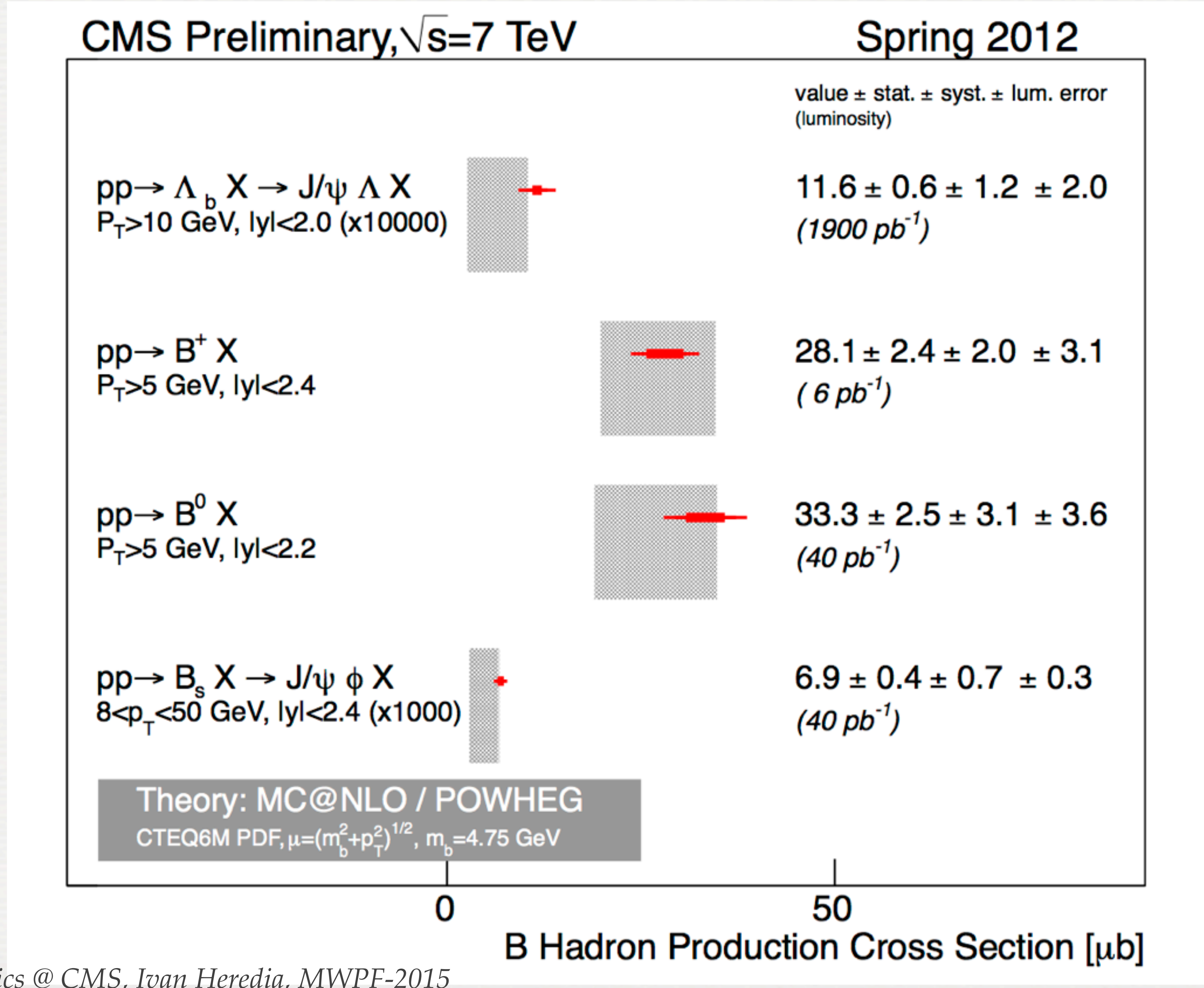
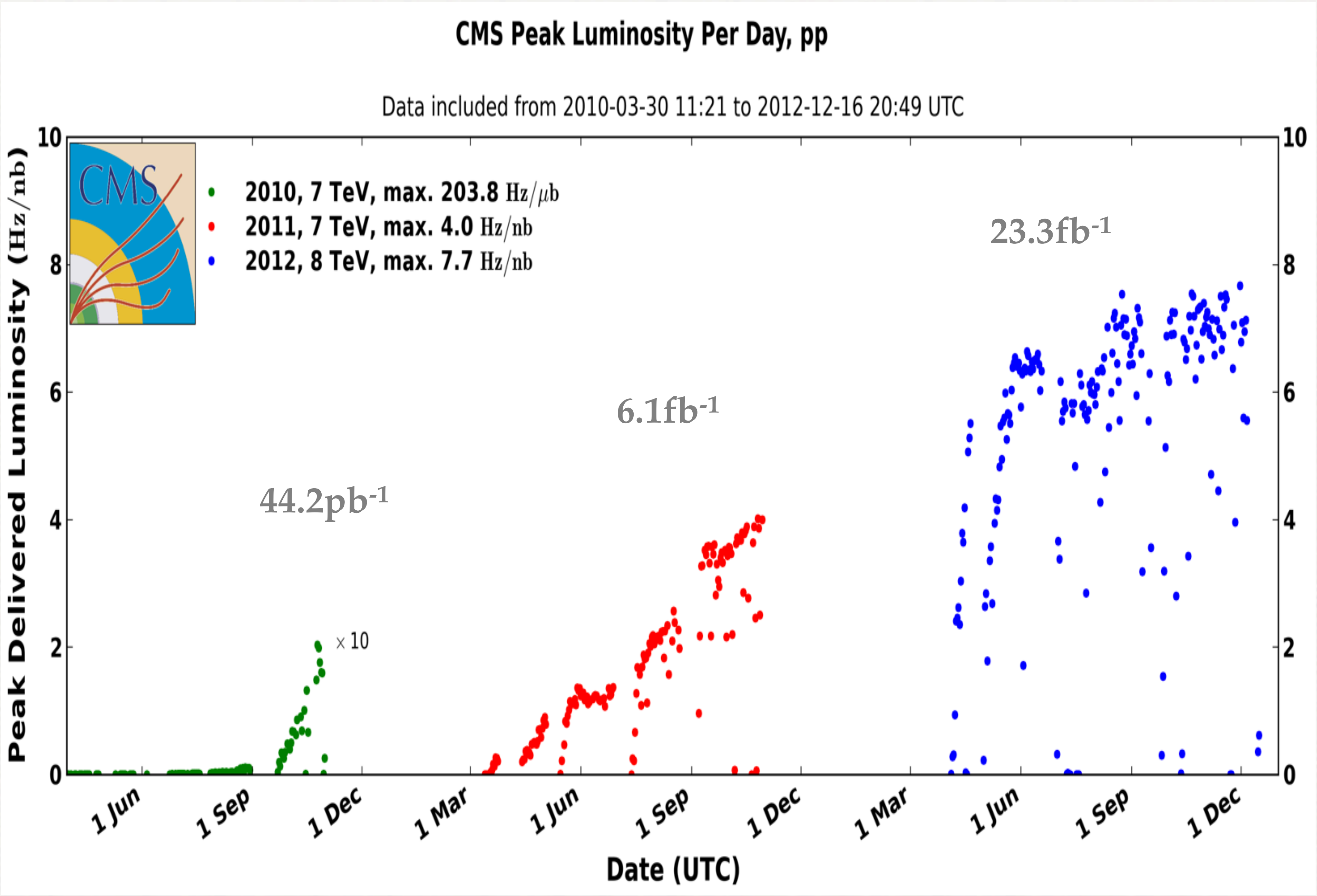
THANKS!!!

BACK-UP

B CROSS SECTION VS THEORY



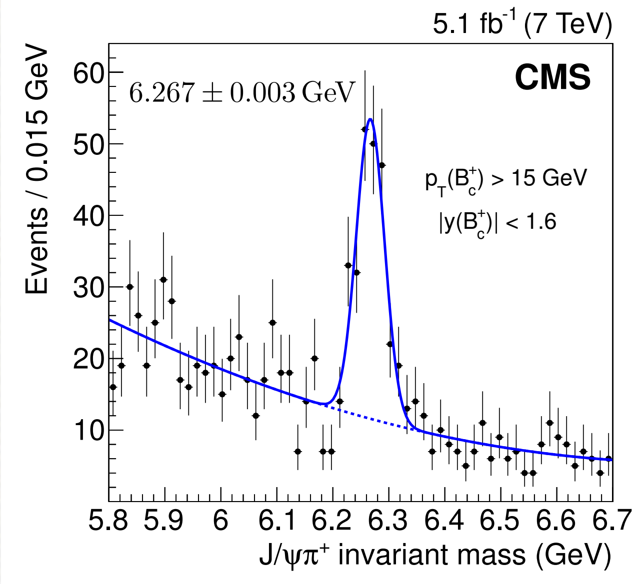
LUMINOSITY

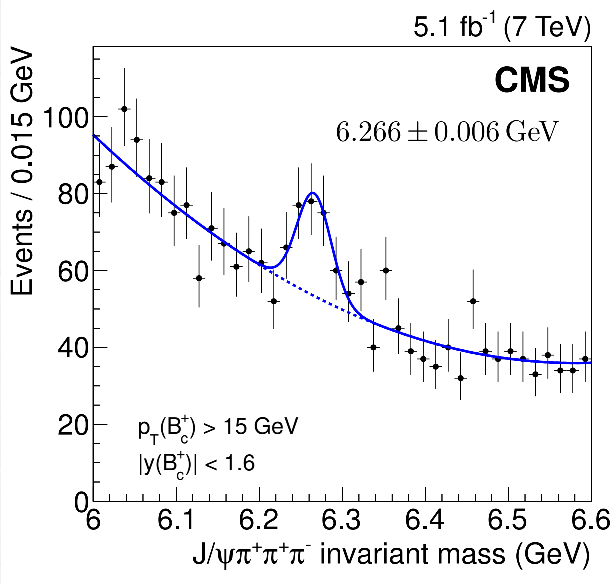


Thursday, November 5, 15

B_c^+ MESON @ 7 TEV

- *b* and *c* heavy quarks competing in decay (decays faster).
- Reconstructed in $J/\psi\pi^+$ and $J/\psi\pi^+\pi^+\pi^-$.
- Cross section measurements could help improve B_c (double heavy) production models.



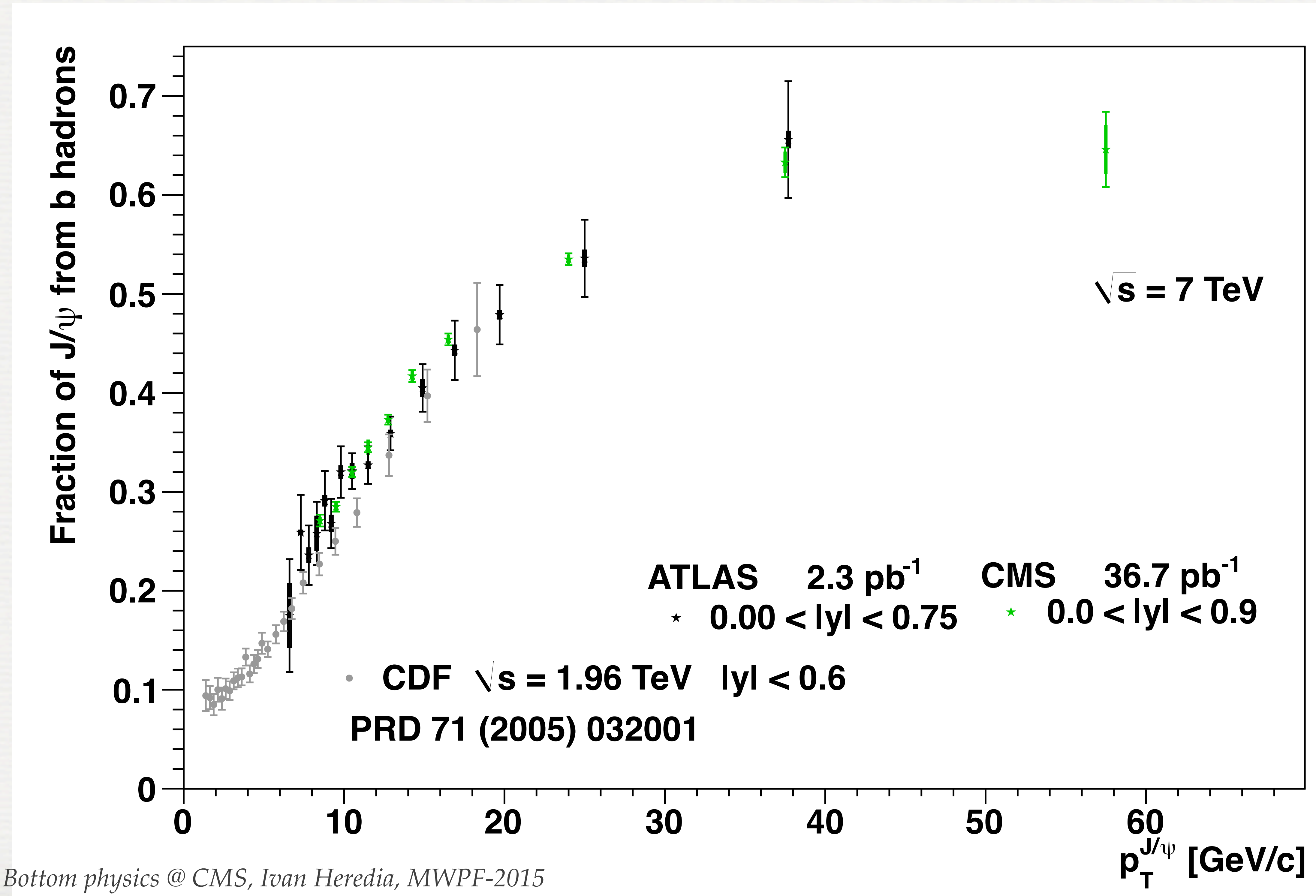


Results ($\sqrt{s}$ = 7 TeV) JHEP 01 (2015) 063

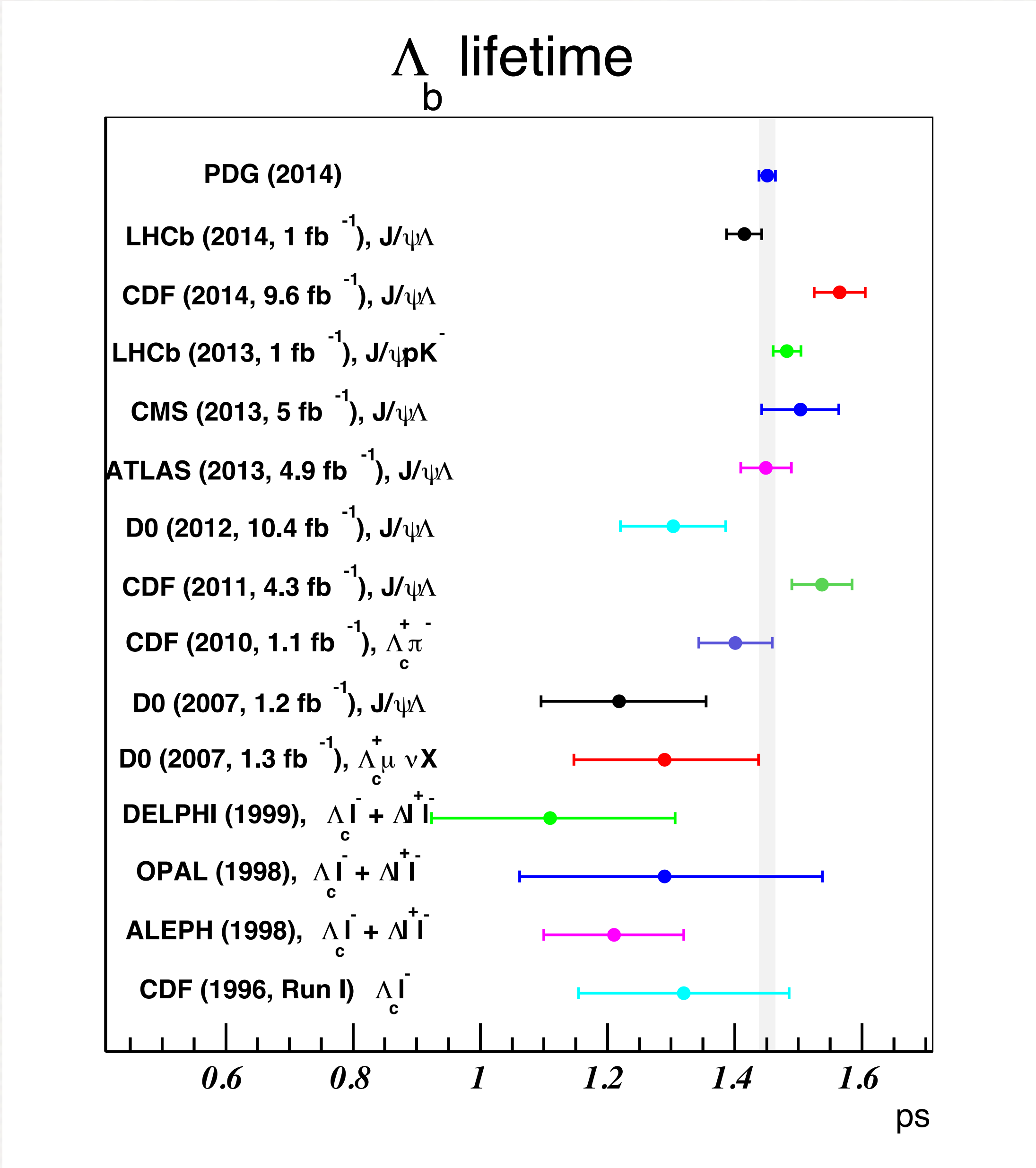
$$\frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)} = [0.48 \pm 0.05\,(\text{stat}) \pm 0.03\,(\text{syst}) \pm 0.05\,(\tau_{B_c})]\%$$

$$\frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+\pi^+\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 2.55 \pm 0.80\,(\text{stat}) \pm 0.33\,(\text{syst})^{+0.04}_{-0.01}\,(\tau_{B_c})$$

FRACTION OF NON-PROMPT J/PSI

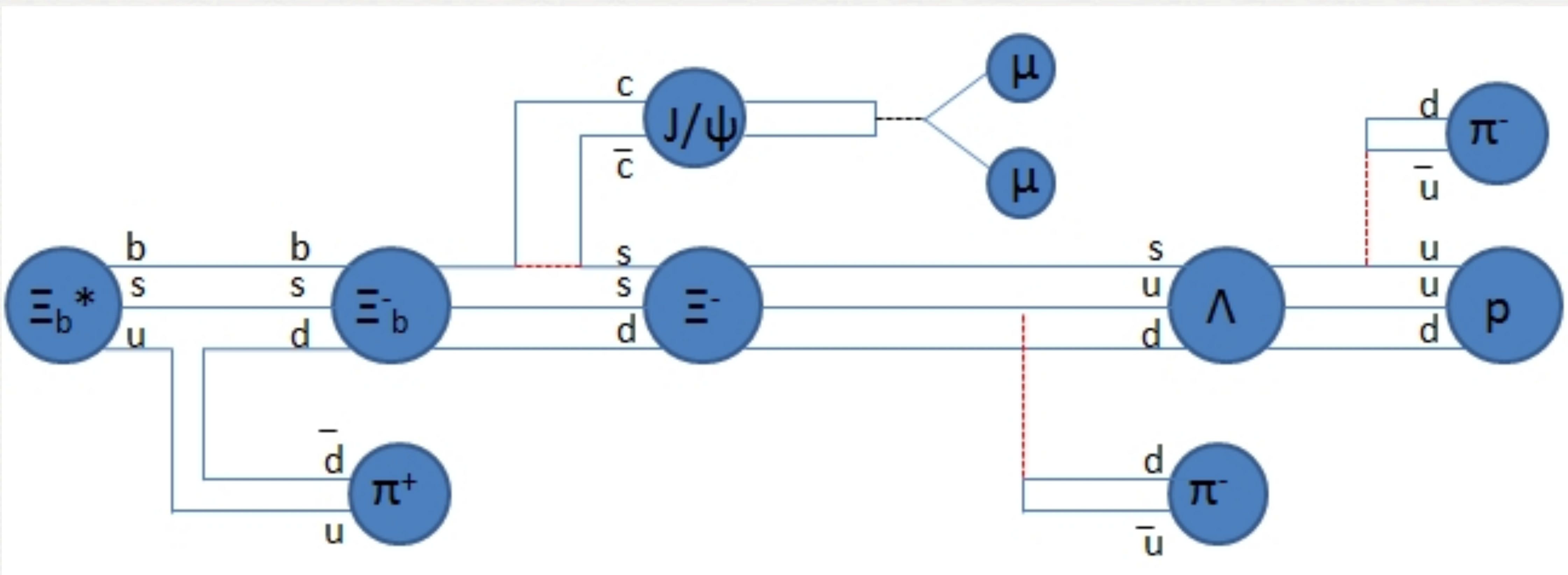


Λ_b LIFETIME HISTORY



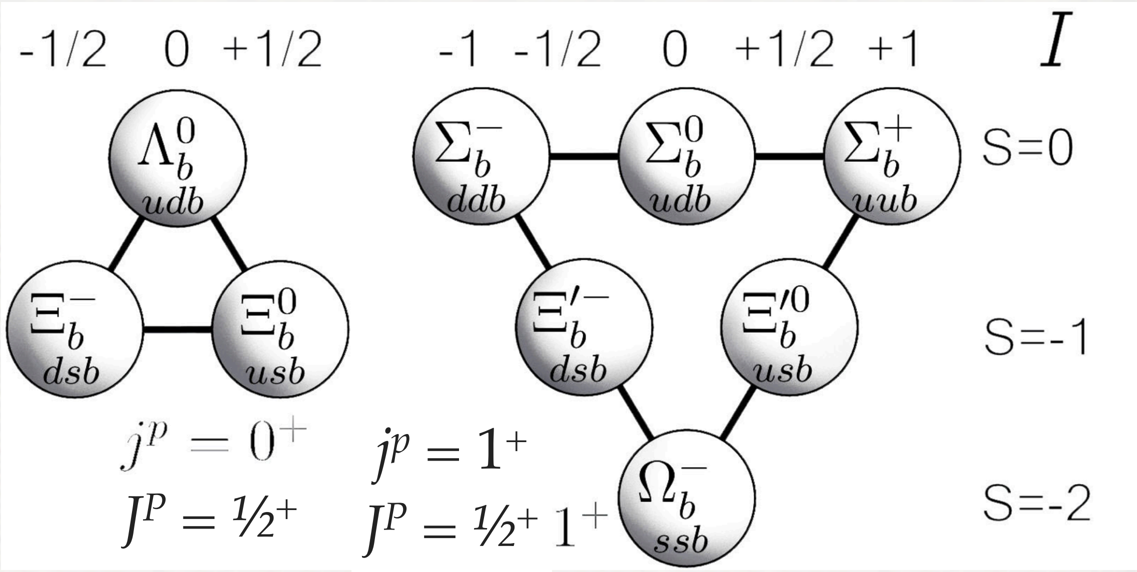
Thursday, November 5, 15

OBSERVATION OF Ξ_b^{*0}



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).



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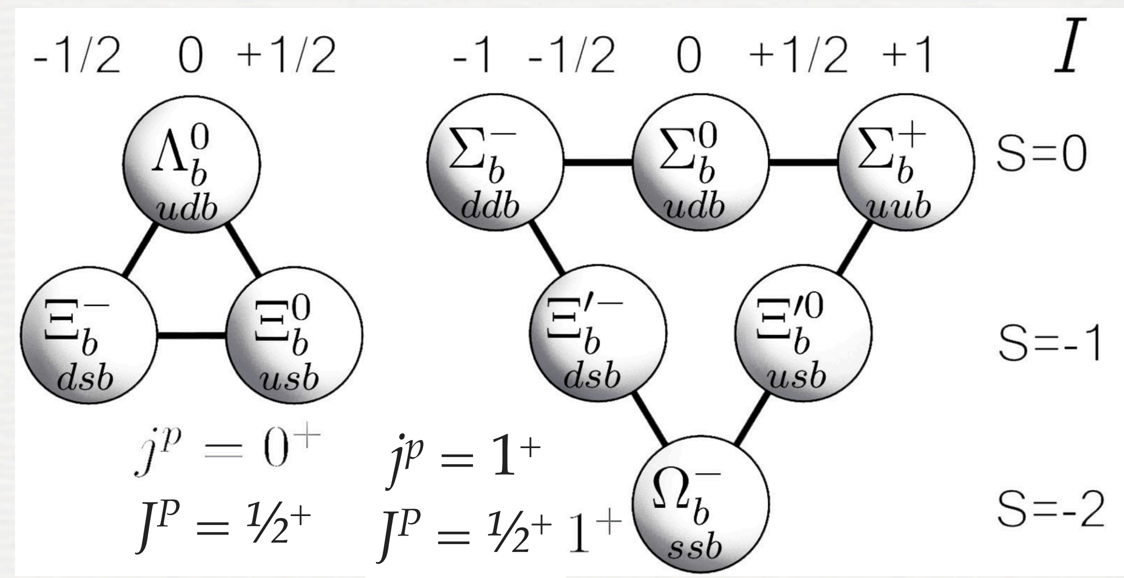

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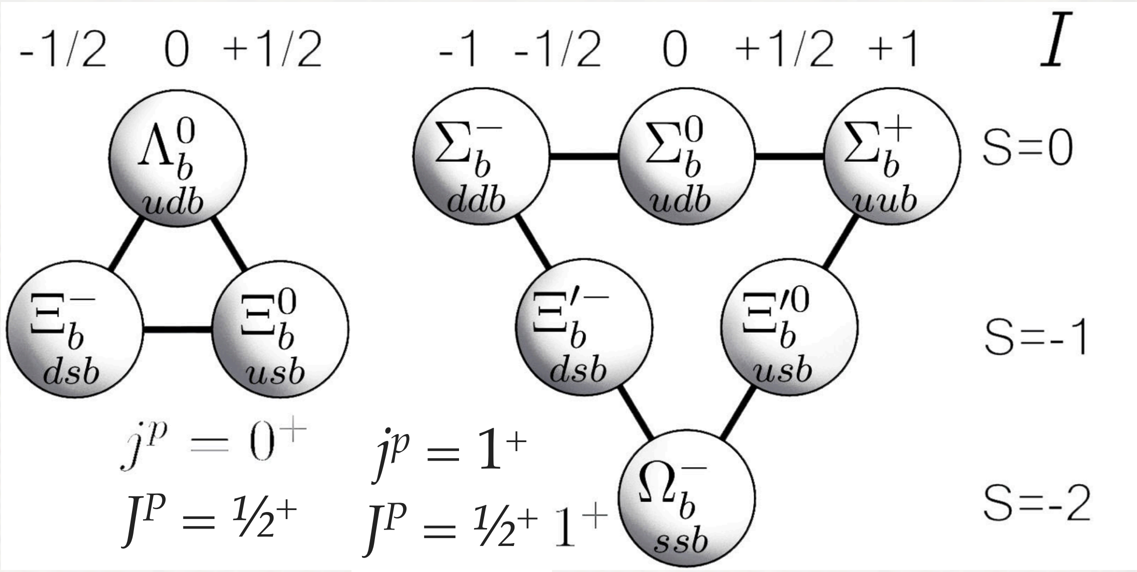

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- Theory: $m_{\Xi_b'^0} - m_{\Xi_b^-} < m_\pi$ $\Rightarrow$ kinematically forbidden.
- Then look for:

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

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

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  - To train ⇔ test ⇔ apply (1/3 sample).
  - Divide 2011-12, barrel & endcap ⇒ *12 BDT*!
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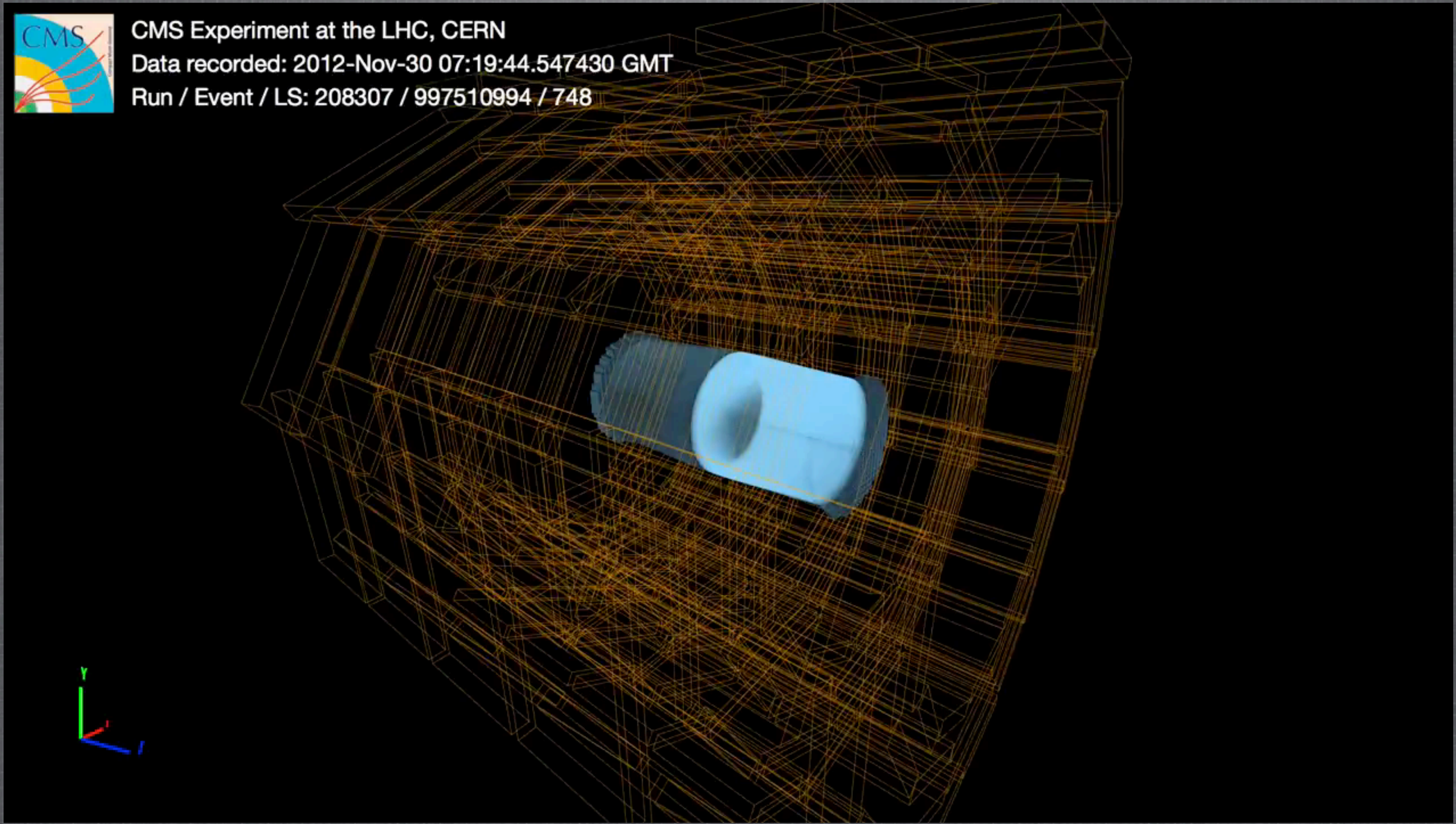
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \frac{N_S}{N^{B^+}_{\text{obs}}} \frac{f_u}{f_s} \frac{\varepsilon^{B^+}_{\text{tot}}}{\varepsilon_{\text{tot}}} \mathcal{B}(B^+)$$

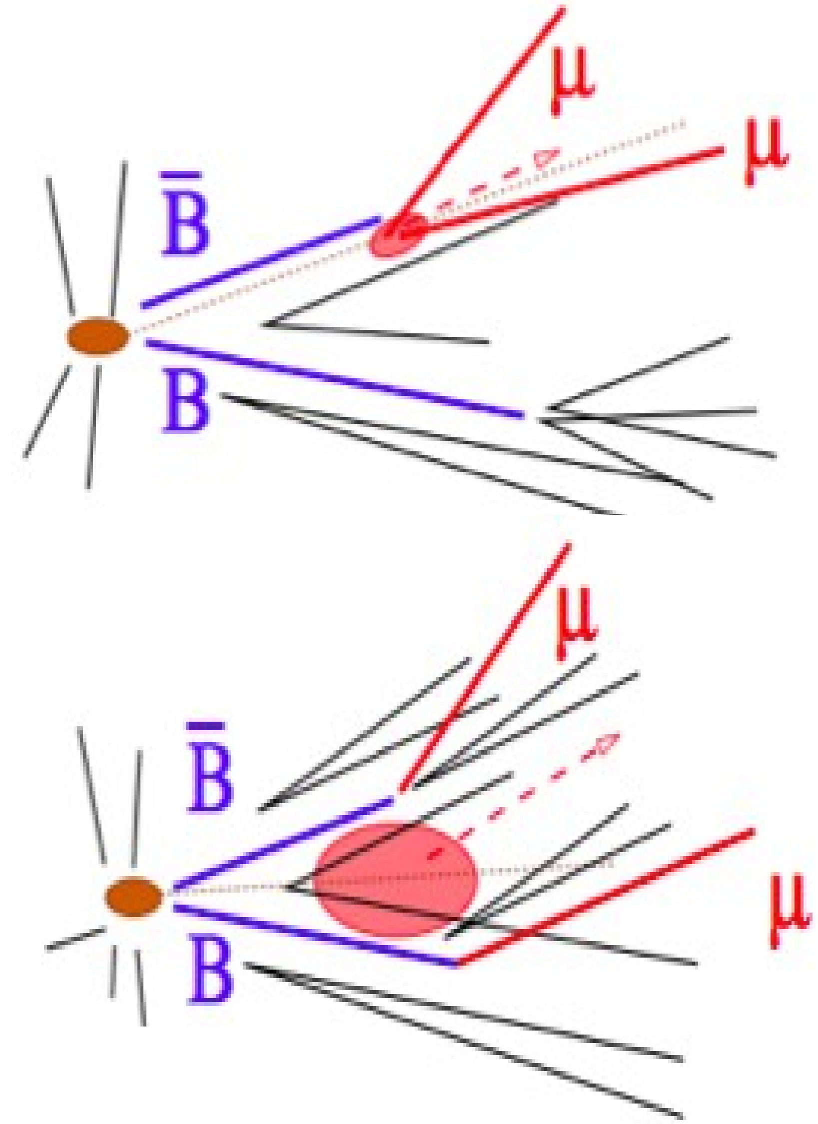
efficiencies from MC



Dimuon trigger + blind analysis

$B \to \mu^+\mu^-$

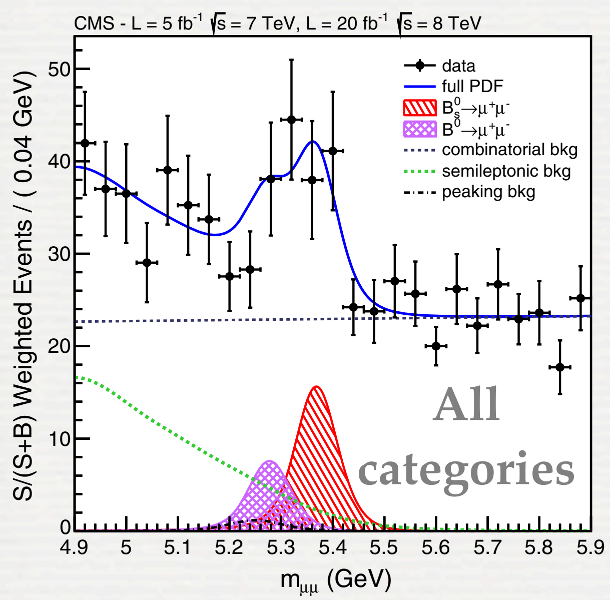
- Signal:
  - Two isolated muons from a secondary vertex
  - $M(\mu^+\mu^-) \sim M(B^0_{s(d)})$
  - Momentum aligned with flight direction

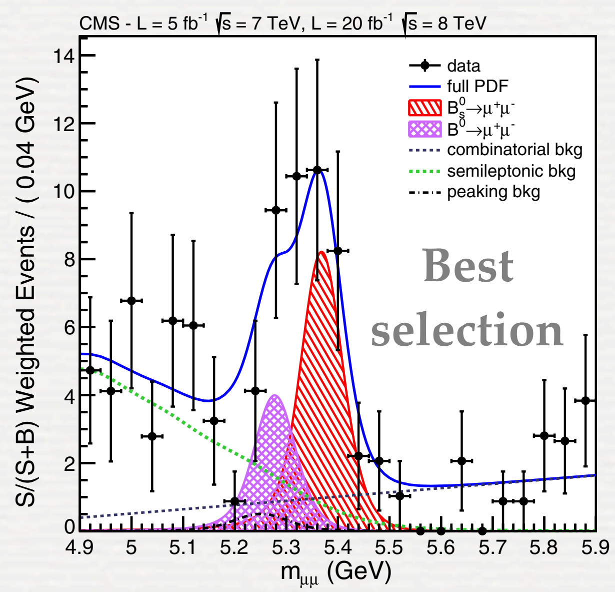


- BKG:
  - Combinatorial from uncorrelated B semileptonic decays
  - Physical:
    - Peaking $B \to hh'$ (h=misidentified K, π) (BR~$10^{-7}/10^{-5}$)
    - Non Peaking $B \to h\mu\nu$, $B \to h\mu\mu$, $\Lambda_b \to p\mu\nu$

RESULTS

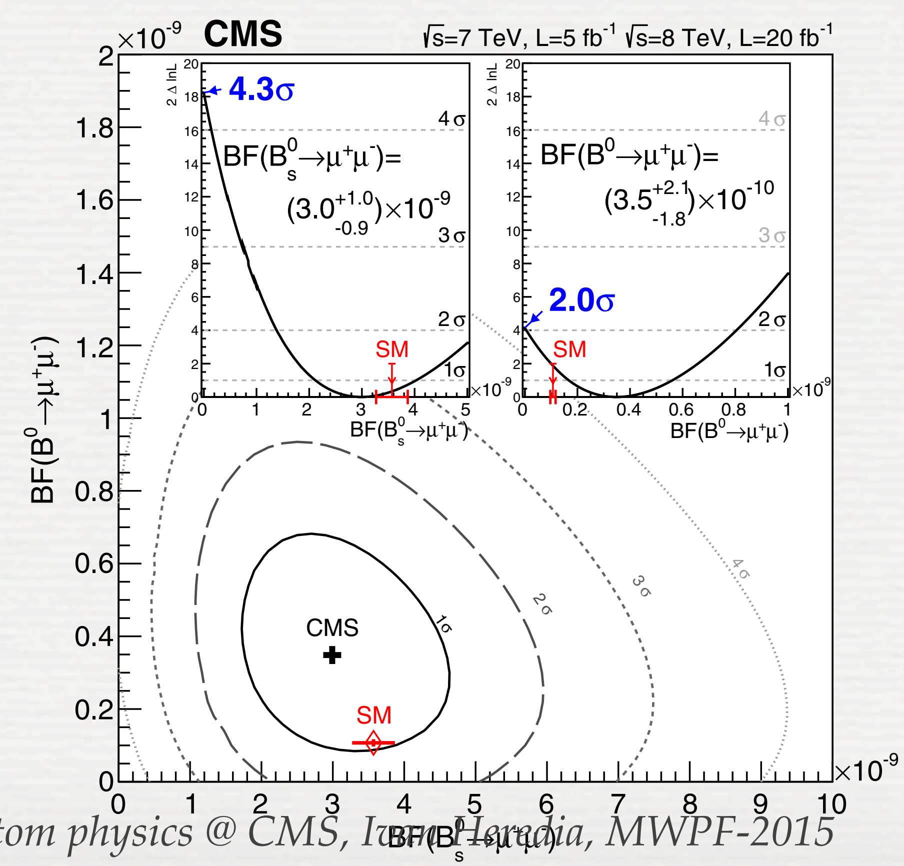
$B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$





Results (full sample) PRL 111 (2013) 101804

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



RESULTS

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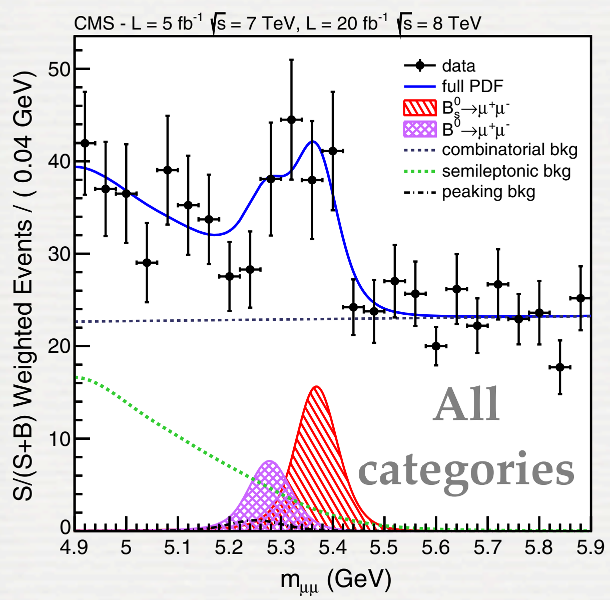

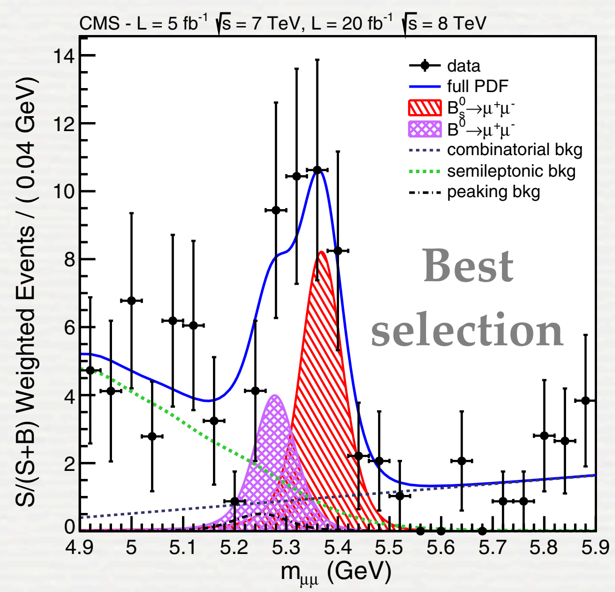

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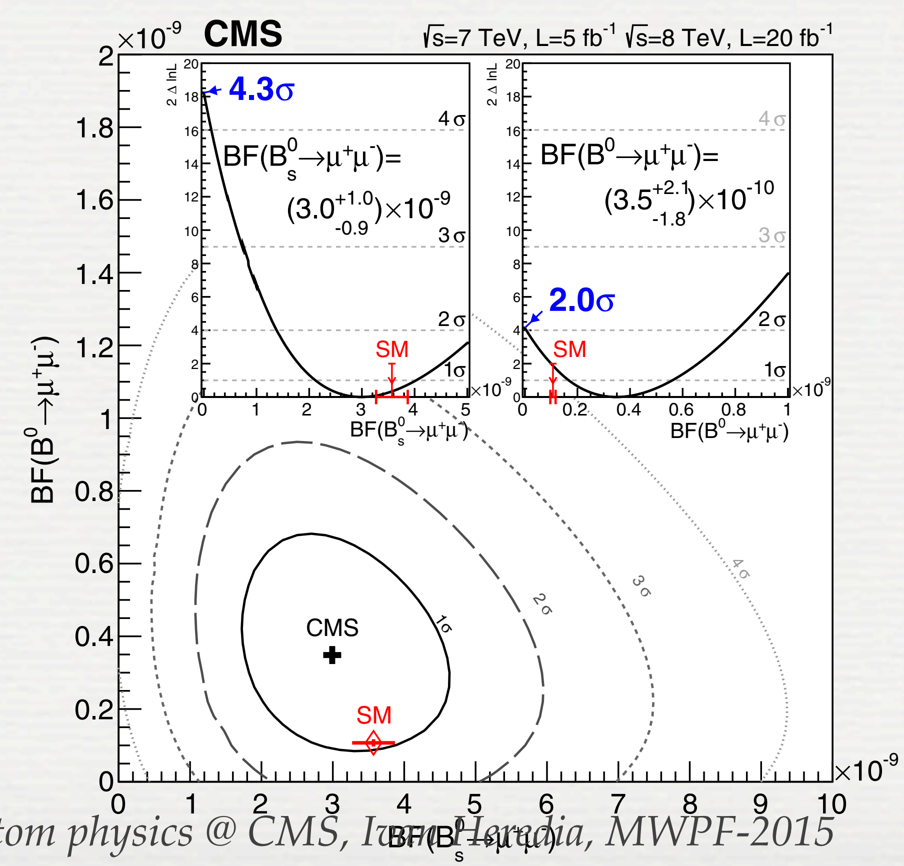
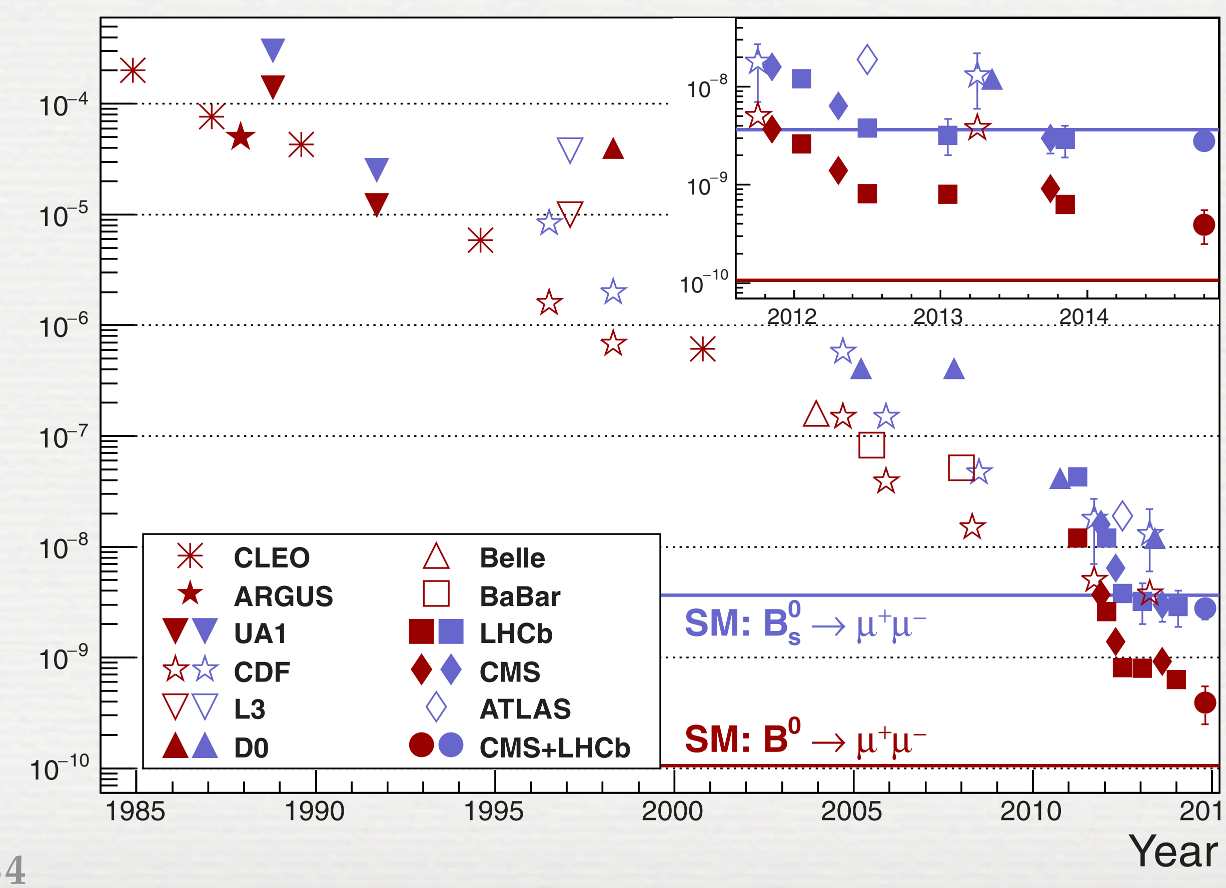
Previous CMS results:

PRL 107 (2011) 191802 & JHEP 04 (2012) 033





ADDITIONAL RESULTS OF $B^0 \to K^{*0}\mu^+\mu^-$

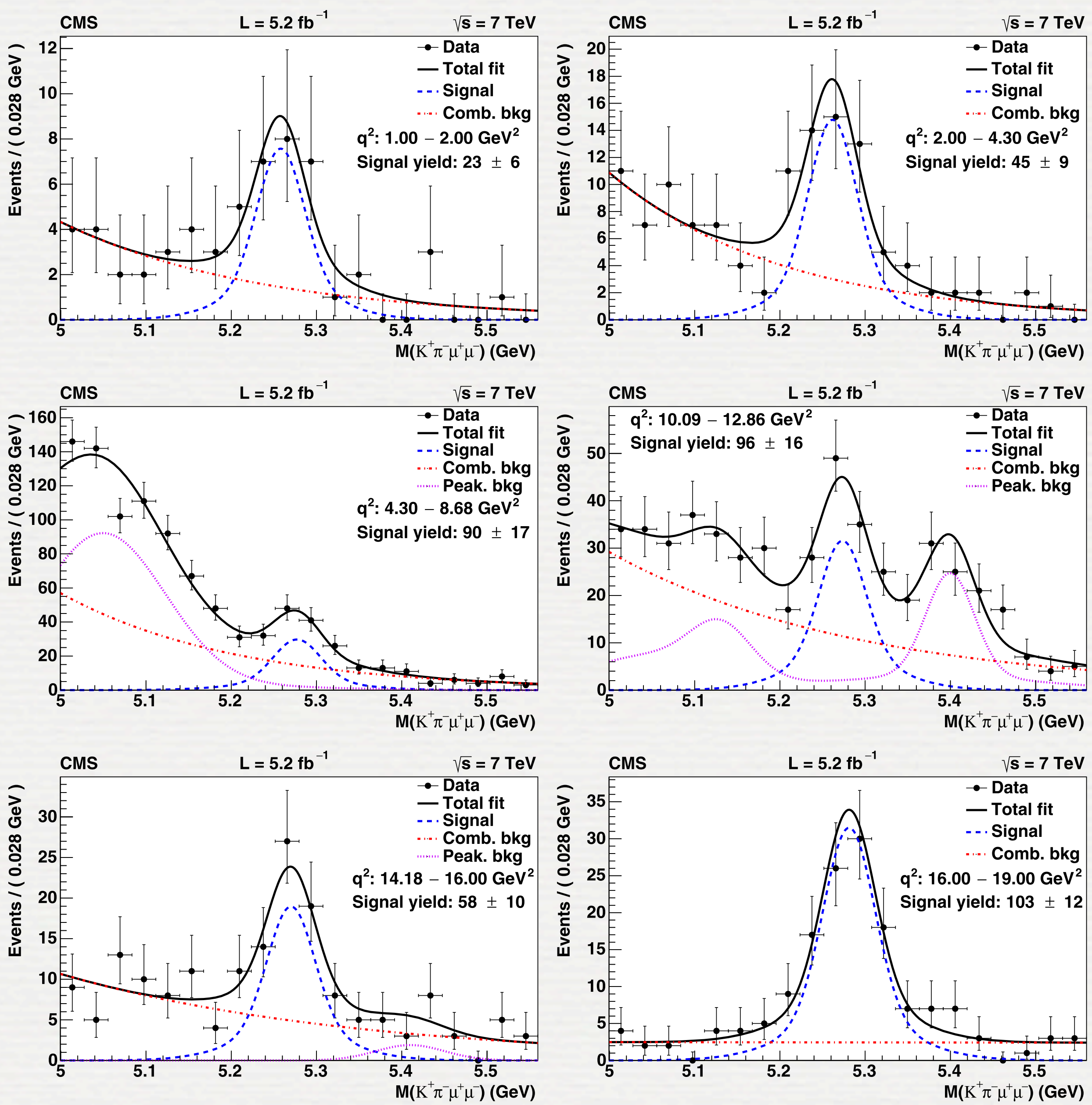
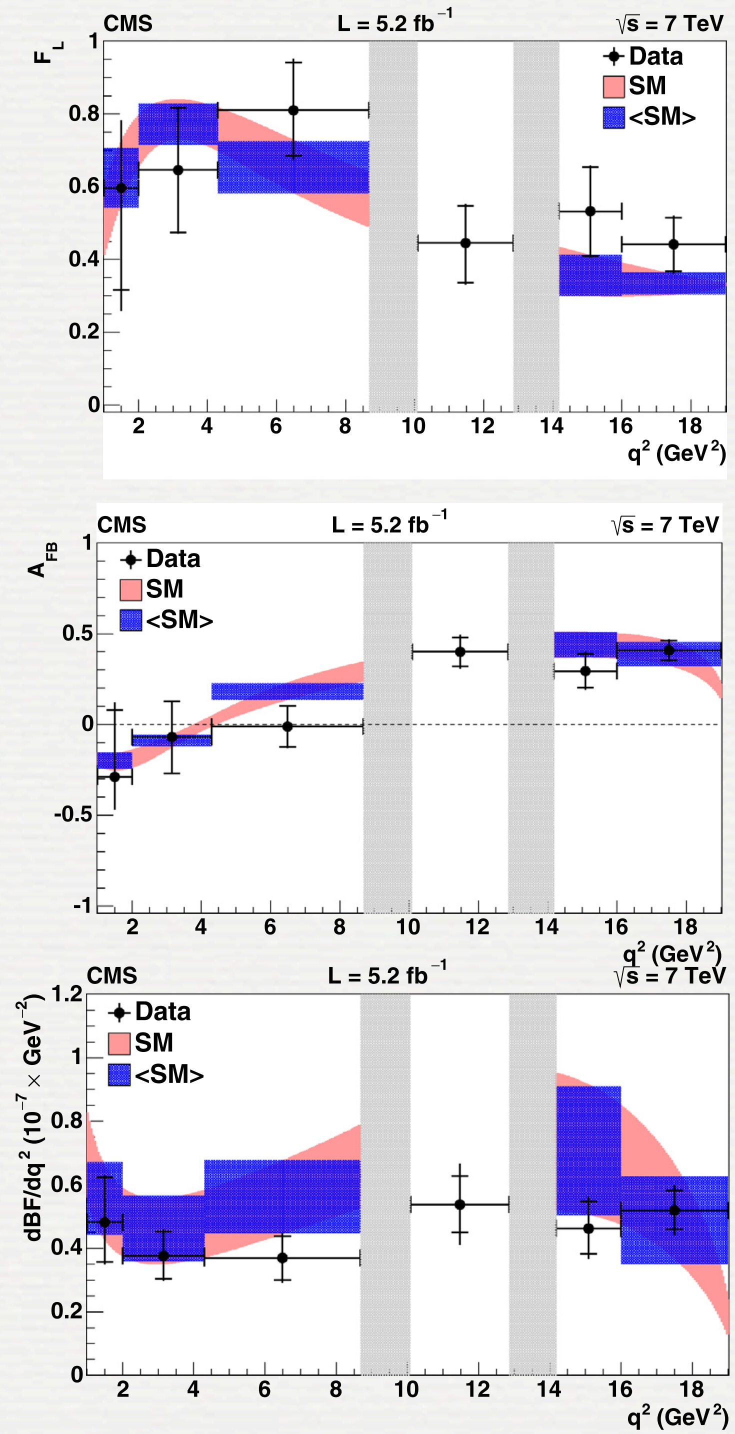


Fig. 3. The $K^+\pi^-\mu^+\mu^-$ invariant-mass distributions for each of the signal q^2 bins. Overlaid on each mass distribution is the projection of the unbinned maximum-likelihood fit results for the overall fit (solid line), the signal contribution (dashed line), the combinatorial background contribution (dot-dashed line), and the peaking background contribution (dotted line).



Rare B decays: New Physics probes

- Weak decay of hadron M into final state F described via an Effective Hamiltonian expressed by means of Operator Product Expansion:

$$A(M \to F) = \langle F | H_{eff} | M \rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \langle F | Q_i(\mu) | M \rangle$$

$C_i(\mu)$: Wilson Coefficients (perturbative short distance couplings)
$Q_i(\mu)$: Hadronic Matrix Elements (non -perturbative long distance effects)

- NP could modify Wilson Coefficients $C_i(\mu)$ and/or add new operators $Q_i(\mu)$

- Complementary information from different rare decays:

$B \to \mu\mu$: Scalar/Pseudoscalar interactions

$B \to K^{(*)}\mu\mu$: Vector/axial interactions

THEORY OF $B^0 \to K^*(892)^0 \mu^+ \mu^-$

Rare semileptonic $|\Delta B| = |\Delta S| = 1$ decays are described by an effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i \mathcal{C}_i(\mu) \mathcal{O}_i(\mu). \qquad (2)$$

In the SM $b \to s\ell^+\ell^-$ processes are mainly governed by the operators $\mathcal{O}_{7,9,10}$, which will be referred to as the SM operator basis. Beyond the SM chirality-flipped ones $\mathcal{O}_{7',9',10'}$, collectively denoted here by SM$'$, may appear.

Semileptonic penguin operators

$$\mathcal{O}_{7(7')} = \frac{m_b}{e}[\bar{s}\sigma^{\mu\nu}P_{R(L)}b]F_{\mu\nu}, \quad \text{(magnetic)}$$

$$\mathcal{O}_{9(9')} = [\bar{s}\gamma_\mu P_{L(R)}b][\bar{\ell}\gamma^\mu \ell], \quad \text{(vector)}$$

$$\mathcal{O}_{10(10')} = [\bar{s}\gamma_\mu P_{L(R)}b][\bar{\ell}\gamma^\mu \gamma_5 \ell]. \quad \text{(axial)}$$

$$\frac{8\pi}{3}\frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_K d\phi} = (J_{1s} + J_{2s}\cos 2\theta_\ell + J_{6s}\cos\theta_\ell)\sin^2\theta_K + (J_{1c} + J_{2c}\cos 2\theta_\ell + J_{6c}\cos\theta_\ell)\cos^2\theta_K$$
$$+ (J_3 \cos 2\phi + J_9 \sin 2\phi)\sin^2\theta_K \sin^2\theta_\ell + (J_4\cos\phi + J_8\sin\phi)\sin 2\theta_K \sin 2\theta_\ell$$
$$+ (J_5\cos\phi + J_7\sin\phi)\sin 2\theta_K \sin\theta_\ell,$$

$$\langle J_i \rangle = \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 J_i(q^2)$$

$$\frac{d\langle\Gamma\rangle}{d\cos\theta_\ell} = \langle J_{1s}\rangle + \frac{\langle J_{1c}\rangle}{2} + \left(\langle J_{6s}\rangle + \frac{\langle J_{6c}\rangle}{2}\right)\cos\theta_\ell + \left(\langle J_{2s}\rangle + \frac{\langle J_{2c}\rangle}{2}\right)\cos 2\theta_\ell, \qquad \text{(A5)}$$

$$\frac{d\langle\Gamma\rangle}{d\cos\theta_K} = \frac{3}{2}\left[\left(\langle J_{1s}\rangle - \frac{1}{3}\langle J_{2s}\rangle\right)\sin^2\theta_K + \left(\langle J_{1c}\rangle - \frac{1}{3}\langle J_{2c}\rangle\right)\cos^2\theta_K\right] \qquad \text{(A6)}$$

$$\langle A_{\text{FB}}\rangle\langle\Gamma\rangle = \langle J_{6s}\rangle + \frac{\langle J_{6c}\rangle}{2};$$

$$\langle F_L\rangle = \frac{1}{\langle\Gamma\rangle}\left(\langle J_{1c}\rangle - \frac{1}{3}\langle J_{2c}\rangle\right),$$

$$\langle F_T\rangle = \frac{2}{\langle\Gamma\rangle}\left(\langle J_{1s}\rangle - \frac{1}{3}\langle J_{2s}\rangle\right),$$

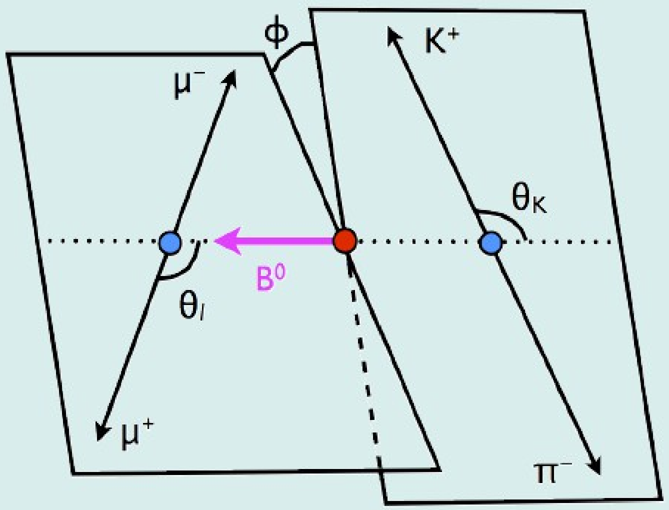
$B \to K^* \mu^+\mu^-$ at LHCb

JHEP 08 (2013) 131

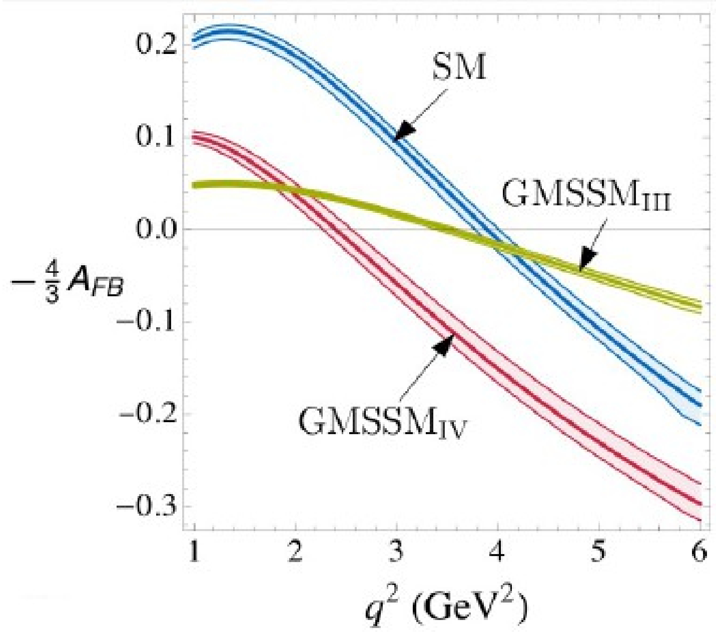
Decay described in three angles (θ_l, θ_K, φ) and dimuon mass q^2

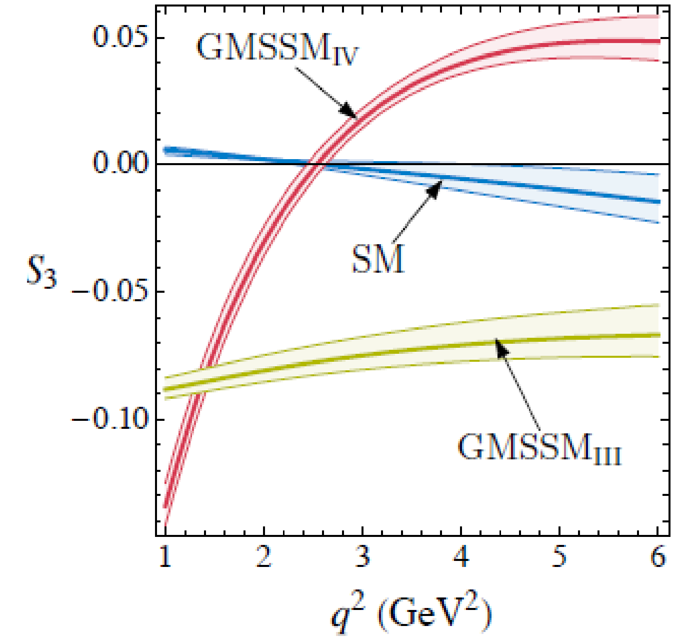
Fit to θ_l, θ_K, φ and q^2 to extract the interesting parameters

$$\frac{1}{\Gamma}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\hat{\phi}\, dq^2} = \frac{9}{16\pi}\Big[F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) + F_L\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell-1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell + S_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi}\Big]$$



Altmannshofer et al. [JHEP 01 (2009) 019





- Forward-backward asymmetry $\mathbf{S_6 = 4/3\ A_{FB}}$
- Transverse asymmetry $\mathbf{S_3 = (1-F_L)A_T^2}$
- Fraction of longitudinal K* polarization $\mathbf{F_L}$
- CP asymmetry $\mathbf{S_9}$

P'$_5$ anomaly

PRL 111 191801 (2013)

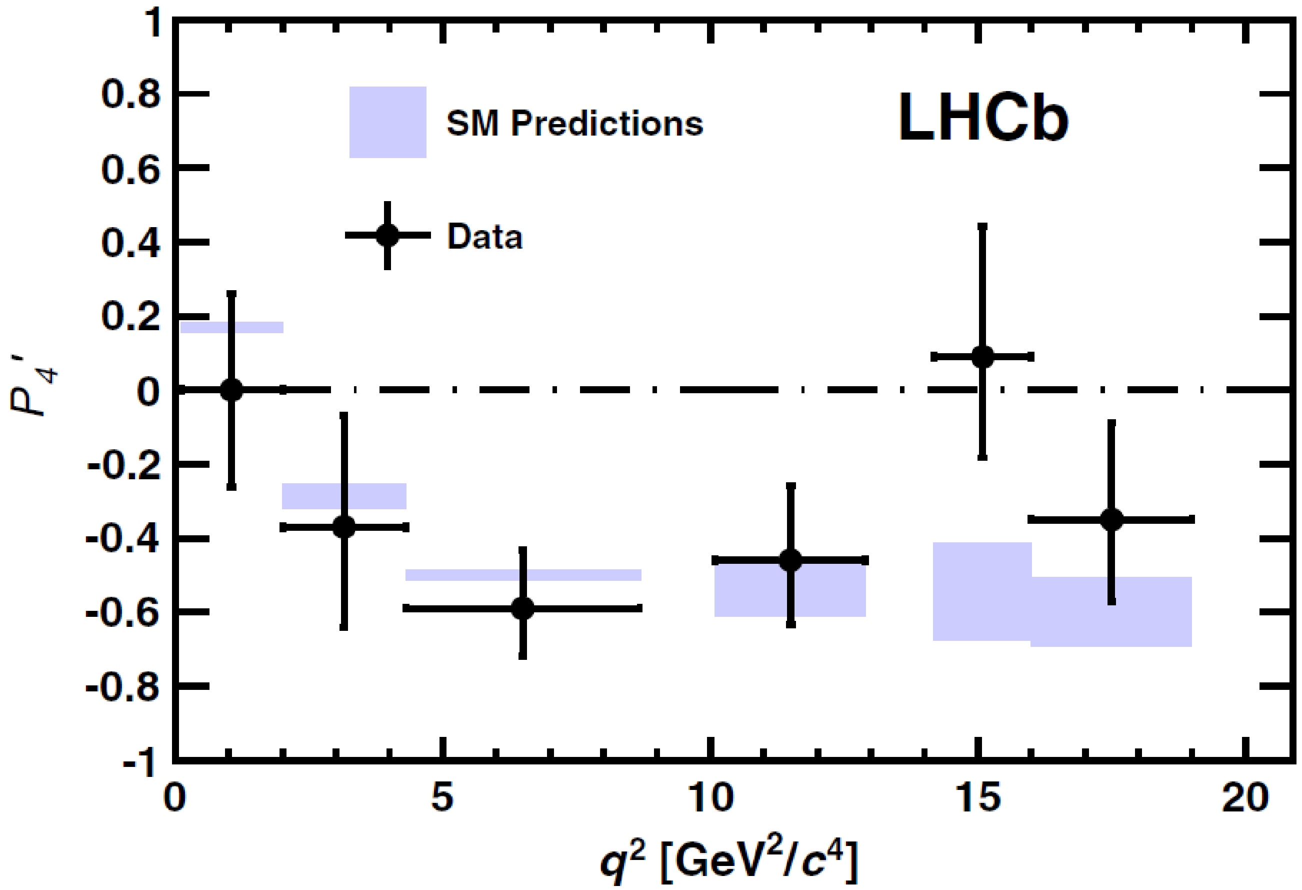
LHCb also measured

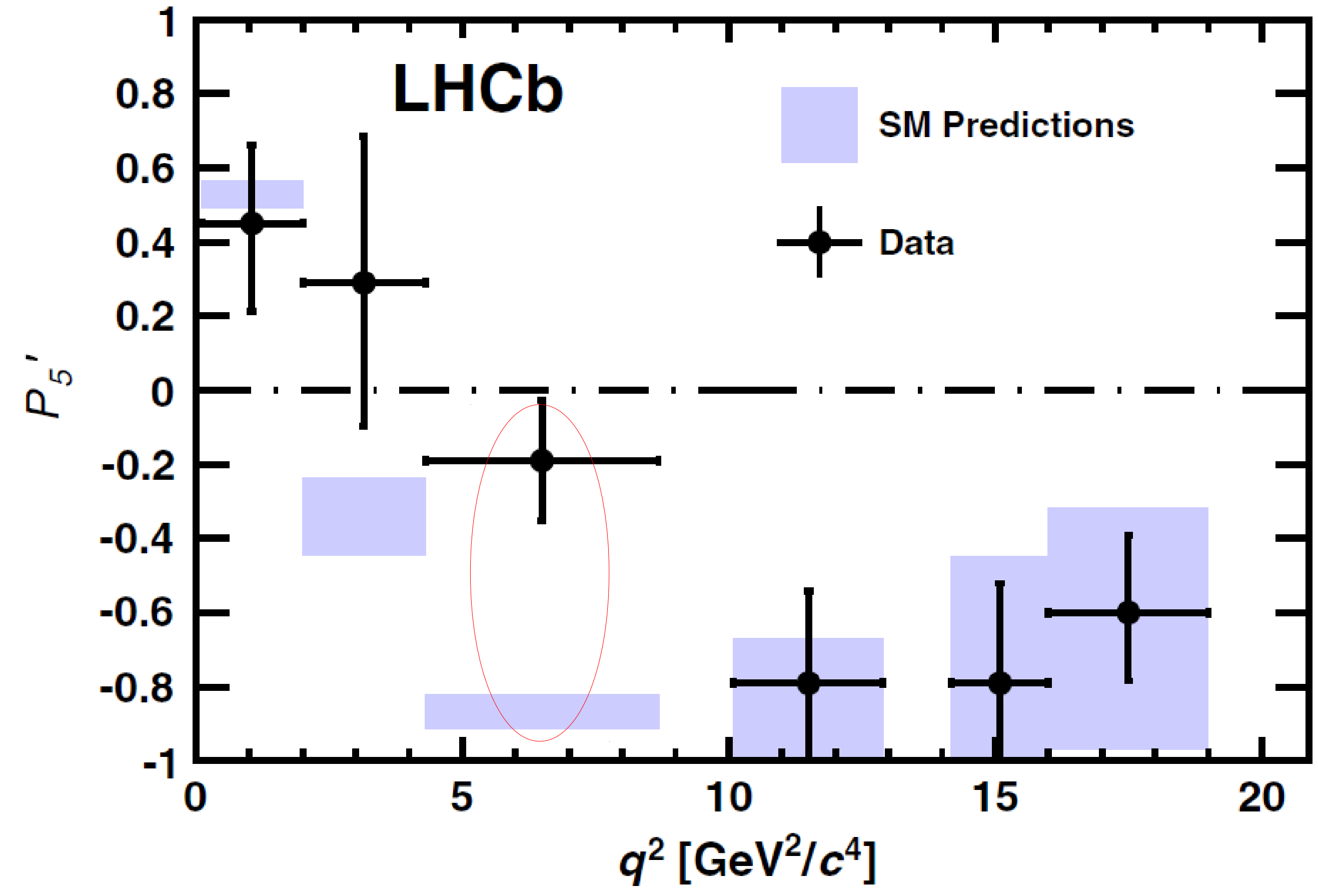
$$P'_{4,5} = \frac{S_{4,5}}{\sqrt{F_L(1-F_L)}}$$

$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

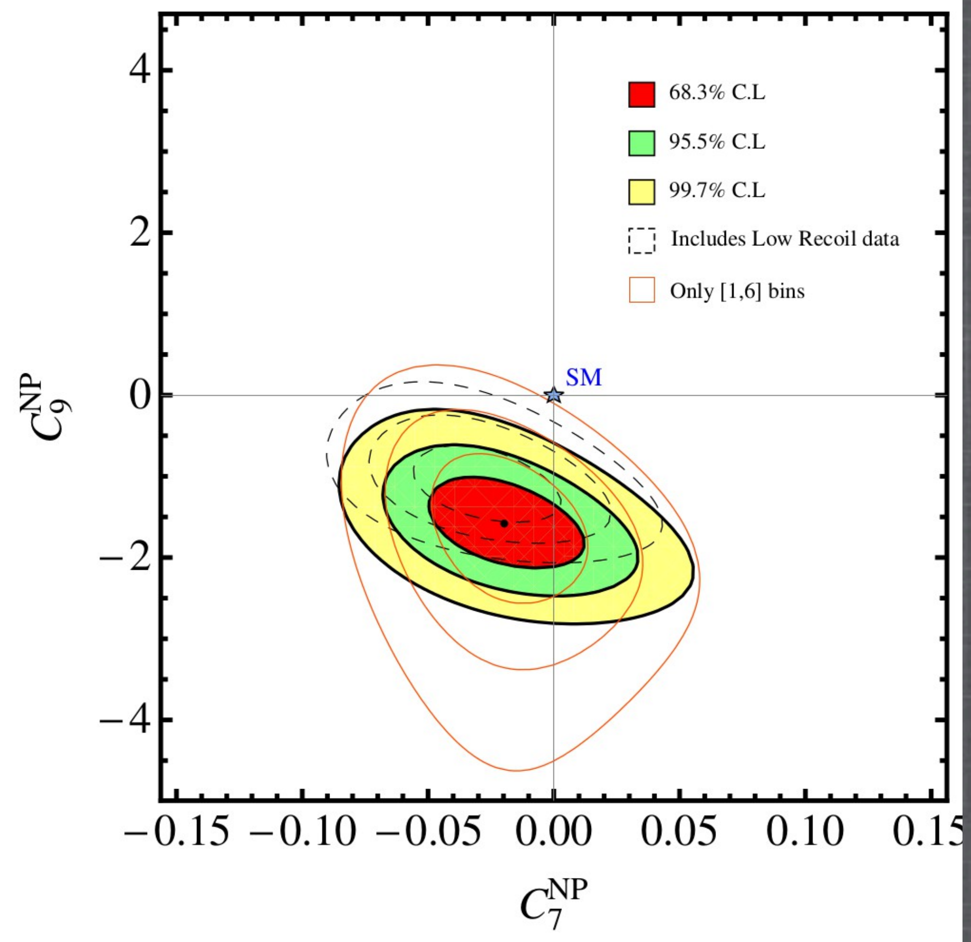
which are quite free from form-factor uncertainties [Decotes-Genon et al. JHEP 05 (2013) 137]

Local discrepancy in P'$_5$ at 3.7σ (probability that at least one bin varies by this much is 0.5%



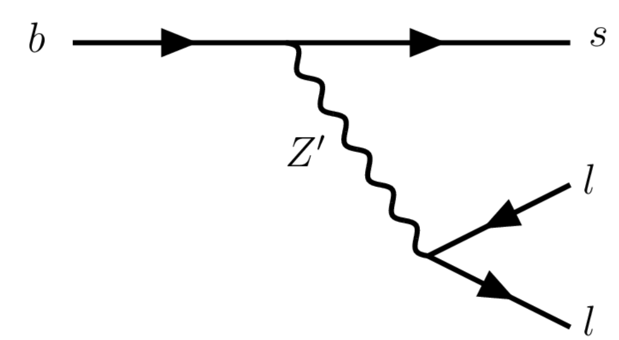


P'_5 anomaly



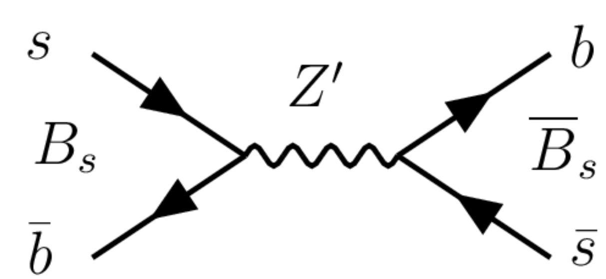
Many theoretical papers to understand data

Altmannshofer & Straub perform a global analysis and find discrepancies at the level of 3σ. Data best described by **modified C_9**, by introducing a **flavour-changing Z' boson** at O(1TeV or higher). [EPJC 73 2646 (2013), Gaul, Goertz & Haisch, JHEP 01 (2014) 069]



Data could be also explained by floating **form-factor uncertainties**. In this way the discrepancy can be reduced to ≈ 2σ. [Jaeger & Camalich, JHEP 05 (2013) 043]

Lattice QCD predictions + **measurements in related channels** can help clarify the situation



STATUS OF $B \rightarrow X\mu^+\mu^-$

# of events	BaBar $433fb^{-1}$	Belle $605fb^{-1}$	CDF $9.6fb^{-1}$	LHCb 1 / 3 fb^{-1}	ATLAS $5fb^{-1}$	CMS $5fb^{-1}$
$B^0 \rightarrow K^{*0} \ell^+\ell^-$	137±44*	247±54*	288±20	2361±56	466±34	415±29
$B^+ \rightarrow K^{*+} \ell^+\ell^-$			24±6	162±16		
$B^+ \rightarrow K^+ \ell^+\ell^-$	153±41*	162±38*	319±23	4746±81		
$B^0 \rightarrow K^0_s \ell^+\ell^-$			32±8	176±17		
$B_s \rightarrow \phi \ell^+\ell^-$			62±9	174±15		
$\Lambda_b \rightarrow \Lambda \ell^+\ell^-$			51±7	78±12		
$B^+ \rightarrow \pi^+ \ell^+\ell^-$		limit		25±7		

Babar arXiv:1204.3933
Belle arXiv:0904.0770
CDF arXiv:1107.3753 + 1108.0695 + ICHEP 2012

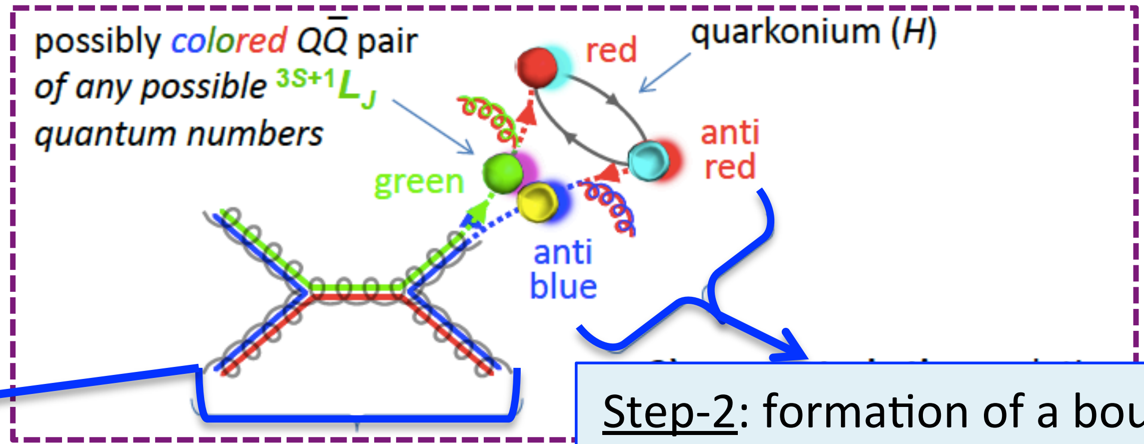
ATLAS (preliminary) [ATLAS-CONF-2013-038]
CMS (preliminary) [CMS-BPH-11-009]

LHCb arxiv:1403.8044 +1305.2168 +1306.2577 +JHEP12(2012)125

*mixture of B^0 and $B^{\pm}$ and $\ell = e,\mu$
other experiments: $\ell = \mu$ only

Reference theory of production & polarization of quarkonia

- **NRQCD** : effective field theory that treats heavy quarkonia as non-relativistic systems. Inclusive quarkonium production can be factorized in two distinct steps:



Step-1: $Q\bar{Q}$ production in the regime of perturbative QCD

Step-2: formation of a bound state driven by non-pert. QCD

Inclusive xsection for producing quarkonium (***H***) with enough large momentum transfer p_T :

$$\sigma(A+B \to H+X) = \sum_n \sigma\left(A+B \to [Q\bar{Q}]_n + X\right) \odot P\left([Q\bar{Q}]_n \to H\right) \quad , \quad n = {}^{2S+1}L_J^{[C]}$$

Short-distance coefficients (SDCs)

calculated by perturbative QCD (expansions in α_S)

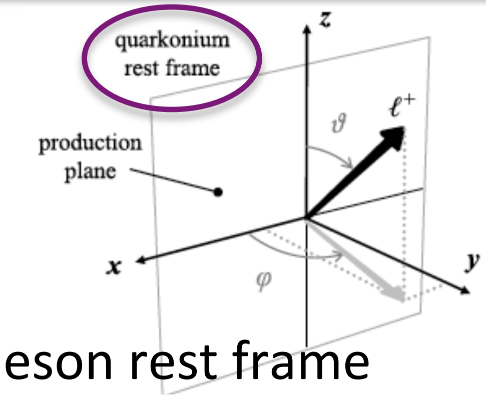
Long-distance matrix elements (LDMEs)

determined from fits to experimental data

relative relevance given by $v = \upsilon/c \ll 1$ **(scaling rules)**

- Theoretical predictions are organized as double expansions in α_S and *v*. Truncation of *v-expansion* for *S-wave* states in NRQCD includes 4 terms:
  - Color Singlet (CS) term
  - 3 Color Octet (CO) terms
- NRQCD predicts the existence of intermediate CO states in nature, that subsequently evolve into physical color-singlet quarkonia by non-perturbative emission of soft gluons.
- Recent developments to explain production Xsections & polarization get reasonable agreement with data excluding data at low p_T: **unpolarized CO contribution dominates the production** [PLB 737 (2014) 98 (data-driven approach)] [PRL 113 (2014) 022001 (leading-power fragm. formalism)]

Polarization of S-wave states



- The polarization of a vector meson decaying into a lepton pair is reflected in the leptons' angular distributions. The most general 2D angular distribution W for the dileptons is specified by 3 polarization parameters $\lambda_\theta,\ \lambda_\phi,\ \lambda_{\theta\phi}$:

$$W \equiv \frac{d^2 N}{d(\cos\theta)d\phi} \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi}\sin 2\theta \cos\phi\right)$$

where θ & ϕ for $\vec{p}(\ell^+)$ in meson rest frame

The choice of a polarization frame that is not unique: there are 3 conventional frames: HX, CS, PX.

- Two extreme angular decay distributions:

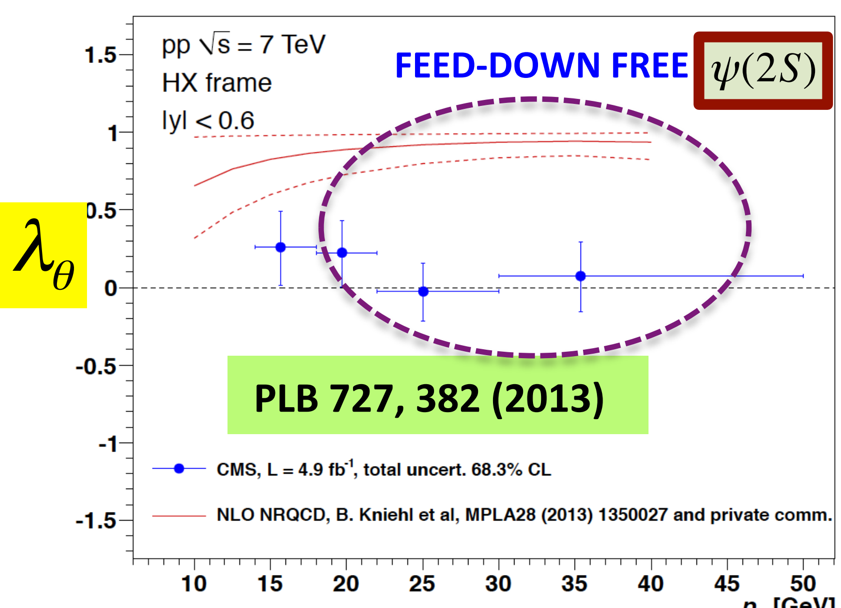
Transverse Pol. $\lambda_\theta = +1$ $(\lambda_\phi = 0,\ \lambda_{\theta\phi} = 0)$

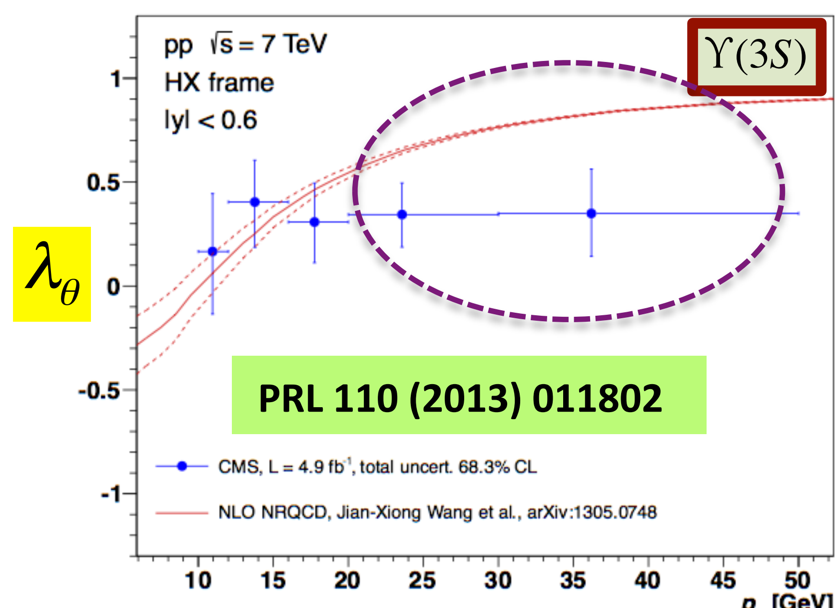
Longitudinal Pol. $\lambda_\theta = -1$

Each CS and CO term has a specific polarization; @NLO, in HX----->

- $CS\ \ {}^3S_1^{[1]}:\ \lambda_\theta = -1$ [longitudinal]
- $CO\ \ {}^1S_0^{[8]}:\ \lambda_\theta = 0$ [isotropic]
- $CO\ \ {}^3S_1^{[8]}:\ \lambda_\theta = +1$ (@ high p_T) [transverse]

- All LHC results compatible with each other: the polarizations cluster around the unpolarized limit $(\lambda_\theta = 0,\ \lambda_\phi = 0,\ \lambda_{\theta\phi} = 0)$
Thus the dominant production mechanism must be CO ${}^1S_0^{[8]}$





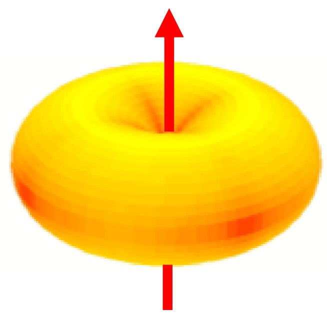
If the ${}^3S_1^{[8]}$ term becomes dominant @higher p_T/M, the quarkonia @ high p_T should be transversely polarized: need analysis with 2012 data and with Run-II data ! Test if this hierarchy among CO contributions holds also for P-wave states !

Full angular decay distribution

- Two extreme angular decay distributions

Longitudinal polarization
$J_z = 0$

$\lambda_\vartheta = -1$
$\lambda_\varphi = 0$
$\lambda_{\vartheta\varphi} = 0$

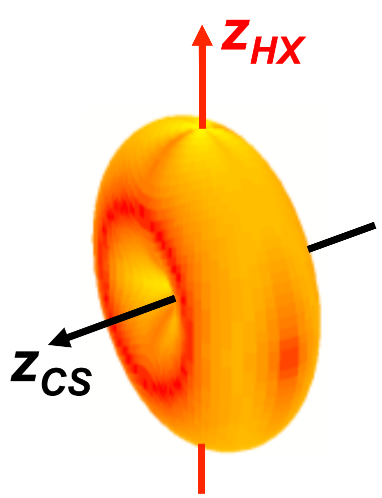


Transverse polarization
$J_z = \pm 1$

$\lambda_\vartheta = +1$
$\lambda_\varphi = 0$
$\lambda_{\vartheta\varphi} = 0$

- Unless the full angular distribution is measured, two very different physical cases are indistinguishable.

$\tilde{\lambda} = -1$



$\lambda_\vartheta = +1$
$\lambda_\varphi = -1$

$\lambda_\vartheta = -1$
$\lambda_\varphi = 0$

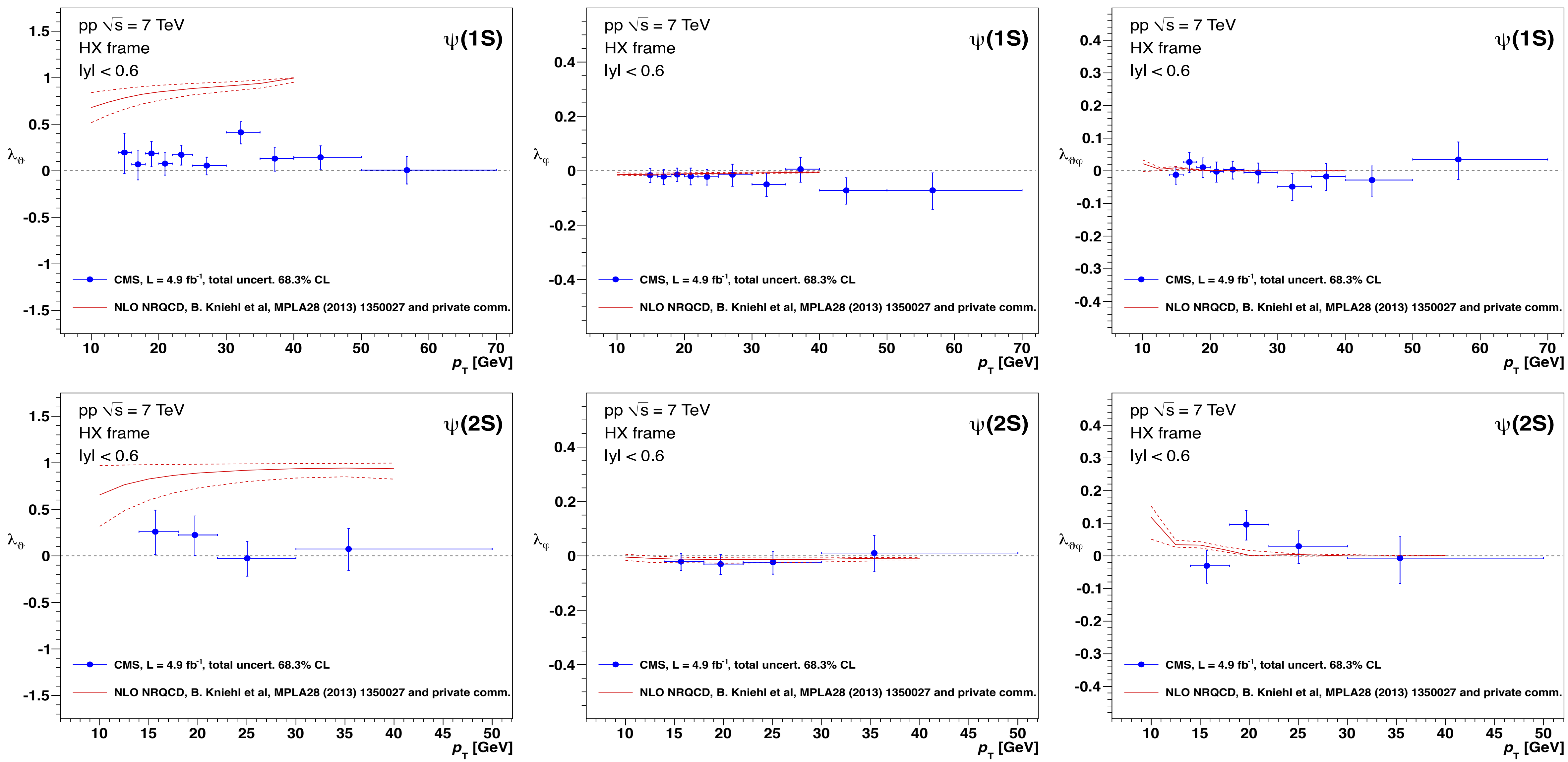
$\lambda_\vartheta = +1$
$\lambda_\varphi = 0$

$\tilde{\lambda} = +1$

- The shape of the distribution is invariant and can be characterized by the frame invariant parameter $\tilde{\lambda} = (\lambda_\vartheta + 3\lambda_\varphi)/(1 - \lambda_\varphi)$

J/ψ & ψ' POLARIZATIONS VS. NRQCD

HX frame:



X(3872) PROMPT PRODUCTION IN pp

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

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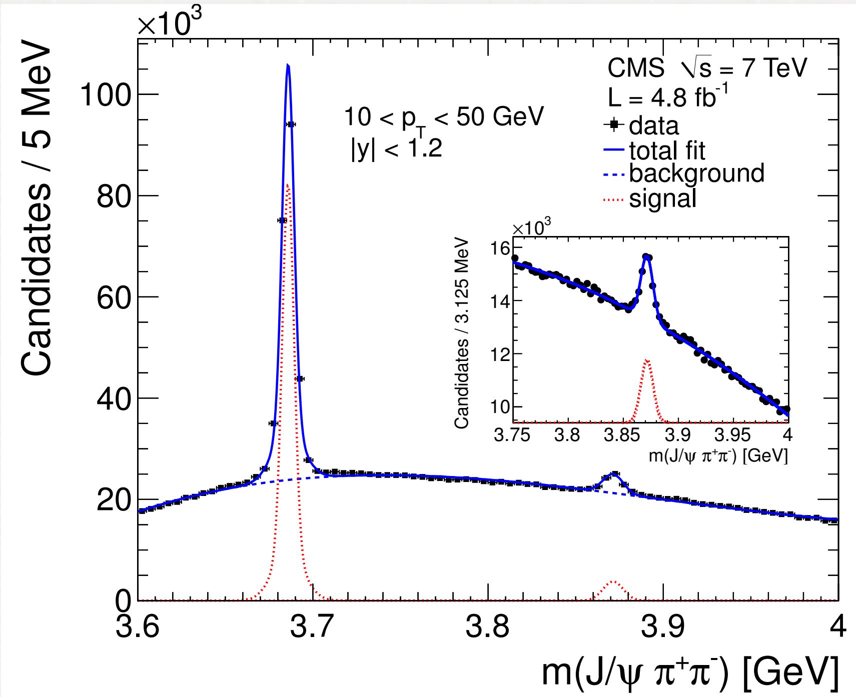

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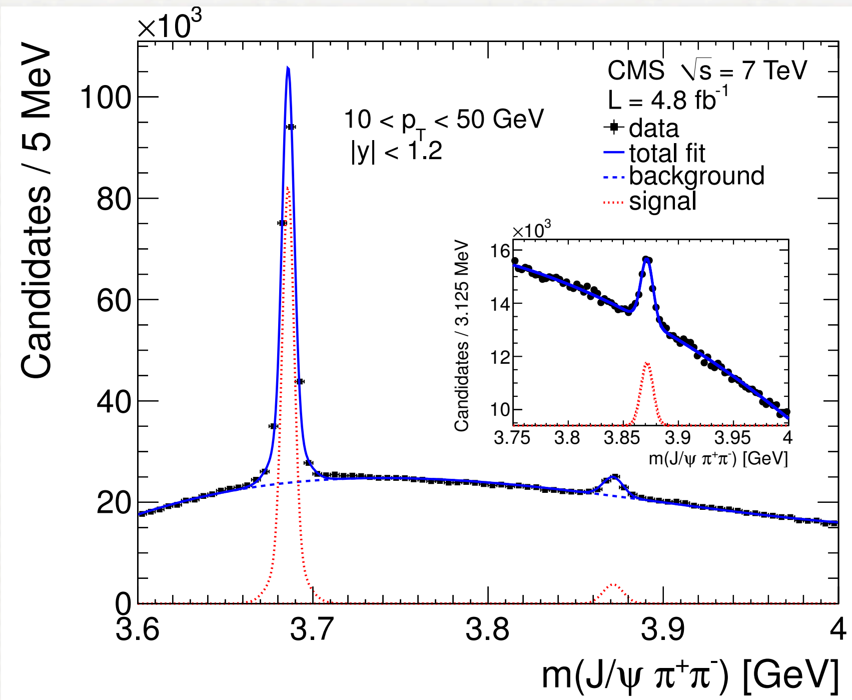

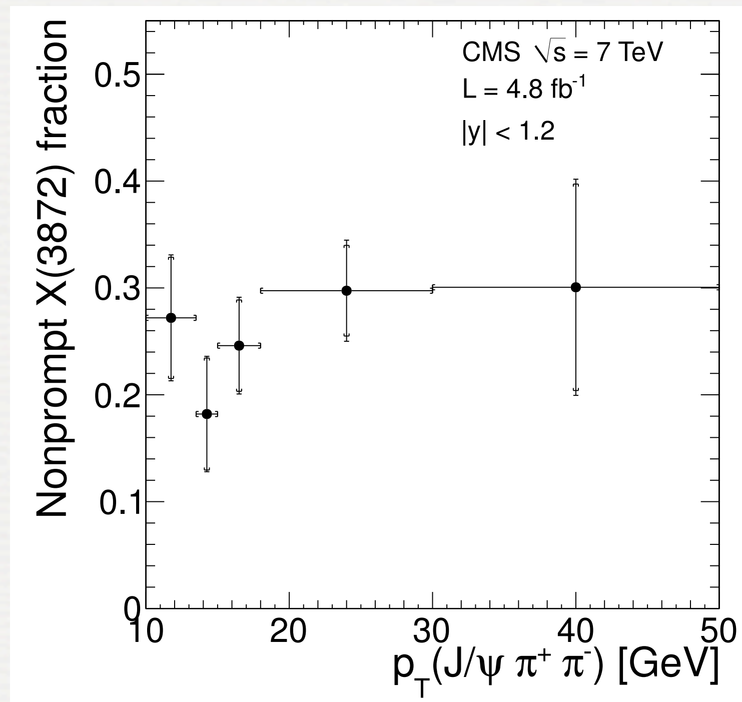

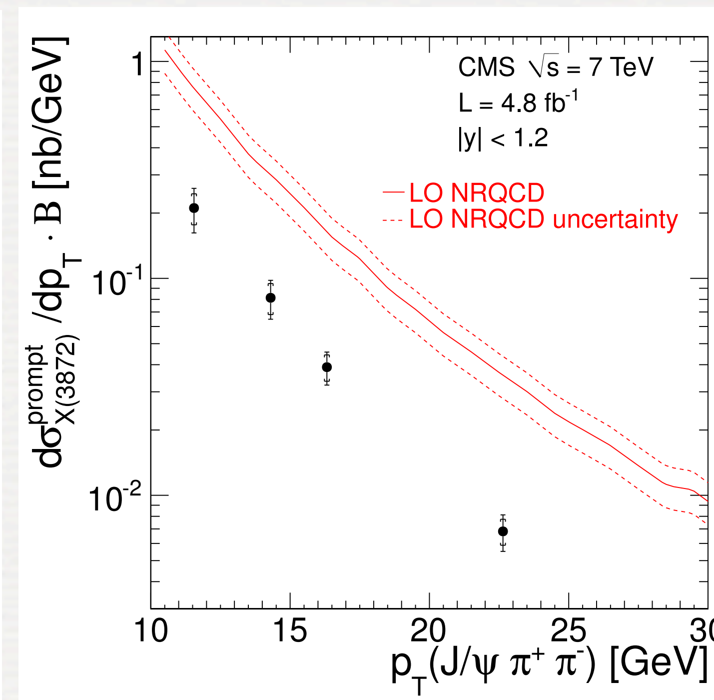

Results ($\sqrt{s} = 7$ TeV)

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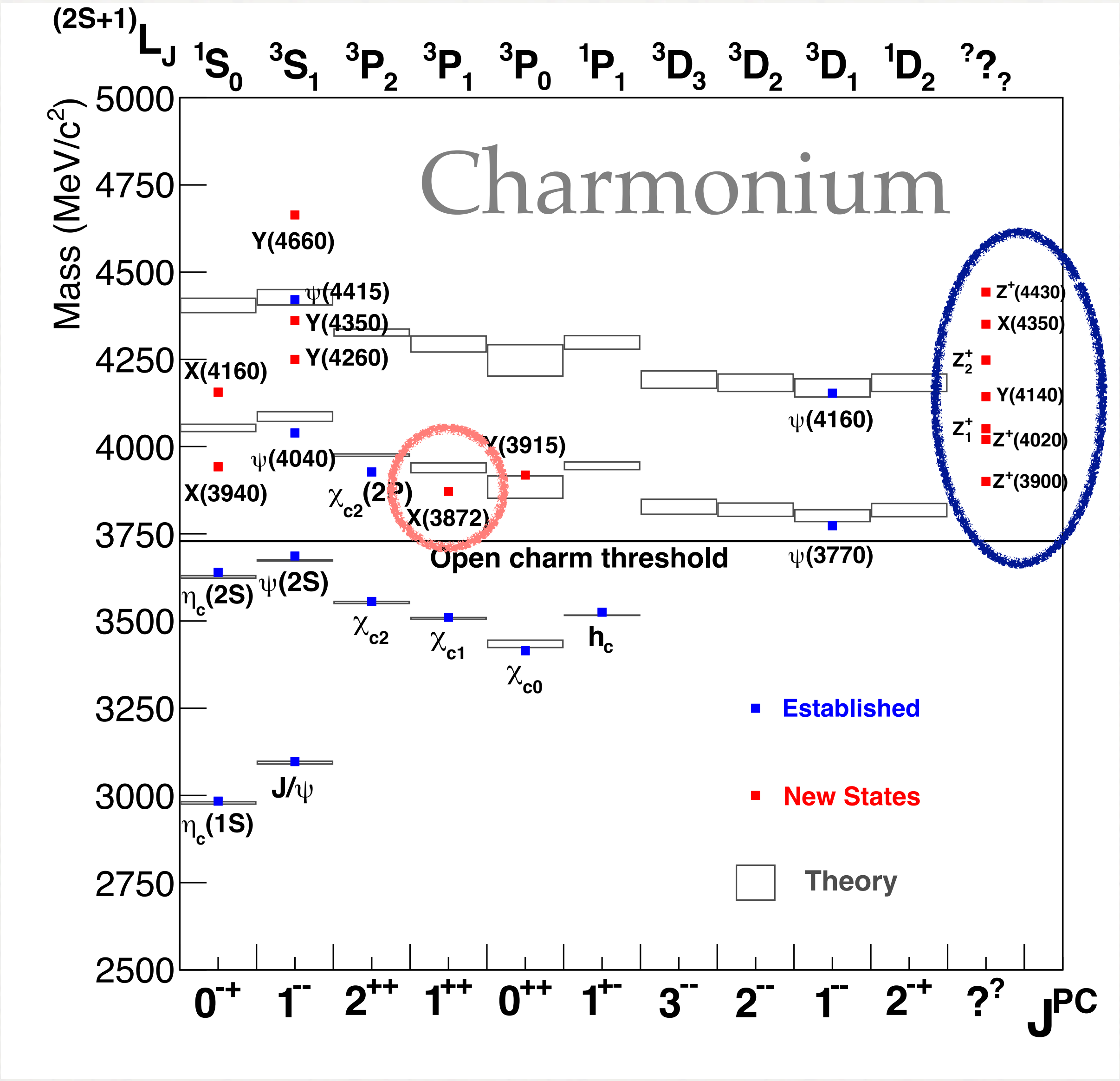
- Unpolarized $J^{PC} = 1^{++}$ state assumed.
- **Fraction of X(3872) coming from b hadrons (NP) is 0.263 ± 0.023 ± 0.016.**
- No p_T dependence of NP (or P) fraction.
- **NRQCD predictions (assuming $c\bar{c}$) for P fraction is evidently off.**
- $R = 0.0656 \pm 0.0029 \pm 0.0065$, where $R = \frac{\sigma(\mathrm{pp}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

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

WHAT IS THE X(3872) PARTICLE?



Thursday, November 5, 15

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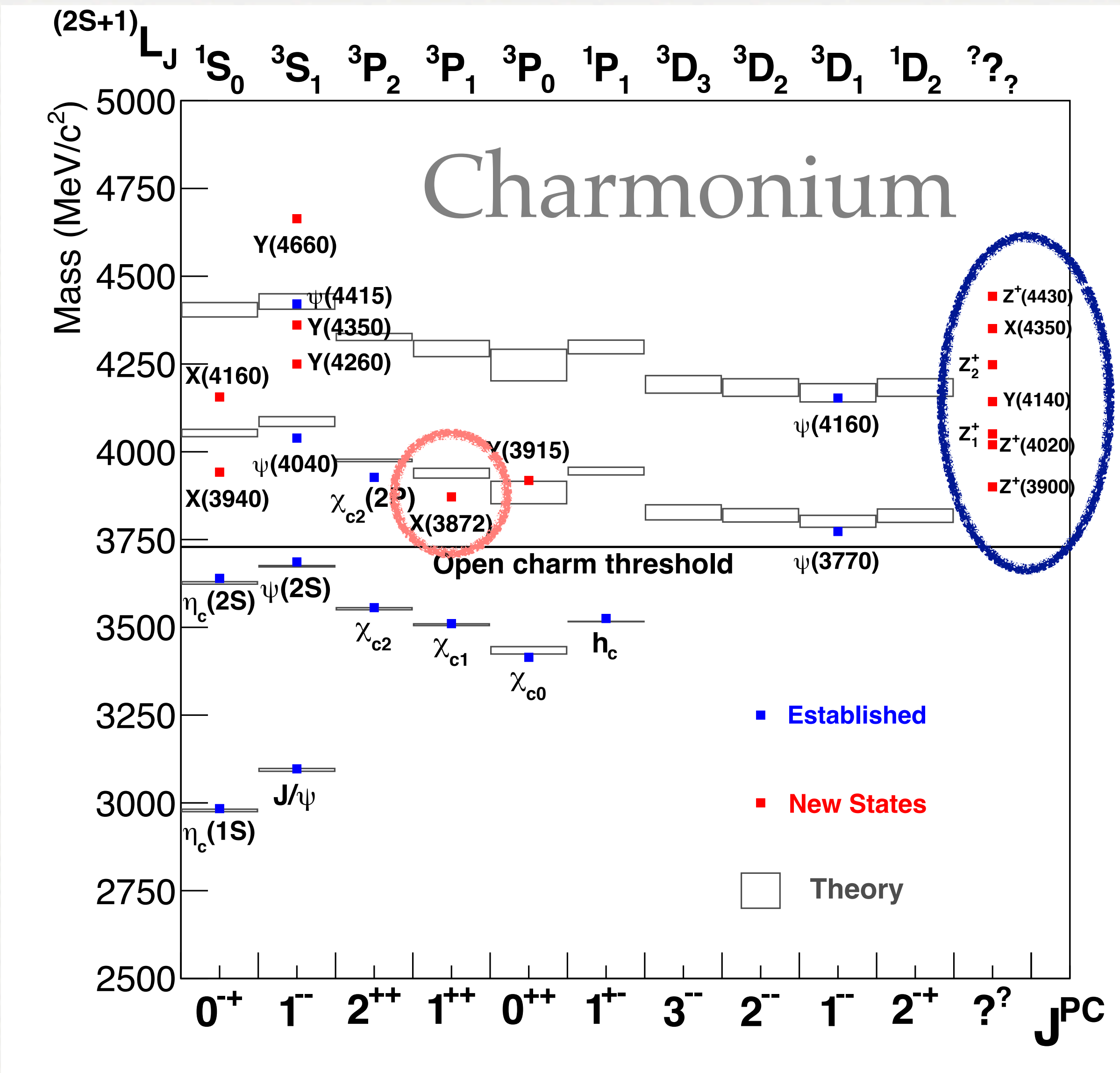

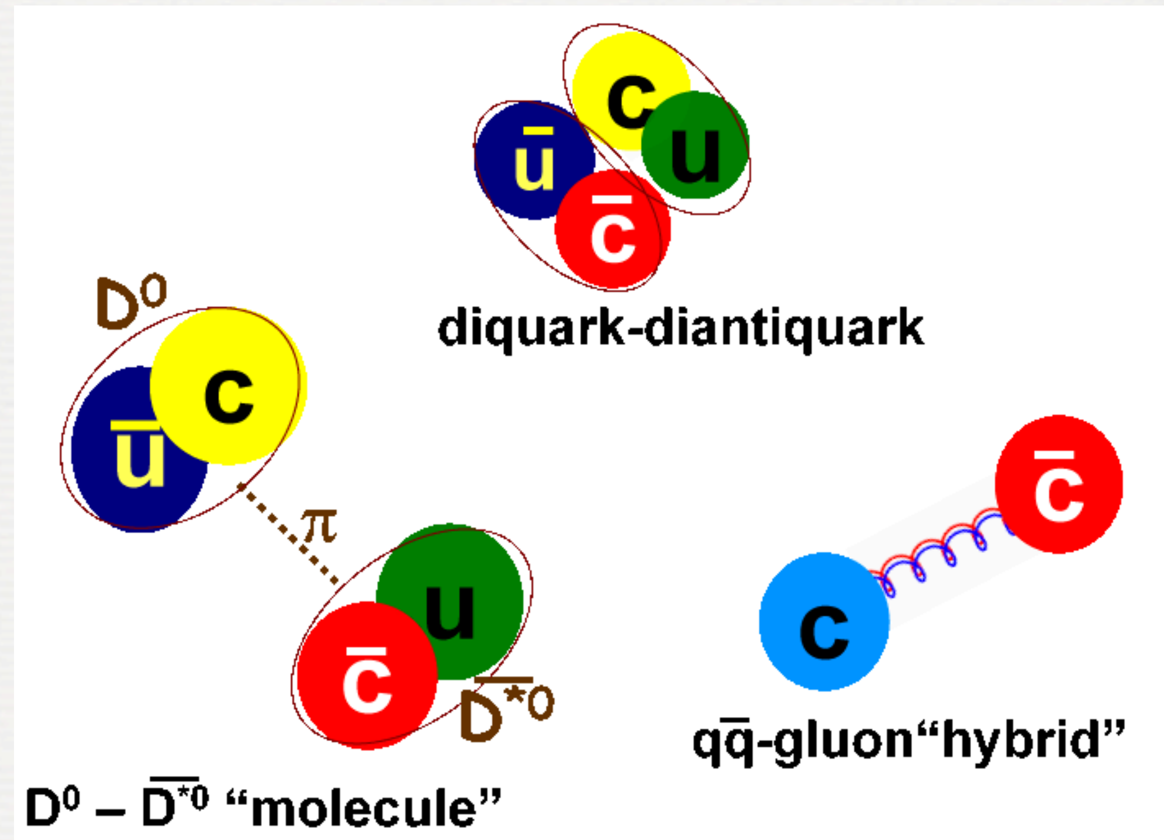

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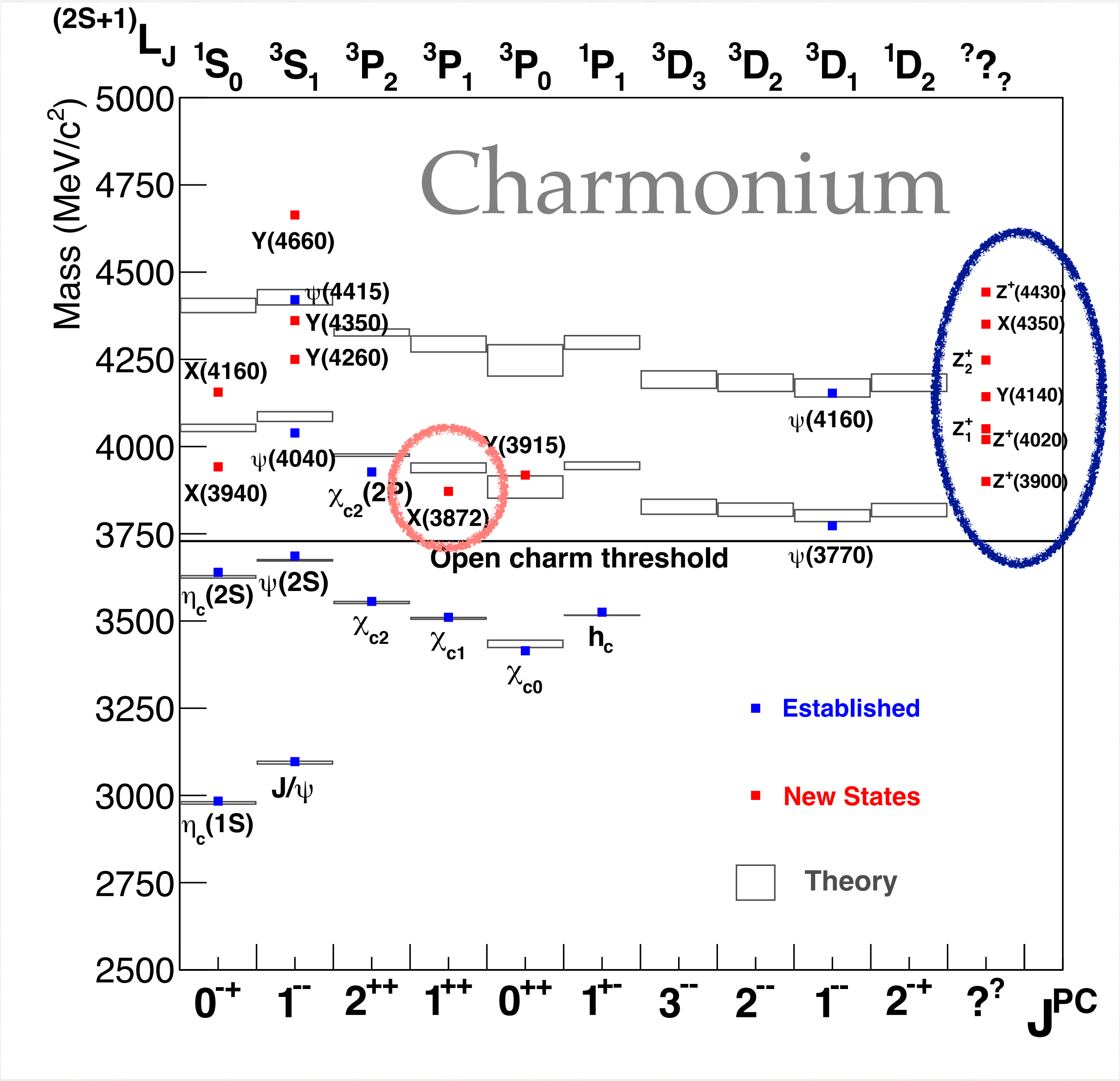

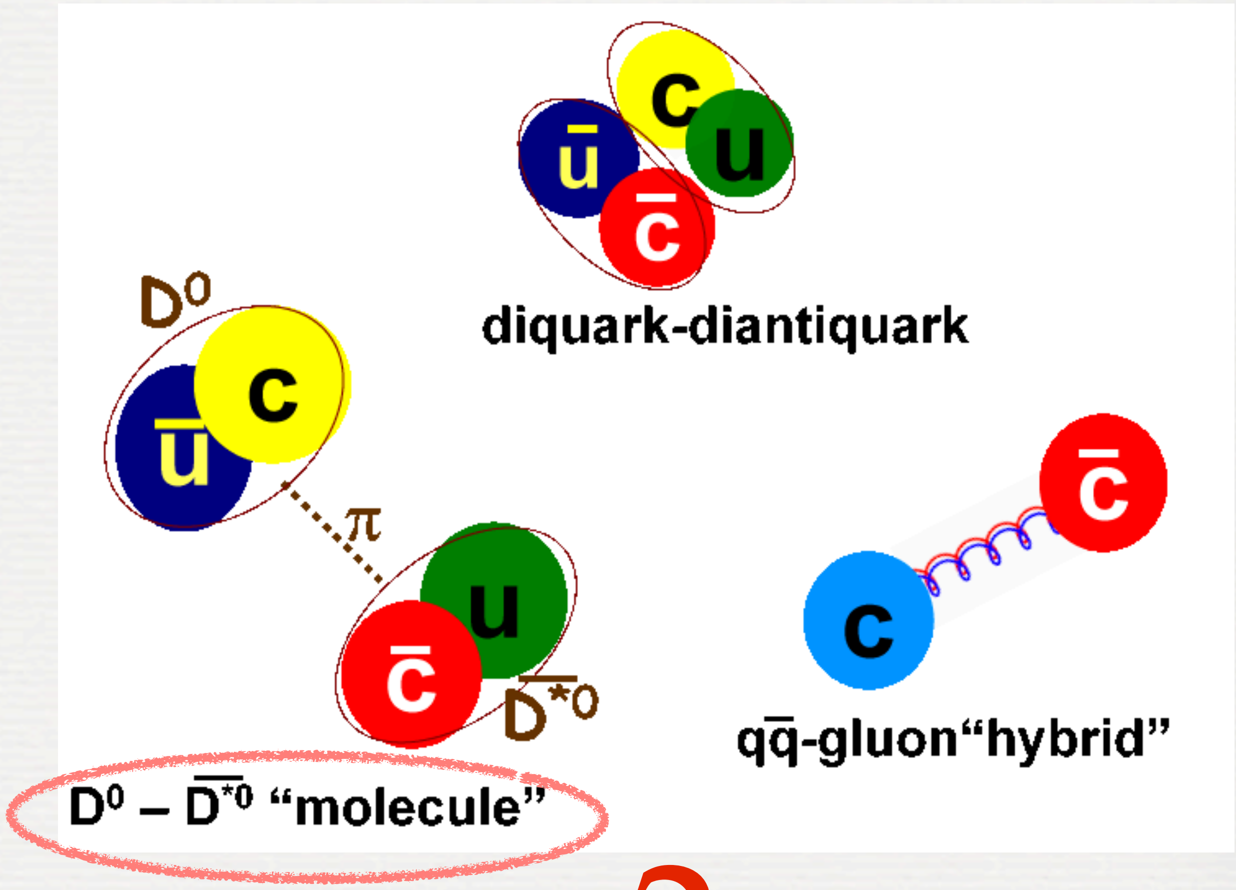

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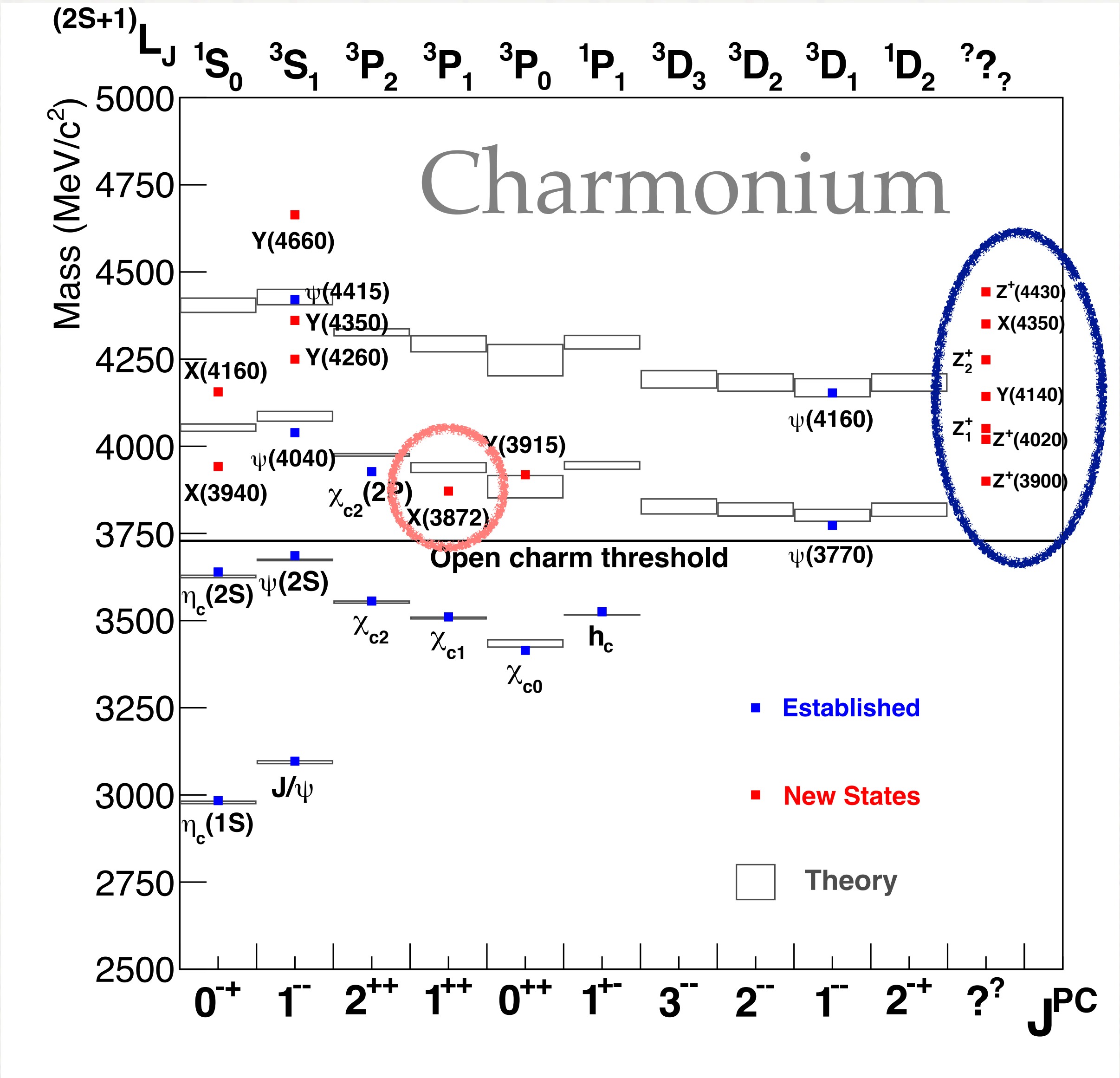
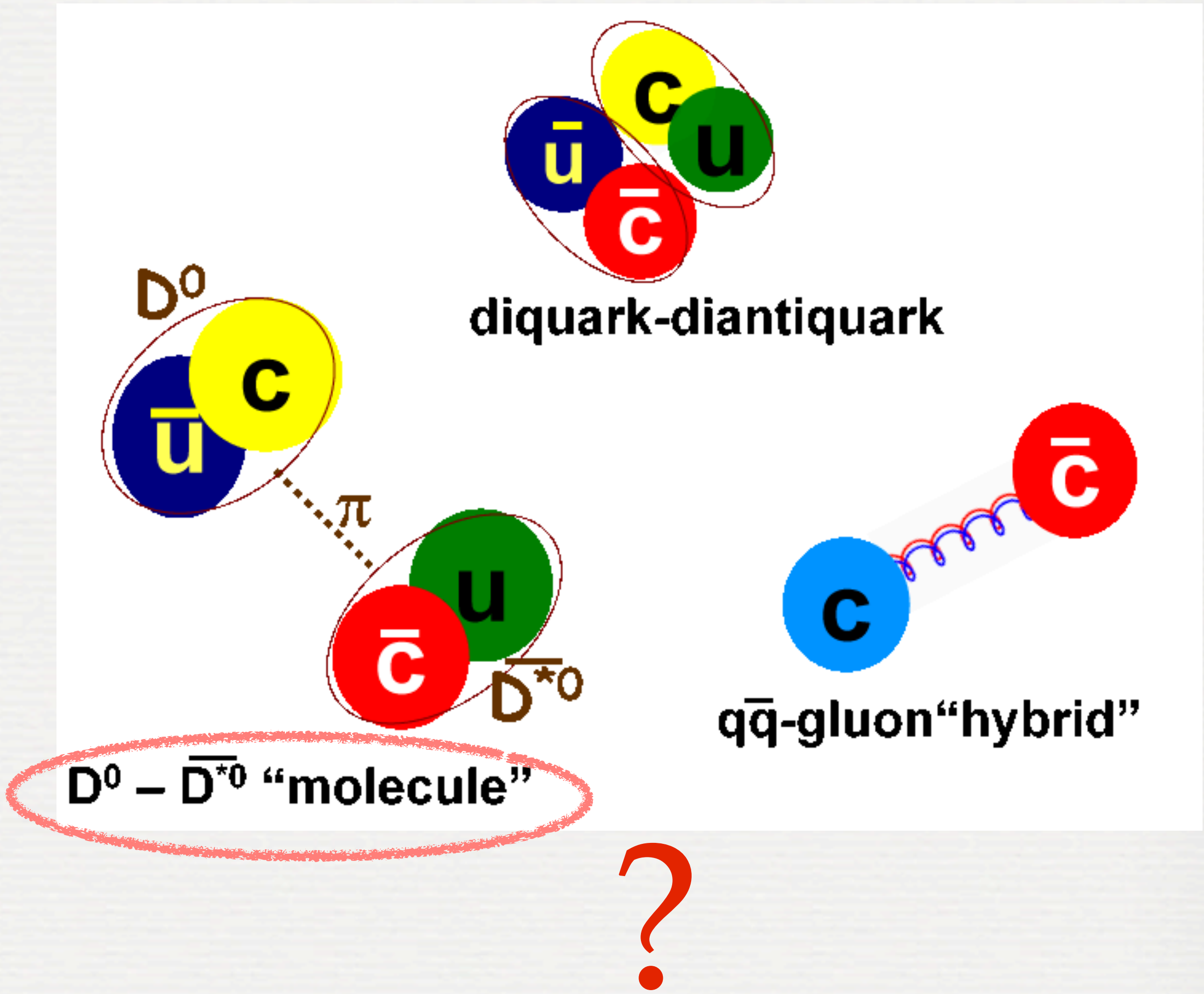




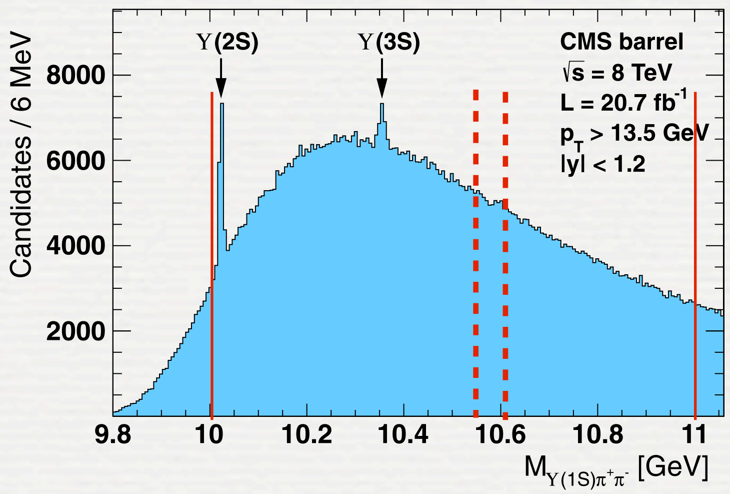
Is there bottonium counterpart of the X(3872) ... let's name it X_b?

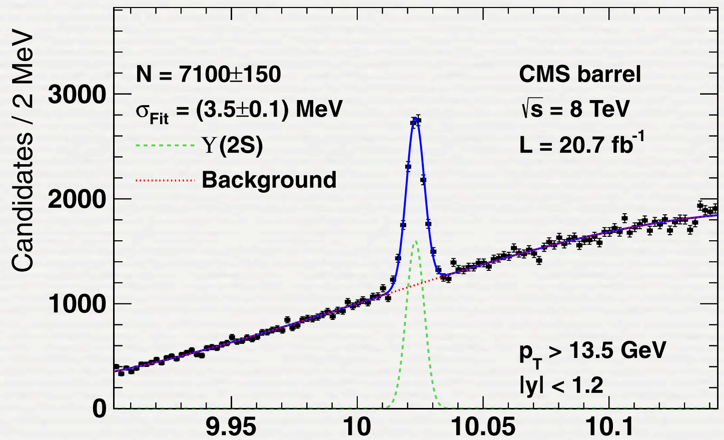
SEARCH FOR THE EXOTIC BOTTONIUM X_b

- 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).

SEARCH FOR THE EXOTIC BOTTONIUM X_b

- Assume X_b exists:
  - $X_b \to Y(1S)\pi^+\pi^-$.
  - $R = R_{X_b/Y(2S)} \approx 6.5\% \; (= R_{X/\psi(2S)})$
    $\Rightarrow X_b$ expected > 5σ.
  - Narrow resonance Γ < 1.2 MeV.
  - Close to the $B\overline{B}$ or $B\overline{B}^*$ thresholds (10.562-10.604 GeV).
- Y trigger, optimize Y(2S) signal.





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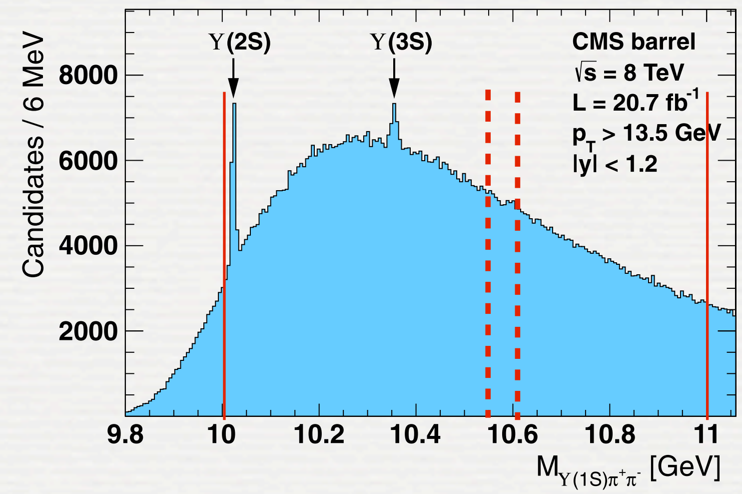
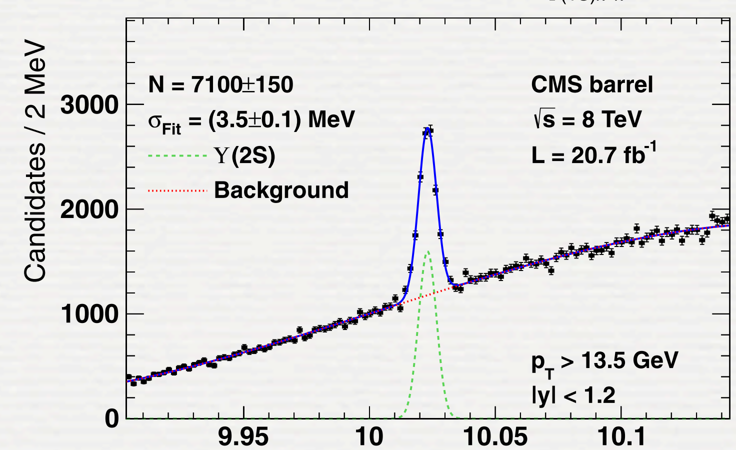
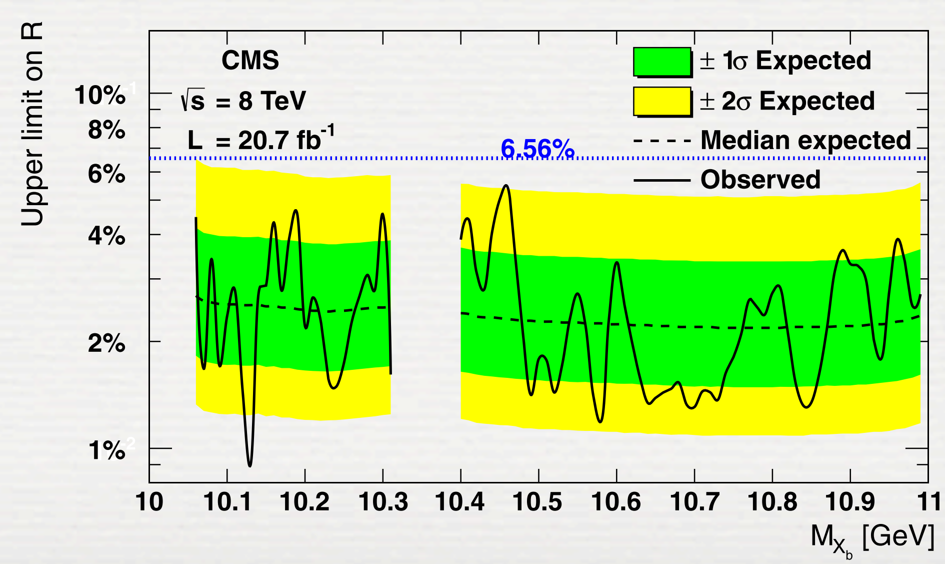
- Fit every 10 MeV, width fixed to MC.



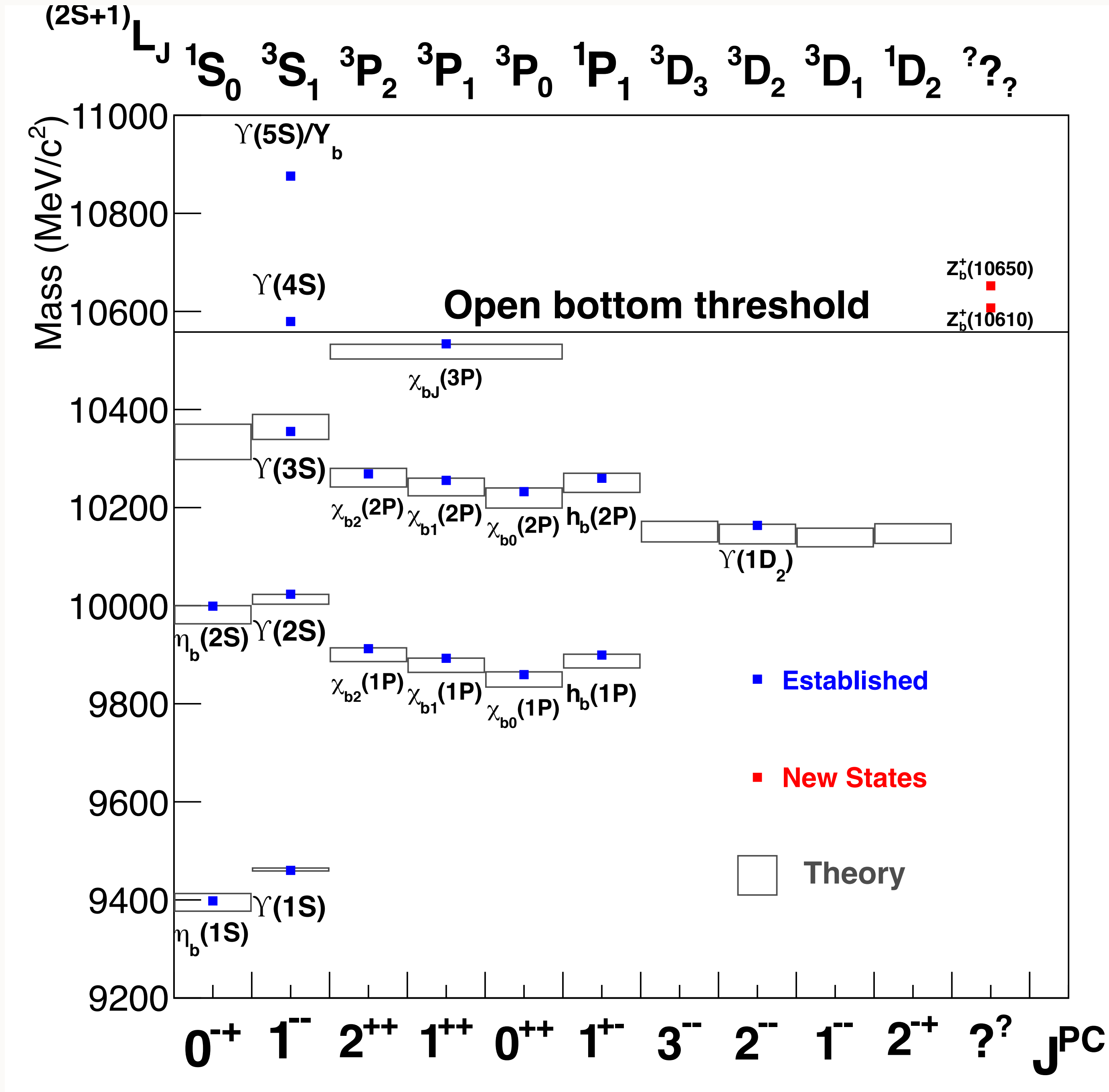




Results($\sqrt{s} = 8$TeV) PLB 727 (2013) 57

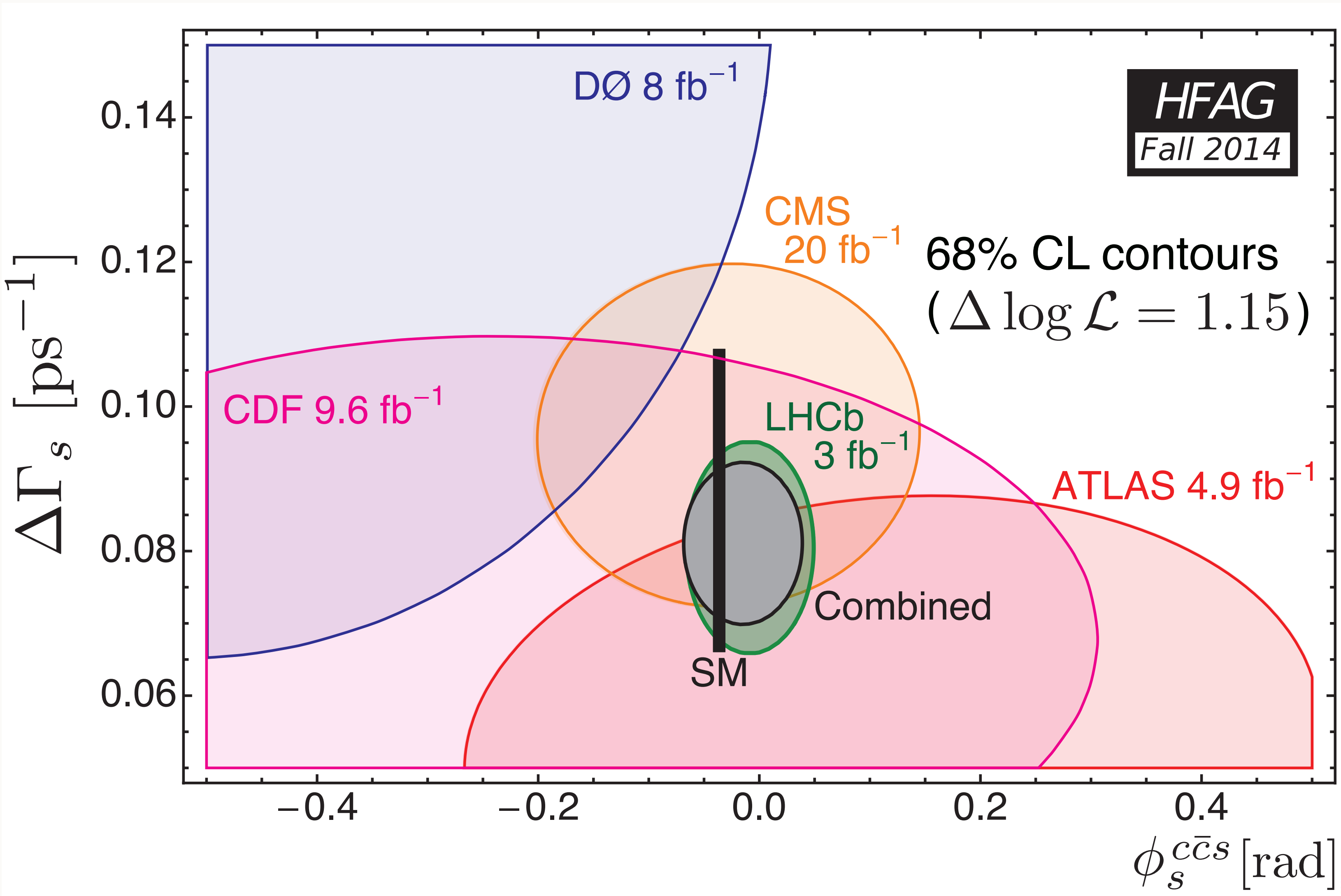
$$\frac{\sigma(pp \to X_b \to \Upsilon(1S)\pi^+\pi^-)}{\sigma(pp \to \Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-)} < (0.9 \div 5.4)\%@95\%C.L.$$

BOTTONIUM



(2S+1)LJ
1S0 3S1 3P2 3P1 3P0 1P1 3D3 3D2 3D1 1D2 ??
Mass (MeV/c2)
11000
10800
10600
10400
10200
10000
9800
9600
9400
9200
ϒ(5S)/Yb
ϒ(4S)
Open bottom threshold
Zb+(10650)
Zb+(10610)
χbJ(3P)
ϒ(3S)
χb2(2P) χb1(2P) χb0(2P) hb(2P)
ϒ(1D2)
ηb(2S) ϒ(2S)
χb2(1P) χb1(1P) χb0(1P) hb(1P)
Established
New States
Theory
ϒ(1S)
ηb(1S)
0-+ 1-- 2++ 1++ 0++ 1+- 3-- 2-- 1-- 2-+ ?? JPC

CPV IN Bs



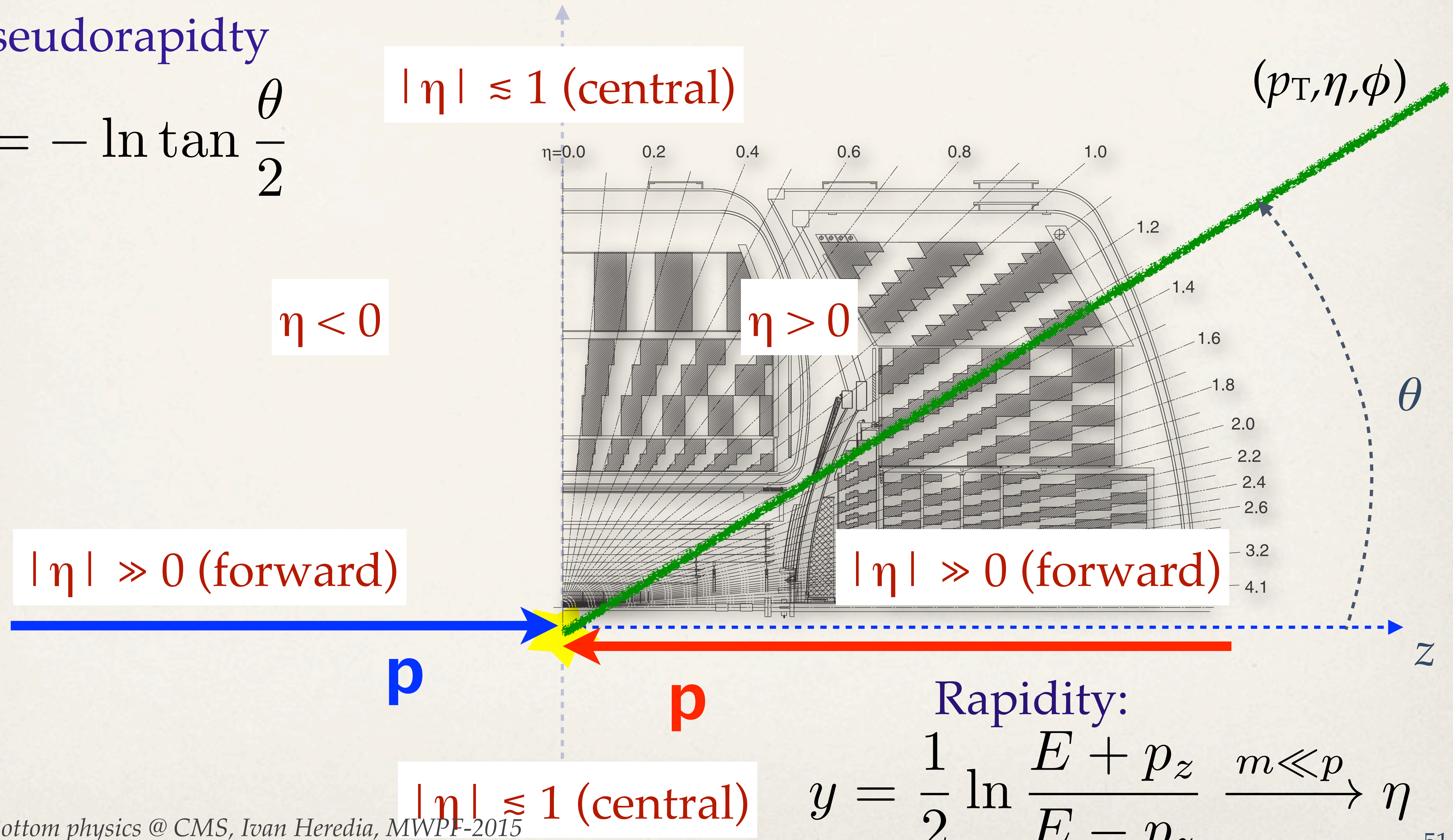
Parameter	Fit result
ϕ_s [rad]	-0.075 ± 0.097
$\Delta\Gamma_s$ [ps^{-1}]	0.095 ± 0.013
$\lvert A_0\rvert^2$	0.510 ± 0.005
$\lvert A_S\rvert^2$	$0.012\,^{+0.009}_{-0.007}$
$\lvert A_\perp\rvert^2$	0.243 ± 0.008
$\delta_\parallel$ [rad]	$3.48\,^{+0.07}_{-0.09}$
$\delta_{S\perp}$ [rad]	$0.37\,^{+0.28}_{-0.12}$
$\delta_\perp$ [rad]	2.98 ± 0.36
$c\tau$ [μm]	447.2 ± 2.9

arXiv:1507.07527v1 [hep-ex] 27 Jul 2015

Central & forward

Pseudorapidty

$$\eta = -\ln\tan\frac{\theta}{2}$$



Rapidity:

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} \xrightarrow{m \ll p} \eta$$