Heavy Flavor Physics at CMS

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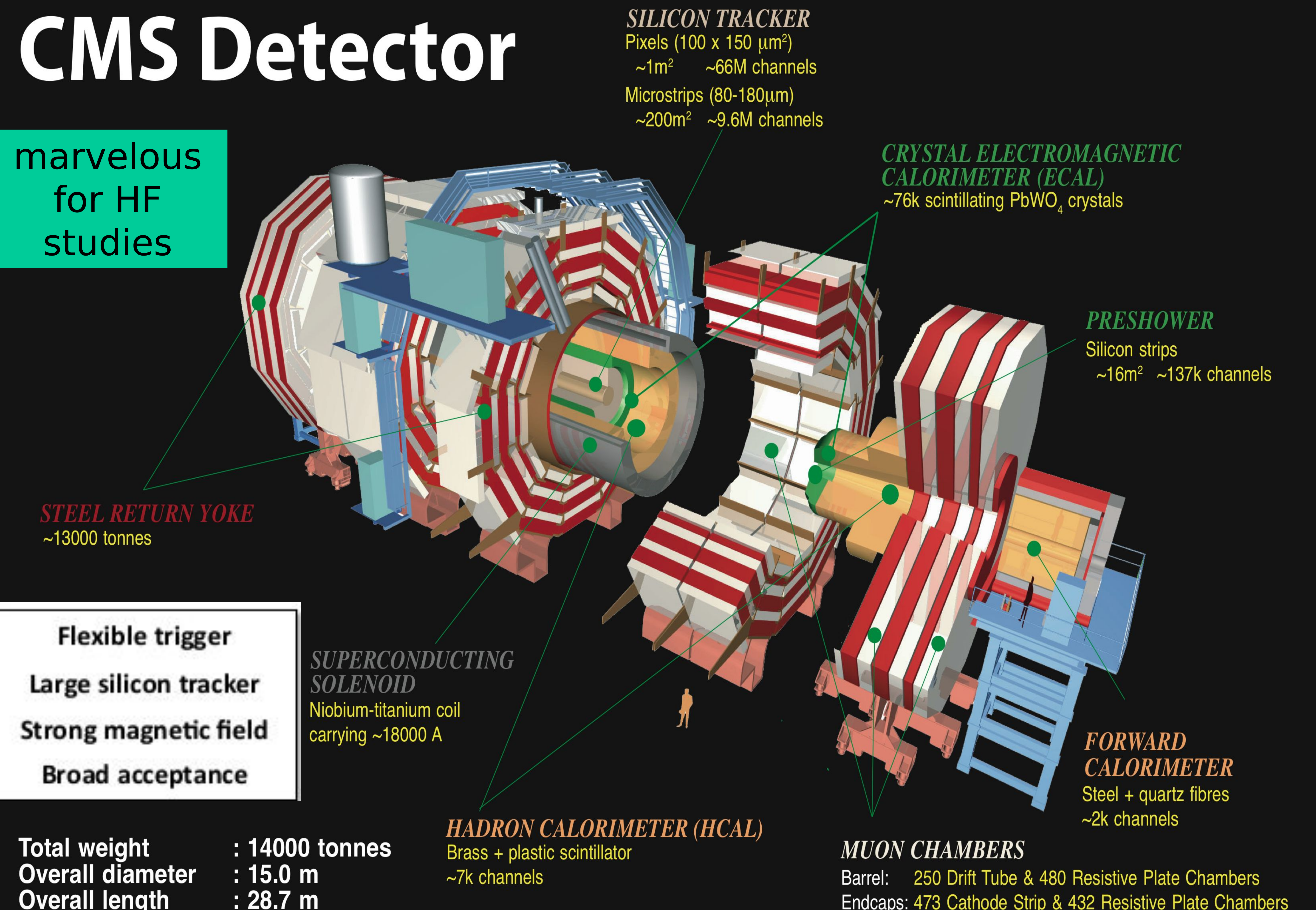
第十三届重味物理和**CP**破坏研讨会

兰州，**2015.7.22**

CMS Detector

marvelous for HF studies

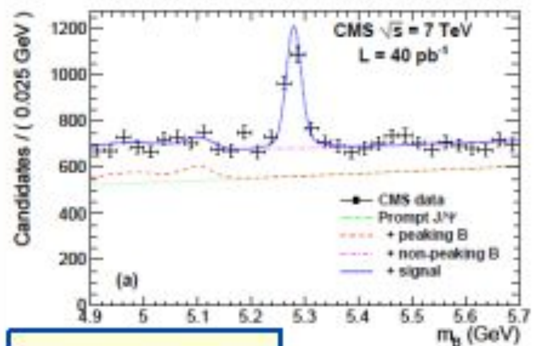


- Flexible trigger
- Large silicon tracker
- Strong magnetic field
- Broad acceptance

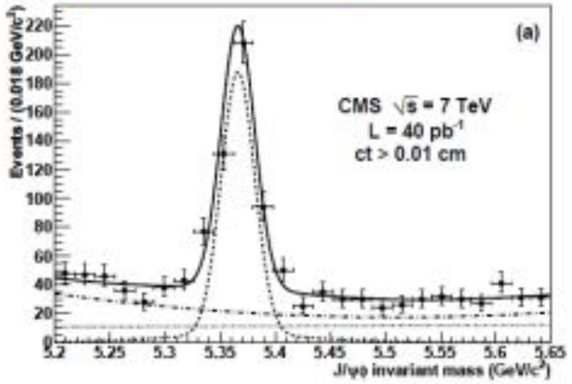
Total weight	: 14000 tonnes
Overall diameter	: 15.0 m
Overall length	: 28.7 m
Magnetic field	: 3.8 T

The Beautiful Harvest of CMS

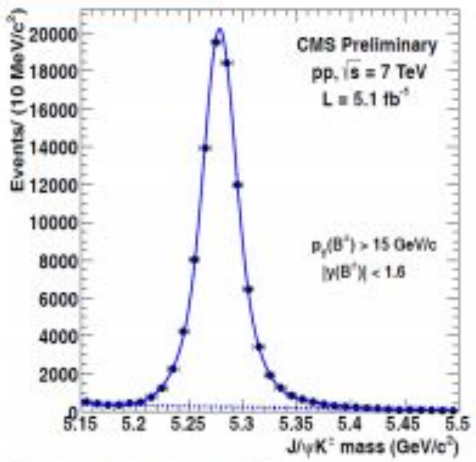
$B^0 \to J/\psi\, K_S$



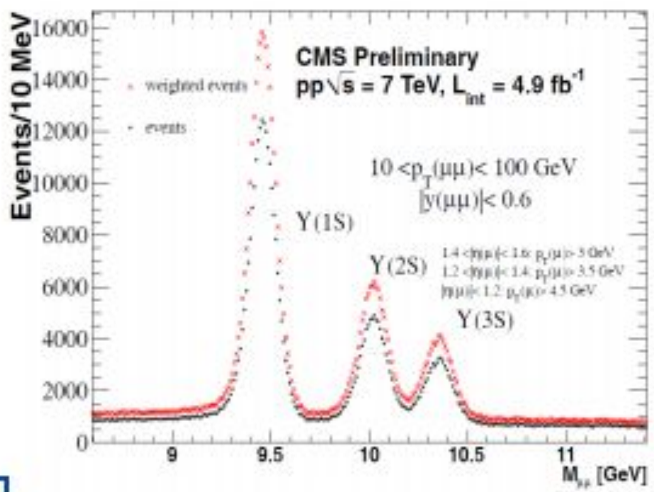
$B_S^0 \to J/\psi\, \phi$



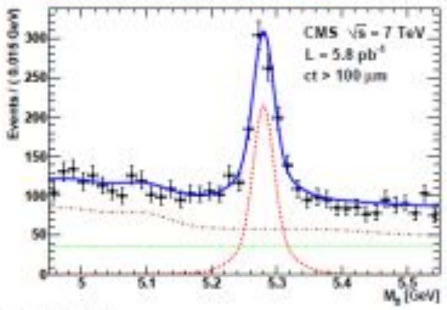
$B_c \to J/\psi\, K$



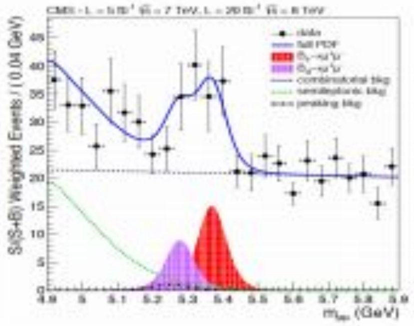
$\Upsilon \to \mu\mu$



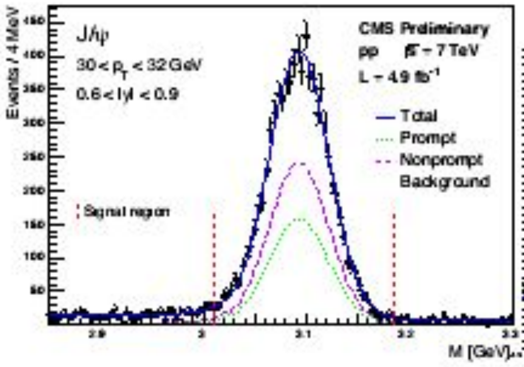
$B^+ \to J/\psi\, K^+$



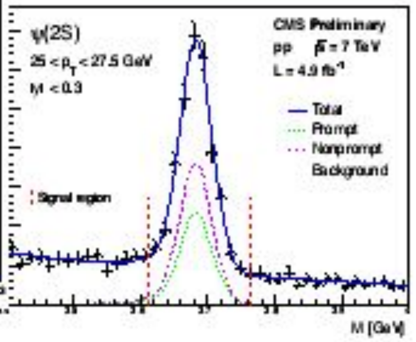
$B^0 \to \mu\mu$



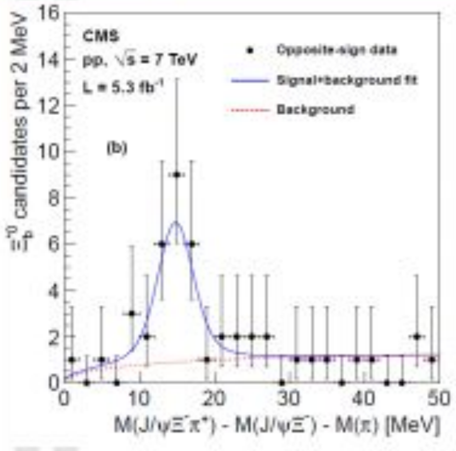
$J/\psi \to \mu\mu$



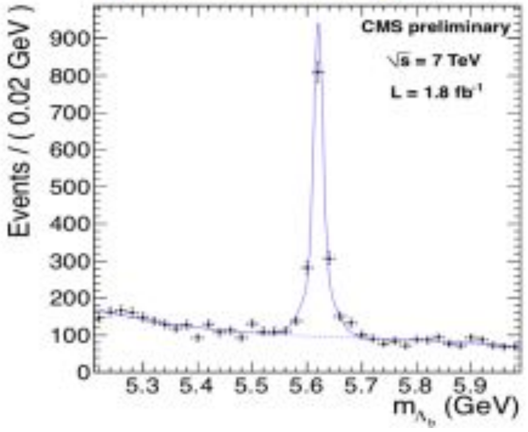
$\psi(2S) \to \mu\mu$



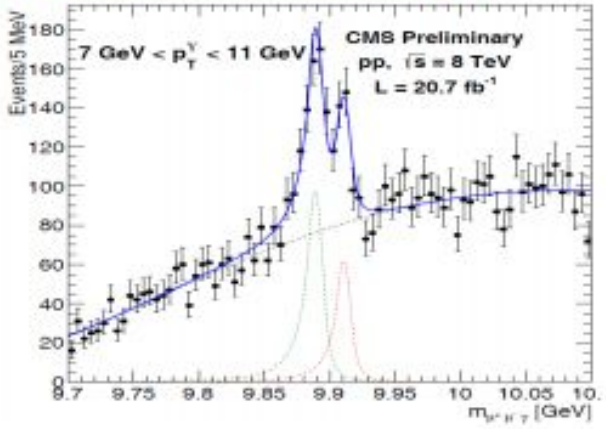
$\Xi_b^{*0} \to \Xi_b^- \pi^+ \to \Xi^- J/\psi \pi^+$



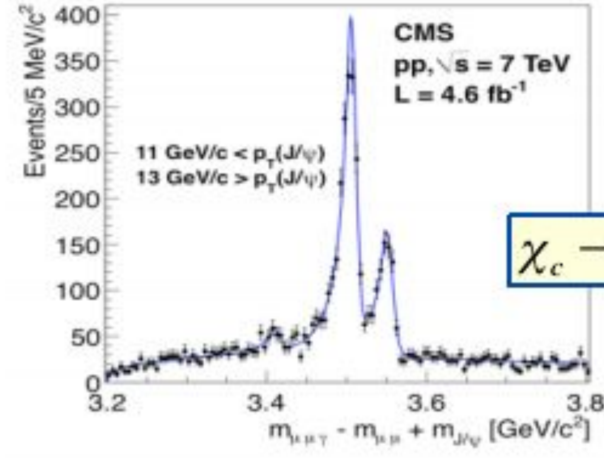
$\Lambda_b \to J/\psi\, \Lambda$



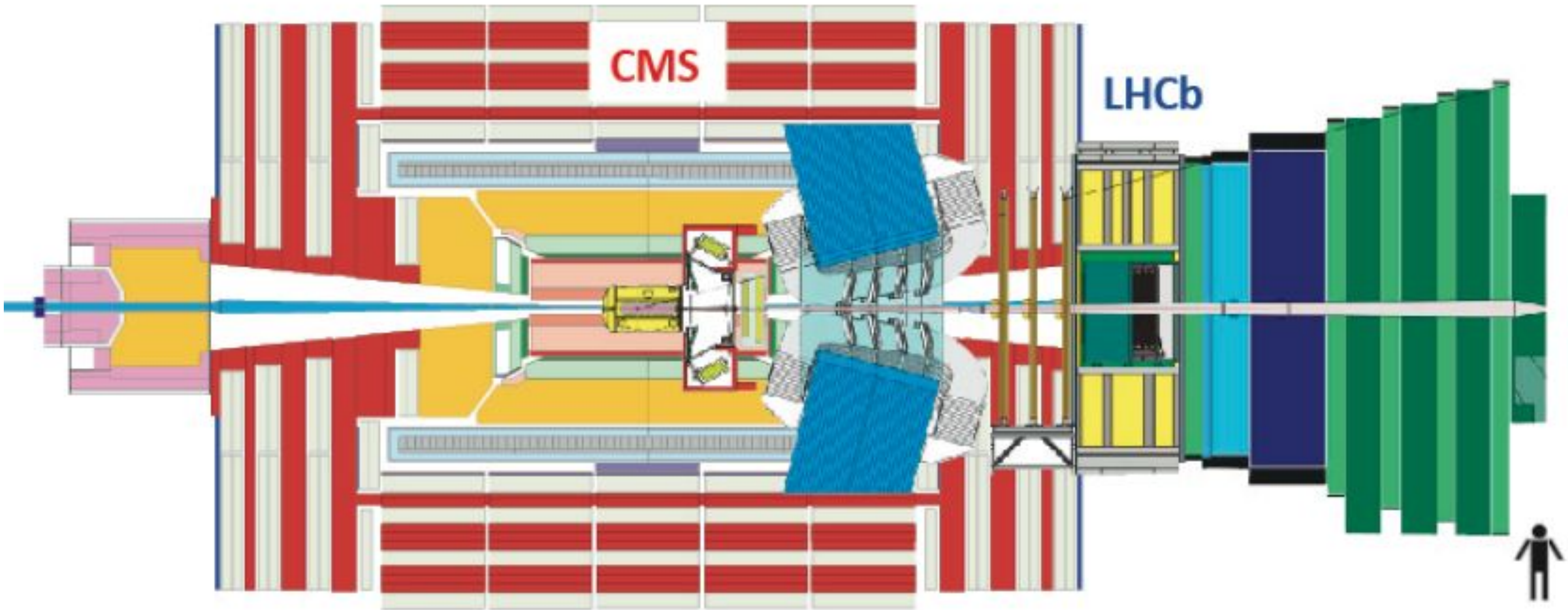
$\chi_{b1,2}(1P) \to \Upsilon(1S) + \gamma$



$\chi_c \to J/\psi + \gamma$



CMS is complementary to LHCb



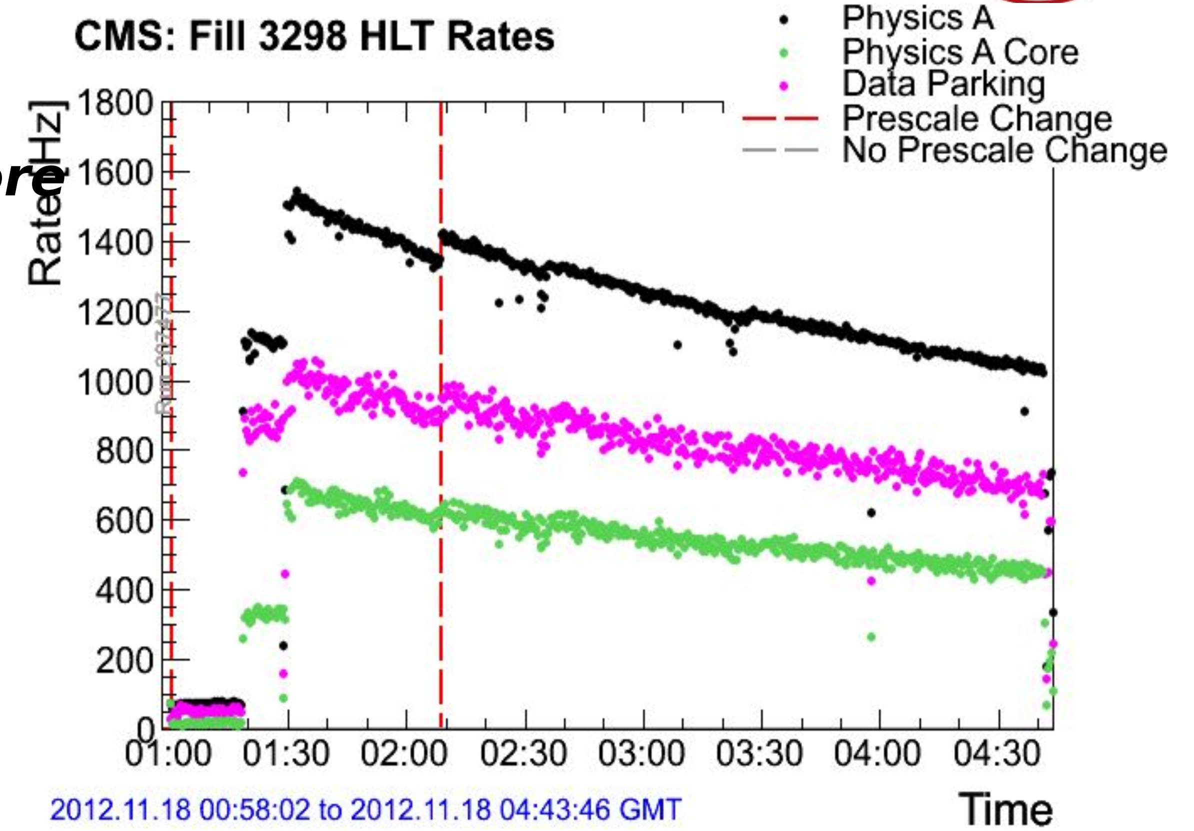
- **Measured σ(pp→bbX) cross-section (at 7 TeV):**
  - **CMS (28.1 ± 2.4 ± 2.0 ± 3.1) μb (pT (B)>5 GeV and |η|<2.4)**
    - **[Nucl.Phys. B864 (2012) 341-381]**
  - **LHCb (75.3 ± 5.4 ± 13.0) μb (2<η<6)**
    - **[Phys.Rev.Lett.106:252001,2011]**
  - **Each experiment: O(10^{10})/fb bb pairs on tape**
    - **BaBar and Belle: data sample of ~10^{9} B B pairs.**

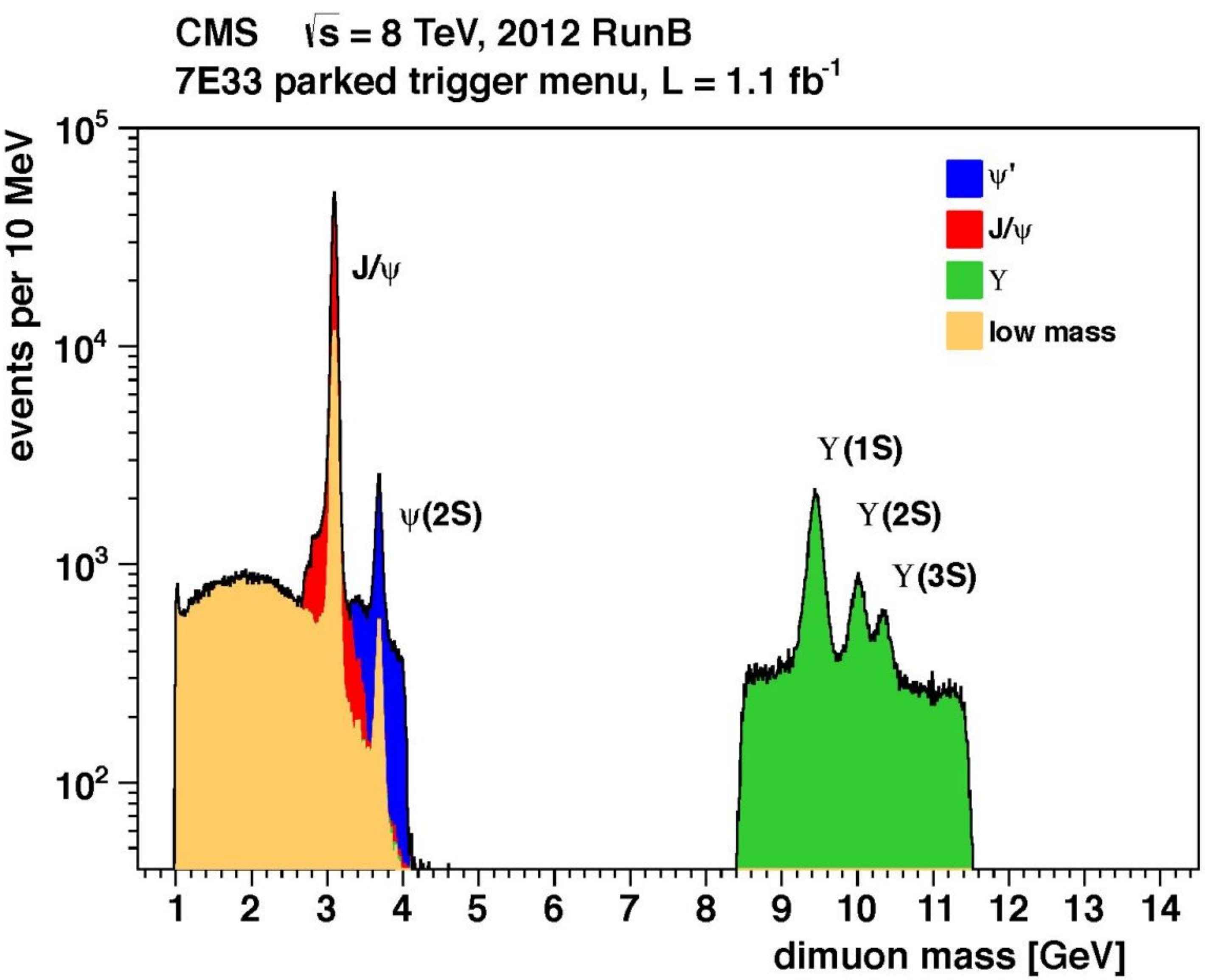
Data Parking

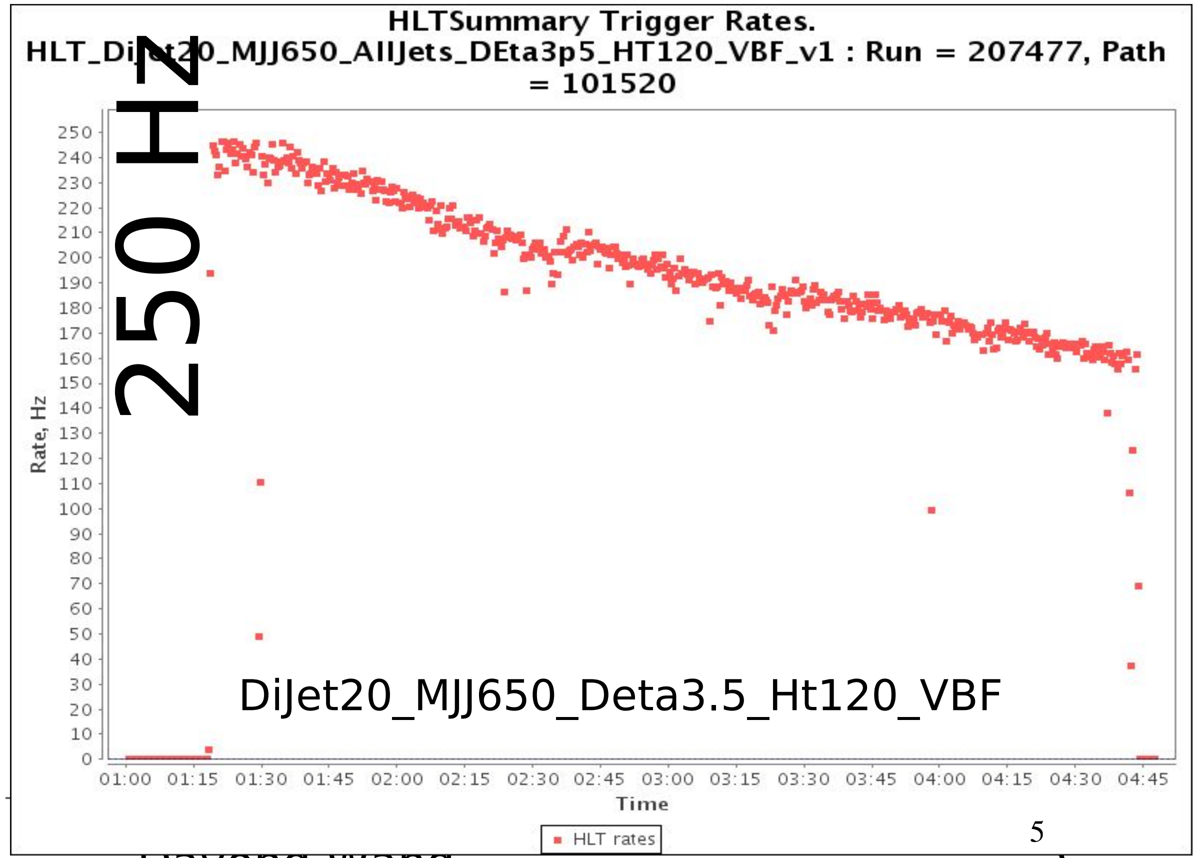
We don't want CMS physicists to relax after summer 2013

Keeping almost x2 of additional data that before was discarded!

"Parked data": to be reconstructed 2013.





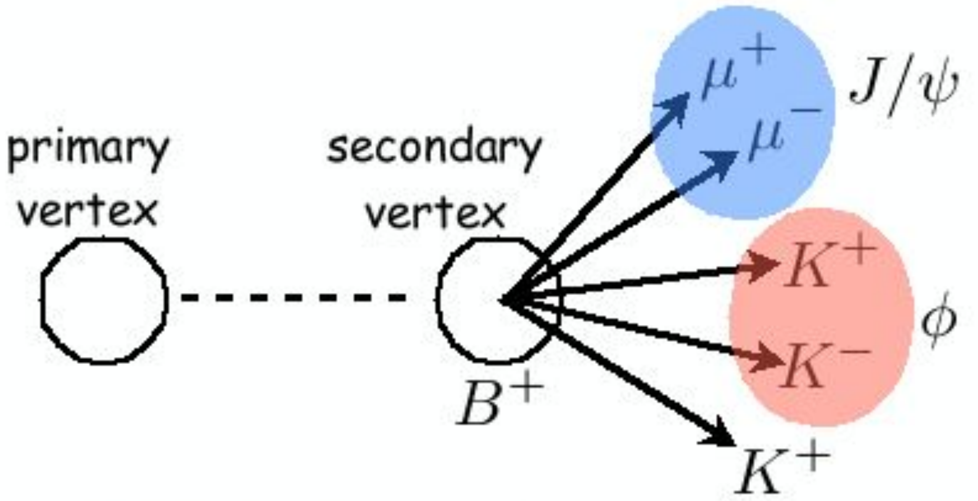


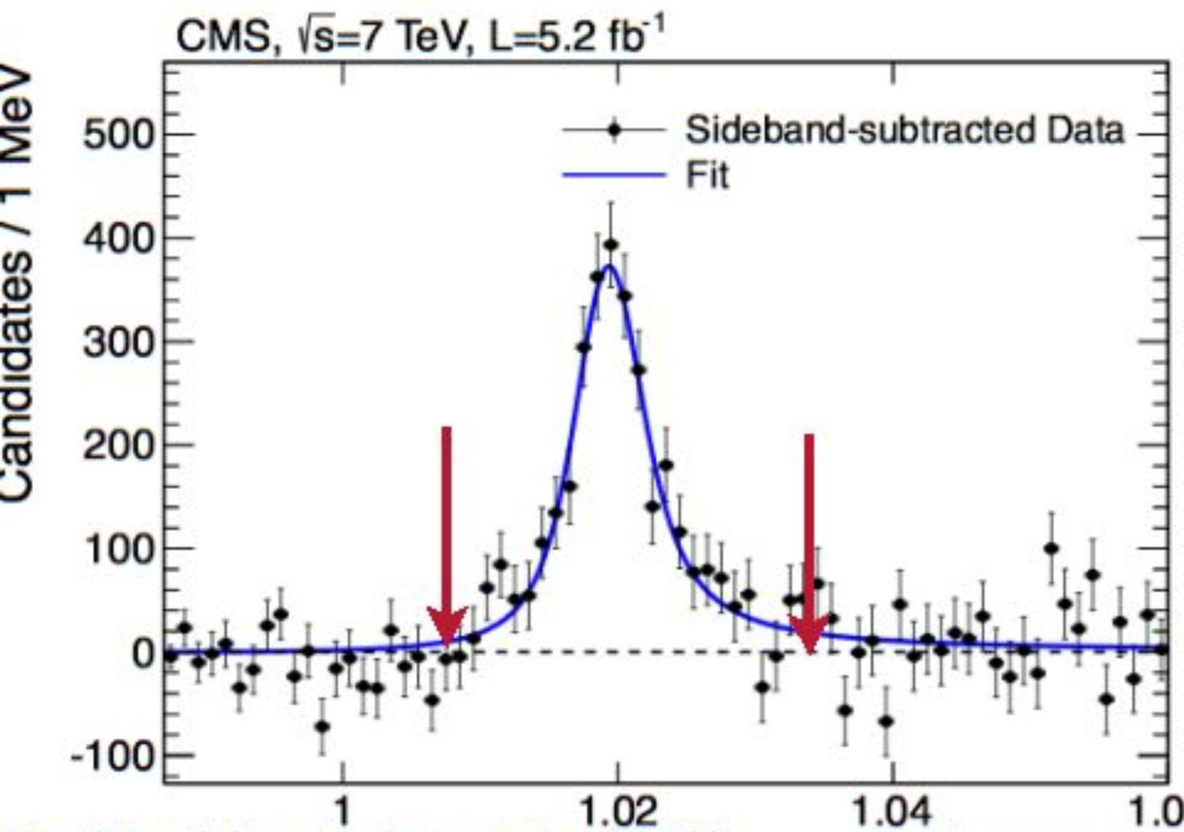
Selected topics with Recent Results from CMS-BPH

- **Spectroscopy： Y(4140), CPV**
  - **IHEP**
- **Production: polar/prod xs, media**
  - **PKU, IHEP**
- **Rare decays: B->mumu**
- **Property: b->sll angular analysis**
  - **PKU**

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

CMS Search in the J/ψϕ Mass Spectrum

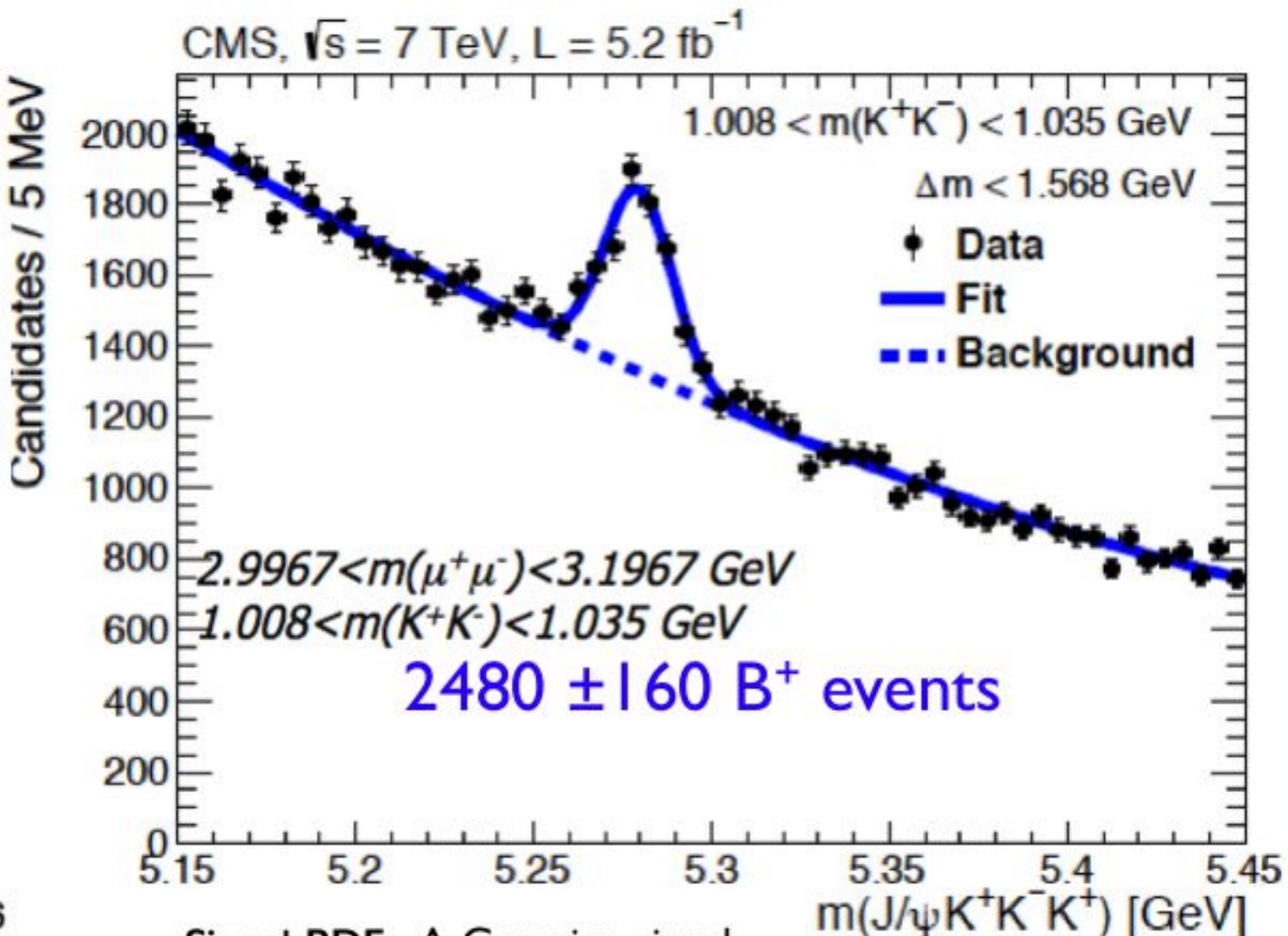




The B^+ sideband subtracted $m(K^+K^-)$ where $m(J/\psi\phi)$ is within $\mp 3\sigma$ of $m(B^+)$

Largest $B^+ \to J/\psi\phi K^+$ sample

collected in the world up to date



Signal PDF: A Gaussian signal

Background PDF: A second order Chebychev polynomial

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11026

PLB 734 (2014) 261

Observation of Peaks in the J/ψϕ Mass Spectrum in B Decays

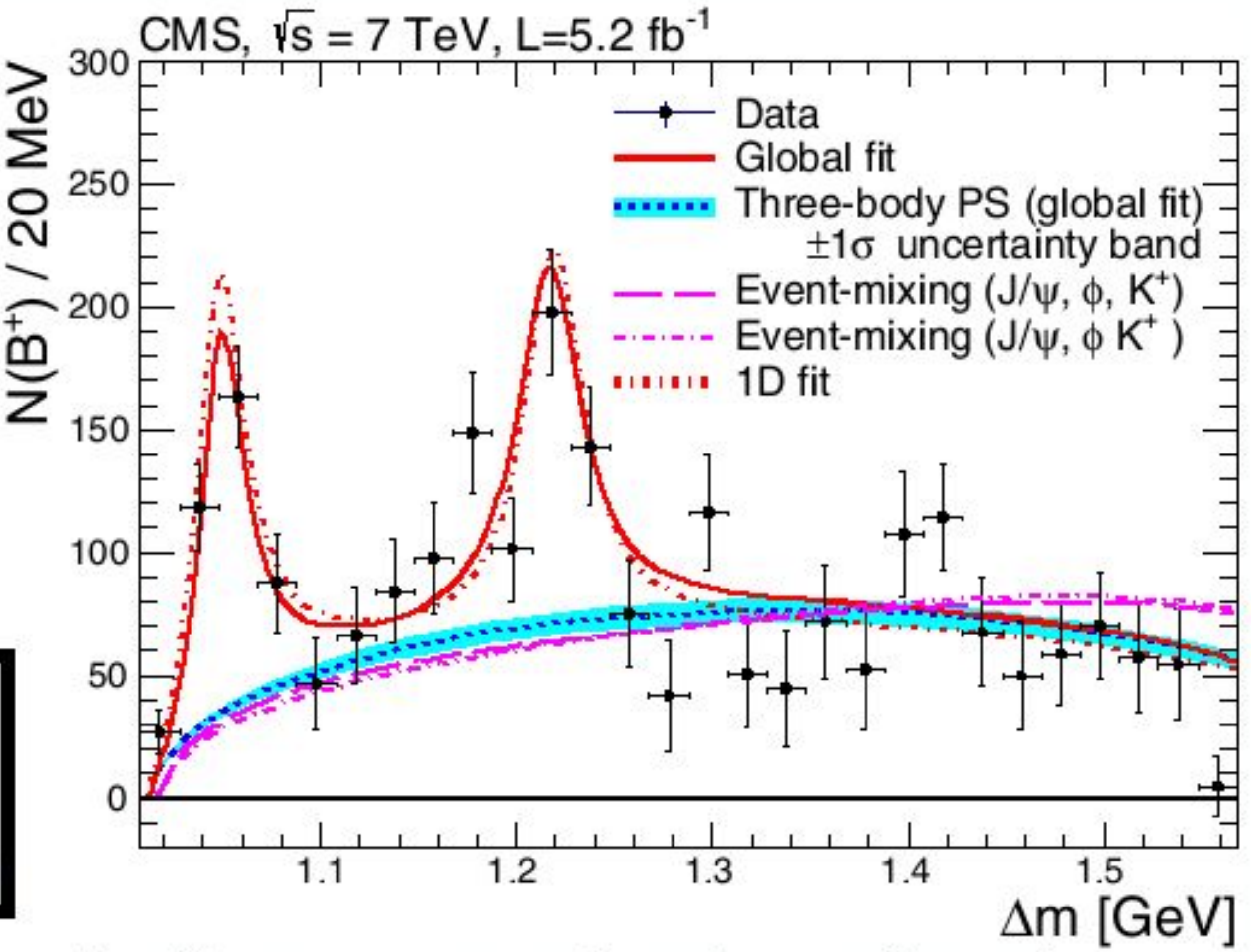
The $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ is used to investigate the possible structures

$\Delta m > 1.568$ GeV region is excluded to avoid background from $Bs \to \psi(2S)\varphi \to J/\psi\pi^+\pi^-\varphi$ decays

The Δm Spectrum is extracted by BACKGROUND SUBTRACTION

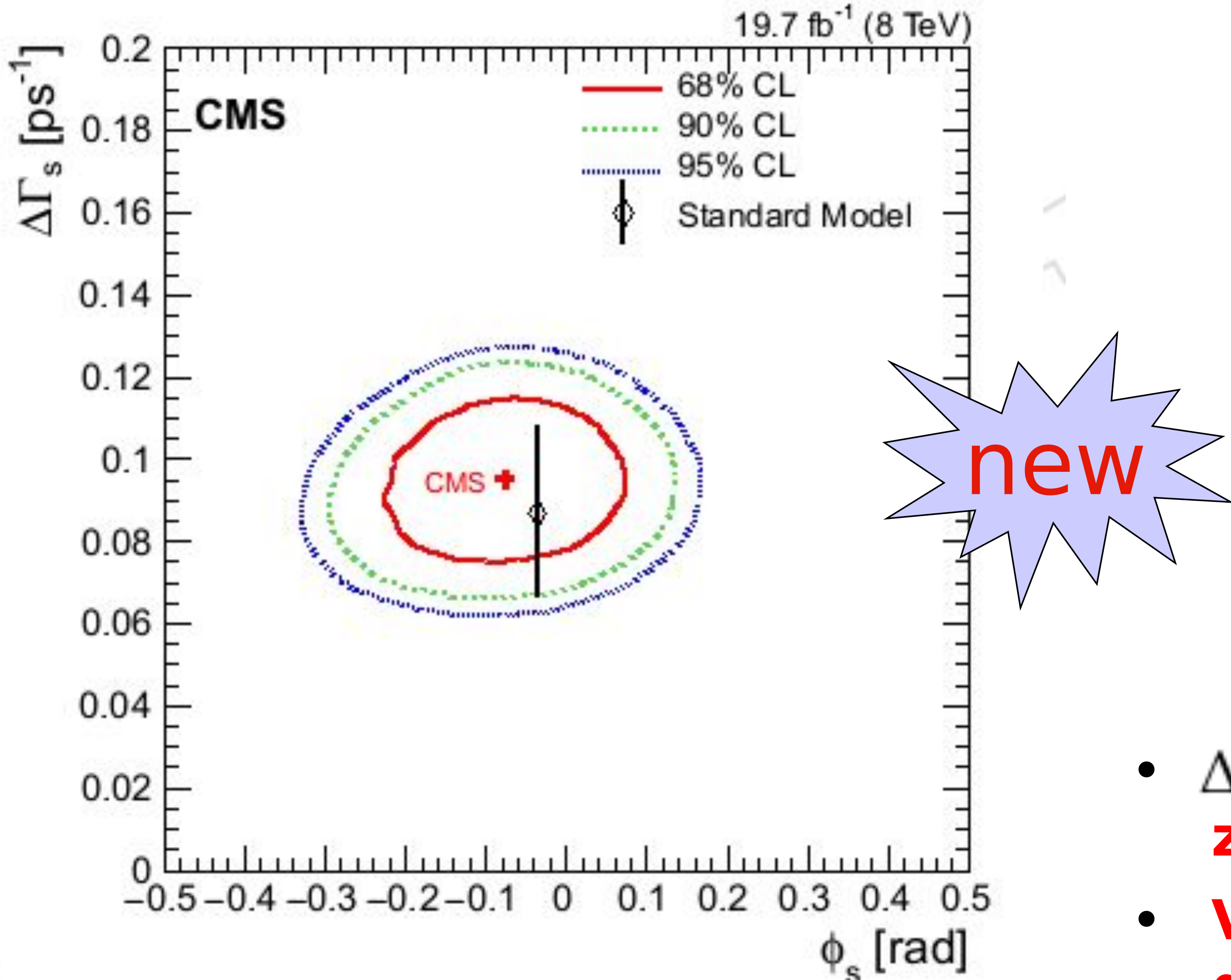
- ➡ Divide the dataset into the 20 MeV Δm bins
- ➡ Extract the number of B signal for each Δm by fitting the J/ψφK spectrum
  - ➡ Mean is fixed to the PDG value of B mass
  - ➡ RMS is fixed to the number predicted by simulation

Yield	Mass (MeV)	Γ (MeV)
310 ± 70	4148.0 ± 2.4(stat) ± 6.3(syst)	28^{+15}_{-11}(stat) ± 19(syst)
418 ± 170	4313.8 ± 5.3(stat) ± 7.3(syst)	38^{+30}_{-15}(stat) ± 16(syst)



- CMS observed a J/ψϕ structure at 4148MeV with a significance greater than 5σ confirms the existence of Y(4140) from CDF
  - CDF Y(4140): $m=4143.4^{+2.9}_{-3.0}$ (stat) ± 0.6 (syst), $\Gamma=15.3^{+10.4}_{-6.1}$(stat)±2.5(syst) MeV
- Evidence for a second structure at ~4314MeV in the same mass spectrum
- Later D0 also confirmed Y(4140) with a significance of 3σ

$B_s^0 \to J/\psi\phi$ updated results



Parameter	Fit result
$\|A_0\|^2$	0.510 ± 0.005
$\|A_S\|^2$	$0.012^{+0.009}_{-0.007}$
$\|A_\perp\|^2$	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
$\Delta\Gamma_s$ [ps^{-1}]	0.095 ± 0.013
ϕ_s [rad]	-0.075 ± 0.097

$$\phi_s = -0.075 \pm 0.097\,(\text{stat.}) \pm 0.031\,(\text{syst.})\ \text{rad}\,,$$
$$\Delta\Gamma_s = 0.095 \pm 0.013\,(\text{stat.}) \pm 0.007\,(\text{syst.})\ \text{ps}^{-1}\,.$$

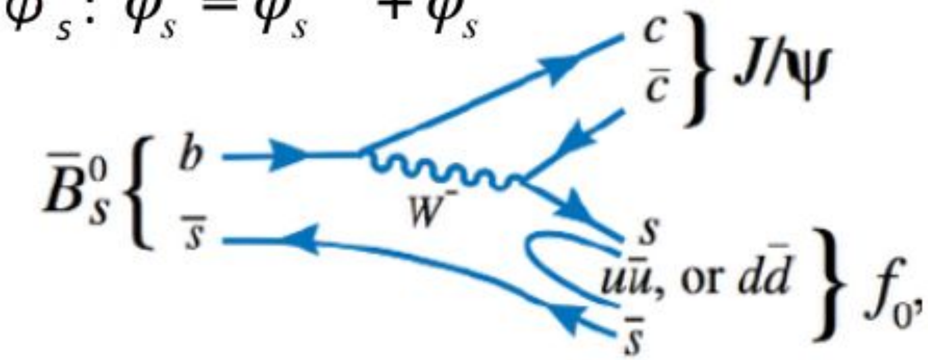
- $\Delta\Gamma_s$ **confirmed to be non zero**
- **Very competitive** ϕ_s **determination**

  Good agreement with SM

  Statistical uncertainties dominant

$B_s^0 \to J/\psi\, f_0(980)$: analysis strategy

- The decay $B_s^0 \to J/\psi(\to \mu^+\mu^-) f_0(\to \pi^+\pi^-)$ is:
  - useful to study the CPV phase ϕ_s by measuring the lifetime of the CP-odd part of B_s^0 meson
  - **sensitive to NP**: many NP scenarios predict enhanced values of ϕ_s: $\phi_s = \phi_s^{SM} + \phi_s^{NP}$
  - useful to study f_0(980) structure (tetraquark system?)



- **Analysis target:**

$$R_{f_0/\phi} \equiv \frac{BF(B_s^0 \to J/\psi\, f_0(980); f_0(980) \to \pi^+\pi^-)}{BF(B_s^0 \to J/\psi\,\phi; \phi \to K^+K^-)}$$

where many uncertainties cancel out:
- *b* quark production Xsection
- $BF(J/\psi \to \mu^+\mu^-)$
- integrated luminosity
- tracking efficiency and muon ID

- $B_s^0 \to J/\psi\, f_0$ **lifetime** needed to measure the lifetime of the B_s^0 CP-odd part (useful input in the fit for ϕ_s) → future analysis

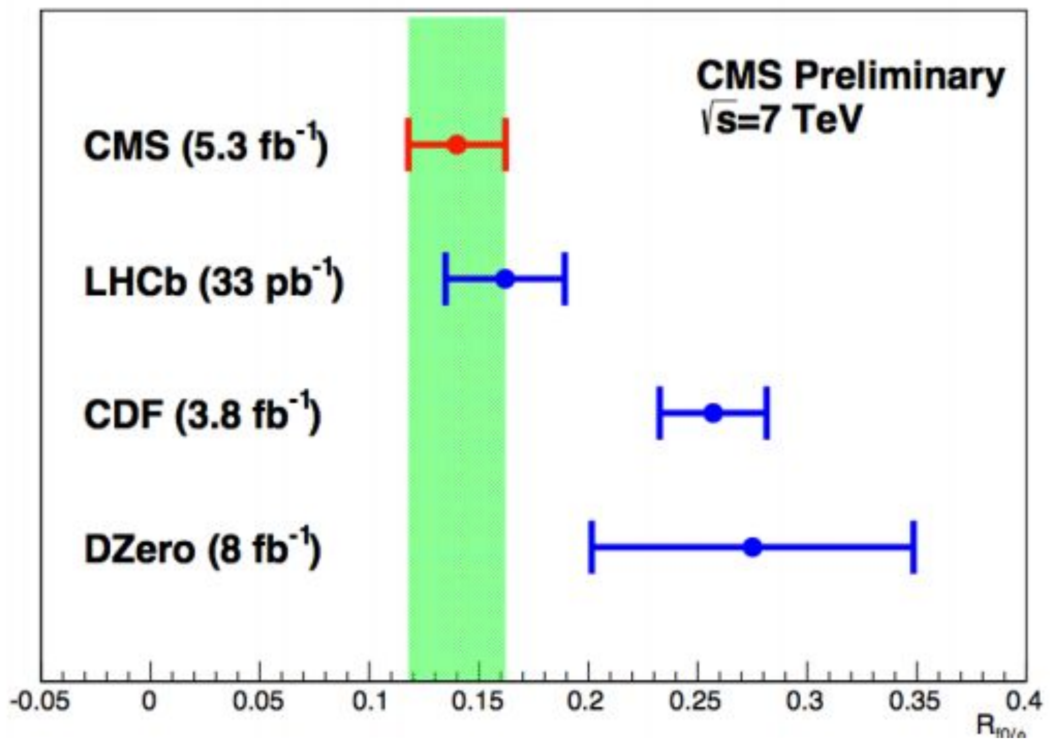
- **Experimentally:** $R_{f_0/\phi} = \frac{N_{f_0}}{N_\phi} \times \frac{\varepsilon_\phi}{\varepsilon_{f_0}}$ where

$$N_{(f_0,\phi)} = \text{ observed yield of } B_s^0 \to J/\psi(f_0,\phi)$$
$$N_{(f_0,\phi)} = \text{ detection efficiency of } B_s^0 \to J/\psi(f_0,\phi)$$

$B_s^0 \to J/\psi f_0$: results ($\sqrt{s} = 7 TeV$)

- **Result** (using 2011 data) with **873 ±49** signal events: $R_{f_0/\phi} = 0.140 \pm 0.013(\text{stat}) \pm 0.018(\text{syst})$

Systematics' source	Uncertainty (%)
Fit model	2.1
f_0 mass window width	6.4
MC simulation (f_0 natural width)	8.6
Decay model in MC generation	6.2



- This measurement is consistent with
  - theoretical prediction [PRD 79 (2009) 074024]
  - previous measurements
- It is the most precise measurement of the ratio to date!

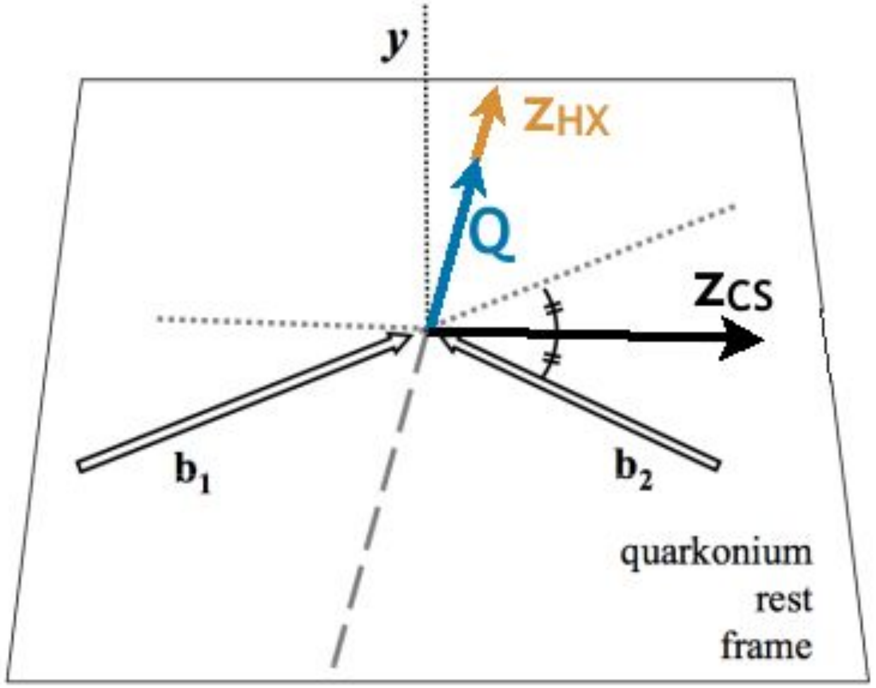
Quarkonium polarization

- Polarization is measured through the angular decay distribution of the quarkonium decaying into two muons

$$W(\cos\vartheta,\varphi|\vec{\lambda}) = \frac{3/(4\pi)}{(3+\lambda_\vartheta)}(1+\lambda_\vartheta\cos^2\vartheta+\lambda_\varphi\sin^2\vartheta\cos 2\varphi+\lambda_{\vartheta\varphi}\sin 2\vartheta\cos\varphi)$$

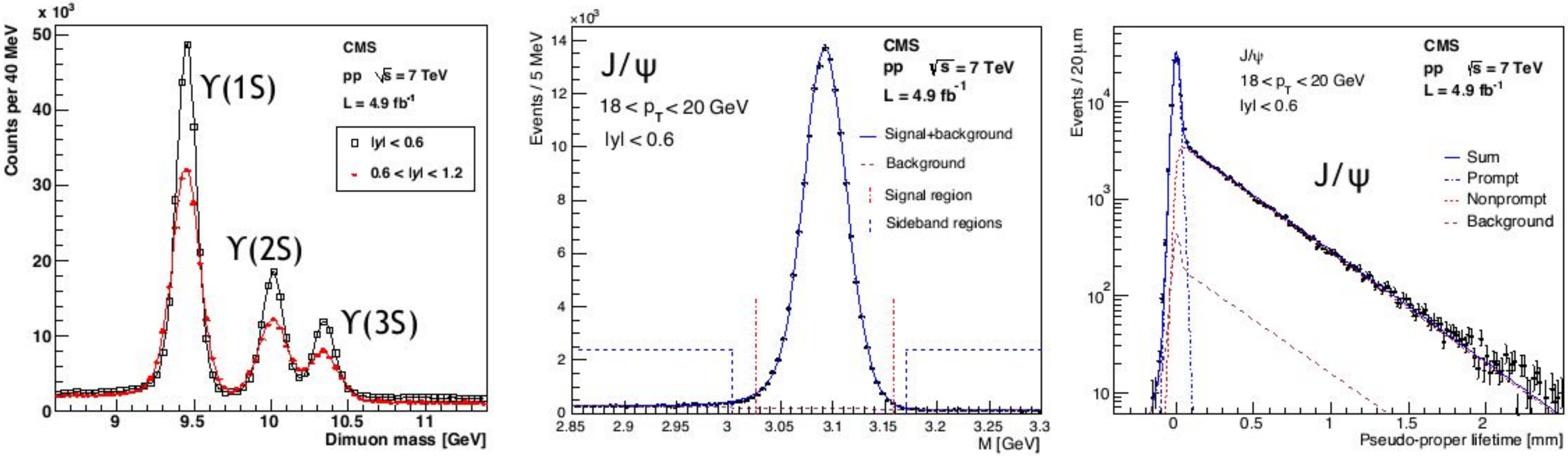
where λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$ are the polarization parameters

- Angular decay distribution is measured with respect to a certain reference frame
  - center-of-mass helicity HX (polar axis z_{HX} ≈ direction of quarkonium momentum)
  - Collins-Soper CS (z_{CS} ≈ direction of relative velocity of colliding particles)
  - perpendicular helicity PX ($z_{PX} \perp z_{CS}$)



Quarkonium polarization measurements

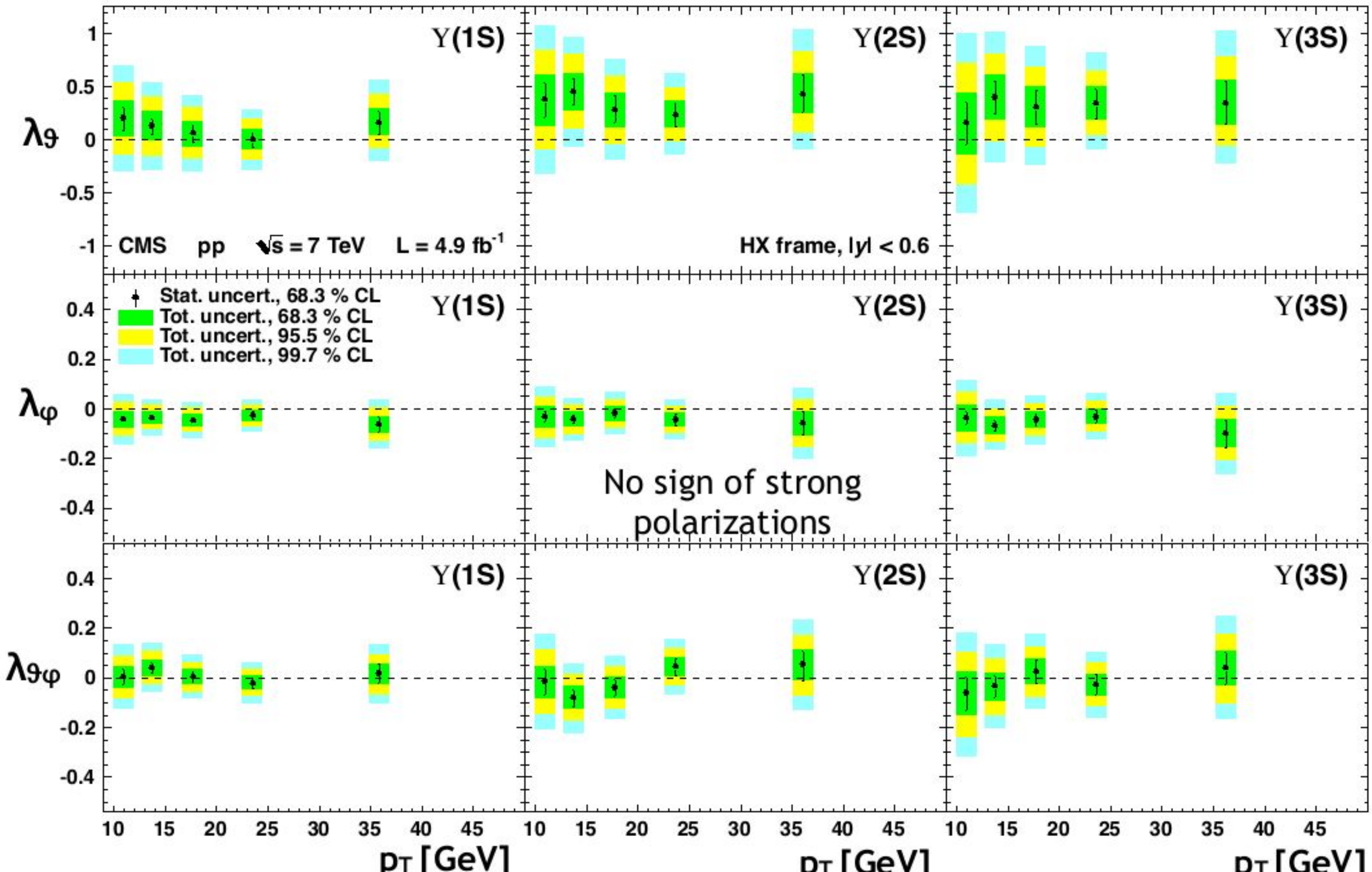
- CMS measured λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$ and $\tilde{\lambda}$ in three different reference frames (HX, CS, PX) for the J/ψ, ψ(2S), Υ(1S), Υ(2S) and Υ(3S) mesons
- As a function of transverse momentum, p_T, and dimuon rapidity, |y|
- The non-prompt term (B decays) is subtracted in the ψ(nS) cases



PKU

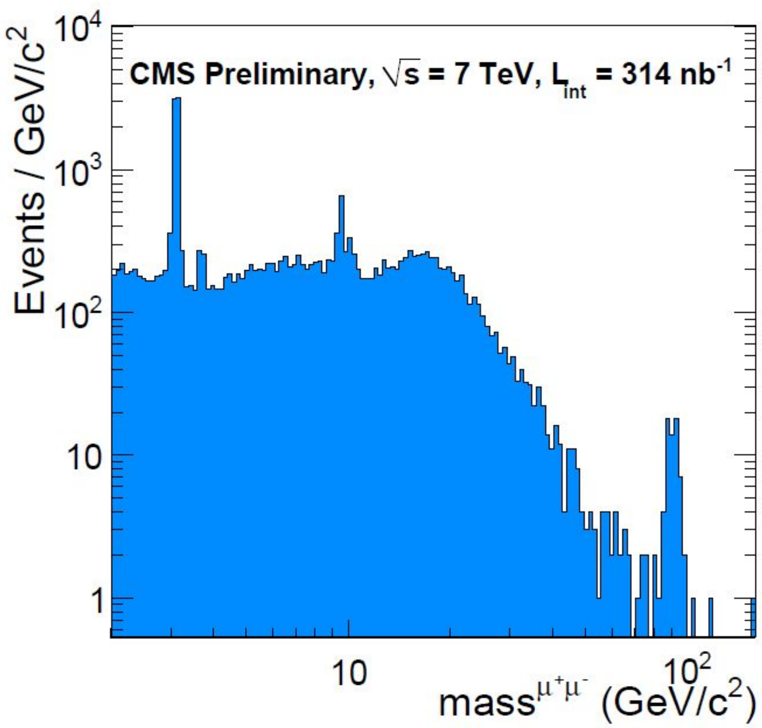
Details in PRL 110, 081802 (2013) and PLB 727, 381 (2013)

Υ(nS) polarization in the HX frame, |y|< 0.6

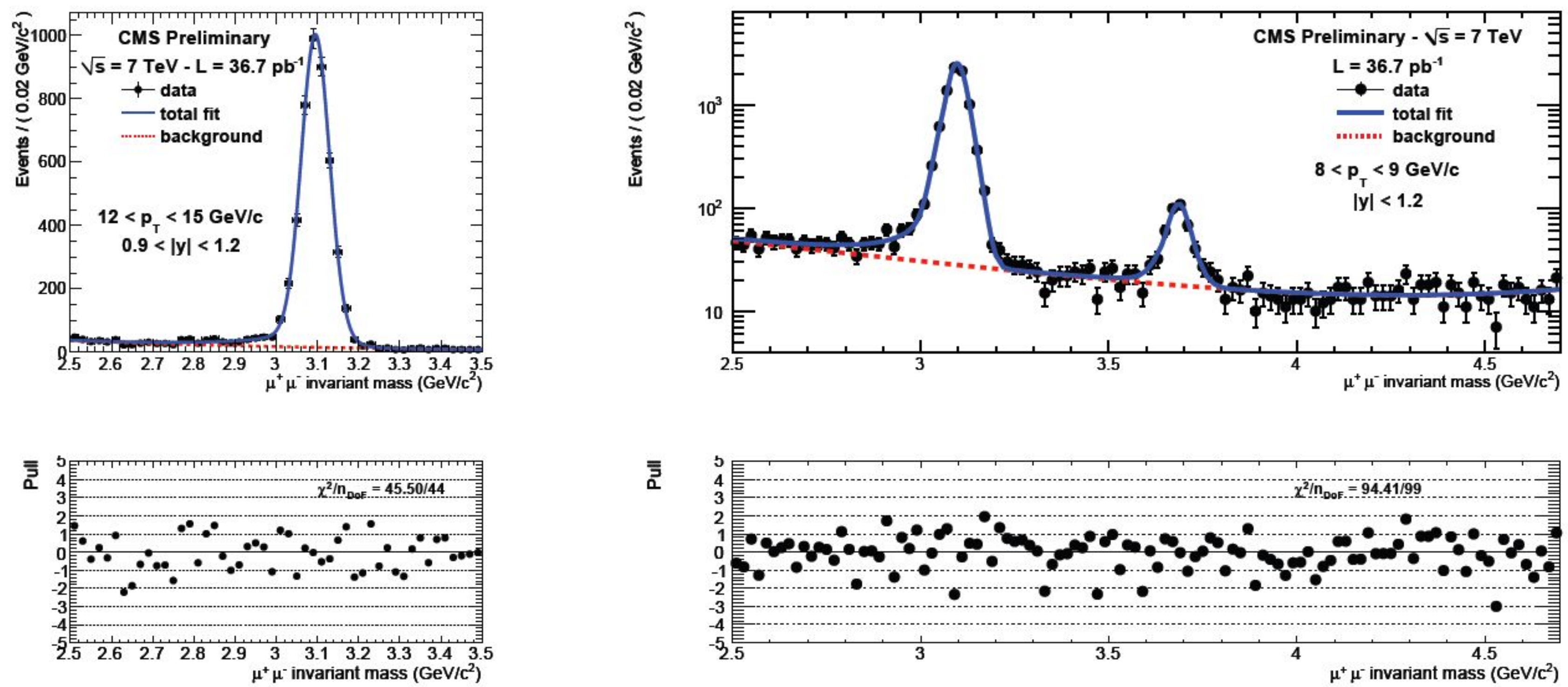


Measuring J/ψ and ψ(2S) production Xsec.

- **Crystal Ball function for signal, Exponential function for background;**



CMS dimuon mass spectrum
(standard cuts)



J/ψ and ψ(2S) mass spectrum

with standard cuts, in 12 < $p_T^{J/\psi}$ < *15GeV/c and* 0.9<$|y^{J/\psi}|$ < *1.2 (middle),* 8.0< $p_T^{J/\psi}$ < *9.0GeV/c and* $|y^{J/\psi}|$ < *1.2 (right).*

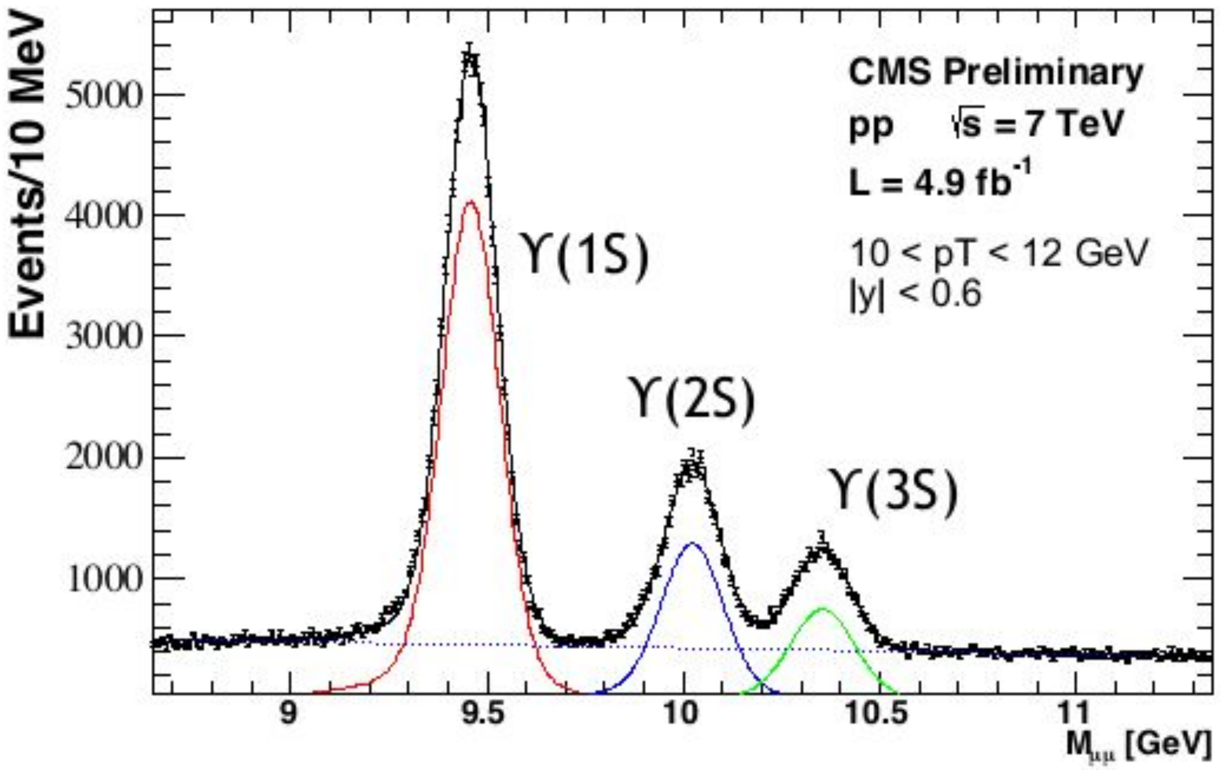
CMS AN-2010/138,
CMS PAS BPH-10-002, 10-014,
EPJC 71,1575,2011,
Phys.Rev.D83:112004,2011

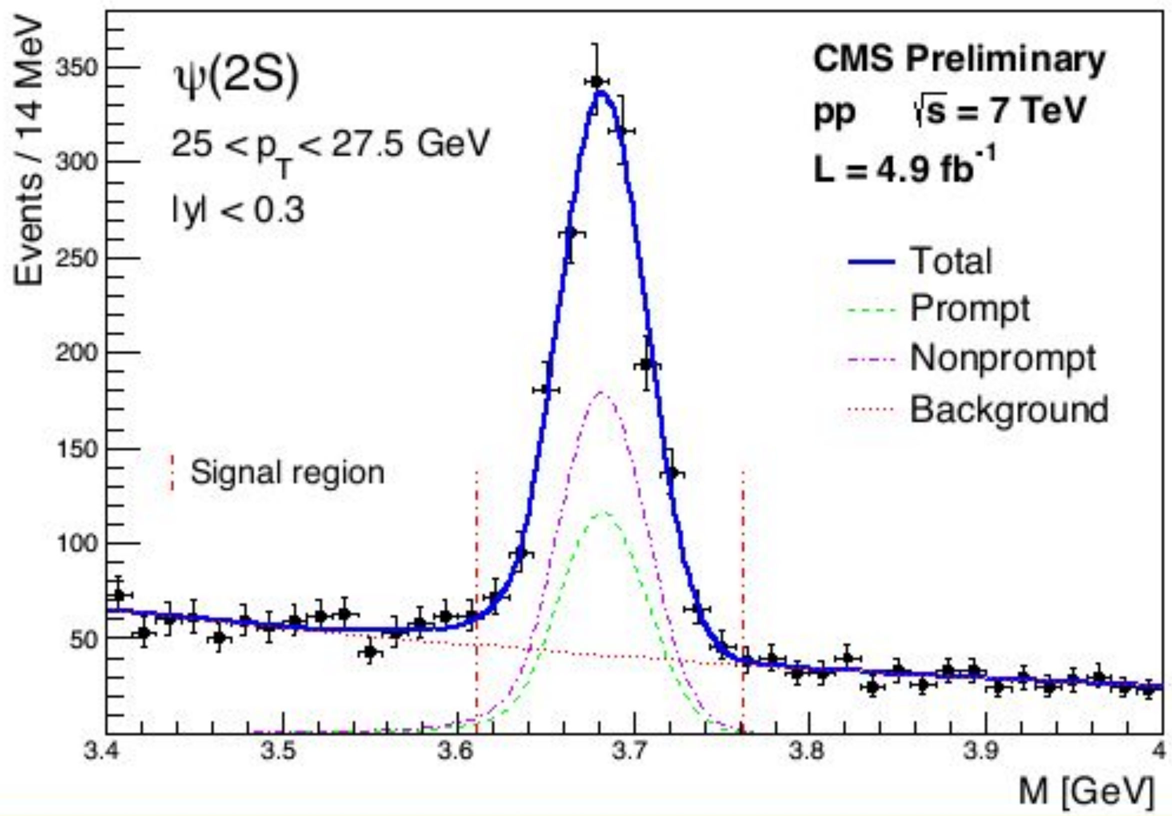
Shuang Guo from PKU,
Presentation at HQL2010, Paris

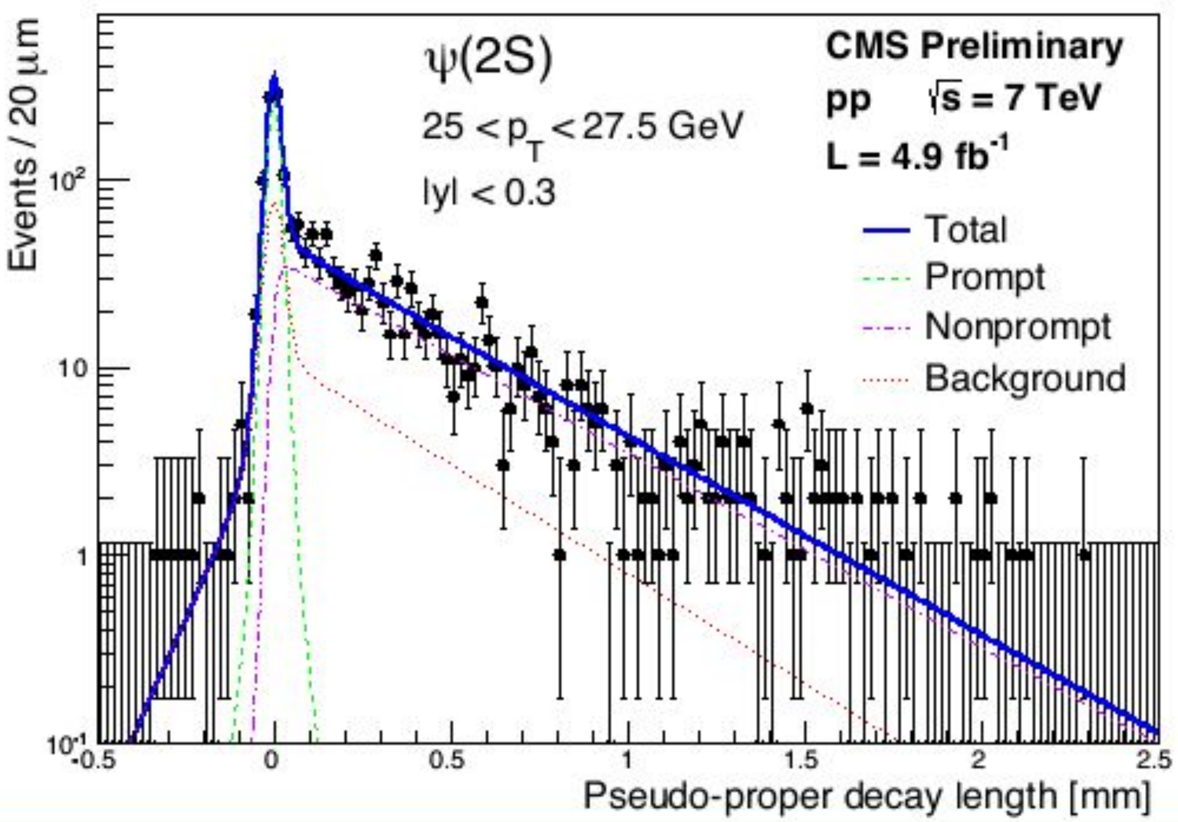
S-wave quarkonium production cross sections

- Extraction of yields through unbinned maximum likelihood fits to invariant mass and decay length

Details in CMS-PAS-BPH-14-001 and CMS-PAS-BPH-12-006



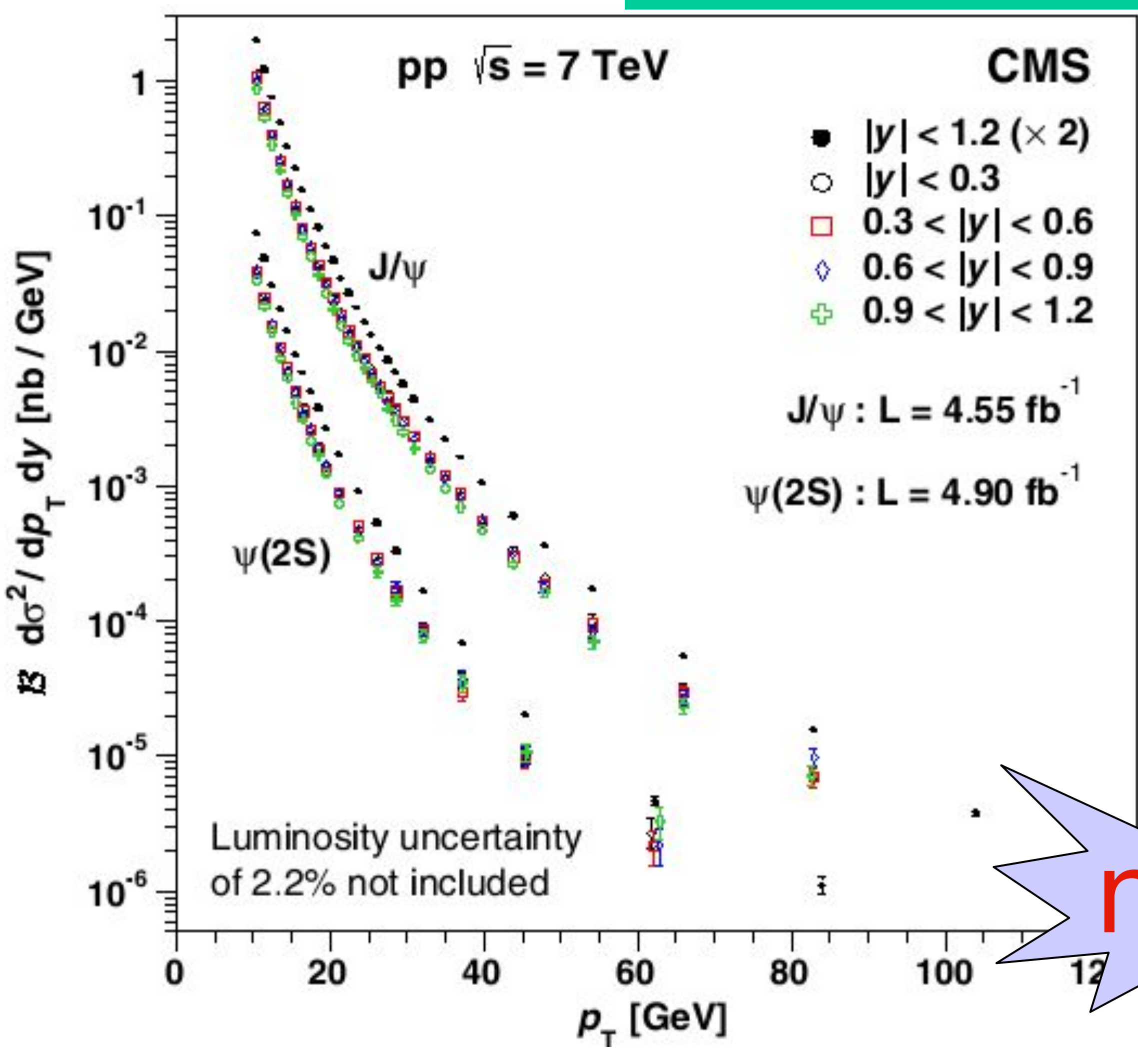


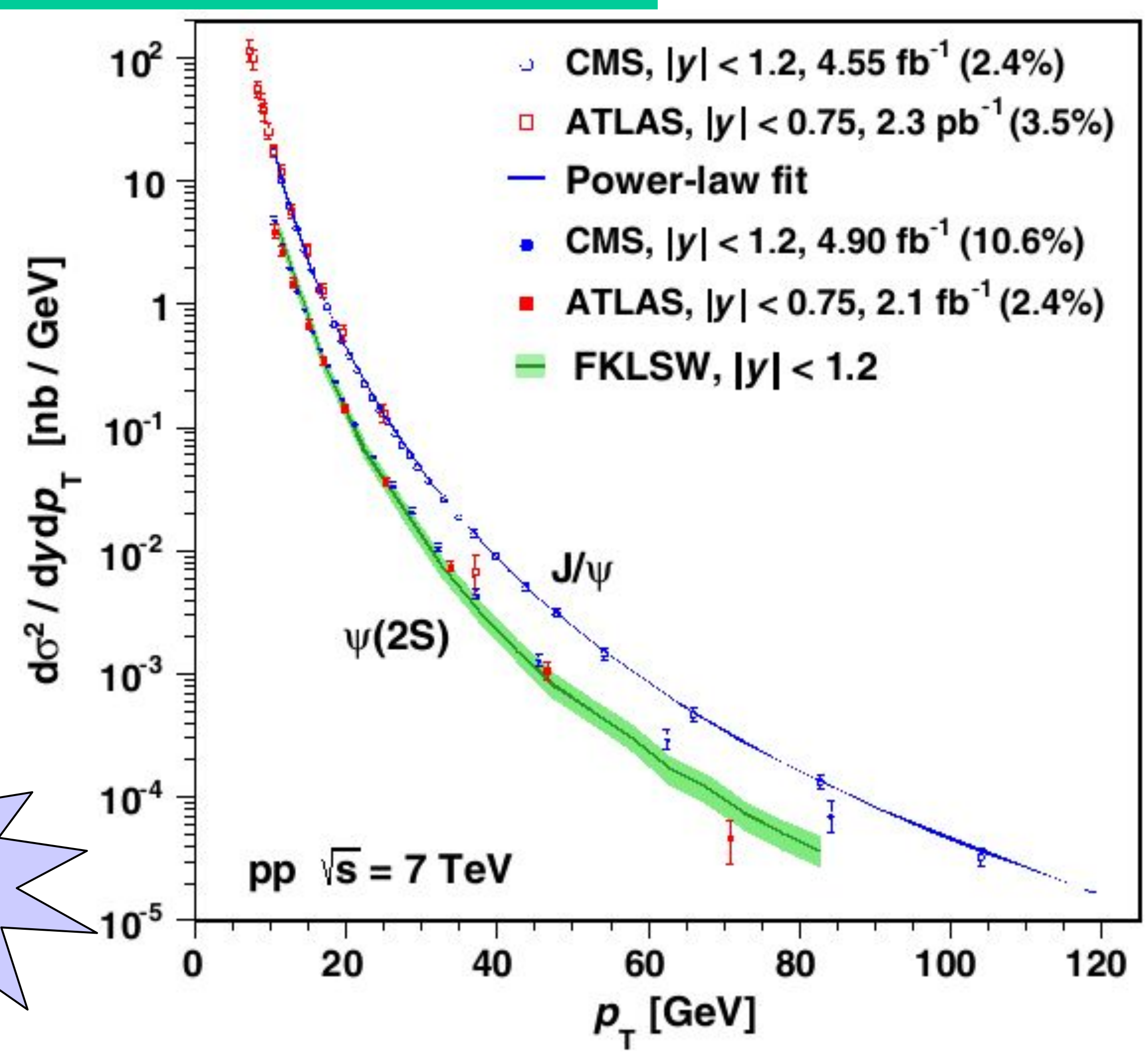


Prompt ψ(nS) production cross section

- Measurements were made as a function of p_T in four bins of dimuon rapidity as well as integrated in rapidity ($|y| < 1.2$)
- Prompt J/ψ and ψ(2S) cross sections up to p_T around 100 GeV

PKU, PRL114 (2015) 191802

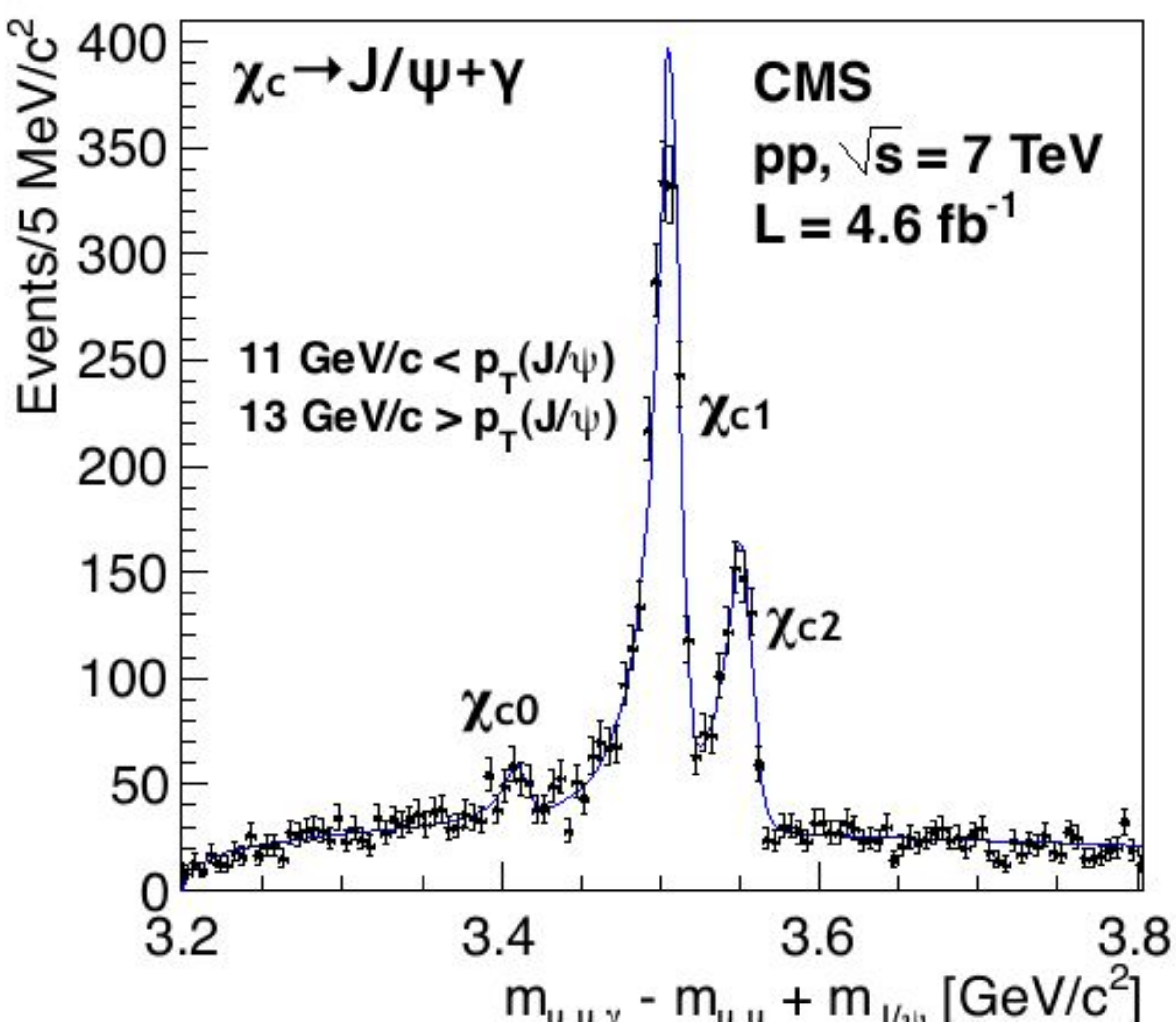


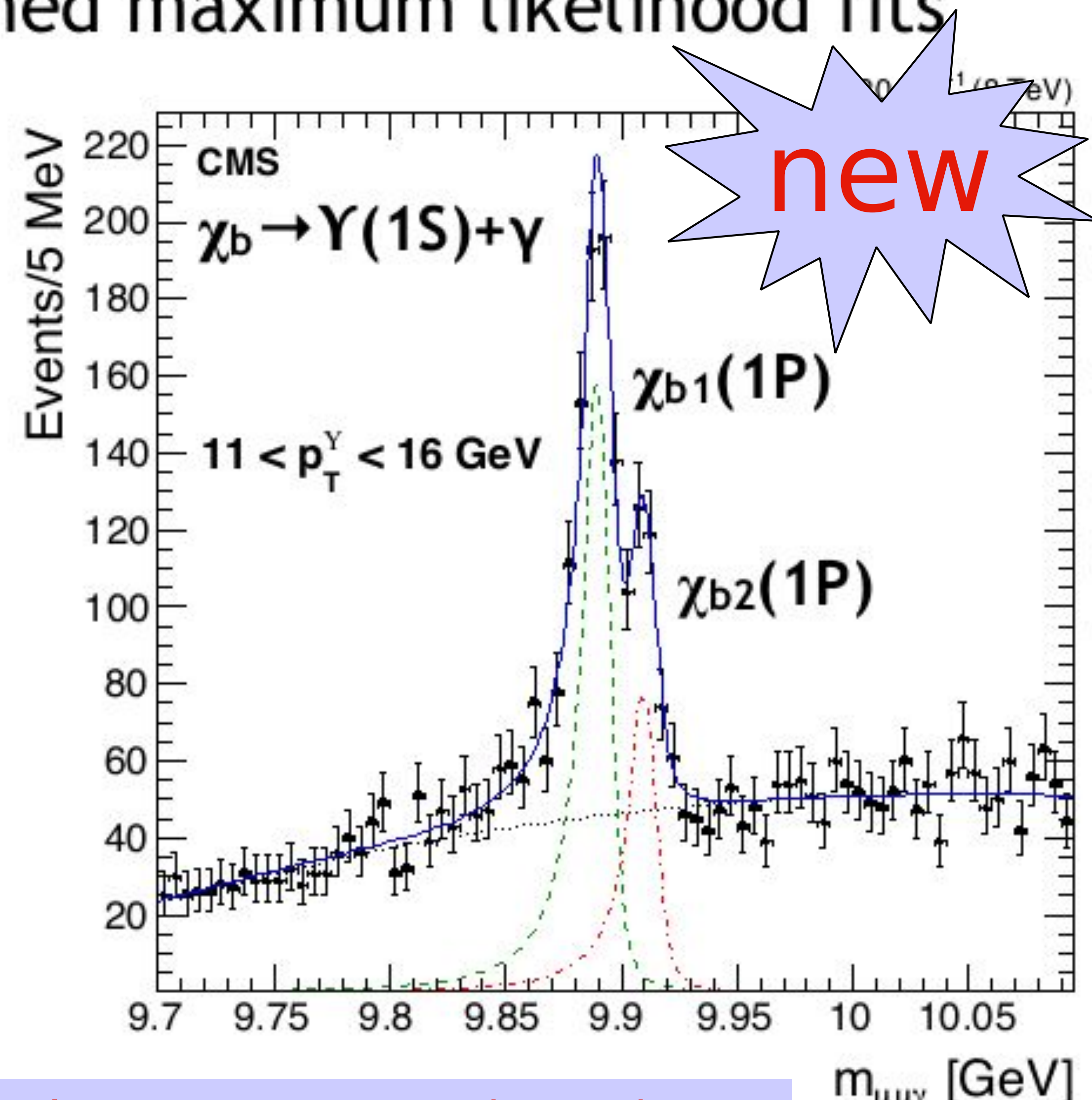


new

P-wave quarkonium production

- χ states are measured through their radiative decays to S-wave quarkonia with the photon converting into an e^+e^- pair
- Excellent χ mass (≈6 MeV, $|y_{\mu\mu}|<1$ or $|\eta_\gamma|<1$) and conversion vertex resolutions
- Yield extraction through unbinned maximum likelihood fits





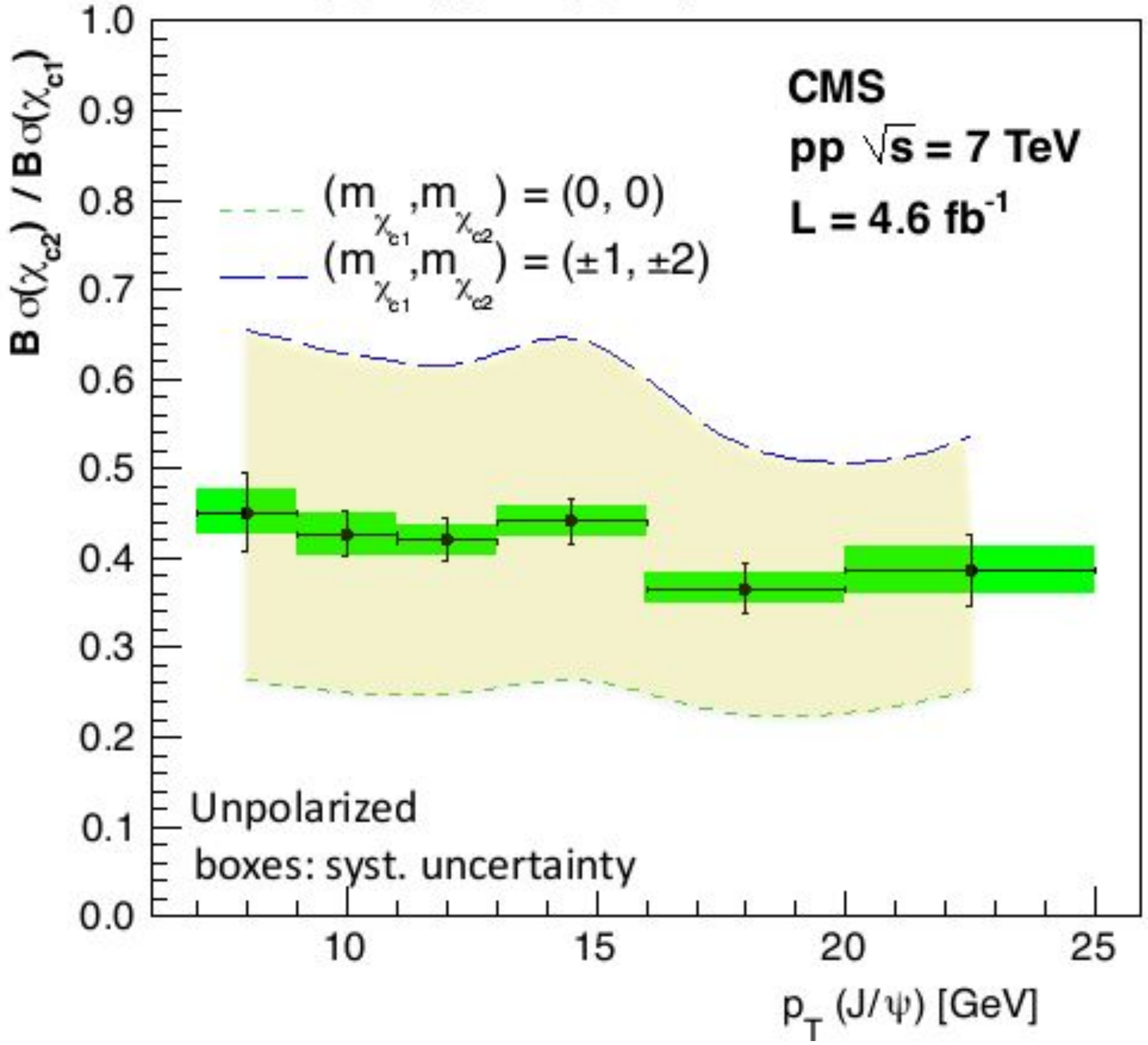
Details in EPJC 72, 2251 (2012) and arXiv:1409:5761

Phys. Lett. B 743 (2015) 383

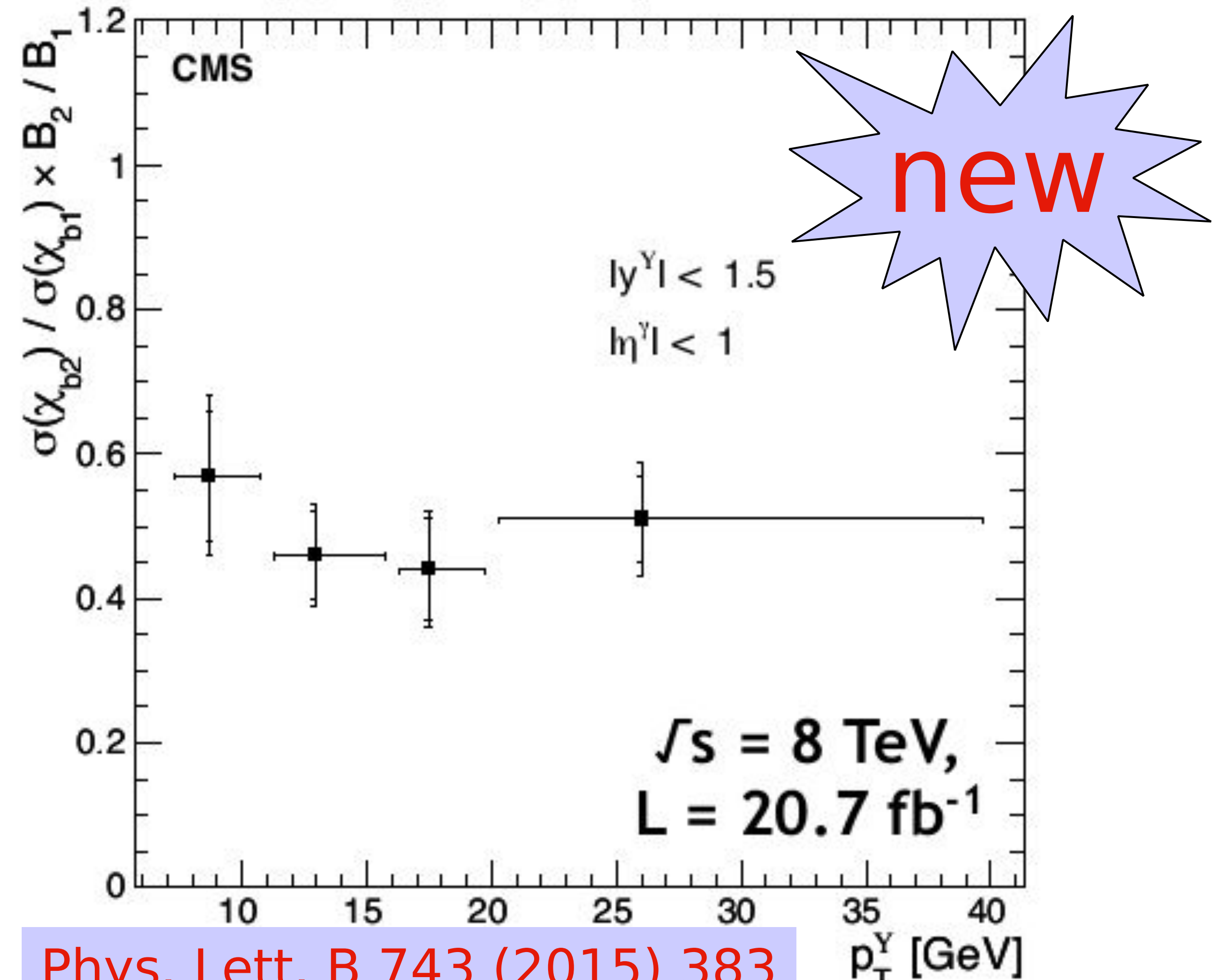
Relative production rate of P-wave states

- Prompt χ_{c2}/χ_{c1} and $\chi_{b2}(1P)/\chi_{b1}(1P)$ cross section ratios seem to be rather flat with p_T
- Prompt χ_{c2}/χ_{c1} ratio: Care is needed regarding the assumed polarizations; they can significantly change the result

$\sigma(\chi_{c2})/\sigma(\chi_{c1}) \times B_2/B_1$

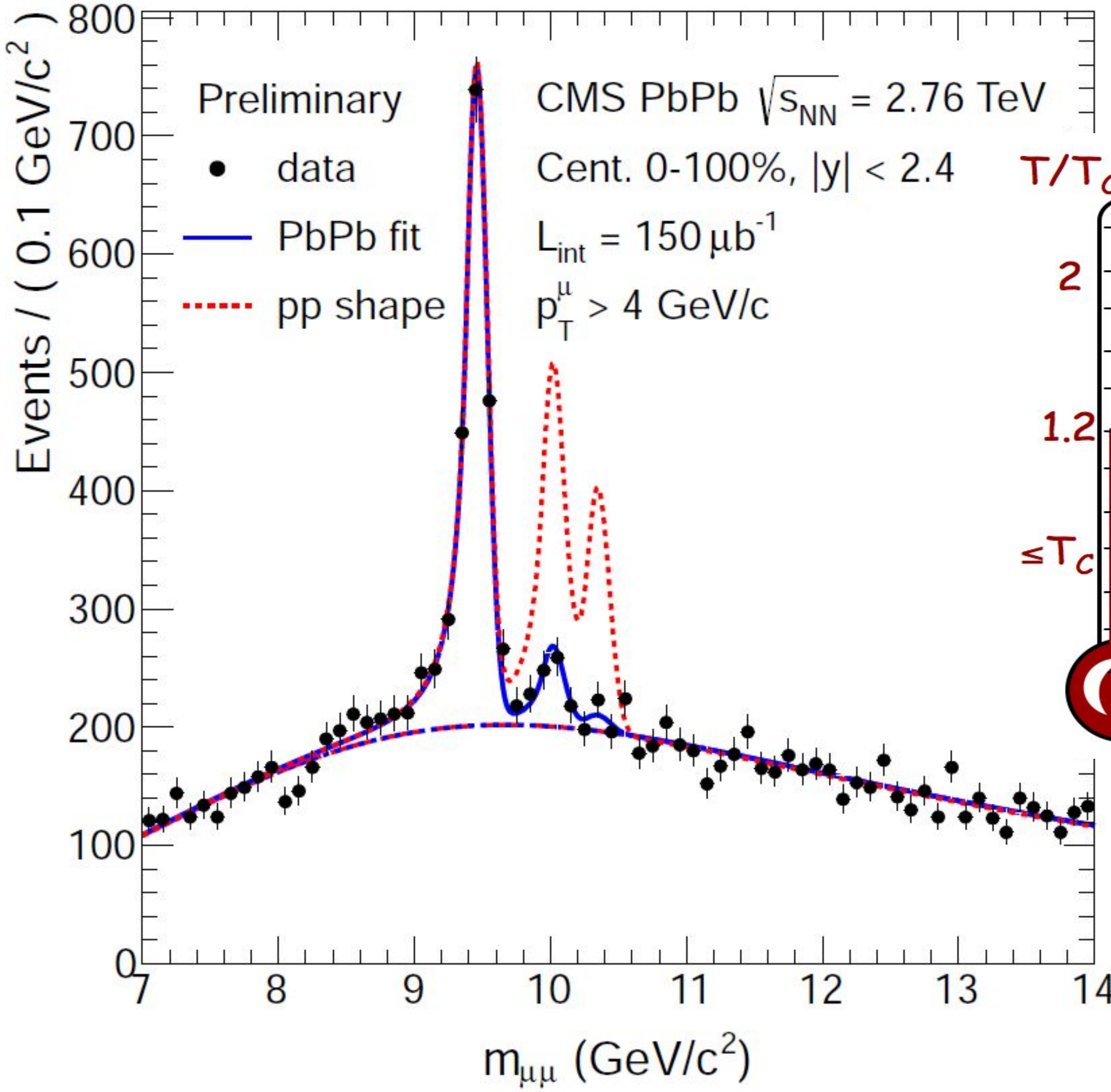


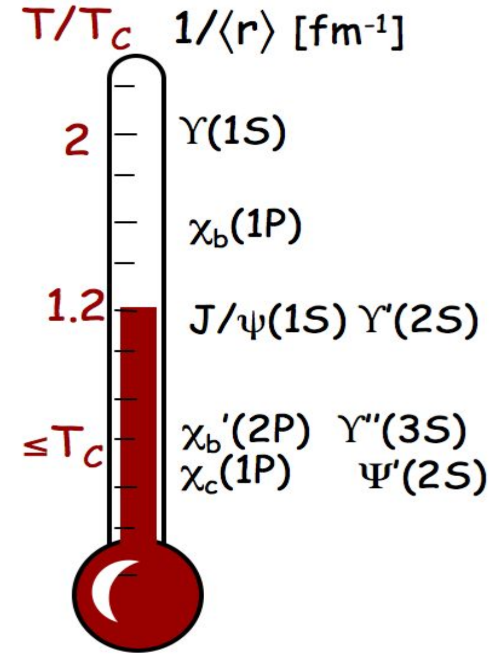
$\sigma(\chi_{b2})/\sigma(\chi_{b1}) \times B_2/B_1$

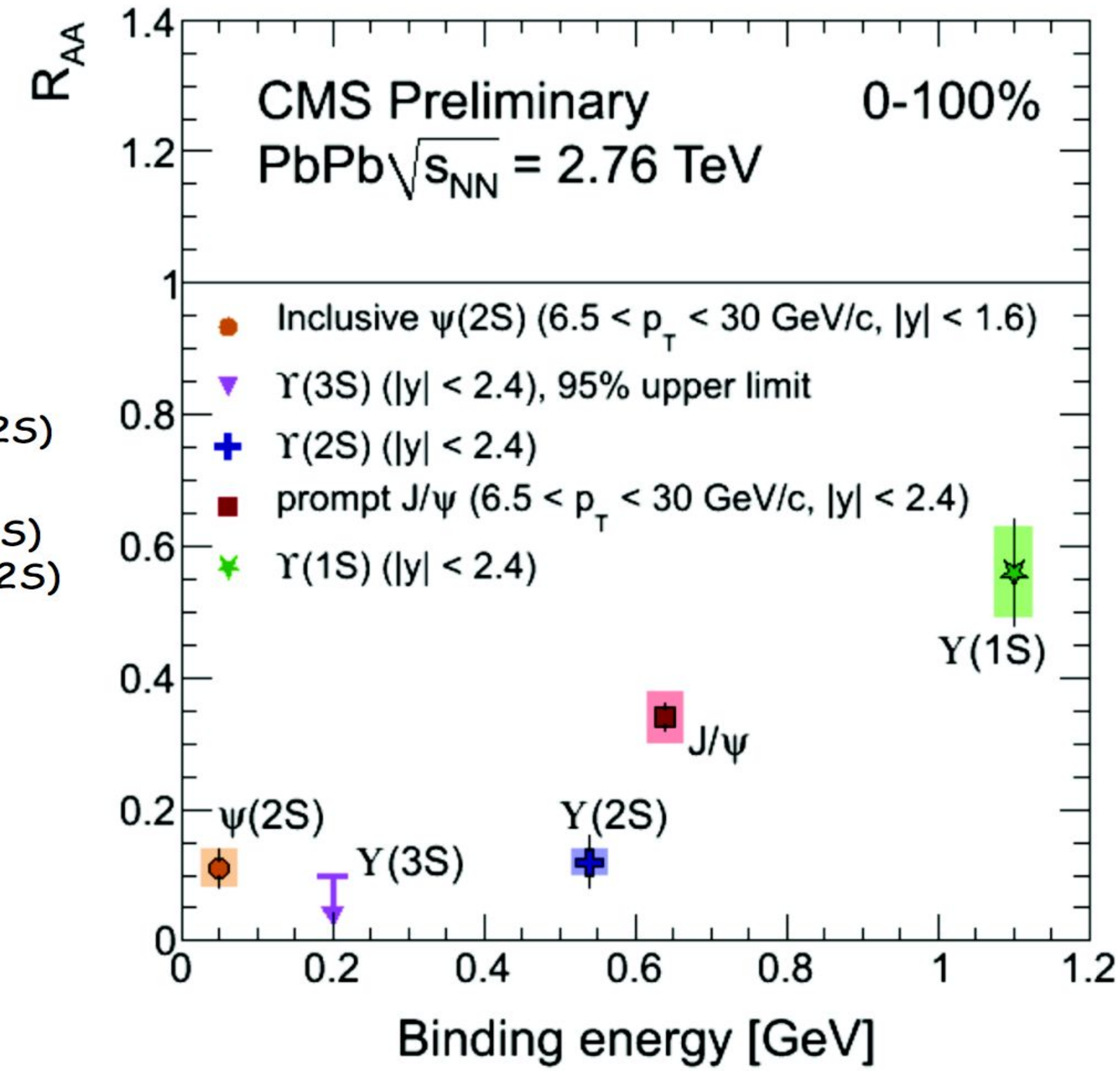


Phys. Lett. B 743 (2015) 383

Quarkonia suppression in PbPb



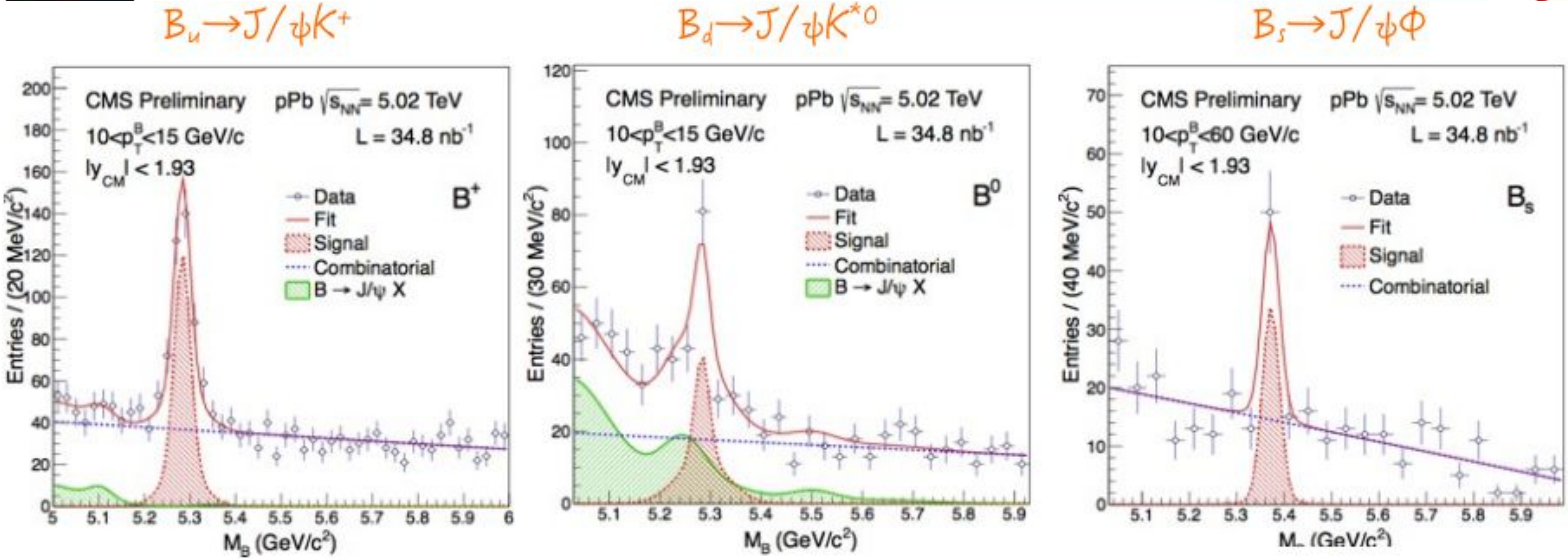




PRL 109, 222301 (2012)
CMS-PAS HIN-12-007
CMS-PAS HIN-12-014

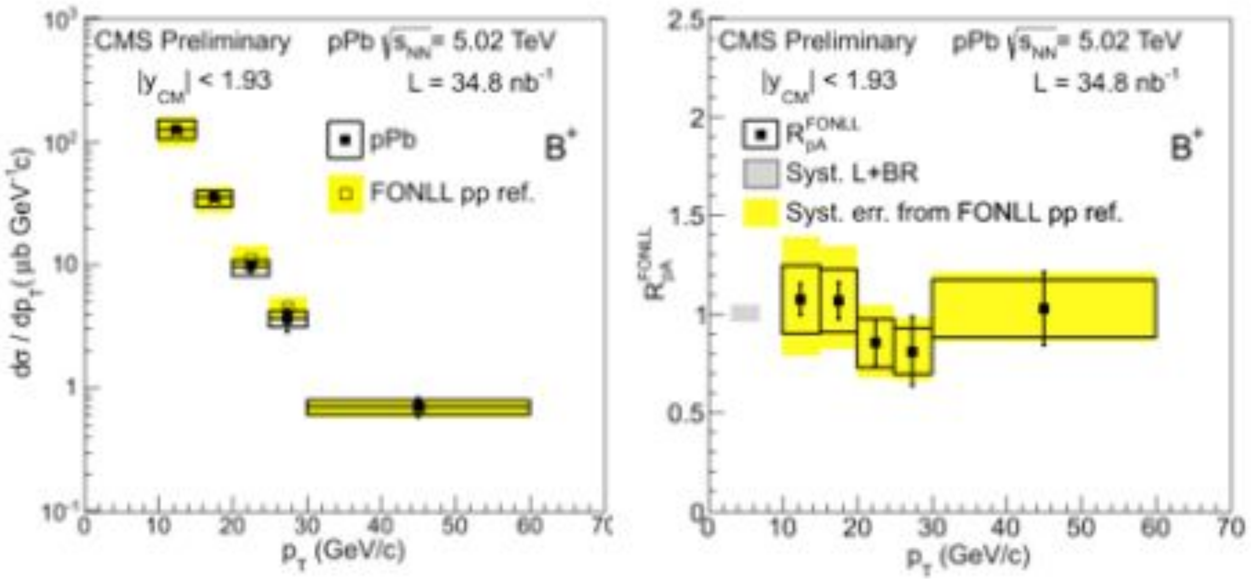
- First separate measurement, in HI collisions, of the relative suppression of ϒ(2S) and ϒ(3S) excited states wrt to the ground state.
- Suppression pattern as expected in the sequential melting scenario.
- Double ratio indicates ϒ(2S) is ~ five times more suppressed than ϒ(1s).
- Measured centrality dependence of ϒ(1S) and ϒ(2S) R_{AA}.

Excl B meson production in pPb



CMS-PAS-HIN-14-004

- new exclusive probes to study mechanisms of energy loss and its energy dependence
- next: attempt to reconstruct B peaks in Pb-Pb (to come in Run II)

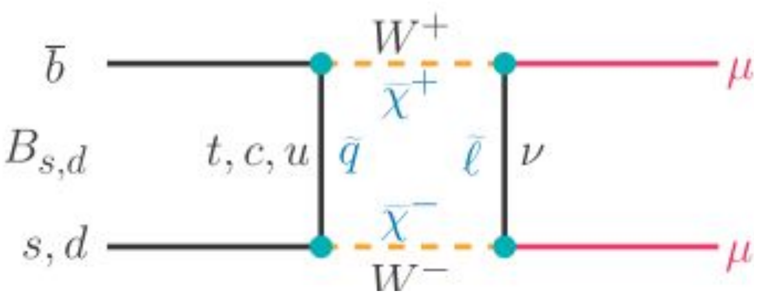


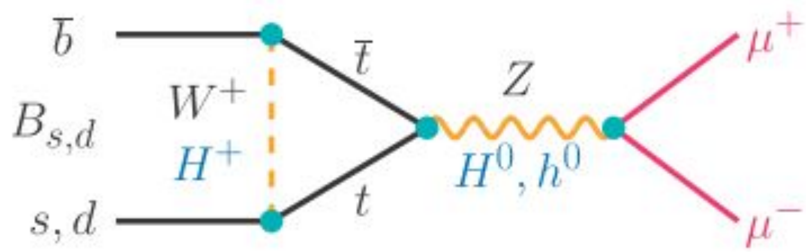
B mesons reco'd from collisions involving ions for 1st time

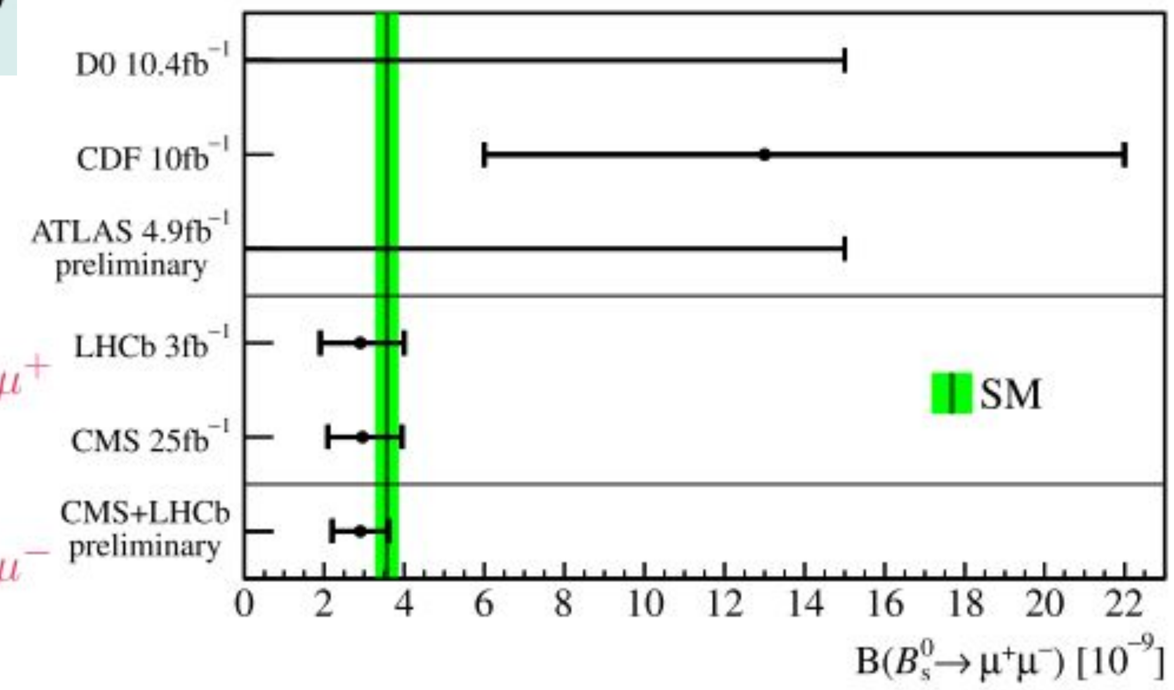
$B_s^0 \to \mu^+\mu^-$ CMS can do it quite well

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.65 \pm 0.23) \cdot 10^{-9}$$

Phys. Rev. Lett. 112, 101801 (2014)







$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 3.0\,^{+1.0}_{-0.9} \times 10^{-9}$$

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

ATLAS: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.5 \times 10^{-8}$

CMS: Phys. Rev. Lett. 111 (2013) 101804

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.9\,^{+1.1}_{-1.0}\,^{+0.3}_{-0.1} \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.7\,^{+2.4}_{-2.1}\,^{+0.6}_{-0.4} \times 10^{-10}$$

$B_s^0 \to \mu^+\mu^-$ First observation

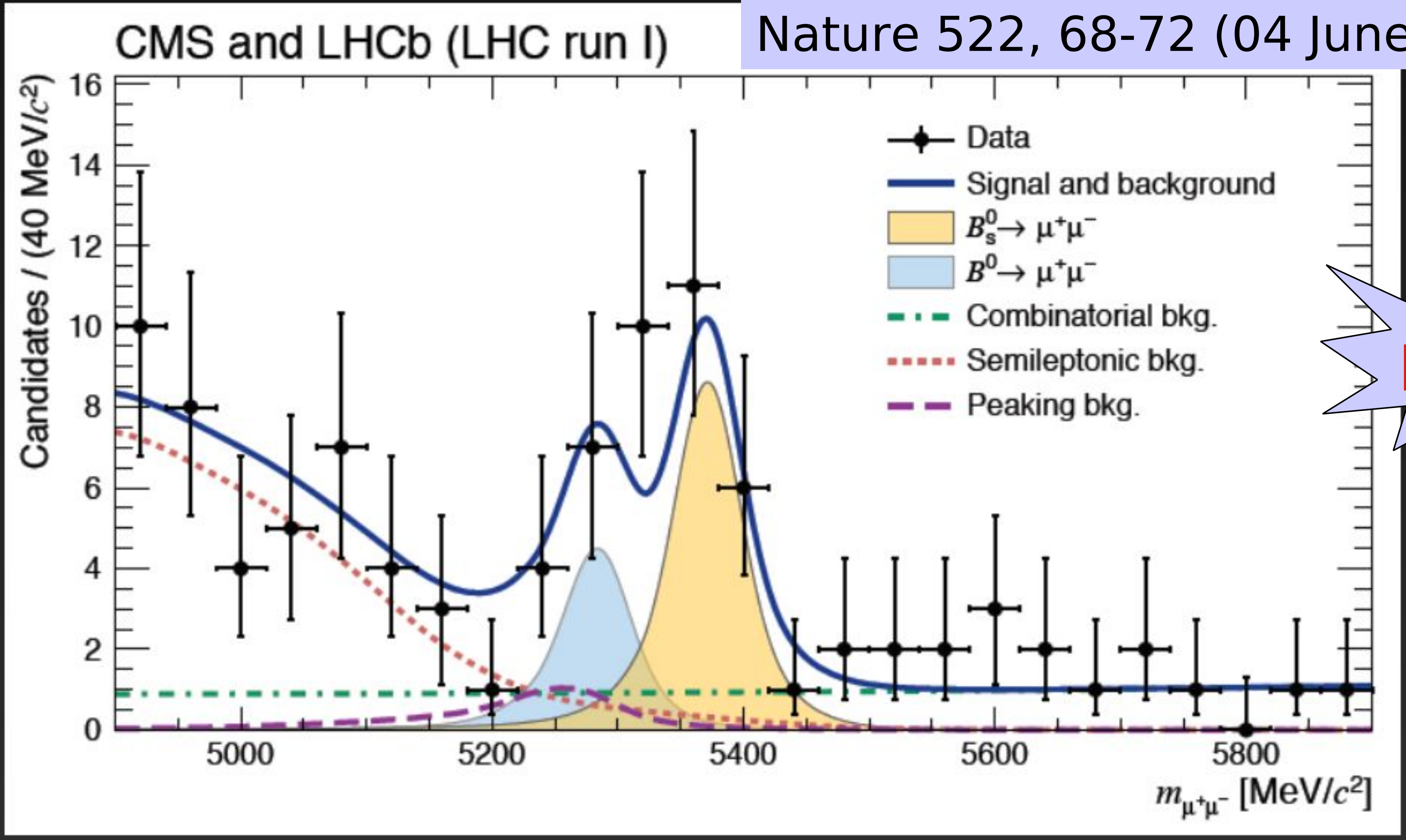
LHCb:Phys. Rev. Lett. 111 (2013) 101805

CMS&LHCb: "deep" combination

Results of combination

6 most sensitive cathegories

Nature 522, 68-72 (04 June 2015)



new

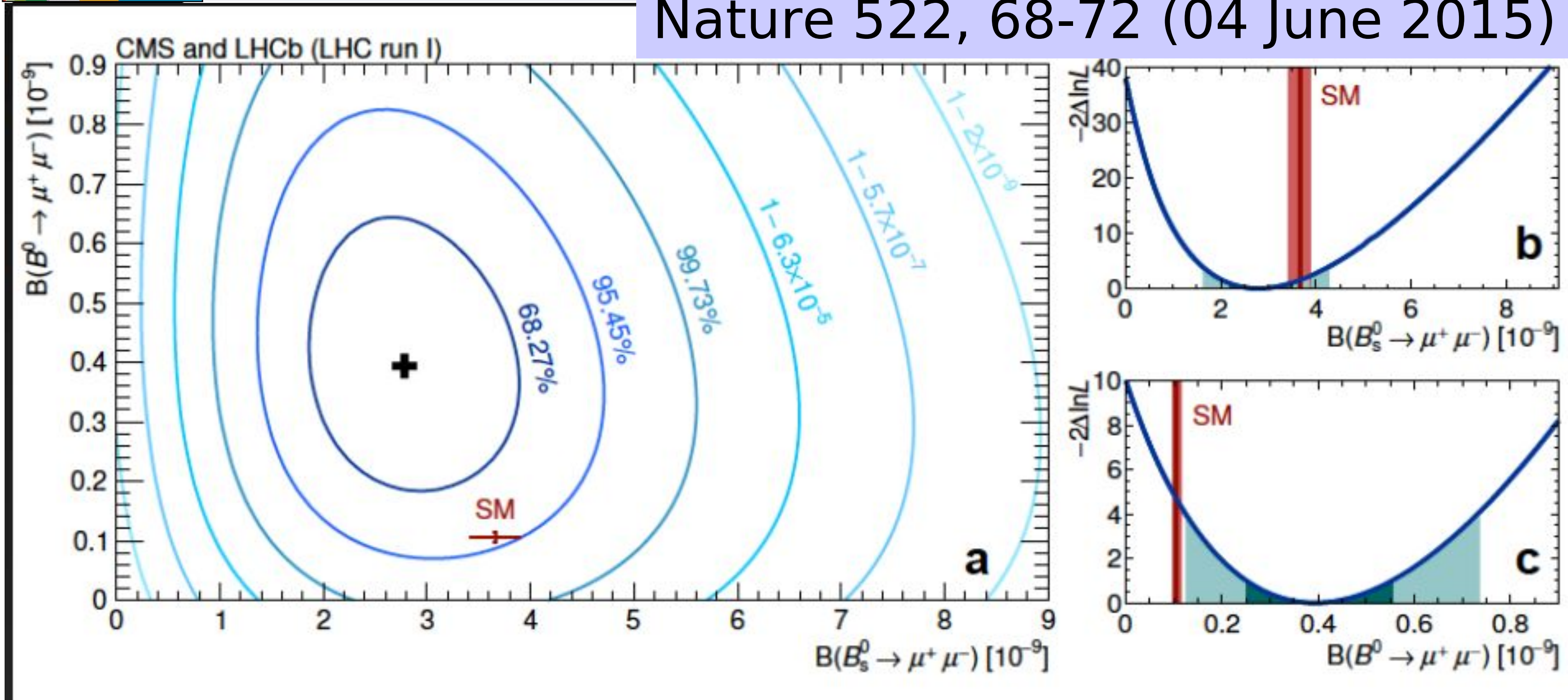
$BR(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$ (6.2 σ significance)

$BR(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$ (3.0 σ significance*)

*Feldman Cousin

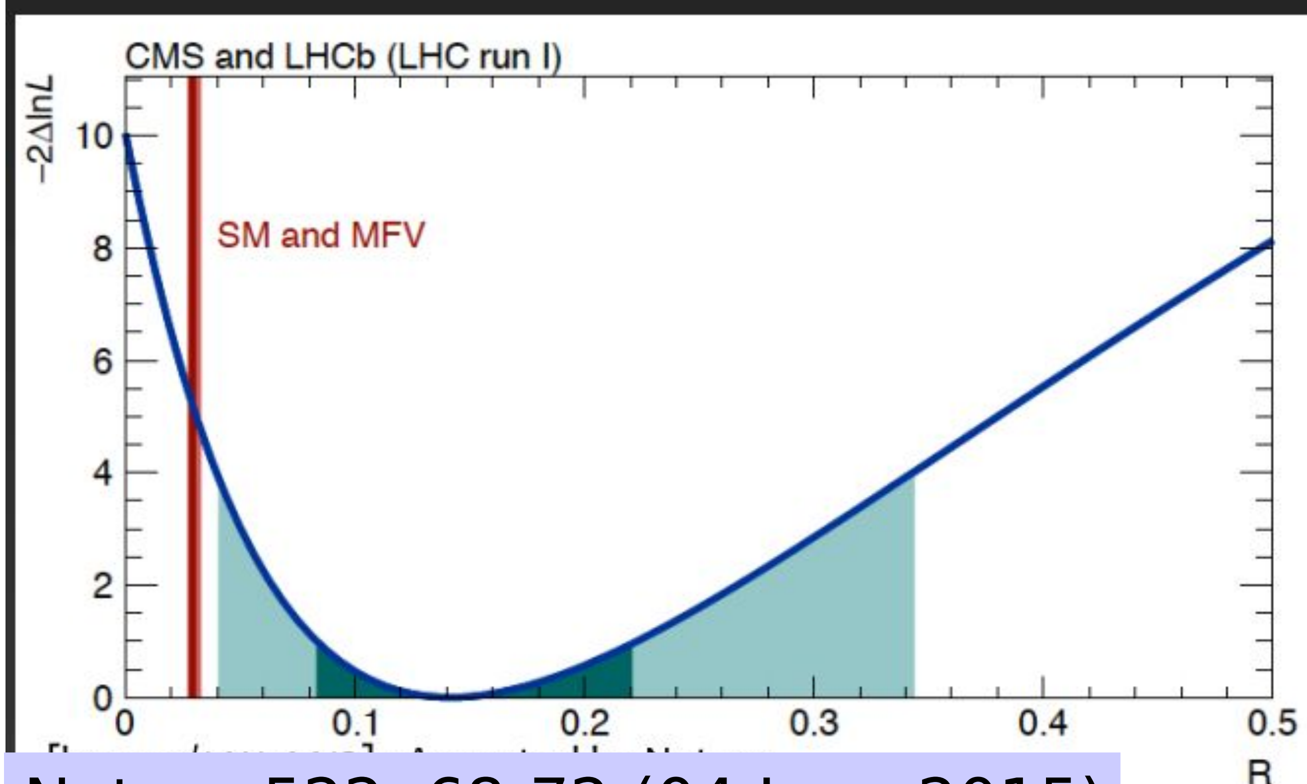
Confidence intervals

Nature 522, 68-72 (04 June 2015)



Confidence intervals

new



Measurement of the ratio

$R = BR(B^0 \rightarrow \mu^+\mu^-) / BR(B_s^0 \rightarrow \mu^+\mu^-)$

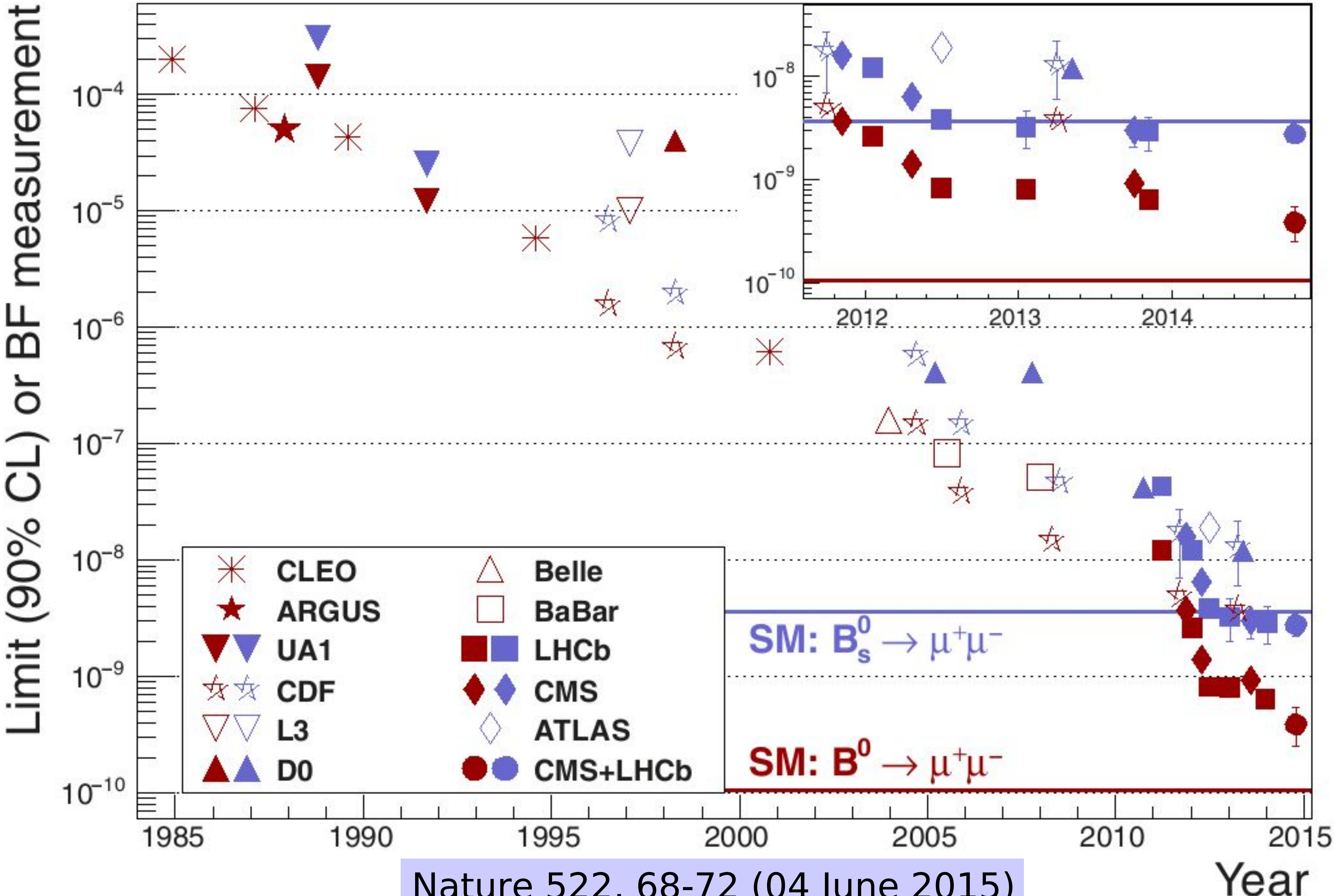
$R = 0.14^{+0.08}_{-0.06}$

compatible with the SM prediction

$R = 0.0295^{+0.0028}_{-0.0025}$ at the 2.3σ level

Nature 522, 68-72 (04 June 2015)

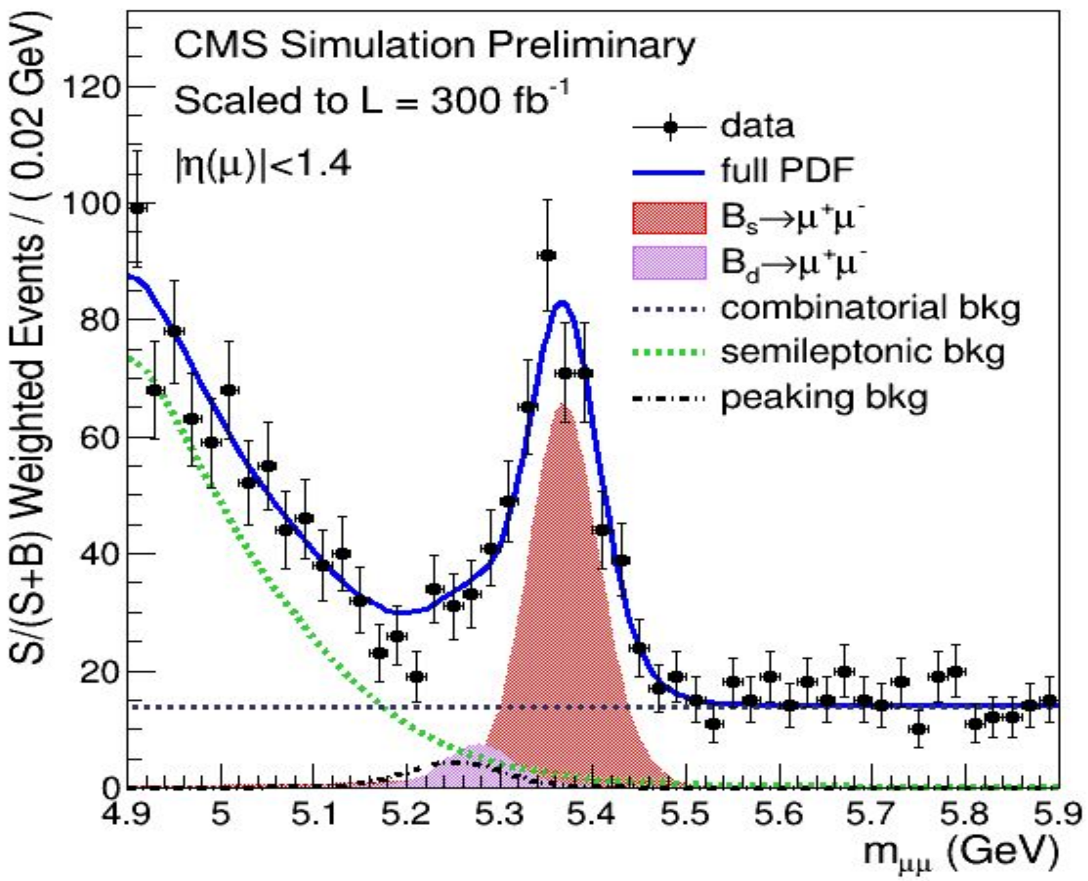
$B_s^0 \to \mu^+\mu^-$ History: 30 years

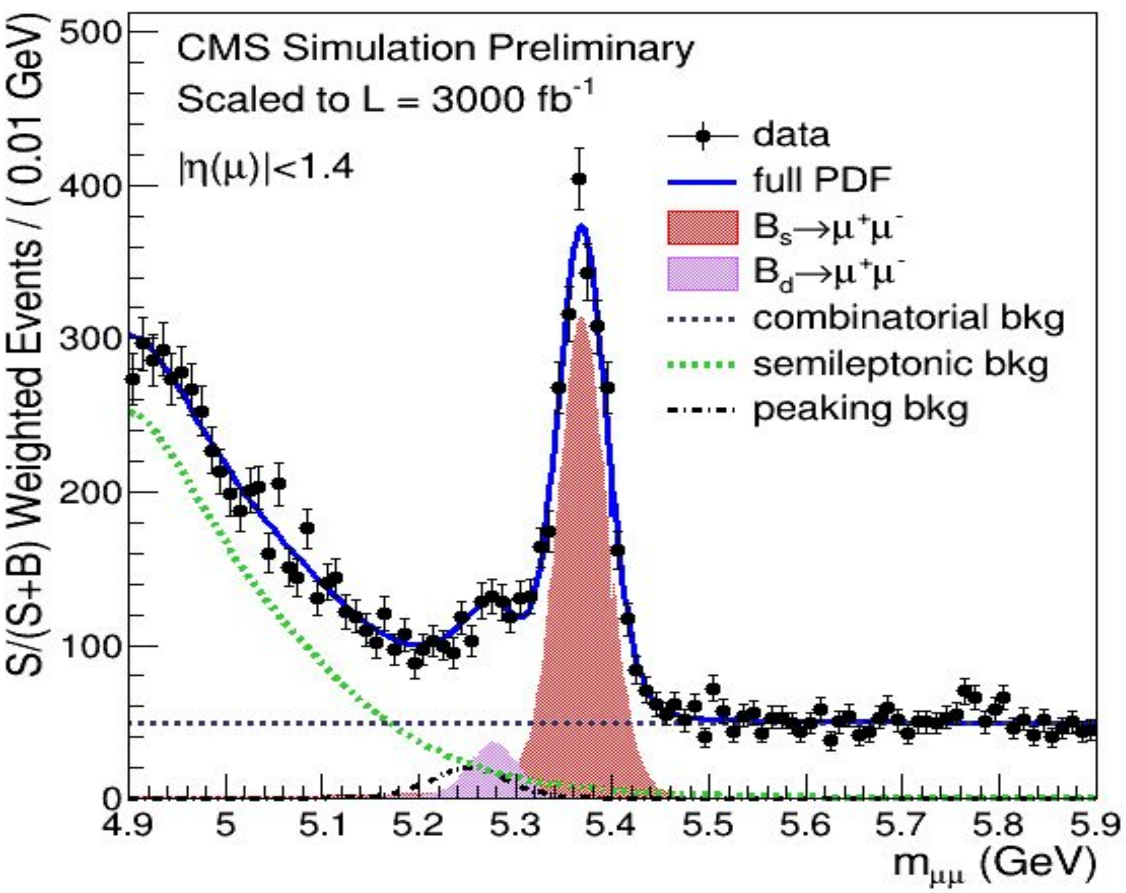


Nature 522, 68-72 (04 June 2015)

Future projection

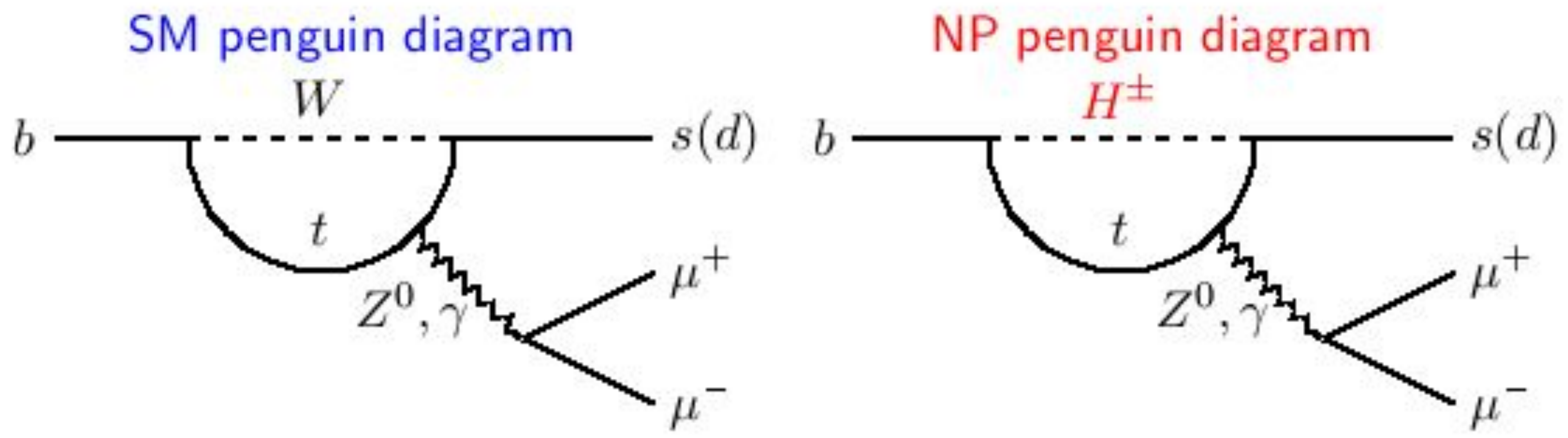
- **Extrapolations using Phase I/II detector setups and L1 triggers**
- **Invariant mass resolution from full GEANT4 simulation**
- **Restrict analysis to barrel region**





L (fb^{-1})	No. of B_s^0	No. of B^0	$\delta\mathcal{B}/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\delta\mathcal{B}/\mathcal{B}(B^0 \to \mu^+\mu^-)$	B^0 sign.	$\delta\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B_s^0\to\mu^+\mu^-)}$
20	16.5	2.0	35%	>100%	0.0–1.5 σ	>100%
100	144	18	15%	66%	0.5–2.4 σ	71%
300	433	54	12%	45%	1.3–3.3 σ	47%
3000	2096	256	12%	18%	5.4–7.6 σ	21%

b->s mumu: indirect probe of NP



- Rare FCNC decays are loop-suppressed in the Standard Model (SM)
- New heavy particles in SM extensions can appear in competing diagrams can affect $\mathcal{B}$ and angular distributions

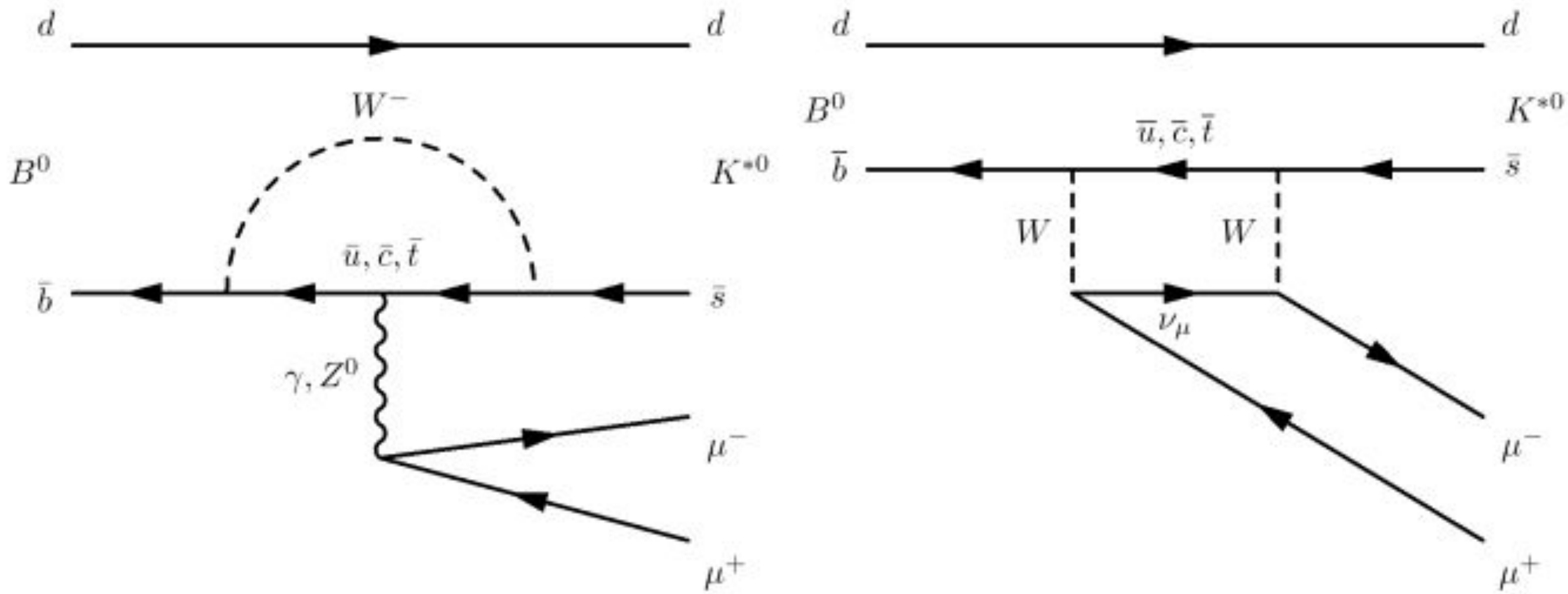
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{tq}}^* \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left handed}} + \underbrace{\mathcal{C}_i' \mathcal{O}_i'}_{\text{Right handed, } \frac{m_s}{m_b} \text{ suppressed}} + \sum \frac{c}{\Lambda_{\text{NP}}^2} \mathcal{O}_{\text{NP}}$$

$i = 1, 2$	Tree
$i = 3-6, 8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9, 10$	EW penguin
$i = S, P$	(Pseudo)scalar penguin

- Model independent description in effective field theory
- Wilson coeff. $\mathcal{C}_i^{(\prime)}$ encode short-distance physics, $\mathcal{O}_i^{(\prime)}$ corr. operators

B → K(*)μ⁺ μ⁻

- $B \to K\mu^+\mu^-$ and $B \to K^*\mu^+\mu^-$ proceed dominantly through penguin and box diagrams.



- Integrating out the short distance dynamics → Wilson Coefficients:
  - $\mathcal{C}_7$ electromagnetic
  - $\mathcal{C}_9$ semi-leptonic vector
  - $\mathcal{C}_{10}$ semi-leptonic axial vector
- Observables depend on four-momentum transferred to dimuon, q^2.

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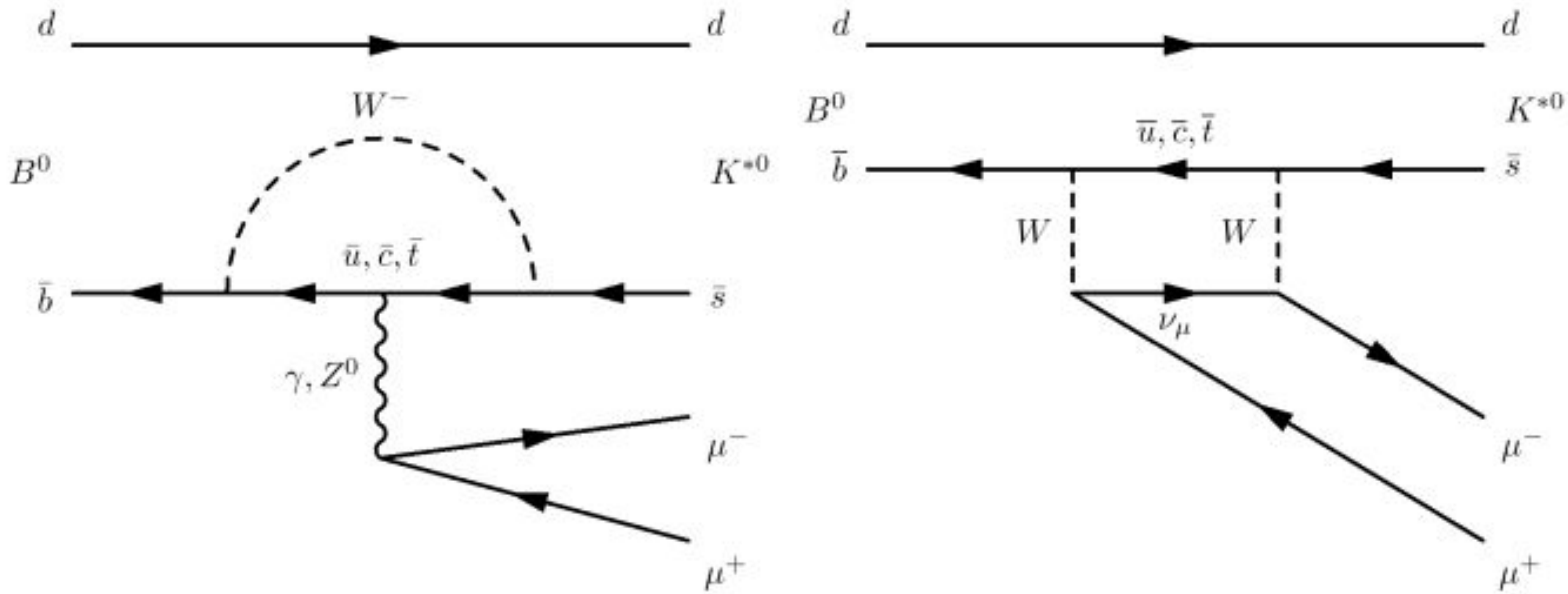

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  - $\mathcal{C}_{10}$ semi-leptonic axial vector
- Observables depend on four-momentum transferred to dimuon, q^2.

Decay parameters for $B \rightarrow K^{*0}\mu^+\mu^-$

- **Decay is characterized by 3 angular variables**

$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2}$$

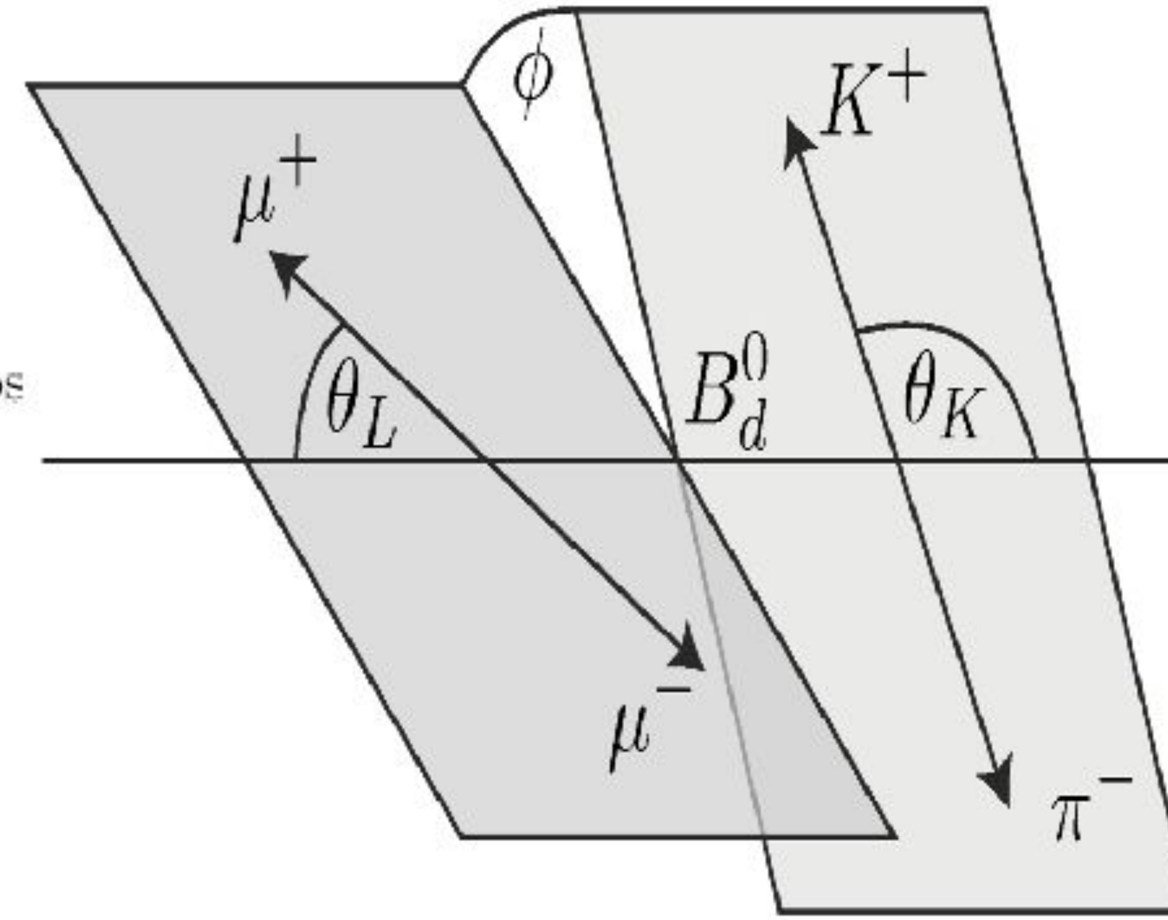
$$=\frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos$$

$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$

$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$

$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$

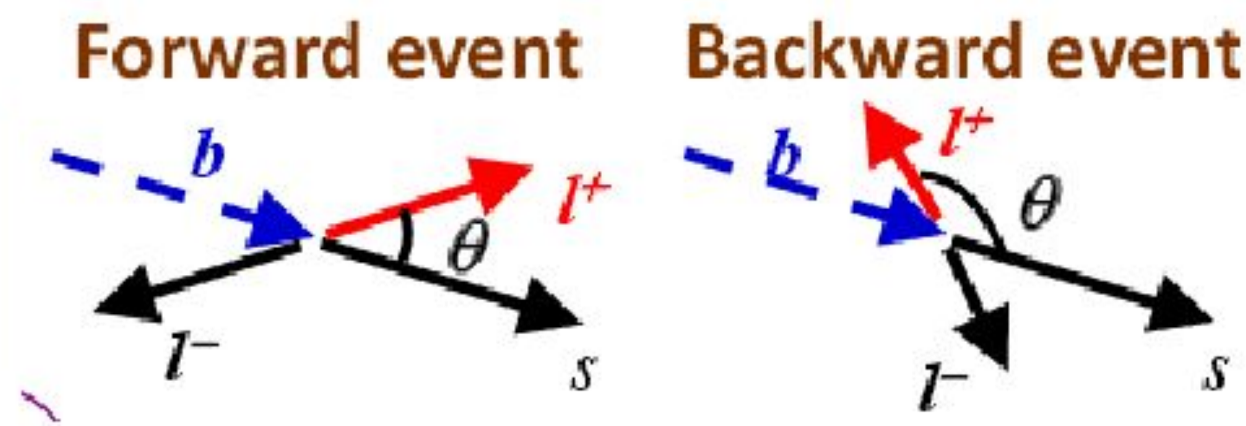
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$



- **One of the interesting parameter is muon forward-backward asymmetry (A_{FB}) which is sensitive to new physics**

dimuon invariant mass

$$A_{FB} \propto -\mathrm{Re}\left[\left(2C_7^{eff} + \frac{q^2}{m_b^2}C_9^{eff}\right)C_{10}\right]$$



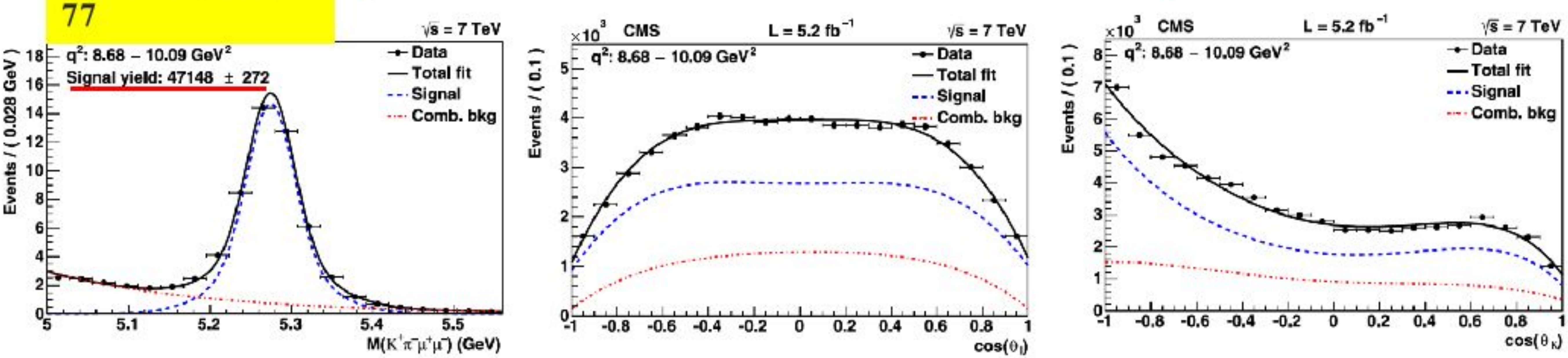
A tour of the analysis

- Reject candidate events having the di-muon mass compatible with J/ψ or ψ' ➡ these events are used for the normalization and cross-check purpose
- Fit in bins of q^2 to the $K\pi\mu\mu$ mass and two angular variables (θ_ℓ, θ_K) to
  - estimate F_S and A_S in the $B^0 \to K^{\star 0} J/\psi$ channel
  - measure F_L and A_{FB} in the signal sample
- Determine the differential branching fraction, normalized w.r.t. $B^0 \to K^{\star 0} J/\psi$

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

Y: event yield
ϵ: efficiency

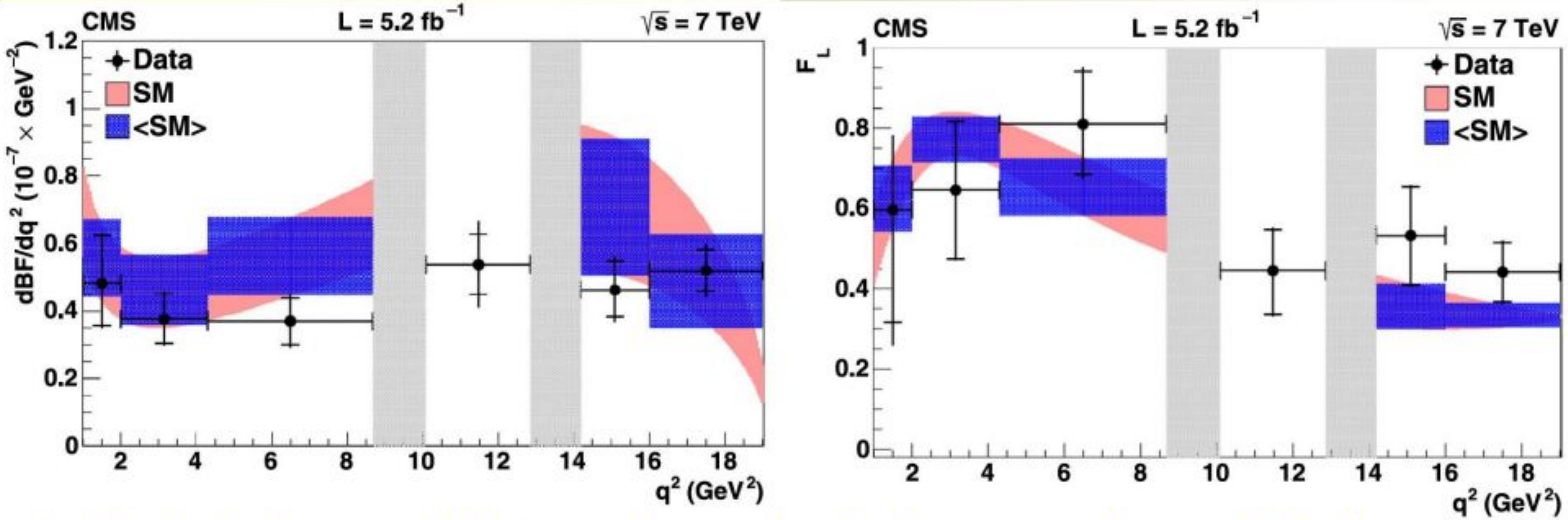
PLB 727 (2013) 77



- Projections of fit in $M(K\pi\mu\mu)$, $\cos(\theta_\ell)$ and $\cos(\theta_K)$ distributions for the q^2 bin associated with the $B^0 \to K^{\star 0} J/\psi$ decay

$F_S = 0.01 \pm 0.01,\ A_S = -0.10 \pm 0.01$

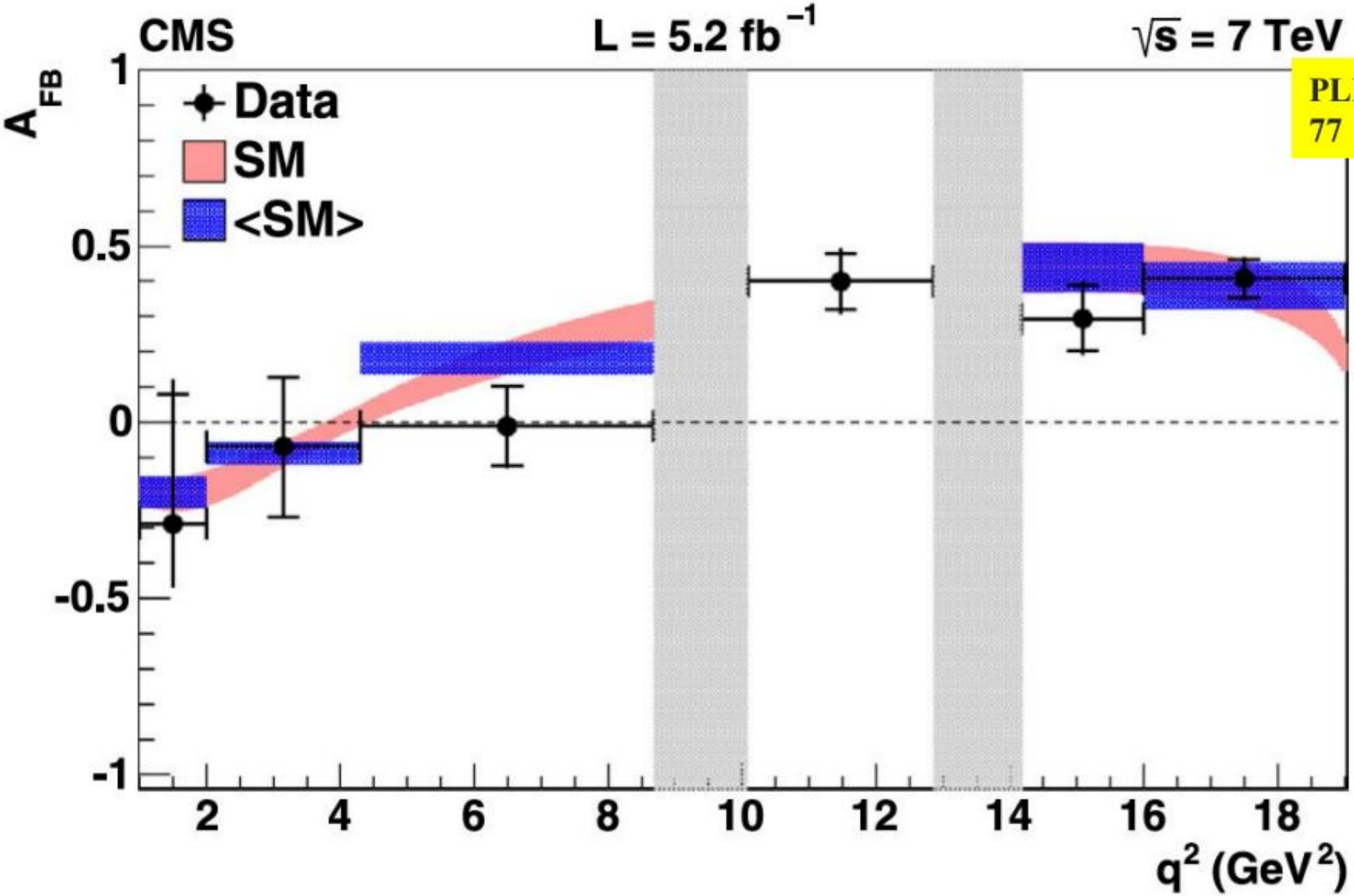
Results on $d\mathcal{BF}/dq^2$ and F_L



- ➢ Statistical uncertainties are shown by the inner error bars, while the outer ones give the total uncertainties including systematic
- SM predictions as a function of q^2
- the same after rate average over q^2 bins
- ➢ Reliable predictions do not exist for the intermediate region between the J/ψ and ψ' resonances ($10.09 < q^2 < 12.86$ GeV^2)
- ➢ No significant deviations with respect to the SM

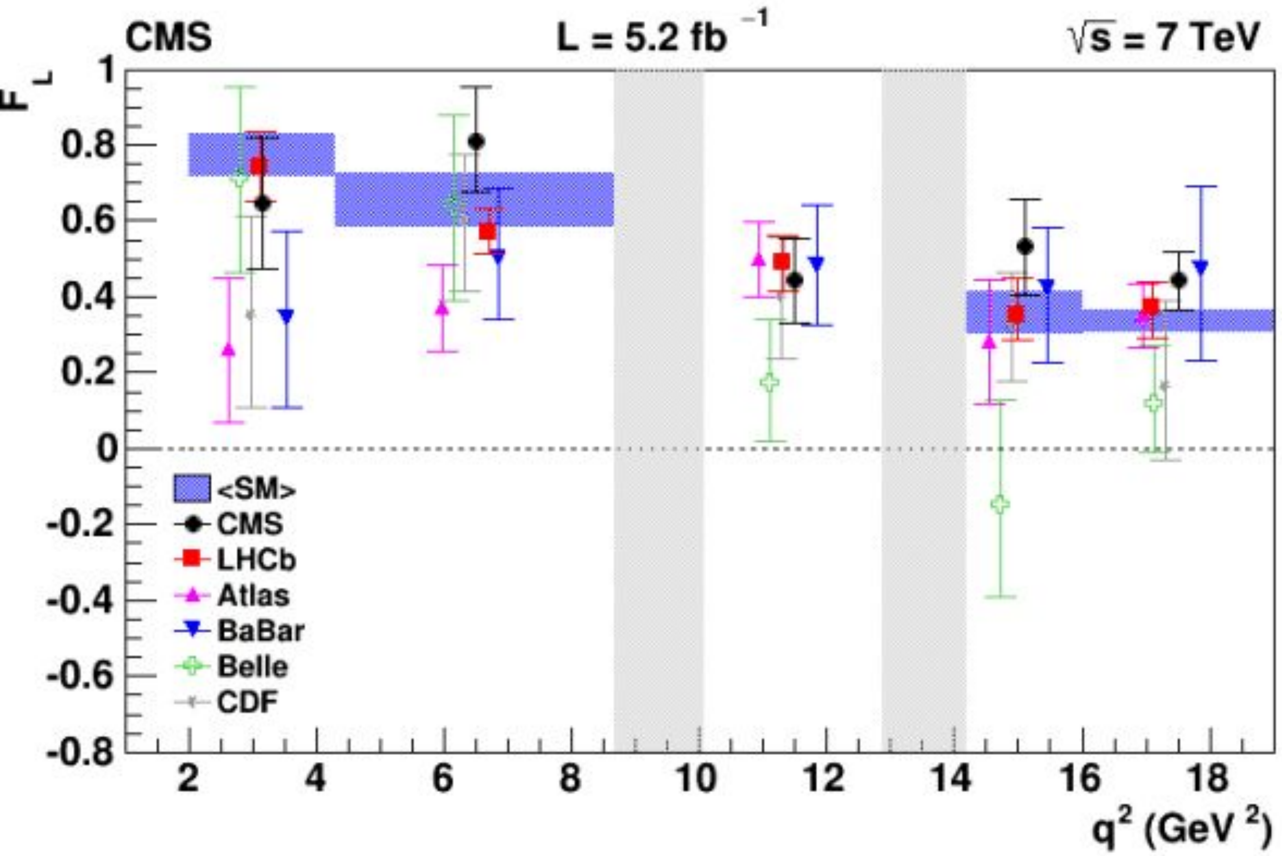
PLB 727 (2013) 77

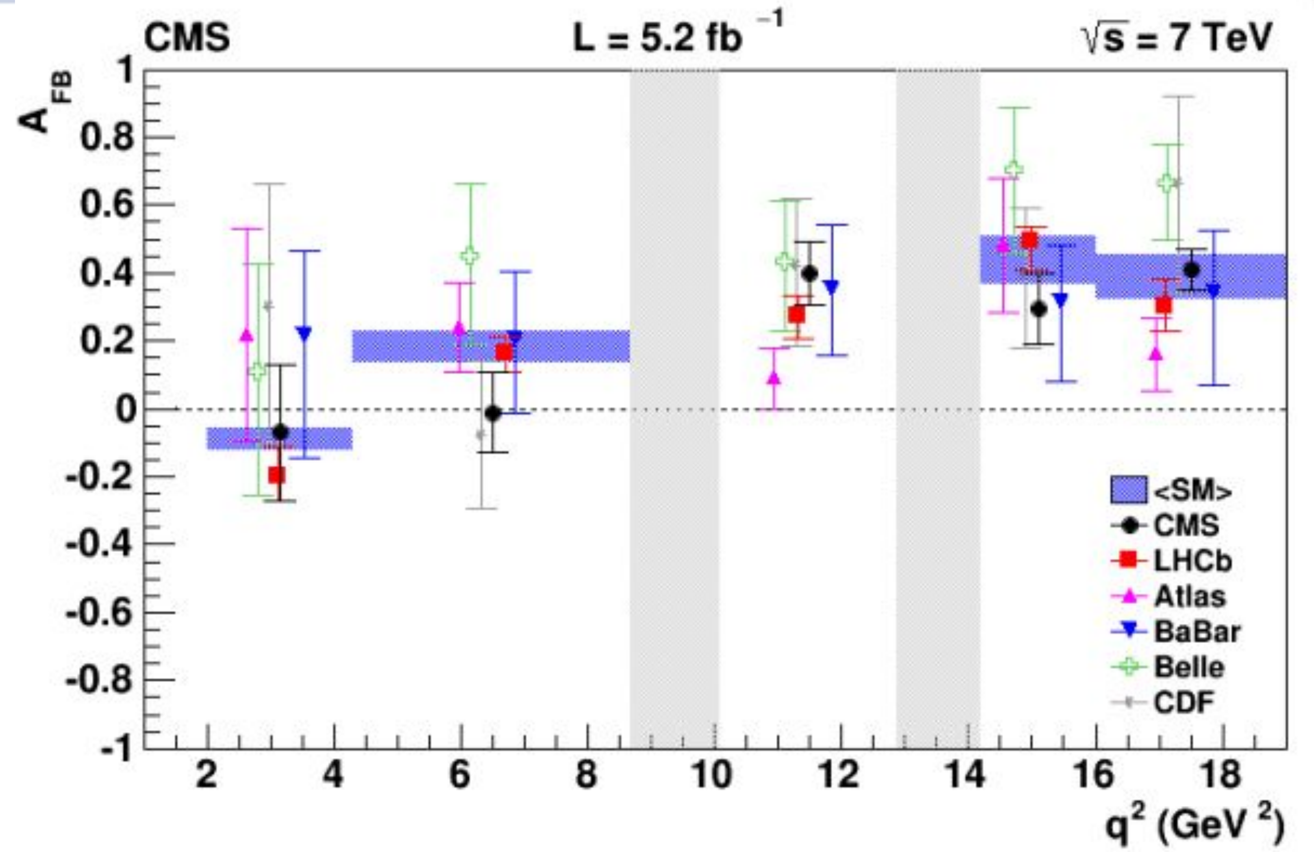
Muon forward-backward asymmetry

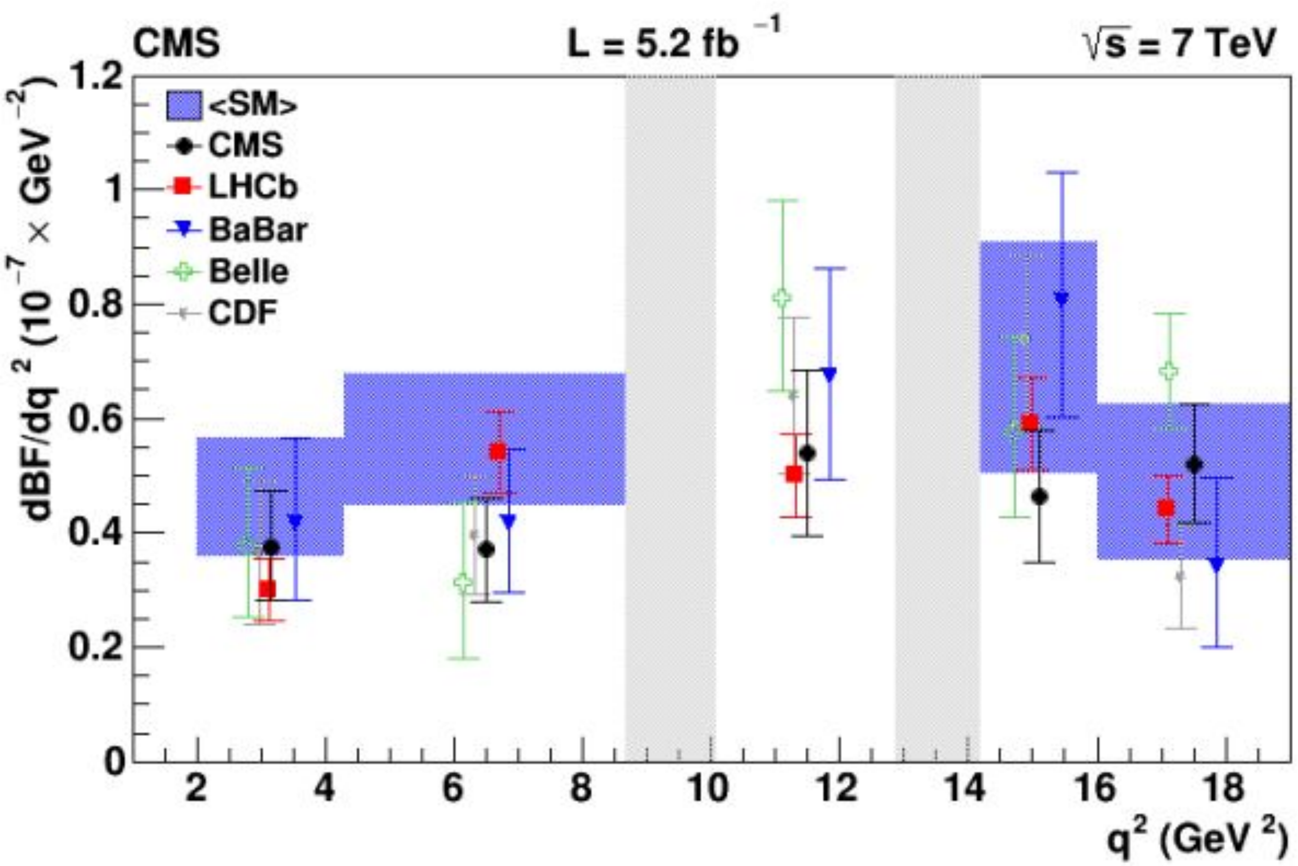


PLB 727 (2013) 77

Comparison: 7TeV results







- CMS uncertainties are better than CDF, Belle, BaBar but not as good as LHCb (LHCb statistics: ~1 fb^{-1})
- CMS measurements are the second best

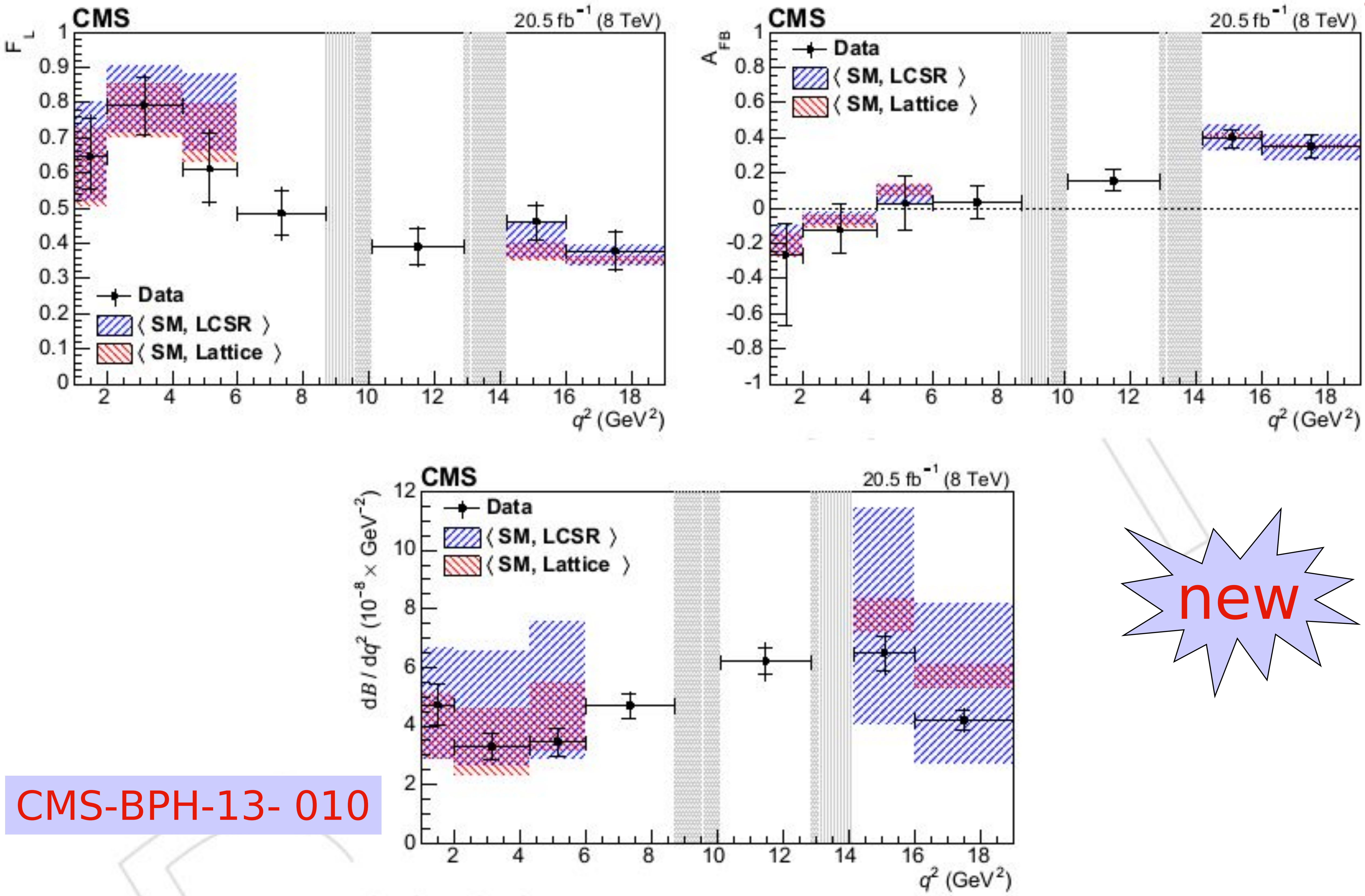
BaBar: *Phys. Rev. D* ***79*** *(2009) 031102*

Belle: *Phys. Rev. Lett.* ***103*** *(2009) 171801*

CDF: *Phys. Rev. Lett.* ***108*** *(2012) 081807*

LHCb: *Phys. Rev. Lett.* ***108*** *(2012) 181806*

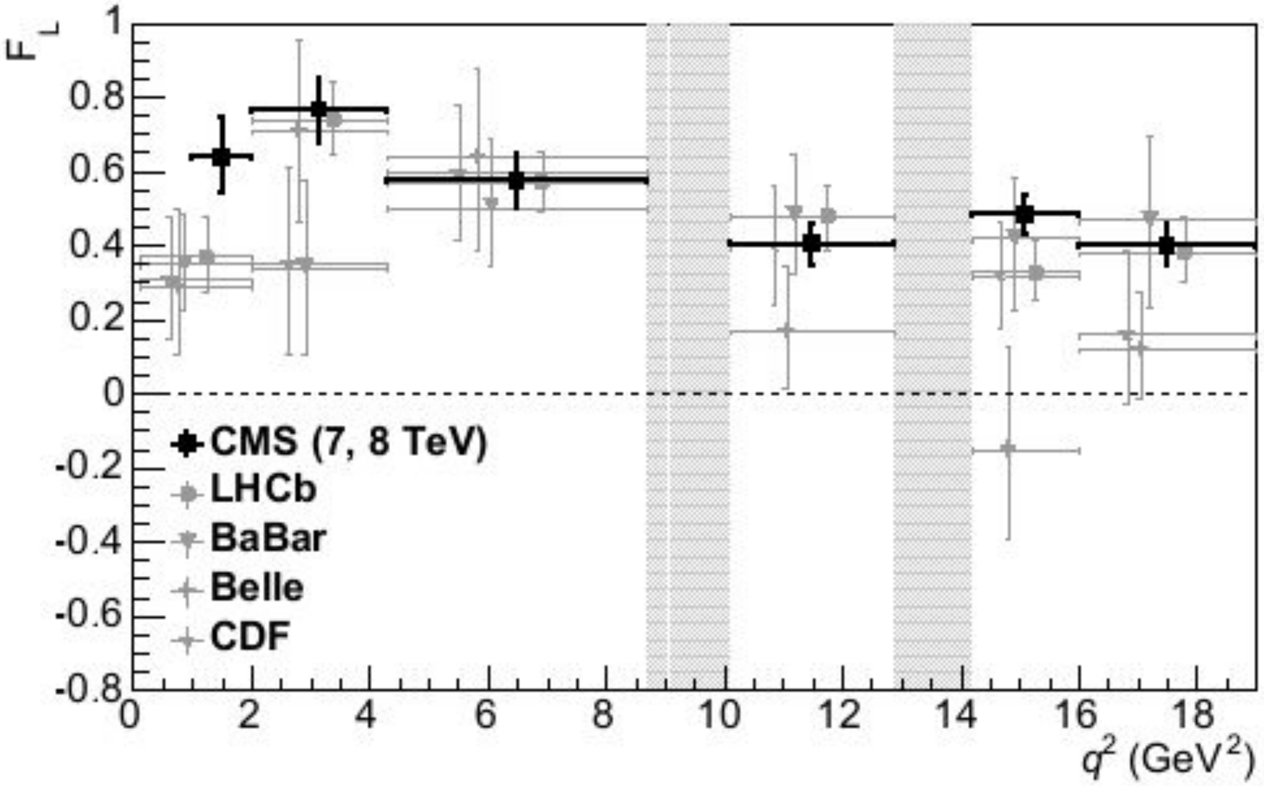
2012 Data Results

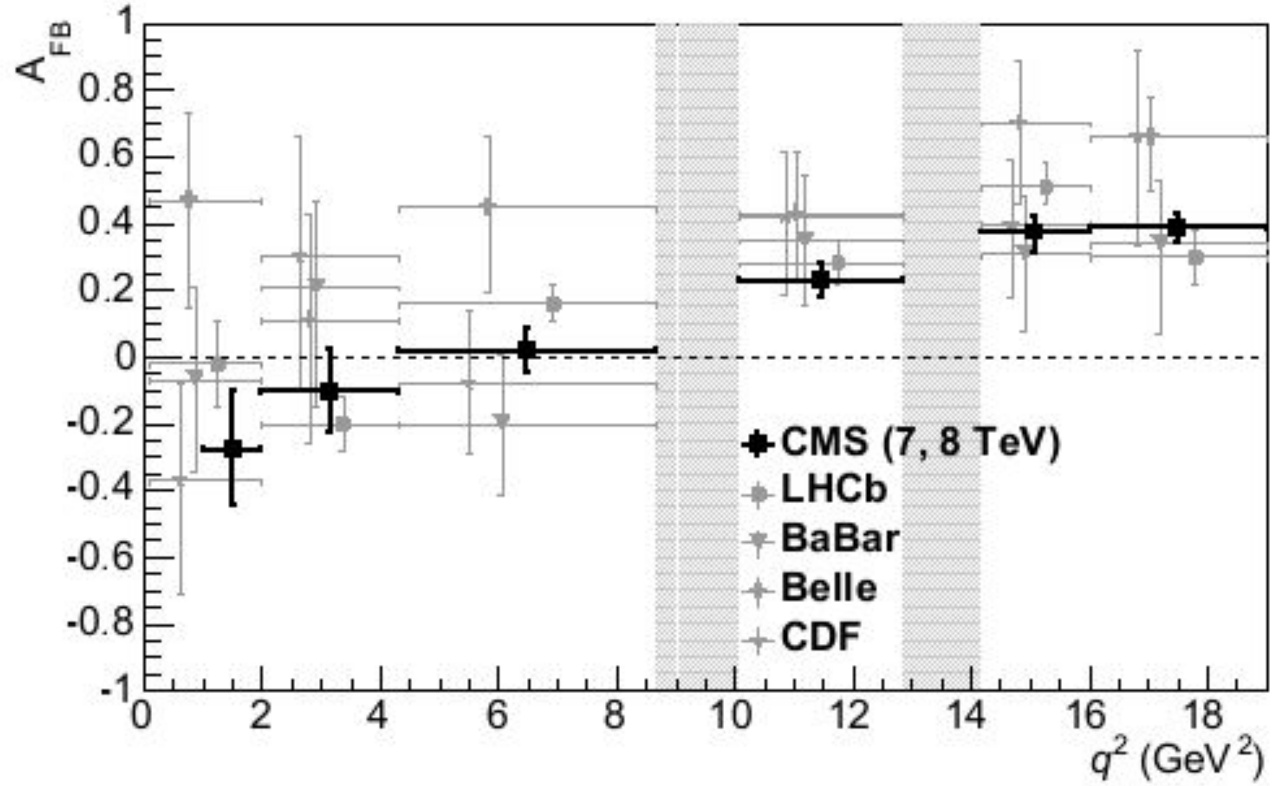


new

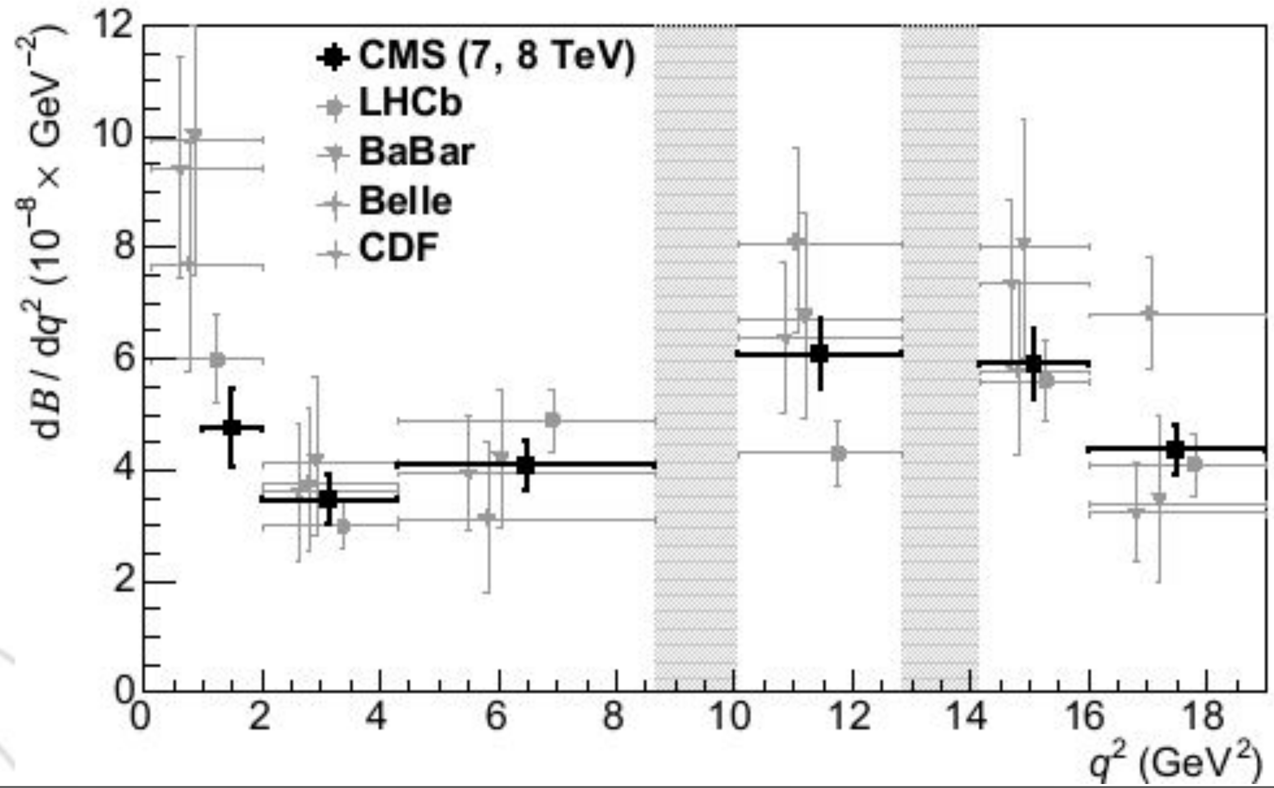
CMS-BPH-13- 010

Combined results 7/8TeV





The most precise results to date



new

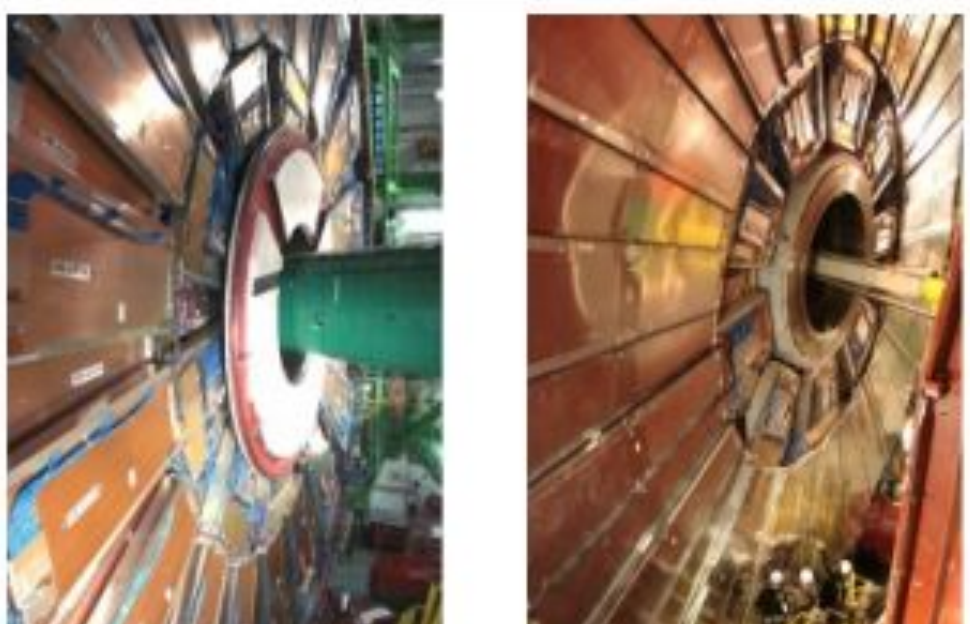
sister anayses going on, PKU

We are back and more robust

Silicon tracker operation at −15 ℃ to increase longevity

Updated DAQ2

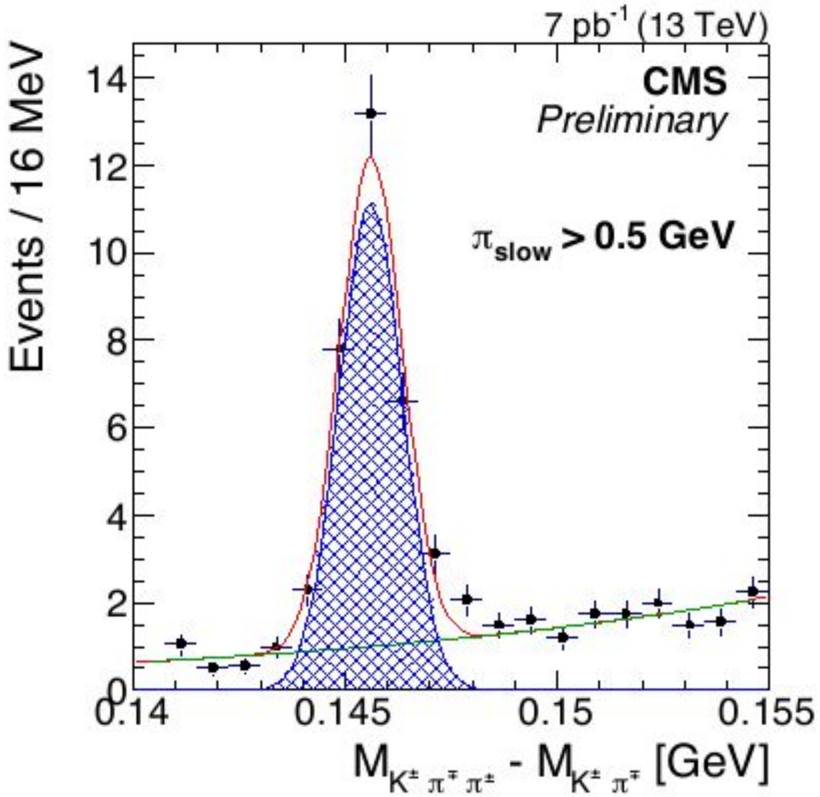
New beam pipe with reduced diameter → ready for installation of upgraded pixels in 2017

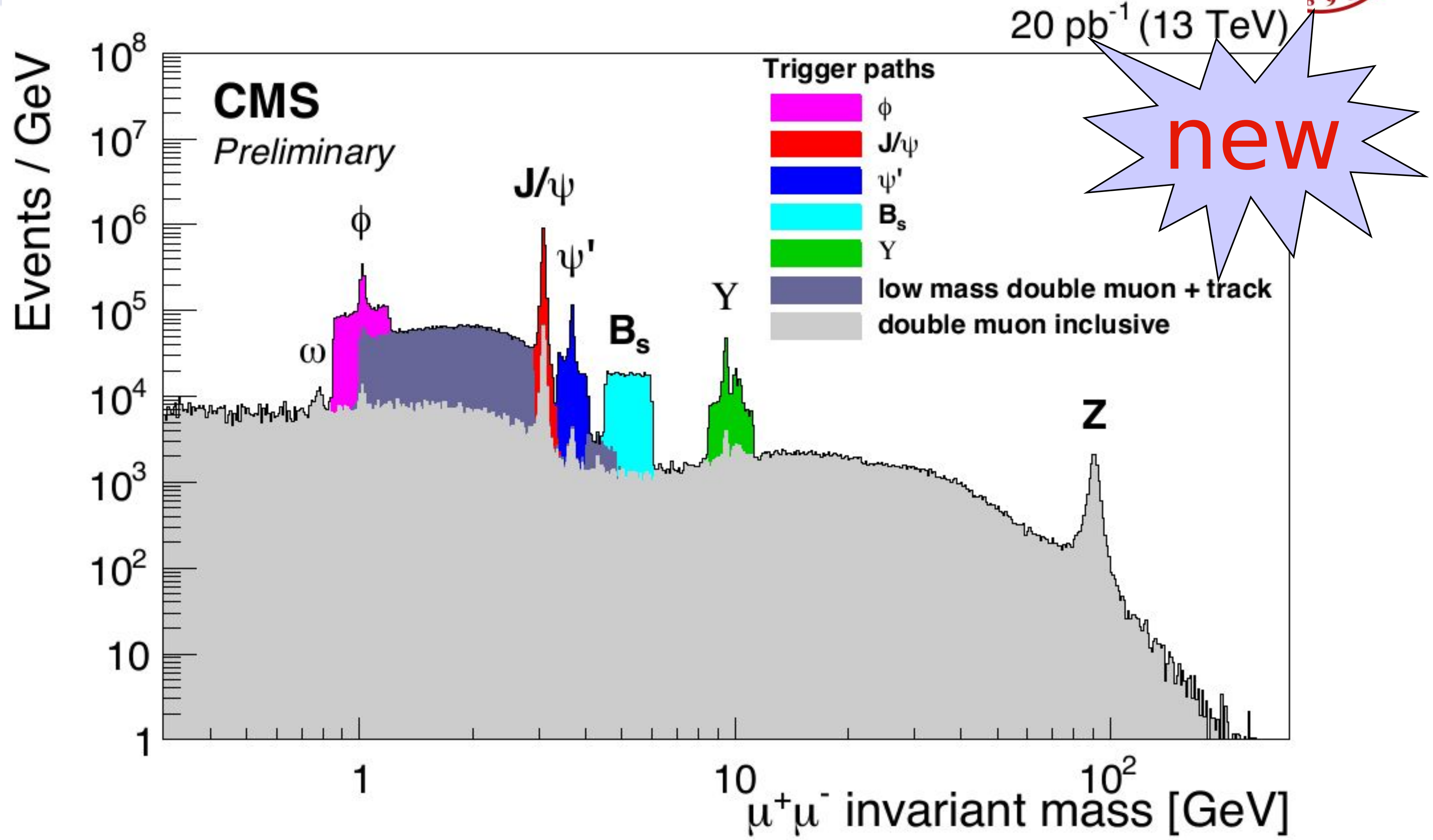


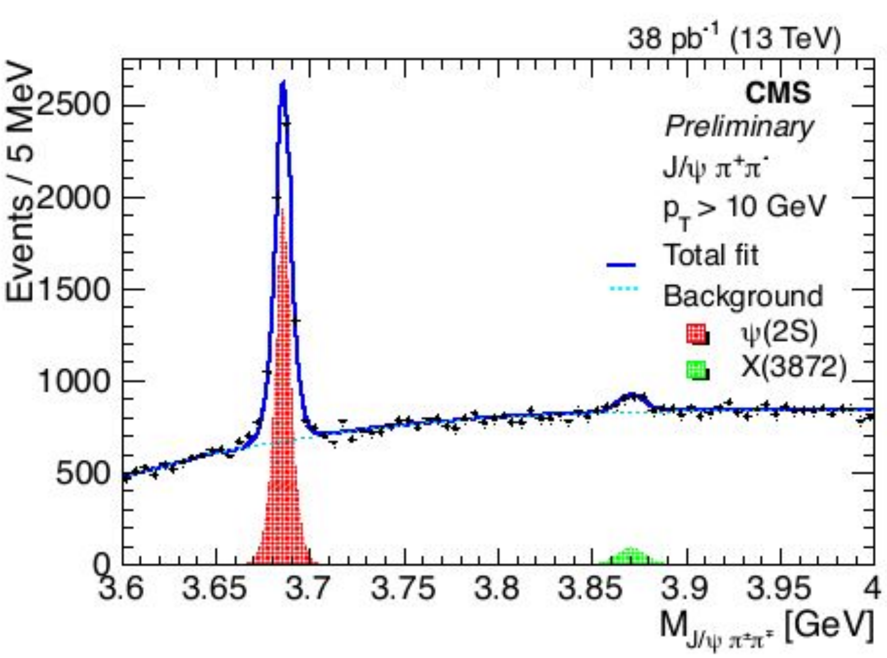
New RPC and CSC stations at high |η|

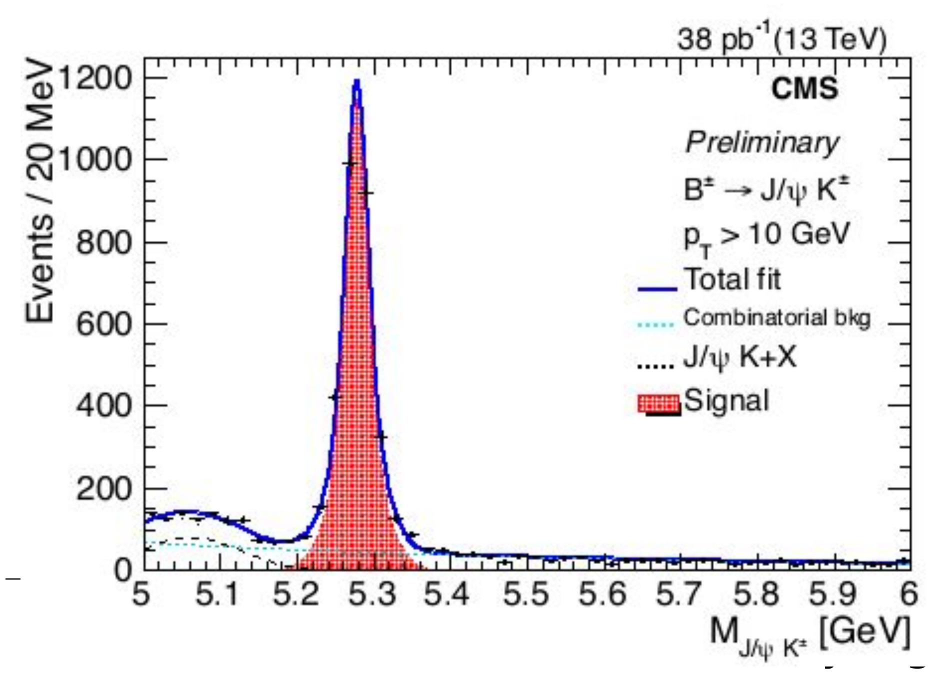
Very first 13TeV data

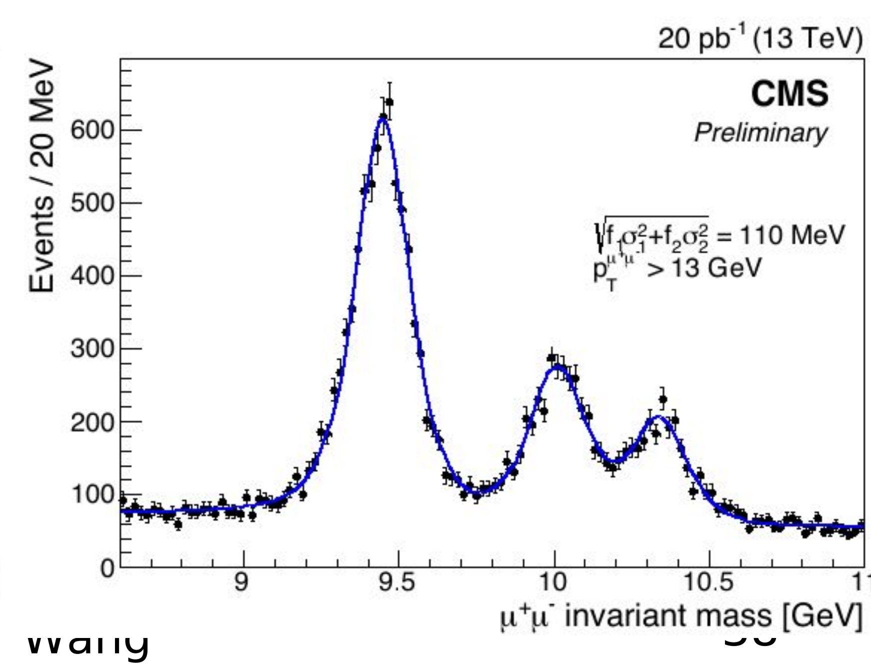
- **data taken in 2015.07.07-07.13, 20~38pb-1**











13TeV Early Analyses

- **The early analysis team was setup to take advantage of first Run II data and deliver fast physics results**
- **Focus on :**
  - **– Inclusive b-hadron cross section measurement @13 TeV**
  - **– Exclusive b-hadron cross section measurement @13 TeV**
  - **– S-wave quarkonia cross section measurement @13 TeV**
- **Exploit the “low-PU” run unprescaled single-muon trigger to perform these measurements down to zero pT**

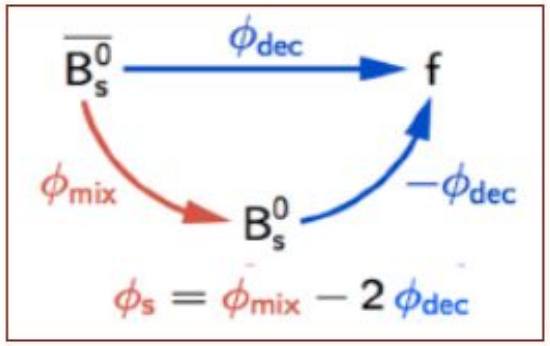
keep tuned

Thanks for your attention

extra slides...

CPV in $B_s^0 \to J/\psi\phi$: a tiny effect sensitive to NP

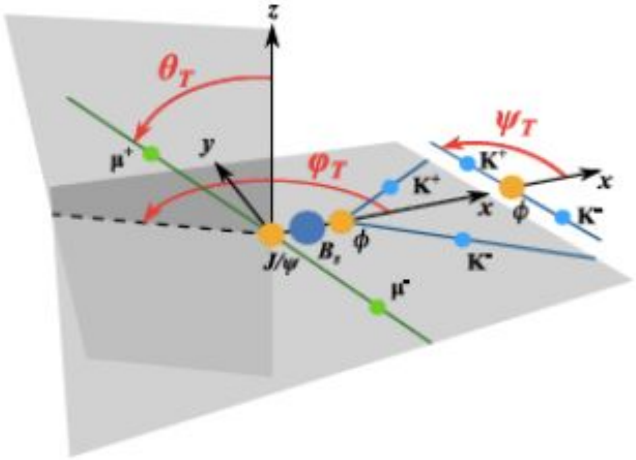
- When B_s^0 & $\bar{B}_s^0$ decay to a *CP* eigenstate (as in flavor-blind $B_s^0 \to J/\psi\phi\ (f_0)$) the weak phase ϕ_S arises from the interference between direct decays & decays with mixing (B mesons mix via box diagrams)



Theoretically clean decay mode: tiny CPV ruled by $\phi_S^{SM} \approx -2\beta_S = -2\arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \cong -0.0363^{+0.0016}_{-0.0015}\,rad$

[PRD 84 (2011) 033005]

⇨ Sensitivity to NP in mixing: many NP scenarios predict enhanced values of ϕ_S



- $J/\psi\phi$ final state : admixture of CP-odd and CP-even eigenstates
  … to be disentangled by angular analysis (3 angles)

- The differential decay rate for $B_s^0 \to J/\psi\phi$ can be expressed as :

$$\frac{d^4\Gamma(B_s(t))}{d\Theta dt} = \sum_{i=1}^{10} O_i(\alpha,t)\cdot g_i(\Theta)$$

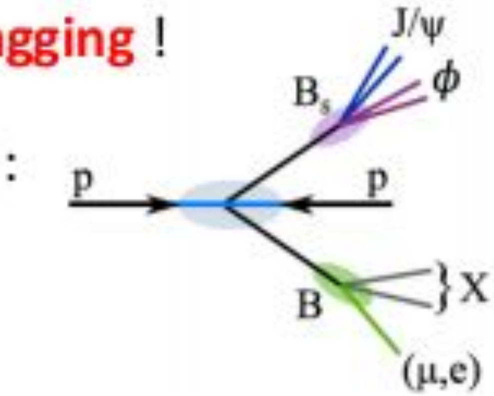
Time-dependent functions | Angular-dependent functions

where:
- Θ, t : measured angles & B_s^0 proper decay time
- α : physics param. of interest: $\phi_S, \Delta\Gamma_S, c\tau; |A_0|^2, |A_S|^2, |A_\perp|^2; \delta_\parallel, \delta_\perp, \delta_{S\perp}$
- $O_i(\alpha,t) = N_i e^{-t/\tau}[a_i \cdot \cosh\left(\frac{\Delta\Gamma_S ct}{2}\right) + b_i \cdot \sinh\left(\frac{\Delta\Gamma_S ct}{2}\right) + c_i \cdot \cos(\Delta m_S t) + d_i \cdot \sin(\Delta m_S t)]$

- ***b**$_i$* & ***d**$_i$* proportional to $\sin\phi_s$ & $\cos\phi_s$

$B_s^0 \to J/\psi\phi$: analysis strategy

- How to tell B_s^0 flavour at production ? Use Opposite-Side Lepton ($\mu + e$) **Flavour Tagging** !



  - Search for a second B-hadron in the OS of the event decaying semi-leptonically :
  - Lepton charge-flavour correlation is diluted (⇨ mistag) by:
    - sequential cascade: $b \to cX \to \ell X'$ decays
    - oscillations: opposite side *B*-meson mixing
    - leptons from other sources (DIF, charmed mesons)
  - Tagging performance measured by self-tagging $B^+ \to J/\psi K^+$ and validated with MC ($B^+ \to J/\psi K^+$, $B_s^0 \to J/\psi\phi$)

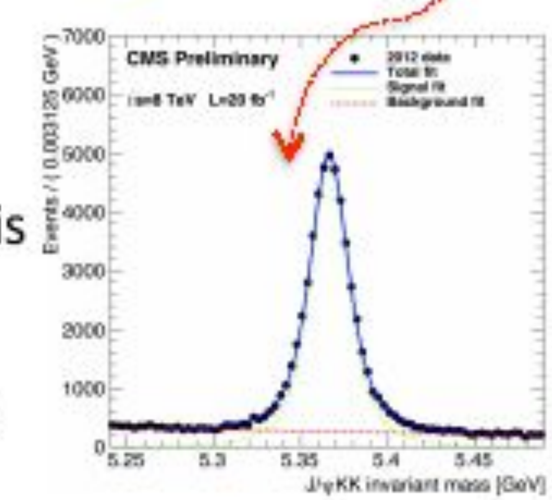
$$[P_{tag} = \varepsilon_{tag} \cdot D^2 = \varepsilon_{tag} \cdot (1-2\omega)^2]$$

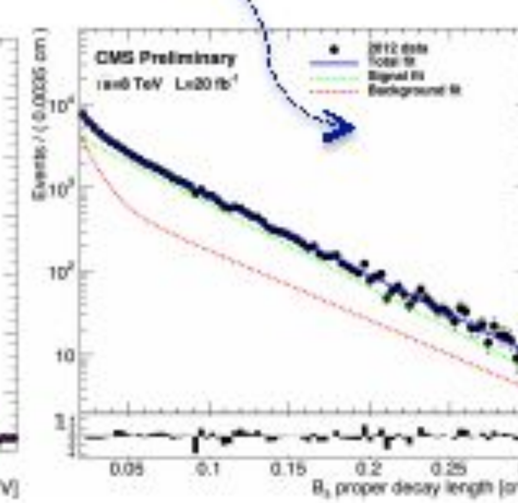
  - PDF modified to include tagging info in c_i & d_i

- Ext. UML fit used to extract the physics param. α by including :
  - 3 angles Θ
  - invariant mass
  - proper decay length *ct*

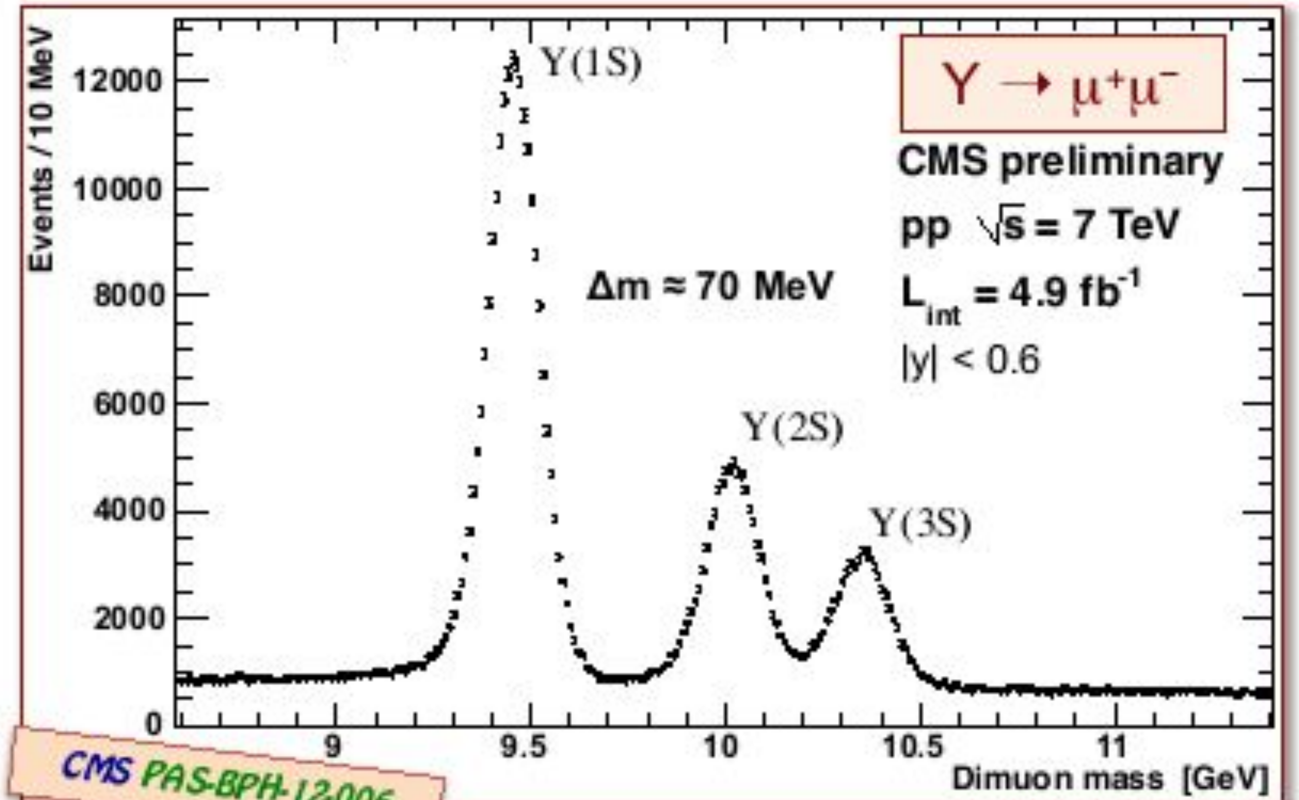
  ... of B_s^0 candidate

  - Δm_S with a gaussian constrained to world average
  - $\Delta\Gamma_S > 0$ by using previous LHCb result
  - Uncertainty on proper decay time computed on event basis & included in the fit together with its resolution (~70fs)
  - $|\lambda|$ include eventual contribution from CPV in direct decay; assumed =1 in the fit & left free to assign a systematic

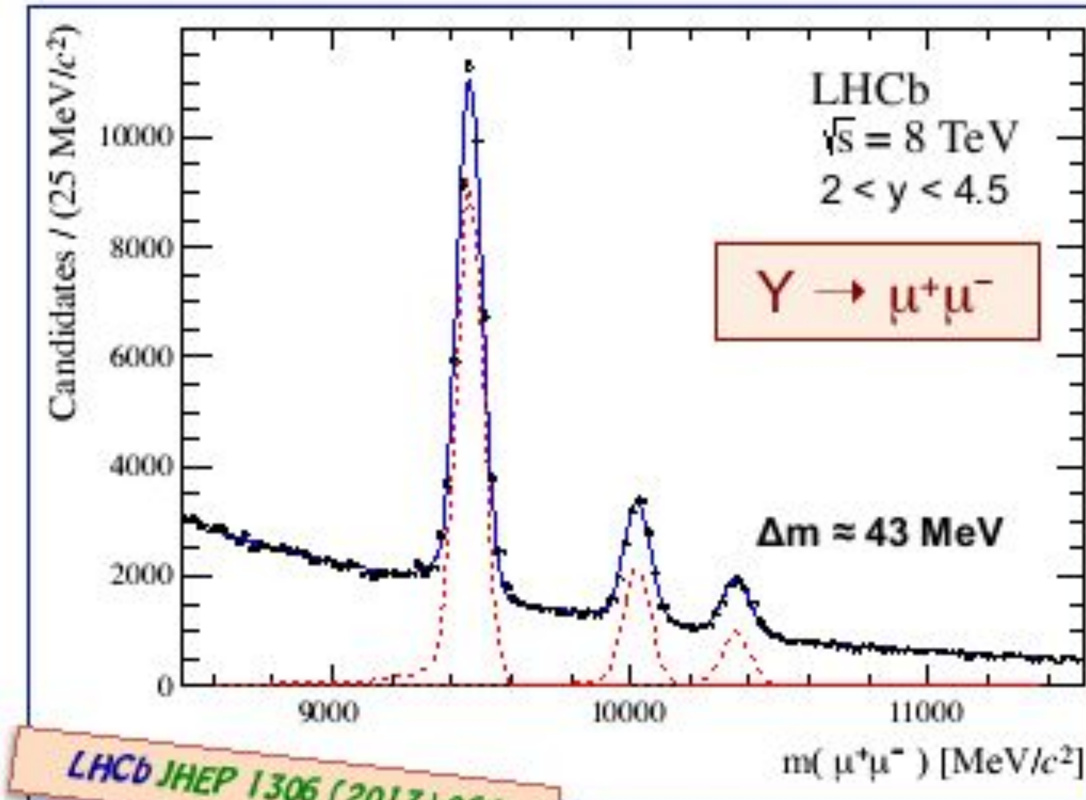




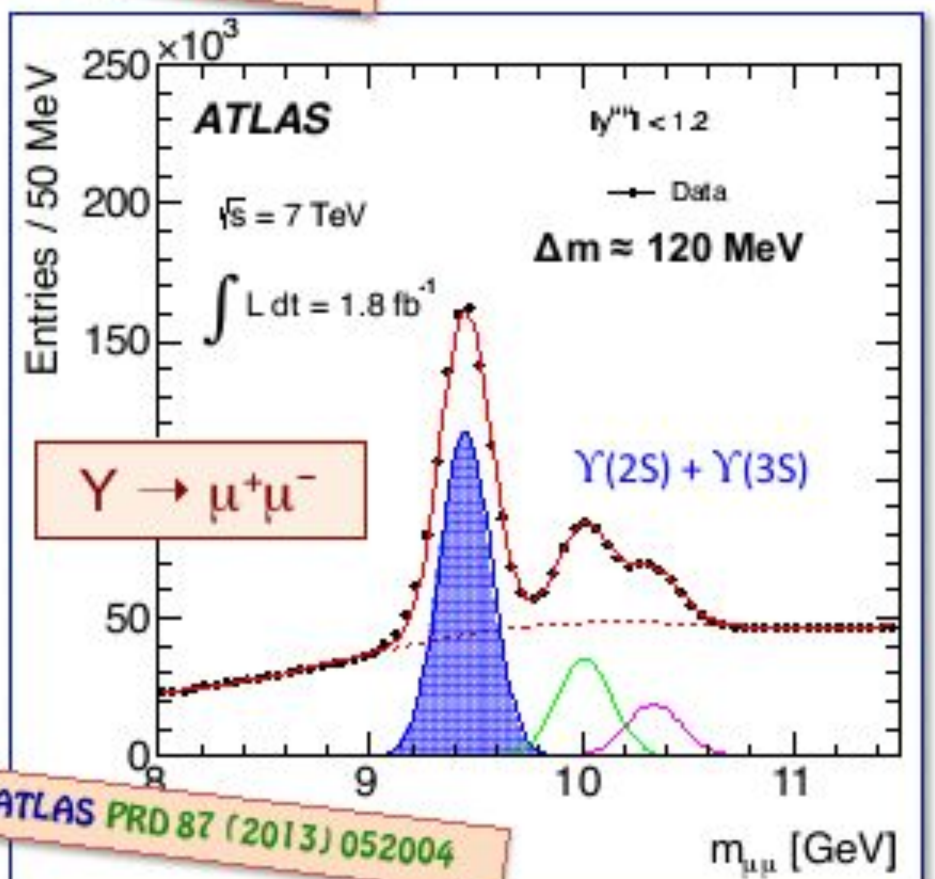
CMS: quarkonium detection performance vs. ATLAS/LHCb



CMS PAS-BPH-12-006



LHCb JHEP 1306 (2013) 064



ATLAS PRD 87 (2013) 052004

High-p_T reach, Υ(nS) cross sections:

CMS: p_T up to 85 GeV
ATLAS: p_T up to 65 GeV
LHCb: p_T up to 14 GeV

Quarkonium reconstruction performance in dimuon decay:

Excellent dimuon mass resolution

High p_T coverage

Excellent decay length resolution

S-wave → $\mu^+\mu^-$

Flexible trigger

Large silicon tracker

Strong magnetic field

Broad acceptance

Other inputs to the toy experiments: $3000 fb^{-1}$

These are the details of the extrapolations made in order to find the inputs to the toy experiments for the Phase-2 3000 fb^{-1} scenario:

- **Barrel only (muon $|\eta| < 1.4$)**
- **Muon efficiency & fate rate: the same as 8 TeV analysis**
- **Uncertainty on B^+ normalization channel: 3%**
- **Uncertainty of the peaking backgrounds: 10%**
- **Uncertainty of the semileptonic backgrounds: 20%**
- **Uncertainty of the f_s/f_u ratio: 5%**
- **Trigger & PU performance:**
  - **35% reduction of efficiency on signal and normalization channel**
  - **30% reduction of efficiency on backgrounds**

As written in slide 4, in addition to these extrapolations, the invariant mass resolution coming from the full Geant4 simulation of the Phase-2 CMS detector is used (≈ 28 MeV)

Multiple analyses and joint measurements

- ✓ **FCNC process b->sl+l- to probe NP: BR**
- ✓ **resonance search & studies**
- ✓ **Angular measurement: FL, A_{FB}**
- ✓ **Isospin asymmetry A_I**
- ✓ **CP asymmetry A_{CP}**

Isospin asymmetry (A_I):

$$A_I = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

CP asymmetry (A_{CP}):

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-) - \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-) + \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}$$

$$\mathcal{A}_{CP} = \frac{\Gamma(B^- \to K^-\mu^+\mu^-) - \Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^- \to K^-\mu^+\mu^-) + \Gamma(B^+ \to K^+\mu^+\mu^-)}$$

- ✓ **Majorana neutrino study with conjugate channel: K-mu+mu+**
- ✓ **Rk measurement**