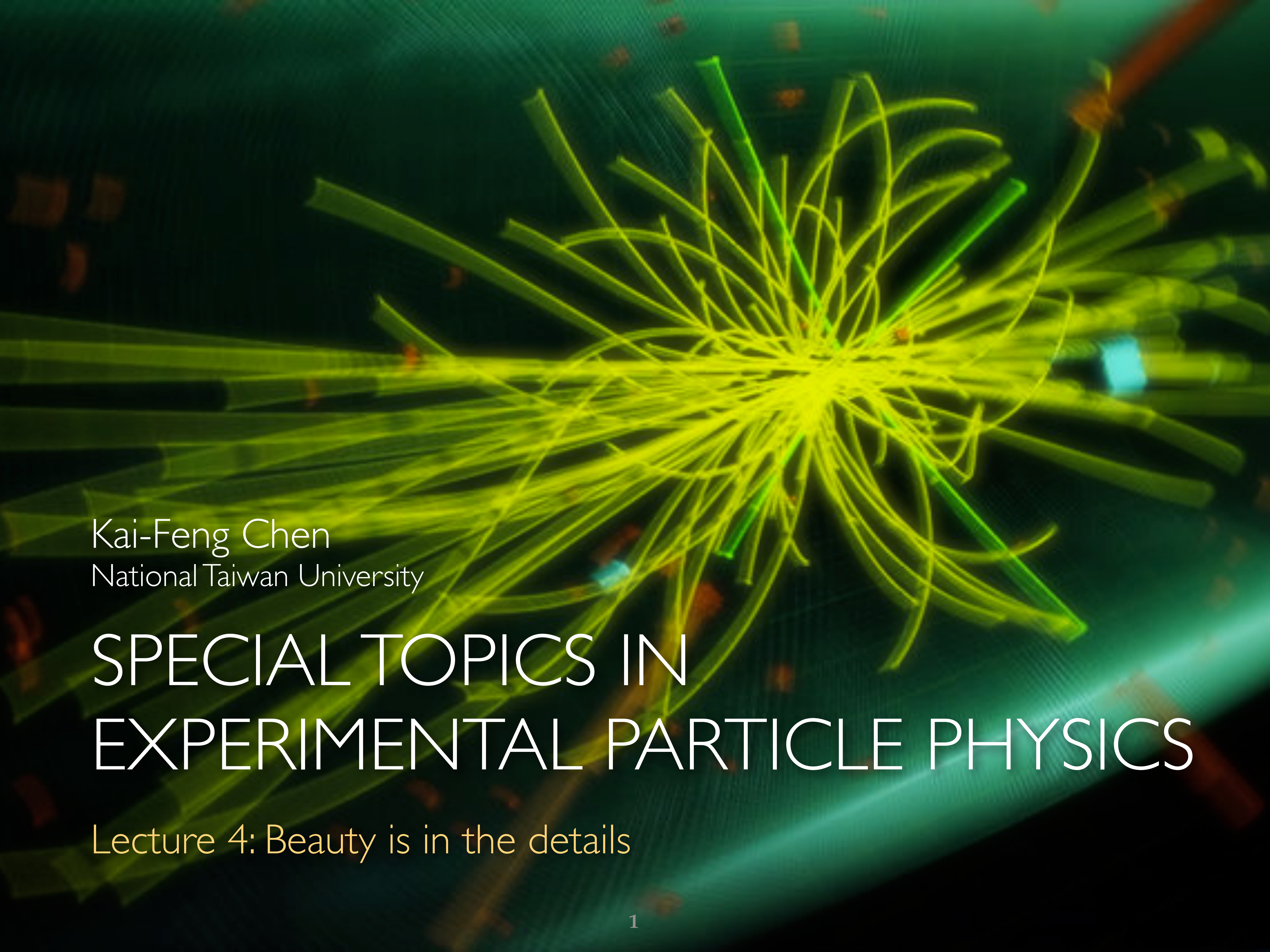


Kai-Feng Chen

National Taiwan University

SPECIAL TOPICS IN EXPERIMENTAL PARTICLE PHYSICS

Lecture 4: Beauty is in the details

LOOKING FOR NEW PHYSICS?

Want to open a deathly locked safe?

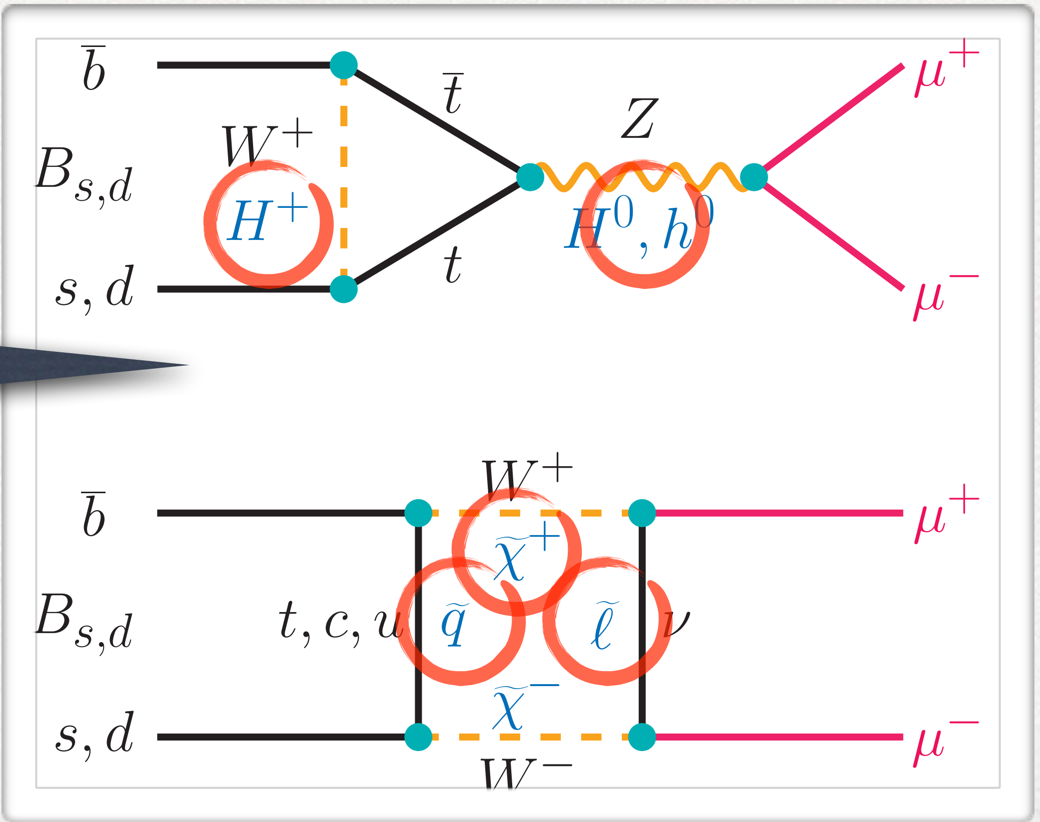
Through
high energy...?

Through
high precision...?

LOOKING FOR NEW PHYSICS?

- Through **HIGH ENERGY**:
  - Produce **"real"** new particles and can be discovered via their decays or any other interactions with the detectors.
- Through **HIGH PRECISION**:
  - **"Virtual"** new particles participate in the loop processes and can be discovered by seeing any deviations from the Standard Model.

If these particles cannot be observed in the direct searches, this is the place one shall still look for!



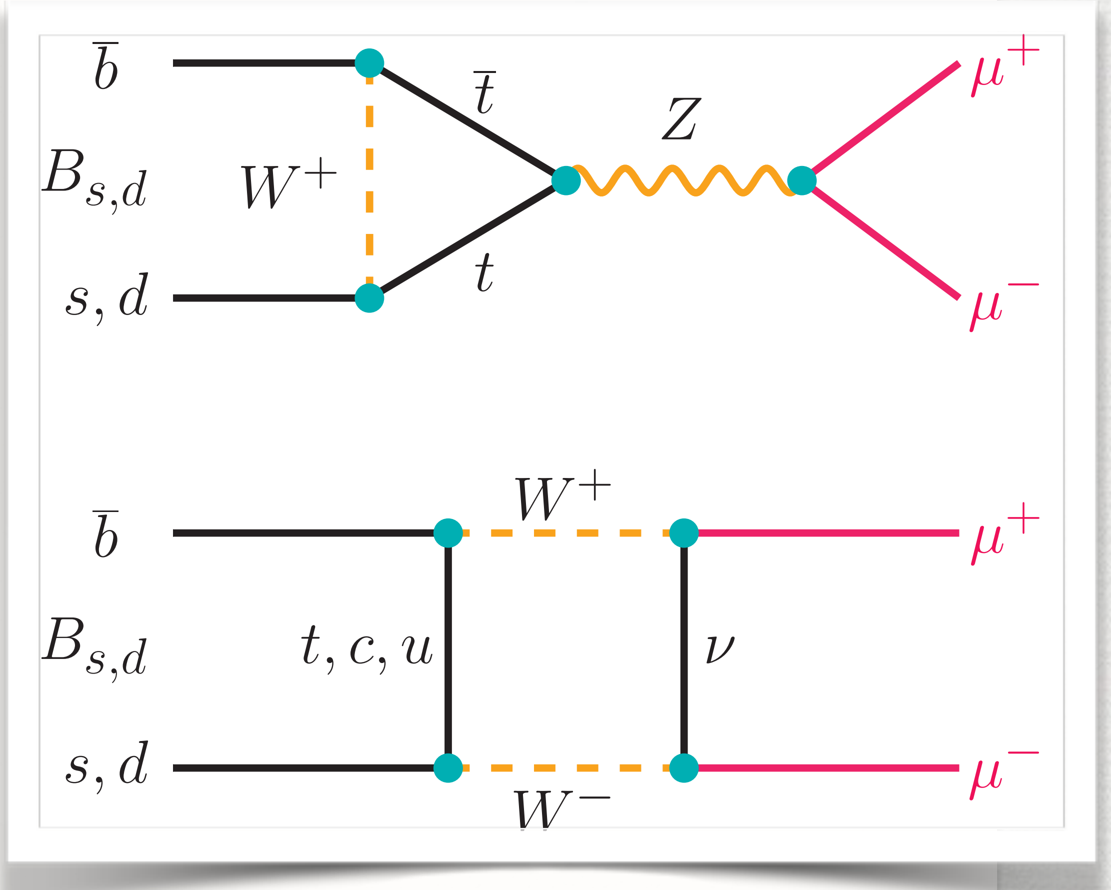
Both direct and indirect searches are necessary and complement each other!

THE PHYSICS: $B_{s,d} \to \mu^+\mu^-$

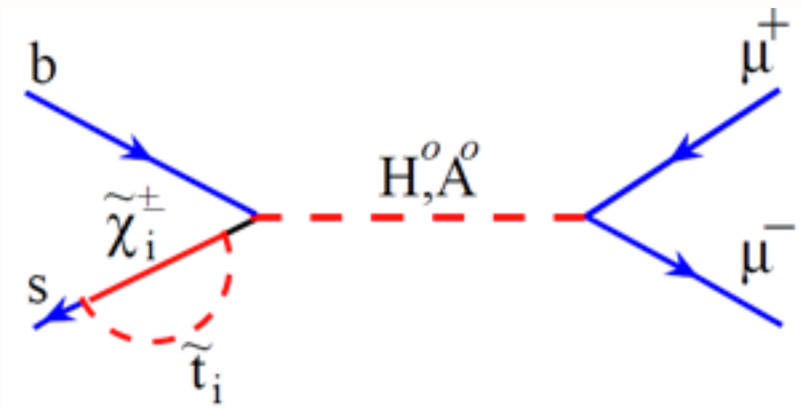
- In the Standard Model, $B_{s,d} \to \mu^+\mu^-$ decays are highly suppressed:
  - FCNC processes, only proceed through Z-pengiun, and box diagrams (suppressed by $[m_W/m_t]^2$).
  - Cabibbo suppressed: $|V_{tq}|^2$
  - Helicity suppressed: $[m_\mu/m_B]^2$
- Resulting **tiny branching fractions**, (~1/300M) but rather *robust*:

$$B(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$B(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

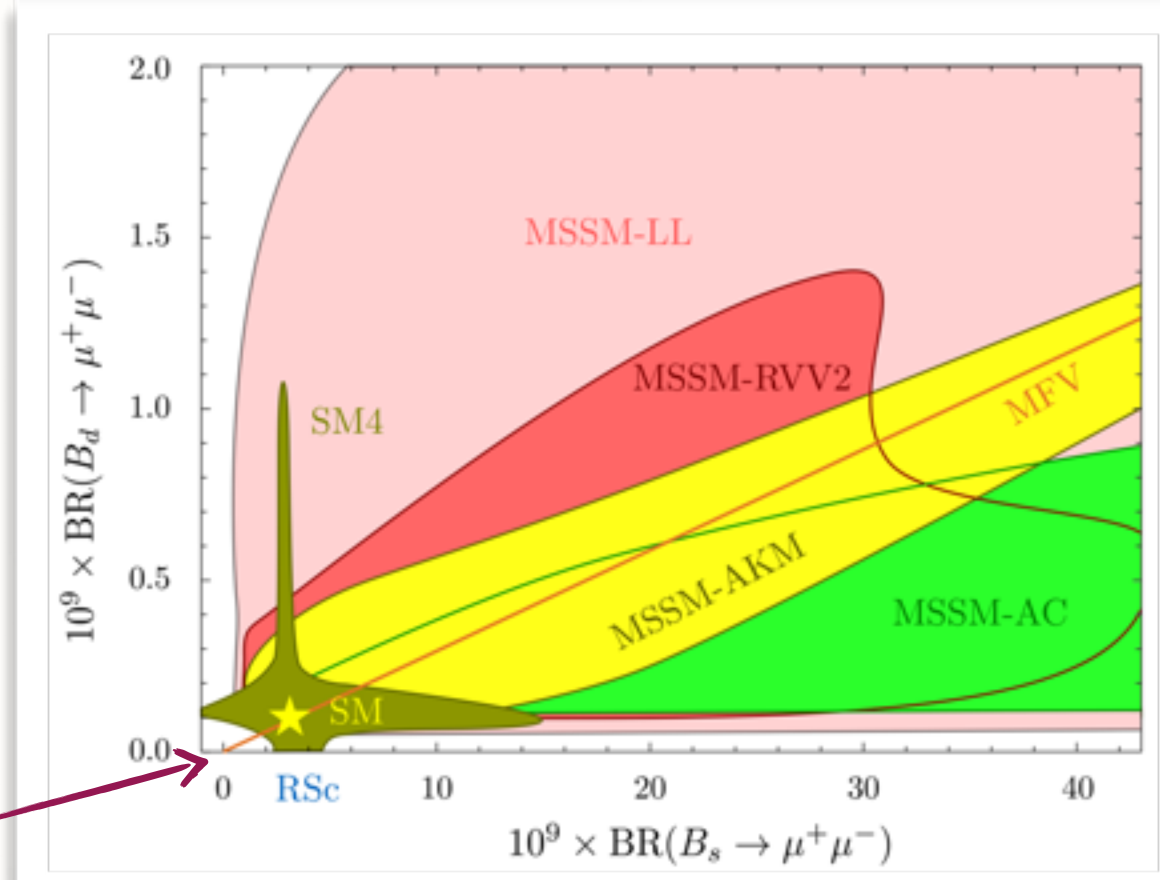
Ref: Bobeth et al, PRL 112, 101801 (2014)



THE PHYSICS: $B_{s,d} \rightarrow \mu^+\mu^-$



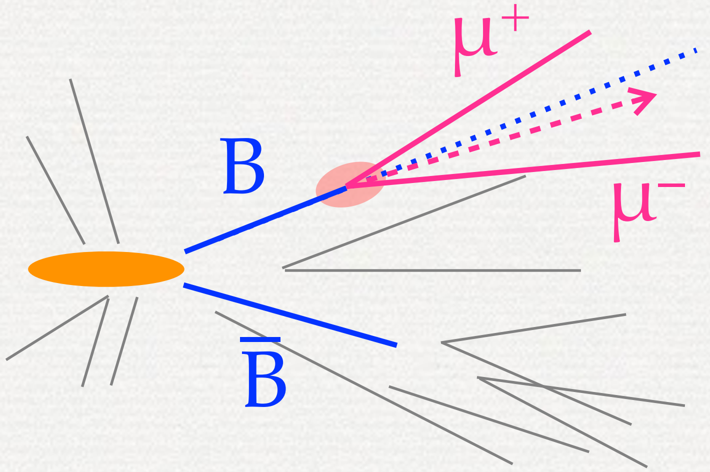
- Loop diagram + Suppressed SM + Theoretically clean = *An excellent place to look for new physics*.
- Sensitive to extended Higgs sectors ⇒ Constrains NP parameter spaces.
- Some of the new physics scenarios may boost the B→μμ decay rates by 10~20 times easily, for example:
  - **2HDM**: B ∝ $\tan^4\beta$ & $m(H^+)$
  - **MSSM**: B ∝ $\tan^6\beta$
- B_s/B_d ratio – a stringent test of minimal flavor violation hypothesis.



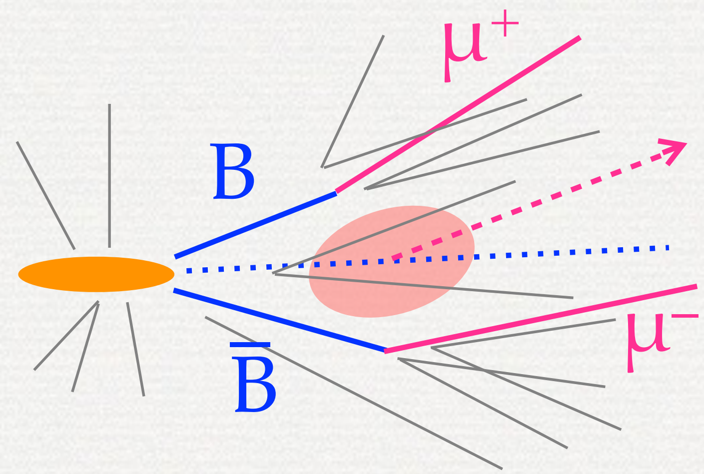
Ref: D. M. Straub, arXiv: 1012.3893

ANALYSIS ASPECTS

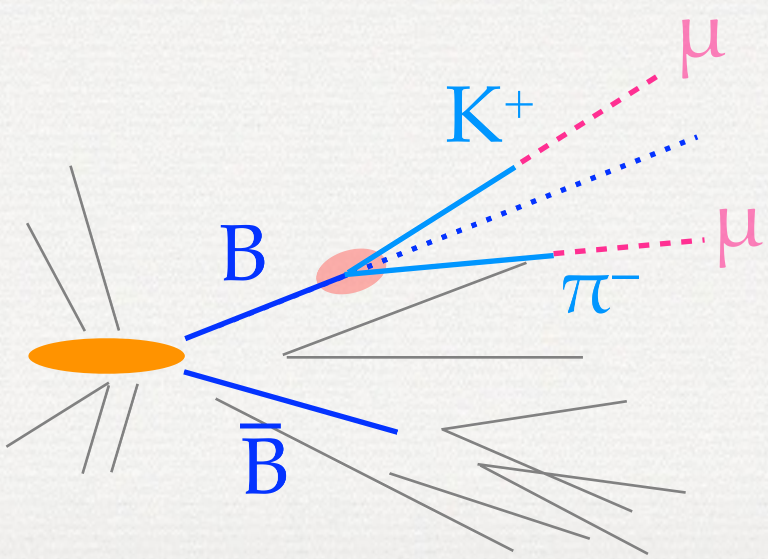
- **The $B_{s,d} \to \mu^+\mu^-$ signal**
  - two muons from one displaced vertex; momentum aligned with its flight direction; invariant mass peaking at $M(B_{s,d})$.



- **Background sources**
  - two semileptonic B decays
  - one semileptonic B + a misidentified hadron
  - rare background from single B meson decays: e.g. **$B \to K\pi/KK$** (*peaking*), $B_s \to K^-\mu^+\upsilon$ (*not peaking*)



Powerful background suppression reached by muon quality, well-reconstructed secondary vertex, isolation, pointing angle, and $M(\mu\mu)$ resolution.



ANALYSIS ASPECTS (II)

- Event classification is carried out by **Boosted Decision Tree (BDT)** method by including several topological and kinematical variables for background suppression.
- Calibrations/validations with $B^+ \to J/\psi K^+$, $B^0 \to K^-\pi^+$ and $B_s \to J/\psi\phi$.
- Normalized to the reference channel $\mathbf{B^+ \to J/\psi(\to\mu^+\mu^-)\,K^+}$ (LHCb also take $B^0 \to K\pi$ as normalization):

$$\mathcal{B}(B_{s,d}\to\mu^+\mu^-) = \frac{N_S}{N(B^\pm\to J/\psi K^\pm)} \times \mathcal{B}(B^\pm\to J/\psi K^\pm) \times \frac{A(B^\pm)}{A(B_s)}\,\frac{\varepsilon^{ana}(B^\pm)}{\varepsilon^{ana}(B_s)}\,\frac{\varepsilon^{\mu}(B^\pm)}{\varepsilon^{\mu}(B_s)}\,\frac{\varepsilon^{trig}(B^\pm)}{\varepsilon^{trig}(B_s)}\,\frac{f_u}{f_s}$$

Acceptance

Selection efficiency

muon identification

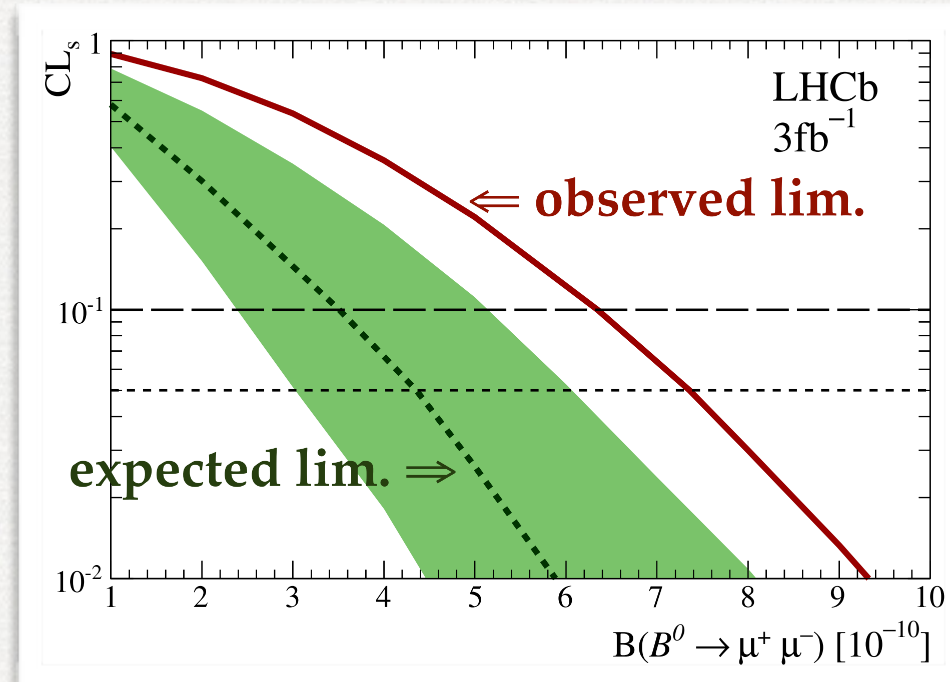
Trigger efficiency

B-hadronization composition (LHCb JHEP 04 (2013) 001: 0.256±0.020)

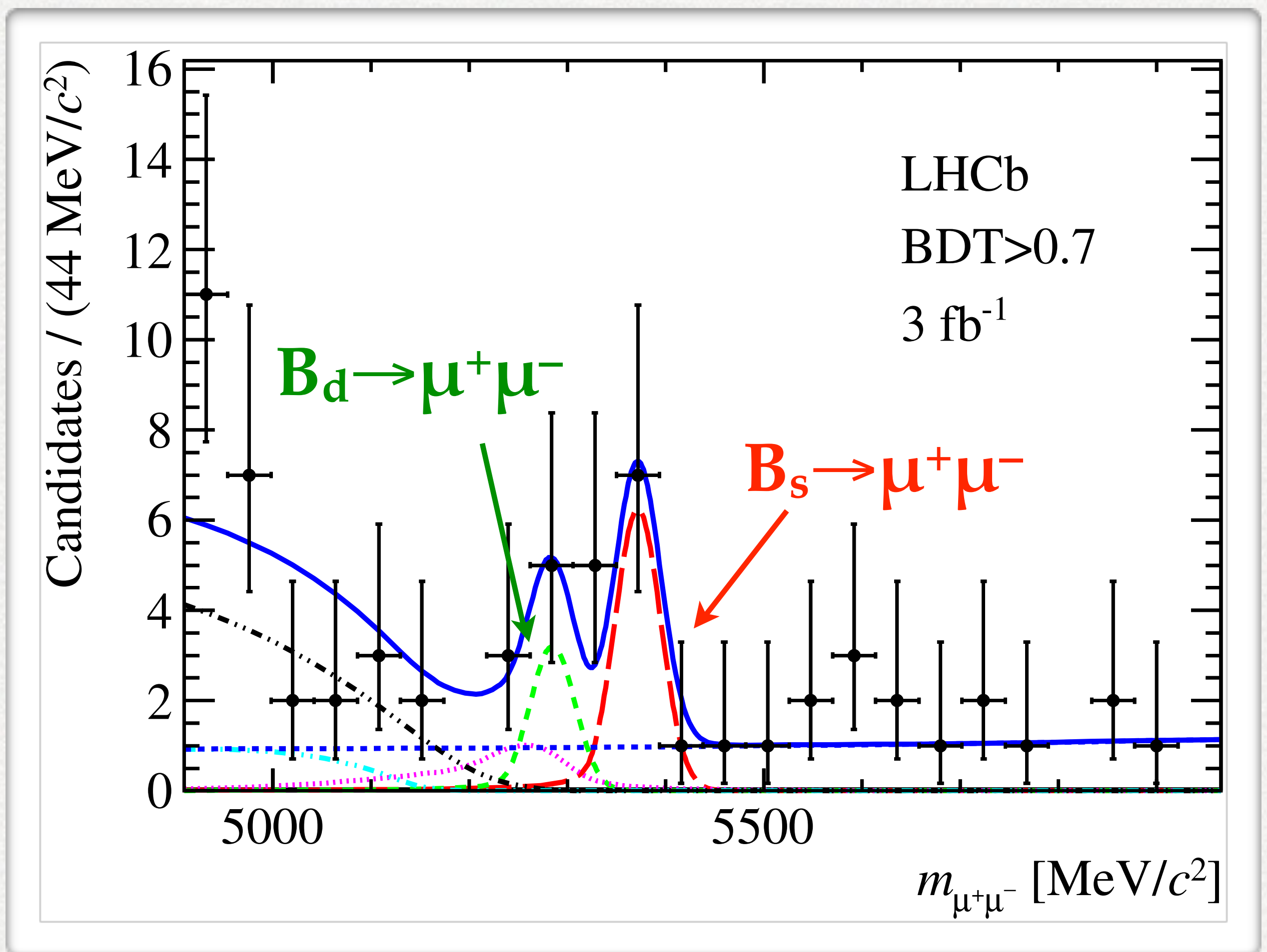
Similar trigger & selection for reducing systematics

LHCB RESULTS: $B_{s,d} \to \mu^+\mu^-$

- LHCb updated the analysis with full dataset (~3 fb^{-1}) with an improved BDT; the results are consistent with the predictions.
- The significance for $B_s \to \mu\mu$ decay is **4.0σ** (5.0σ expected).



⬆ An upper limit on the decay rate of $B_d \to \mu\mu$ is given.



Channel	Branching fraction
$B_s \to \mu^+\mu^-$	$(2.9^{+1.1}_{-1.0}) \times 10^{-9}$
$B_d \to \mu^+\mu^-$	$< 7.4 \times 10^{-10}$ @ 95% CL

ref. LHCb PRL 111 (2013) 101805

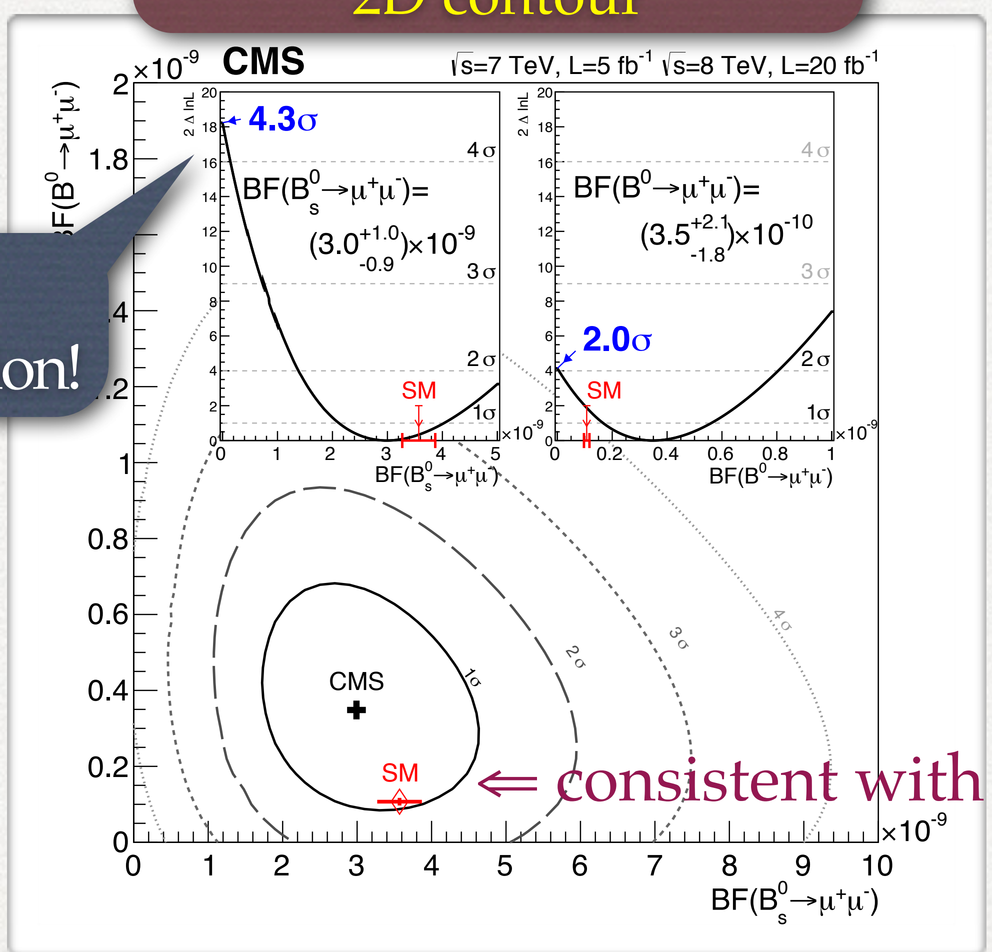
CMS RESULTS: $B_{s,d} \to \mu^+\mu^-$

Ref. CMS PRL 111 (2013) 101804

- Branching fractions extraction with unbined maximum likelihood fit in 12 categorized BDT bins.
- A simpler "1D-BDT" fit is used as a cross check.

Channel	Branching fraction
$B_s \to \mu^+\mu^-$	$(3.0^{+1.0}_{-0.9})$x 10^{-9}
$B_d \to \mu^+\mu^-$	<1.1x10^{-9} @ 95% CL

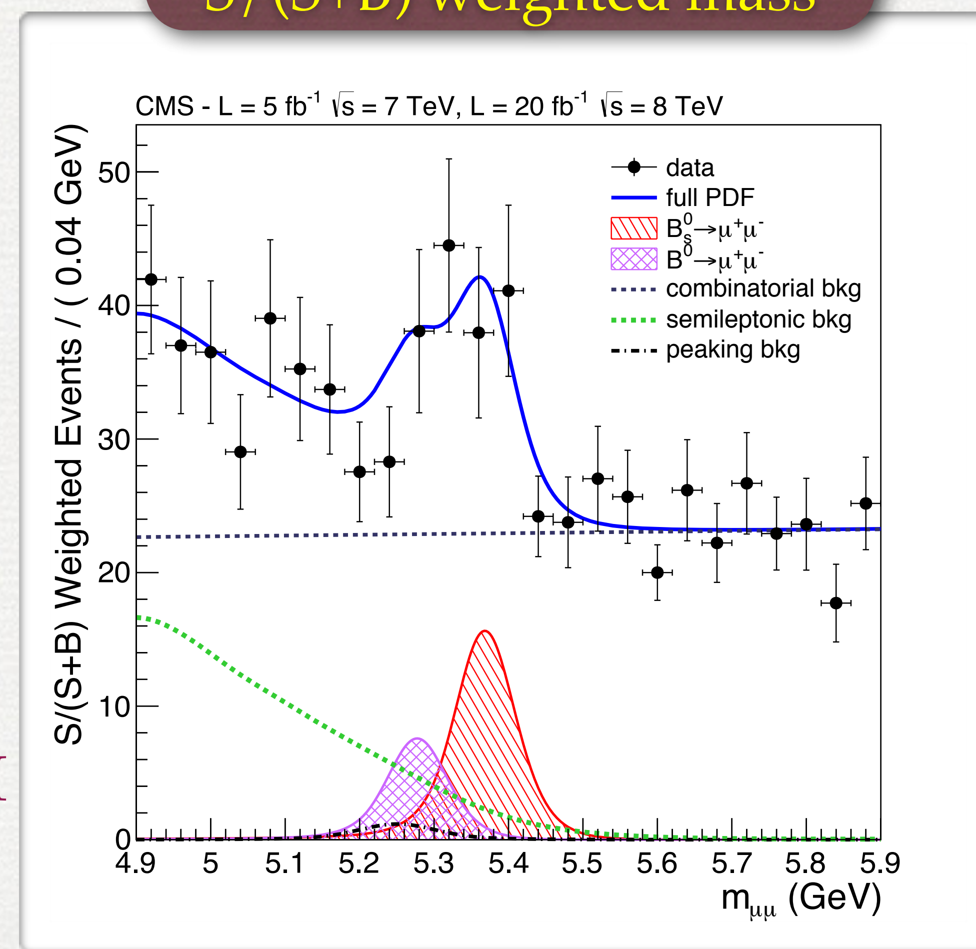
2D contour



4.3σ observation!

⇐ consistent with SM

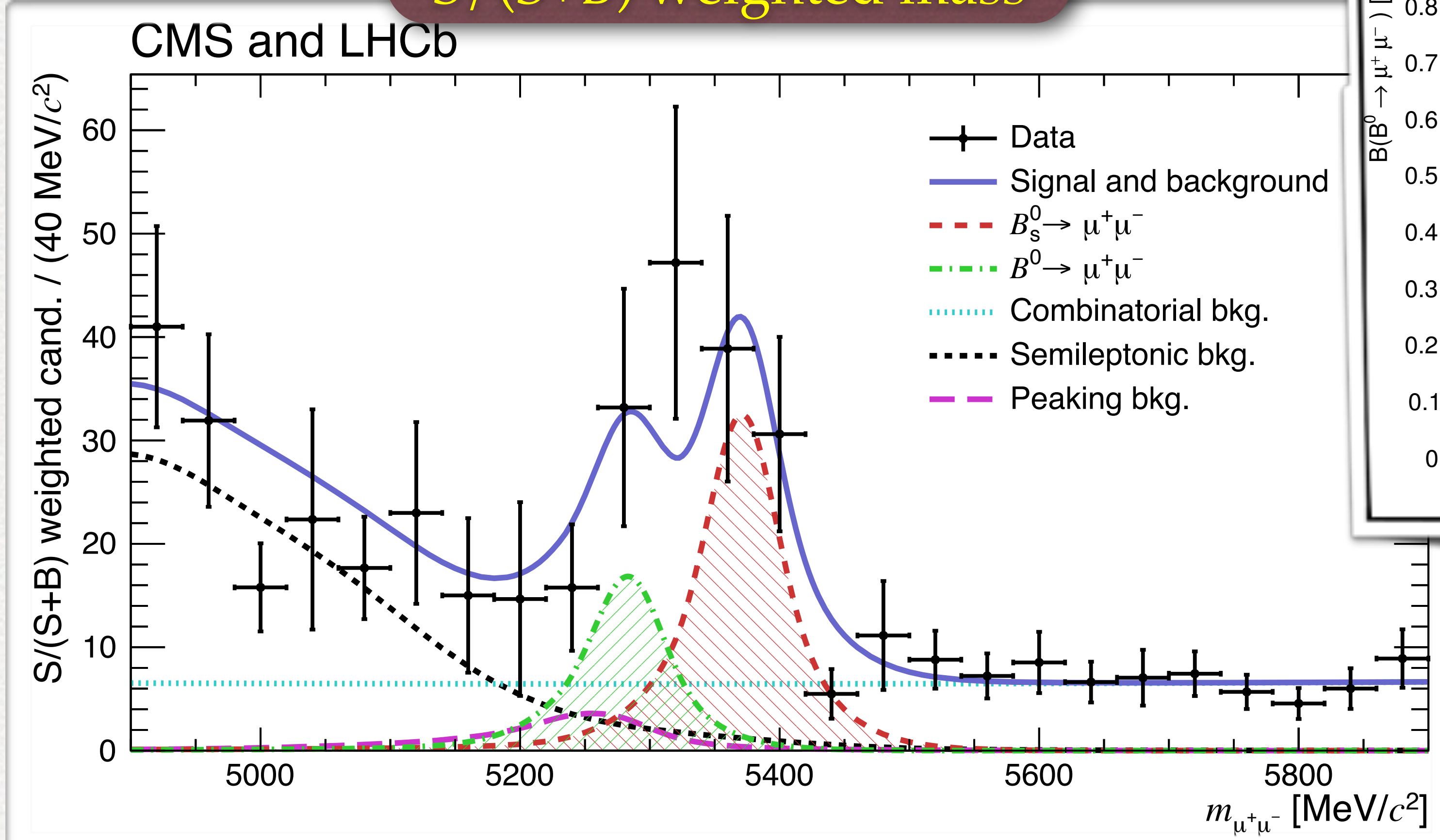
S/(S+B) weighted mass



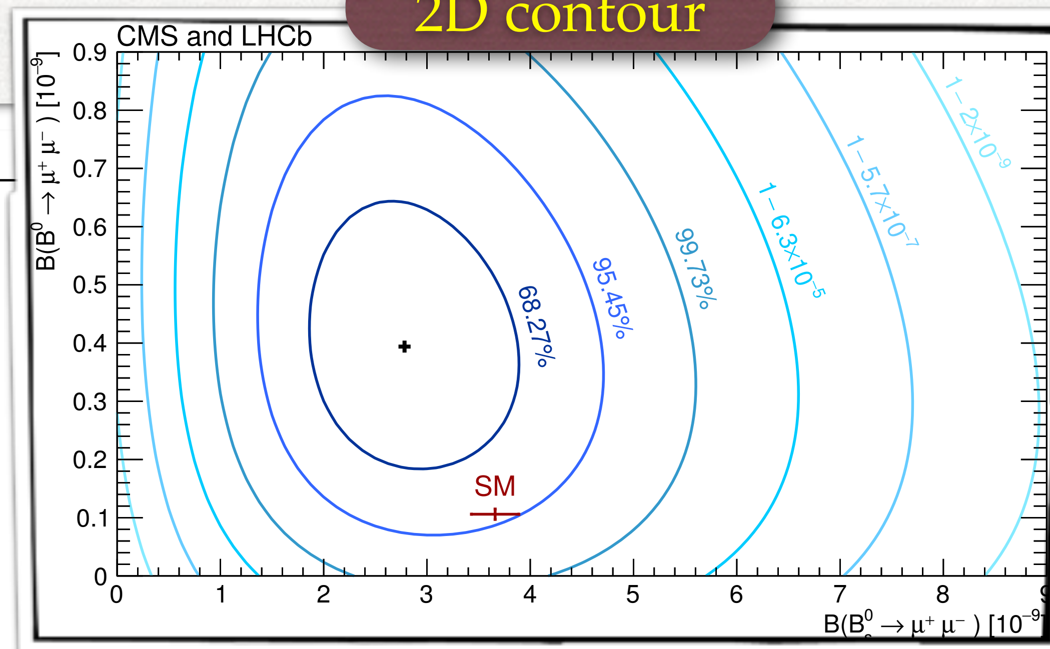
CMS+LHCB COMBINATION

- A full combination for CMS and LHCb analyses for $B_{s,d} \rightarrow \mu+\mu-$ at likelihood level has been carried out.
- The observed significance for $Bs \rightarrow \mu+\mu-$ is **6.2σ**; it also produces **3σ** evidence for an excess of events in the search for $B_d \rightarrow \mu+\mu-$ decays.

S/(S+B) weighted mass



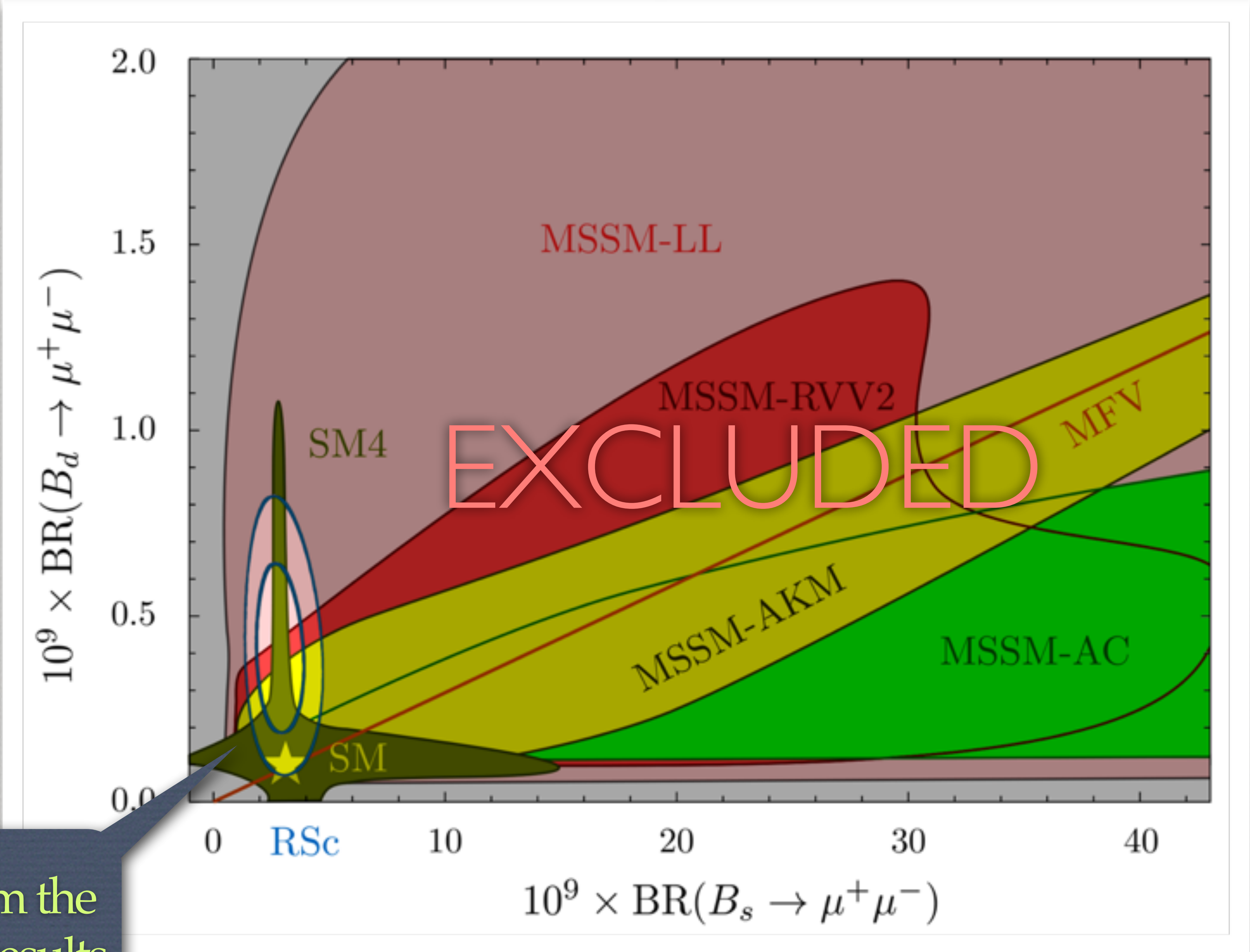
2D contour



Channel	Branching fraction
$B_s \rightarrow \mu^+\mu^-$	$(2.8^{+0.7}_{-0.6})\text{x } 10^{-9}$
$B_d \rightarrow \mu^+\mu^-$	$(3.9^{+1.6}_{-1.4})\text{x } 10^{-10}$

The combined paper is in preparation, targeting Nature.

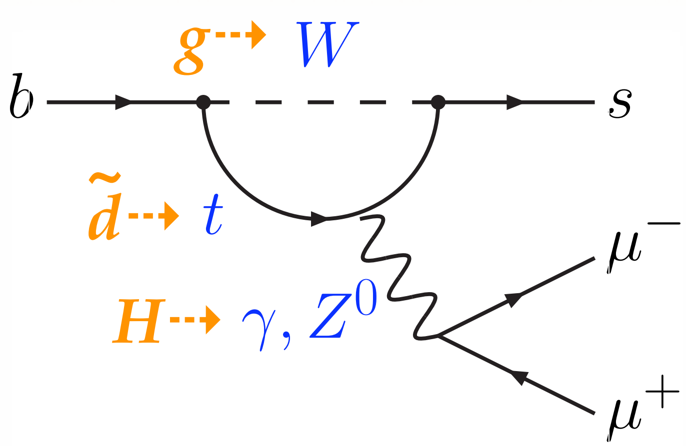
CMS+LHCB COMBINATION

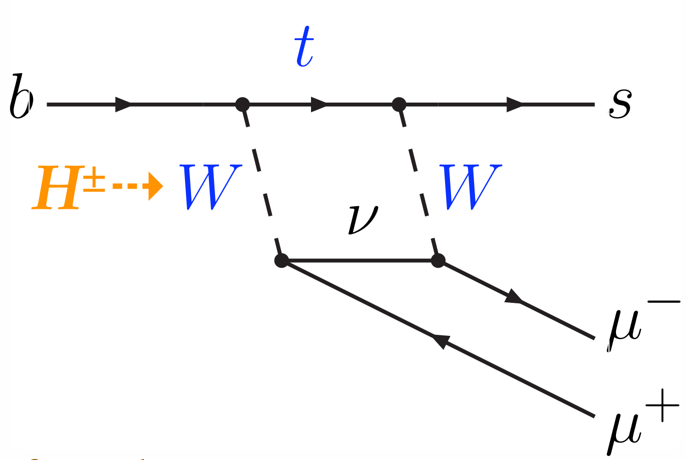


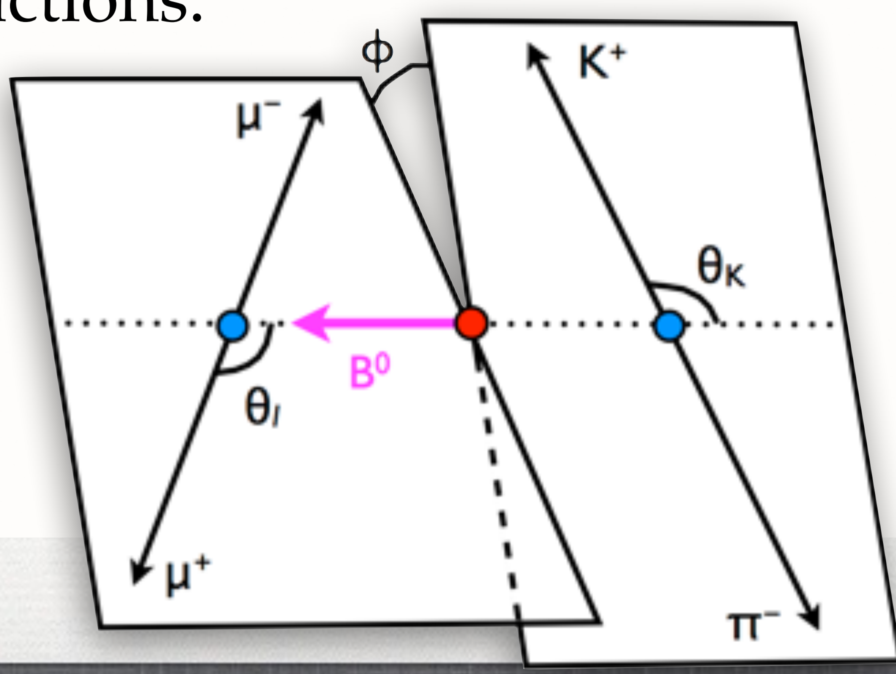
Contours from the combination results

ANGULAR ANALYSIS OF $B^0 \to K^{*0}\mu^+\mu^-$

- The $B \to K^*\mu\mu$ decay is proceed with FCNC process, **sensitive to new physics beyond the Standard Model**.
- Robust theoretical calculations.
- Single channel with many measurements (and as a function of q^2): branching fractions, A_{FB}, polarization,... etc., which allows detailed tests of the structure of the underlying interactions.







Four-particle final states lead to 3 angular observables **(θ_K, θ_L, ϕ)**.

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

- The full angular distribution actually depends on 11 different terms:

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

LHCb: drop 4 terms by folding $\phi \to \phi+\pi$ for $\phi<0$

Parameters (S_3, S_6, S_9,...) can be converted to ordinary parameters (A_{FB}, F_L, etc.) + S-wave modeling in addition.

- Alternatively by integrating out 1 or 2 angles to reduce the model:

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

CMS: integrated out ϕ
(and adding S-wave)
ATLAS: further integrated out θ_K or θ_L

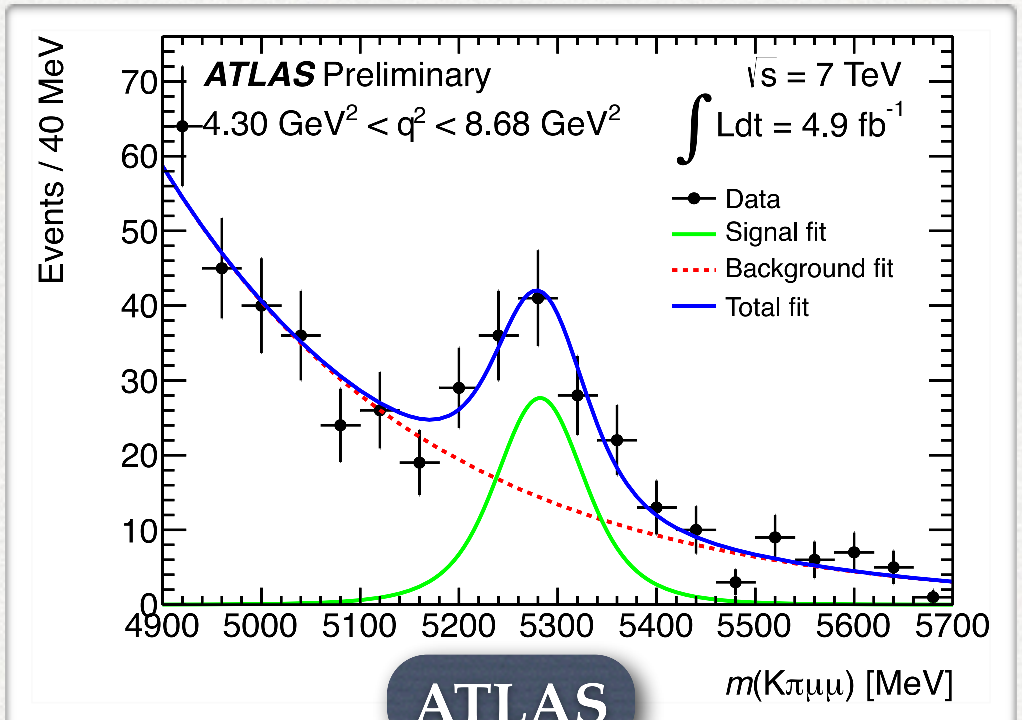
→ **Extract physics parameters (F_L, A_{FB} , etc.) in bins of q^2.**

$B^0 \rightarrow K^{*0}\mu^+\mu^-$ EVENTS

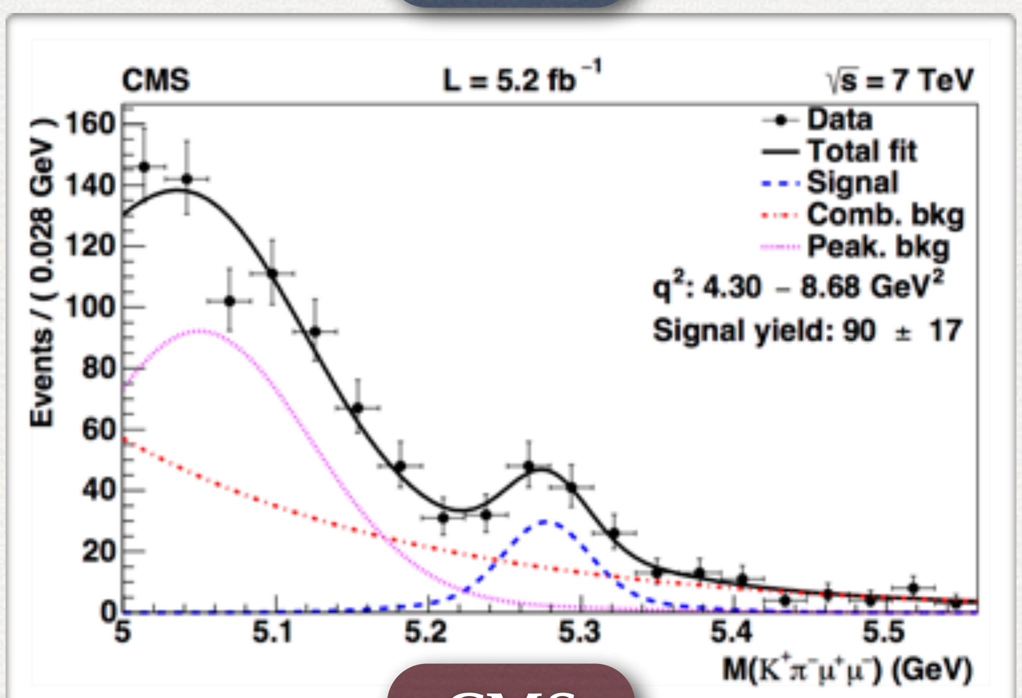
- Clear signals have been reconstructed in bins of q^2! (*plots are from an example bin of* $4.30 < q^2 < 8.68$ *GeV*^{2})

	ATLAS	CMS	LHCb
Luminosity	5 fb^{-1}	5 fb^{-1}	1 fb^{-1}
Yields (tot.)	466±34	415±29	2361±56

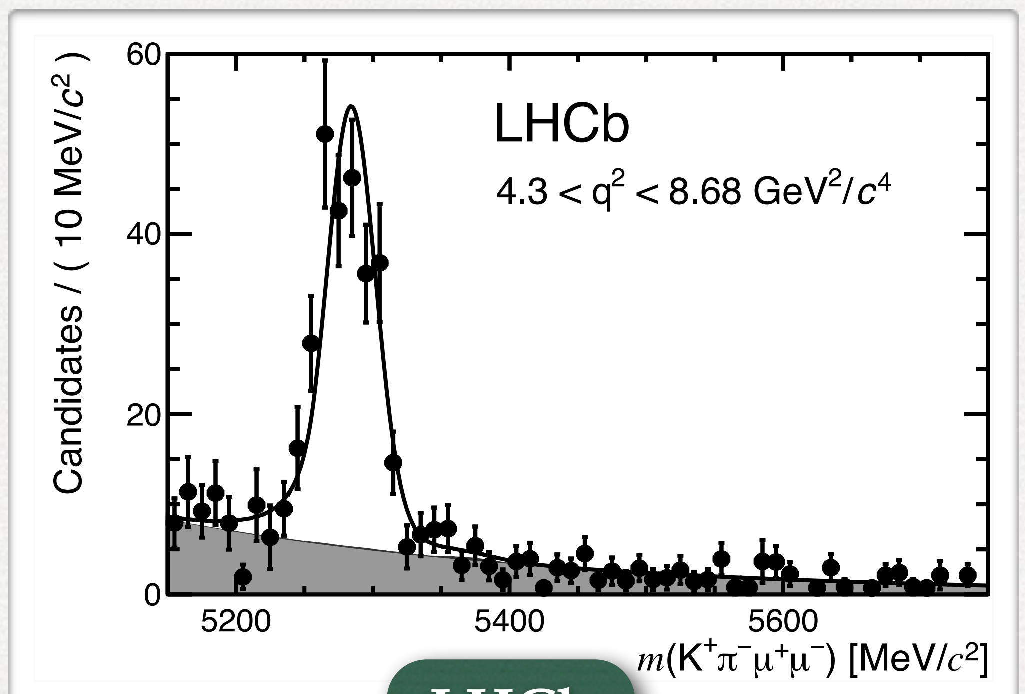
Ref. ATLAS-CONF-2013-038
CMS PLB 727 (2013) 77
LHCb JHEP 08 (2013) 131



ATLAS



CMS

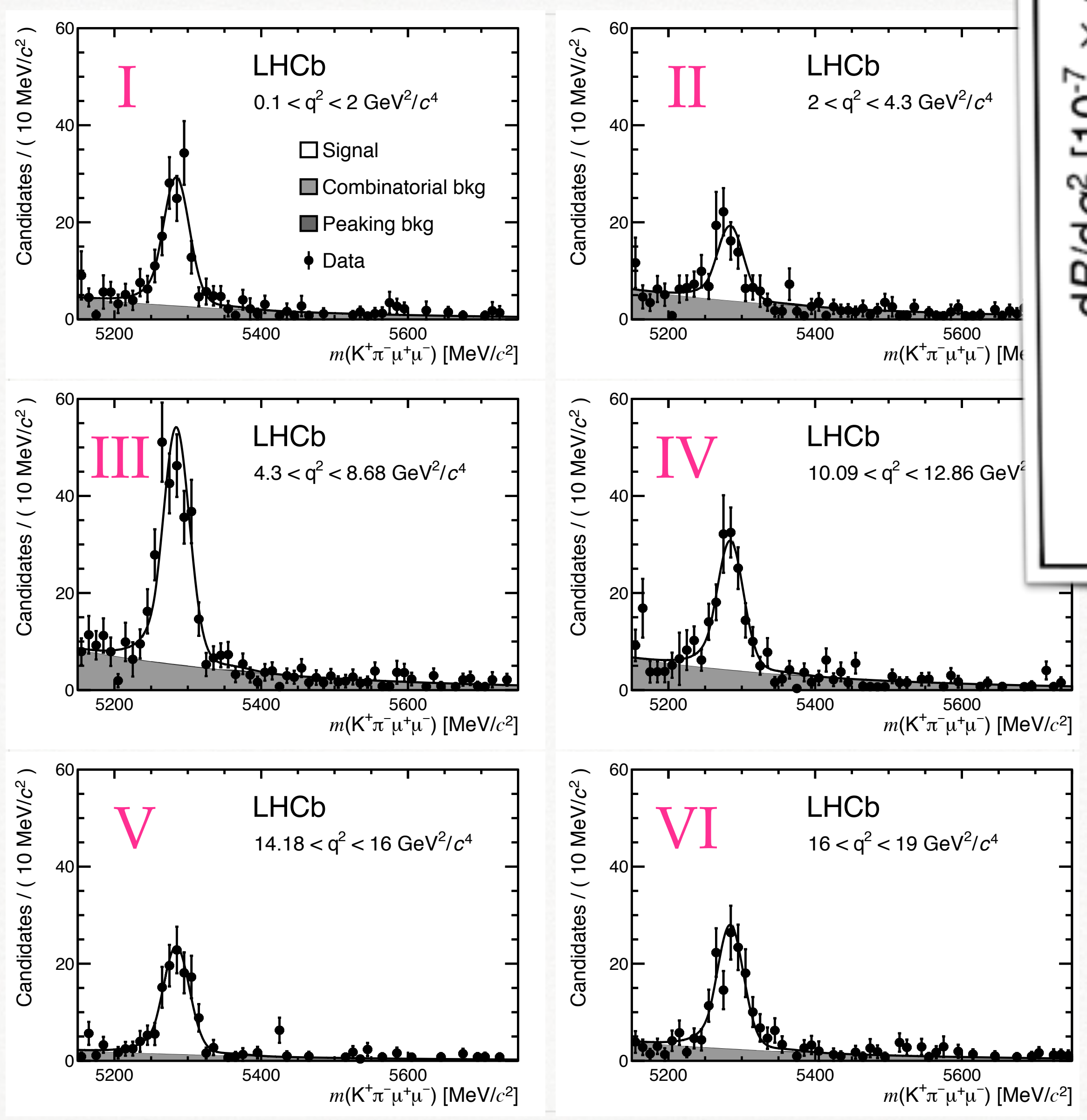


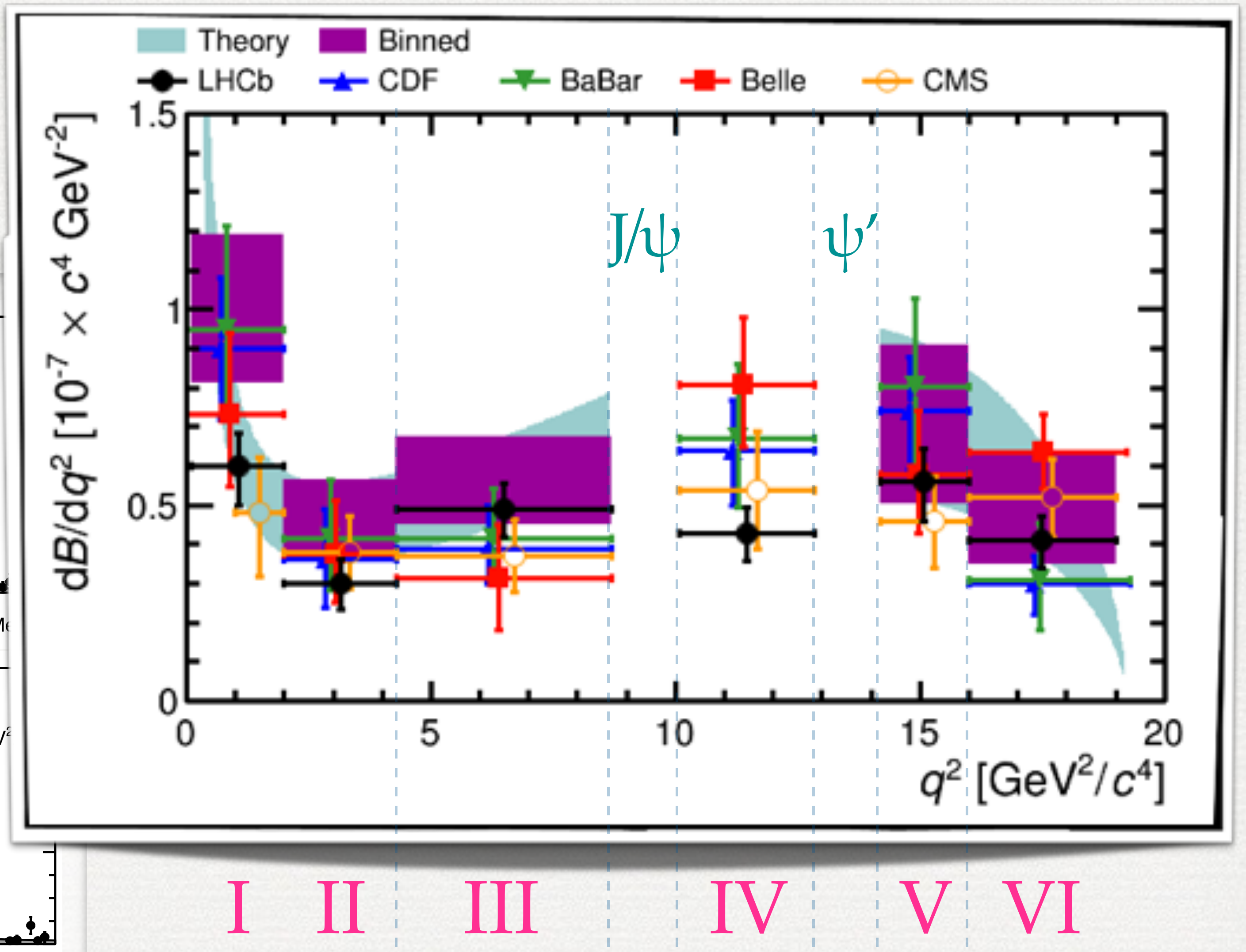
LHCb

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

Bin-by-bin on q^2 yield extraction

(*take LHCb has an example*)

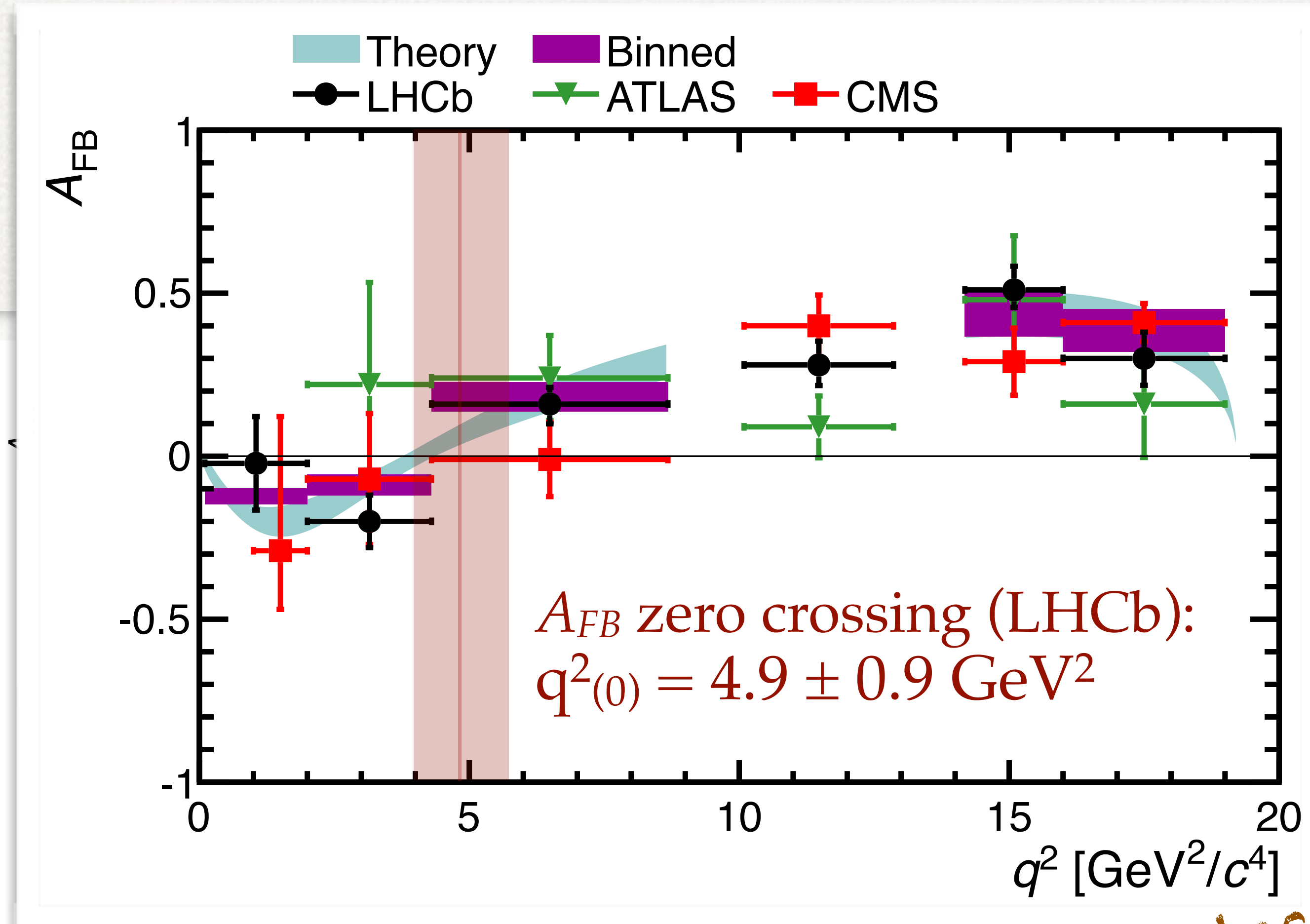


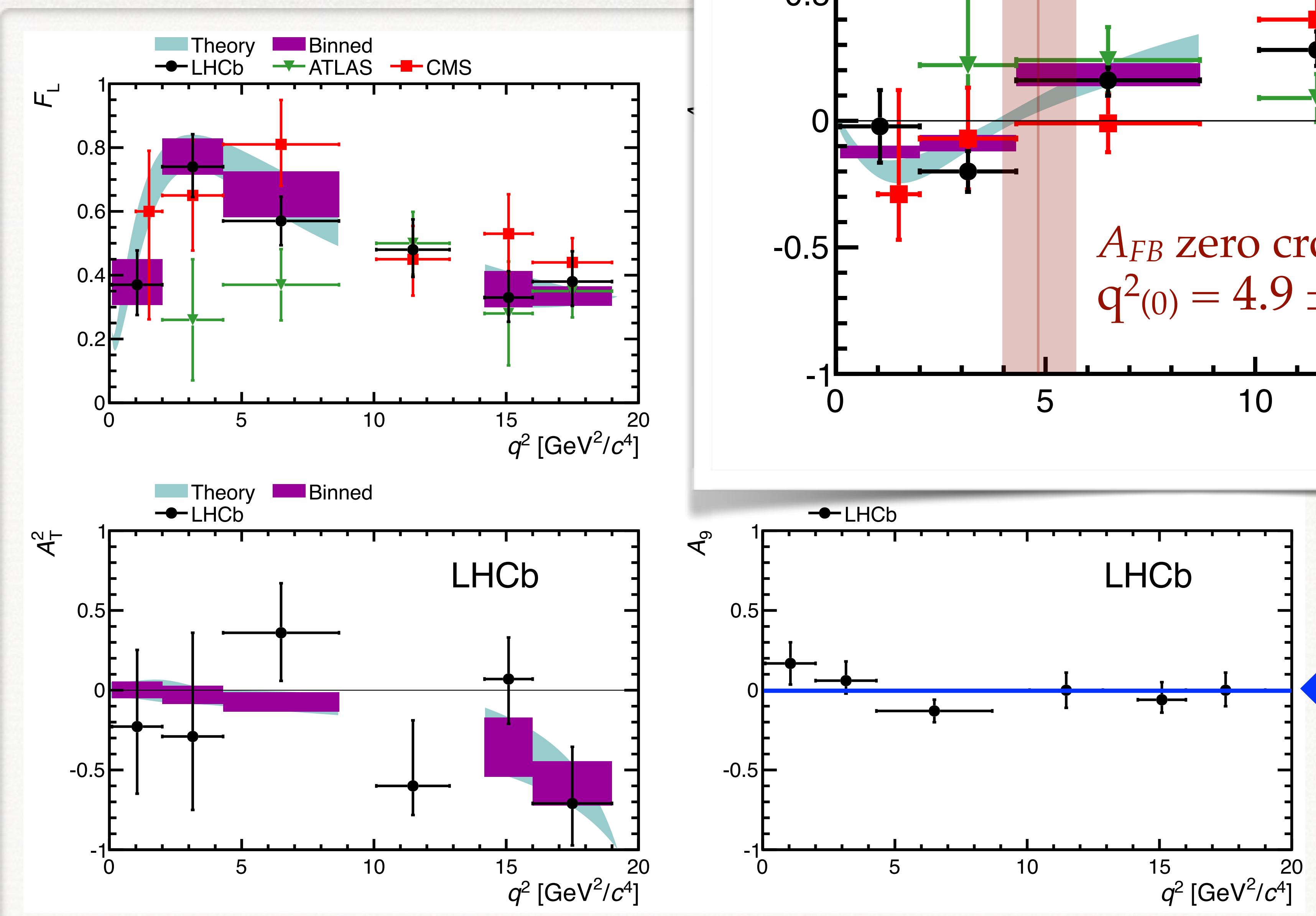


- The differential cross sections are in agreement with the prediction.
- The events in the J/ψ and ψ′ regions are used as control channel.

ANGULAR ANALYSIS

Extract physics parameters from likelihood fits to the angular distributions.





More or less consistent with SM...

SM

Ref. for TH bands:
Bobeth et al. JHEP 07 (2011) 067

(*The A_T and A9 can only be measured with the full model introduced by LHCb*)

NEW OBSERVABLES

Ref. LHCb PRL 111, 191801 (2013)
Decotes-Genon et al. JHEP 05 (2013) 137

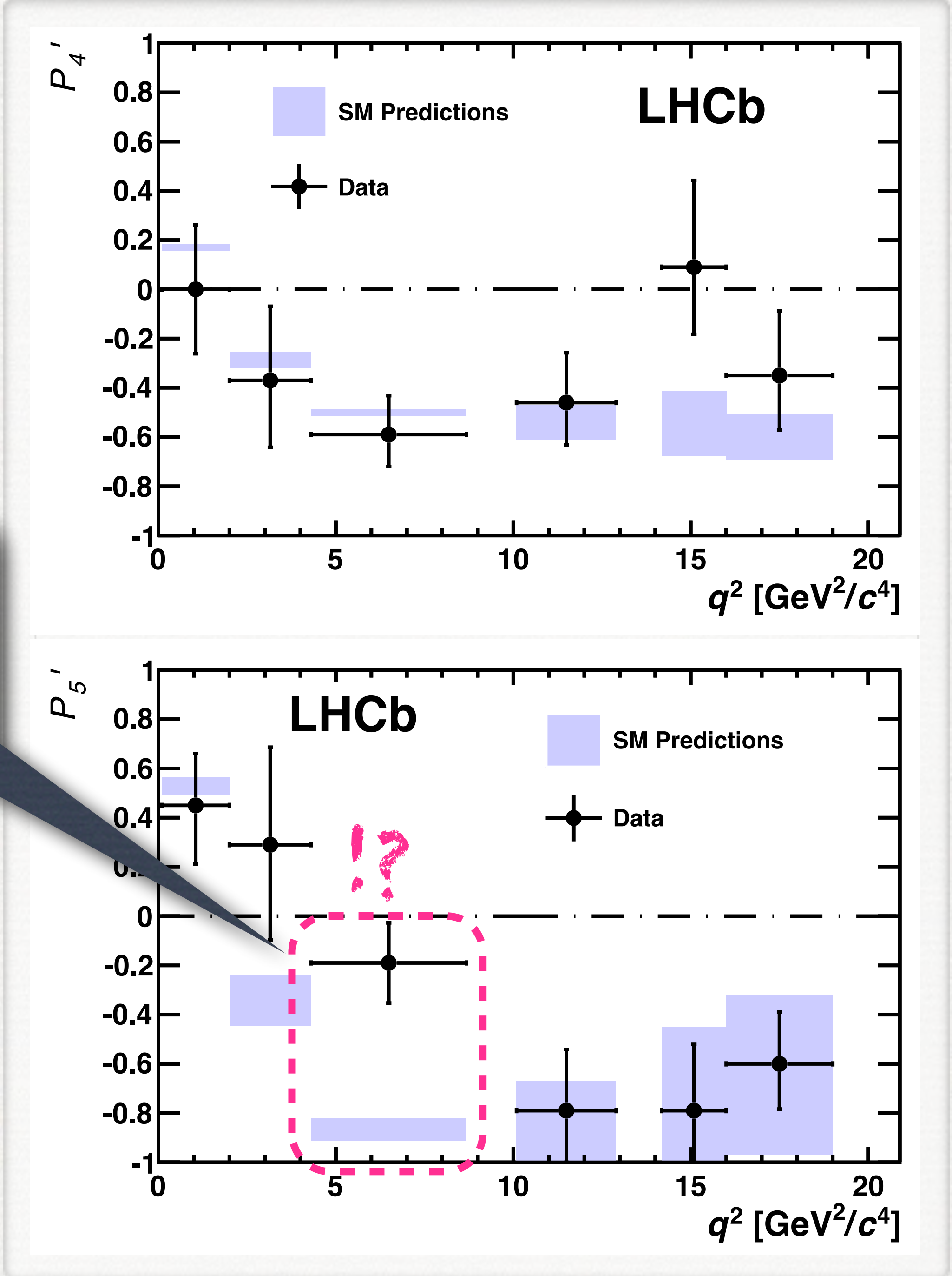
- Apply different folding to the angular distributions to access remaining parameters.
- Newly proposed observables designed to cancel the leading form factor uncertainties.

e.g. $P'_{4,5} = \dfrac{S_{4,5}}{\sqrt{F_L(1-F_L)}}$

3.7σ discrepancy in $4.3<q^2<8.68$ GeV^2 bin
Including the look elsewhere effect (LEE):
~0.5% probability (**2.8σ**)

- Simply statistical fluctuation?
- Theory error underestimated?
- New physics?
  (SUSY is difficult, Z′ might work, etc.)

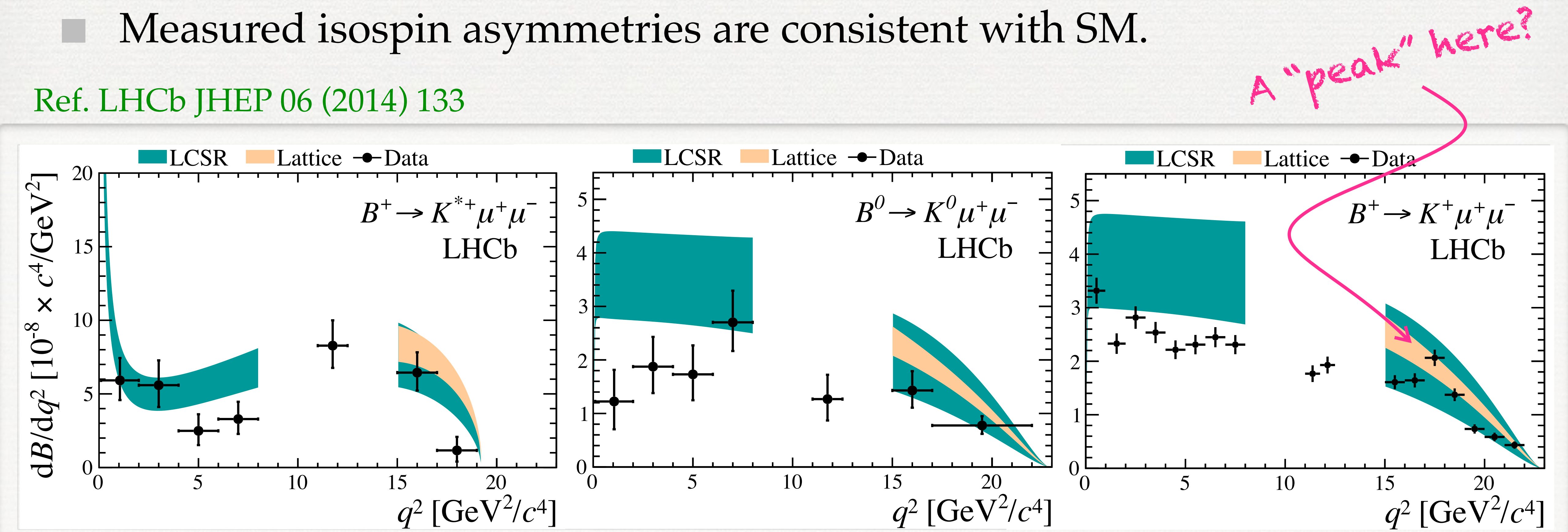
Check with more data/channels!



OTHER $B \to K^{(*)}\mu^+\mu^-$ DECAYS

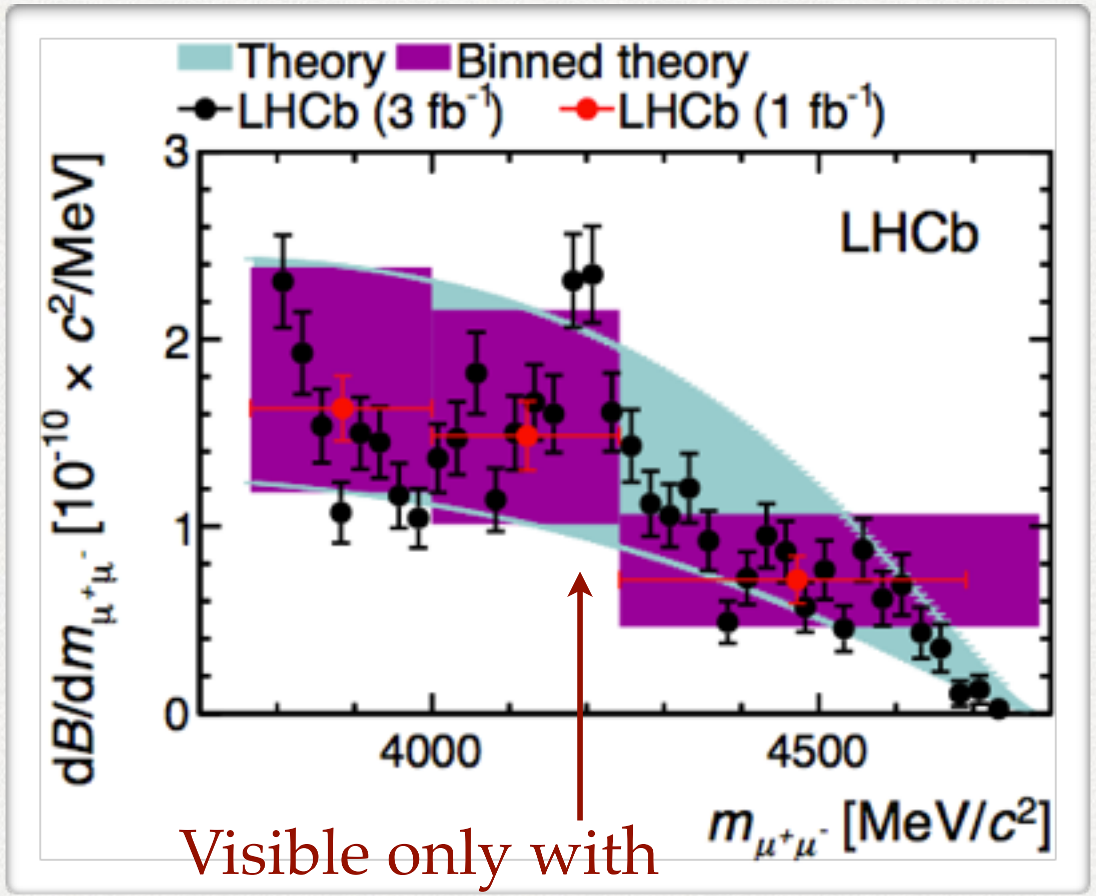
- In addition to K^{*0} $\mu\mu$, other channels with K^+, K_S, K^{*+} are also studied:
  - Channels with K_S are more challenging due to the long lifetime.
  - Clear signal observed in all channels by LHCb; differential branching fractions are normalized by $B \to J/\psi K^{(*)}$.
- Measurements of differential branching fractions consistently below SM
  - However the SM calculations are under revision.
- Measured isospin asymmetries are consistent with SM.

Ref. LHCb JHEP 06 (2014) 133



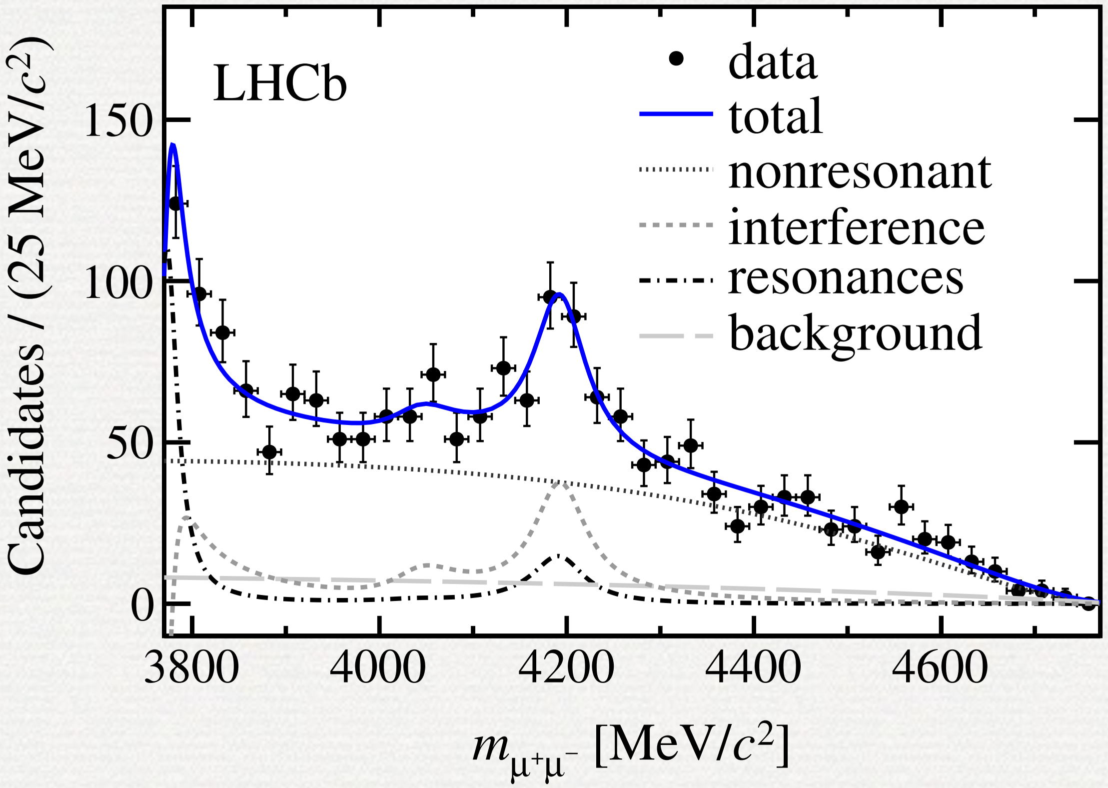
RESONANCE IN $B^+ \to K^+ \mu\mu$ DECAYS

- Sometimes an unexpected discovery may simply "pop-up" from the experimental data!
  - Observation of a resonance structure at high q^2, which is from $B^+ \to \psi(4160) K^+$ decay [first observation of this channel].
  - Non-trivial influence for the understanding of $b \to s\ell\ell$ decays.



Visible only with large statistics!

M~4191±9 MeV / Γ~65±22 MeV



Ref. LHCb PRL 111, 112003 (2013)

LEPTON UNIVERSALITY

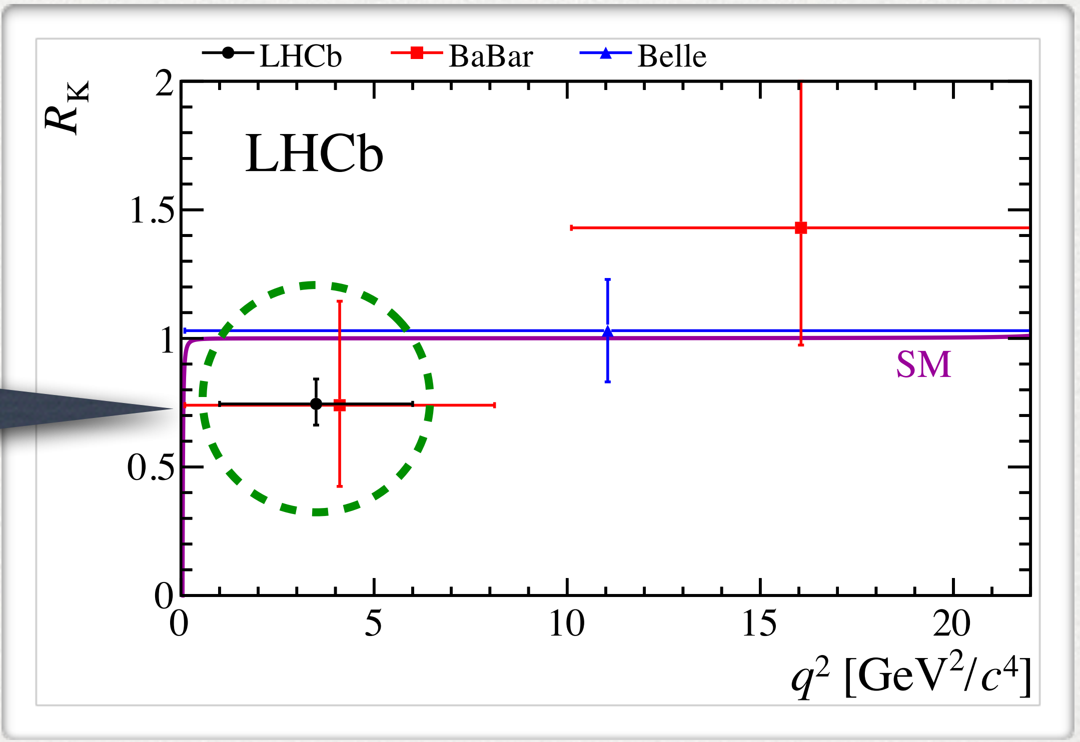
- In the Standard Model, couplings to all leptons are universal – one can test the **lepton universality** by measuring:

$$R_K = \frac{\int \frac{d\Gamma}{dq^2}[B^+ \to K^+\mu^+\mu^-]dq^2}{\int \frac{d\Gamma}{dq^2}[B^+ \to K^+e^+e^-]dq^2}$$

In SM:
$R_K(1<q^2<6) \sim 1 \pm \mathcal{O}(10^{-3})$

- Measuring $B^+ \to K^+e^+e^-$ is challenging due to the bremsstrahlung radiation of the electrons.
  - Correct for bremsstrahlung with calorimeter photons.
  - double-ratio with $B^+ \to J/\psi(e^+e^-)K^+$.

Ref. LHCb arXiv:1406.6482



LHCb measures w/ 3fb^{-1} data

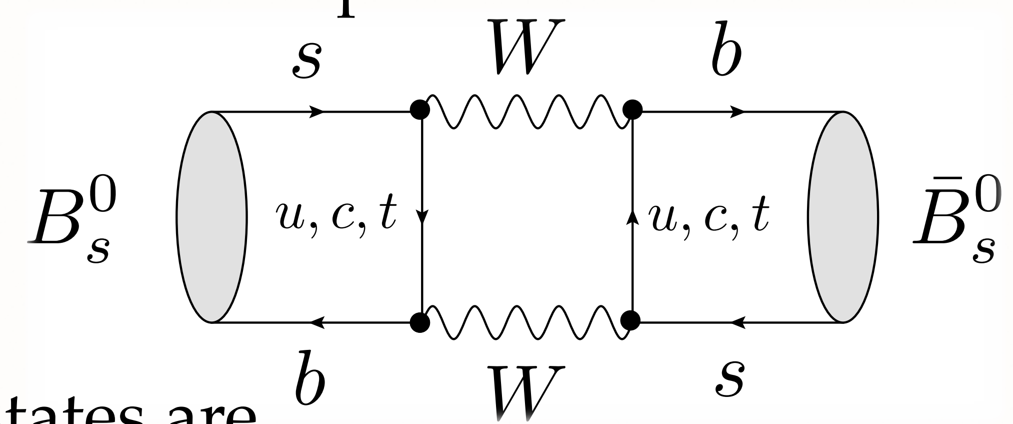
$R_K(1<q^2<6) = 0.745\,^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$

Compatible with SM prediction within 2.6σ.

B_s MIXING

- Neutral B_s mesons show the quantum-mechanical phenomenon of "mixing" with presence of the box diagram.
- Produced B_s meson state evolves with a time-dependent linear combination of two eigenstates.

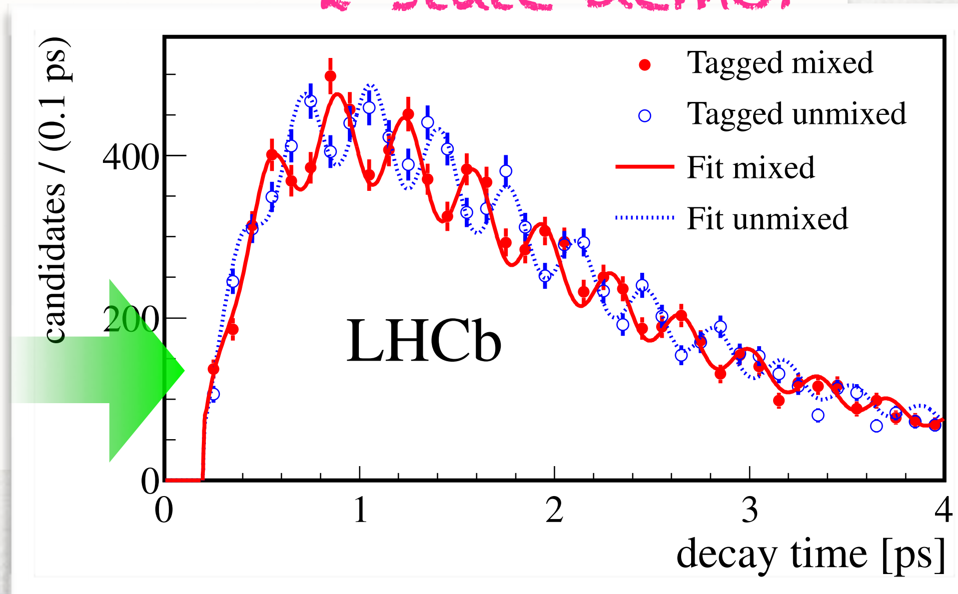
$$|B_H\rangle = p|B_s\rangle - q|\overline{B}_s\rangle$$
$$|B_L\rangle = p|B_s\rangle + q|\overline{B}_s\rangle$$



- The "heavy" and "light" mass eigenstates are characterized by:

Mass difference: $\Delta m_s \equiv M_H - M_L$
Decay width difference: $\Delta\Gamma_s \equiv \Gamma_L -$

A perfect QM 2-state demo!



Oscillation frequency proportion to $\Delta m_s \sim 17.768 \pm 0.023 \pm 0.006\ ps^{-1}$

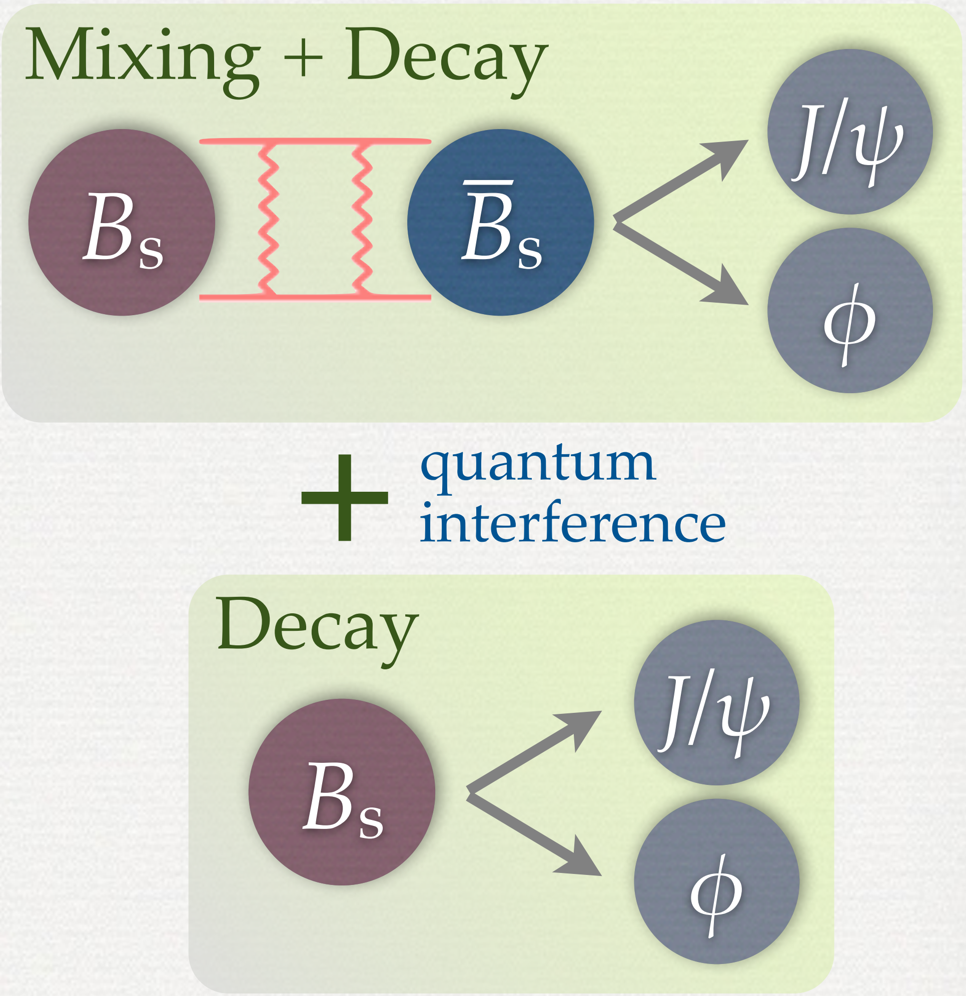
Ref. LHCb NJP 15 (2013) 053021

CP VIOLATION IN B_s MIXING

- When B_s and anti-B_s decay to exactly the same final state (e.g. $B_s \to J/\psi\,\phi$), the **weak phase ϕ_s** arises from the interference between direct decays and decays with mixing.
- The amplitude of CP violation $\propto \sin\phi_s$, where

$\phi_s \approx -2\beta_s$, $\beta_s = \arg(-V_{ts}V^*_{tb}/V_{cs}V^*_{cb})$

in SM $\phi_s \approx (-0.0363^{+0.0016}_{-0.0015})$ rad



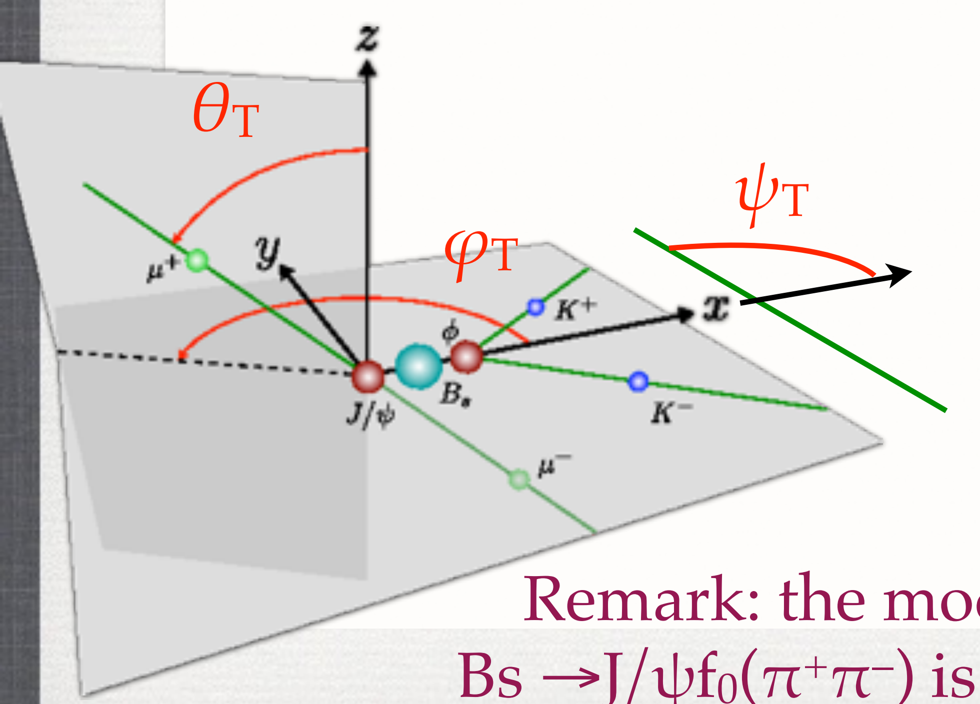
- Many **new physics scenarios** may enhance the value of ϕ_s.
- Experimentally clean — the final states can be fully reconstructed with small background.

ANALYSIS OF $B_s \to J/\psi\phi$

- Two vector mesons in the final state – an admixture of CP states.
- Angular analysis is introduced to disentangle CP-odd and CP-even components.
- A *complex* model: $$\frac{d^4\Gamma[B_s(t)]}{d\Theta dt} = \sum_{i=1}^{10} \mathcal{O}_i(\alpha, t) \cdot g_i(\Theta)$$

$$\mathcal{O}_i(\alpha, t) \propto e^{-\Gamma_s t}\left[a_i \cosh\left(\frac{1}{2}\Delta\Gamma_s t\right) + b_i \sinh\left(\frac{1}{2}\Delta\Gamma_s t\right) + c_i \cos\left(\Delta m_s t\right) + d_i \sin\left(\Delta m_s t\right)\right]$$

Proportional to **sinϕ_s** or **cosϕ_s**
(see the reference below for the full model)



α: physics parameters to be determined, include ϕ_s, $\Delta\Gamma_s$, Γ_s, ...

Θ: decay angles, either in transversity bases (left fig.), or helicity bases (similar to $K^*\mu\mu$)

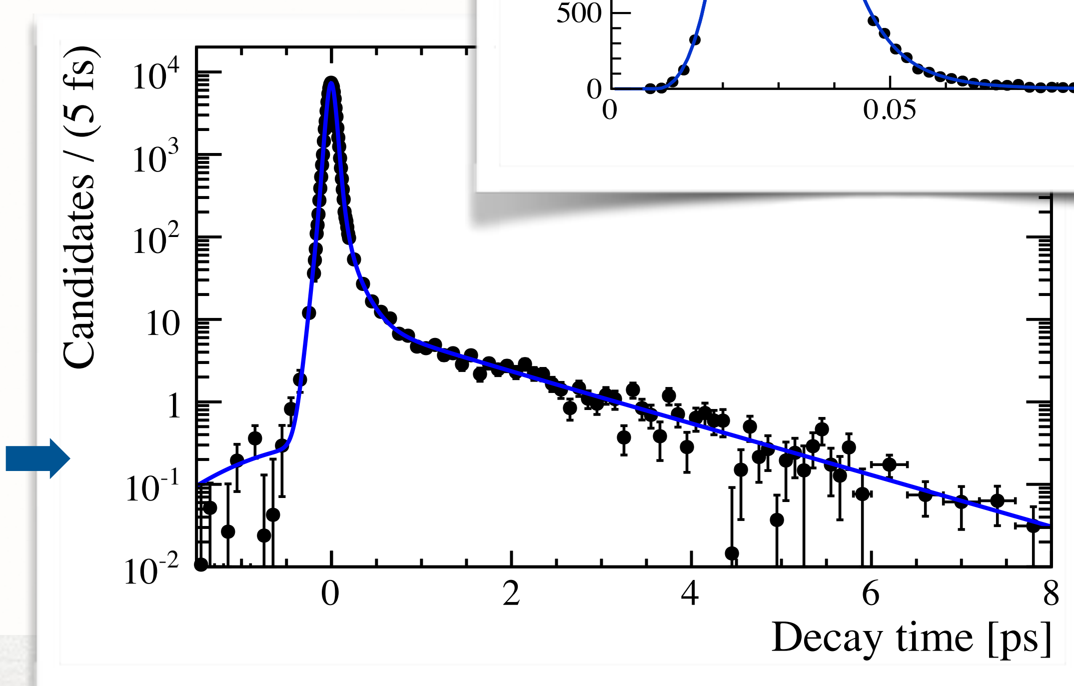
Remark: the model for $Bs \to J/\psi f_0(\pi^+\pi^-)$ is simpler!

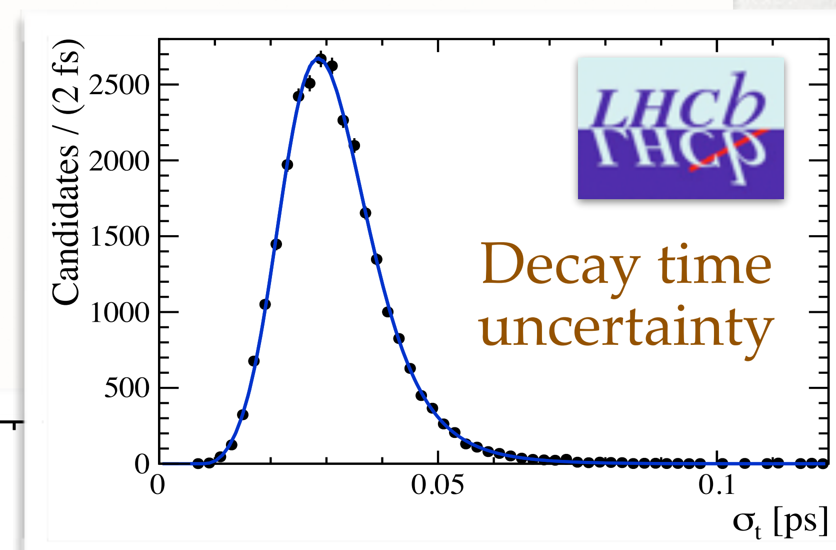
Ref. LHCb PRD 87, 112010 (2013)

EFFICIENCY & RESOLUTION

- Key elements for the measurement: **decay time resolution** and **angular efficiency** modeling.
- Angular efficiency can be modeled with a 3D function of decay angles.
- Decay time resolution is estimated from **B_s decay vertex finding** for each candidate and is included in the final fit convoluted with a Gaussian-type resolution function.
  - ATLAS: ~90 fs
  - CMS: ~70 fs
  - LHCb: ~45 fs

Without resolution one should see a δ-function ~ 0 (prompt J/ψ background) and simple exponential to the right (=straight line in log scale)



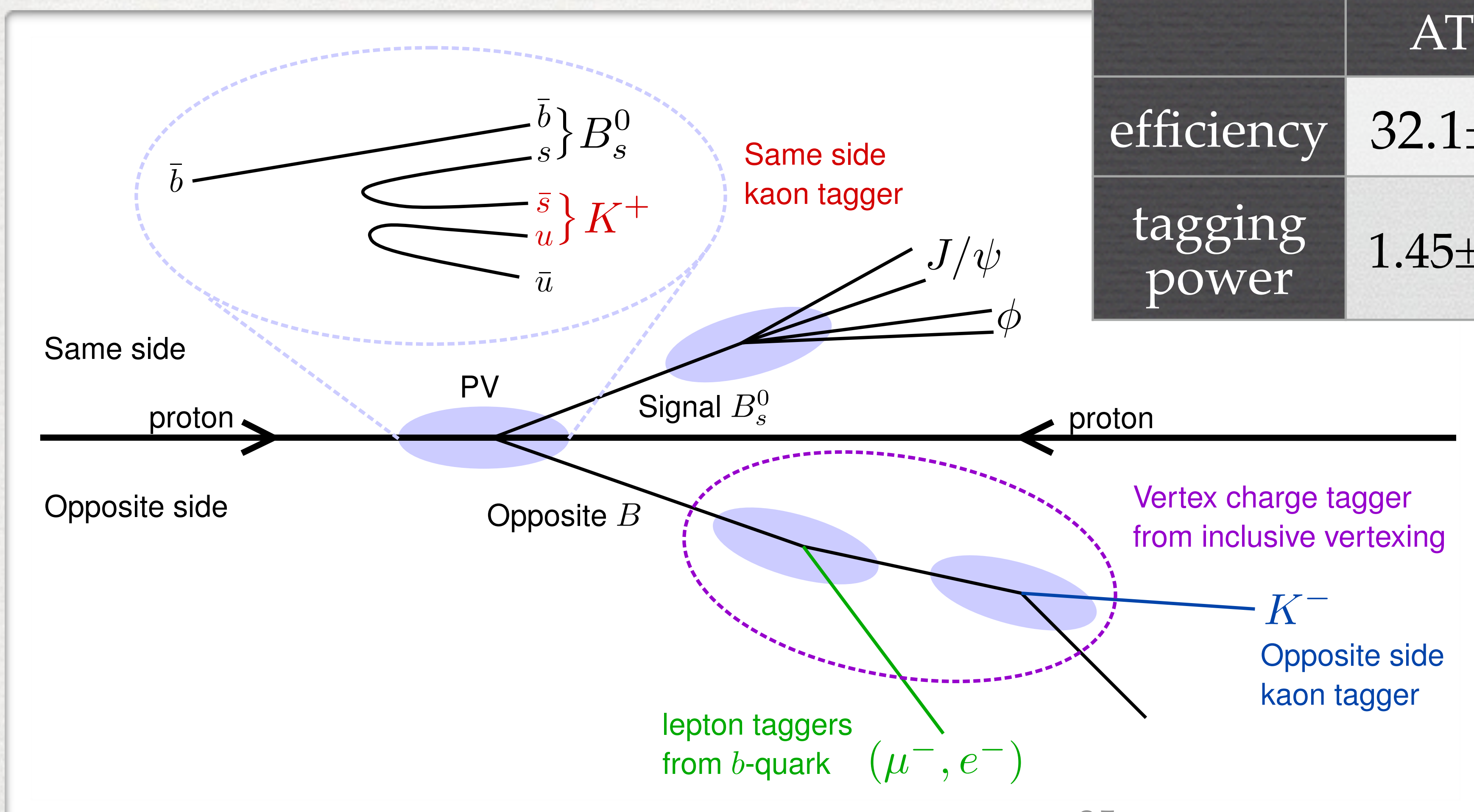


FLAVOUR TAGGING

- **Flavour tagging** is another essential piece of the analysis.
- Determination for the flavour of the B_s meson at production with
  - opposite-side tagging (OST): partial reconstruction of another b hadron in the event.
  - same-side tagging (SST): identify the residual strange quark associated with B_s meson production.

Tagging power = efficiency x (1–2ω)

ω: wrong tag fraction



	ATLAS	CMS	LHCb
efficiency	32.1±0.1%	7.67±0.04%	39.4±0.3%
tagging power	1.45±0.05%	0.97±0.04%	3.13±0.23%

ATLAS: OST(μ + jet change)

CMS: OST(μ + e)

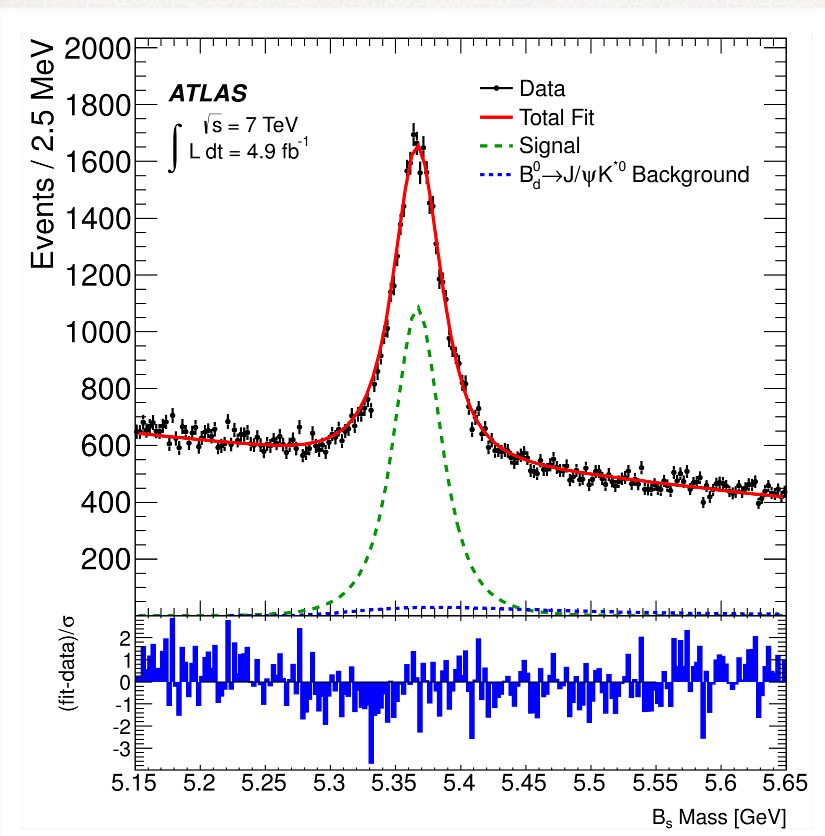
LHCb: OST(all) + SST

CANDIDATE EVENTS

- All with clean signals!
- Likelihood fits applied to extract the yields.

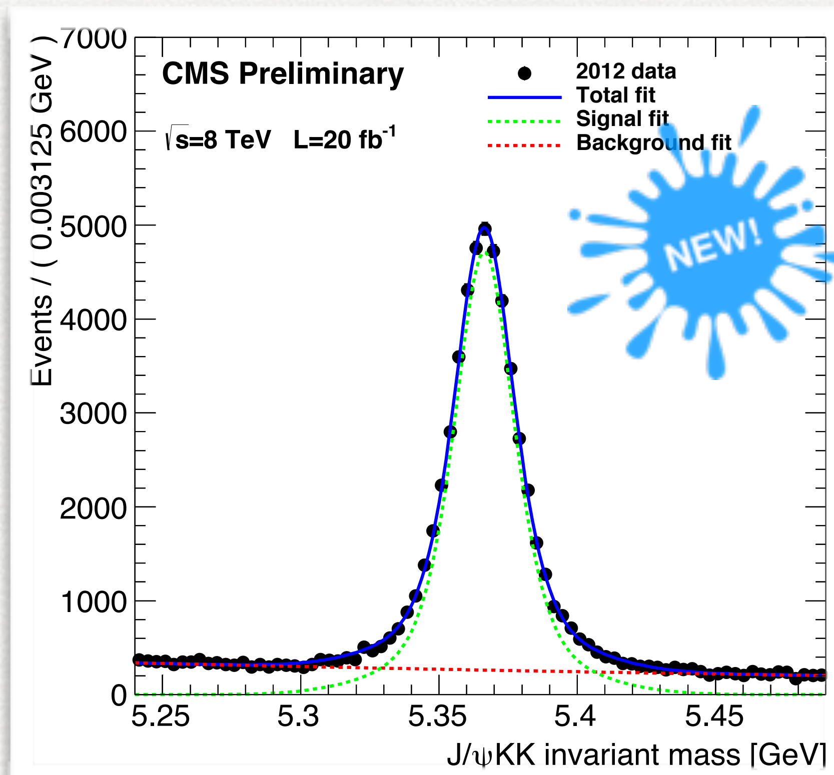
Ref. LHCb PRD 87, 112010 (2013)
LHCb arXiv:1405.4140

Ref. ATLAS JHEP 12 (2012) 072

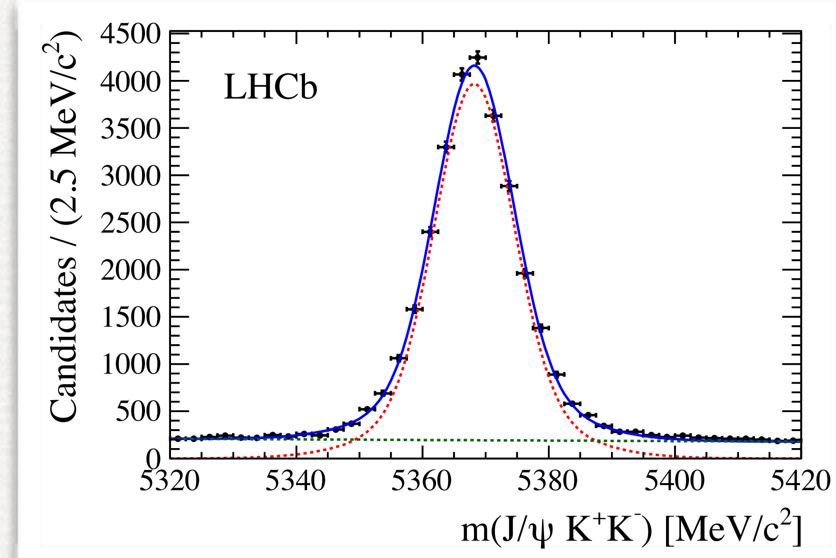


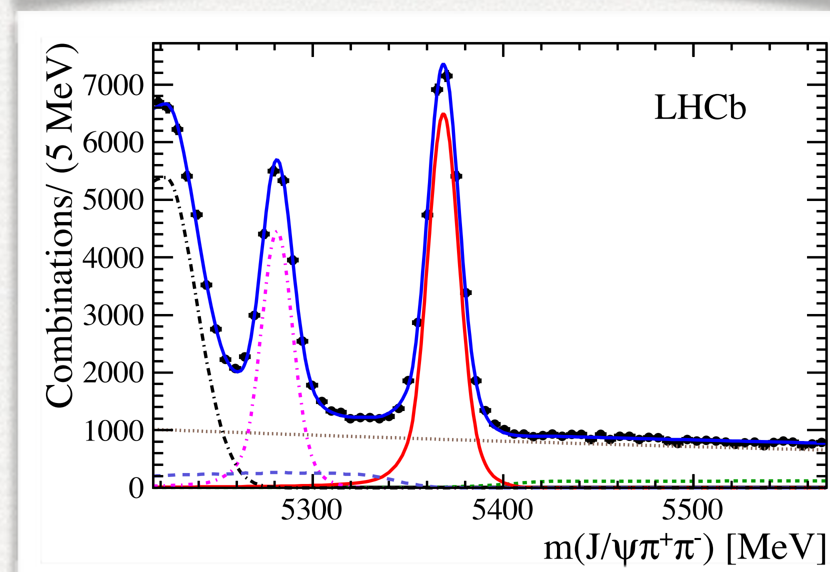
ATLAS 5 fb^{-1}
N(B_s) = 22690 ± 160

Ref. CMS PAS BPH-13-012



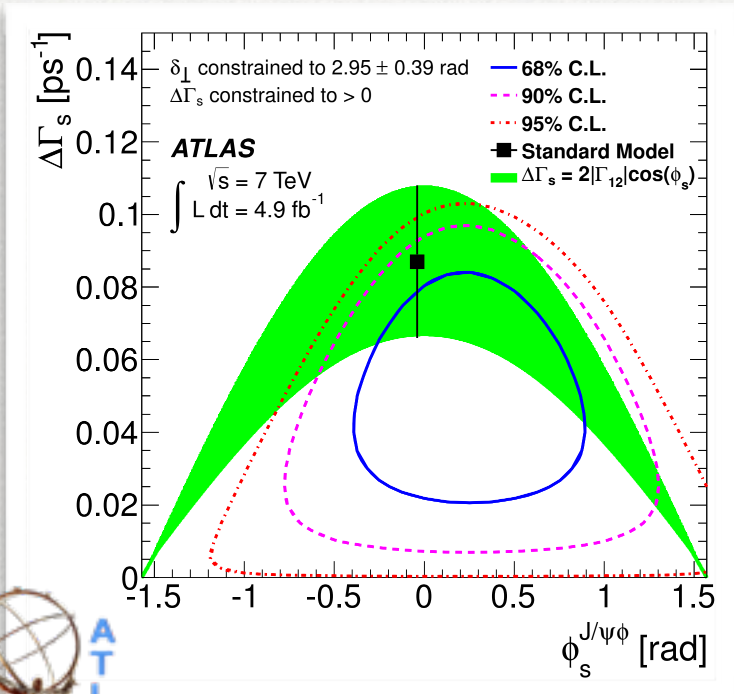
CMS 20 fb^{-1}
N(B_s) ~ 49000

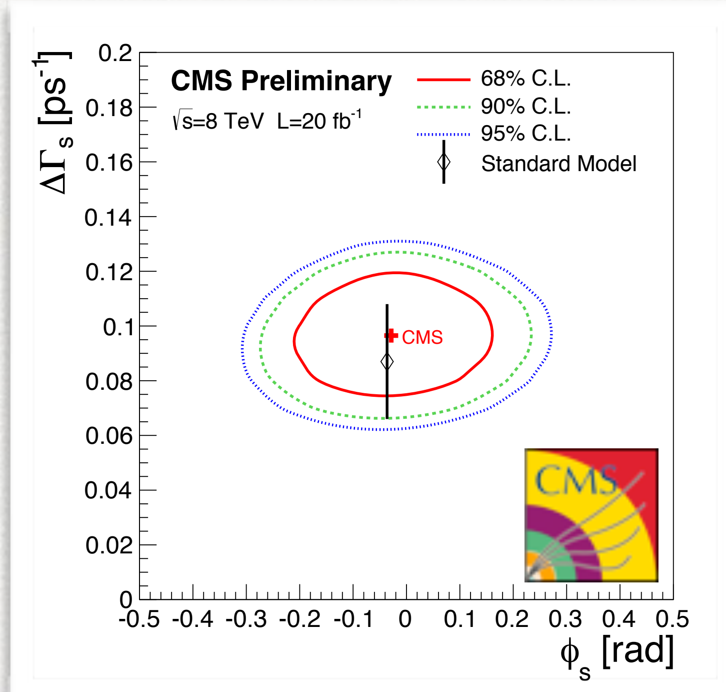


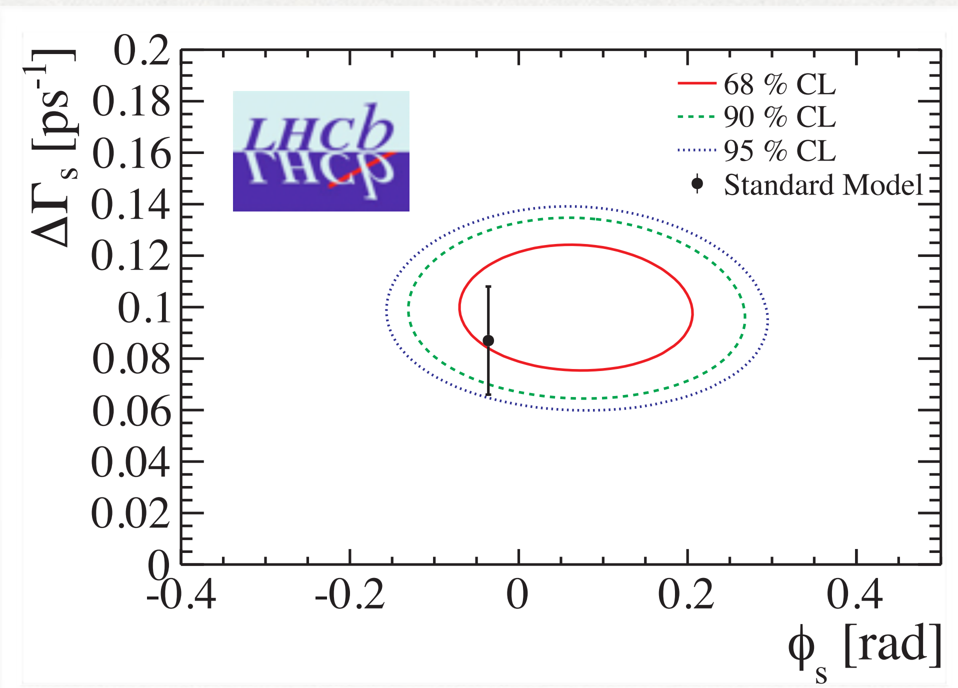


LHCb
N($B_s \to J/\psi KK$) = 27617 ± 115 @ 1 fb^{-1}
N($B_s \to J/\psi \pi\pi$) ~ 27100 @ 3 fb^{-1}

EXTRACTION OF ϕ_s & $\Delta\Gamma_s$







ATLAS 5 fb^{-1}

ϕ_s = 0. 12 ± 0.25 ± 0.05 rad

$\Delta\Gamma_s$ = 0.053 ± 0.021 ± 0.10 ps^{-1}

CMS 20 fb^{-1}

ϕ_s = –0.03 ± 0.11 ± 0.03 rad

$\Delta\Gamma_s$ = 0.096 ± 0.014 ± 0.007 ps^{-1}

LHCb $B_s \to J/\psi KK$ @ 1 fb^{-1}

ϕ_s = 0.07 ± 0.09 ± 0.01 rad

$\Delta\Gamma_s$ = 0.100 ± 0.016 ± 0.003 ps^{-1}

LHCb $B_s \to J/\psi\pi\pi$ @ 3 fb^{-1}

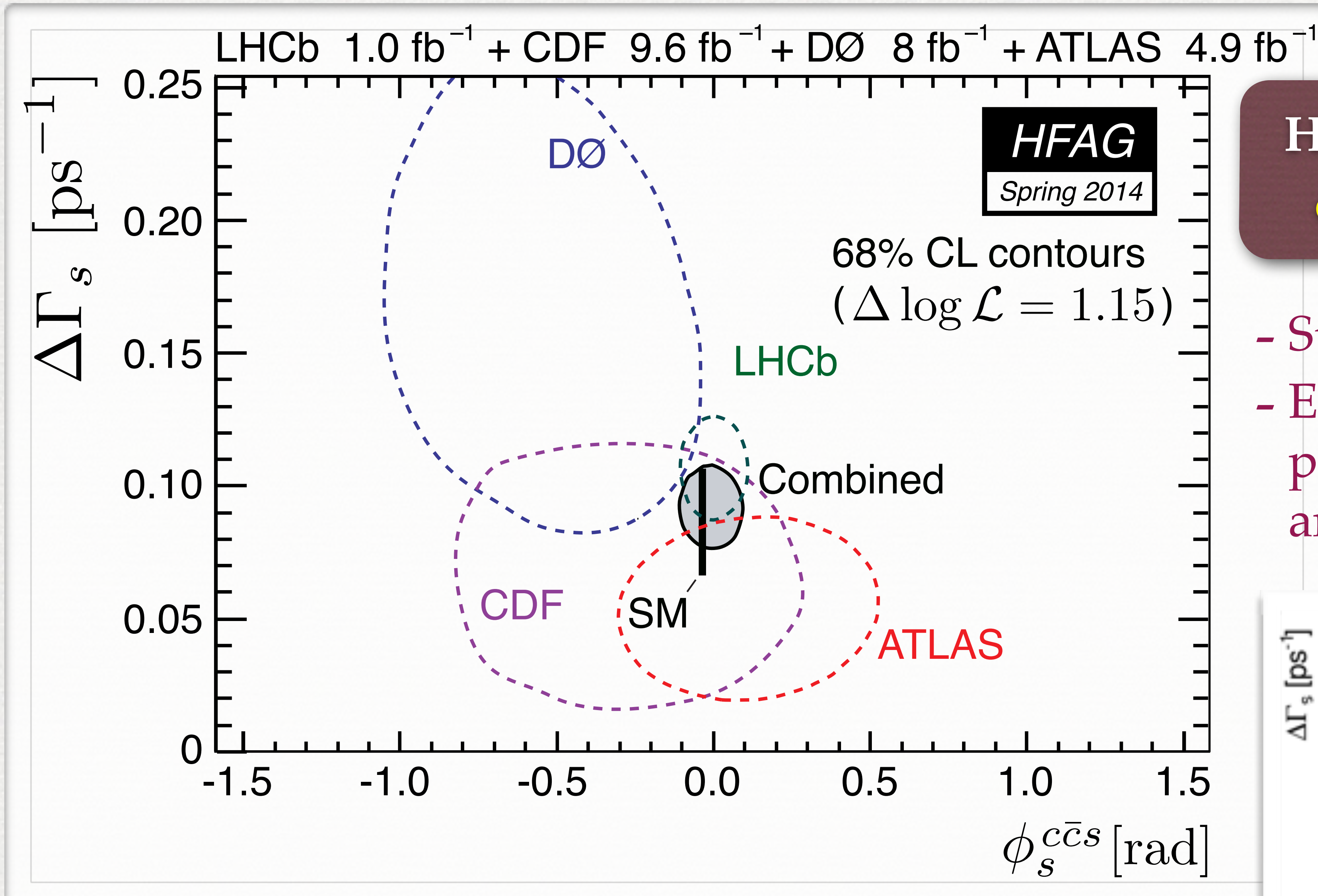
ϕ_s = 0.075 ± 0.067 ± 0.008 rad

LHCb combination

ϕ_s = 0.070 ± 0.055 rad

$\phi_s/\Delta\Gamma_s$ COMBINATION: $B_s \to J/\psi\phi$

Ref. http://www.slac.stanford.edu/xorg/hfag/osc/spring_2014/

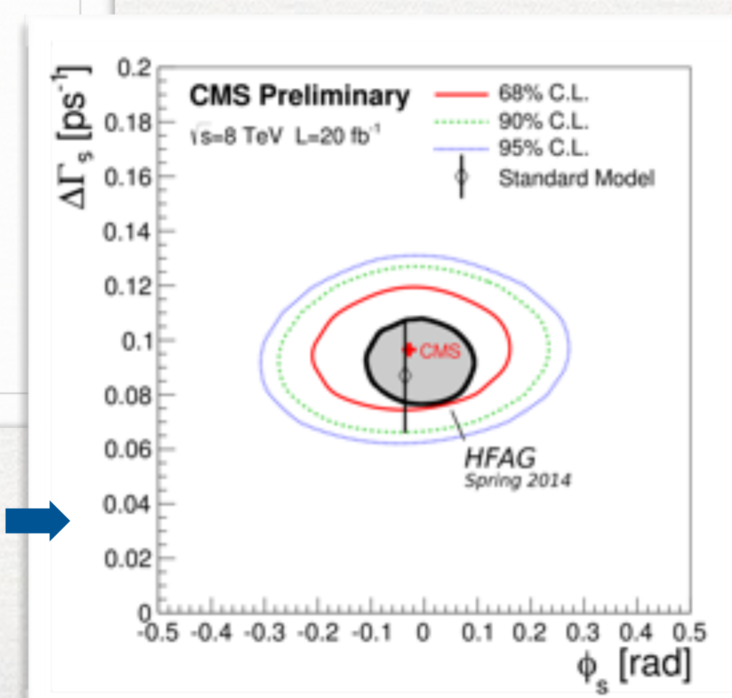


HFAG Spring 2014 Average

$\phi_s = +0.00 \pm 0.07$ **rad**

- Still statistics dominant.
- Expected to improve the precision with new CMS result and LHCb full data update.

New CMS result has not yet been included in the average.



SUMMARY

- Three important B-physics analyses at the LHC are discussed
  - First observation of very rare decay of $B_s \to \mu\mu$.
  - Extended measurements for $B \to K^{(*)}\mu\mu$ decays.
  - Weak phrase ϕ_s measured through the $B_s \to J/\psi\phi$ decays.
- B-physics studies play an important role for the search of physics beyond the SM. No striking signal yet, but some tensions do emerge. More data will help to clarify them.
- Topics which are not covered:
  - Many b-hadron production, decay, and property measurements.
  - Quarkonia measurements and exotic quarkonia searches.

BACKUP SLIDES