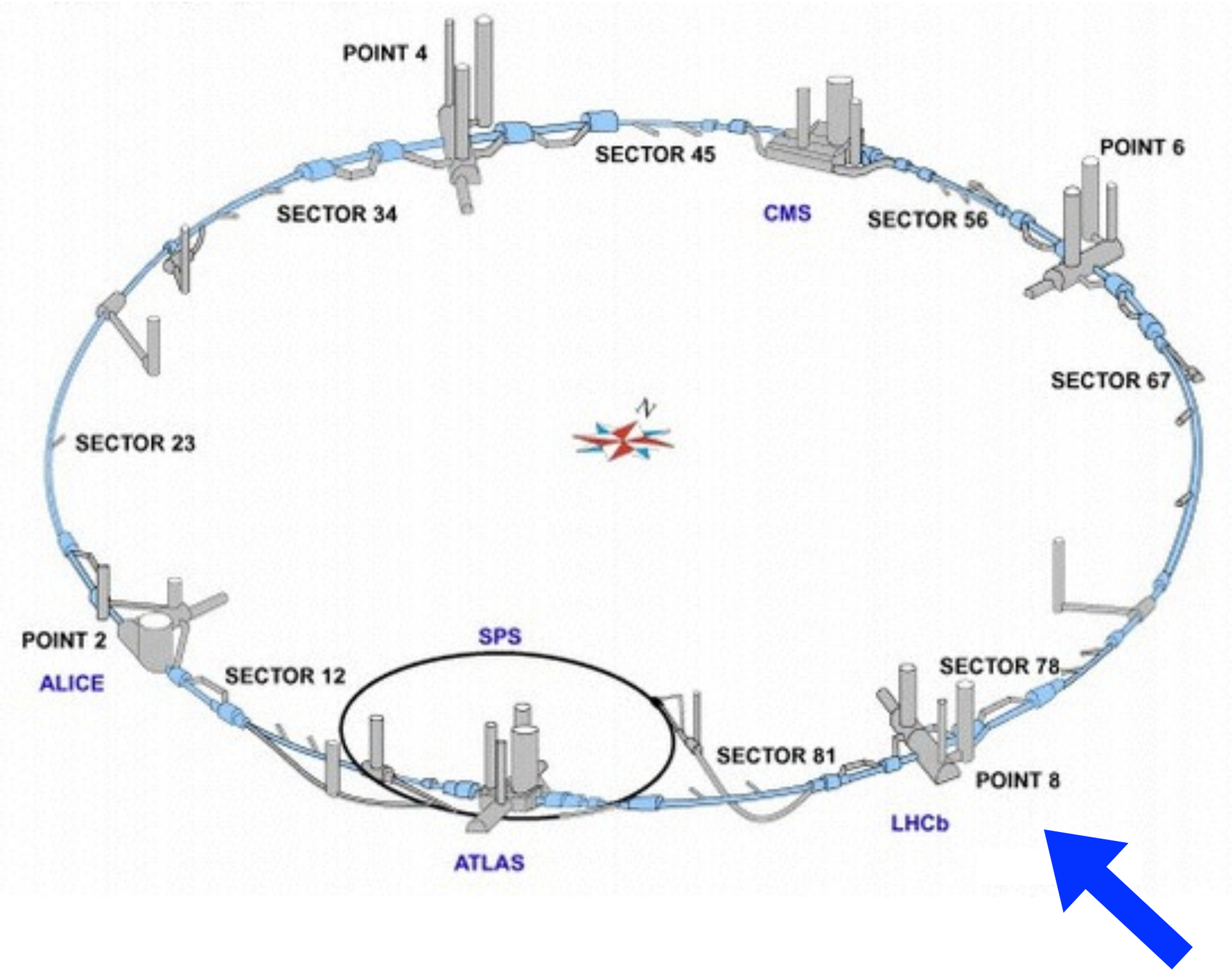
Recent results from LHCb

Mat Charles (LPNHE & UPMC, Paris)
on behalf of the LHCb collaboration

42nd SLAC Summer Institute (Aug 4-15, 2014)

What is LHCb?


POINT 4
SECTOR 45
POINT 6
SECTOR 34
CMS
SECTOR 56
SECTOR 67
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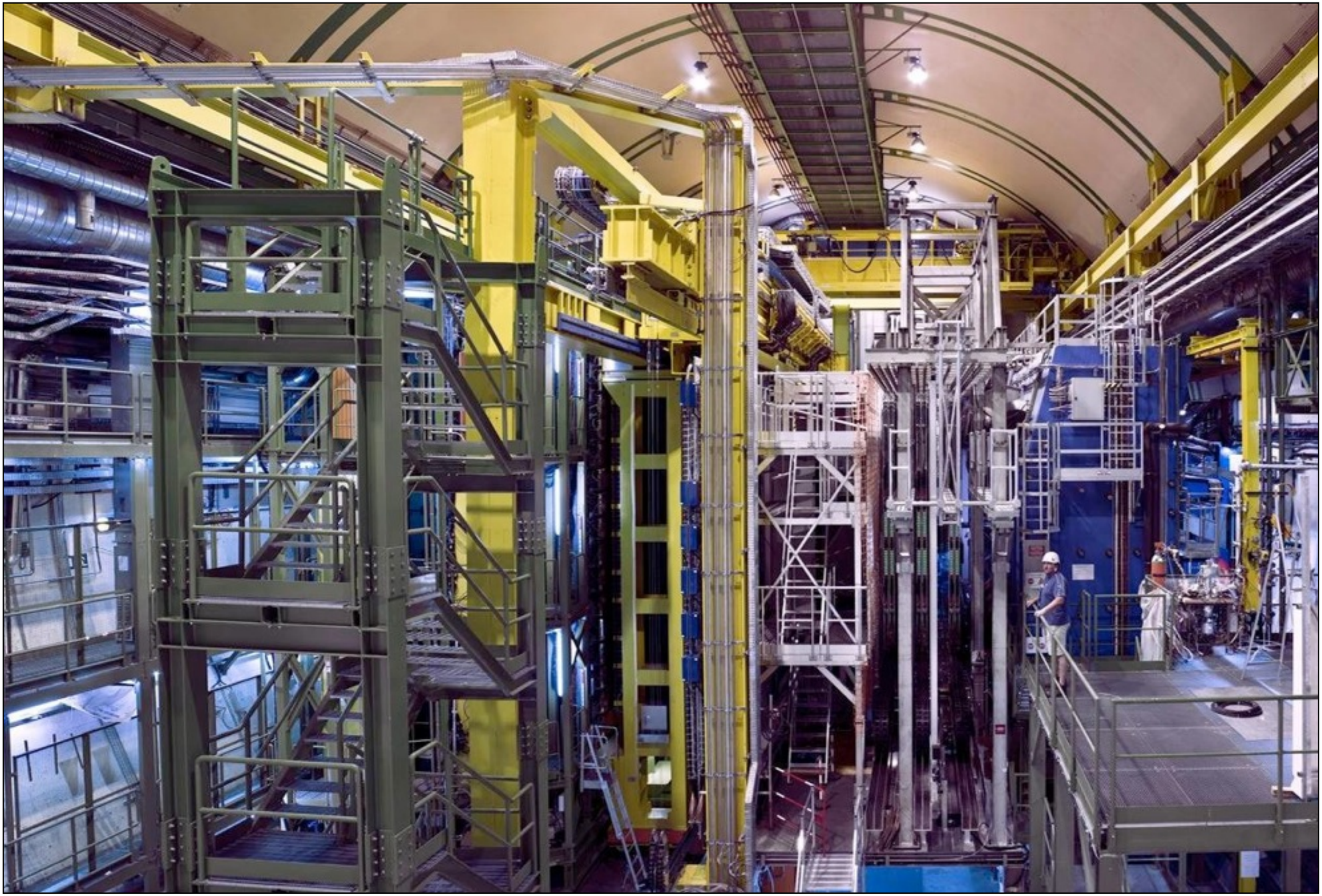
POINT 2
SPS
SECTOR 78
ALICE
SECTOR 12
SECTOR 81
POINT 8
LHCb
ATLAS

What is LHCb?



What physics are we trying to do?

We want to find New Physics beyond the Standard Model

Direct searches

Get/make particles on-mass-shell.
Detect them directly.
Colliders need $\int L$ and $\sqrt{s}$.

Indirect searches

Look for subtle deviations from SM due to new, often heavy virtual particles.
Constrain or detect NP.

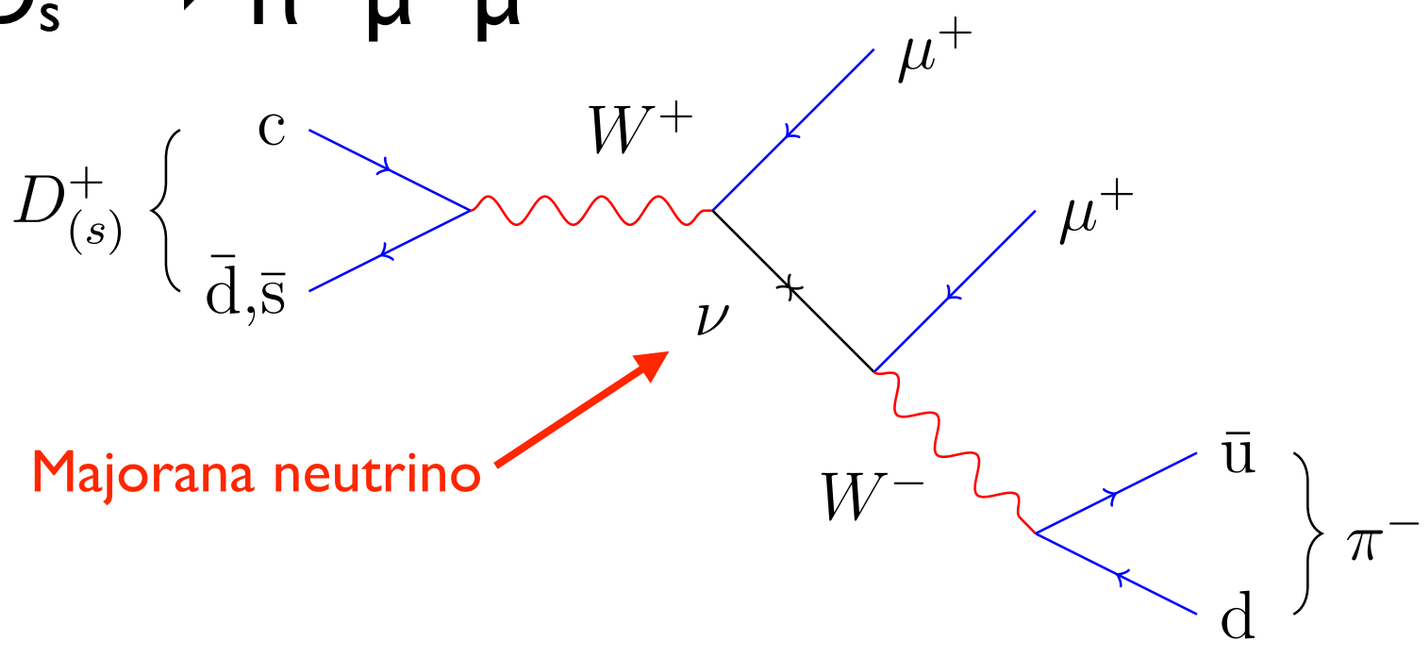
We do other physics too! An example later.

Indirect searches

Some processes are forbidden in SM but allowed with NP.

Example: $D_s^+ \to \pi^- \mu^+ \mu^+$

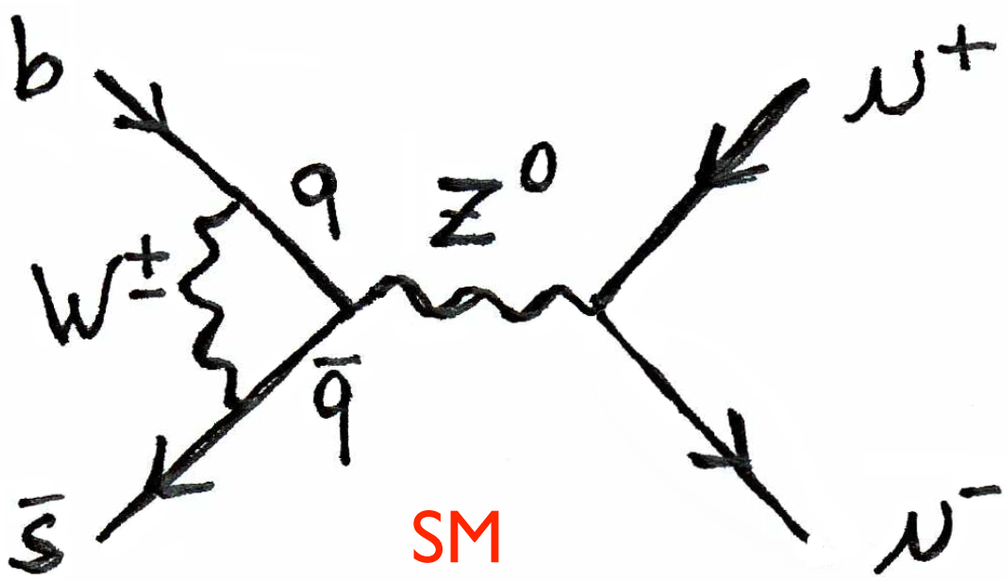
PLB 724 (2013) 203

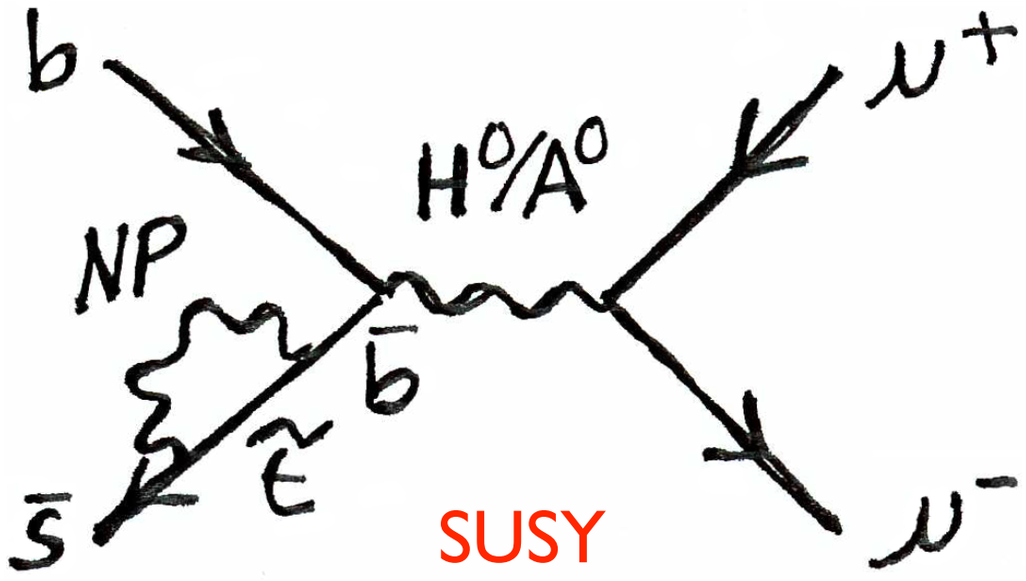


Some are allowed in SM but could have a contribution from NP.

Example: $B_s^0 \to \mu^+ \mu^-$

PRL 111, 101805 (2013)





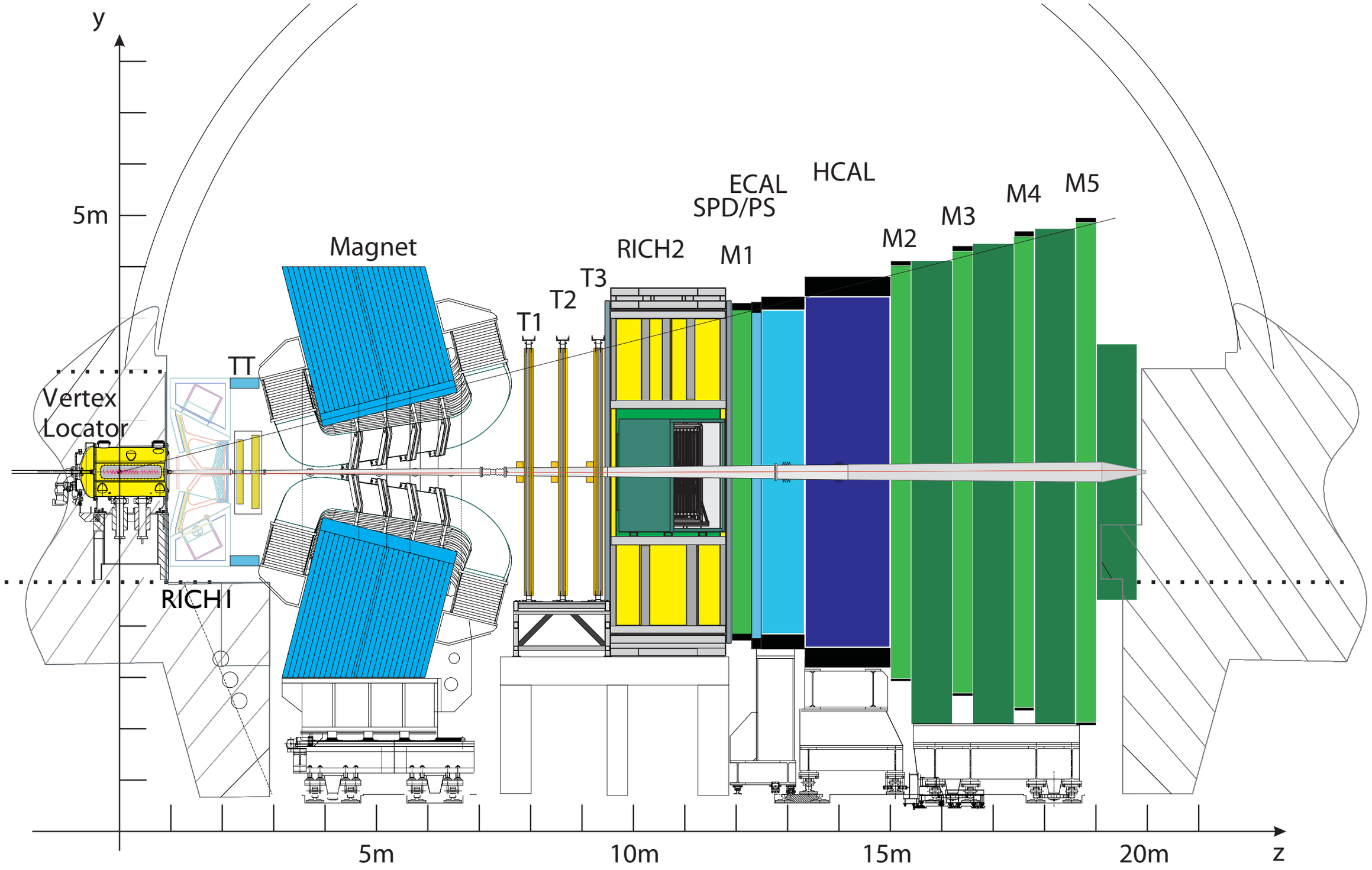
What makes a good search?

- SM prediction is precise
- Potential NP contribution is big enough to see
  - large compared to SM uncertainties
  - large compared to experimental uncertainties
- Null result can be turned into limits on NP parameters

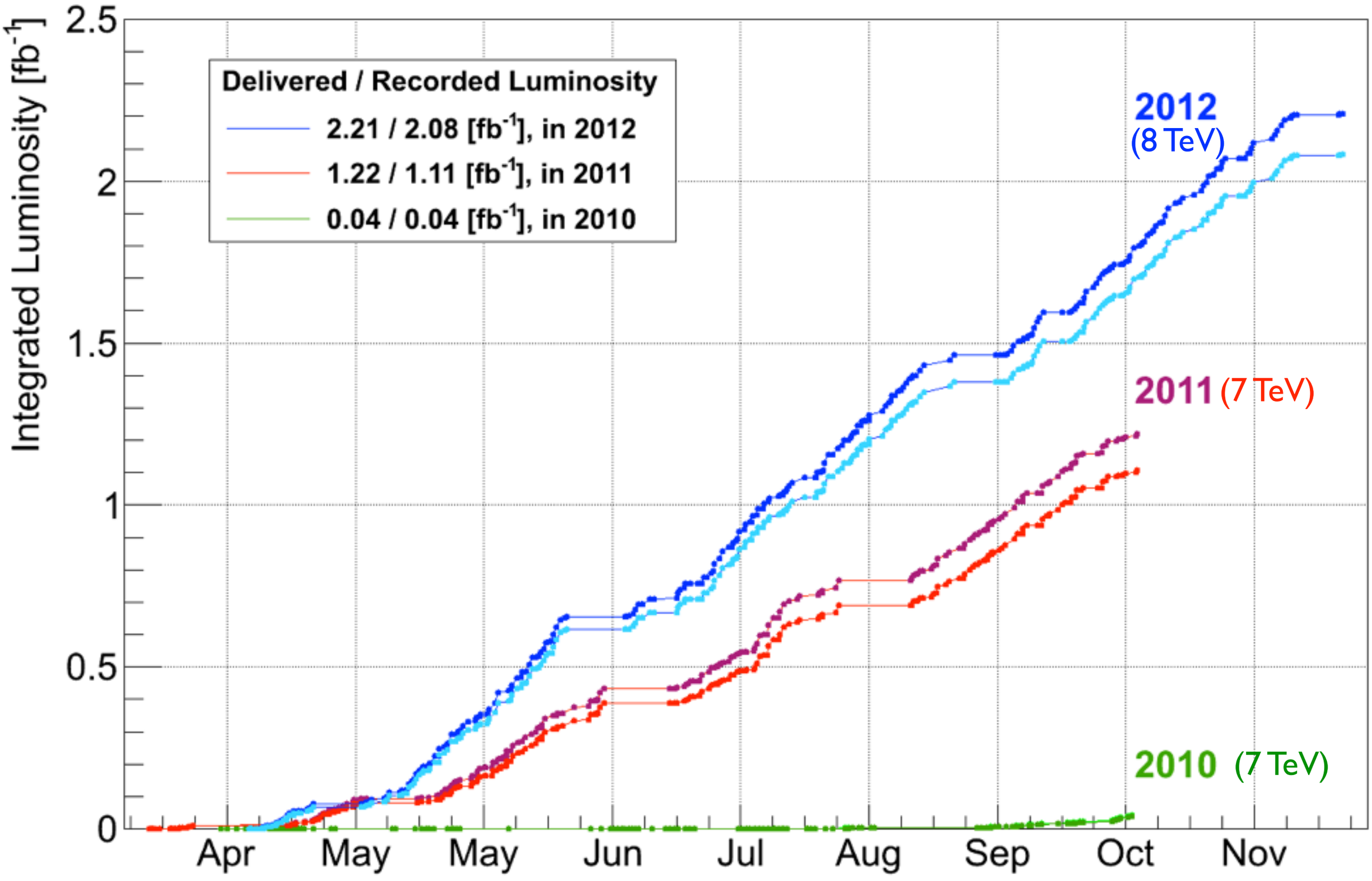
What do we need?

- Lots and lots of decays via loop diagrams
  - → heavy flavour decays
  - → at the LHC where $\sigma(b\bar{b})$ and $\sigma(c\bar{c})$ are huge
  - → in the corner of phase space where most b- and c-hadrons go
- Ability to identify the rare, interesting processes against a background of lots of similar-looking SM decays
  - → particle identification -- muons and hadrons
  - → momentum resolution, to separate peaks and improve S/B
  - → decay time resolution, for time-dependent effects
- A very clever trigger to pick out good events in real time
  - → non-empty bunch crossings at 15 MHz in 2012, even more soon
  - → in 2012, ccbar events in our acceptance: 500 kHz
  - → disk space to write out events at about 5 kHz

The LHCb detector



The LHCb data



Recent and/or interesting results

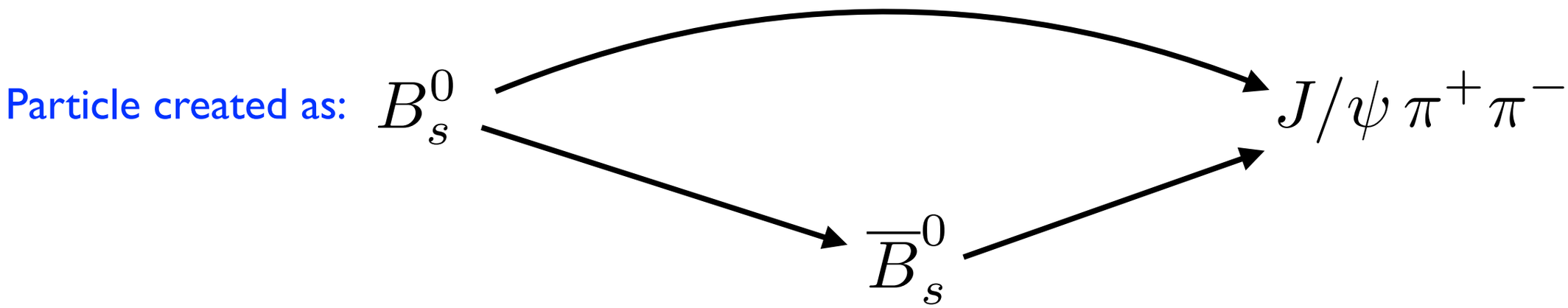
- Search for CPV in B — LHCb-PAPER-2014-019
- The Z(4430) — PRL 112, 222002 (2014)

Snapshot: latest public results from LHCb website:

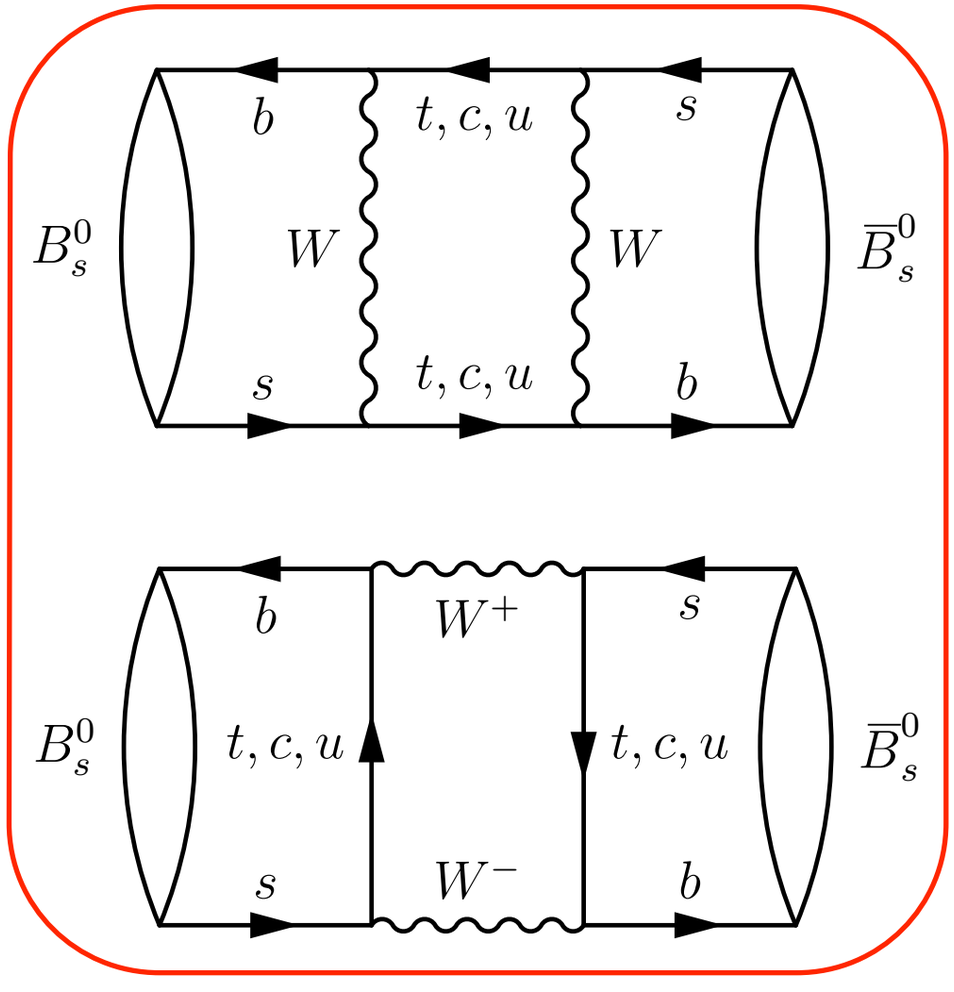
LHCb Papers

N°	Title	Journal	Code	Submit Date	Lead Group
200	Measurement of CP asymmetry in $B_s^0 \to D_s^{\mp} K^{\pm}$ decays	Submitted	LHCB-PAPER-2014-038	25 07 2014	
199	Measurement of CP violation and constraints on the CKM angle γ in $B^{\pm} \to DK^{\pm}$ with $D \to K_S^0 \pi^+ \pi^-$ decays		LHCB-PAPER-2014-017	25 07 2014	
198	Evidence of CP violation in $B^+ \to p\bar{p}K^+$ decays		LHCB-PAPER-2014-034	22 07 2014	
197	Measurement of CP violation in $B_s^0 \to \phi\phi$ decays		LHCB-PAPER-2014-026	08 07 2014	
196	Measurement of the ratio of B_c^+ branching fractions to		LHCB-PAPER-	25 07 2014	

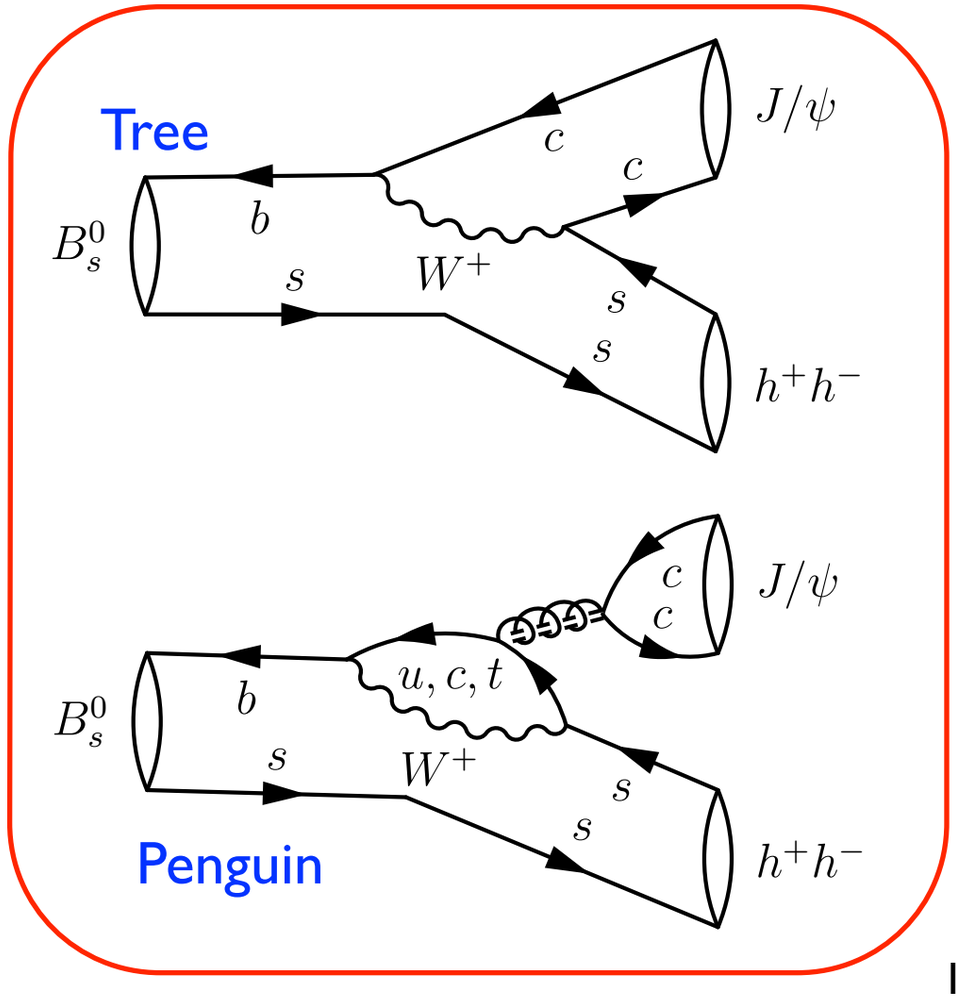
$B_s^0 \to J/\psi\,\pi^+\pi^-$



mixing diagrams



decay diagrams



$B_s^0 \to J/\psi\, \pi^+ \pi^-$

Q: What is CP violation?

A: Decay rate for a process and its CP conjugate process differ.

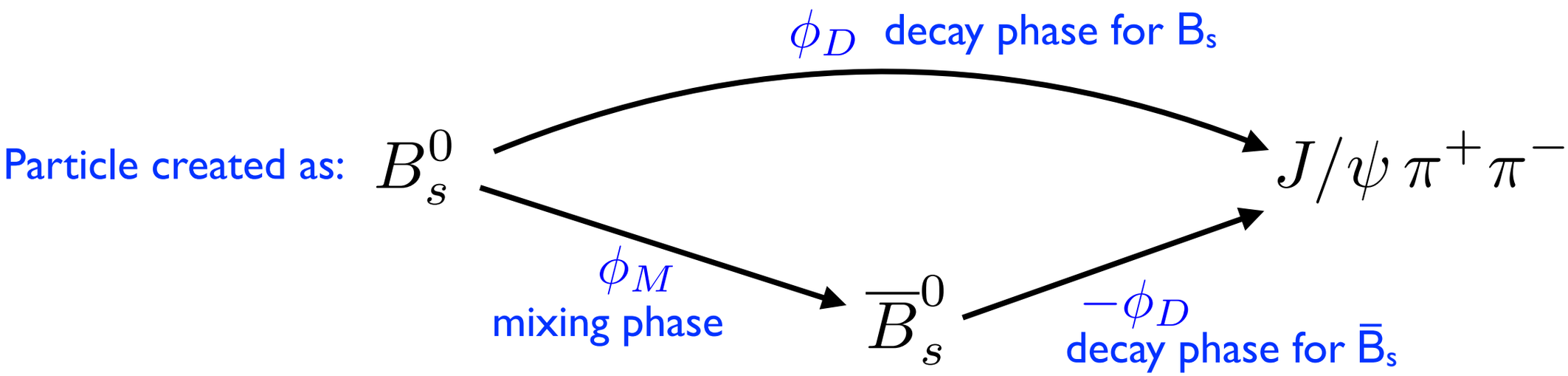
Several related mechanisms:

- When mixing is unbalanced (more $B \to \bar{B}$ than $\bar{B} \to B$, or vice versa)
- From interference between mixed and unmixed decays
- From interference between two decay diagrams (direct CPV)

First two kinds are mixing-induced (indirect) and generate a time-dependent asymmetry.

LHCb-PAPER-2014-019

$B_s^0 \to J/\psi\,\pi^+\pi^-$



Phase for upper path: [const] + ϕ_D

Phase for lower path: [const] + $\phi_M - \phi_D$

=> Phase difference: $\phi_s = \phi_M - 2\phi_D$

SM expectation: $\phi_D \approx 0$ and

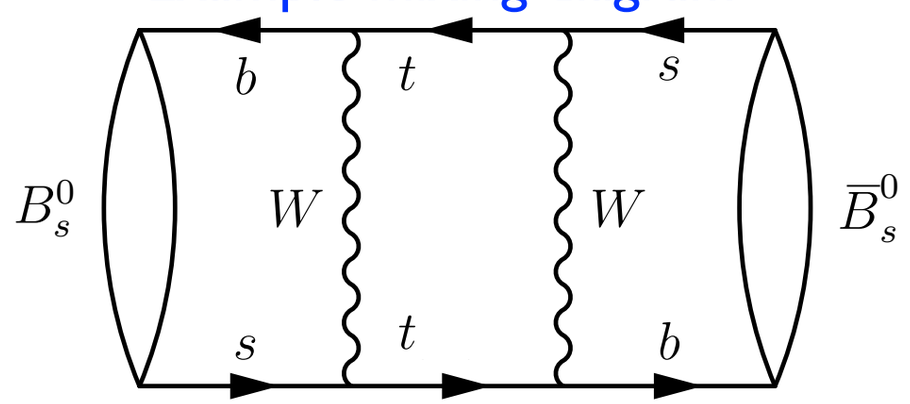
$\phi_M = -2\ \arg(V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx -0.04$

i.e. $\phi_{s,SM} \approx -0.04$ CKMFitter: PRD84 (2011) 033005

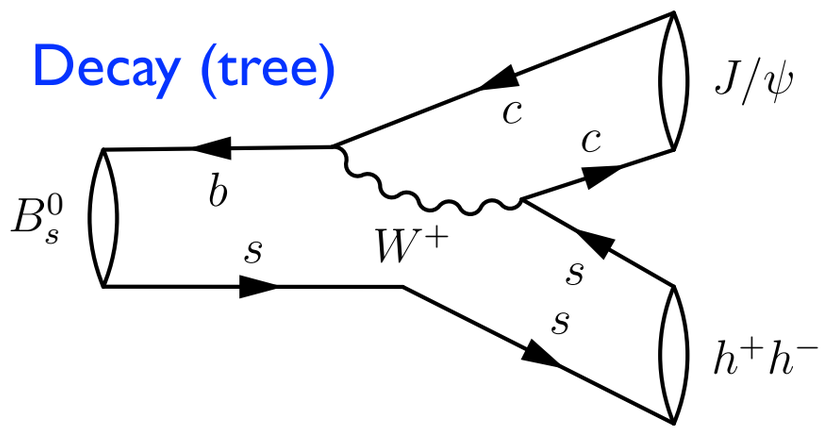
NP phase large? $\phi_s = \phi_{s,SM} + \phi_{s,NP}$

Dunietz et al: PRD 63 (2001) 114015

Example mixing diagram



Decay (tree)



LHCb-PAPER-2014-019

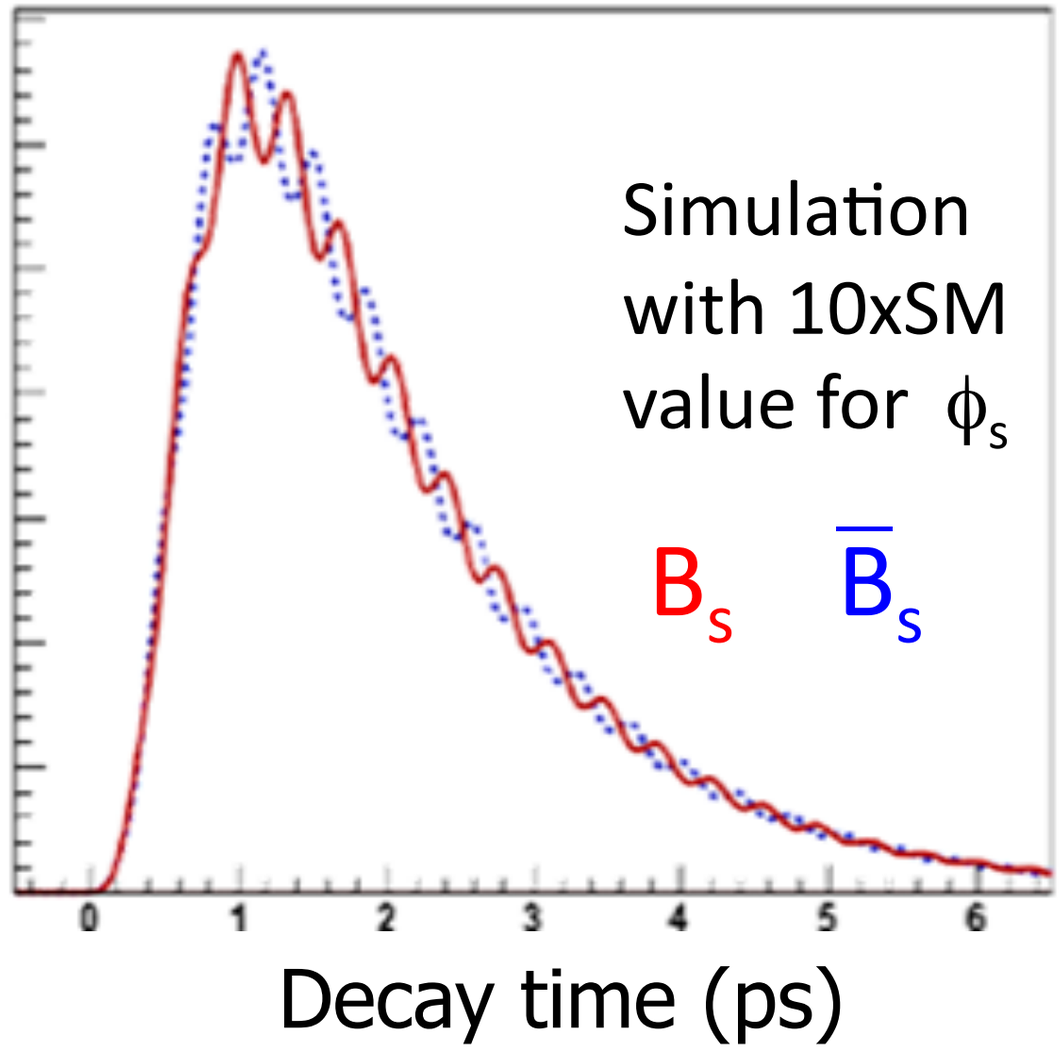
$B_s^0 \to J/\psi\, \pi^+ \pi^-$

Final state has both CP-even and CP-odd components.
Full fit used in the paper includes both. But it's >97% CP-odd, and in the limit that it's pure CP-odd the decay rate simplifies to:

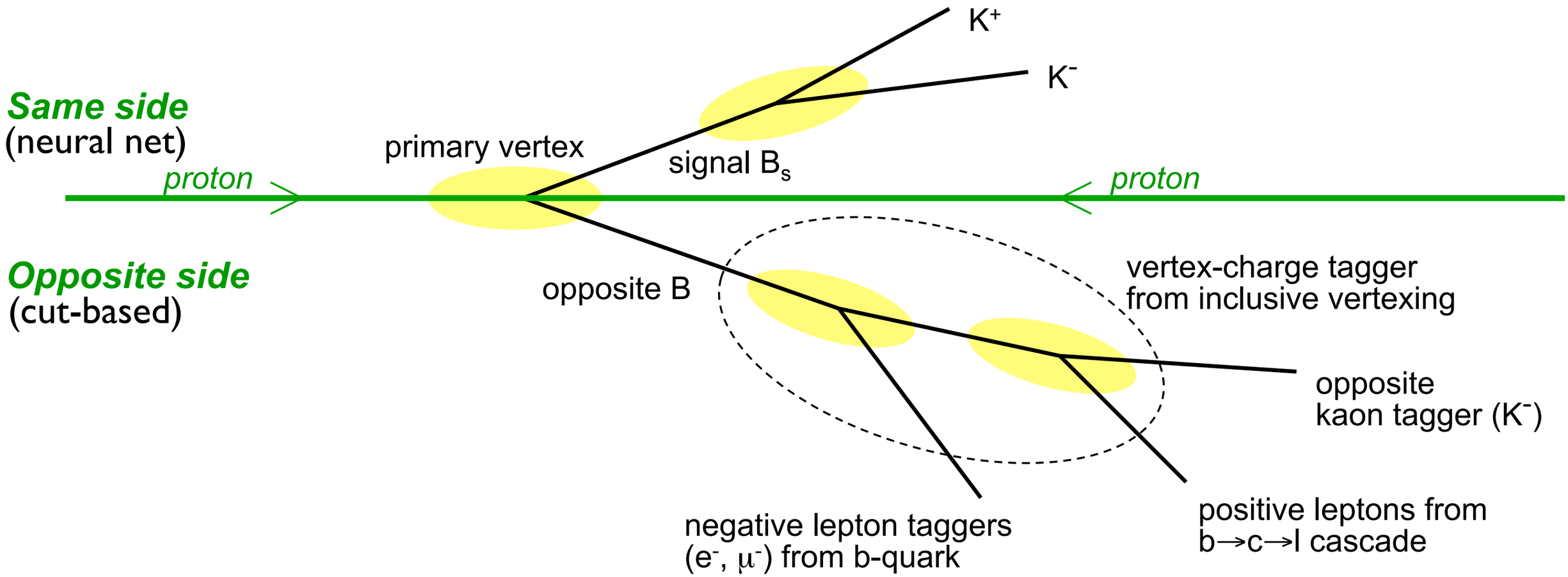
$$\Gamma\left(\overline{(}B_s^0 \to f_-\right) = \mathcal{N} e^{-\Gamma_s t}\left\{\frac{e^{\Delta\Gamma_s t/2}}{2}(1+\cos\phi_s) + \frac{e^{-\Delta\Gamma_s t/2}}{2}(1-\cos\phi_s) \pm \sin\phi_s \sin\left(\Delta m_s\, t\right)\right\}$$

Signature for CPV: oscillation with frequency Δm_s and opposite sign for B_s and $\overline{B}_s$.

To see it we need to:
(1) tag the initial state (B_s or $\overline{B}_s$?)
(2) resolve the oscillations



$B_s^0 \to J/\psi\, \pi^+ \pi^-$: tagging

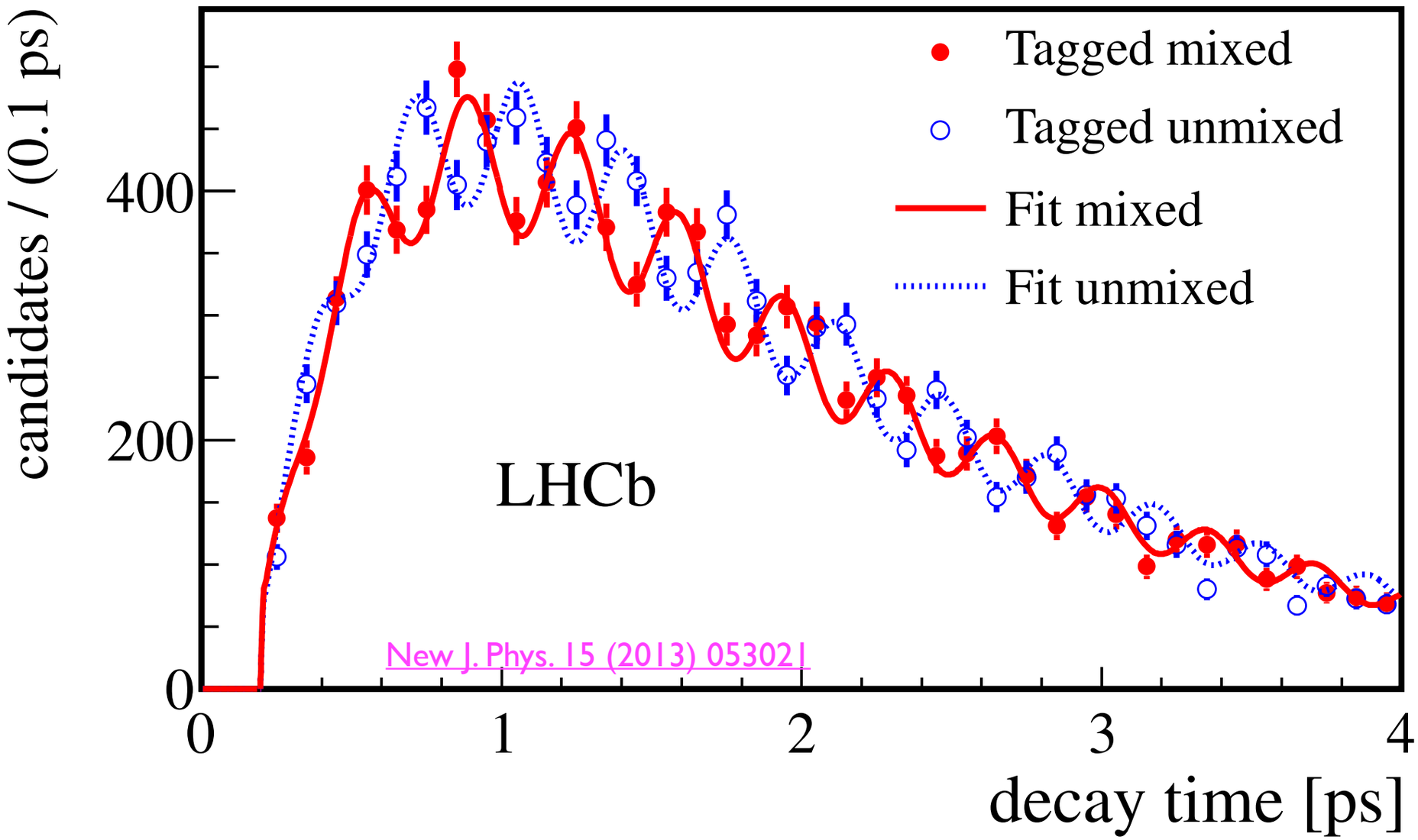


Tagging power: $\varepsilon_{tag}(1-2w_{tag})^2 = 3.9\%$ for $J/\psi\, \pi^+ \pi^-$

LHCb-PAPER-2014-019

$B_s^0 \to J/\psi\, \pi^+\, \pi^-$: resolution

From another LHCb analysis measuring Δm_s with $B_s^0 \to D_s^- \pi^+$:



$$\Delta m_s = 17.768 \pm 0.023\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1}$$

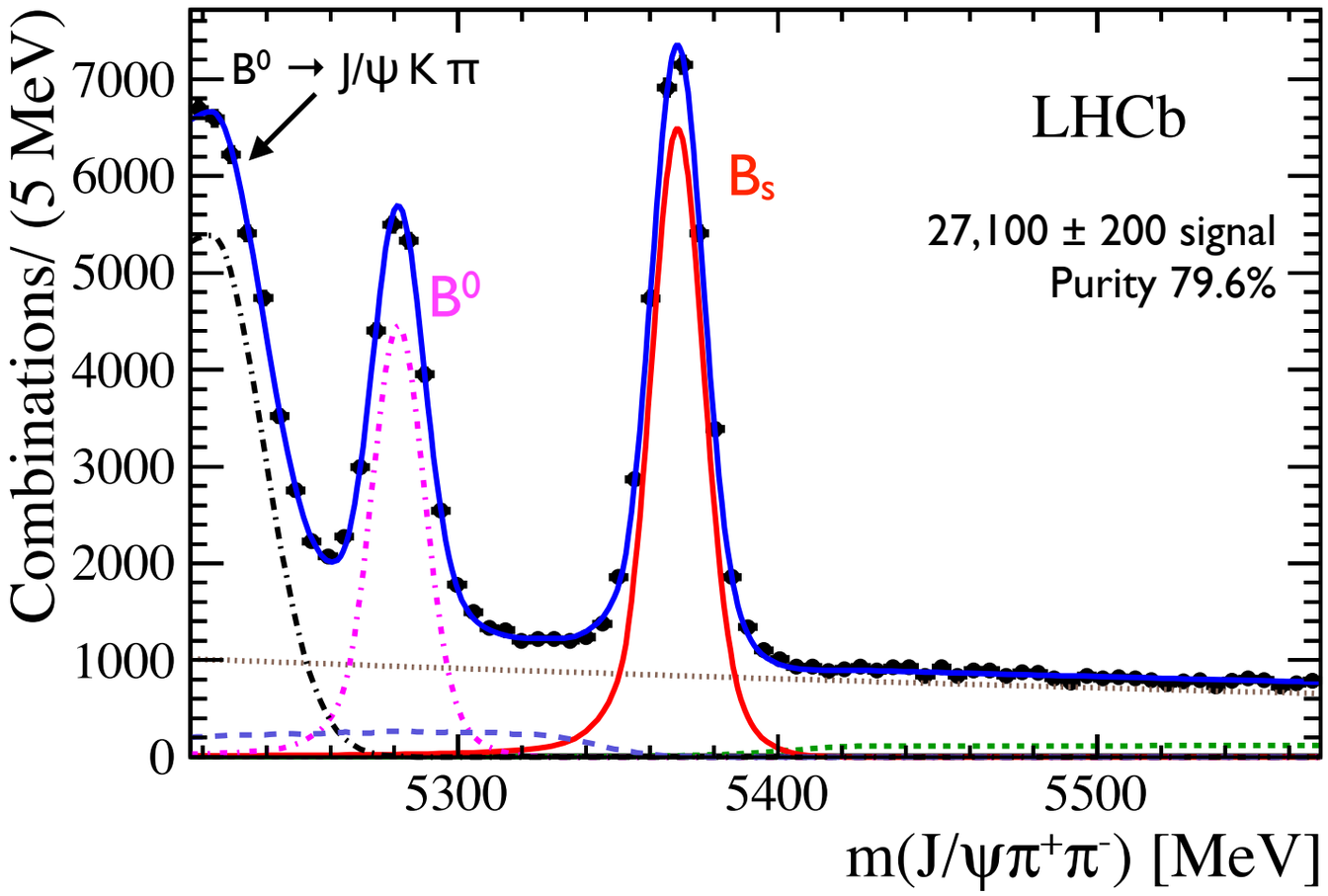
Oscillation period = $2\pi/\Delta m_s$ = 354 fs » avg resolution = 40.3 fs

(mean lifetime: 1516 ± 11 fs)

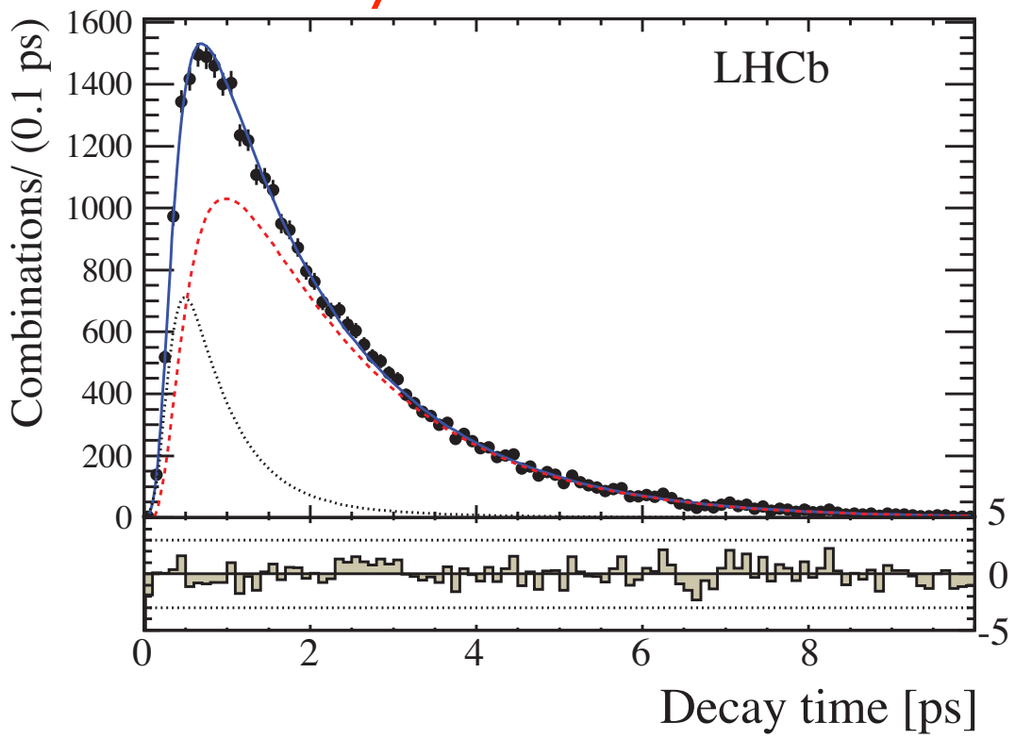
(for $J/\psi\, \pi^+\, \pi^-$)

LHCb-PAPER-2014-019

$B_s^0 \to J/\psi\,\pi^+\pi^-$: the data



Decay time distribution

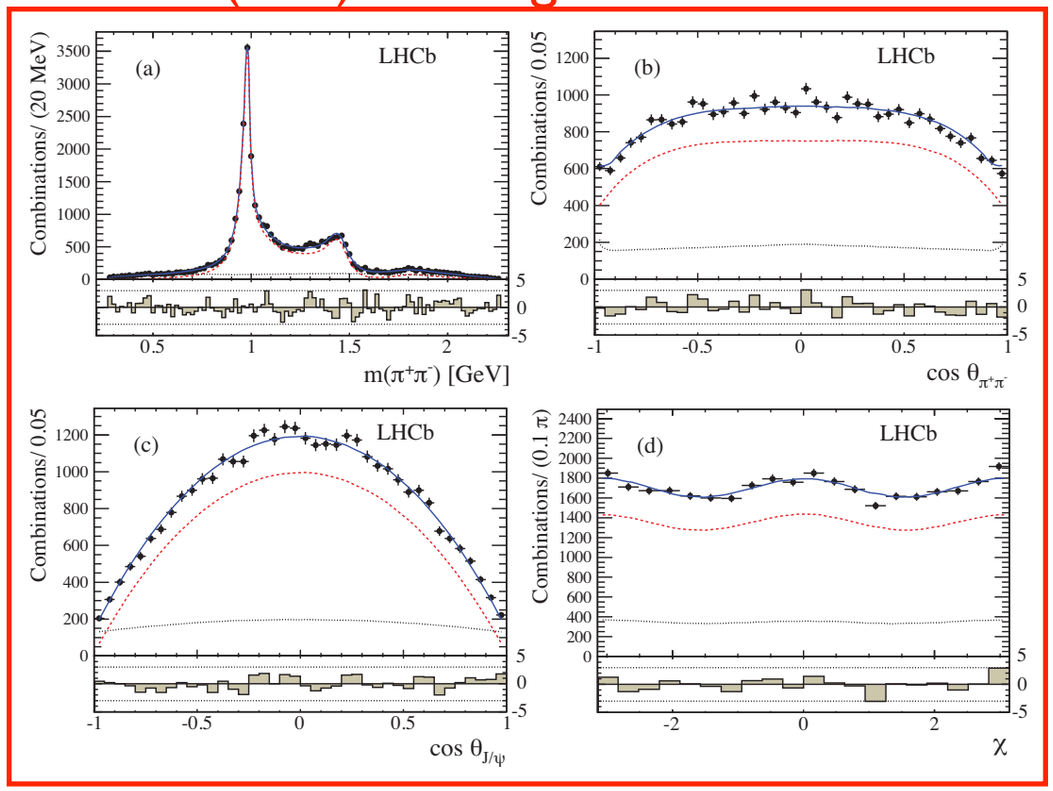


Previous angular analysis of the ππ structure used as input.

Amplitudes & phases of components (J/ψ f etc) floated.

PRD 90, 012003 (2014)

m(ππ) and angular variables



LHCb-PAPER-2014-019

$B_s^0 \to J/\psi\, \pi^+ \pi^-$

Resolve oscillations

Tagging

BDT selection

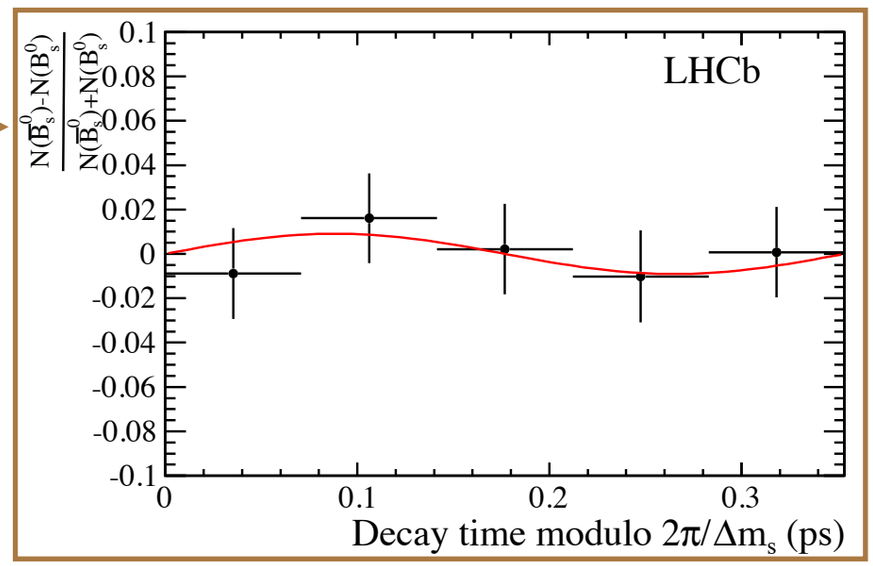
Trigger on muons
$J/\psi \to \mu^+ \mu^-$

Full angular analysis of ππ resonant & CP components as input
PRD 90, 012003 (2014)

Γ_s, $\Delta\Gamma_s$, Δm_s as inputs (Gaussian-constrained)
PRD 87, 112010 (2013)
New J. Phys. 15 (2013) 053021

Lifetime acceptance from $B^0 \to J/\psi\, K^{*0}$, corrected with MC

Likelihood fit to $m(J/\psi\, \pi^+ \pi^-)$, $m(\pi^+ \pi^-)$, tag, decay time, angles

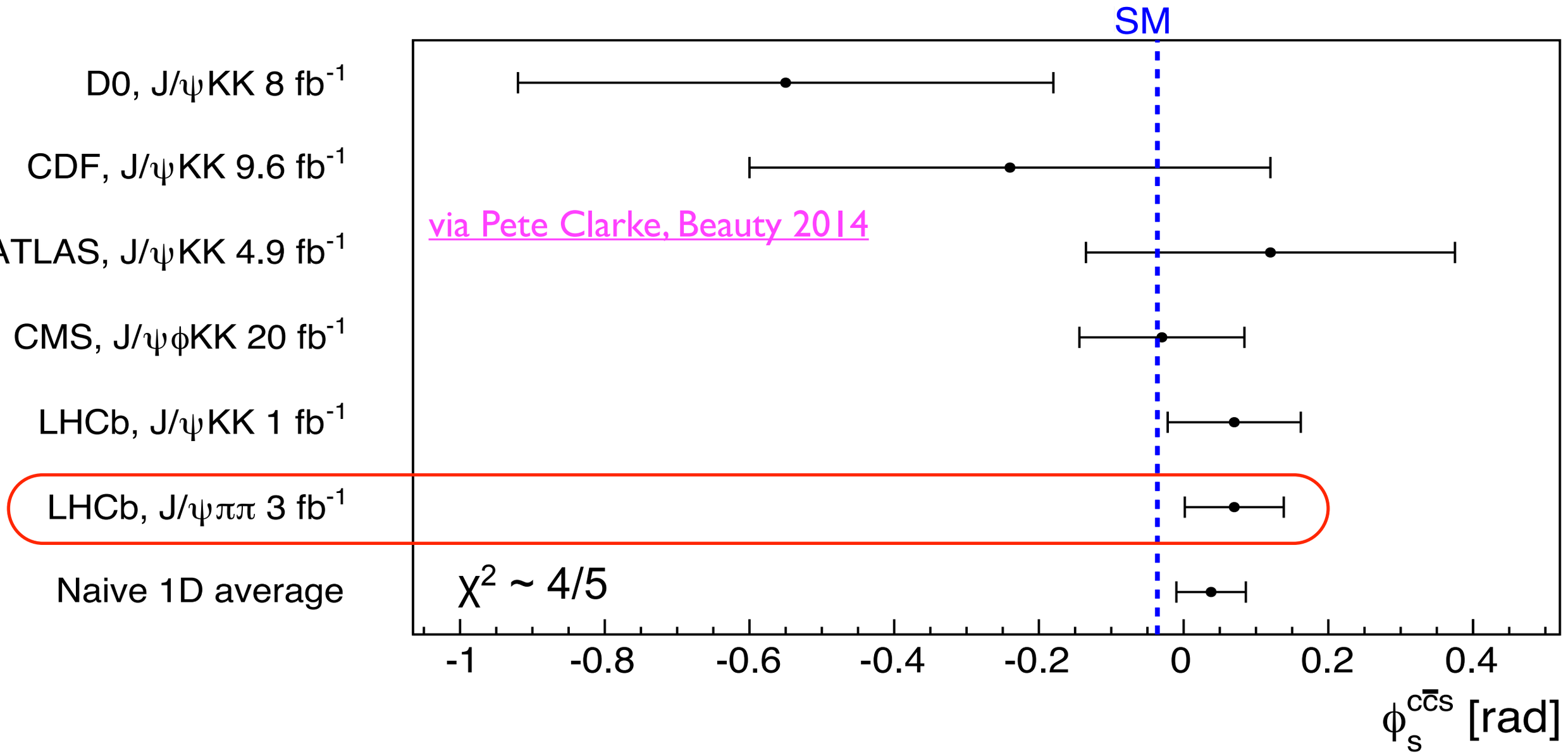


No CPV in mixing, decay: $\phi_s = 75 \pm 67 \pm 8$ mrad.

Allowing such CPV: $\phi_s = 70 \pm 68 \pm 8$ mrad, $|\lambda| = 0.89 \pm 0.05 \pm 0.01$.

LHCb-PAPER-2014-019

In context



via Pete Clarke, Beauty 2014

No sign of NP in this observable with current sensitivity.

$Z(4430)^-$

- 2007: Belle reports a structure in the $(\pi^\pm \psi')$ projection of $B^0 \to K^+ \pi^- \psi'$ & $B^+ \to K^0 \pi^+ \psi'$
- The $Z(4430)^- \to \pi^- \psi'$ would be an exotic meson
  - Minimum quark content is $c\bar{c}d\bar{u}$, i.e. can't be a regular $q\bar{q}$ state!
- 2008: BaBar data can be described without exotic mesons
  - i.e. does not confirm the Z^-, but doesn't formally exclude it either.
- 2009, 2013: Follow-on analyses from Belle.
- 2014: LHCb study of $B^0 \to K^+ \pi^- \psi', \psi' \to \mu^+ \mu^-$
  - includes model-independent test, not discussed here.

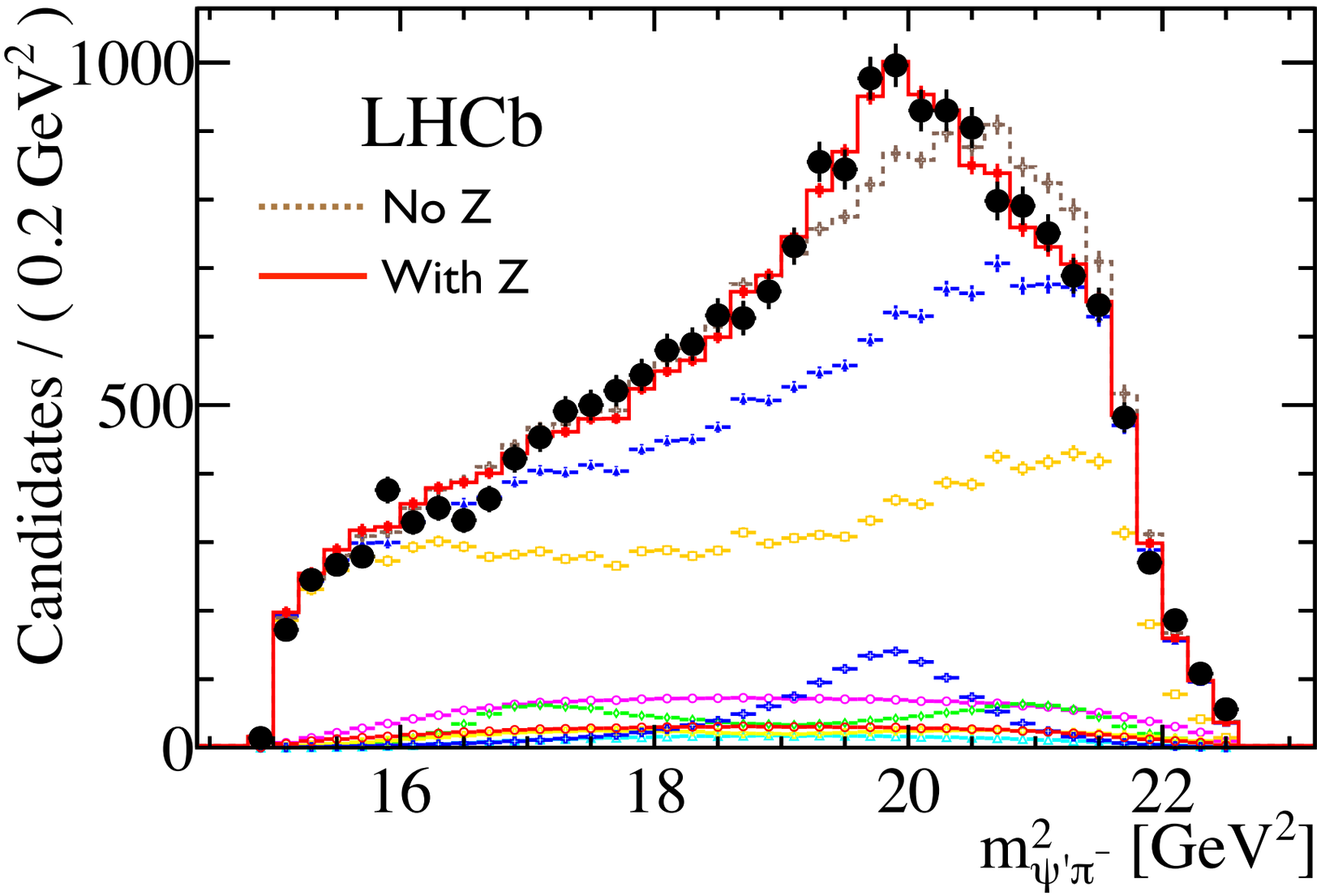
$\psi' = \psi(2S)$, m=3686 MeV/c^2

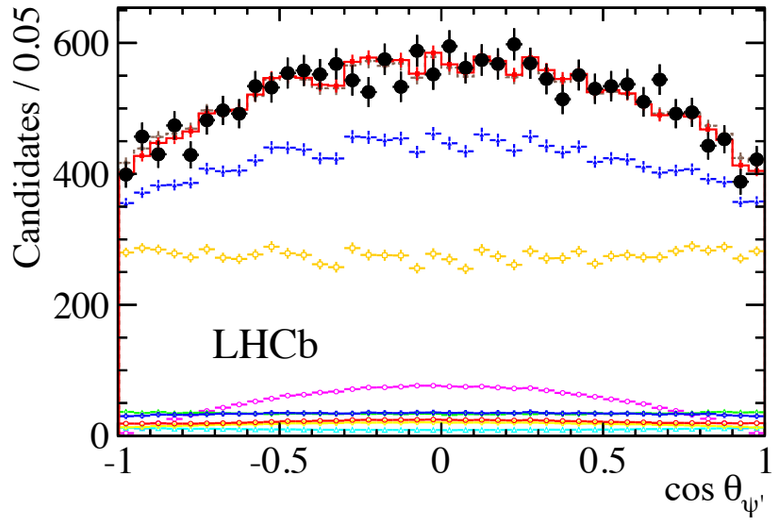
Belle: PRL 100:142001,2008, PRD 80:031104,2009, PRD 88, 074026 (2013) (approx 2k B signal)
BaBar: PRD 79:112001,2009 (approx 2.5k B signal in these modes)
LHCb: PRL 112, 222002 (2014) (approx 25k B signal)

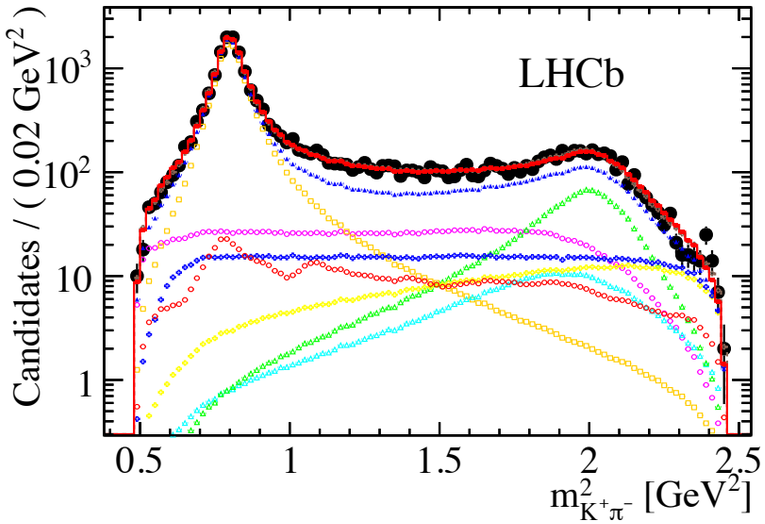
PRL 112, 222002 (2014)

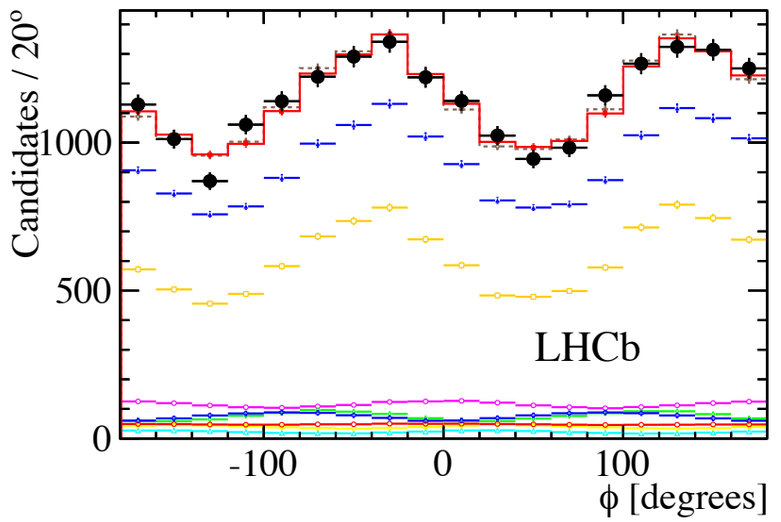
$Z(4430)^-$

- 4D amplitude analysis, like Belle.
- Model includes all known, accessible K^*
- 4D binned χ^2 => p-value < 2 x 10^{-6}
- Adding $Z(4430)^-$, p-value rises to 12%.









PRL 112, 222002 (2014)

$Z(4430)^-$

- In 4D, defining a binning for a χ^2 is tricky. Instead use one of:
  - Wilks' theorem: $-2\ln(L)$ follows a χ^2 distribution (under conditions)
  - Toy MC studies
- Reject no-Z hypothesis at > 10σ
- Spin-parity 1^+ favoured
  - Reject 0^-, 1^-, 2^+, 2^- at more than 9σ; 0^+ parity-forbidden

$$M_{Z_1^-} = 4475 \pm 7^{+15}_{-25}\ \mathrm{MeV}/c^2,\ \Gamma_{Z_1^-} = 172 \pm 13^{+37}_{-34}\ \mathrm{MeV}$$

- Hints of another Z with $J^P=0^-$, but resonant character not yet established. If real, it has:

$$M_{Z_0^-} = 4239 \pm 18^{+45}_{-10}\ \mathrm{MeV}/c^2,\ \Gamma_{Z_0^-} = 220 \pm 47^{+108}_{-74}\ \mathrm{MeV}$$

PRL 112, 222002 (2014)

$Z(4430)^-$

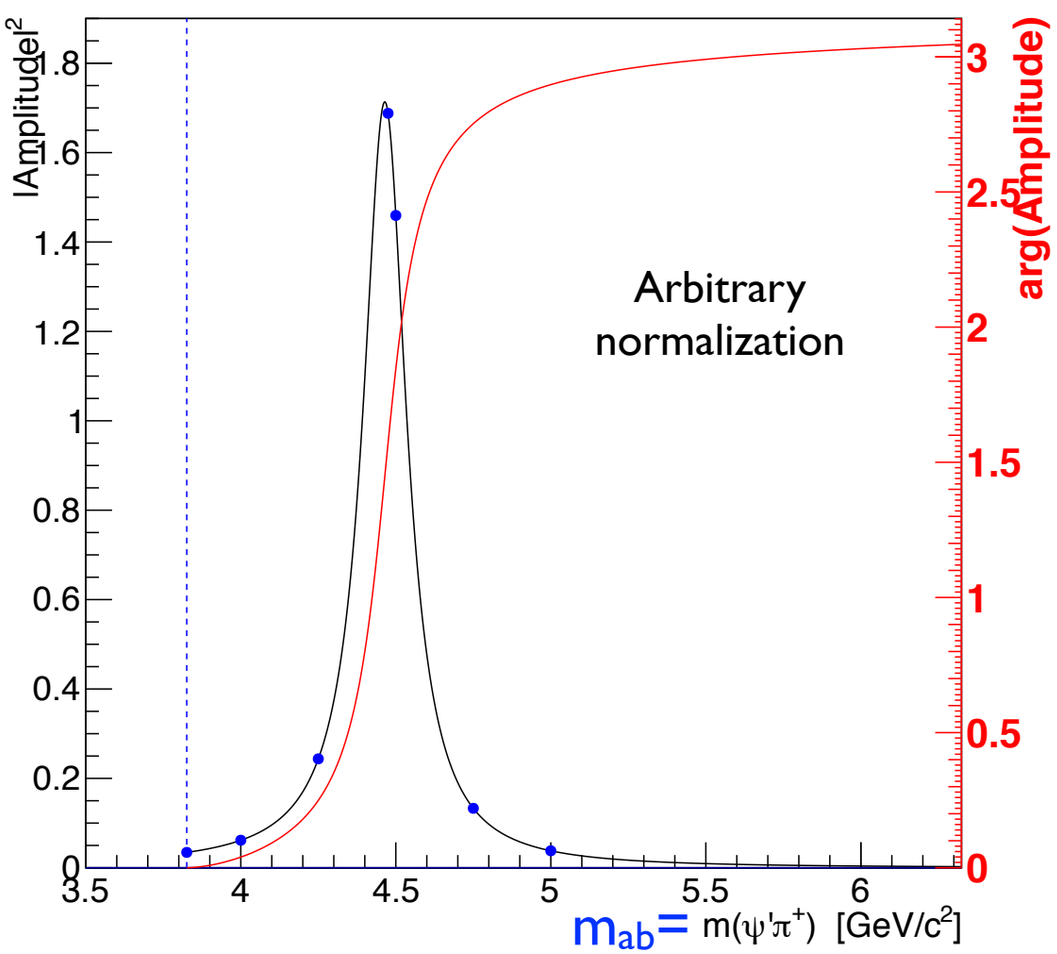
Looks good -- but how do we know it's a real resonance?

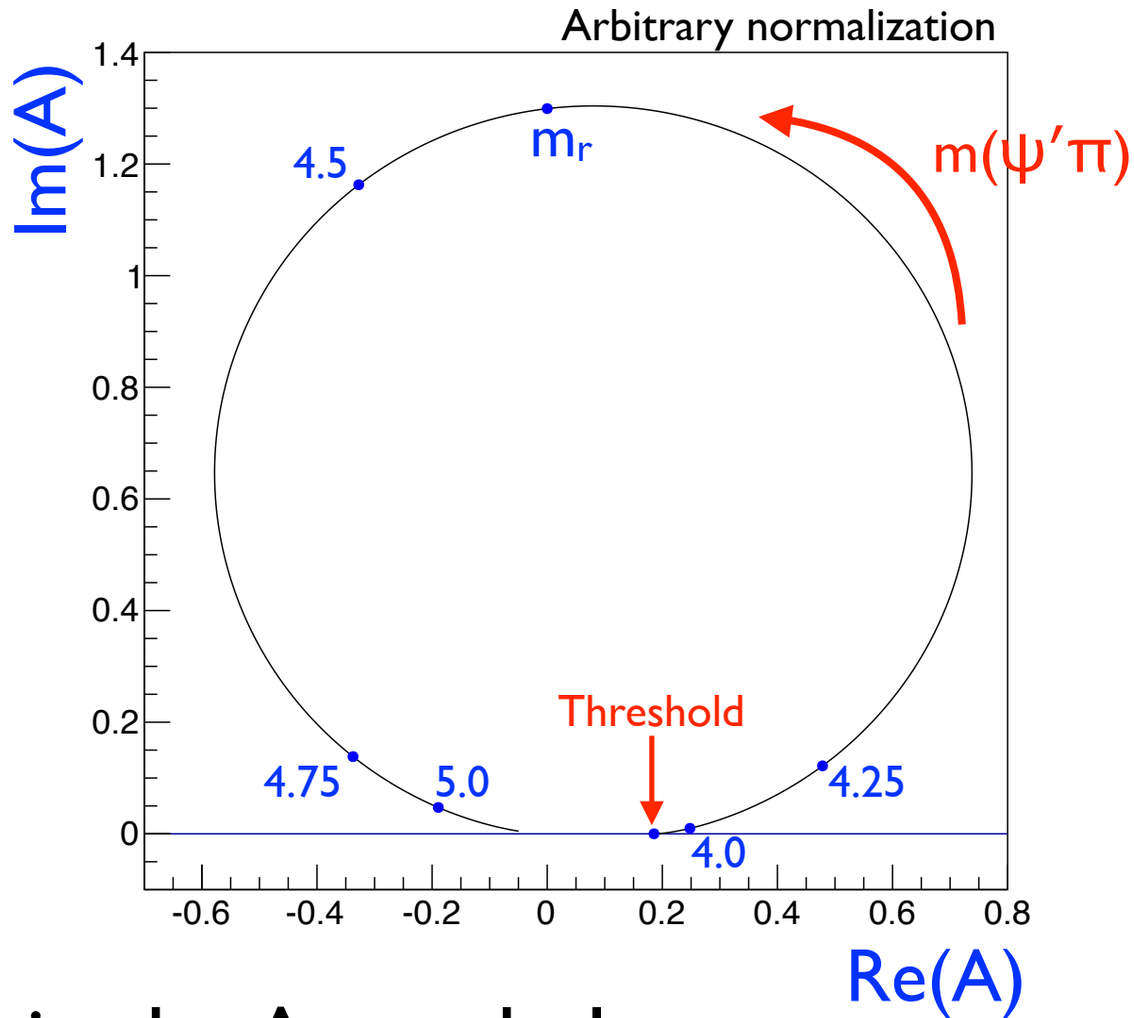
Breit-Wigner propagator:

$$T_r = \frac{1}{m_r^2 - m_{ab}^2 - i m_r \Gamma_{ab}}$$

$m_{ab} = m(\pi^- \psi')$
$m_r = m(Z)$

Magnitude and phase change as you move across resonance:





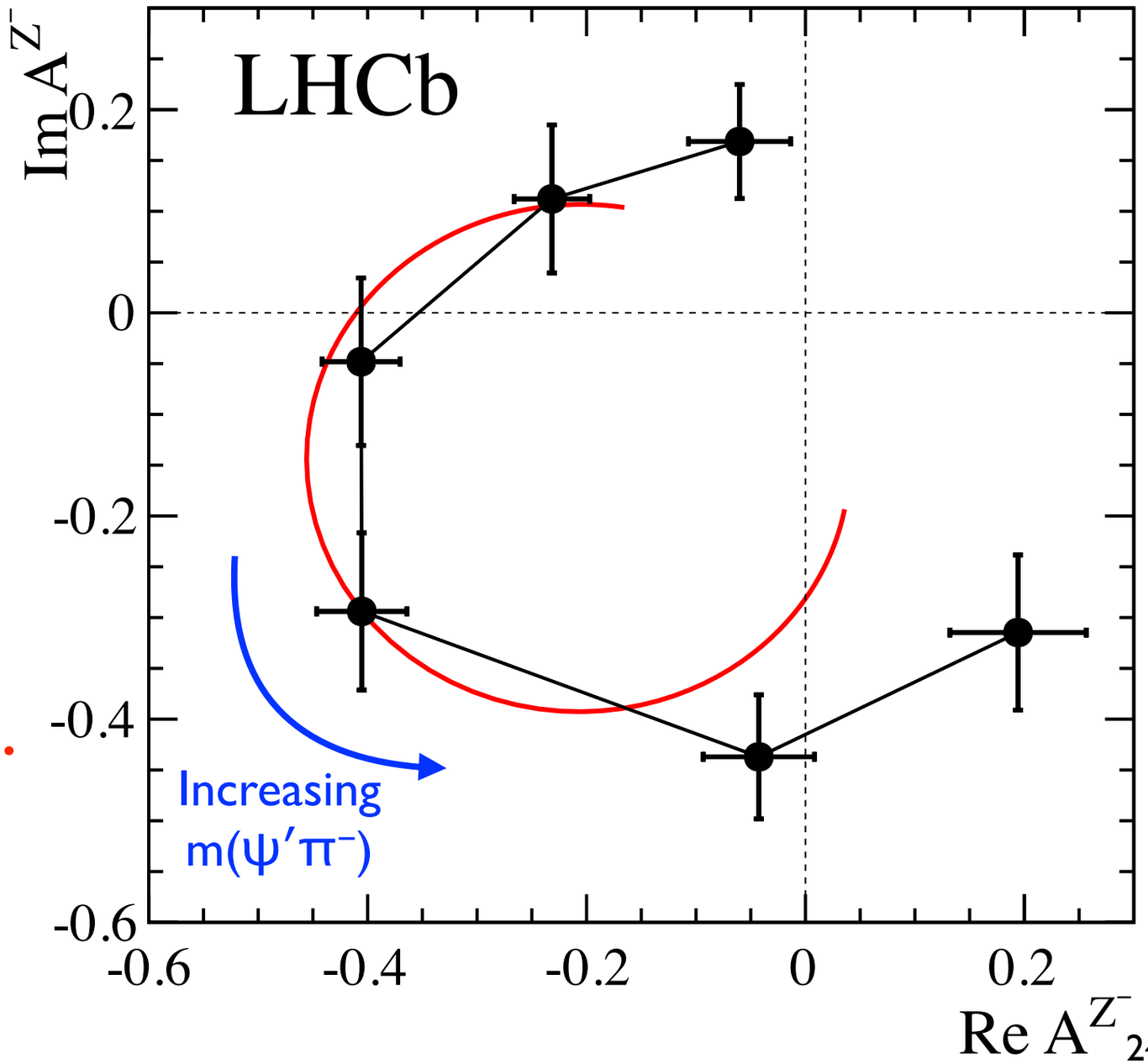
Not just a peak in mass, but a circle in the Argand plane.

PRL 112, 222002 (2014)

$Z(4430)^-$

- Amplitude fit describes Z as a Breit-Wigner. But...
- Can instead parameterise it as six independent complex amplitudes at six equidistant points in the peak range, 18.0-21.5 GeV^2/c^4.
- Plot real & imaginary parts:
- Classic unitarity circle behaviour for a resonance!
- Circle offset due to phase convention: $K^*(892)$ real.

This is a genuine exotic state!
Minimum quark content: $c\bar{c}d\bar{u}$.



Red curve: Scaled BW formula for $m=4475$ MeV/c^2, $\Gamma=176$ MeV.

What's next?

- Many analyses on Run 1 (3/fb) still in progress
  - ~~200~~ 201 papers and counting...
- Then: Run 2!
  - Beam to start Q1 2015
  - Data-taking to start Q2 2015 (probably slow ramp-up)
  - Expecting 5-7/fb at LHCb during Run 2
  - $\sqrt{s}$: increases from 8 TeV to ~ 13 TeV => $\sigma(c\bar{c})$ and $\sigma(b\bar{b})$ will ~ double.
- ... and then the upgrade (approx 2018-2019) in preparation for a 5x bump in luminosity.
- Lots to do!

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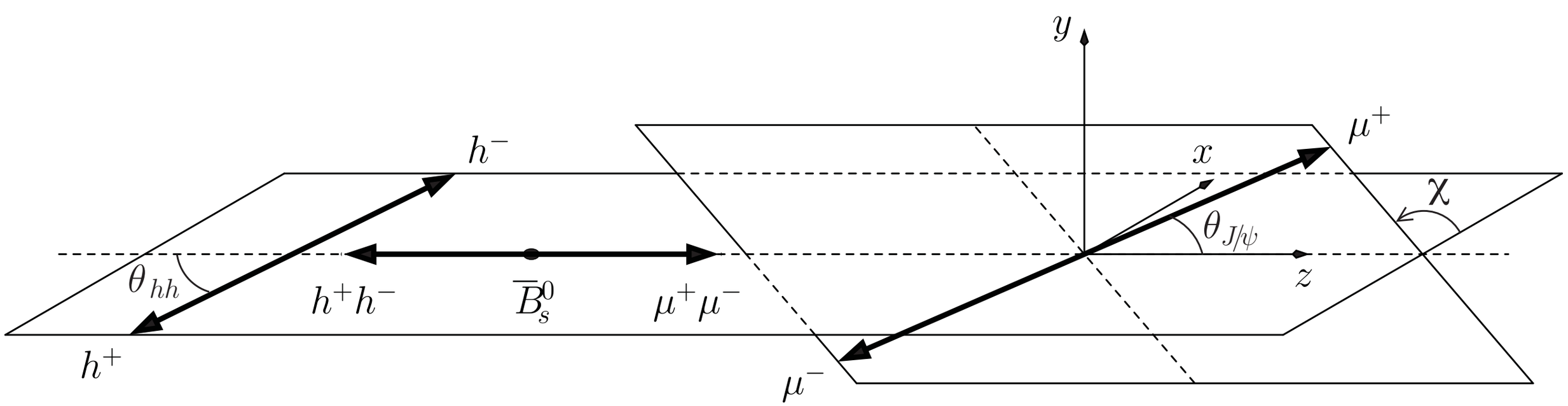
$B_s^0 \to J/\psi\,\pi^+\pi^-$: angles

the helicity basis. These consist of the angle between the μ^+ direction in the J/ψ rest frame with respect to the J/ψ direction in the $\overline{(B}{}_s^0)$ rest frame $\theta_{J/\psi}$, the angle between the h^+ direction in the h^+h^- rest frame with respect to the h^+h^- direction in the B_s^0 rest frame θ_{hh}, and the angle between the J/ψ and h^+h^- decay planes in the $\overline{B}{}_s^0$ rest frame χ [4, 9].



$B_s^0 \to J/\psi\,\pi^+\,\pi^-$: systematics

Table 2: Systematic uncertainties. The total is the sum in quadrature of each entry.

Sources	ϕ_s(mrad)	λ
Decay time acceptance	±0.6	±0.0008
Mass acceptance	±0.3	±0.0003
Background time PDF	±0.2	±0.0011
Background mass distribution PDF	±0.6	±0.0016
Resonance model	±6.0	±0.0100
Resonance parameters	±0.7	±0.0007
Other fixed parameters	±0.4	±0.0009
Production asymmetry	±5.8	±0.0017
Total	±8.4	±0.010

Including different resonances could change the *CP*-even fraction in the decay, and thus the ϕ_s result. In Ref. [10] two acceptable solutions were found for the contributing components. For our main result we use the one with five resonant components. The other solution adds a 5.9% nonresonant component. Evaluating ϕ_s for the second solution gives a small difference of 3 mrad. Adding a $\rho(770)$ component causes the largest change for ϕ_s and λ and is taken as the systematic uncertainty, even though vector particles must conserve the zero isospin of the dipion system, which forbids the decay into $\rho(770)$. The resonance masses and widths of $f_2(1270)$ and $f_2'(1525)$ are fixed in the fit.

The production ratio of B_s^0 to B_s^0 is estimated to be $R_{\rm P} = (1.00\pm0.05)$ [30]. To include this effect, the $\overline{B}{}_s^0$ decay rate, $\bar{\Gamma}$, used in Eq. (4) is multiplied by $R_{\rm P}$. The uncertainty due to this source is estimated by varying $R_{\rm P}$ within its error. The uncertainties are added in

$Z(4430)^-$

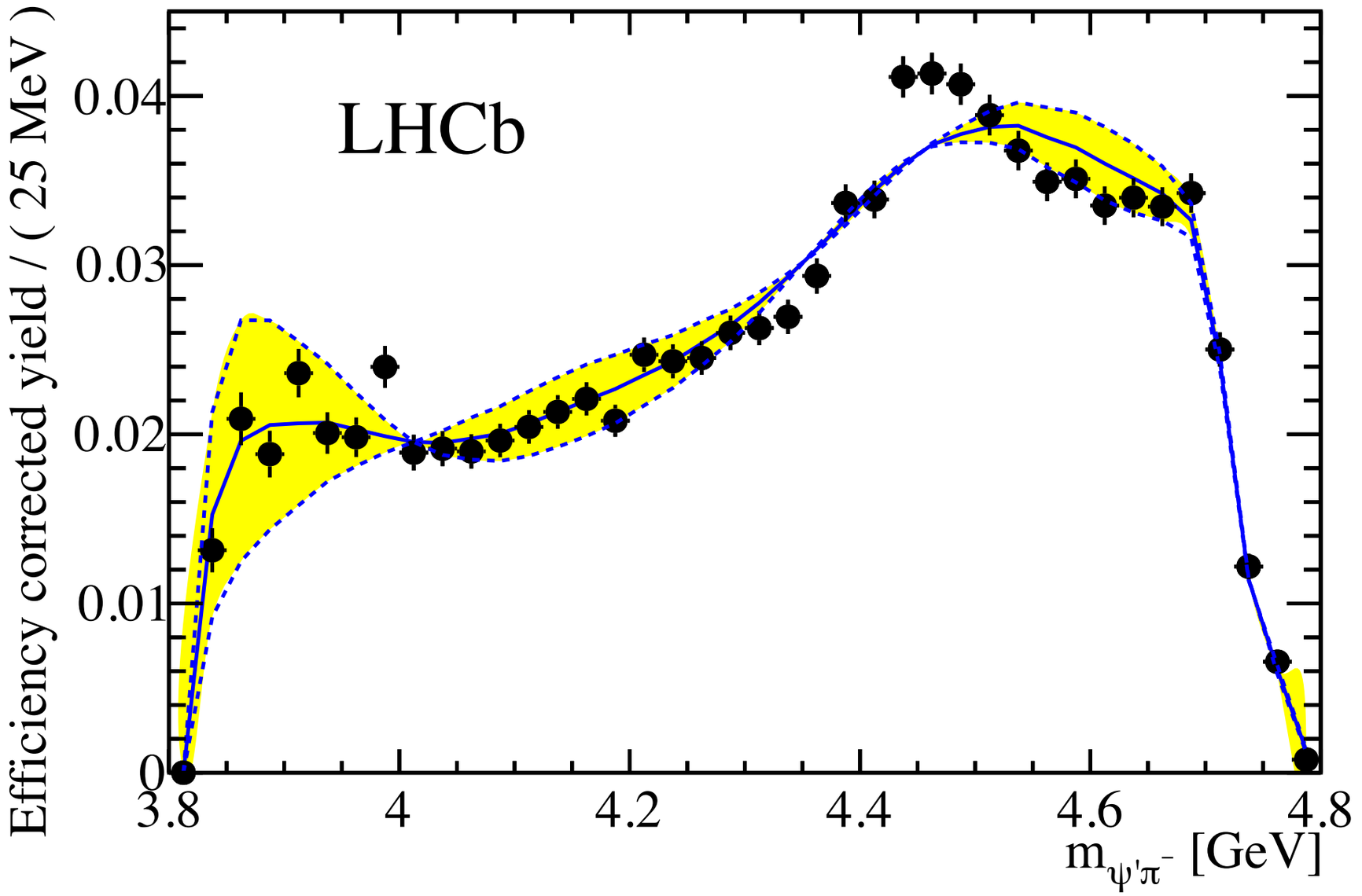
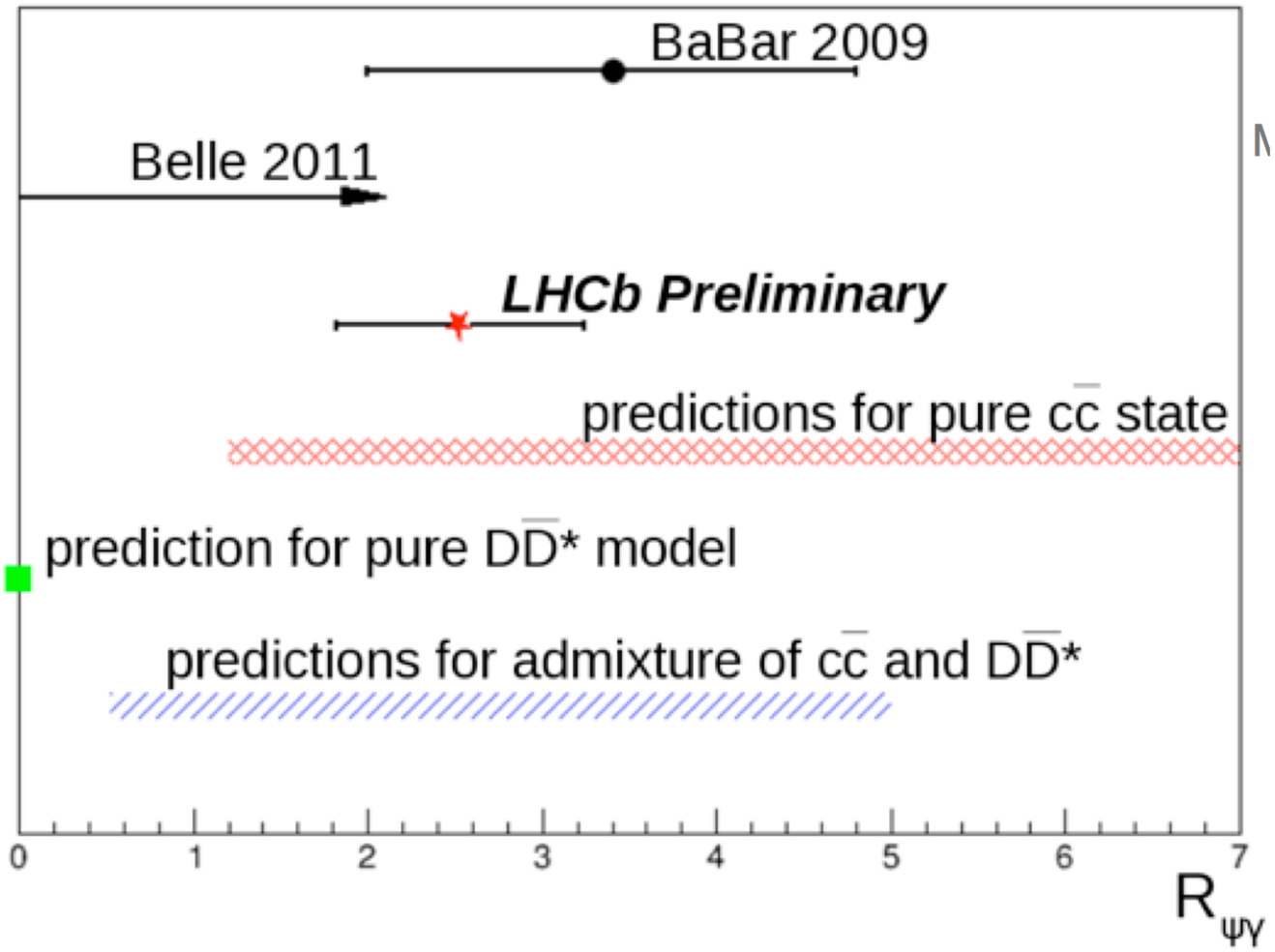


Figure 1: Background-subtracted and efficiency-corrected $m_{\psi'\pi-}$ distribution (black data points), superimposed with the reflections of $\cos\theta_{K^*}$ moments up to order four allowing for $J(K^*) \leq 2$ (blue line) and their correlated statistical uncertainty (yellow band bounded by blue dashed lines). The distributions have been normalized to unity.

Exotics : X(3872) nature/2

arXiv:1404.0275
7+8 TeV / 3 fb^{-1}



X→Ψ'γ confirmed

$R_{\psi\gamma}$ = Br(X→Ψ'γ)/Br(X→J/Ψγ) = 2.46 ± 0.64 (stat.) ± 0.29 (syst.)

DD̄* molecule ruled out

Via P. Ghez, BEACH 2014.