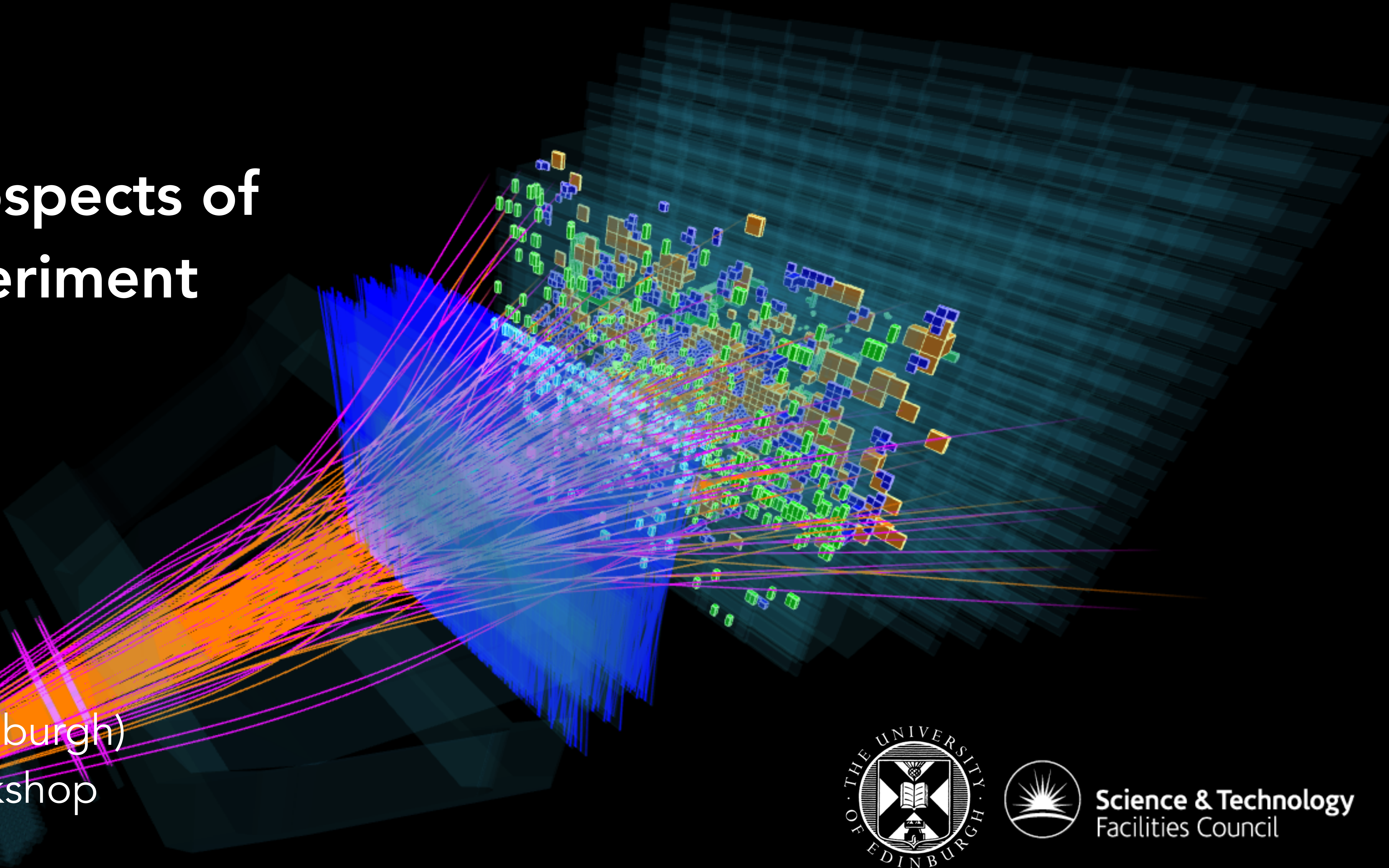


Status and prospects of the LHCb experiment

The *b* quark @ 40

@GreigCowan (Edinburgh)
Higgs-Maxwell workshop
8th February 2017

The LHCb collaboration

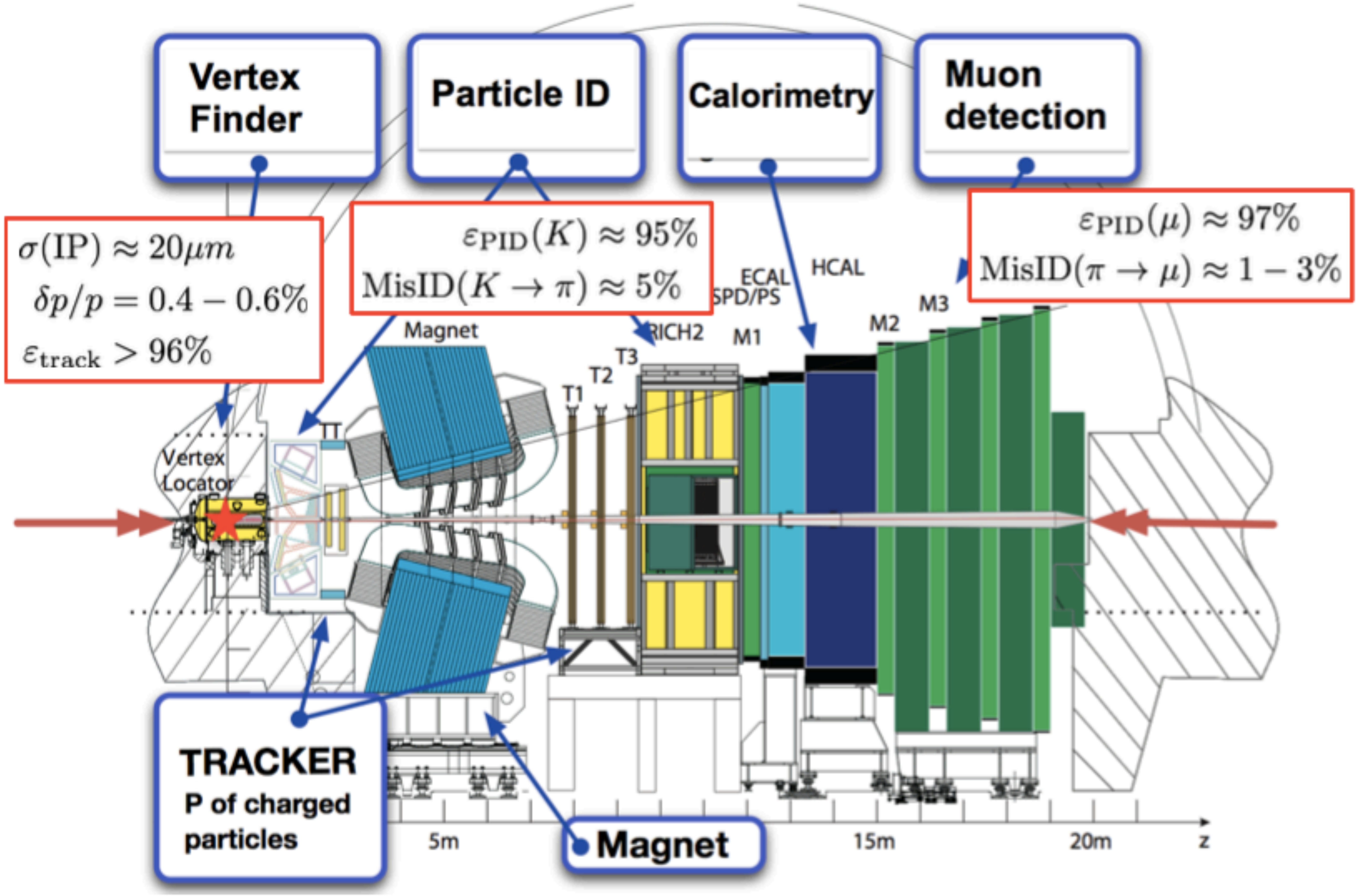
http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html

- $\sim$900 physicists from $\sim$ 70 universities/laboratories in 16 countries.
- Running since 2010, $>$ 360 papers.
- $\mathcal{O}(100k)$ $b\bar{b}$ pairs produced/sec.

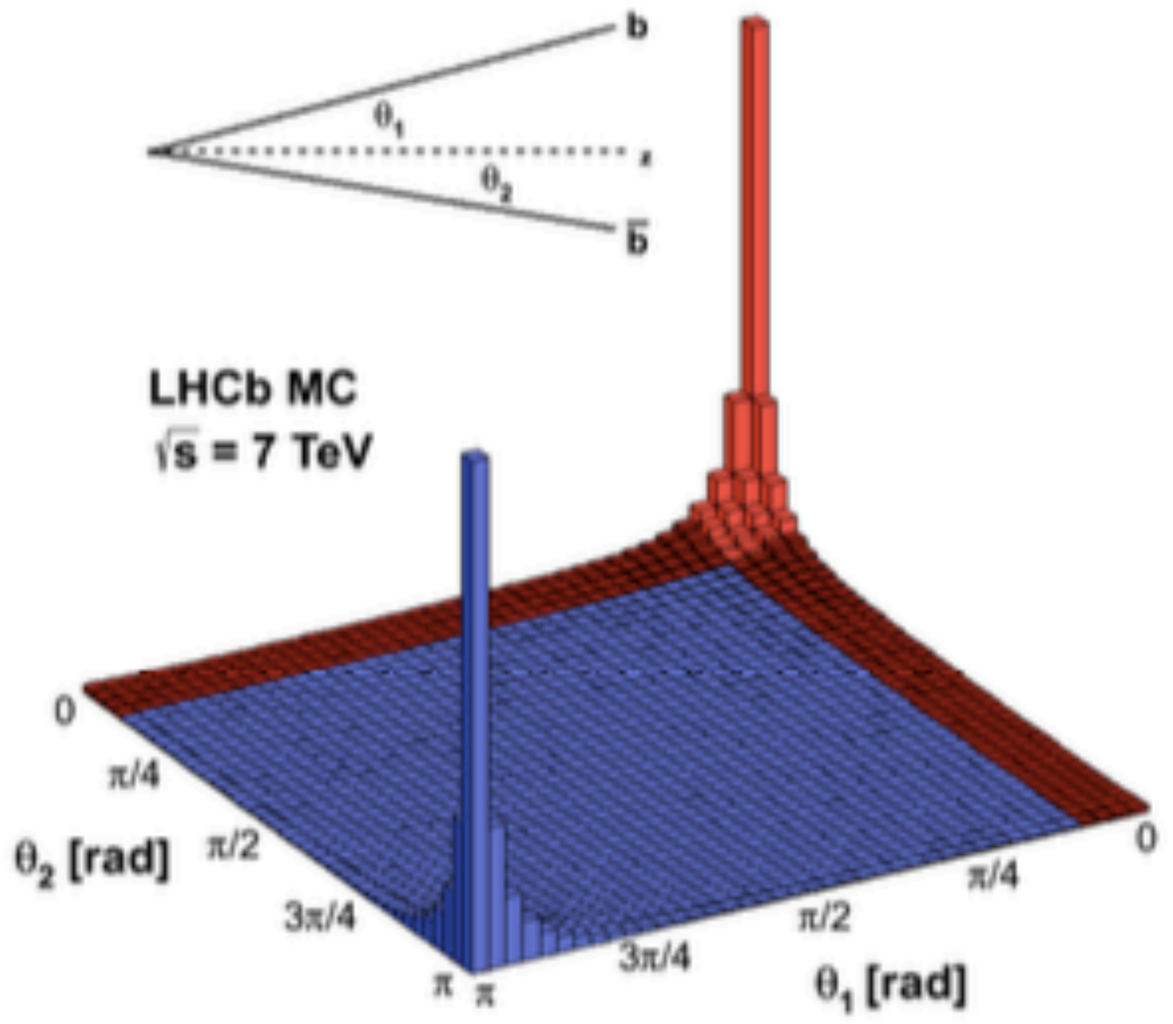
LHCb

- CP violation in the b sector
- $b \to sll$ FCNC decays
- Lepton (non-)universality
- Exotic hadron spectroscopy (pentaquarks)

The LHCb detector

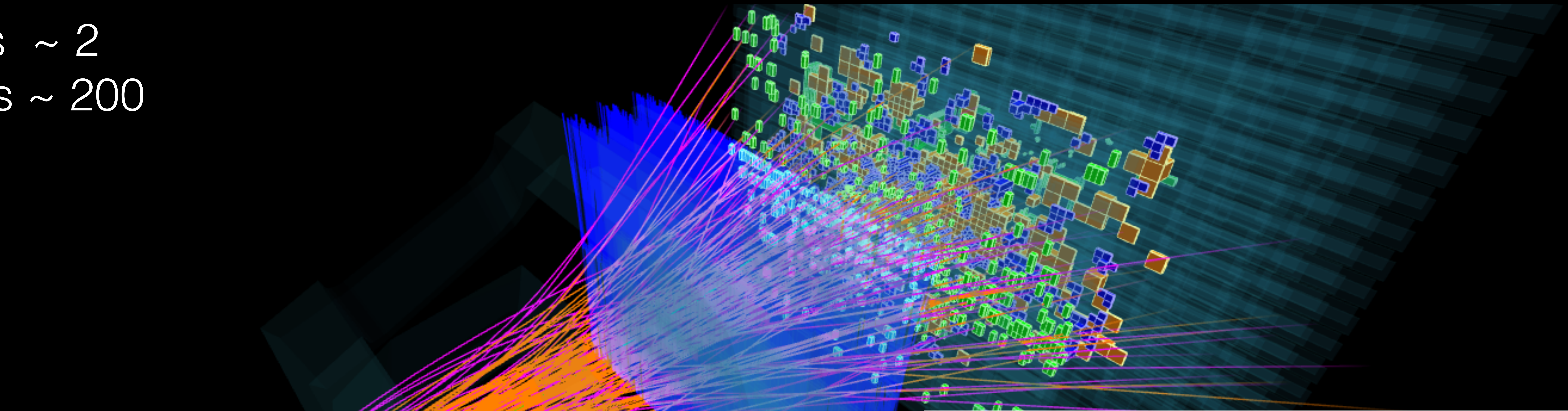


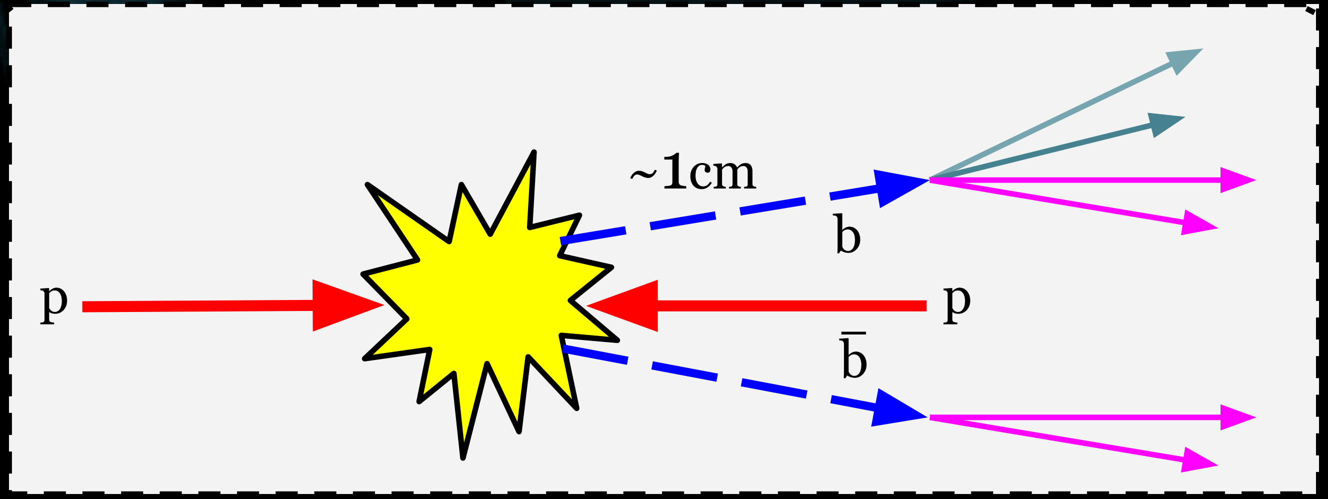
- Covers 4% of solid angle, but accepts 40% of heavy quark production cross section.

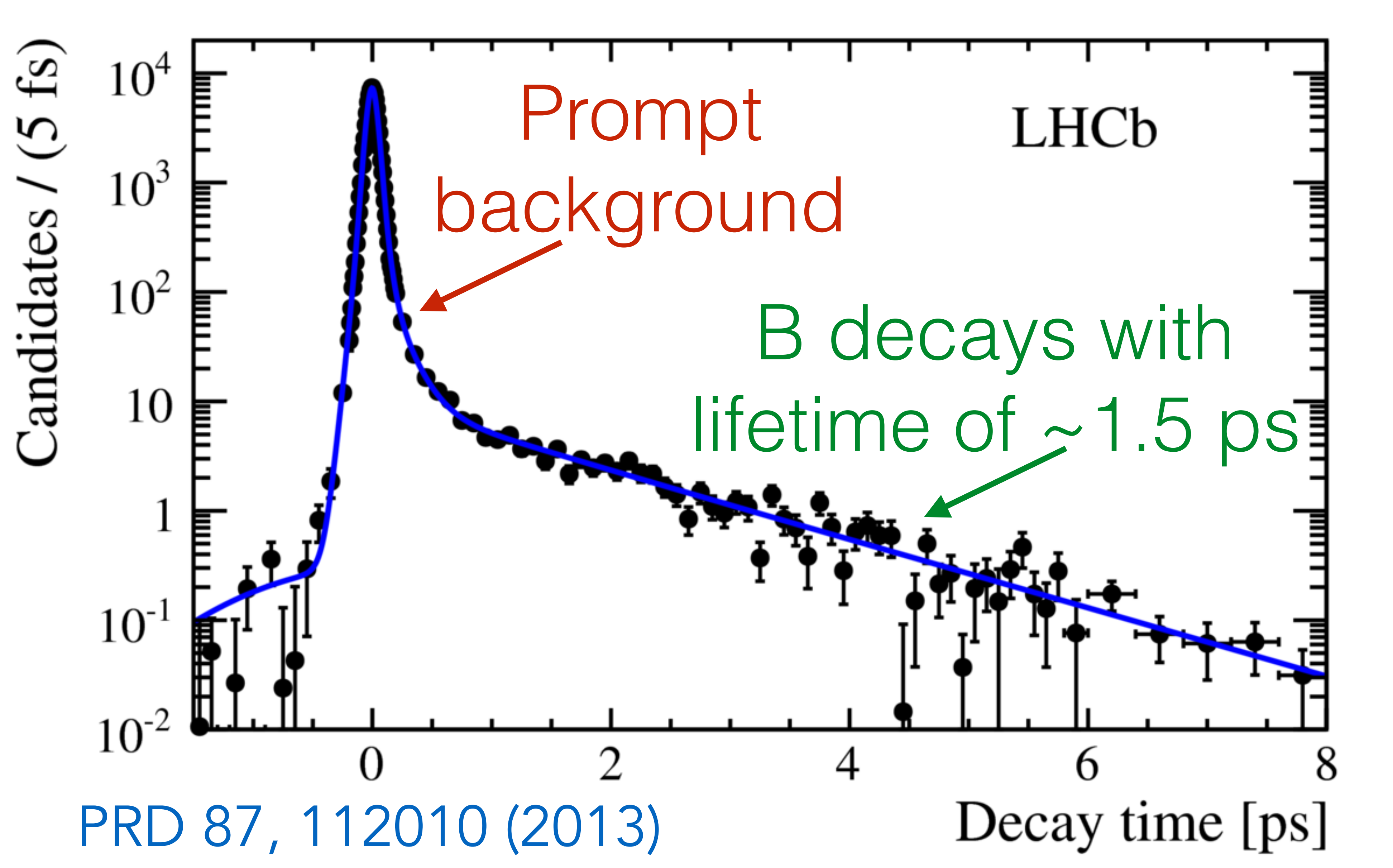


A typical LHCb event

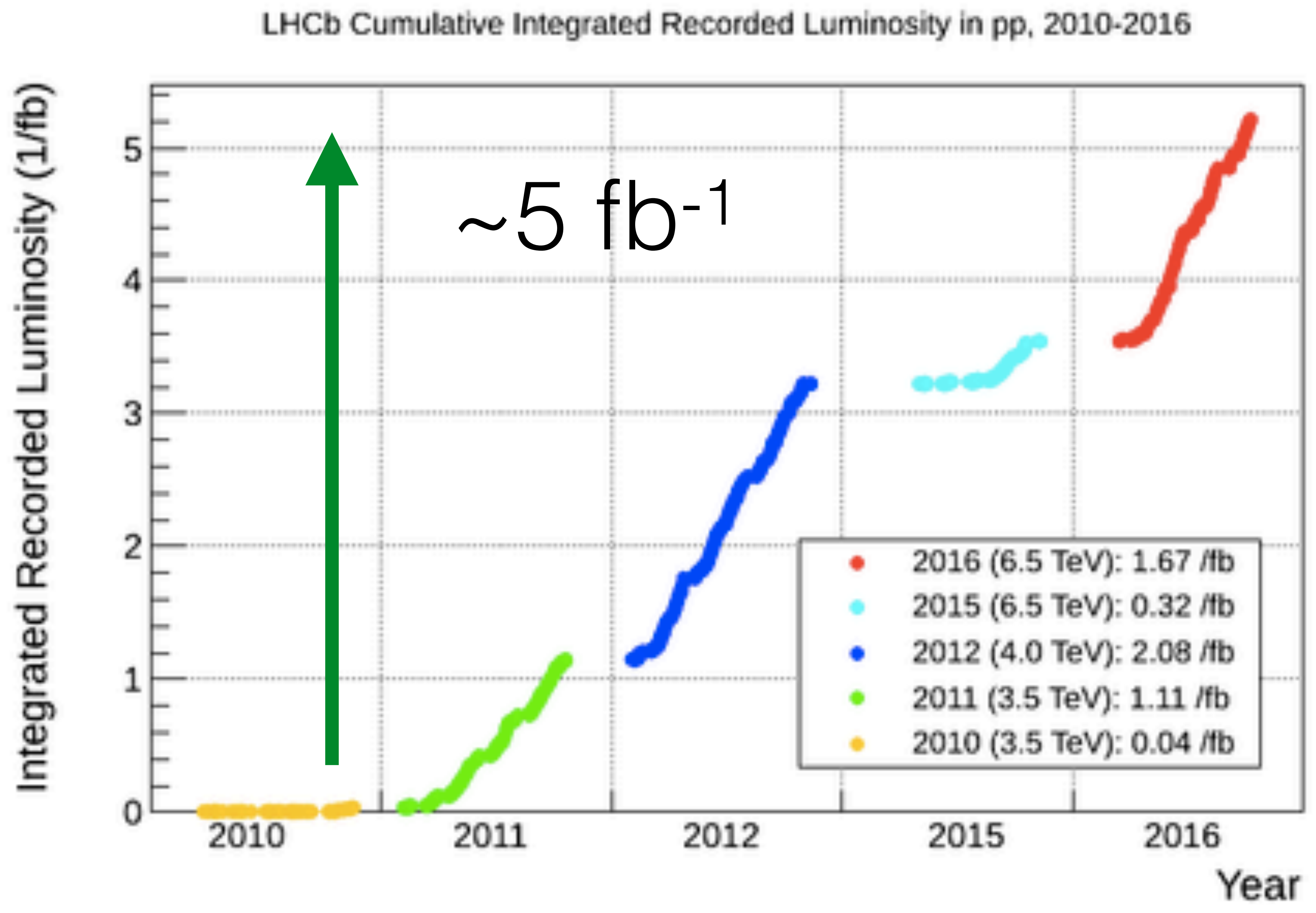
nPVs ~ 2
nTracks ~ 200

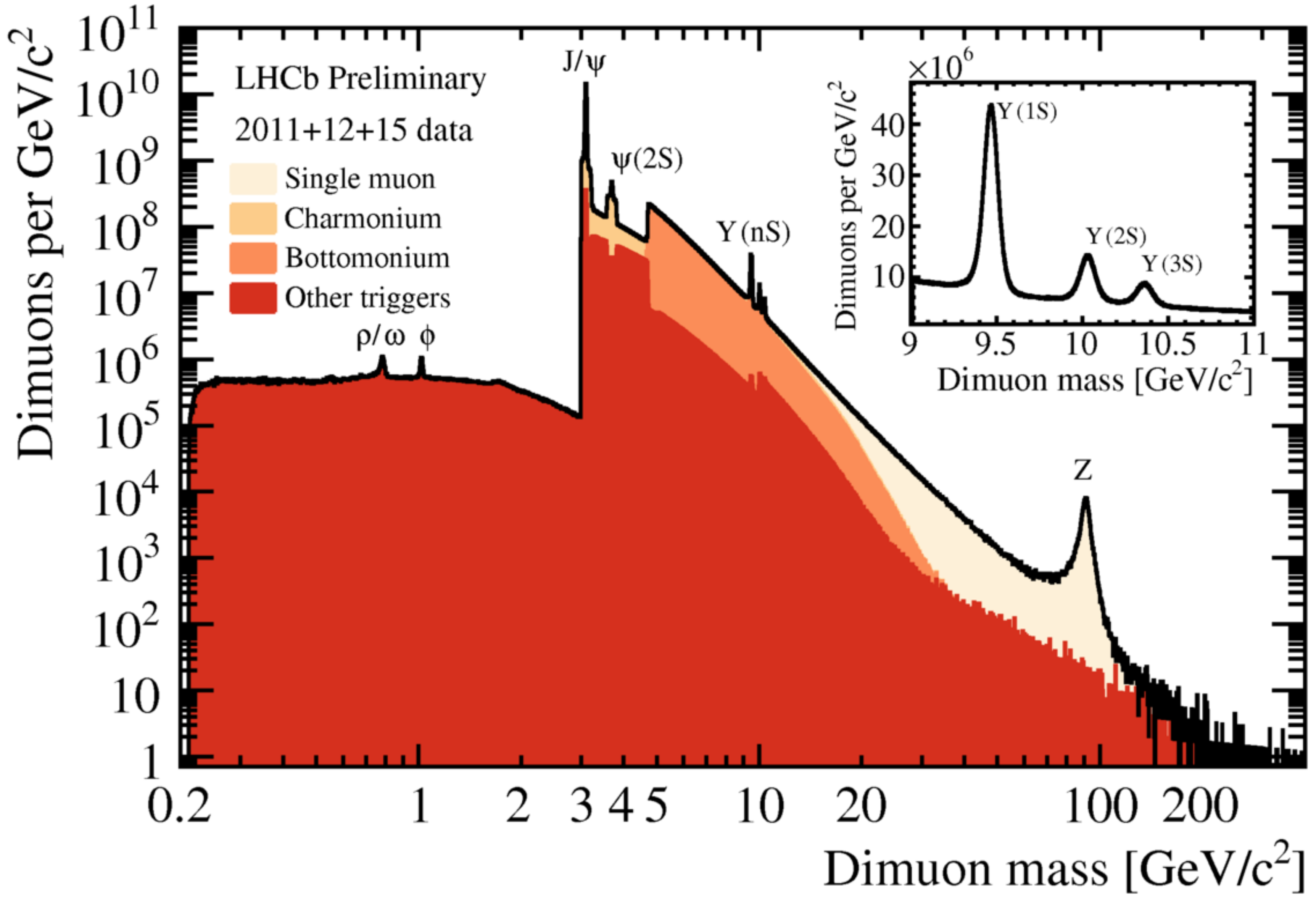


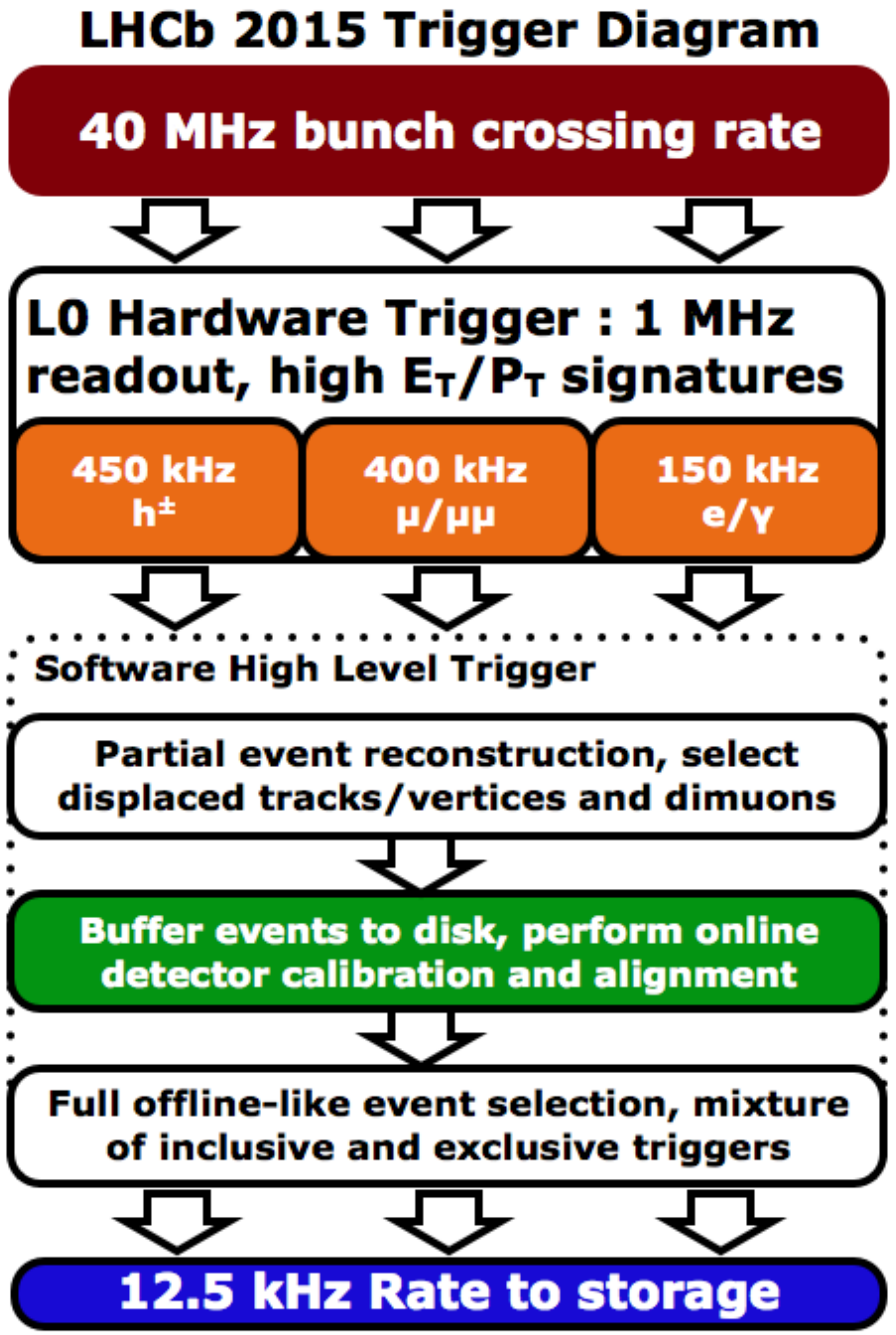


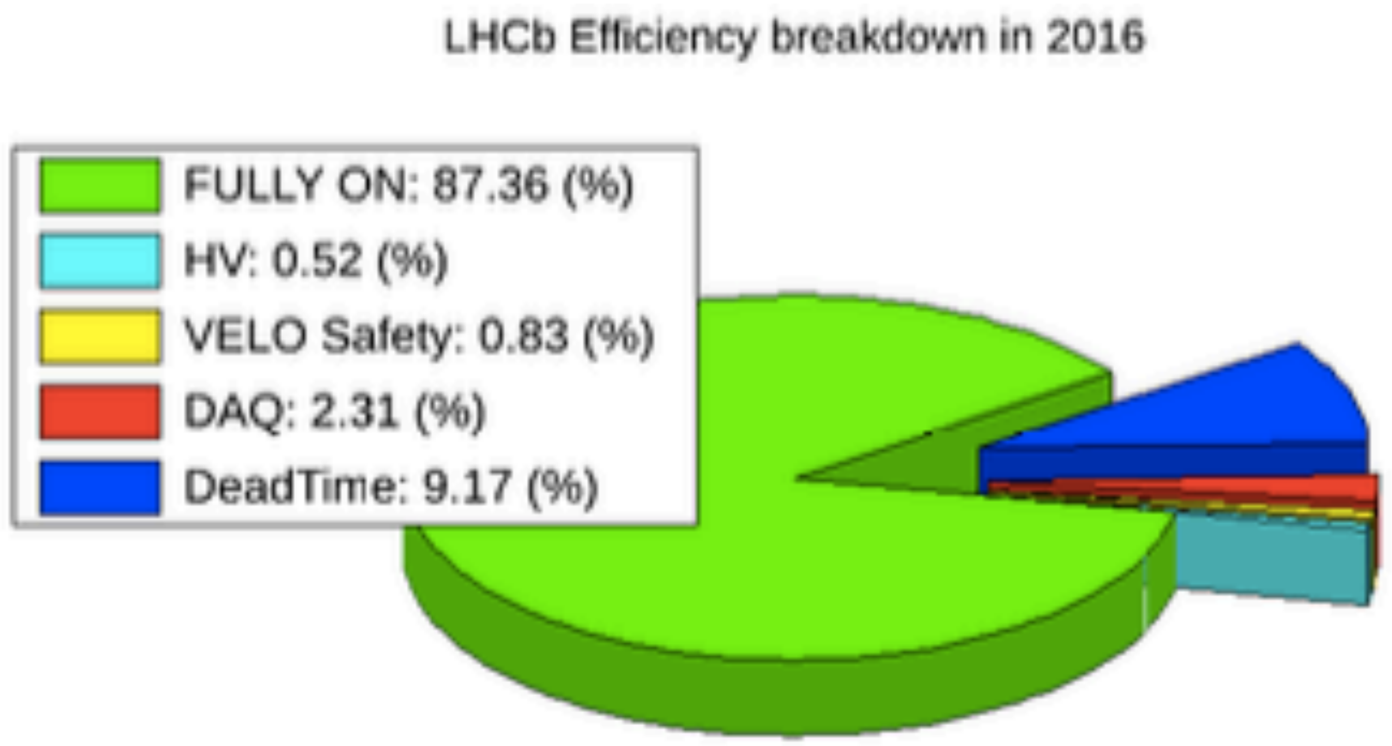


Run 1 and 2





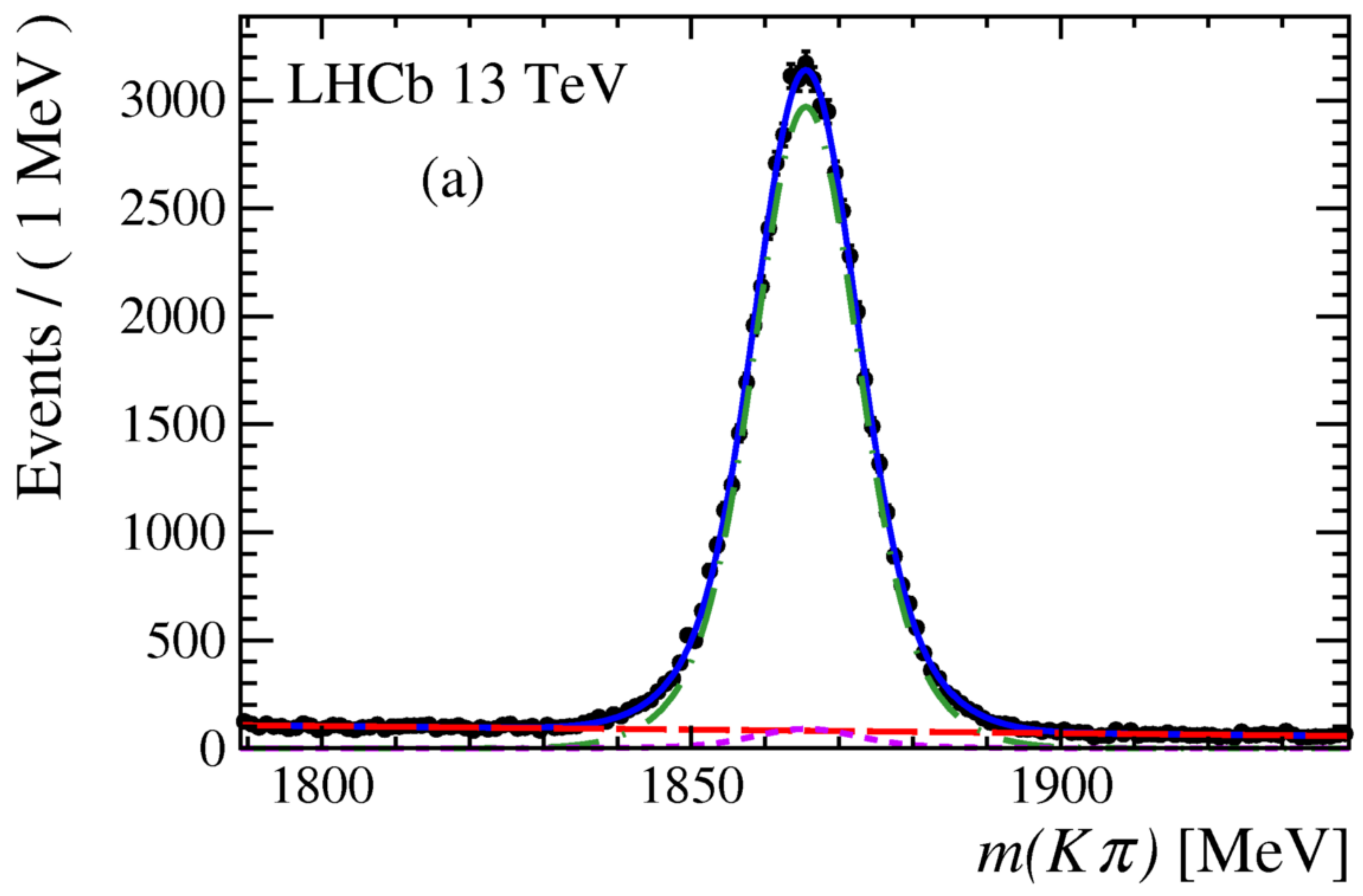


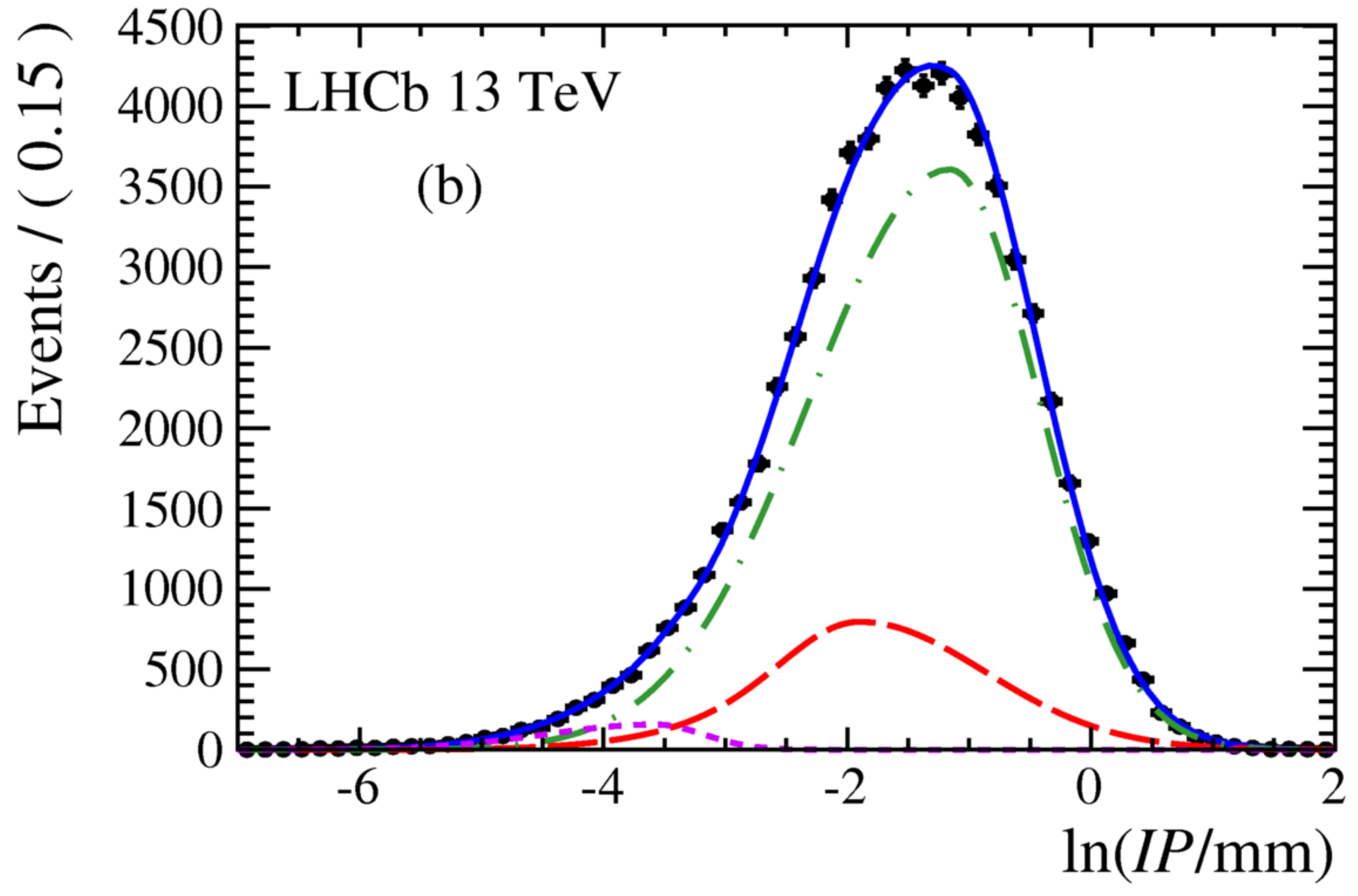


- $\langle \mathcal{L} \rangle_{2011} \sim 2.7 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\langle \mathcal{L} \rangle_{2012} \sim 4.0 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

b-quark cross-section

- b-quark production cross-section in pp→bbX.
- Use semileptonic decays.
- Use open-charm mass and IP distribution to separate **D-from-B** and **prompt** components.
- Some indications that the cross-section does not follow predictions.

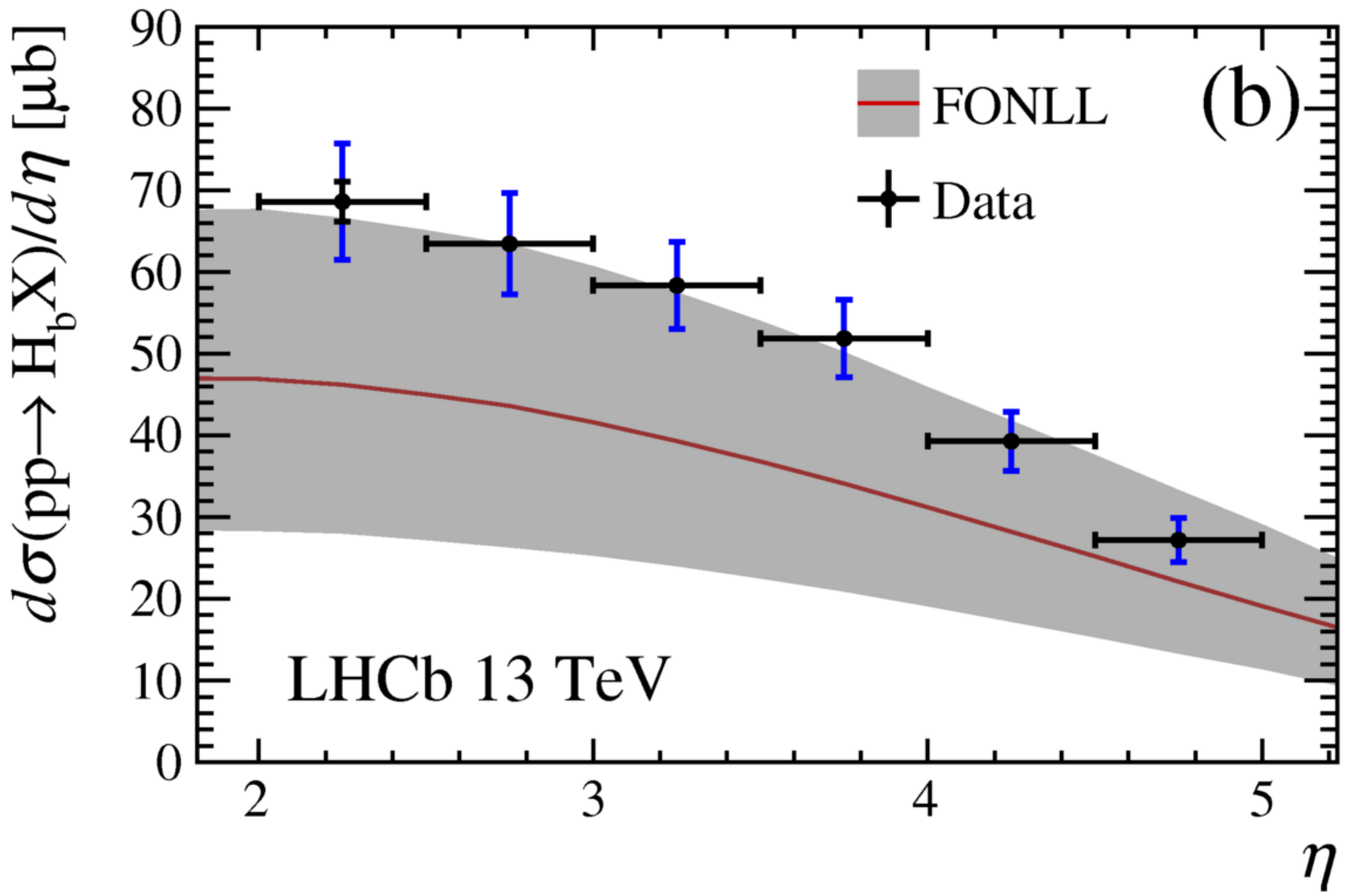




Dominated by luminosity measurement

σ(7 TeV) = 72.0±0.3± 6.8μb

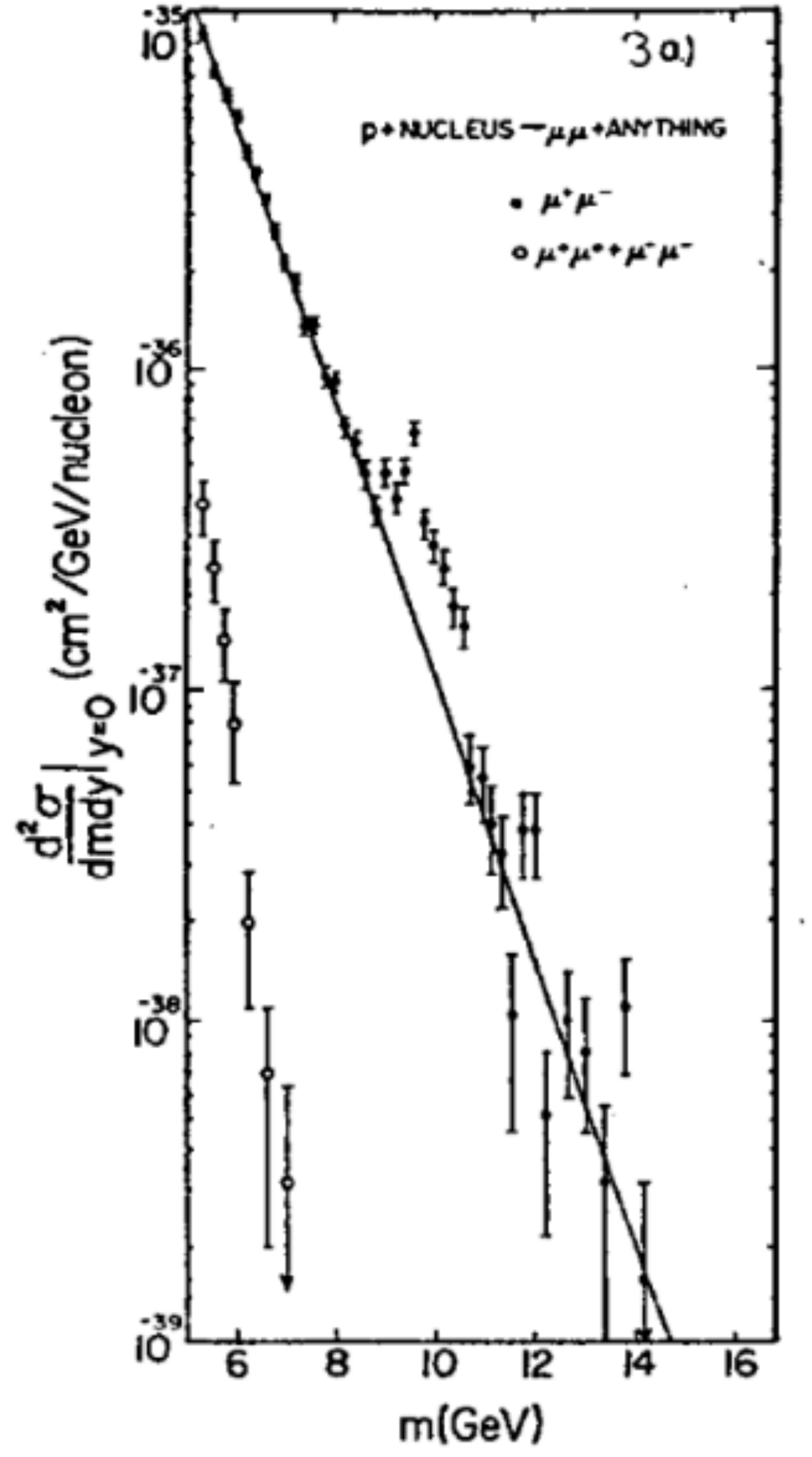
σ(13 TeV) = 154.3±1.5±14.3μb



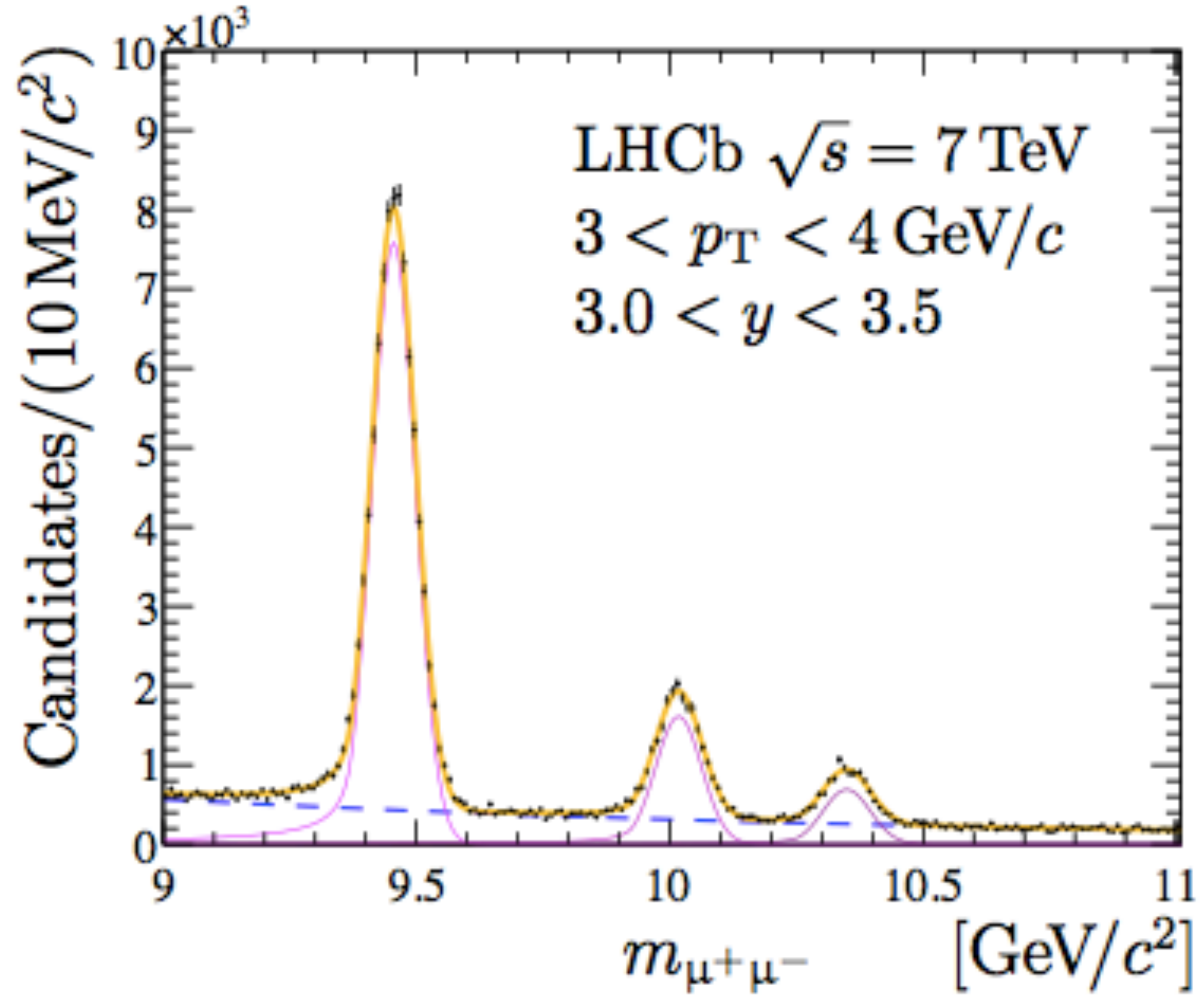
[PRL 118, 052002 (2017)]

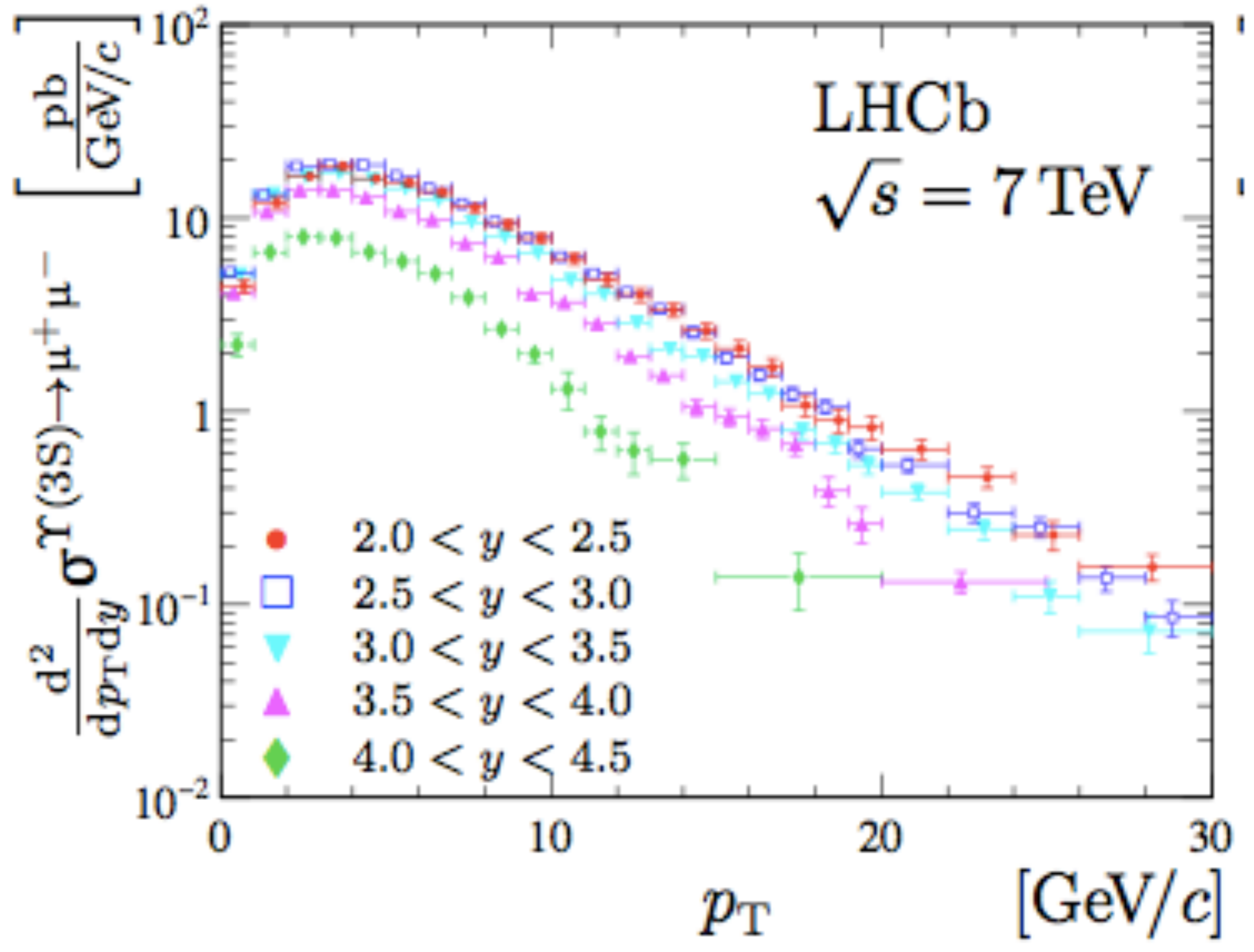
The b-quark: then and now

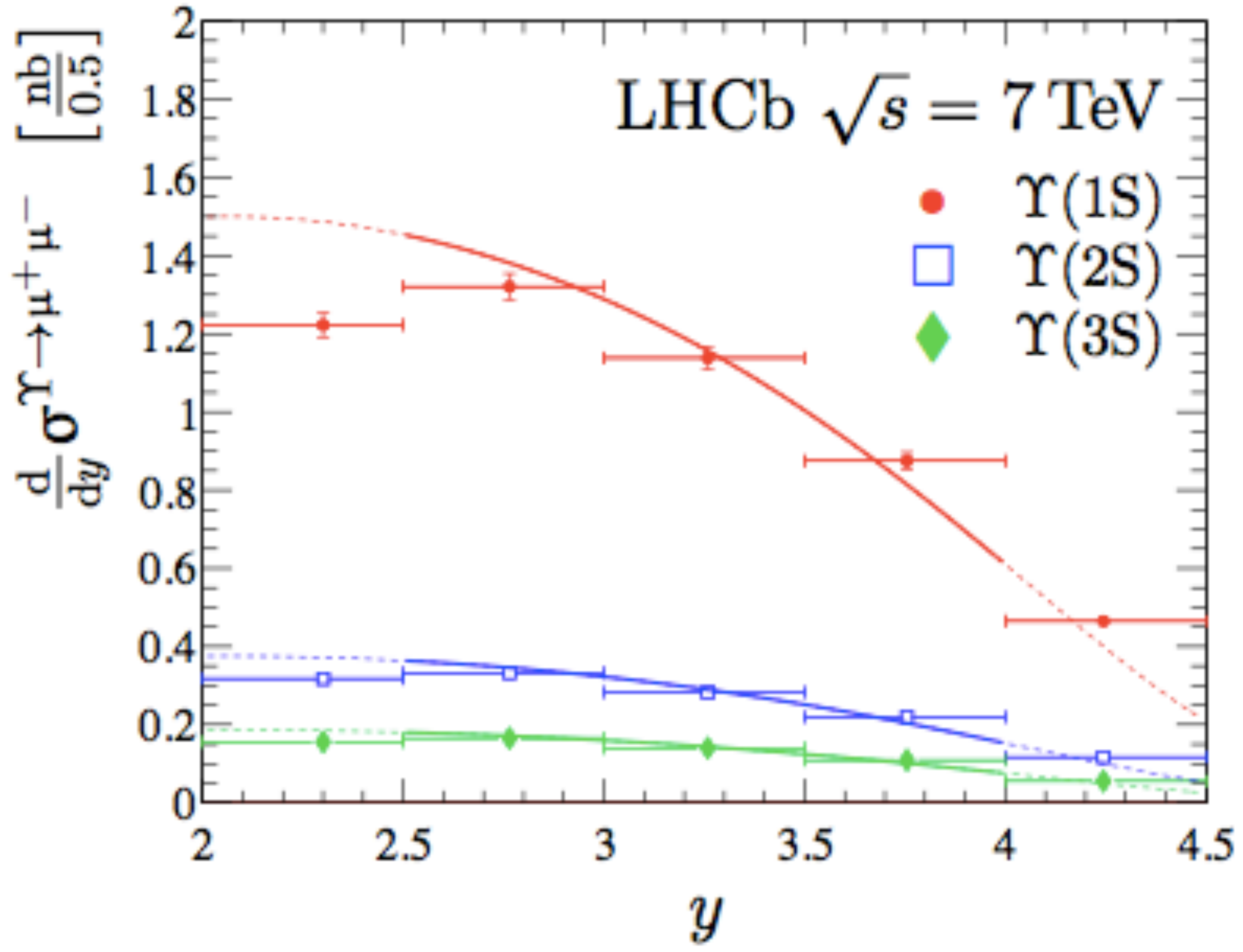
[FNAL-E-0288, PRL 39 (1977) 252]



[LHCb, JHEP 1511 (2015) 103]

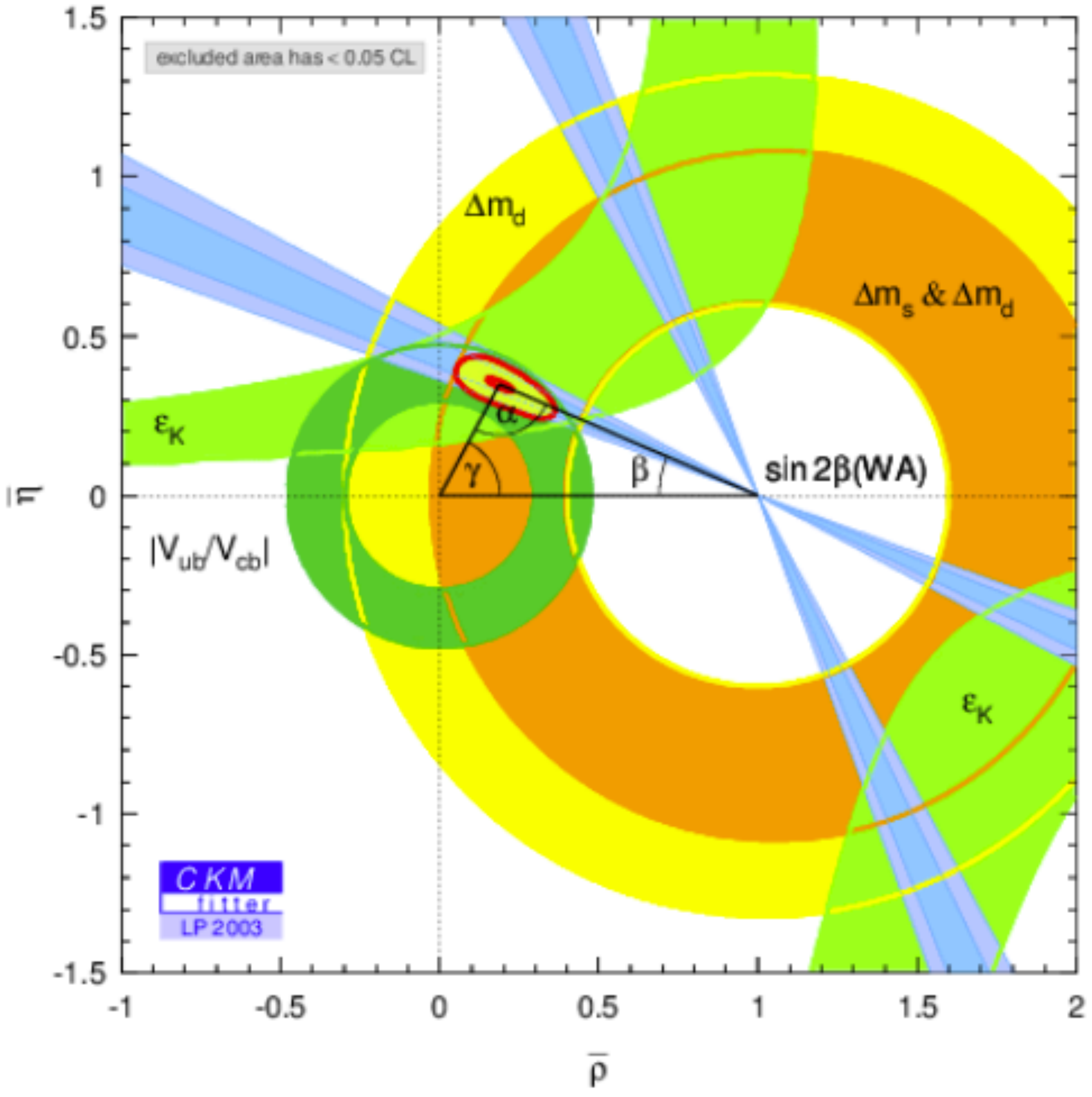


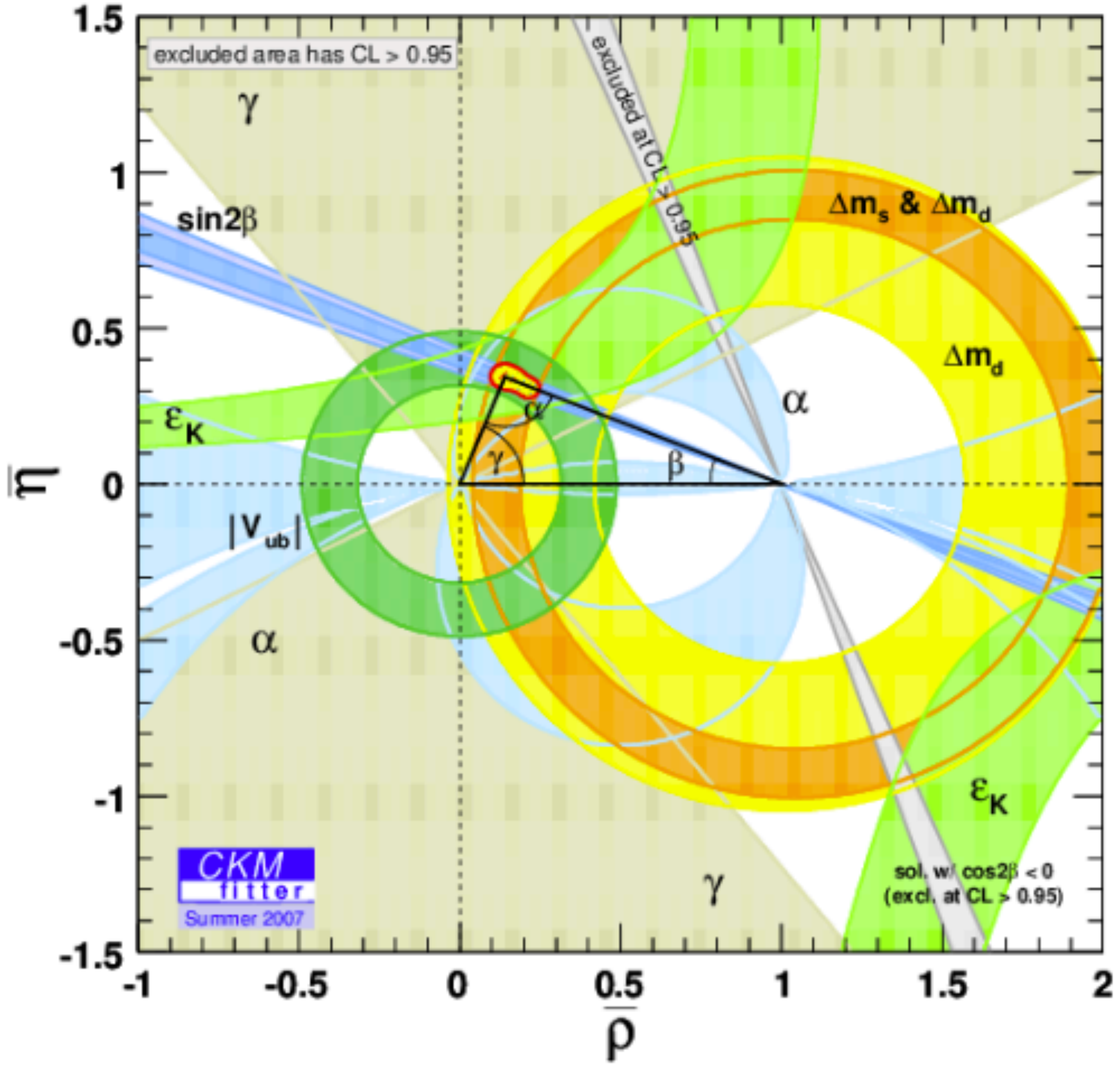


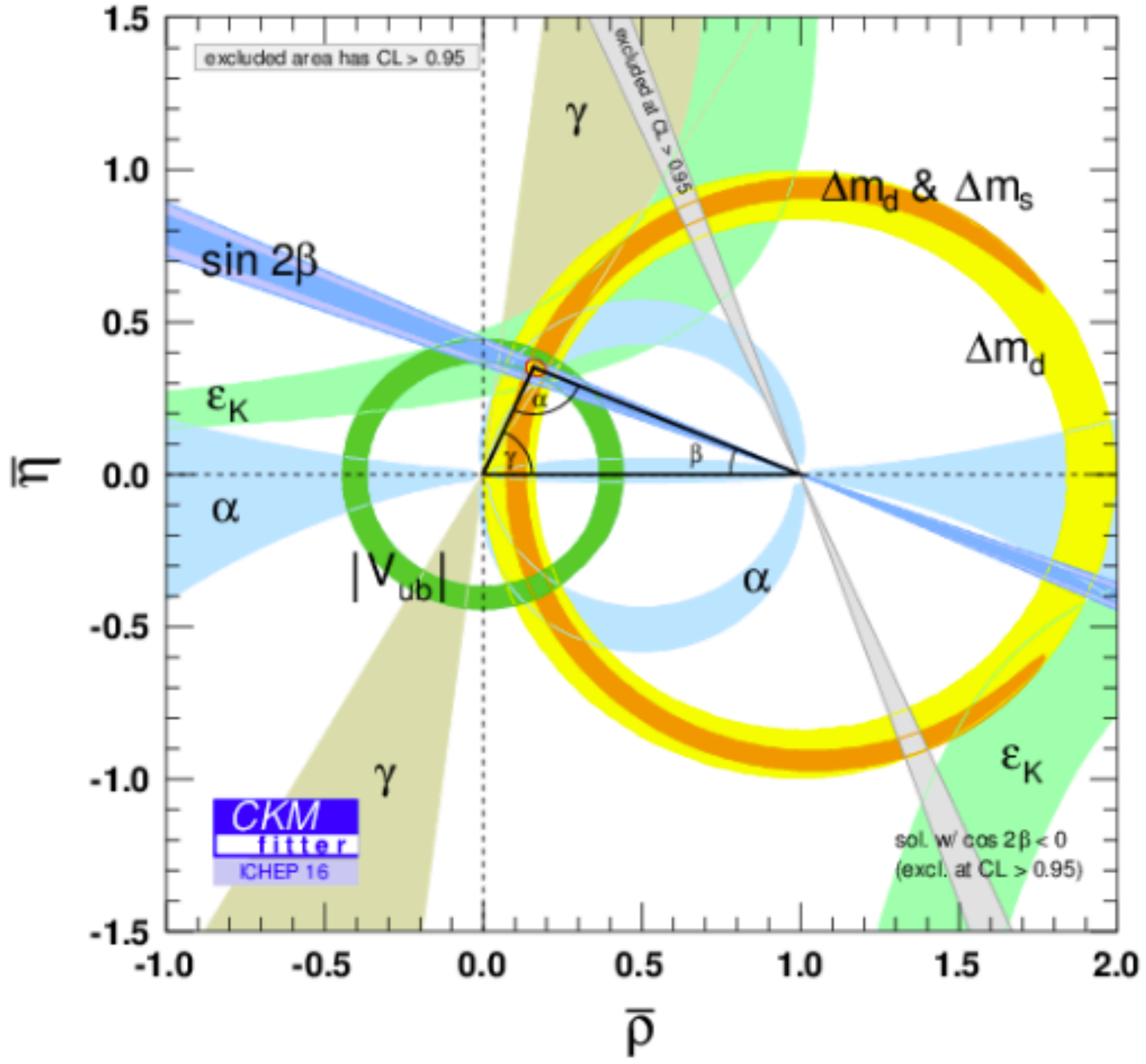


Excellent mass resolution
from LHCb's tracking system

CP violation in the (b) quark sector





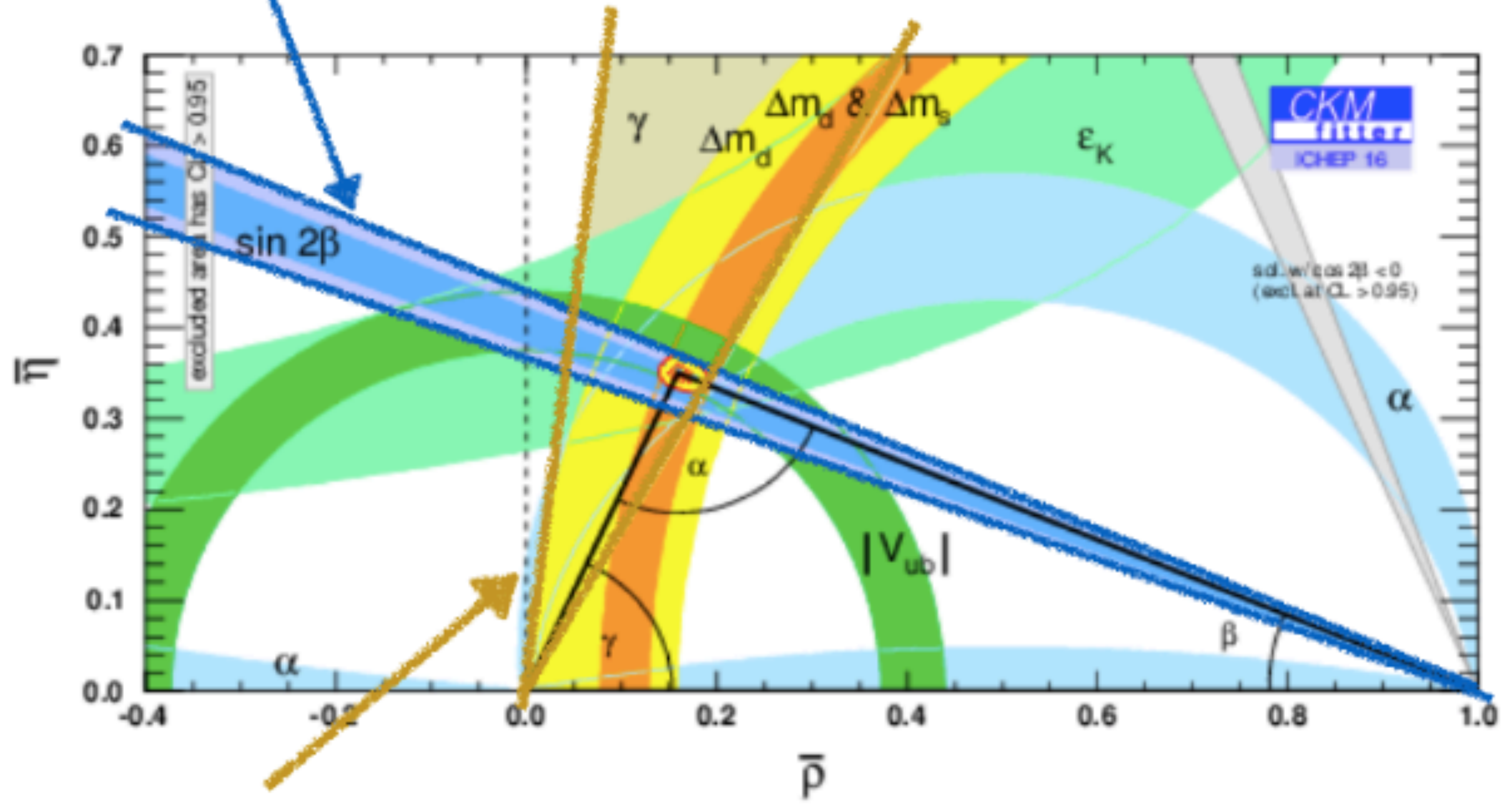


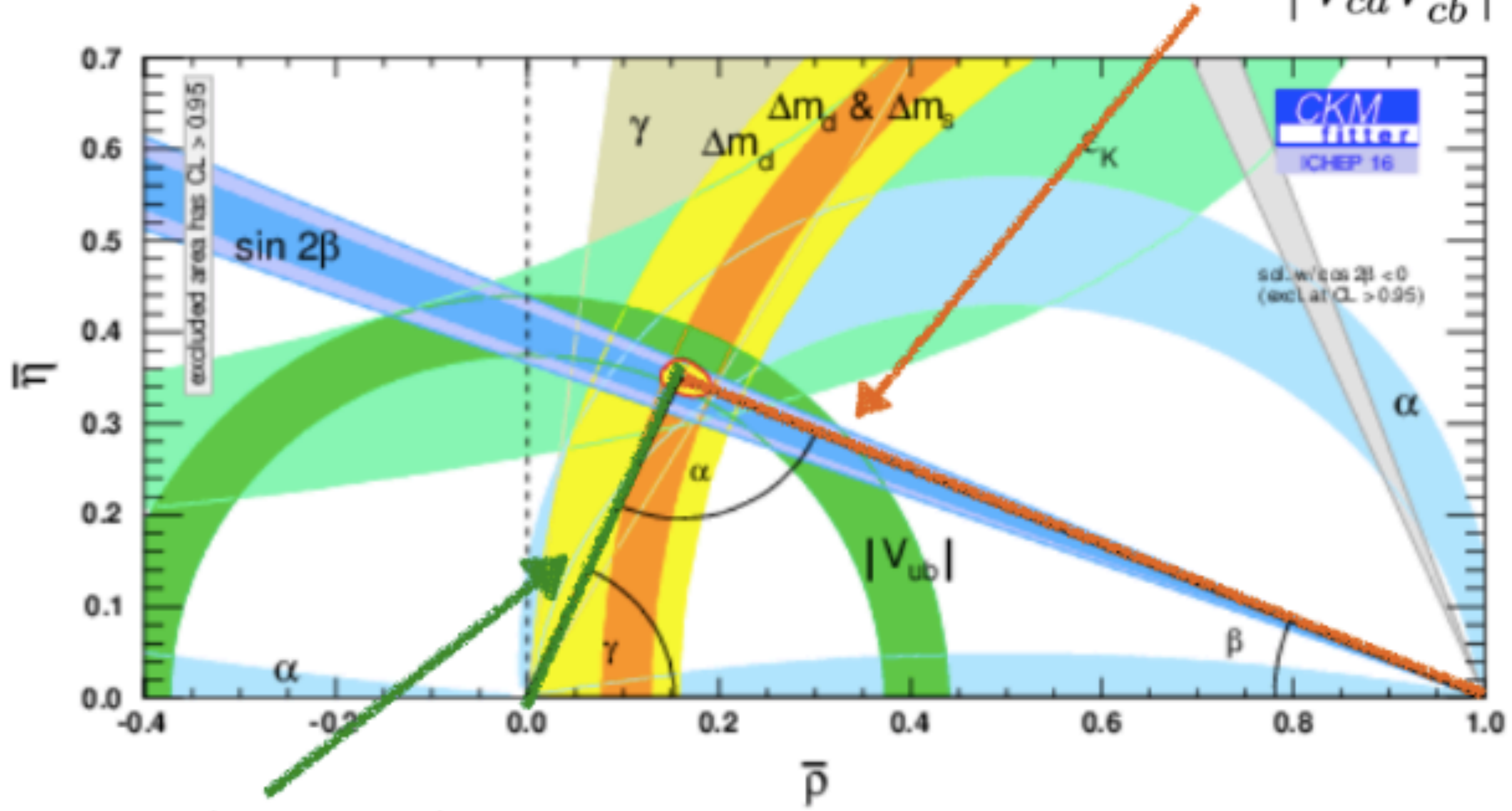
CKM metrology

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$ From decay-time dependent CP-violation in neutral B mesons

From neutral B meson mixing oscillation frequencies with input from Lattice QCD ($f_{B_q}, \hat{B}_{B_q}$) $R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right|$





$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ From interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$

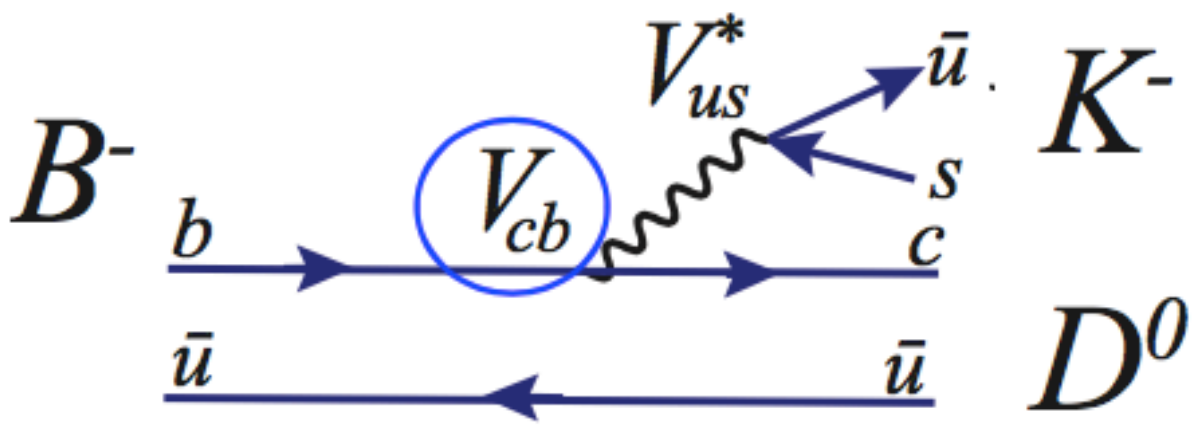
$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right|$ From $b \to u$ semileptonic b-hadron decays

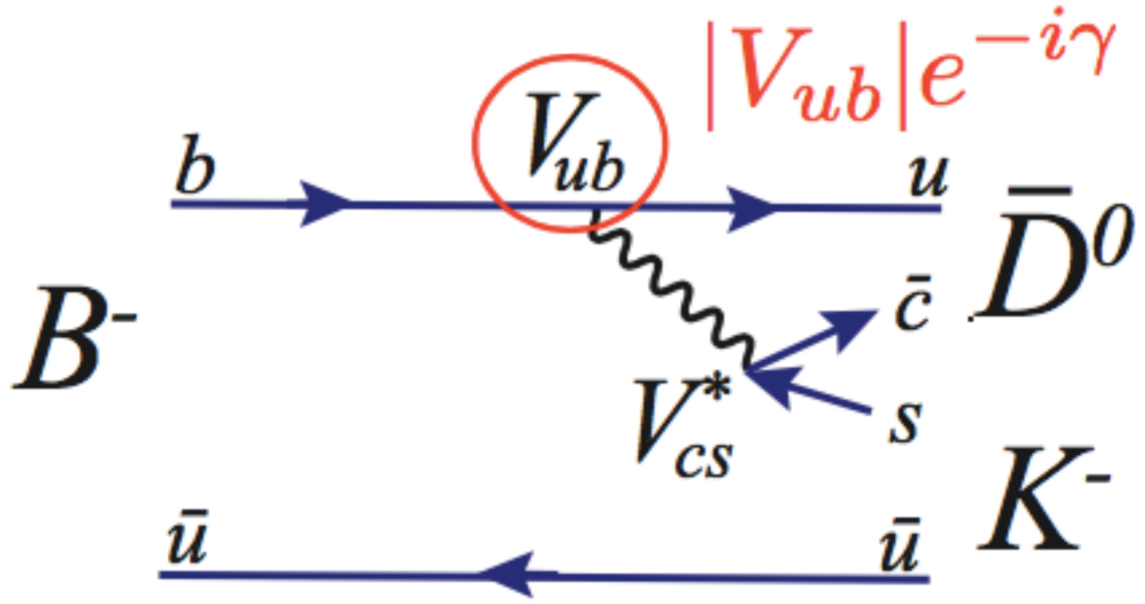
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta}) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Wolfenstein parameterisation

CKM angle γ

- Extracted from tree-level decays.
- "Standard candle" for SM.
  - $|\delta\gamma| \leq O(10^{-7})$ [Brod, Zupan JHEP 1401 (2014) 051]
- Exploit interference between amplitudes, e.g.



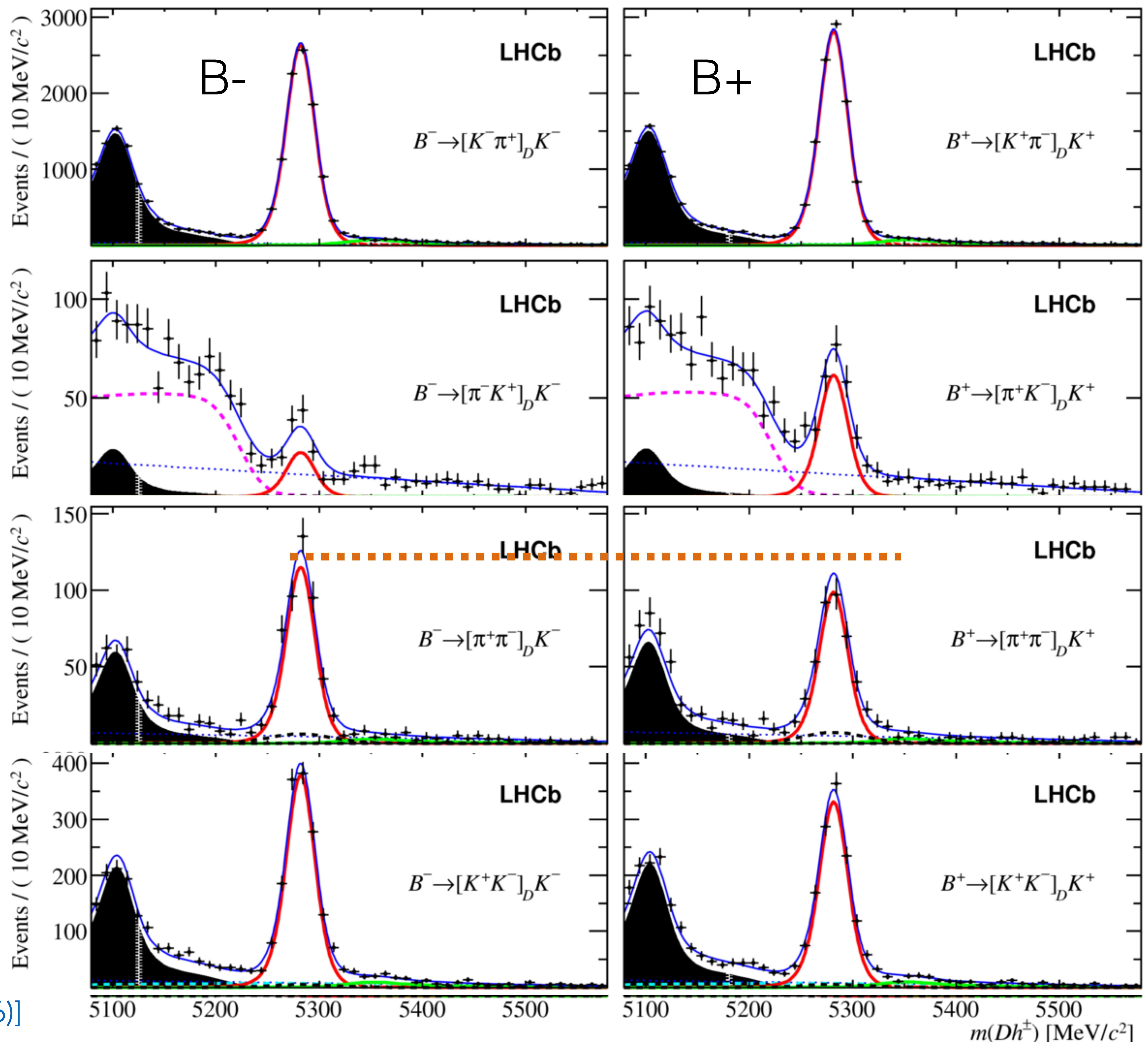


$$\begin{tikzcd} & D^0K^- \arrow[dr, "A_D r_D e^{i\delta_D}"] & \\ B^- \arrow[ur, "A_B"] \arrow[dr, "A_B r_b e^{i(\delta_B-\gamma)}"'] & & f_D K^- \\ & \overline{D}^0 K^- \arrow[ur, "A_D"'] & \end{tikzcd}$$

$f_D = \pi^+\pi^-, K^+K^-$	GLW	[PLB 253 (1991) 483, PLB 265 (1991) 172]
$K^+\pi^-$	ADS	[PRL 78 (1997) 3257]
$K_S^0\pi^+\pi^-$	GGSZ	[PRD68 (2003) 054018]

γ from $B \to DK^+$

- ADS favoured modes
  - 29,470 ± 230 $B^{\pm} \to (K^{\pm}\pi^{\mp})_D K^{\pm}$ events
- ADS suppressed modes
  - 553 ± 34 $B^{\pm} \to (\pi^{\pm}K^{\mp})_D K^{\pm}$
  - **CP violation at 8σ**
- GLW modes
  - 1,162 ± 48 $B^{\pm} \to (\pi^+\pi^-)_D K^{\pm}$
  - 3,816 ± 92 $B^{\pm} \to (K^+K^-)_D K^{\pm}$
  - **CP violation at 5σ (combined)**



[PLB 760, 117 (2016)]

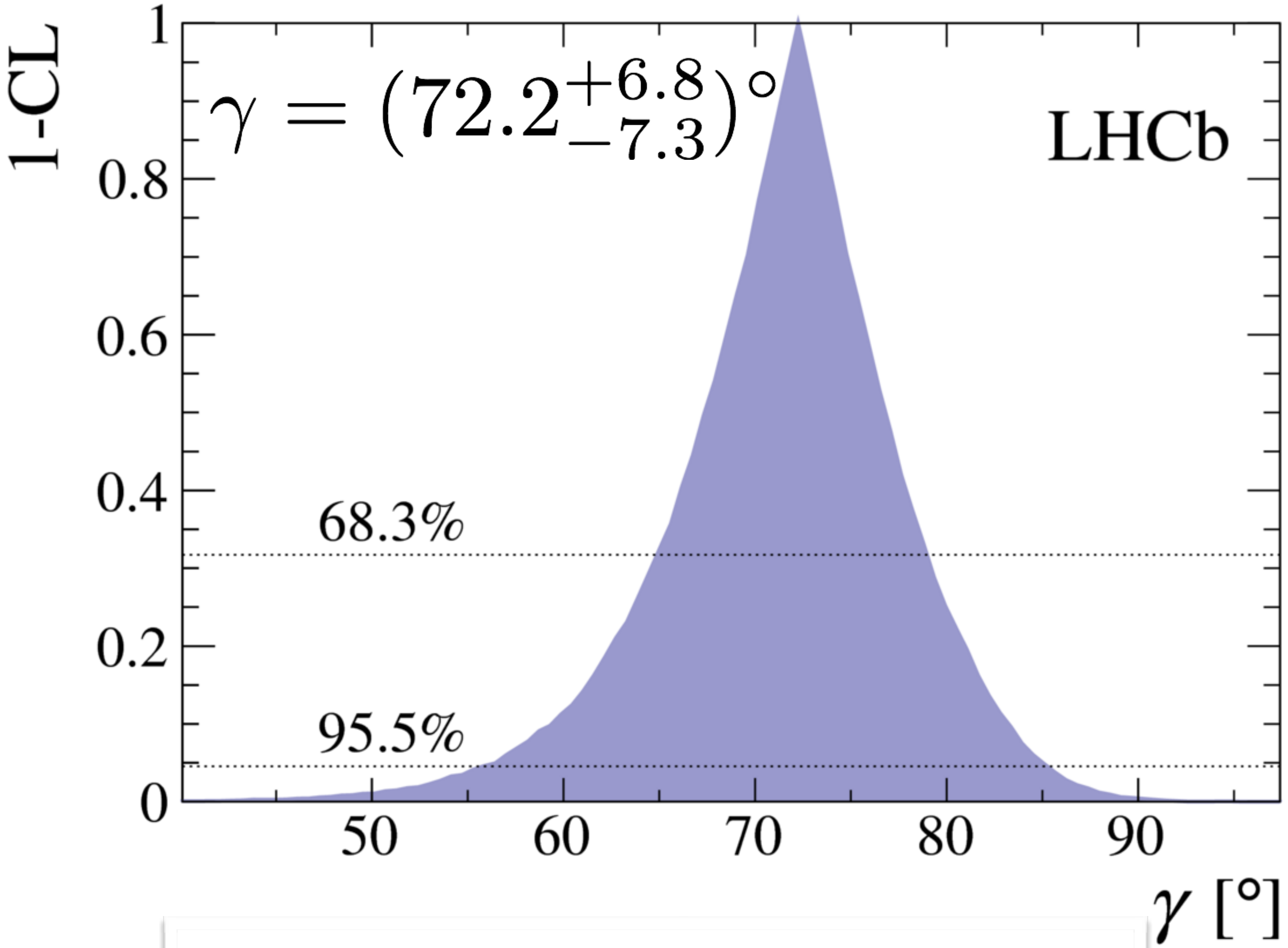
γ from combination of measurements

- Combination of $B \rightarrow DK^{+}$ measurements

[JHEP 12 (2016) 087]

- Most precise measurement of γ

B decay	D decay	Method
$B^+ \to Dh^+$	$D \to h^+h^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$	GLW/ADS
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ
$B^+ \to DK^+$	$D \to K^0_S K^-\pi^+$	GLS
$B^+ \to Dh^+\pi^-\pi^+$	$D \to h^+h^-$	GLW/ADS
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ
$B^0_s \to D^{\mp}_s K^{\pm}$	$D^+_s \to h^+h^-\pi^+$	TD

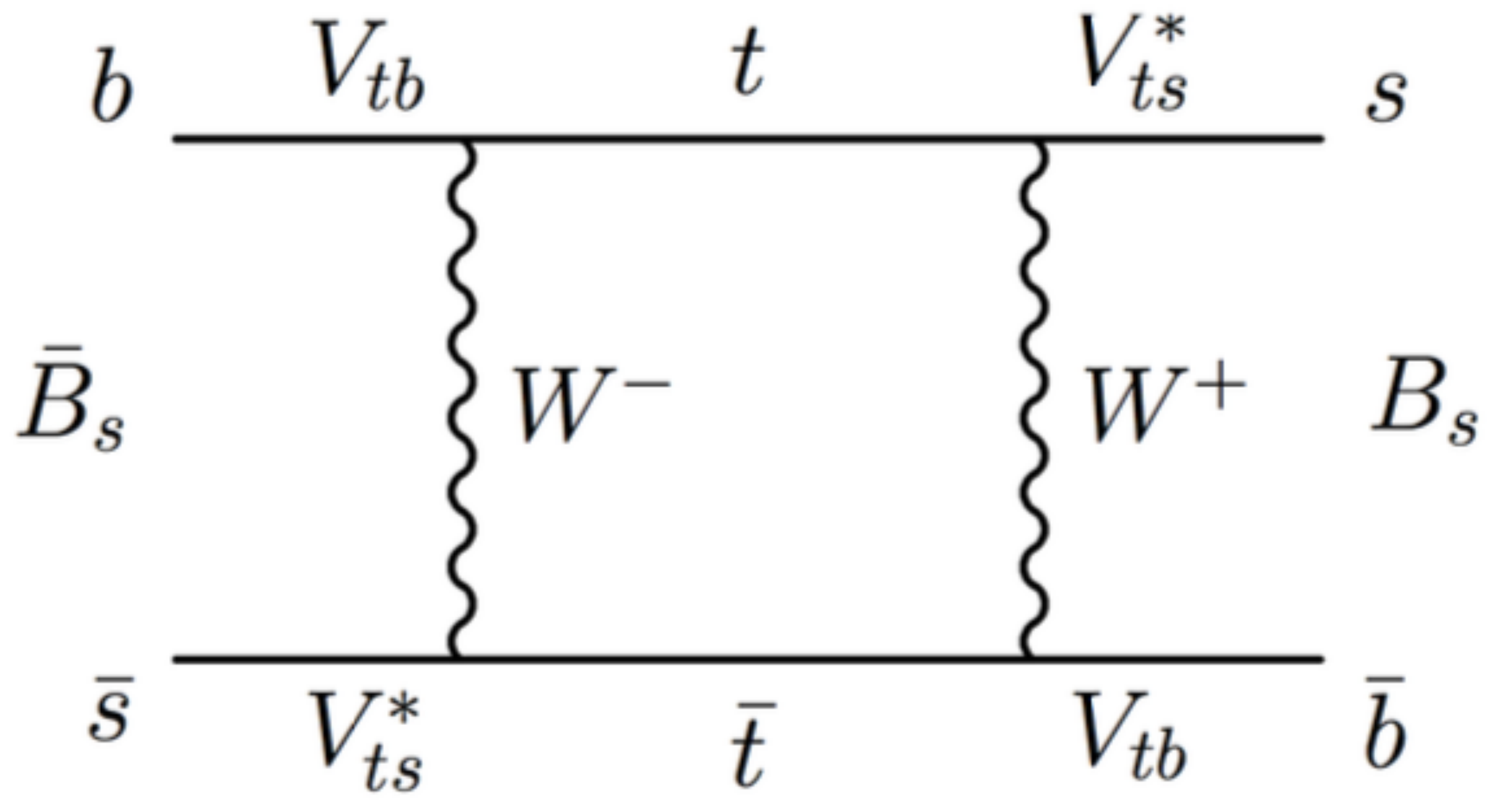


Belle/BaBar sensitivity ~ 15°

Neutral B meson oscillations

- Mass and weak eigenstates are not the same.
- Oscillation frequency given by mass difference between heavy and light states.
- Ratio of oscillation frequencies can be computed precisely in Lattice QCD (see next talk)
- Measure time evolution of flavour-defined states.

$$\mathrm{Prob}(B^0 \to B^0) = \frac{\Gamma e^{-\Gamma t}}{2}[\cosh(\Delta\Gamma/2t) + \cos(\Delta m t)]$$
$$\mathrm{Prob}(B^0 \to \overline{B}^0) = \frac{\Gamma e^{-\Gamma t}}{2}[\cosh(\Delta\Gamma/2t) - \cos(\Delta m t)]|q/p|^2$$
$$\mathrm{Prob}(\overline{B}^0 \to B^0) = \frac{\Gamma e^{-\Gamma t}}{2}[\cosh(\Delta\Gamma/2t) - \cos(\Delta m t)]|p/q|^2$$
$$\mathrm{Prob}(\overline{B}^0 \to \overline{B}^0) = \frac{\Gamma e^{-\Gamma t}}{2}[\cosh(\Delta\Gamma/2t) + \cos(\Delta m t)]$$



$$|B^0_{\mathrm{L,H}}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle$$

$$\frac{\Delta m_d}{\Delta m_s} = \left(\frac{f_{B^0}\sqrt{\hat{B}_{B^0}}}{f_{B^0_s}\sqrt{\hat{B}_{B^0_s}}}\right)^2 \frac{m_{B^0}}{m_{B^0_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

[Fermilab-MILC PRD 93 (2016) 113016]

$$\Delta m \equiv (m_H - m_L)$$
$$\Gamma \equiv (\Gamma_L + \Gamma_H)/2$$
$$\Delta\Gamma \equiv \Gamma_L - \Gamma_H$$

Observables we want to measure

Flavour tagging

[EPJC 72:2022 (2012)]

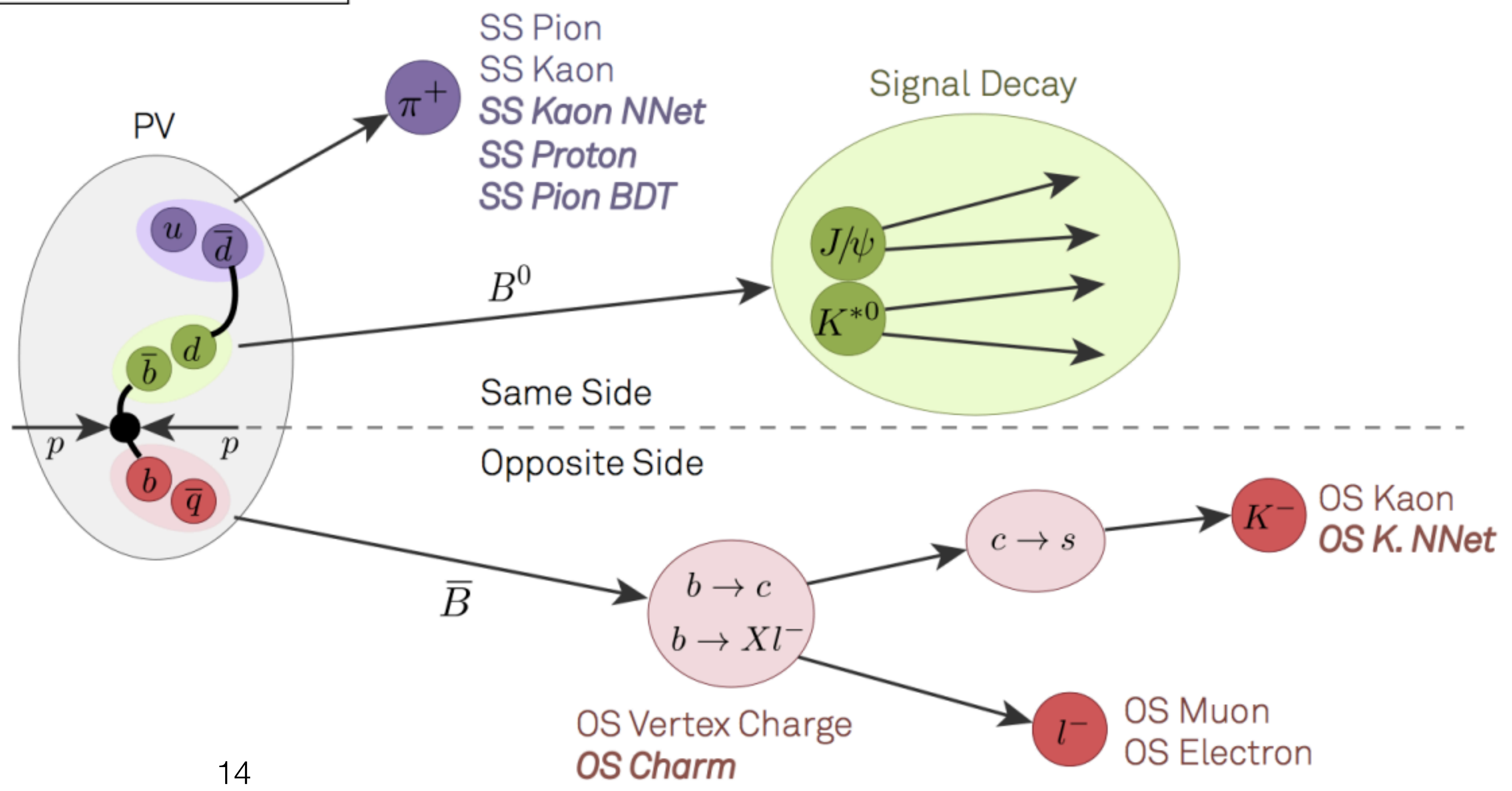
- Measurements of time-dependent asymmetries and decay rates require knowledge of B flavour at the production time.

Typical tagging power @ LHCb
~ 4% modes with Jpsi
~8% for open-charm

$$A_{CP}(t) \equiv \frac{\Gamma_{\overline{B}^0\to f} - \Gamma_{B^0\to f}}{\Gamma_{\overline{B}^0\to f} + \Gamma_{B^0\to f}} = \frac{S_f \sin(\Delta m\, t) - C_f \cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + A_{\Delta\Gamma} \sinh(\Delta\Gamma\, t/2)}$$

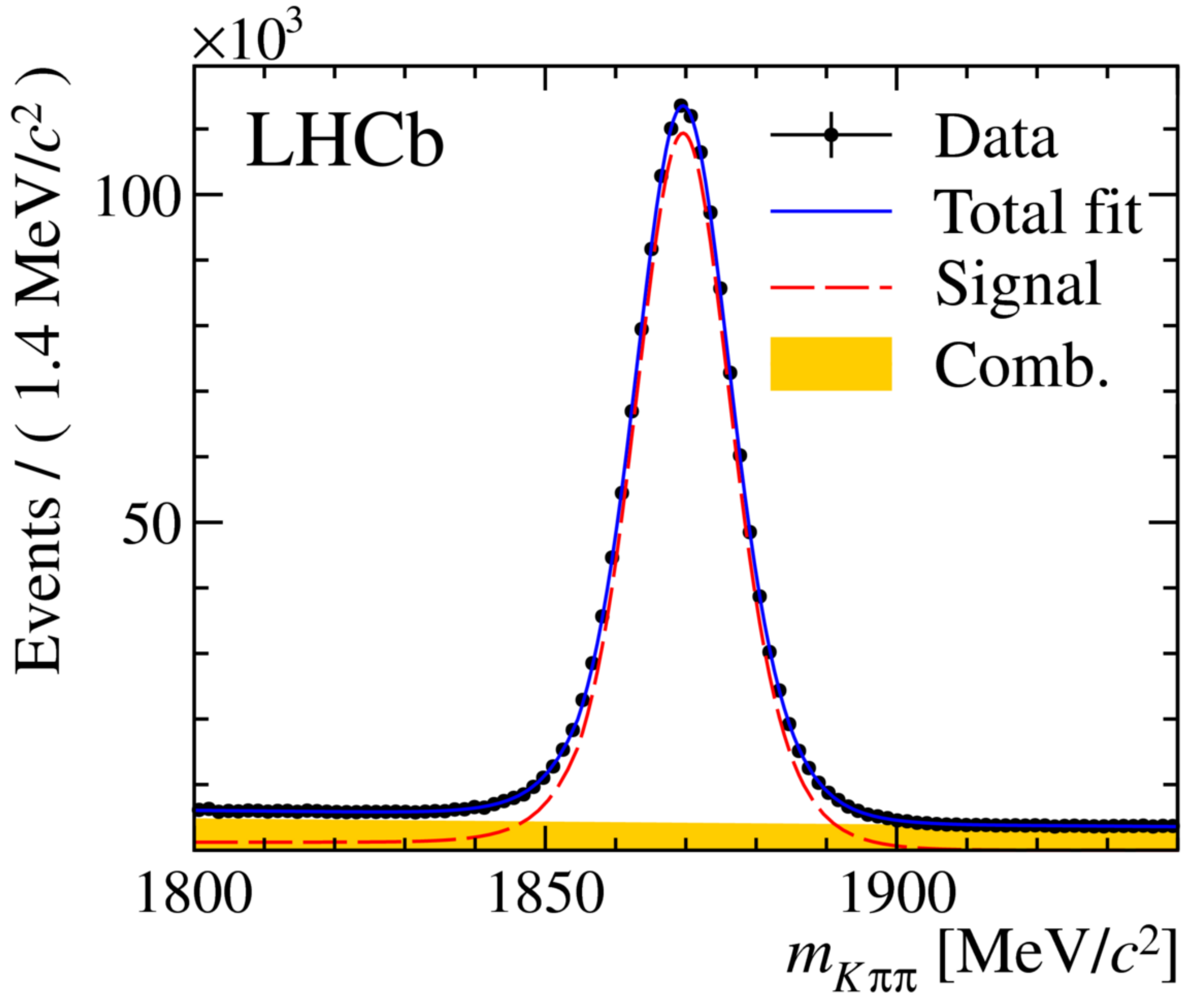
Same Side (SS): correlation between flavour of the b-hadron and charge of the particle (pion,kaon,proton) produced next to the signal b-hadron in the hadronisation process.

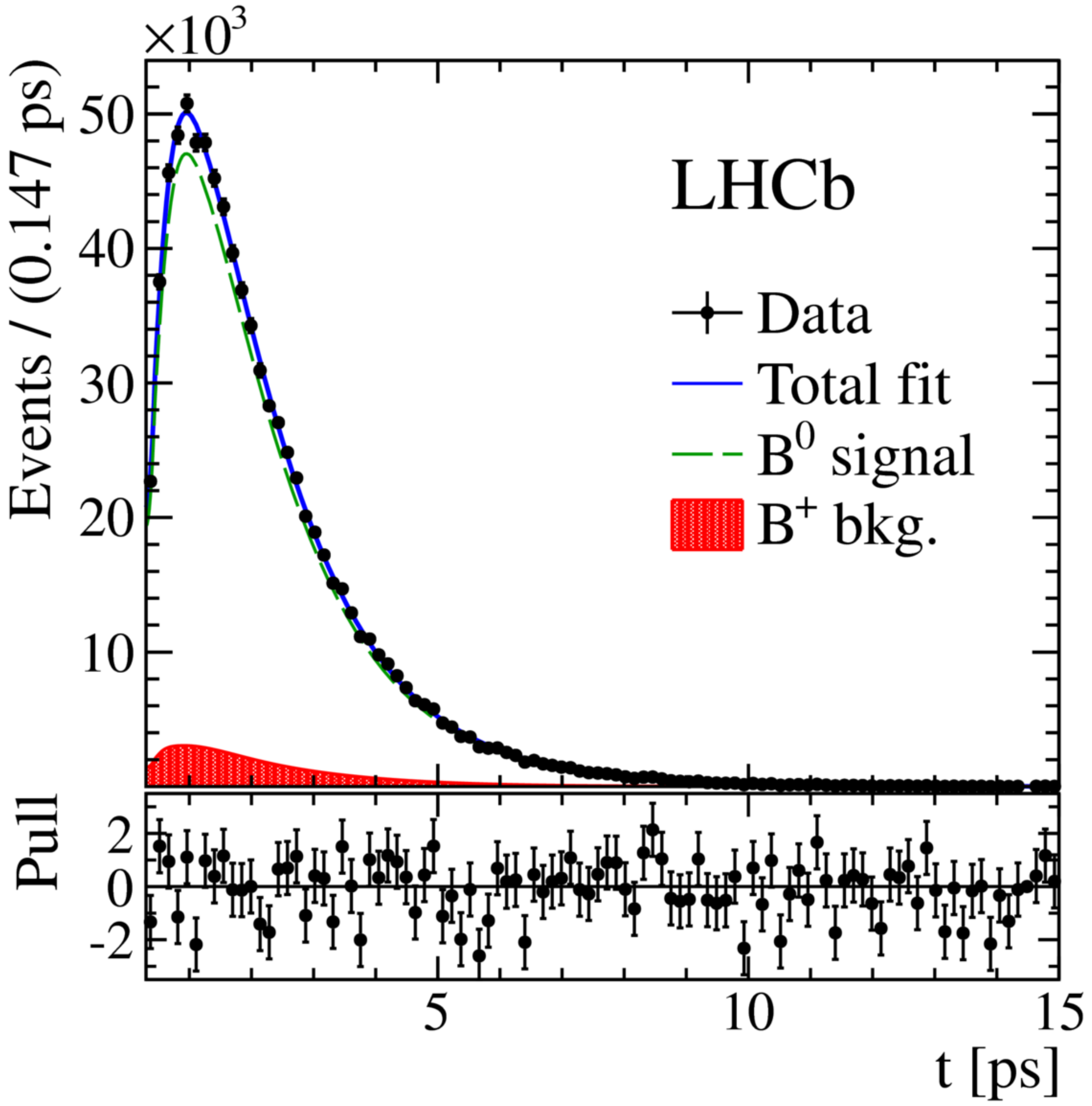
Opposite Side (OS): correlation between flavour of the b-hadron and charge of a particle (pion, kaon,lepton,charmed hadron) or the reconstructed secondary vertex produced from the other b-hadron in the event.

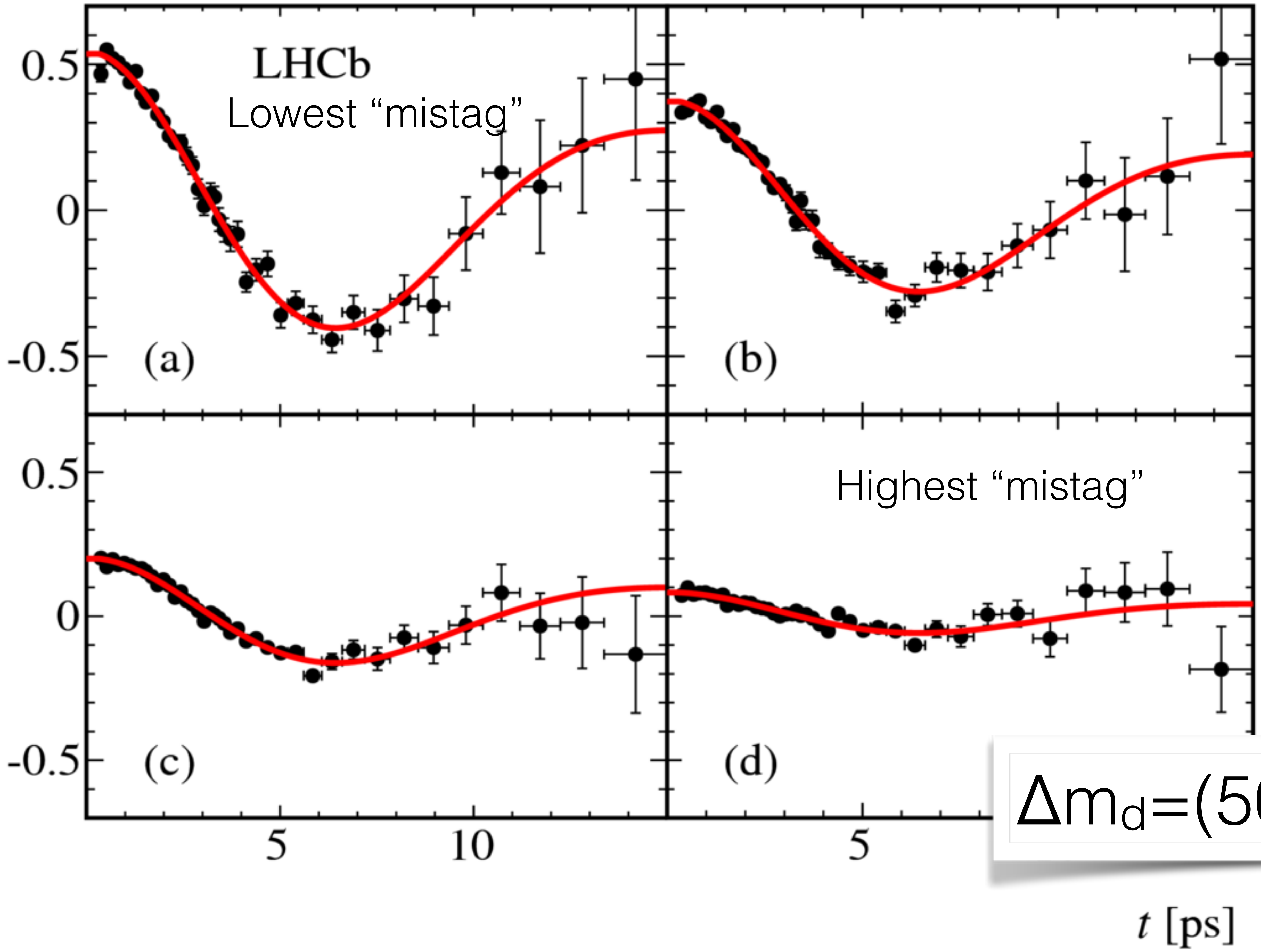


Neutral B^0 meson oscillations

[EPJC 76 (2016) 412]







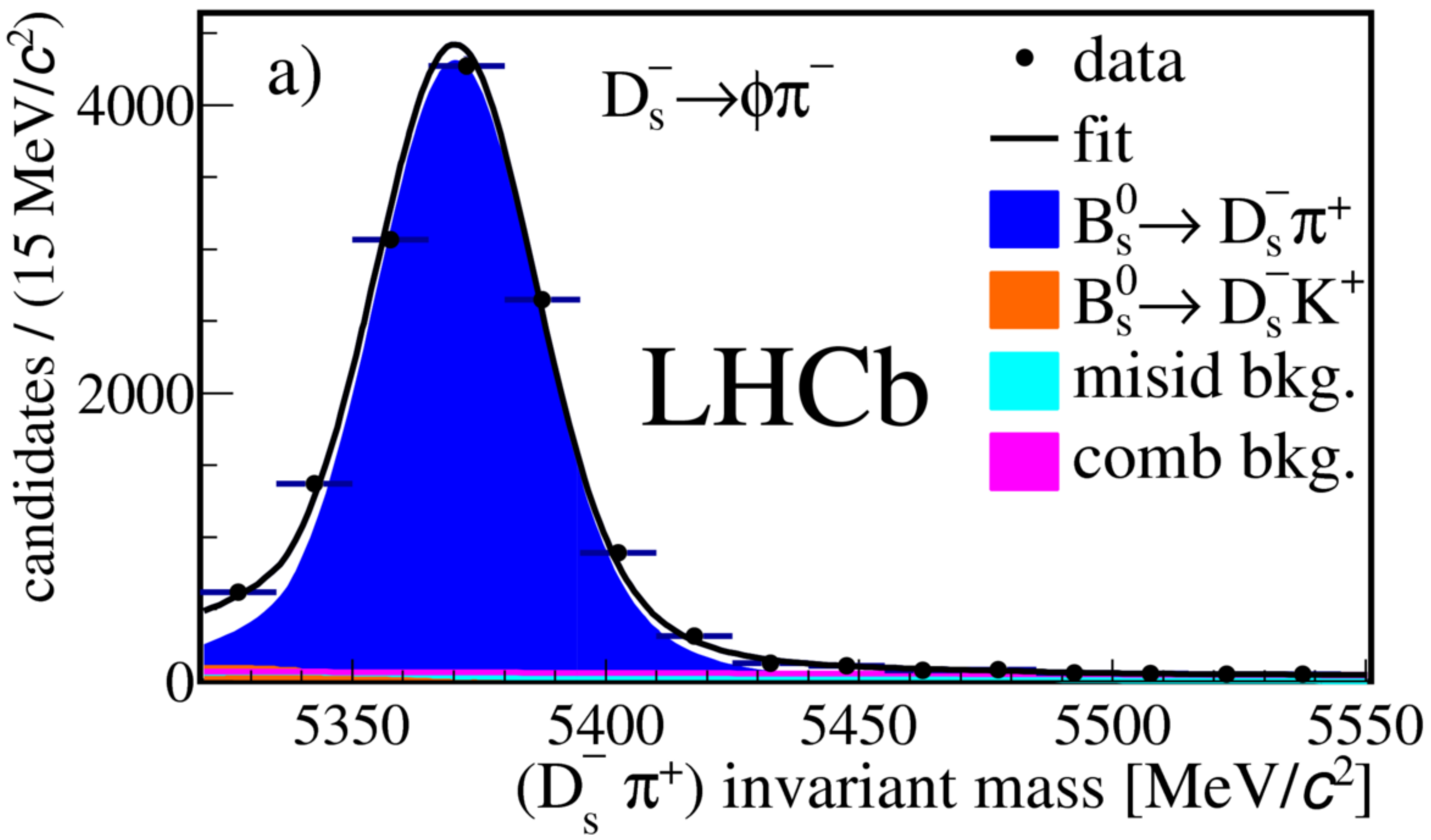
$B^0 \rightarrow D^- \mu^+ \nu_\mu X$

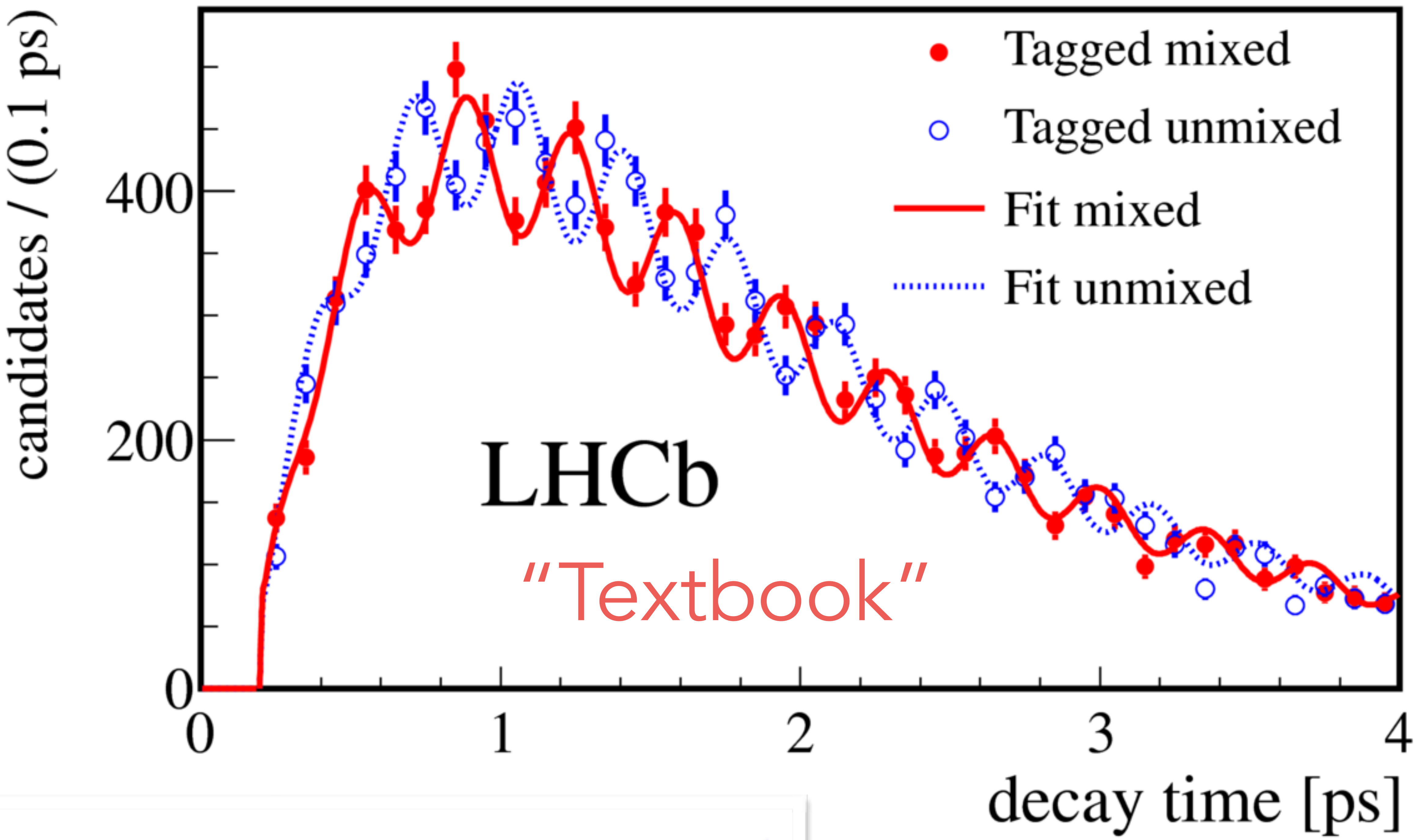
$\Delta m_d = (505.0 \pm 2.1 \pm 1.0)\,\mathrm{ns}^{-1}$

- Huge sample of semileptonic decays.
- Main systematic from B^+ backgrounds.

Neutral B^0_s meson oscillations

[NJP 15 (2013) 053021]





$$\Delta m_s = 17.768 \pm 0.023 \pm 0.006 \ \ \mathrm{ps}^{-1}$$

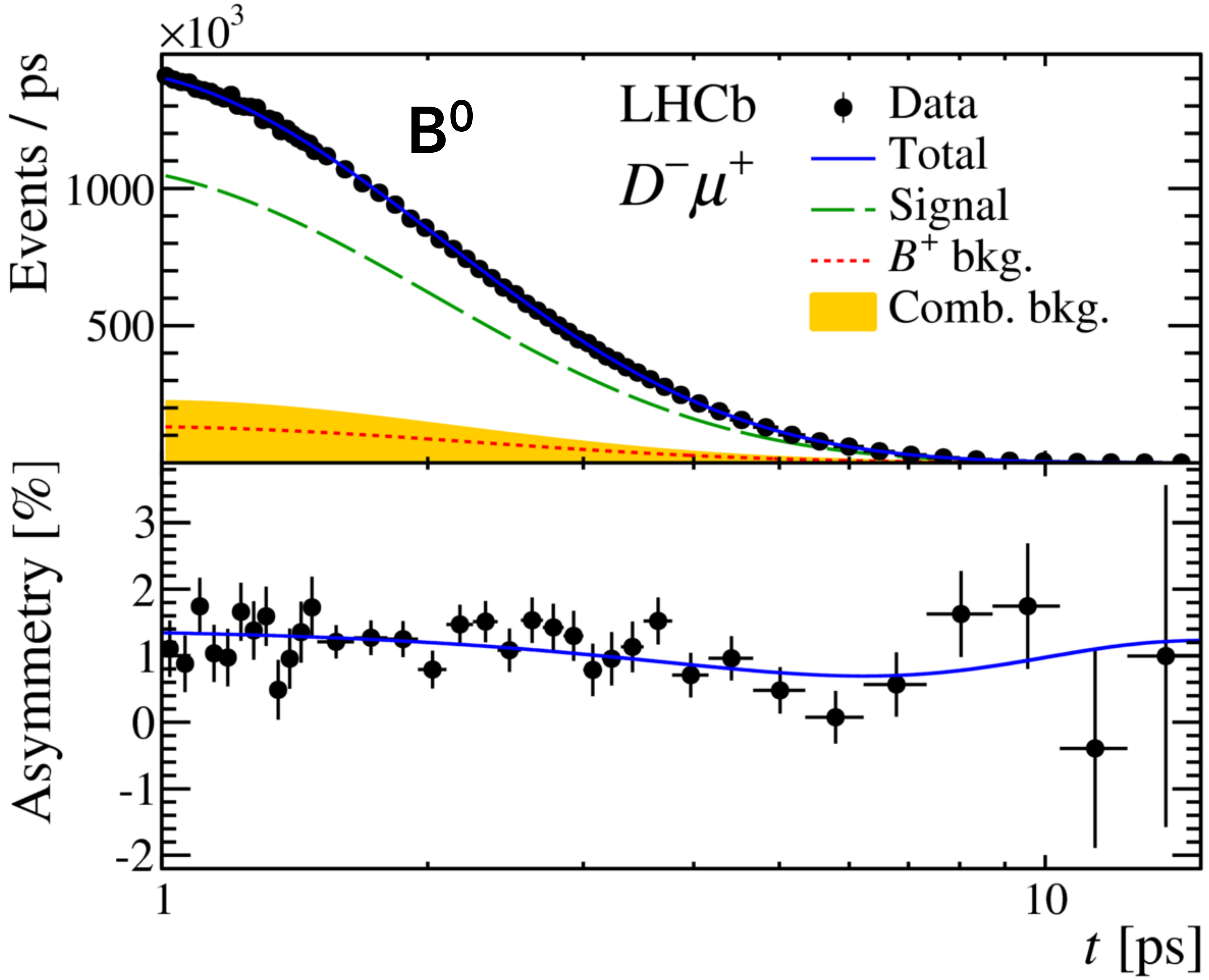
- 34k $B_s^0 \to D_s^- \pi^+$ events, 4 different Ds decay modes.
- Dominant systematic uncertainty from momentum scale of LHCb.

CPV in neutral B meson mixing

- So-called semileptonic asymmetry sensitive to CPV in mixing.
- $B^0 \to D^{(*)-}\mu^+\nu X$ and $B^0_s \to D_s^-\mu^+\nu X$
- Decay-time dependent measurement for B^0, independent for B$_s$.

[PRL 114, 041601 (2015)]

[PRL 117, 061803 (2016)]



$$A_{\rm SL} \equiv \frac{\Gamma(\overline{B^0} \to B^0 \to f) - \Gamma(B^0 \to \overline{B^0} \to \bar{f})}{\Gamma(\overline{B^0} \to B^0 \to f) + \Gamma(B^0 \to \overline{B^0} \to \bar{f})} = \frac{|p/q|^2 - |q/p|^2}{|p/q|^2 + |q/p|^2}$$

[Artuso et al. arXiv:1511.09466] - tiny in SM

$$A^d_{\rm SL} = (-4.1 \pm 0.6) \times 10^{-4}$$
$$A^s_{\rm SL} = (+2.22 \pm 0.27) \times 10^{-5}$$

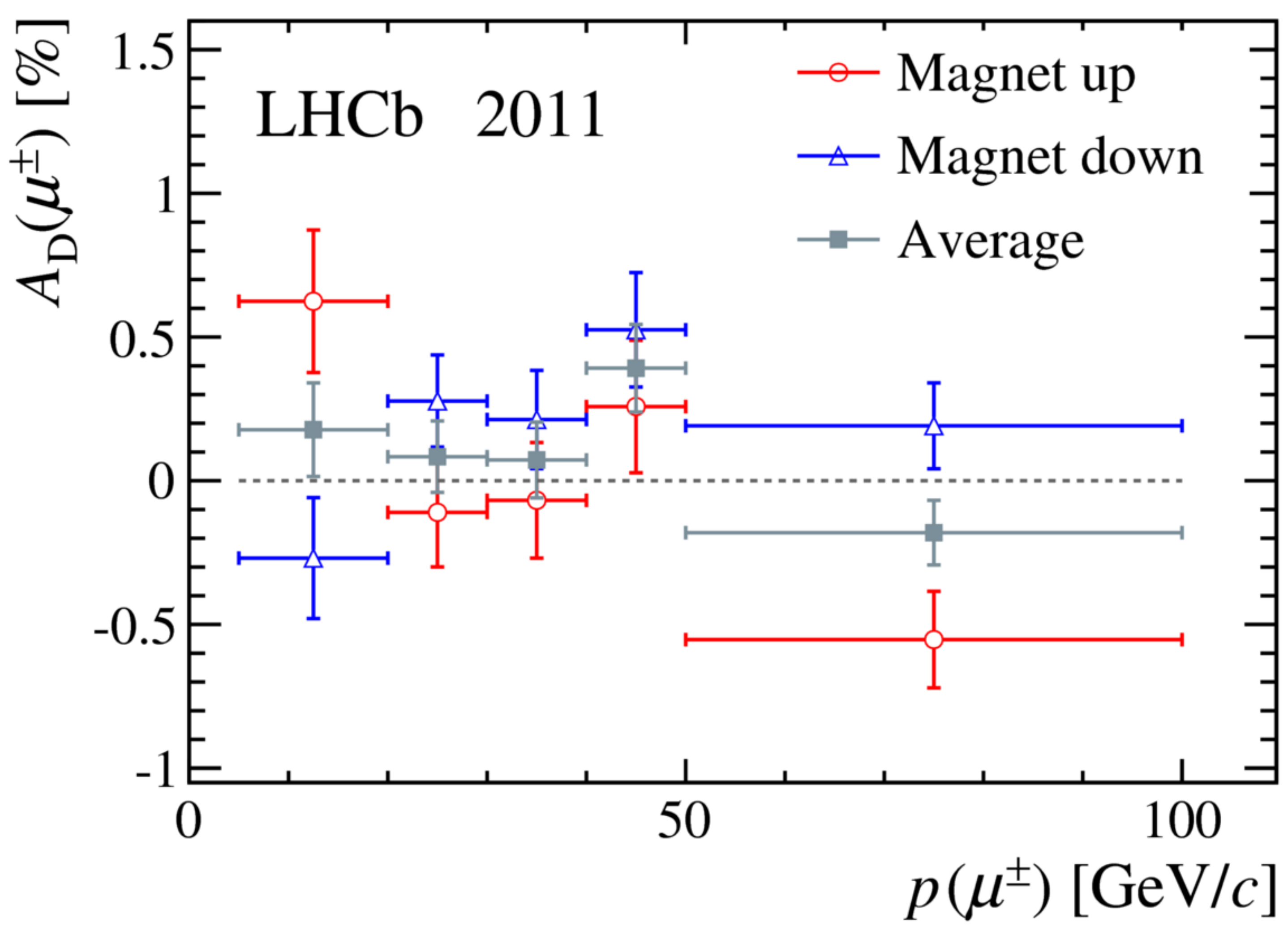
$$A_{\rm meas}(t) = \frac{N(f,t) - N(\bar{f},t)}{N(f,t) + N(\bar{f},t)} = \frac{A_{\rm SL}}{2}\left(1 - \frac{\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2)}\right)$$

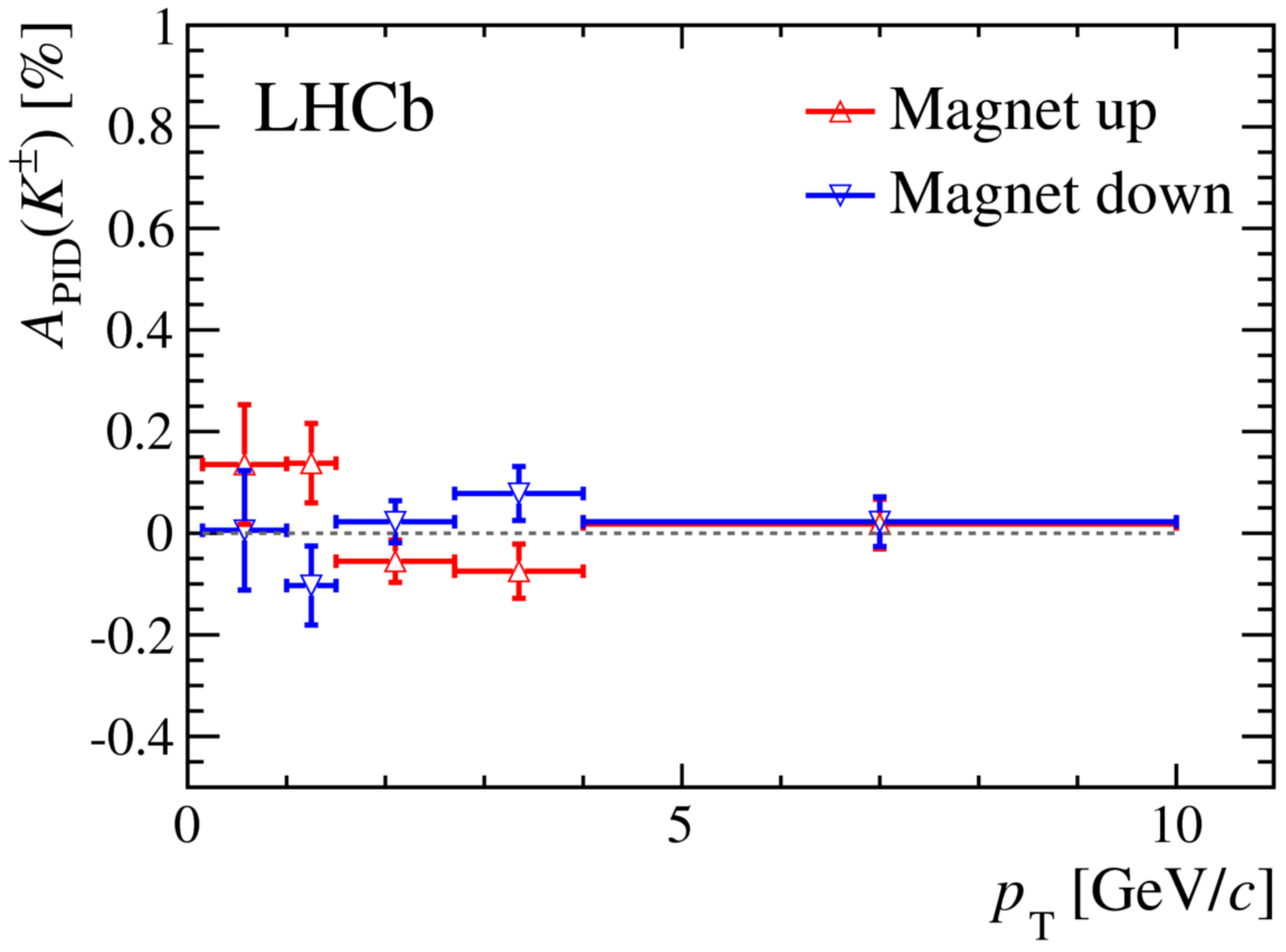
Visible asymmetry only from detector effects

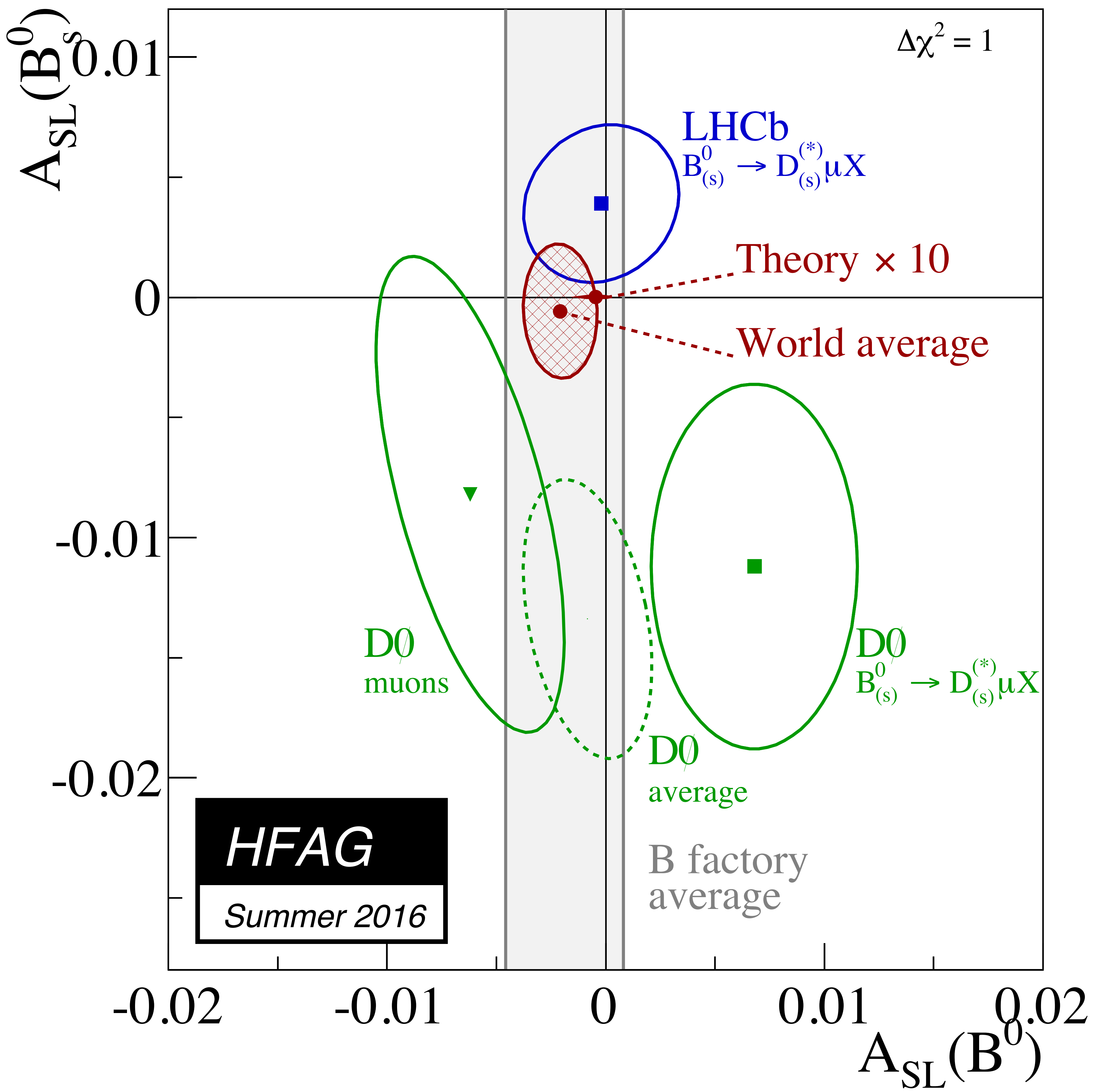
CPV in neutral B meson mixing

- Crucial to understand production and detection asymmetries using control samples
- Reversal of LHCb magnet polarity a big help here!
- Dominant systematic from background

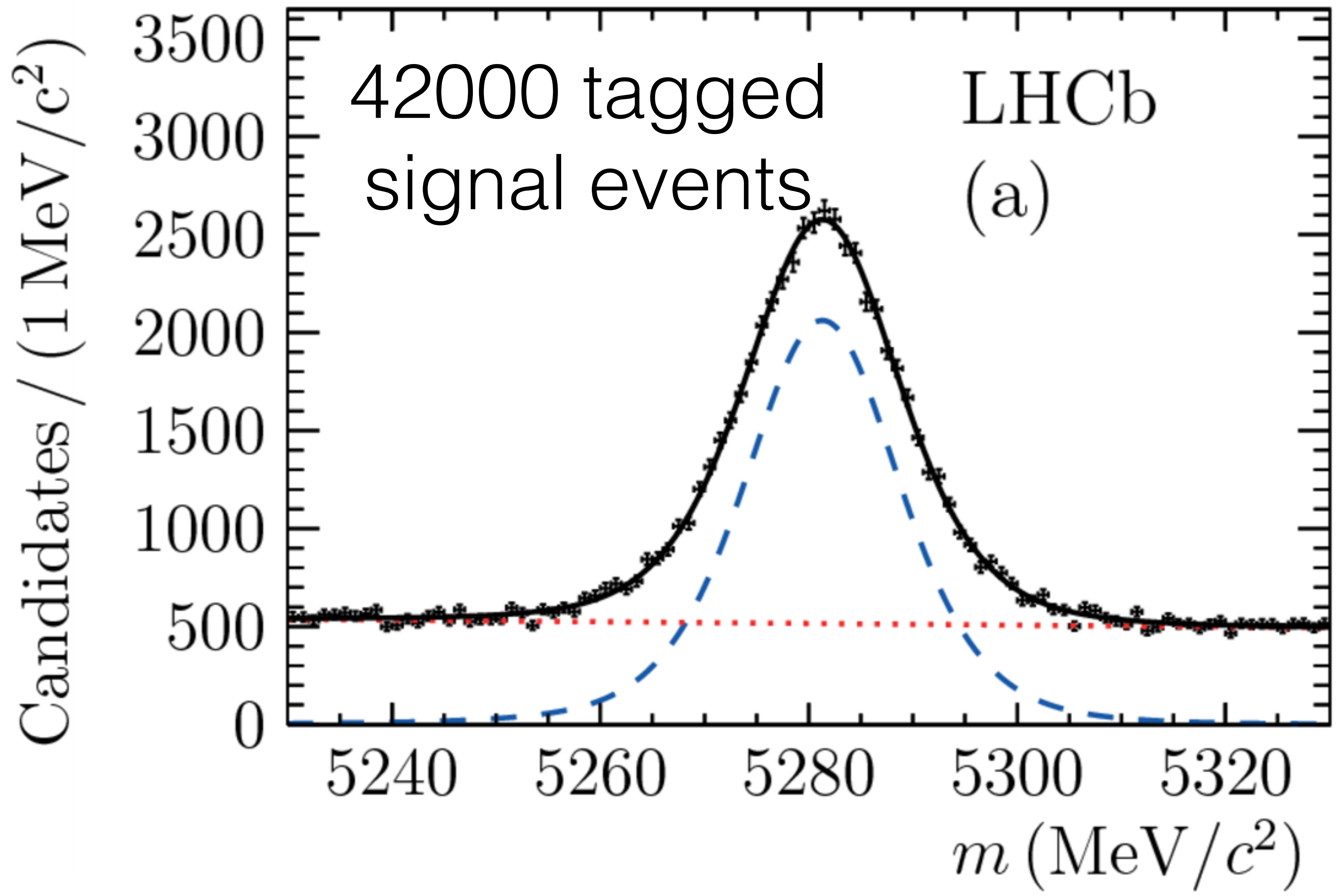
$A_{SL}(B^0)=(-0.02\pm0.19\pm0.30)\%$
$A_{SL}(B_s)=(+0.39\pm0.26\pm0.20)\%$







CP violation in mixing+decay in the B^0 system

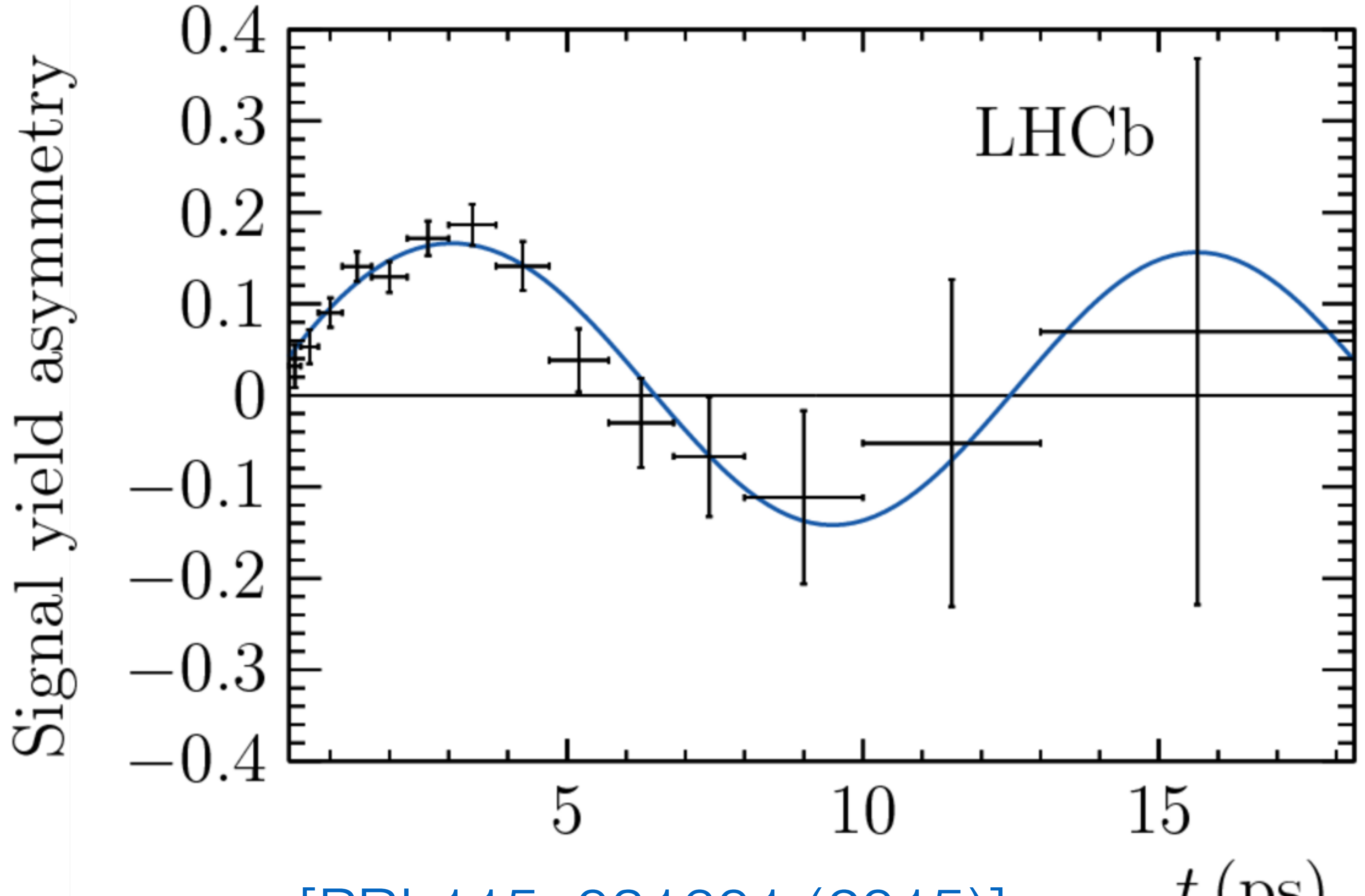


$$A_{CP}(t) \equiv \frac{\Gamma_{\overline{B}^0 \to f} - \Gamma_{B^0 \to f}}{\Gamma_{\overline{B}^0 \to f} + \Gamma_{B^0 \to f}} = \frac{S_f \sin(\Delta m\, t) - C_f \cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + A_{\Delta\Gamma} \sinh(\Delta\Gamma\, t/2)}$$

$$B^0 \to J/\psi K^0_S$$

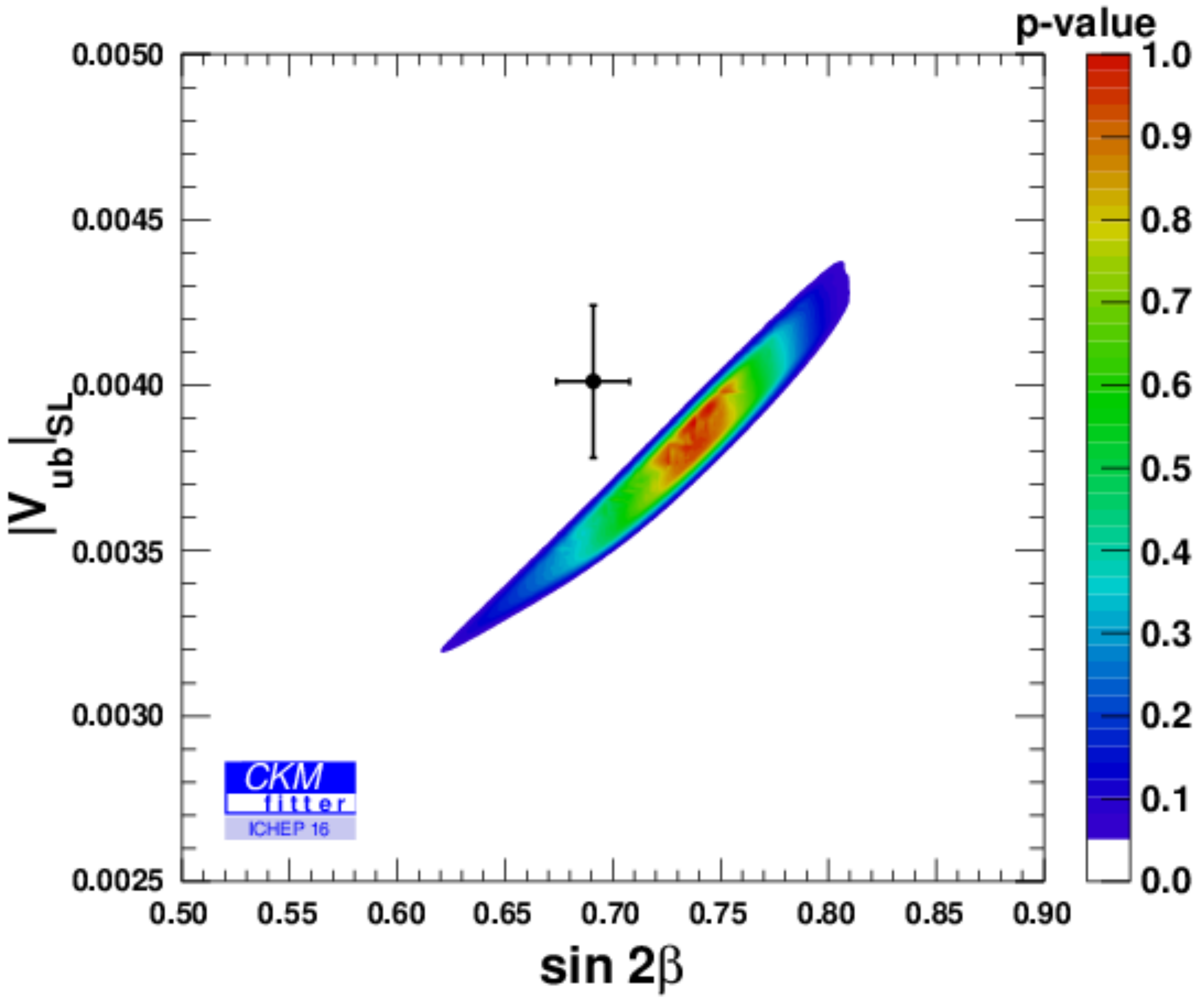
S = +0.731±0.035 (stat) ±0.020 (syst)
C = −0.038±0.032 (stat) ±0.005 (syst)

$$S_{J/\psi\, K^0_S} \approx \sin 2\beta$$

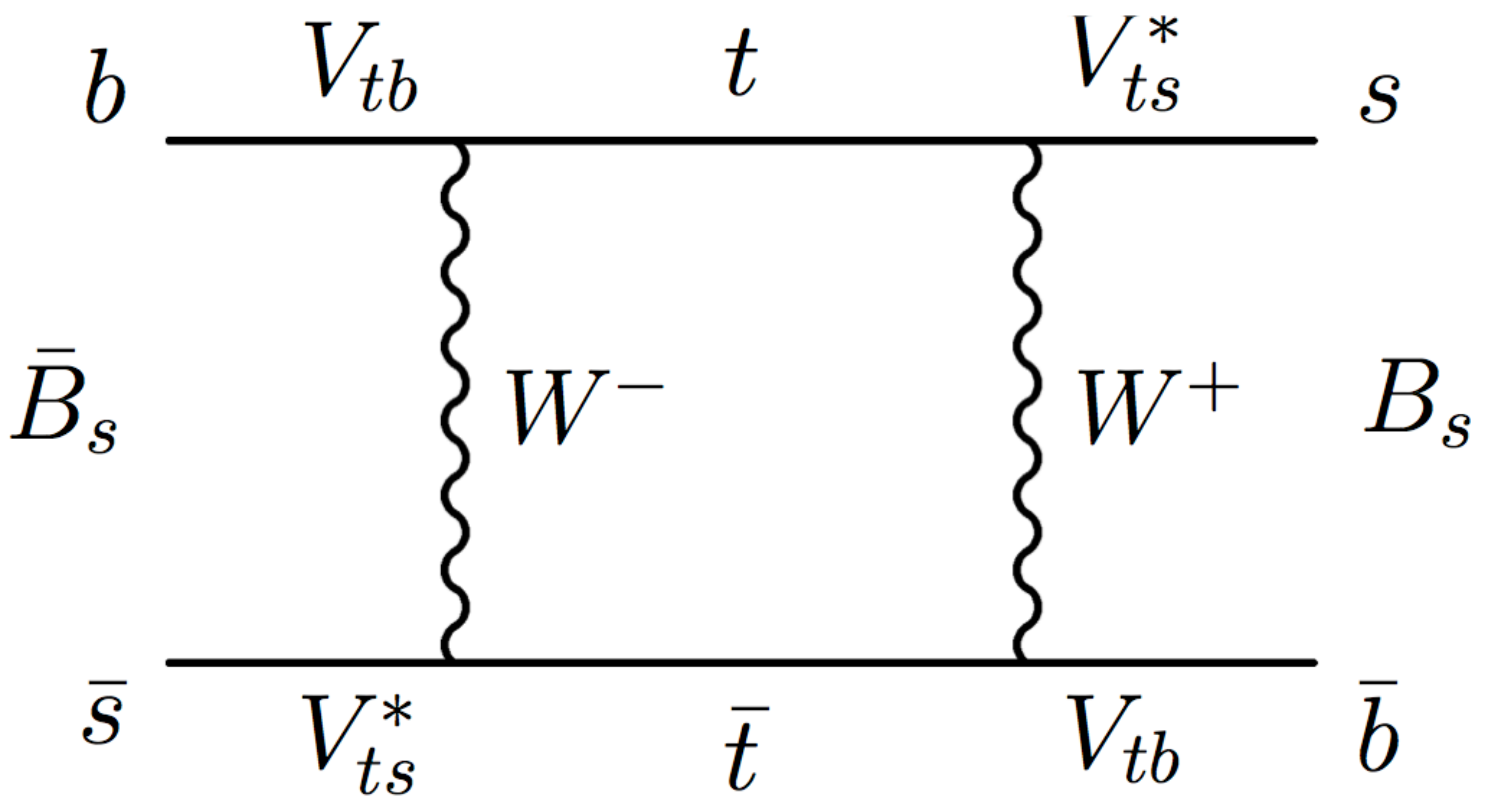


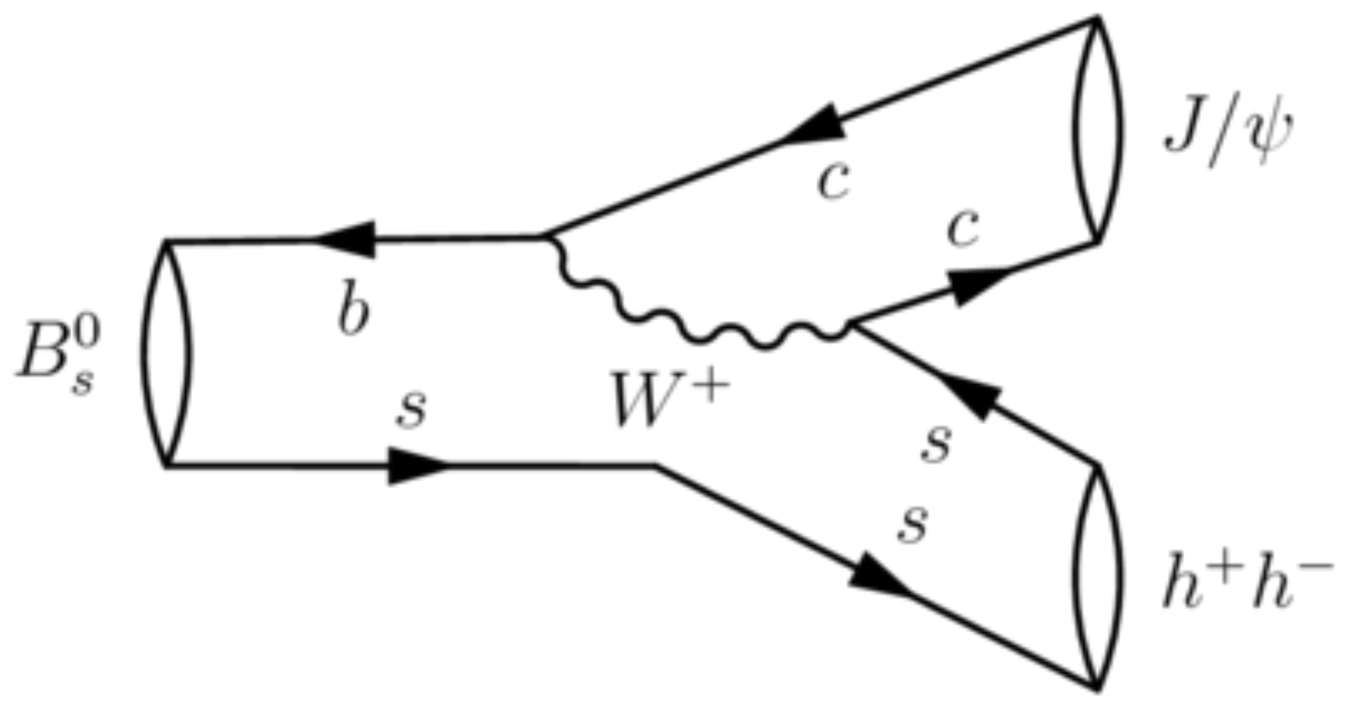
[PRL115, 031601 (2015)]

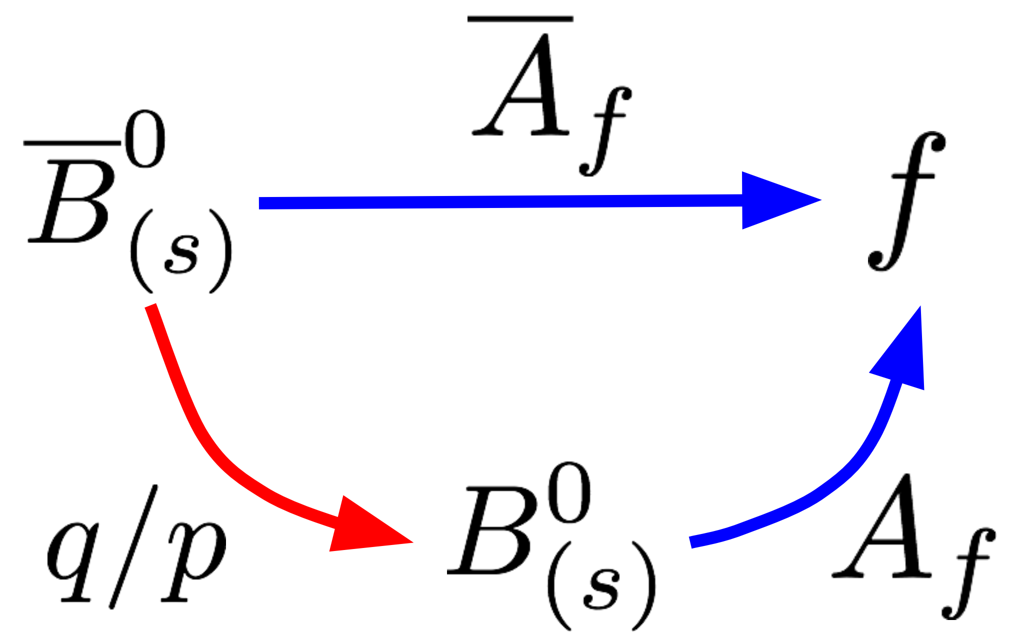
- Similar precision to the B-factories, but LHCb measurement pulled world average up towards indirect determination from global fit



B_s CPV in mixing+decay: ϕ_s







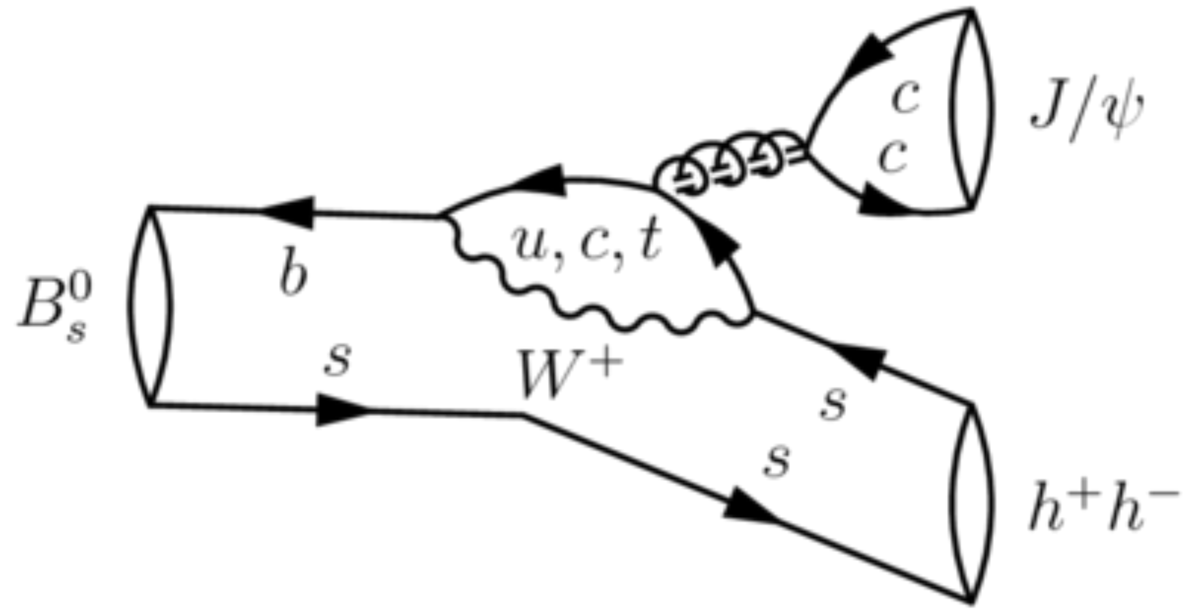
$$\phi_{mix} = 2\,\arg(\mathrm{V_{tb}V_{ts}^*}) \qquad \phi_{dec} = \arg(\mathrm{V_{cb}V_{cs}^*})$$

CP violation in interference between mixing and decay: $\phi_s \equiv -\arg(\lambda_f) \equiv -\arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$

$$\phi_s \overset{\mathrm{SM}}{=} -2\arg\left(-\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right) \equiv -2\beta_s$$

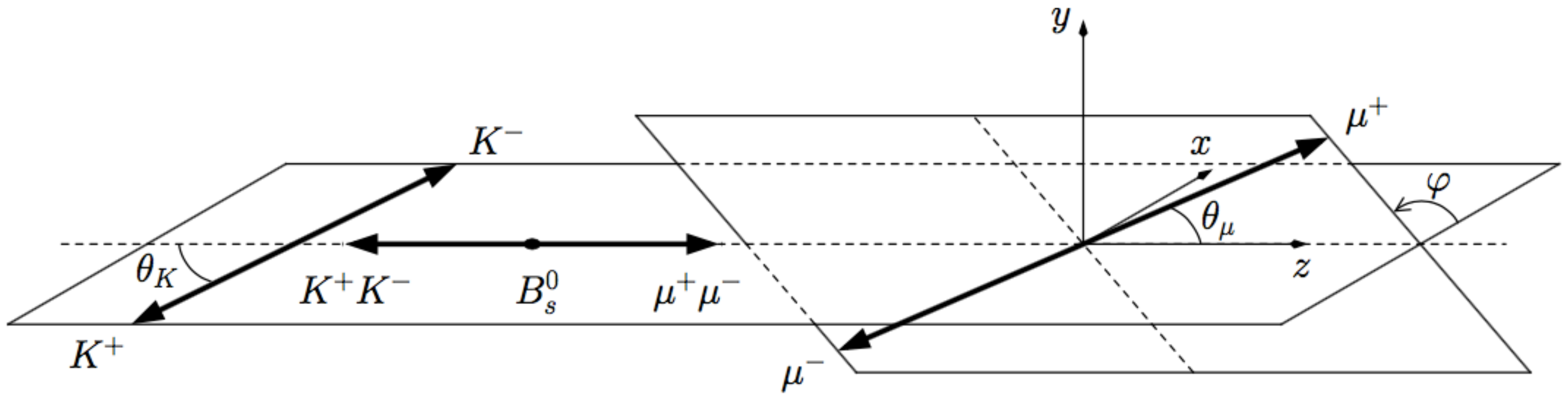
$$\phi_s \overset{\mathrm{SM}}{=} -0.0376 \pm 0.0008\,\mathrm{rad}$$ [CKMFitter]

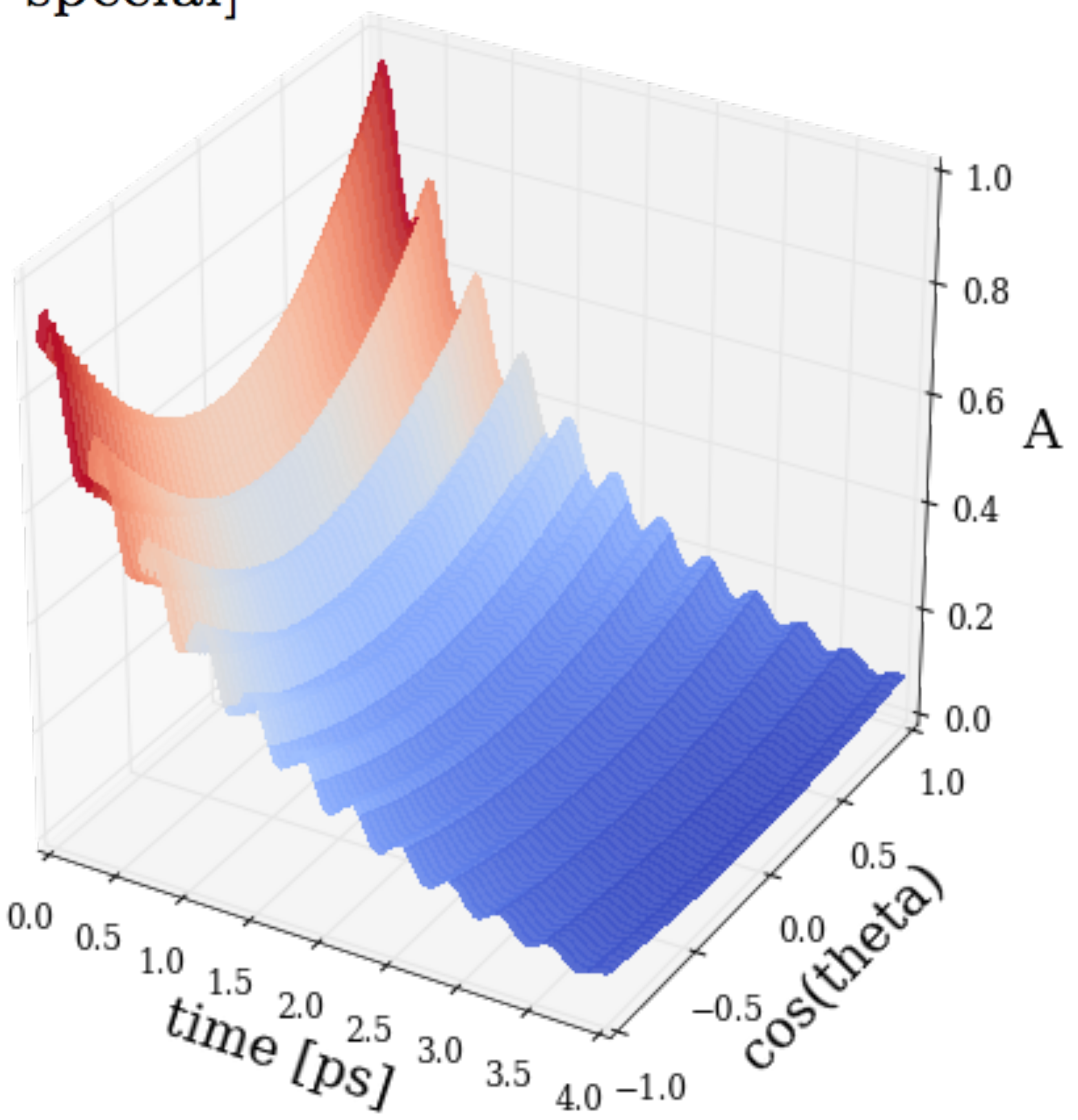
Assuming we ignore sub-leading hadronic contributions

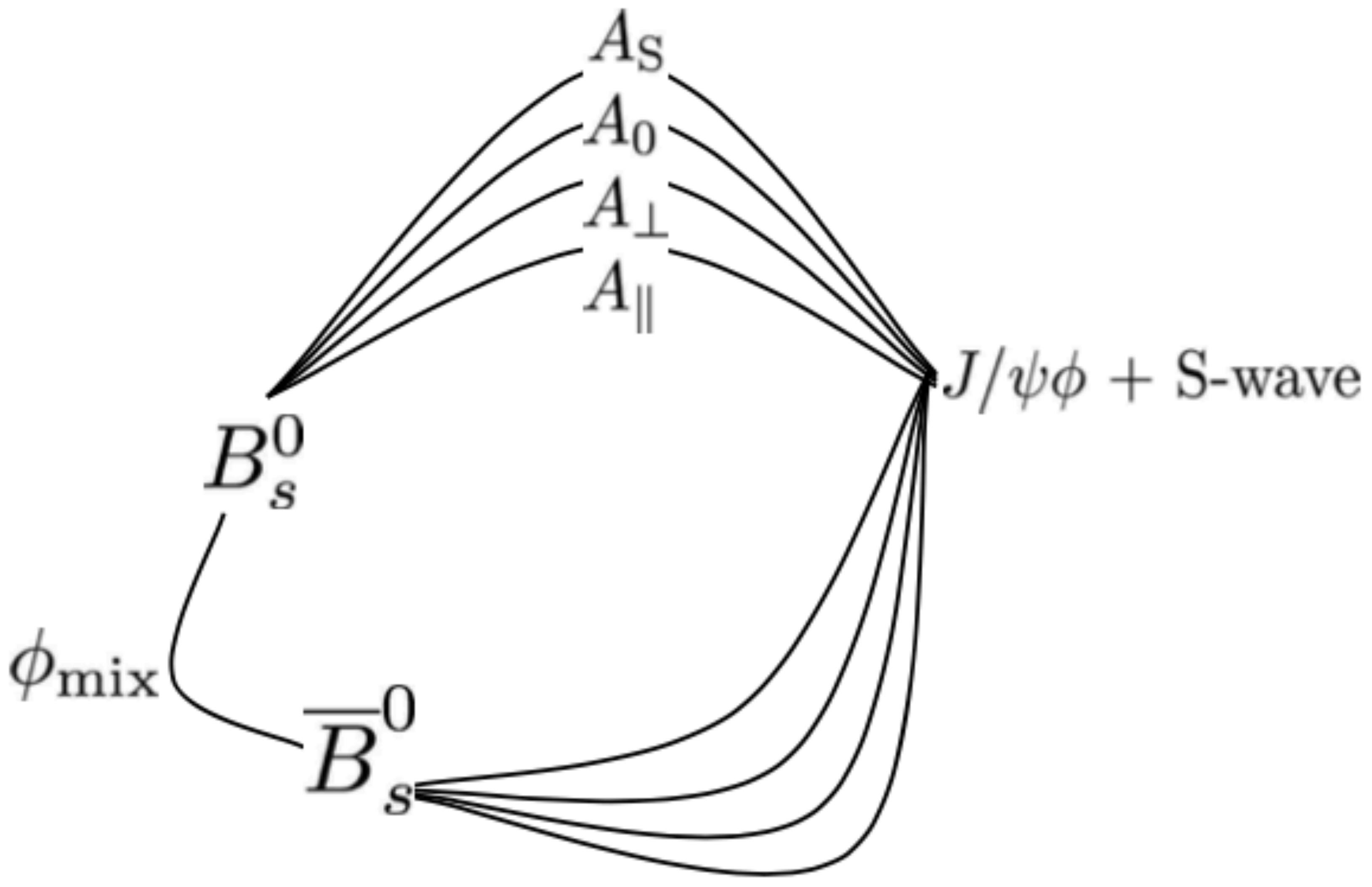


B_s CPV in mixing+decay: ϕ_s

- $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$
- Time-dependent tagged analyses ($\sigma_t \sim 45\,\mathrm{fs}, \varepsilon\mathcal{D}^2 \sim 4\%$).
- $B_s^0 \to J/\psi\,\phi$ is $P \to VV$ decay so use angular information to disentangle CP-odd and CP-even components.
- Measure $\phi_s, \Delta m_s, \Gamma_s, \Delta\Gamma_s, |\lambda_f| \ldots$
  [this makes $B_s^0 \to J/\psi\,\phi$ special]



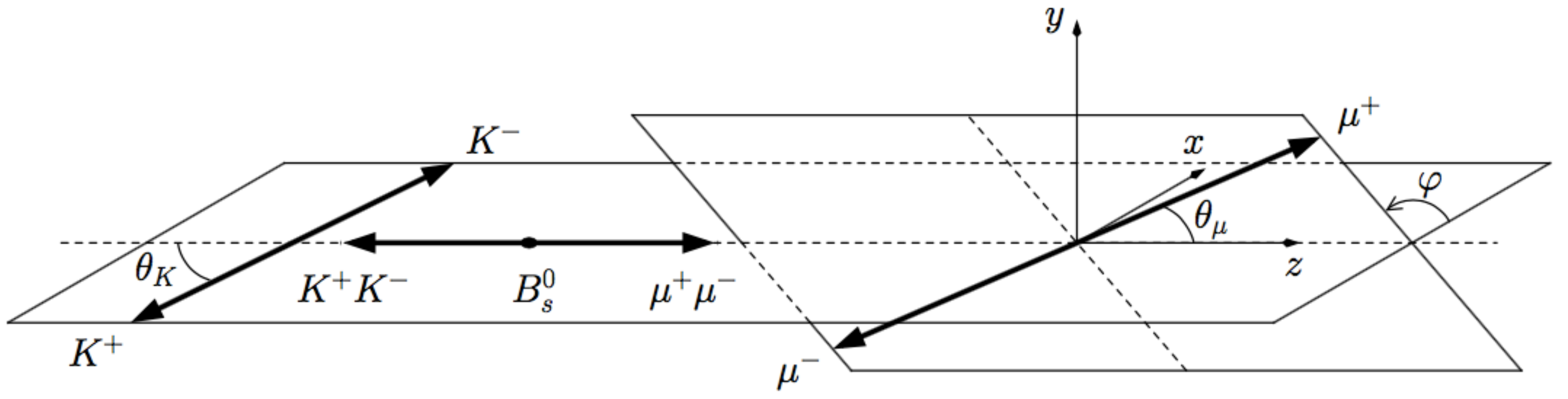


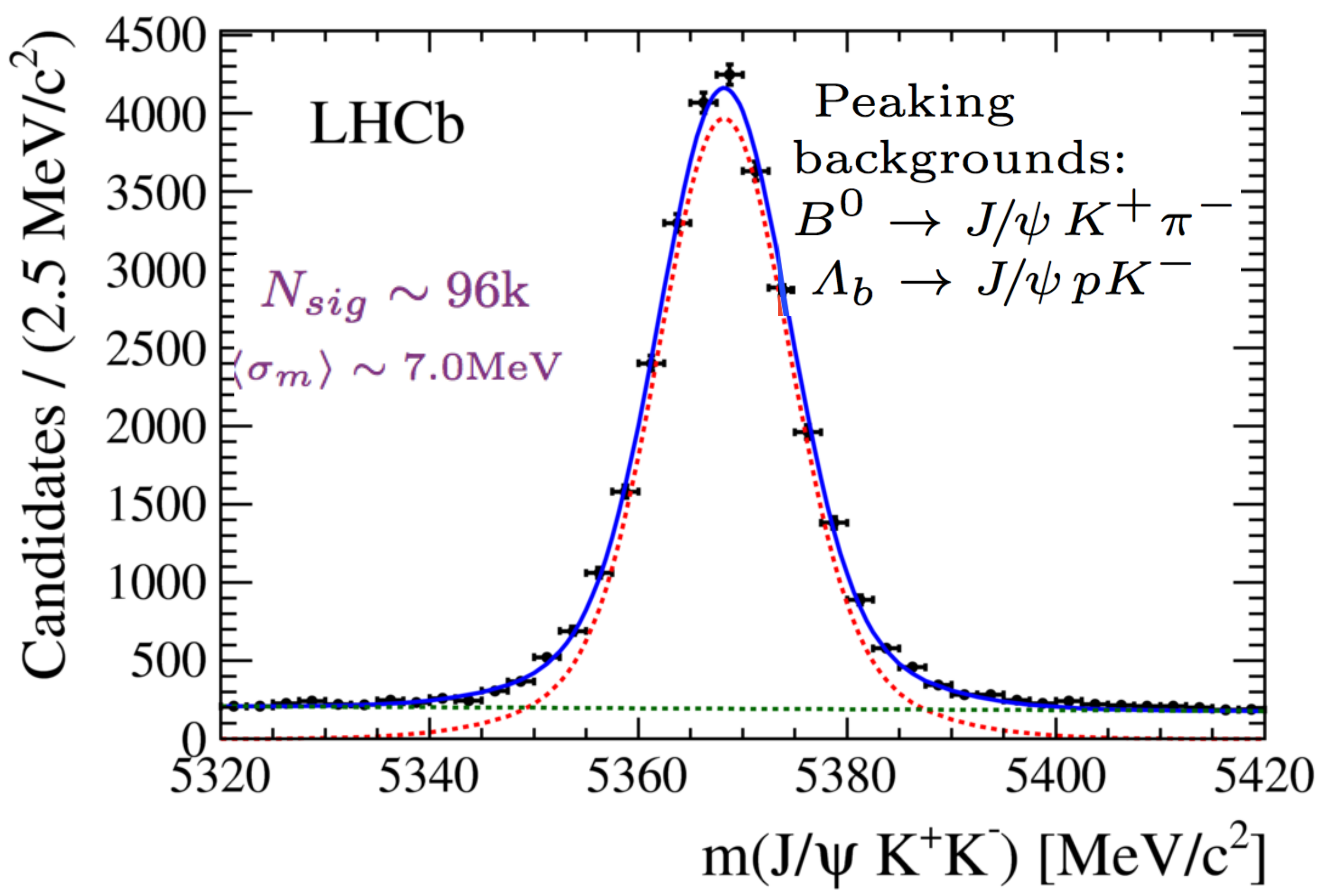


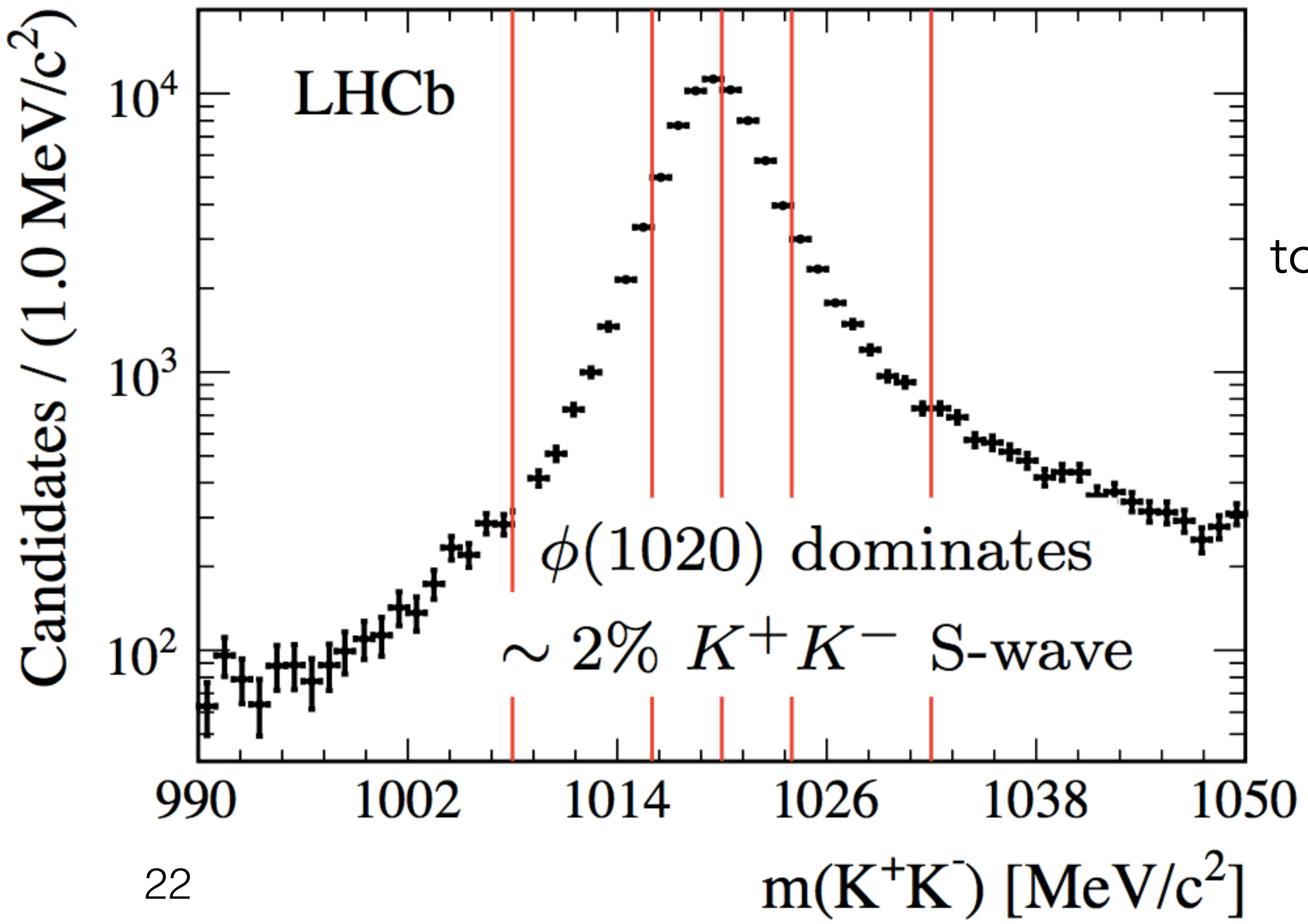
$$\mathrm{CP}|\,\mathrm{J}/\psi\phi\rangle_\ell \quad = \quad (-1)^\ell|\,\mathrm{J}/\psi\phi\rangle_\ell$$

B_s CPV in mixing+decay: ϕ_s

- $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$
- Time-dependent tagged analyses ($\sigma_t \sim 45\,\mathrm{fs}, \varepsilon\mathcal{D}^2 \sim 4\%$).
- $B_s^0 \to J/\psi\,\phi$ is $P \to VV$ decay so use angular information to disentangle *CP*-odd and *CP*-even components.
- Measure $\phi_s, \Delta m_s, \Gamma_s, \Delta\Gamma_s, |\lambda_f| \ldots$
  [this makes $B_s^0 \to J/\psi\,\phi$ special]

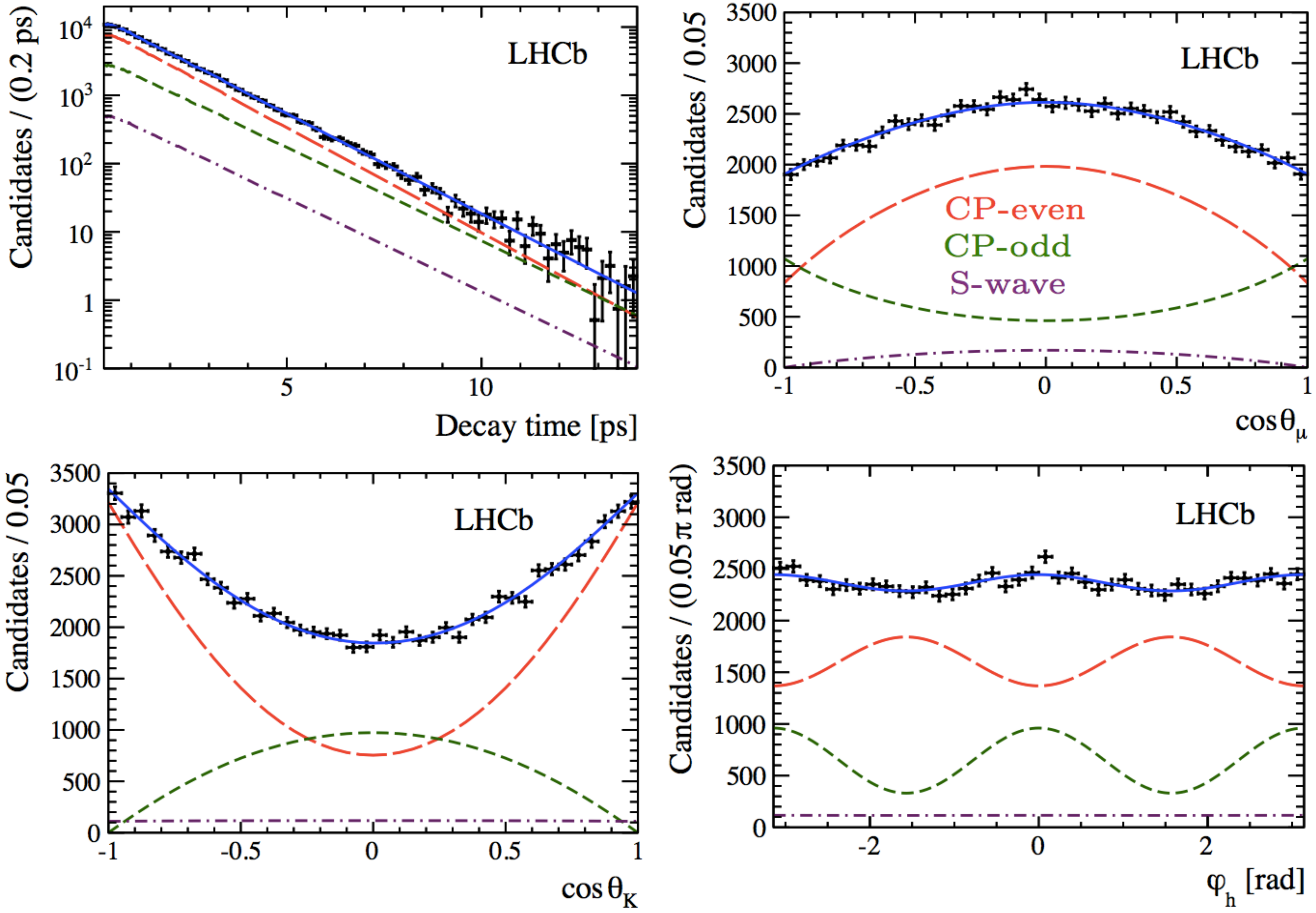






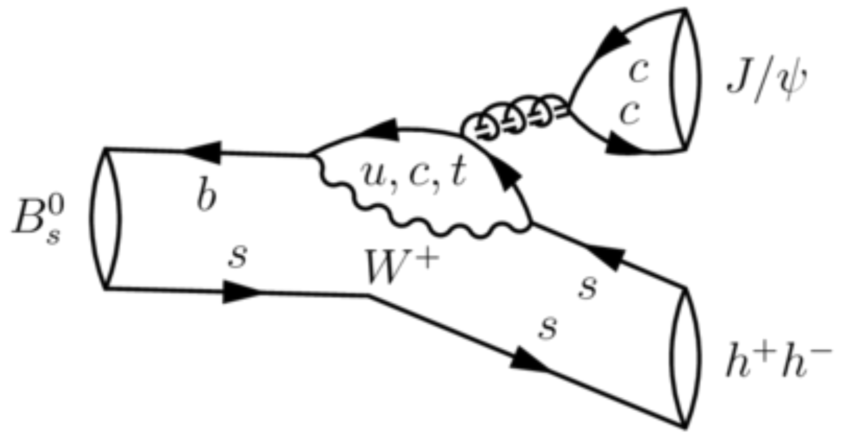
Make flavour tagged decay-time dependent angular fit in 6 bins of mKK to account for KK S-wave

B_s CPV in mixing+decay: φs



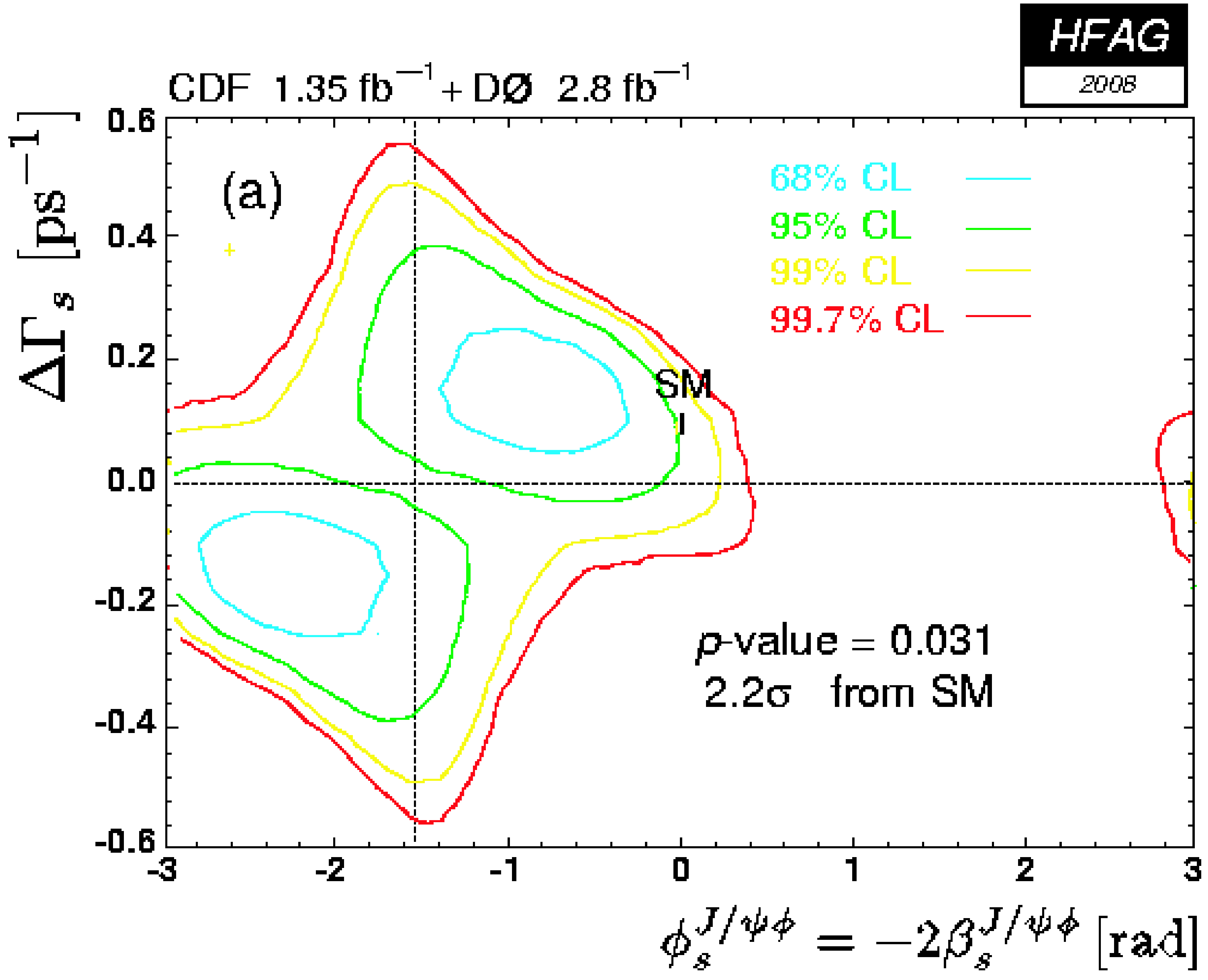
ϕ_s	$-0.058 \pm 0.049 \pm 0.006$ rad
$\lvert\lambda\rvert$	$0.964 \pm 0.019 \pm 0.007$
Γ_s	$0.6603 \pm 0.0027 \pm 0.0015\ \mathrm{ps}^{-1}$
$\Delta\Gamma_s$	$0.0805 \pm 0.0091 \pm 0.0032\ \mathrm{ps}^{-1}$
Δm_s	$17.711\ ^{+0.055}_{-0.057} \pm 0.011\ \mathrm{ps}^{-1}$

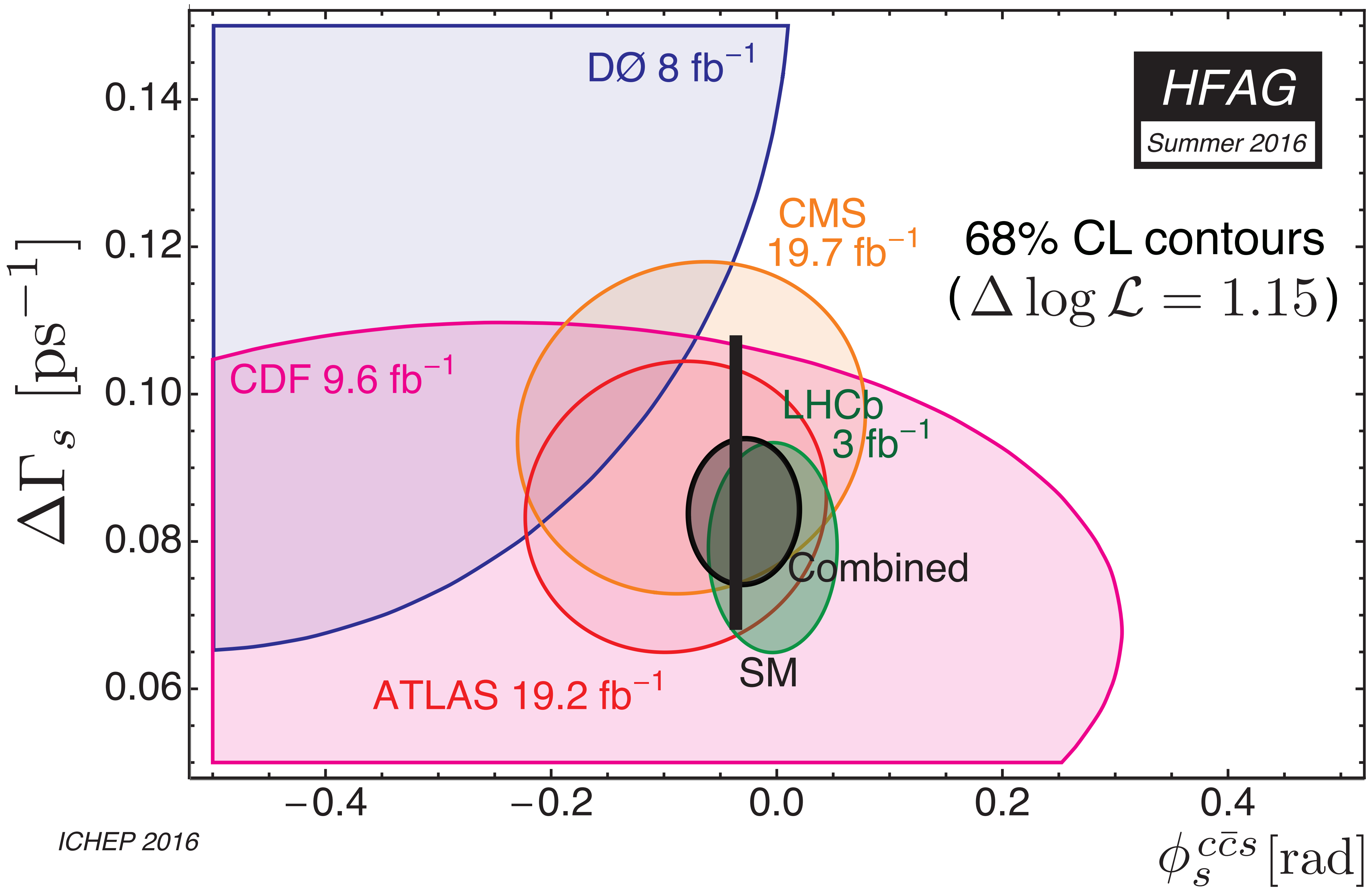
- Everything consistent with the SM
- Dominant sysmtematics from decay-time and angular efficiencies
- No sign of polarisation dependent φs
  - Penguin pollution likely to be small



[PRL 114 (2015) 041801]

ϕ_s-$\Delta\Gamma_s$ global combination





$$\sigma(\phi_s) \sim \pm 0.400 \text{ rad}$$
$$\sigma(\Delta\Gamma_s) \sim \pm 0.060 \text{ ps}^{-1}$$

$$\phi_s = -0.030 \pm 0.033 \text{ rad}$$
$$\Delta\Gamma_s = 0.086 \pm 0.006 \, \text{ps}^{-1}$$

Dominated by LHCb [PRL 114 (2015) 041801]

Unfortunately, new physics not a large effect…

Important to control size of unknown hadronic

φs from charmless B decays

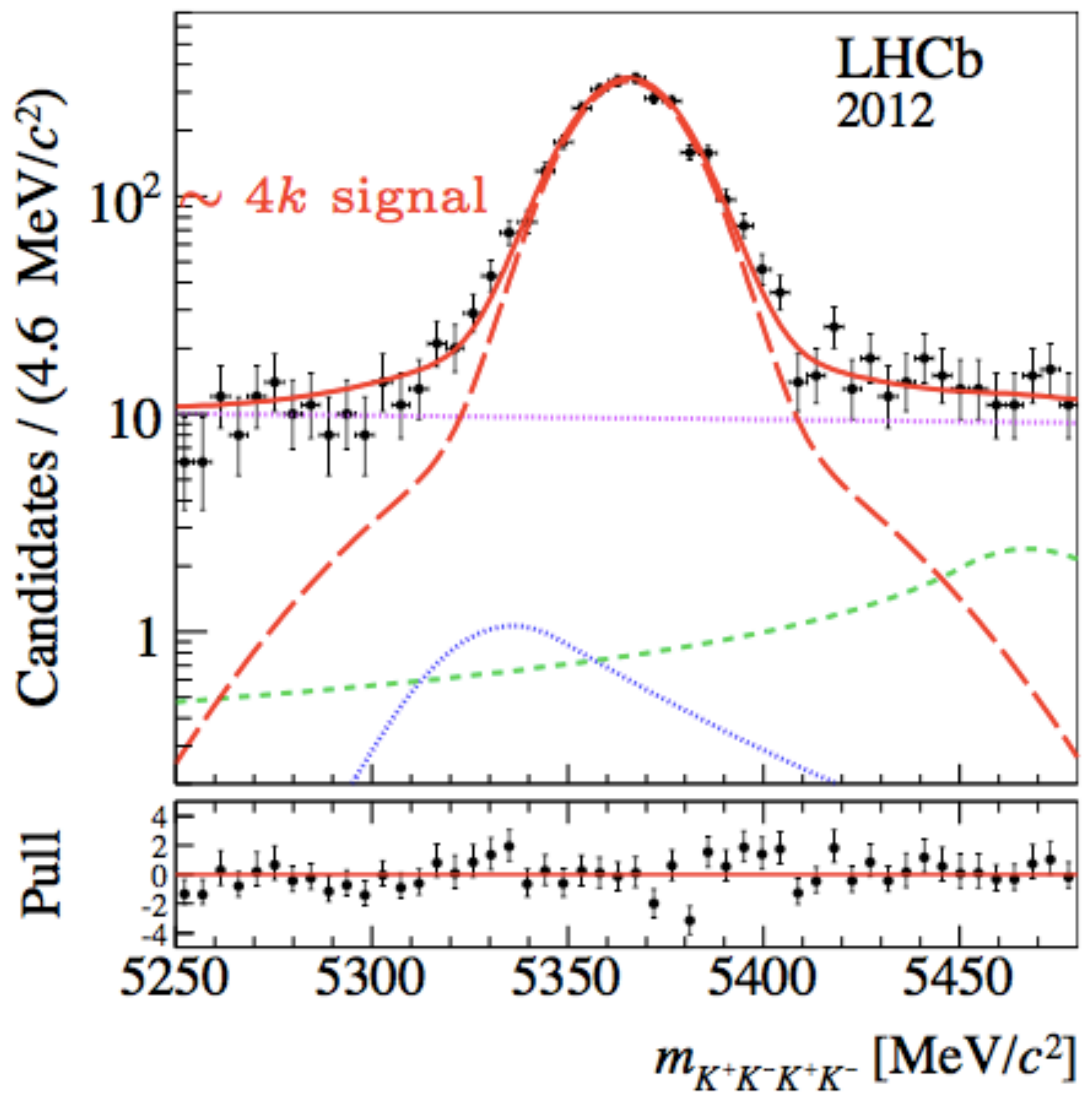
- $B_s^0 \to \phi\phi$: $b \to s$ penguin decays sensitive to NP in the loops.
- $\phi \to KK$: 5 different polarisation amplitudes $\Rightarrow$ angular analysis.
- Decay time resolution: ~ 43 fs.
- Tagging power: $\varepsilon(1-2\omega)^2 = 3.04 \pm 0.24\%$
- Angular efficiency from MC.

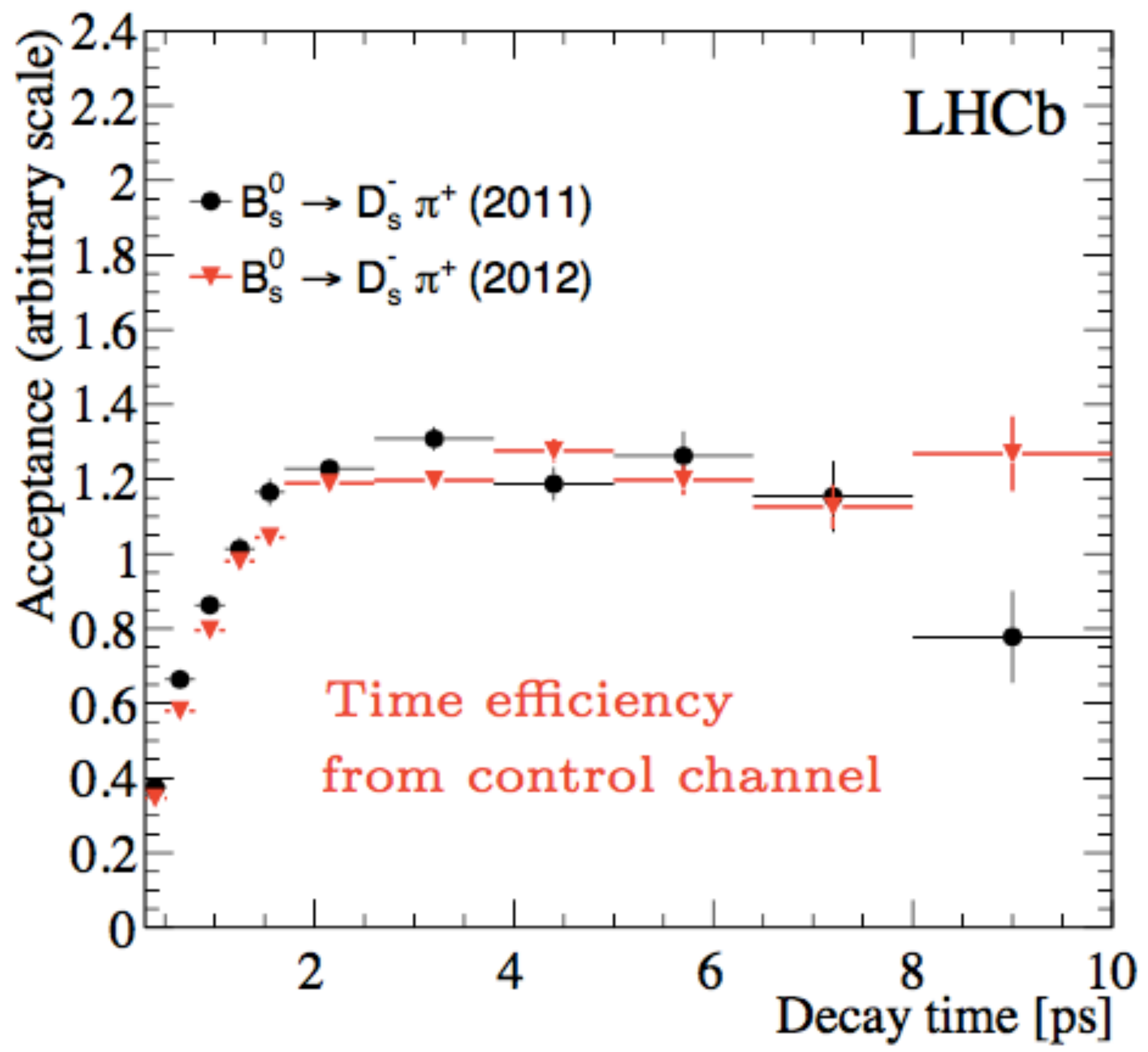
$$|\phi_s^{s\bar{s}s}|^{\mathrm{SM}} < 0.02\,\mathrm{rad}$$

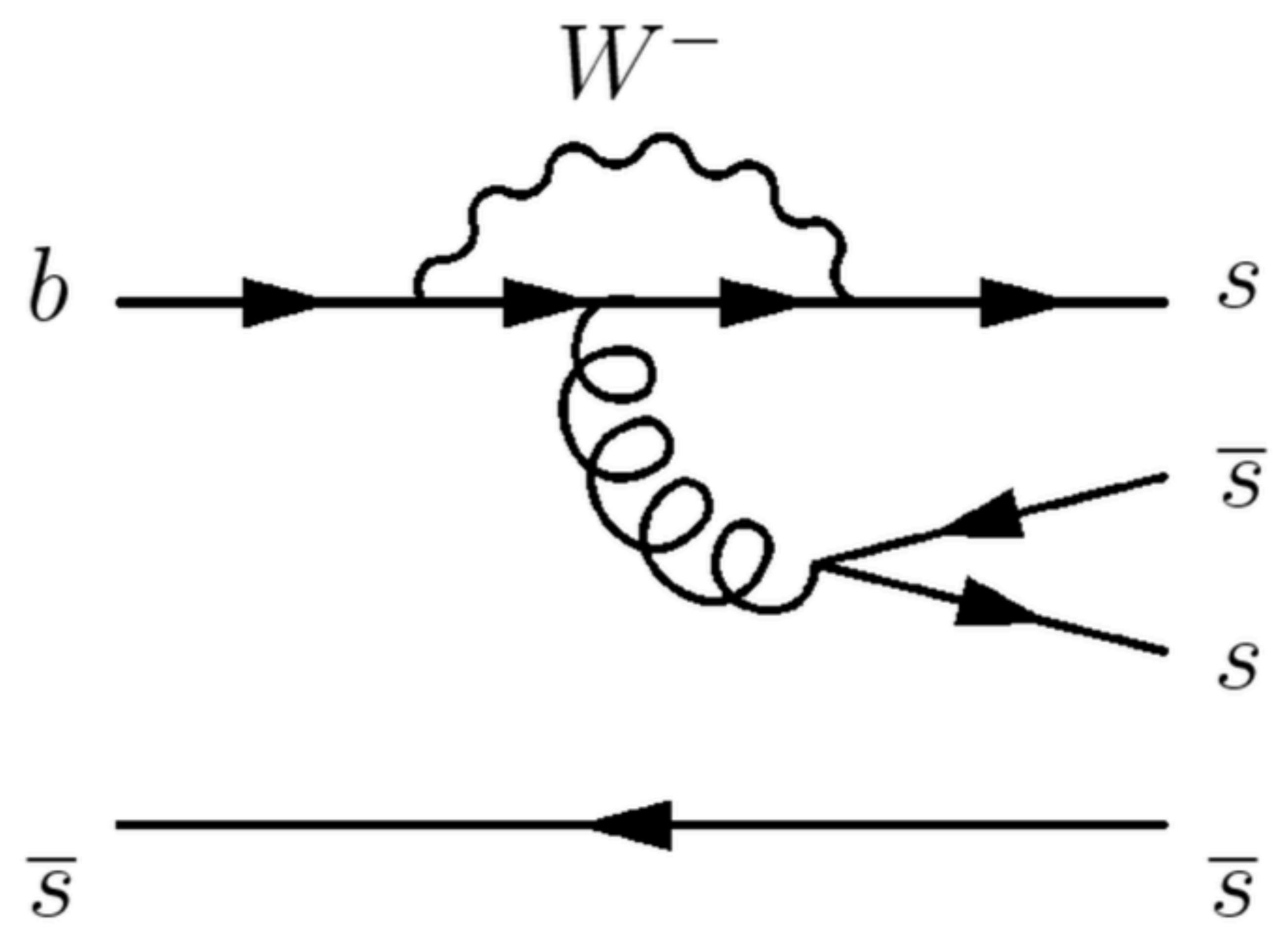
[Bartsch et al. arXiv:0810.0249]

[Beneke et al. NPB 774 (2007) 64-101]

[Cheng et al. PRD 80 (2009) 114026]





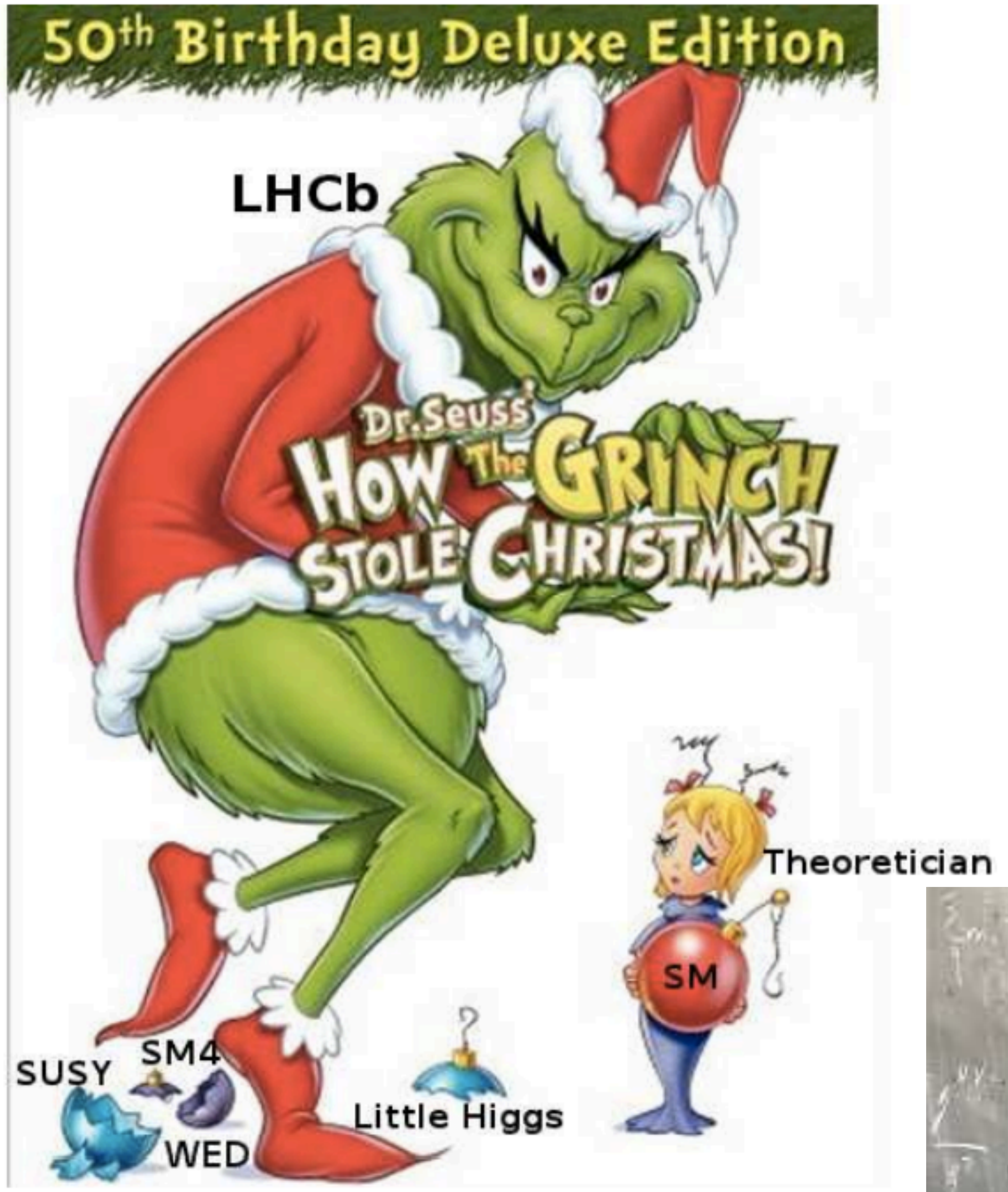


$\phi_s^{s\bar{s}s}$ [rad]	$-0.17 \pm 0.15 \pm 0.03$
$\lvert\lambda\rvert$	$1.04 \pm 0.07 \pm 0.03$

[PRD 90 (2014) 052011]

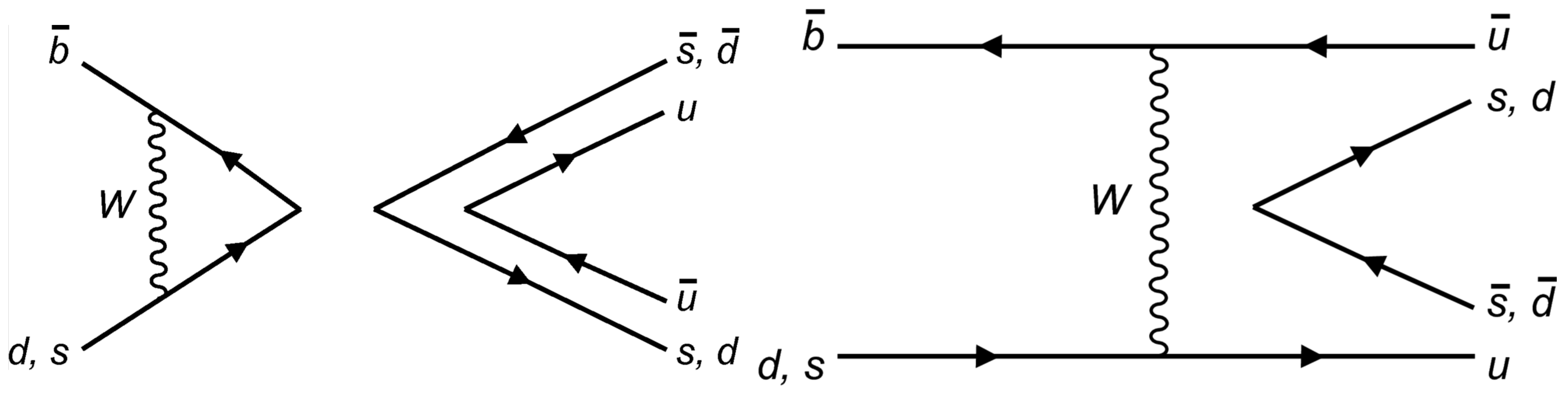
As an aside...

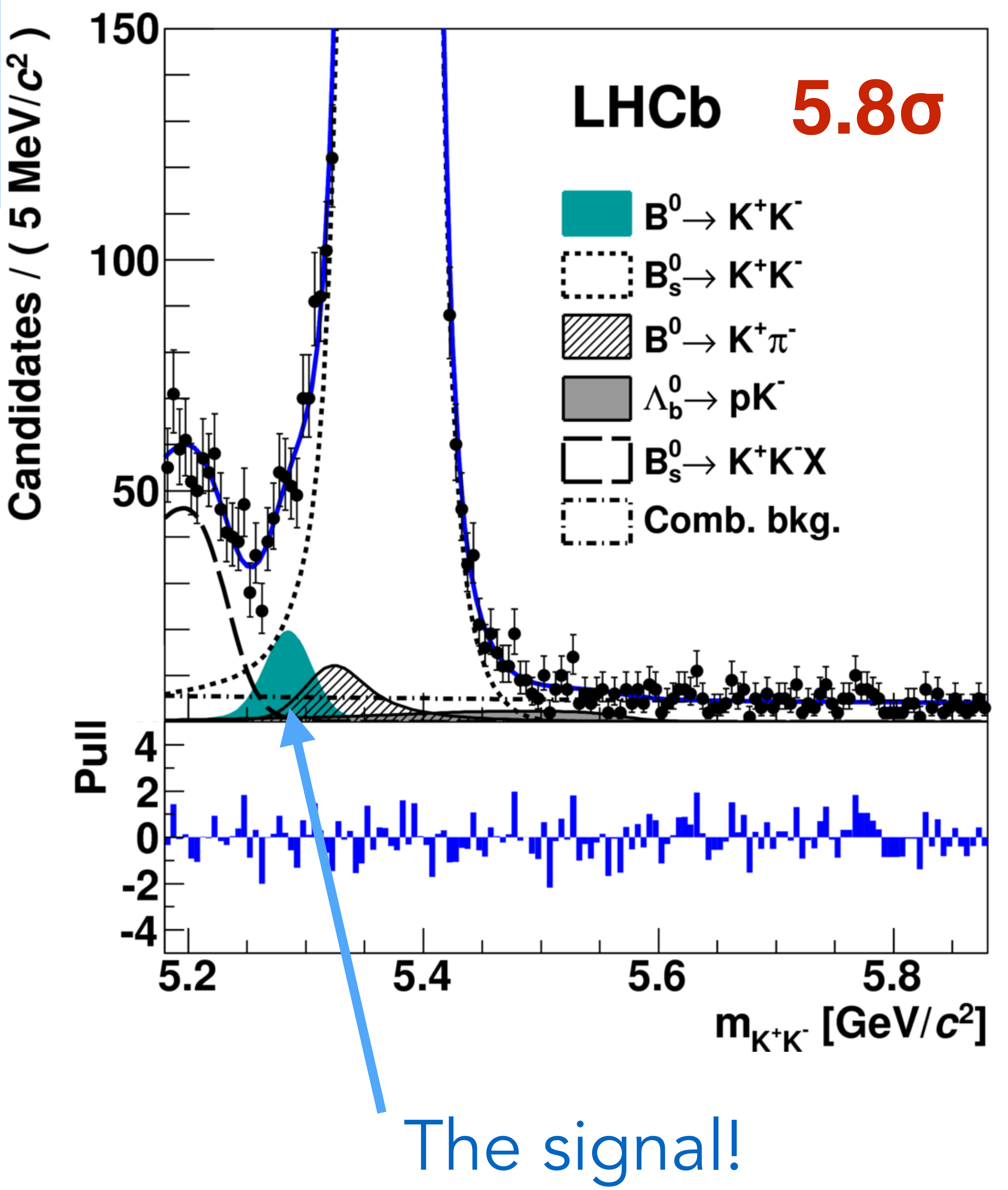
- When LHCb Run 1 results started to appear, the space for new physics contributions started to shrink, which prompted this response from certain theorists…



Lepton-Photon 2011

Charmless rare decays





Requires excellent RICH PID

- Particular class of decays that can proceed only through so-called annihilation diagrams
- B0->K+K- decay observed for the first time after many years of searches.
- This is the rarest B meson decay to a fully hadronic final state

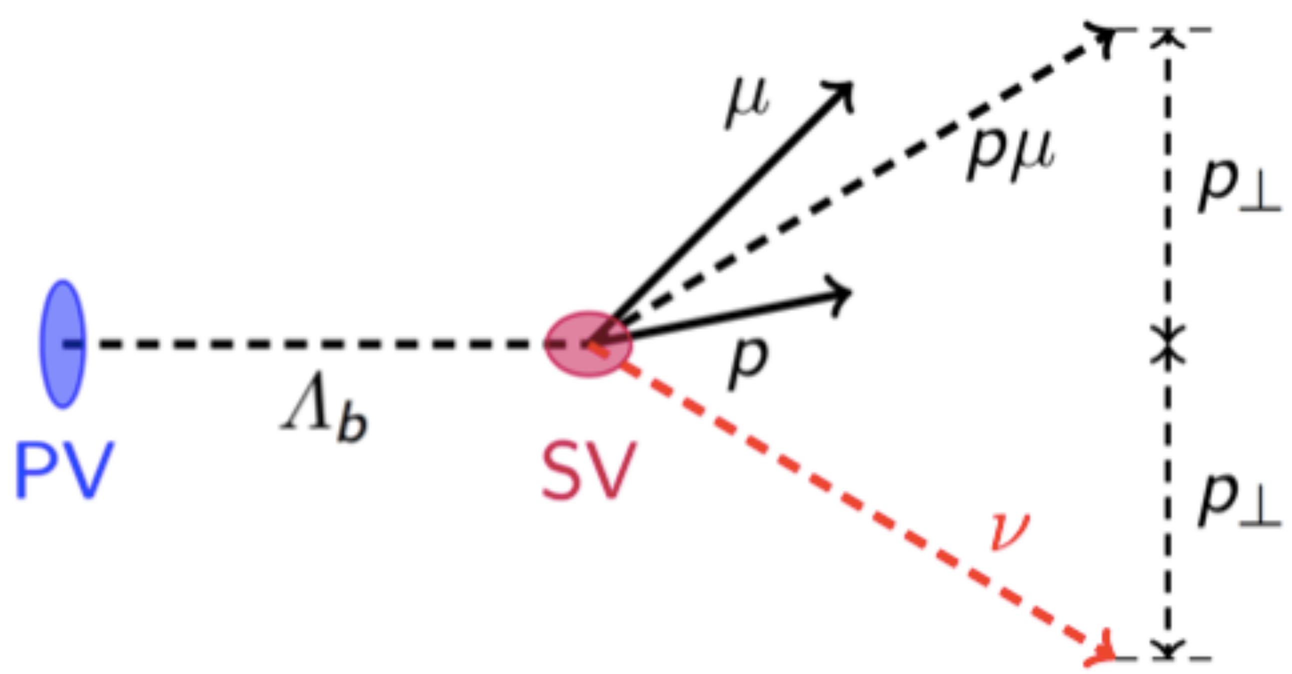
$$\mathcal{B}(B^0 \to K^+K^-) = (7.80 \pm 1.27 \pm 0.81 \pm 0.21) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \pi^+\pi^-) = (6.91 \pm 0.54 \pm 0.63 \pm 0.19 \pm 0.40) \times 10^{-7}$$

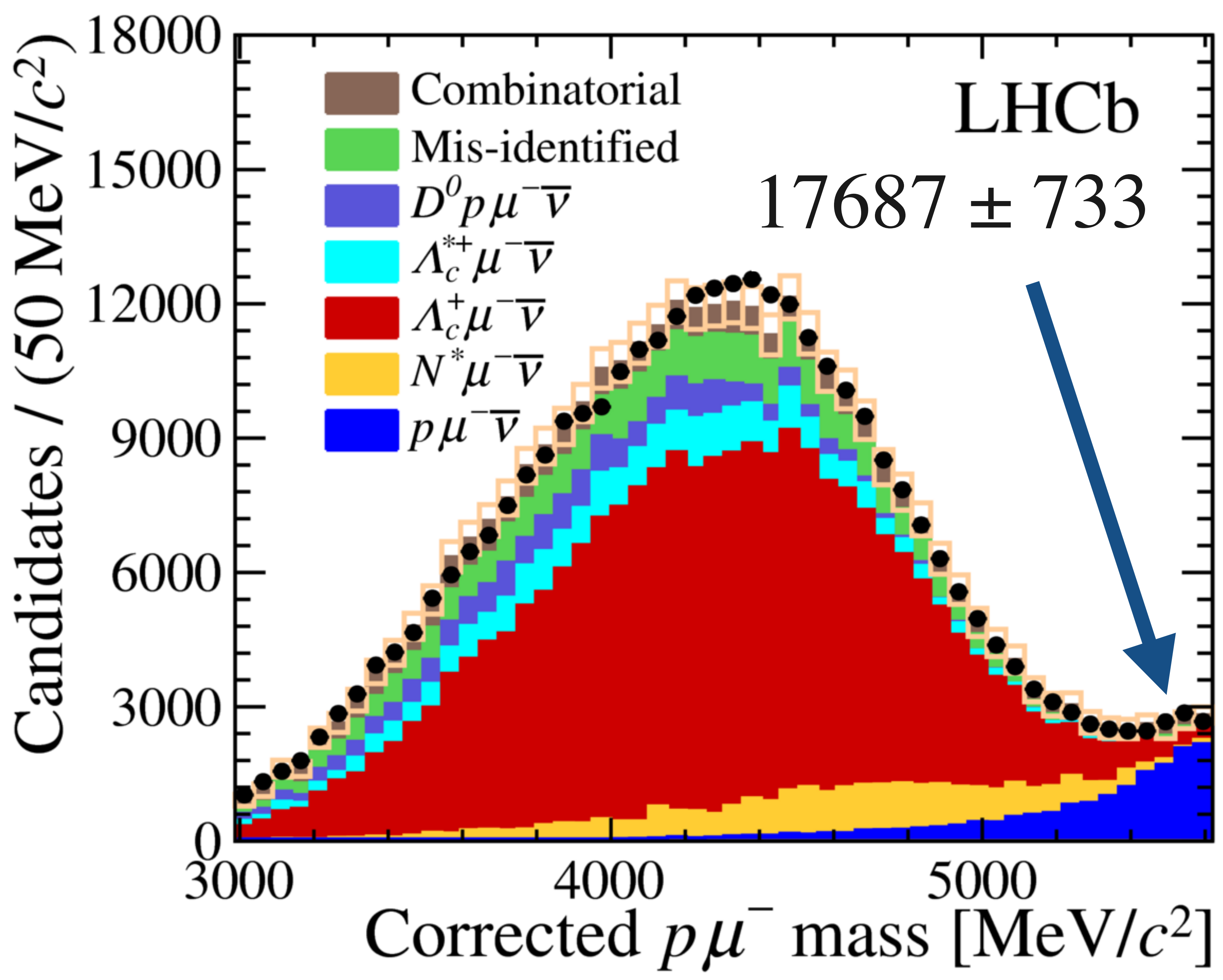
[ARXIV:1610.08288]

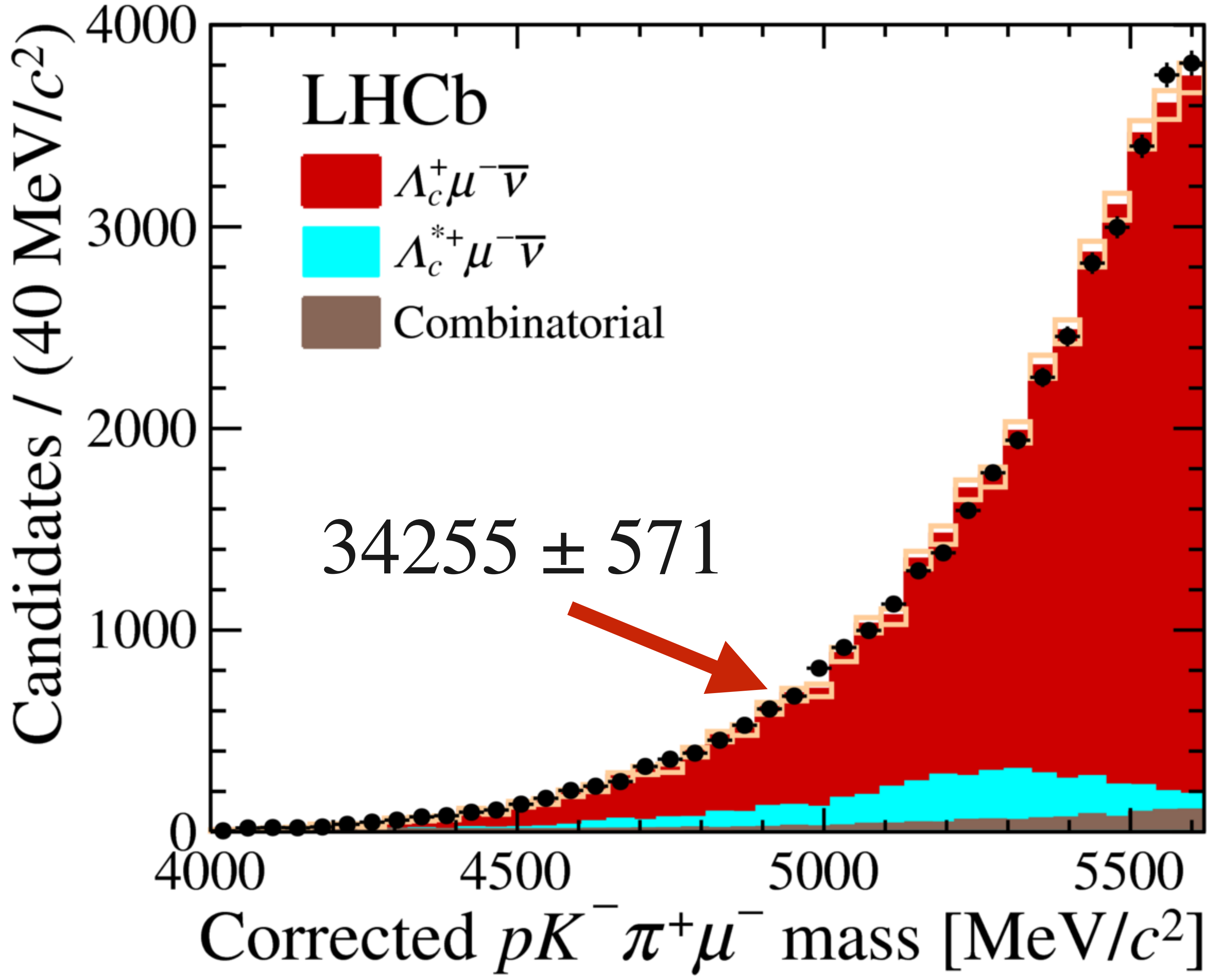
$|V_{ub}|$ measurement with $\Lambda_b \to p\mu\bar{\nu}_\mu$

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b \to p\mu\nu)_{q^2>15\,\mathrm{GeV}}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}}} R_{\mathrm{FF}}$$

$$m_{\mathrm{corr}} = \sqrt{m_{h\mu}^2 + p_{\mathrm{T}}^2} + p_{\mathrm{T}}$$







Most precise measurement

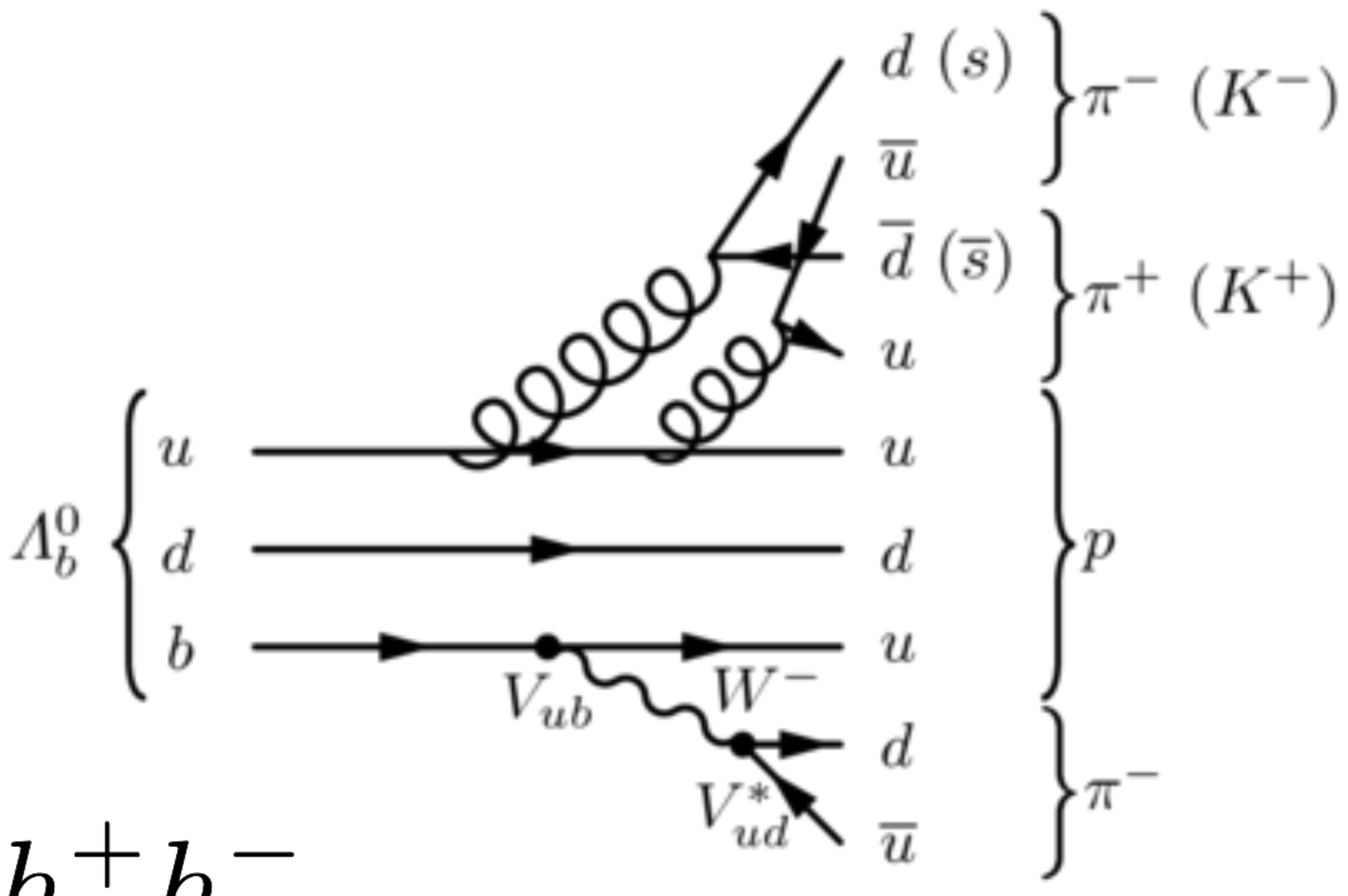
$$|V_{ub}| = (3.27 \pm \underbrace{0.15}_{\text{exp.}} \pm \underbrace{0.17}_{\text{LQCD}} \pm \underbrace{0.06}_{|V_{cb}|}) \times 10^{-3}$$

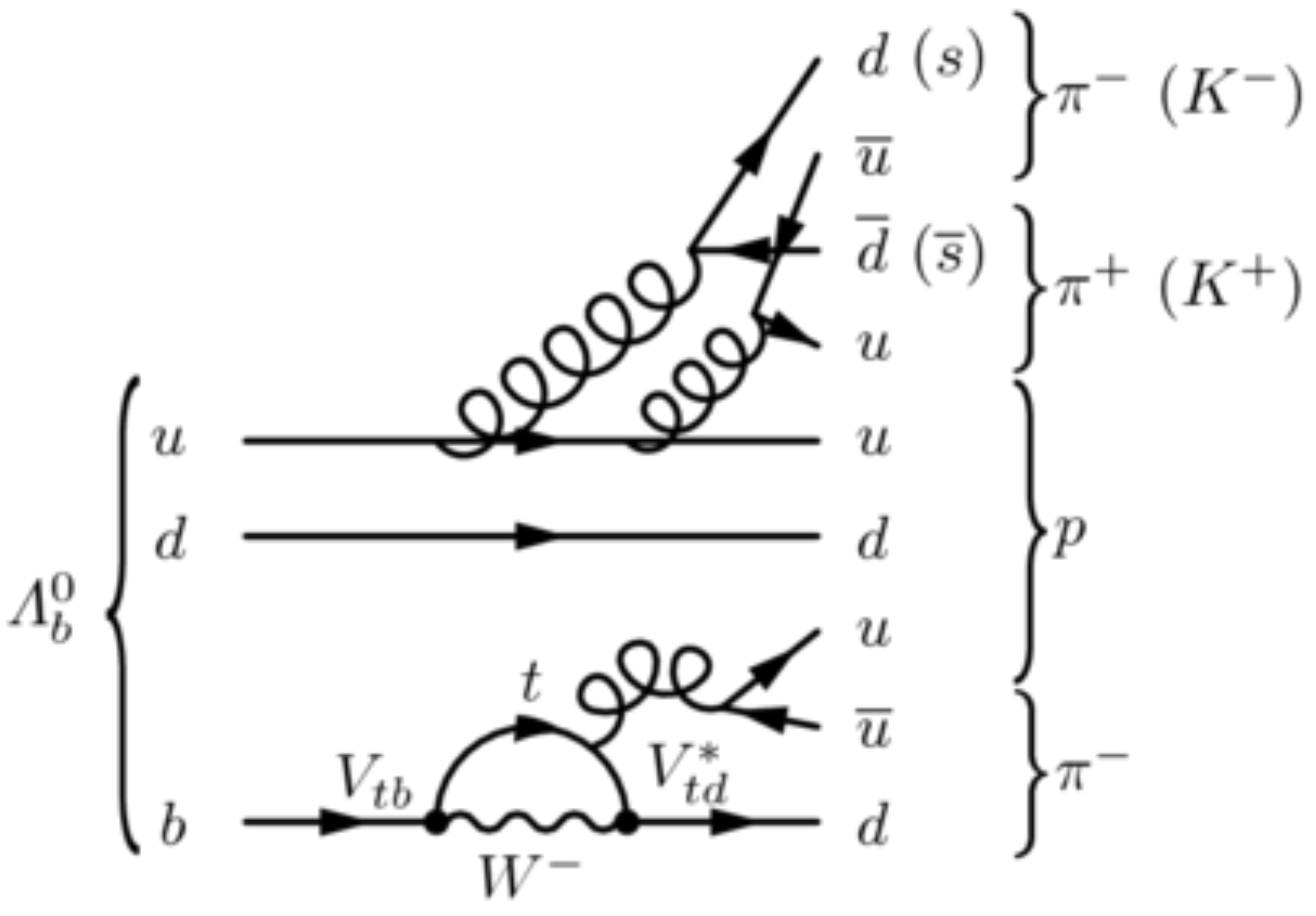
- Background estimated using control samples.
- Largest expt uncertainty from BR(L_c -> pKpi)
- In agreement with other exclusive measurements (see other talks today)

[LatticeQCD for R_{FF} - Detmold et al., PRD 92 (2015) 034503]

CP-violation in b-baryon decays

- Never observed CPV in baryon sector before - potential for non-zero CPV effects in SM.
- Transitions governed by $b \to udu$ tree and $b \to duu$ penguin amplitudes of similar magnitude. Large relative weak phase alpha





$$\Lambda_b^0 \to p h^- h^+ h^-$$

$$\boxed{V_{ub} \sim \lambda^3}$$

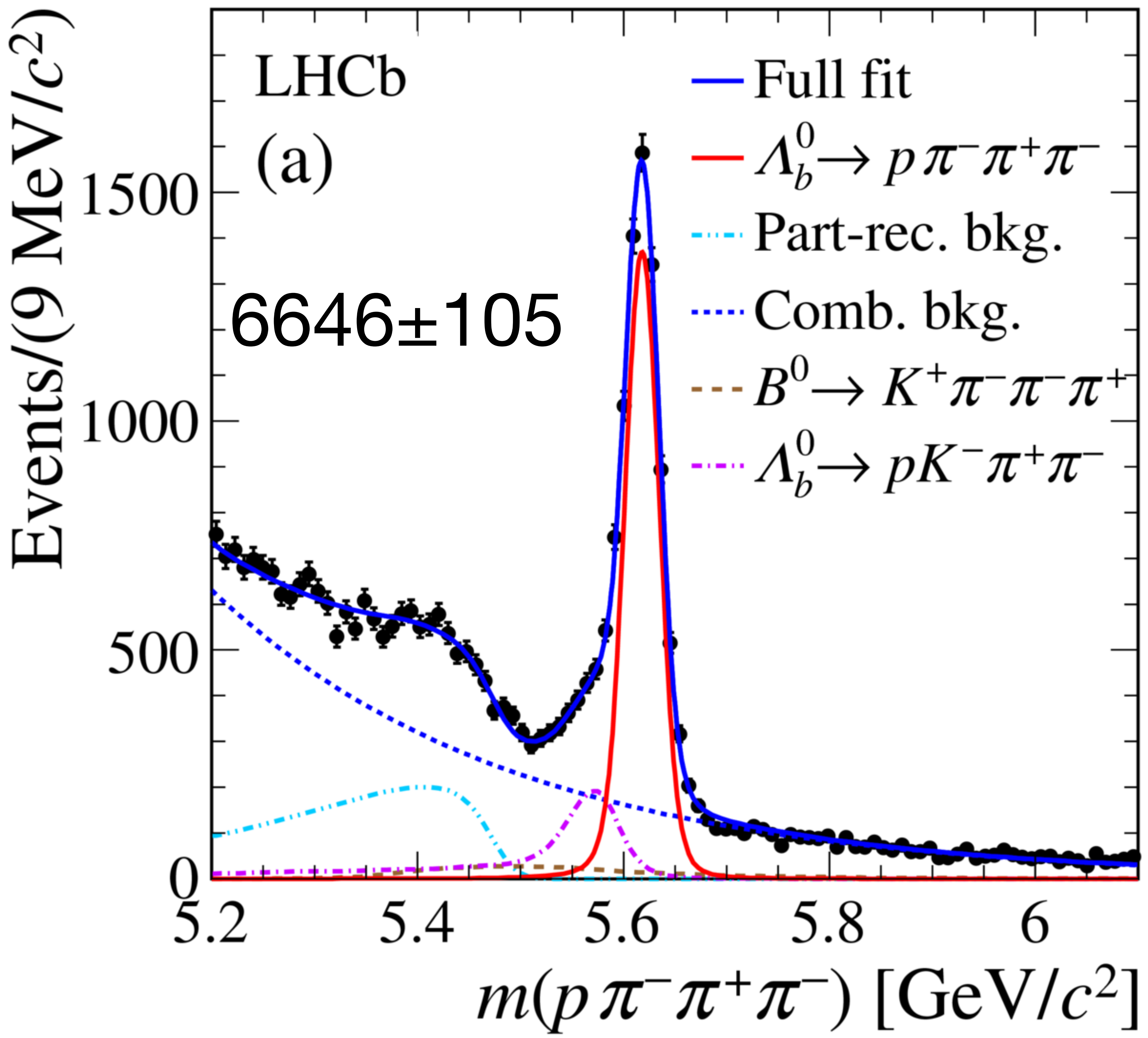
$$\boxed{\sum_{x=u,c,t} V_{bx} V_{xd} \sim \lambda^3}$$

CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

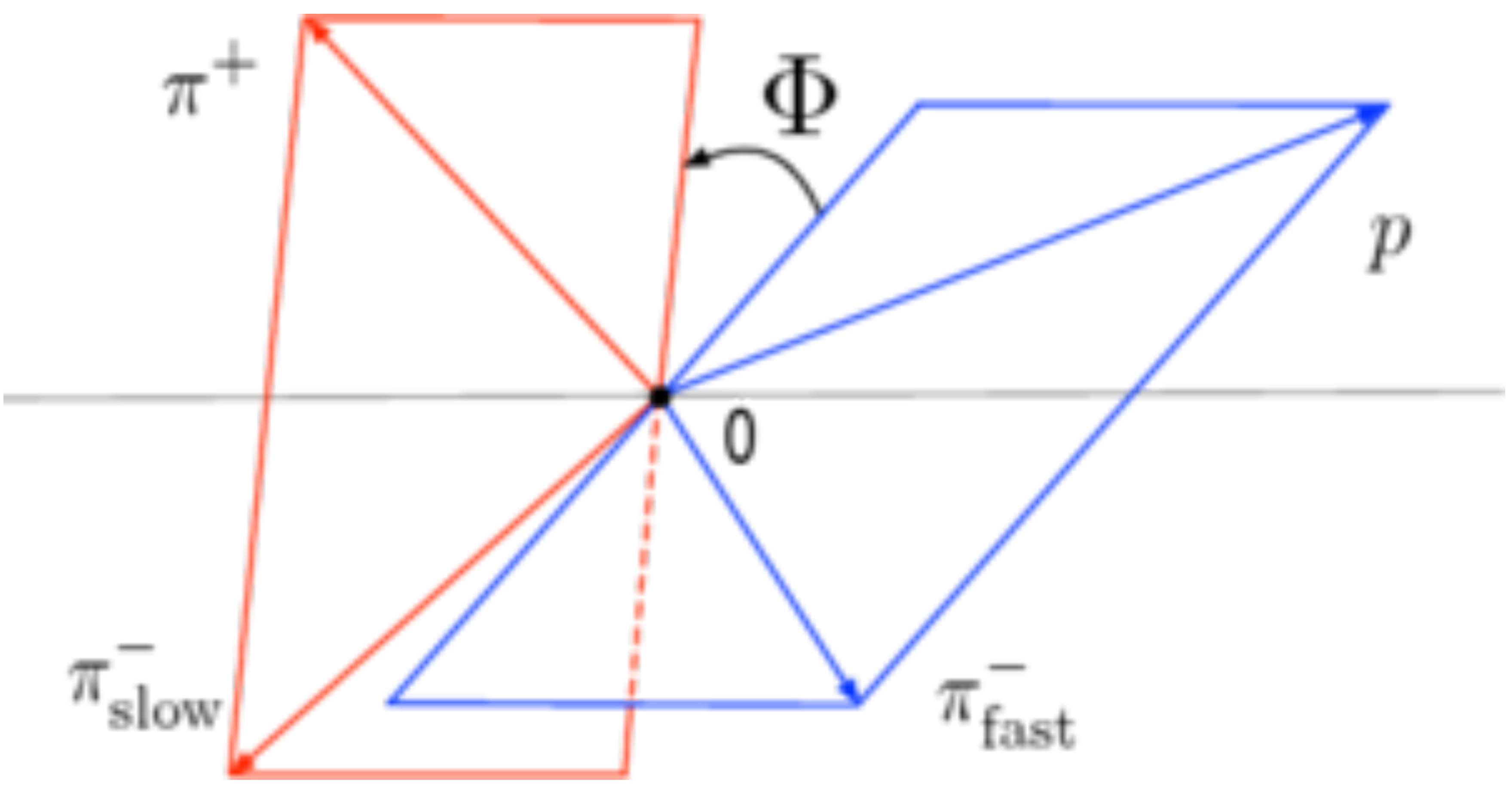
[arXiv:1609.05216, accepted Nature Physics]

- Search for localised CPV effects, enhanced sensitivity
- Use 4-body topology to build P-violating asymmetries

P-odd, T-odd triple products

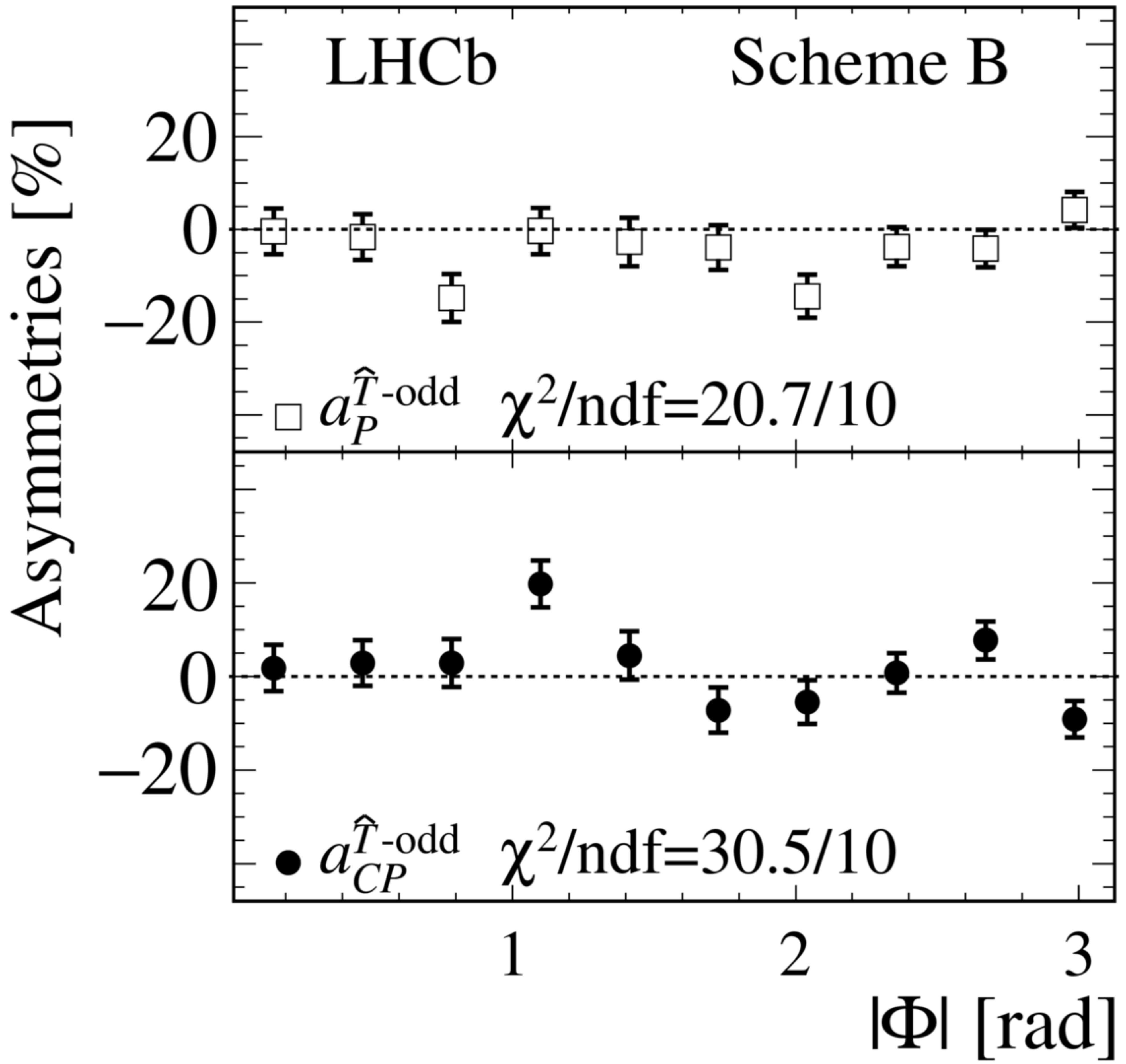


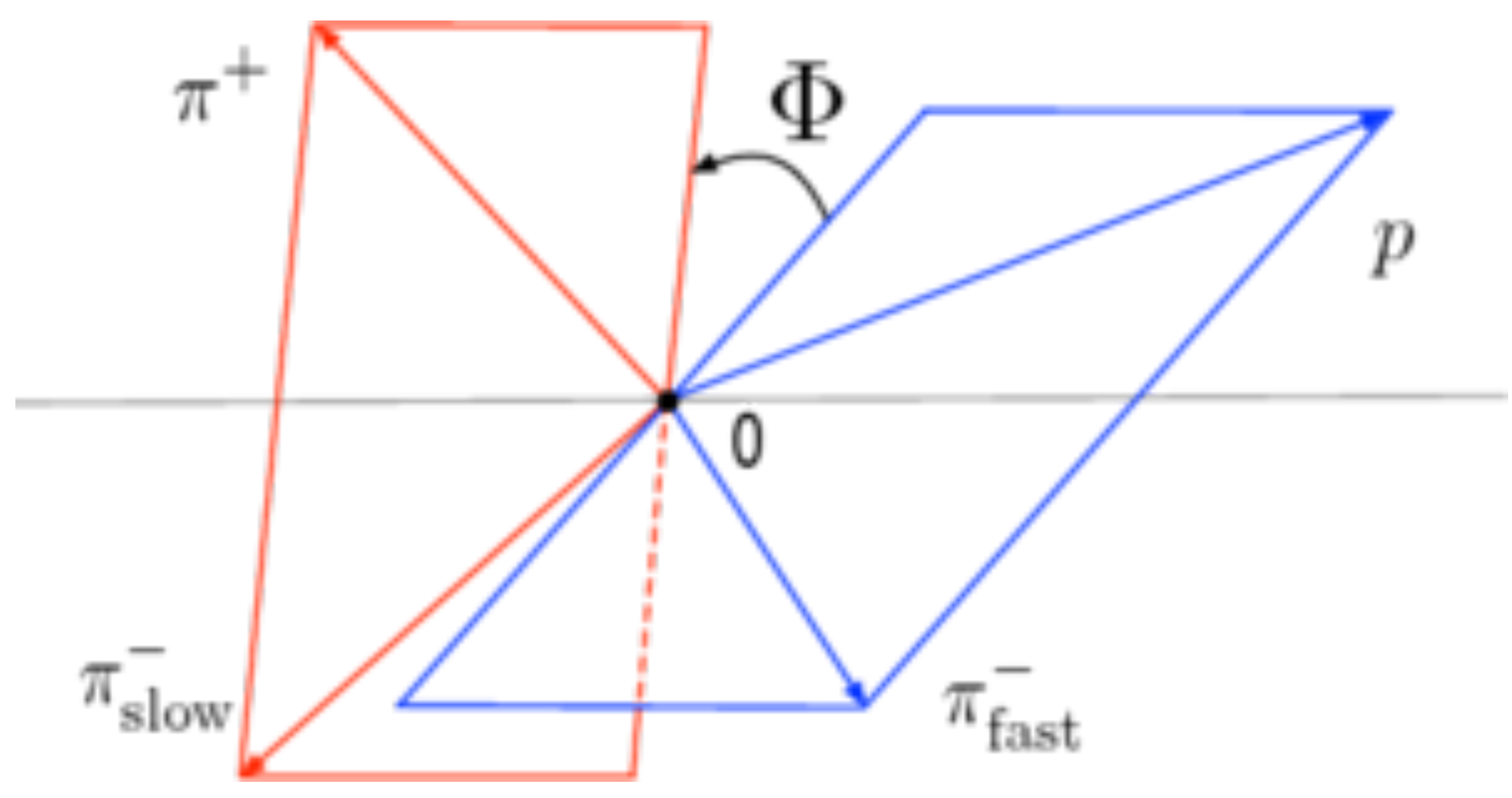
$$C_{\widehat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \;\propto \sin\Phi \text{ , for } \Lambda_b^0$$
$$\overline{C}_{\widehat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}) \;\propto \sin\overline{\Phi} \text{ , for } \overline{\Lambda}_b^0$$



First evidence for CPV in b-baryon decays

[arXiv:1609.05216, accepted Nature Physics]





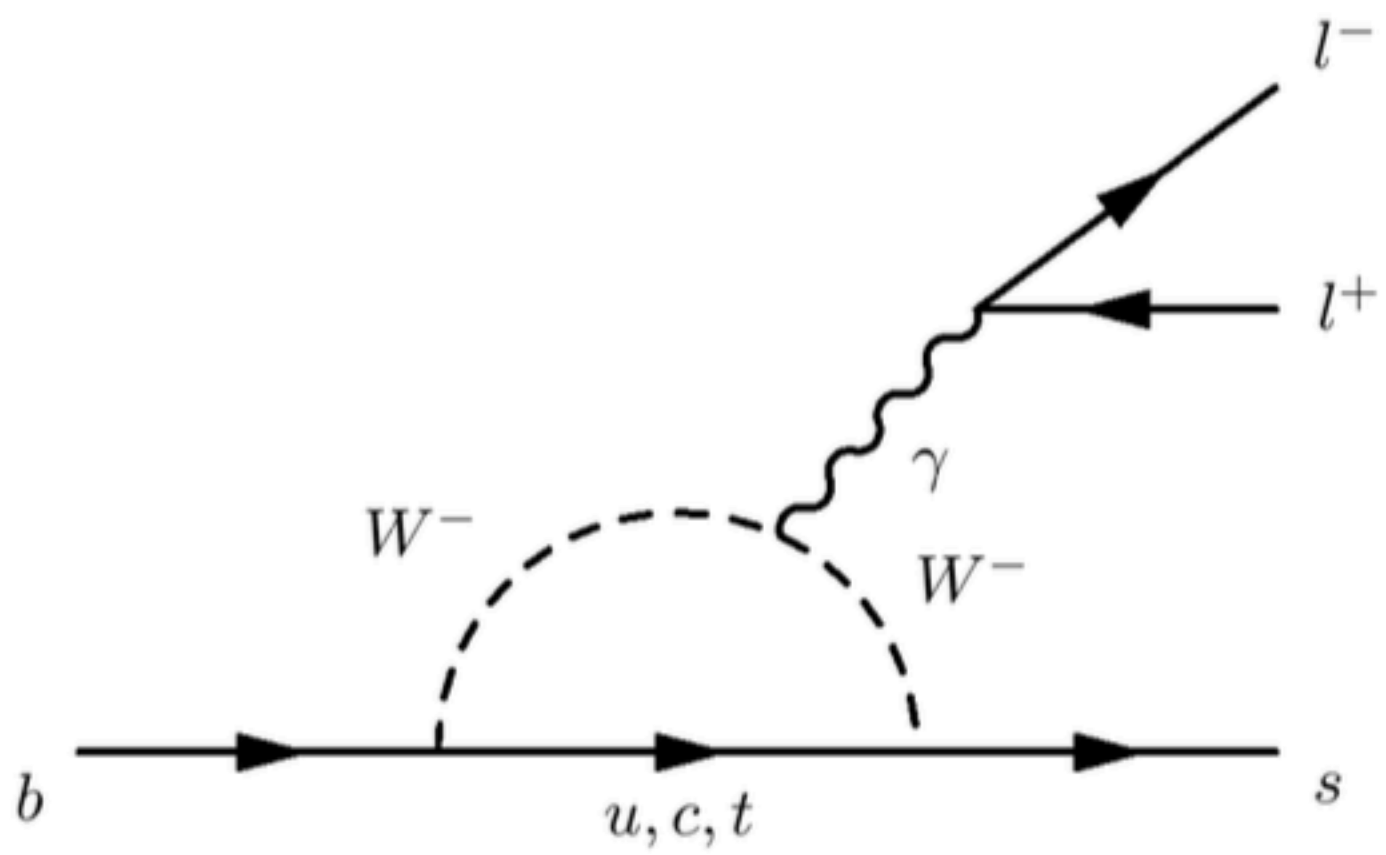
$$\overline{A}_{\hat{T}}(\overline{C}_{\hat{T}}) = \frac{\overline{N}(-\overline{C}_{\hat{T}} > 0) - \overline{N}(-\overline{C}_{\hat{T}} < 0)}{\overline{N}(-\overline{C}_{\hat{T}} > 0) + \overline{N}(-\overline{C}_{\hat{T}} < 0)}$$

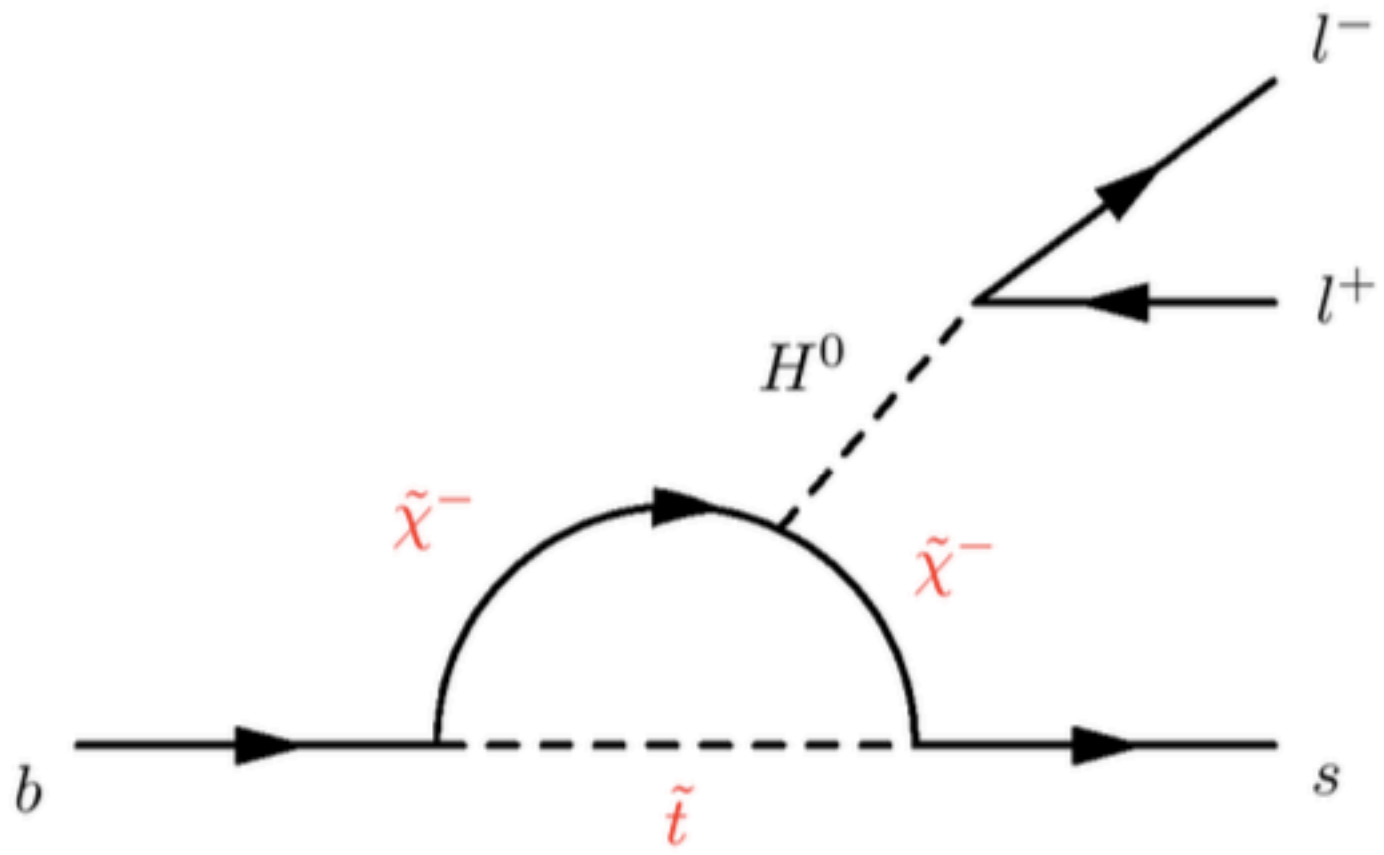
$$A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$$

- CP-symmetry p-value = $9.8\text{x}10^{-4}$
- Deviation at 3.3σ

$$a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \overline{A}_{\hat{T}})$$

Rare (FCNC) b-hadron decays



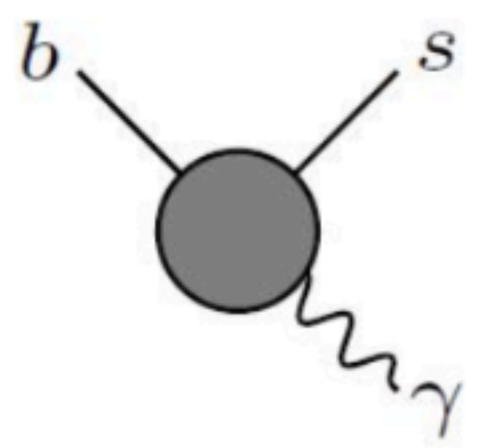


Theoretical framework

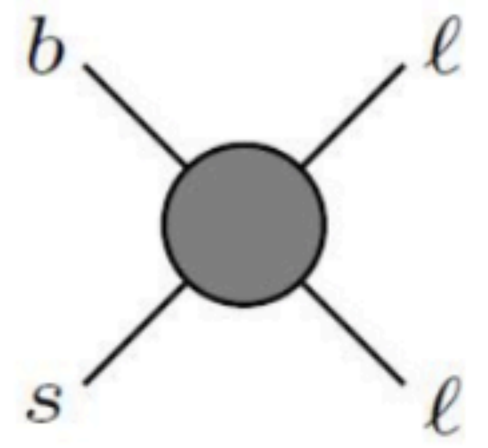
- Use effective Hamiltonian to describe b -> s transitions.

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\ \underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\text{right-handed part}}\ ]$$

i = 1,2	Tree
i = 3 – 6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin



i=7 photon penguin



i=9, 10, P, S

- ***C_i* Wilson coefficients**: short-distance physics (perturbative) couplings, μ=energy scale.
- ***O_i* operators**: long-distance (non perturbative) matrix elements, e.g. from lattice QCD calculations.
- New physics can modify *C_i* Wilson coefficients and/or add new operators.

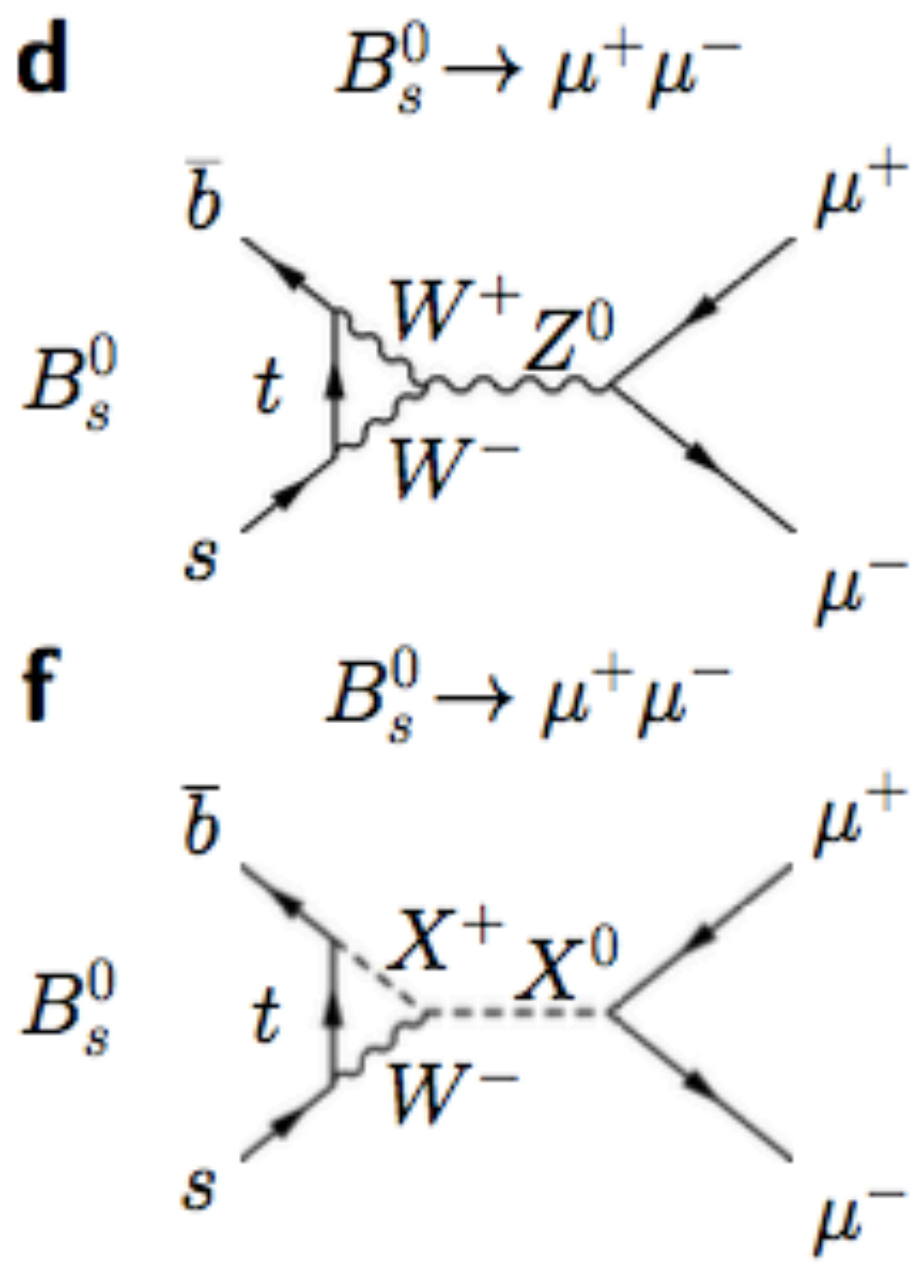
Observation of $B^0_{(s)} \to \mu^+\mu^-$

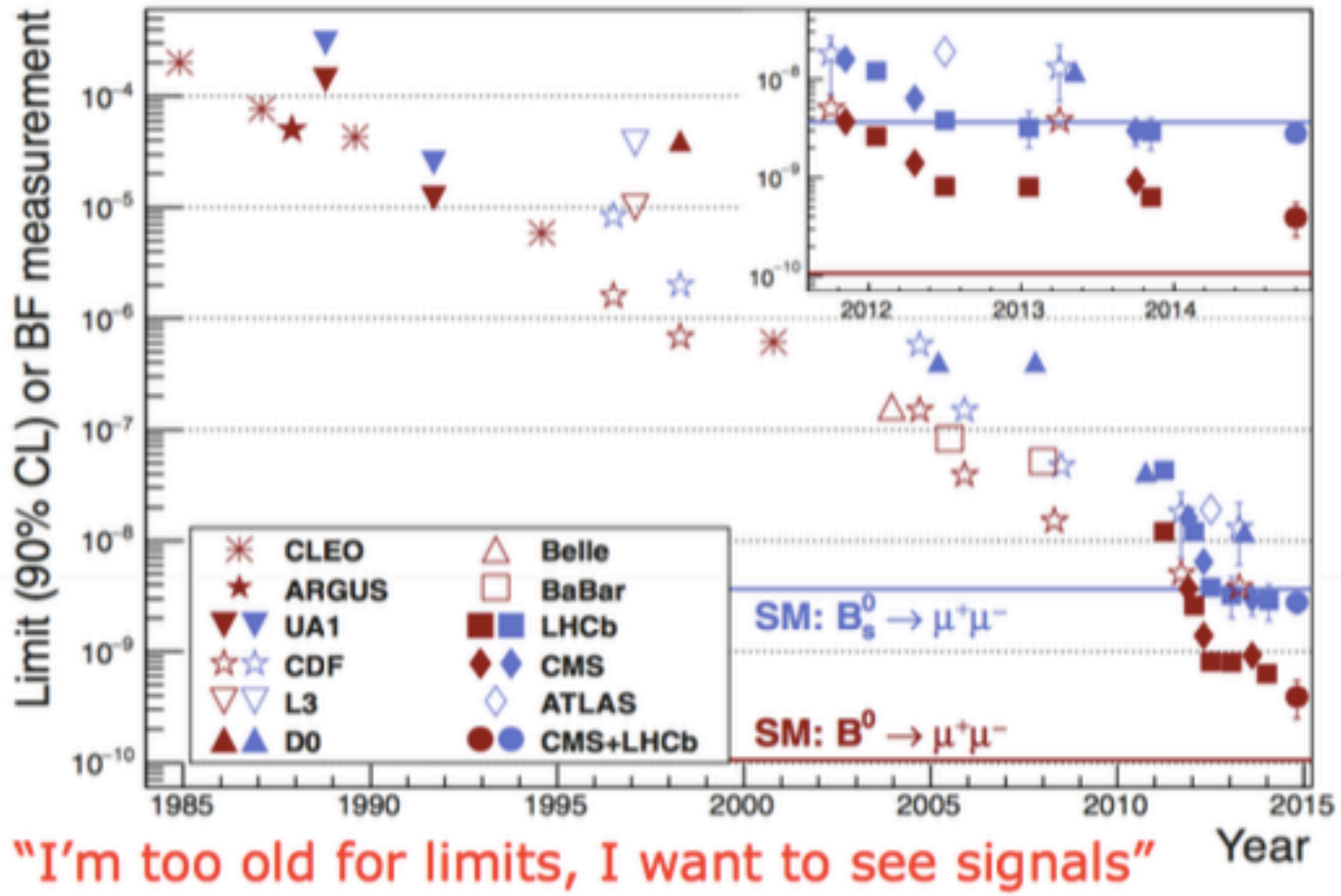
- CKM, loop and helicity suppressed ($(m_\mu/m_B)^2$).
  - $\mathcal{B}(B^0_s \to \mu\mu)_{\rm SM} = (3.66 \pm 0.23) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu\mu)_{\rm SM} = (1.06 \pm 0.09) \times 10^{-10}$
  - [PRL 112, 101801 (2014)]

$$\mathcal{B}(B_q \to \ell^+\ell^-)_{\rm SM} = \tau_{B_q} \frac{G_F^2 \alpha_{\rm EM}^2}{16\pi^2} f_{B_q}^2 m_l^2 m_{B_q} \sqrt{1 - \frac{4m_\ell^2}{m_{B_q}^2}} |V_{tb}V_{tq}|^2 |C_{10}^{\rm SM}|^2$$

30 years of effort!

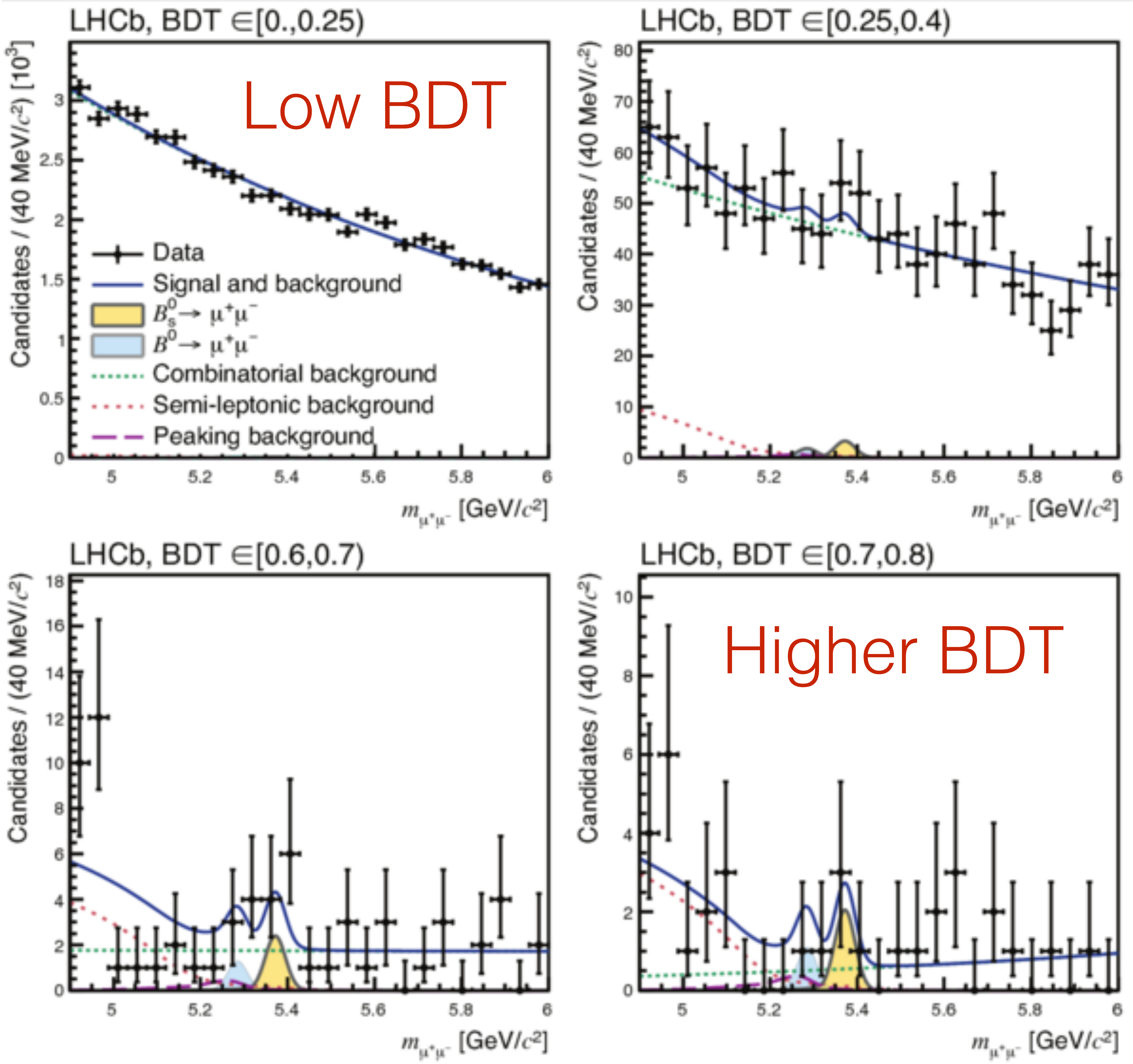
- Sensitive to scalar and pseudoscalar NP couplings, e.g., in MSSM $\mathcal{B} \propto (\tan\beta)^6$



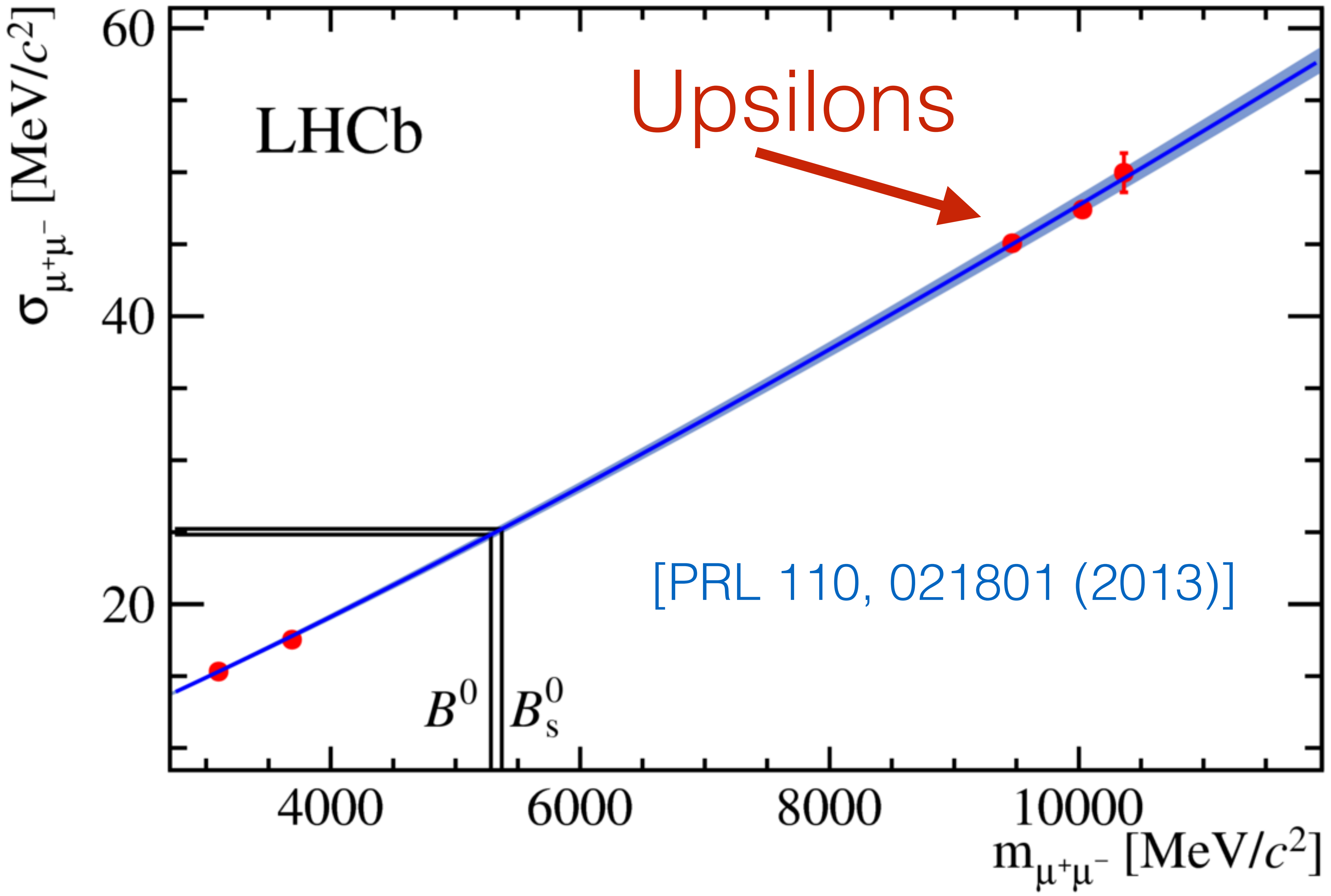


"I'm too old for limits, I want to see signals"
Francis Halzen (EPS '15)

Observation of $B^0_{(s)} \to \mu^+\mu^-$



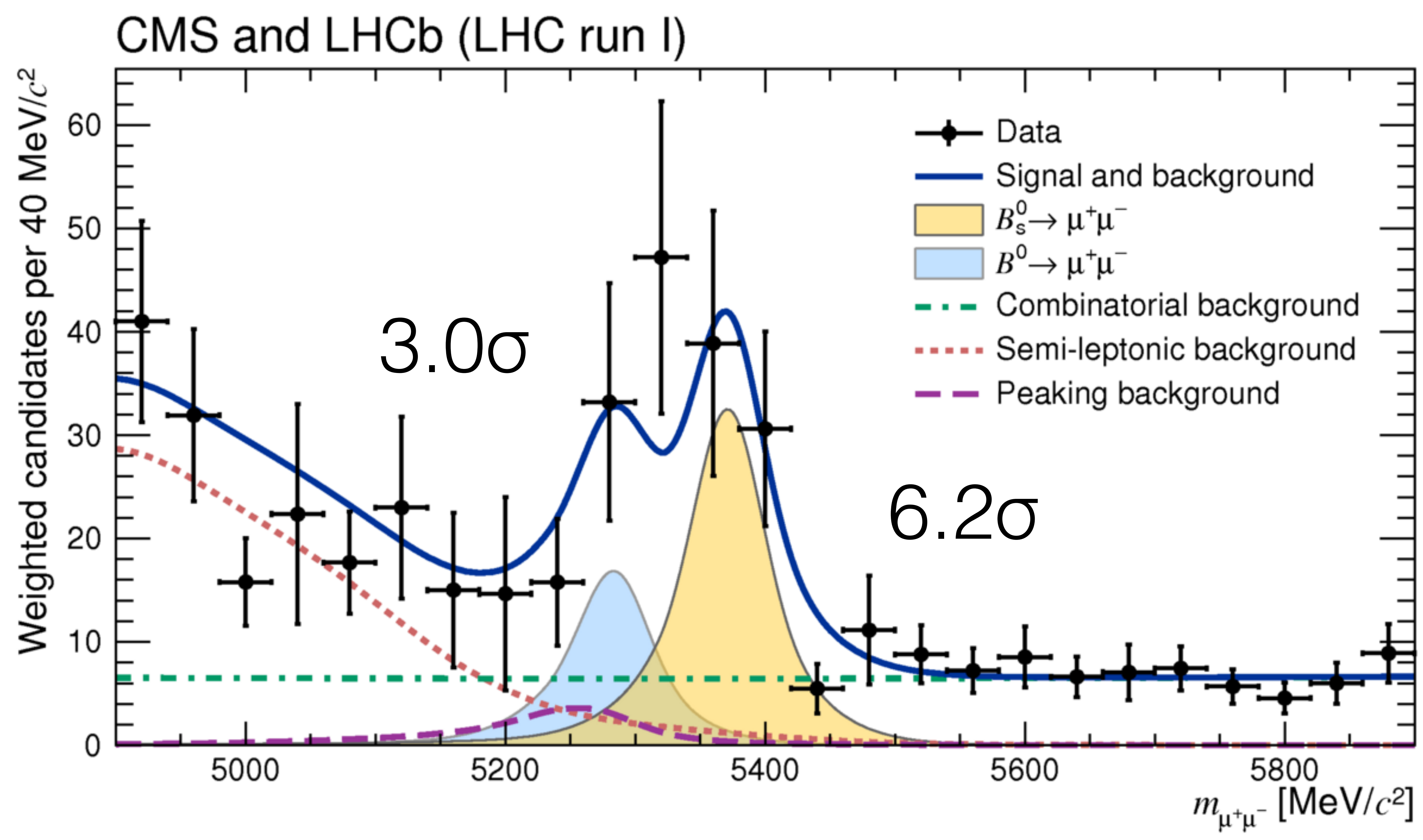
[Nature 522, 68-72 (2015)]



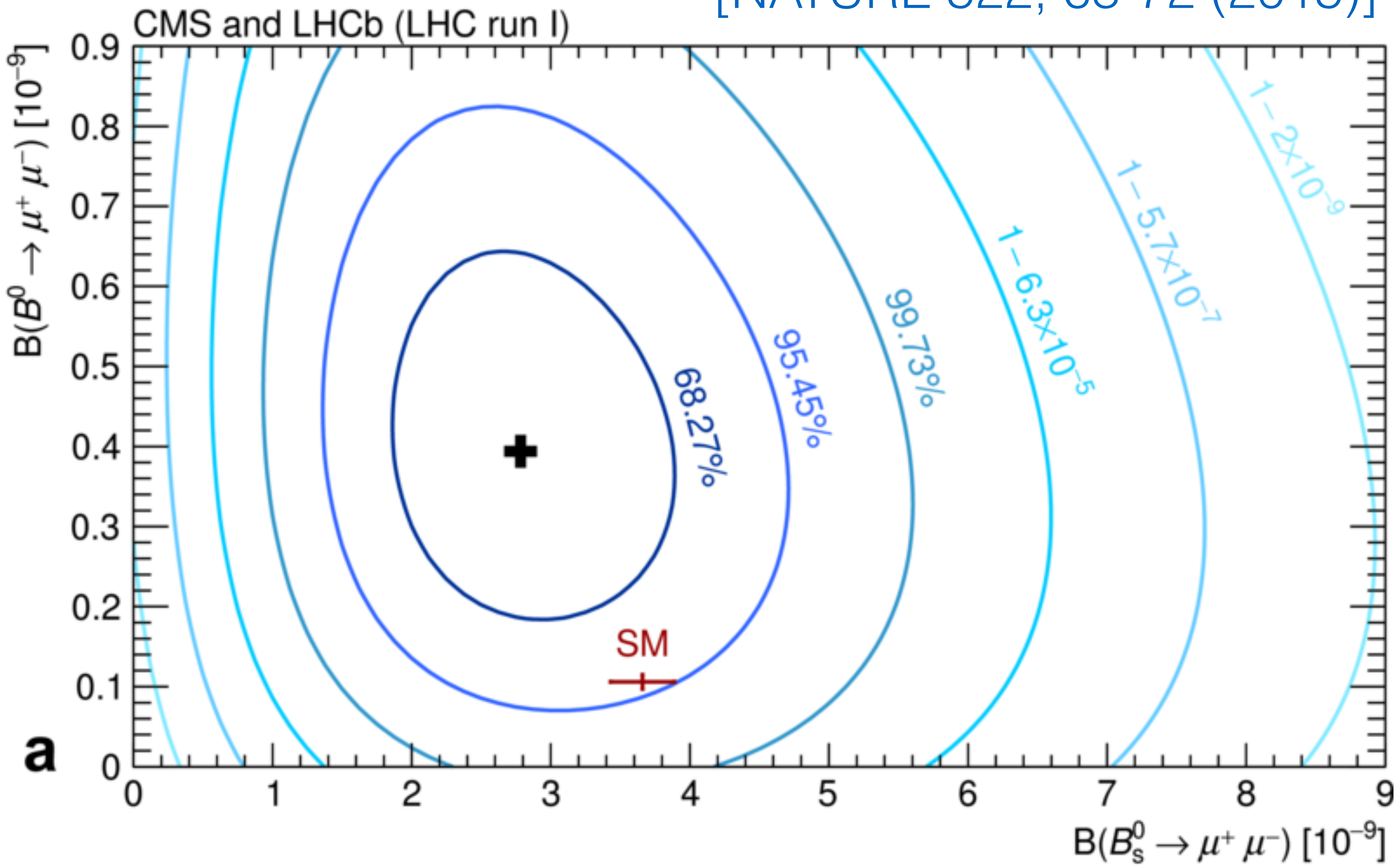
Calibrate mass resolution using Jpsi and Upsilon control modes

Use multi-variate techniques to suppress background.

Observation of $B^0_{(s)} \to \mu^+\mu^-$



[NATURE 522, 68-72 (2015)]

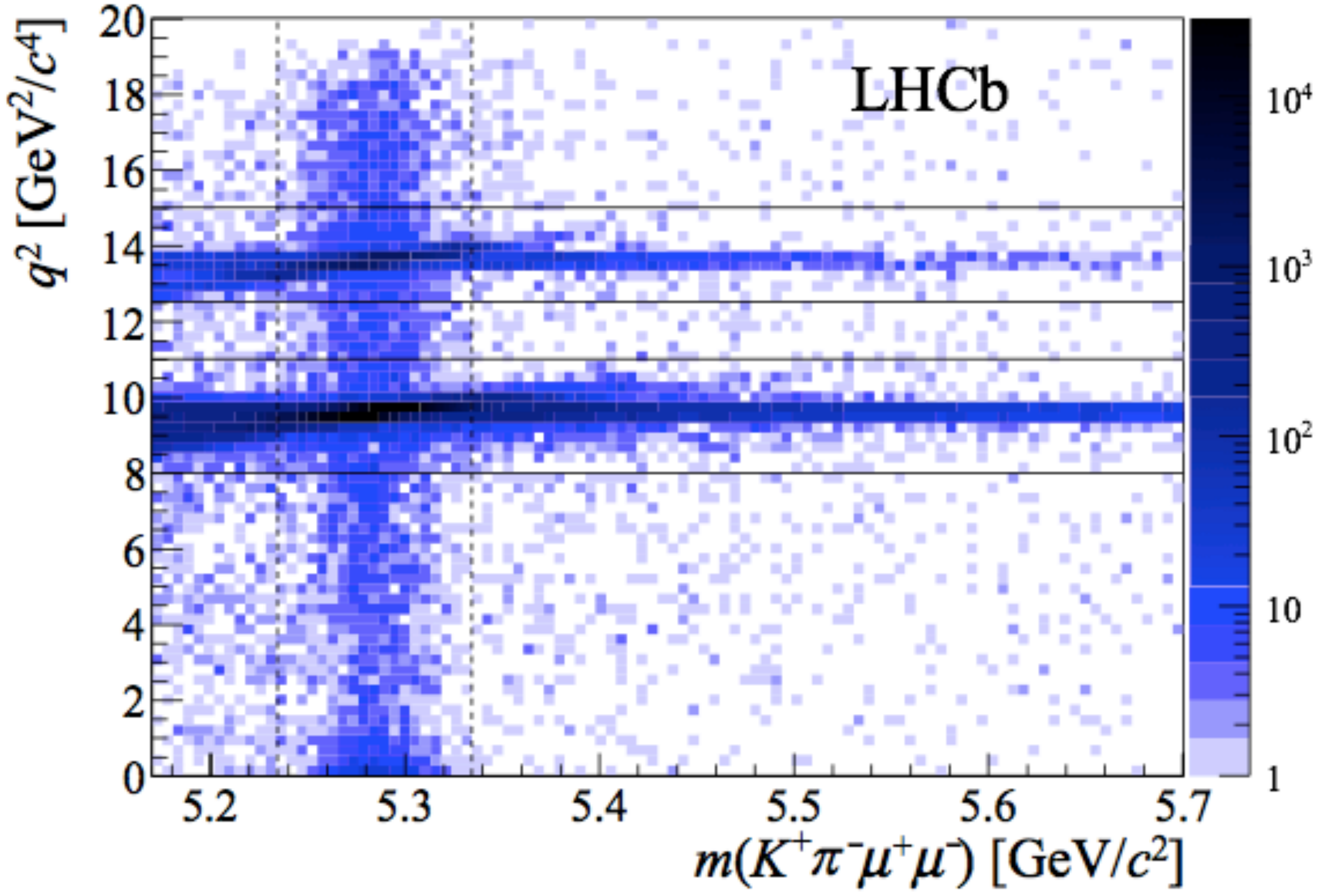


$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

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

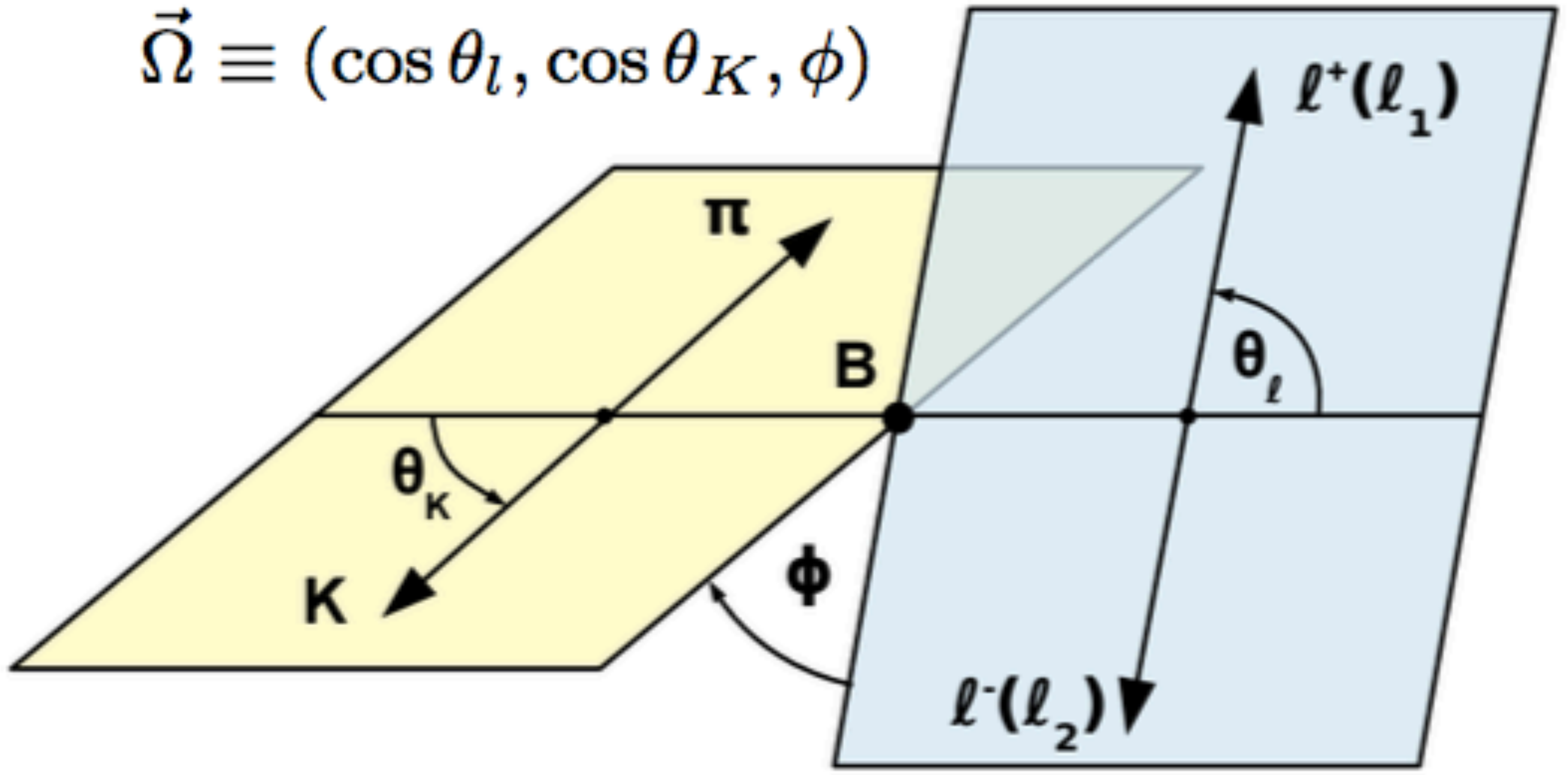
- Overall consistency with SM at 2σ.
- ATLAS sets an upper limit of BR(Bs) < 3.0×10^{-9} [EPJC 76 (2016) 513]

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



2398 ± 57 events, excluding the charmonia.

$\vec{\Omega} \equiv (\cos\theta_l, \cos\theta_K, \phi)$



$$\frac{\mathrm{d}^4\Gamma[\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_{j=1}^{11} I_j(q^2) f_j(\vec{\Omega}), \quad I_j \to \bar{I}_j \text{ for } B^0$$

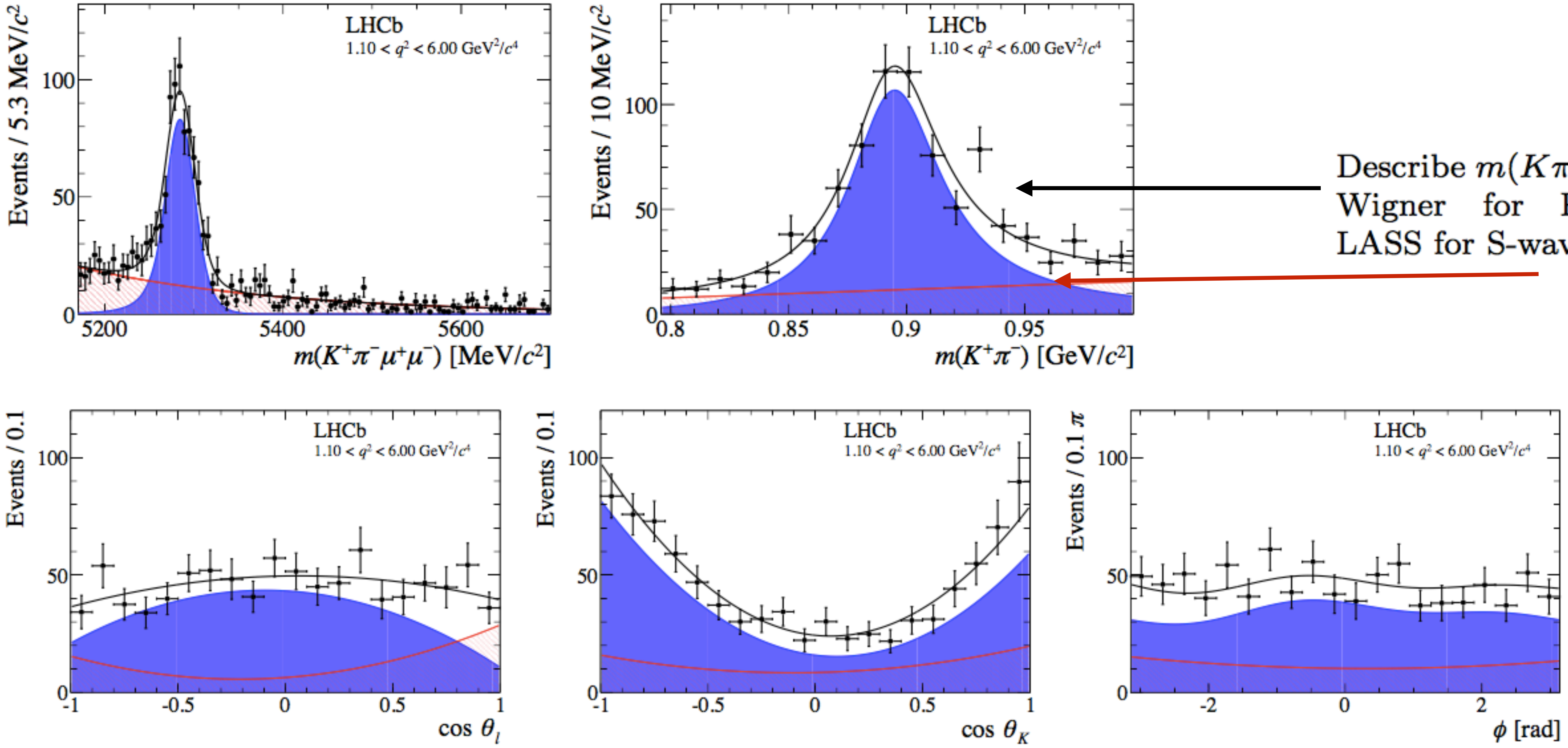
$$S_j = (I_j + \bar{I}_j) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right), \quad A_j = (I_j - \bar{I}_j) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)$$

In the end we measure each S_j and A_j in each bin of q^2.

- Di-muon final state is experimentally clean signature, but BR $\sim 10^{-7}$.
- $P \to VV'$ decay, fully described by $q^2 \equiv m(\mu^+\mu^-)^2$ and 3 helicity angles.
- $B^0 \to K^*\mu^+\mu^-$ has rich system of observables (rates, angles, asymmetries) that are sensitive to NP.

[JHEP 02 (2016) 104]

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

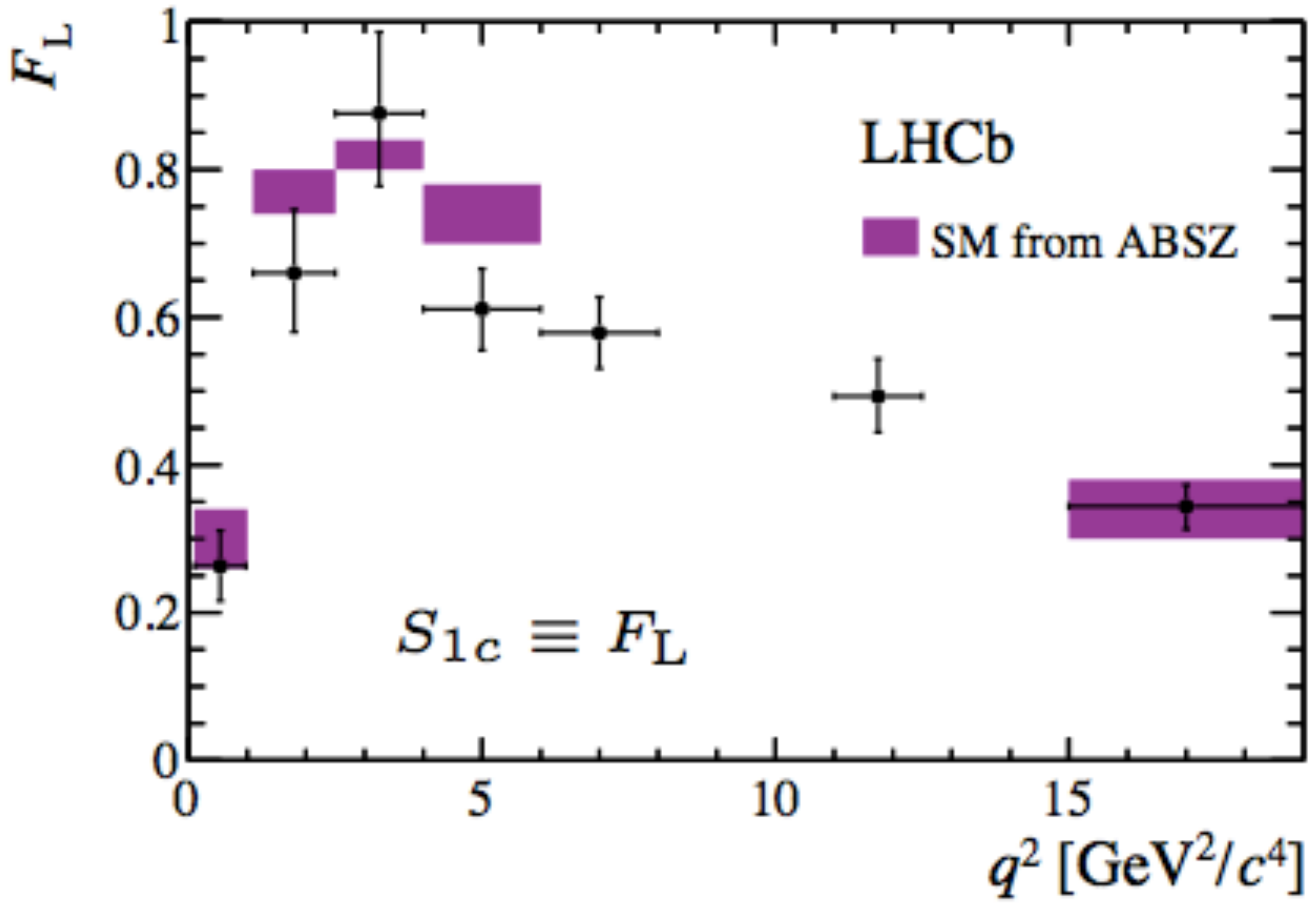


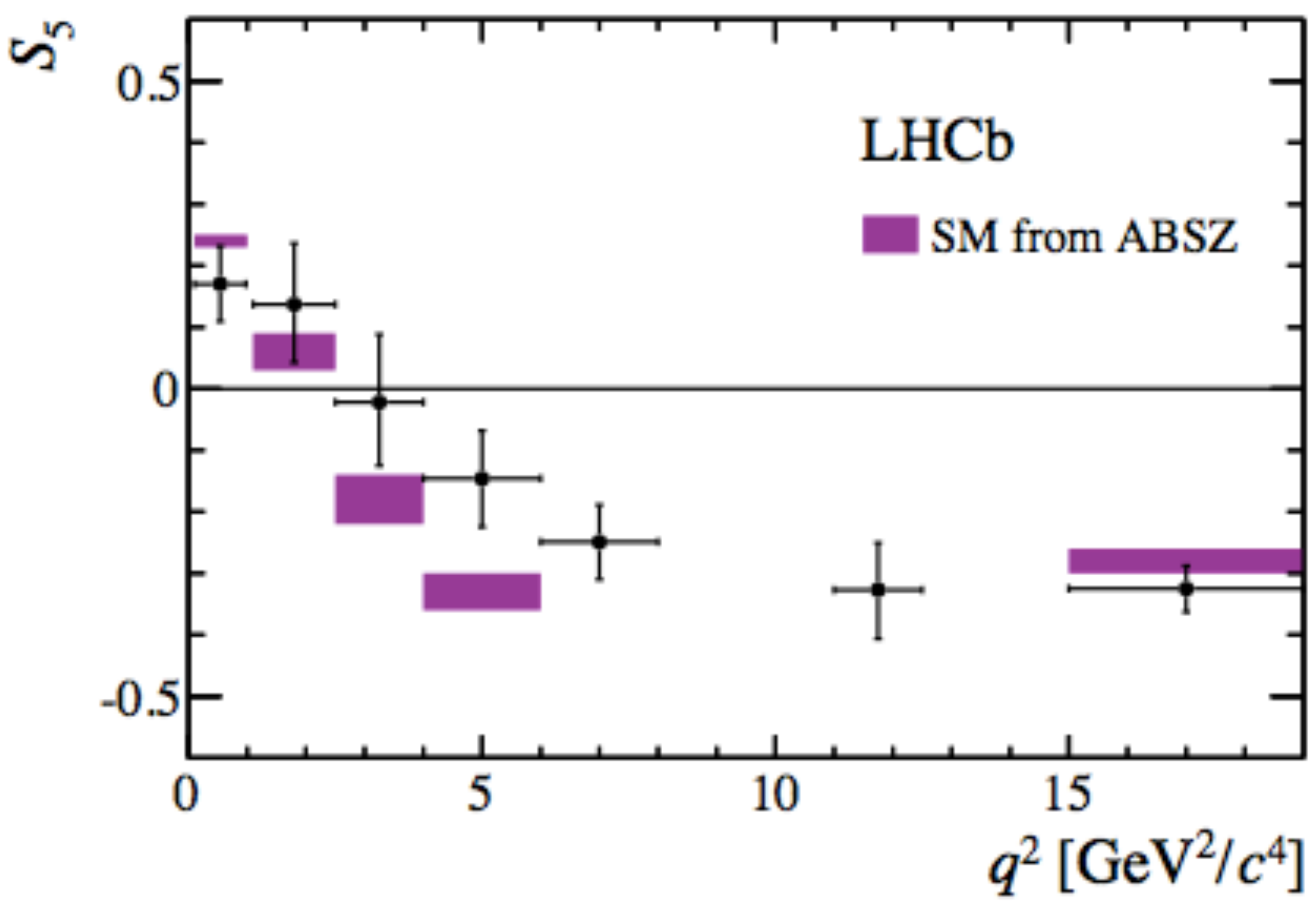
Describe $m(K\pi)$ with Breit-Wigner for P-wave and LASS for S-wave $K^+\pi^-$

- S_i, A_i's extracted using a max likelihood fit.

[JHEP 02 (2016) 104]

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





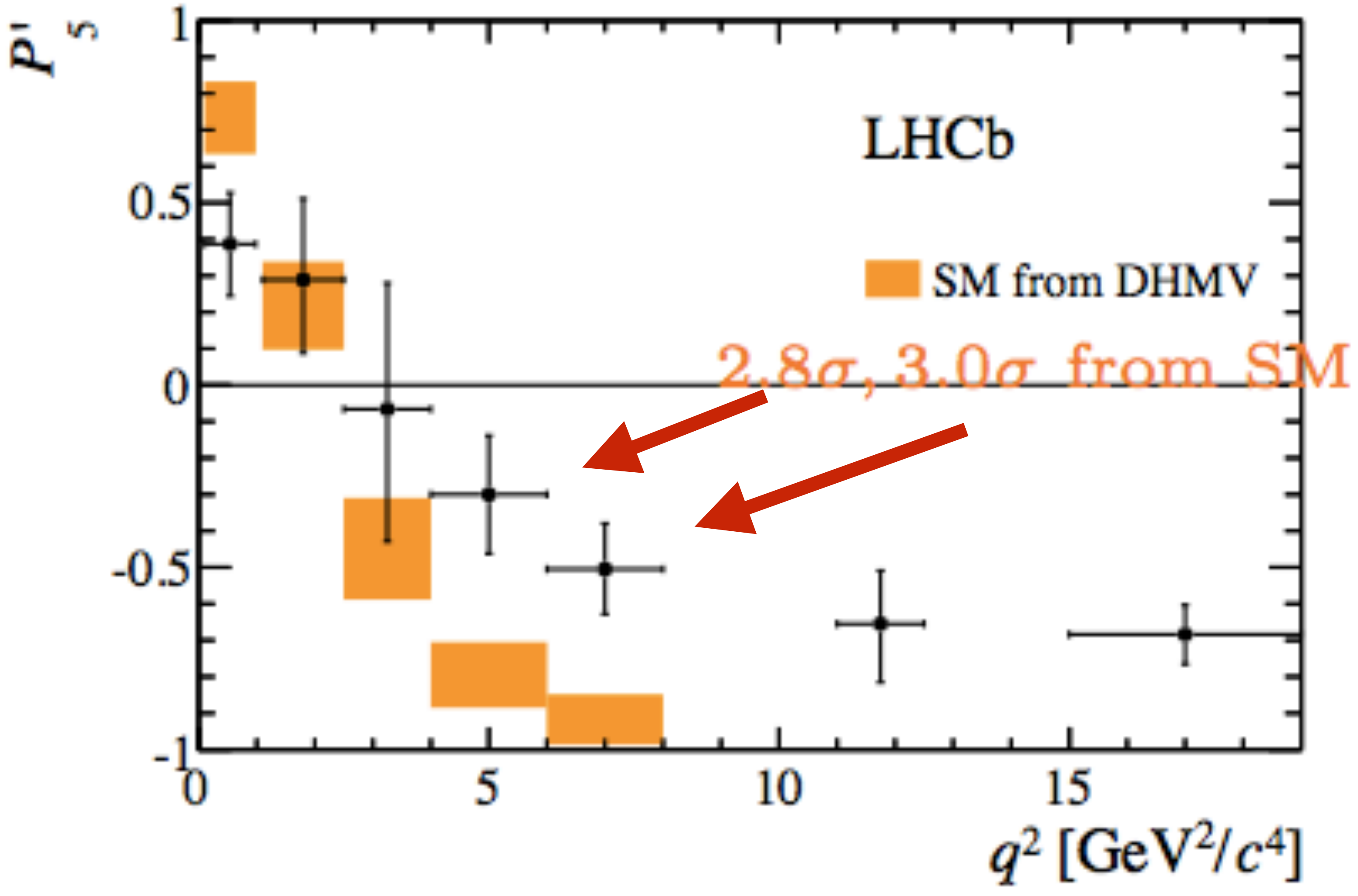
- "Theoretically clean" observables - less dependent on hadronic form factors [Descotes-Genon et al, JHEP 05 (2013) 137].
- These divide out the hadronic uncertainties to leading order.

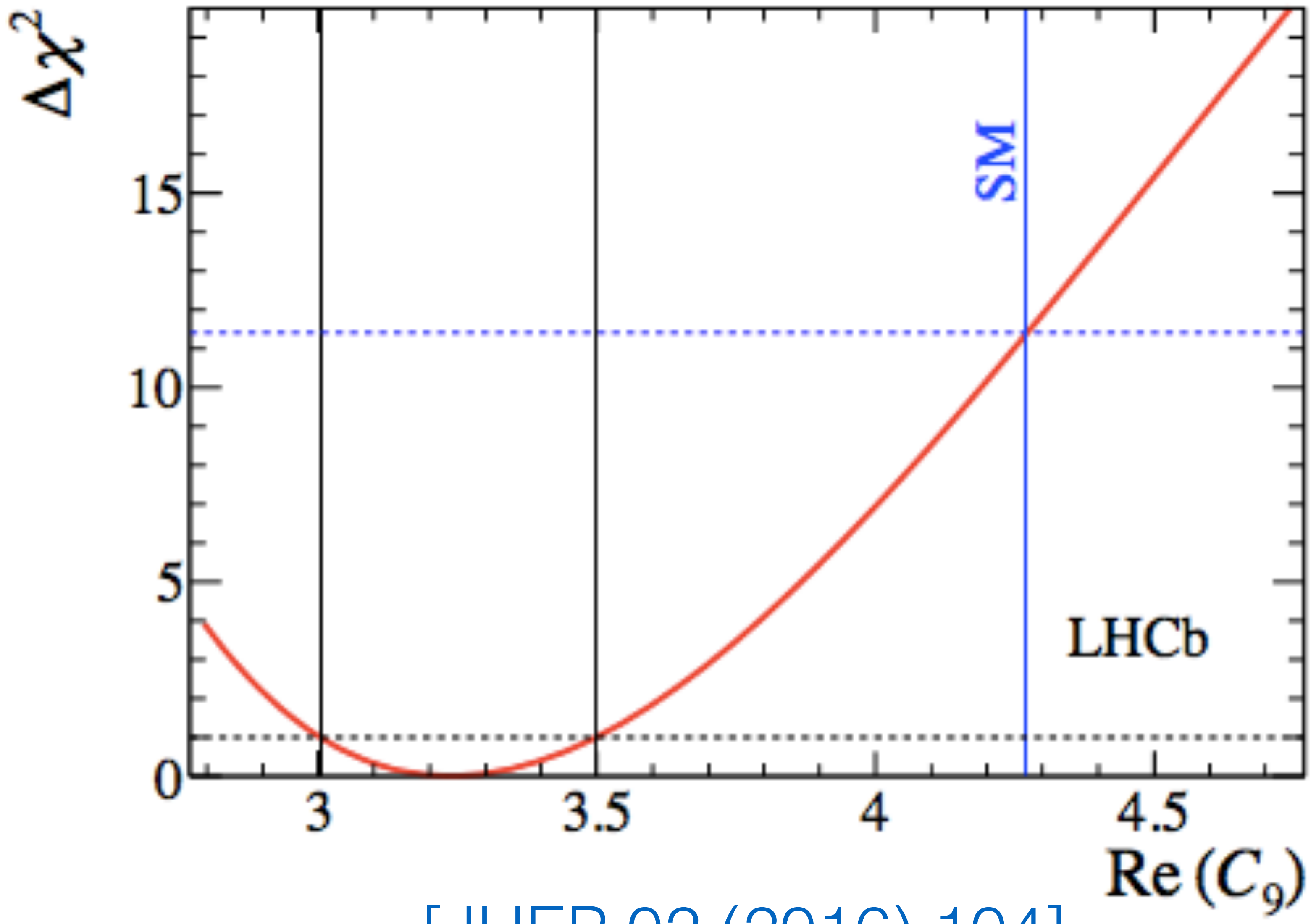
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

- χ^2-fit between the CP-averaged observables (including correlations) and SM prediction from [EOS software] in q^2 bins.

$\Delta\mathrm{Re}(\mathcal{C}_9) = -1.04 \pm 0.25 \Rightarrow 3.4\sigma$ from SM

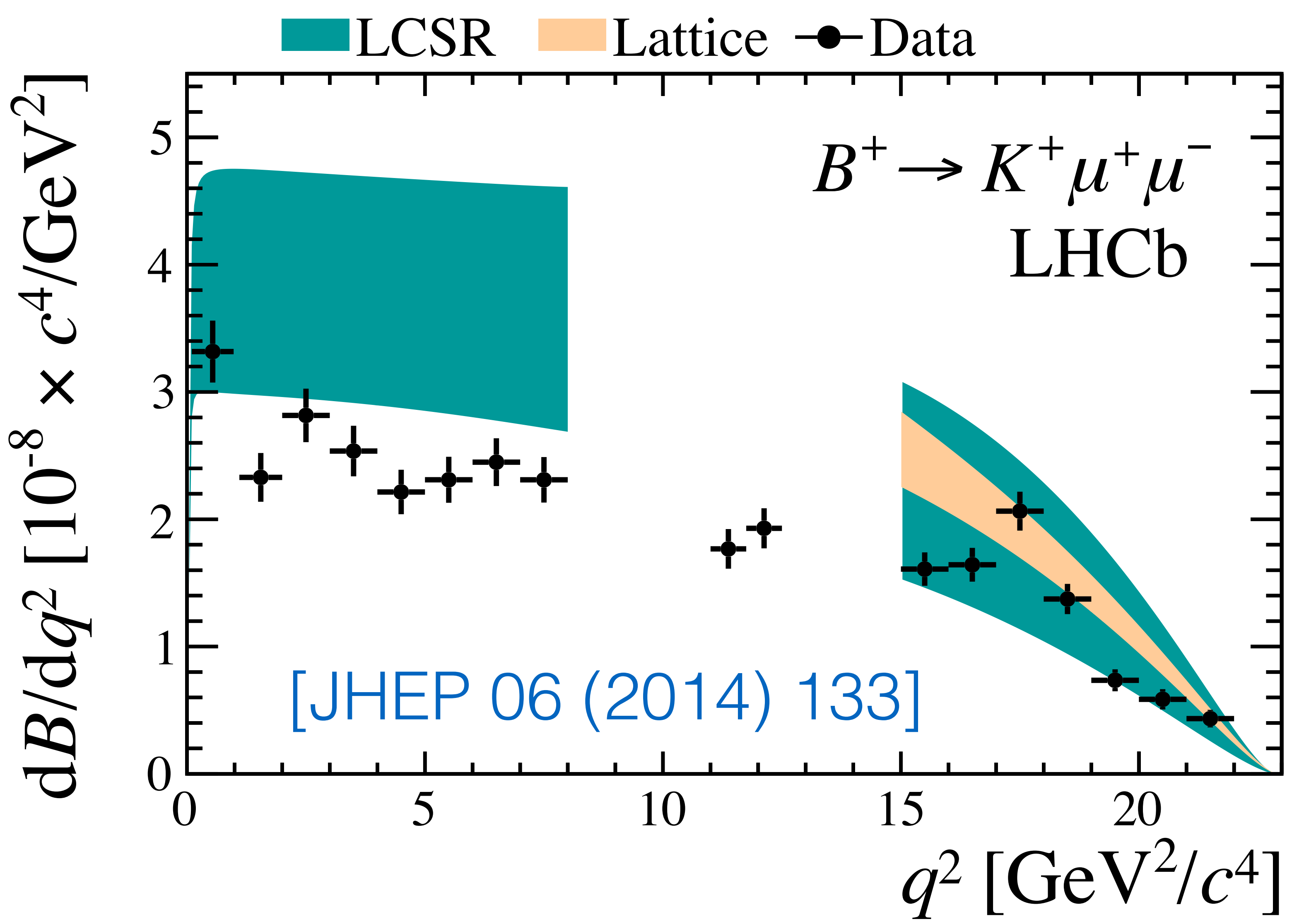
- Possible Z'? Leptoquarks? [many authors]
- How well do we understand QCD-effects? [Lyon, Zwicky]

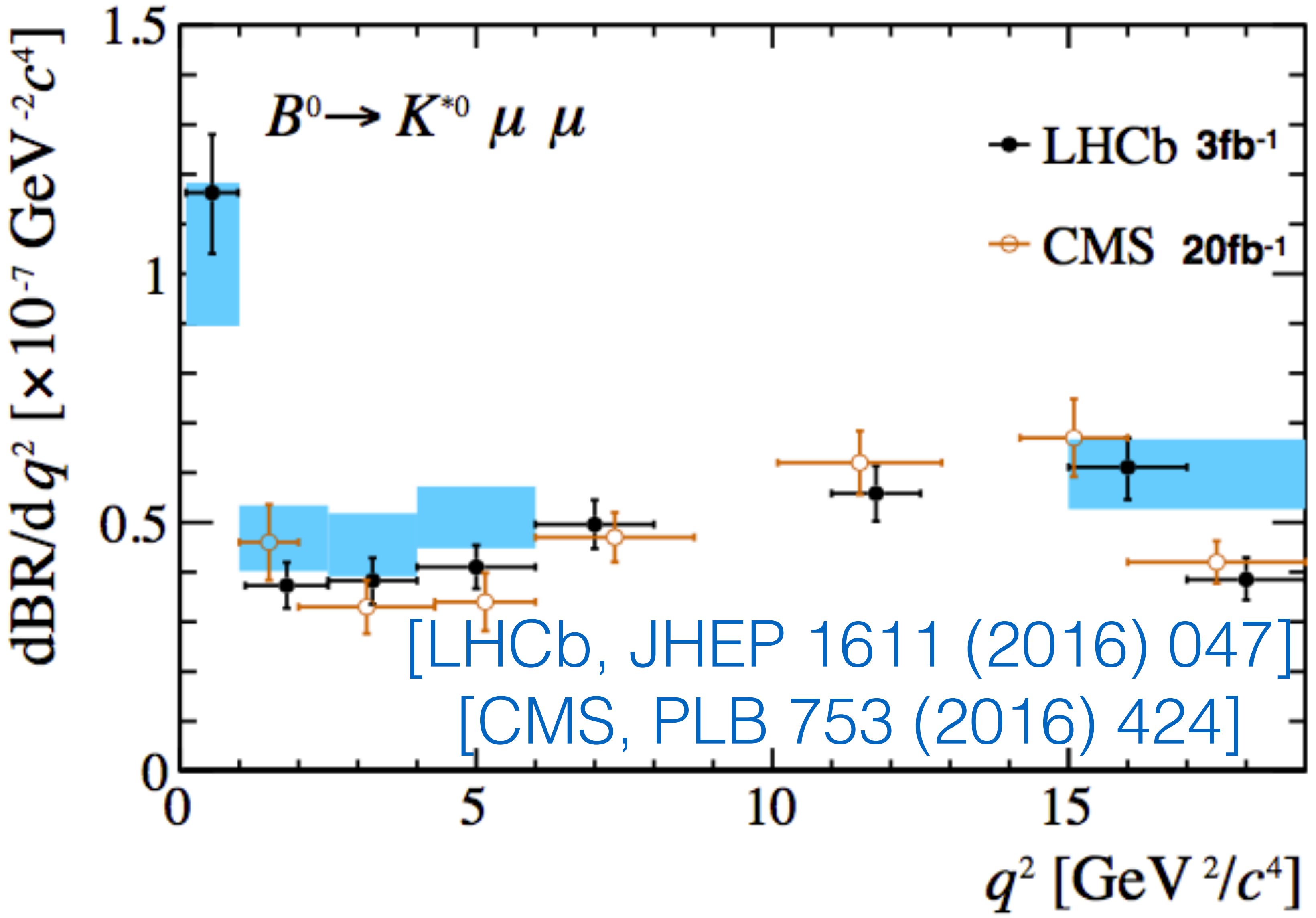


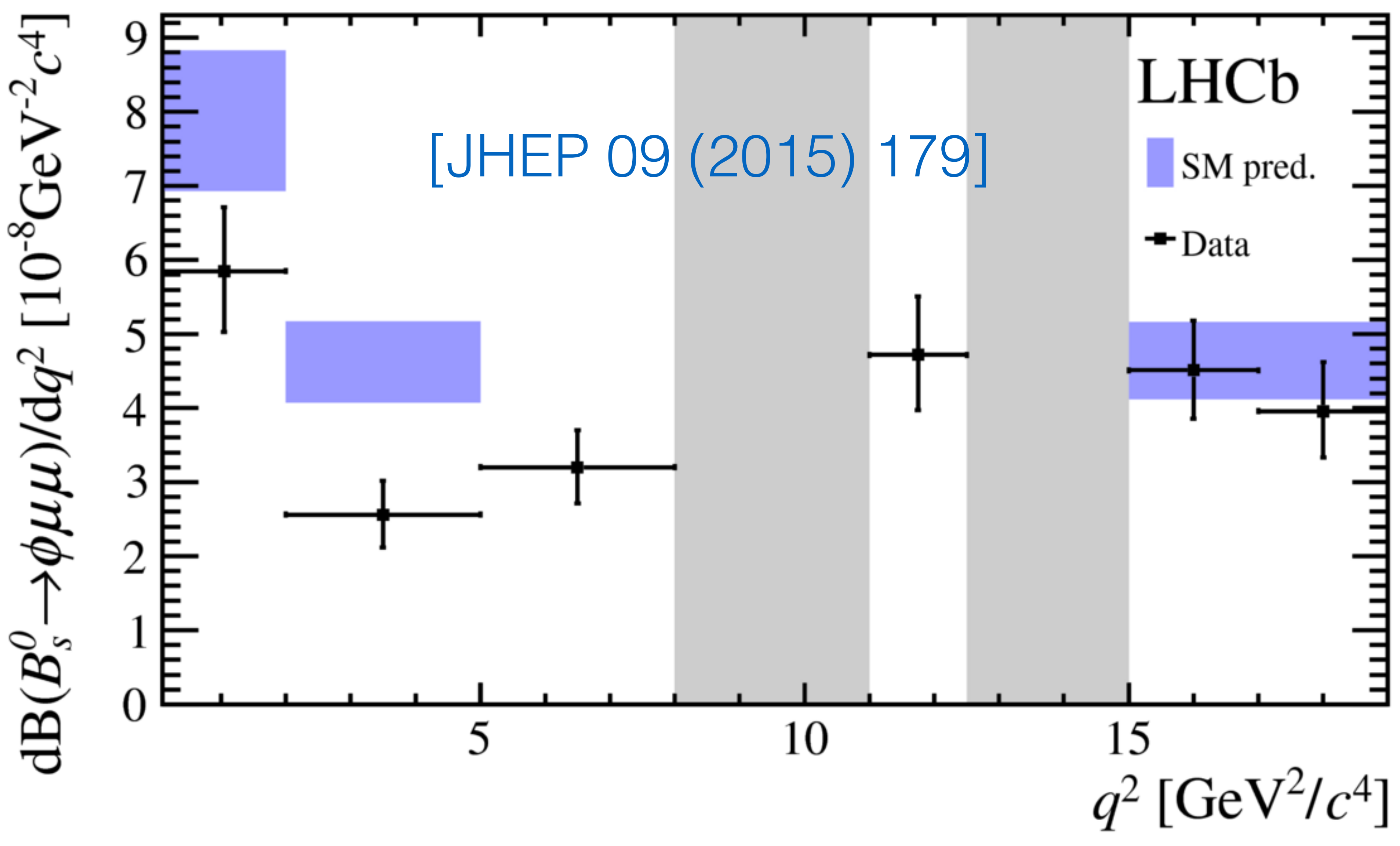


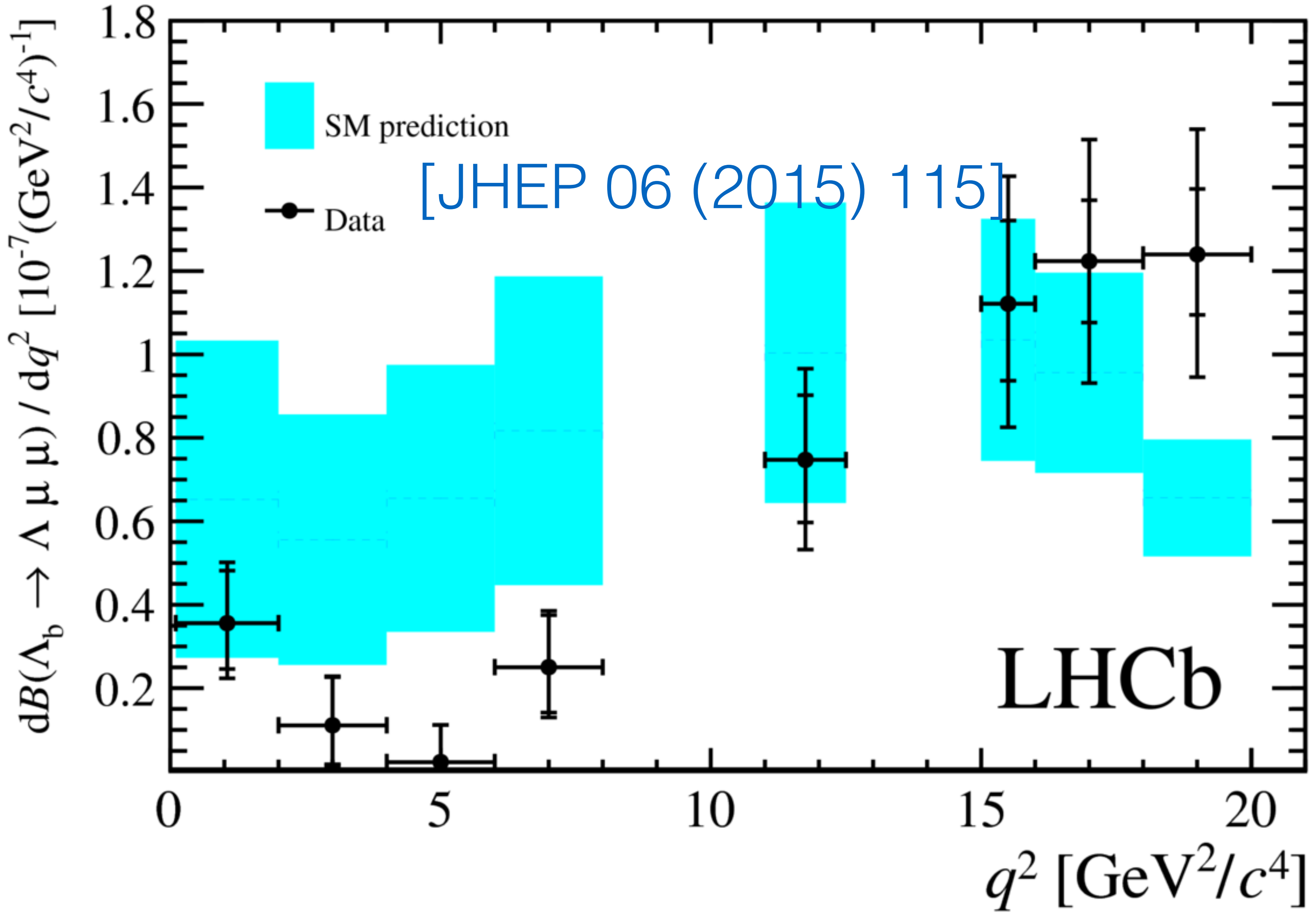
[JHEP 02 (2016) 104]

$b \to s\mu^+\mu^-$ branching fractions



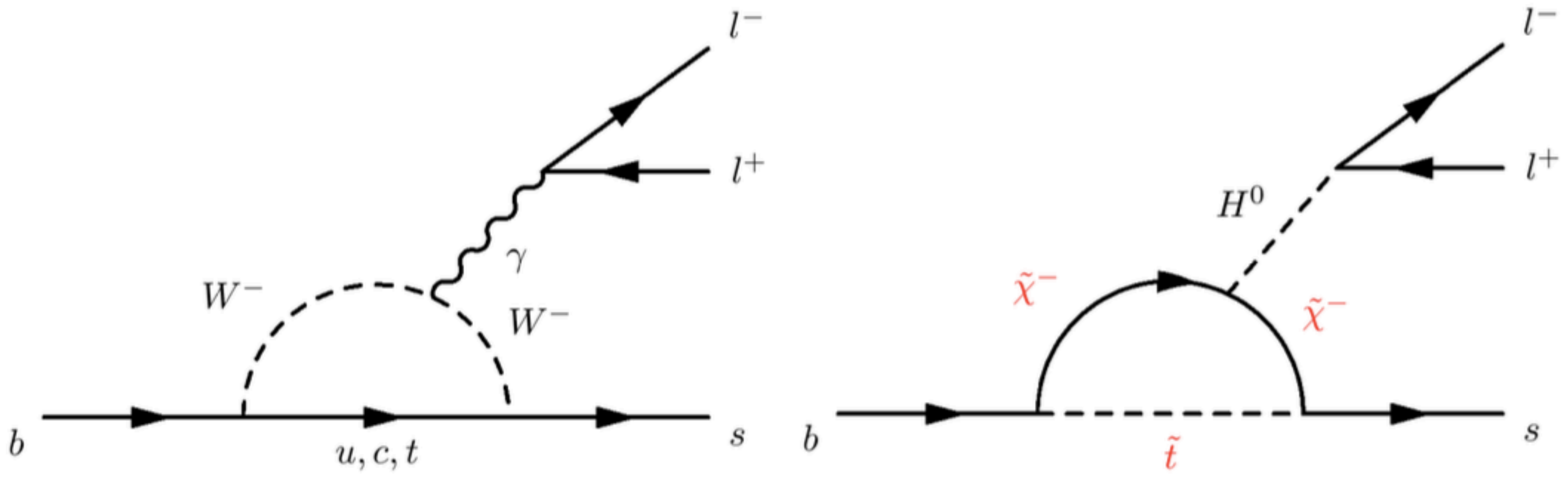






- Many BR's of similar decay modes are lower than predictions.
- QCD effect?
- See Guadagnoli talk.

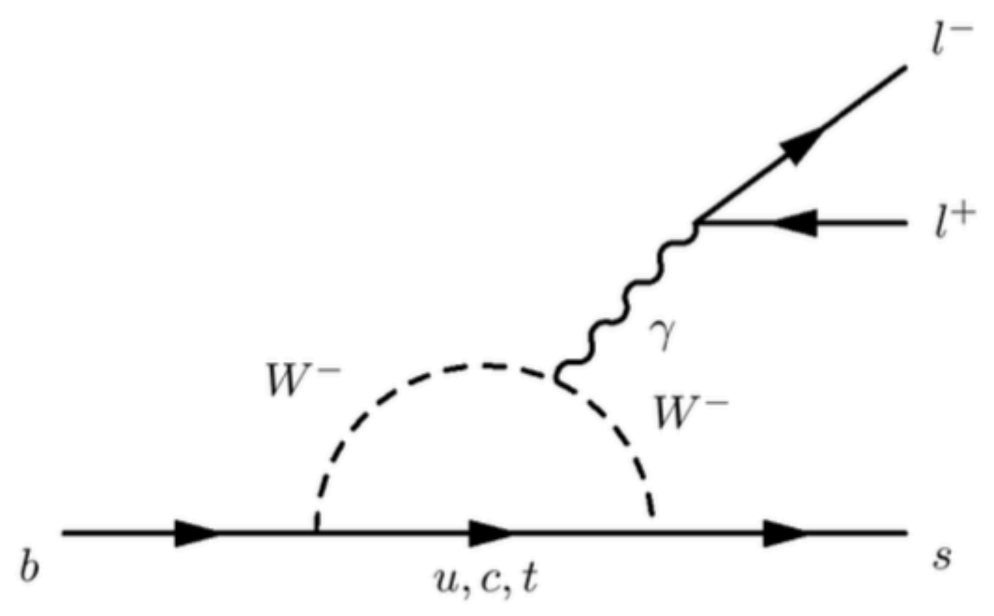
Lepton flavour universality



$B^0 \to K^+\mu^+\mu^-$

- In the SM only the Higgs boson has non-universal lepton couplings.
- This results in SM predictions of ~unity for various decay-rate ratios.
- Take double ratio with $B^+ \to J/\psi K^+$ to cancel possible systematic uncertainties.
- Electron reconstruction is challenging, huge tail due to Bremstrahlung.

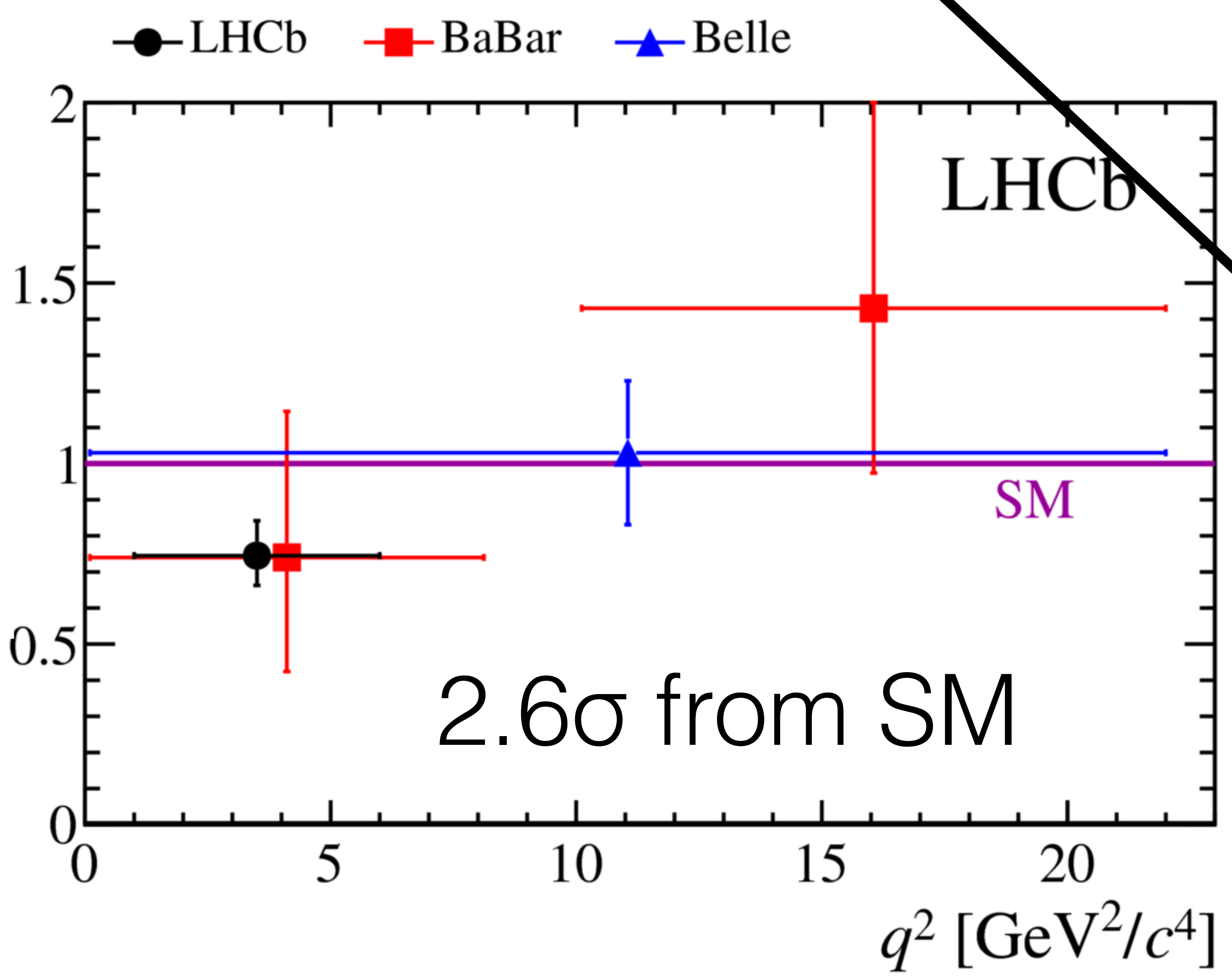
[PRL 113 (2014) 151601]

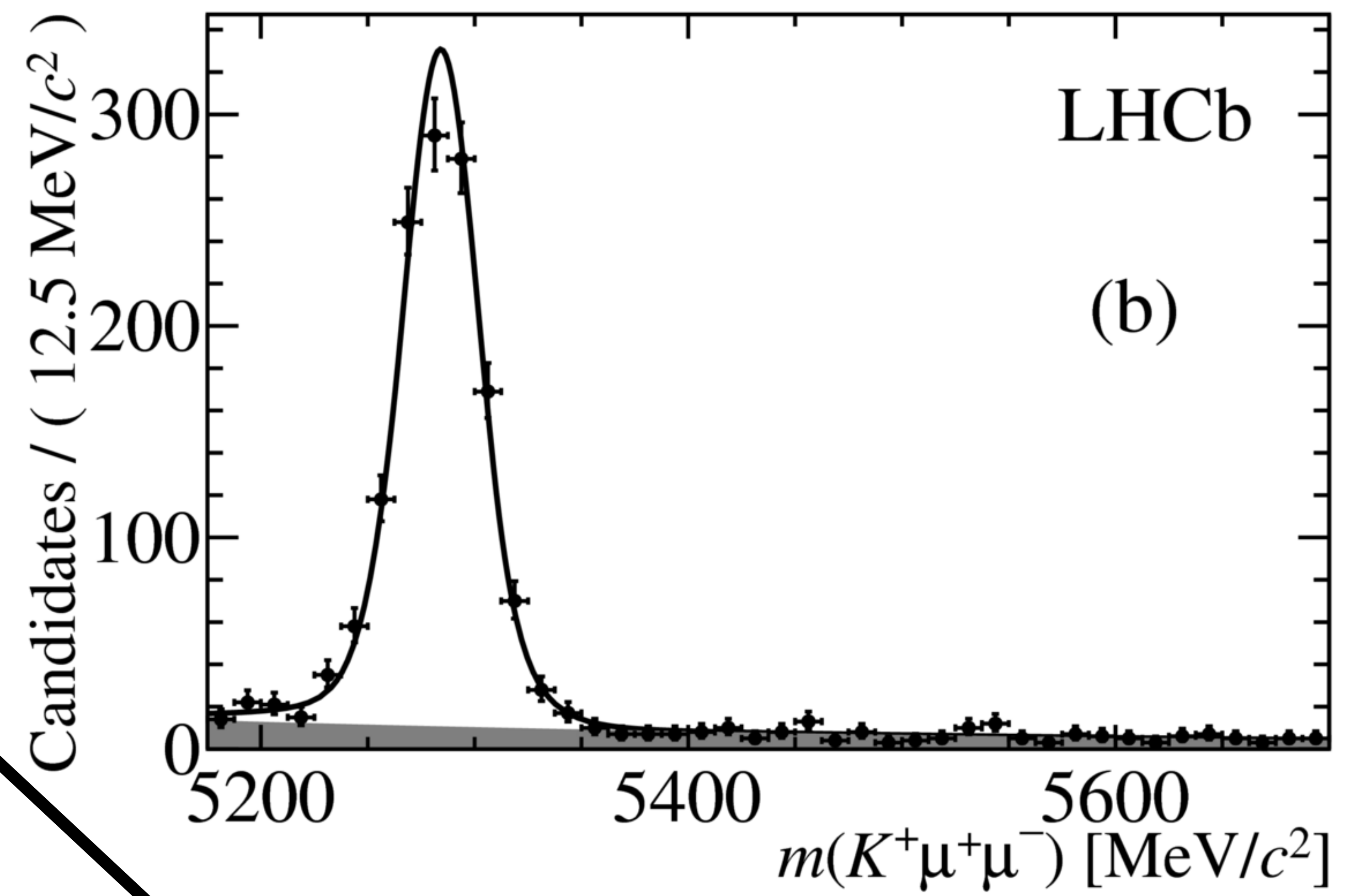


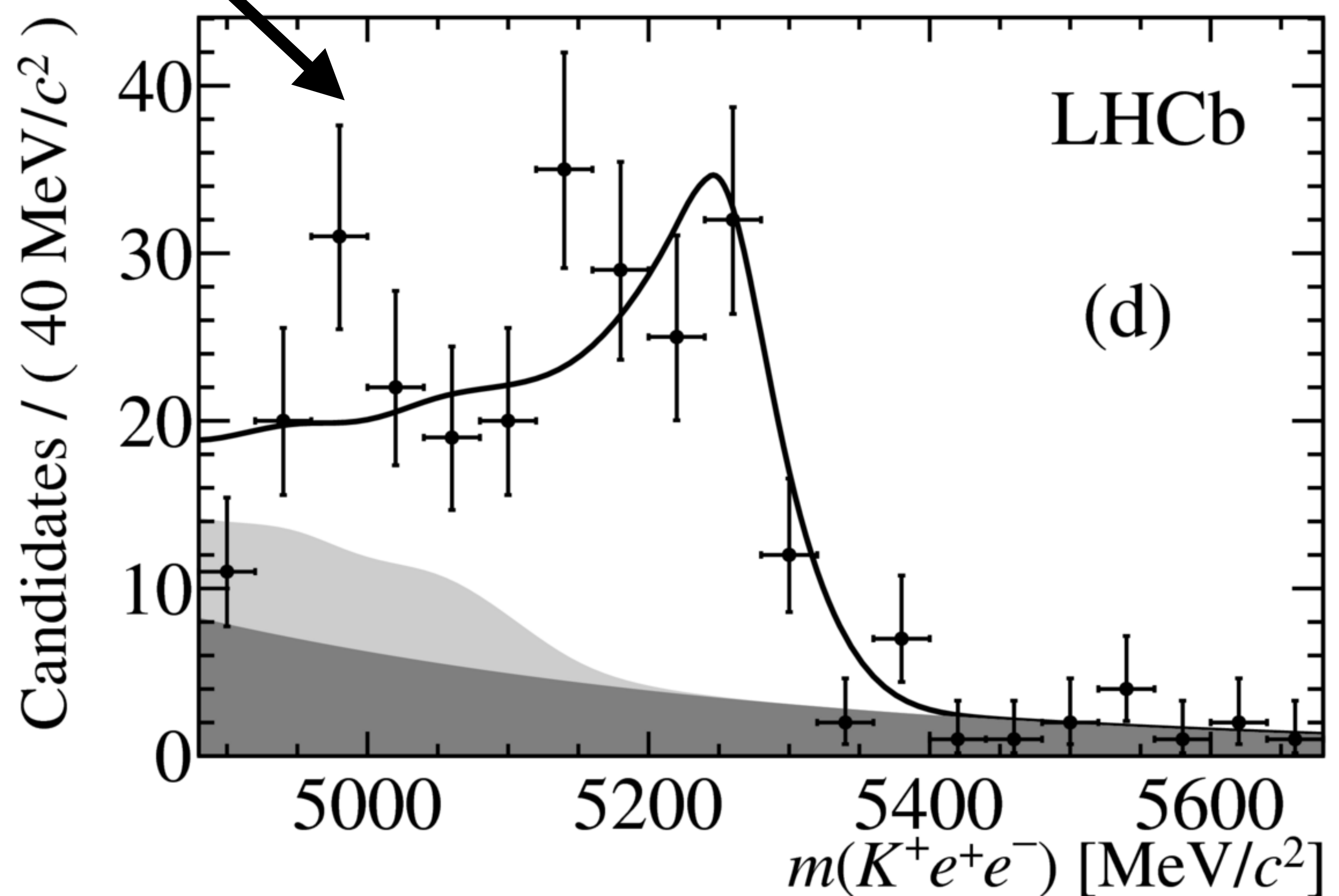
$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \stackrel{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-2})$$

[Isidori et al. EPJC 76 (2016)]

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

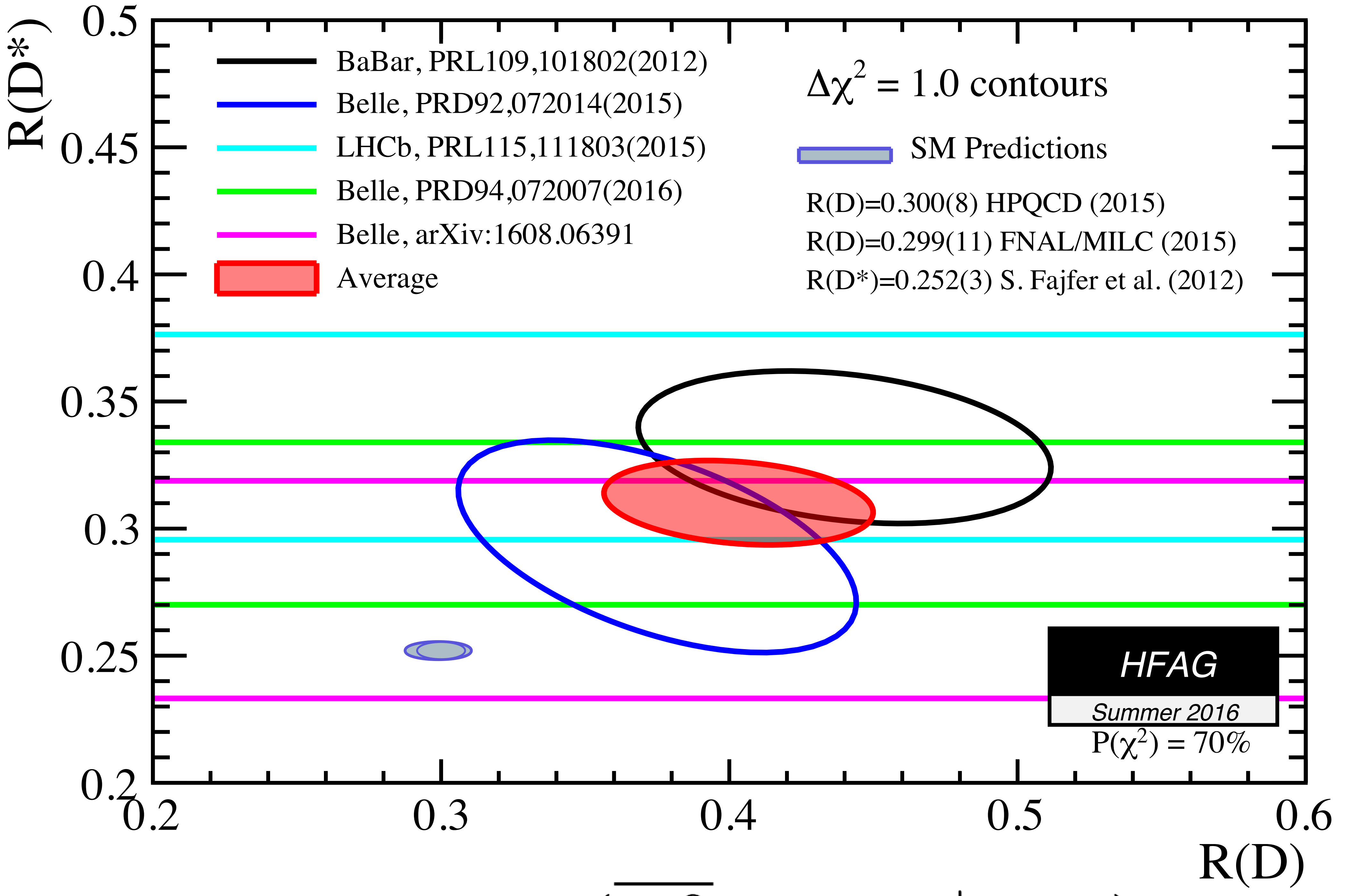






Can expect update soon with Run 2…

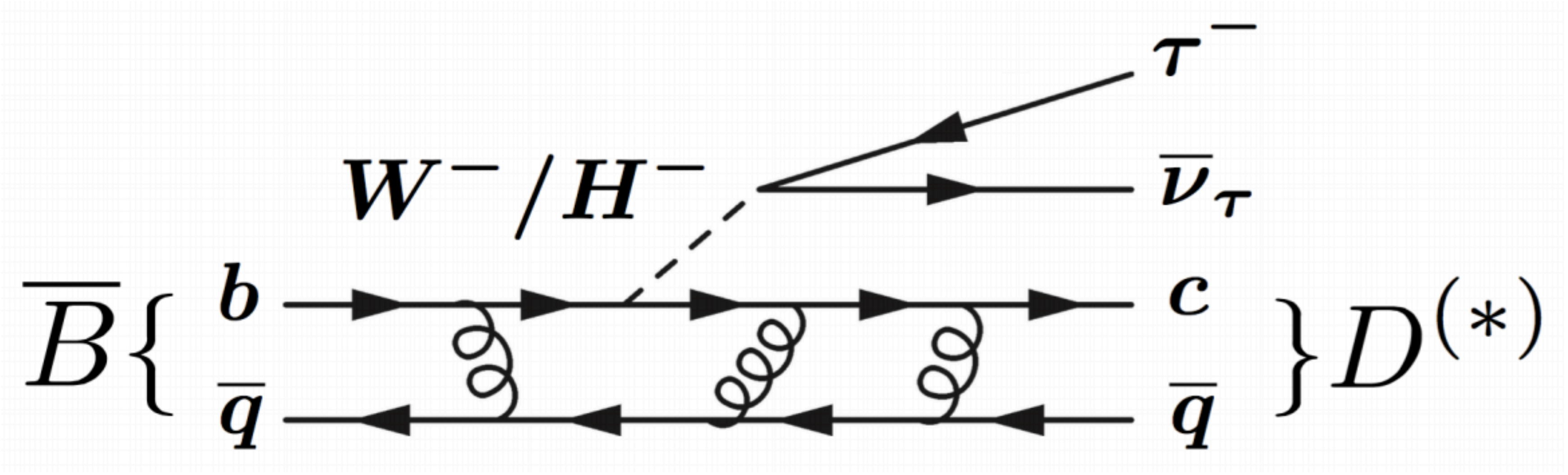
Lepton universality

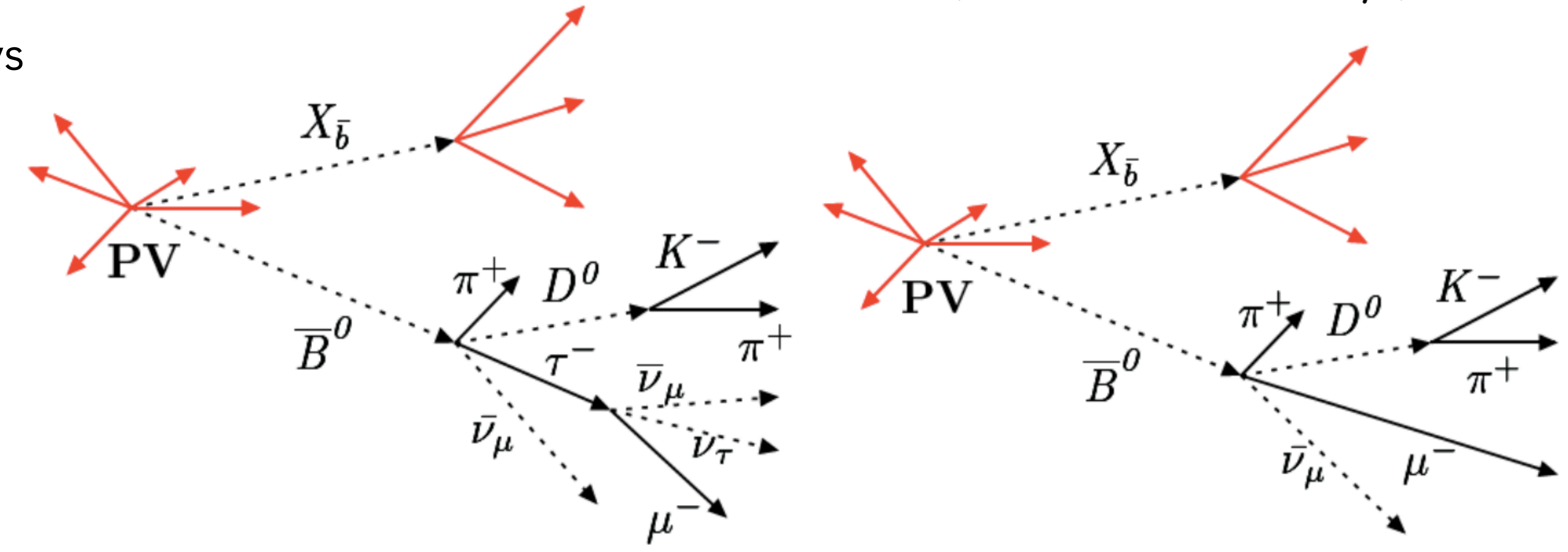


- CKM mechanism well tested, but room for NP if coupling more to 3rd generation (e.g., charged Higgs).
- Study tree-level decays, $\overline{B}^0 \to D^{*+} l^- \nu$
- Theoretically clean predictions since only lepton mass differs.
- **Experimental challenges at LHCb:**
  - Missing neutrino, so no narrow peak to fit
  - Signal and normalisation mode have identical final state
  - Background from partially reconstructed decays

$$R(D^*) \equiv \frac{\mathcal{B}(\overline{B^0} \to D^{*+} \tau \nu_\tau)}{\mathcal{B}(\overline{B^0} \to D^{*+} \mu \nu_\mu)}$$

$$\mathcal{B}(\tau \to \mu \nu_\mu \nu_\tau) = (17.41 \pm 0.04)\%$$

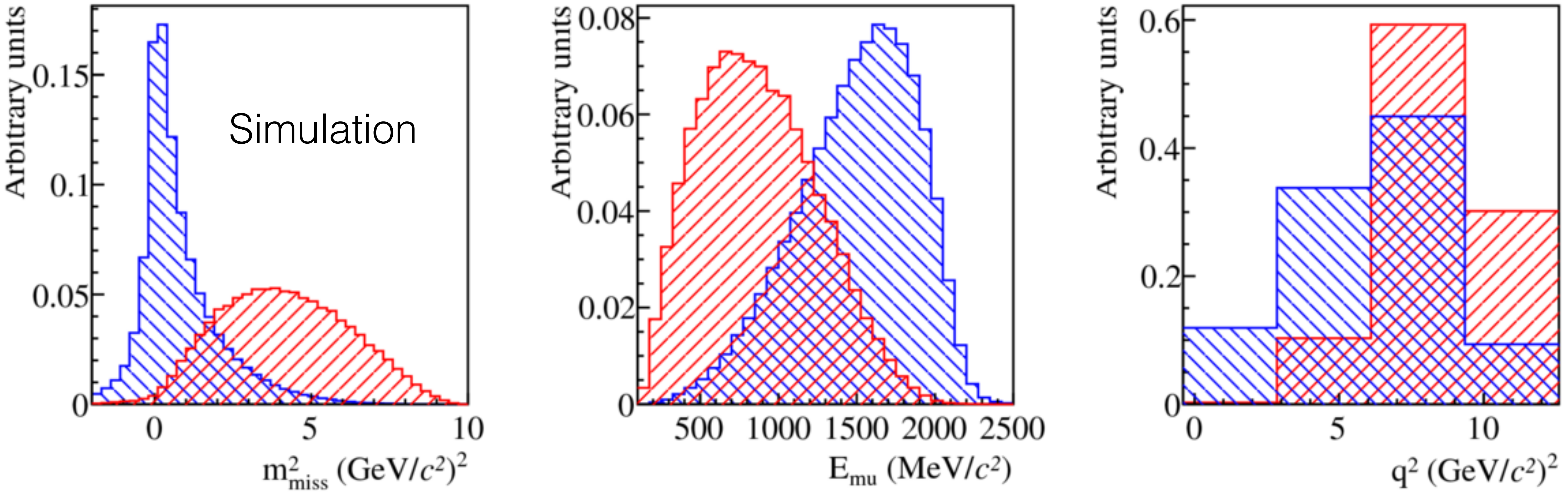


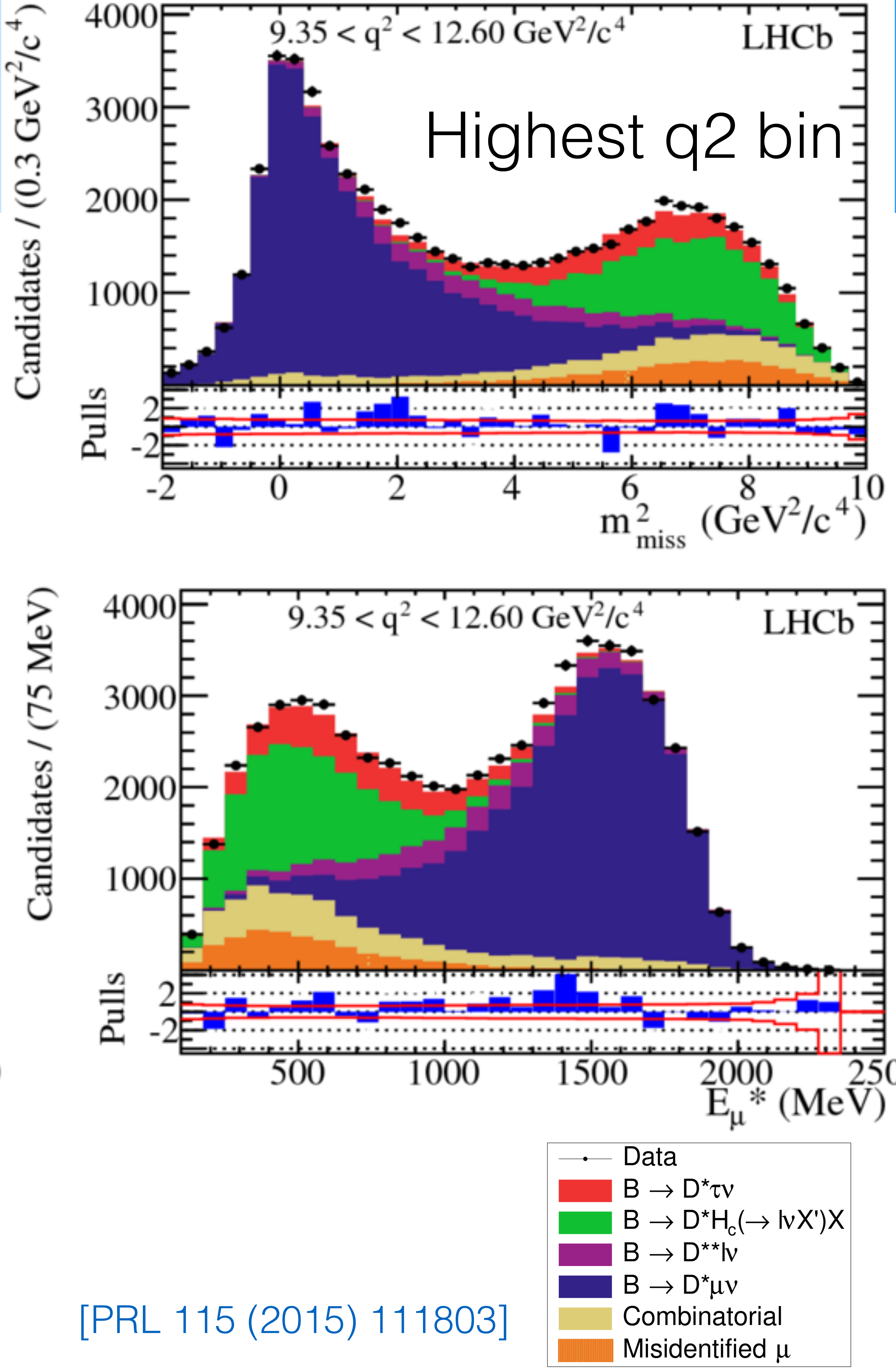


Lepton universality

- Separate signal from normsalisation using kinematic variables.
- Backgrounds estimated from data control samples.
- Template fit in bins of q2

$$\overline{B}^0 \to D^{*+}\mu^-\nu \quad \overline{B}^0 \to D^{*+}\tau^-\nu$$



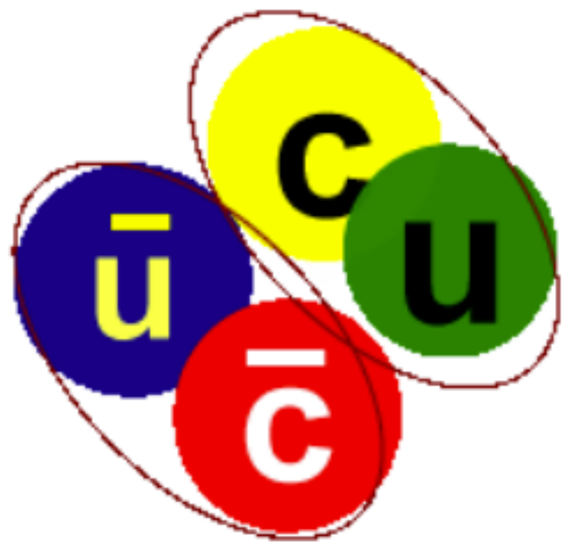


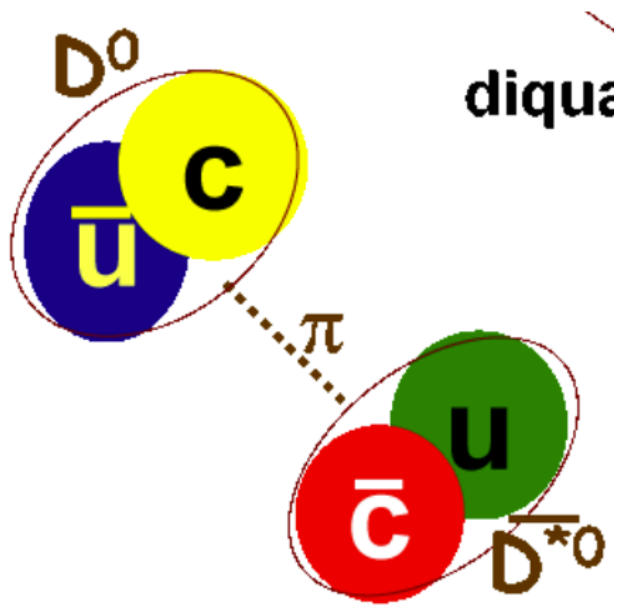
$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

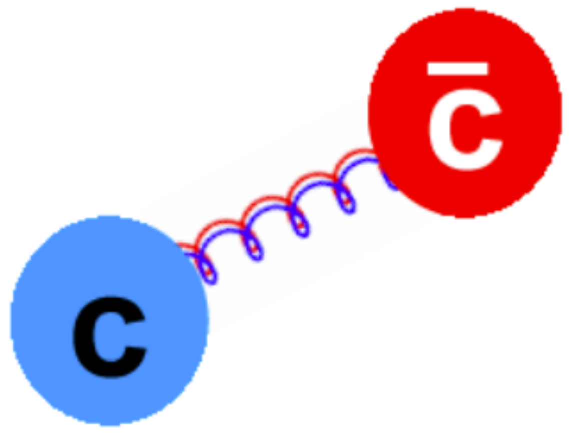
Many other "R" measurements ongoing

[PRL 115 (2015) 111803]

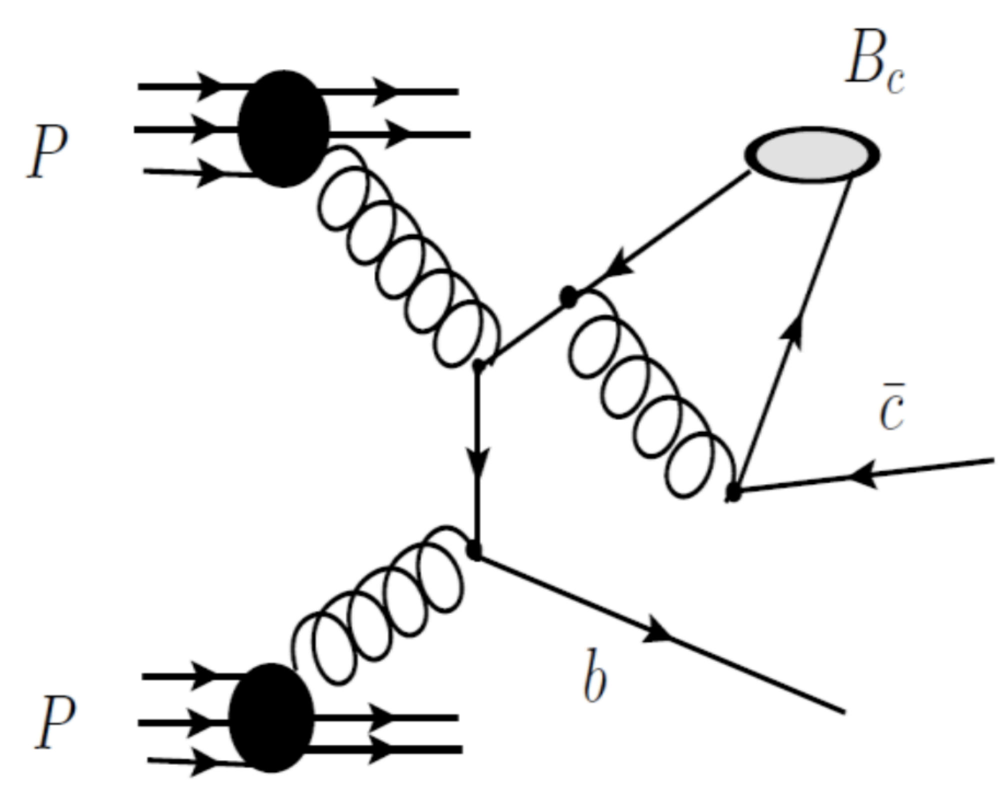
(Exotic) hadron spectroscopy







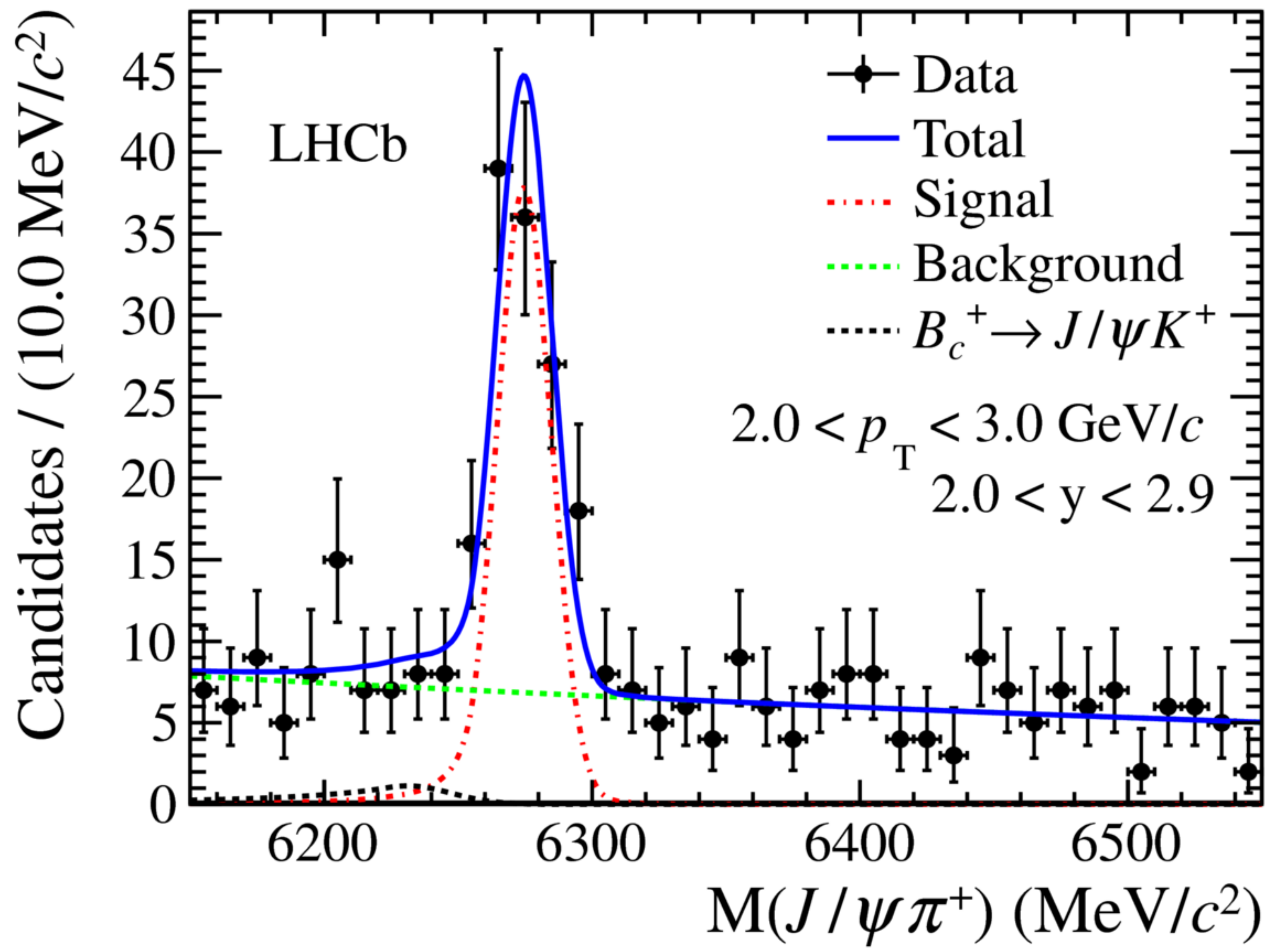
B_c physics: production

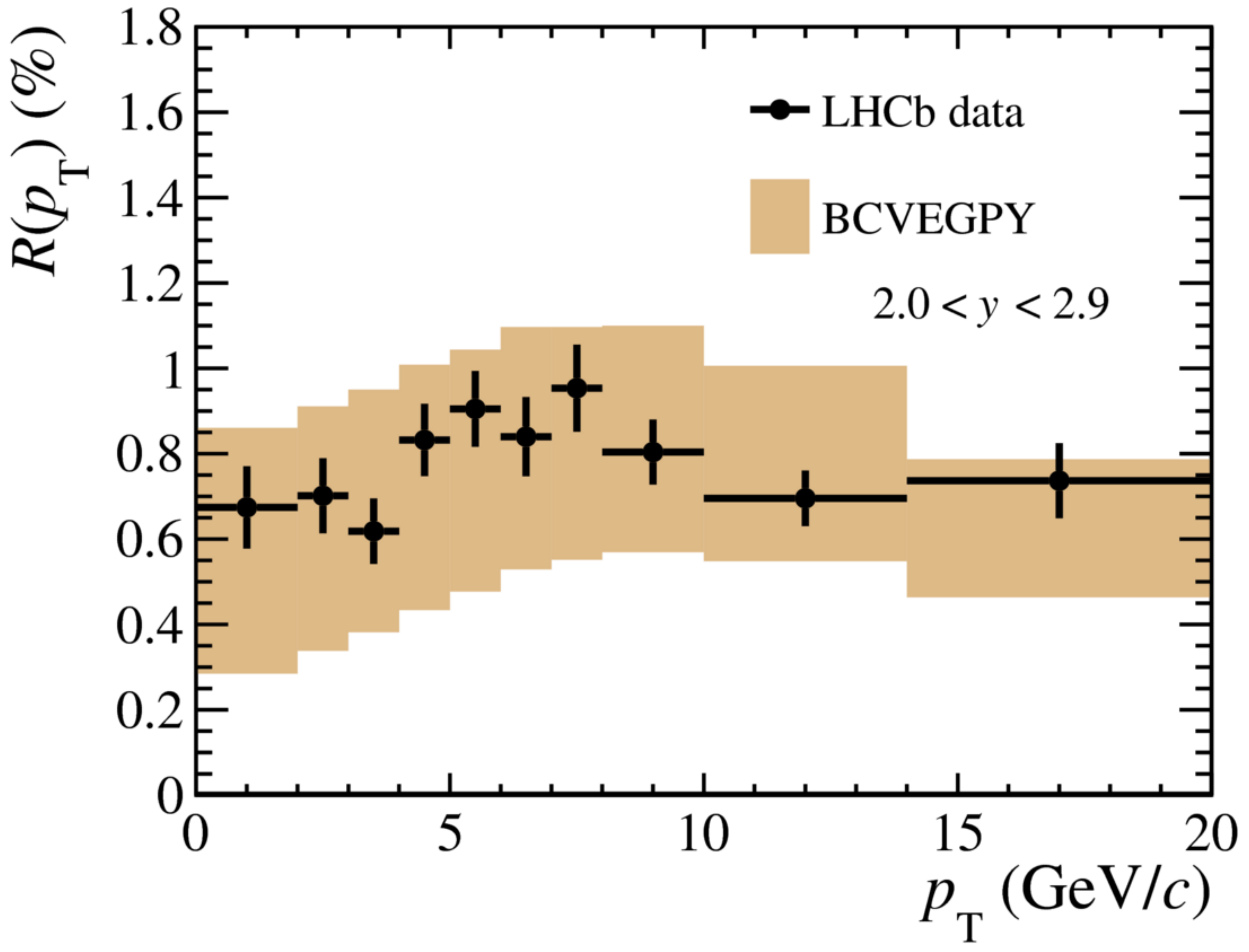


- At the LHC, all types of b-hadrons are produced, including B_c mesons.
- LHCb making huge progress measuring production and decay properties.

[PRL 114, 132001 (2015)] [PRL 109 (2012) 232001] for compatible 7 TeV results

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



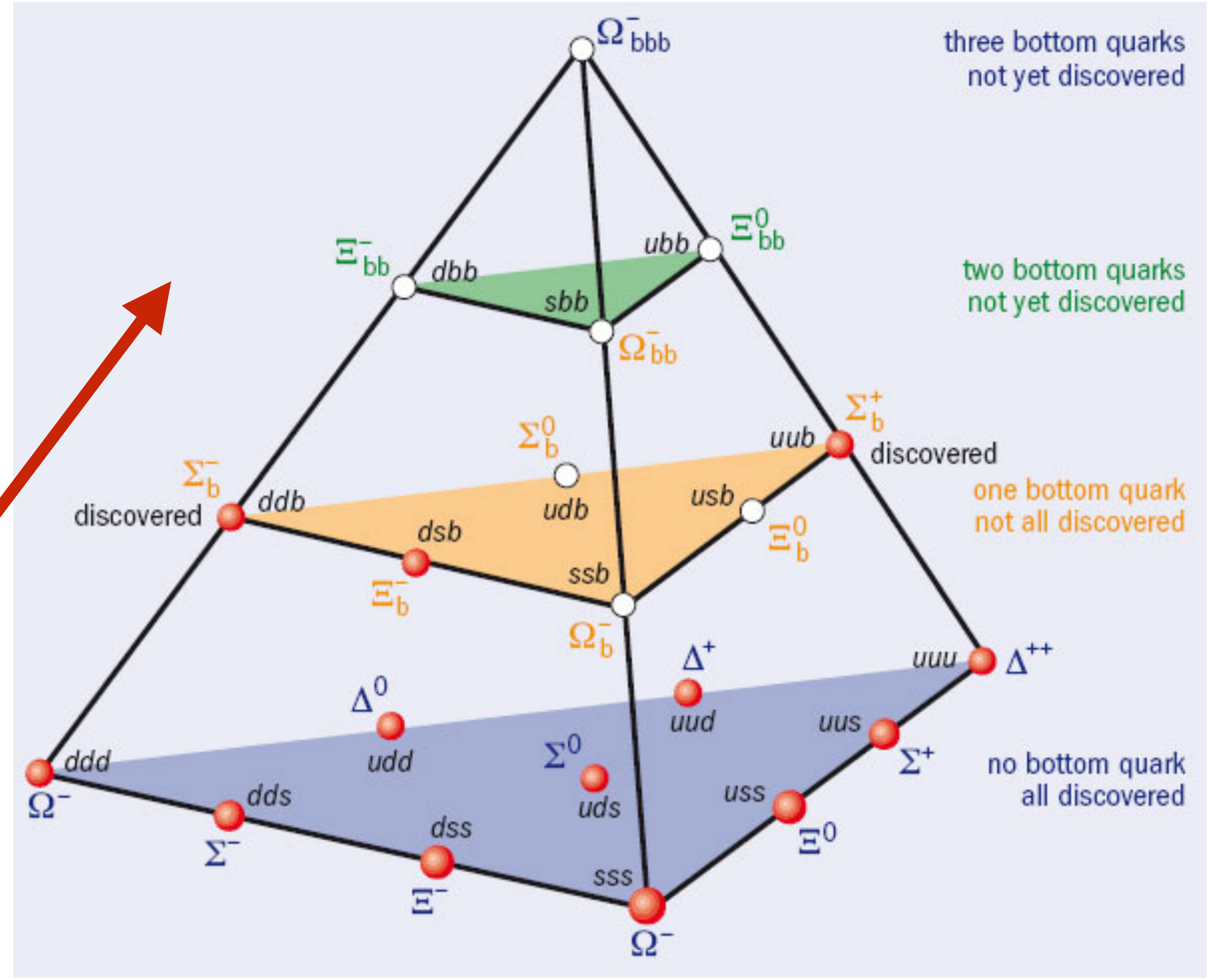


$$R = (0.683 \pm 0.018 \pm 0.009)\%$$

BCVEGPY

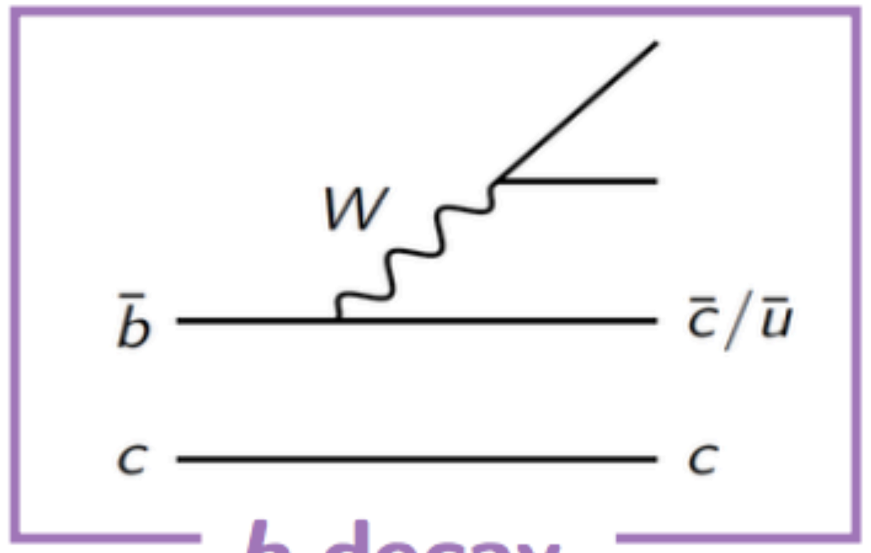
$$\sigma(B_c^+) \sim 0.47\ \mu\text{b} \ @ \sqrt{s} = 8\ \text{TeV}$$

Ability to produce Bc has ignited interest in searching for doubly- (and triply-) heavy baryons, e.g., Ξ_{bb}, Ξ_{bc}...

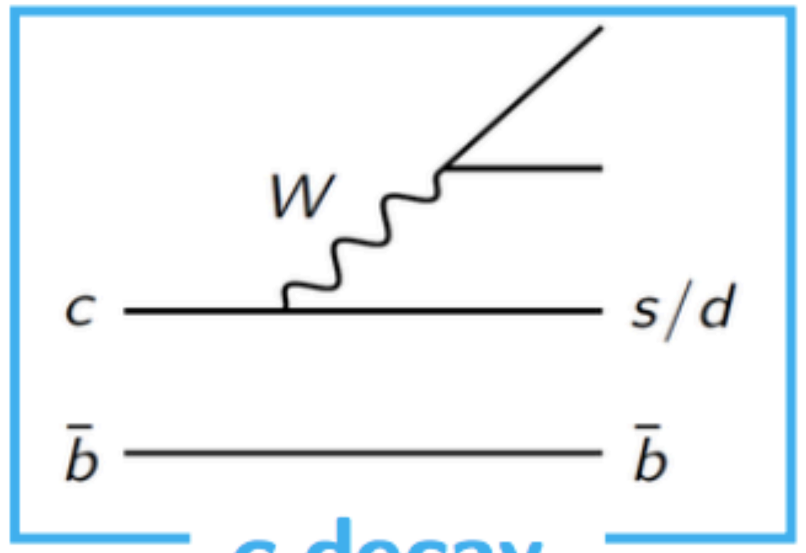


B_c physics: decay

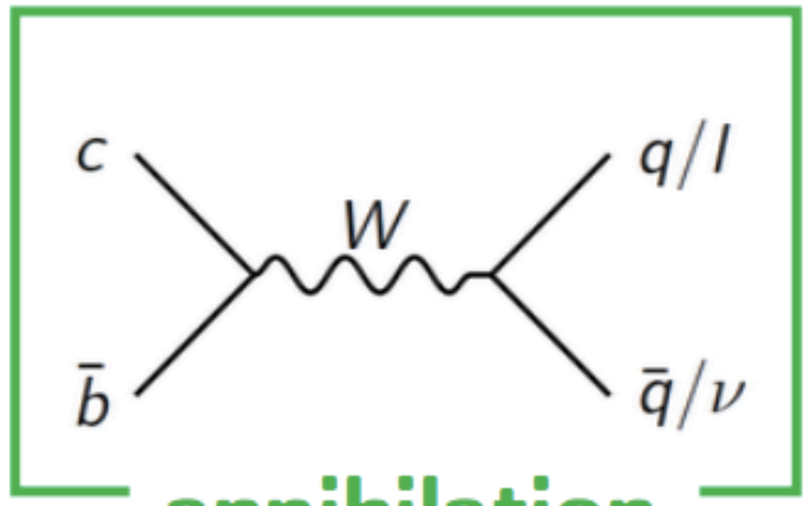
- Lifetime of B_c is much shorted than other b hadrons due to presence of the c-quark.
- Dominant systematic from decay time efficiency.
- Many new decay modes found.



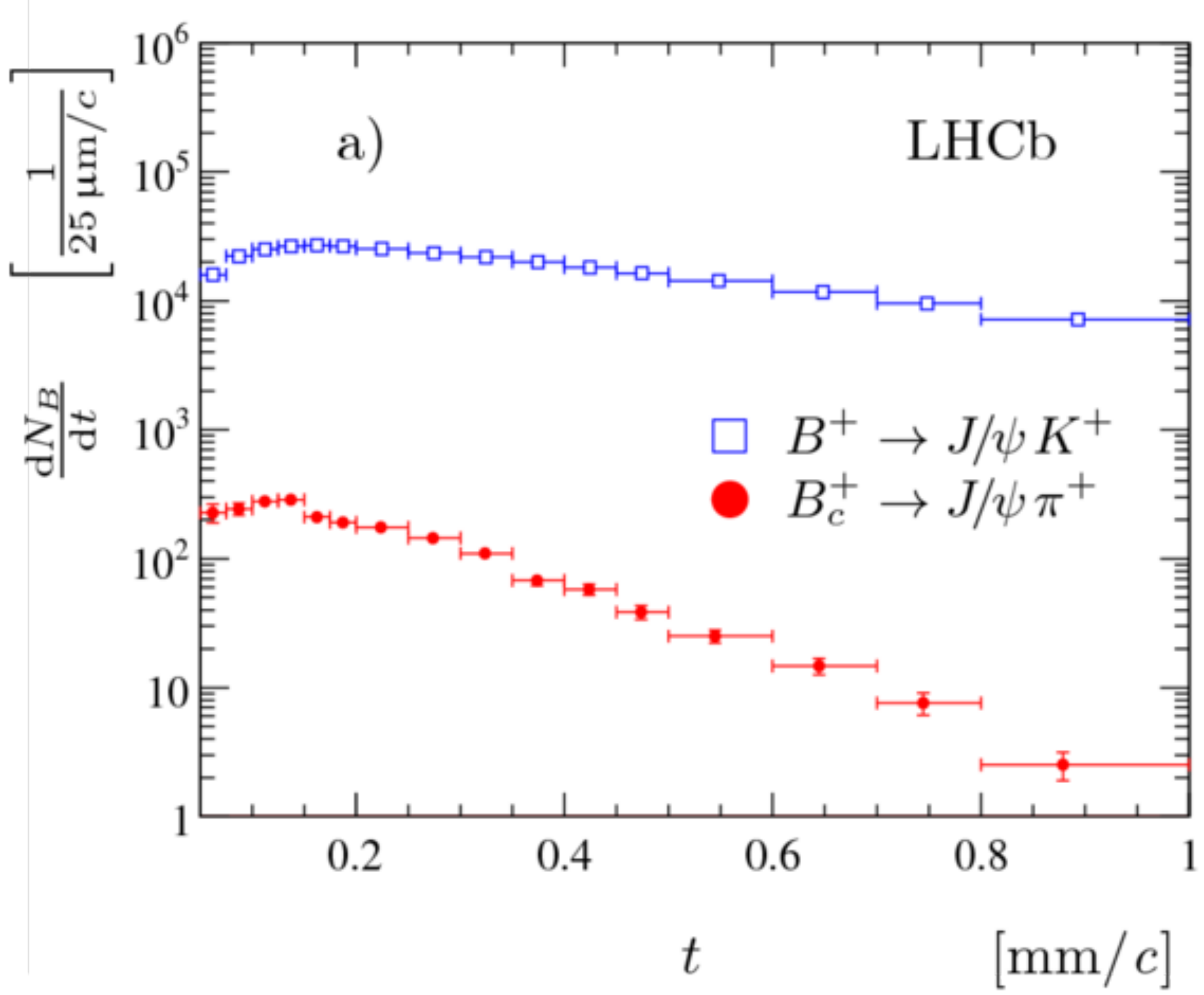
b decay
~ 20%

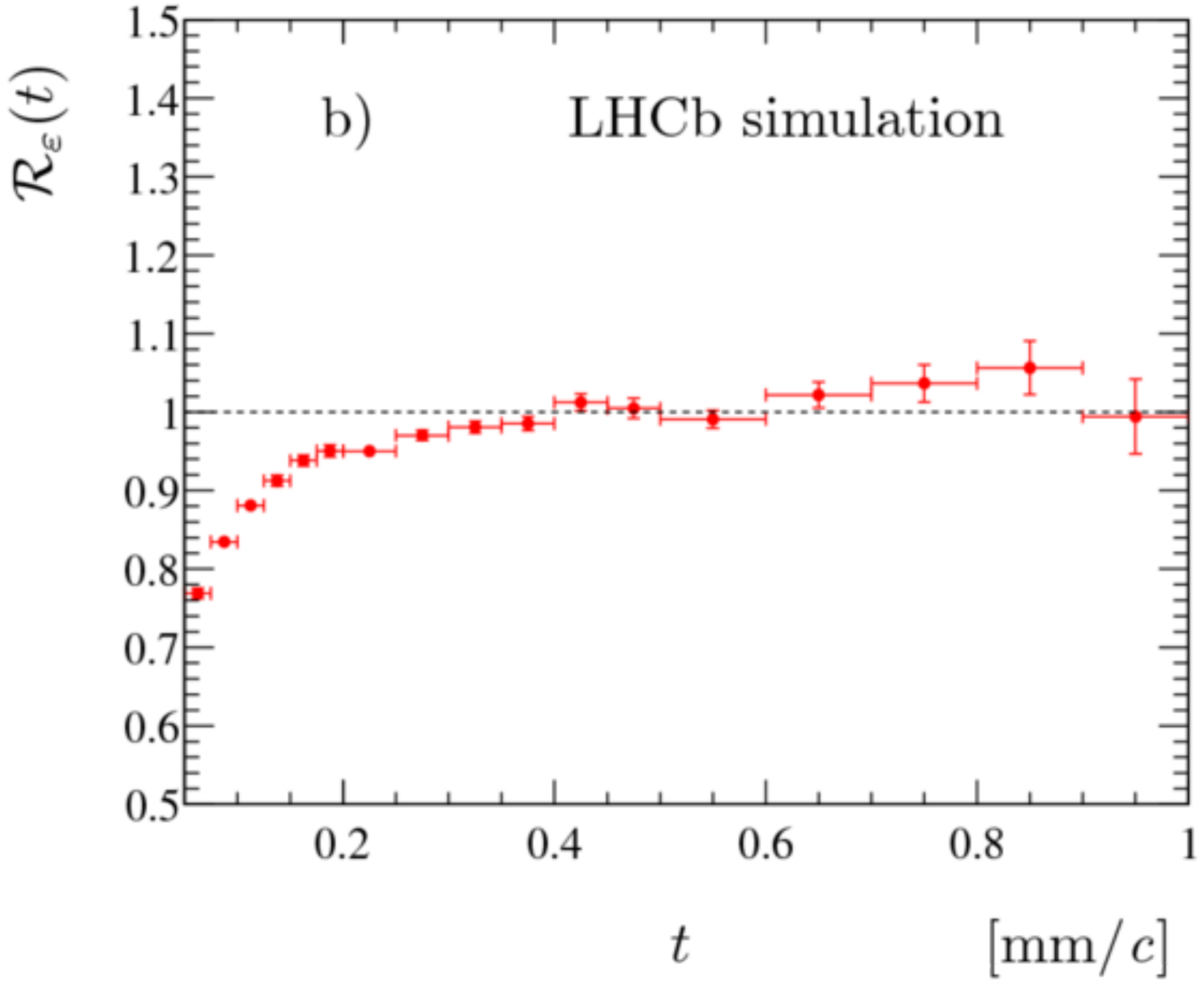


c decay
~ 70%

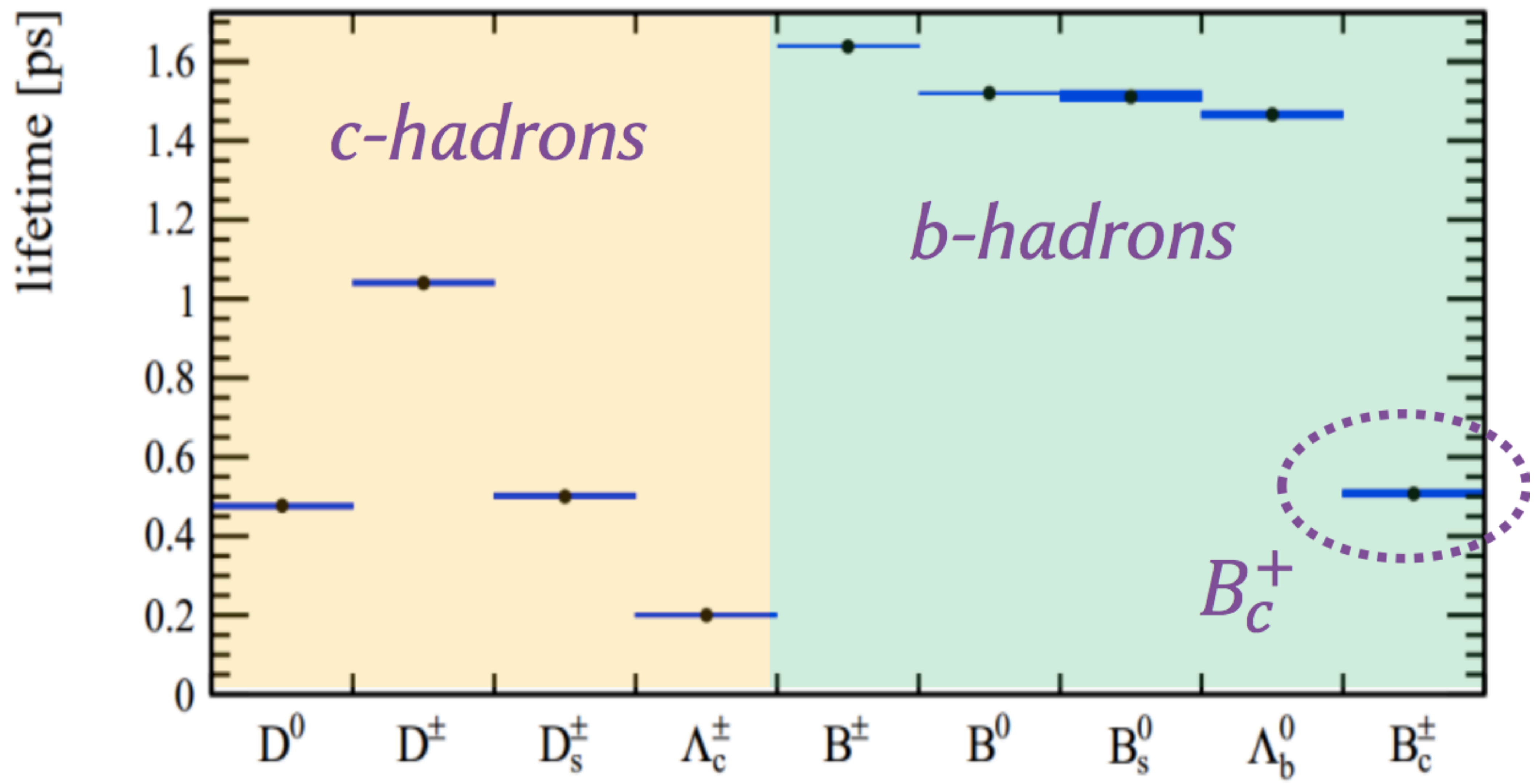


annihilation
~ 10%





[PRL 109 (2012) 232001]

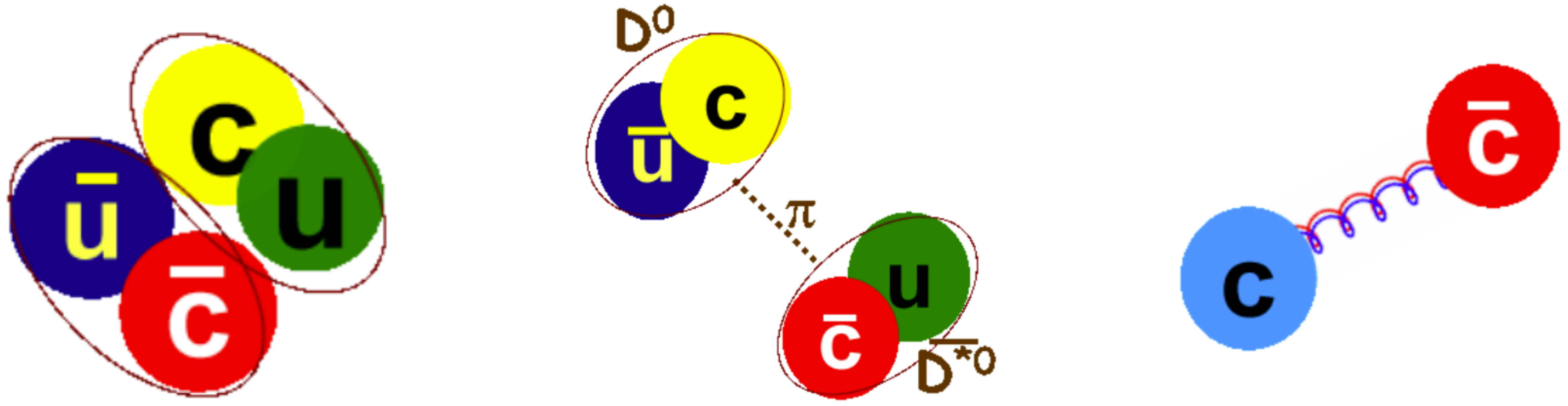


[PRL 109 (2012) 232001]
$\tau_{B_c} = 513.4 \pm 11.0 \pm 5.7$ fs

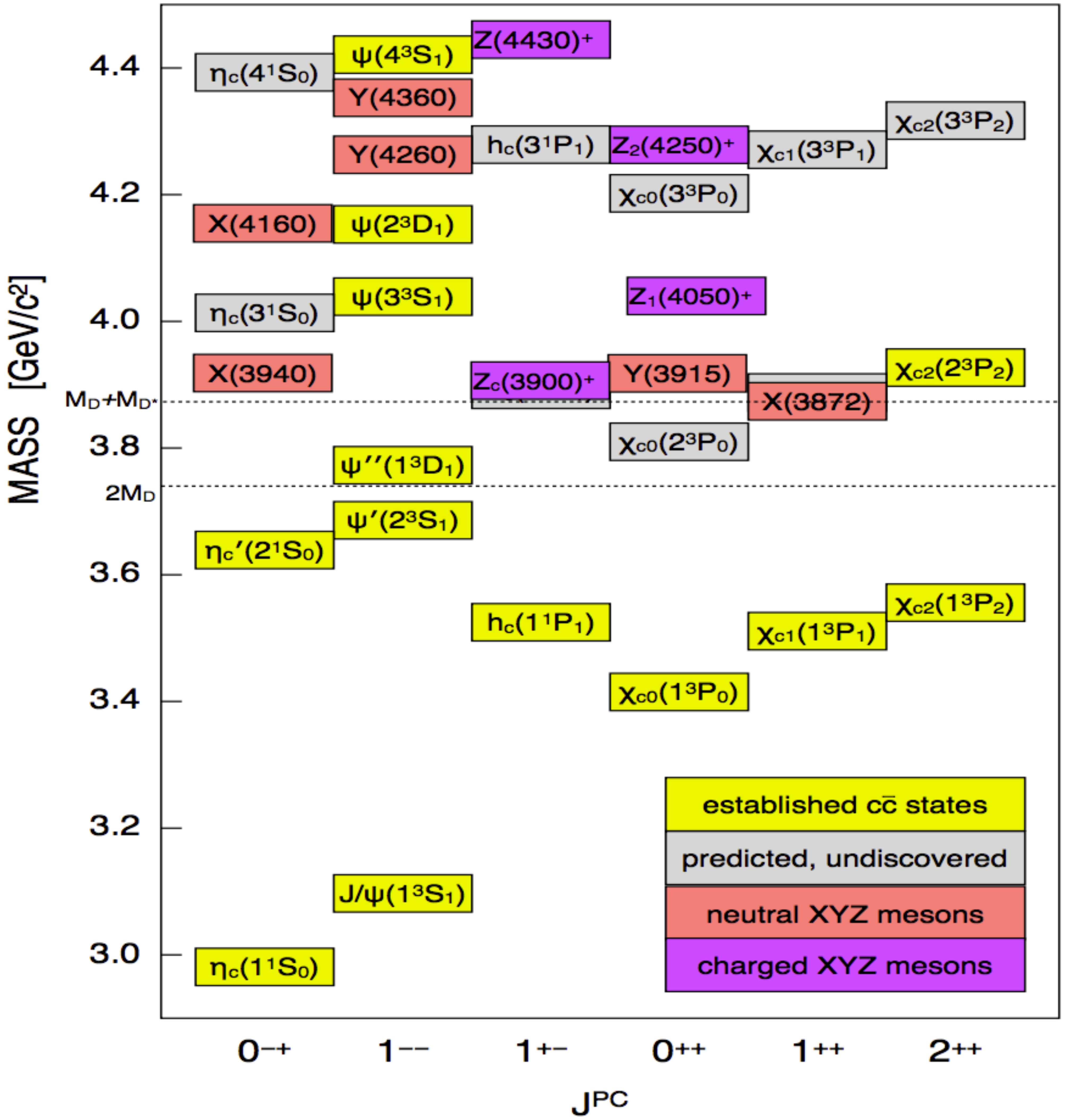
[EPJC 74 (2014) 2839]
$\tau_{B_c} = 509 \pm 8 \pm 12$ fs

Exotic charmonium spectroscopy ($c\bar{c}$)

- Many different exotic (XYZ) states have been seen since ~2003.
- BESIII, Belle/BaBar, CDF/D0, LHC.
- Are these $[QQ][\overline{qq}]$ (tetraquarks), mesonic molecules, hybrids, threshold effects…?
- **No clear pattern:** need experimental, theoretical study to understand strong interaction dynamics that can cause their production and structure.



[Godfrey, Olsen, Ann.Rev.Nucl.Part.Sci.58:51-73,2008]

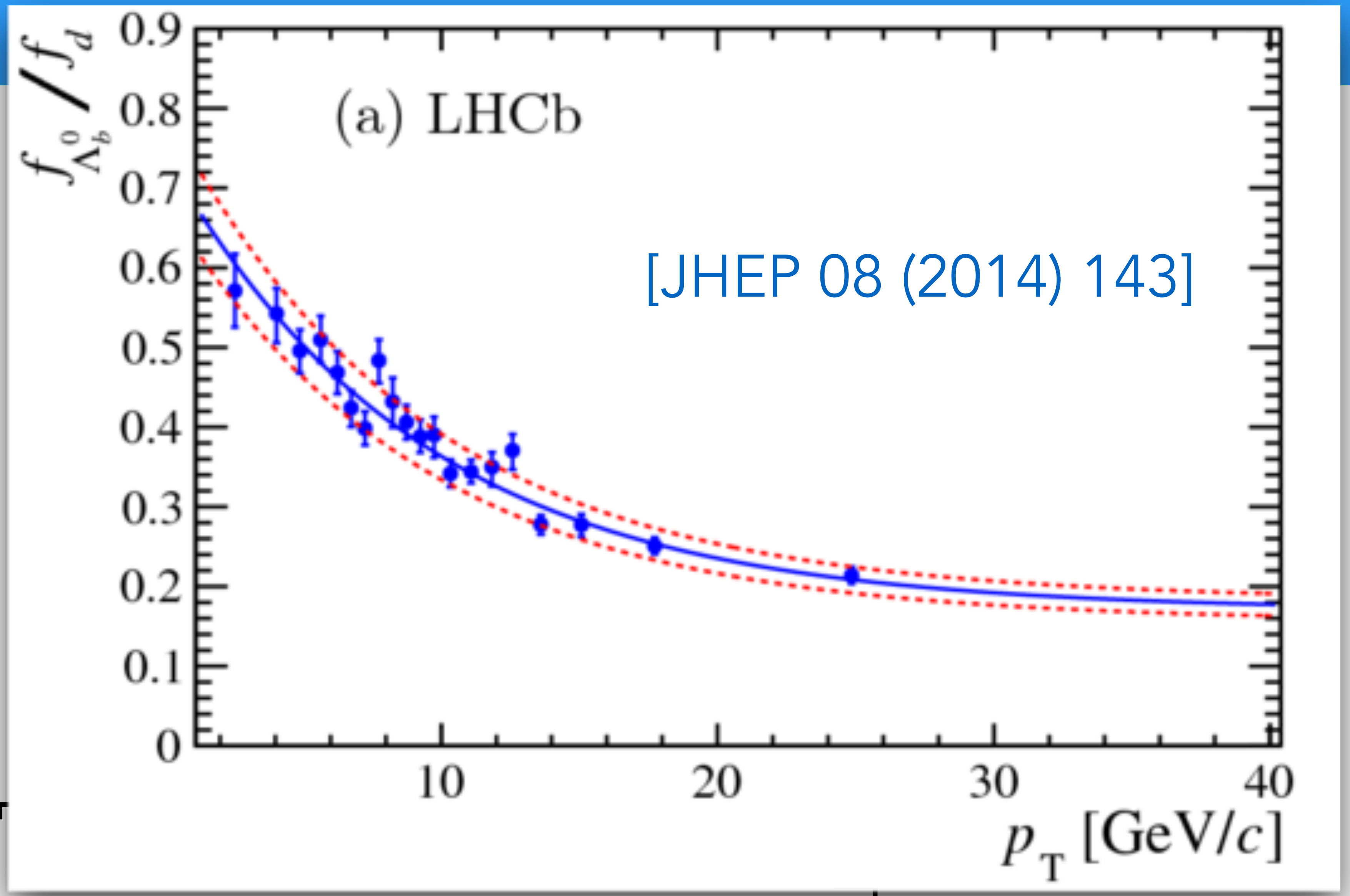


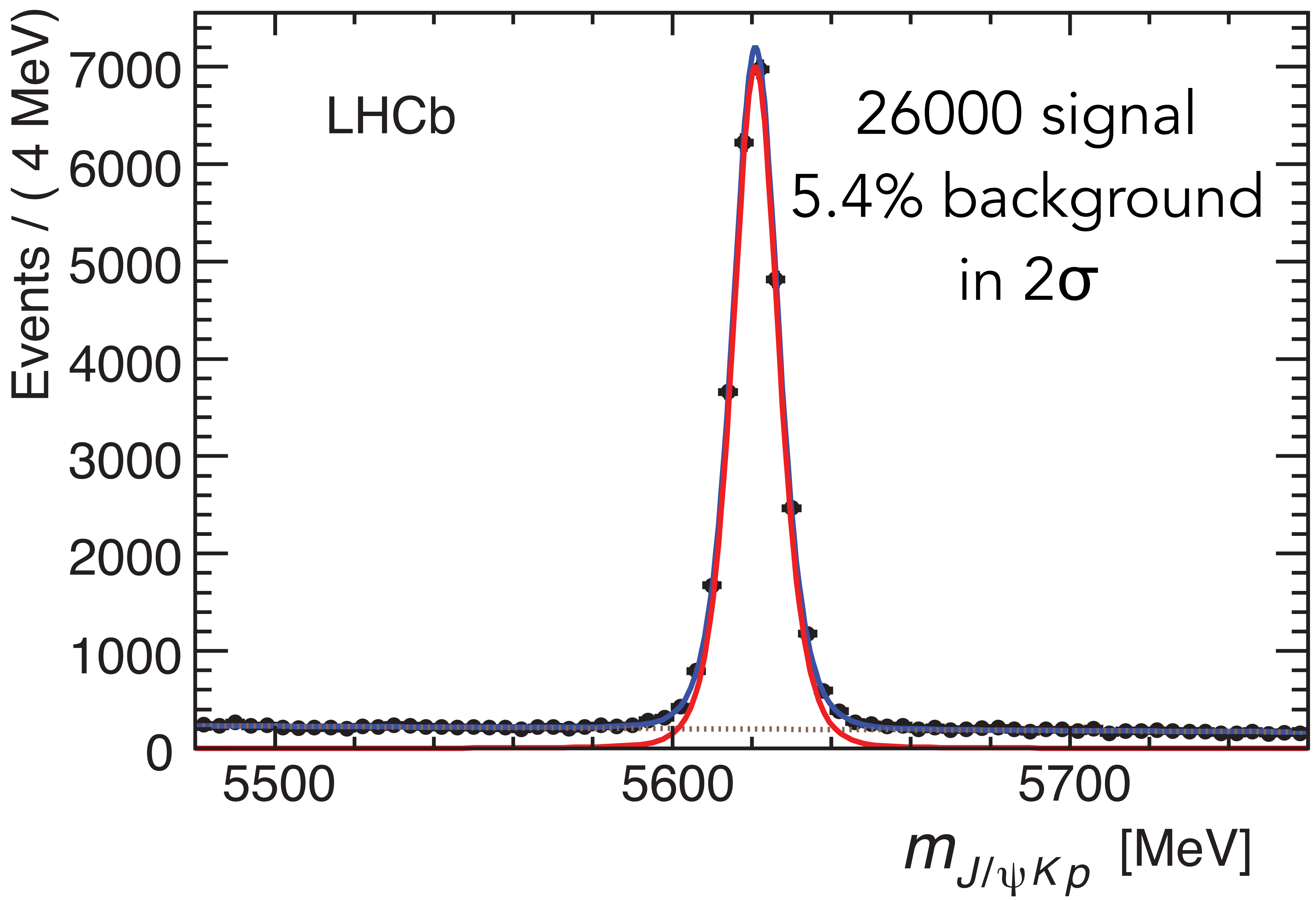
[Olsen arXiv:1403.1254]

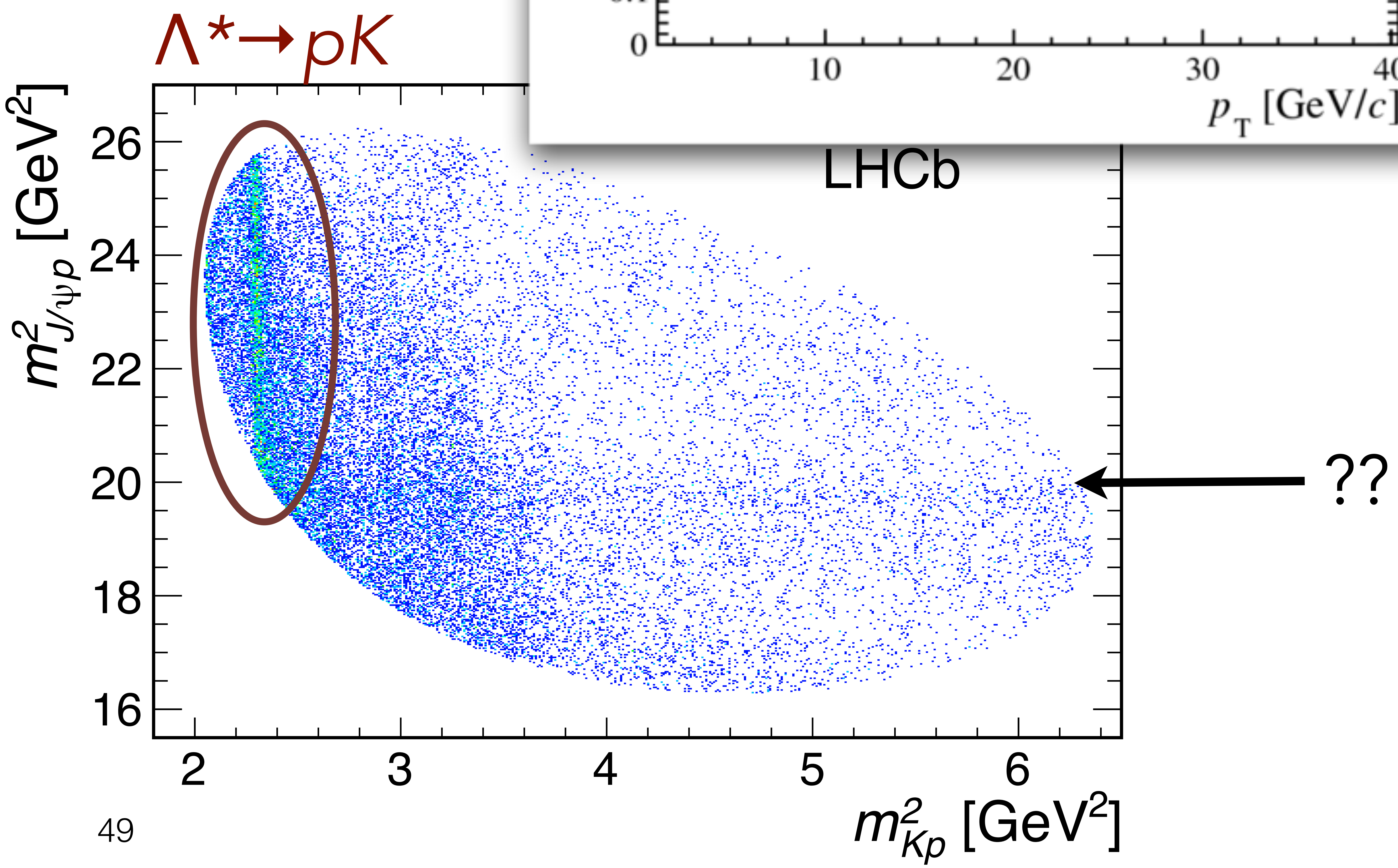
Lattice calculations being done to look for exotic states e.g., [TWQCD PLB 646 (2007) 95–99]

Pentaquark observation [PRL 115 (2015) 072001]

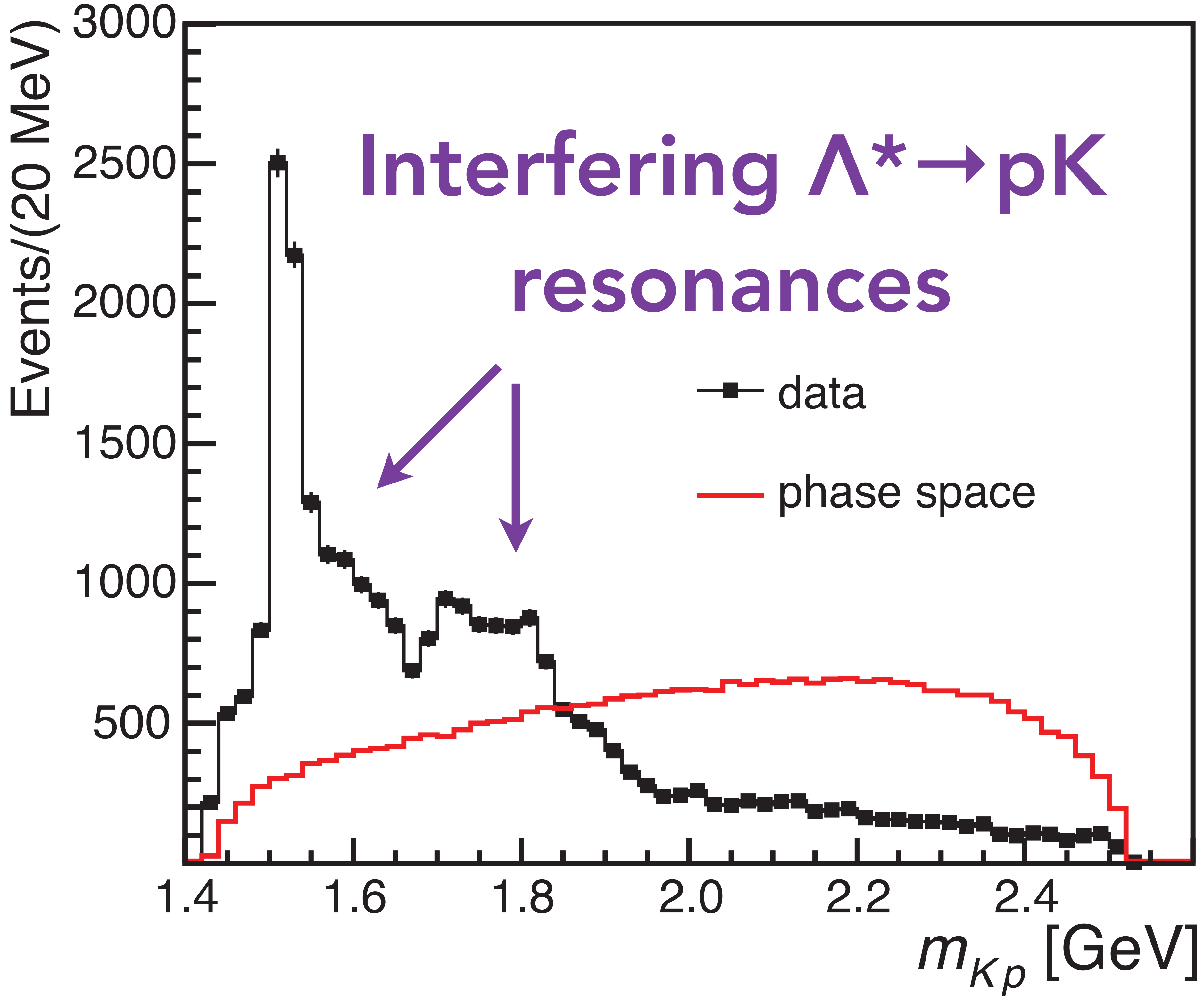
- Take advantage of large production of b-baryons at LHC $\Lambda_b^0 \to J/\psi p K^-$

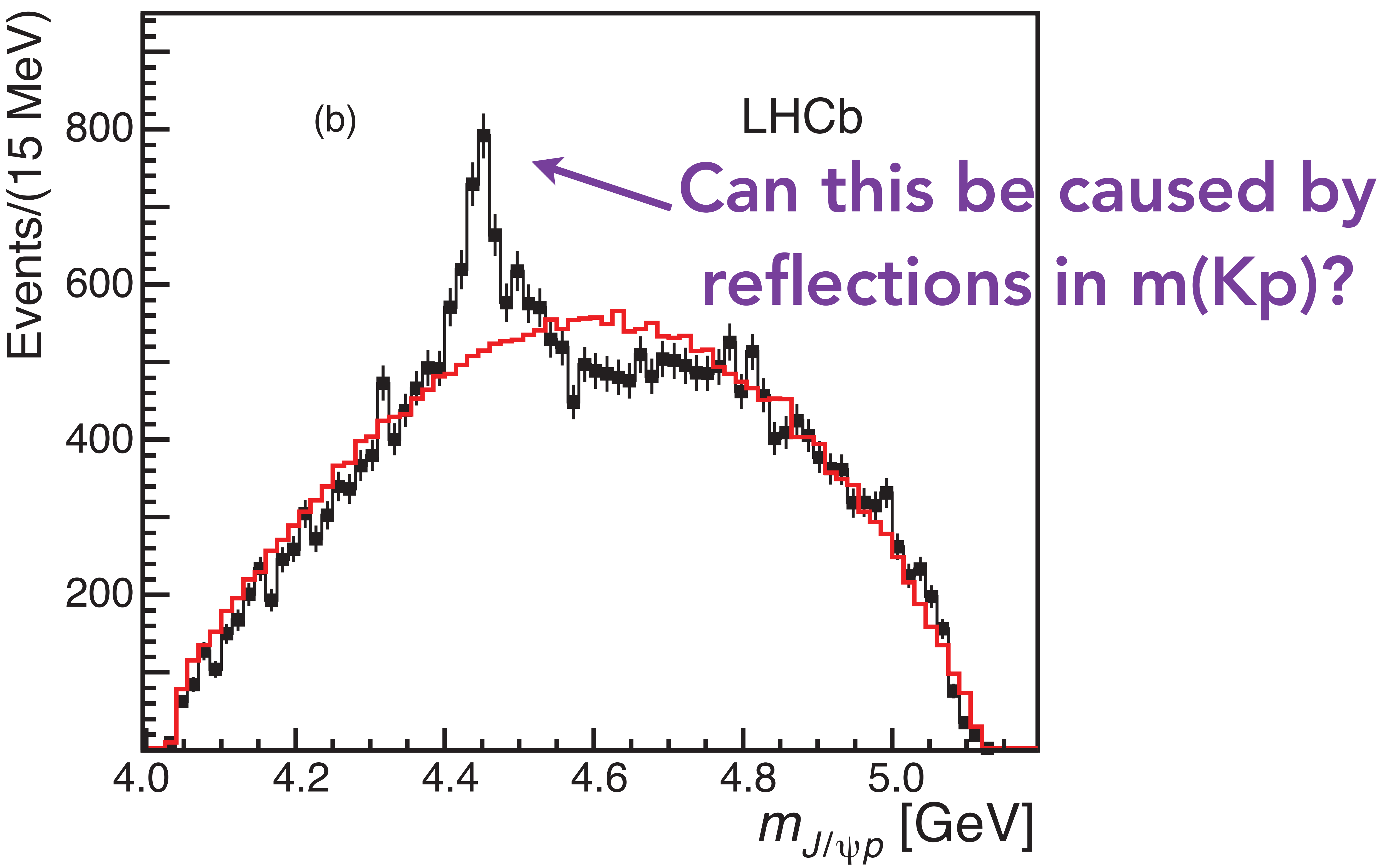


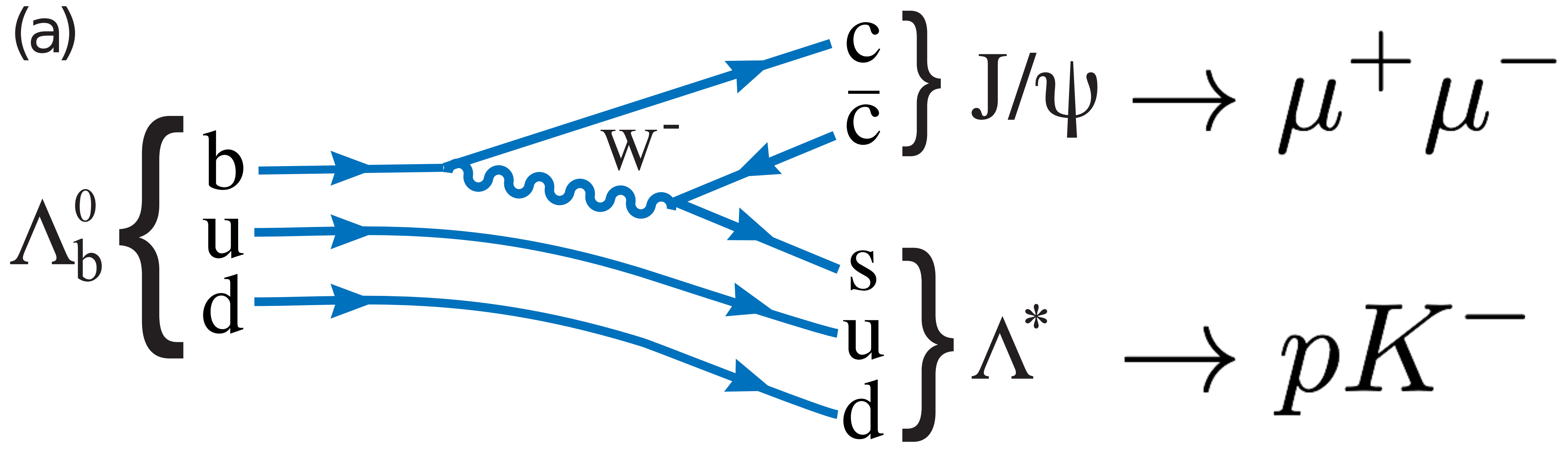


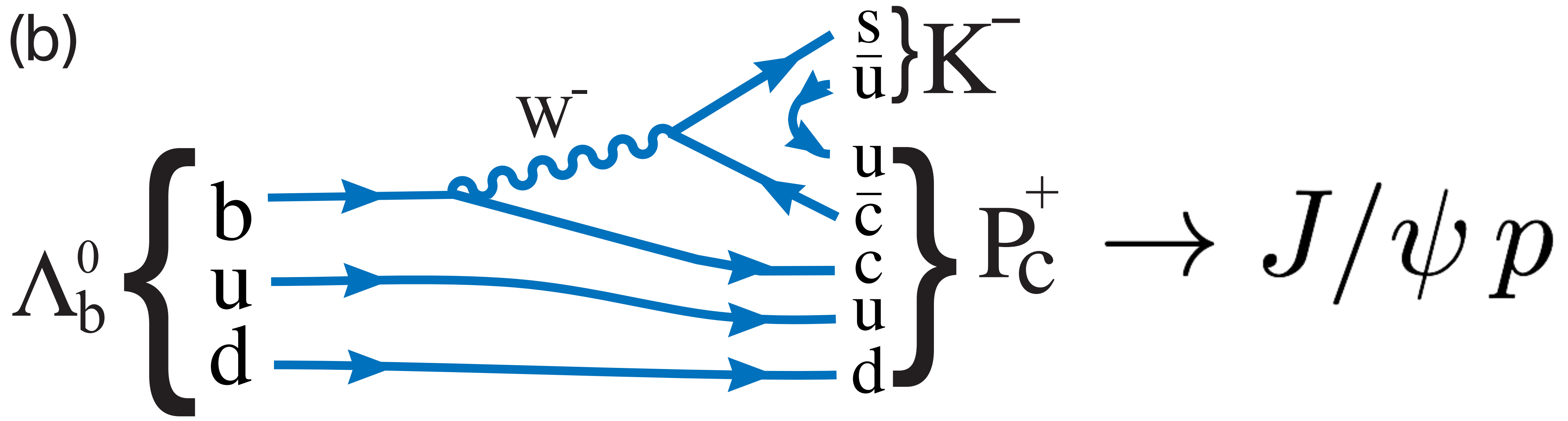


Pentaquark observation [PRL 115 (2015) 072001]

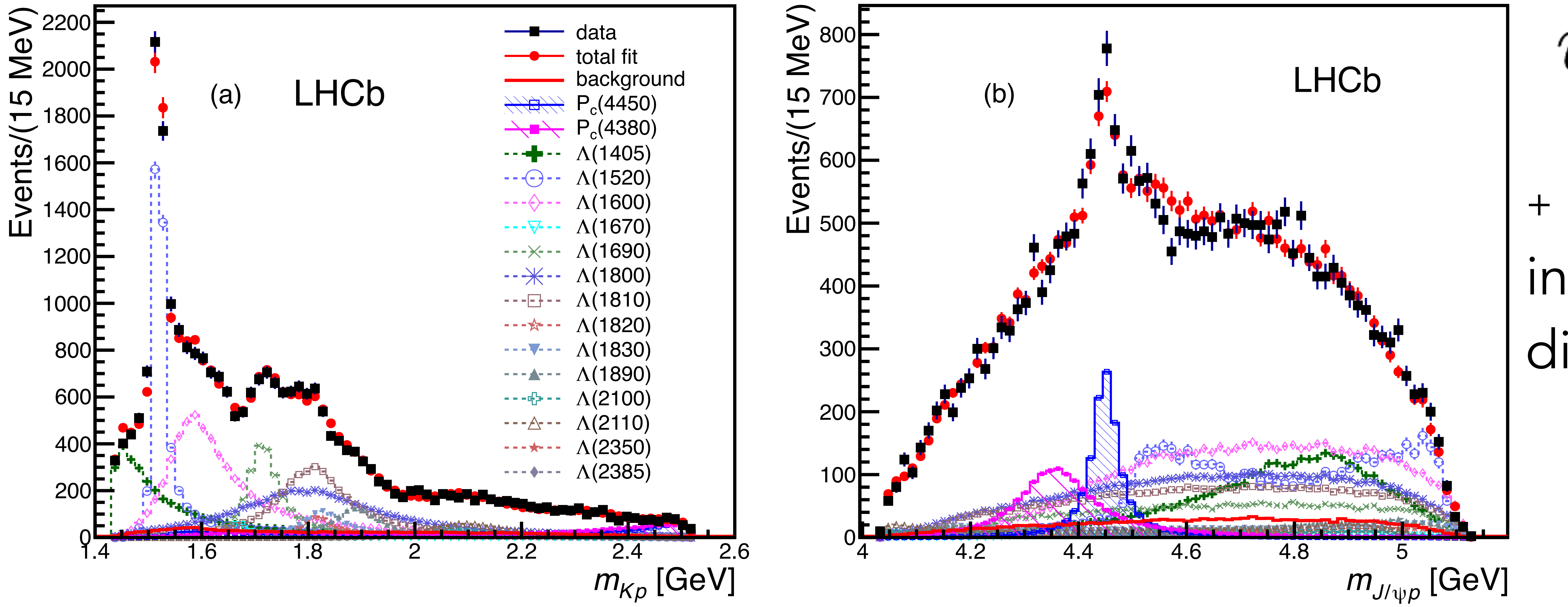








Amplitude model [PRL 115 (2015) 072001]



$uud c\bar{c}$

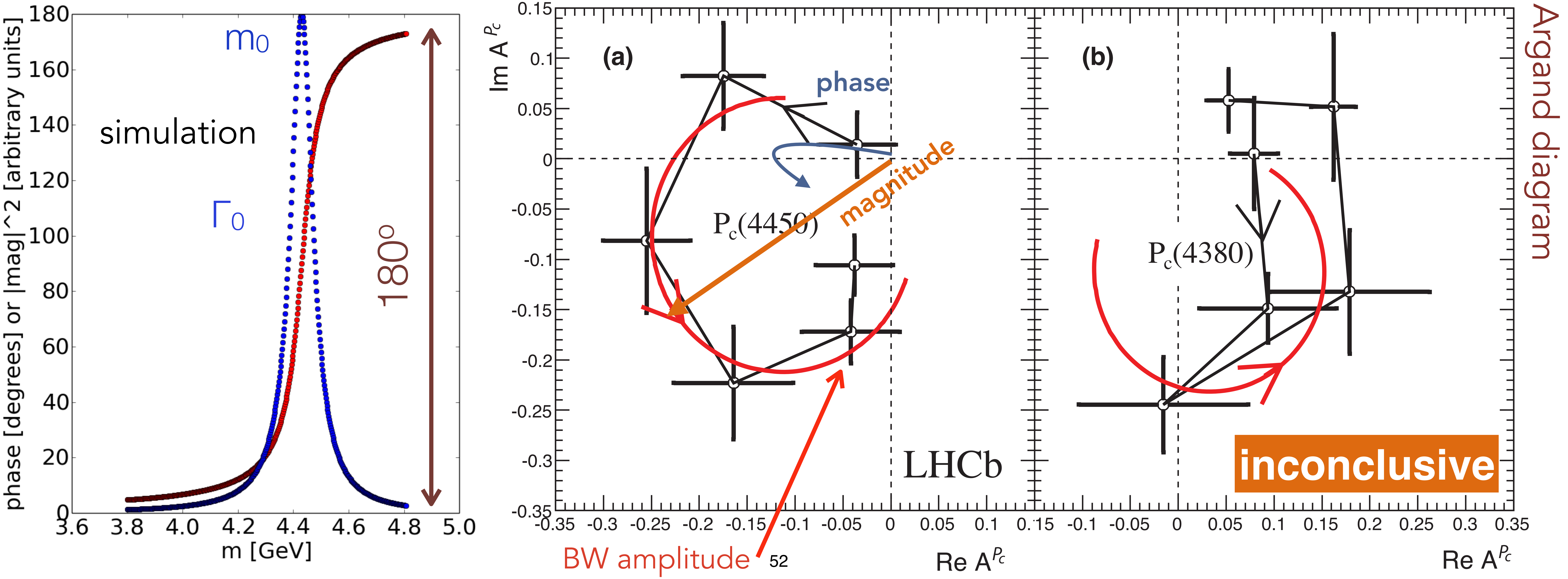
+ good fit in angular dimensions

- $J^P = (3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$ also give good fits: **need more data.**
- Addition of other resonances does not give improvement.
- Significance evaluated using toy simulation, including systematics.

	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass [MeV/c^2]	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width [MeV/c^2]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Fit fraction [%]	$8.4 \pm 0.7 \pm 4.2$	$4.1 \pm 0.5 \pm 1.1$
Significance	9σ	12σ

Resonant behaviour - a bound state?

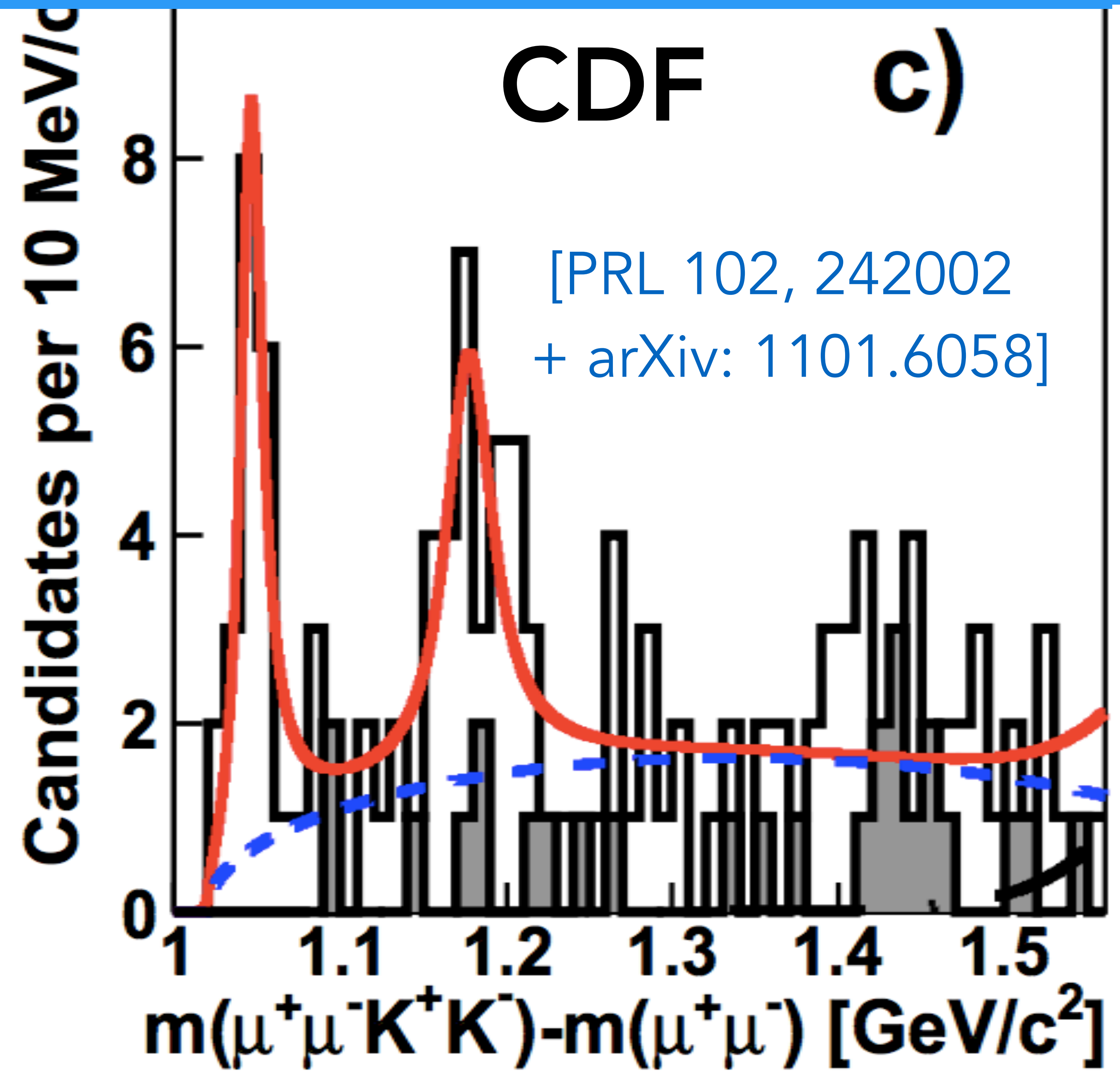
- Replace BW amplitude with 6 independent complex numbers in 6 bins of *m(J/ψp)* in region of P_c^+ mass peak.
- Allows P_c^+ shape to be constrained only by amplitudes in Kp sector.
- Observe rapid change of phase near maximum of magnitude ⇒ **resonance!**



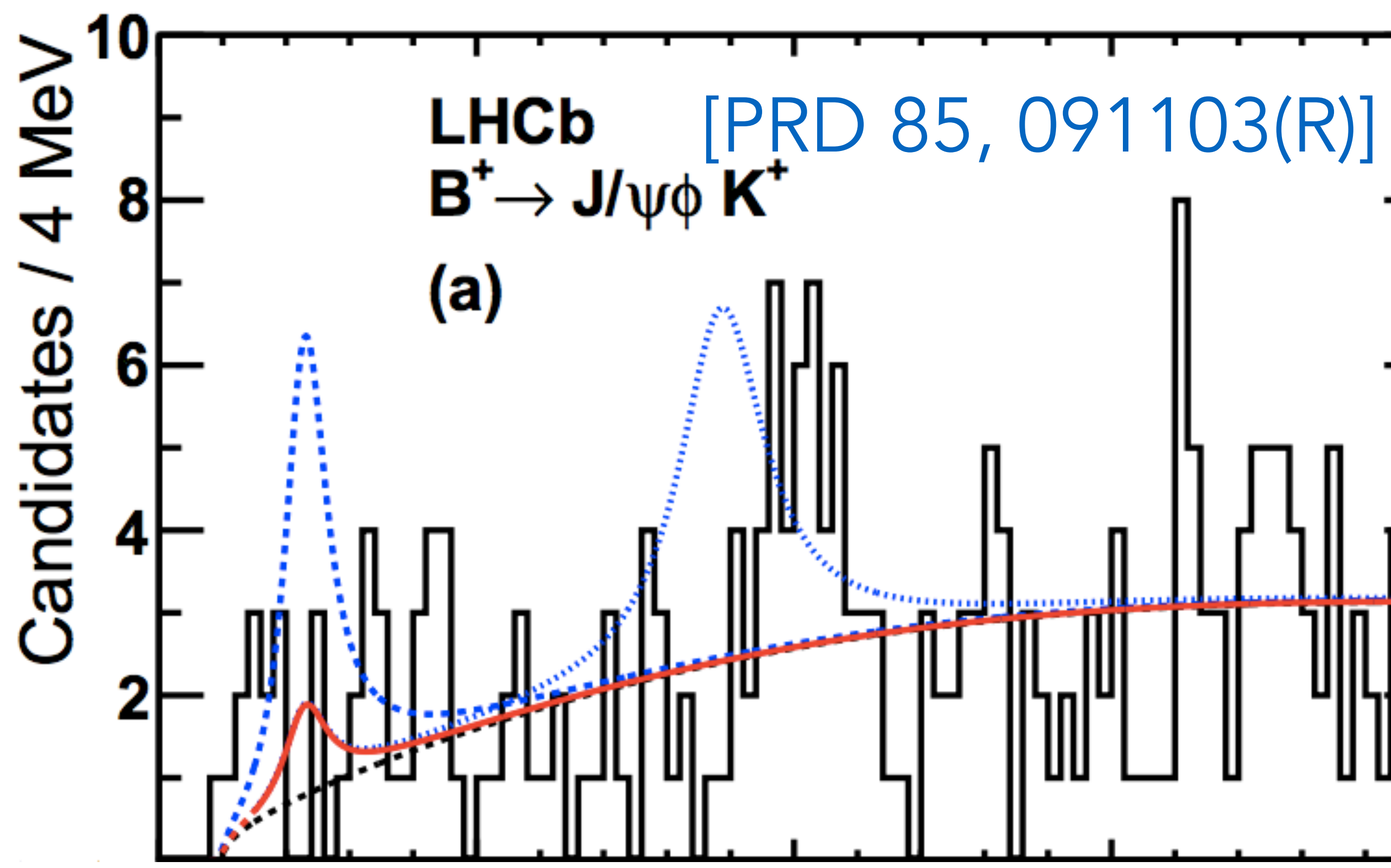
X(4140): some history $B^{\pm/0} \to X K^{\pm/0}, X \to J/\psi\phi$

- **Seen** by CDF, D0 and CMS
- **Not seen** by LHCb, BaBar, BES-III or Belle (in γγ fusion).
- Well above open-charm threshold but has **narrow width** → not conventional $c\bar{c}$.
- Also second state at higher mass…
- **Full amplitude analysis of decay is essential!**

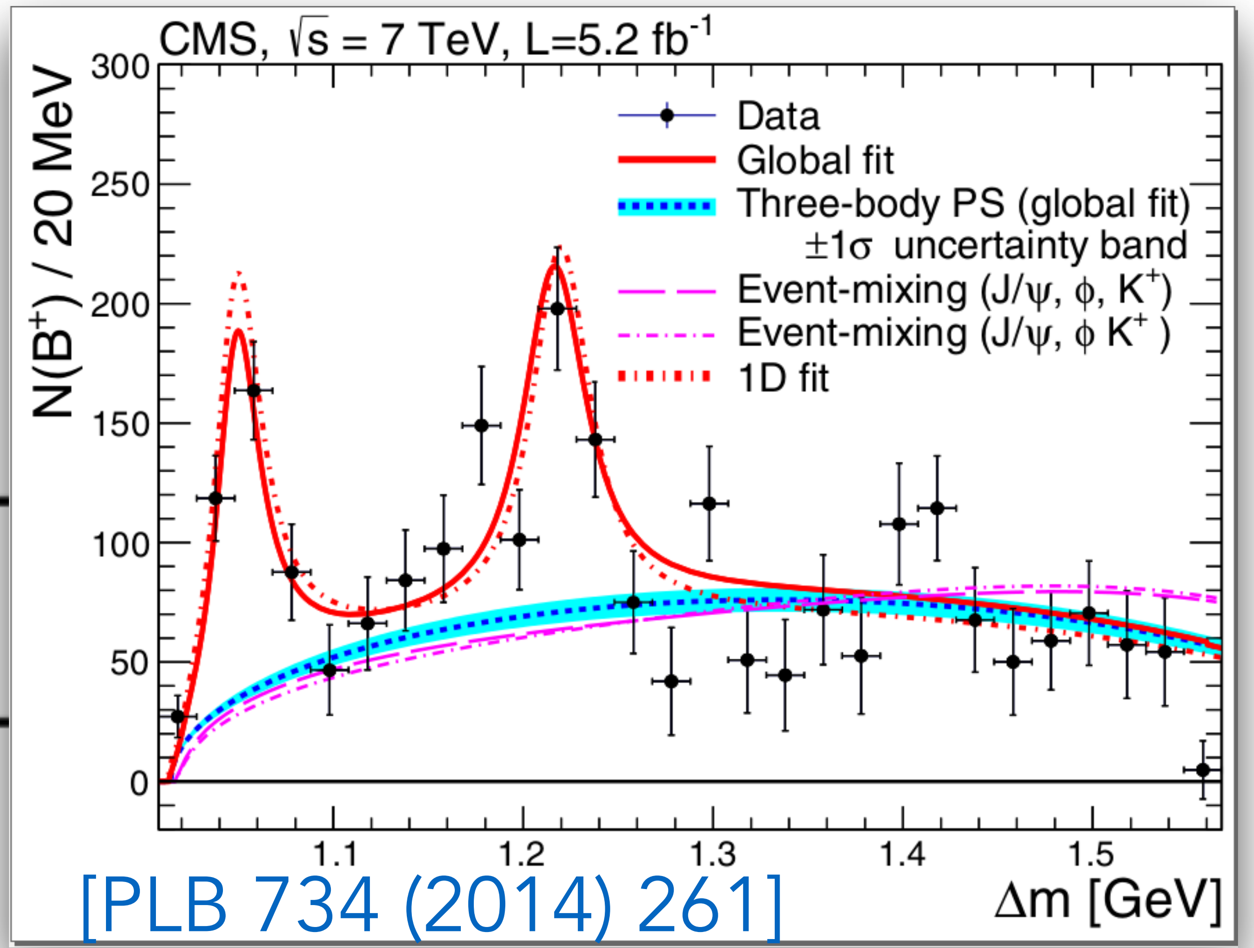
$c\bar{c}s\bar{s}$



[PRL 102, 242002 + arXiv: 1101.6058]



[PRD 85, 091103(R)]



[PLB 734 (2014) 261]

Experiment	$Y(4140)$	$Y(4274)$
CDF [69]	$M = 4143.0 \pm 2.9 \pm 1.2, \boxed{\Gamma = 11.7^{+8.3}_{-5.0} \pm 3.7}$	–
CDF [100]	$M = 4143.4^{+2.9}_{-3.0} \pm 0.6, \boxed{\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5}$	$M = 4274.4^{+8.4}_{-6.7} \pm 1.9, \Gamma = 32.3^{+21.9}_{-15.3} \pm 7.6$
DØ [102]	$M = 4159.0 \pm 4.3 \pm 6.6, \boxed{\Gamma = 19.9 \pm 12.6^{+1.0}_{-8.0}}$	–
CMS [74]	$M = 4148.0 \pm 2.4 \pm 6.3, \boxed{\Gamma = 28^{+15}_{-11} \pm 19}$	$M = 4313.8 \pm 5.3 \pm 7.3, \Gamma = 38^{+30}_{-15} \pm 16$

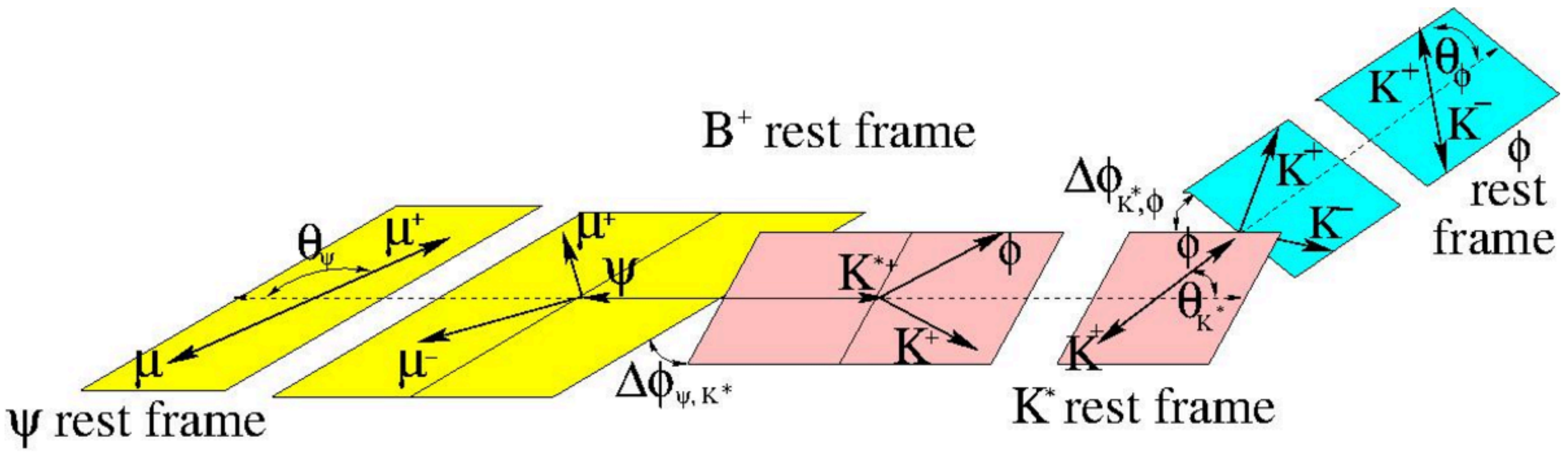
[D0 PRD 89, 012004]
[Belle PRL 104, 112004]
[BES-III PRD 91 (2015) 032002]

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

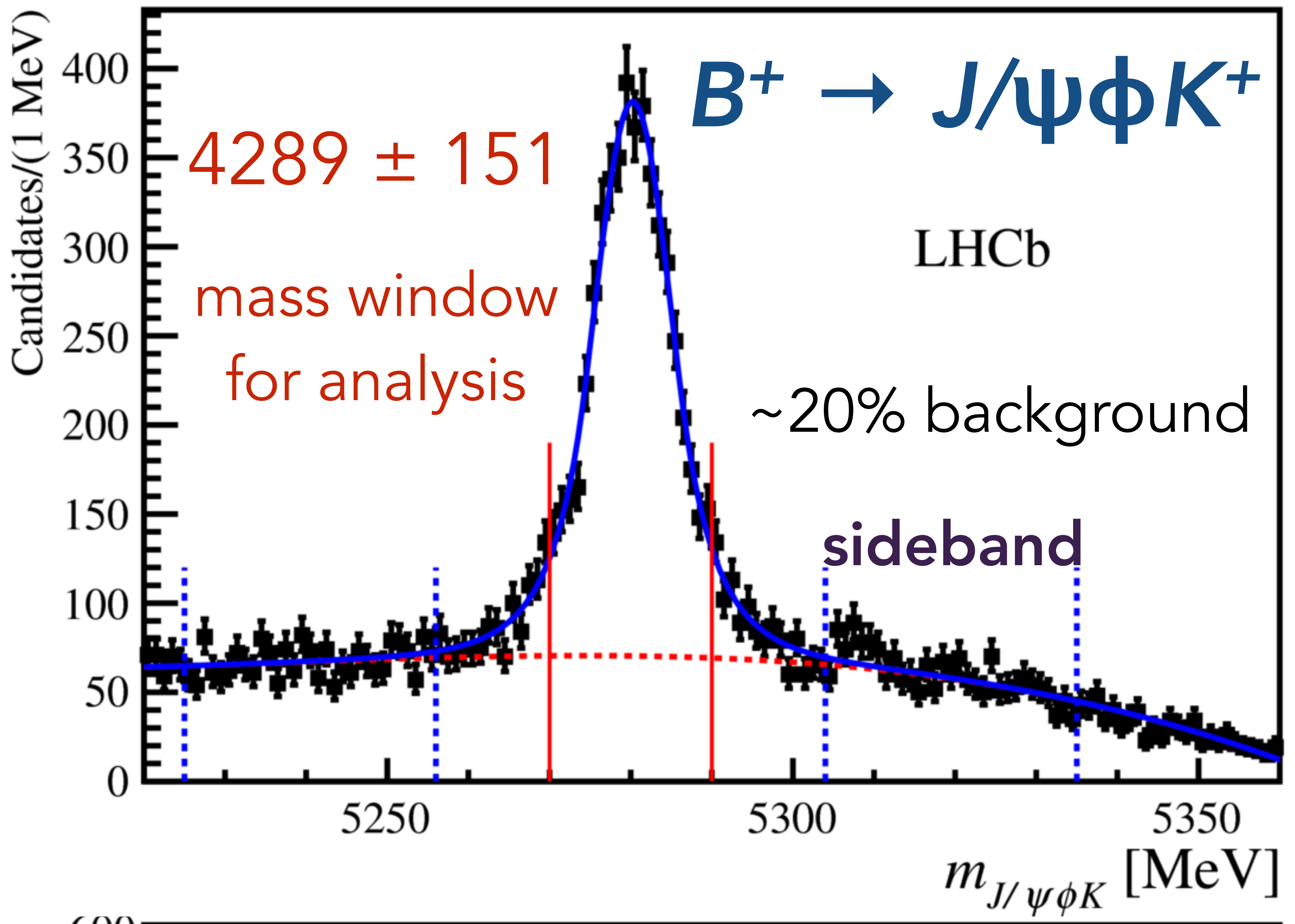
- Run-1 (3/fb),
- First 6D amplitude analysis to understand structure in final state
- Three interfering decay chains
  - $B^+ \to K^{*+} J/\psi$, $K^{*+} \to \phi K^+$
  - $B^+ \to X K^+$, $X \to J/\psi\phi$
  - $B^+ \to Z^+\phi$, $Z^+ \to J/\psi K^+$

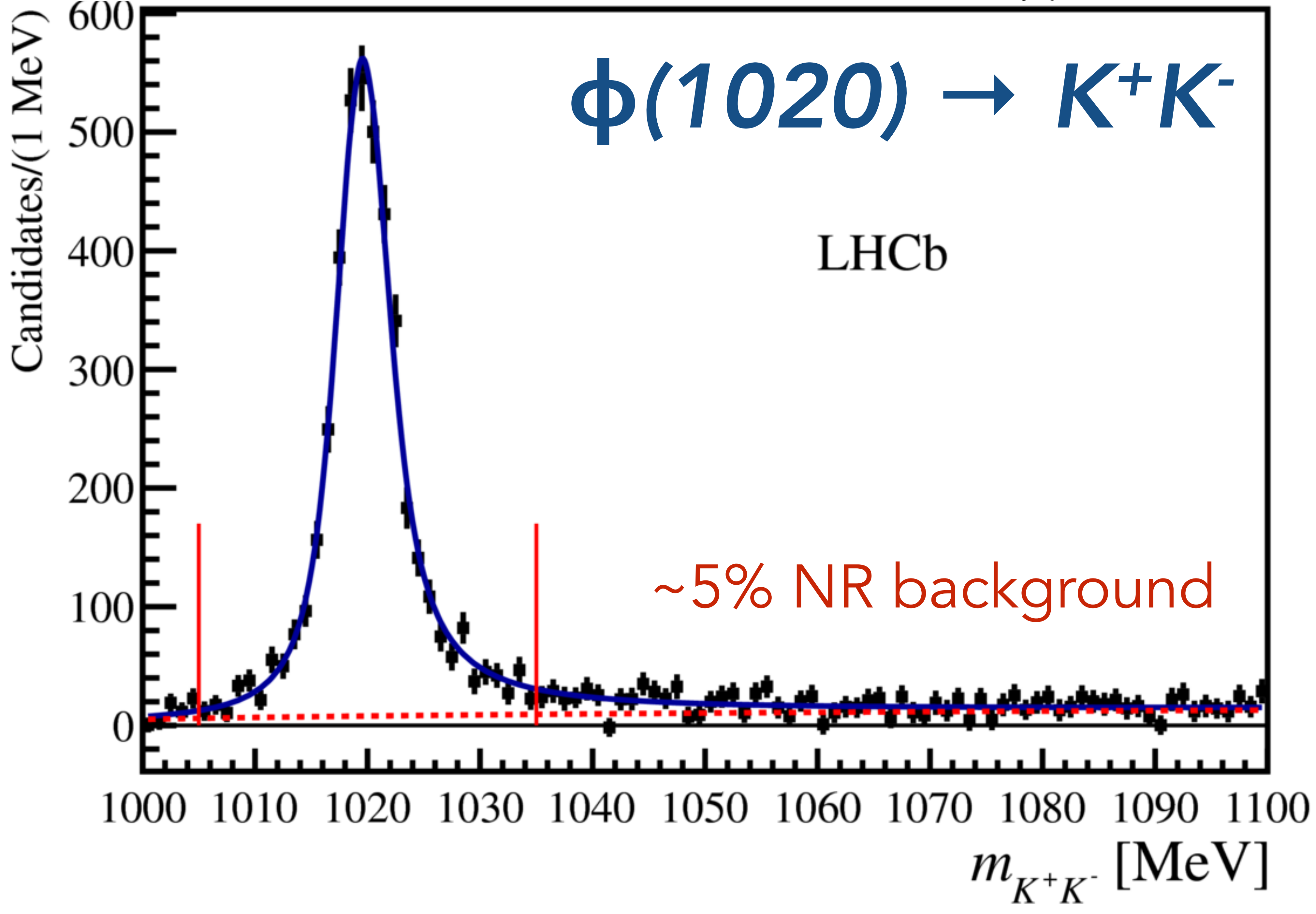
arxiv:1606.07895

arxiv:1606.07898

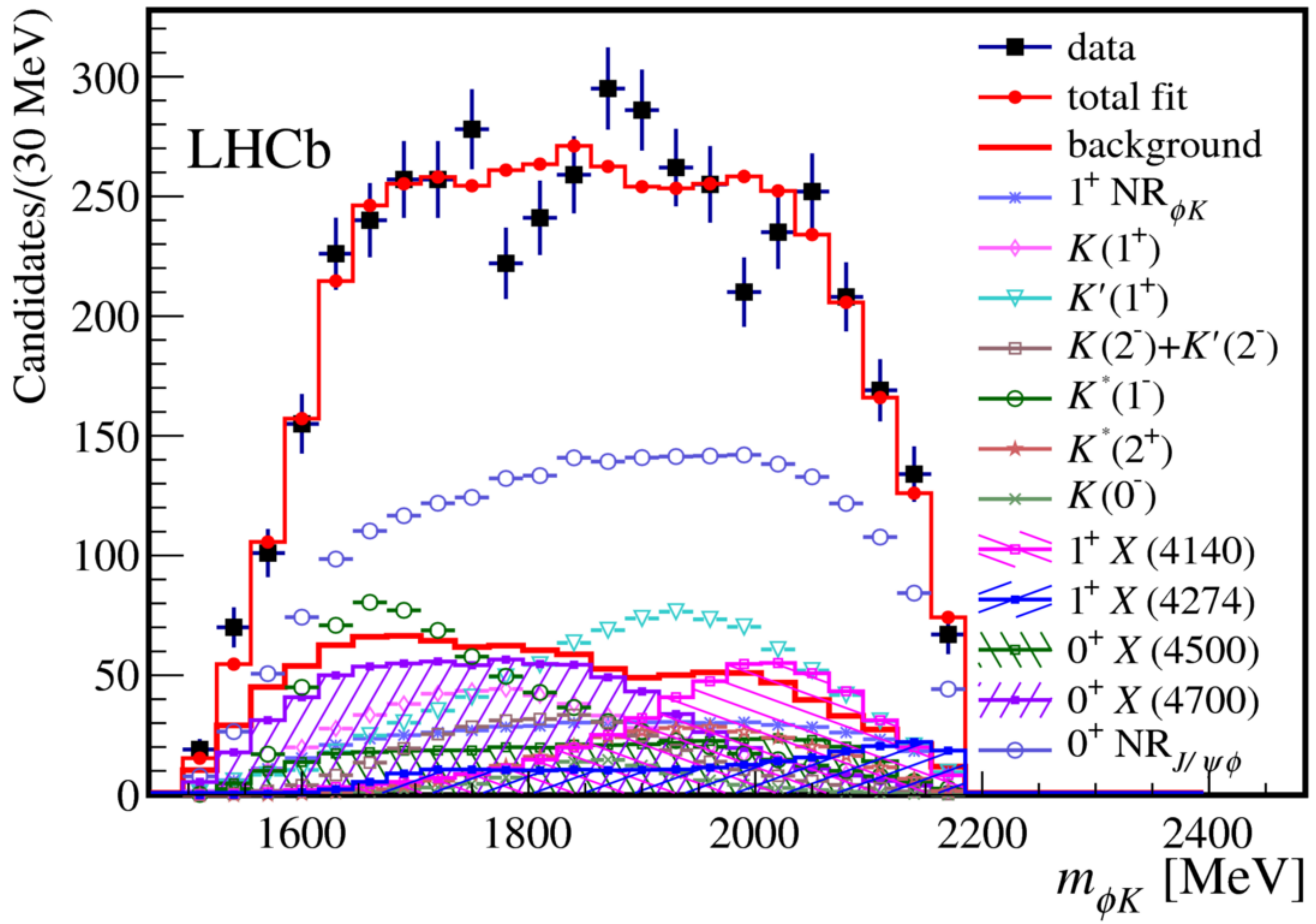


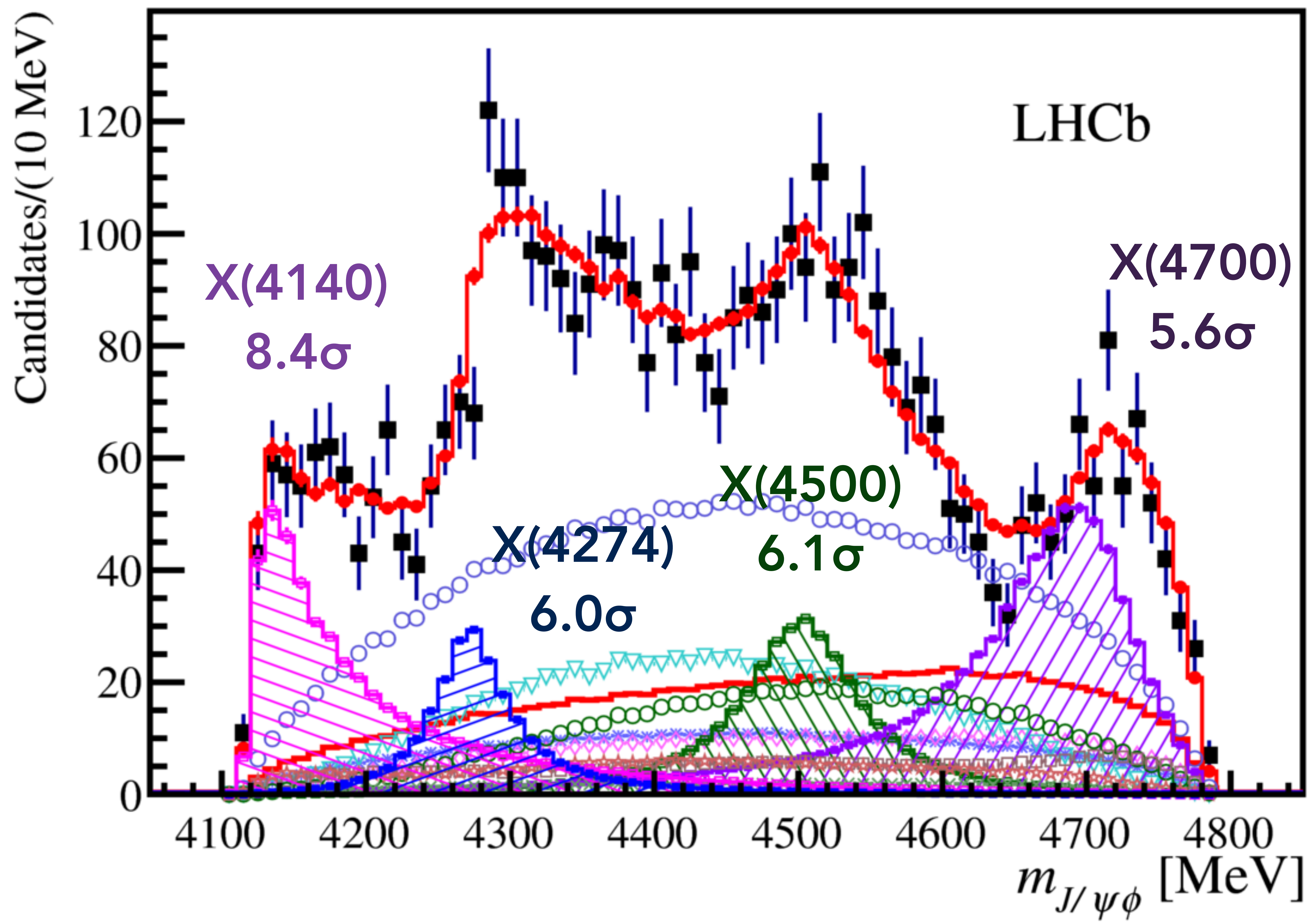
$$\Omega \equiv (\theta_{K^*}, \theta_\psi, \Delta\phi_{\psi,K^*}, \theta_\phi, \Delta\phi_{K^*,\phi})$$





Fit results including exotic components



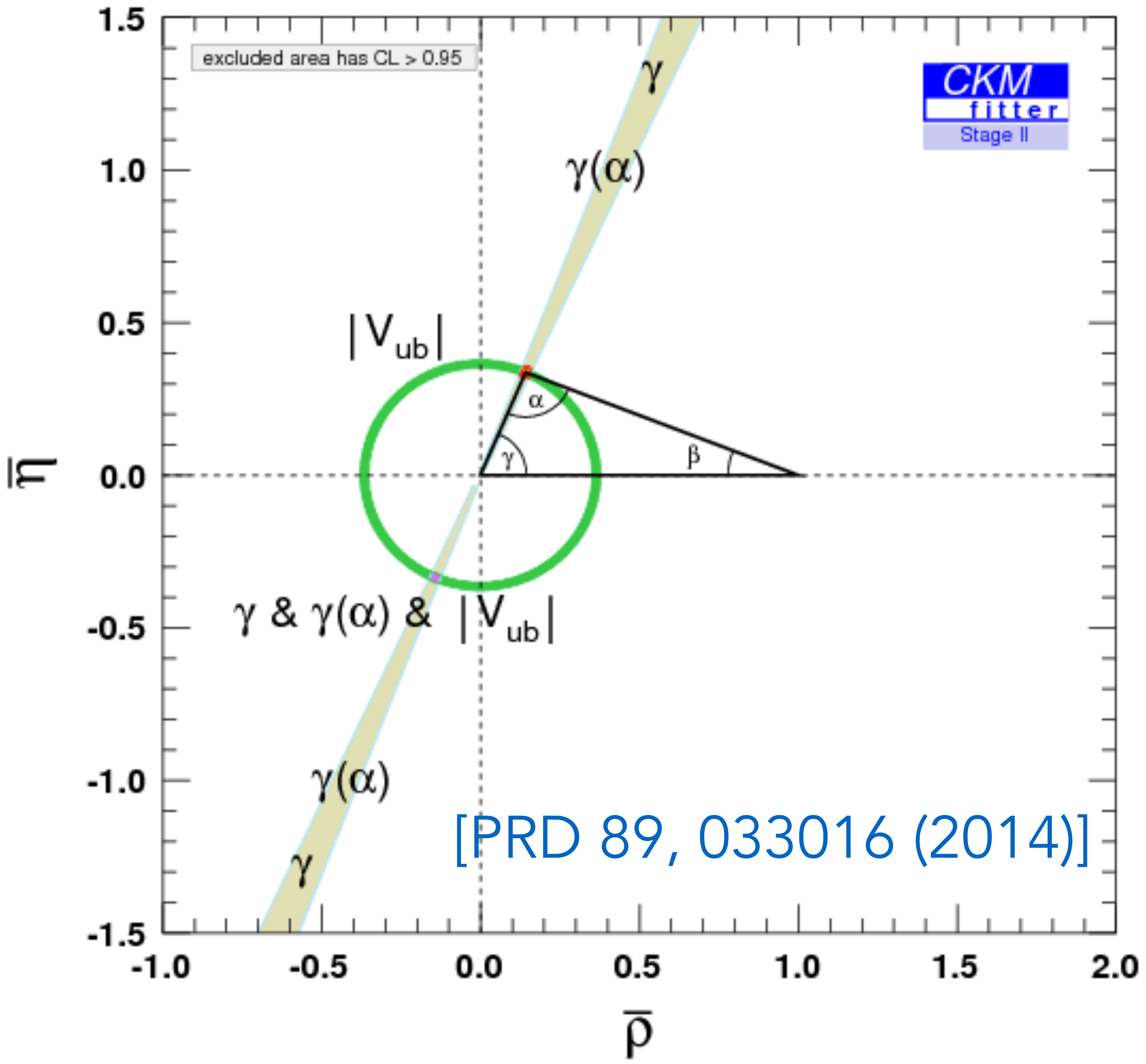


- 7 K^* states, 4 exotic X states and NR $J/\psi\varphi$ and φK^* components.
- Inclusion of exotic Z states does not improve fit.

98 free parameters in fit

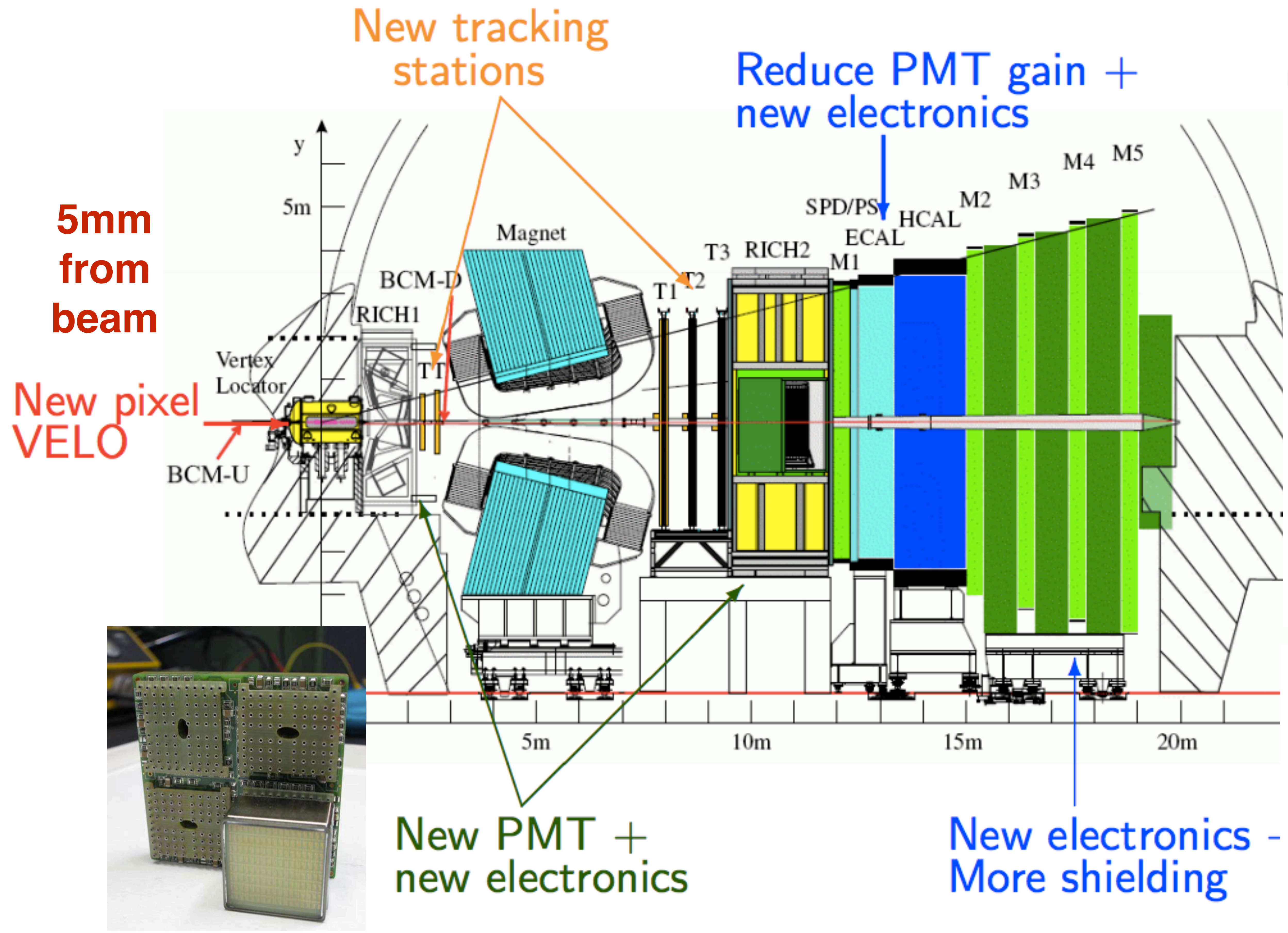
p-value = 22%

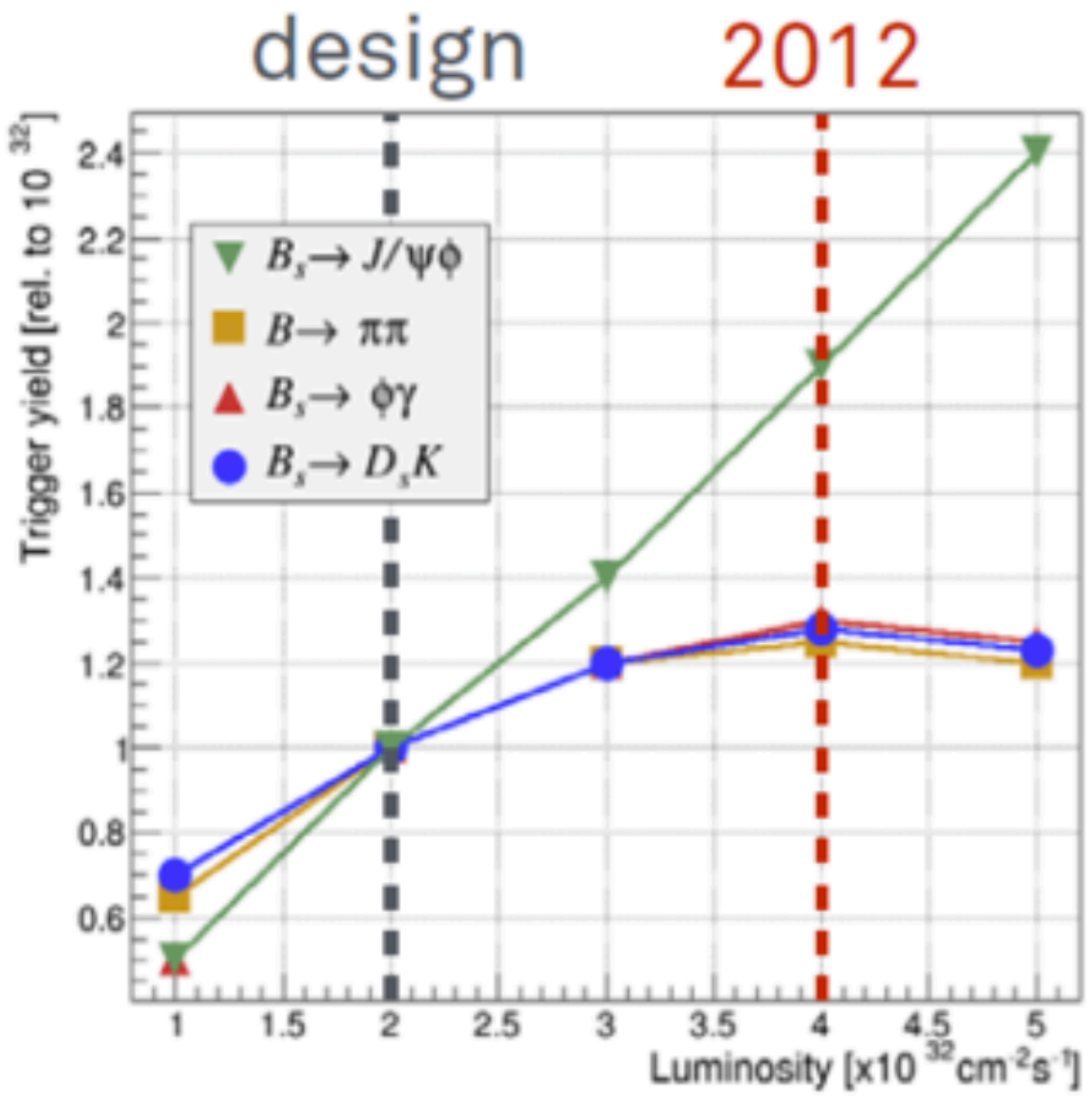
Looking to the future

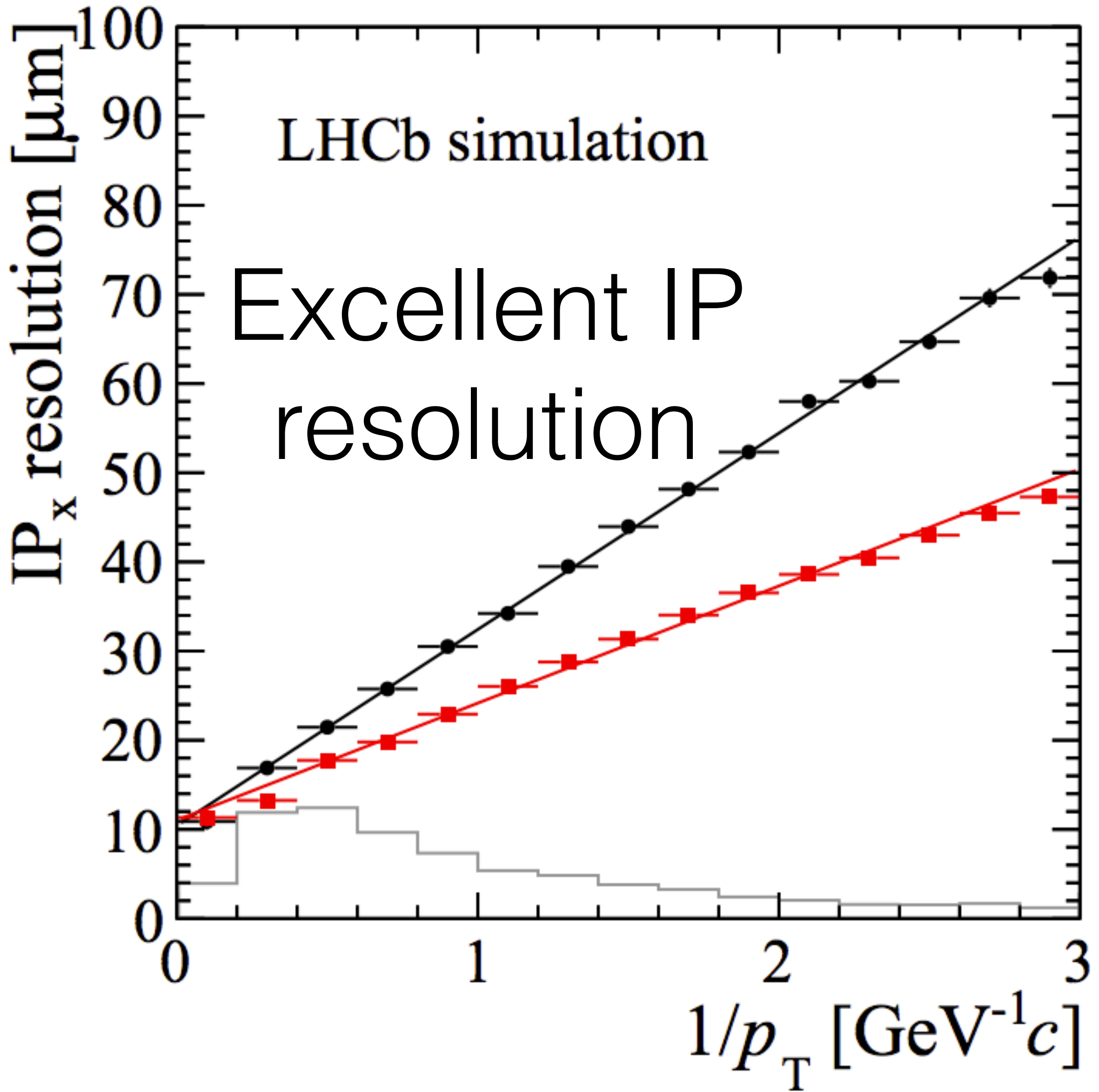


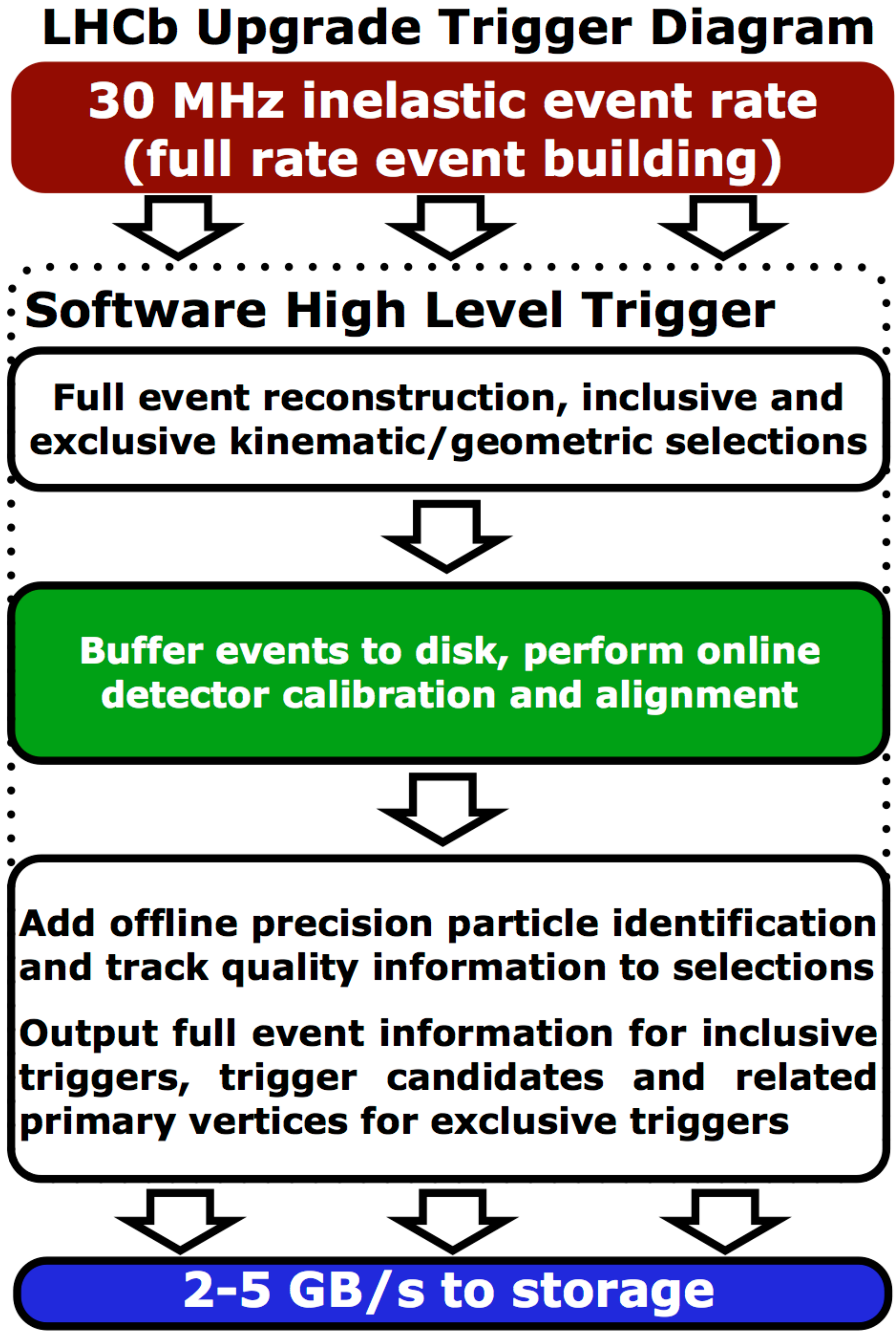
[PRD 89, 033016 (2014)]

LHCb upgrade (phase 1)









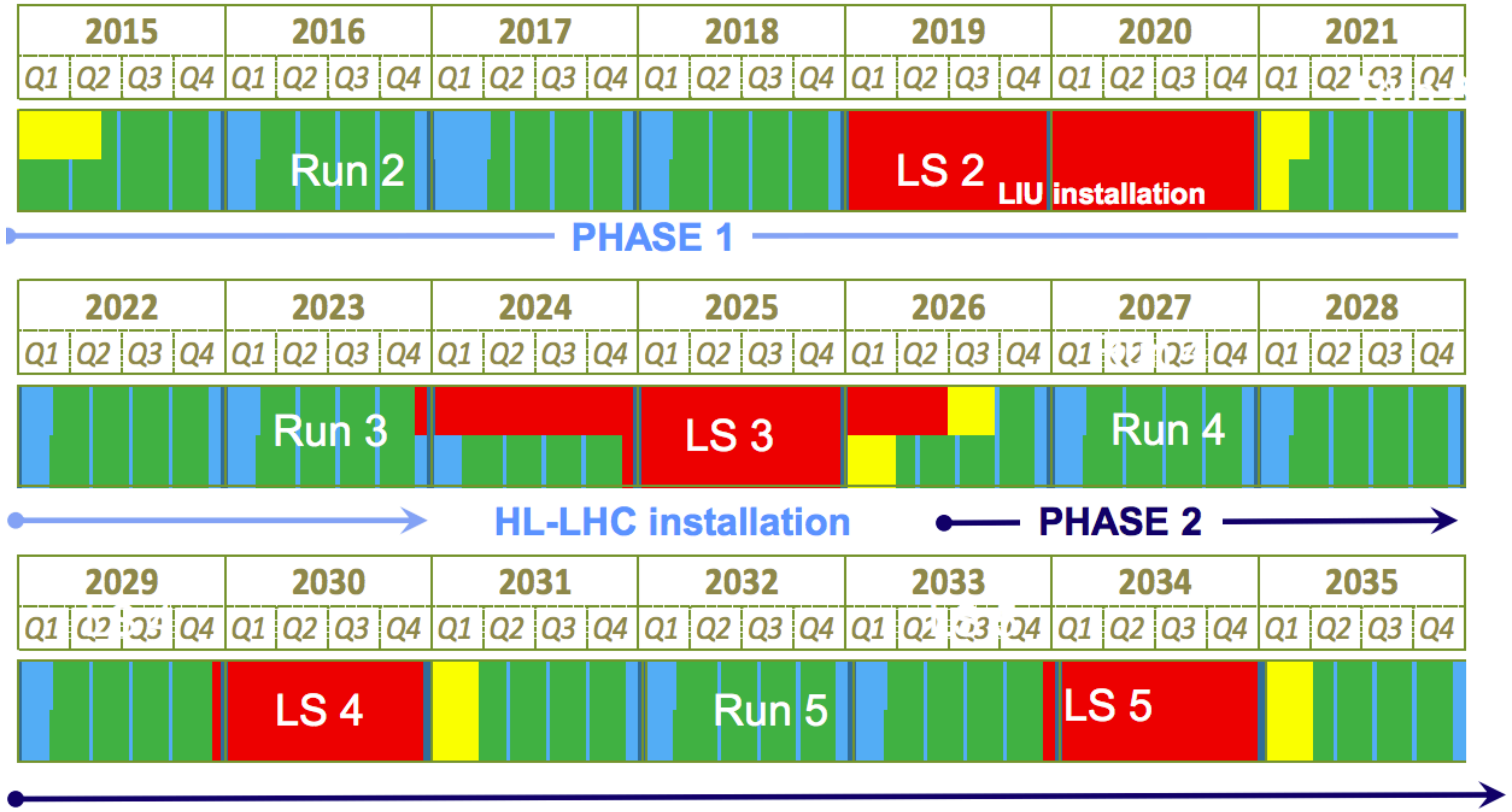
- Many LHCb measurements will be statistically limited after Run 1+2.
- Increase luminosity from ~4x10^{32} to ~2x10^{33}

LHCb upgrade (phase 1)

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\; f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\mathrm{sl}}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\; A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

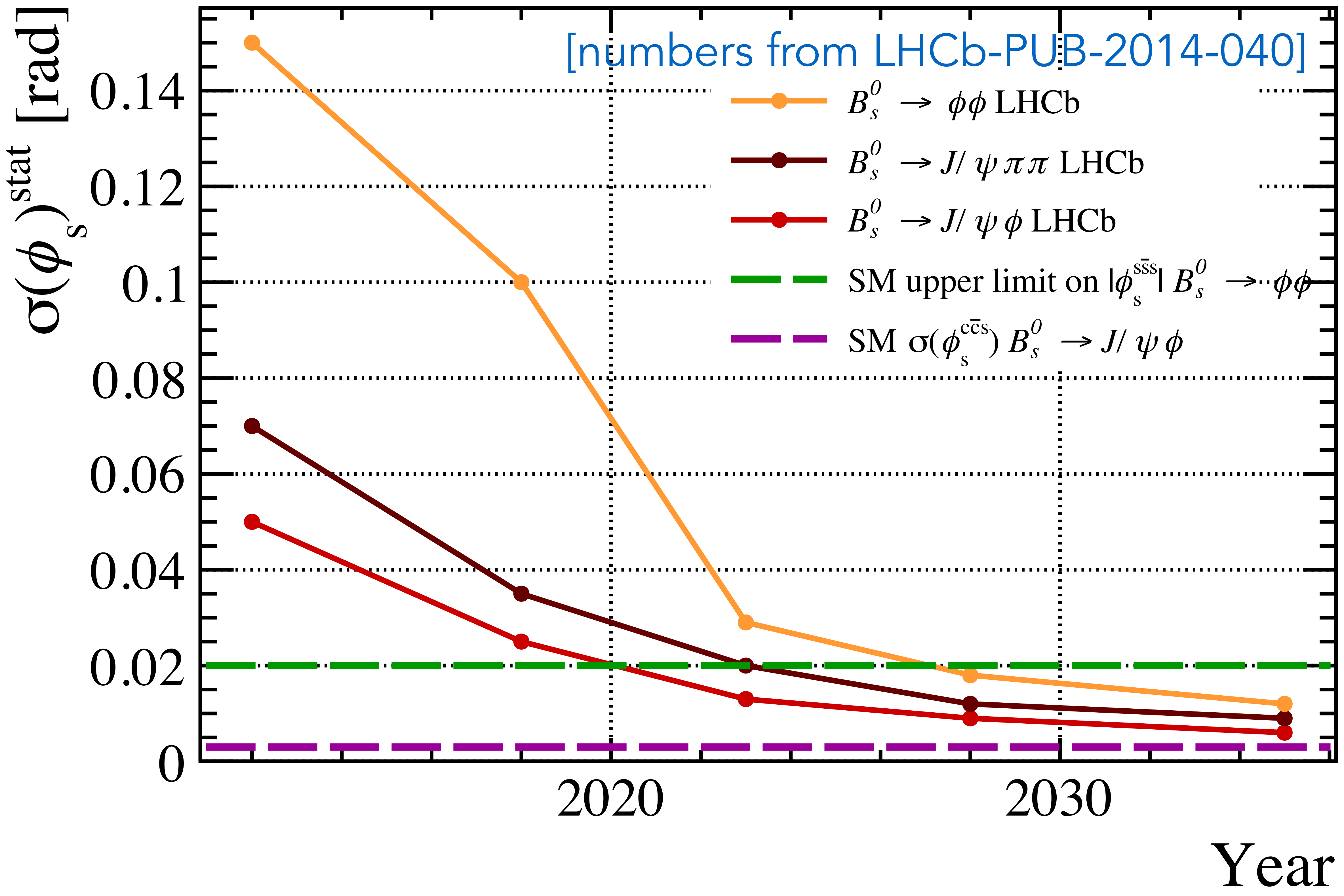
LHCb upgrade (phase 1b and 2)

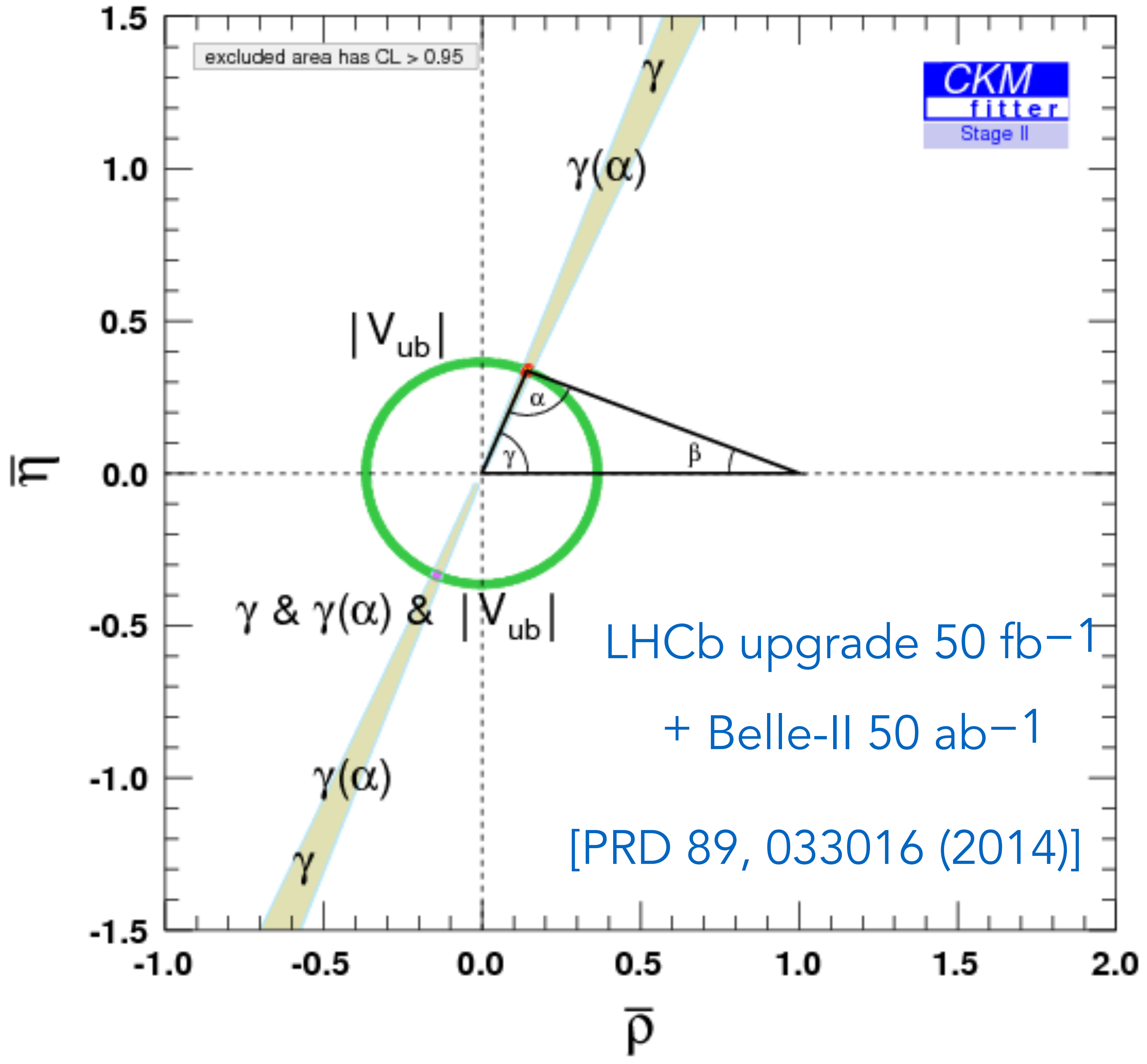
- LHCb-upgrade will be installed in LS2 and operate during Run-3.
- Putting together plans for LHCb-upgrade in LS3 so that it can operate in Run-4 (HL-LHC operation).
  - Stations in the magnet (to improve reconstruction of multi-body final states).
  - Improvements to PID via time-of-flight (TORCH project)
- Increase luminosity to 10^{34}.



	LHC era			HL-LHC era	
$\int \mathcal{L}\, dt$	2010-12 (Run-1)	2015-18 (Run-2)	2021-23 (Run-3)	2026-29 (Run-4)	2031++ (Run-5)
ATLAS, CMS	$25\,\mathrm{fb}^{-1}$	$100\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$	$\rightarrow$	$3000\,\mathrm{fb}^{-1}$
LHCb	$3\,\mathrm{fb}^{-1}$	$8\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$46\,\mathrm{fb}^{-1}$	$100\,\mathrm{fb}^{-1}$

LHCb upgrade (phase 1b and 2)





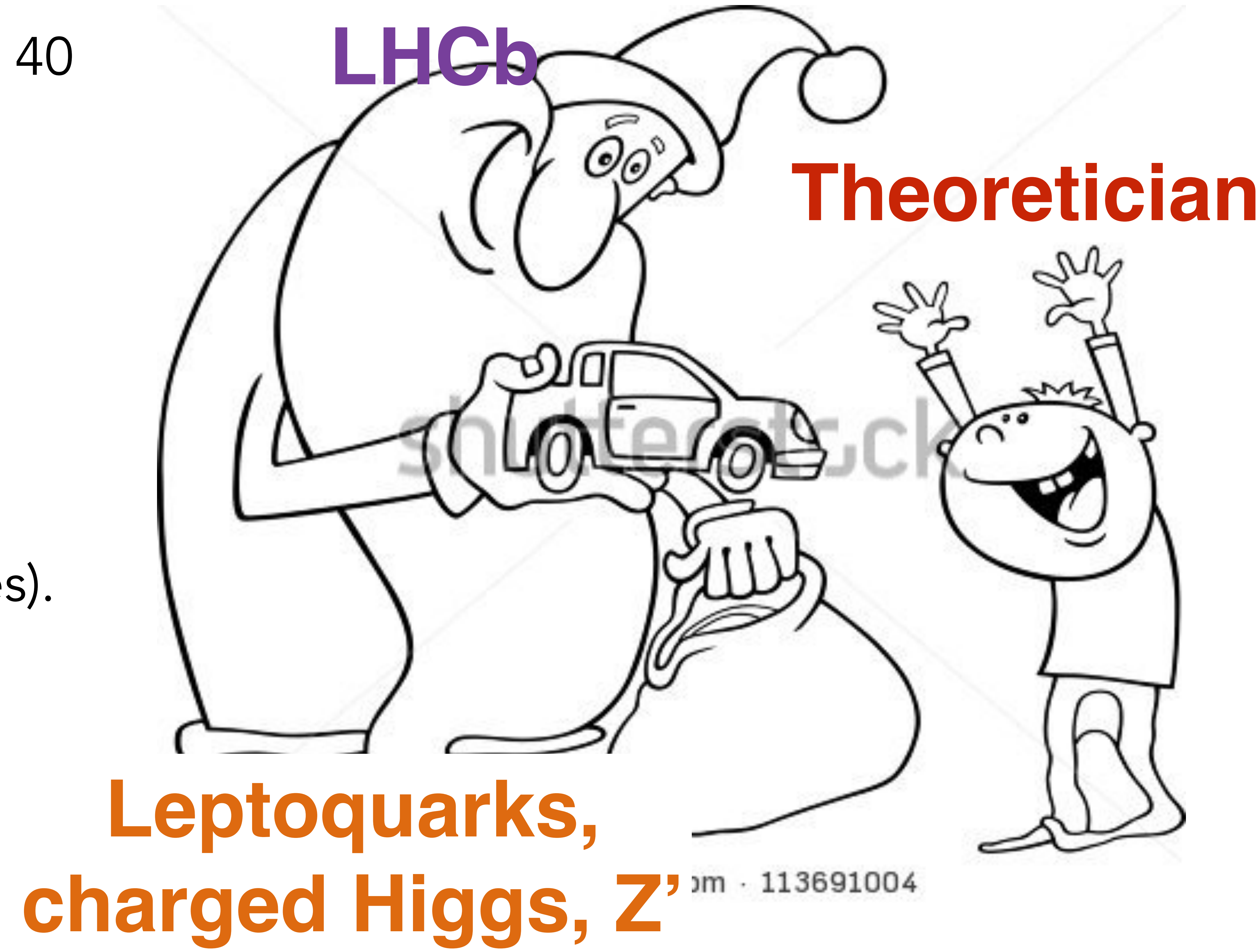
- ~440k $B^0 \to K^{*0}\mu^+\mu^-$
- ~8M $B \to D\tau\nu, \tau \to \mu\nu\nu$
- Charm physics and spectroscopy.
- Preparing EoI document now.

2025: $\sigma_{LHCb}(\gamma) \sim \sigma_{Belle-II}(\gamma) < 1^\circ$

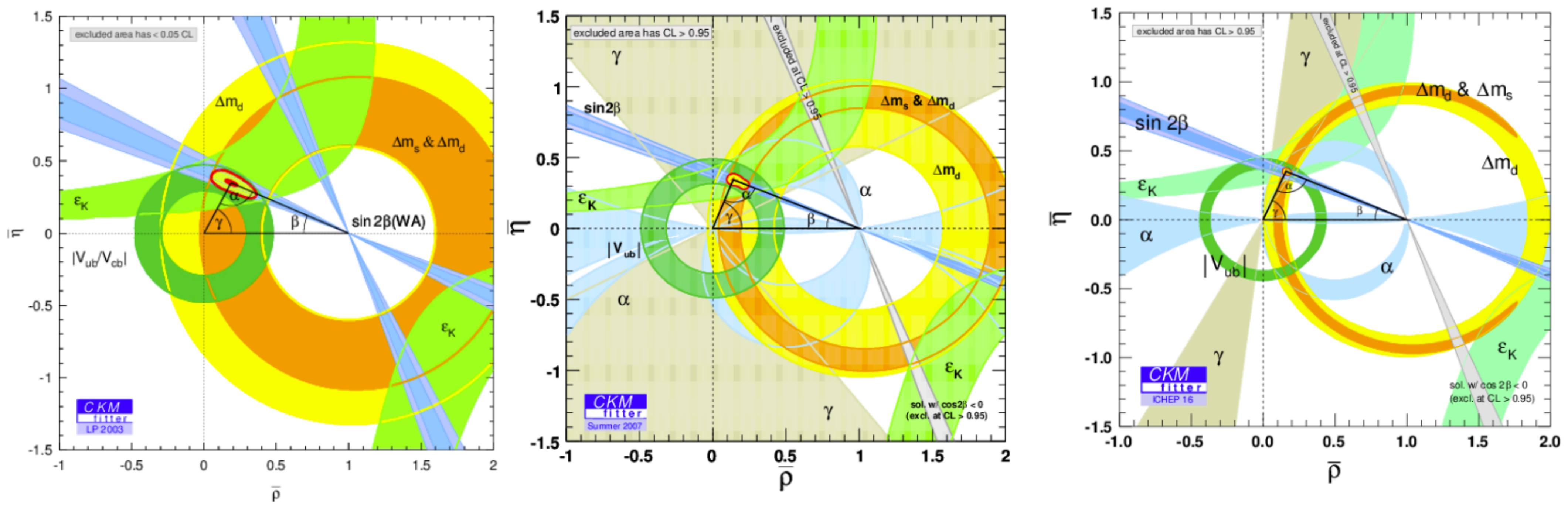
$\sigma_{syst} < 1^\circ$

Summary

- Huge progress in understanding the b-quark properties over the past 40 years and from using it as a **platform for further exploration**.
- LHCb delivering many **precision** results and opening new areas of investigation.
  - b-baryons, B_c mesons, very rare decays, charm, exotic spectroscopy…
- Several anomalies in Run 1 data (lepton universality, b -> s ll processes).
  - **How will these develop as we add Run 2 and study more channels?**
- Phase-1 upgrade to be installed in 2019, ready for Run 3.
- Starting to plans for phase-1b and phase-2 upgrades to that we can extend programme into HL-LHC era (~2035).

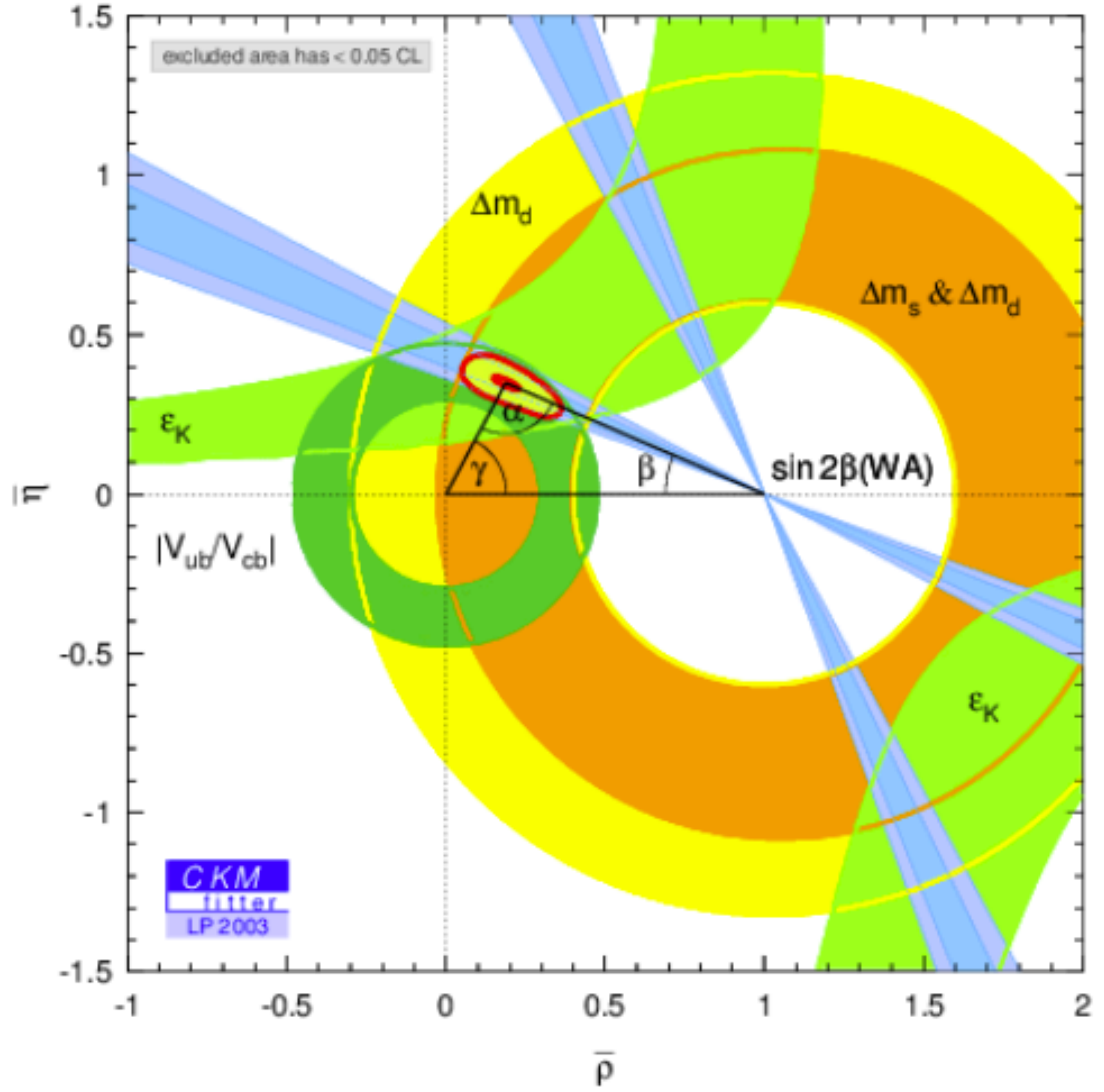


Should be plenty of new results for the 50th anniversary!

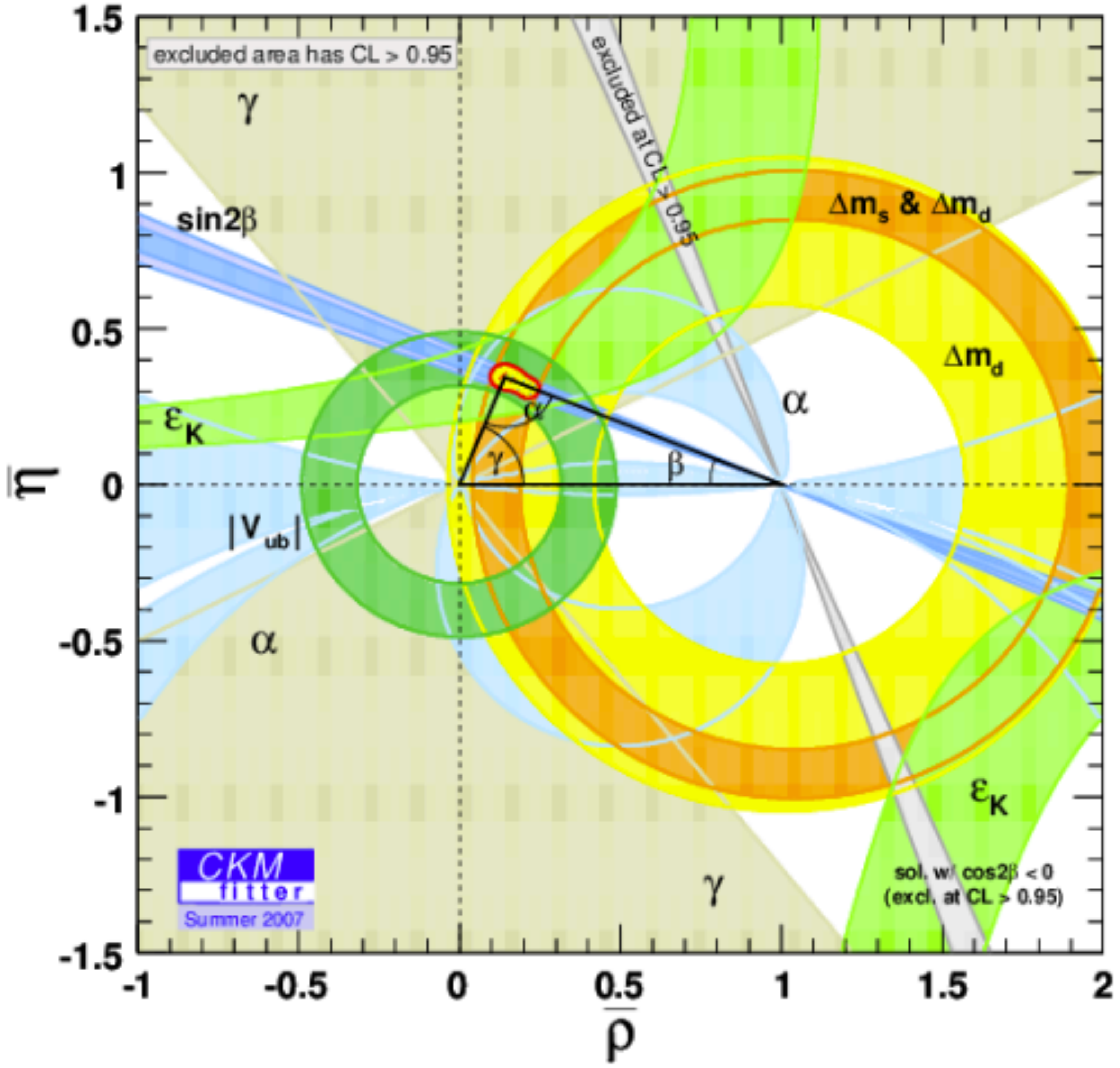


Remarkable progress

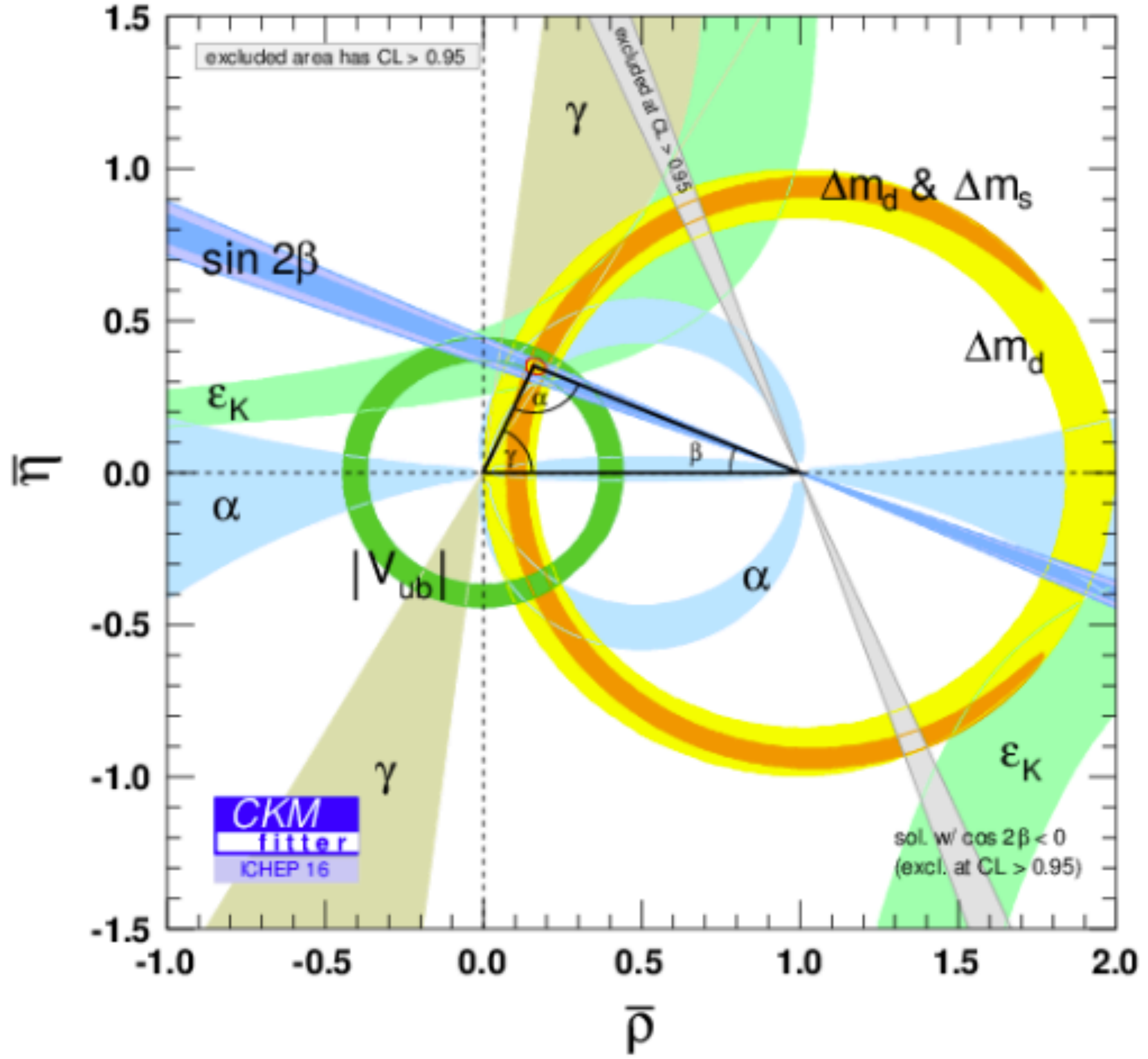
2003



2007



2016

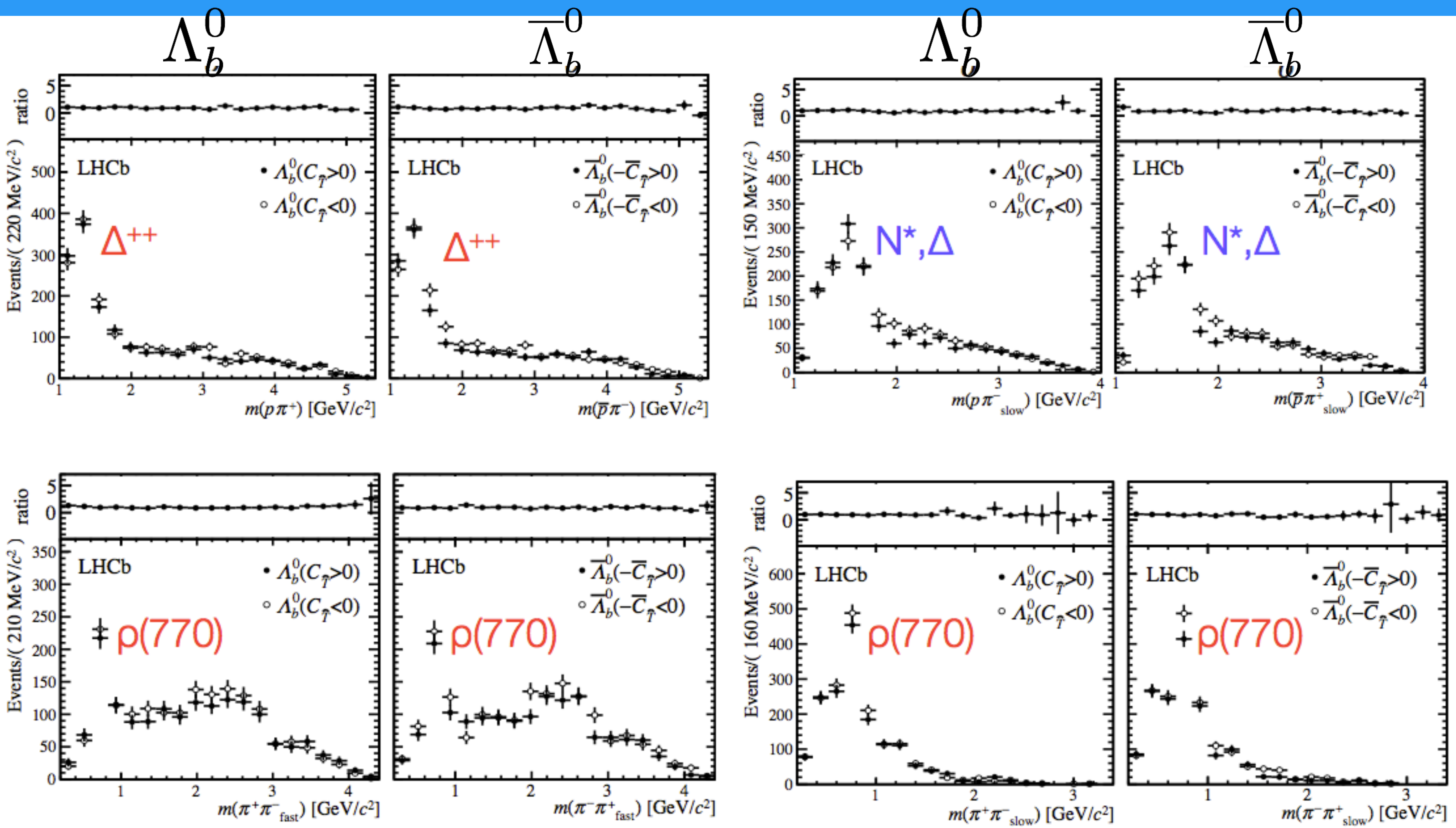


Overall picture is consistent with SM
Still room for new physics

$$\bar{\rho} = 0.150 \pm 0.012$$
$$\bar{\eta} = 0.354 \pm 0.007$$

2008: K + M

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ phase space distributions



- Background subtracted using sPlot

[arXiv:1609.05216, accepted Nature Physics]

$|V_{ub}|$ measurement with $\Lambda_b \to p\mu\bar{\nu}_\mu$

- Challenging at hadron collider to separate $b \to u\mu\nu$ and $b \to c\mu\nu$ processes without beam energy constraint of e+e- machine.

- Use Λ_b flight direction and mass to determine q^2 with two-fold ambiguity (neutrino). Require both solutions >15 GeV^2 to minimise migration to low q^2 bins

- To cancel many systematic uncertainties we measure the branching ratio relative to $\Lambda_b \to \Lambda_c\mu\bar{\nu}_\mu,\ \Lambda_c \to pK\pi$

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b \to p\mu\nu)_{q^2>15\,\mathrm{GeV}}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}}} R_{\mathrm{FF}}$$

$$m_{\mathrm{corr}} = \sqrt{m_{h\mu}^2 + p_{\mathrm{T}}^2} + p_{\mathrm{T}}$$

[Nature Physics 10 (2015) 1038]