Beauty decays as a probe of fundamental physics: the synergy between LHCb & lattice QCD

A blueprint for discussion

Marina Artuso

based on results by the LHCb collaboration

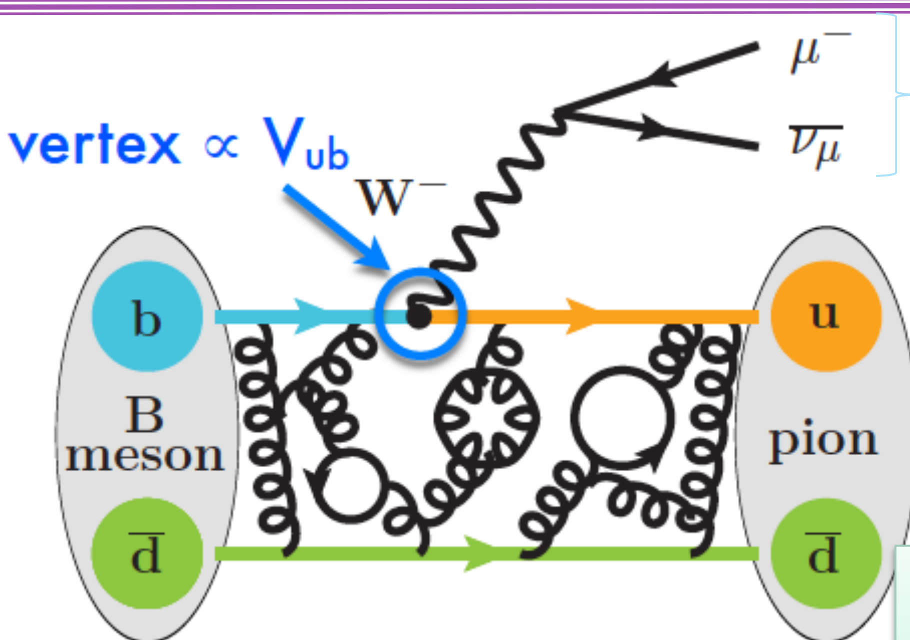
Prologue

- Some "case studies" will be presented to motivate brainstorming on future opportunities
- Experimental details on the measurements presented will be uneven
- This talk is not meant as a compendium of LHCb contributions to flavor physics!

LATTICE INPUT TO MEASURE QUARK MIXING PARAMETERS V_{UB} AND V_{CB}

V_{xb} and semileptonic b decays

Illustration focused on V_{ub}, change u➛c for V_{cb}.



$q^2=m^2(\mu\nu)$

"exclusive" study a specific final state

"inclusive" study an inclusive property of the decay (E_μ, M_{had}, q^2)

Experimental observables

What we want to know

Lattice QCD, LC sum rules, HQE..

$(\Gamma, d\Gamma/dq^2 \ldots = |V_{ub}|^2$ x (**Hadronic matrix element**) x (known factors)

Tension between inclusive and exclusive determinations of V_{xb}

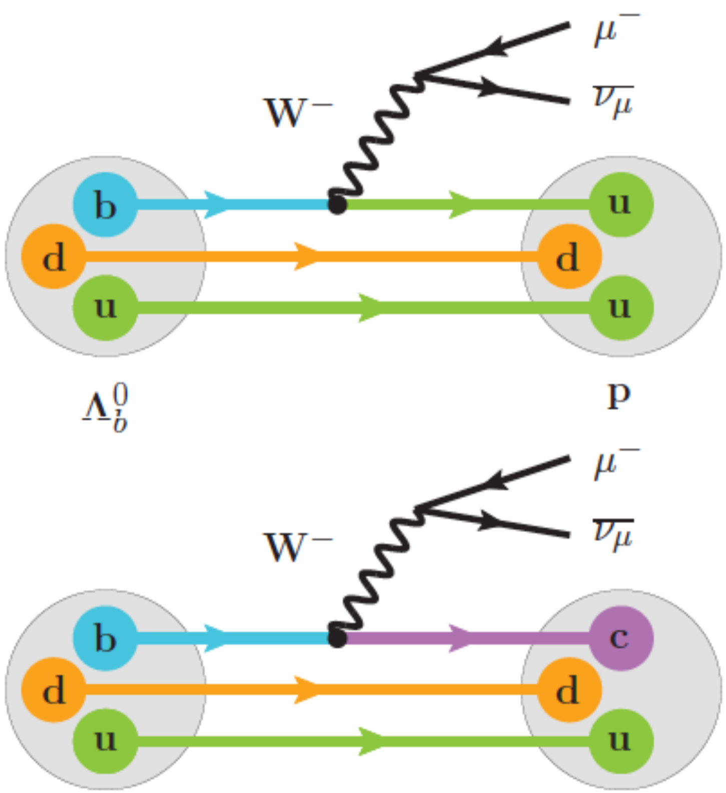
PDG2014

	Inclusive	Exclusive
V_{cb}	$(42.2\pm0.6)\times10^{-3}$	$(39.5\pm0.8)\times10^{-3}$
V_{ub}	$(4.41\pm0.15^{+0.15}_{-0.17})\times10^{-3}$	$(3.28\pm0.29)\times10^{-3}$

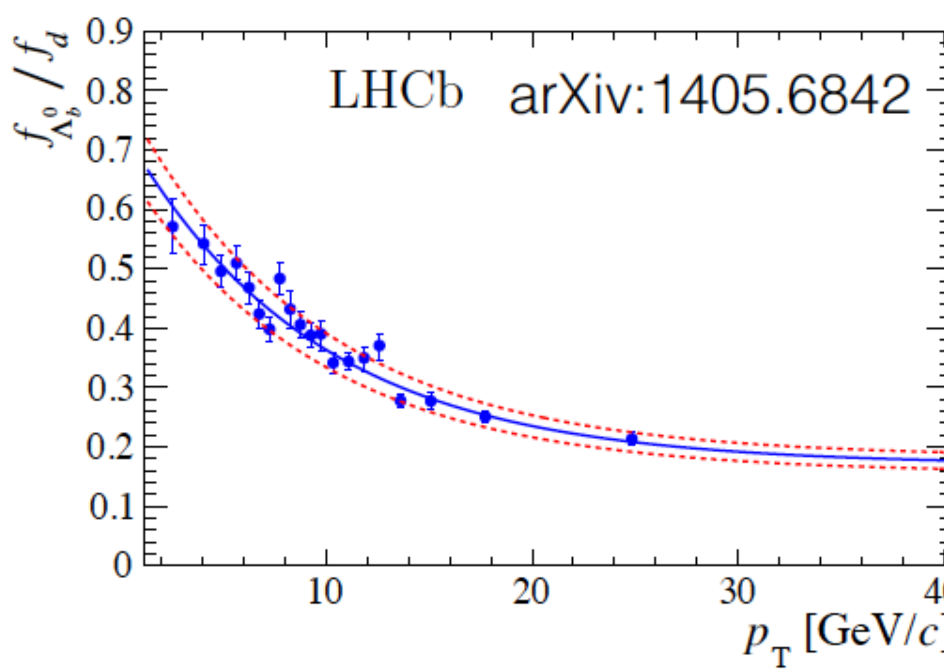
- Failure LQCD & Sum rules to predicted exclusive form-factors correctly?
- Failure of the HQE to evaluate the hadronic matrix element correctly?
- New physics?

Additional information needed!

Why Λ_b semileptonic decays?

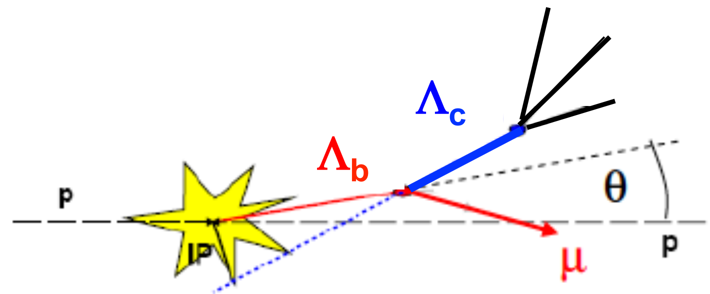


- Use of b-baryon decays provides complementary information to B mesons
- At LHCb Λ_b are produced copiously



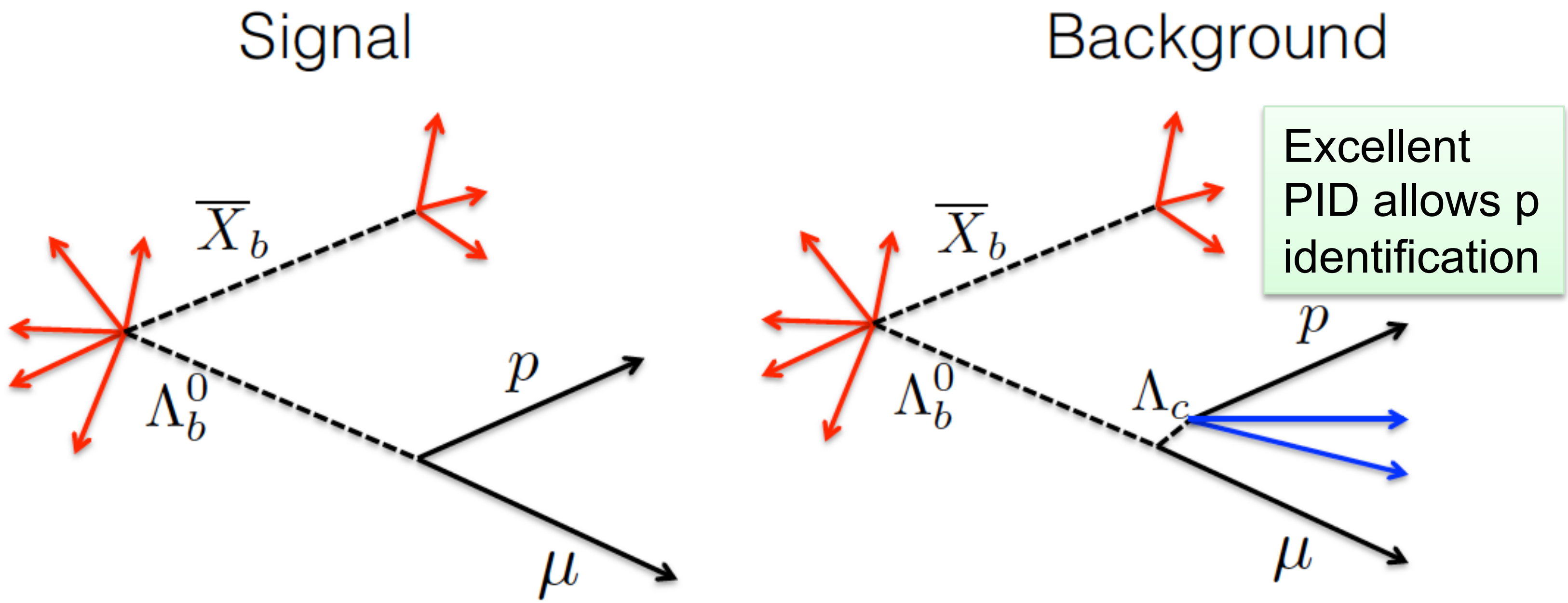
$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu / \Lambda_b \to \Lambda_c\mu\nu$

1) Kinematic constraints allow determination of magnitude of Λ_b momentum (modulo 2-fold ambiguity)
2) LHCb determines the ratio $\Lambda_b \to p\mu\nu/\Lambda_b \to \Lambda_c\mu\nu$ in high q^2 region
   - ⇨ Minimize background from Cabibbo favored decays in $\Lambda_b \to p\mu\nu$
   - ⇨ Use region where lattice predictions are expected to be more reliable



3) Use normalization factor derived from Lattice QCD calculation to extract $|V_{ub}/V_{cb}|^2$

The $\Lambda_b \to p\mu\nu$ signal at LHCb



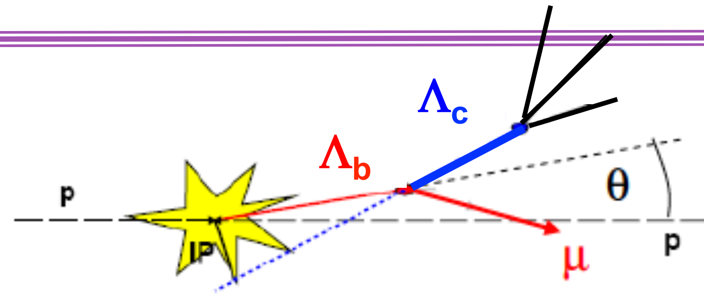
Cabibbo favored decays typically have additional tracks forming a good secondary vertex with the proton emitted in the semileptonic decay ⇨ train multivariate classifier to distinguish between these two configurations, get 90% rejection & 80% efficiency

The corrected mass

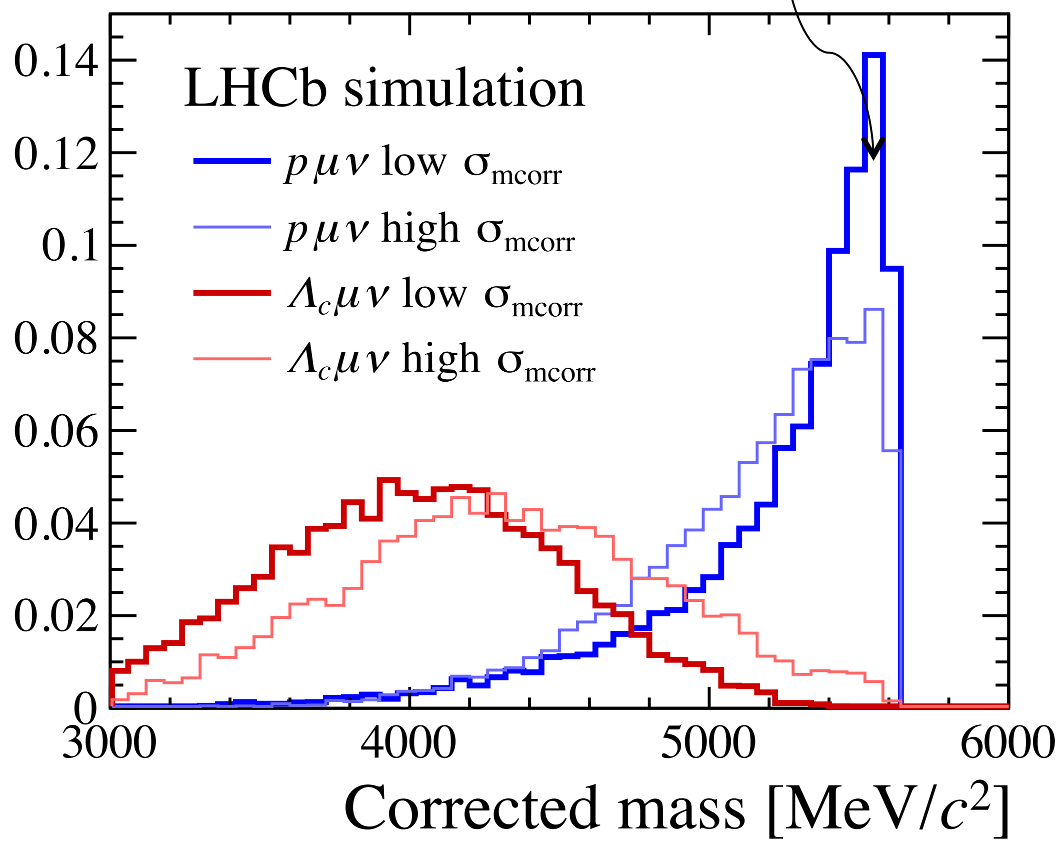
- Displaced vertex information allow to define the corrected mass

$$M_{corr} = \sqrt{M_{p\mu}^2 + p_\perp^2} + p_\perp$$

- M_{corr} is used to disentangle different fit components
- Uncertainty in M_{corr} is used to discriminate between signal and background



M_{corr} peaks at Λ_b mass!

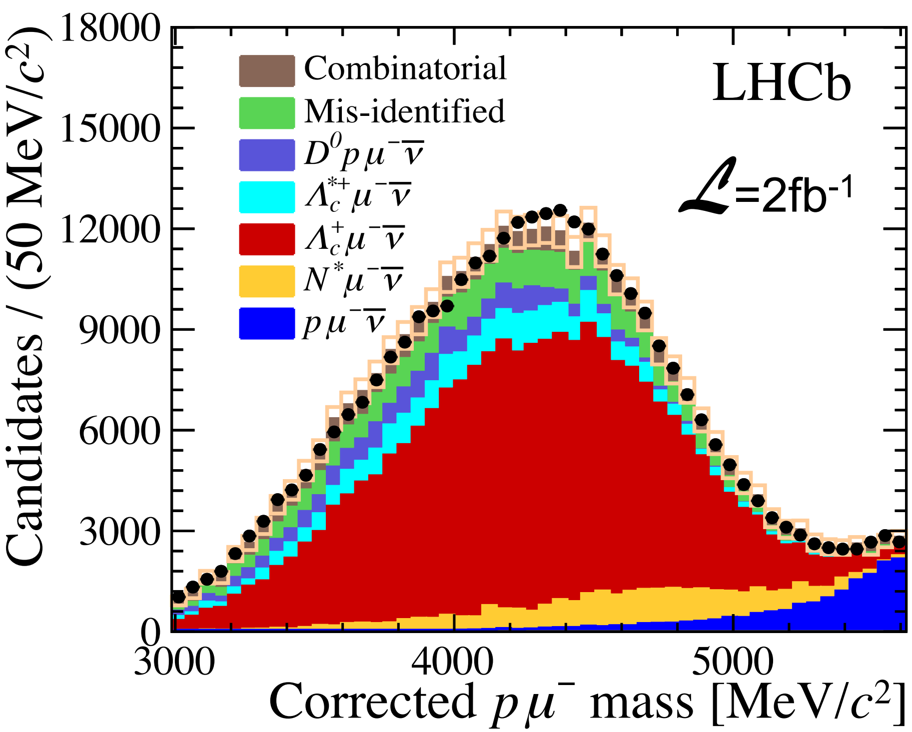


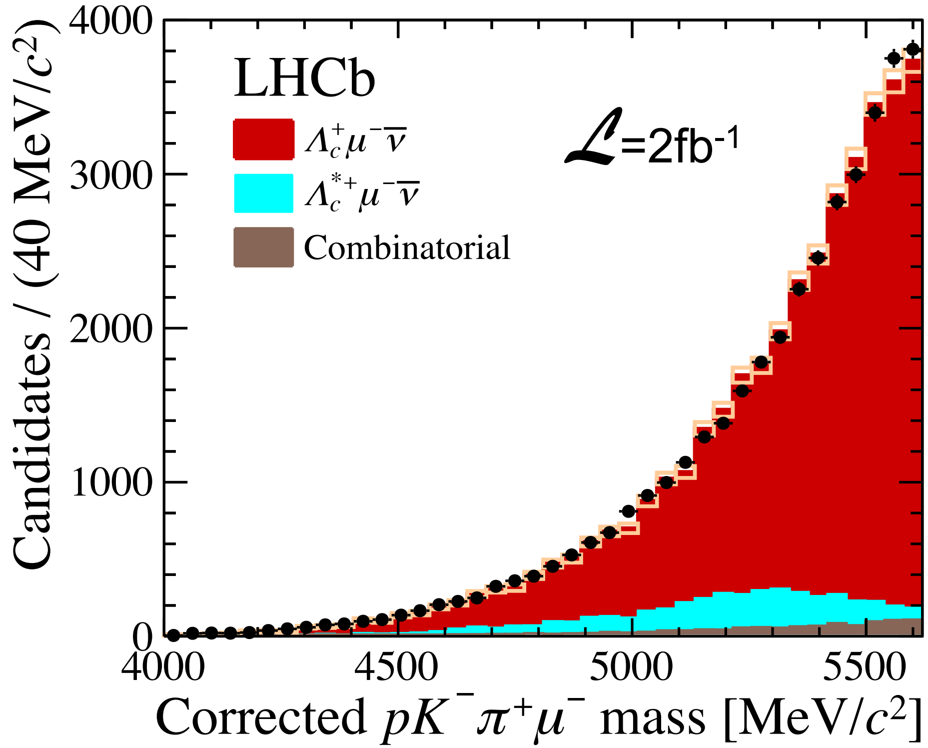
The signal fits

arXiv:1504.01568

$N(\Lambda_b \rightarrow p\mu\nu) = 17687 \pm 733$

$N(\Lambda_b \rightarrow \Lambda_c\mu\nu) = 34255 \pm 571$





Experimental result

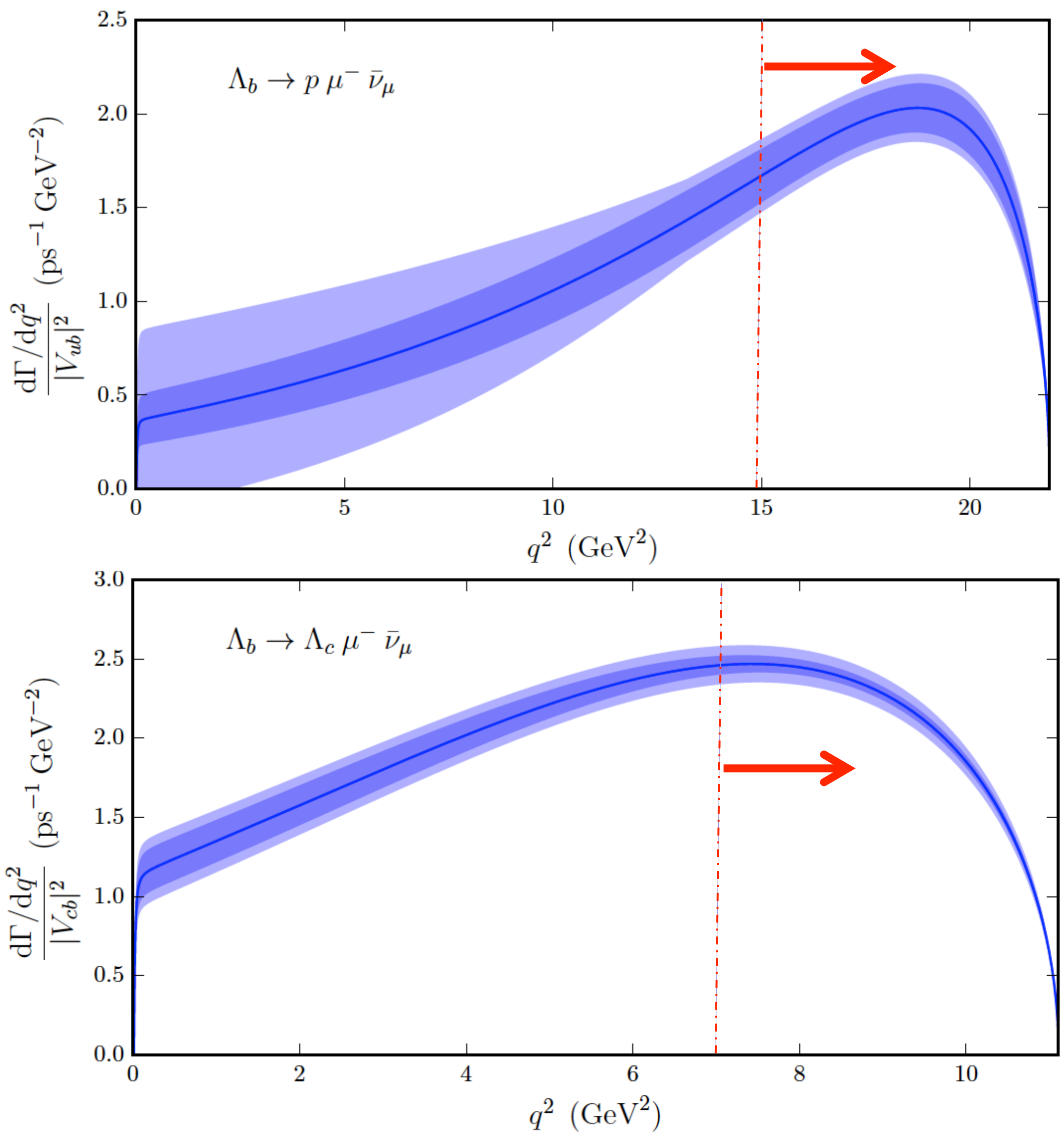
arXiv:1504:01568

$$R_{\exp} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)\big|_{q^2 > 15\,GeV^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)\big|_{q^2 > 7\,GeV^2}} = \left(1.0 \pm 0.04(stat) \pm 0.08(syst)\right) \times 10^{-2}$$

Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	3.2
Tracking	3.0
Λ_c^+ selection efficiency	3.0
$\Lambda_b^0 \to N^\star\mu^-\bar{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.0
Form factors	0.5
Λ_b^0 kinematics	0.5
q^2 migration	0.4
Particle Identification Efficiency	0.2
Total	$^{+7.8}_{-8.2}$

Theory input

arXiv:1503.01421v3
Detmold,Lehner,Meinel



- Most recent calculation uses 2+1 flavors of dynamical domain-wall fermions, RBC & UKQCD configurations & q^2 dependence parameterized with z-expansion
- LHCb uses q^2>15 GeV^2 for $\Lambda_b \to p\mu\nu$ and q^2>7 GeV^2 $\Lambda_b \to \Lambda_c\mu\nu$

⇨Most reliable theory prediction

Theory input II

□ Theory normalization

arXiv:1503.01421v3

$$R_{TH} \equiv \frac{\frac{1}{|V_{ub}|^2}\int_{15GeV^2}^{q^2_{max}} \frac{d\Gamma(\Lambda_b^0 \to p\mu\bar{\nu}_\mu)}{dq^2}dq^2}{\frac{1}{|V_{cb}|^2}\int_{7GeV^2}^{q^2_{max}} \frac{d\Gamma(\Lambda_b^0 \to \Lambda_c^0\mu\bar{\nu}_\mu)}{dq^2}dq^2} = \frac{(12.31 \pm 0.76 \pm 0.77)\,ps^{-1}}{(8.37 \pm 0.16 \pm 0.34)\,ps^{-1}} = 1.471 \pm 0.095 \pm 0.110$$

4.9% theoretical error on $|V_{ub}/V_{cb}|$

$$\frac{\Gamma(\Lambda_b^0 \to p\mu\bar{\nu}_\mu)}{|V_{ub}^2|} = (25.7 \pm 2.6 \pm 4.6)\,ps^{-1}$$

$$\frac{\Gamma(\Lambda_b^0 \to \Lambda_c^+\mu\bar{\nu}_\mu)}{|V_{cb}^2|} = (21.5 \pm 0.8 \pm 1.1)\,ps^{-1}$$

Using the full Γ_c width, theoretical error on $|V_{cb}|$ 3.2%, using Γ_c in $q^2 \geq 7\,GeV^2$ region, theoretical error 2.2%

V_{ub}

arXiv:1504.01568

- Using:

$$V_{ub} = V_{cb}^{excl}\sqrt{R_{exp} / R_{TH}} = V_{cb}^{excl}\sqrt{\frac{(1.0 \pm 0.04 \pm 0.08)\times 10^{-2}}{1.471 \pm 0.095 \pm 0.110}}$$

and

$$\left|V_{cb}^{excl}\right| = (39.5 \pm 0.8)\times 10^{-3}$$

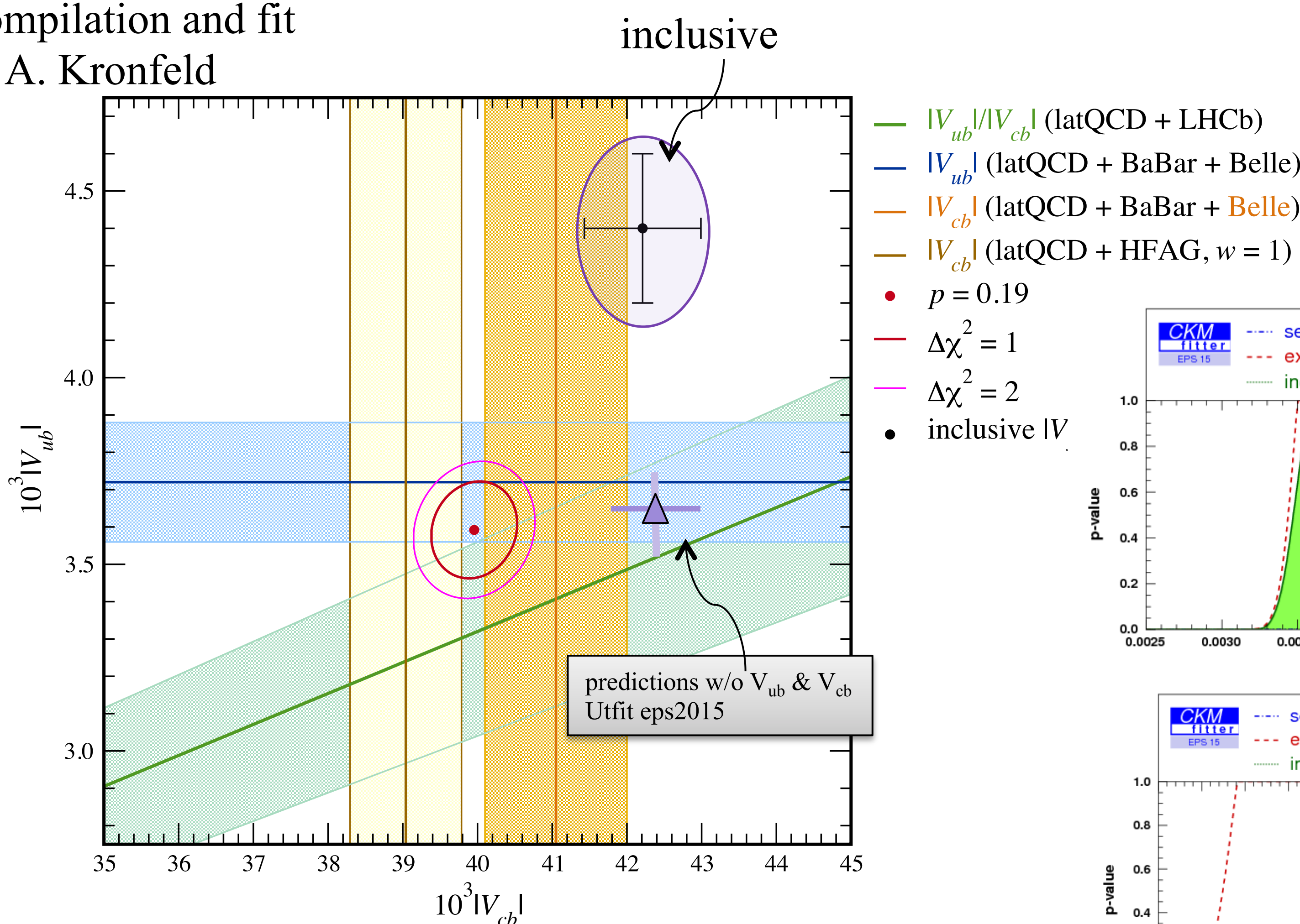
PDG2014

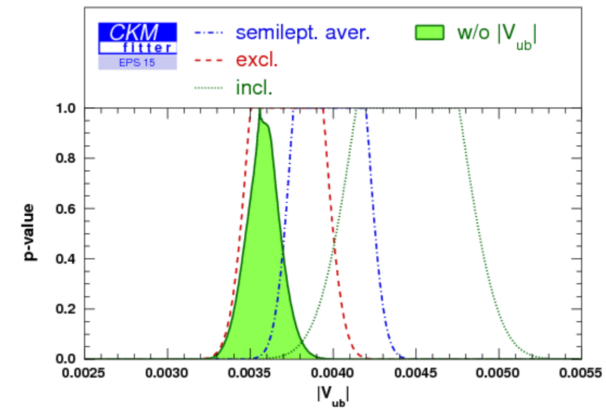
LHCb gets: $$\left|V_{ub}\right| = (3.27 \pm \underbrace{0.15}_{\text{exp}} \pm \underbrace{0.16}_{\text{lattice}} \pm \underbrace{0.06}_{V_{cb}\text{ norm.}})\times 10^{-3}$$

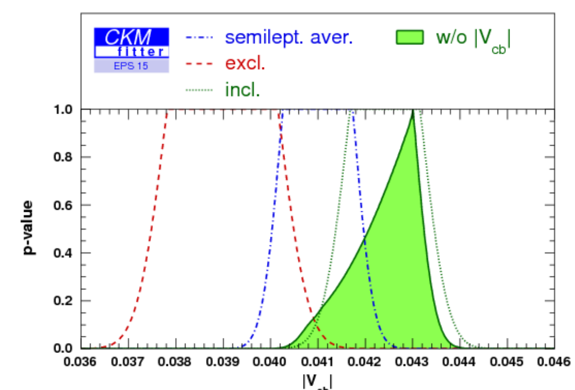
Next: study different q^2 regions

$|V_{xb}|$ current status

Compilation and fit
by A. Kronfeld







THEORY VALIDATION

Lattice QCD & experiment II

- Quoting A. Kronfeld "Any large scale computer endeavor is a bit inscrutable, so it becomes more persuasive if the code's combination of principle and pragmatism can make predictions"
- How can we do more?

Remembering the good old times

Predictions with Lattice QCD

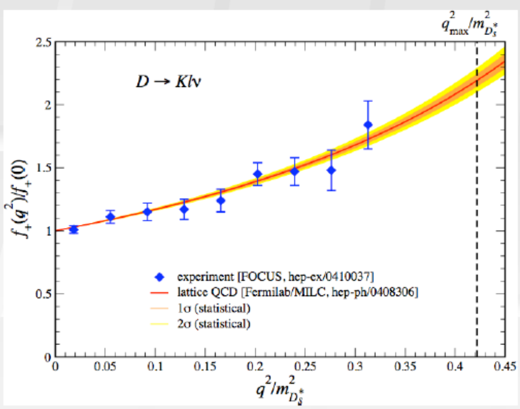
Fermilab Lattice, MILC, and HPQCD Collaborations

Semileptonic D Decays

C. Aubin, C. Bernard, C. DeTar, M. DiPierro, A. El-Khadra, Steven Gottlieb, E.B. Gregory, U.M. Heller, J. Hetrick, A.S. Kronfeld, P.B. Mackenzie, D. Menscher, M. Nobes, M. Okamoto, M.B. Oktay, J. Osborn, J. Simone, R. Sugar, D. Toussaint, H.D. Trottier
(Fermilab Lattice, MILC, and HPQCD Collaborations)
Phys. Rev. Lett. **94**, 011601 (2005) [arXiv:hep-ph/0408306].

When our paper was posted on the arXiv, we knew the normalization of the $D \to \pi l\nu$ and $D \to Kl\nu$ form factors agreed with measurements from the BES Collaboration and the CLEO Collaboration. This agreement had been seen throughout the cycle of conference proceedings and journal publications. So this is almost, but not quite, a *prediction*.

More spectacularly, two months after our paper was posted on the arXiv, the FOCUS Collaboration finished a measurement of the shape of the $D \to Kl\nu$ form factor. Their data are plotted over our curve (with 1 and $2\sigma_{stat}$ bands) and agree excellently.



Leptonic D Decays

C. Aubin, C. Bernard, C. DeTar, M. DiPierro, E. D. Freeland, Steven Gottlieb, U. M. Heller, J. E. Hetrick, A. X. El-Khadra, A. S. Kronfeld, L. Levkova, P. B. Mackenzie, D. Menscher, F. Maresca, M. Nobes, M. Okamoto, D. Renner, J. Simone, R. Sugar, D. Toussaint, H. D. Trottier
(Fermilab Lattice, MILC, and HPQCD Collaborations)
arXiv:hep-lat/0506030 → *Phys. Rev. Lett.*

QCD's influence on the leptonic decay $D_{(s)} \to l\nu$ is parameterized by decay constants f_D and f_{Ds}. Until 2005, the only measurements were based on only a few events and had, hence, uncertainties of 20–60%.

For the 2005 Lepton-Photon Symposium, CLEO-c planned to announce a measurement of f_D with 5–10% uncertainty. The challenge to (lattice) QCD was set.

We took up the challenge, finding [hep-lat/0506030]

$$f_{D^+} = 201 \pm 3 \pm 17 \text{ MeV},$$
$$f_{Ds} = 249 \pm 3 \pm 16 \text{ MeV}.$$

Afterwards, CLEO-c showed its new result. With 47 ± 8 events [hep-ex/0508057]

$$f_{D^+} = 223 \pm 17 \pm 3 \text{ MeV}$$

At this year's Moriond Winter Conference, the BaBar Collaboration showed a nice measurement of f_{Ds} [http://moriond.in2p3.fr/EW/2006/Transparencies/J.W.Berryhill.pdf]:

$$f_{Ds} = 279 \pm 17 \pm 20 \text{ MeV}.$$

Mass of B_c Meson

Ian F. Allison, Christine T.H. Davies, Alan Gray, Andreas S. Kronfeld, Paul B. Mackenzie, James N. Simone
(HPQCD and Fermilab Lattice Collaborations)
Phys. Rev. Lett. **94**, 172001 (2005) [arXiv:hep-lat/0411027].

The B_c meson consists of a bottom quark and a charmed antiquark. It was first observed by CDF during Run I of the Tevatron. The decay mode was $B_c \to J/\psi l\nu$, the neutrino was missed, so the mass resolution was ± 400 MeV. DØ confirmed the observation in Run 2, also in semileptonic decay.

From *B Physics at the Tevatron: Run II and Beyond* [hep-ph/0201071], it was clear that nonleptonic modes would be much, much better.

At Lattice 2004, we presented results that were in almost final form. By mid-November, we posted our paper on the arXiv:

$$m_{Bc} = 6304 \pm 12\ ^{+18}_{-0} \text{ MeV}.$$

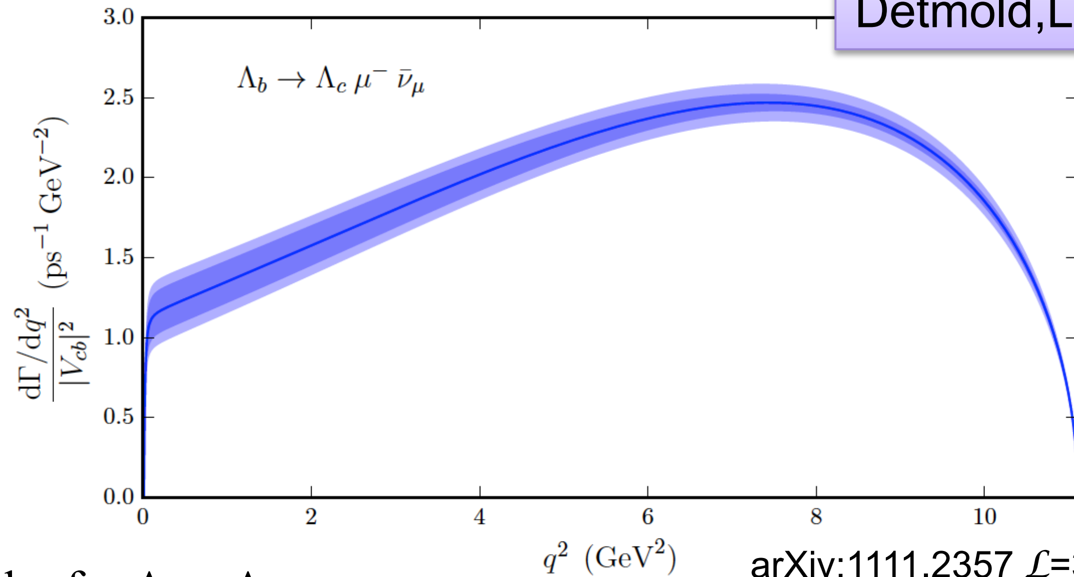
Later, CDF presented evidence for $B_c \to J/\psi\pi$ decay, reconstructing a mass [hep-ex/0505076]

$$m_{Bc} = 6287 \pm 5 \text{ MeV}.$$

Our result is based on computing the mass splitting $\Delta_{\psi\Upsilon} = m_{Bc} - (\bar{m}_\psi + m_\Upsilon)/2$, which is astonishingly flat as a function of lattice spacing:

Examples on where we can follow this path

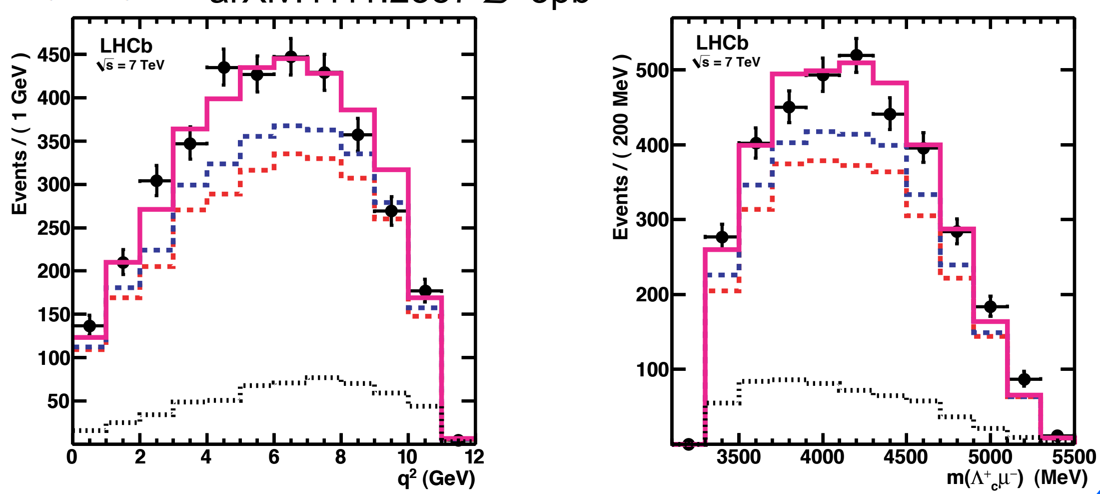
arXiv:1503.01421v3
Detmold,Lehner,Meinel



Placeholder for $\Lambda_b \to \Lambda_c \mu\nu$ Study currently under review within the collaboration:

- ❑ note access to full q^2 (w) region
- ❑ Final result with 3fb-1
- ❑ With normalization mode & lattice input $|V_{cb}|$

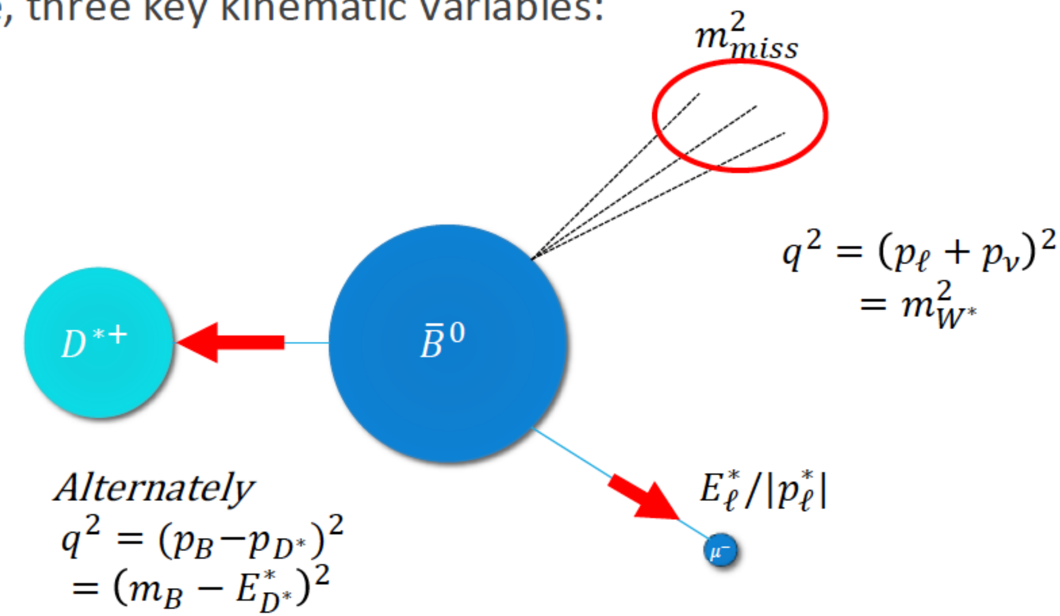
arXiv:1111.2357 $\mathcal{L}$=3pb^{-1}



HADRONIC MATRIX ELEMENT AND NEW PHYSICS

$B \to D^* \tau \nu$ at LHCb

- In B rest frame, three key kinematic variables:



$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}$	$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}$
$m^2_{miss} > 0$	$m^2_{miss} = 0$
E^*_l spectrum is soft	E^*_l spectrum is hard
$m^2_\tau \le q^2 \le 10.6\ \mathrm{GeV}^2$	$\approx 0 \le q^2 \le 10.6\ \mathrm{GeV}^2$

- Approximation to determine B momentum $(\gamma\beta_z)_B \sim (\gamma\beta_z)_{D^*\mu}$

(18% B momentum resolution, moderate effect on relevant kinematic variables)

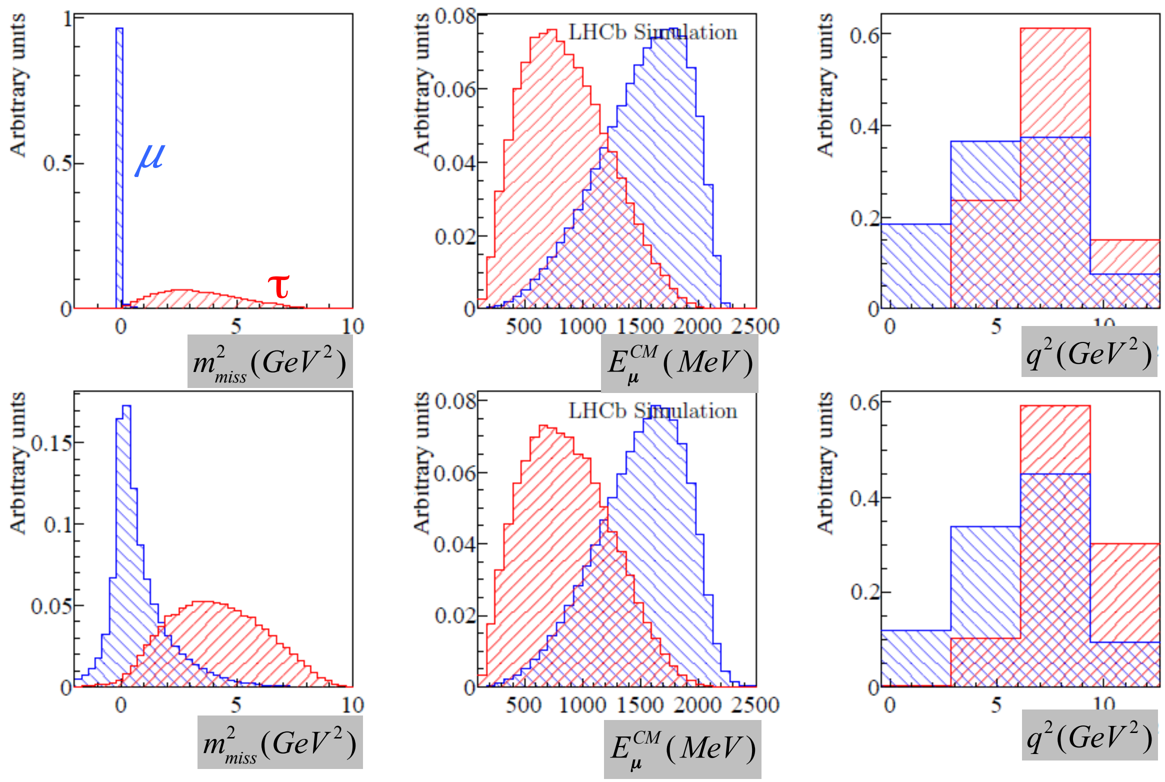
- Use isolation TMVA to discriminate between signals and variety of backgrounds

B momentum approximation

LHCb-PAPER-2015-025
arXiv:1506.08614

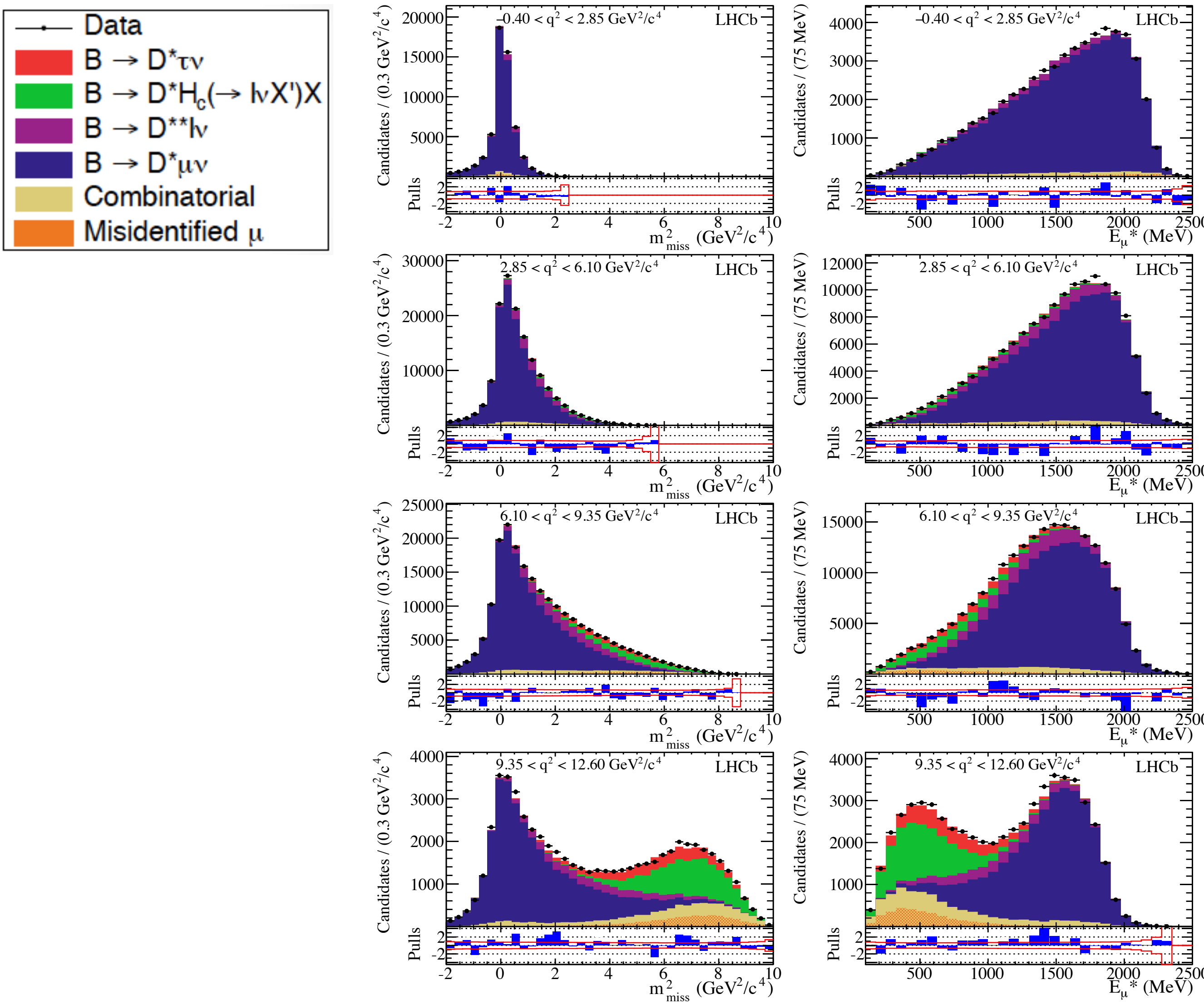
MC B momentum

Approximate B momentum



B→D*τν fit

LHCb-PAPER-2015-025
arXiv:1506.08614



Fit in 4 q^2 bins: fit variables E_m(CM)& m_{miss}^2:

- ❑ templates for each component using approximate B momentum

Systematic uncertainties

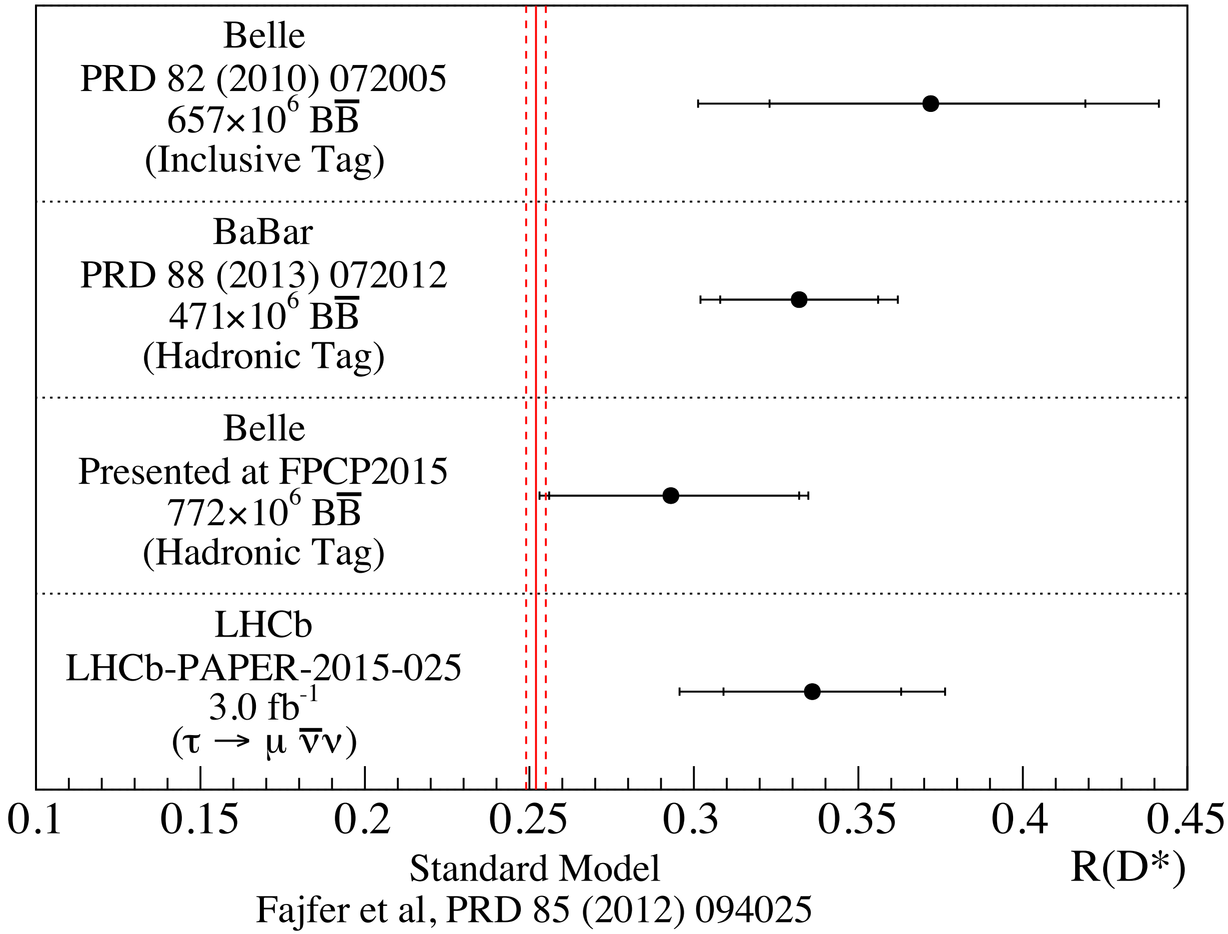
arXiv:1506.08614

Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

Expected to be reduced for future R(D)+R(D*)

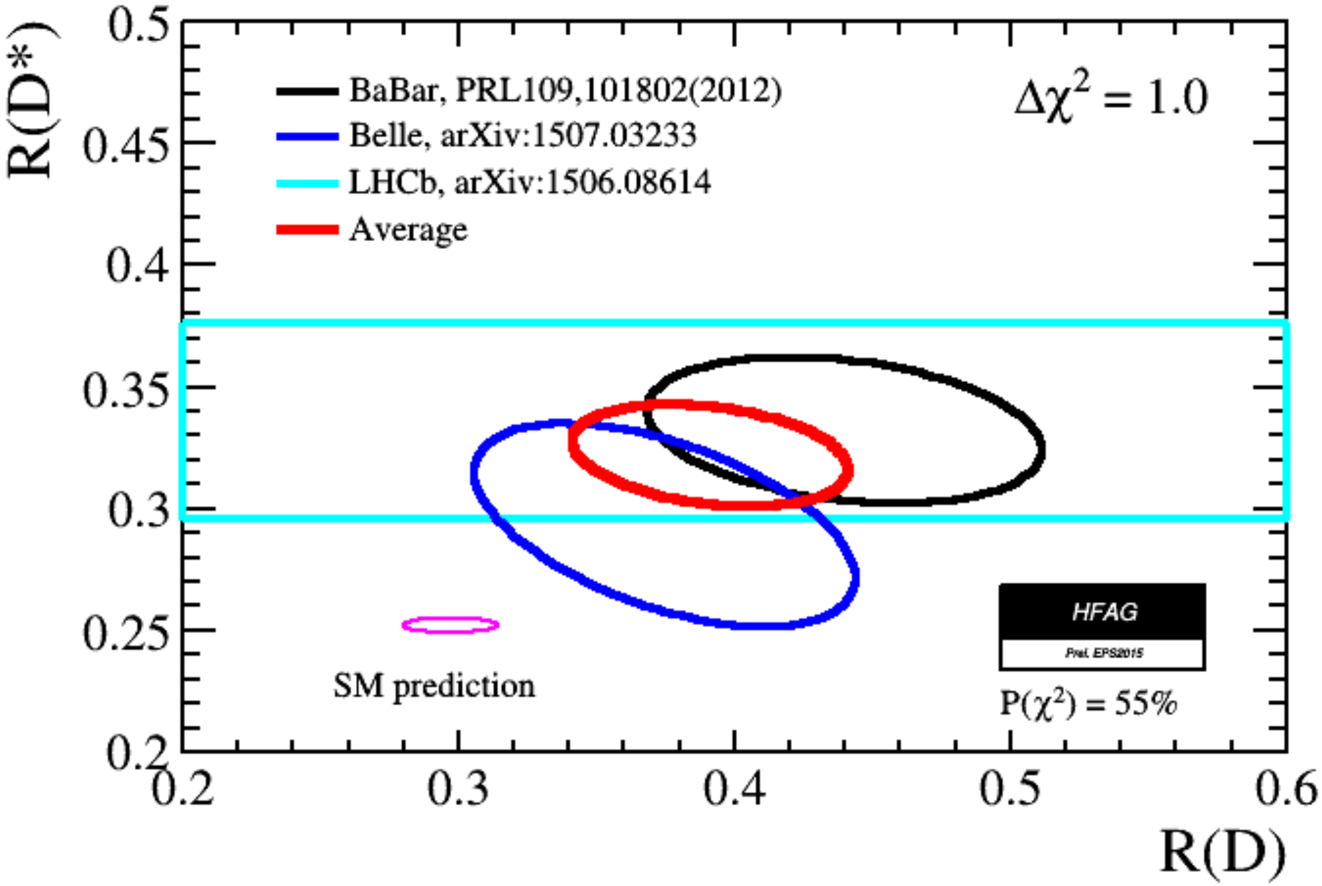
Will scale down with more data (Run2)

$B \to D^{(*)}\tau\nu$ summary



In progress at LHCb $B \to D^{*}\tau\nu$, with $\tau \to 3\pi(\pi^0)$

Combined R(D*) data



$R_{D^*}^{ave} = 0.322 \pm 0.022$

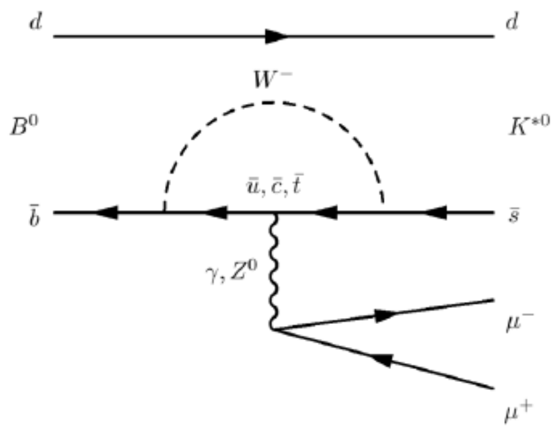
$R_{D}^{ave} = 0.391 \pm 0.050$

$\rho = -0.29$

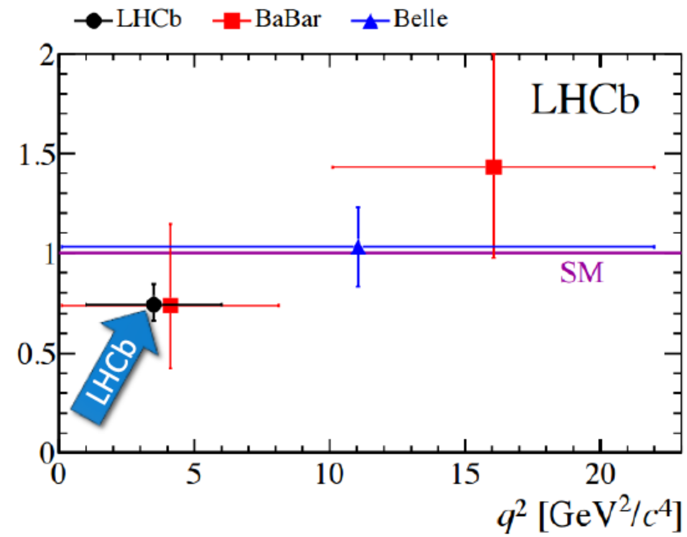
Plot and average from HFAG

SM p-value $1.1\text{x}10^{-4}$ ~3.9σ

Lepton flavor violation in $B \to K^{(*)}\ell\ell$?



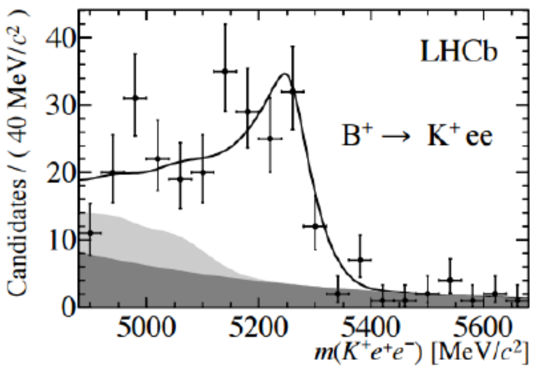
$$R_K = \frac{B(B^0 \to K^{*0}\mu^+\mu^-)}{B(B^0 \to K^{*0}e^+e^-)}$$

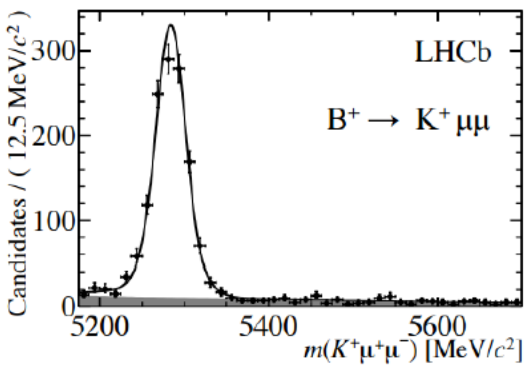


LHCb

(left: electron triggered category)

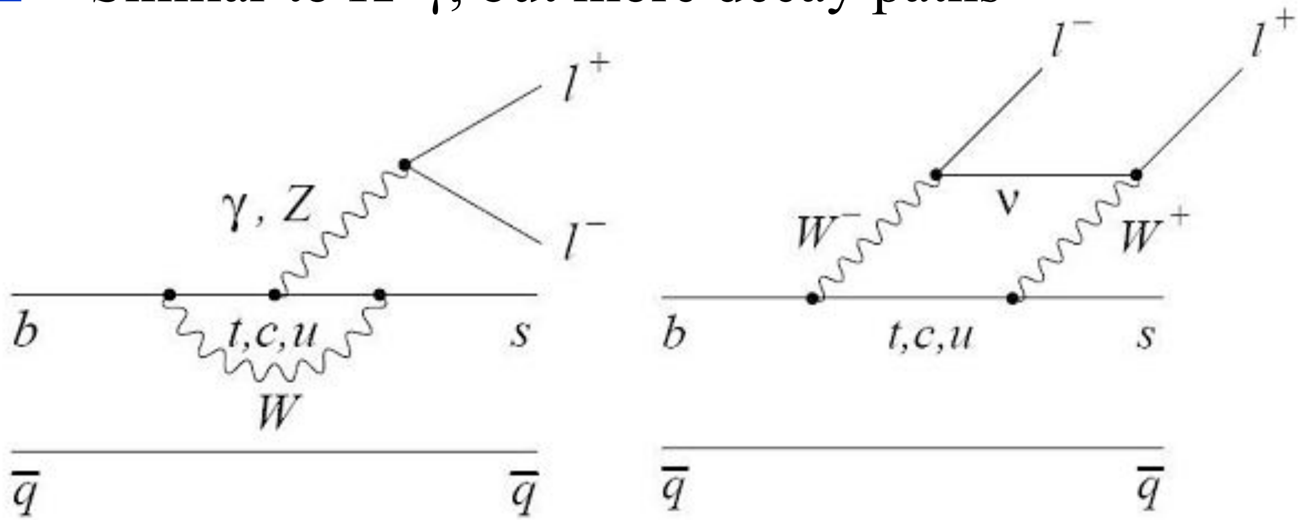
PRL 113 (2014) 151601





$B \to K^{(*)} \ell^+ \ell^-$

- Similar to K*γ, but more decay paths



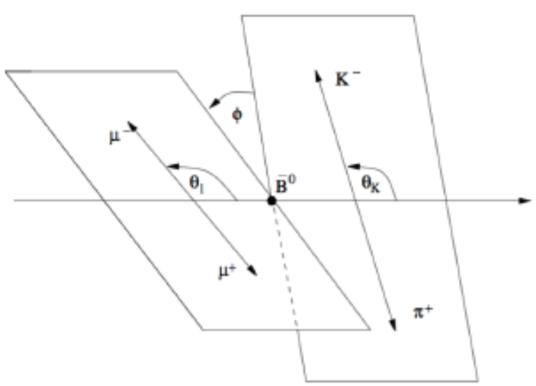
+ new particles in loops

- Several variables can be examined, e.g. muon forward-backward asymmetry, A_{FB} is well predicted in SM
- Not all the variables are equal! The never ending struggle to tame strong interaction effects!

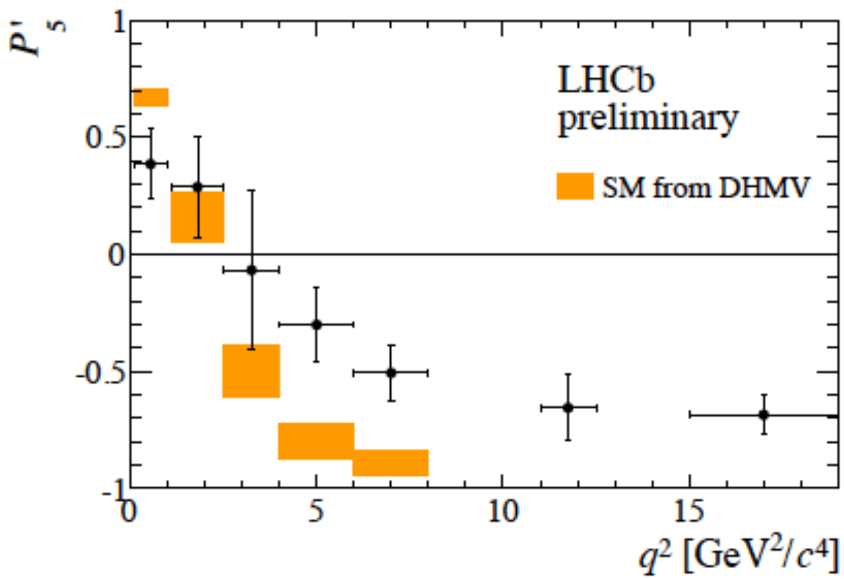
New observables in $B \to K^{(*)} l^+ l^-$

Goal: express differential decay rate in terms of parameters that are less sensitive to the hadronic matrix element uncertainty ⇔ prevent NP from hiding under strong interaction effects

$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \sqrt{F_L(1-F_L)}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi + (1-F_L)A_{Re}^T\sin^2\theta_K\cos\theta_\ell + \sqrt{F_L(1-F_L)}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi + \sqrt{F_L(1-F_L)}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$



The P'_5 anomaly in the decay $B \rightarrow K^{(*)}\mu^+\mu^-$



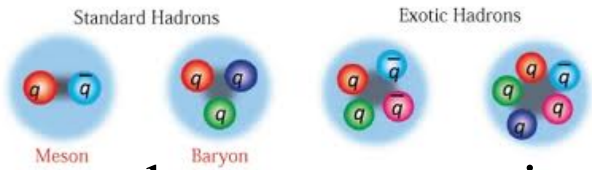
P'_5 in $B \rightarrow K^*\mu^+\mu^-$
[LHCb-CONF-2015-002]

- 3.7σ discrepancy with respect to the Standard Model in the region $4.3<q^2<8.68$ GeV^2

Input from lattice:

- Form factors from first principles
- "Understanding non-factorizable contributions is probably the most important open issue which theoretical predictions must conform" Horgan et al, arXiv:1501.00367

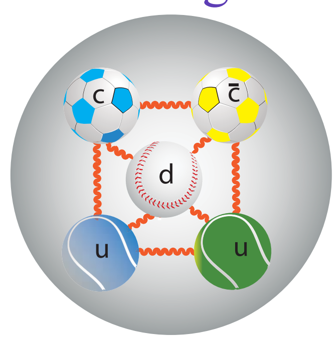
exotic hadrons & QCD



- theory perspective:
  - lattice QCD is poised to predict mass and decay properties of ordinary hadrons, but also exotica (glueballs, tetraquarks, pentaquarks…)

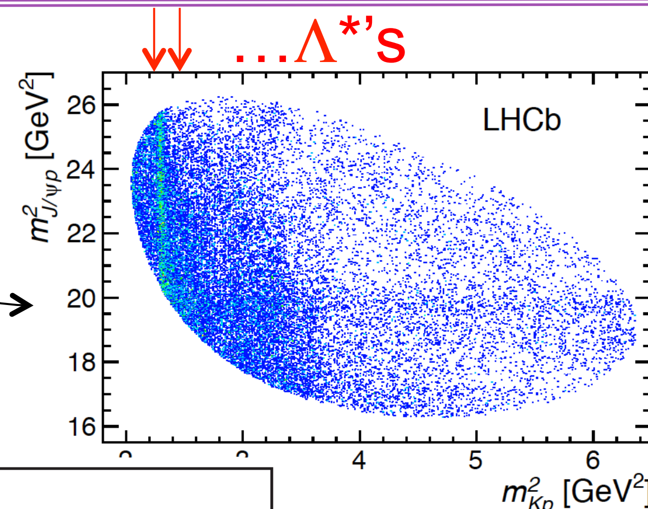
"Multiquark correlations inside hadrons can have a significant and in some cases even striking impact on the hadron spectrum. We show how such correlations in general, and mesons with a dominant tetraquark content in particular, emerge holographically in the AdS/QCD framework." Forkel arXiv:1206.5745

- experimental perspective:
  - Nature of scalar nonet still a mystery
  - zoo of exotic X,Y,Z particles containing b and c quarks are being discovered
  - the new kid on the block!

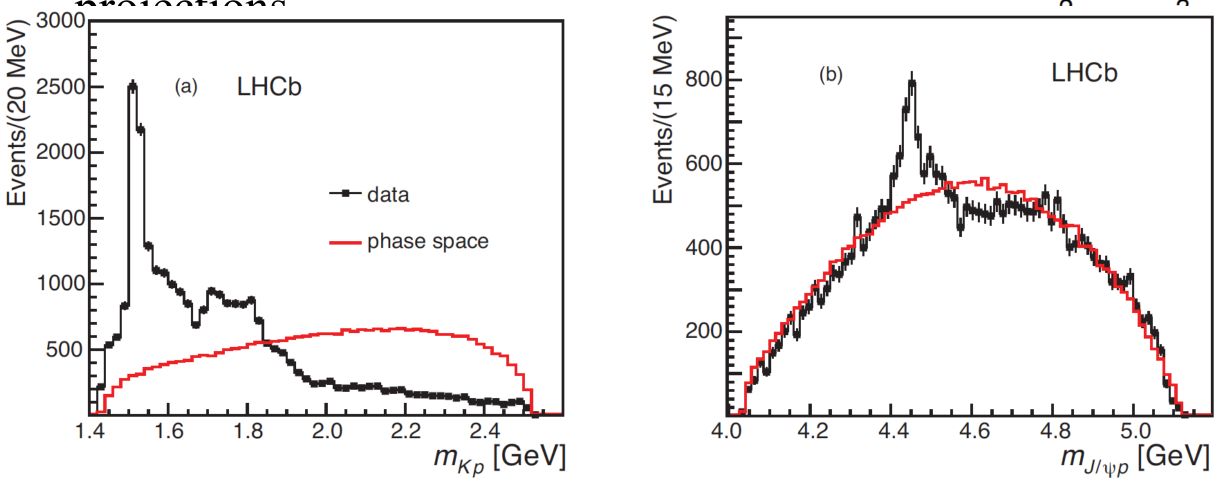


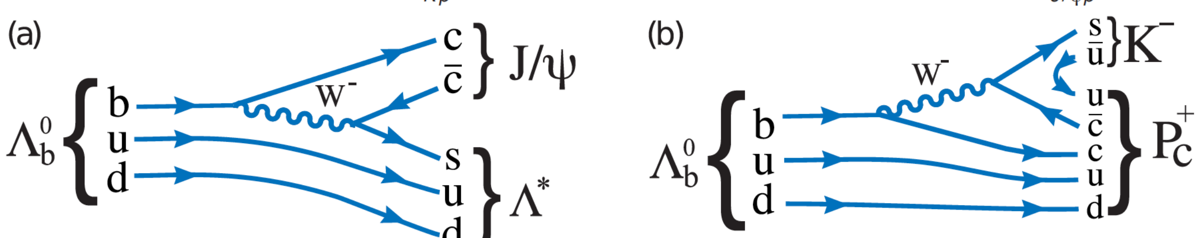
P_c states in $\Lambda_b \rightarrow J/\psi K^- p$

- Dalitz plot show an unusual feature
  [arXiv:1507.03414]



projections





Decay amplitude analysis

- Are there "artifacts" that can produce a peak?
  - Many checks done that shows this is not the case: e.g. changing p to K, or π to K allows us to veto misidentified $B_s \to J/\psi K^- K^+$ & $B^0 \to J/\psi K^- \pi^+$
  - Clones & ghost tracks eliminated
  - Ξ_b decays checked as a source
- Can interferences between Λ^* resonances generate a peak in the $J/\psi p$ mass spectra?
  - Implemented a decay amplitude analysis that incorporates both decay sequences

Matrix Element

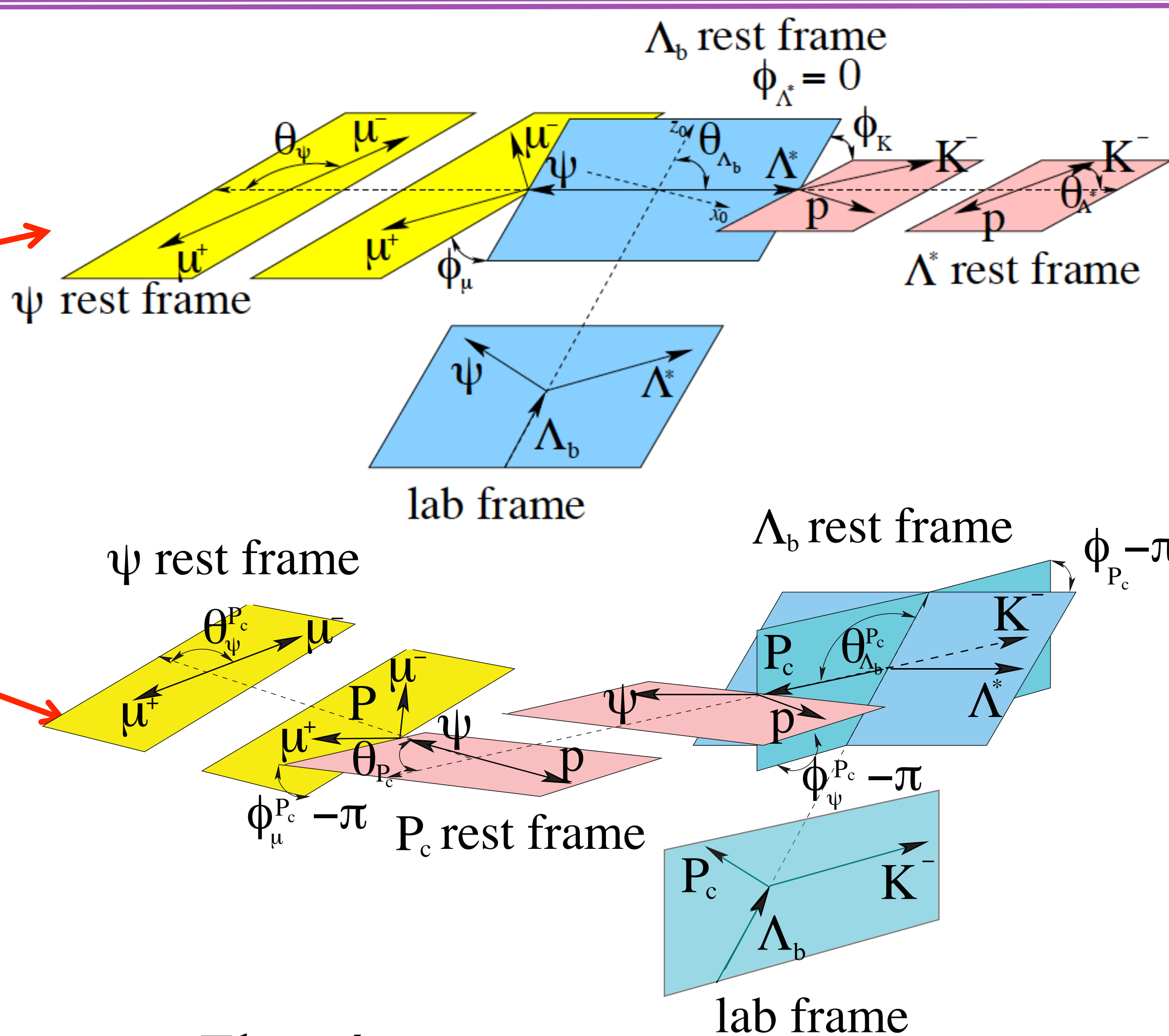
- Two interfering channels:

$\Lambda_b \to J/\psi \Lambda^*$,
$\Lambda^* \to K^- p$

&

$\Lambda_b \to P_c^+ K^-$,
$P_c^+ \to J/\psi\, p$

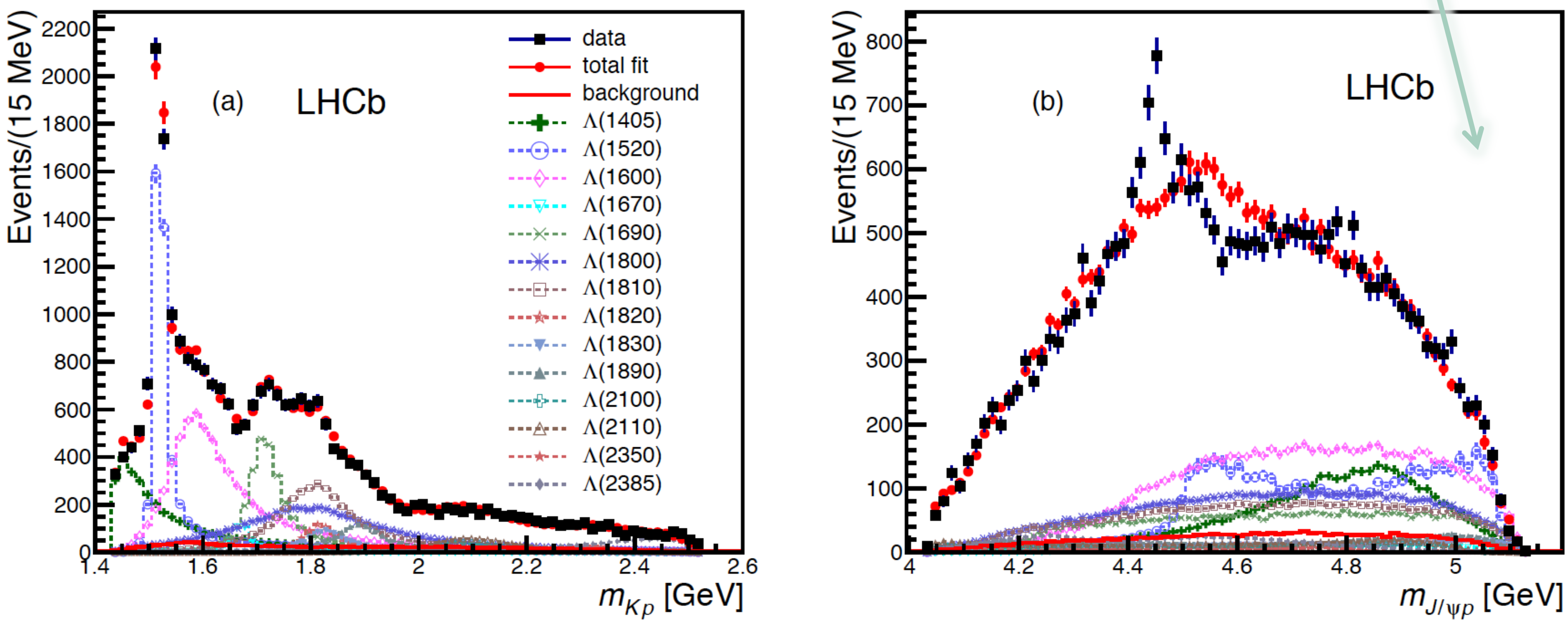
- Use m(K⁻p) & 5 decay ∠'s as fit parameters



- Mass shapes: Breit-Wigner or Flatte´

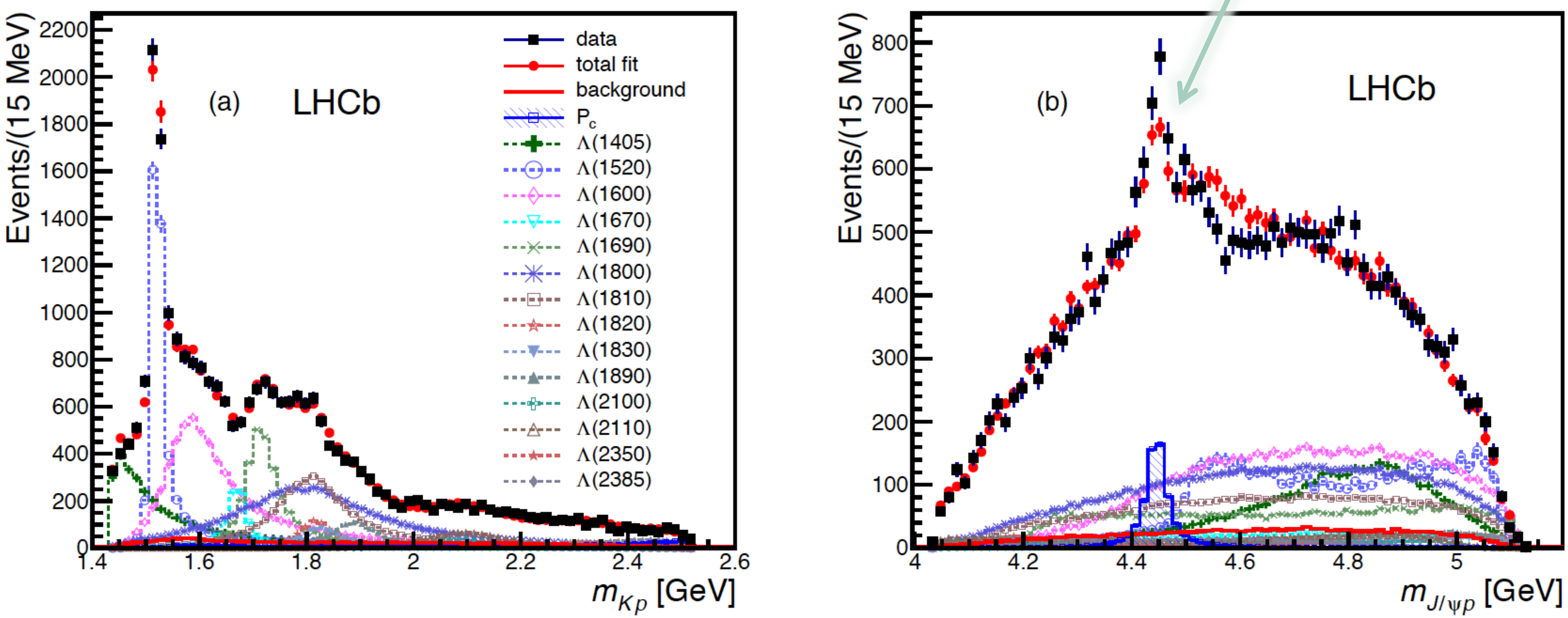
Results without P_c states

- Use extended model, so all possible known Λ^* amplitudes. m_{Kp} looks fine, but not $m_{J/\psi p}$
- Additions of non-resonant, extra Λ^*'s doesn't help



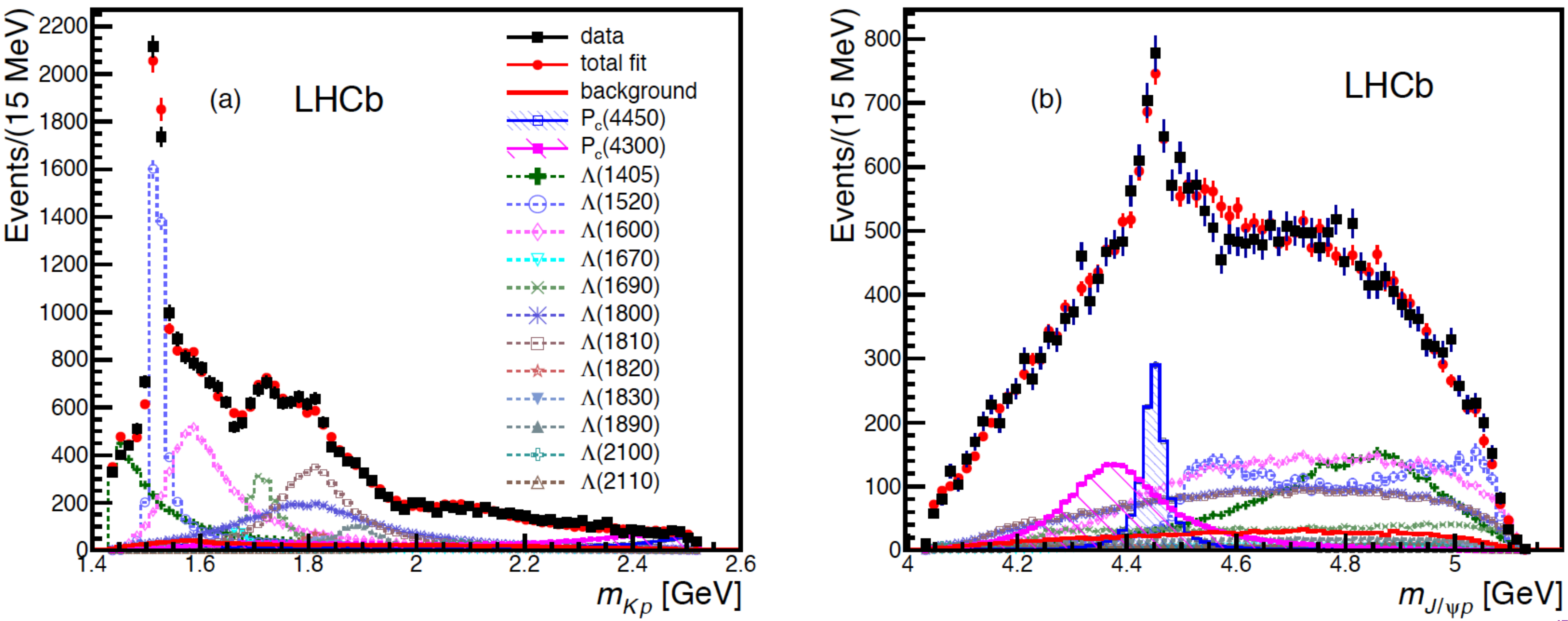
Extended model with 1 P_c

- Try all J^P up to $7/2^{\pm}$
- Best fit has $J^P = 5/2^{\pm}$. Still not a good fit

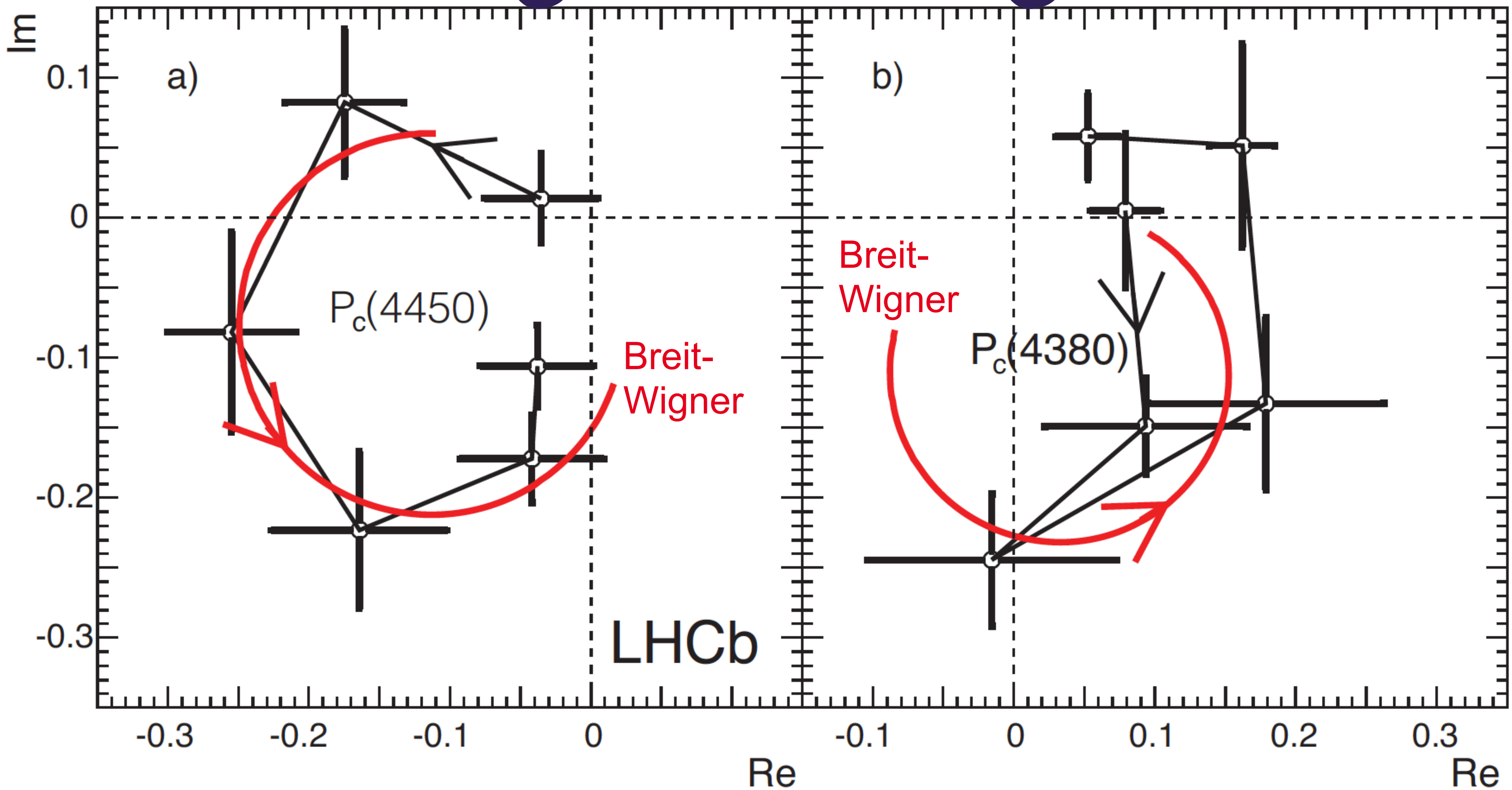


Reduced model with 2 P_c's

- Best fit has J^P=(3/2⁻, 5/2⁺), also (3/2⁺, 5/2⁻) & (5/2⁺, 3/2⁻) are preferred



Argand diagrams



- Amplitudes for 6 bins between +Γ & -Γ

What are we seeing?

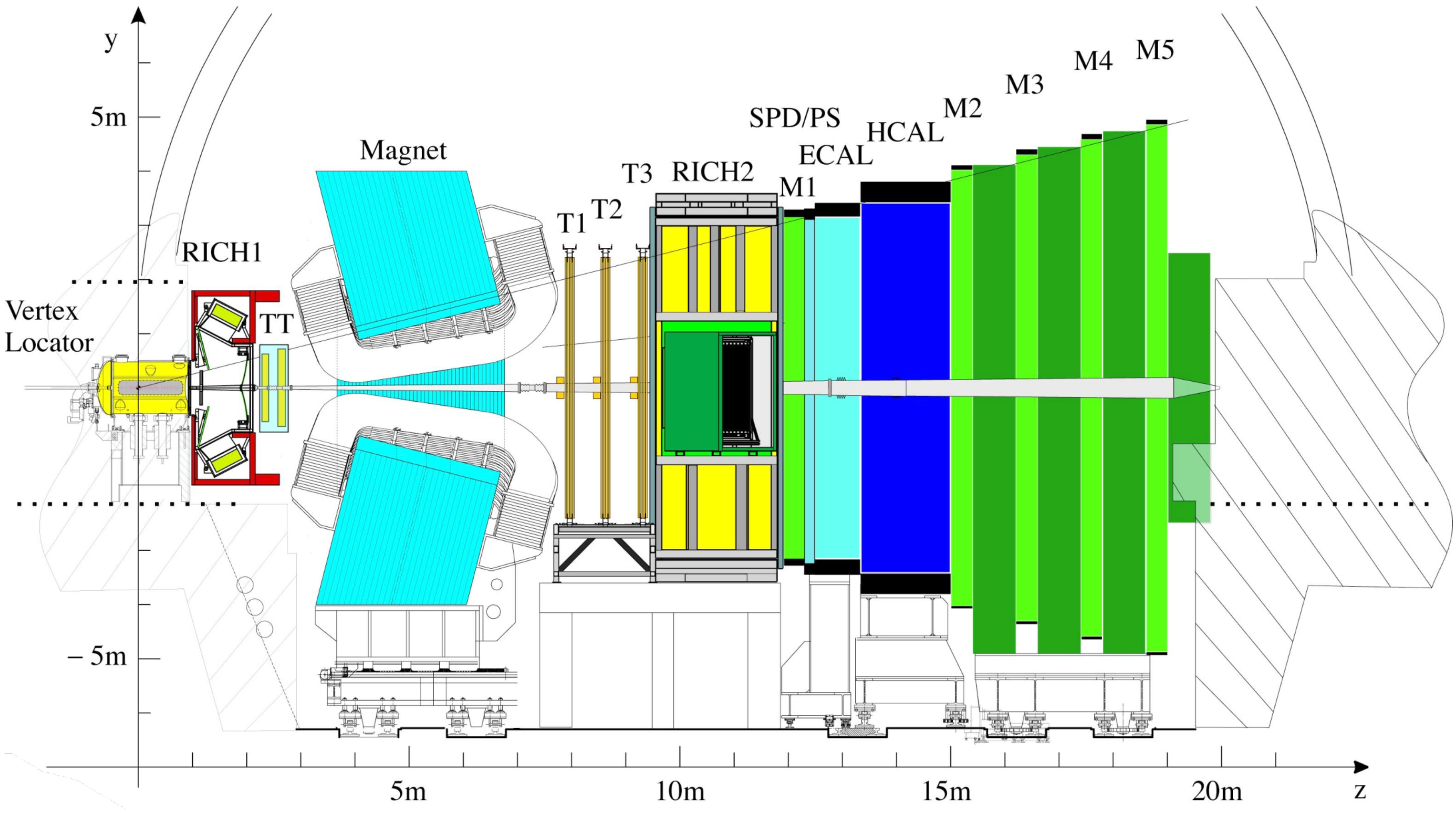
- New manifestation of QCD (different hadron structure)?
- Rescattering effect?
- Can lattice predict spectra of more exotic hadronic structures (tetraquarks, pentaquarks, dibaryons, others…)?

Conclusions and outlook

- LHCb is adding a wealth of data that allow to probe in novel ways the Standard Model and offer new insight on new physics model.
- Theoretical input on the hadronic matrix element mediating the decays that we use to probe the fundamental quantities is crucial
- Testable predictions are critical component to this joint theoretical and experimental effort

THE END

The LHCb detector

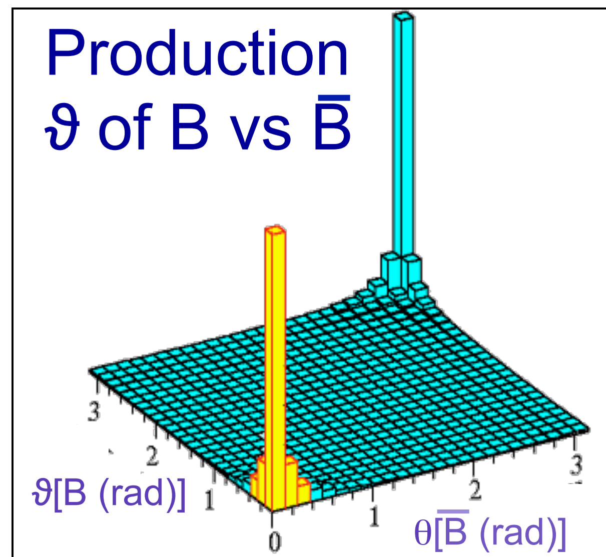


The Forward Direction at the LHC

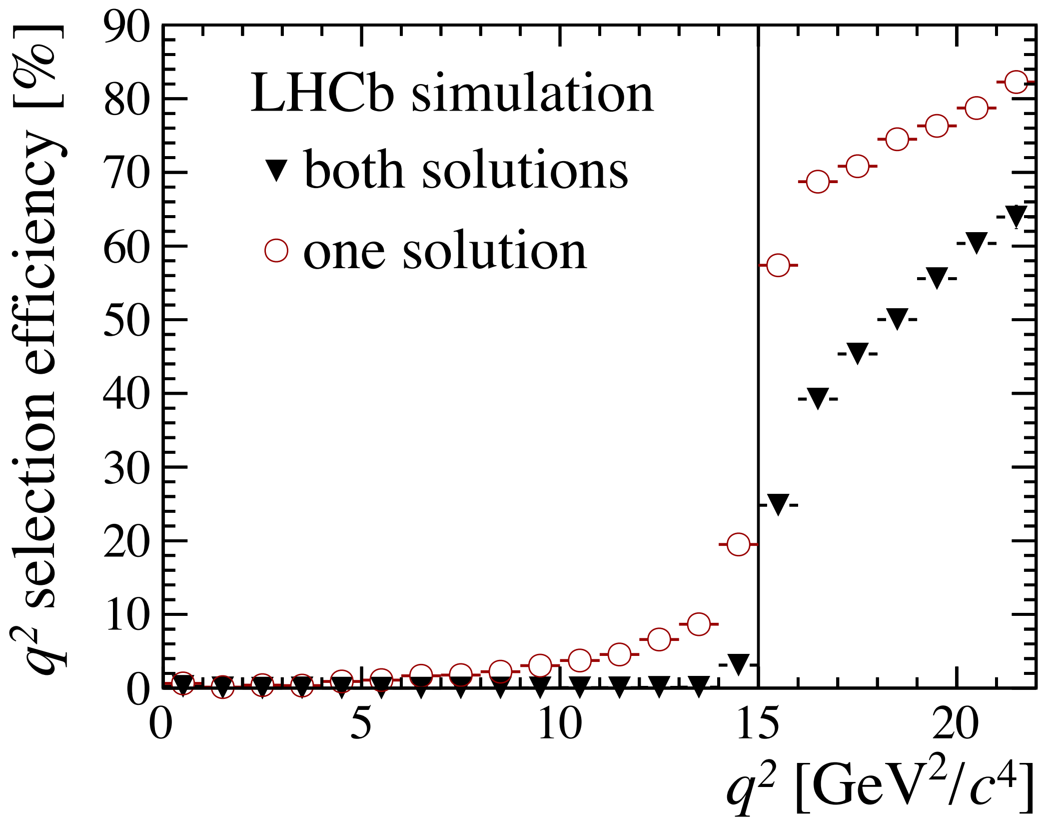
- In the forward region at LHC the $b\bar{b}$ production σ is large
- The hadrons containing the b & $\bar{b}$ quarks are both likely to be in the acceptance. Essential for "flavor tagging"
- LHCb uses the forward direction where the B's are moving with considerable momentum ~100 GeV, thus minimizing multiple scattering
- At $\mathcal{L}=4\times10^{32}/cm^2/s$, we get $\sim10^{12}$ B hadrons in 10^7 sec in the LHCb acceptance.

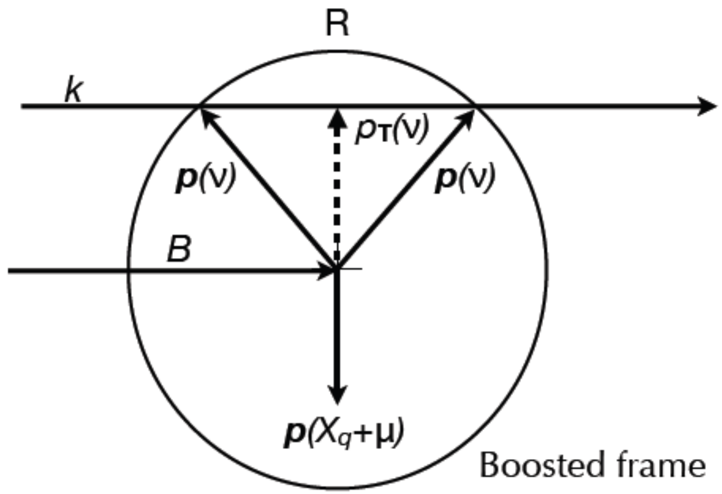
arXiv:1009.2731

Measured cross section at 7 TeV in LHCb acceptance is ~90 μb



The two-fold ambiguity

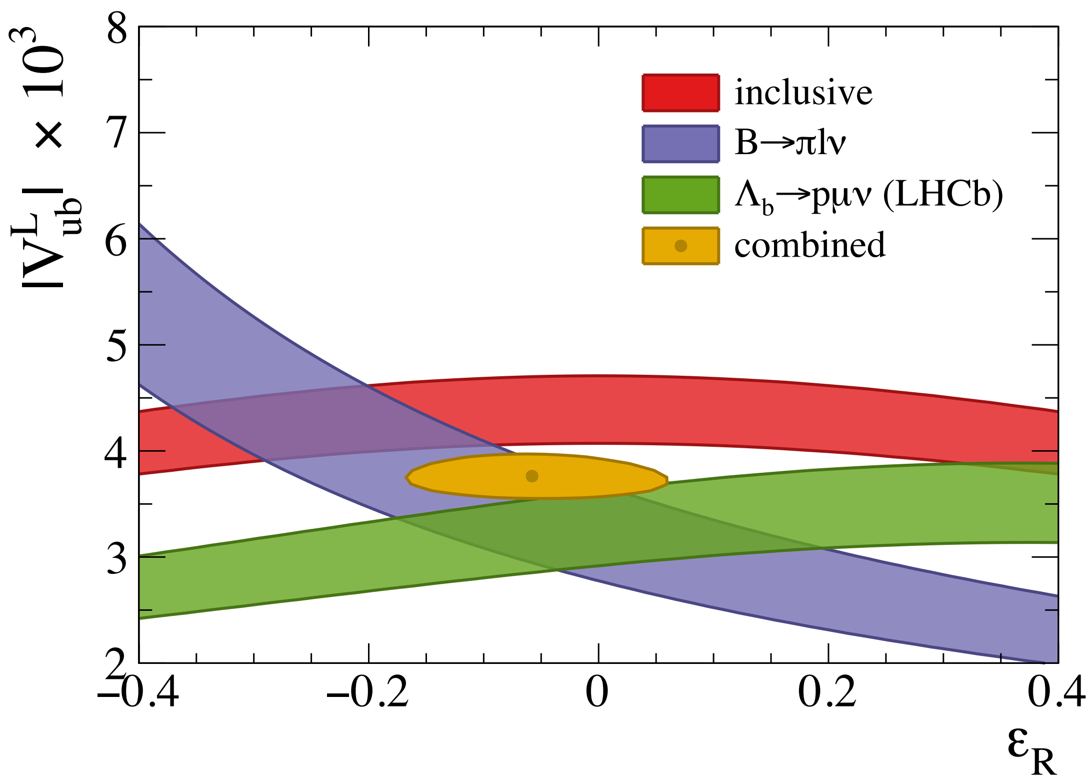




New physics in $|V_{ub}|$?

Conjecture that discrepancy between $|V_{ub}|$ from inclusive and exclusive determinations could be attributed to right-handed currents.

arXiv:0907.2461
arXiv:1033.4022 (V_{cb})
arXiv:1408.2516v1



Constraint from this measurement disfavors this solution of the puzzle

Cross-checks

- Many done, some listed here:
- Signal found using different selections by others
- Two independently coded fitters using different background subtractions (sFit & cFit)
- Split data shows consistency: 2011/2012, magnet up/down, $\Lambda_b/\overline{\Lambda}_b$, $\Lambda_b(p_T \text{ low})/\Lambda_b(p_T \text{ high})$
- Extended model fits tried without P_c states, but two additional high mass Λ^* resonances allowing masses & widths to vary, or 4 non-resonant terms of J up to 3/2

Systematic uncertainties

Source	M_0 (MeV) low	M_0 (MeV) high	Γ_0 (MeV) low	Γ_0 (MeV) high	Fit fractions (%) low	Fit fractions (%) high	$\Lambda(1405)$	$\Lambda(1520)$
Extended vs. reduced	21	0.2	54	10	3.14	0.32	1.37	0.15
Λ^* masses & widths	7	0.7	20	4	0.58	0.37	2.49	2.45
Proton ID	2	0.3	1	2	0.27	0.14	0.20	0.05
$10 < p_p < 100$ GeV	0	1.2	1	1	0.09	0.03	0.31	0.01
Nonresonant	3	0.3	34	2	2.35	0.13	3.28	0.39
Separate sidebands	0	0	5	0	0.24	0.14	0.02	0.03
J^P $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$	10	1.2	34	10	0.76	0.44		
$d = 1.5 - 4.5$ GeV^{-1}	9	0.6	19	3	0.29	0.42	0.36	1.91
$L_{\Lambda_b^0}^{P_c}$ $\Lambda_b^0 \to P_c^+$ (low/high)K^-	6	0.7	4	8	0.37	0.16		
L_{P_c} P_c^+ (low/high) $\to J/\psi p$	4	0.4	31	7	0.63	0.37		
$L_{\Lambda_b^0}^{\Lambda_n^*}$ $\Lambda_b^0 \to J/\psi \Lambda^*$	11	0.3	20	2	0.81	0.53	3.34	2.31
Efficiencies	1	0.4	4	0	0.13	0.02	0.26	0.23
Change $\Lambda(1405)$ coupling	0	0	0	0	0	0	1.90	0
Overall	29	2.5	86	19	4.21	1.05	5.82	3.89
sFit/cFit cross check	5	1.0	11	3	0.46	0.01	0.45	0.13

Models: extended & reduced

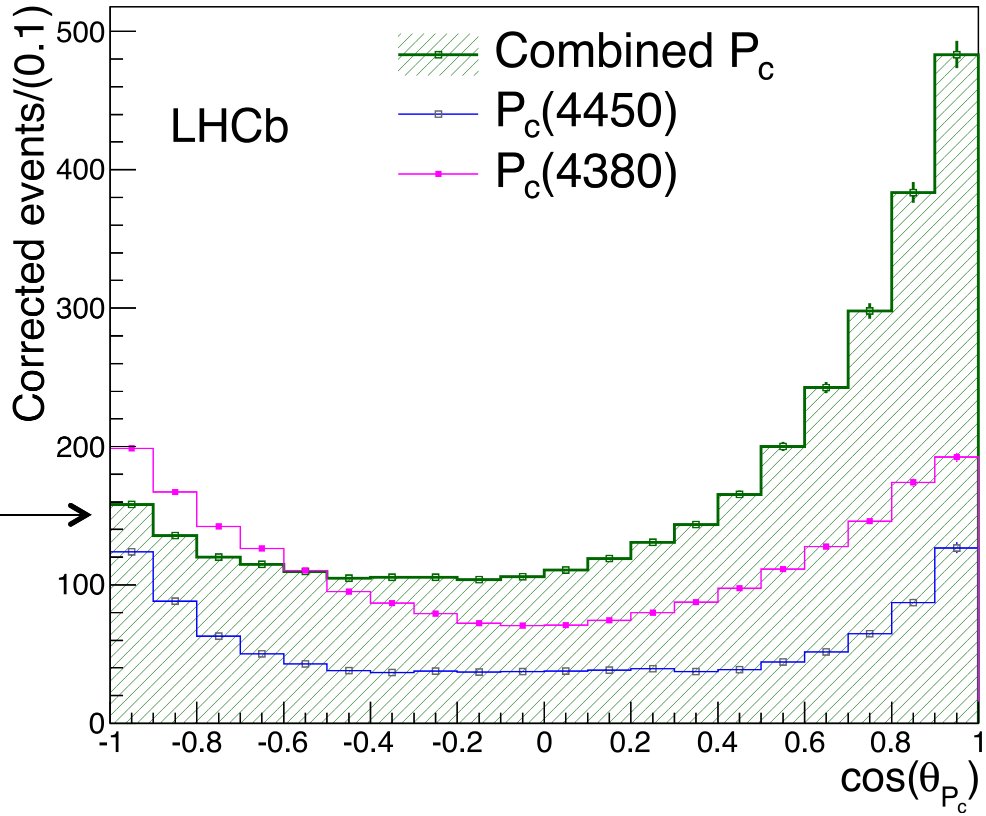
- Consider all Λ* states & all allowed L values

	State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
Flatte´	$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
BW	$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
↓	$\Lambda(1600)$	$1/2^+$	1600	150	3	4
	$\Lambda(1670)$	$1/2^-$	1670	35	3	4
	$\Lambda(1690)$	$3/2^-$	1690	60	5	6
	$\Lambda(1800)$	$1/2^-$	1800	300	4	4
	$\Lambda(1810)$	$1/2^+$	1810	150	3	4
	$\Lambda(1820)$	$5/2^+$	1820	80	1	6
	$\Lambda(1830)$	$5/2^-$	1830	95	1	6
	$\Lambda(1890)$	$3/2^+$	1890	100	3	6
	$\Lambda(2100)$	$7/2^-$	2100	200	1	6
	$\Lambda(2110)$	$5/2^+$	2110	200	1	6
	$\Lambda(2350)$	$9/2^+$	2350	150	0	6
	$\Lambda(2585)$	?	$\approx$2585	200	0	6
					# parameters 64	146

Data demands 2 states

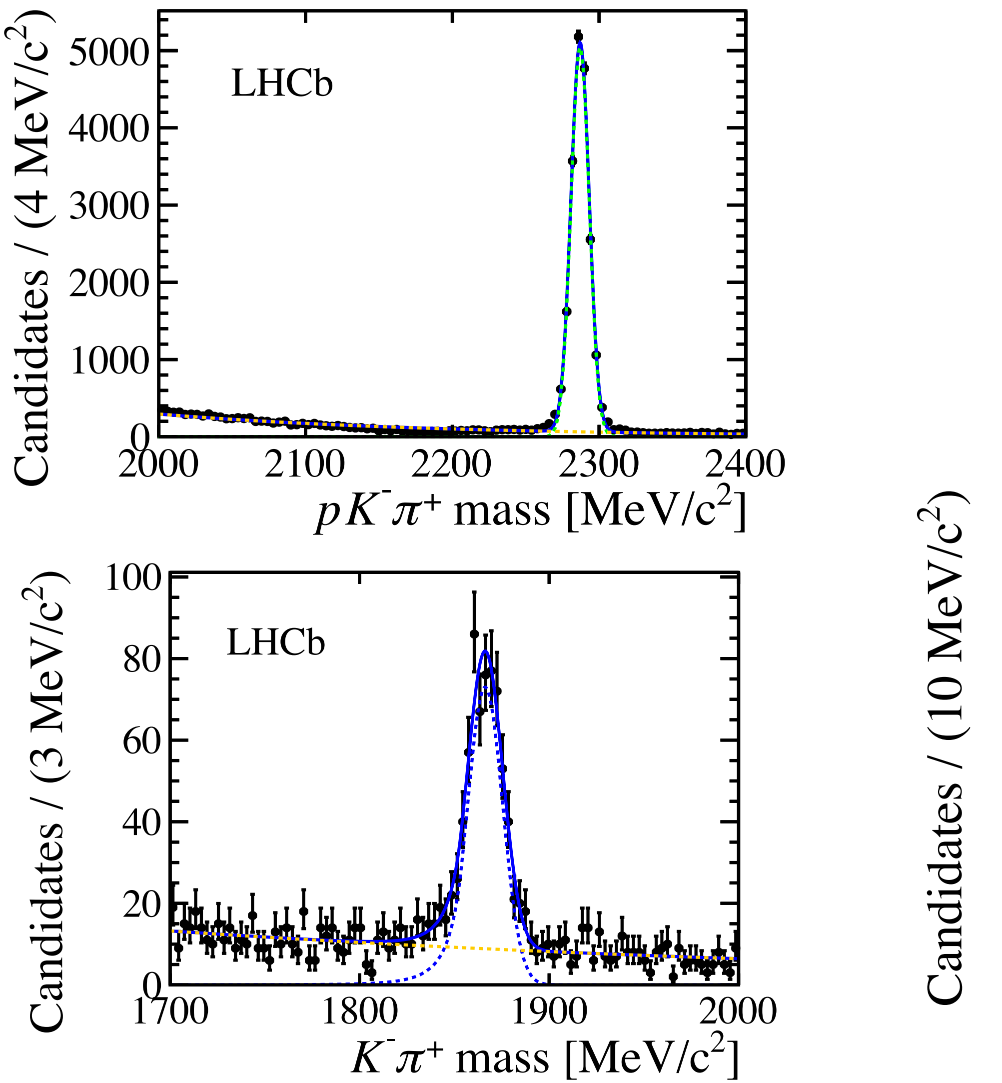
- Interference between opposite parity states needed to explain P_c decay angular distribution
- Fit projections

Large m(Kp) region negative interference



Small m(Kp) region positive interference

Experimental background studies



- After selection reconstruct additional tracks to determine background yields