LHCb Physics

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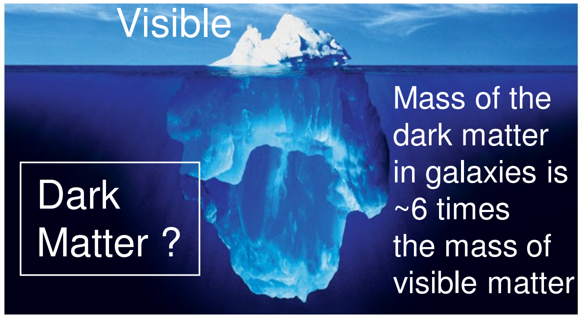
About this talk

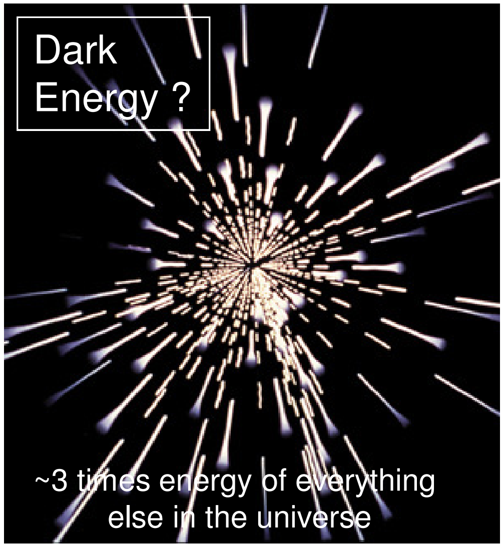
- General introduction to the LHCb experiment, and its future.
- Physics program of LHCb is too broad to try to be complete today.
- Can't even discuss all use cases of amplitude analyses, and range of amplitude formalisms used.
- Pick a few topics which fit together. Many biased by personal contributions to LHCb.
- Do not go deeply into discussion of the results or experimental details; concentrate on the approaches in the amplitude parameterizations illustrating material covered in the lecture today morning.

Evidence for Beyond Standard Model physics



Dark Matter ?

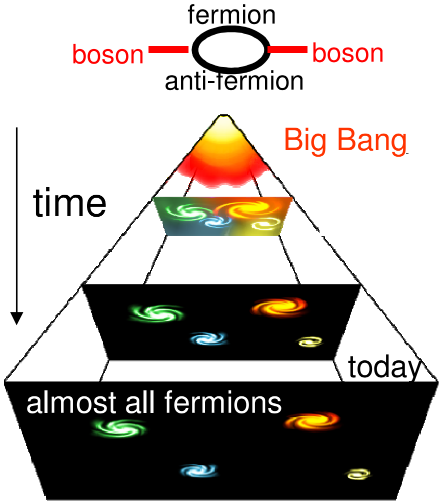
Mass of the dark matter in galaxies is ~6 times the mass of visible matter



Dark Energy ?

~3 times energy of everything else in the universe

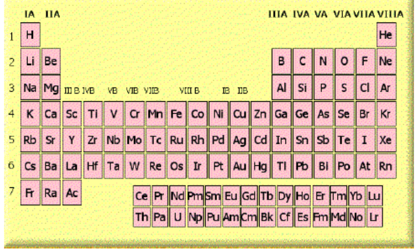
Baryogensis ?



Hierarchy problem ?
$M_H << M_{Planck}$

GUT?
How does gravity fits in?

end of 19th centaury → atoms, QED



	IA	IIA	III B	IVB	VB	VIB	VIIB	VIII B			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg											Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	Ac															
					Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
					Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

mid 20th centaury → quarks, QCD

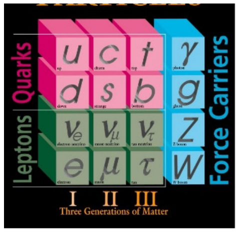
	Q= -1	*Q*= 0	*Q*=+1
S=+1		K^0	K^+
S= 0	π^+	π^0 ,η	π^+
S= -1	K^+	K^0	

	Q= -1	*Q*= 0	*Q*=+1
S= 0		n	p
S= -1	Σ^-	Σ^0 ,Λ	Σ^+
S= -2	Ξ^+	Ξ^0	

	Q=-1	*Q*= 0	*Q*=+1	*Q*=+2
S= 0	Δ^-	Δ^0	Δ^+	Δ^{++}
S= -1	Σ^{*-}	Σ^{*0}	Σ^{*+}	
S= -2	Ξ^{*-}	Ξ^{*0}		
S= -3	Ω^-			

Generation problem ?

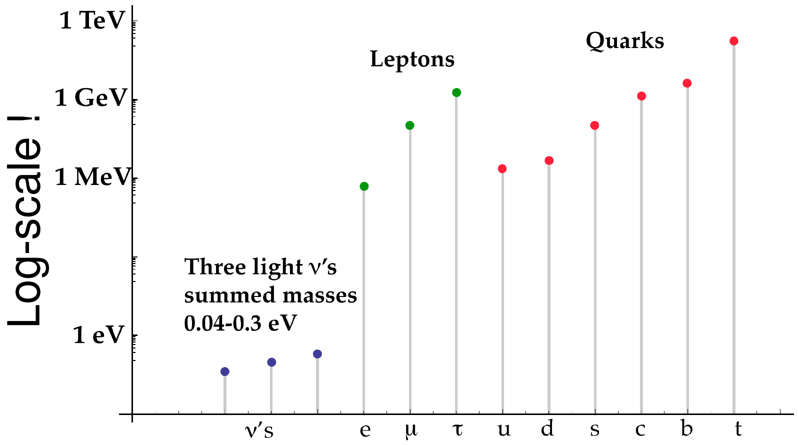
now → ?



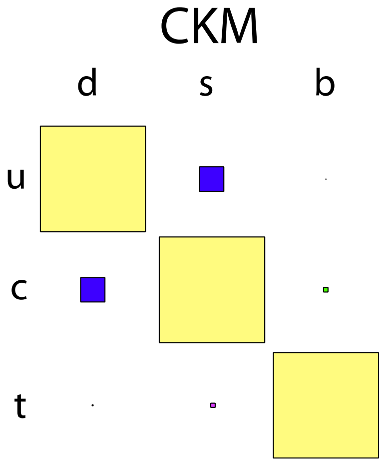
- Unknown particles and forces exist, likely hiding at higher energy scales

Evidence for Beyond Standard Model physics

Origin of hierarchy in masses and mixing of fermions?

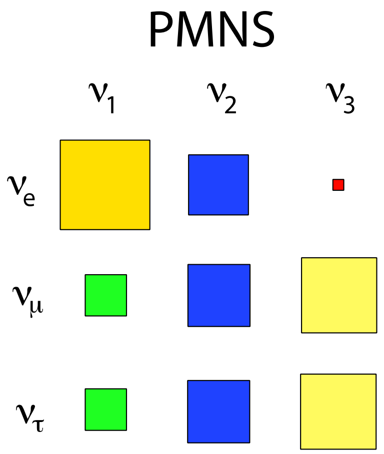


12 orders of magnitude differences not explained; t quark as heavy as Tungsten



Cabibbo-
Kobyashi-
Maskawa- quark
mixing matrix

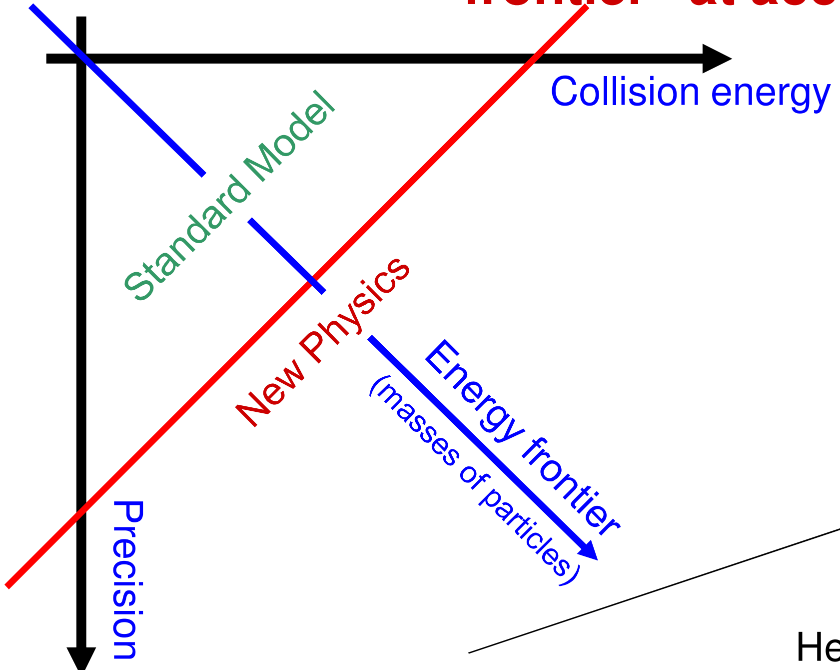
Area ~V^2



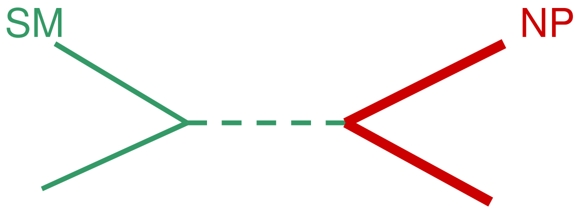
Pontecorvo–
Maki–
Nakagawa–
Sakata neutrino
mixing matrix

Why these values? Are the two related? Are they related to masses?

Two complementary ways of advancing “energy frontier” at accelerator-based experiments



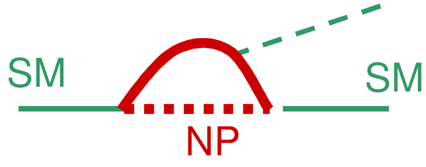
Tree diagrams, for example



Want high CM energy to exceed
the production threshold

(CDF, D0)
ATLAS, CMS

Loop diagrams, for example

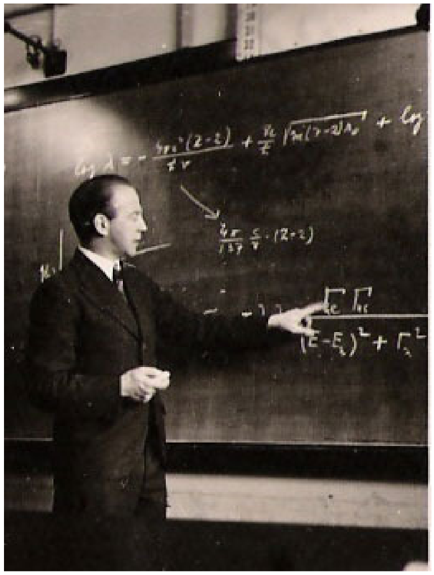


Want high precision since NP particles are highly virtual here, thus probabilities small

Heisenberg’s
uncertainty
principle:

$$\Delta E \, \Delta t = \hbar/2$$

i.e. $\Delta m \, \Delta t = \hbar/2$

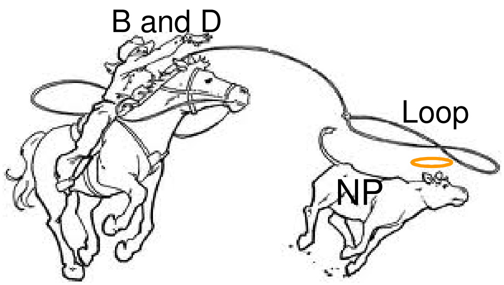


Belle II (BaBar)
LHCb

Rare kaon decays and “g-2” discussed by Andrzej Kupsc also belong to this category

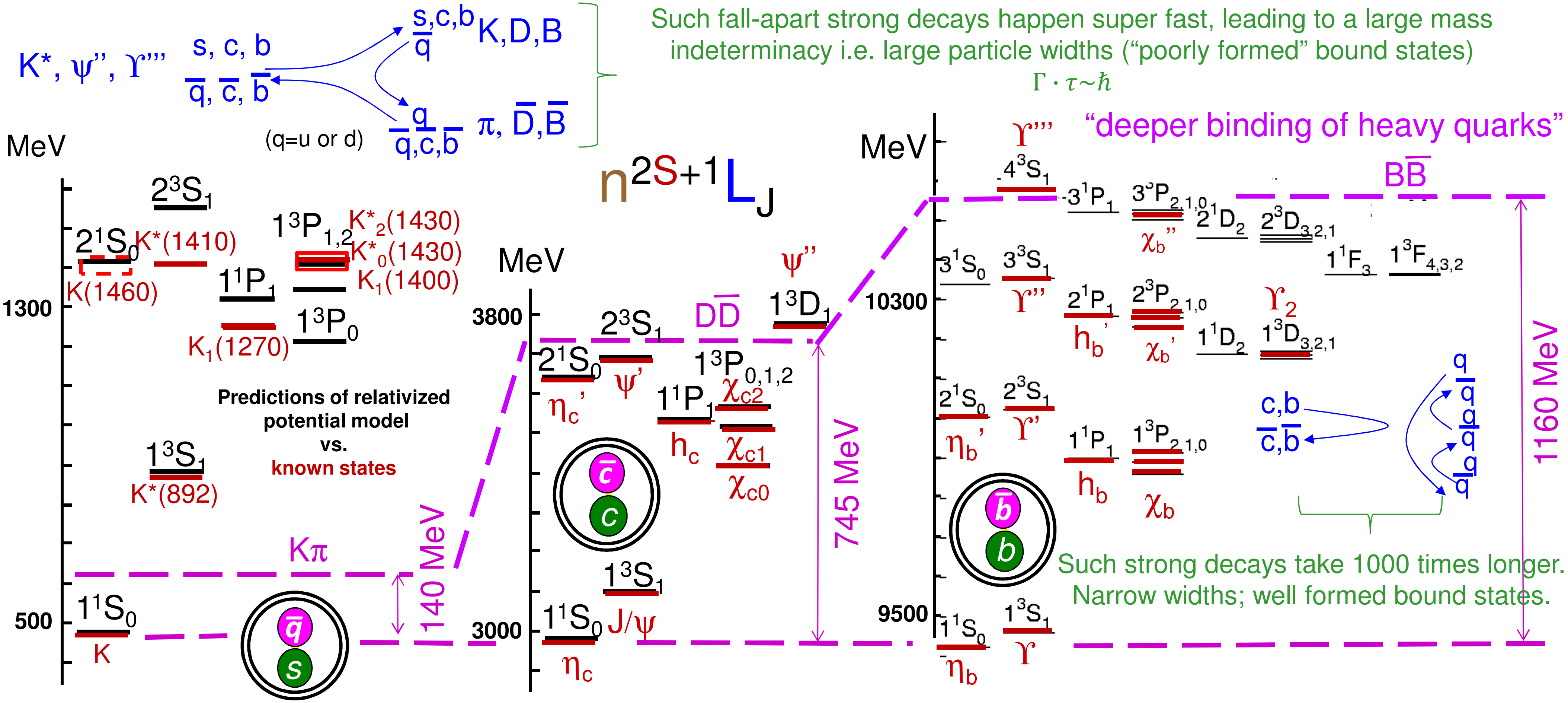
LHCb Physics Program

Main physics goal of LHCb:



- A lot of secondary physics goals of LHCb:
  - Hadron spectroscopy with heavy quarks (see the next slide)
  - Light hadron spectroscopy
  - Rare kaon decays
  - W,Z^0 production at forward angles and proton structure functions
  - Heavy-ion collisions
  - …

Heavy flavors and hadron spectroscopy:



Such fall-apart strong decays happen super fast, leading to a large mass indeterminacy i.e. large particle widths ("poorly formed" bound states)

$\Gamma \cdot \tau \sim \hbar$

"deeper binding of heavy quarks"

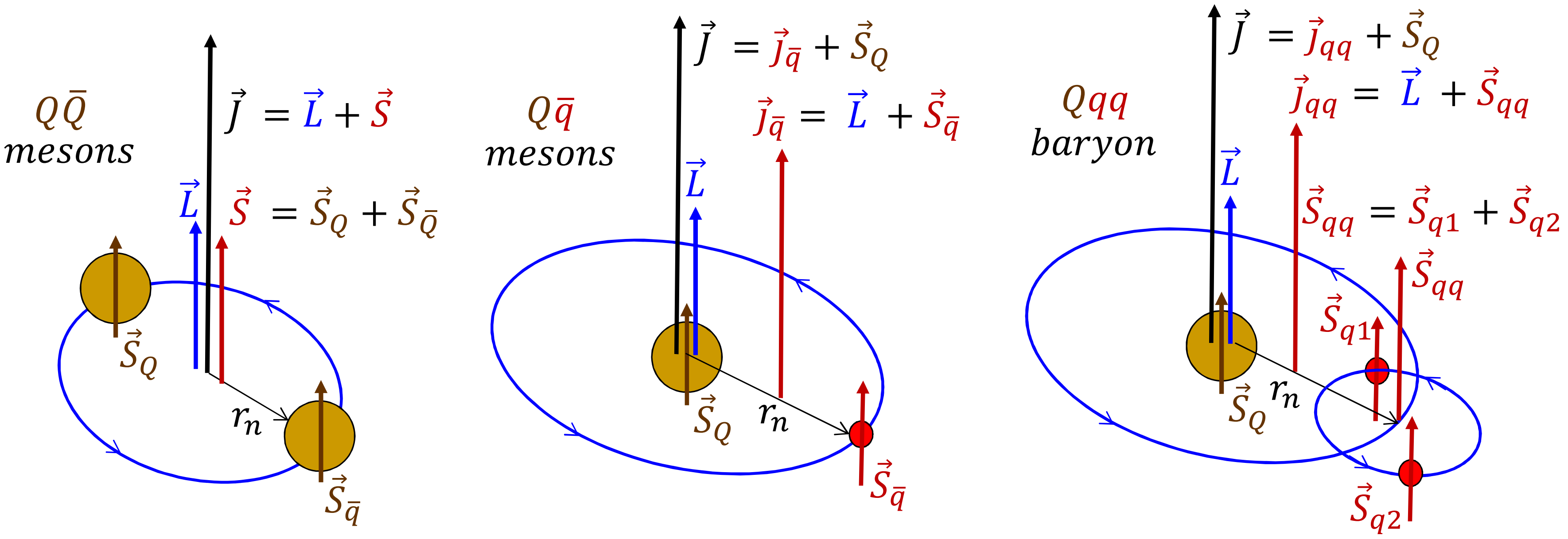
Predictions of relativized potential model vs. known states

Such strong decays take 1000 times longer. Narrow widths; well formed bound states.

All excitations above the open flavor threshold.
Wide (short-lived) and highly relativistic (light quarks).
Only qualitative spectroscopy.

Plenty of excitations below the open flavor threshold.
Narrow (long-lived) and non-relativistic (heavy quarks).
Quantitative spectroscopy.

Heavy quark hadrons in LHCb



$Q\bar{Q}$ *mesons*

$\vec{J} = \vec{L} + \vec{S}$

$\vec{S} = \vec{S}_Q + \vec{S}_{\bar{Q}}$

$Q\bar{q}$ *mesons*

$\vec{J} = \vec{j}_{\bar{q}} + \vec{S}_Q$

$\vec{j}_{\bar{q}} = \vec{L} + \vec{S}_{\bar{q}}$

Qqq *baryon*

$\vec{J} = \vec{j}_{qq} + \vec{S}_Q$

$\vec{j}_{qq} = \vec{L} + \vec{S}_{qq}$

$\vec{S}_{qq} = \vec{S}_{q1} + \vec{S}_{q2}$

Expect to detect
QQq
baryons soon

In usual diaquark model: S_{qq}=0,1

n_{qq} =1 $\vec{L}_{qq}$=0

Scalar and axial-vector diquarks

- Well established spectroscopy of conventional hadrons with heavy quarks creates suitable environment for studies of exotic hadrons:

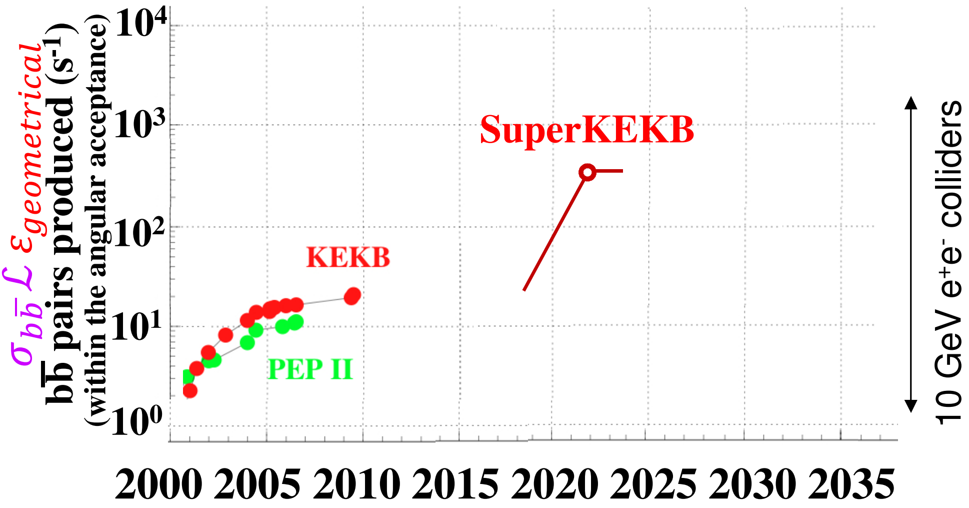
$Q\bar{Q}q\bar{q}$

tetraquarks or
meson − meson
molecules

$Q\bar{Q}qqq$

pentaquarks or
baryon − meson
molecules

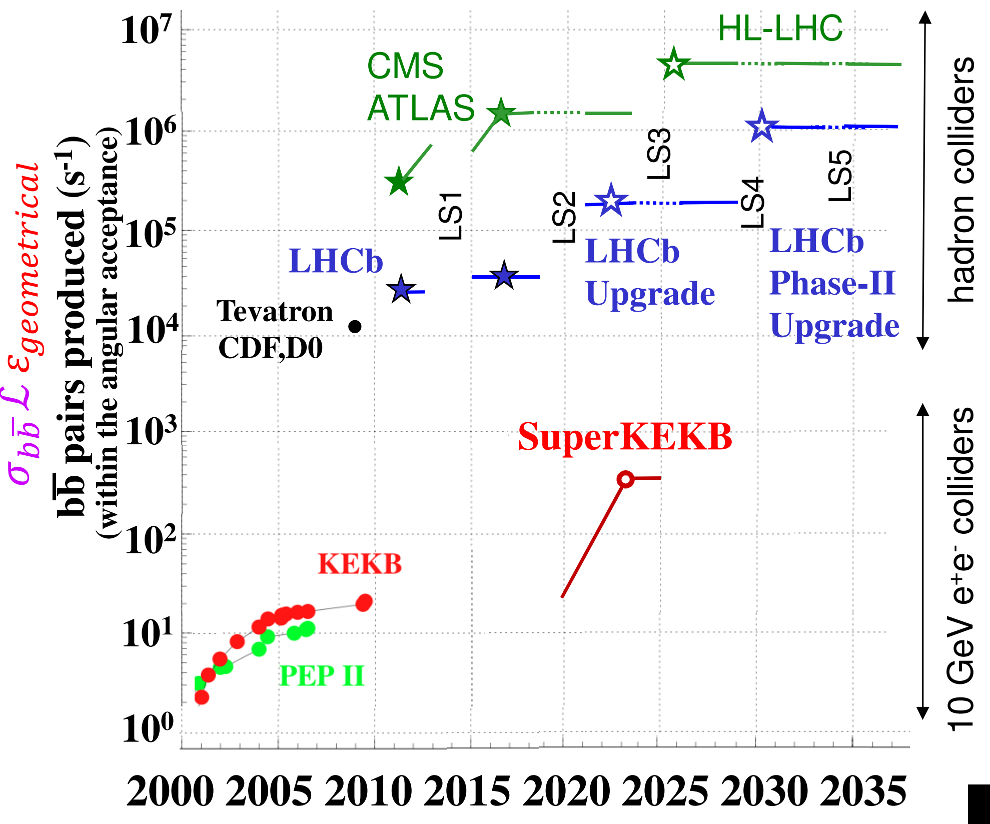
Colliders and $b\bar{b}$ rates



- The past decade was a golden age of 10 GeV e^+e^- b-factories

- Super KEK B-factory, with Belle II experiment, is under construction in Japan, with a luminosity upgrade by almost 2 orders of magnitude

Colliders and $b\bar{b}$ rates

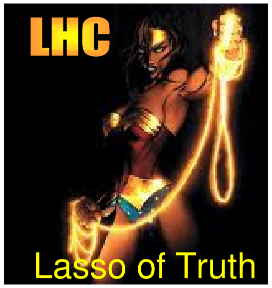


$$\int \mathcal{L}\, dt$$

CDF 10 fb^{-1} , D0 8 fb^{-1}

	Run I	Run II	Run III	Run IV	Run V+VI
LHCb	3 fb^{-1}	5 fb^{-1}	50 fb^{-1}		300 fb^{-1}
ATLAS,CMS	25 fb^{-1}	450 fb^{-1}		3000 fb^{-1}	

- Tremendous rate potential at hadron colliders
  - **physics reach determined by the detector capabilities not by the machine**
- Collect all b-hadron species at the same time:
  - **additional gain by a factor of ~10-100 in integrated B_s rates at hadronic colliders**
  - **time dependent CPV studies of B_s possible**
  - **also get Λ_b, B_c which are out of reach of the 10 GeV e$^+$e$^-$ factories**
- Charm rates factor of 10 higher than beauty rates:
  - **nuisance and great physics opportunity at the same time**



detected events N = produced events $\sigma_{b\bar{b}} \int \mathcal{L}\, dt$ x detector efficiency ε

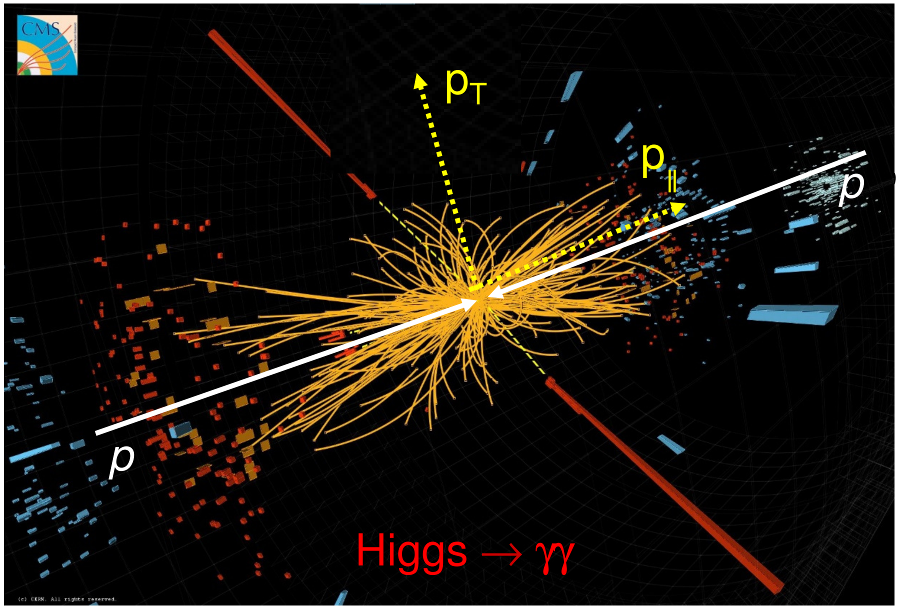
large

$\varepsilon = \varepsilon_{geometrical} \cdot \varepsilon_{trigger} \cdot \varepsilon_{rest}$

major challenge for b,c physics at hadron colliders

Hadron colliders

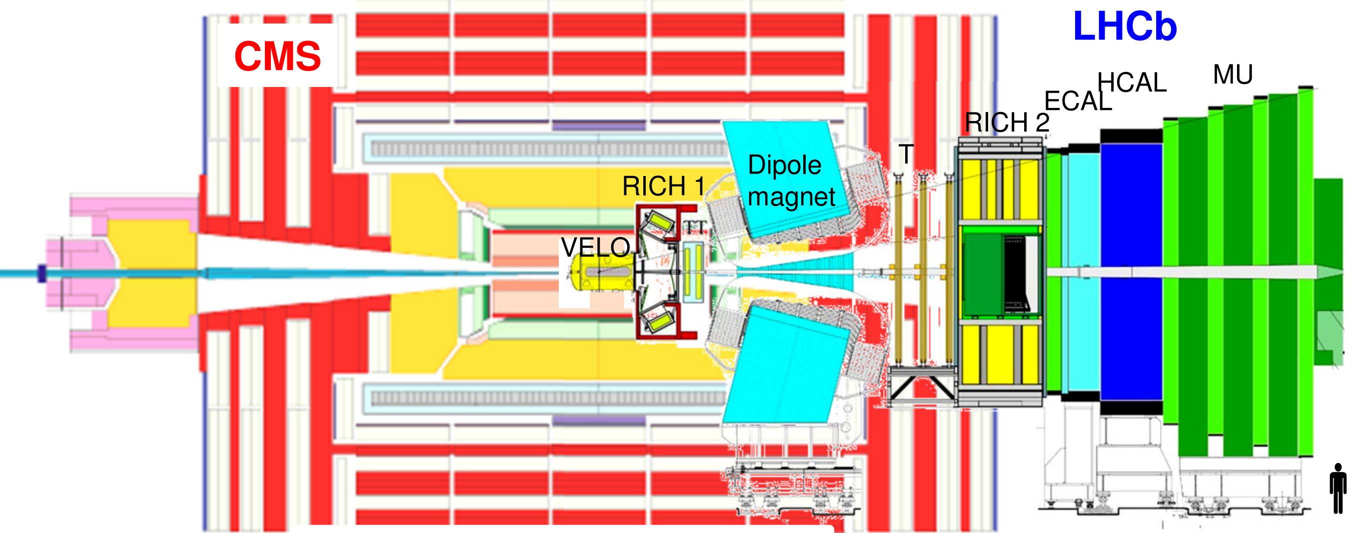
p_T of decay products ~ mass of decaying particle

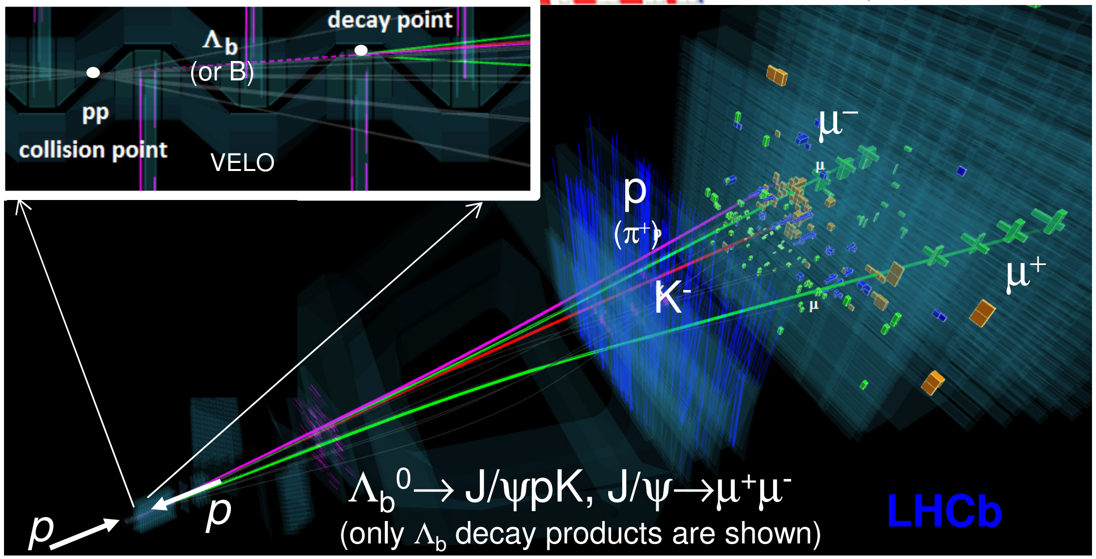


CDF, D0, ATLAS and CMS were optimized to “high-p_T physics” – searches for the heaviest on-mass-shell particles [m(Higgs)~126 GeV].

Taking advantage of enormous rates of b,c-hadrons requires a detector optimized to “intermediate-p_T” particles [m(B)~5 GeV, m(D)~2 GeV].

LHCb vs central detectors





$\Lambda_b^0 \rightarrow J/\psi pK$, $J/\psi \rightarrow \mu^+\mu^-$
(only Λ_b decay products are shown)

Trigger on muons or decay points detached from pp collision point

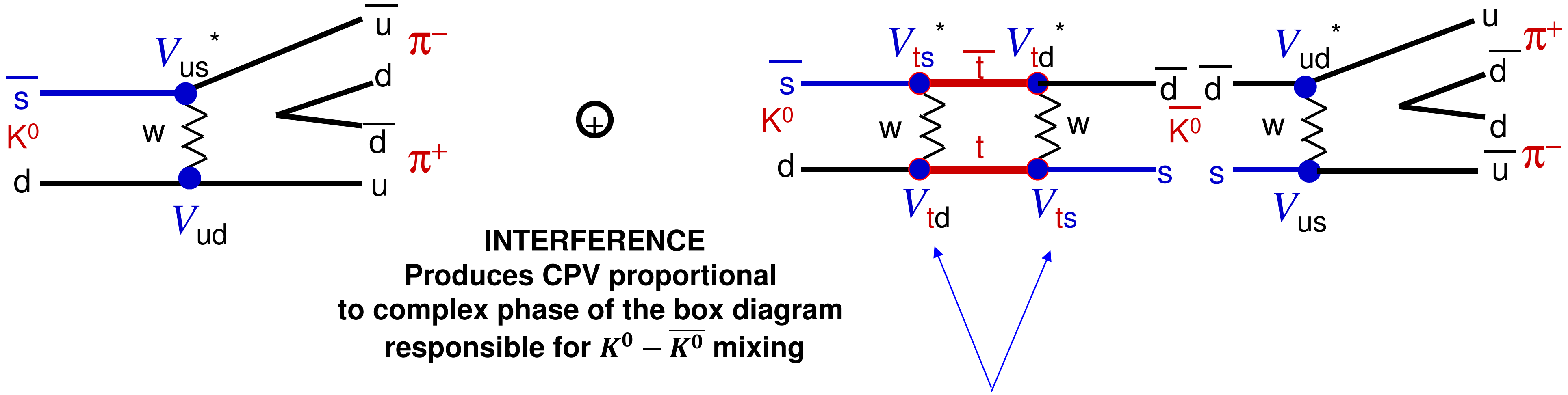
- Advantages of LHCb (forward spectrometer):
  - comparable b cross-section in much smaller solid angle; smaller number of electronic channels; smaller event size; much larger trigger bandwidth to tape (Run I ~5 kHz, Run II ~12 kHz)
  - b and c physics dominate the trigger bandwidth (e.g. CMS b-trigger rate ~25 Hz; almost 3 orders of magnitude less than LHCb)
  - large p for small p_T (in central region p~p_T); can identify muons to lower p_T values
  - large bandwidth important for triggering on purely hadronic final states (central detectors limited to dimuon trigger)
  - large bandwidth important for collecting very large charm samples
  - space for RICH detectors: p/K/π separation; crucial for background suppression in many channels; increased flavor tagging
- Limitation of present LHCb detector:
  - luminosity limited by the detector readout capabilities (upgrades of the detector will allow increasing the luminosity)
  - compared to Belle: poor γ (i.e. π^0) and K_s detection (will be improved in Phase II upgrade)

LHCb collaboration

- The collaboration is of “modest” size:
  - 940 Physicists (~ $\frac{1}{10}$ of all at CERN)
  - 70 Institutes (~ $\frac{1}{10}$ in US)
  - 16 Countries

Loops as low energy windows to high energy physics

- An early example how decays of low mass particle can reveal physics at much higher mass scale was 1964 discovery of CP violation in K^0 decays ($m(K^0)$=0.5 GeV) which offered the first glimpse of the top-quark existence ($m(t)$=172 GeV, observed on-mass shell in 1995):



INTERFERENCE
Produces CPV proportional
to complex phase of the box diagram
responsible for $K^0 - \overline{K^0}$ mixing

Quark-mixing elements $V_{qq'}$ in q→ q'W can be complex,
only if more than two quark generations

Kobayashi-Maskawa hypotheses (1972)

Quark flavor transitions – CKM matrix

- Described by CKM matrix in SM
- A complex phase in 3-generation matrix gives a rise to CPV in SM
- Wolfenstein's parameterization depicts the measured structure of CKM well

λ=0.226±0.001 (sinθ$_C$)

A=0.81±0.02

ρ,η see next

Good to λ^3~1%

$$\begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & V=\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}+\delta V \end{array}$$

$$\delta V=\begin{pmatrix} 0 & 0 & 0 \\ -iA^2\lambda^5\eta & 0 & 0 \\ A\lambda^5(\rho+i\eta)/2 & -A\lambda^4(1/2-\rho-i\eta) & 0 \end{pmatrix}$$

Complex phase η

mostly in V_{td}, V_{ub} (λ^3)

then a bit in V_{ts} (λ^4)

even less in V_{cd} (λ^5)

$\lambda^0=1$

$\lambda^1=0.23$

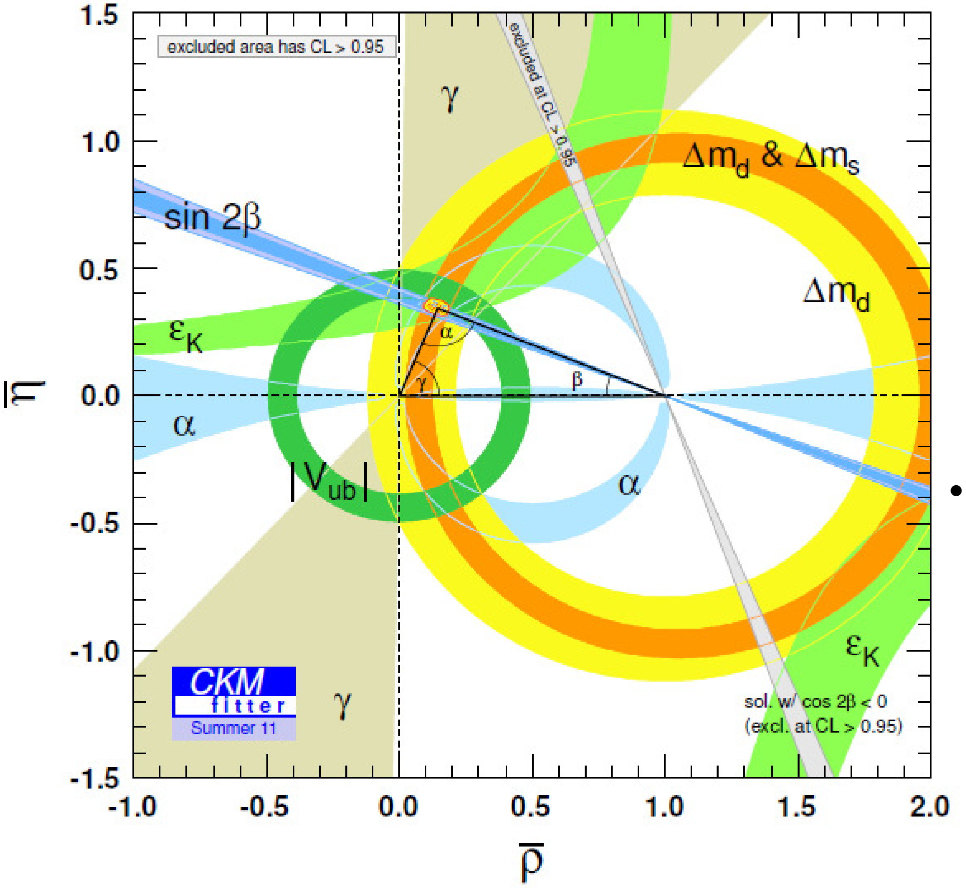
$\lambda^2=0.051$

$\lambda^3=0.012$

$\lambda^4=0.0026$

$\lambda^5=0.0006$

Quark flavor transitions – unitarity triangle



- After a decade of e^+e^- B-factory experiments the KM hypothesis is well verified

Kobayashi & Maskawa
Nobel Prize 2008

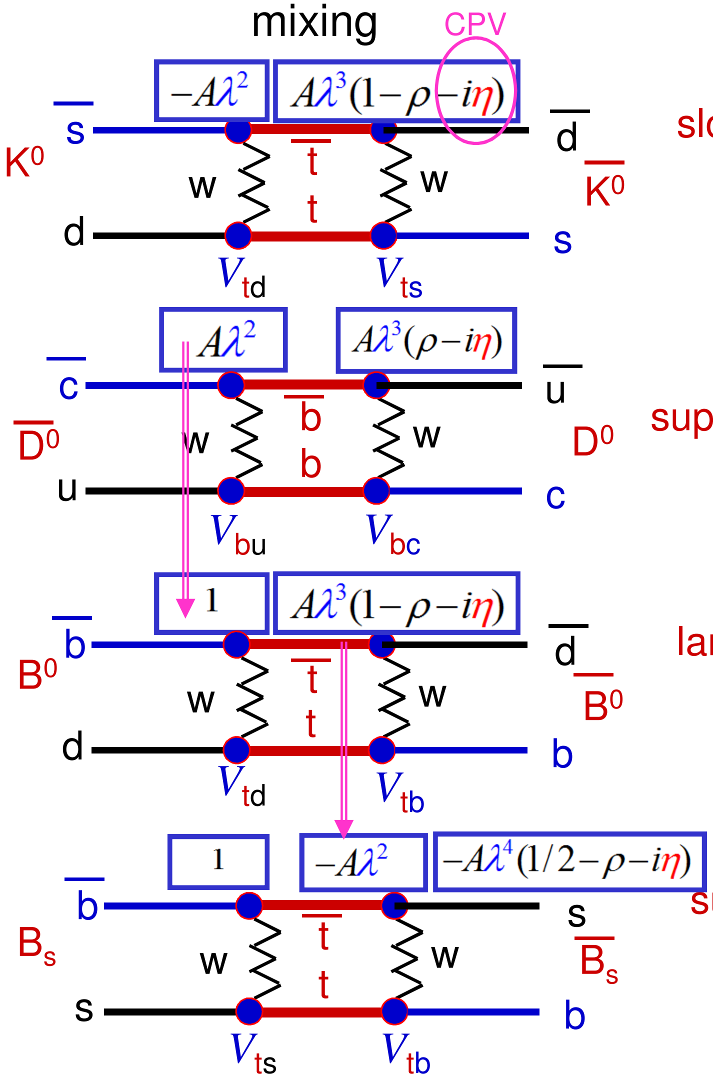
- The game now is looking for NP in corrections to CKM picture

Note: $\bar{\rho} = \rho(1-\lambda^2/2)$
$\bar{\eta} = \eta(1-\lambda^2/2)$

Trees: γ, V_{ub}
Loops: everything else

Importance of B_s physics: example indirect CPV

mixing



slow mixing, small CPV

CPV discovery
KM hypothesis

super slow mixing, very small CPV

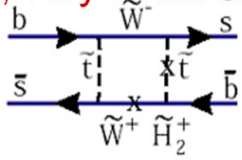
long distance diagrams can come into play
good place to look for non-SM CPV, but SM "background" not well predicted

large mixing, large CPV

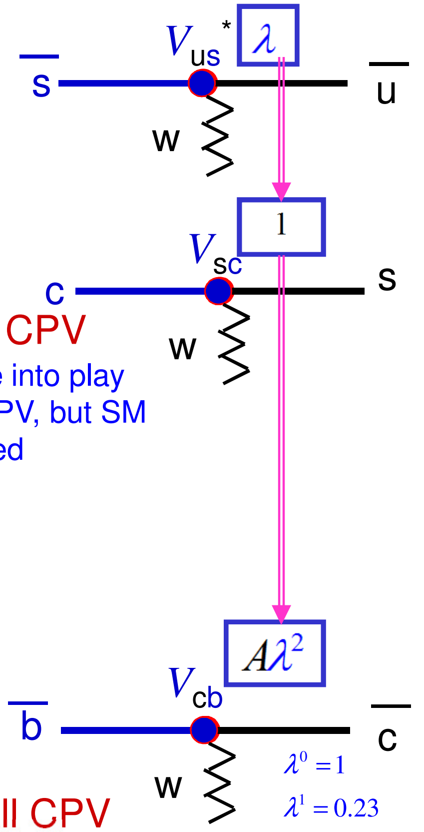
good place
to test SM CPV

super fast mixing, very small CPV

good place
to look for
non-SM CPV

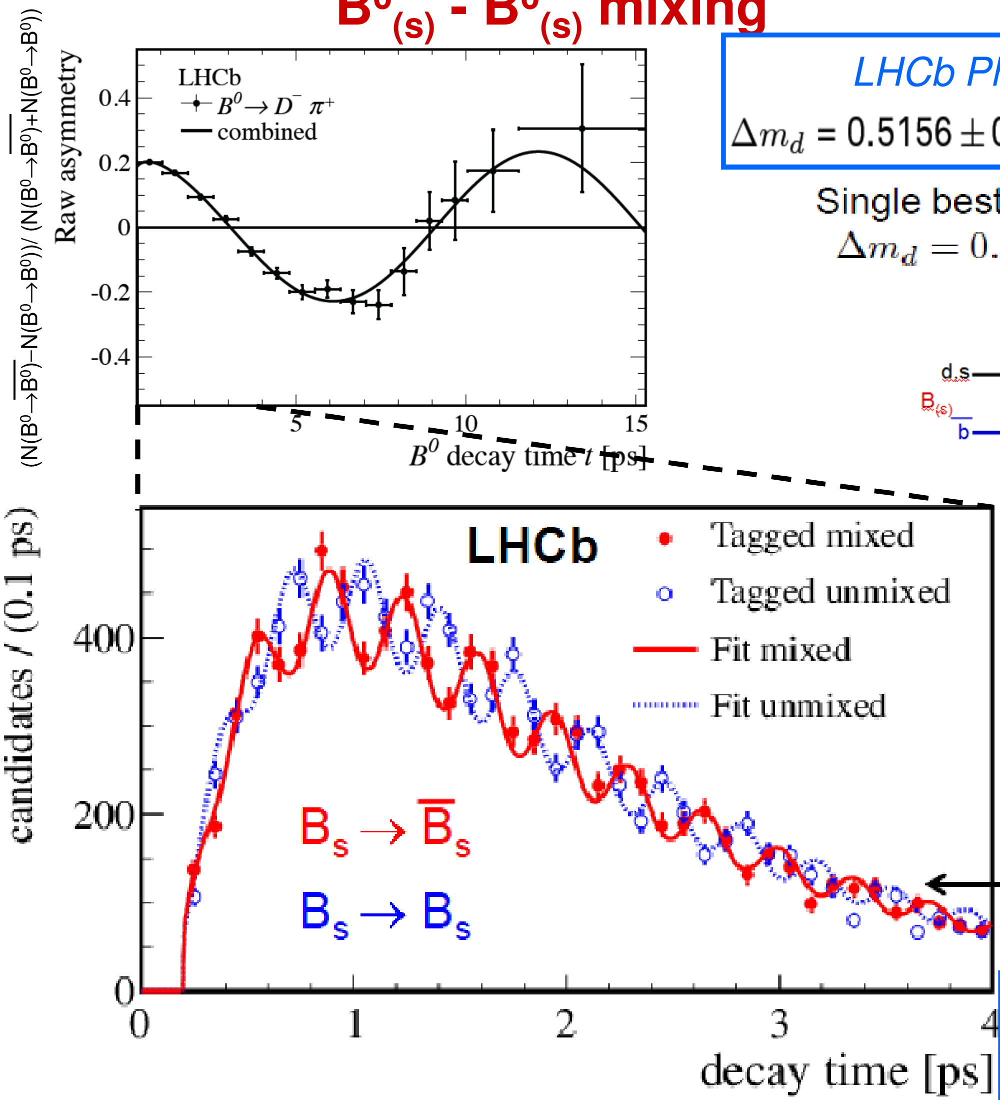


dominant decay (lifetime)



$\lambda^0 = 1$
$\lambda^1 = 0.23$
$\lambda^2 = 0.051$
$\lambda^3 = 0.012$
$\lambda^4 = 0.0026$
$\lambda^5 = 0.0006$

$B^0_{(s)}$ - $\overline{B^0}_{(s)}$ mixing



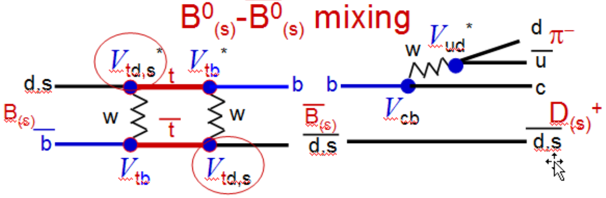
LHCb Phys.Lett. B719, 318 (2013)

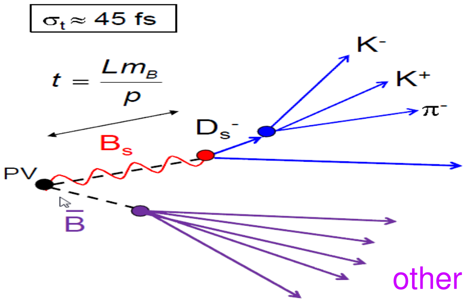
Δm_d = 0.5156 ± 0.0051 (stat) ± 0.0033 (syst) ps^{-1}

Single best measurement by BELLE

$$\Delta m_d = 0.511 \pm 0.005 \pm 0.006\,\text{ps}^{-1}$$

$B^0_{(s)}$-$\overline{B^0}_{(s)}$ mixing





charge of π tags the b flavor at decay

other B tags the b flavor at birth

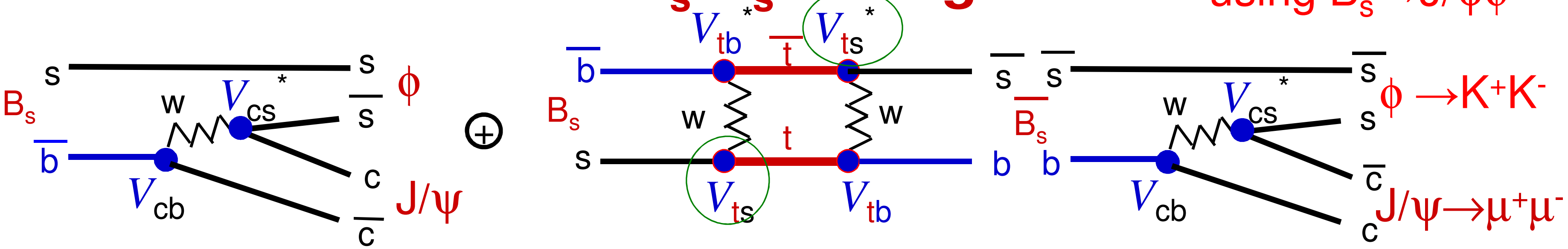
Decay time modulation ~cos($\Delta m_s t$)

New J. Phys. 15 (2013) 053021

Δm_s = 17.768± 0.023 ± 0.006 ps^{-1}

Phase of B_s-$\overline{B}_s$ mixing

using $B_s \rightarrow J/\psi\phi$



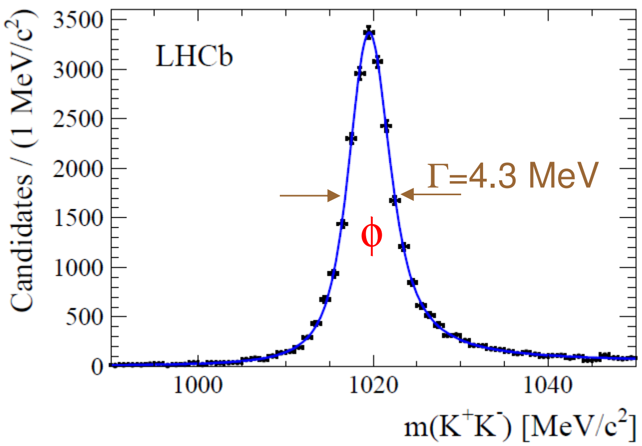
Interference of mixing and decay produces **indirect CPV.**

No SM phase in the lowest order. Small V_{ts} phase suppressed by λ^2:

LHCb
PRD 87, 112010 (2013)
PRL 114, 041801 (2015)
arXiv:1704.08217 (2017)

$$\varphi_s^{SM} = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \sim -2^{o}$$

[$-36.5^{+1.3}_{-1.2}$ mrad PRD91,073007 (2015)]



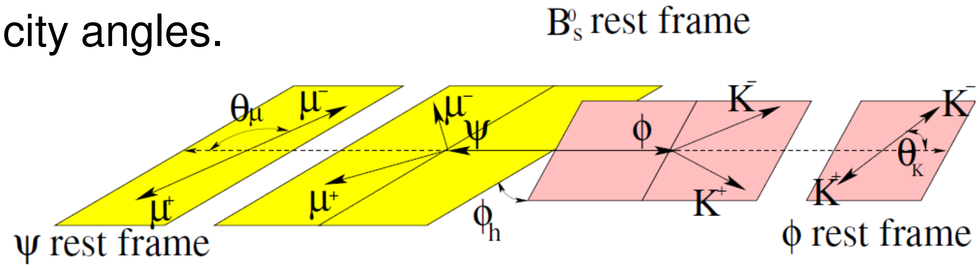
Need **time dependent analysis** to extract φ_s from the data because of the $\boldsymbol{B_s - \overline{B_s}}$ mixing

$J/\psi\phi$ is a mixture of CP-odd and CP-even states, which have different φ_s dependence; need **angular analysis** to disentangle them

$\phi \rightarrow K^+K^-$ (P-wave decay) is a very narrow and prominent resonance in $B_s \rightarrow J/\psi\, K^+K^-$, however, there is a small admixture of non-resonant K^+K^- S-wave under it. Allow both contributions.

Determination of φ_s from $B_s\to J/\psi\phi$

Use helicity angles.



$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\ d\Omega} \propto \sum_{k=1}^{10} h_k(t)\ f_k(\cos\theta_K, \cos\theta_\mu, \varphi_h)$$

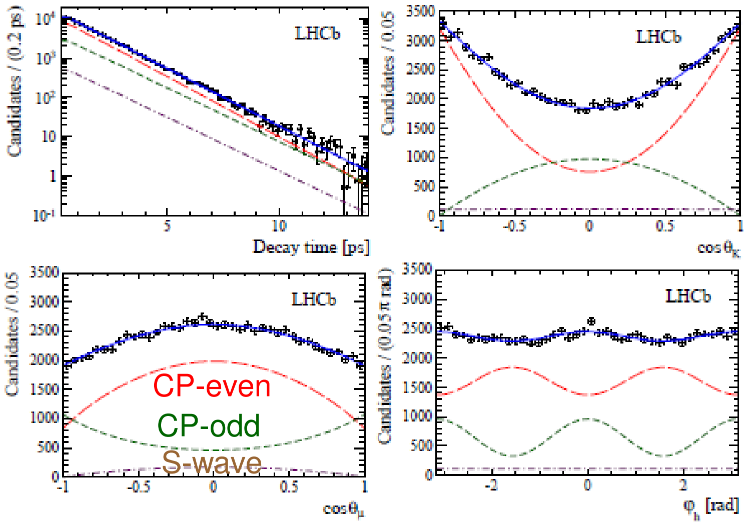
$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right],$$

k	$f_k(\theta_\mu, \theta_K, \varphi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K\ \sin^2\theta_\mu$	$\lvert A_0\rvert^2$	1	D	C	$-S$
2	$\sin^2\theta_K\ (1-\sin^2\theta_\mu\ \cos^2\varphi_h)$	$\lvert A_\parallel\rvert^2$	1	D	C	$-S$
3	$\sin^2\theta_K\ (1-\sin^2\theta_\mu\ \sin^2\varphi_h)$	$\lvert A_\perp\rvert^2$	1	$-D$	C	S
4	$\sin^2\theta_K\ \sin^2\theta_\mu\ \sin 2\varphi_h$	$\lvert A_\parallel A_\perp\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{2}\sqrt{2}\sin 2\theta_K\ \sin 2\theta_\mu\ \cos\varphi_h$	$\lvert A_0A_\parallel\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$-\frac{1}{2}\sqrt{2}\sin 2\theta_K\ \sin 2\theta_\mu\ \sin\varphi_h$	$\lvert A_0A_\perp\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}\sin^2\theta_\mu$	$\lvert A_S\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\theta_K\ \sin 2\theta_\mu\ \cos\varphi_h$	$\lvert A_SA_\parallel\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$-\frac{1}{3}\sqrt{6}\sin\theta_K\ \sin 2\theta_\mu\ \sin\varphi_h$	$\lvert A_SA_\perp\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\theta_K\ \sin^2\theta_\mu$	$\lvert A_SA_0\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

$$C \equiv \frac{1-|\lambda|^2}{1+|\lambda|^2}, \qquad S \equiv -\frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2}, \qquad D \equiv -\frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2}.$$

LHCb PRD 87, 112010 (2013)

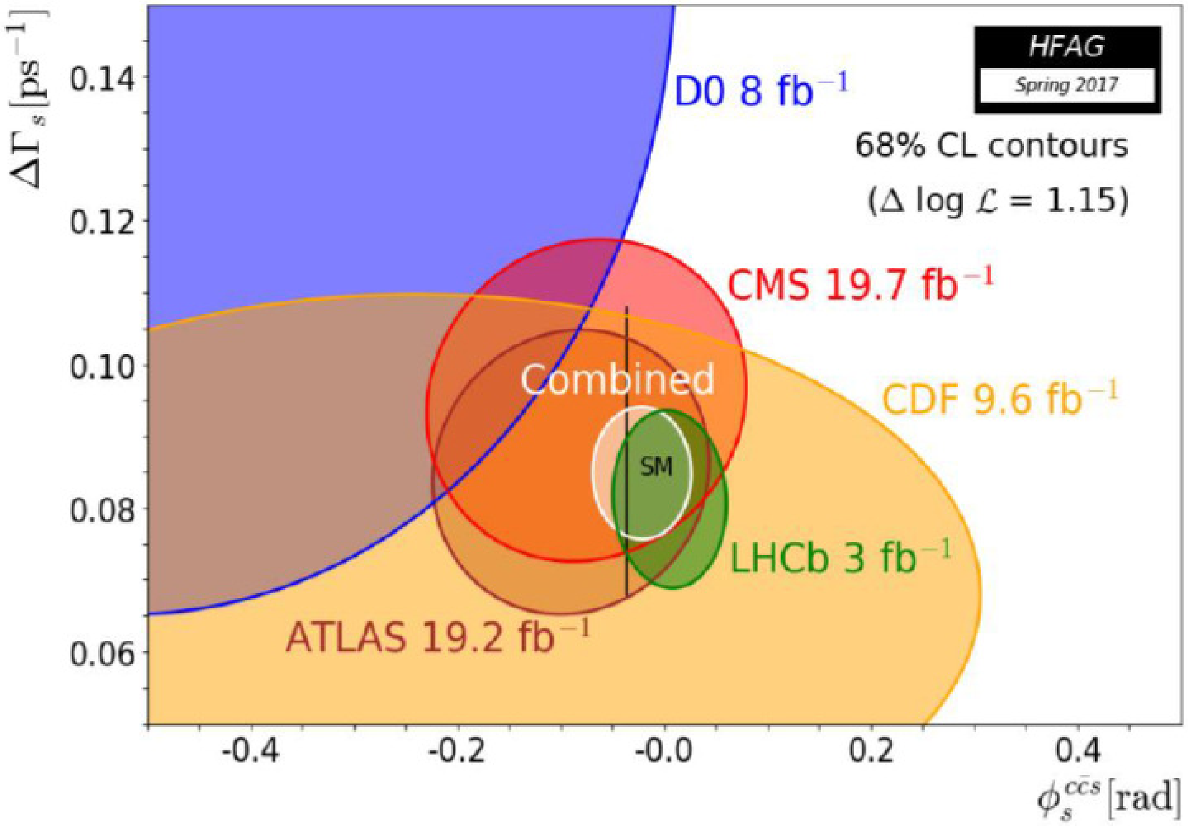
Fit in the narrow $s=m_{KK}^2$ range around m_ϕ^2



A_0, $A_\perp$, $A_\parallel$ (A_S) related to helicity couplings $H_{\lambda_\psi}^{B_s\to\psi\phi}$, λ_ψ= -1,0,+1 ($H_{\lambda_\psi=0}^{B_s\to\psi[KK]_{S-wave}}$) affected by the strong interactions, thus to be determined from the data (nuisance parameters).

See also LHCb PRL 114, 041801 (2015)

Status of of φ_s determination



T. Gershon at Moriond EW

The LHCb results shown here include the results from other B_s decay, however, they are dominated by $B_s \to J/\psi\phi$

The LHCb has the best sensitivity in spite of the smaller integrated luminosity.

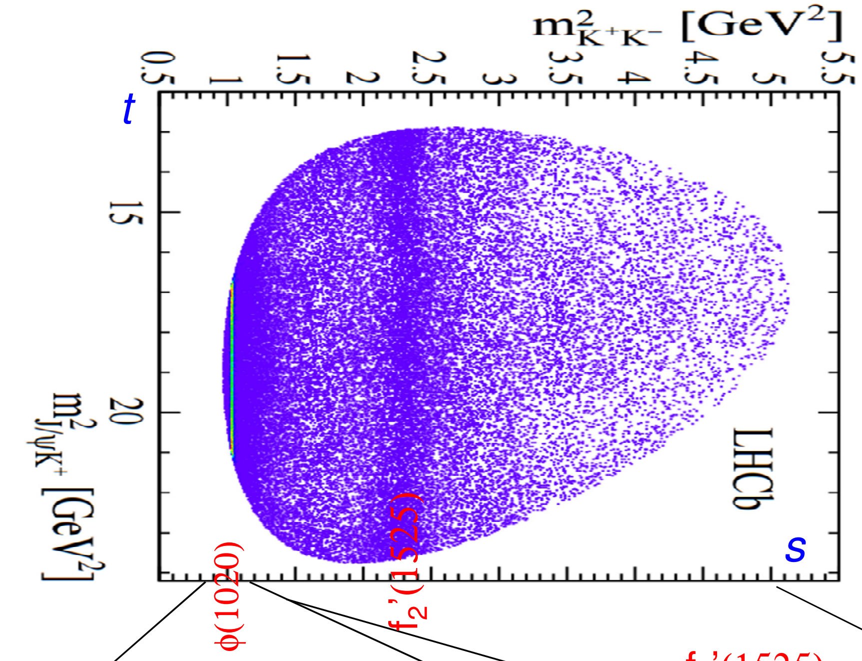
The results are consistent with the SM predictions – no sign of NP.

The experimental error much larger than the theoretical uncertainty on the SM value, and dominated by the statistical error.
Increased data statistics will reach to higher NP energy scales (LHCb upgrades!)

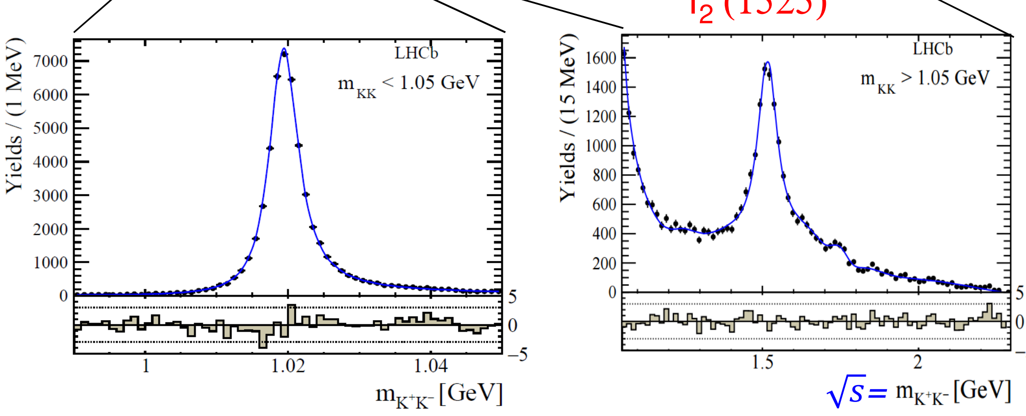
- Many other sensitive probes for NP in weak decays of b and c quarks.
- Move on to the results on exotic hadrons for the rest of my talk.

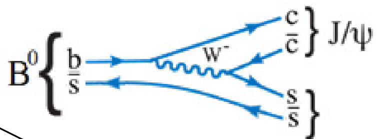
Other hadronic structures in $B_s \to J/\psi\ K^+K^-$

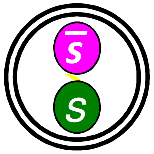
LHCb arXiv:1704.08217 (2017)



No evidence for horizontal bands, thus no sign of exotic $J/\psi K^+$ resonances

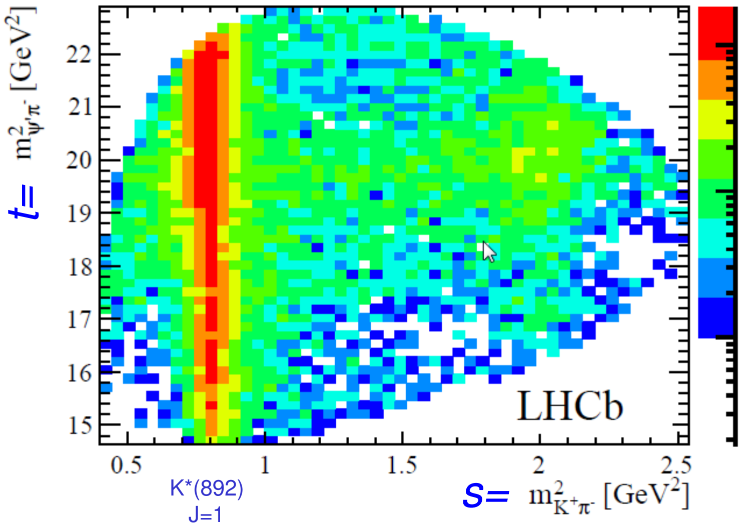


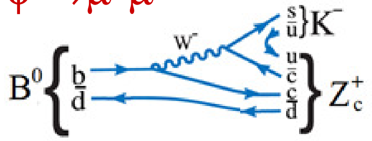




Component	Fit fraction (%)
$\phi(1020)$	$70.5 \pm 0.6 \pm 1.2$
$f_2(1270)$	$1.6 \pm 0.3 \pm 0.2$
$f_2'(1525)$	$10.7 \pm 0.7 \pm 0.9$
$\phi(1680)$	$4.0 \pm 0.3 \pm 0.3$
$f_2(1750)$	$0.59\,^{+0.23}_{-0.16} \pm 0.21$
$f_2(1950)$	$0.44\,^{+0.15}_{-0.10} \pm 0.14$
S-wave	$10.69 \pm 0.12 \pm 0.57$

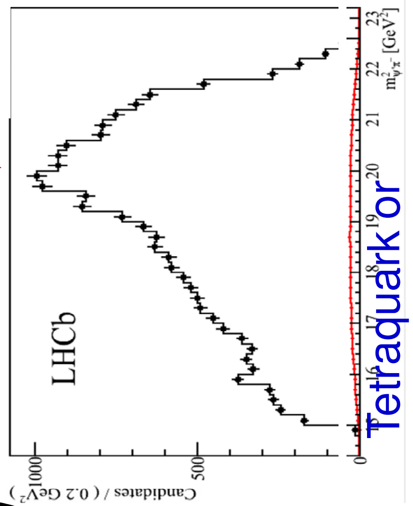
$B^0 \to \psi'\pi^+K^-$ $\psi' \to \mu^+\mu^-$





$Z_c\,(4430)^+$
$\to \psi'\pi^+$
?

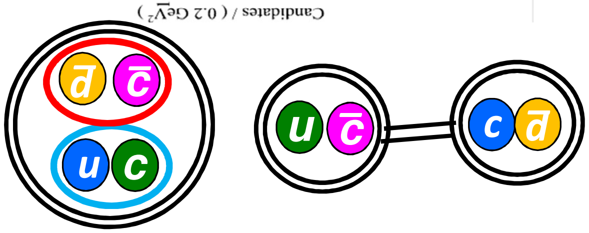
Broad horizontal band



Tetraquark or meson-meson molecule

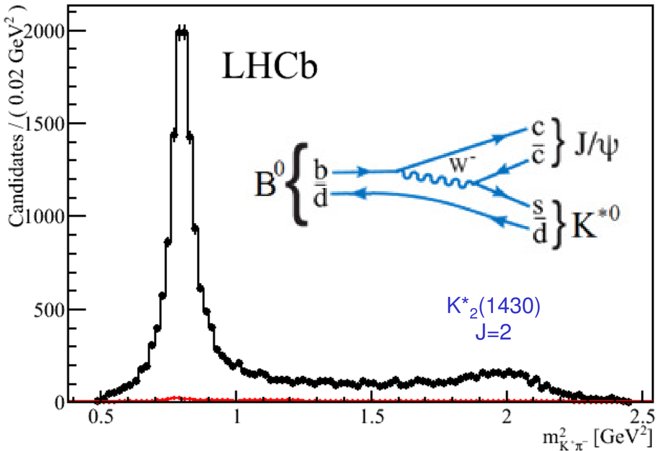
Claimed by Belle (the first $J/\psi\pi^+$ state):
PRL 100, 142001 (2008)
PRD 80, 031104 (2009)
PRD 88, 074026 (2013)
PRD 90, 112009 (2014)

Not seen by BaBar:
PRD 79, 112001 (2009)

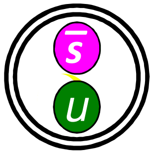


Is it a reflection of interfering K^*'s $\to \pi^+K^-$?

Proper amplitude analysis necessary to check

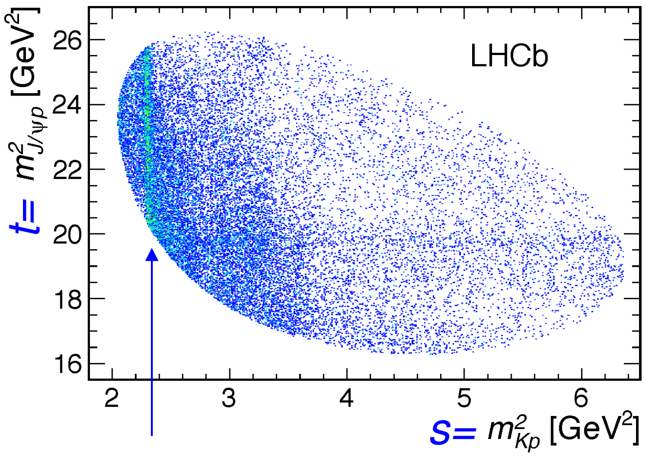


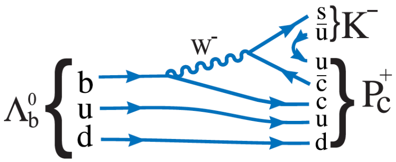
Kaon excitations



LHCb has more than a factor of 10 larger data sample (3 fb^{-1}) than either Belle or BaBar and has smaller backgrounds
PRL 112, 222002 (2014)

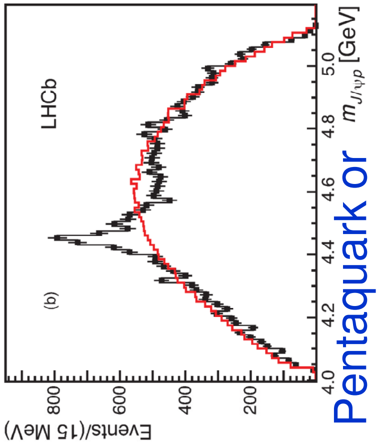
$\Lambda_b^0 \rightarrow J/\psi p K^-$: unexpected narrow structure in $m_{J/\psi p}$





$P_c^+ \rightarrow J/\psi$ p
?

Narrow horizontal band

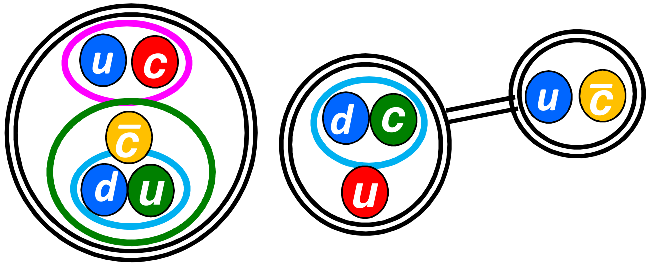


Pentaquark or baryon-meson molecule

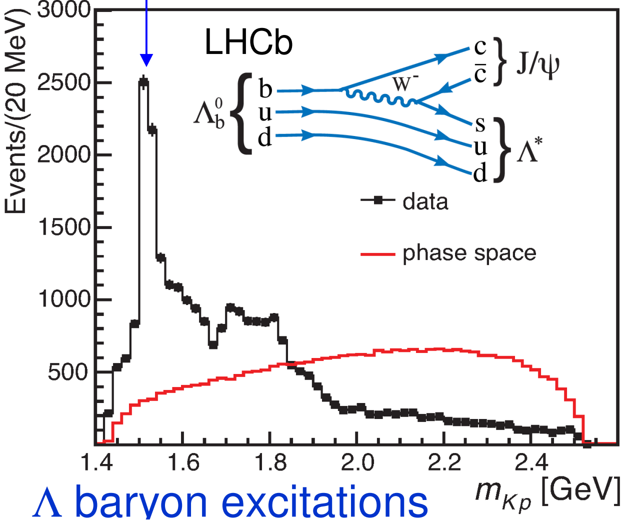
LHCb PRL 115, 07201 (2015)
Similar statistics (26k events) and background level (~5%) as $B^0 \rightarrow \psi' \pi^+ K^-$

See also Nathan Jurik, PhD Syracuse, Aug 2016 CERN-THESIS-2016-086

$\Lambda(1520)$ and other Λ^*'s → p K^-

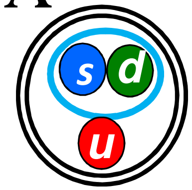


Is it a reflection of interfering Λ^*'s → p K^- ?



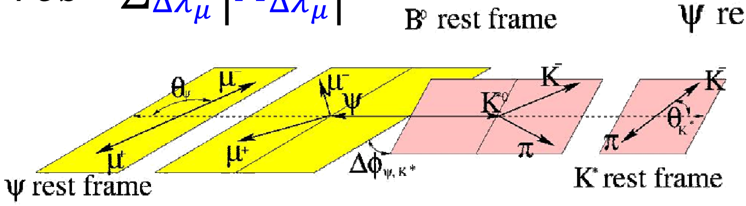
Λ baryon excitations

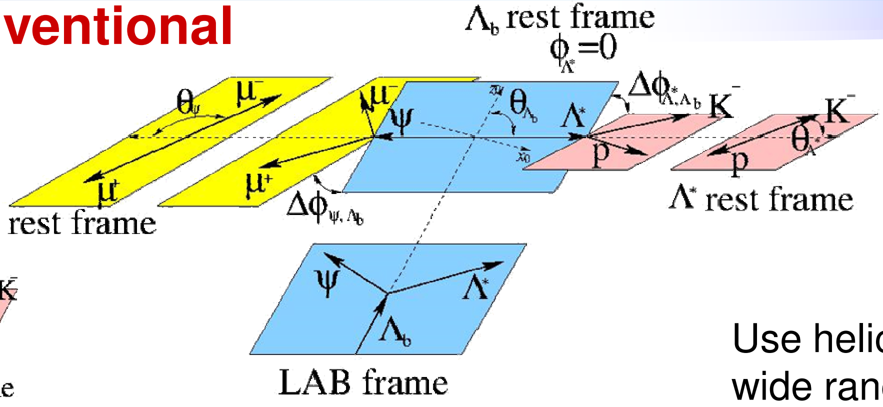
Λ^*



Matrix element for conventional resonances

$$Prob \sim \sum_{\Delta\lambda_\mu} \left| M^{K^*}_{\Delta\lambda_\mu} \right|^2$$





Use helicity amplitudes, now in wide range of $s=m_{K\pi}^2$ or m_{Kp}^2.

4D maximum likelihood fit

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

$$M^{K^*}_{\Delta\lambda_\mu} = \sum_n \sum_{\lambda_\psi=-1,0,1} H^{B\to\psi K^*_n}_{\lambda_\psi} R(m_{K\pi}{}^2 \,|\, M_{K^*_n}, \Gamma_{K^*_n}) \times D^{J_{K^*}}_{\lambda_\psi,0}(0,\theta_{K^*},0)^* D^1_{\lambda_\psi,\Delta\lambda_\mu}(\Delta\phi_{\psi,K^*},\theta_\psi,0)^*$$

1-3 independent **complex** helicity couplings H per K* resonance

6D maximum likelihood fit

$$\Omega \equiv (\theta_{\Lambda_b}, \theta_{\Lambda^*}, \Delta\phi_{\Lambda^*,\Lambda_b}, \theta_\psi, \Delta\phi_{\psi,\Lambda_b})$$

$$M^{\Lambda^*}_{\lambda_{\Lambda_b},\lambda_p,\Delta\lambda_\mu} = \sum_n \sum_{\lambda_\Lambda} \sum_{\lambda_\psi=-1,0,1} H^{\Lambda_b\to\psi\Lambda^*_n}_{\lambda_\psi,\lambda_{\Lambda^*}} D^{\frac{1}{2}}_{\lambda_{\Lambda_b},\lambda_{\Lambda^*}-\lambda_\psi}(0,\theta_{\Lambda^*},0)^* R(m_{Kp}{}^2 \,|\, M_{\Lambda^*_n}, \Gamma_{\Lambda^*_n}) \times H^{\Lambda^*_n\to pK}_{\lambda_p} D^{J_{\Lambda^*}}_{\lambda_{\Lambda^*},\lambda_p}(\Delta\phi_{\Lambda^*,\Lambda_b},\theta_{K^*},0)^* D^1_{\lambda_\psi,\Delta\lambda_\mu}(\Delta\phi_{\psi,\Lambda_b},\theta_\psi,0)^*$$

4-6 independent **complex** helicity couplings H per Λ* resonance

Blatt-Weisskopf factors

$$\underbrace{R(s \,|\, M_n, \Gamma_{0n})}_{\text{Fixed to known values of well established K* or Λ* states}} \sim \frac{p(s)^l \, q(s)^{l'} \cdot B_l(p) B_{l'}(q)}{M_n{}^2 - s - i M_n \Gamma_n(s)}$$

Approximate the *s*-dependence via a sum of Breit-Wigner amplitudes, each with independent complex helicity couplings.

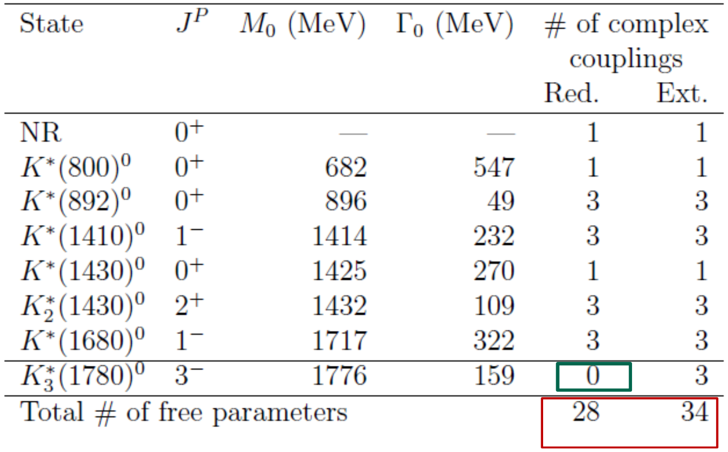
This model is commonly used but has a number of theoretical shortcomings [desired properties of transition amplitudes are the subject of this workshop!].

Model of conventional resonances

Well established states from PDG

Only natural parities in decays to Kπ

No high-M_0 high-J^P

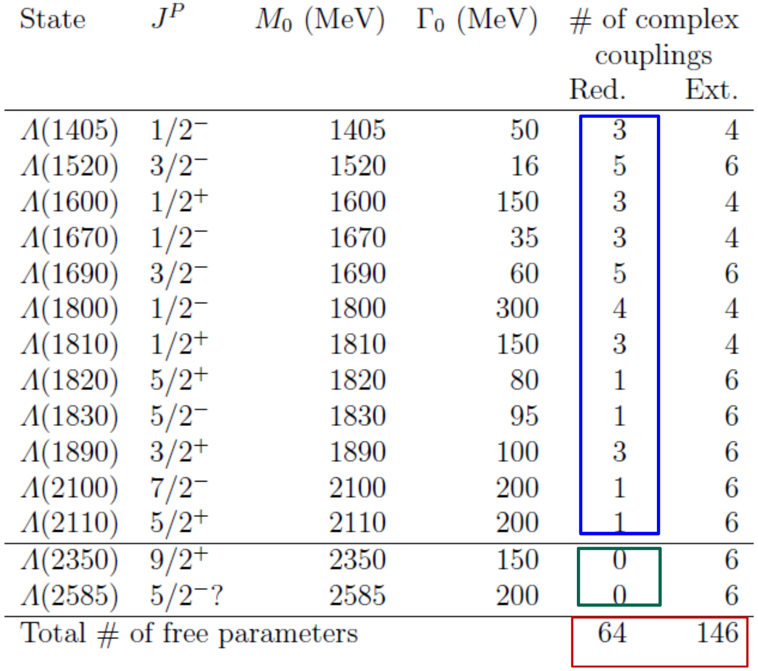


State	J^P	M_0 (MeV)	Γ_0 (MeV)	# of complex couplings Red.	Ext.
NR	0^+	—	—	1	1
$K^*(800)^0$	0^+	682	547	1	1
$K^*(892)^0$	0^+	896	49	3	3
$K^*(1410)^0$	1^-	1414	232	3	3
$K^*(1430)^0$	0^+	1425	270	1	1
$K_2^*(1430)^0$	2^+	1432	109	3	3
$K^*(1680)^0$	1^-	1717	322	3	3
$K_3^*(1780)^0$	3^-	1776	159	0	3
Total # of free parameters				28	34

No constraint on parity in decays to Kp

No high-M_0 high-J^P & limit L

All states all L

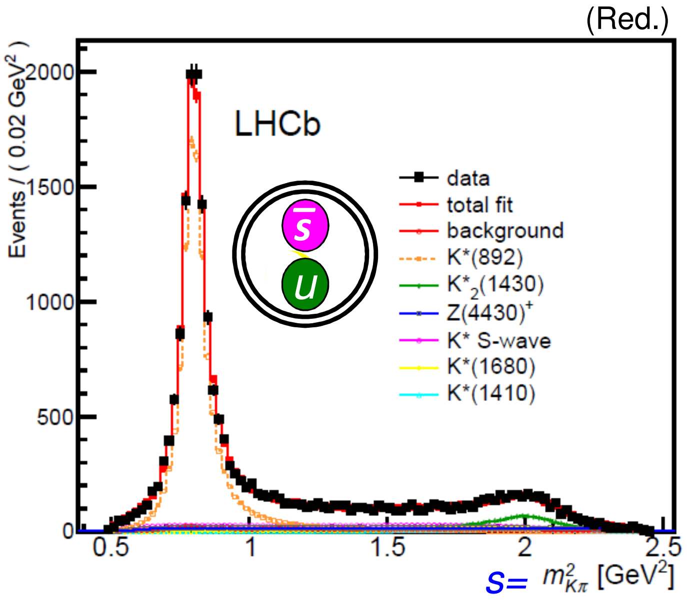


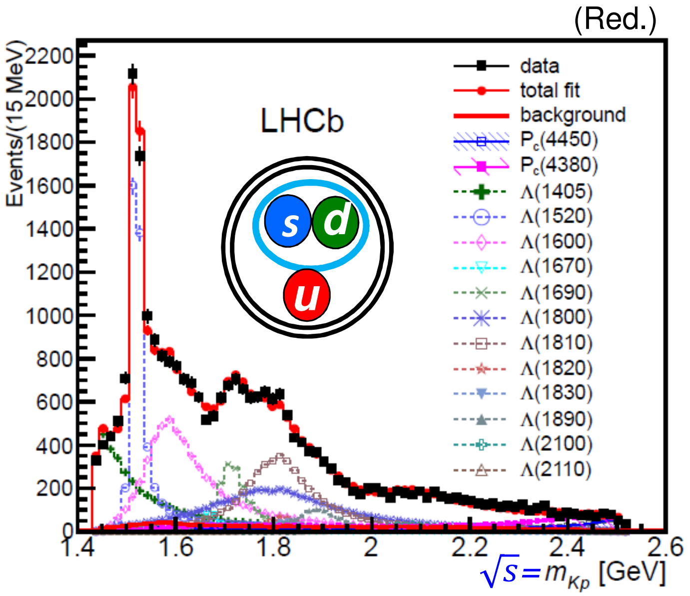
State	J^P	M_0 (MeV)	Γ_0 (MeV)	# of complex couplings Red.	Ext.
$\Lambda(1405)$	$1/2^-$	1405	50	3	4
$\Lambda(1520)$	$3/2^-$	1520	16	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	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
$\Lambda(2585)$	$5/2^-?$	2585	200	0	6
Total # of free parameters				64	146

Large number of free parameters leads to problems with CPU, fit ambiguities

- A factor 2-4 more free parameters to fit in the Λ_b analysis than in the B analysis

Mass distributions of conventional hadrons

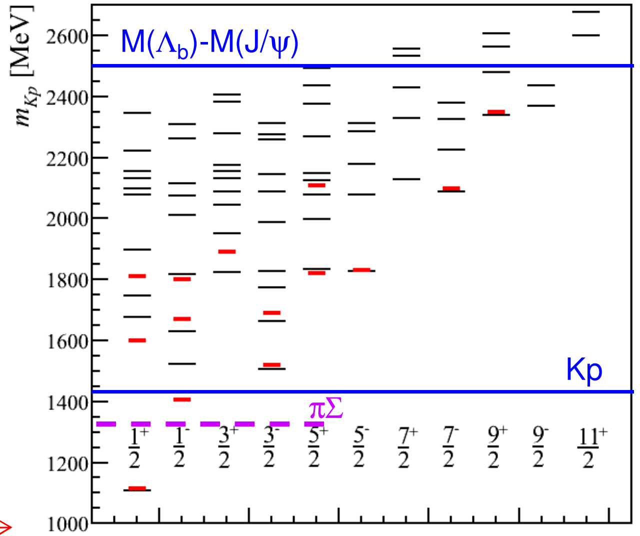




Λ* mass predictions by Loring-Metsch-Petry EPJ, A10, 447 (2001)

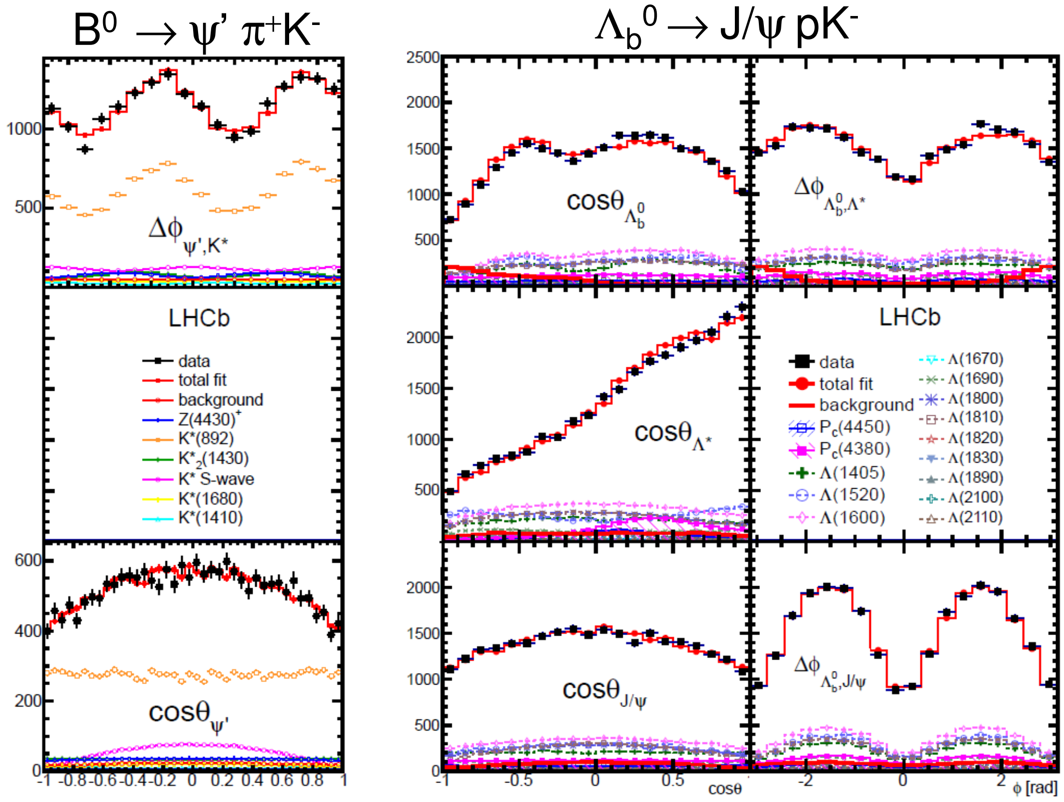
vs

Well-established Λ*s



- The models based on well established conventional resonances (without or with exotics) describe these projections well:
  - They dominate the rate
  - If exotics present (as shown above) they spread across wide range of these masses
  - A large number of free parameters in helicity couplings make up for deficiency of the model:
    - While all expected K* resonances in the fitted mass range are well established experimentally, there is a good reason to worry about missing Λ* resonances →

Fitting decay angles important for resolving overlapping resonances

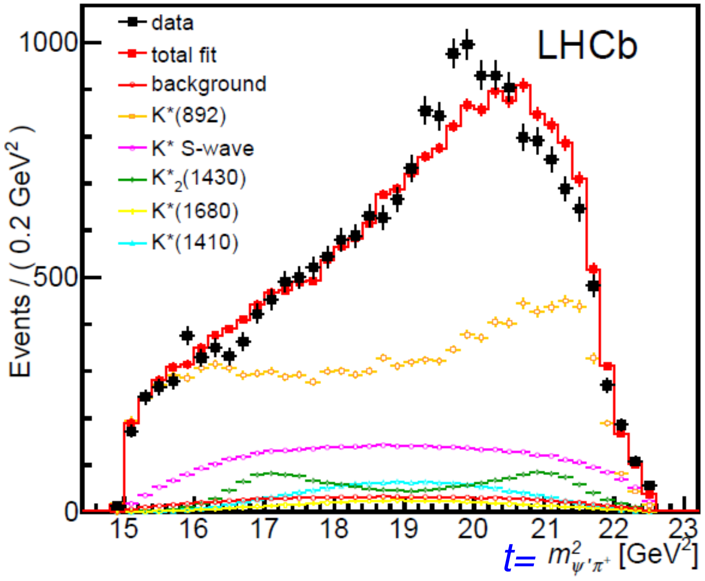


(Notice that if exotics are present, it is not possible to extract partial waves for conventional hadrons without a global fit to the data, which includes both conventional and exotic contributions)

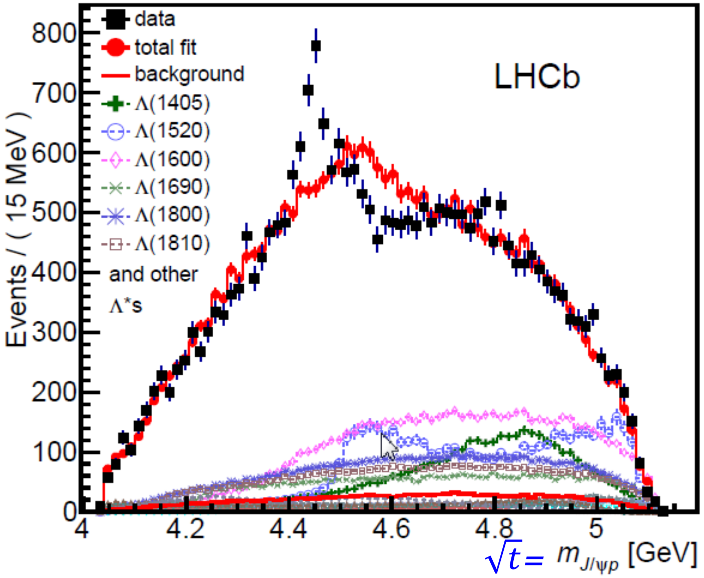
- They greatly increase discrimination power between resonances of different J^P
- Without using full decay phase-space difficult to do efficiency correction correctly

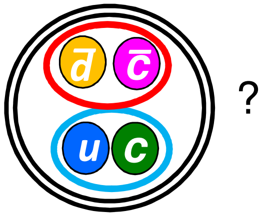
Mass distributions sensitive to exotic hadrons

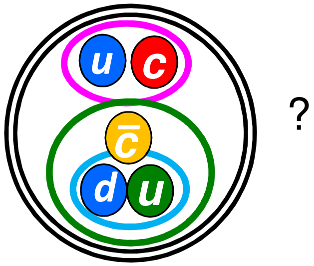
$B^0 \rightarrow \psi' \pi^+ K^-$



$\Lambda_b^0 \rightarrow J/\psi\, pK^-$ (Ext.)

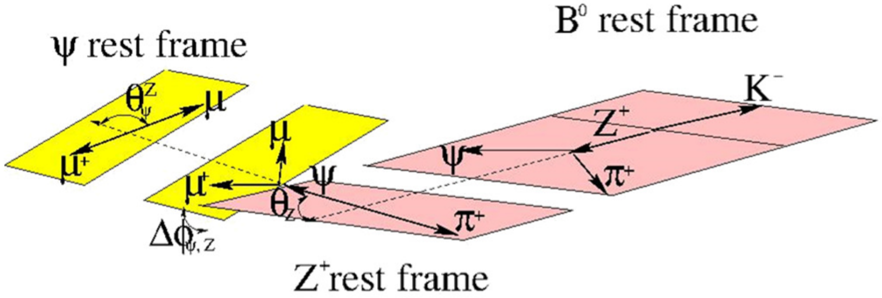


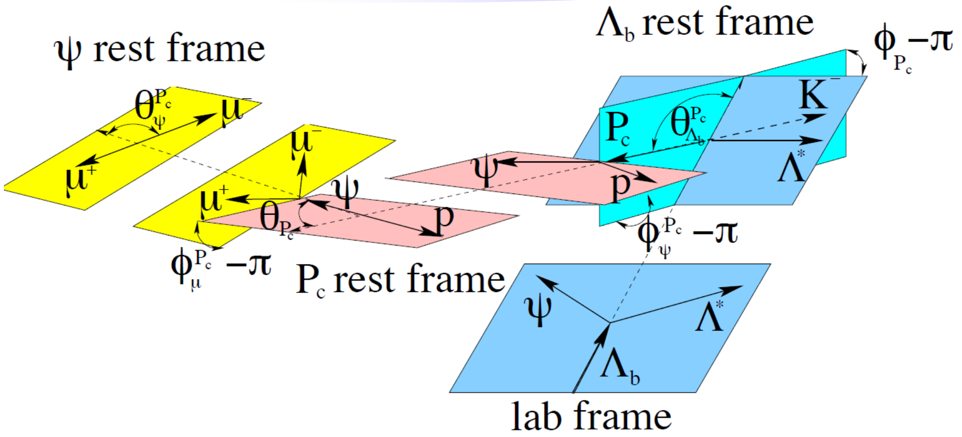




- We cannot describe $m_{\psi'\pi}$ or $m_{J/\psi p}$ distributions with the conventional resonances alone

Matrix element for exotic resonances





$$M^Z_{\Delta\lambda_\mu} = \sum_{\lambda_\psi=-1,0,1} H^{Z\to\psi\pi}_{\lambda_\psi} R(m_{\psi\pi} \,|\, M_Z, \Gamma_Z)$$
$$\times D^{J_Z}_{\lambda_\psi,\lambda_\psi}(0,\theta_Z,0)^* D^1_{\lambda_\psi,\Delta\lambda_\mu}(\Delta\phi_{\psi,Z},\theta_\psi^Z,0)^*$$

1 mass, 3 angles
all derivable from the K* variables

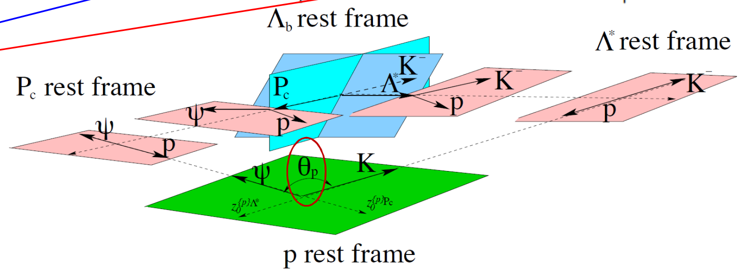
$$\mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu^{P_c}} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi^{P_c}} \mathcal{H}^{\Lambda_b^0\to P_{cj}K}_{\lambda_{P_c},0} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{P_c}}(\phi_{P_c},\theta^{P_c}_{\Lambda_b^0},0)^*$$
$$\mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_j(m_{\psi p})\ \ D^1_{\lambda_\psi^{P_c},\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*$$

1 mass, 5 angles
all derivable from the Λ* variables

$$\left|M(m_{K\pi},\Omega \,|\, M_Z,\Gamma_Z,J_Z,A^{Z\to\psi\pi}_{\lambda_\psi},\ A^{B\to\psi K_n^*}_{\lambda_\psi})\right|^2 = \sum_{\Delta\lambda_\mu=-1,1}\left|M^{K^*}_{\Delta\lambda_\mu} + e^{i\Delta\lambda_\mu\alpha_\mu} M^Z_{\Delta\lambda_\mu}\right|^2$$

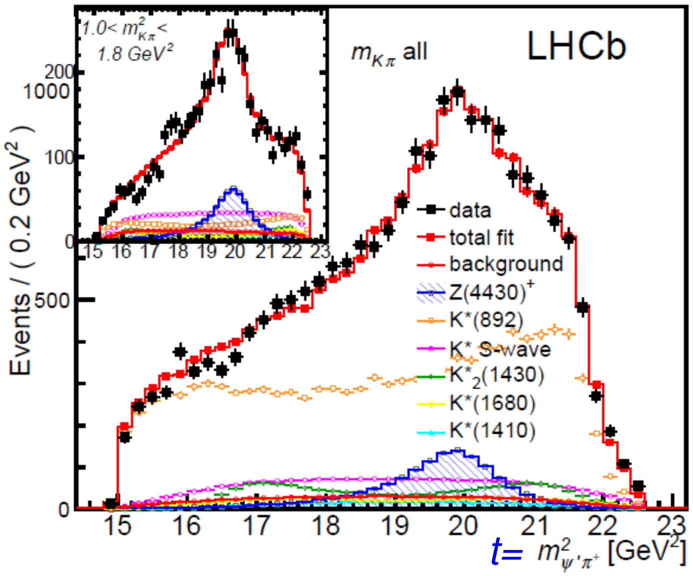
$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}} \sum_{\lambda_p} \sum_{\Delta\lambda_\mu} \left| \mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} + e^{i\,\Delta\lambda_\mu\alpha_\mu} \sum_{\lambda_p^{P_c}} d^{\frac{1}{2}}_{\lambda_p^{P_c},\lambda_p}(\theta_p)\, \mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu}\right|^2$$

Additional rotations of spin states correcting for helicity frames for the final state particles (μ,p) being different in s- and t-decay channels *[Wigner rotations mentioned in Mikhail Mikhasenko's lecture today]*

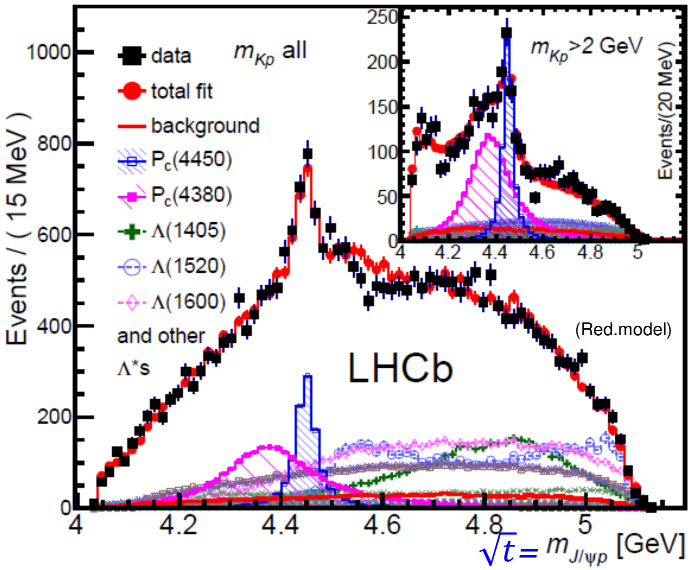


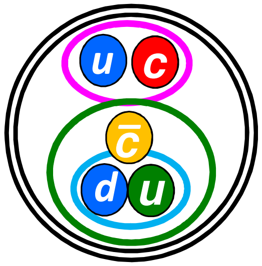
Including exotic hadron contributions

$B^0 \to \psi' \pi^+ K^-$



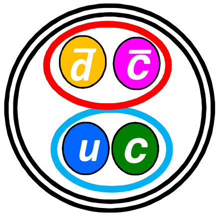
$\Lambda_b^0 \to J/\psi\, pK^-$





State	Mass (MeV)	Width (MeV)	Fit frac. (%)	Sig.
$Z_c(4430)^+$	$4475\pm 7^{+15}_{-25}$	$172\pm13^{+37}_{-34}$	$5.9\pm0.9^{+1.5}_{-3.3}$	14σ
Belle	$4485\pm22^{+28}_{-11}$	$200\pm46^{+26}_{-35}$	$10.3\pm3.5^{+4.3}_{-2.3}$	5σ

- $J^P=1^+$ at 9.7σ incl. syst. (in Belle at 3.4σ)



State	Mass (MeV)	Width (MeV)	Fit fract. (%)	Sig.
$P_c(4450)^+$	4449.8±1.7±2.5	39± 5±19	4.1±0.5±1.1	12σ
$P_c(4380)^+$	4380 ±8±29	205±18±86	8.4±0.7±4.2	9σ

- Best fit has J^P=($3/2^-$, $5/2^+$), also ($3/2^+$, $5/2^-$) & ($5/2^+$, $3/2^-$) are preferred. ($5/2^-$,$3/2^+$) cannot be ruled out within systematics

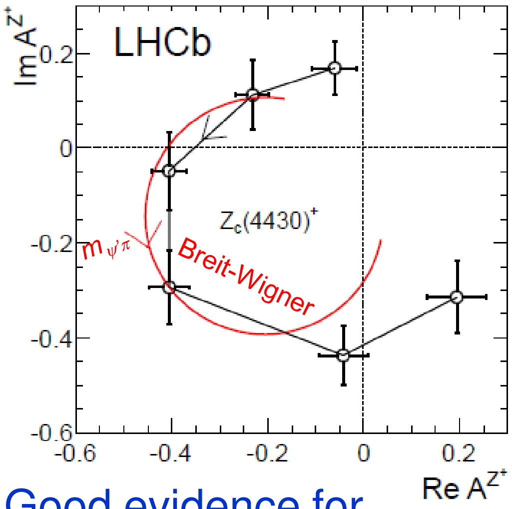
The lack of clear J^P determination for the P_c states is troubling:

- Is underlying Λ* "background" modeled properly?
- Is *s*- and *t*-dependence parametrization too naïve?

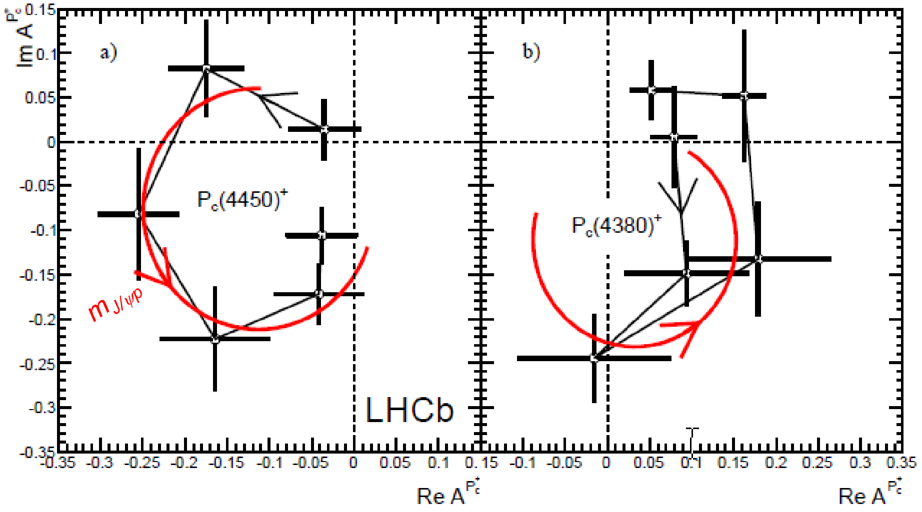
Argand diagrams: exotic hadron amplitudes without Breit-Wigner assumption

Exotic hadron amplitudes for 6 $m_{\psi'\pi}/m_{J/\psi p}$ bins near the peak mass

(all other model parameters fitted simultaneously)



Good evidence for resonant character



Large errors

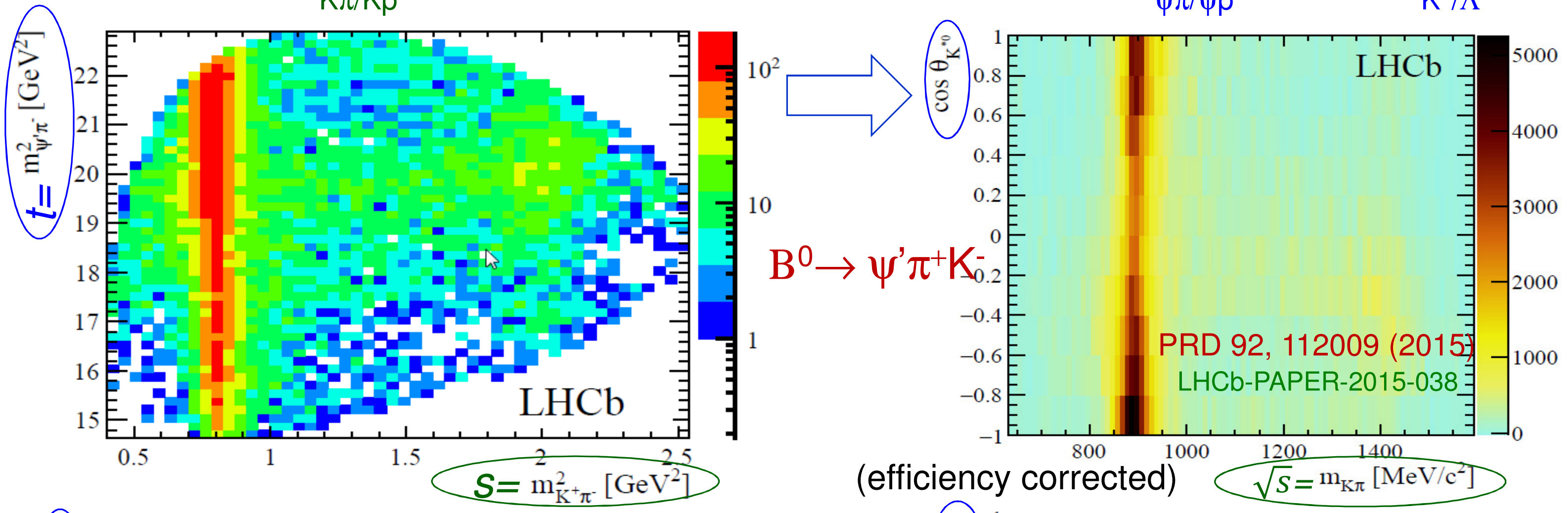
Need larger data samples, and good control of the model of conventional resonances, to make these studies more conclusive.

Such studies make exotic hadron amplitude model-independent, but the results are still dependent on the model of conventional hadrons. Simultaneous PWA of the latter is not possible since exotics reflect into variables characterizing conventional hadrons.

However, we can assume exotics are not present and test for their presence in model-independent way - next few slides.

Rectangular Dalitz plane: variables of conventional hadrons

- For fixed $m_{K\pi/Kp}$ there is one-to-one relation between $m_{\psi\pi/\psi p}$ and $\cos\theta_{K^*/\Lambda^*}$

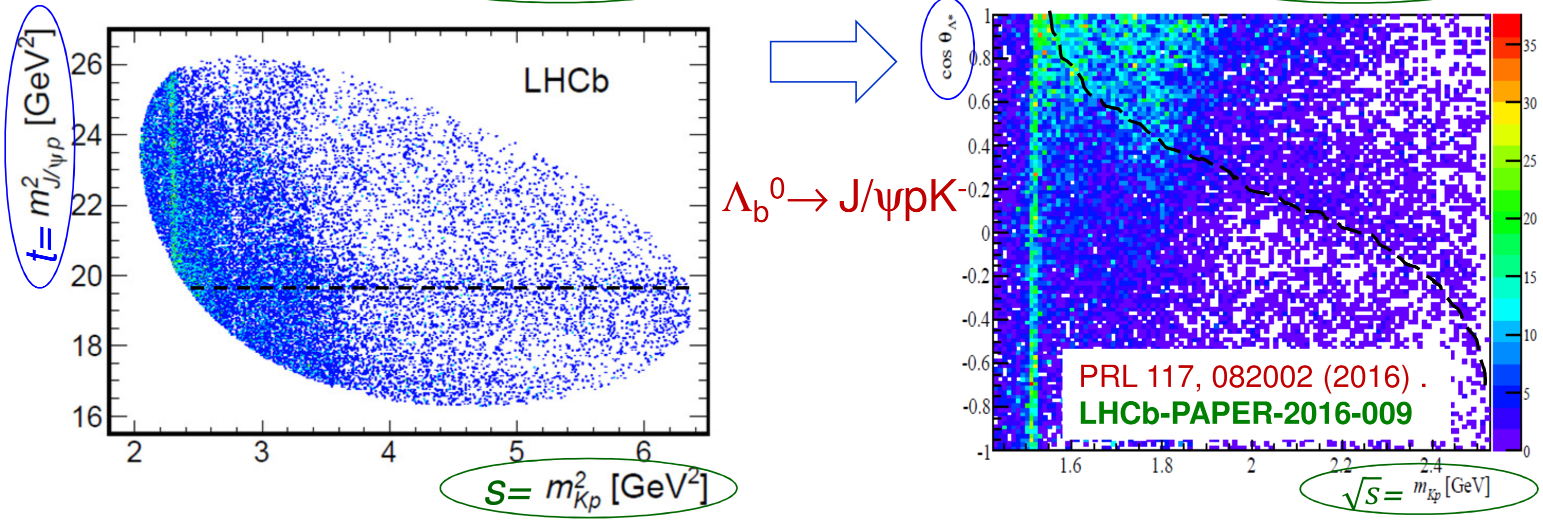


$B^0 \rightarrow \psi'\pi^+K^-$

PRD 92, 112009 (2015)

LHCb-PAPER-2015-038

(efficiency corrected)

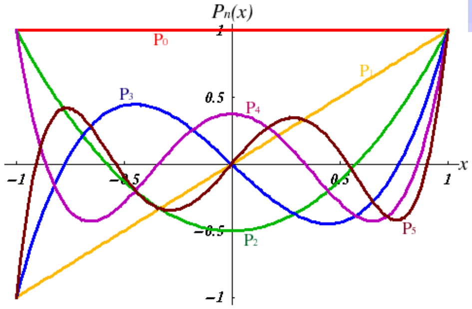


$\Lambda_b^0 \rightarrow J/\psi pK^-$

PRL 117, 082002 (2016) .

LHCb-PAPER-2016-009

Legendre moments



$$\frac{dN}{d\cos\theta} = \sum_{l=0}^{l_{\max}} \left\langle P_l^U \right\rangle P_l(\cos\theta) \qquad \theta = \theta_{K^*} \quad \text{or} \quad \theta_{\Lambda^*}$$

$$\left\langle P_l^U \right\rangle = \int_{-1}^{+1} \frac{dN}{d\cos\theta} P_l(\cos\theta) d\cos\theta \propto \sum_{i=1}^{n_{events}} \frac{1}{\varepsilon_i} P_l(\cos\theta_i)$$

Decomposition into $<P_l>$ corresponds to decomposition into “frequencies”

With $l_{\max} \to \infty$ can reproduce any $\frac{dN}{d\cos\theta}$

Smooth cosθ structures produce low rank moments

Sharp cosθ structures produce low and high rank moments

The sharper the structure the higher l_{max} required

K*/Λ* can contribute only to low-rank moments

$l_{\max} = J_1 + J_2$ for interfering resonances

In K*/Λ*-only hypothesis (**H_0**)

$$\boxed{l_{\max} = 2J_{\max}}$$

J_{max} is the highest spin of K*/Λ* resonance possible

Reflections of exotic hadrons can contribute to low **and high** rank moments:

- **Detecting non-zero moments above $2J_{max}$ signals presence of exotics**
- The narrower the peak the higher the **$2J_{max}$** required. **The sensitivity is better for narrower exotic hadrons.**
- Exotic hadron contributions spread over wide range of $m_{K\pi}/m_{Kp}$. An effective way of testing H_0 is to **aggregate the information about $\cos\theta_{K\pi/Kp}$ moments in a function of $m_{\psi'\pi}/m_{J/\psi p}$.**

Setting highest rank of Legendre moments

The sensitivity of the method improves by considering $l_{max}(m_{K\pi}/m_{Kp}) = 2\ J_{max}(m_{K\pi}/m_{Kp})$ dependence:

it can be set from **know K*/Λ* resonances**, **quark model predictions** as a guide

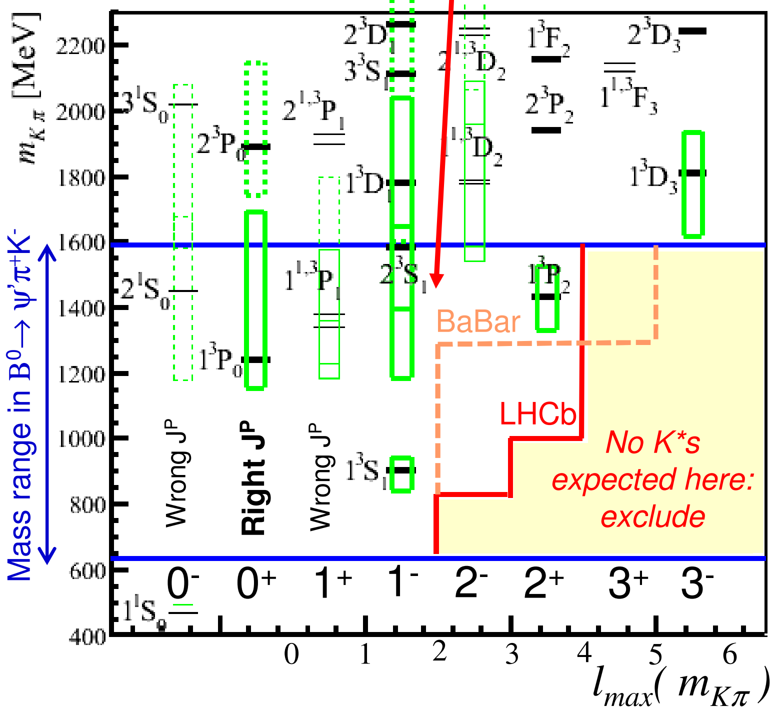
All predicted states are known!

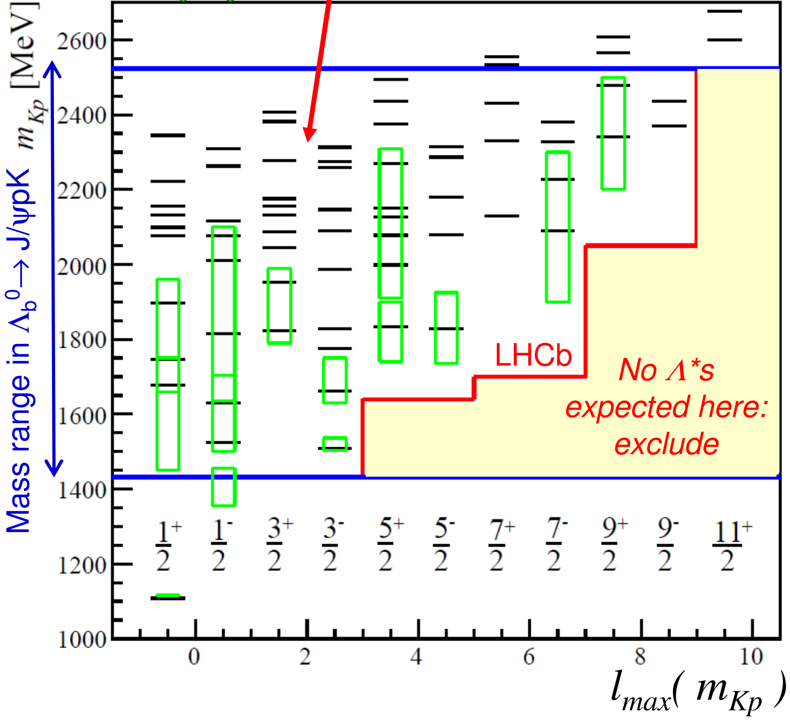
Much fewer known states than predicted!

K* mass predictions by Godfrey-Isgur, PRD 32, 189 (1985)

Known K* / Λ* states: boxes $M_0 \pm \Gamma_0$

Λ* mass predictions by Loring-Metsch-Petry EPJ, A10, 447 (2001)

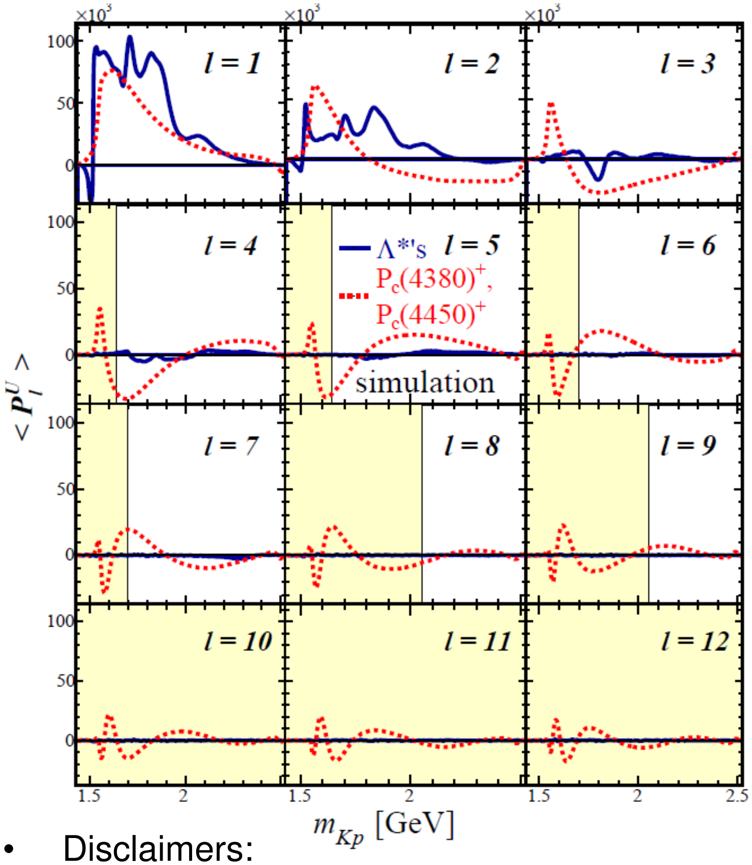




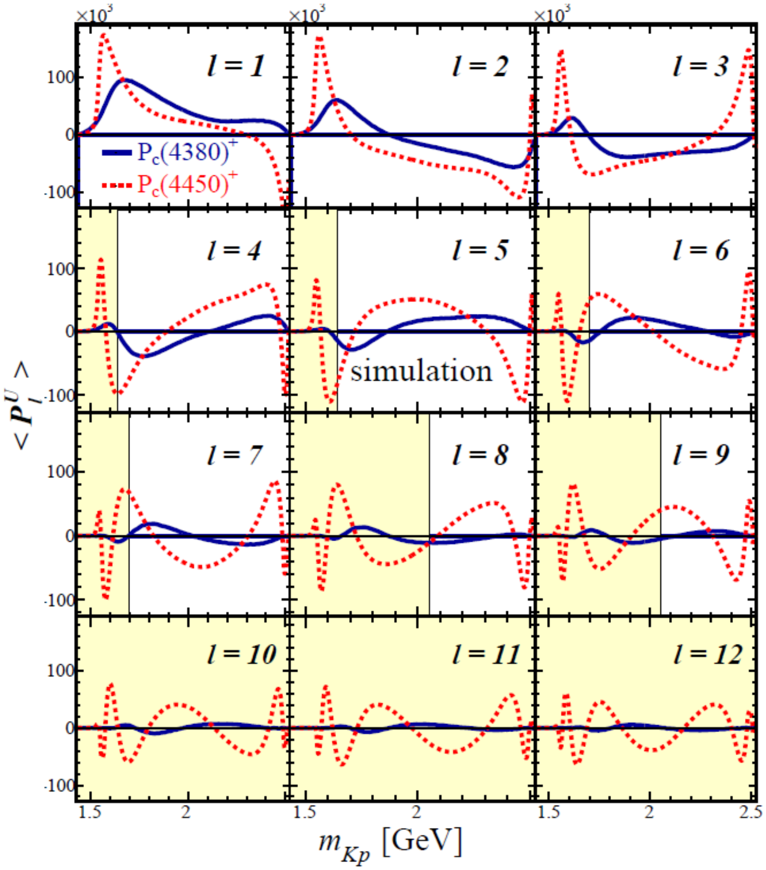
- Because the J/ψ mass is smaller than ψ' mass, must allow for higher excitations in the $\Lambda_b^0 \to J/\psi pK$ analysis, higher l_{max}

Illustrations using amplitude models of $\Lambda_b^0 \to J/\psi p K^-$

Only exotic hadrons can contribute to excluded moments



The narrower the exotic hadron the better the sensitivity



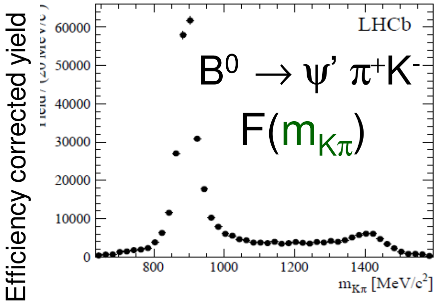
- Disclaimers:
  - these are high statistics simulations to eliminate any statistical fluctuations (vertical scale is arbitrary)
  - exotic hadron contributions are usually only a few % fit fractions, thus the amplitudes of the red curves is expected to be small in the real data

Test the hypothesis (H_0) that the data contain only conventional hadrons

Form a model of the data implementing this hypothesis:

$$\mathrm{PDF}(m_{K\pi/Kp},\cos\theta_{K^*/\Lambda^*}\,|H_0) = F(m_{K\pi/Kp})\,F(\cos\theta_{K^*/\Lambda^*}\,|\,m_{K\pi/Kp})$$

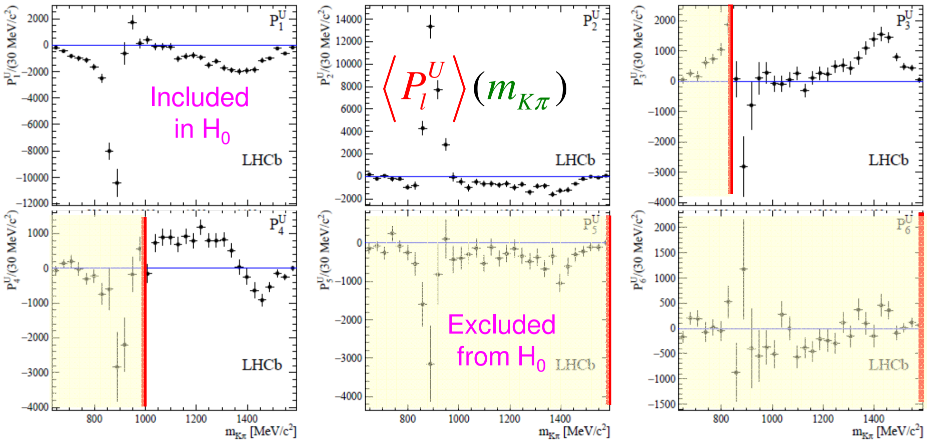
$$F(\cos\theta_{K^*/\Lambda^*}\,|\,m_{K\pi/Kp}) = \sum_{l=0}^{l_{\max}(m_{K\pi/Kp})} \left\langle P_l^U \right\rangle(m_{K\pi/Kp})\; P_l(\cos\theta_{K^*/\Lambda^*})$$



$B^0 \to \psi' \pi^+ K^-$

$F(m_{K\pi})$

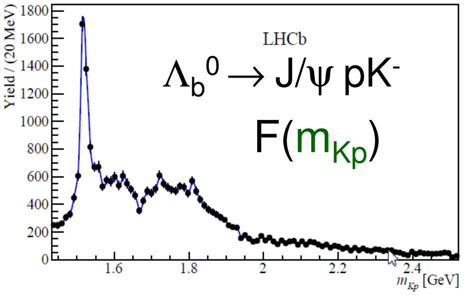
$l_{max}(m_{K\pi})$



Included in H_0

$\left\langle P_l^U \right\rangle(m_{K\pi})$

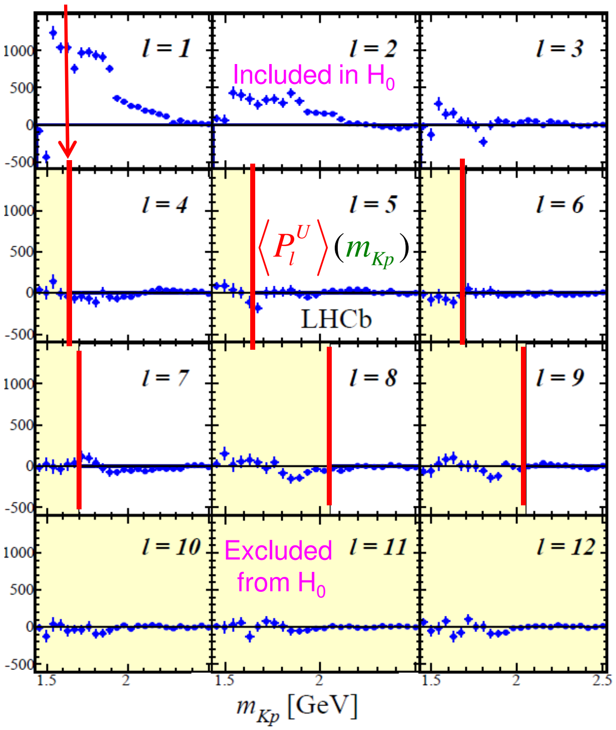
Excluded from H_0



$\Lambda_b^0 \to J/\psi\, pK^-$

$F(m_{Kp})$

$l_{max}(m_{Kp})$



Included in H_0

$\left\langle P_l^U \right\rangle(m_{Kp})$

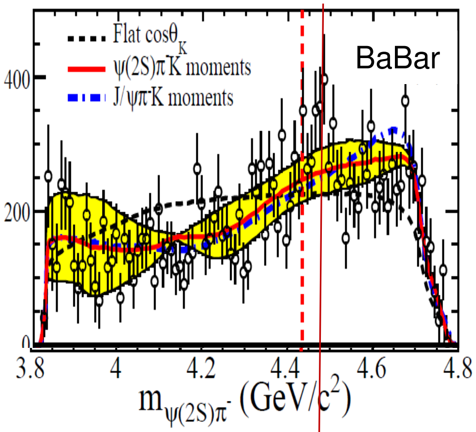
Excluded from H_0

Test H_0 model on $m_{\psi'\pi/\psi p}$ distribution

$$\mathrm{PDF}(m_{\psi'\pi/\psi p}|\mathrm{H}_0)=\int dm_{K\pi/Kp}\mathrm{PDF}(m_{K\pi/Kp},\cos\theta_{K^*/\Lambda^*}(m_{\psi'\pi/\psi p})\,|\,\mathrm{H}_0)\left|\frac{\partial\cos\theta_{K^*/\Lambda^*}(m_{\psi'\pi/\psi p})}{\partial m_{\psi'\pi/\psi p}}\right|$$

$B^0 \rightarrow \psi' \pi^+K^-$

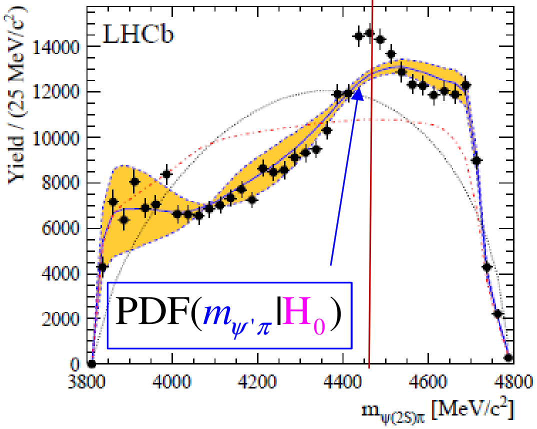
BaBar PRD 79, 112001 (2009)



BaBar did not have enough statistics to see Z(4430) this way.

Negative results like this impossible to interpret without amplitude analysis since Z-K* interfere!

LHCb PRD 92, 112009 (2015)

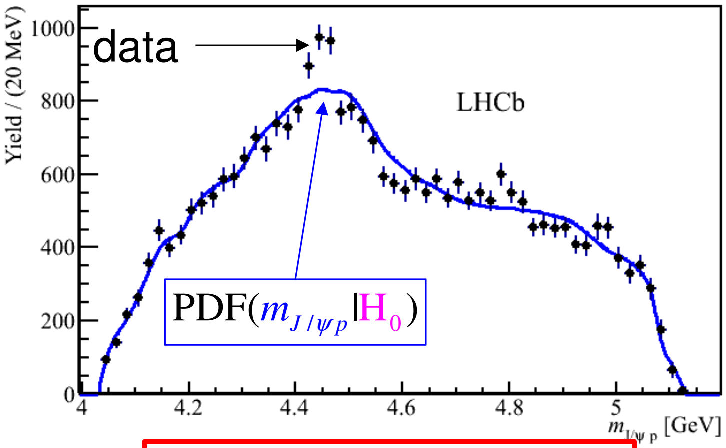


LHCb data inconsistent with K* contributions alone

$\Lambda_b \rightarrow J/\psi\ p\ K^-$

PRL 117, 082002 (2016) .

LHCb-PAPER-2016-009



LHCb data inconsistent with Λ^* contributions alone

This model independent proof of the presence of exotic hadron contributions is especially important for the Λ_b data, because of the difficulties in construction of a complete model of Λ excitations

Rejection of H_0 can be quantified

Test variable:

(quasi) log-likelihood-ratio

$$\Delta(\text{-2lnL}) \equiv -2\sum_{i=1}^{n_{events}} \frac{1}{\varepsilon_i}\ln\frac{\text{PDF}(m_{\psi'\pi}|H_0)}{\text{PDF}(m_{\psi'\pi}|H_1)}$$

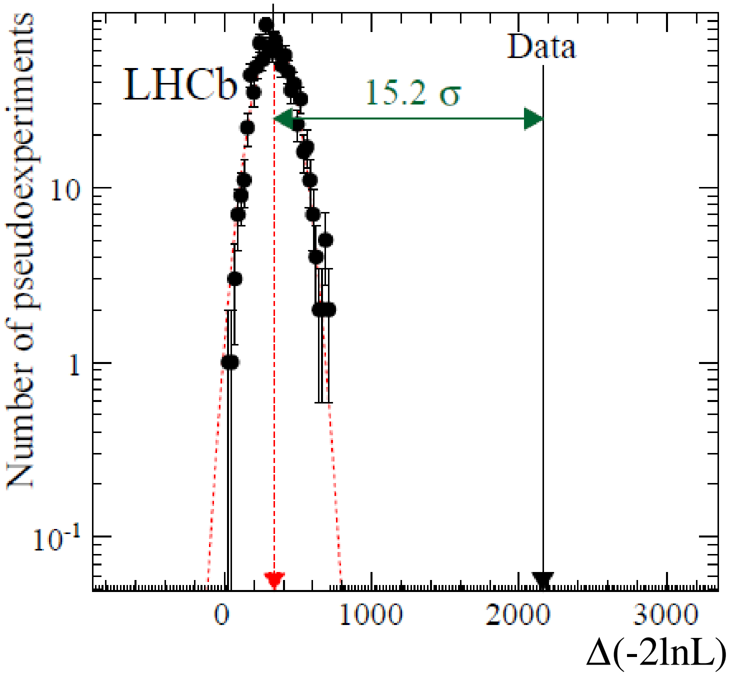
$$\Delta(\text{-2lnL}) \equiv -2\sum_{i=1}^{n_{events}} \ln\frac{\text{PDF}(m_{J/\psi p}|H_0)/I_{H_0}}{\text{PDF}(m_{J/\psi p}|H_1)/I_{H_1}}$$

$$I_H = \int \text{PDF}(m_{J/\psi p}|H)\,\varepsilon(m_{J/\psi p})\, d\, m_{J/\psi p}$$

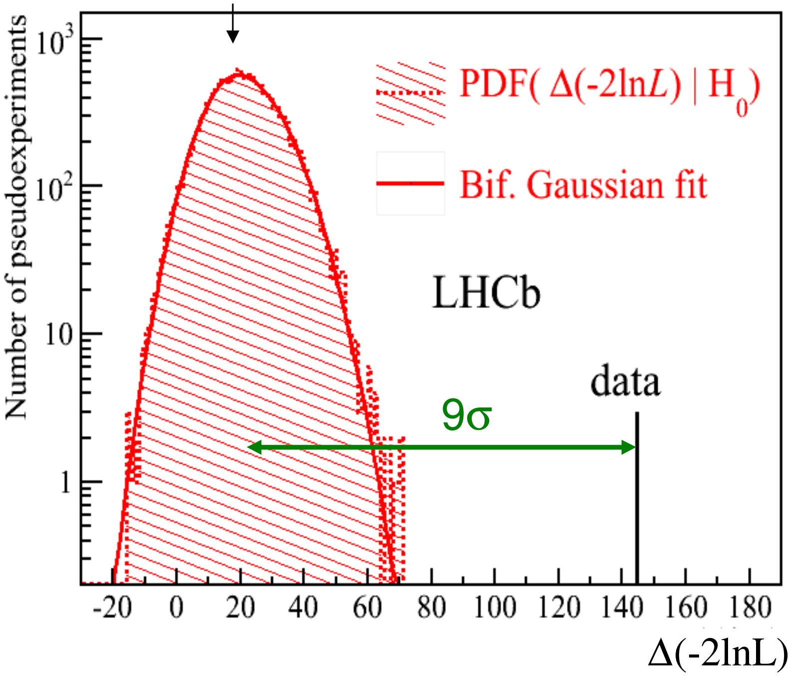
H_0: $l_{max}(m_{K\pi})$ H_1: l_{max}^{H1}=30 H_0: $l_{max}(m_{Kp})$ H_1: l_{max}^{H1}=31

This variable tests a significance of moments between $l_{max}(m_{K\pi/Kp})$ and l_{max}^{H1}

PDF(Δ(-2lnL) |H_0) $B^0 \rightarrow \psi' \pi^+ K^-$



PDF(Δ(-2lnL) |H_0) $\Lambda_b \rightarrow J/\psi\ p\ K^-$



However, this approach cannot characterize exotics – amplitude analysis is still necessary.

Summary

- LHCb is the first hadron collider experiment optimized to heavy flavor physics, taking advantage of enormous b,c production rates
- Thanks to that it has unique data sets, and ambitious upgrade program, with data sample sizes to be increased by a factor of ~10 (100) in 10 (20) years.
- Searches for New Physics, as well as hadron spectroscopy studies often rely on complicated fits of amplitude models to the data
- It is possible, that some of our spectroscopic results are already limited by the choices of amplitude parameterization (J^P of P_c^+ states?)
- Future searches for NP in loops may also require better amplitude parameterizations
- Some JPAC physicists are now directly affiliated with LHCb to help us cope with these problems