S. Stone

LHCb Run 2 & (Mostly) Run 1 Results

See Hassan Jawahery's talk for many hot new results

USLUA, Nov. 2, 2017

Dark matter & Majorana ν's

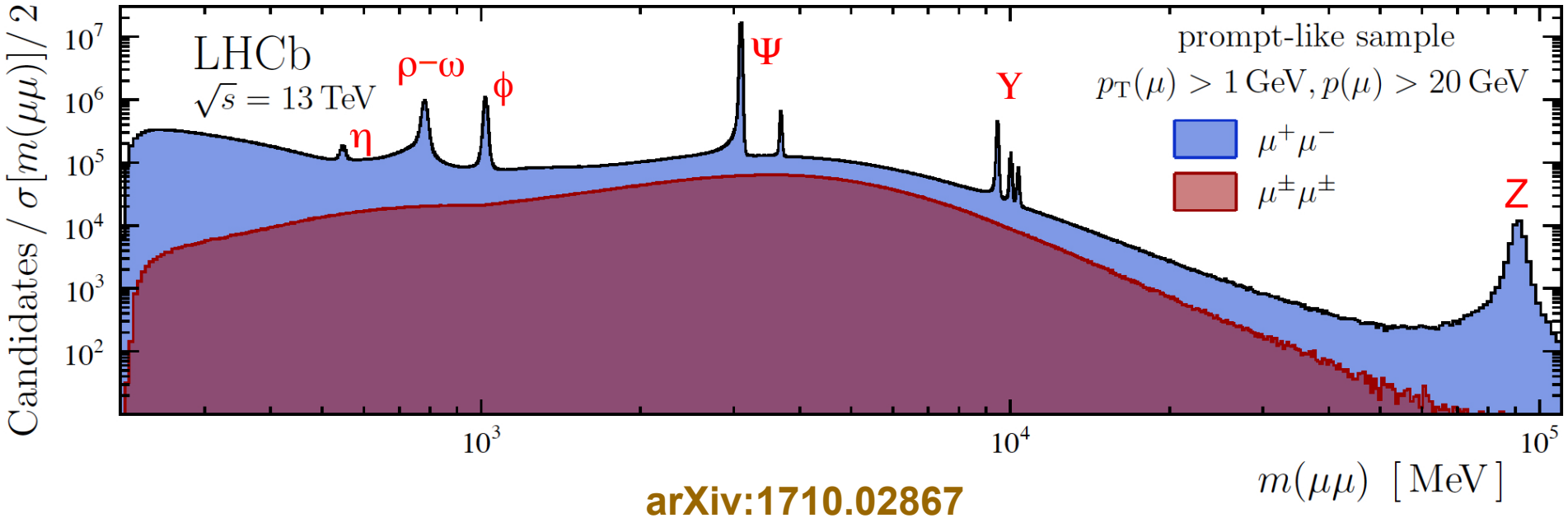
USLUA, Nov. 2, 2017

Dark Photons?

- One of the most important questions in modern physics is that of the composition of dark matter
- One possible manifestation is described by the oxymoron "dark photon (A′)," where the coupling to the EM current is suppressed by a factor of ε, compared with γ's
- A′ can be produced promptly or have finite lifetimes, especially if is ε small
- A′ can decay into $\mu^+\mu^-$, just like $\gamma \rightarrow \mu^+\mu^-$

A' Trigger

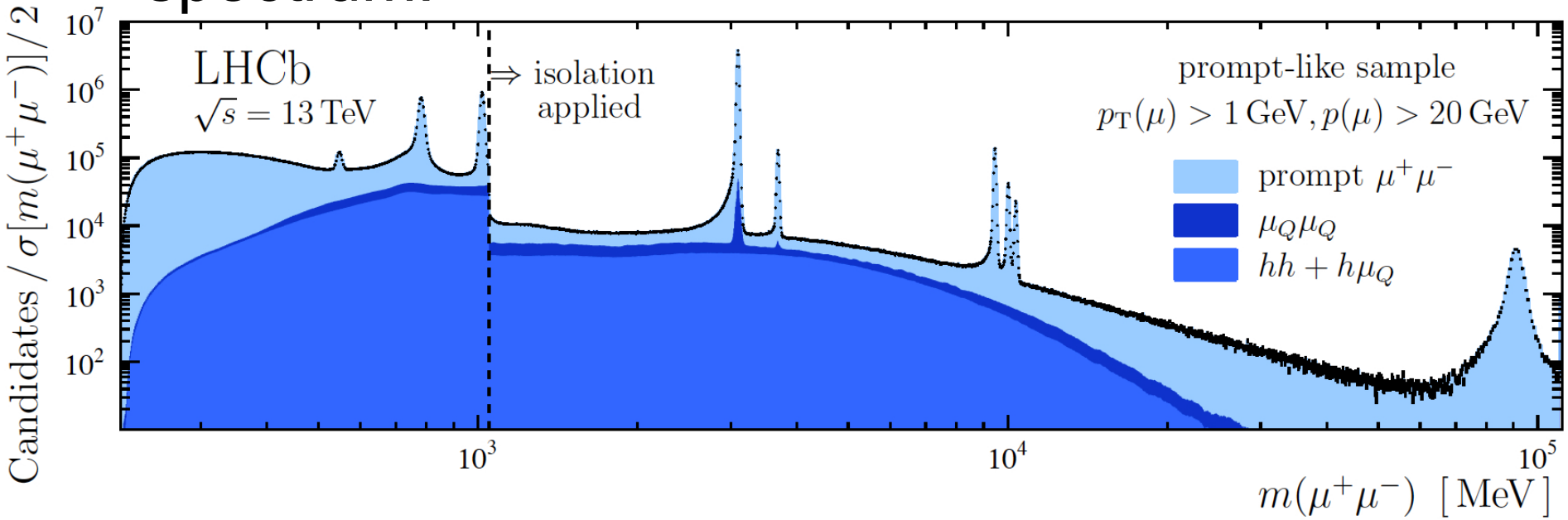
- New low mass dimuon trigger. Only online reconstructed tracks are kept, not "raw" event
- Trigger output from 1.6/fb of "turbo" data



arXiv:1710.02867

A′ Search - Prompt

- Insist that dimuon candidate be “isolated” from jets for $m(\mu^+\mu^-)>m(\phi)$. Resulting mass spectrum:

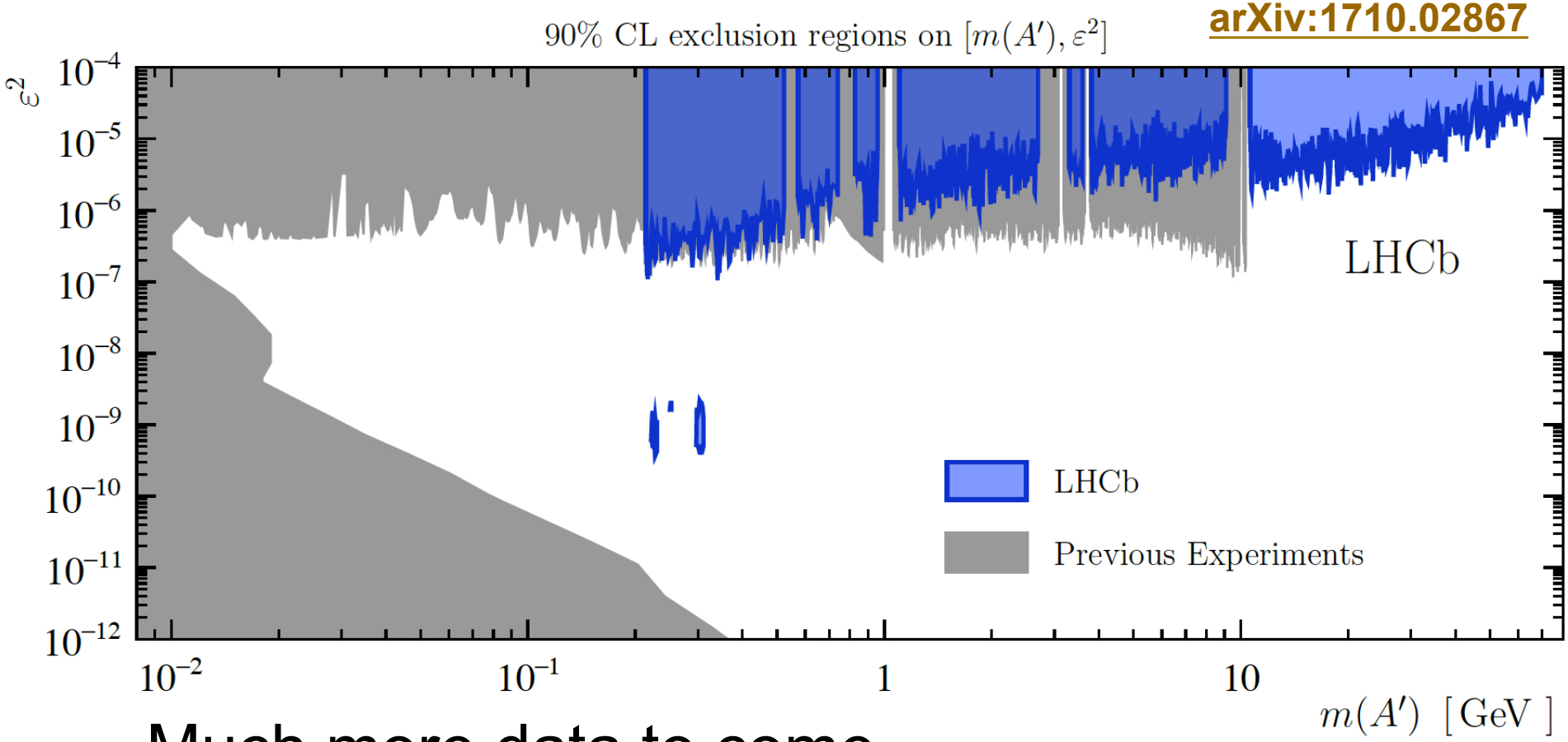


- $\mu_Q\mu_Q$ indicates real μ backgrounds, hh two hadrons... No signals found in prompt sample

A′ Results

- Add in non-prompt search

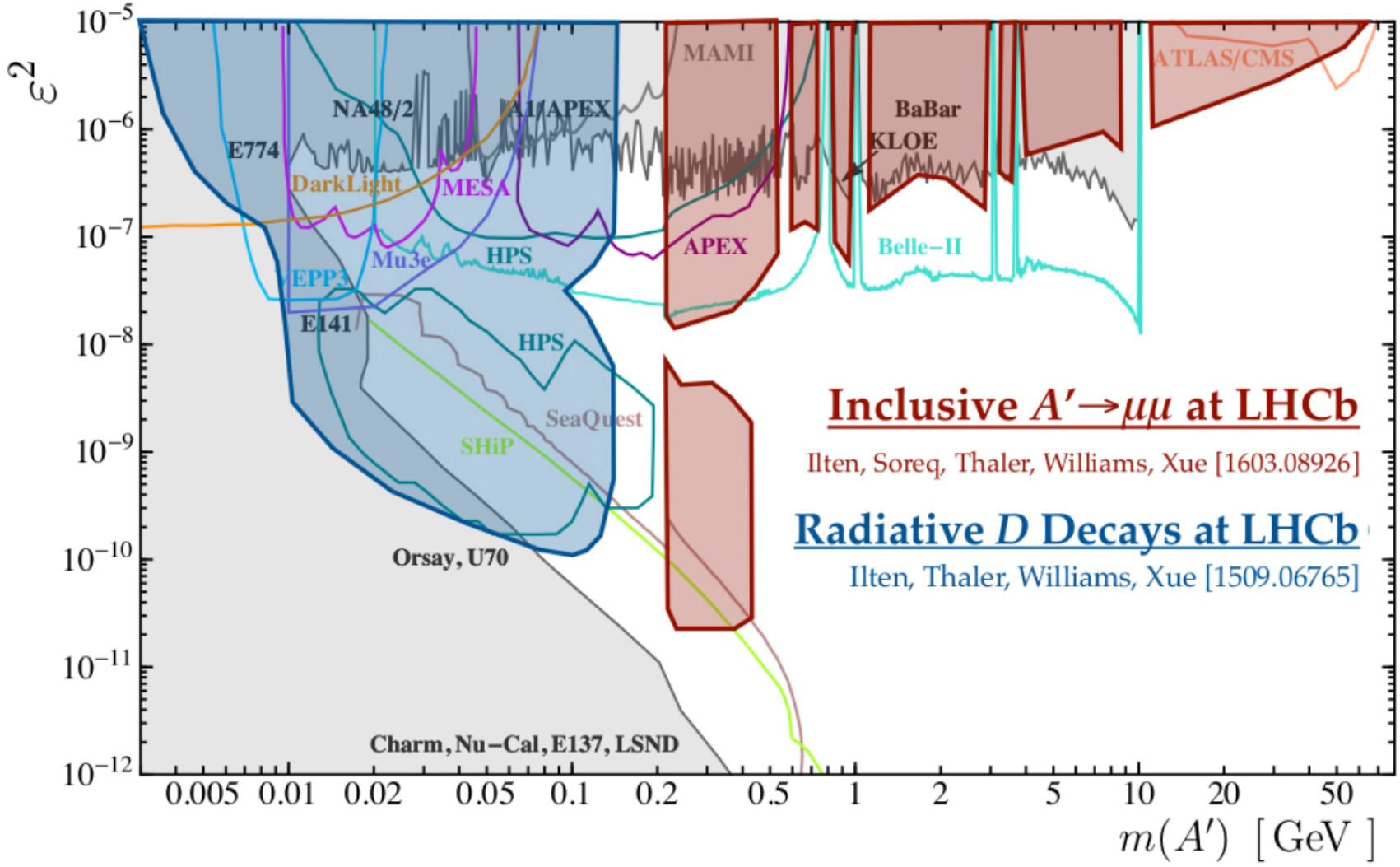
arXiv:1710.02867



- Much more data to come

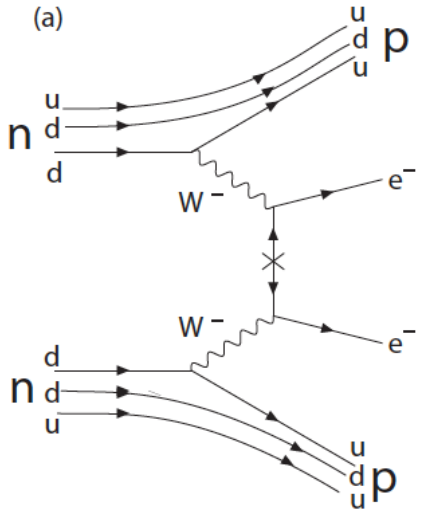
Projected Run III Reach

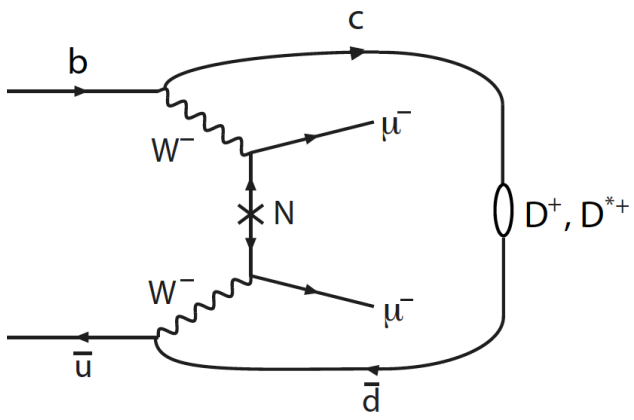
- For A′ masses < 2m(μ) use $\gamma \rightarrow e^+e^-$



Majorana ν's

- Are ν's Fermions or Majorana particles, i.e. are they there own antiparticles?
- Several ways of looking for presence of heavy ν's (N) in heavy quark decays if they are Majorana & couple to "ordinary" ν's
- Modes analogous to ν–less nuclear β decay





Simplest Channels:
$B^- \rightarrow D^+ \ell^- \ell'^-$ &
$B^- \rightarrow D^{*+} \ell^- \ell'^-$
ℓ^- & ℓ'^- can be e^-, μ^- or τ^-.

Limits on $D^{(*)+}\ell^-\ell'^-$

- Upper limits in e^-e^- mode not competitive with nuclear β decay
- Others unique since measure coupling of Majorana ν to μ^-

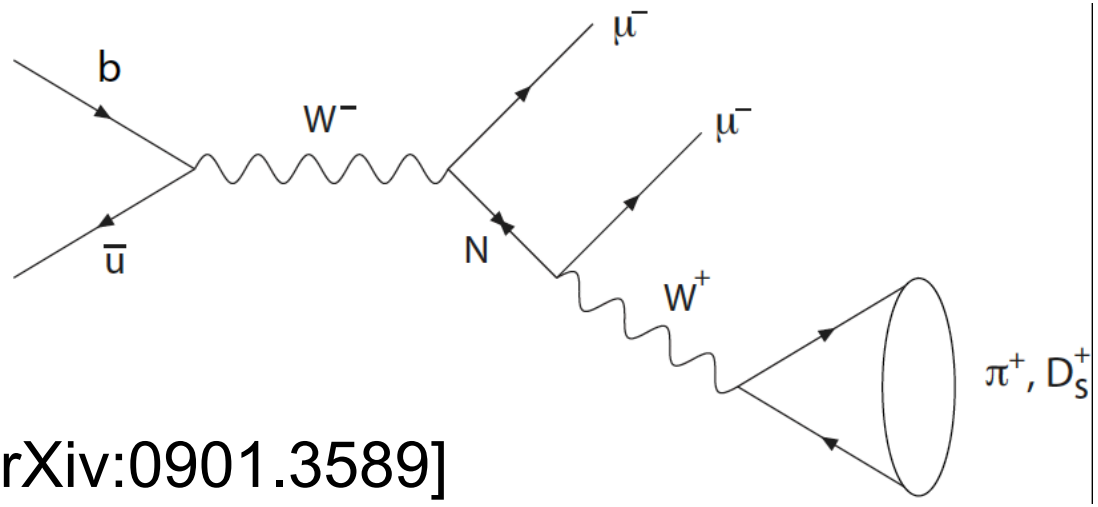
Mode	Exp.	u. l. x 10^{-6}
$B^-\to D^+e^-e^-$	Belle	< 2.6
$B^-\to D^+e^-\mu^-$	Belle	< 1.8
$B^-\to D^+\mu^-\mu^-$	Belle	< 1.0
$B^-\to D^+\mu^-\mu^-$	LHCb	< 0.69
$B^-\to D^{*+}\mu^-\mu^-$	LHCb	< 3.6

LHCb Phys.Rev. D85 (2012) 112004, 0.4/fb

Belle [arXiv:1107.064]

On-Shell ν

- Can also look for Majorana ν (N), where $N \rightarrow W^+\mu^-$



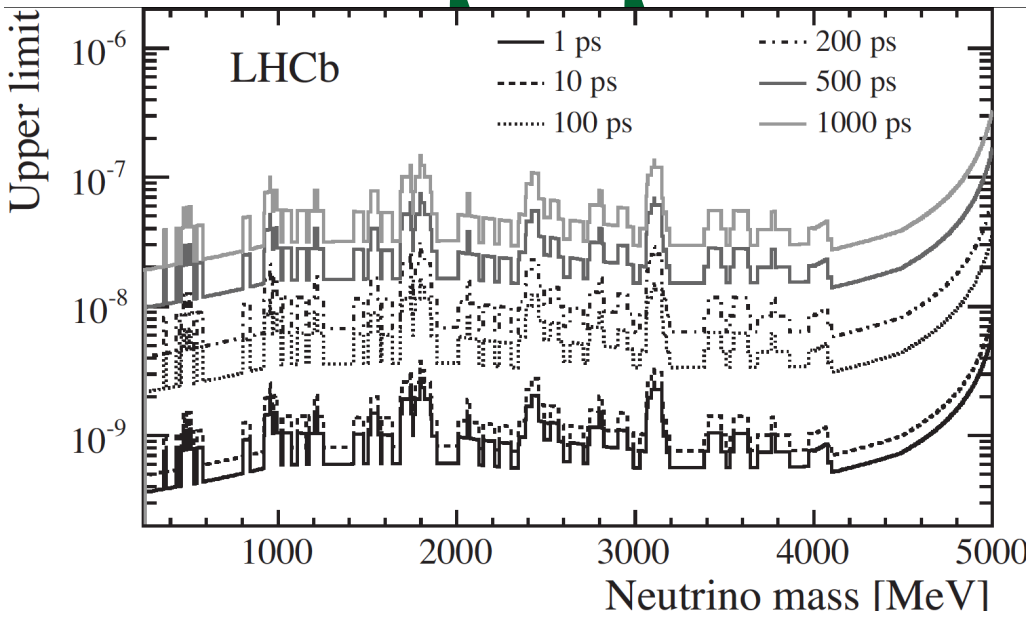
- A. Atre, T. Han,

S. Pascoli, & B. Zhang [arXiv:0901.3589]

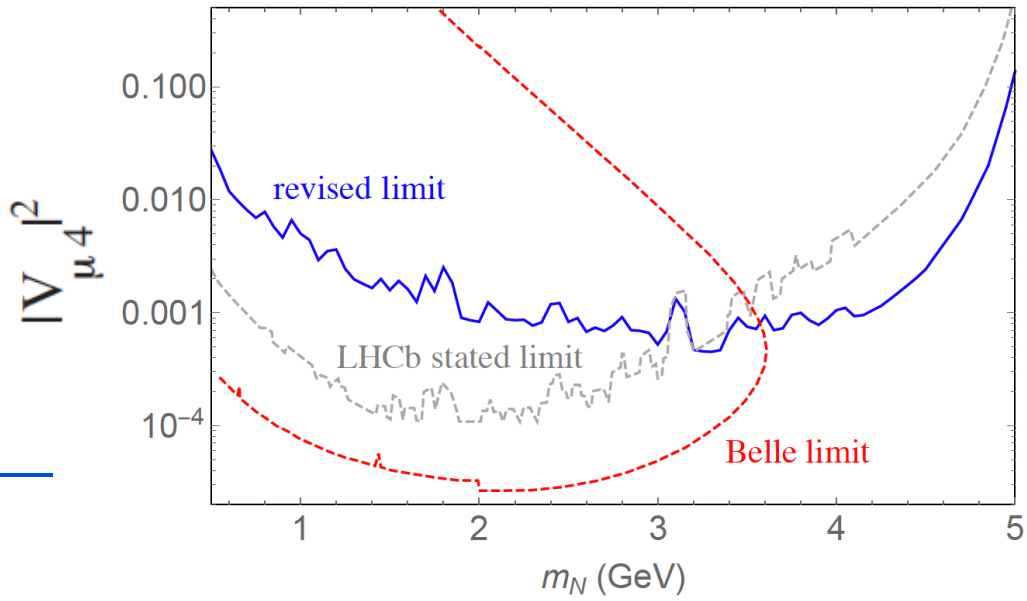
- Many other ways of searching:
  - $K^- \rightarrow \pi^- N$
  - $\mu^- \rightarrow e^- \gamma$
  - $\tau^- \rightarrow \mu^+ \pi^- \pi^-$
  - …..

$B^- \rightarrow \pi^+ \mu^- \mu^-$

LHCb search as a function of Majorana mass and lifetime, *Phys.Rev.Lett. 112 (2014) 131802*



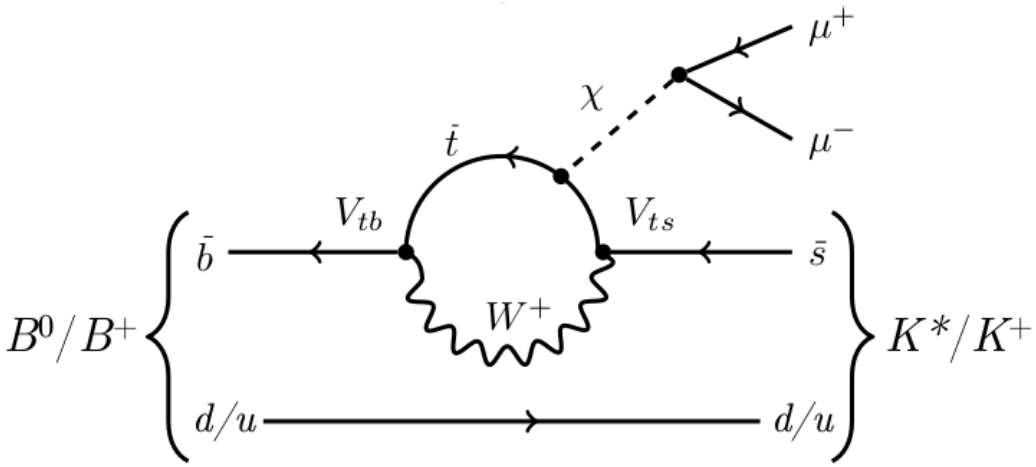
Revised limits from *Shuve & Peskin Phys.Rev. D94 (2016), 113007*



Hidden sector bosons

- Consider an object χ that couples to $t\bar{t}$ & $\mu^+\mu^-$
- can be anything

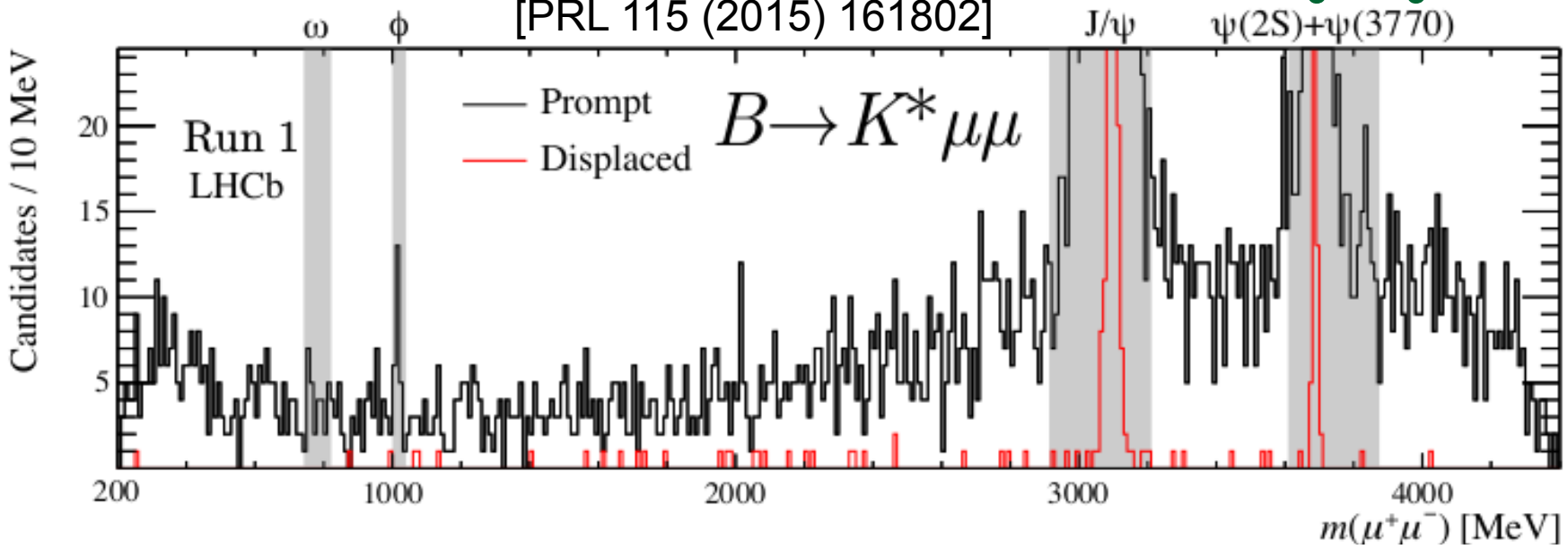
& there are specific models for axion, [LNP 741 (2008) 3] or inflaton [JHEP 05 (2010) 10]

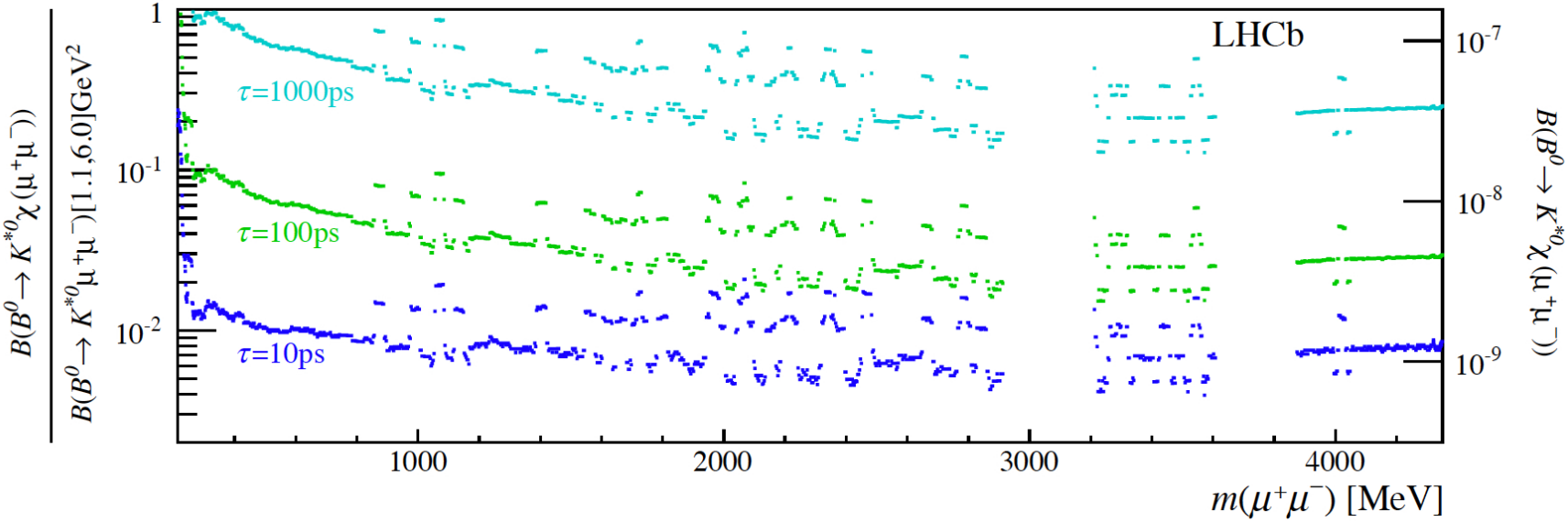


- In these searches allow for prompt or χ with finite lifetimes

Results $K^{*0}\mu\mu$

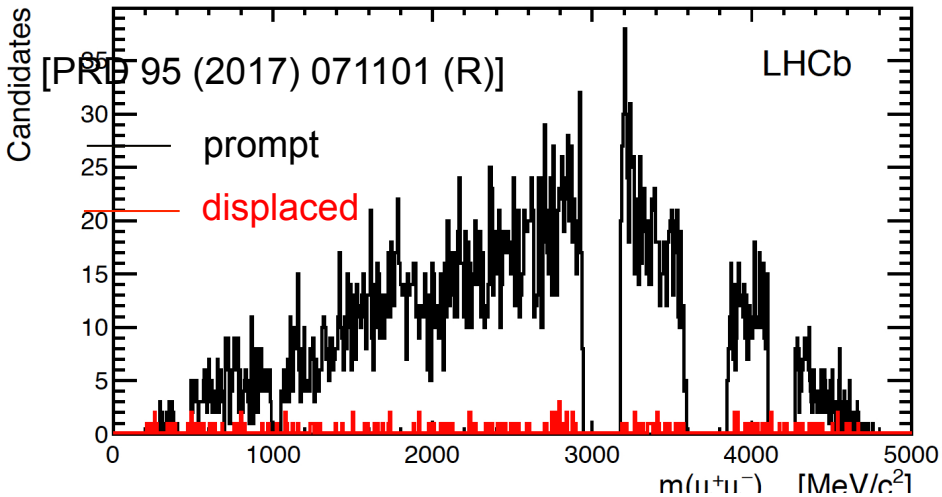
[PRL 115 (2015) 161802]

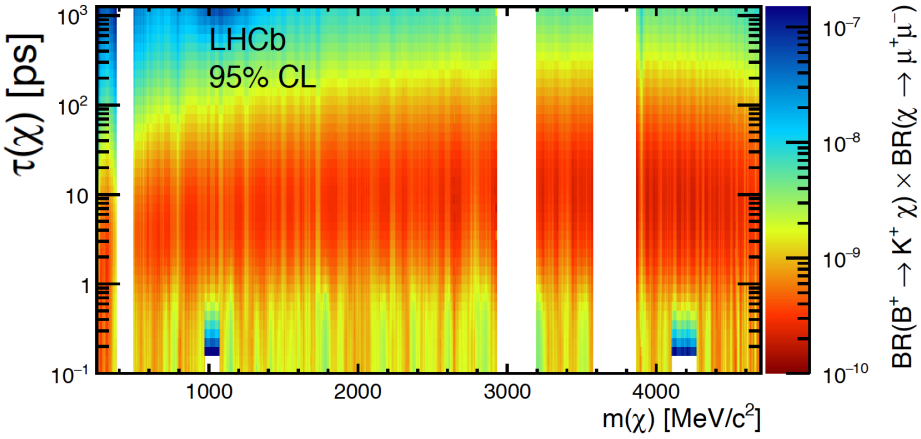


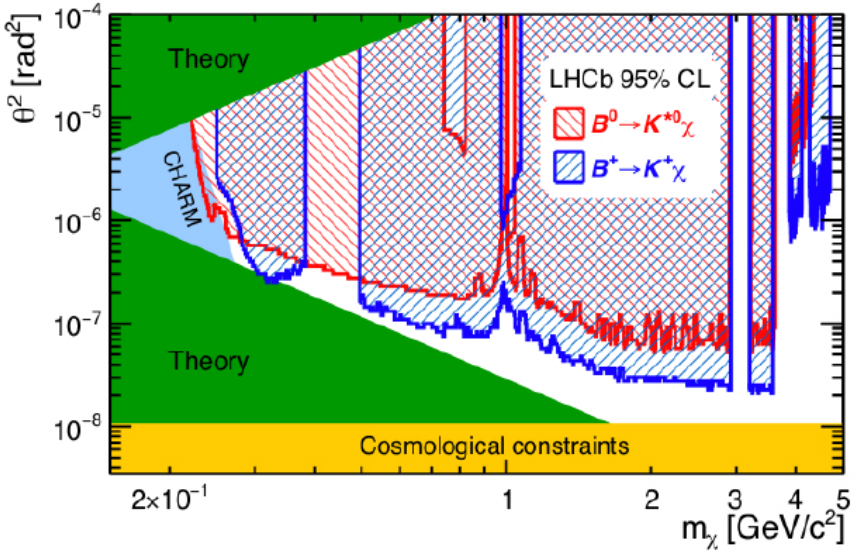


Results $K^+\mu\mu$

- Nothing seen
- Upper limits as function of τ & mass
- Combined limits with $K^*\mu\mu$



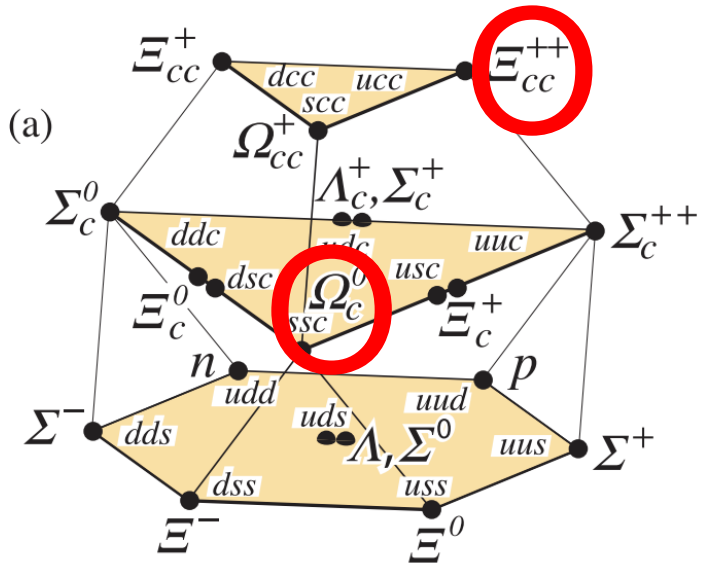




Thy: arXiv:0911.4938, arXiv:0912.0390, arXiv:1303.4395

θ^2 is inflaton coupling to the SM fields via mixing with the Higgs

Charmed -Strange Baryons

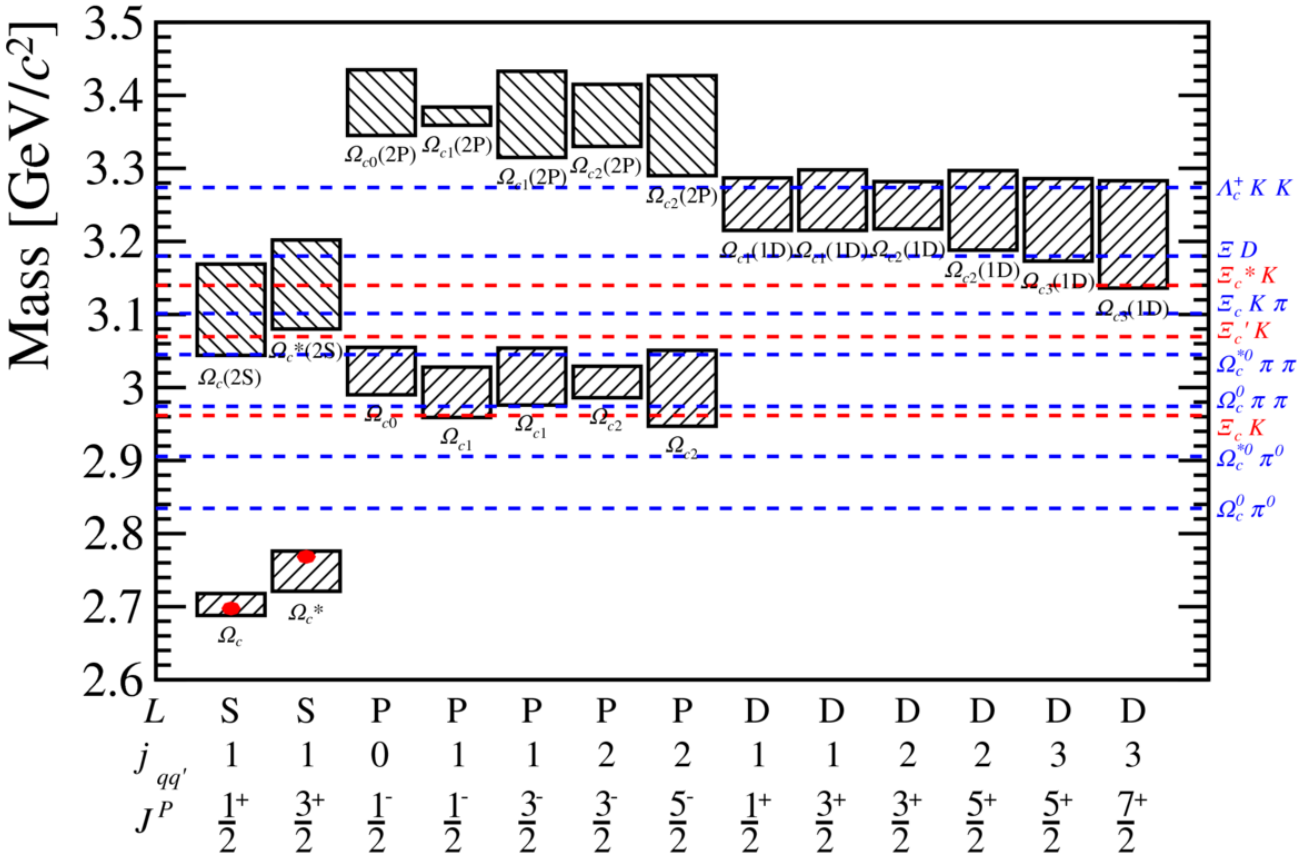


Why study?

- What is the structure of baryons, do di-quarks dominate? Implications for pentaquarks, tetraquarks…. Need to understand QCD

- Predictions

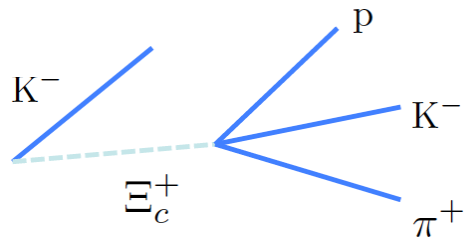
of css masses

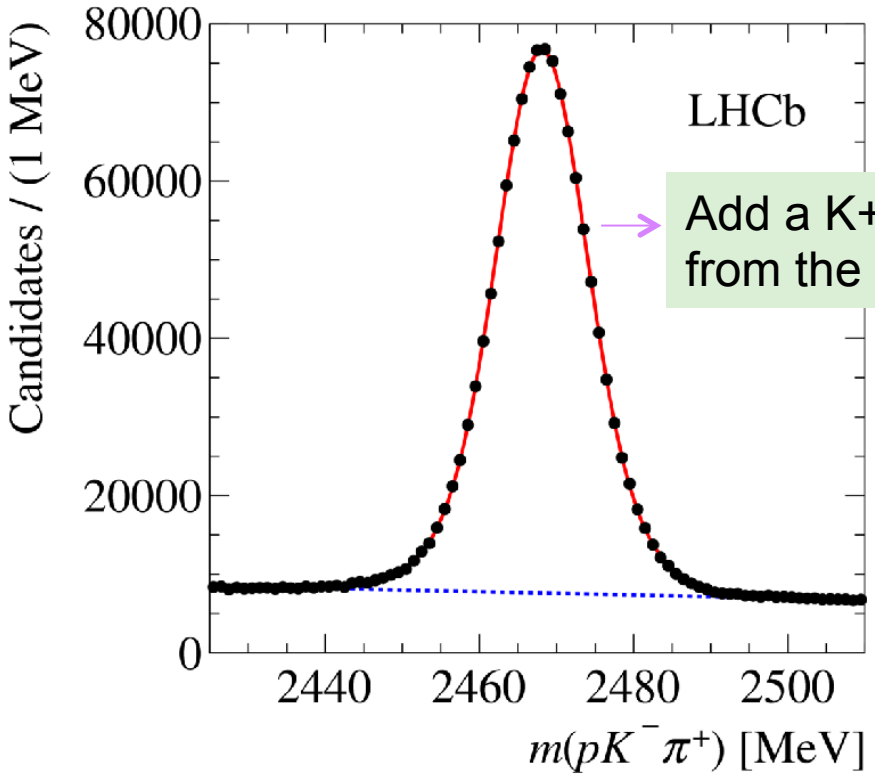


Excited Ω_c states

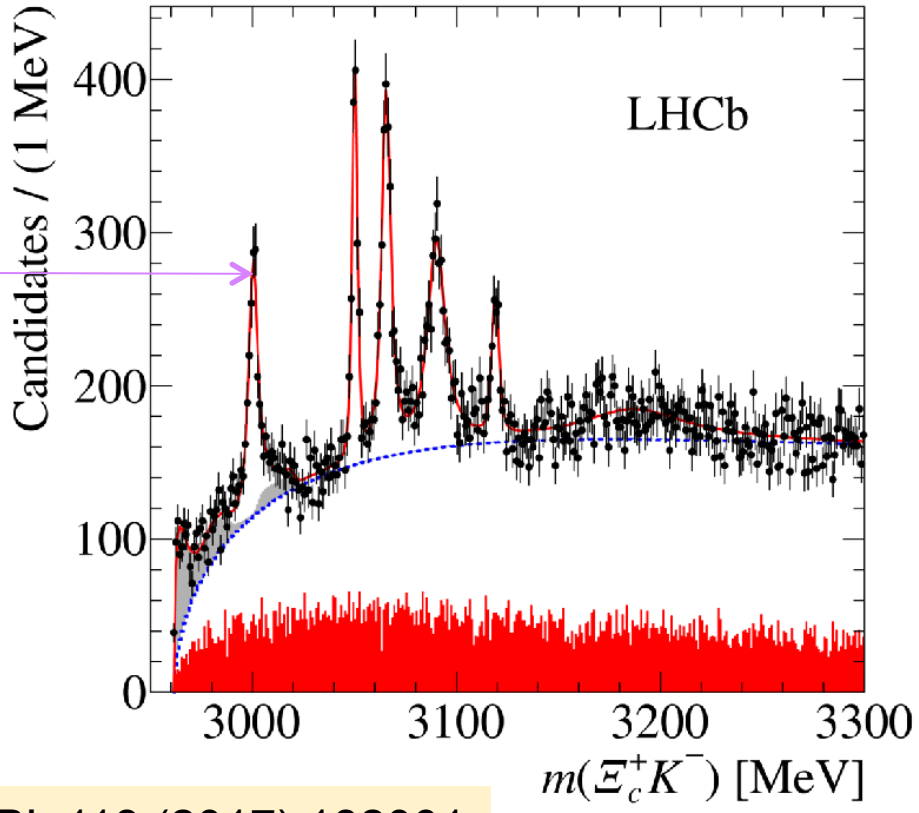
- Reconstruct Ξ_c states in $pK^-\pi^+$,

Cabibbo suppressed but all charged at one vertex





Add a K+ from the PV



PRL 118 (2017) 182001

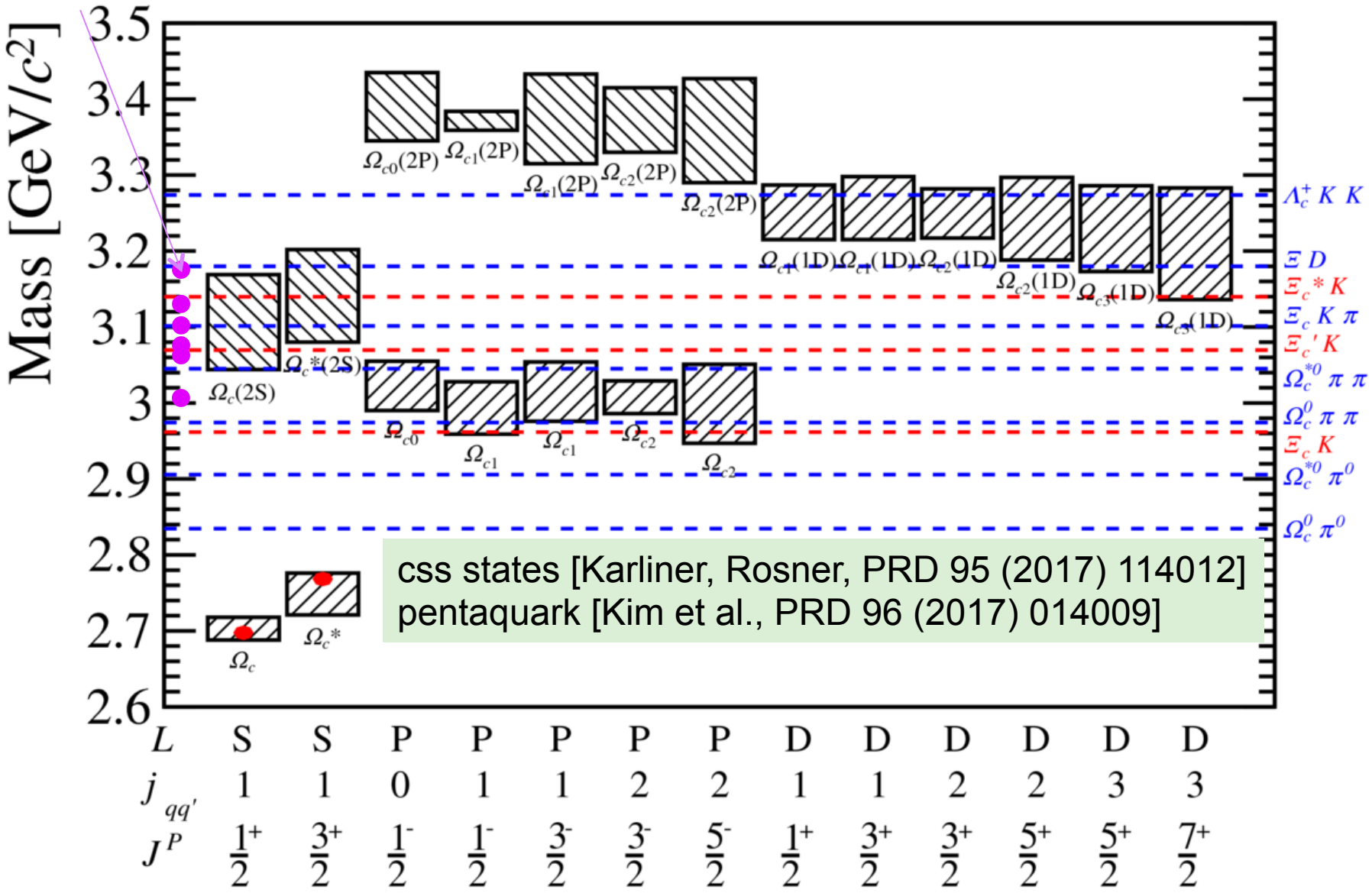
Measured masses & Γ

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2\,\mathrm{MeV}, 95\%$ CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		$< 2.6\,\mathrm{MeV}, 95\%$ CL		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	

- Why are these states so narrow? Explained by cs diquark?
- Which states are they? Need J^P
- Are they really css states, or are they pentaquarks?

Compare to theory

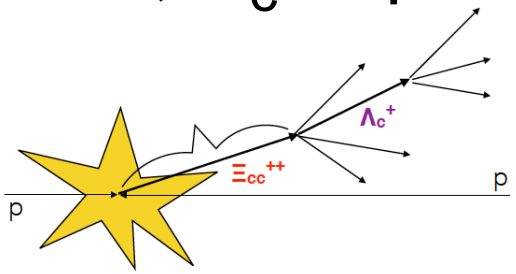
LHCb states

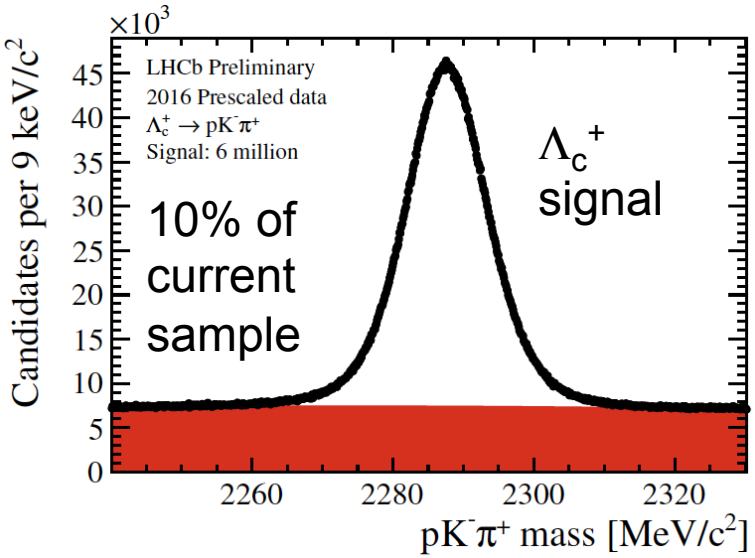


css states [Karliner, Rosner, PRD 95 (2017) 114012]
pentaquark [Kim et al., PRD 96 (2017) 014009]

A doubly charmed baryon

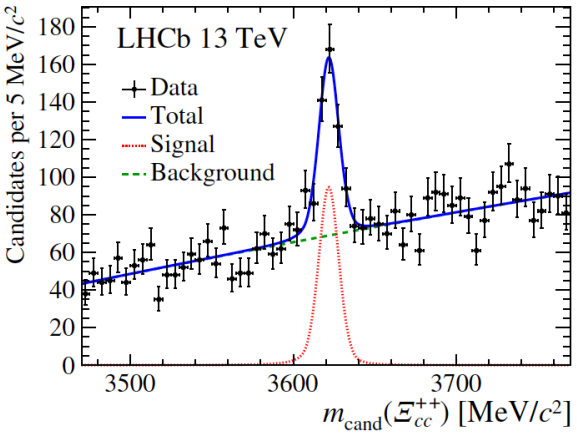
- Here we look for a baryon with quark content: ccu, called the Ξ_{cc}^{++}
- Selex measured the isospin partner (ccd) at a mass of 3518.87±1.7 MeV using a Σ^- beam in the $\Lambda_c^+ K^- \pi^+$ decay mode
- Not confirmed by Focus, BaBar, Belle
- LHCb looks for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$, $\Lambda_c^+ \rightarrow p K^- \pi^+$

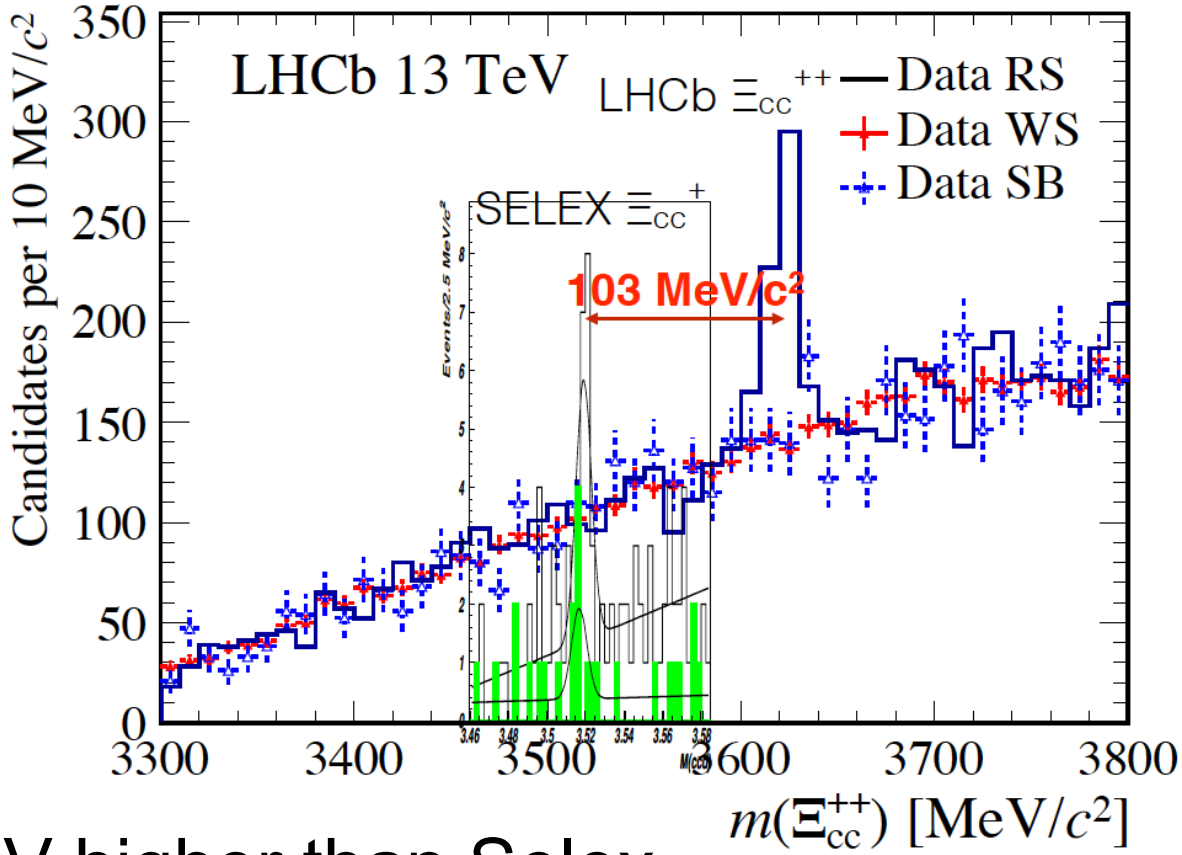




LHCb finds

- LHCb signal





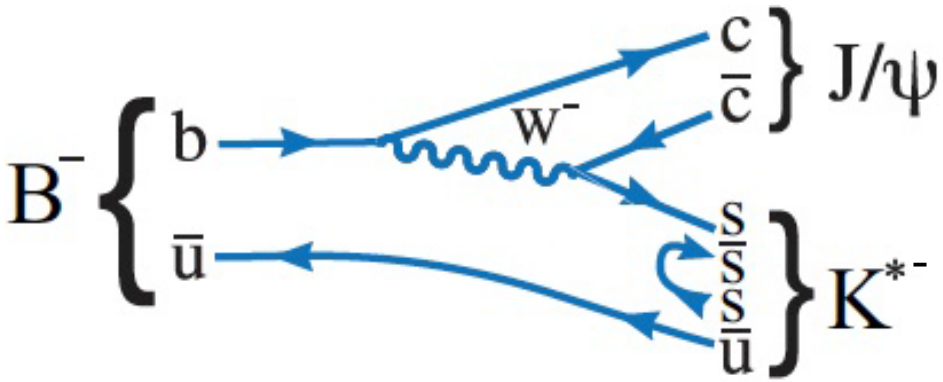
- Mass of Ξ_{cc}^{++} is 3621.40±0.72±0.30 MeV, about 103 MeV higher than Selex & consistent with theoretical expectations
- Can be explained with cc diquark orbited by u quark

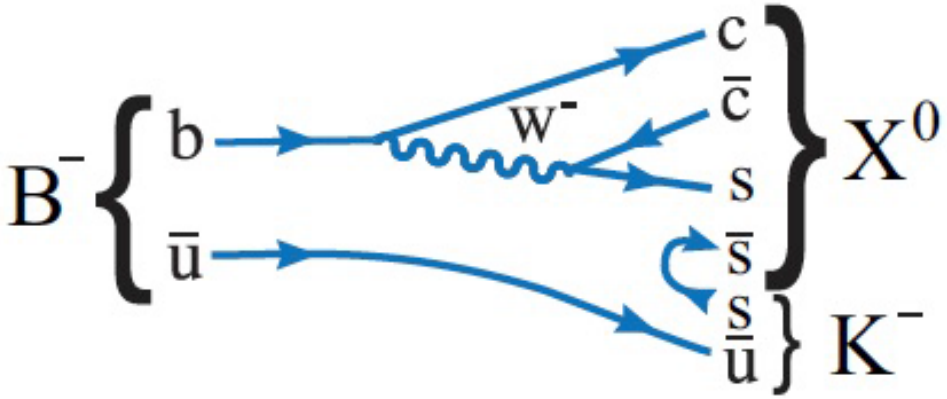
[PRL 119 (2017) 112001]

Exotics

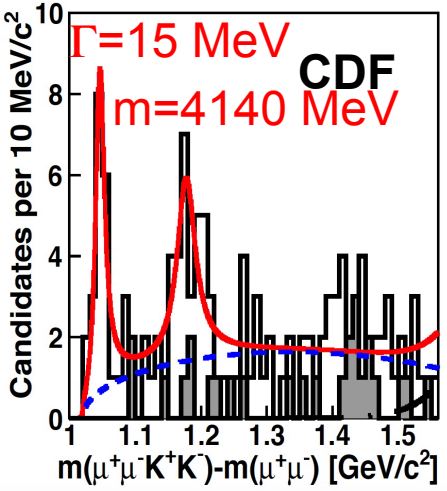
$B^- \rightarrow J/\psi\, \phi\, K^-$

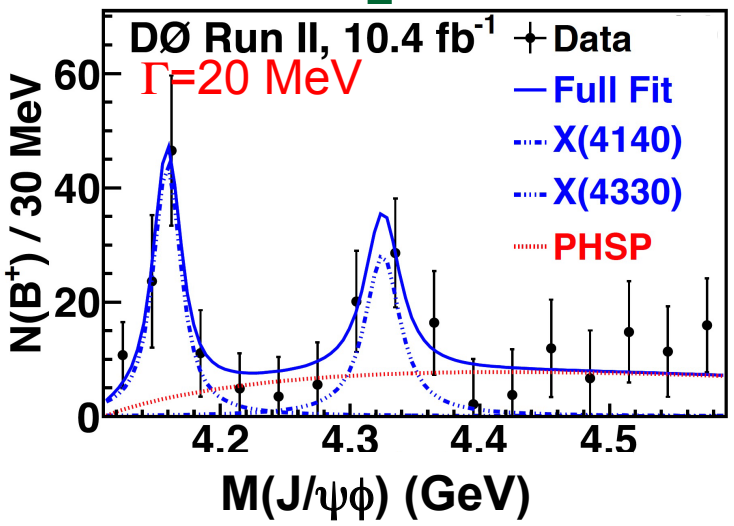
- Possible diagrams:

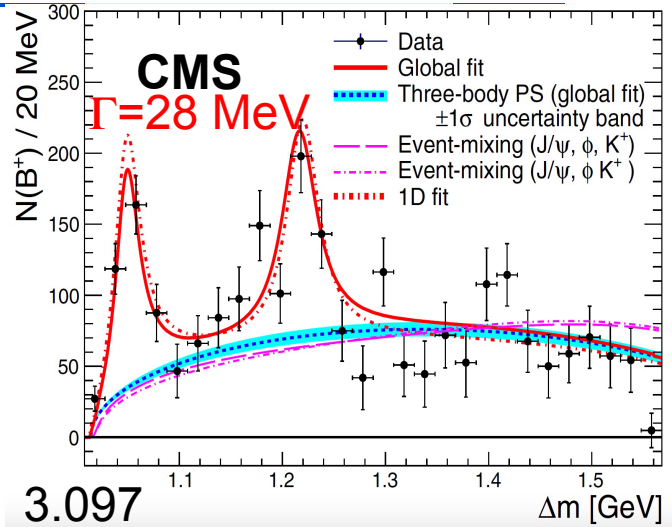


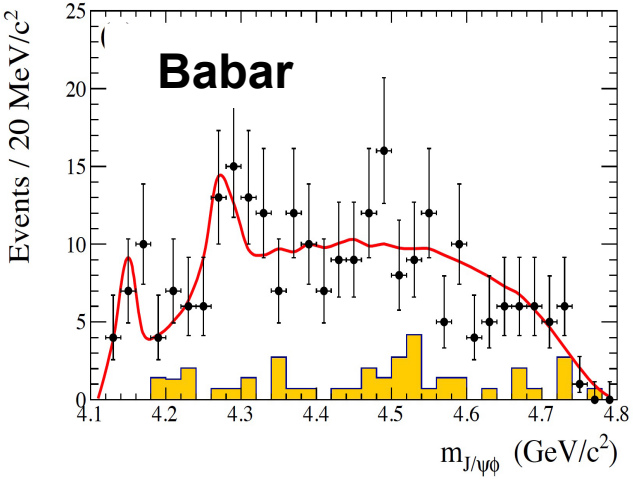


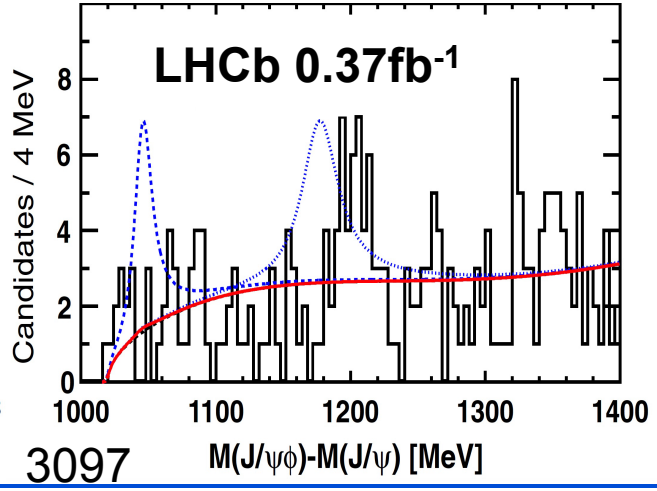
Some past results

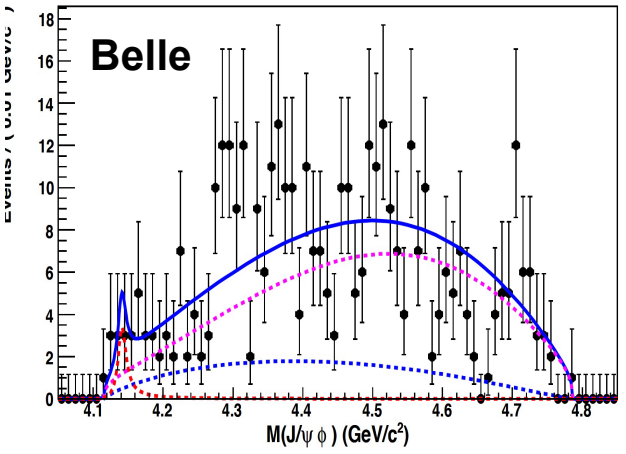












Detailed history

- One or two new resonant states claimed

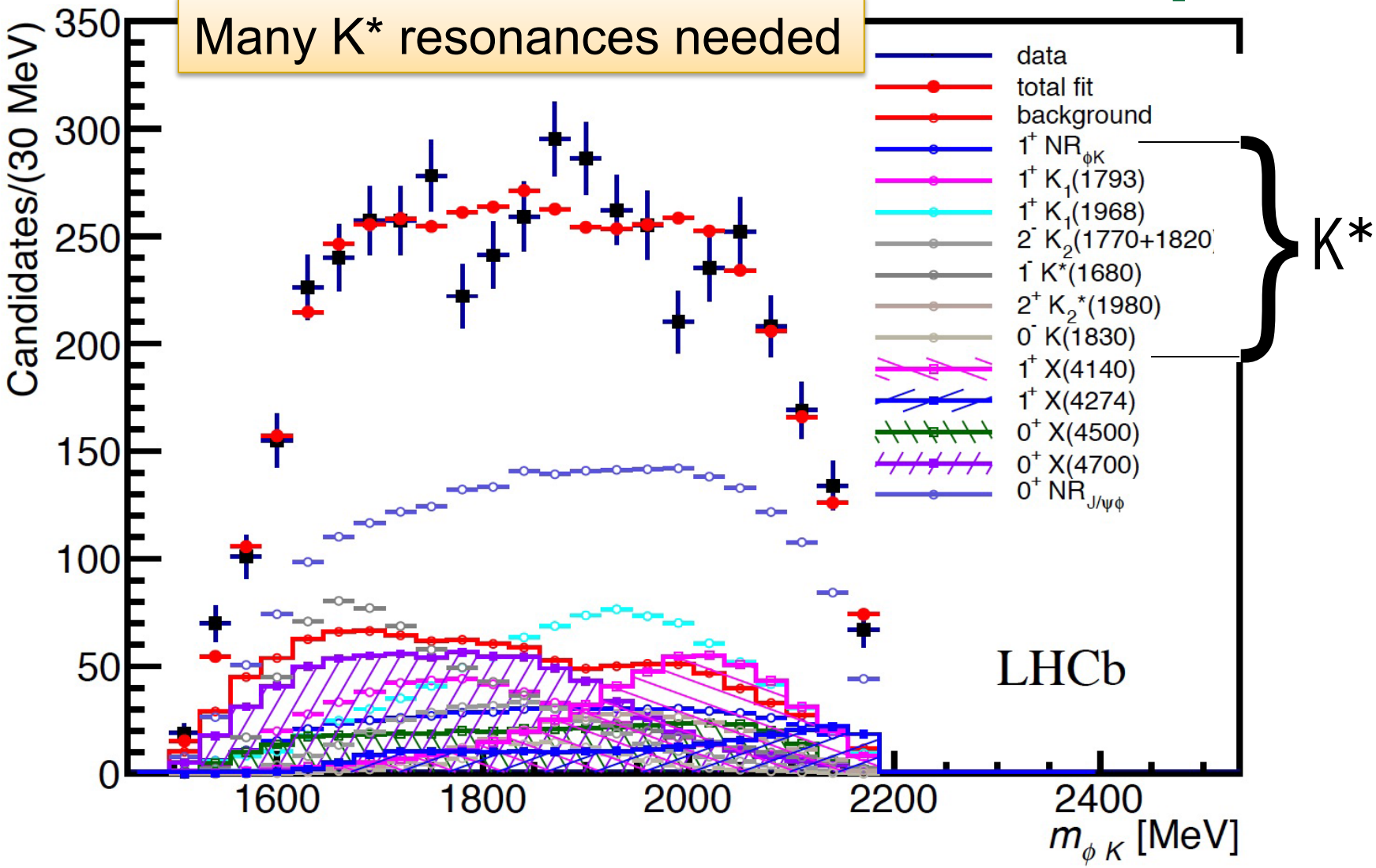
Year	exp. (/fb)	# B^-	mass (MeV)	Γ (MeV)	σ	mass (MeV)	Γ (MeV)	σ
2008	CDF (2.7)	58±10	4143.0	11.7	3.8			
2009	Belle	325±21	4143 fix	11.7 fix	1.9			
2011	CDF (6.0)	115±12	4143.4	15.3	5.0	4274.4	32.3	3.1
2011	LHCb (0.37)	346±20	4143.4 fix	15.3 fix	ul	4274.4 fix	32.3 fix	
2013	CMS (5.2)	2480±160	4148.0	28.0	5.0	4313.8	38	
2013	D0 (10.4)	215±37	4159.0	19.9	3.1	4328.5	30 fix	
2014	Babar (422)	189±14	4143.4 fix	15.3 fix	1,6	4274.4 fix	32.3 fix	1.2

New LHCb (3/fb)

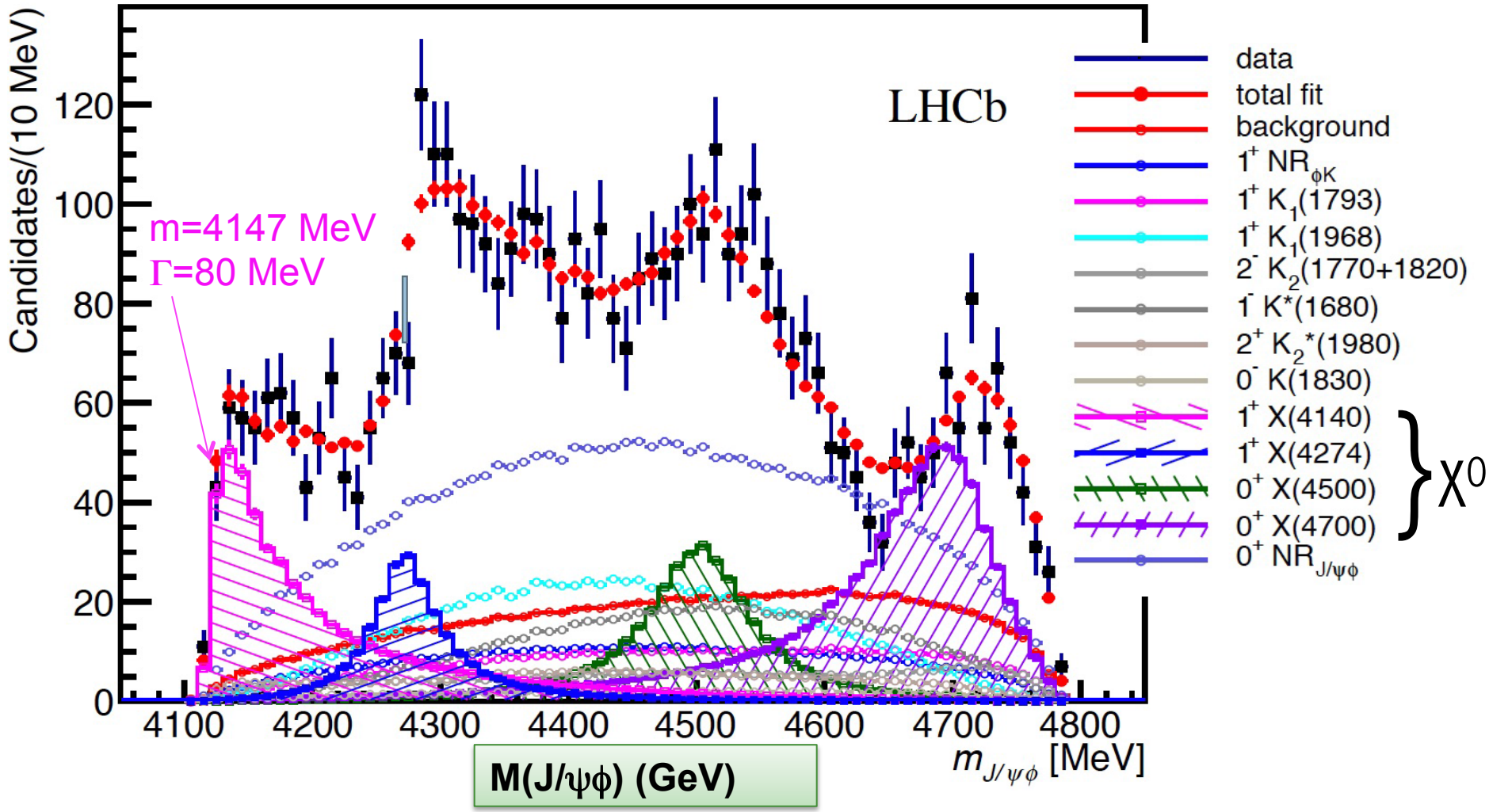
- LHCb has 4289±150 events [arXiv:1406.0755]
- Again do a full amplitude fit including interferences between $B^- \to J/\psi K^{*-}$, $K^{*-} \to \phi K^-$, and $B^- \to X^0 K^-$, $X^0 \to J/\psi\phi$.
- $B^- \to \phi Z^-$, $Z^- \to J/\psi K^-$ is also included in the amplitude fit, but used only as a source of systematic uncertainty

Results of fit: m(φK)

Many K* resonances needed



Full amplitude fit results



- 4 visible structures fit with BW amplitudes

Phys.Rev.Lett. 118 (2017) 022003

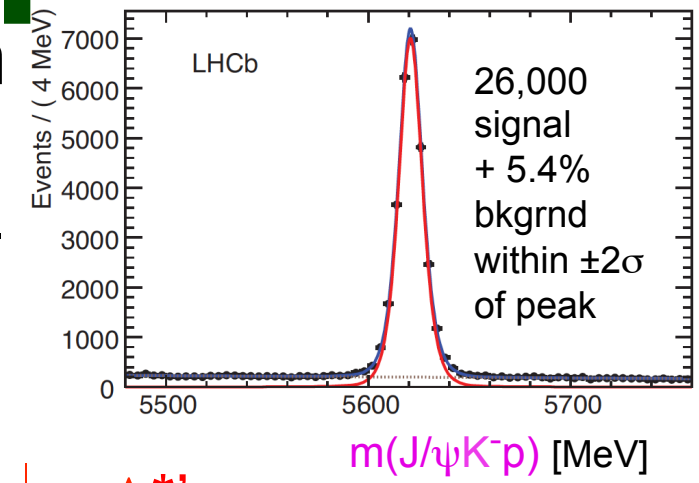
Results of fit

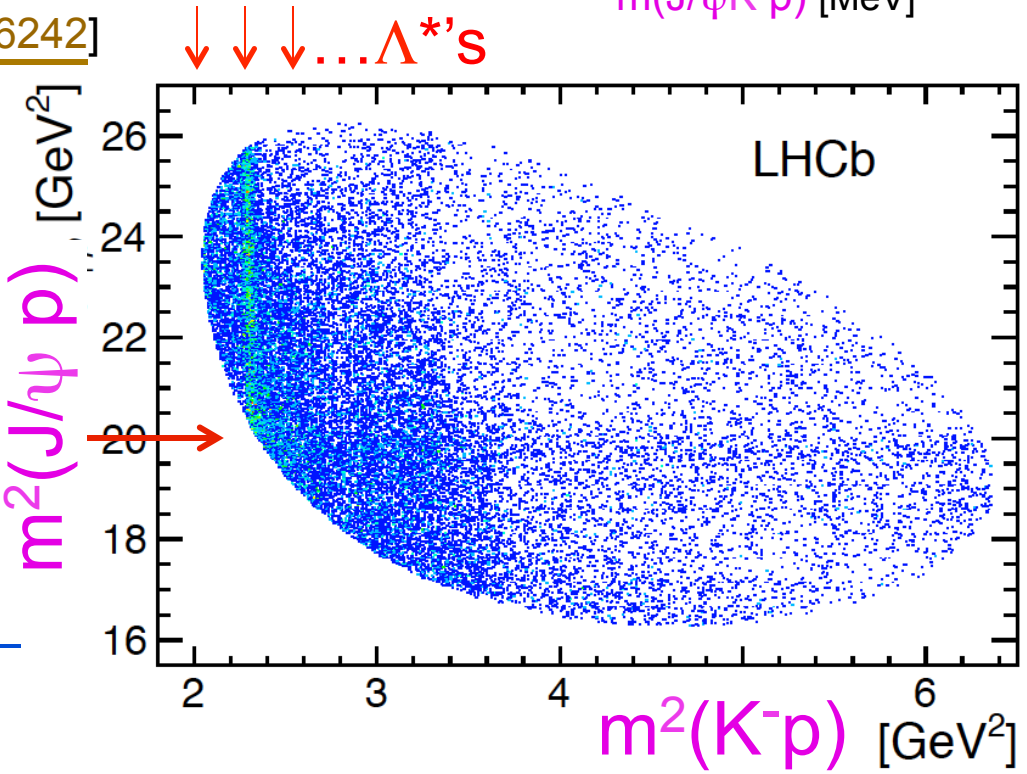
- J^P also measured all with >4σ significances

Particle	J^P	Signif-icance	Mass (MeV)	Γ (MeV)	Fit Fraction (%)
X(4140)	1^+	8.4 σ	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	$13.0 \pm 3.2^{+4.8}_{-2.0}$
X(4274)	1^+	6.0 σ	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	$7.1 \pm 2.5^{+3.5}_{-2.4}$
X(4500)	0^+	6.1 σ	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	$6.6 \pm 2.4^{+3.5}_{-2.3}$
X(4700)	0^+	5.6 σ	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	$12 \pm 5^{+9}_{-5}$
NR	0^+	6.4 σ			$46 \pm 11^{+11}_{-21}$

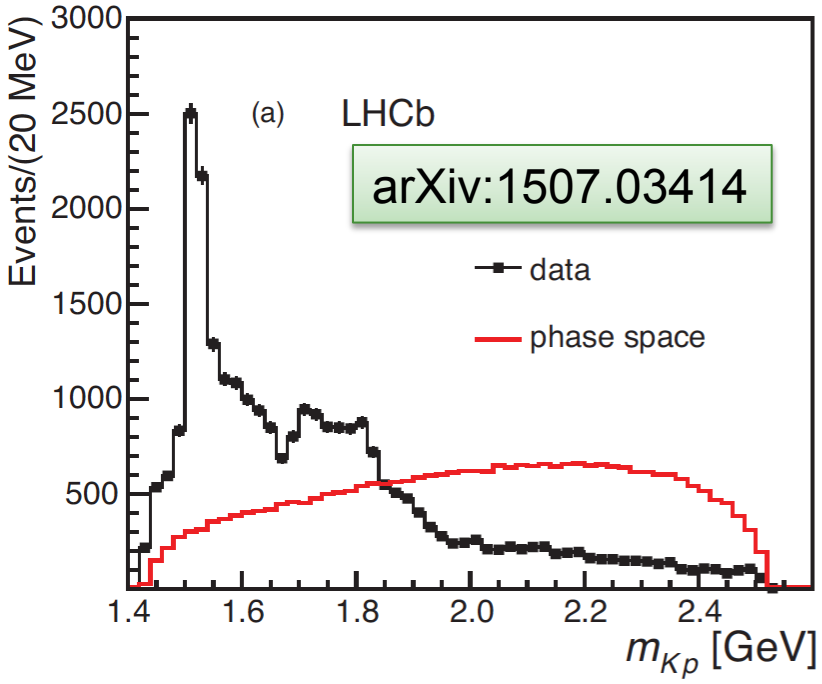
Pentaquarks

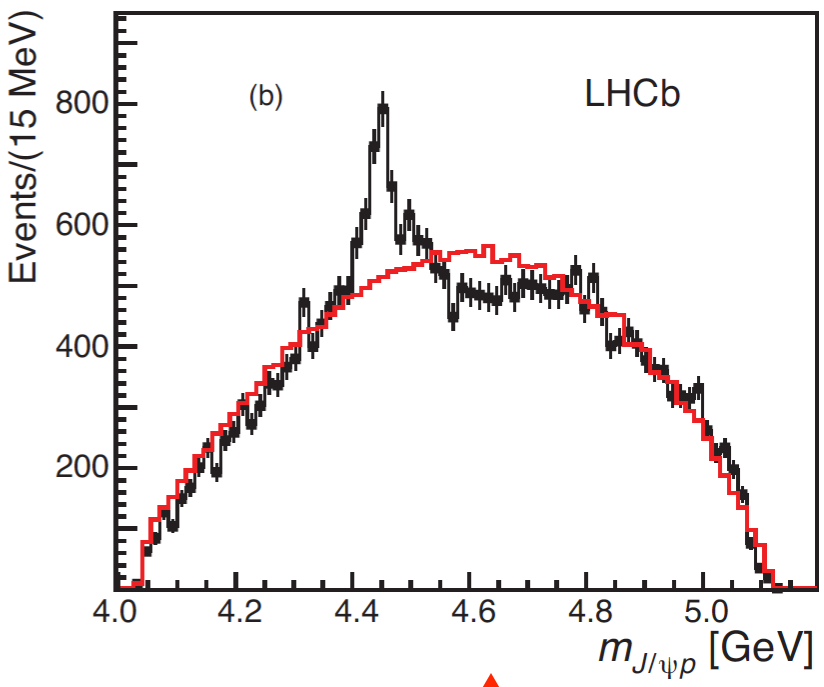
- $\Lambda_b \rightarrow J/\psi K^- p$, first looked for in LHCb as a potential background for $B^0 \rightarrow J/\psi K^+ K^-$
- Large signal found, used for Λ_b lifetime [arXiv:1402.6242]
- Dalitz plot showed an unusual feature [arXiv:1507.03414]

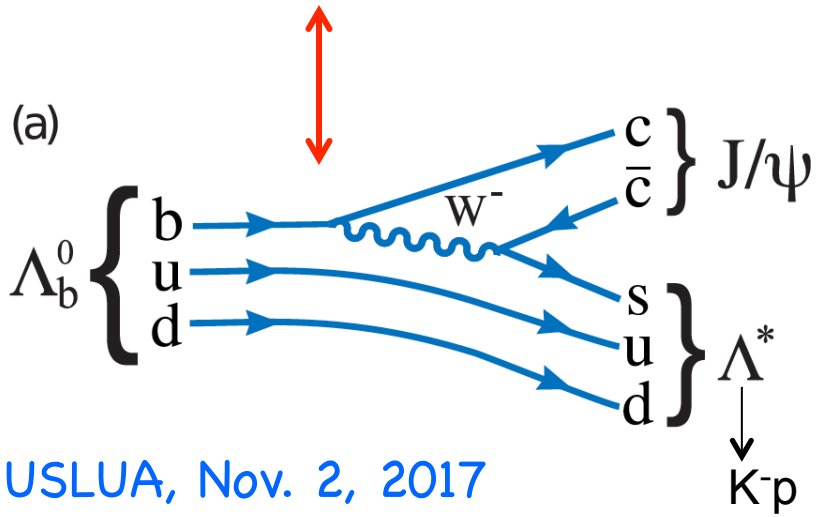


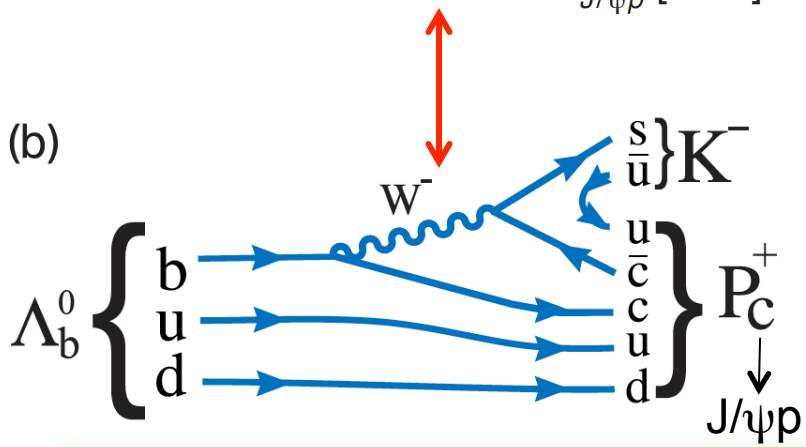


Projections





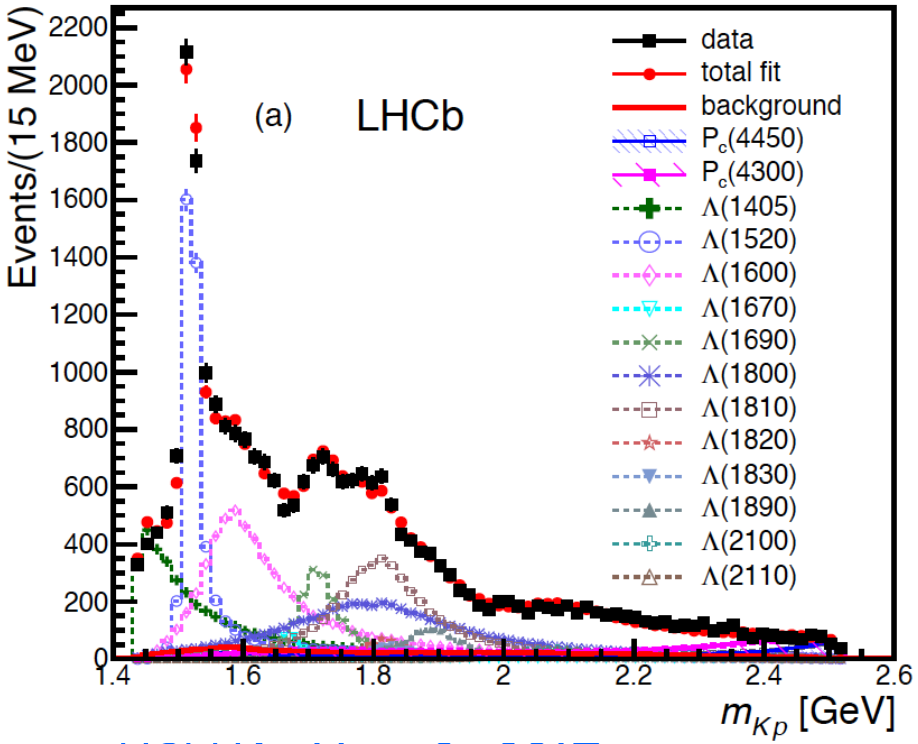


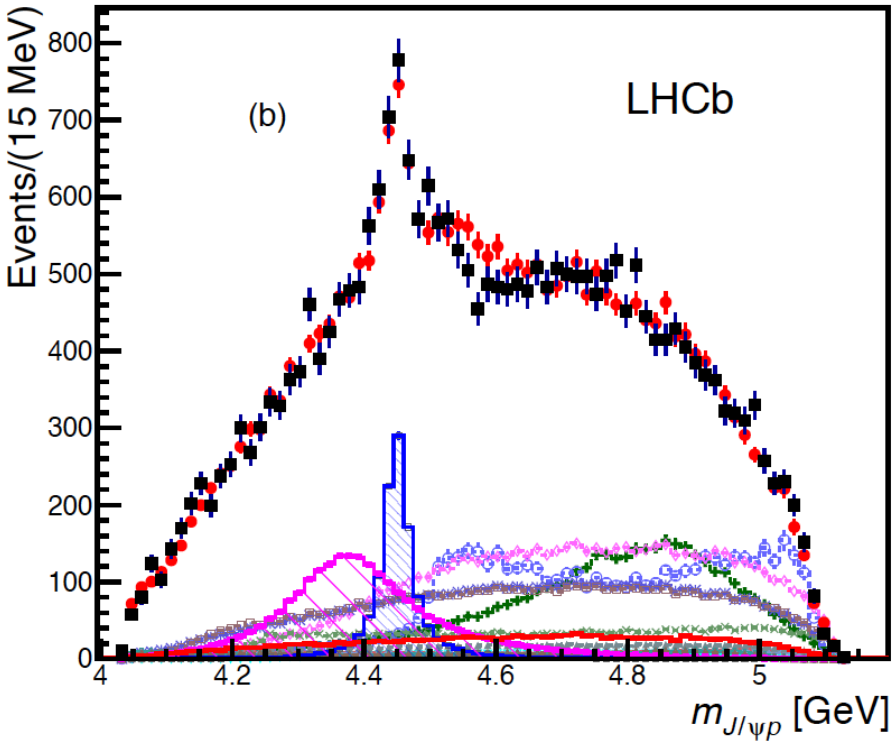


Does this diagram exist?

Model with 2 P_c's

- Do a full amplitude fit. No solution with zero or one P_c states. Best fit has two states, masses 4380±30 MeV, & 4450±3 MeV with J^P=($3/2^-$, $5/2^+$), also ($3/2^+$, $5/2^-$) & ($5/2^+$, $3/2^-$) are allowed

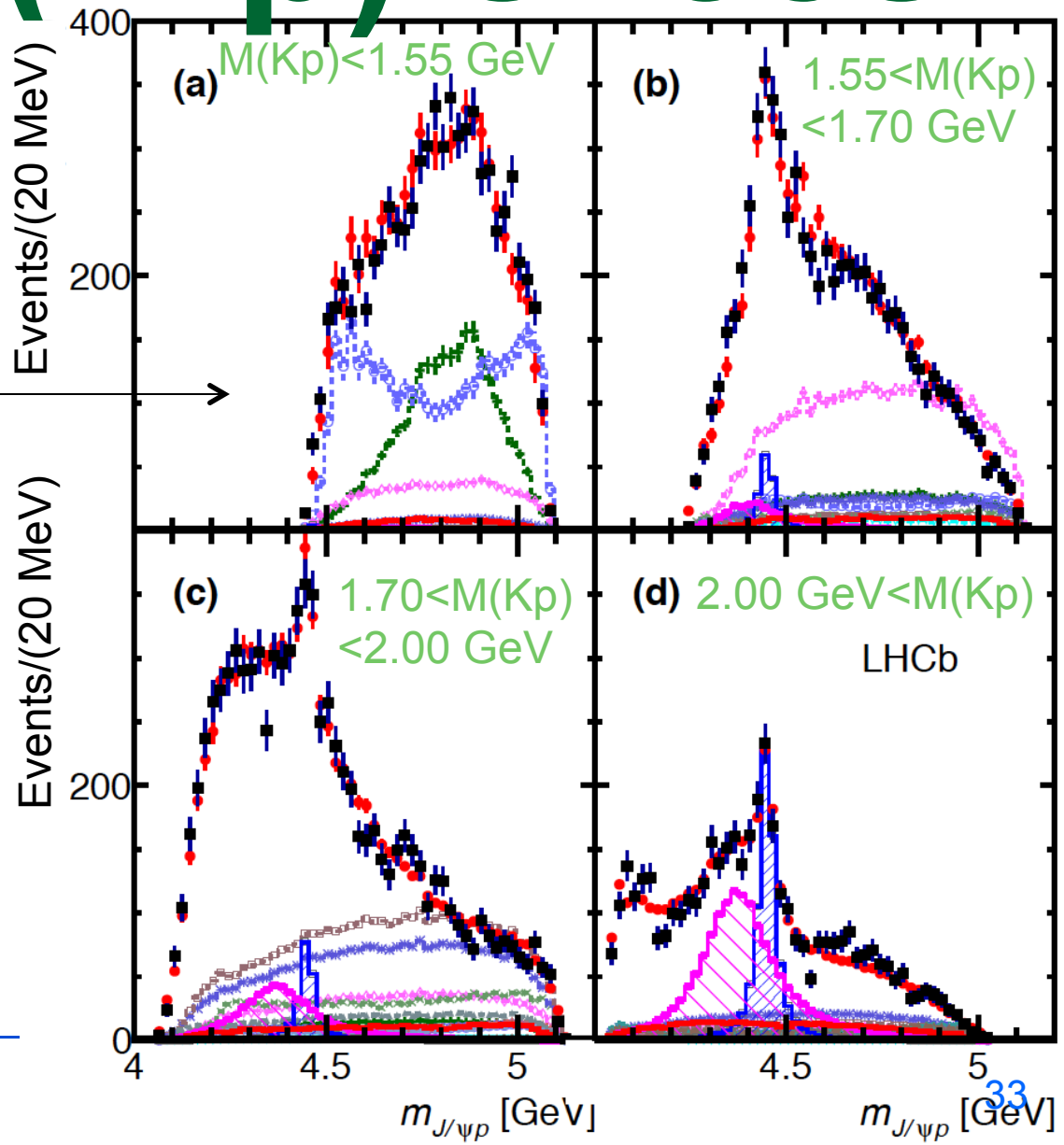




In m(K⁻p) slices

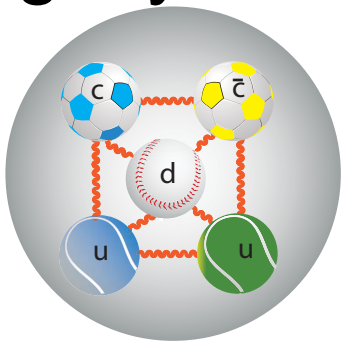
P_c's cannot appear in first interval as they would be outside of the Dalitz plot boundary

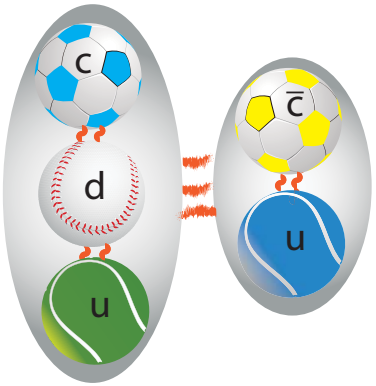
- data
- total fit
- background
- $P_c(4450)$
- $P_c(4380)$
- $\Lambda(1405)$
- $\Lambda(1520)$
- $\Lambda(1600)$
- $\Lambda(1670)$
- $\Lambda(1690)$
- $\Lambda(1800)$
- $\Lambda(1810)$
- $\Lambda(1820)$
- $\Lambda(1830)$
- $\Lambda(1890)$
- $\Lambda(2100)$
- $\Lambda(2110)$



Internal binding?

- Tightly bound or Molecularly bound





- Need to find new states & new decay modes
- Many predicted, e.g. $P_c \rightarrow \Lambda_c D^*$, $\eta_c p$ - high multiplicity final states

Conclusions

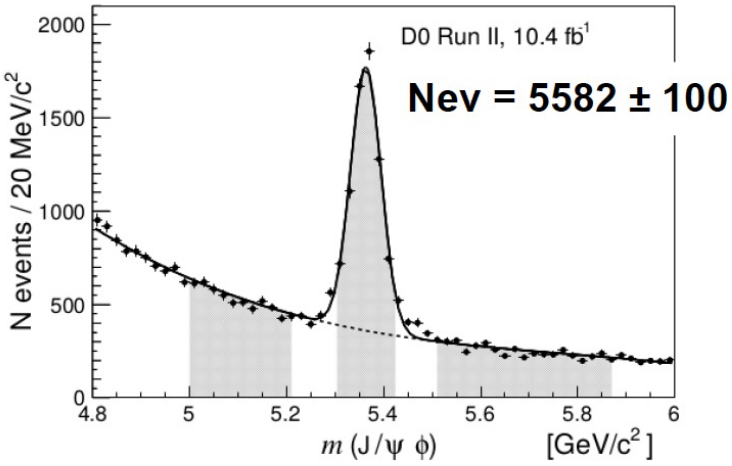
- LHCb is looking for physics beyond the standard model in many new areas
- These searches are enhanced by use of special software triggers that use the online data as the final sample. This will be greatly enhanced in the upgrade as the “hardware” trigger will go away
- Many properties of LHCb make these searches unique: particle ID, muon detection to low p_T, etc…

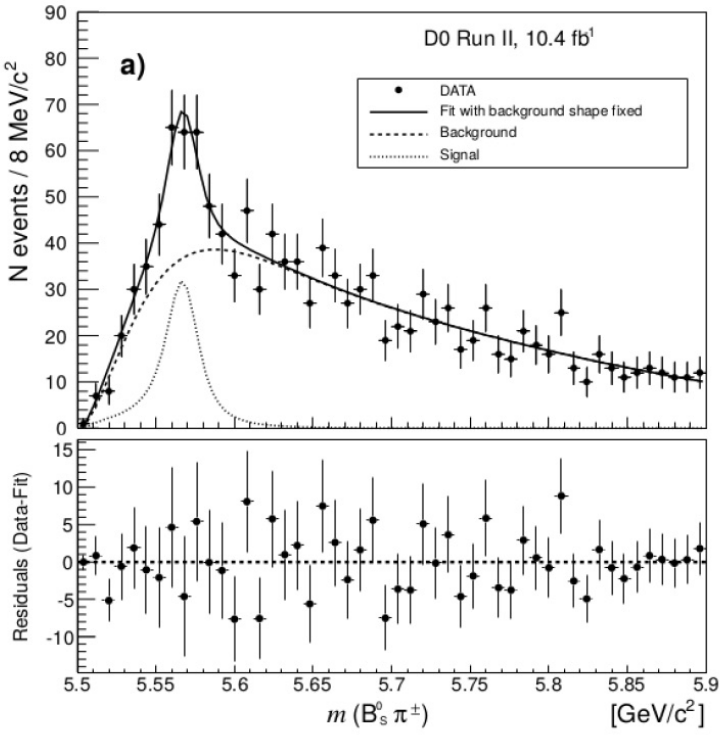
The End

The $\bar{b}s\bar{u}d$ tetraquark

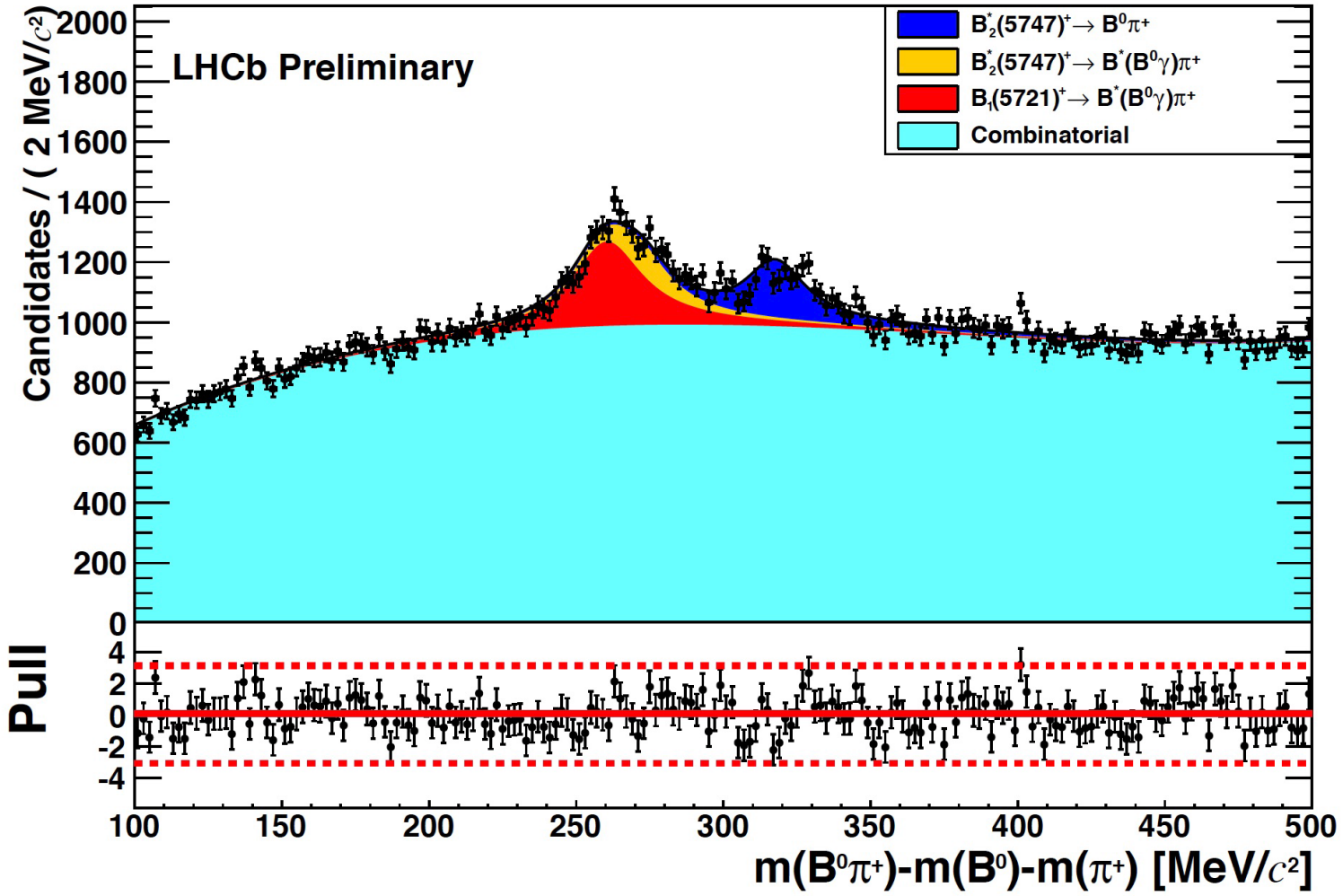
- D0 announced a new state on 24 Feb: X(5568) → $B_s\pi$ arXiv:1602.07588
- CERN seminar 21 March (Monday)
- High production rate and significance of 5.1sigma
- Generated several citations → investigation by other collaborations

$$m = 5567.8 \pm 2.9\,(\text{stat})\,^{+0.9}_{-1.9}\,(\text{syst})\ \text{MeV}/c^2$$
$$\Gamma = 21.9 \pm 6.4\,(\text{stat})\,^{+5.0}_{-2.5}\,(\text{syst})\ \text{MeV}/c^2$$
$$(8.6 \pm 1.9 \pm 1.4)\%$$





B** states at LHCb



$B_s\pi^{\pm}$

- Very large, clean Bs samples, different final states

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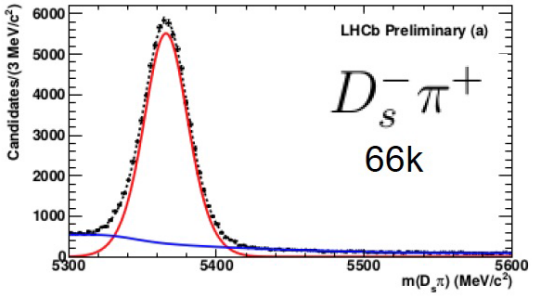
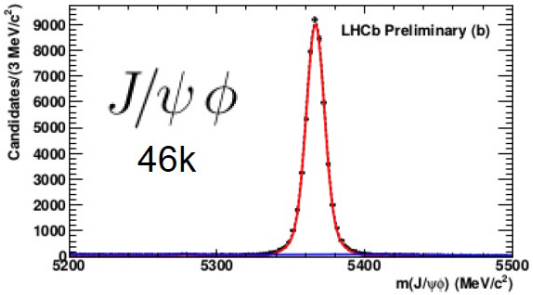
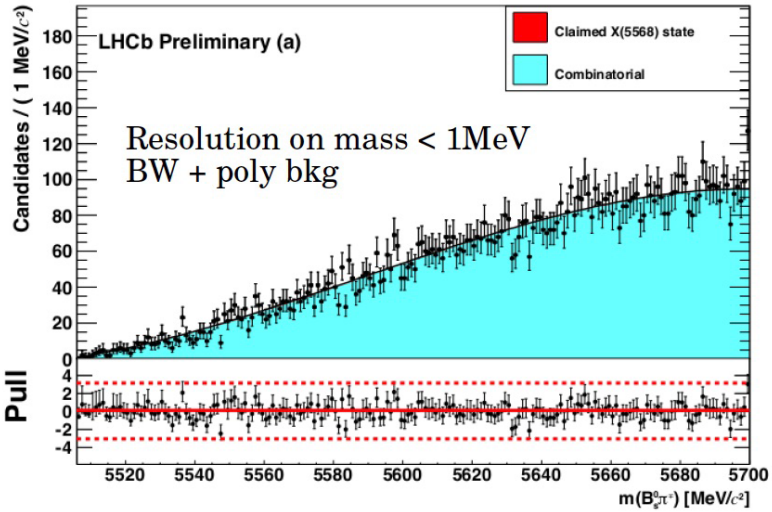




- Slightly different selection compared to what shown at Moriond QCD
- Add a pion → no peak observed at 5568 MeV
- Several cross check with B plus pion modes
- We can put an UL on production

$$\rho_X^{\mathrm{LHCb}} \equiv \frac{\sigma(pp \to X(5568) + \text{anything}) \times \mathcal{B}\left(X(5568) \to B_s^0\pi\right)}{\sigma(pp \to B_s^0 + \text{anything})}$$

$$= \frac{N(X)}{N(B_s^0)} \times \frac{1}{\epsilon^{\mathrm{rel}}(X)}$$

$$\begin{aligned}
\rho_X^{\mathrm{LHCb}}(B_s^0\ p_{\mathrm{T}} > \ 5\,\mathrm{GeV}/c) &< 0.009\,(0.010)\ @\ 90\,(95)\,\%\ \mathrm{CL}\,, \\
\rho_X^{\mathrm{LHCb}}(B_s^0\ p_{\mathrm{T}} > 10\,\mathrm{GeV}/c) &< 0.016\,(0.018)\ @\ 90\,(95)\,\%\ \mathrm{CL}\,.
\end{aligned}$$