Multiquark Hadrons

Stephen Lars Olsen Institute for Basic Science **Daejeon KOREA**

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The XYZ mesons

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K + (J/\psi\,\pi^+\pi^-)$	Belle [82, 89] , BaBar [85], LHCb [90]
				$p\bar{p} \to (J/\psi\,\pi^+\pi^-) + ...$	CDF [83, 91, 92, 125], D0 [84]
				$B \to K + (J/\psi\,\pi^+\pi^-\pi^0)$	Belle [94] , BaBar [59]
				$B \to K + (D^0\bar{D}^0\pi^0)$	Belle [95] , BaBar [96]
				$B \to K + (J/\psi\,\gamma)$	BaBar [126], Belle [127] , LHCb [128]
				$B \to K + (\psi'\,\gamma)$	BaBar [126], Belle [127] , LHCb [128]
				$pp \to (J/\psi\,\pi^+\pi^-) + ...$	LHCb [86], CMS [87]
$X(3915)$	3917.4 ± 2.7	28^{+10}_{-9}	0^{++}	$B \to K + (J/\psi\,\omega)$	Belle [58] , BaBar [59]
				$e^+e^- \to e^+e^- + (J/\psi\,\omega)$	Belle [60] , BaBar [61]
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^- + (D\bar{D})$	Belle [64] , BaBar [65]
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27]
				$e^+e^- \to J/\psi + (...)$	Belle [26]
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma + (D\bar{D})$	BaBar [129], Belle [130]
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	Belle [32]
$Y(4140)$	4144 ± 3	17 ± 9	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [74, 75], CMS [77]
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27]
$Y(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	BaBar [30, 131], CLEO [132] , Belle [32]
				$e^+e^- \to (J/\psi\,\pi^+\pi^-)$	CLEO [133]
				$e^+e^- \to (J/\psi\,\pi^0\pi^0)$	CLEO [133]
$Y(4274)$	4292 ± 6	34 ± 16	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [75], CMS [77]
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(J/\psi\,\phi)$	Belle [81]
$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	BaBar [31], Belle [33]
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [134]
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	Belle [33]
$Z_c^+(3900)$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII [39], Belle [40]
				$Y(4260) \to \pi^- + (D\bar{D}^*)^+$	BESIII [56]
$Z_c^+(4020)$	4024 ± 2	10 ± 3	$1(?)^{+(?)-}$	$Y(4260) \to \pi^- + (h_c\,\pi^+)$	BESIII [41]
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$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [43], BaBar [53]
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$B \to K + (J/\psi\,\pi^+)$	Belle [51]
$Z_2^+(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [43], BaBar [53]
$Z^+(4430)$	4477 ± 20	181 ± 31	1^{+-}	$B \to K + (\psi'\,\pi^+)$	Belle [44, 46, 47], LHCb [48]
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$Y_b(10890)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$	Belle [117]
$Z_b^+(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	"$\Upsilon(5S)'' \to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n = 1, 2, 3$	Belle [119, 122]
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$Z_b^0(10610)$	$10609\pm\ 6$		1^{+-}	"$\Upsilon(5S)'' \to \pi^0 + (\Upsilon(nS)\,\pi^0)$, $n = 1, 2, 3$	Belle [121]
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Now lots of charged Z_c mesons

and two Z_b mesons

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The list keeps growing

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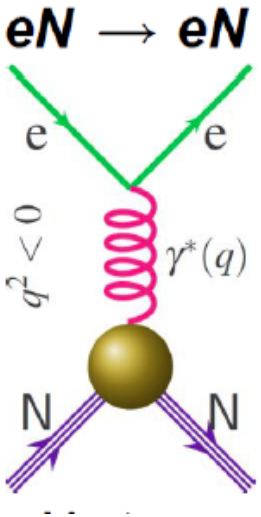
New preliminary result from BESIII

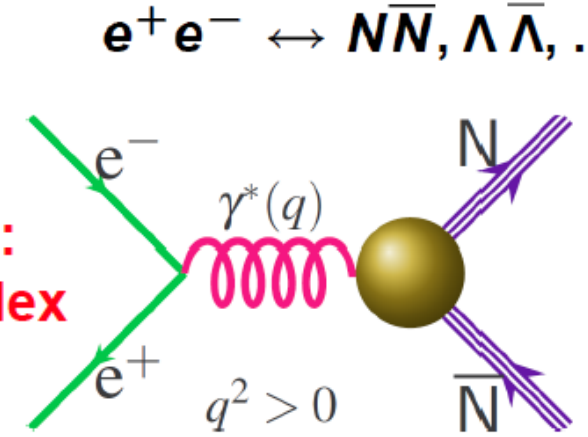
on the time-like form-factor of the Λ

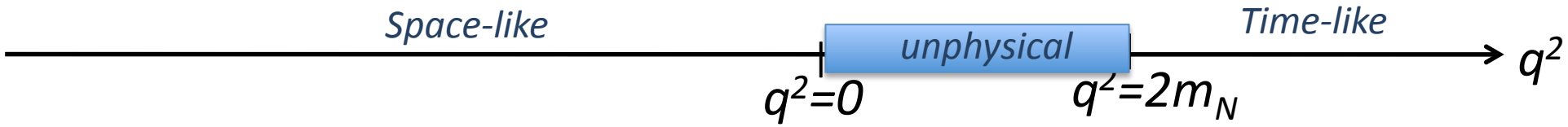
space-like & time-like form-factors

Space-like:
FF real



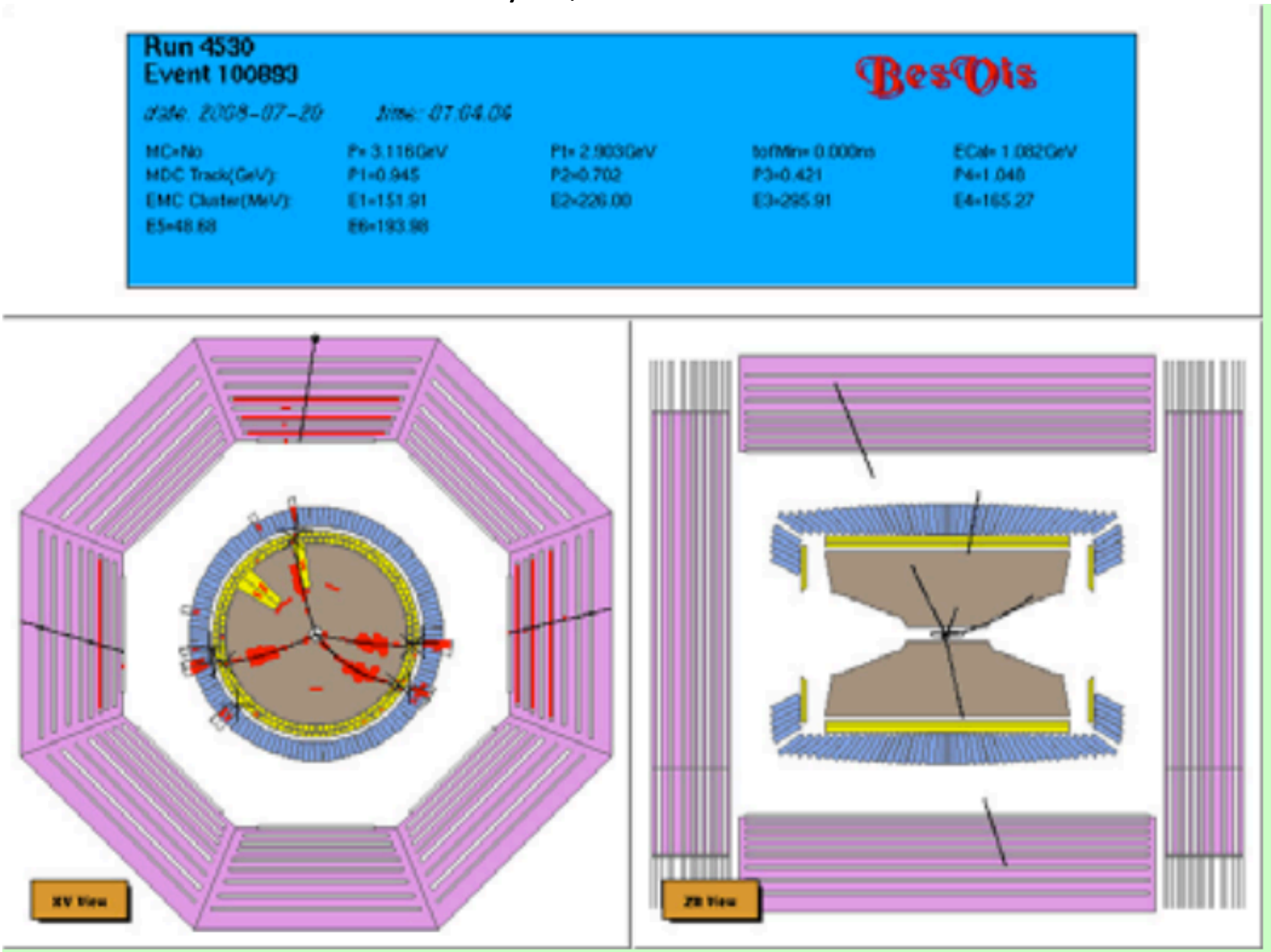
Time-like:
FF complex





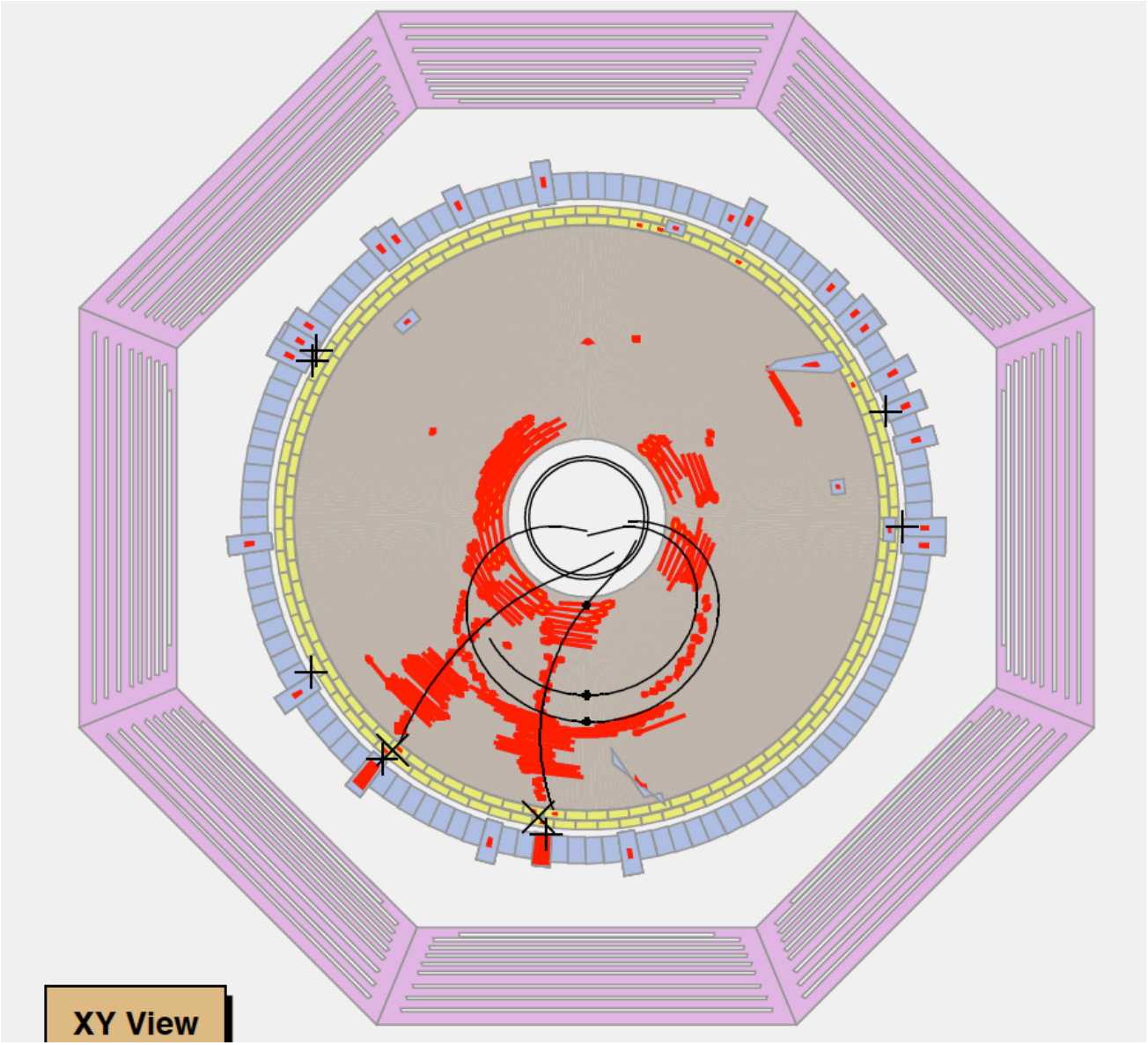
First event in BESIII

July 20, 2007



First collision event

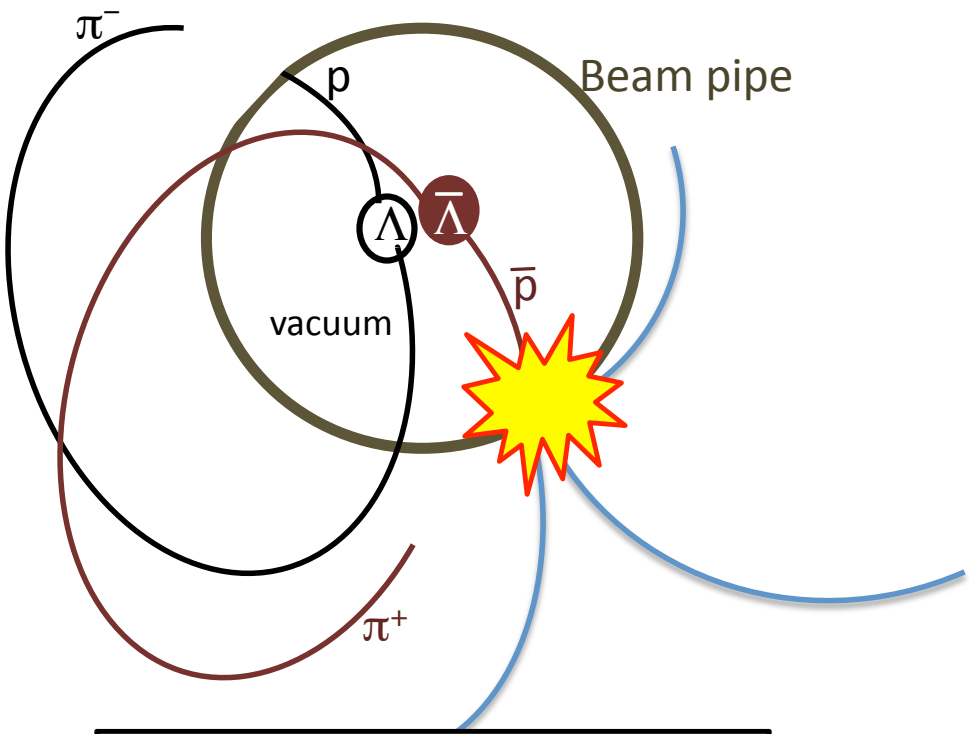
events we don’t usually show in public



What would a $\Lambda\bar{\Lambda}$ at rest look like in BESIII

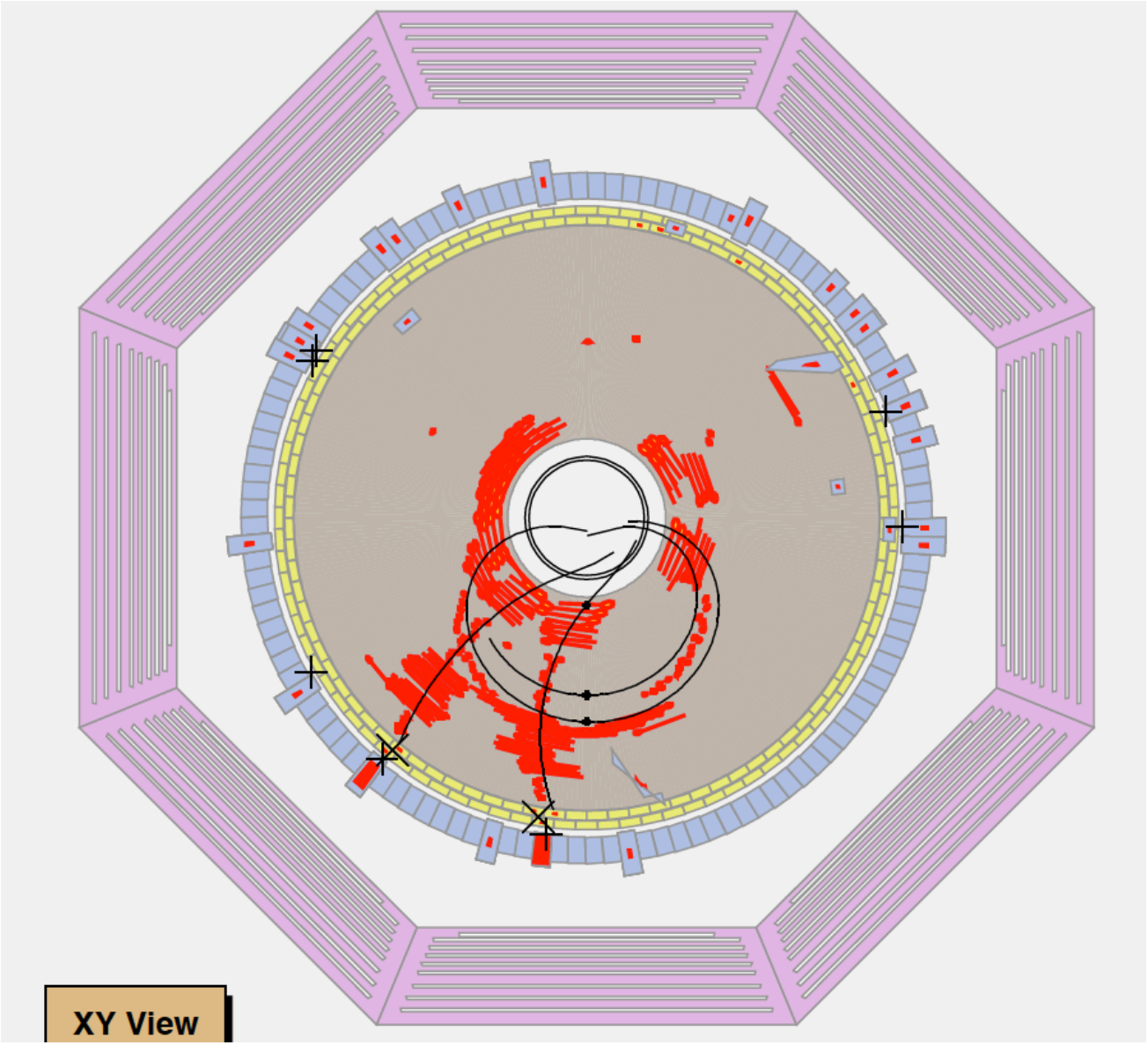
For $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$

Tracking volume



1 π^+ && 1 π^- with p≈100 MeV/c
at least 1 track from r≈3cm

about like this



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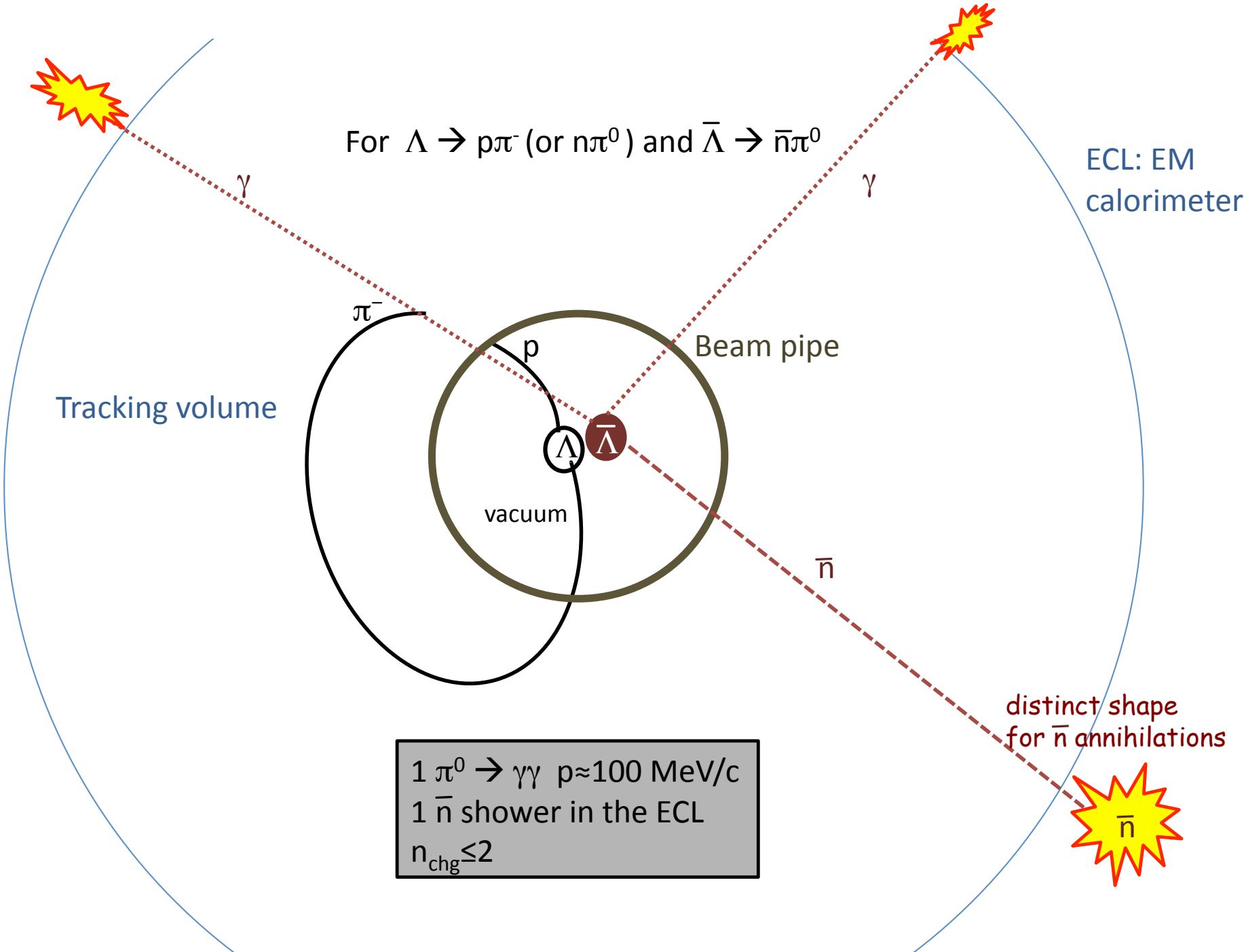
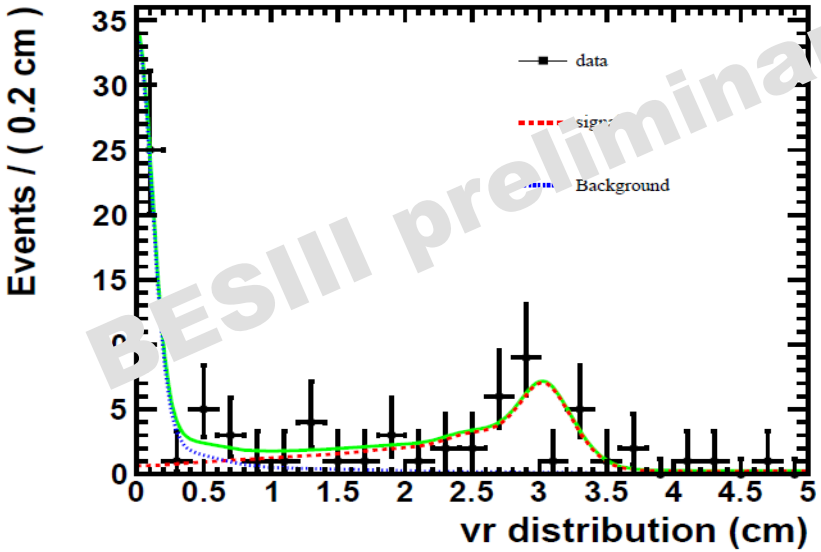
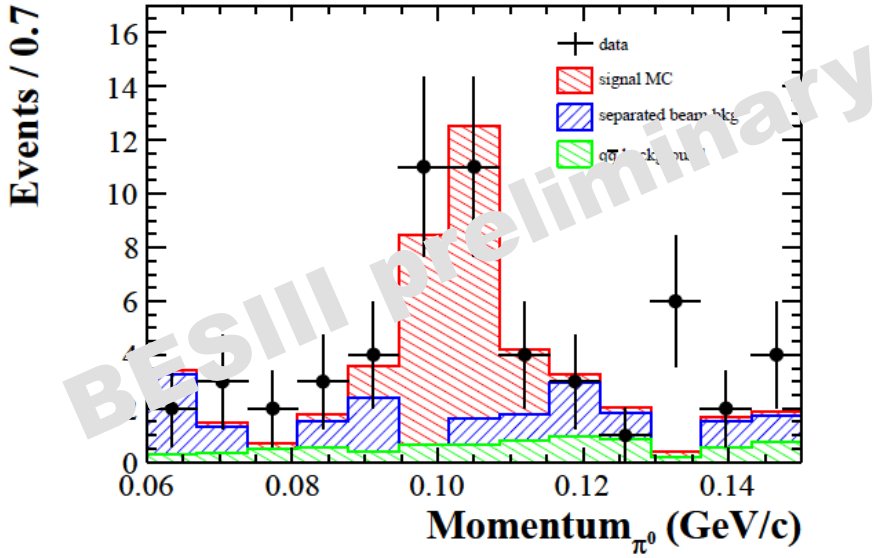


@ $E_{cm} = 2m_{\Lambda} + 1$ MeV

For $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$



For $\Lambda \to p\pi^-$ (or $n\pi^0$) and $\Lambda \to \bar{n}\pi^0$



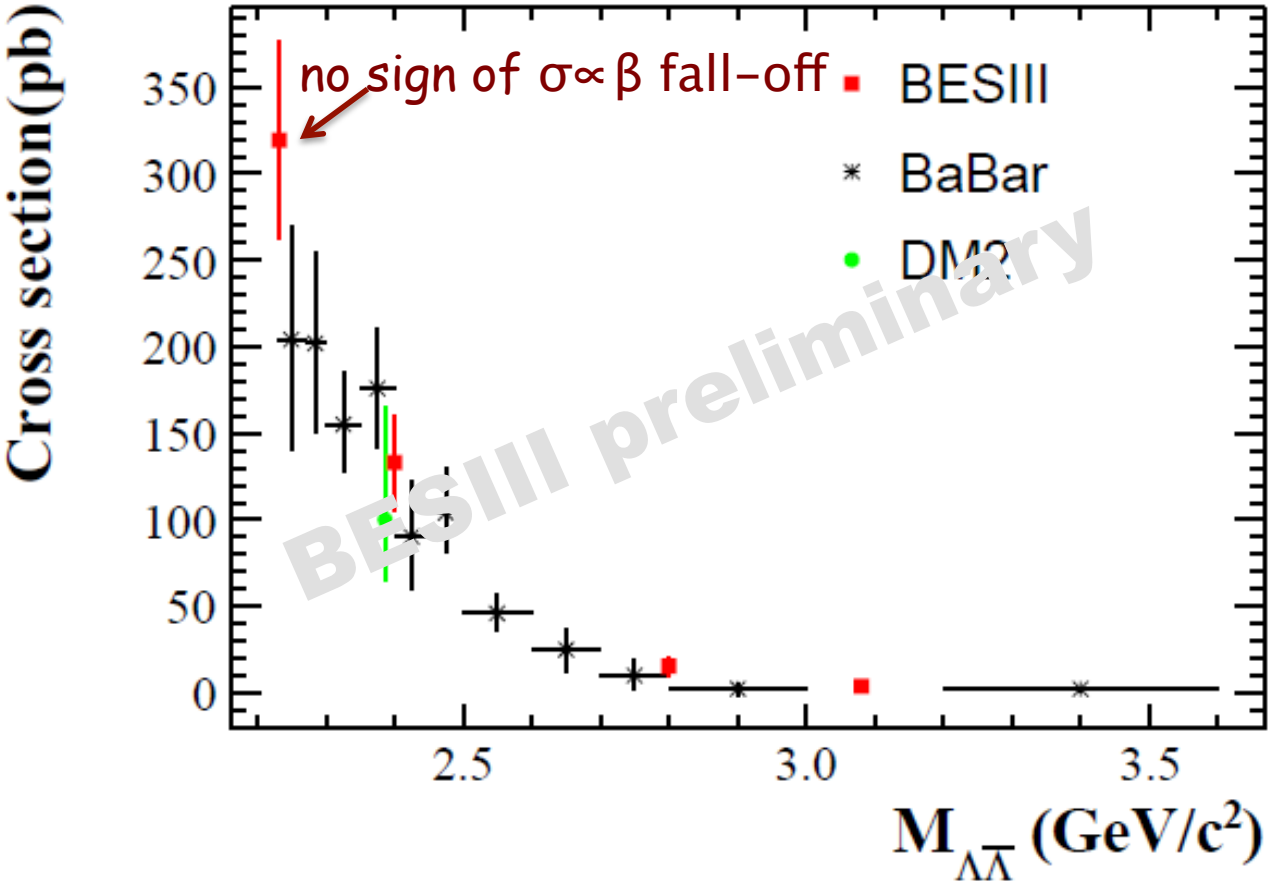
$\sqrt{s}$ (MeV)	Reconstruction	σ_{Born} (pb)
2232.4	$\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$	$325 \pm 53 \pm 46$
	$\bar{\Lambda} \to \bar{n}\pi^0$	$(3.0 \pm 1.0 \pm 0.4) \times 10^2$
	combined	320 ± 58
2400.0		$133 \pm 20 \pm 19$
2800.0		$15.3 \pm 5.4 \pm 2.0$
3080.0		$3.9 \pm 1.1 \pm 0.5$

two methods are consistent

conventional analyses at higher energies

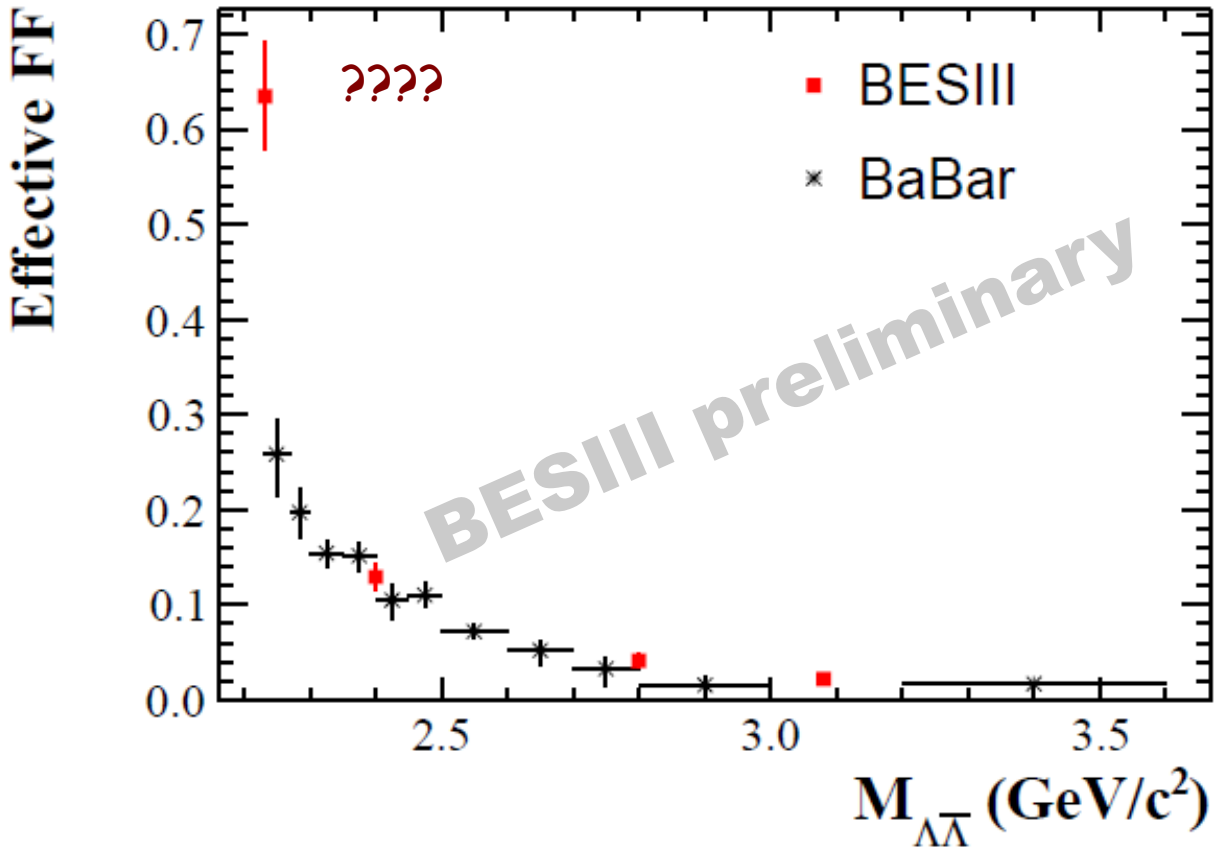
Cross section: $e^+e^- \rightarrow \gamma^* \rightarrow \Lambda\bar{\Lambda}$

$$\sigma_{\Lambda\bar{\Lambda}}(m) = \frac{4\pi\alpha^2\beta}{3m^2}\left[\left|G_M(m)\right|^2 + \frac{1}{2\tau}\left|G_E(m)\right|^2\right] = \frac{4\pi\alpha^2\beta}{3m^2}\left|G_{eff}(m)\right|^2\left(1+1/2\tau\right)$$



Effective time-like form-factor of the Λ

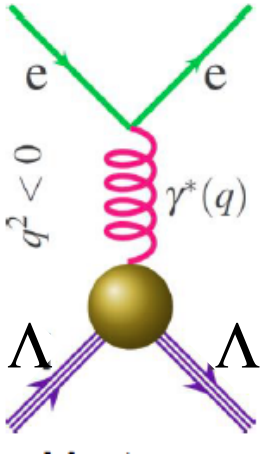
$$\left|G_{eff}(m)\right| = \sqrt{\frac{3m^2\sigma_{\Lambda\bar{\Lambda}}}{4\pi\alpha^2\beta(1+1/2\tau)}}$$



Relation to the Λ's time-like Form-Factor

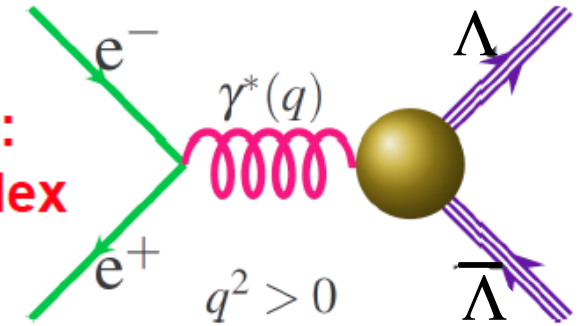
Space-like:
FF real

$e\Lambda \rightarrow e\Lambda$

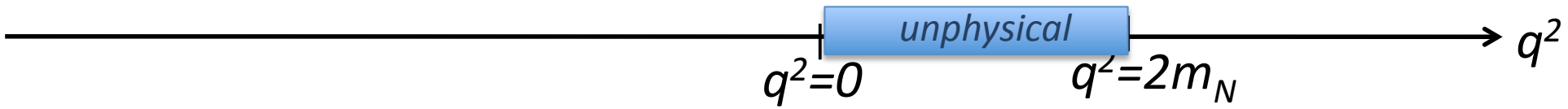


Time-like:
FF complex

$e^+e^- \rightarrow \gamma^* \rightarrow \Lambda\bar{\Lambda}$

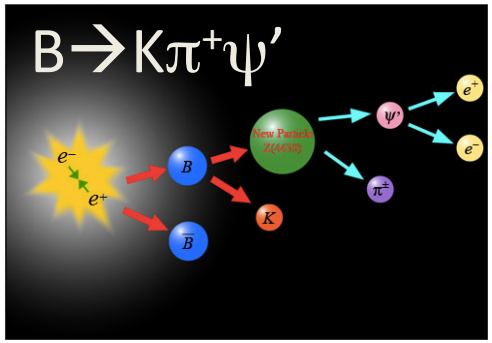


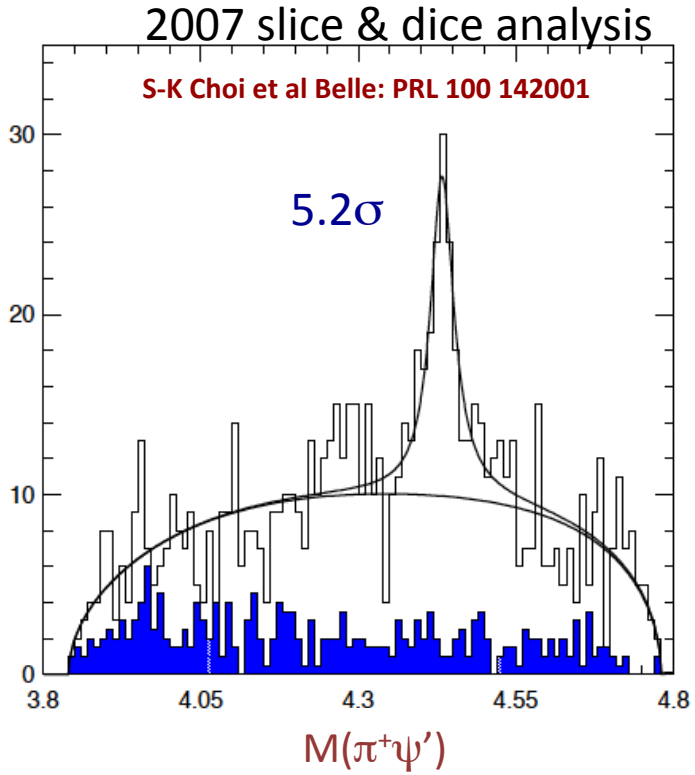
Is there some structure here?



The Z(4430)

Found by Belle in 2007



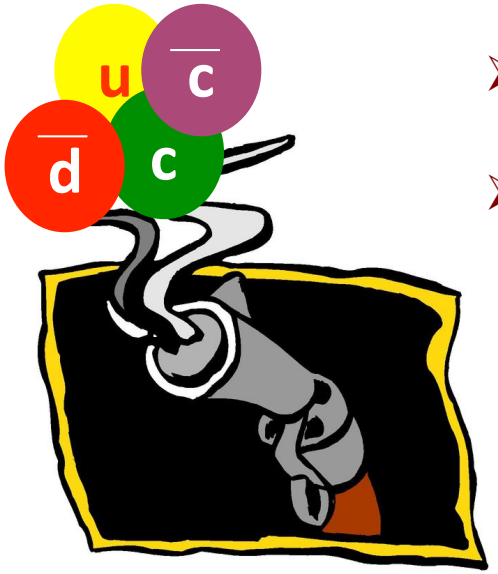


$$M = 4433 \pm 4 \pm 2 \text{ MeV}$$

$$\Gamma = 45^{+18+30}_{-13-13} \text{ MeV}$$

$$Bf(B^0 \to Z^-_{4430} K^+) \times Bf(Z^-_{4430} \to \pi^- \psi') = (4.1 \pm 1.9 \pm 1.4) \times 10^{-5}$$

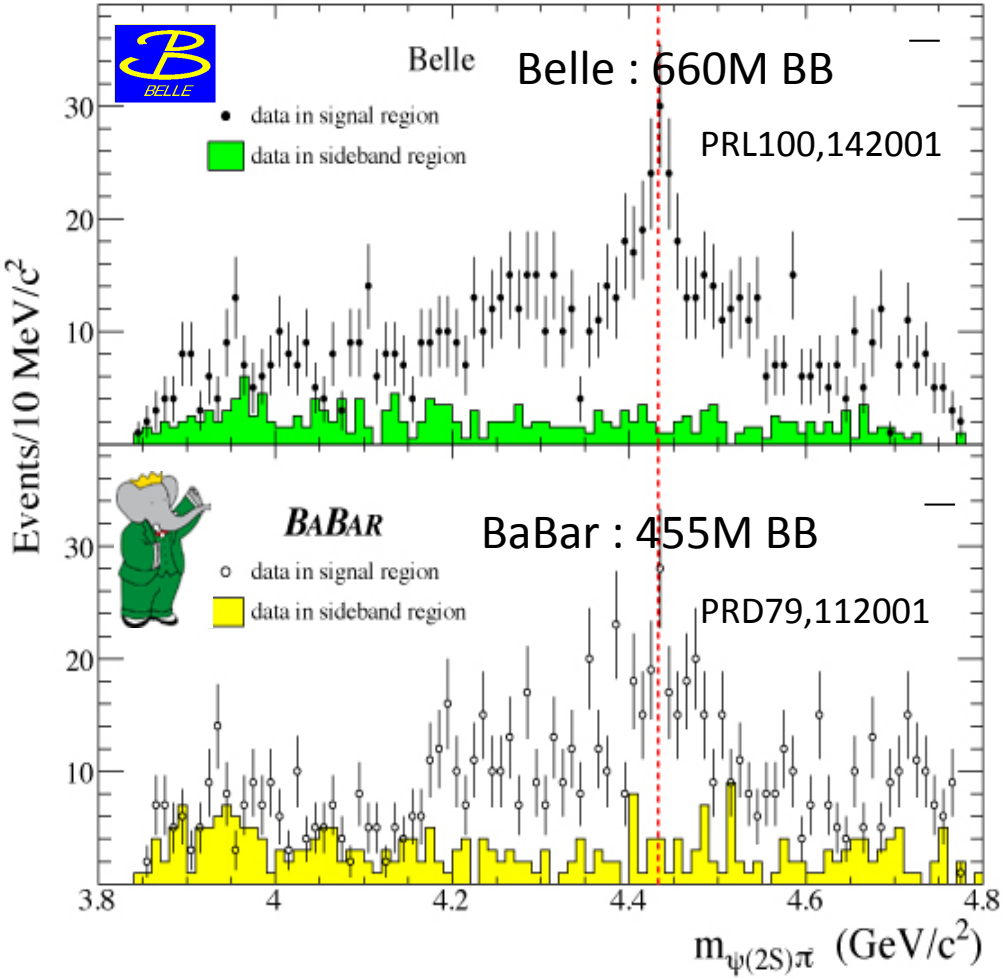
Z(4430), "smoking gun" multiquark meson?



- decays to ψ' ➔ must contain $c\bar{c}$ pair
- electrically charged ➔ must contain $u\bar{d}$ pair

If it is a real meson …

Neither confirmed nor contradicted by BaBar



$Z(4430)^{\pm} \rightarrow \psi(2S)\pi^{\pm}$

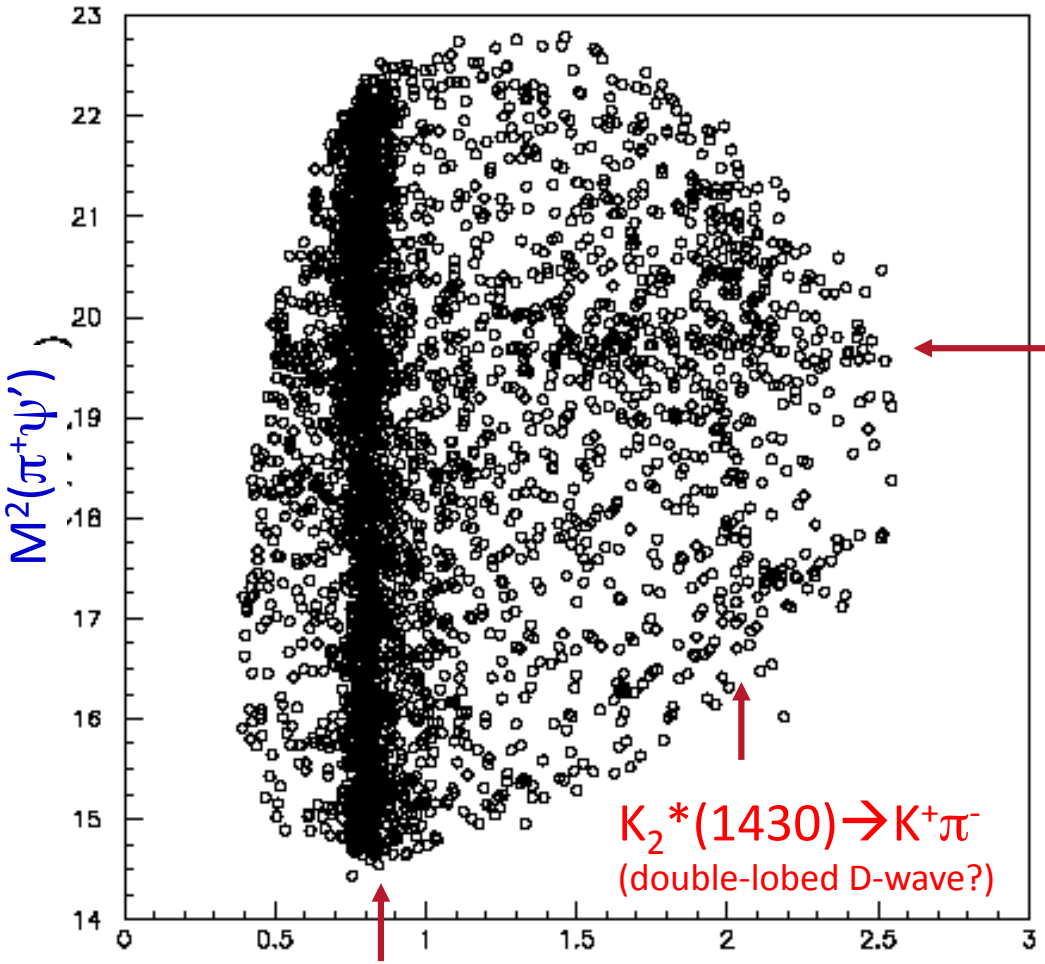
Significant signal at Belle

v.s.

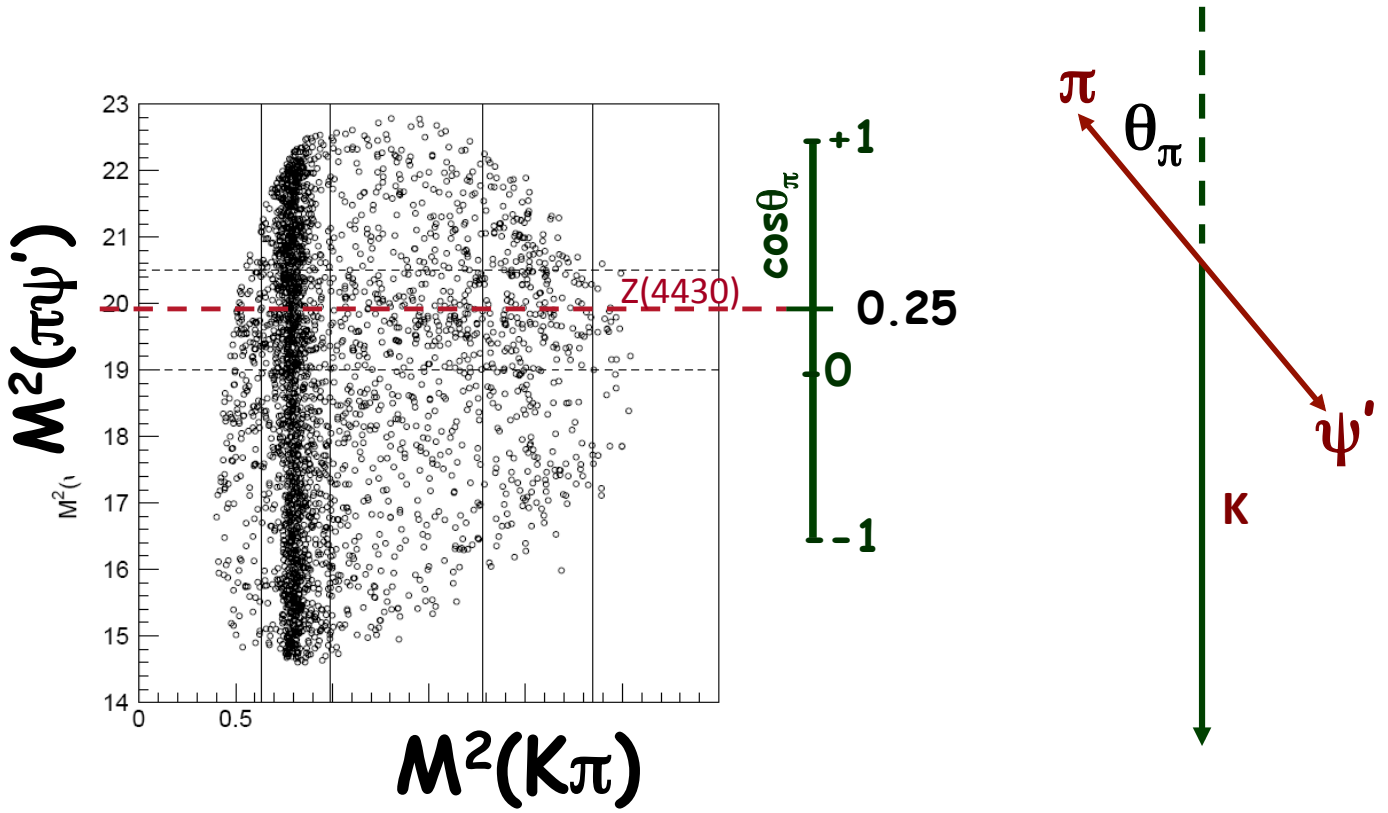
Only hint with 1.9σ at BaBar

Statistically, both are not contradicting with each other, but clear answer is to be given by higher statistics data.

Dalitz Plot

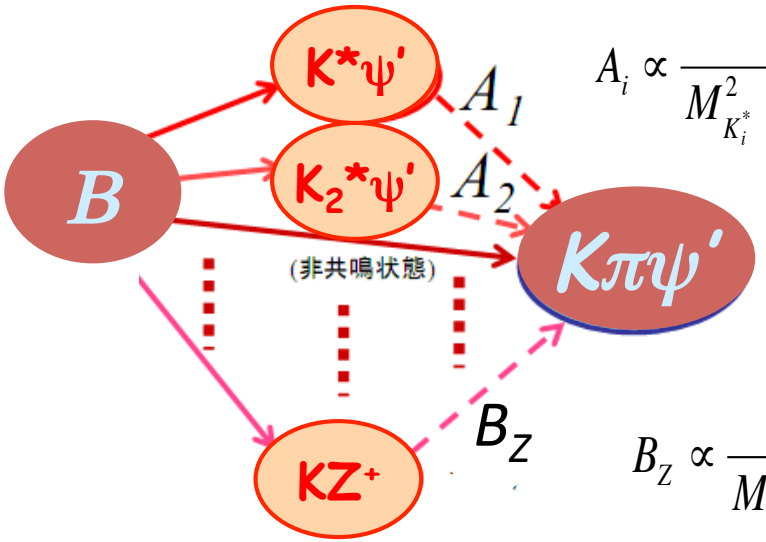

23
22
21
20
19
18
17
16
15
14
0
0.5
1
1.5
2
2.5
3
$M^2(\pi^+\psi')$
$M^2(K^+\pi^-)$
Z(4430)?
$K_2^*(1430)\rightarrow K^+\pi^-$
(double-lobed D-wave?)
$K^*(890)\rightarrow K^+\pi^-$

“Reading” a Dalitz plot



M ($\pi\psi'$) & $\cos\theta_\pi$ are tightly correlated;
a peak in $\cos\theta_\pi$ ➔ peak in M($\pi\psi'$)

2-body isobar model for →Kπψ'



$$A_i \propto \frac{1}{M^2_{K^*_i} - m^2_{K\pi} - iM_{K^*_i}\Gamma_{K^*_i}}$$

$$B_Z \propto \frac{1}{M^2_Z - m^2_{\psi'\pi} - iM_Z\Gamma_z}$$

Does $|M|^2 \propto \left|\sum_i \alpha_i A_i^{BW}\right|^2$ fit the data?

Or do you need $|M|^2 \propto \left|\left(\sum_i \alpha_i A_i^{BW}\right) + \beta B_Z^2\right|^2$?

Our default model

κψ'

K*(890)ψ'

K*(1410)ψ'

K_0*(1430)ψ'

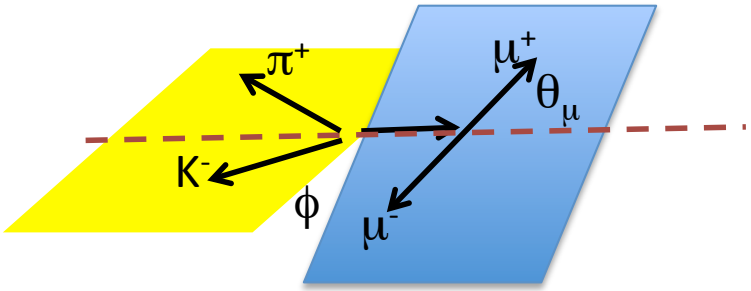
K_2*(1430)ψ'

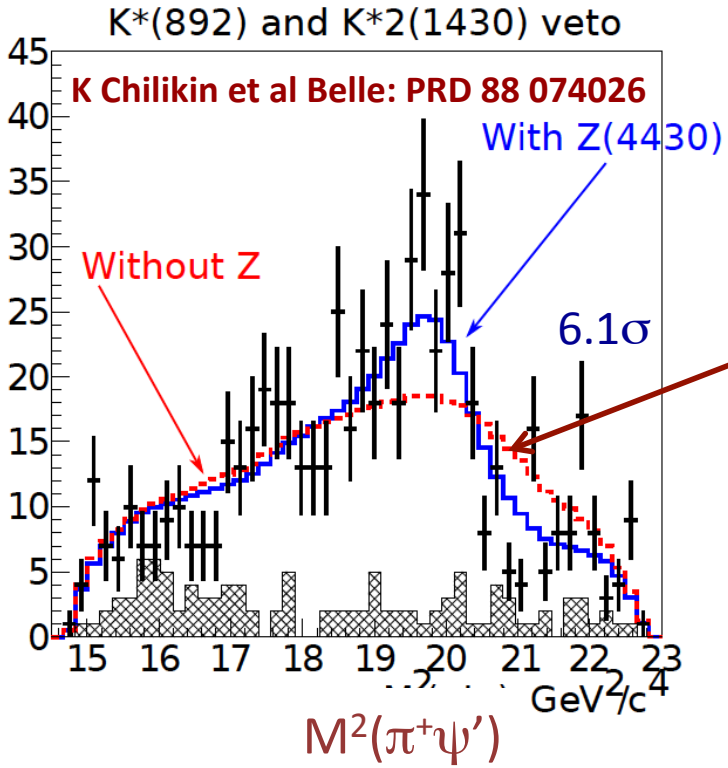
K*(1680)ψ'

KZ+

2013: 4-Dim ampl. Analysis from Belle

4-dim ampl. anal: $M_{K\pi}$, $M_{\pi\psi'}$, θ_μ, ϕ





higher mass & broader width:

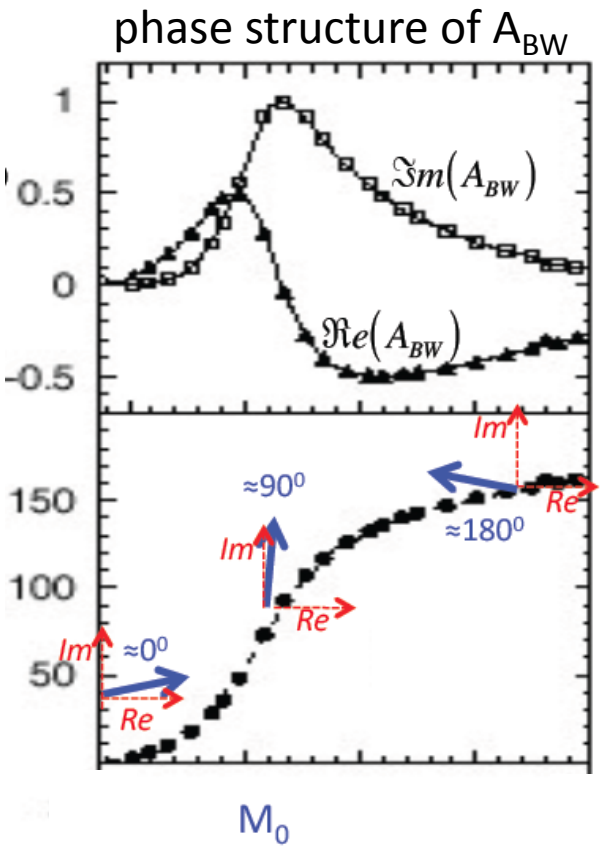
$$M = 4485^{+22+28}_{-22-11}\ \text{MeV}$$

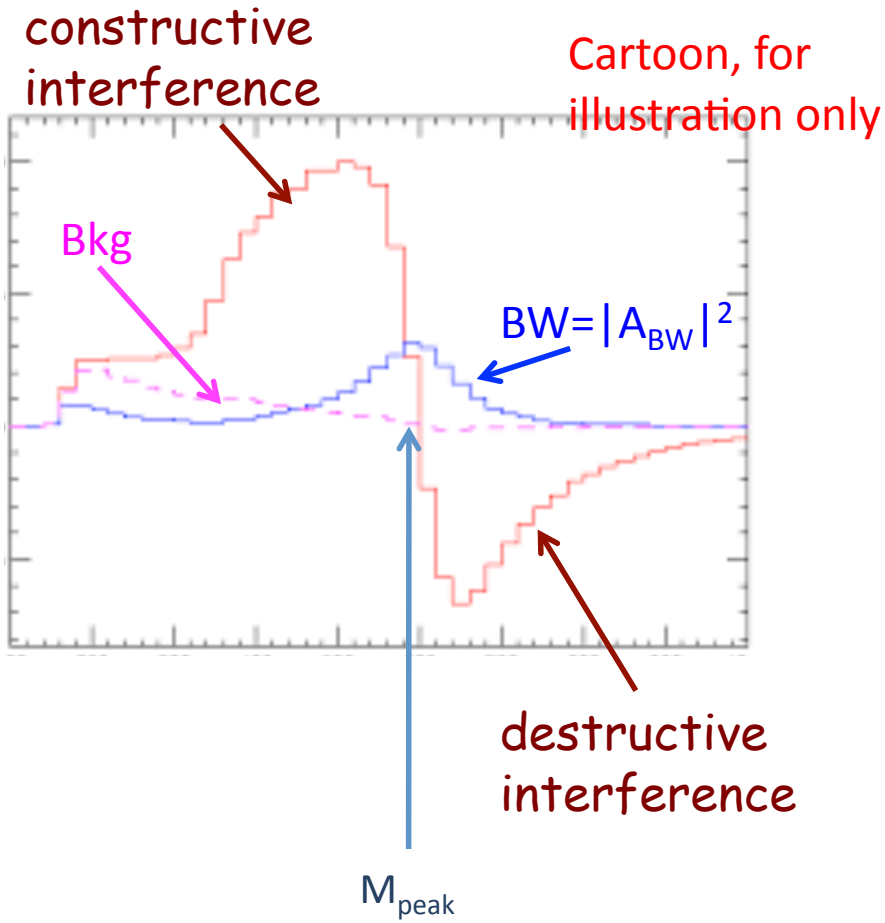
$$\Gamma = 200^{+41+26}_{-46-35}\ \text{MeV}$$

strong interference between Z & K* amps

$$Bf(B^0 \to Z(4430)^- K^+) \times Bf(Z(4430)^- \to \pi^- \psi') = (6.0^{+1.7+2.5}_{-2.0-1.4}) \times 10^{-5}$$

BW resonance on a large coherent background





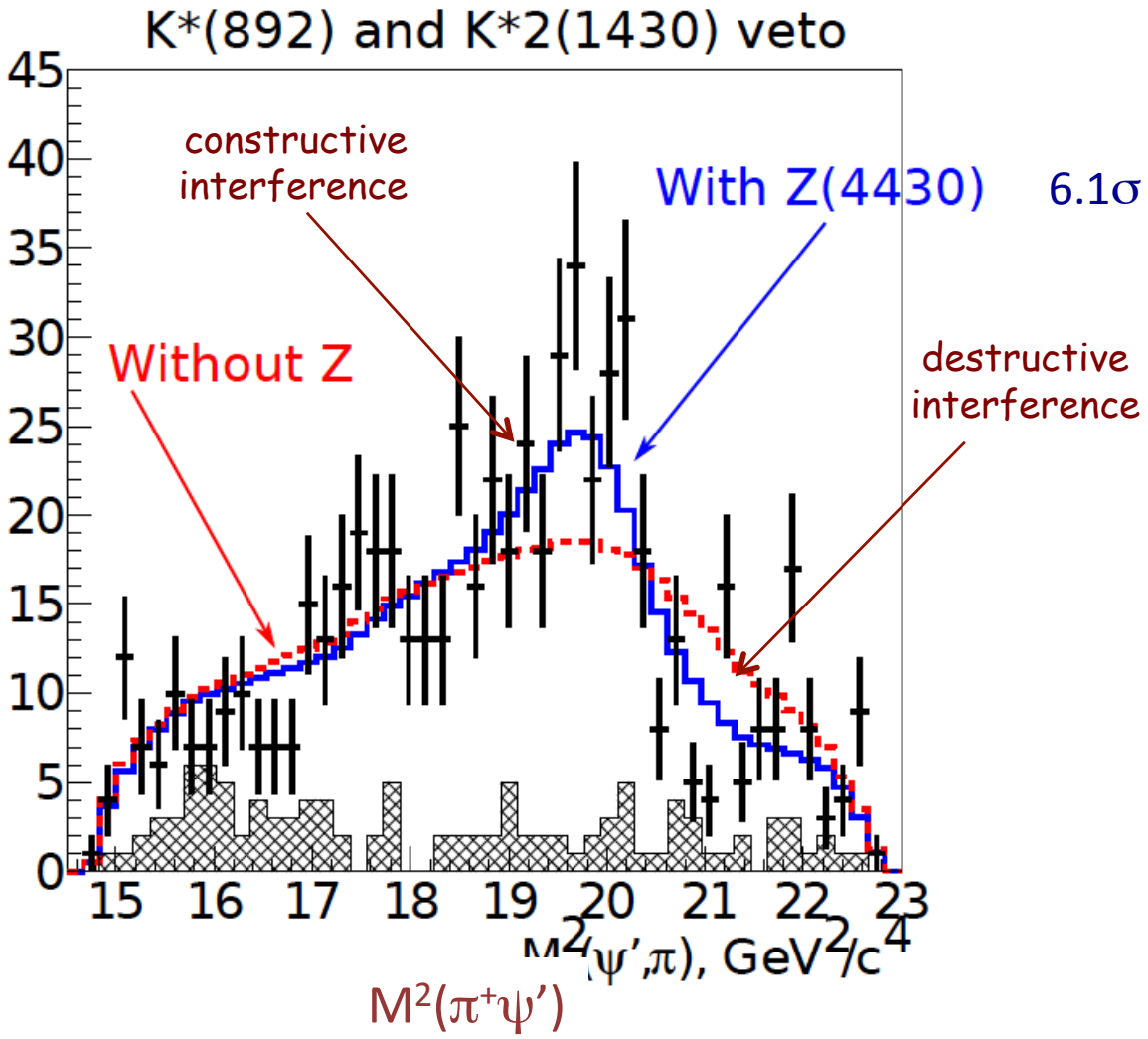
Shape of Z(4430) “peak”

2008 1-dim fit

$$M = 4433 \pm 4 \pm 2 \text{ MeV}$$
$$\Gamma = 45^{+18+30}_{-13-13} \text{ MeV}$$

2013 4-dim fit

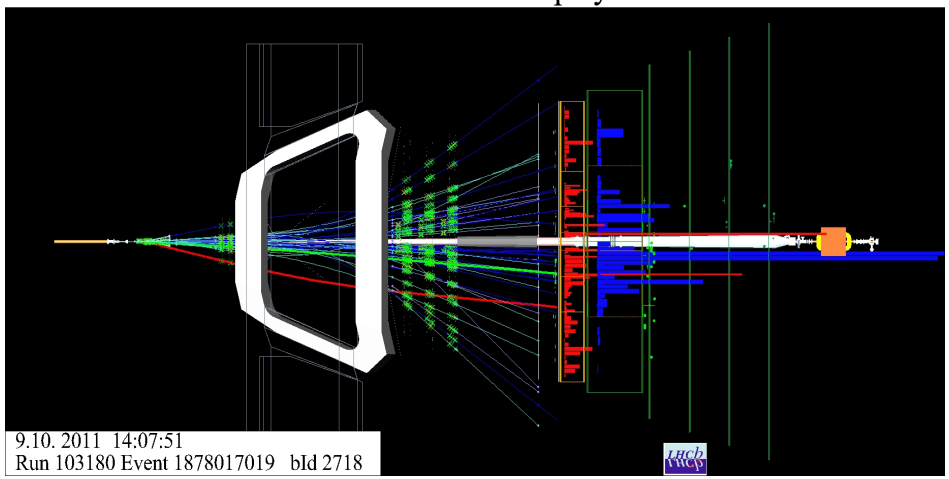
$$M = 4485^{+22+28}_{-22-11} \text{ MeV}$$
$$\Gamma = 200^{+41+26}_{-46-35} \text{ MeV}$$



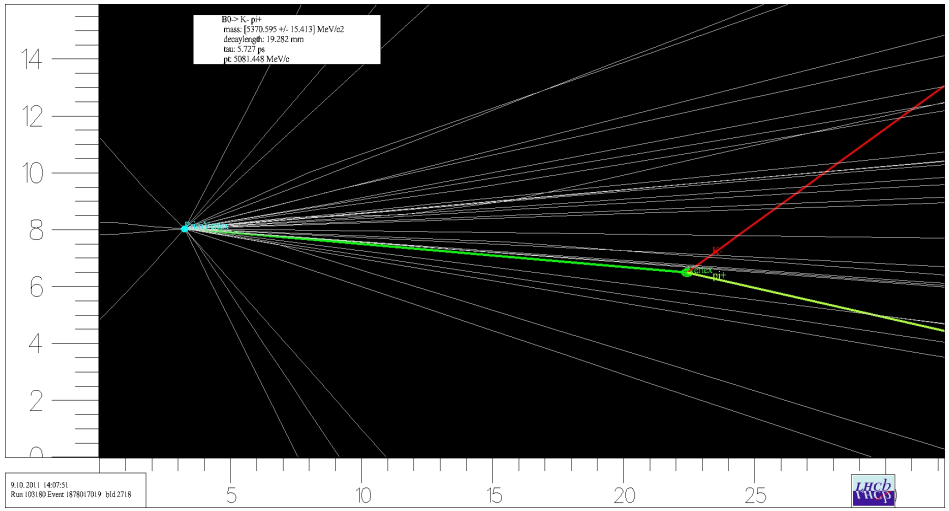
K Chilikin et al Belle: PRD 88 074026

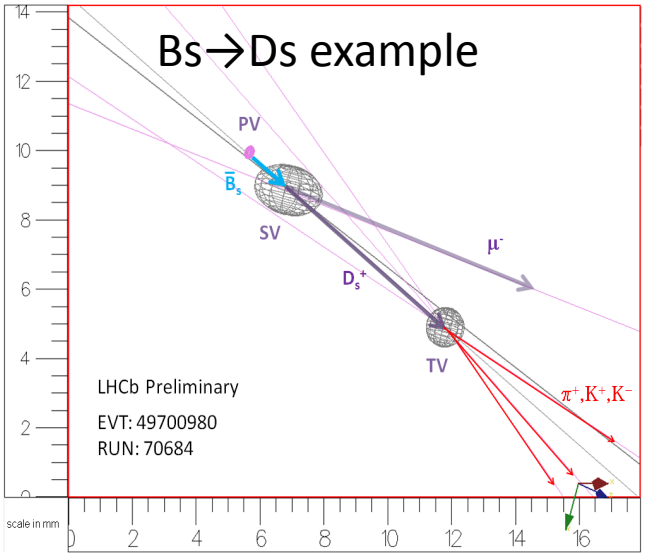
LHCb

LHCb Event Display



B→K⁺π⁻ example





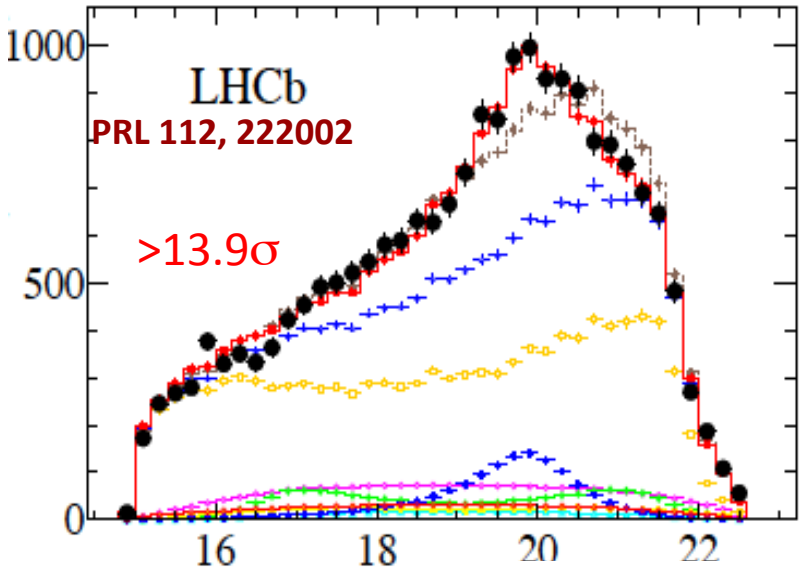
- Very large cross section in forward region in pp collision.
- ~2K B mesons /fb^{-1} wrt e$^+$e$^-$ B-factories
- Flight length of bottom and charm hadrons ~5-10×σ_{vtx}

Z(4430) confirmed by LHCb last year

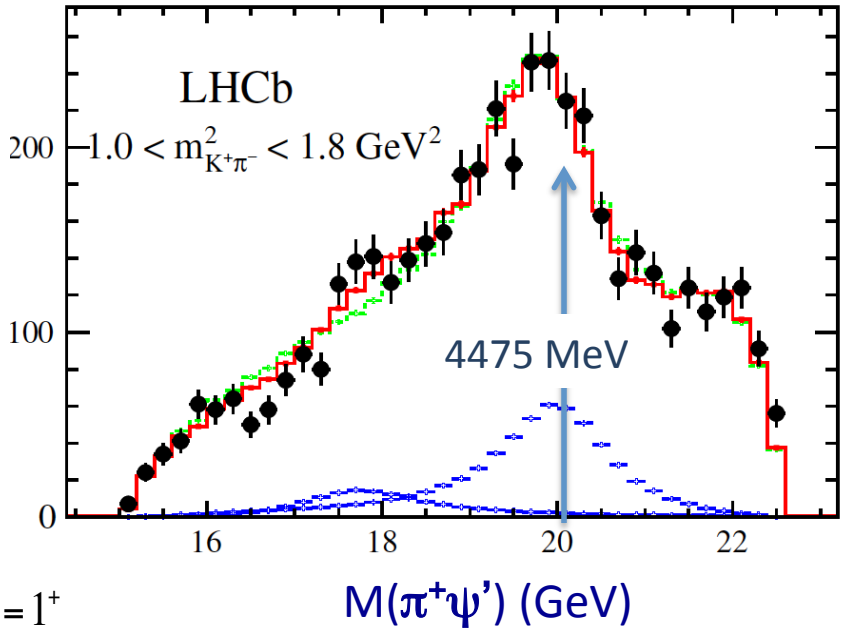
$B \to K\pi^+\psi'$: 4-dim amplitude analysis

R. Aaij et al LHCb: PRL 112 222002

All Kπ masses



K* veto

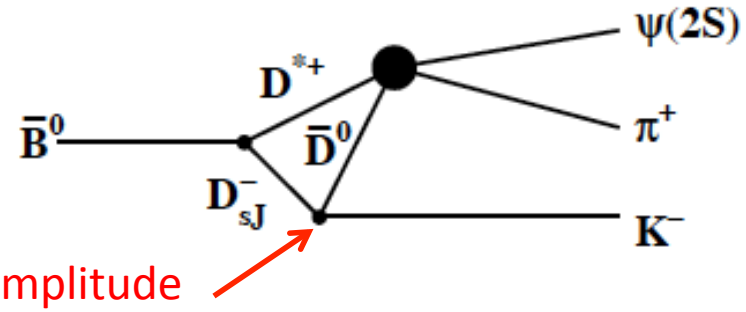


$J^P = 1^+$

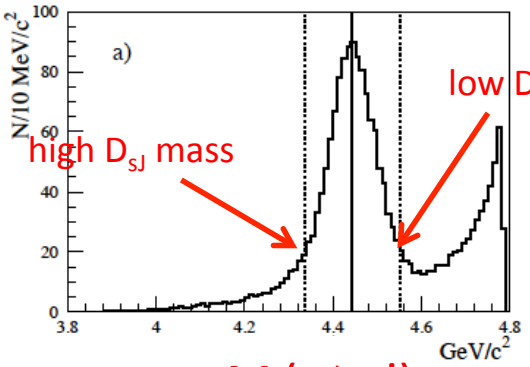
$M = 4475 \pm 7^{+15}_{-25}$ MeV

$\Gamma = 172 \pm 13^{+37}_{-34}$ MeV

Rescattering process?



BW amplitude
(with BW phase)

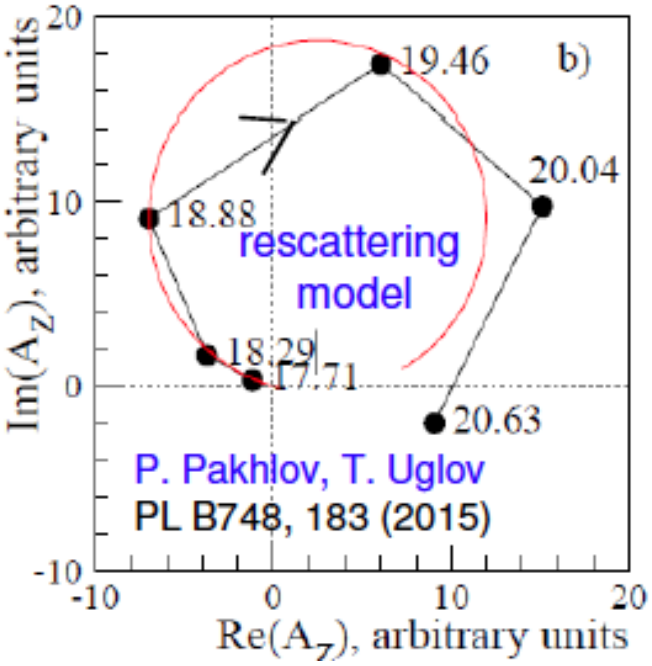


high D_{sJ} mass

low D_{sJ} mass

M ($\pi^+\psi'$)

clockwise phase motion

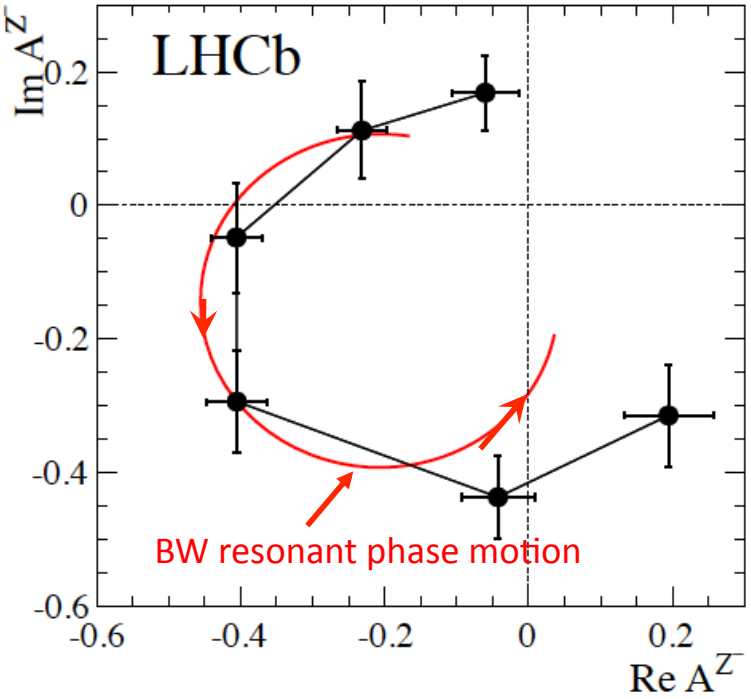


Pakhlov, PLB 702 (2011) 139

Meng & Chao, arXiv:0708.4222

phase motion reported by LHCb

counter-clockwise phase motion



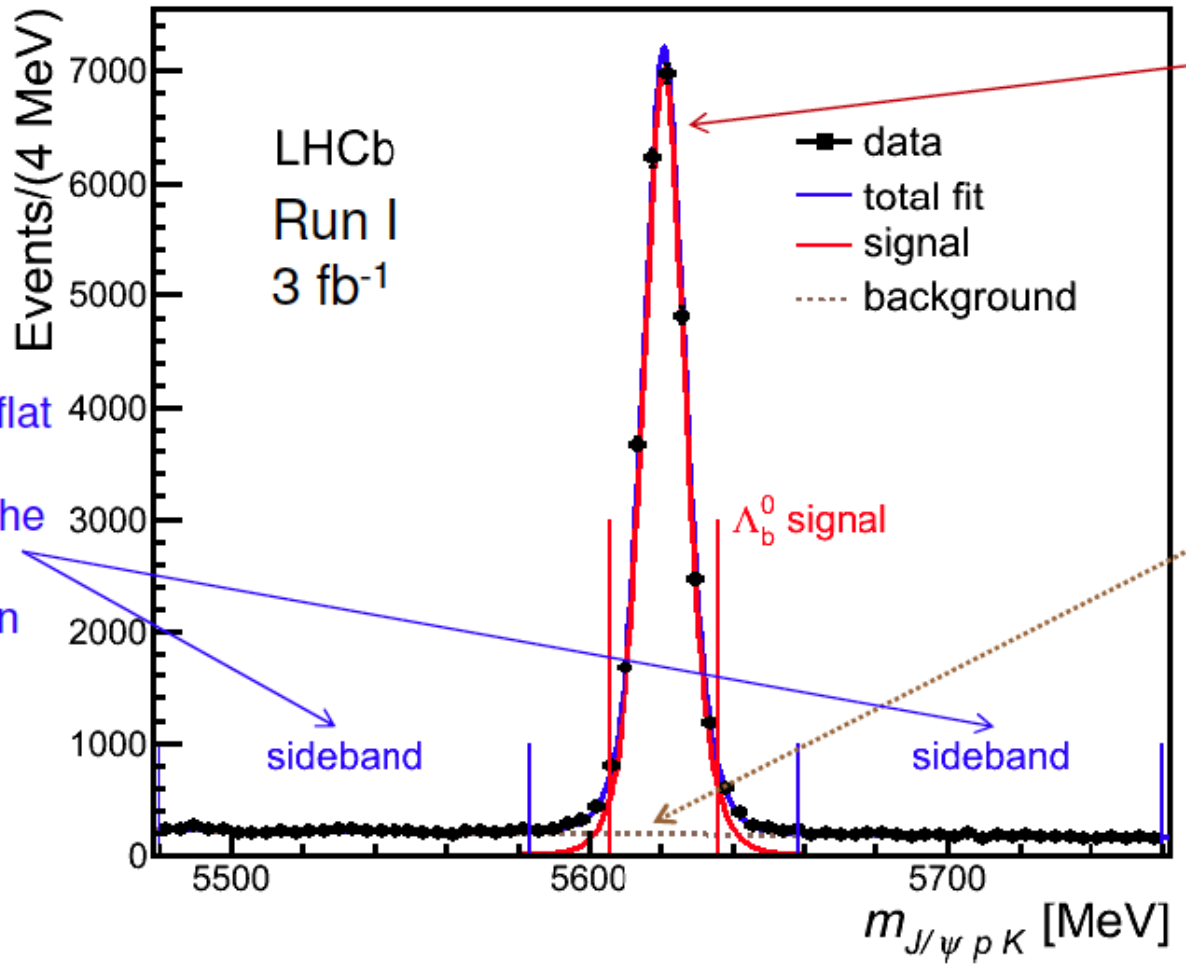
BW-like resonance behavior is clearly established

Pentaquark-like states from LHCb

Slide from Tomasz Skwarnicki's talk at LP2015, Lubjana

LHCb $\Lambda_b^0 \to J/\psi\, p\, K^-$

LHCb-PAPER-2015-029, arXiv:1507.03414, PRL 115, 07201



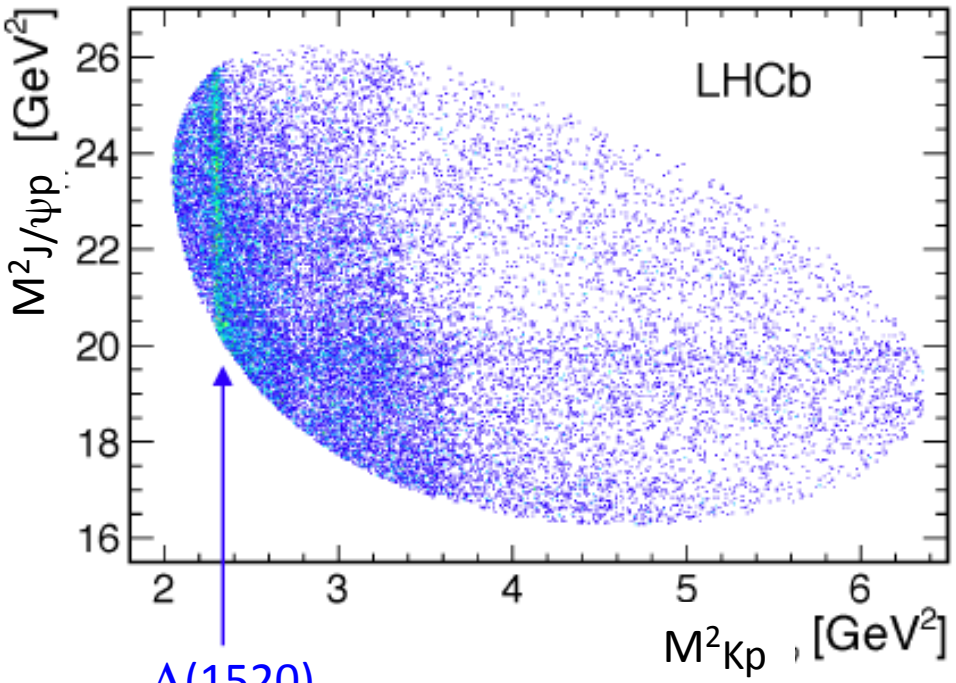
26,007±166 Λ_b^0 candidates

The sideband distributions are flat → no major reflections from the other b-hadrons after the selection

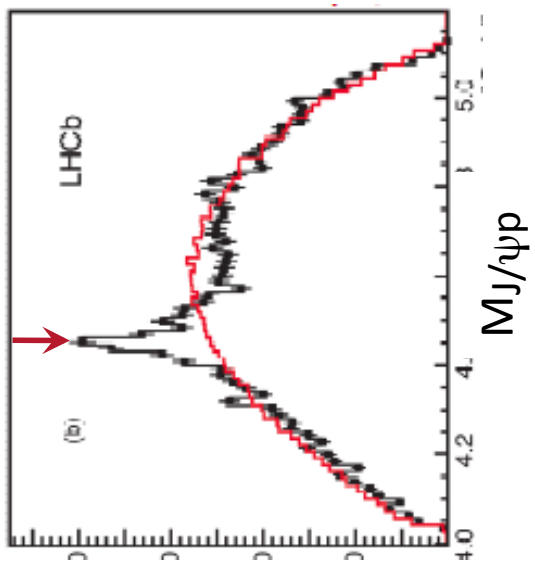
The background is only 5.4% in the signal region!

- The decay first observed by LHCb and used to measure Λ_b^0 lifetime:
  - LHCb-PAPER-2013-032 (PRL 111, 102003)

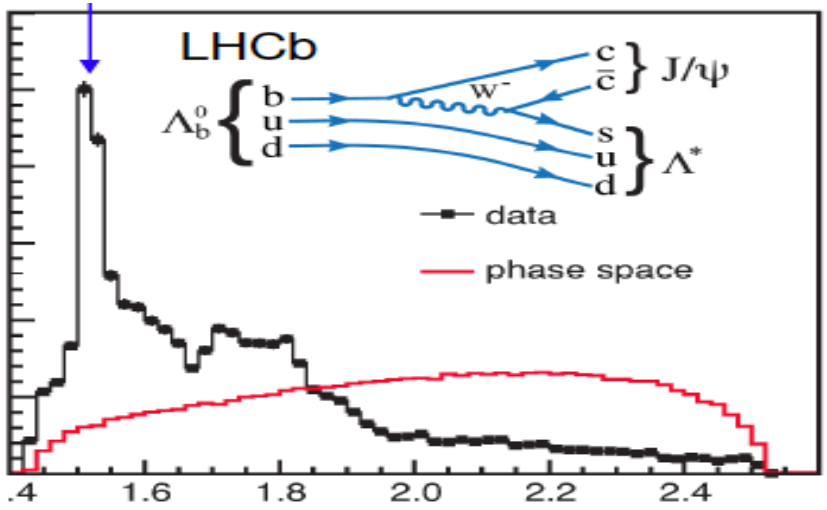
$\Lambda_b \rightarrow K^- p J/\psi$ Dalitz plot



??

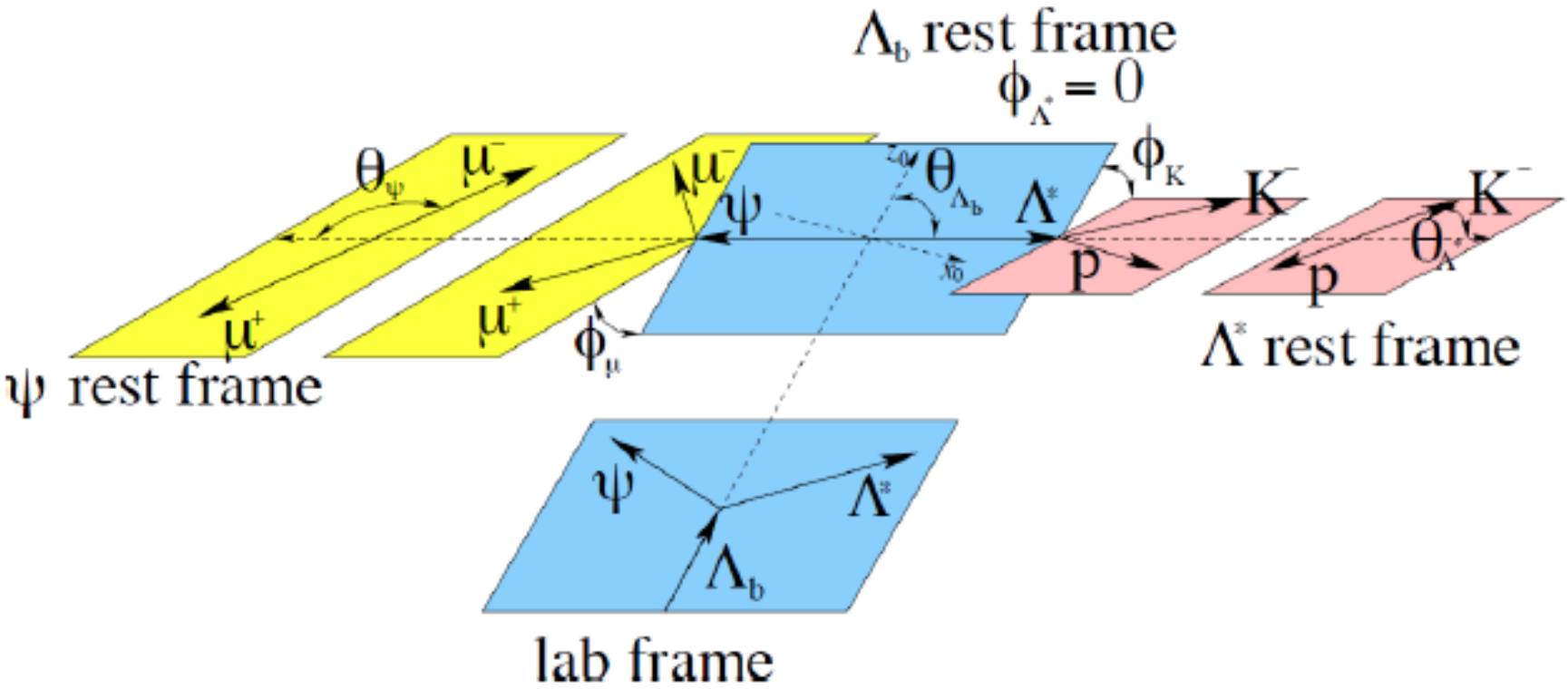


$\Lambda(1520)$



Amp. anal. for $\Lambda_b \rightarrow K^- p J/\psi$; $J/\psi \rightarrow \mu^+\mu^-$

6 variables: M_{Kp} and five angles



Include all known Λ^* resonances

All known Λ^* states

State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	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
$\Lambda(2585)$	$5/2^-?$	$\approx$2585	200	0	6
			# of fit parameters:	64	146

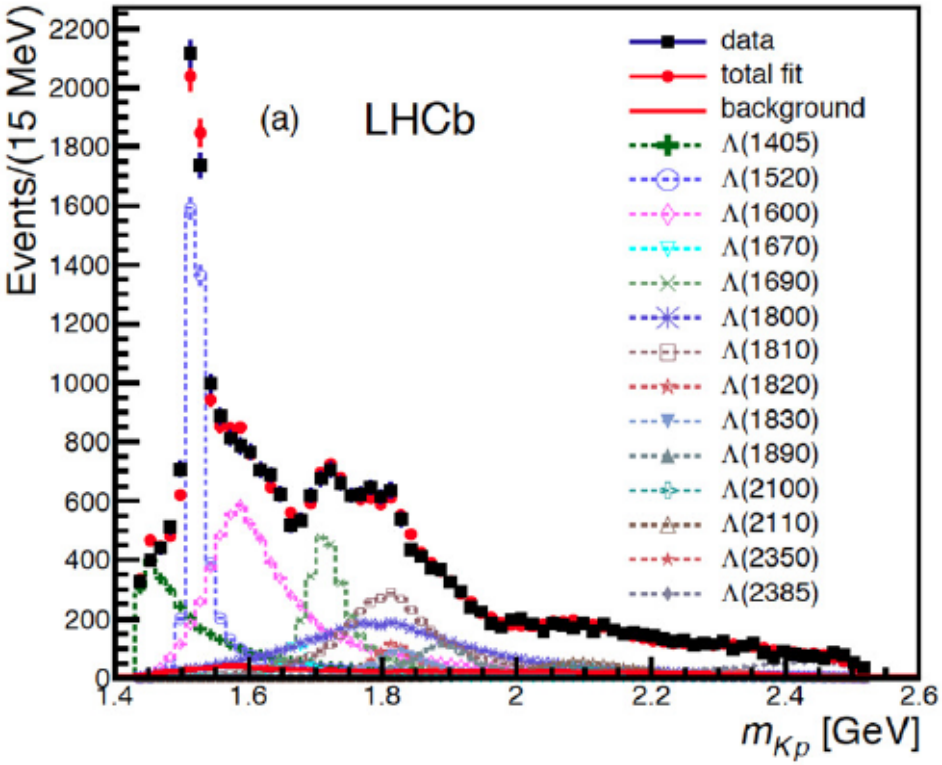
PRL 115, 07201 (2015)

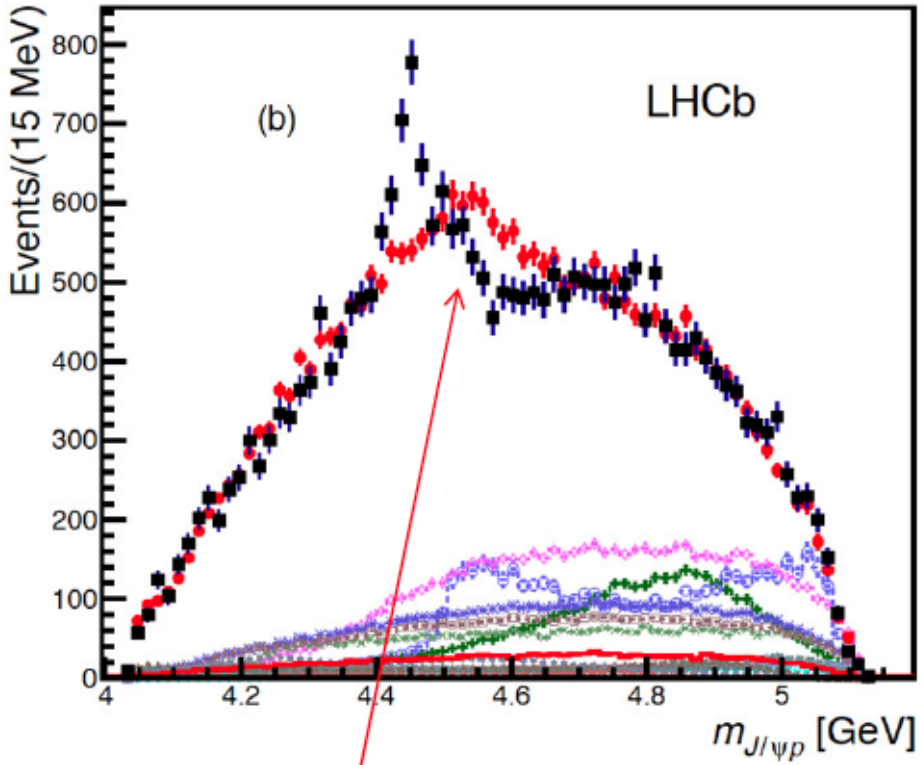
Significance and results

- significance of $P_c(4450)^+$ state is 12σ
- significance of $P_c(4380)^+$ state is 9σ

State	Mass (MeV)	Width (MeV)	Fit fraction (%)
$P_c(4380)^+$	**4380 ±8±29**	**205±18±86**	**8.4±0.7±4.2**
$P_c(4450)^+$	**4449.8±1.7±2.5**	**39± 5±19**	**4.1±0.5±1.1**
$\Lambda(1405)$	LHCb-PAPER-2015-029, arXiv:1507.03414, PRL 115, 07201		15±1±6
$\Lambda(1520)$			19±1±4

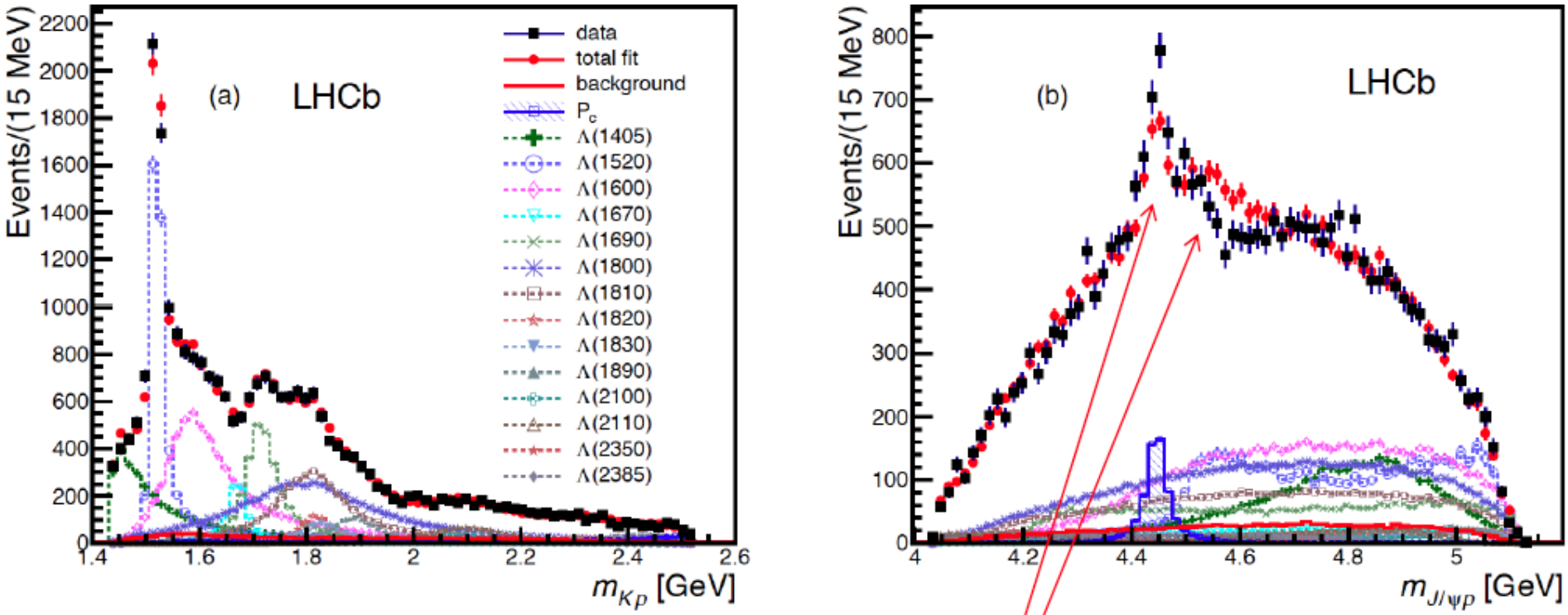
Fit with $\Lambda^* \to pK^-$ contributions only





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

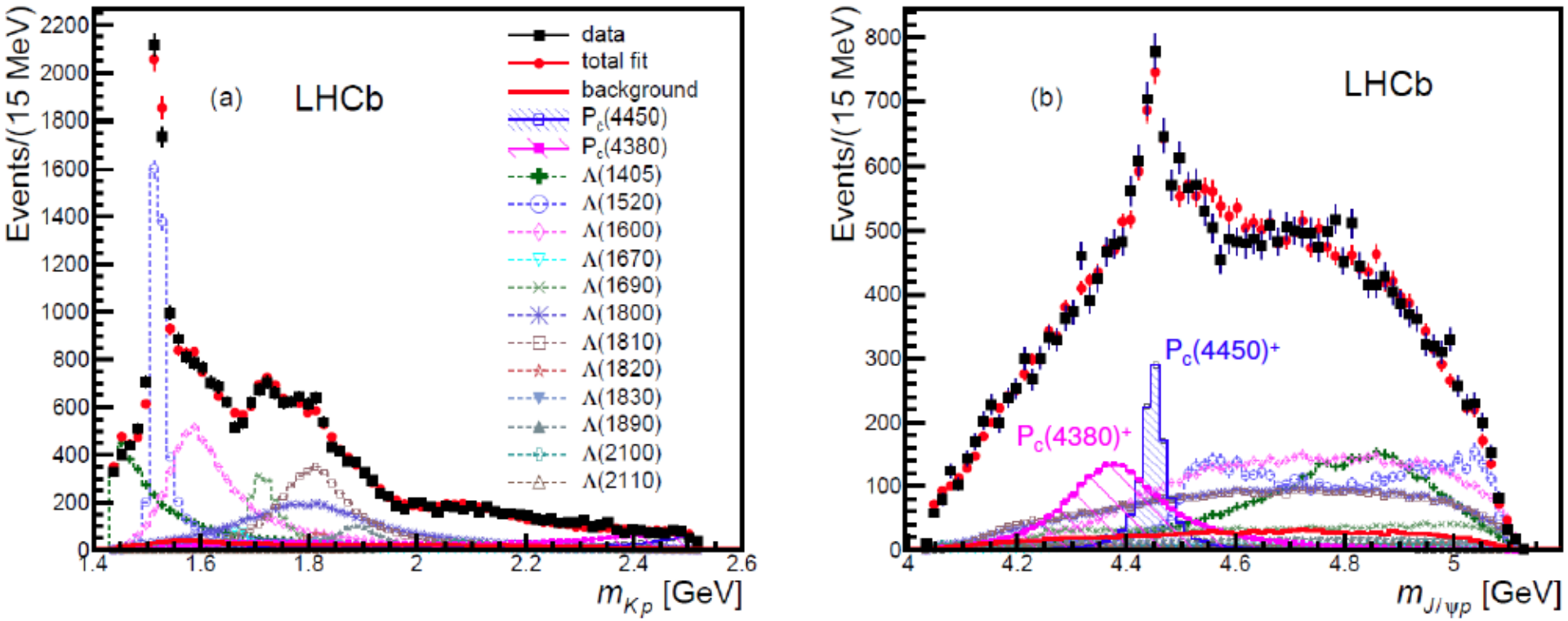
Fit with Λ^*'s and one $P_c^+ \to J/\psi p$ state



(extended Λ^* model)

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

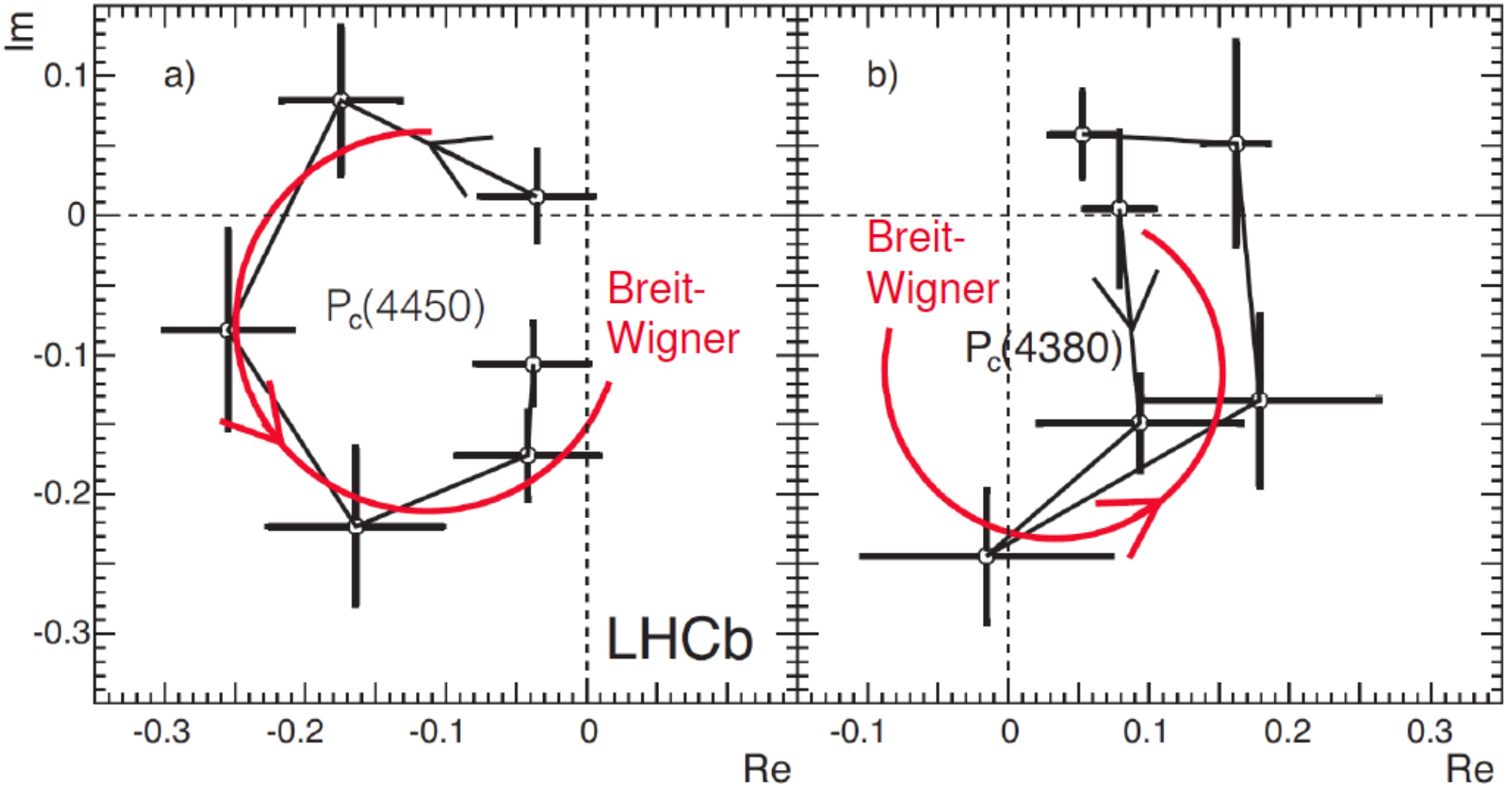
Fit with Λ^*'s and two $P_c^+ \to J/\psi p$ states



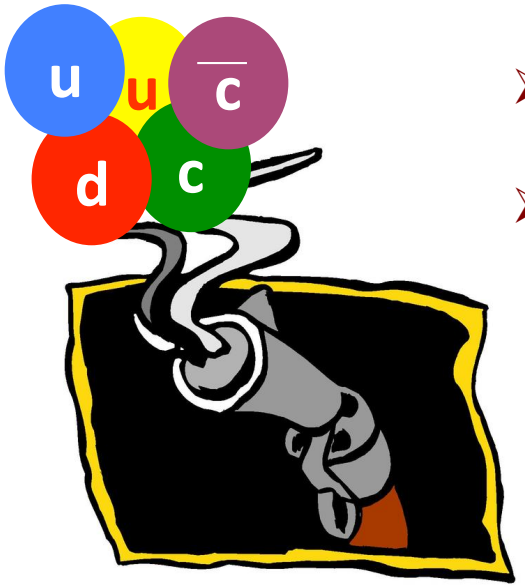
(reduced Λ^* model)

- Obtain good fits even with the reduced Λ^* model
- Best fit has $J^P=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred

Phase motions



$P_c(4380)$ & $P_c(4450)$: contain at least 5 quarks

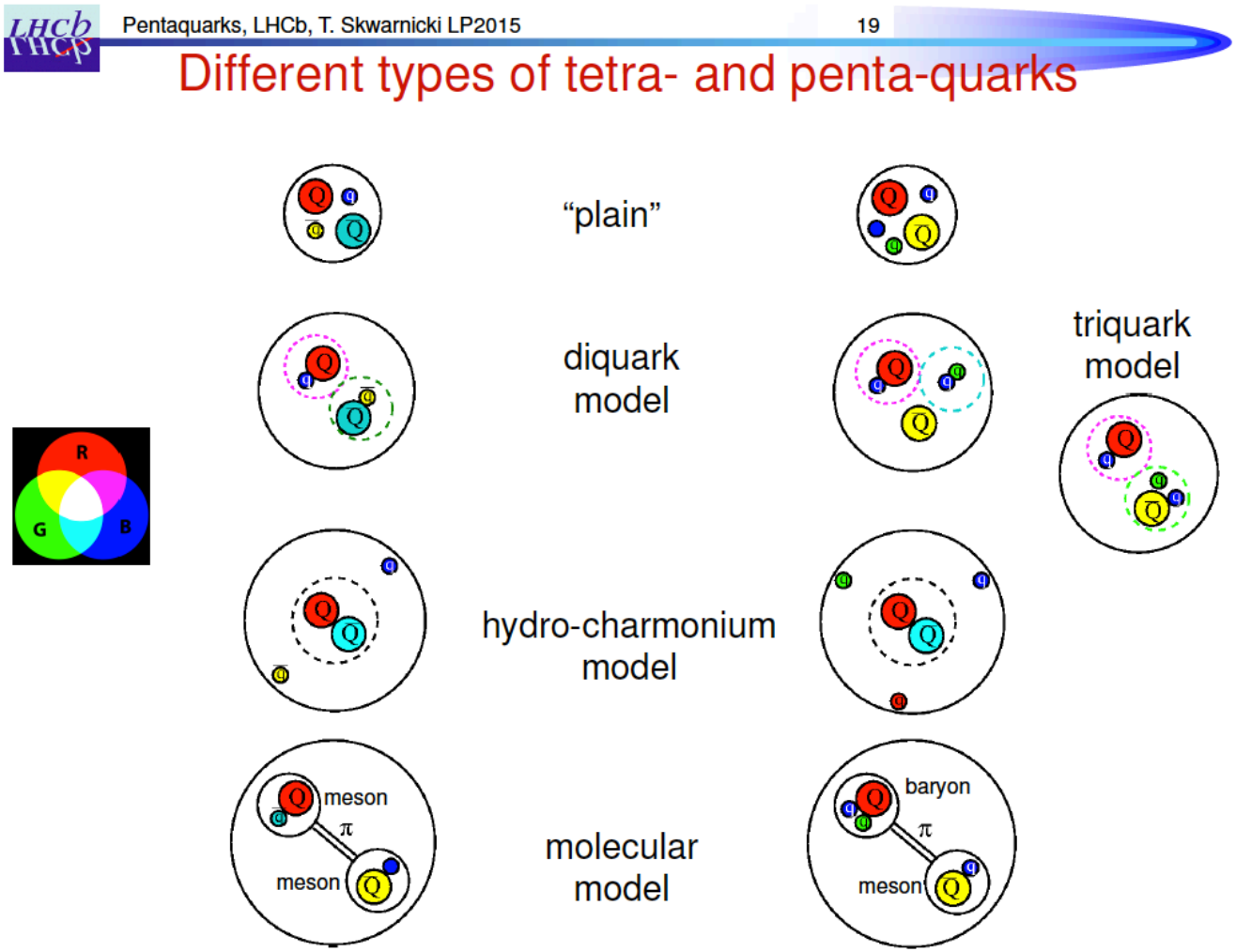


Pentaquark!

- decays to J/ψ ➔ must contain $c\bar{c}$ pair
- Decays to proton ➔ baryon # must be B=1

Tetra- & Penta-quarks have been found

but which ones??



or mixtures of some (all?) of these?

Comments

- Tetra- & Penta-quarks exist and have been observed
  - -molecules? …diquark-diantiquarks? …mixtures?
- Preliminary results from BESIII show anomalous behavior in the Λ time-like form-factor at the $q^2=2m_\Lambda$ threshold
- The game has changed:
  - -experiments: simple peak fitting is not enough; full-blown amplitude analyses are required
  - -theory: cartoons that show that a theory can produce peaks won't suffice fits to data, including phases are necessary

Thank you

どうも　ありがとう

감사합니다