Exotics 2020 from LHCb

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1. $X(2900)$ in $B^+ \to D^+ D^- K^+$
(in preparation)

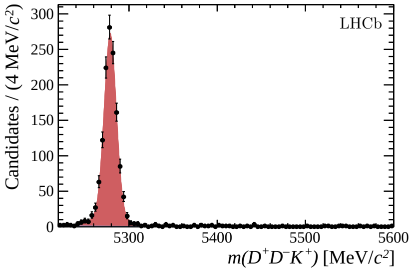
2. $J/\psi J/\psi$ from LHCb
arXiv:2006.16957

3. Spin and parity of the vector-vector system
arXiv:2007.05501

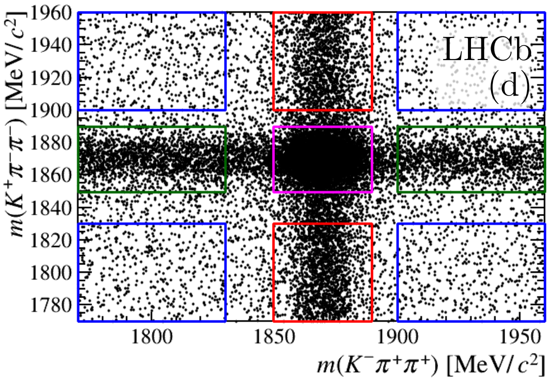
$X(2900)$ in $B^+ \to D^+ D^- K^+$
(in preparation)

$B^+ \to D^+ D^- K^+$ reaction: [CERN seminar by Dan Johnson]

Preliminary



$9\,\mathrm{fb}^{-}1$: Run 1 + Run 2 data

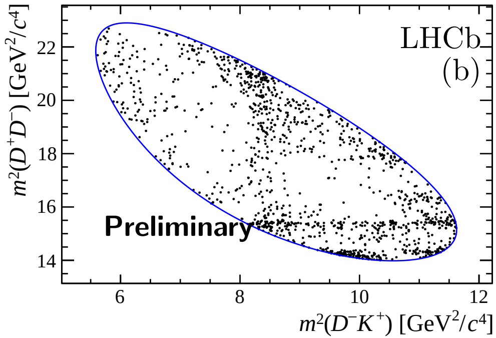


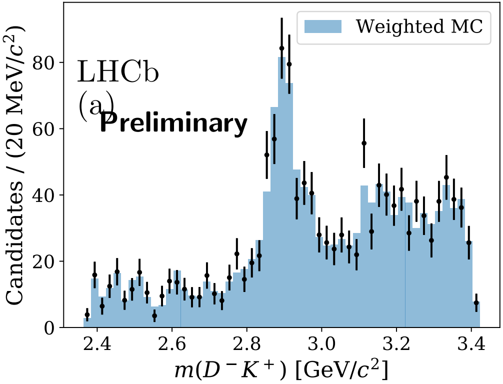
Clean topology, negligible background

- B flights out of interaction point
- $D^\pm \to K^\mp \pi^\pm \pi^\pm$

Dalitz plot for $B^+ \to D^+ D^- K^+$

[LHCb (in preparation)]





- Horisontal lines are resonances in D^+D^-
- Huge peak at 2.9 GeV in D^-K^+: $(\bar{c}d)(\bar{s}u)$
- Peaks in D^+K^+: reflections?

Dalitz plot for $B^+ \to D^+ D^- K^+$

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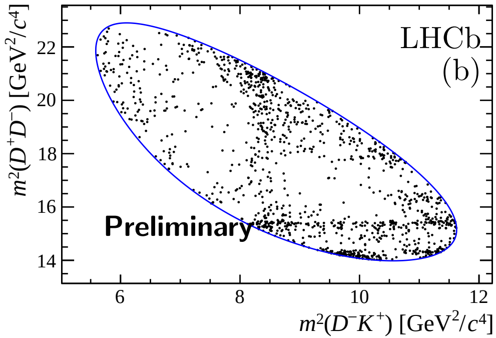

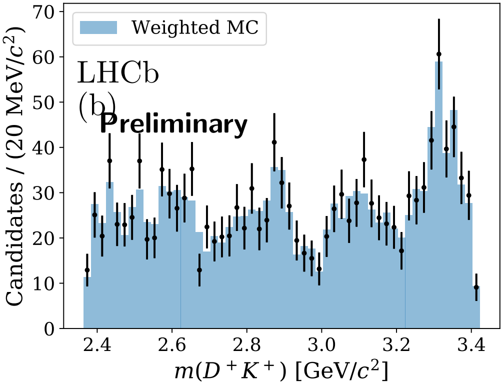

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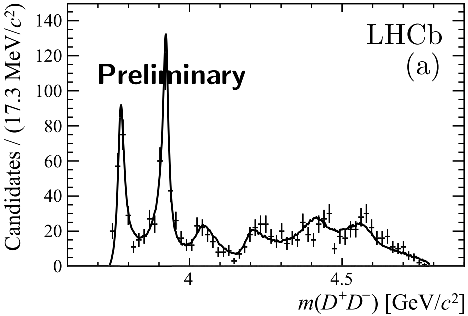
$D\bar{D}$ spectroscopy

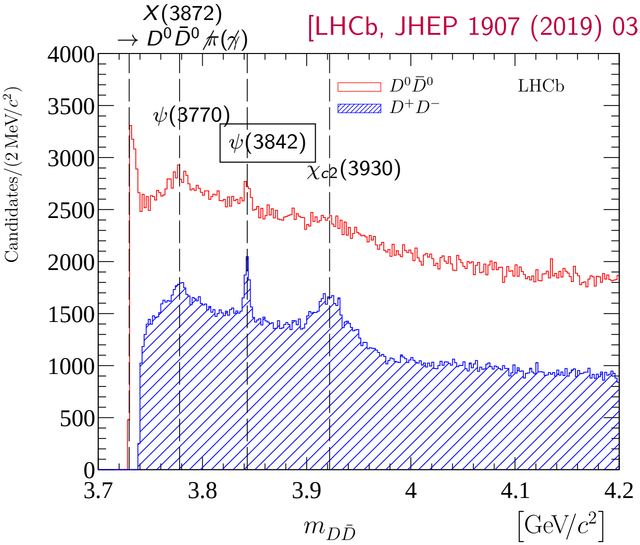


Natural parity chanmonia above D^+D^- threshold:

- $\psi(3770)$, $\chi_{c0}()$, $\chi_{c2}(3930)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$

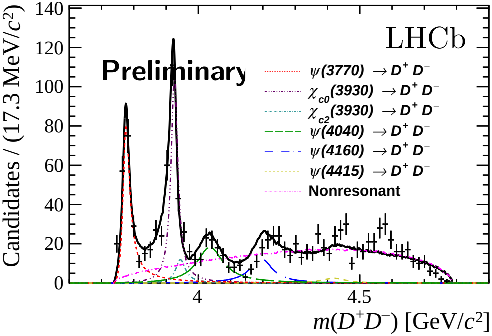
Compare to inclusive DD spectra:

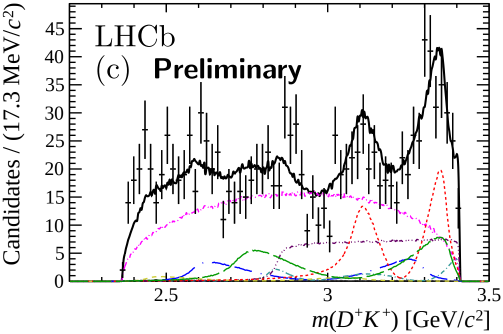
[LHCb, JHEP 1907 (2019) 035]



Fit with no exotics

[LHCb (in preparation)]





- One can get a "reasonable" description of D^+D^- and D^+K^+,
- the D^-K^+ projection has a clear additional structure

Fit with no exotics

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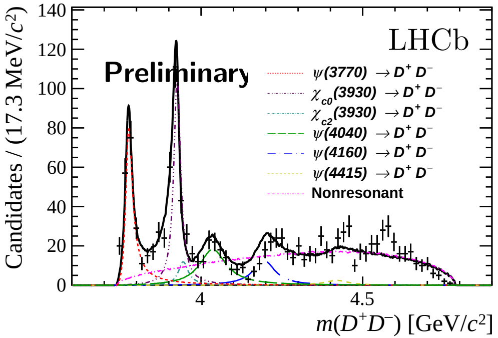

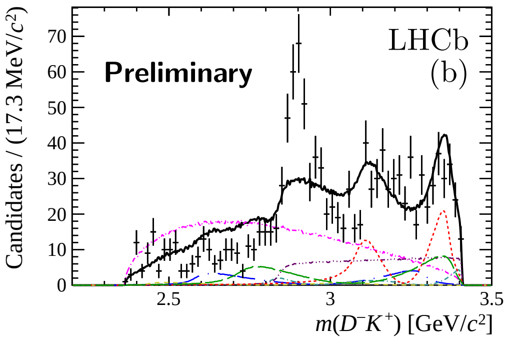

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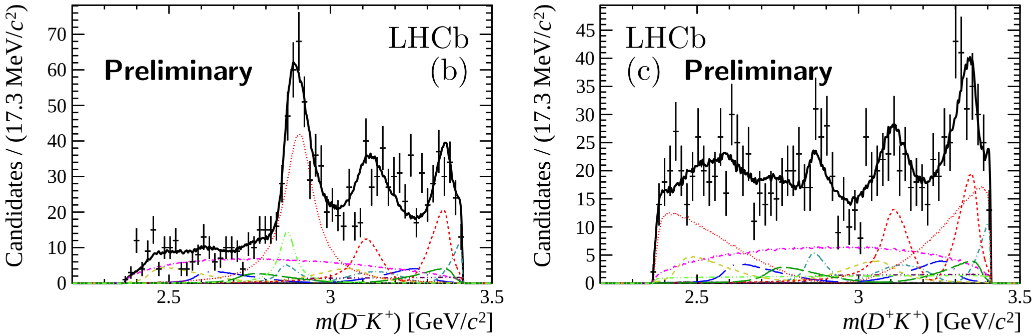
- the D^-K^+ projection has a clear additional structure

Adding exotic structures to $D^- K^+$ channel

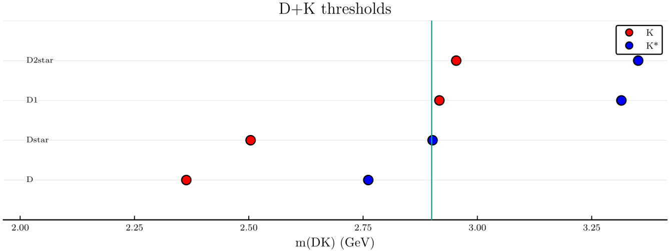
[LHCb (in preparation)]



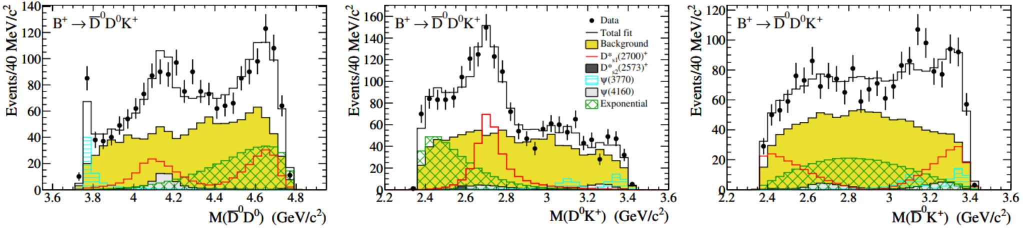
- $X_1(2900)$: $m = (2904 \pm 5 \pm 1)$ MeV, $\Gamma = (100 \pm 10 \pm 4)$ MeV
- $X_0(2900)$: $m = (2866 \pm 6 \pm 2)$ MeV, $\Gamma = (57 \pm 12 \pm 4)$ MeV

Some thoughts on D^-K^+ exotics

- Nearby thresholds: D^*K^*, D_1K
- Isospin of $\bar{c}\bar{s}ud$ can be $I=0$, and $I=1$.
  - $\bar{c}\bar{s}uu$ would show up in $\bar{D}^0K^+$
  - $\bar{c}\bar{s}dd$ would show up in D^+K^0



$B^+ \to D^0\bar{D}^0K^+$ by BaBar [Phys.Rev.D 91 (2015) 5, 052002].

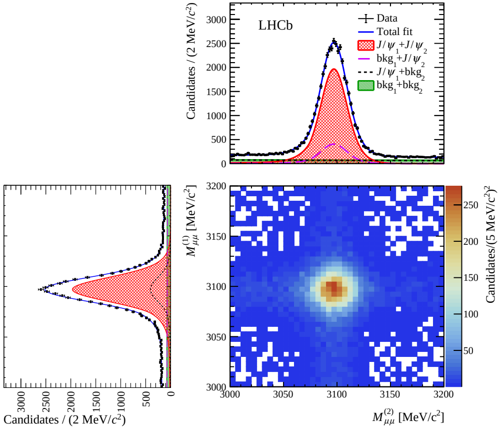


There are many systems to look at in the $B \to DDK$ family

$J/\psi J/\psi$ from LHCb
arXiv:2006.16957

Observation of the prompt $J/\psi J/\psi$ pairs

[LHCb, 2006.16957]



- Full statistics: Run 1 + Run 2
- Inclusive: $pp \to J/\psi J/\psi\, X$ (4μ tracks from the same PV)
- $N_{J/\psi J/\psi} \approx 34\,$k candidates
- Important kinematic variables: $m_{J/\psi J/\psi}$, $p_t(J/\psi J/\psi) = p_{t1} + p_{t2}$.

Understanding the background

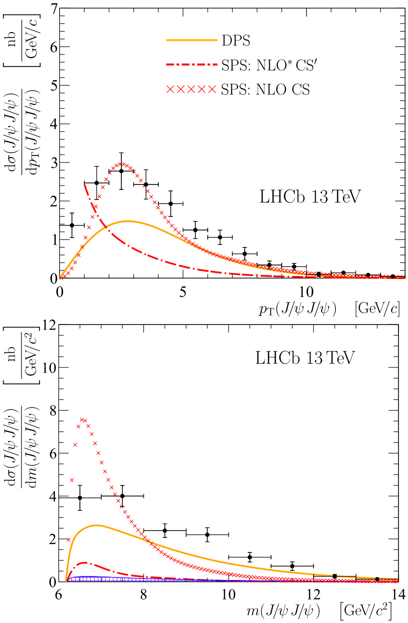
SPS, DPS [LHCb, JHEP 47, arXiv:1612.07451]

Single-parton scattering (SPS)

- $gg \to J/\psi J/\psi$: the $cc\bar{c}\bar{c}$ is produced in a single interaction of partons (gluons)
- Expected to dominate low masses
- Vanishes at high p_t

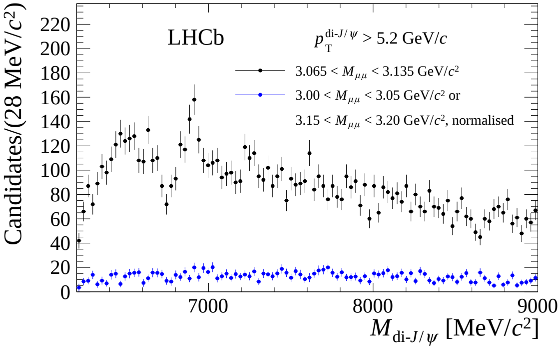
Double-parton scattering (DPS)

- $gg \to J/\psi$ twice: almost uncorrelated J/ψ.
- Expected to dominate at high masses
- Vanishes at high p_t



Spikes at the near-threshold region

[LHCb, 2006.16957]



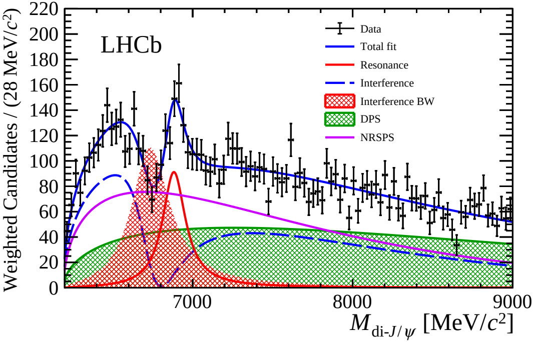
Features

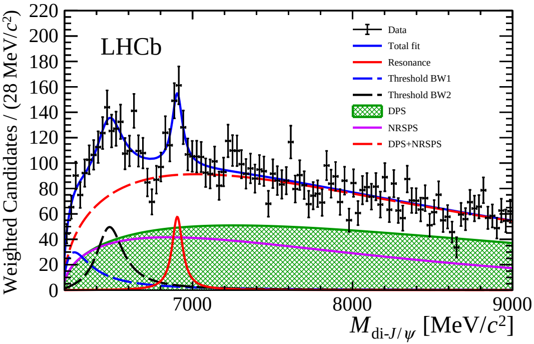
- Rapid start at threshold
- Sharp Deep at 6.8 GeV
- Peak at 6.9 GeV.
- Long continuous spectrum

- Fix DPS model at high energy, > 10 GeV
- Release SPS shape and strength
- Add a couple of poles to the amplitude with BW functions

Two exaggerated models: interference, no interference [LHCb, 2006.16957]

SPS: $gg \to J/\psi J/\psi$



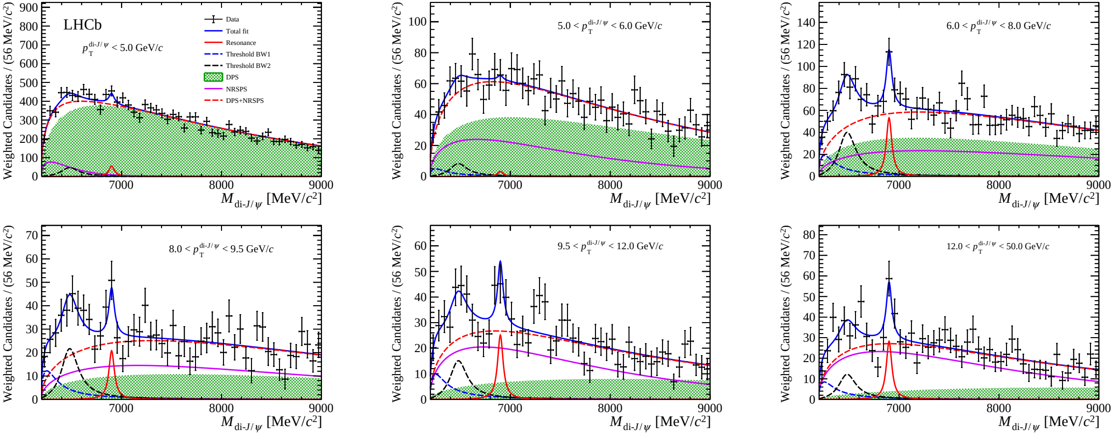


- NRSPS with constant phase fully coherent
- $M = (6886 \pm 11 \pm 11)$ MeV
  $\Gamma = (168 \pm 33 \pm 69)$ MeV

- Incoherent sum of components
- Threshold BWs are to adjust the lineshape.
- $M = (6906 \pm 11 \pm 7)$ MeV
  $\Gamma = (80 \pm 19 \pm 33)$ MeV

Simultaneous fit of $p_t(J/\psi J/\psi)$ bins

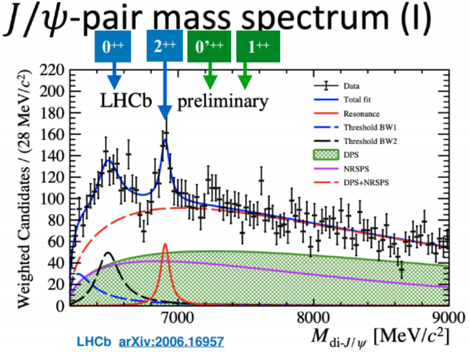
[LHCb, 2006.16957]



- the shape of DPS is determined separately for every bin
- Simulations fit: 7σ significance of the main peak

Some thoughts on the interpretations

- There are predictions for $T_{cc\bar{c}\bar{c}}$ e.g. [1911.00960], [1803.02522]
- Match the observation by adjusting overall scale
- The narrow widths are puzzling
- The dip is a mystery



[courtesy of L.Maiani, 2008.01637]

Measurements of the quantum numbers is critical

[1911.00960]

J^{PC}	$cc\bar{c}\bar{c}$ $N[(S_D, S_{\bar{D}})S, L]J$	E^{th} [MeV]
0^{++}	1[(1, 1)0, 0]0	5883
0^{++}	2[(1, 1)0, 0]0	6573
0^{++}	1[(1, 1)2, 2]0	6835
0^{++}	3[(1, 1)0, 0]0	6948
0^{++}	2[(1, 1)2, 2]0	7133
0^{++}	3[(1, 1)2, 2]0	7387
1^{+-}	1[(1, 1)1, 0]1	6120
1^{+-}	2[(1, 1)1, 0]1	6669
1^{+-}	1[(1, 1)1, 2]1	6829
1^{+-}	3[(1, 1)1, 0]1	7016
1^{+-}	2[(1, 1)1, 2]1	7128
1^{+-}	3[(1, 1)1, 2]1	7382
1^{--}	1[(1, 1)0, 1]1	6580
1^{--}	1[(1, 1)2, 1]1	6584
1^{--}	2[(1, 1)0, 1]1	6940
1^{--}	2[(1, 1)2, 1]1	6943
1^{--}	3[(1, 1)0, 1]1	7226
1^{--}	3[(1, 1)2, 1]1	7229
0^{-+}	1[(1, 1)1, 1]0	6596
0^{-+}	2[(1, 1)1, 1]0	6953
0^{-+}	3[(1, 1)1, 1]0	7236
1^{++}	1[(1, 1)2, 2]1	6832
1^{++}	2[(1, 1)2, 2]1	7130
1^{++}	3[(1, 1)2, 2]1	7384
2^{++}	1[(1, 1)2, 0]2	6246
2^{++}	1[(1, 1)2, 2]2	6827
2^{++}	1[(1, 1)0, 2]2	6827
2^{++}	2[(1, 1)2, 0]2	6739
2^{++}	3[(1, 1)2, 0]2	7071
2^{++}	2[(1, 1)2, 2]2	7125
2^{++}	2[(1, 1)0, 2]2	7126
2^{++}	3[(1, 1)2, 2]2	7380
2^{++}	3[(1, 1)0, 2]2	7380

Spin and parity of the vector-vector system arXiv:2007.05501

$X \to J/\psi J/\psi$ amplitude

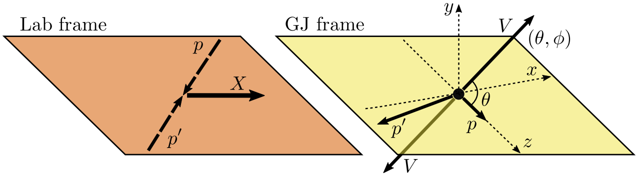
[MM, L. An, R. McNulty, 2007.05501]

Amplitude:

$$A^{M}_{\lambda_1,\lambda_2} = n_J\, d^{J}_{M,\lambda_1-\lambda_2}(\theta) H_{\lambda_1,\lambda_2} (-1)^{1-\lambda_2}$$

Differential width (intensity):

$$I(\theta) = \sum_M \rho_M \sum_{\lambda_1,\lambda_2} |A^{M}_{\lambda_1,\lambda_2}|.$$



Production by *pp* collision

- choose $z \uparrow\uparrow \vec{n} \Rightarrow$ diagonal polarization matrix $\delta_{M,M'}\rho_M$

Intensity for the unpolarized decay

$$I(\theta) = n_J^2 \sum_{M,\lambda_1,\lambda_2} \rho_M |d^{J}_{M,\lambda_1-\lambda_2}(\theta)|^2 |H_{\lambda_1,\lambda_2}|^2$$

What is no polarization $\rho_M = 1$ (quite likely in pp)?

$$I(\theta) = n_J^2 \sum_{\lambda_1,\lambda_2} |H_{\lambda_1,\lambda_2}|^2$$

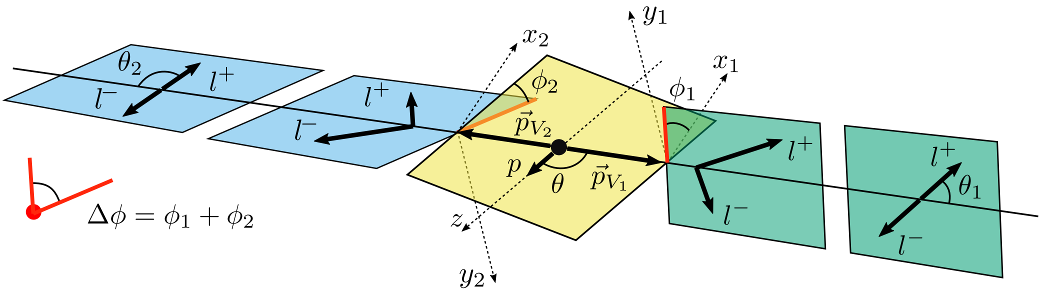
no J: explicit dependence on J disappears. What helps to determine J?

(a) Can helicity couplings tell us something?

(b) Will the decays of J/ψ help?

Four-body decay angles

[MM, L. An, R. McNulty, 2007.05501]



- θ is the polar angle of $(J/\psi)_1$ with respect to the polarization direction
- (θ_1, ϕ_1) are the spherical angles of μ^+ in the $(J/\psi)_1$ helicity frame
- (θ_2, ϕ_2) are the spherical angles of μ^+ in the $(J/\psi)_2$ helicity frame

No polarization $\Rightarrow$ no z $\Rightarrow$ no decay plane (pink) $\Rightarrow$ only $\phi = \phi_1 + \phi_2$ matters.

$X \to V(\mu,\mu)V(\mu,\mu)$ amplitude

$$A^M_{\xi_1,\xi_2} = n_J \sum_{\lambda_1,\lambda_2} d^J_{M,\lambda_1-\lambda_2}(\theta) H_{\lambda_1,\lambda_2} (-1)^{1-\lambda_2}$$
$$\times\, n_1 D^{1*}_{\lambda_1,\xi_1}(\phi_1,\theta_1,0)$$
$$\times\, n_1 D^{1*}_{\lambda_2,\xi_2}(\phi_2,\theta_2,0)$$

- $\xi_i = \lambda_{\mu^+,i} - \lambda_{\mu^-,i}$ difference of muon helicities
- $\xi \in \{-1,1\}$ since $\xi = 0$ is suppressed by $m_\mu / m_{J/\psi}$.

$$F^{(\mu\mu)} = \sum_{\xi\in\{-1,1\}} \int \mathrm{d}\cos\theta\, d^1_{\lambda,\xi}(\theta) d^1_{\lambda',\xi}(\theta) = \frac{1}{3}\begin{pmatrix} 2 & 0 & 1 \\ 0 & 2 & 0 \\ 1 & 0 & 2 \end{pmatrix}_{\lambda,\lambda'}$$

Helicity couplings

[Martin, Spearman (1970) book]

Reappearance of J

$$|\text{two part. state}; \lambda_1, \lambda_2\rangle = |\vec{p}, \lambda_1\rangle \otimes |-\vec{p}, \lambda_2\rangle \, (-1)^{j_2-\lambda_2}$$

$$|JM; \lambda_1, \lambda_2\rangle = n_J \int \frac{\mathrm{d}\Omega}{4\pi} D^{J*}_{M\lambda} \, |\text{two part. state}; \lambda_1, \lambda_2\rangle$$

$$\boxed{H_{\lambda_1,\lambda_2} = \langle JM; \lambda_1, \lambda_2| \, \hat{T} \, |JM\rangle}$$

Parity $\quad \mathcal{P} \, |JM; \lambda_1, \lambda_2\rangle = (-1)^J \eta_V^2 \, |JM; -\lambda_1, -\lambda_2\rangle \, .$

Permutation $1 \leftrightarrow 2 \quad \mathcal{P}_{12} \, |JM; \lambda_1, \lambda_2\rangle = (-1)^J \, |JM; \lambda_2, \lambda_1\rangle \, .$

$\Rightarrow \quad H_{\lambda_1,\lambda_2} = (-1)^J \, \eta_X \, H_{-\lambda_1,-\lambda_2} \, , \qquad H_{\lambda_1,\lambda_2} = (-1)^J H_{\lambda_2,\lambda_1} \, .$

Matrix of helicity couplings

$$H_{\lambda_1,\lambda_2} = \begin{pmatrix} h_{1,1} & h_{1,0} & h_{1,-1} \\ h_{0,1} & h_{0,0} & h_{0,-1} \\ h_{-1,1} & h_{-1,0} & h_{-1,-1} \end{pmatrix}$$

The same-color elements are connected by symmetries.

The symmetry relates the couplings

$$H_{\lambda_1,\lambda_2} = (-1)^J \eta_X H_{-\lambda_1,-\lambda_2}, \qquad H_{\lambda_1,\lambda_2} = (-1)^J H_{\lambda_2,\lambda_1}.$$

Four categories of possible helicity matrices:

group	$\eta_X(-1)^J, (-1)^J$	J^P	symmetry
I	$+,+$	$\boxed{0^+}, 2^+, 4^+, 6^+$	symmetric, S
II	$-,+$	$\boxed{0^-}, 2^-, 4^-, 6^-$	symmetric, S
III	$+,-$	$1^-, 3^-, 5^-, 7^-$	antisymmetric, A
IV	$-,-$	$\boxed{1^+}, 3^+, 5^+, 7^+$	antisymmetric, A

$$H^{(I)} \quad \begin{pmatrix} b & a & c \\ a & d & a \\ c & a & b \end{pmatrix}_S \qquad H^{(II)} \quad \begin{pmatrix} b & a & \\ a & & -a \\ & -a & -b \end{pmatrix}_S \qquad H^{(III)} \quad \begin{pmatrix} & a & \\ -a & & -a \\ & a & \end{pmatrix}_A \qquad H^{(IV)} \quad \begin{pmatrix} & a & c \\ -a & & a \\ -c & -a & \end{pmatrix}_A$$

a, b, c, d are still unknown coefficients, complex in general.

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III	$+, -$	1^-, 3^-, 5^-, 7^-	antisymmetric, A
IV	$-, -$	$\boxed{1^+}$, 3^+, 5^+, 7^+	antisymmetric, A

$\boxed{0^+}$

$$\begin{pmatrix} b & & \\ & d & \\ & & b \end{pmatrix}_S$$

$\boxed{0^-}$

$$\begin{pmatrix} b & & \\ & & \\ & & -b \end{pmatrix}_S$$

$\boxed{1^+}$

$$\begin{pmatrix} & a & \\ -a & & a \\ & -a & \end{pmatrix}_A$$

a, b, c, d are still unknown coefficients, complex in general.

Landau-Yang theorem

"A massive particle with spin 1 cannot decay into two photons", wikipedia

Photons do not carry the longitudinal polarizarion $\Rightarrow H_{0,i} = H_{i,0} = 0$

$$H^{(I)}: \quad \begin{pmatrix} b & a & c \\ a & d & a \\ c & a & b \end{pmatrix}_S \quad \begin{pmatrix} b & & \\ & d & \\ & & b \end{pmatrix}_S \quad \boxed{0^+}$$

$$H^{(II)}: \quad \begin{pmatrix} b & a & \\ a & & -a \\ & -a & -b \end{pmatrix}_S \quad \begin{pmatrix} b & & \\ & & \\ & & -b \end{pmatrix}_S \quad \boxed{0^-}$$

$$H^{(III)}: \quad \begin{pmatrix} & a & \\ -a & & -a \\ & a & \end{pmatrix}_A$$

$$H^{(IV)}: \quad \begin{pmatrix} & a & c \\ -a & & a \\ -c & -a & \end{pmatrix}_A \quad \begin{pmatrix} & a & \\ -a & & a \\ & -a & \end{pmatrix}_A \quad \boxed{1^+}$$

No decay to two photons for 1^+, and group-III: $1^-, 3^-, 5^-, \ldots$

A comment on Higgs decay to ZZ: $J^P = 0^+$

The term in the SM lagrangian:

$$\mathcal{L}_{ZZH} = \frac{m_Z^2}{2v} Z_\mu Z^\mu H$$

Helicity amplitude:

$$A^{H\to ZZ}_{\lambda_1,\lambda_2} = \frac{m_Z^2}{2v}(\epsilon_1^*(\lambda_1)\cdot\epsilon_2^*(\lambda_2)).$$

Matrix of couplings:

$$H_{\lambda_1,\lambda_2} \Rightarrow \frac{1}{\sqrt{3}}\begin{pmatrix}1 & 0 & 0\\ 0 & -1 & 0\\ 0 & 0 & 1\end{pmatrix} + O(p^2)$$

First group: $b = -d = 1$.

Determination of the spin-parity

LLH comparison

- Only group can be determined without polarization
- Already something(!) - to distinguish $0^{\pm}$, $1^{\pm}$, $2^{\pm}$.

Likelihood of hypothesis (model $\mathcal{M}$):

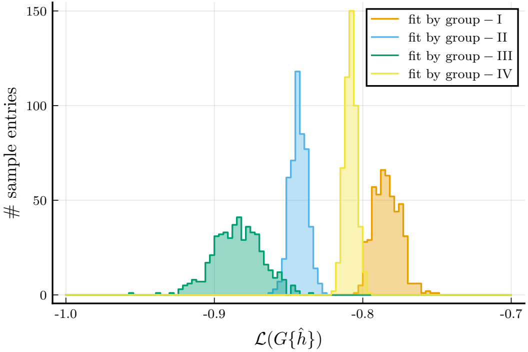
$$\mathrm{LLH}_{\mathcal{M}} = -\sum_{e=1}^{N_{\mathrm{ev}}} \log I(\tau_e | \mathcal{M}\{\hat{h}\}),$$

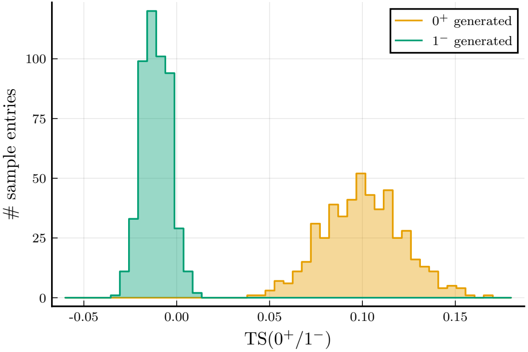
$$\text{Test statistics}: \qquad \mathrm{TS}_{\mathcal{M},\mathcal{M}'} = \mathrm{LLH}_{\mathcal{M}} - \mathrm{LLH}_{\mathcal{M}'}$$

- parameters of the model are unknown couplings $\mathcal{M}\{h\}$
- evaluation of the LLH for the optimized values $\mathcal{M}\{\hat{h}\}$

Numerical result: $T_{cc\bar{c}\bar{c}}(0^{++}) \to J/\psi(\mu^+\mu^-)J/\psi(\mu^+\mu^-)$

fits of a sample with 500 events. 500 MC experiments. [MM, L. An, R. McNulty, 2007.05501]





- The group-I has the highest likelihood (Yes!) $\Rightarrow J^P$ Natural, Even
- Width of distribution is due to the statistics
- LLH barely overlaps. TS separation is even better.

How angular distributions are different [MM, L. An, R. McNulty, 2007.05501]

Net ϕ-dependence distinguishes naturality

$$\frac{2\pi}{N}\frac{\mathrm{d}I}{\mathrm{d}\phi} = 1 + \frac{h_{1,1}h^*_{-1,-1}}{2}\cos(2\phi), \qquad \sum_{\lambda_1,\lambda_2} |H_{\lambda_1\lambda_2}|^2 = 1$$

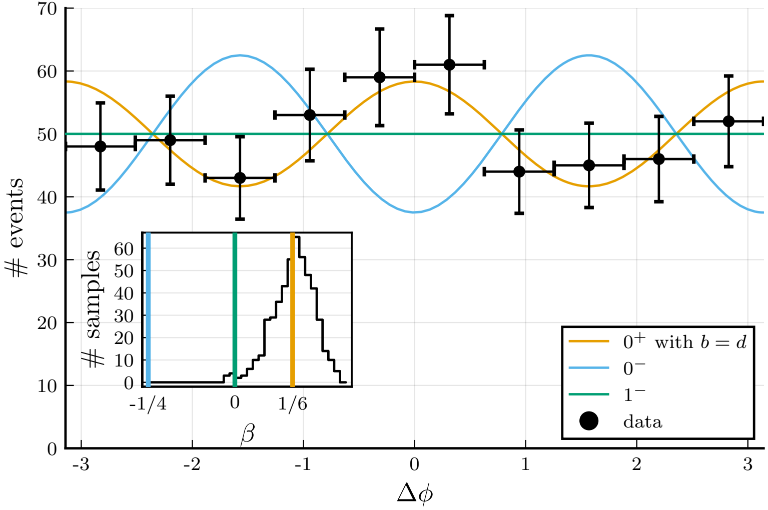
groups	$h_{1,1}h^*_{-1,-1}$	$\mathrm{d}N/\mathrm{d}\phi\,(2\pi/N)$
group-I	$\lvert b\rvert^2$	$1+\lvert b\rvert^2\cos(2\phi)/2$
group-II	$-\lvert b\rvert^2$	$1-\lvert b\rvert^2\cos(2\phi)/2$
group-III	0	flat
group-IV	0	flat

- either fit $\mathrm{d}N/\mathrm{d}\phi$ or calculate the moment $\langle\cos(2\phi)\rangle$
- distinguish groups I vs II vs (III & IV)
- warning: b might be zero $\Rightarrow$ works only if $\langle\cos(2\phi)\rangle \neq 0$

$T_{cc\bar{c}\bar{c}}(0^{++})$ ϕ distribution

[MM, L. An, R. McNulty, 2007.05501]

MS sample, 1000 events



Helicity matrix $H = \mathbb{I}/\sqrt{3}$,

$$h_{1,1} h^*_{-1,-1} = \frac{1}{3}$$

positive $\langle \cos(2\phi) \rangle$ moment,

$$\frac{2\pi}{N} \frac{\mathrm{d}N}{\mathrm{d}\phi} = 1 + \frac{1}{6} \cos(2\phi)$$

- Clearly different to the best one gets with other hypotheses

Summary: Exotics 2020

Two groundbreaking news from LHCb and it is not the end of the year yet

$X(2900)$ in D^-K^+ spectrum

- charm-strange molecule?
- tetraquark of "two generations"?
- kinematic effect

$T_{cc\bar{c}\bar{c}}$ First hints for the $cc\bar{c}\bar{c}$ tetraquarks

- How many states
- How the dip is produced
- How to treat interference with SPS
- Measurements of the quantum numbers are critical

Thank you for your attention

Thanks to LHCb colleagues
Thanks to Ronan and Liupan