Studies of meson-like exotic states at LHCb

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Studies of meson-like exotic states at LHCb

Outline:

- **X(3872)** at LHCb
- Amplitude analysis of $B^+ \to \boldsymbol{J/\psi\phi} K^+$, structures in $\boldsymbol{J/\psi\phi}$
- Amplitude analysis of $B^+ \to \boldsymbol{\psi(2S)\pi^-} K^+$, studies of $\boldsymbol{Z(4430)^-} \to \boldsymbol{\psi(2S)\pi^-}$
- Observation of the decay $\boldsymbol{B_s^0 \to \psi(2S)\pi^- K^+}$
- Non-observation of **X(5568)**
- Search for $\boldsymbol{X_{bb\bar{b}\bar{b}}}$

See other spectroscopy talks from LHCb:

Searches for exotic baryonic states at LHCb	by Paolo Gandini
Heavy quark(onia) spectroscopy at LHCb	by Daniel Johnson
Studies of $\boldsymbol{B_c}$ mesons at LHC	by Jibo He
Recent LHCb results in Charm Spectroscopy	by Jibo He

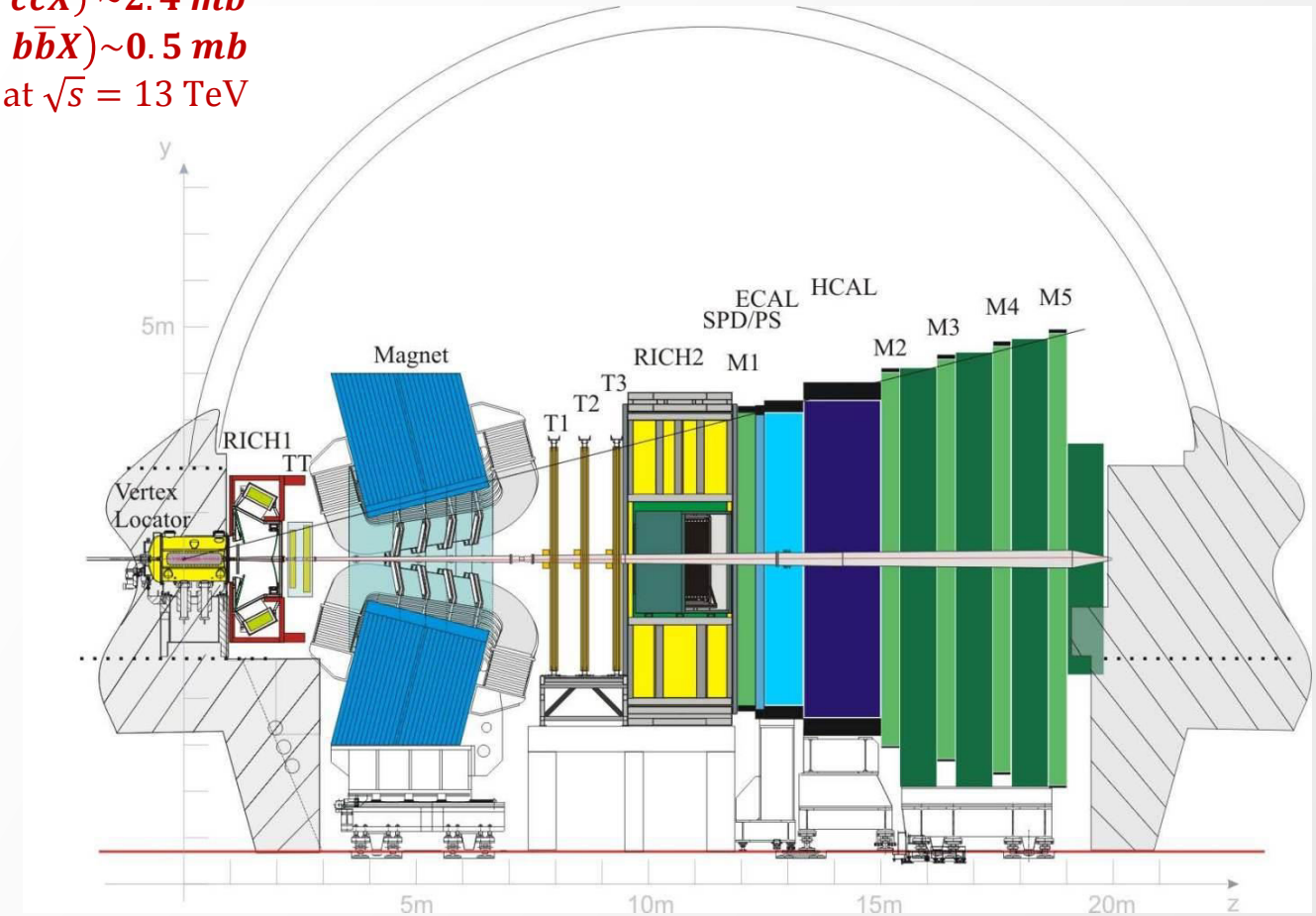
Complete set of the LHCb results in https://cds.cern.ch/collection/LHCb%20Papers?ln=en

LHCb detector

IJMPA 30, 1530022
JINST 3, S08005

- Single-arm spectrometer designed for beauty and charm physics in forward region
- **Large heavy quarks production cross-section compare to *B-factories***

$\boldsymbol{\sigma(pp \to c\bar{c}X) \sim 2.4\ mb}$
$\boldsymbol{\sigma(pp \to b\bar{b}X) \sim 0.5\ mb}$
at $\sqrt{s} = 13$ TeV



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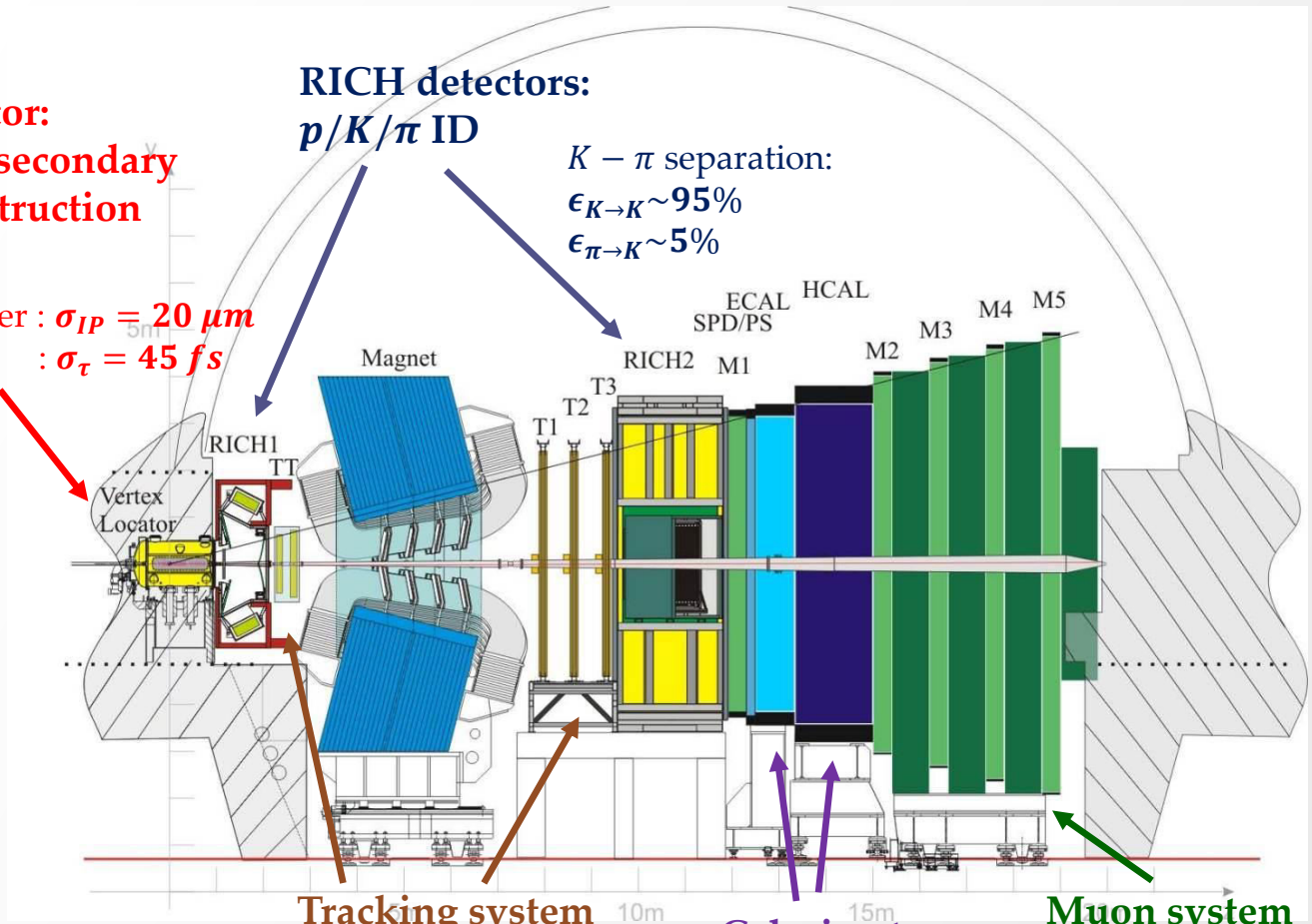
VErtex LOcator:
Primary and secondary vertex reconstruction

Resolution:
Impact parameter : $\sigma_{IP} = 20\ \mu m$
Lifetime : $\sigma_\tau = 45\ fs$

RICH detectors:
$p/K/\pi$ ID

$K-\pi$ separation:
$\epsilon_{K\to K}\sim 95\%$
$\epsilon_{\pi\to K}\sim 5\%$



Tracking system

Calorimeters:
$e/\gamma/\pi^0$ ID

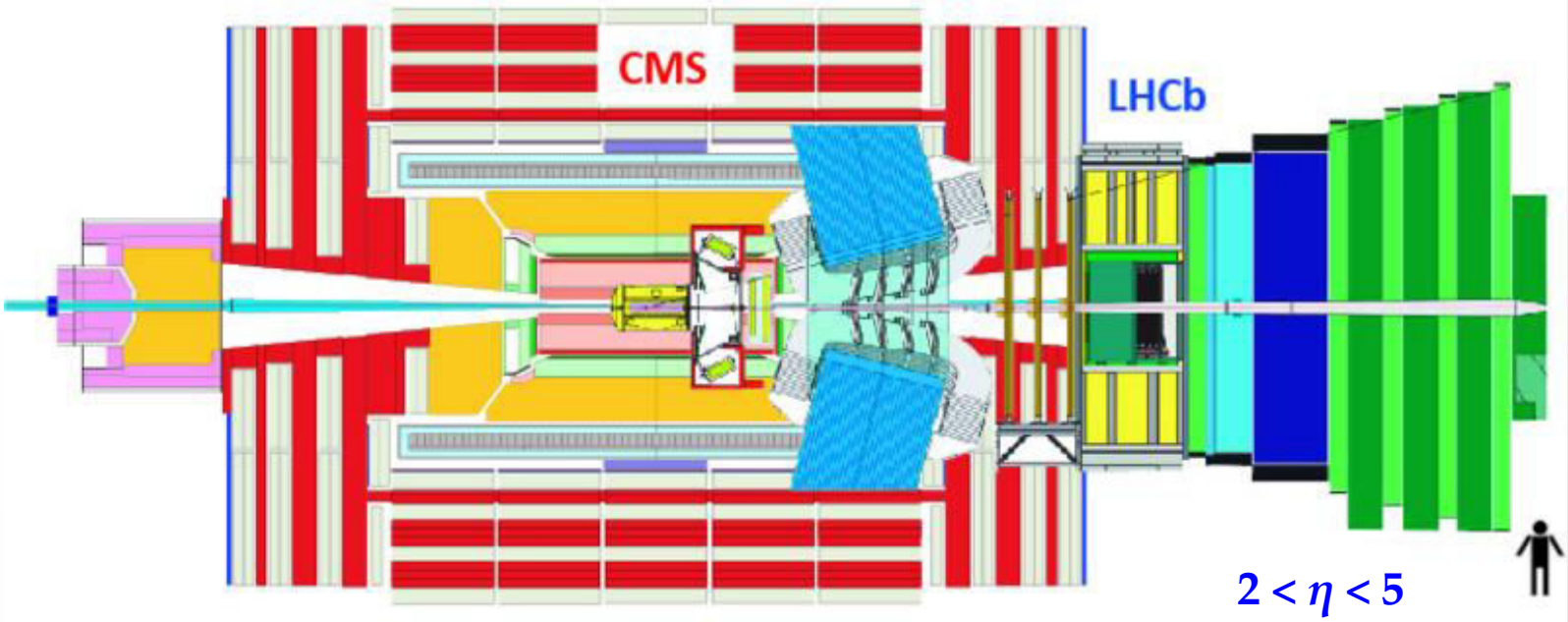
Muon system

$\epsilon_{\mu\to\mu}\sim 97\%$
$\epsilon_{\pi\to\mu}\sim 1-3\%$

- Precise vertex reconstruction with VELO
- Powerful charged hadrons ID by RICH detectors

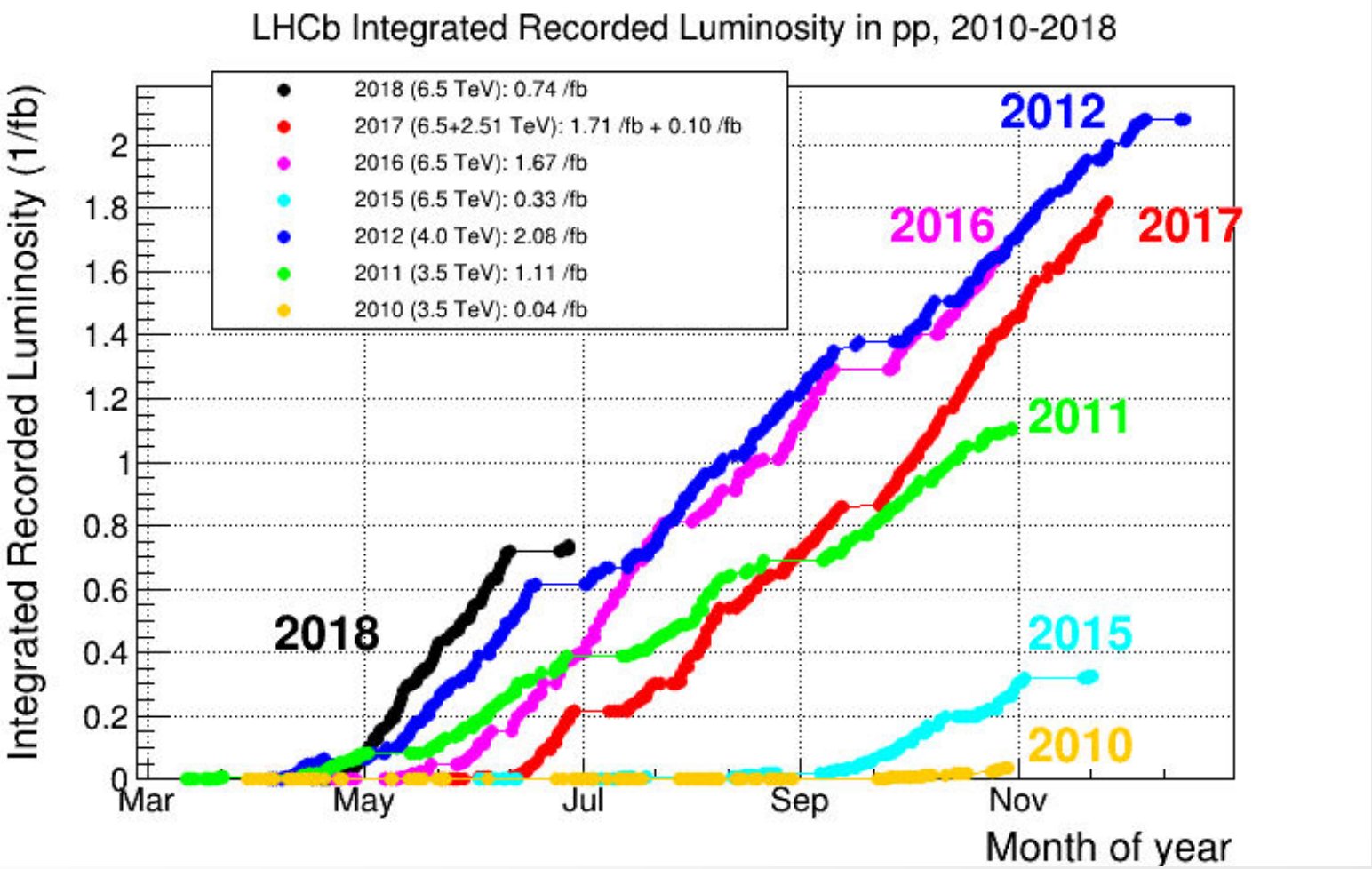
LHCb detector

IJMPA 30, 1530022
JINST 3, S08005



- Coverage complementary to **ATLAS** and **CMS** in p_T and η
- Comparable ***b*-quark** production cross-section in *much smaller solid angle*
- **Large trigger bandwidth for *b-physics***
- Limited instantaneous luminosity

Data samples



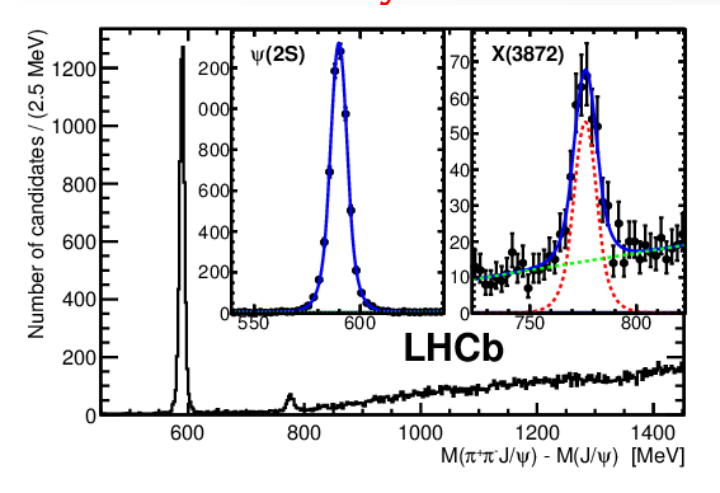
Run I (2011-2012): $3\ fb^{-1}$, $\sqrt{s} = 7{,}8\ TeV$ (***most of results in this talk***)
Run II (2015-2018): $4.4\ fb^{-1}$ ***(so far)***, $\sqrt{s} = 13\ TeV$

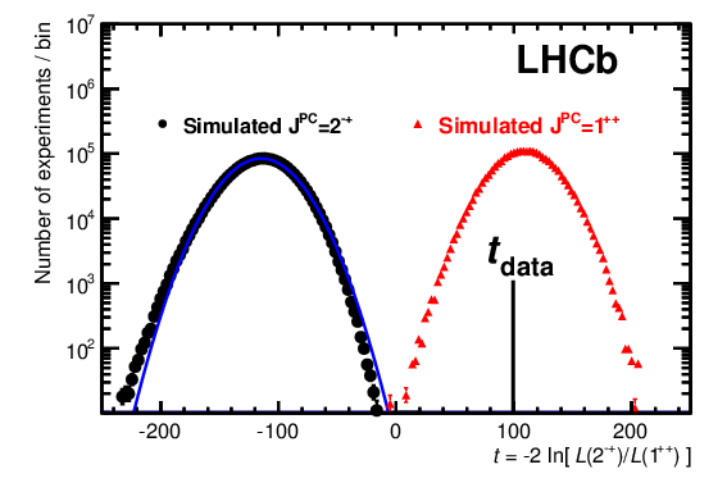
X(3872) at LHCb

- Firstly observed by Belle in 2003 **PRL 91, 262001**

- Close to DD^* threshold, $\boldsymbol{M(DD^*) - M(X(3872)) = 0.01 \pm 0.17\ MeV}$
- Very narrow, $\boldsymbol{\Gamma(X(3872)) < 1.2\ MeV}$ → **rejects pure charmonium model**

- $\boldsymbol{J^{PC} = 1^{++}}$ **established by LHCb [PRL 110, 222001] [PRD 92, 011102]**





$\boldsymbol{J^{PC} = 2^{-+}}$ **rejected at 8.4σ level**

- Evidence of decay $\boldsymbol{X(3872) \to \psi(2S)\gamma}$ **Nucl.Phys. B886, 665-680**

$$\frac{\mathcal{B}(\mathrm{X}(3872) \to \psi(2\mathrm{S})\gamma)}{\mathcal{B}(\mathrm{X}(3872) \to \mathrm{J}/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

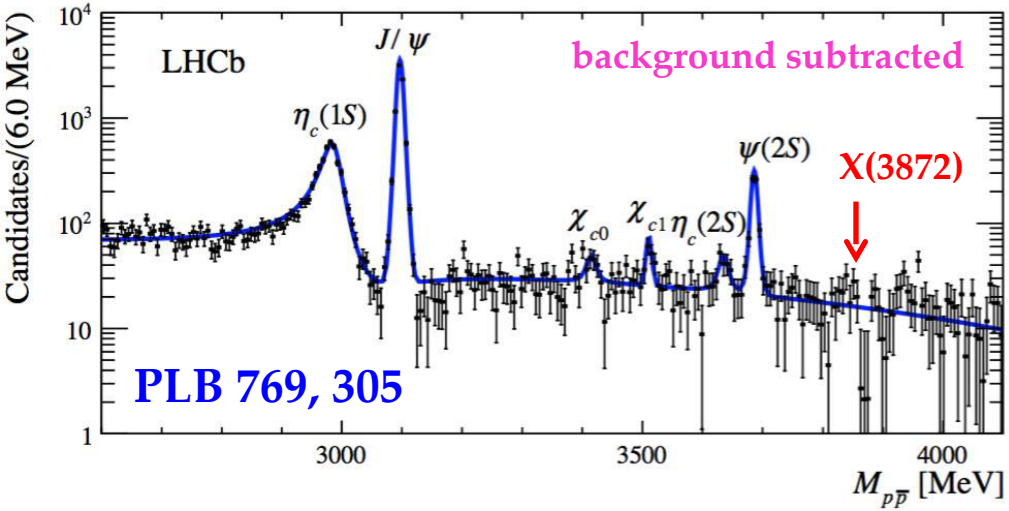
→ **rejects pure molecular model**

- Prompt production measurement at LHCb **EPJC 72, 1972**

Search for $X(3872) \to p\bar{p}$ and $X(3872) \to \phi\phi$

Search for $X(3872) \to p\bar{p}$ and $X(3872) \to \phi\phi$

- $\boldsymbol{B^+ \to p\bar{p}K^+}$: clean environment to study $(c\bar{c}) \to p\bar{p}$

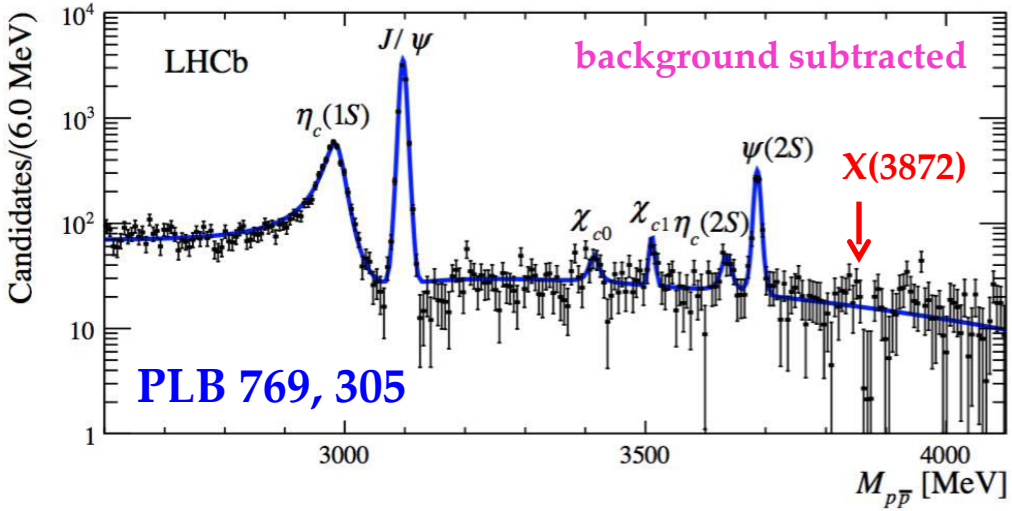


Upper limit:

$$\frac{\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 0.20\,(0.25) \times 10^{-2}$$

Search for $X(3872) \to p\bar{p}$ and $X(3872) \to \phi\phi$

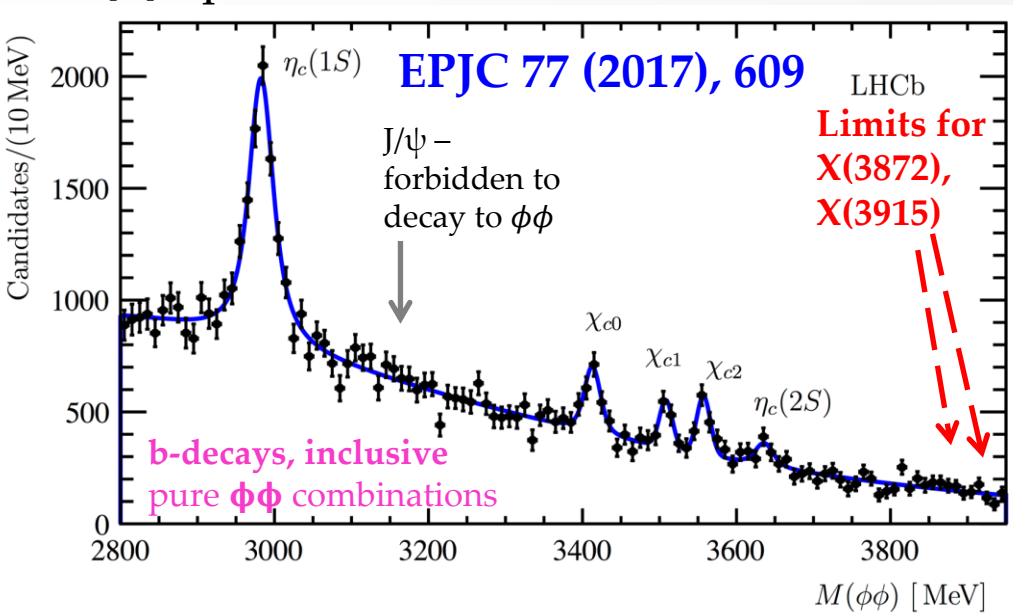
- $\boldsymbol{B^+ \to p\bar{p}K^+}$: clean environment to study $(c\bar{c}) \to p\bar{p}$



Upper limit:

$$\frac{\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 0.20\,(0.25) \times 10^{-2}$$

- **$\phi\phi$** spectrum from inclusive b-hadron decays



Upper limit:

$$\frac{BR(b \to X(3872)X) \times BR(X(3872) \to \phi\phi)}{BR(b \to \chi_{c1}X) \times BR(\chi_{c1} \to \phi\phi)} < 0.39\ (0.34$$

Amplitude analysis of $B^+ \to J/\psi\phi K^+$

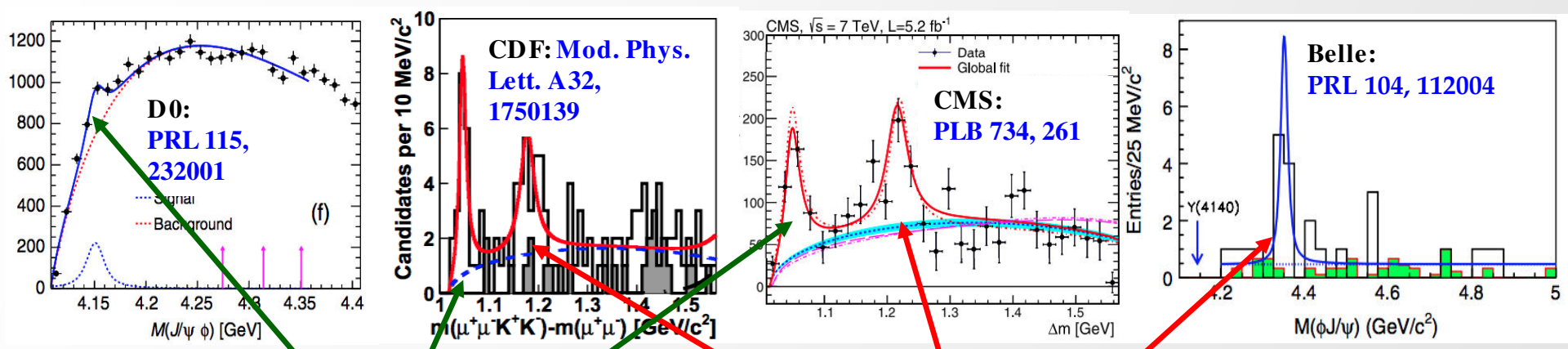
PRD 95, 012002
PRL 118, 022003

$X(4140) \to J/\psi\phi$ historical overview:

- First evidence by CDF with later observation by CMS
- **Claimed to be narrow** (world average for width: $\Gamma(X(4140)) = 15.7 \pm 6.3$ **MeV**
  - charmonium resonances expected to be much broader at this mass region
  - exotic candidate containing no u- or d-quarks
  - ➞ **possible interpretations:**
    - **molecular state**
    - **tetraquark**
    - **hybrid state**
    - **rescattering effect**

$X(4274)$:

- Seen by CDF, CMS and Belle
- No strong observation (significance $< 5\sigma$)



$X(4140)$ $X(4274)$

Amplitude analysis of $B^+ \to J/\psi\phi K^+$

PRD 95, 012002
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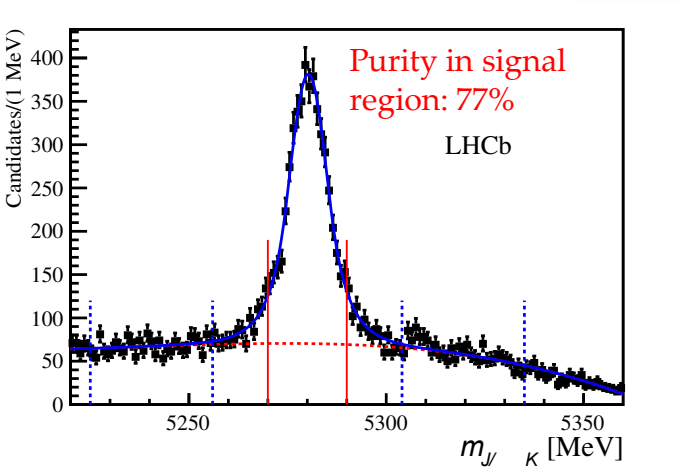
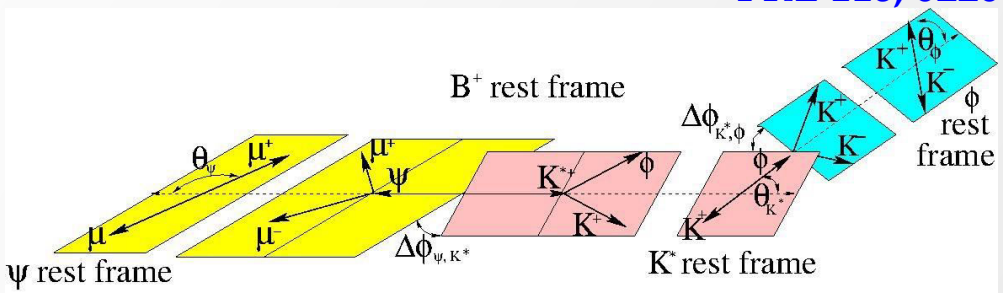
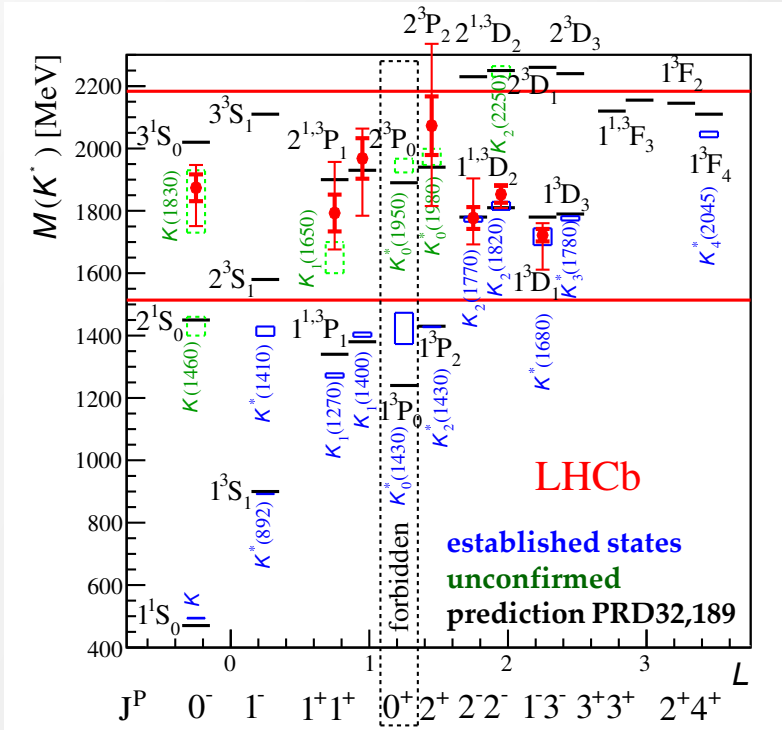




<u>First</u> 6D full amplitute analysis:

- mass $M_{\phi K}$
- helicity angles θ_ψ, θ_{K^*}, θ_ϕ
- angles between decay planes $\Delta\phi_{\psi,K^*}$, $\Delta\phi_{K^*,\phi}$

- Contributions from all possible $\boldsymbol{B^+ \to J/\psi K^{*+}}$
- Not many $K^{*+} \to \phi K^+$ **well established**
- Using **Godfrey-Isgur** model to define **quantum numbers of not established** K^{*+} states
- Masses and widths of all K^{*+} states **are free fit parameters**

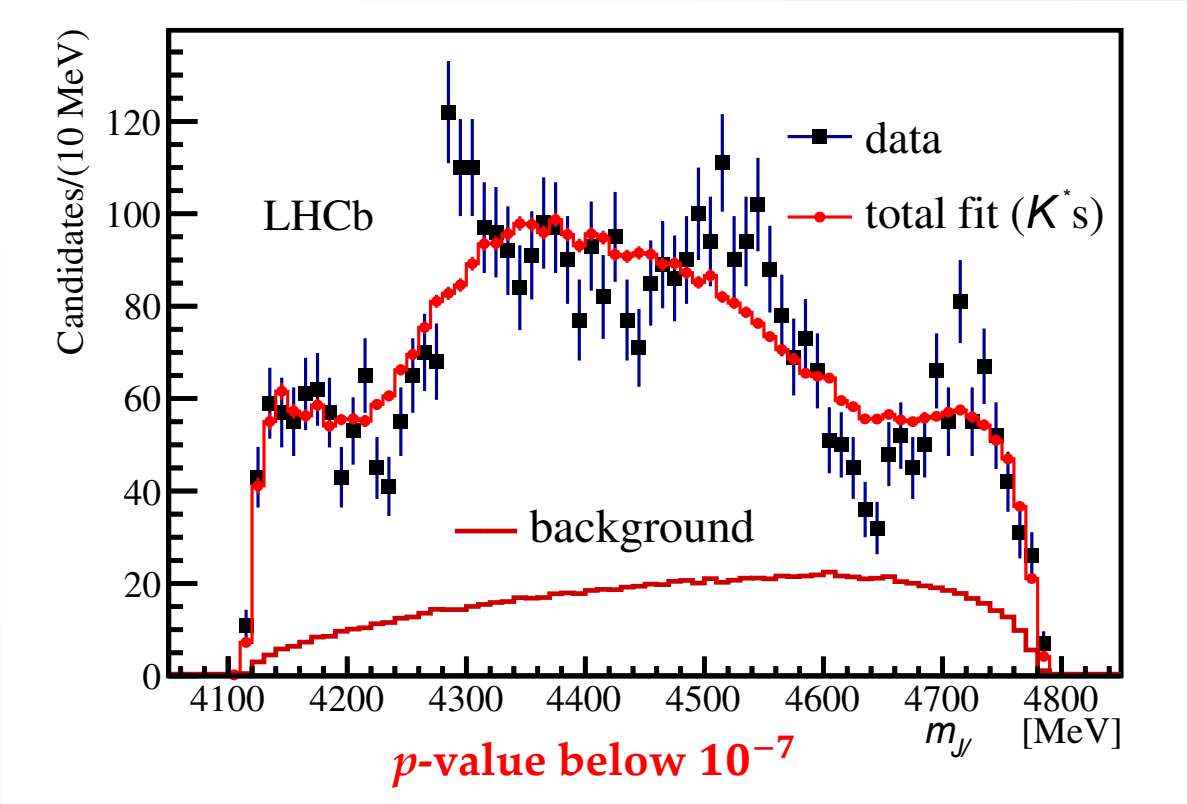


Amplitude analysis of $B^+ \to J/\psi\phi K^+$

PRD 95, 012002
PRL 118, 022003

K^*'s-only hypothesis fit:

- $M_{\phi K}$ and $M_{J/\psi K}$ can be described by model
- $M_{J/\psi\phi}$ is not described by fit



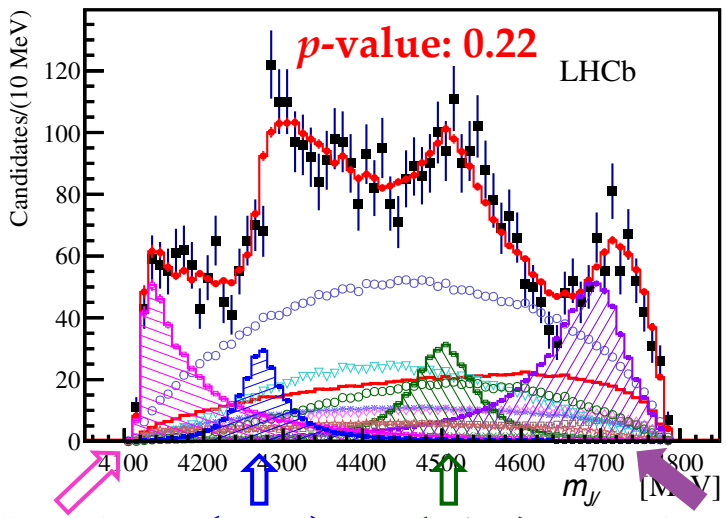
→ non-K^* resonances needed:

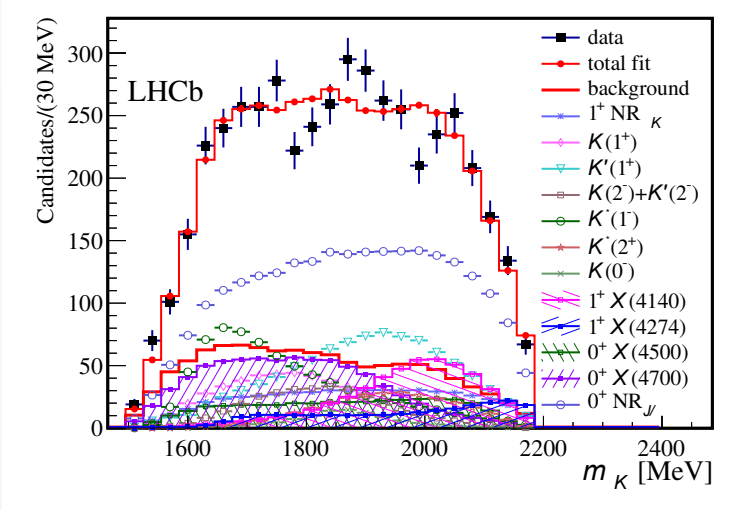
- $Z^+ \to J/\psi K^+$ - does not lead to significant improvements
- $X \to J/\psi\phi$

Amplitude analysis of $B^+ \to J/\psi\phi K^+$

PRD 95, 012002
PRL 118, 022003

After including contributions from **four *X*-states**:





$X(4140)$ **8.4σ** | $X(4274)$ **6.0σ** | $X(4500)$ **6.1σ** | $X(4700)$ **5.6σ**

Most significant ϕK^+ resonance - $K^*(1680)^+$
→ first observation of $\boldsymbol{K^*(1680)^+ \to \phi K^+}$ **(8.5σ)**

	M(MeV)	Γ(MeV)	J^{PC}	
$X(4140)$	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$ (first measurement from amplitude analysis) **⇒ wider than world average (15.7±6.3)**	1^{++} (5.7σ)	**⇒ rule out $D_s^{*+}D_s^{*-}$ molecular model. Cusp model?**
$X(4274)$	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	1^{++} (5.8σ)	**⇒ not molecule or cusp, not a hybrid charmonium. Tetraquark?**
$X(4500)$	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	0^{++} (4.0σ)	**⇒ $D_s^{*+}D_s^{*-}$ state? EPJC 64, 373**
$X(4700)$	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	0^{++} (4.5σ)	

Tetraquark models:

- Lebed-Polosa: 1^{++} *X(4140)*, but 0^{-+} *X(4274)* **PRD 93, 094024**
- Anisovich et al: only one 1^{++} state **IJMPA 30, 1550186**
- Stancu model: 1^{++} *X(4140)* and 1^{++} state a bit higher than *X(4274)* **JPG 37, 075017**

Cusp models (PRD 91, 034009, arXiv:1710.02061) to consider, needs investigations and more data

Amplitude analysis of $B^0 \to \psi(2S)\pi^- K^+$

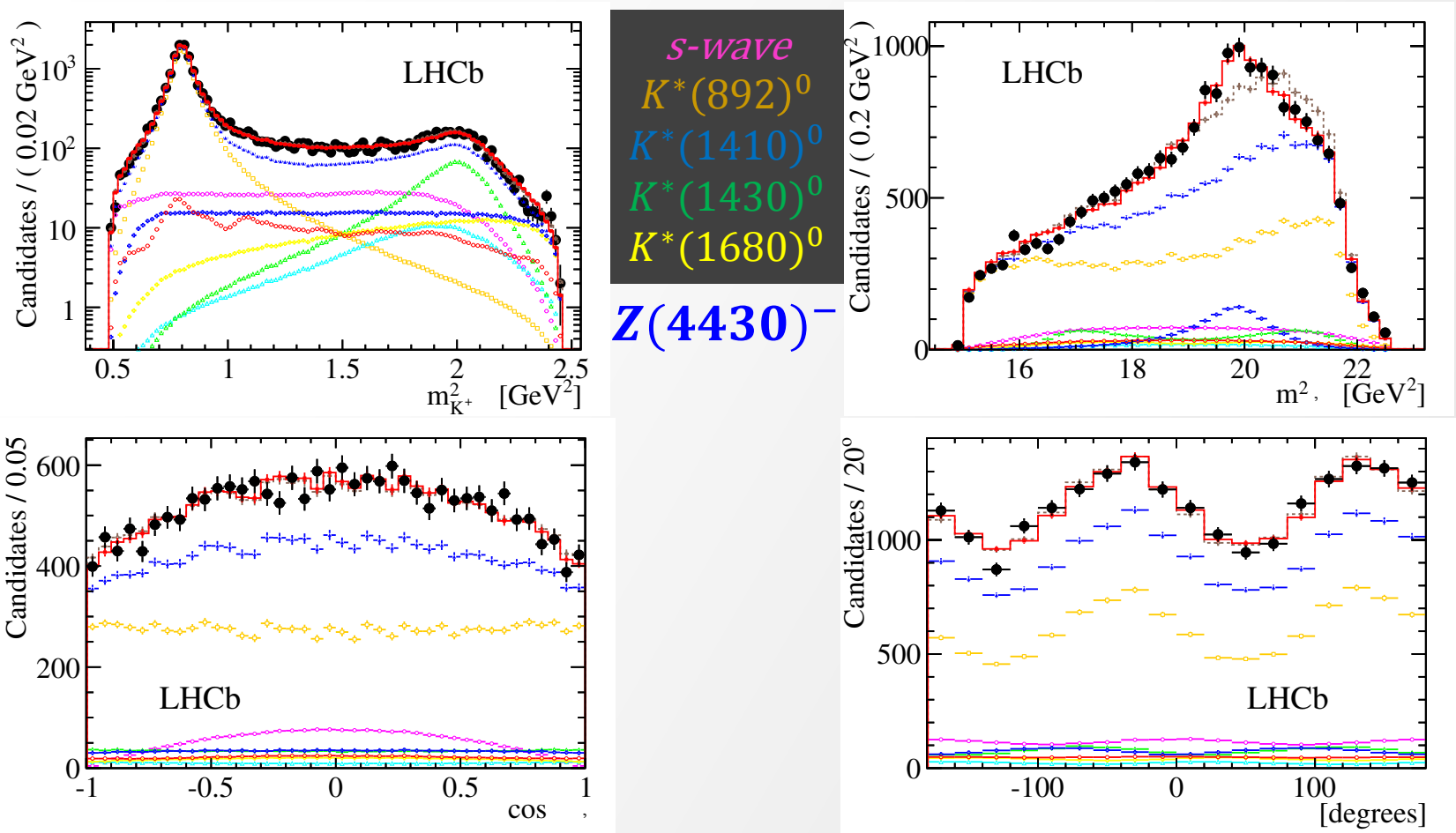
PRD 92, 112009
PRL 112, 222002

$Z(4430)^- \to \psi(2S)\pi^-$ historical overview:

- First seen by Belle **PRD 80, 031104**, confirmed by amplitude analysis **PRD 88, 074026**
- Exotics candidate, minimal content: $c\bar{c}d\bar{u}$
- BaBar can describe data by K^*'s reflections, but could not rule out $Z(4430)^-$ contribution **PRD 79, 112001**

4D amplitude analysis of $B^0 \to \psi(2S)\pi^- K^+$ at LHCb

$[\, m^2(K\pi), m^2(\psi(2S)\pi), \theta_{\psi(2S)}, \varphi_{\psi(2S)} \,]$

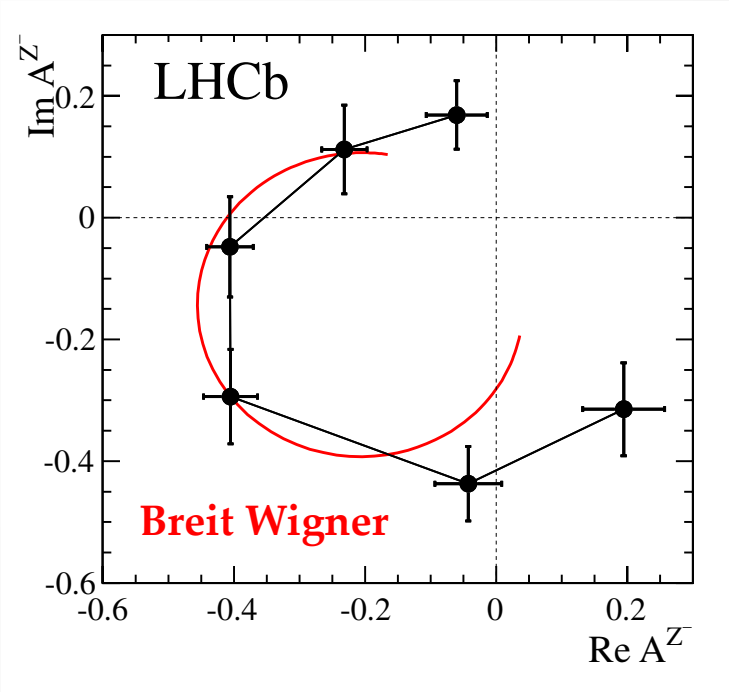


Amplitude analysis of $B^0 \to \psi(2S)\pi^- K^+$

PRD 92, 112009
PRL 112, 222002

- Significance of $Z(4430)^- > \mathbf{13.9\sigma}$
- **Mass and width**: $\mathrm{M}\left(Z(4430)^-\right) = 4475 \pm 7^{+15}_{-25}\ \mathrm{MeV/c^2}$
  $\Gamma(Z(4430)^-) = 172 \pm 13^{+37}_{-34}\ \mathrm{MeV/c^2}$
  → mass and width consistent and more precise than Belle measurement
- $\boldsymbol{J^P = 1^+}$ established (more than $\mathbf{9\sigma}$ over alt. hypotheses)

- **Argand diagram:**

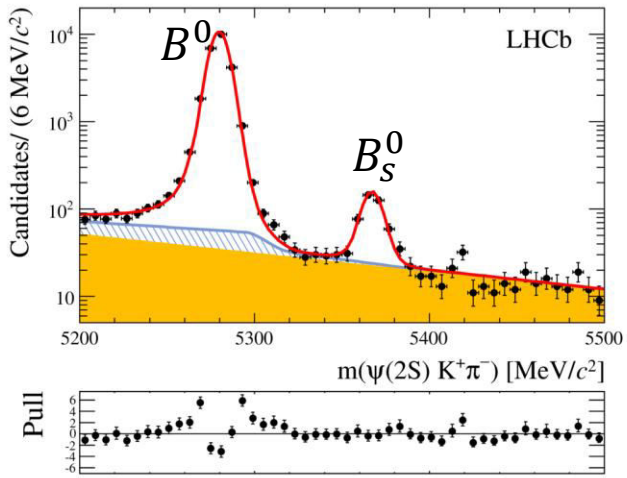


→ suggests resonant behavior
→ more data is needed to distinguish btw resonance and cusp

- **Model independent confirmation by moments analysis PRD 92, 112009**

Observation of the decay $B_s^0 \to \psi(2S)\pi^- K^+$ PLB 747, 484-494

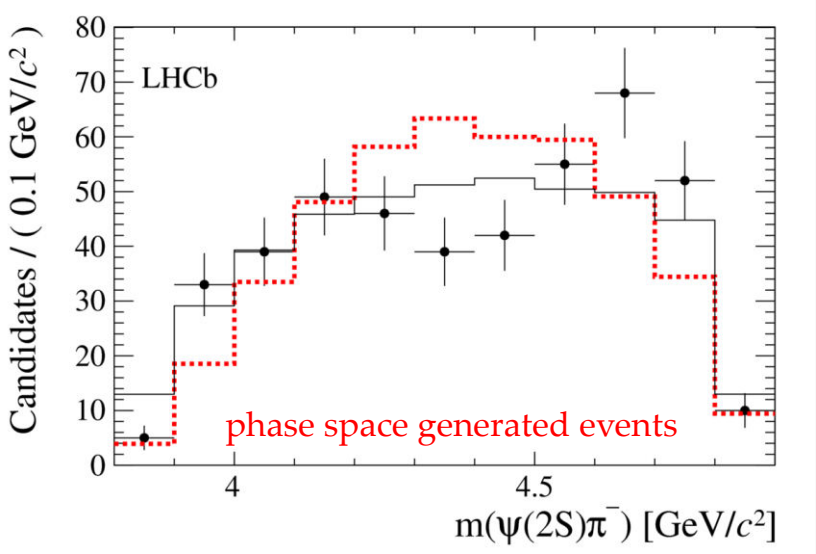
- First observation of the decay



$$\frac{\mathcal{B}(\overline{B}_s^0 \to \psi(2S)K^+\pi^-)}{\mathcal{B}(B^0 \to \psi(2S)K^+\pi^-)} = 5.38 \pm 0.36(stat) \pm 0.22(syst) \pm 0.31\,(f_s/f_d)\,\%$$

$$\frac{\mathcal{B}(\overline{B}_s^0 \to \psi(2S)K^*(892)^0)}{\mathcal{B}(B^0 \to \psi(2S)K^*(892)^0)} = 5.58 \pm 0.57(stat) \pm 0.40(syst) \pm 0.32\,(f_s/f_d)\,\%$$

- No sign of $Z(4430)^-$ in $M(\psi(2S)\pi^-)$ distribution



more data is needed to study possible $Z(4430)^-$ contribution

Non-observation of X(5568)

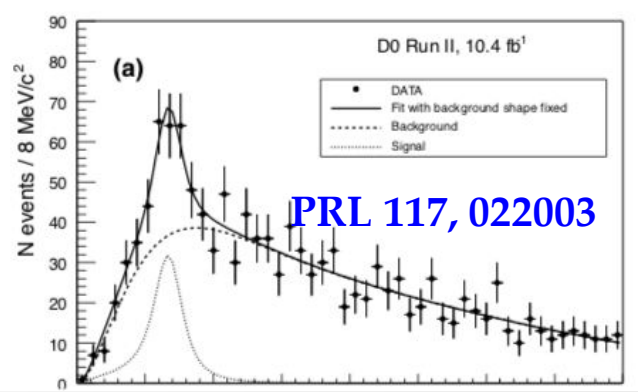
$X(5568) \to B_s^0 \pi^+$:

- Possible tetraquark candidate of four different quarks
- Seen by D0 with $4.8\,\sigma$ significance

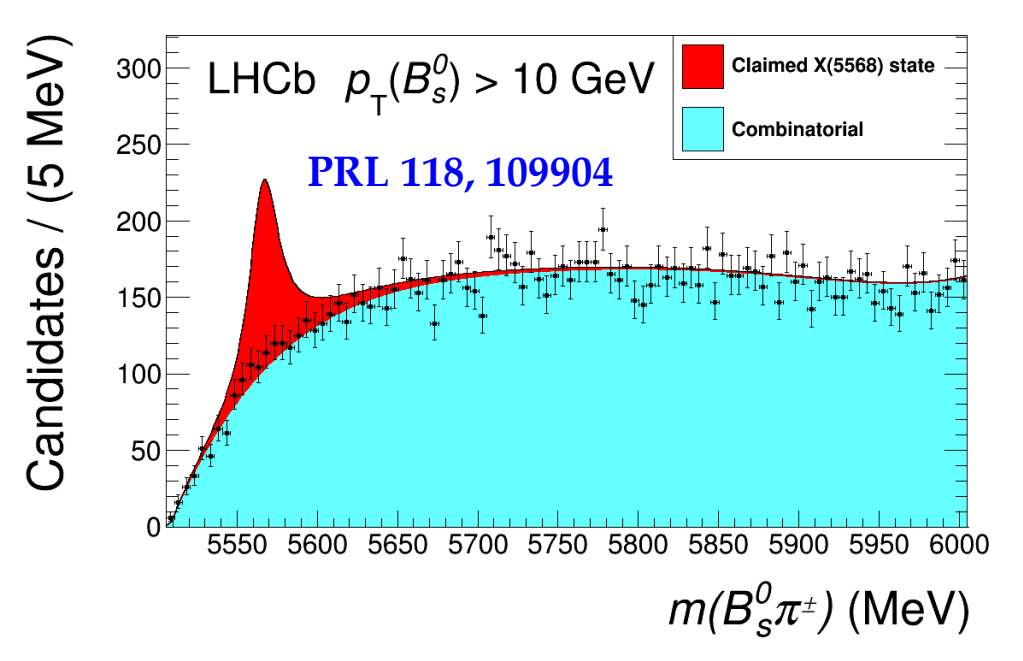
$$m = 5567.8 \pm 2.9\,(\text{stat})^{+0.9}_{-1.9}\,(\text{syst})\ \text{MeV}/c^2$$

$$\Gamma = 21.9 \pm 6.4\,(\text{stat})^{+5.0}_{-2.5}\,(\text{syst})\ \text{MeV}/c^2$$

- Later evidence by D0 using SL decays of B_s^0



$X(5568)$ is not seen at LHCb with a much larger B_s^0 sample :



No evidence at ATLAS (PRL 120, 202007), CMS (PRL 120, 202005) and CDF (PRL 120, 202006)

Search for $X_{bb\bar{b}\bar{b}}$

arXiv:1806.09707

see talk "**Heavy quark(onia) spectroscopy at LHCb**" *by Daniel Johnson*

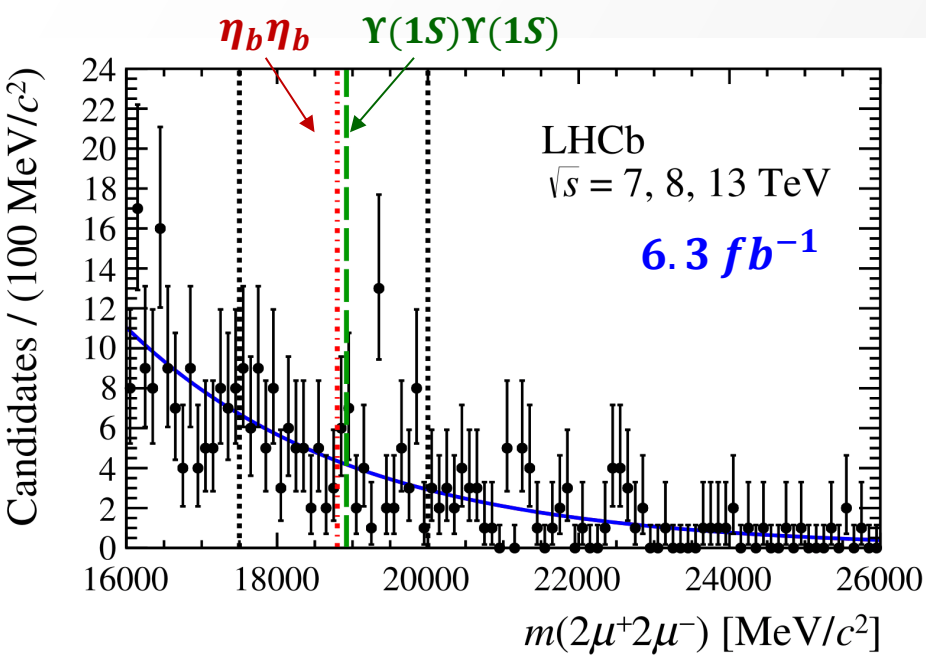
Motivation:

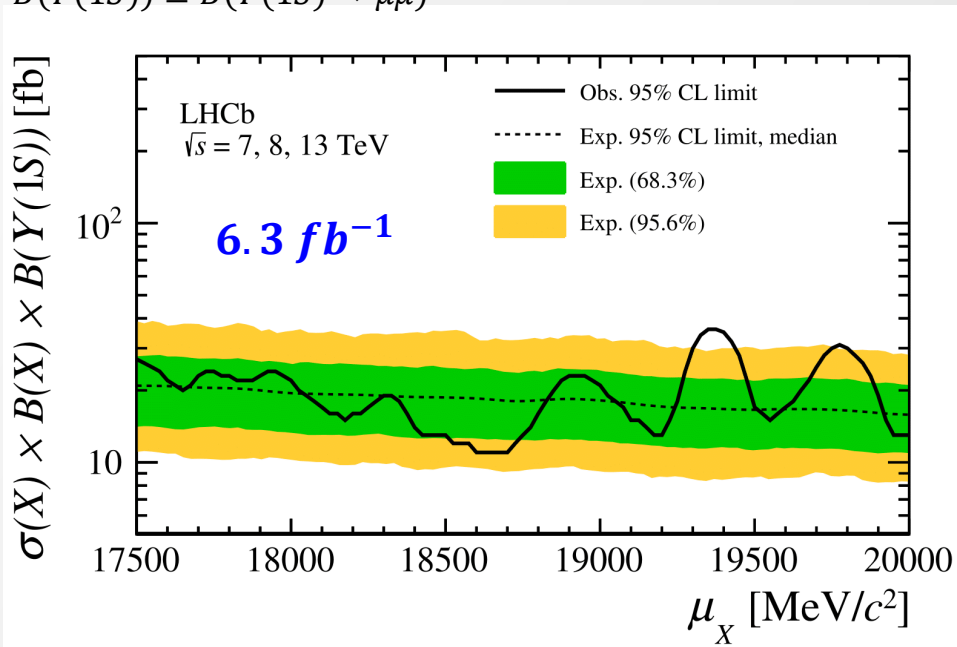
- $bb\bar{b}\bar{b}$ **tetraquark below the** $\eta_b\eta_b$ **threshold (18.8** GeV/c^2**) may be found decaying to** $\Upsilon\mu^+\mu^-$
- Predictions: **(Karliner et al., PRD 95 034011)**
- (cross section × BR) expected at the level ~**4** fb, width ~1.2 MeV

Analysis:

- Data sample: 6 fb^{-1}, **2011-2017(!)** data
- $\Upsilon(1S) \to \mu^+\mu^-$ used as normalization
- Resolution extracted from MC, ~ **65** MeV
- **Upper limits as a function of inv. mass**

$\sigma(X) \equiv \sigma(pp \to X_{bb\bar{b}\bar{b}})$
$B(X) \equiv \sigma(X_{bb\bar{b}\bar{b}} \to \Upsilon(1S)\mu\mu)$
$B(\Upsilon(1S)) \equiv B(\Upsilon(1S) \to \mu\mu)$

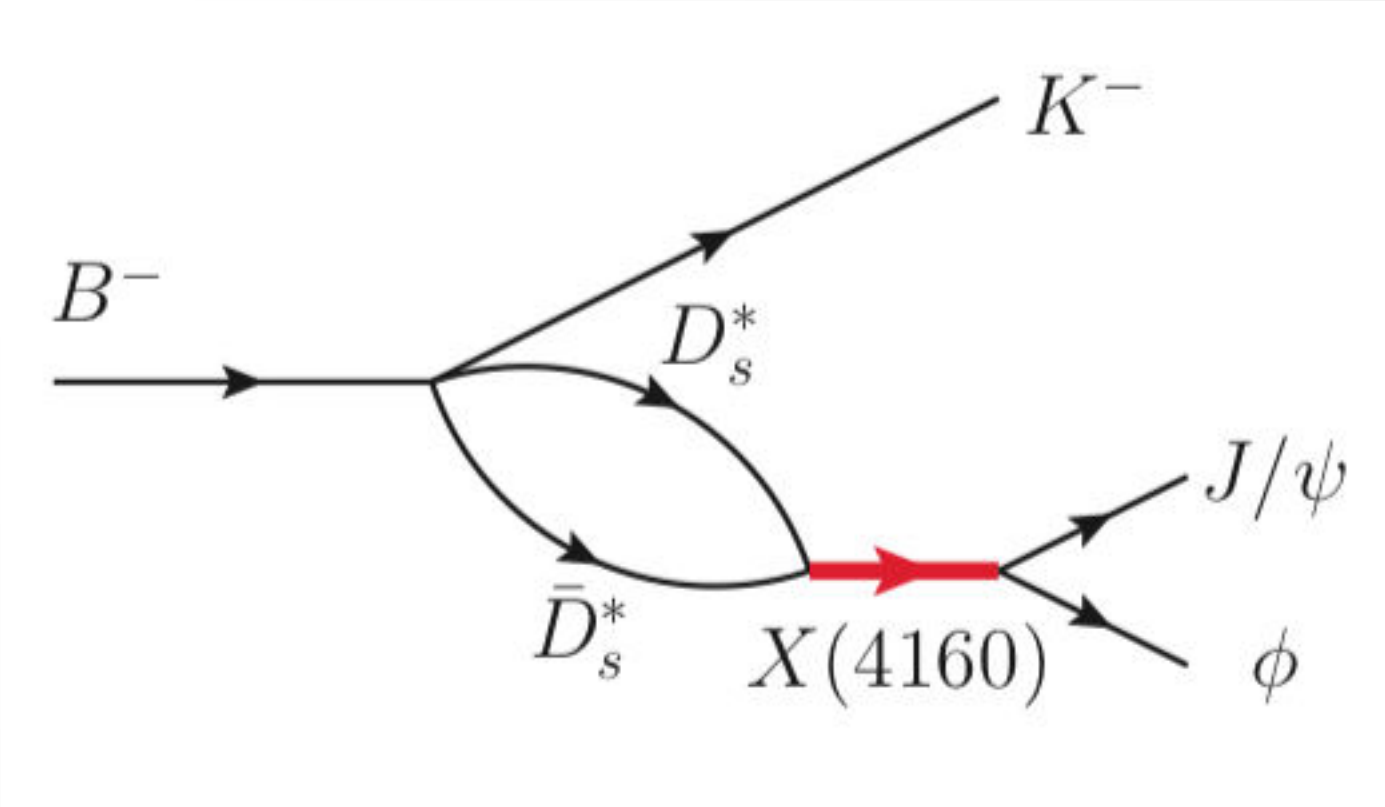




No significant signal, upper limit for mass range 17.5−20.0 GeV/c^2

Summary

- Exotics spectroscopy is an important part of LHCb program
- Large heavy quark production cross-section allows to understand properties of known exotic candidates and discover new states at LHCb
- Many important results published using Run I data:
  - Properties of **X(3872)**
  - Structures in $\boldsymbol{J/\psi\phi}$ spectra: $\boldsymbol{X(4140)}$, $\boldsymbol{X(4274)}$, $\boldsymbol{X(4500)}$ and $\boldsymbol{X(4700)}$
  - Confirmation and properties of **Z(4430)** decaying to $\boldsymbol{\psi(2S)\pi^-}$
  - Search for other exotics sates: **X(5568)**, dibaryon $\boldsymbol{\mathcal{D}_c^+}$
- Results using Run II data coming out:
  - search for $\boldsymbol{X_{bb\bar{b}\bar{b}}}$ using **2011-2017** data
- Much more results to come, stay tuned!



$D_s^{(*)}\bar{D}_s^{(*)}$ cusps to consider

PRD91(2015)034009
arXiv:1710.02061