Exotics, Spectroscopy, Heavy-flavor production (LHCb, Belle II, FCC-ee)

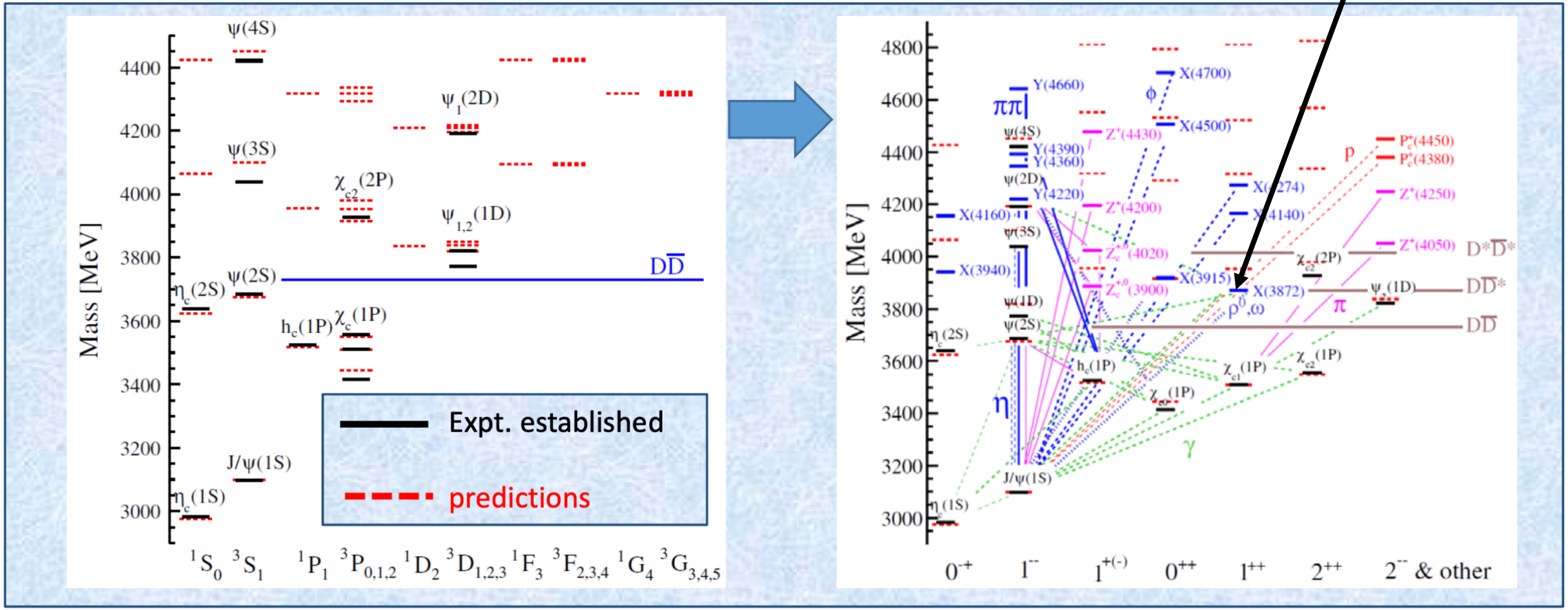
Patrick Robbe, IJCLab, 12 Mar 2020

Introduction

- All flavor physics experiments (BaBar, Belle, LHCb run 1/2) in the recent years had large contributions to hadron spectroscopy, in particular with the emergence of exotics heavy-flavor states.
- Not the first goals of these experiments but attracted a lot of attention
- Together with heavy flavor production measurements, contributed more generally to understanding of QCD, beyond the traditional area of flavor physics (weak interactions)
- NB: other experiments not dedicated to flavor physics had also an important contribution to these subjects, in the past (CDF, D0) or in the recent years and in the future (BES III, ALICE, ATLAS, CMS, PANDA, tau/charm factories…)

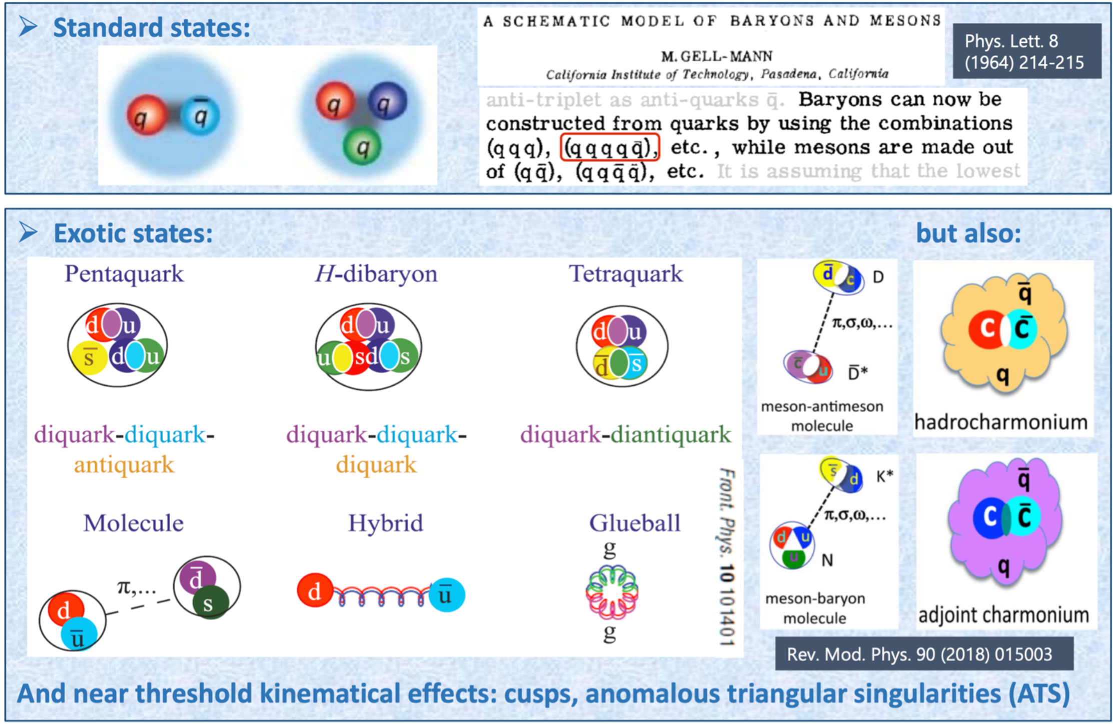
Exotics

X(3872) [Belle PRL 91 (2003) 262001]



Conventional states of the $c\bar{c}$ spectrum + exotic states (X, Y, Z)

Exotics

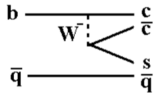


- These states have clear signature of content with 4 quarks : $cc\bar{q}q'$
- Not excluded by QCD, but exact dynamics of quark arrangement is still unknown.
- Most studied state X(3872) = $\chi_{c1}(3872)$ is believed now to be a mixture of a conventional charmonium (2 $^3P_{1^{++}}$) and of a D^{*0}-D^0 molecule
- Study of more decay modes with higher statistics needed to conclude

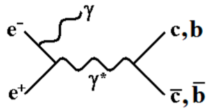
LHCb – Belle II complementarity: production mechanisms (conventional or exotic spectroscopy)

e^+e^- colliders

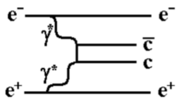
- B decays
  - Charmonium only
  - All quantum numbers available



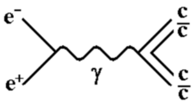
- Direct production / Initial State Radiation (ISR)
  - E_{CM} or below
  - $J^{PC}=1^{--}$ (Y(4220), Y(4360), ...)



- Two-photon interaction
  - $J^{PC} = 0^{-+}, 0^{++}, 2^{++}$



- Double charmonium production
  - Seen for $J^{PC}=1^{--}$ (J/ψ, ψ(2S)) plus J=0 states (h_c, η_c, ...)



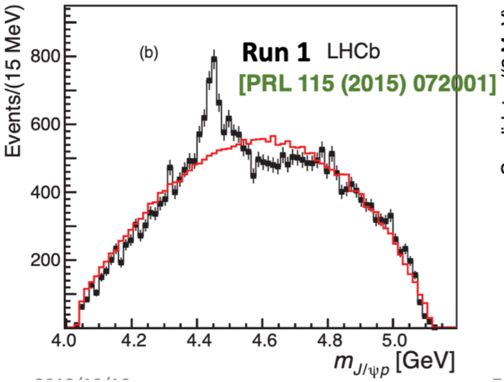
- Quarkonium transitions
  - Hadronic/radiative decays between states

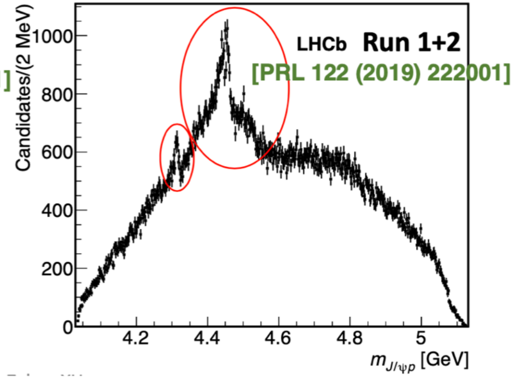
Hadron colliders

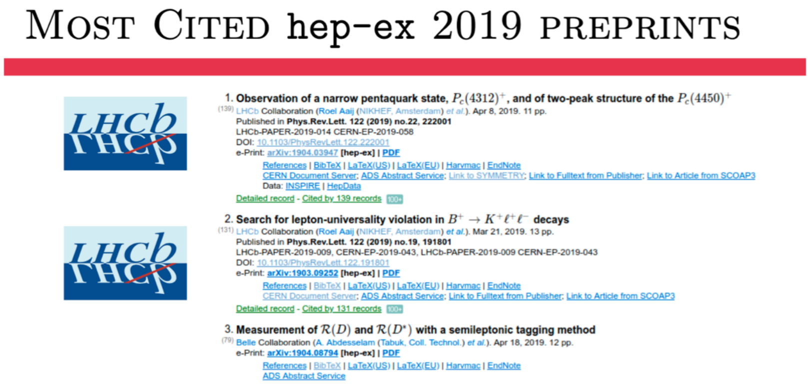
- B decays
  - Charmonium only
  - All quantum numbers available
- Direct (prompt) production (all masses and quantum numbers):
  - Decaying weekly: signatures with displaced vertices
  - Decaying strongly: large background, difficult to observe

Exotics in the baryon sector

- LHCb pentaquarks – produced in Λ_b decays (*ie* not accessible at B-factories), more states with increasing statistics
- Potentially the same rich spectroscopy of states ($c\bar{c}q_1q_2q_3$) to be explored in several decay modes






MOST CITED hep-ex 2019 PREPRINTS

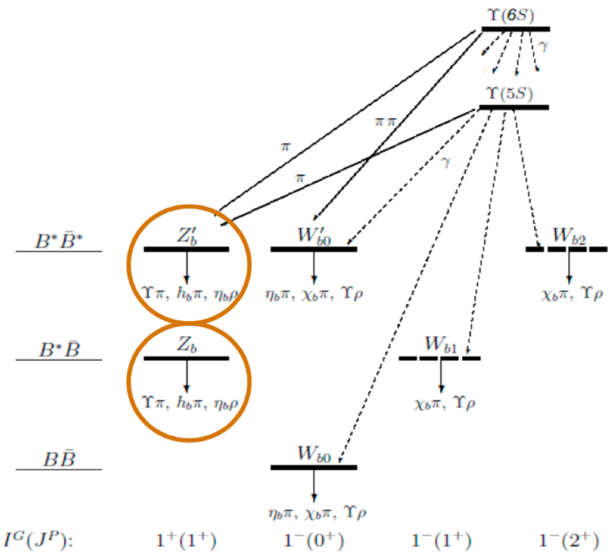
1. **Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$**
(139) LHCb Collaboration (Roel Aaij (NIKHEF, Amsterdam) *et al.*). Apr 8, 2019. 11 pp.
Published in **Phys.Rev.Lett. 122 (2019) no.22, 222001**
LHCb-PAPER-2019-014 CERN-EP-2019-058
DOI: 10.1103/PhysRevLett.122.222001
e-Print: arXiv:1904.03947 **[hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Link to SYMMETRY; Link to Fulltext from Publisher; Link to Article from SCOAP3
Data: INSPIRE | HepData
Detailed record - Cited by 139 records 100+

2. **Search for lepton-universality violation in $B^+ \to K^+\ell^+\ell^-$ decays**
(131) LHCb Collaboration (Roel Aaij (NIKHEF, Amsterdam) *et al.*). Mar 21, 2019. 13 pp.
Published in **Phys.Rev.Lett. 122 (2019) no.19, 191801**
LHCb-PAPER-2019-009, CERN-EP-2019-043, LHCb-PAPER-2019-009 CERN-EP-2019-043
DOI: 10.1103/PhysRevLett.122.191801
e-Print: arXiv:1903.09252 **[hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Link to Fulltext from Publisher; Link to Article from SCOAP3
Detailed record - Cited by 131 records 100+

3. **Measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with a semileptonic tagging method**
(79) Belle Collaboration (A. Abdesselam (Tabuk, Coll. Technol.) *et al.*). Apr 18, 2019. 12 pp.
e-Print: arXiv:1904.08794 **[hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

Exotics in the beauty sector

- First observation of ($b\bar{b}qq'$) exotics (Z_b, Z'_b) at BELLE [PRL 117 (2016) 142001]: must have neutral partners (W_b) unobserved so far.



Exotics in the beauty sector

- Strong decays: very difficult (=impossible) to study them at hadron colliders
- For Belle II: requires dedicated operation at a different center-of-mass energy compared to Υ(4S) used for *B* physics
- Beyond: other similar states are also expected with several heavy quarks. For example, $(cc\bar{q}\bar{q}')$ exotics in $B_c \to D_s^+ \bar{D}^0 D^0$ decays requires LHCb Upgrade 2 statistics to be searched.

Potential Belle II Bottomonium Scenarios

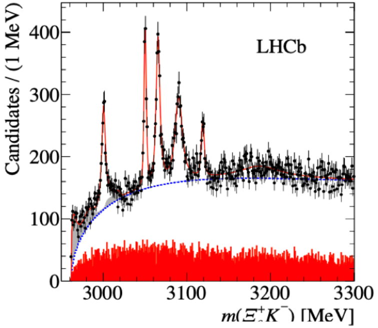
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

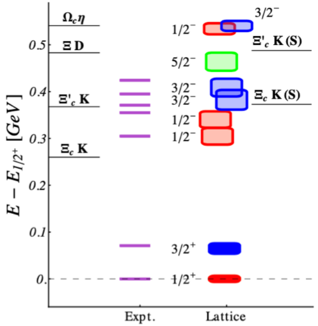
- Above $\Upsilon(4S)$
  - Study of exotic four-quark states
  - $<6 fb^{-1}$ accumulated by Belle at $E_{CM}=\Upsilon(6S)$
  - $1 ab^{-1}$ @ $\Upsilon(5S)$ = order of magnitude increase (also B_s physics)
  - $100 fb^{-1}$ @ $\Upsilon(6S)$ plus ~$400 fb^{-1}$ scan
- Below $\Upsilon(4S)$
  - Bottomonium search/study
  - New Physics in decays
  - Scan for direct production of $\Upsilon(n^3D_1)$
  - $300 fb^{-1}$ @ $\Upsilon(3S)$ = order of magnitude increase
- Dedicated operation <5% of total luminosity

Spectroscopy: conventional hadrons

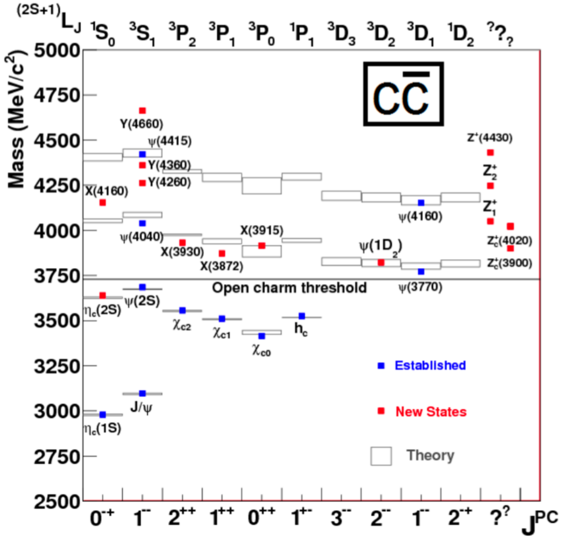
- Many results also for the spectroscopy of conventional hadrons: their properties is a powerful test of Lattice QCD computations

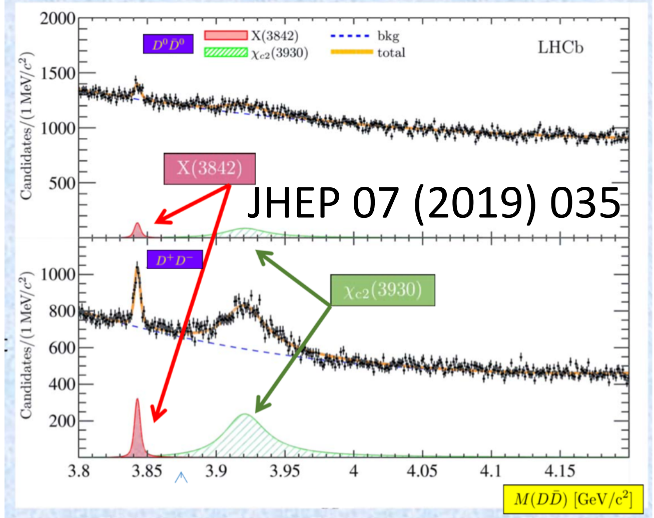
Charm baryons: Ω_c^* [PRL 118 (2017) 182001]





Charmonium spectrum above open charm threshold: still many expected states to observe with more statistics

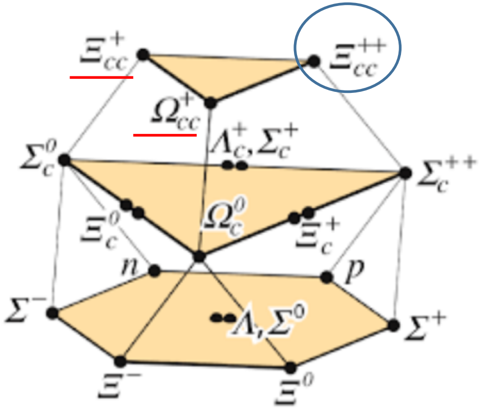




JHEP 07 (2019) 035

Spectroscopy: multi-heavy quark baryons

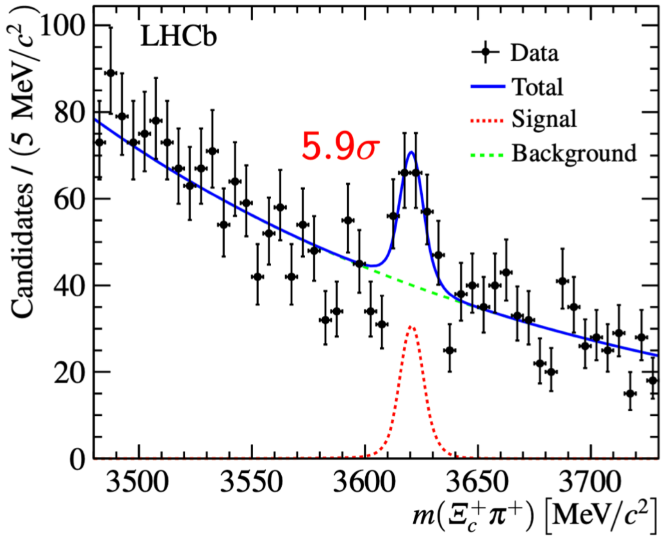
- The discovery of the double-charm baryon at LHCb also attracted a lot of attention: first baryon with two heavy quarks.
- In the end, it is an important confirmation of the quark model, but it also means there are a lot of heavier states with small production rates to be discovered with the statistics of the LHCb upgrades or with the Belle II dataset



+ equivalent baryons with *b* quarks: Ξ_{bc}, Ω_{bc}, ...

[PRL 121 (2018) 162002]

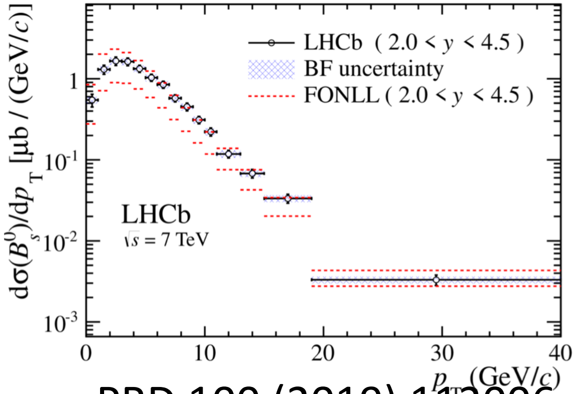
Observation in $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$



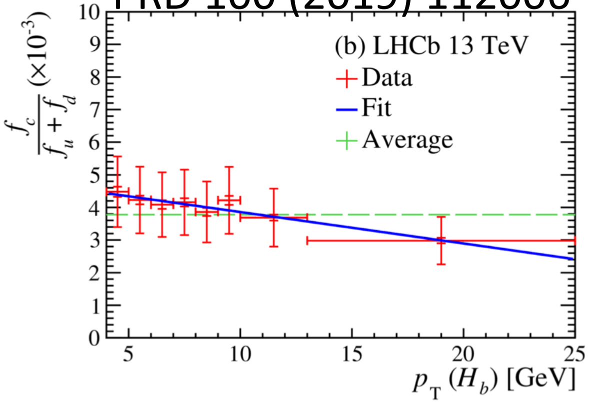
Heavy flavor production

- At LHC energies, heavy flavor production is relatively well known.
- However heavy flavor production is a powerful probe for the behavior of QCD in heavy-ion collisions: for these measurements, precise experiment information about the same production in *pp* collisions is needed.
- For flavor physics itself, precise knowledge of production is important:
  - Tuning of Monte Carlo generators
  - At the LHC, absolute B_s branching fractions are obtained usually from B^0/B^+ branching fractions (from B factories): need to know the fraction of B_s produced f_s/f_d with increasing precision
  - Idem for the B_c which has a very small production rate, but which with the upgrades will become more and more important: knowledge of f_c/f_d mandatory
- Important to continue providing these inputs in the future

JHEP 08 (2013) 117

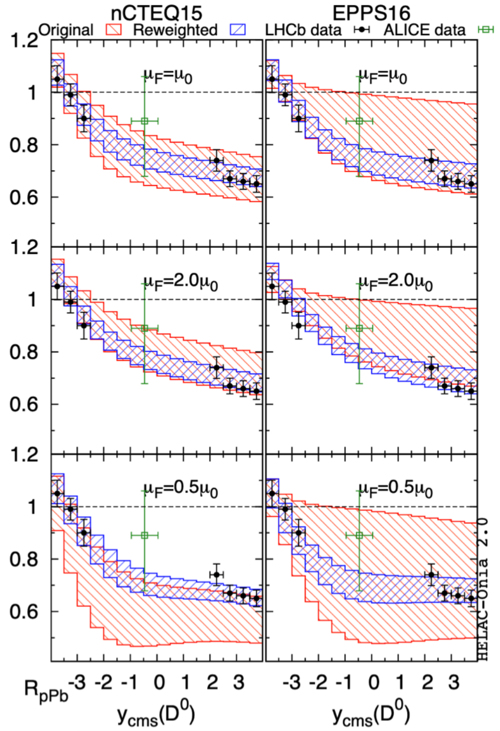


PRD 100 (2019) 112006



Heavy flavour production

Reweighting with D^0 data [A. Kusina, J-P Lansberg, I. Schienbein, H-S Shao, PRL 121 052004]

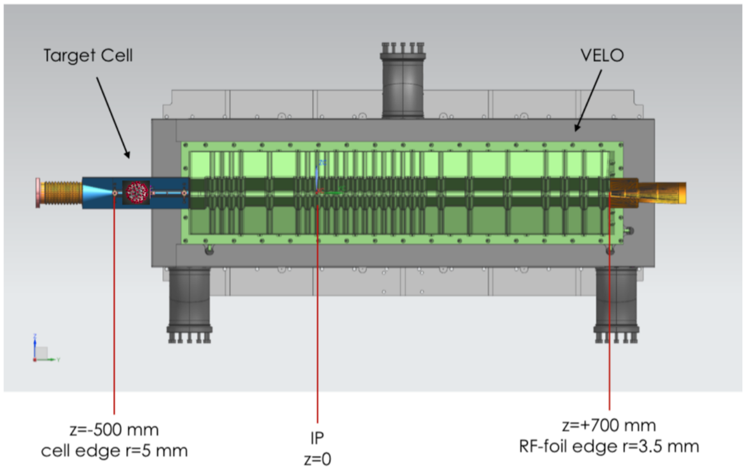


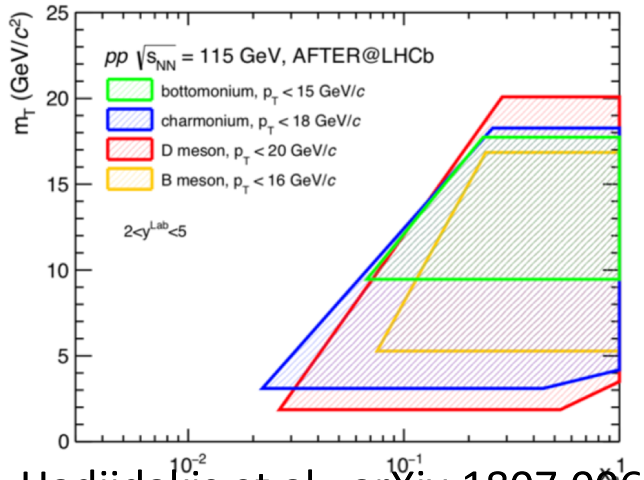
LHCb [JHEP 1710 (2017) 090, 1707.02750]
ALICE [PRL113, 232301 (2014), 1405.3452]

- Charm production measurements in hadron collisions in particular can also provide constraint to determine the nuclear PDFs:
  - Input to simulation of interaction in targets of long baseline neutrino experiments,
  - Charm background for high energy cosmic rays, ...

Heavy flavor production: SMOG2

- Injection of gas at the LHCb interaction to provide fixed target collisions
- Improved system to be installed during Upgrade Phase 1 of LHCb, with plans to upgrade to a polarized gas target after LS3
- Measurement of heavy flavor production in this environment gives access to large *x* quark and gluon pdfs.



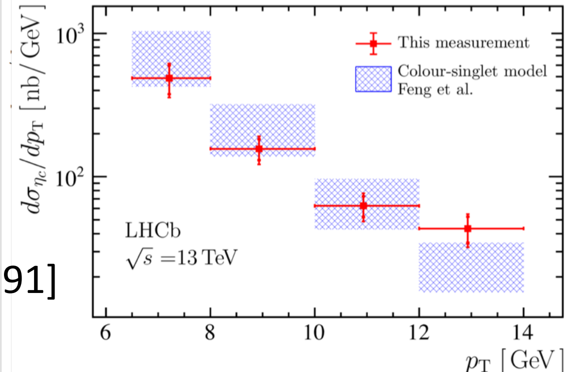


[C. Hadjidakis et al., arXiv:1807.00603]

Quarkonium production

- Despite huge progresses, QCD mechanisms for quarkonium production not well known.
- Computations based on Non-Relativistic QCD give good theory-data agreement for J/ψ or Y(nS) cross-sections, but still has problems to describe for example polarization in hadronic collisions.
- NRQCD relies on Long Distance Matrix Elements obtained from fits to all existing experimental data (including Belle and future Belle II ones) that must be improved and extended.
- Large statistics foreseen will allow to measure new states, such as η_c, with hadronic $p\bar{p}$ decay.

- First measurement of η_c(1S) production measurement at 13 TeV in *pp* collisions



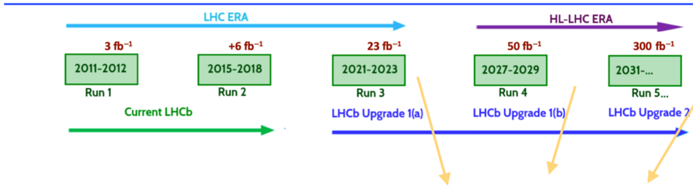
[EPJC 80 (2020) 191]

$$(\sigma_{\eta_c})^{6.5\,\mathrm{GeV}<p_T<14.0\,\mathrm{GeV},\,2.0<y<4.5}_{13\,\mathrm{TeV}} = 1.26 \pm 0.11 \pm 0.08 \pm 0.14\,\mu\mathrm{b}$$

- Result consistent with CS model prediction (**Feng et al. NPB 945 (2019) 114662**)

$$\sigma_{\eta_c} = 1.56^{+0.83+0.38}_{-0.49-0.17}$$

LHCb Upgrade II



Decay mode	LHCb 23 fb^{-1}	LHCb 50 fb^{-1}	LHCb 300 fb^{-1}
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100
$\Lambda_b^0 \to J/\psi pK^-$ [*]	680k	1.4M	8M
$\Xi_b^- \to J/\psi \Lambda K^-$	4k	10k	55k
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$	7k	15k	90k
$\Xi_{bc}^+ \to J/\psi \Xi_c^+$	50	100	600

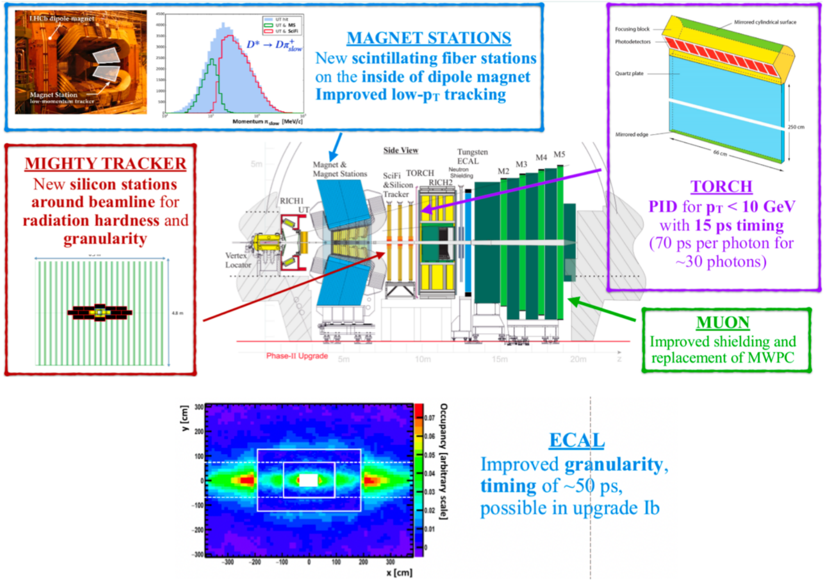
$\chi_{c1}(3872)$ lineshape from multi-channels

$Z_c(4430)$, also explore $B \to D_{(s)}^{(*)}\overline{D}_{(s)}K^-$?

Doubly-charmed tetraquark $\mathcal{T}_{cc}^+ \to D_s^+ D^0$

More information for pentaquarks

[*] updated according to the latest result



- French LHCb members interested in participating to developments for Real Time Analysis, DAQ and Calo (3 contributions to GT08 and GT09) and to contribute to the VELO and Tracker projects.

Conclusions

- Even if not the initial main goals of the experiments, many measurements done in the area of spectroscopy and production with heavy flavor, some of them having received large visibility.
- All LHCb French groups participated in several of these measurements (Ξ_{cc}^{++}, J/ψ, $Y(nS)$, χ_c, χ_b, η_c, D, B and B_c production in *pp* collisions or with SMOG, exotics in $\Lambda_b \to \Lambda_c D p$ or $B \to D D K$)
- Belle II and LHCb upgrades guarantee that this area will remain very active in the next years:
  - Continue understanding of exotic states
  - Observation of many new conventional or exotic heavier states
- Connections to other fields (QCD theory, understanding heavy-ion collisions, ….)