Charmonium(like) production in LHCb

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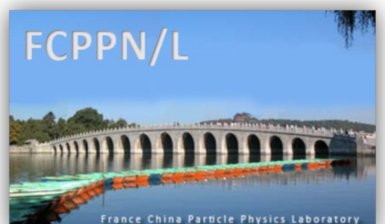
Contacts: Sergey Barsuk (IJCLab), Jibo He (UCAS)

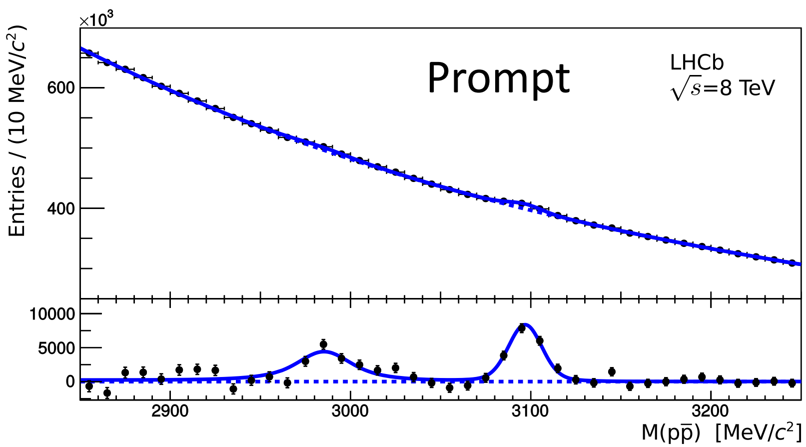
15th 

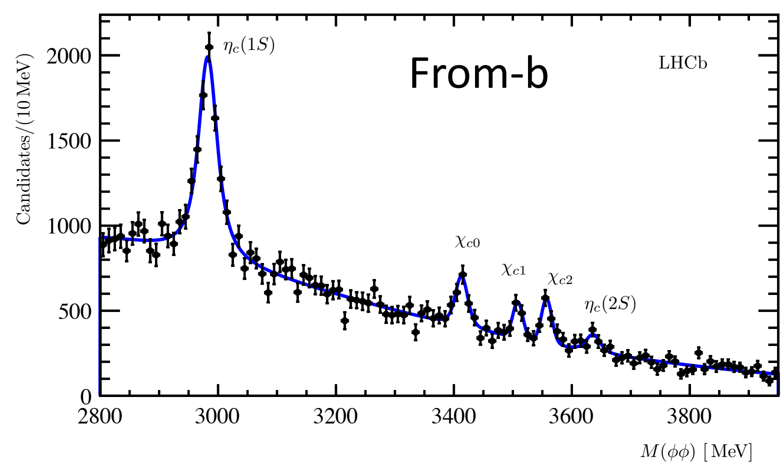
Workshop, Bordeaux

10-14 Jun 2024

Introduction

- Theoretical review given by H.S. Shao. Comprehensive review given by S. Barsuk in FCPPL 2023
- Focus on experimental side of charmonium production using hadronic decays, which can be done only by LHCb so far





Large Hadron Collider

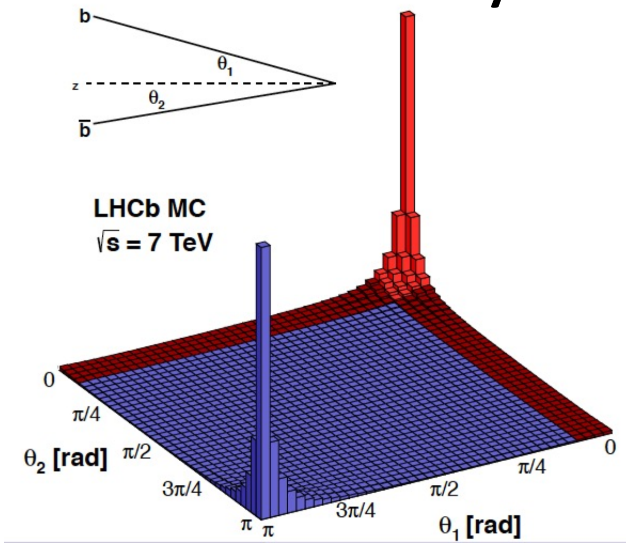
Proton energy: up to 7 TeV (10^{12} eV)
speed: 0.999999991 c

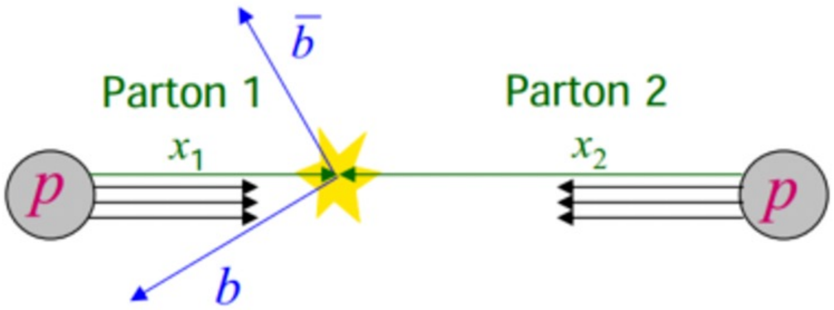
Beauty/charm production

- Large production cross-section @ 7 TeV
  - Minibias ~60 mb
  - Charm ~6 mb
  - Beauty ~0.3 mb c.f. 1nb @$\Upsilon(4S)$

  } Flavour factory!

- Predominantly in forward/backward cones

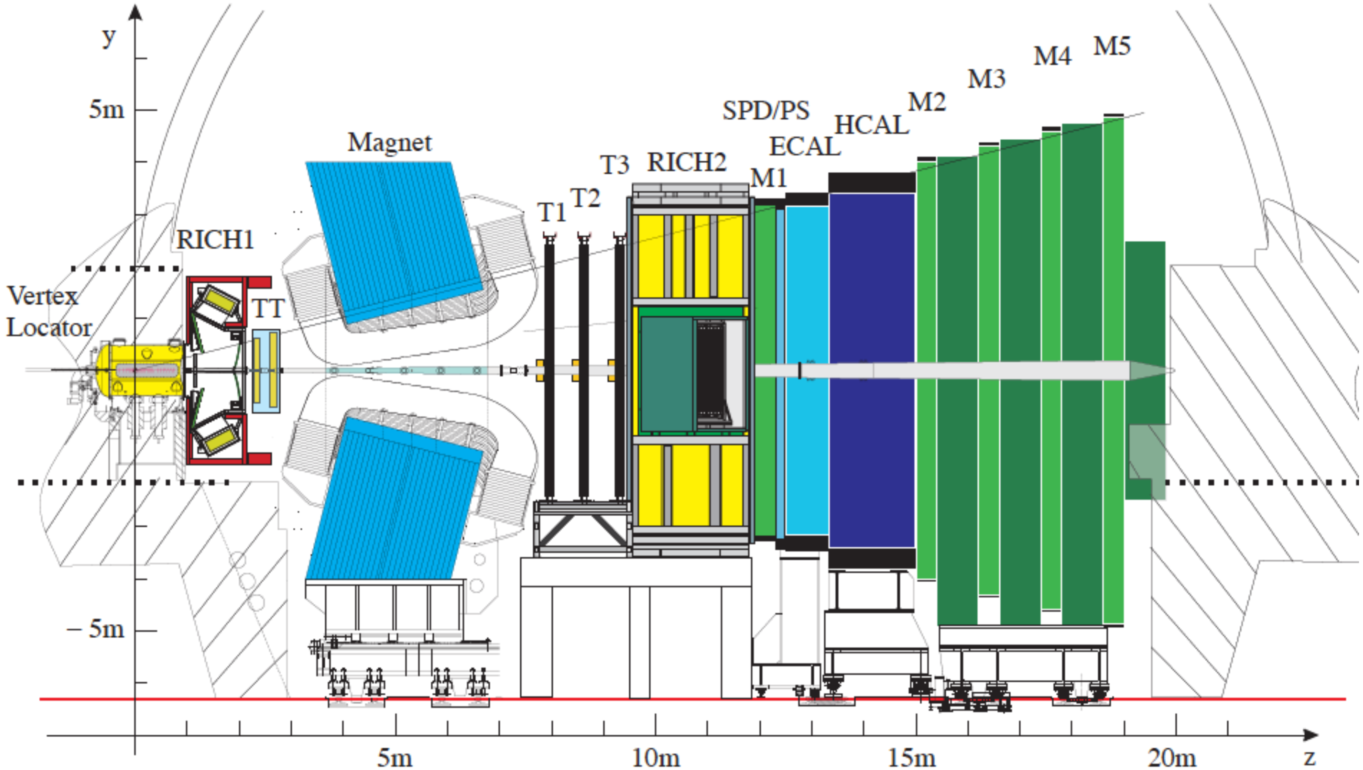




Initial energy of $b\bar{b}$ not known

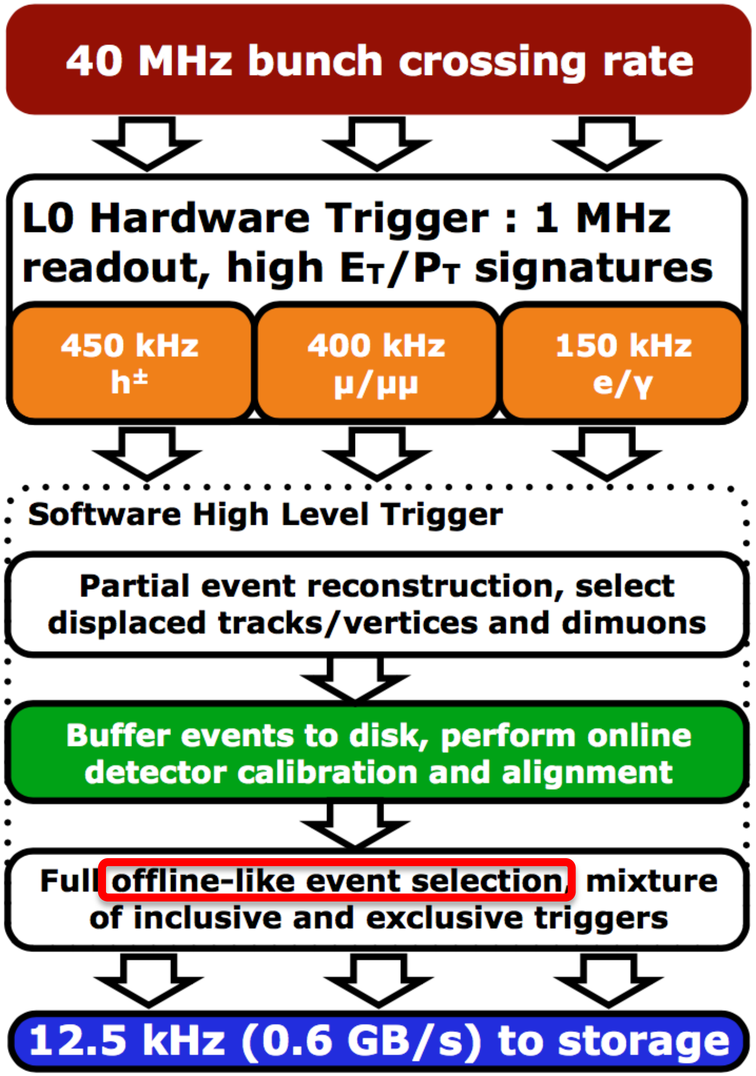
The LHCb experiment

[JINST 3 (2008) S08005]



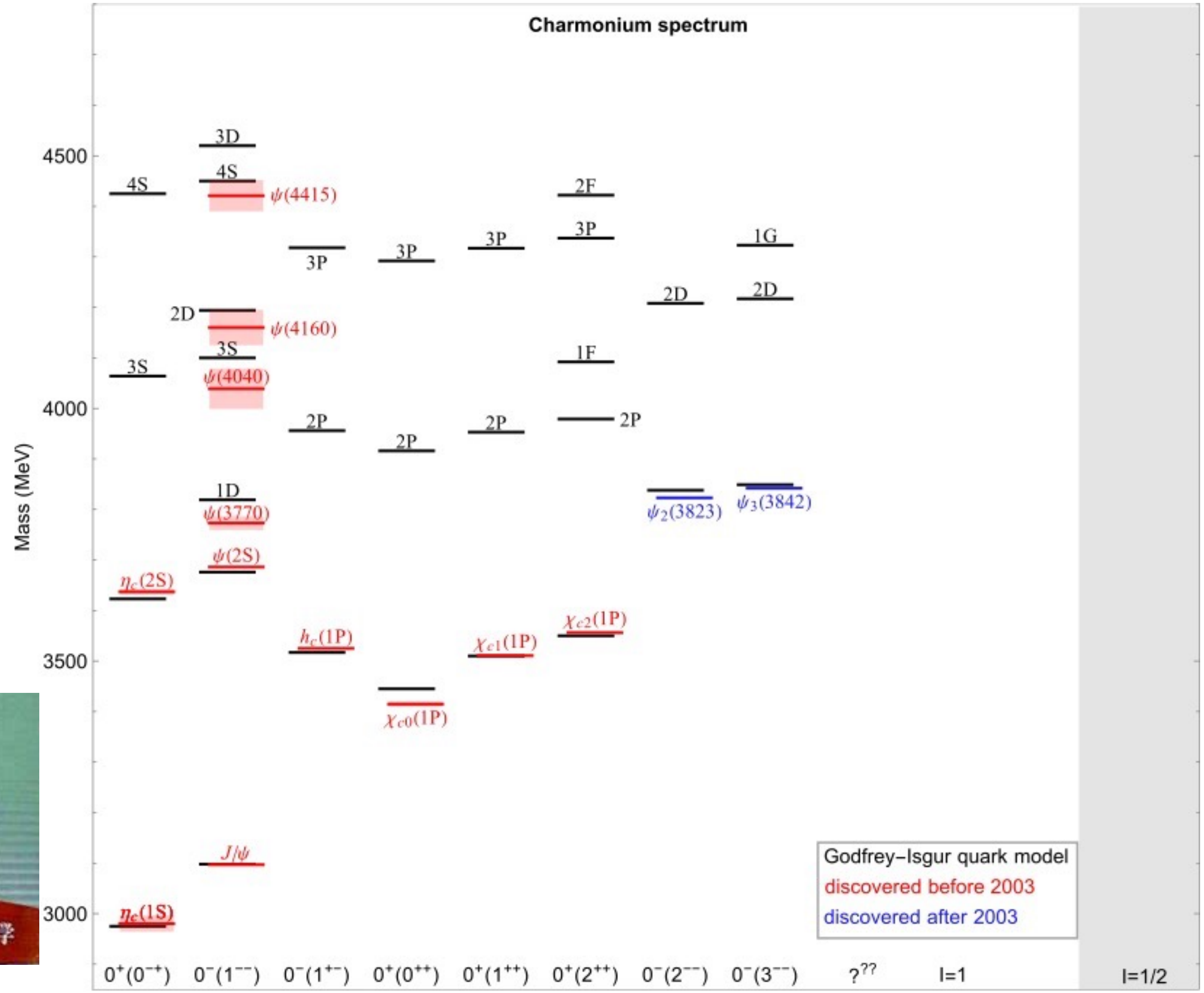
Vertex Locator	$\sigma_{\mathrm{PV,x/y}} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV,z}} \sim 60\ \mu\mathrm{m}$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1 - 3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

The LHCb trigger (2018)



- L0, Hardware
  - $p_T(\mu_1) \times p_T(\mu_2) >$ (1.5 GeV)^2
  - $p_T(\mu) >$ 1.8 GeV
  - $E_T(e) >$ 2.4 GeV
  - $E_T(\gamma) >$ 3.0 GeV
  - $E_T(h) >$ 3.7 GeV
- High Level Trigger
  - Stage1, p_T, IP
  - Stage2, full selection

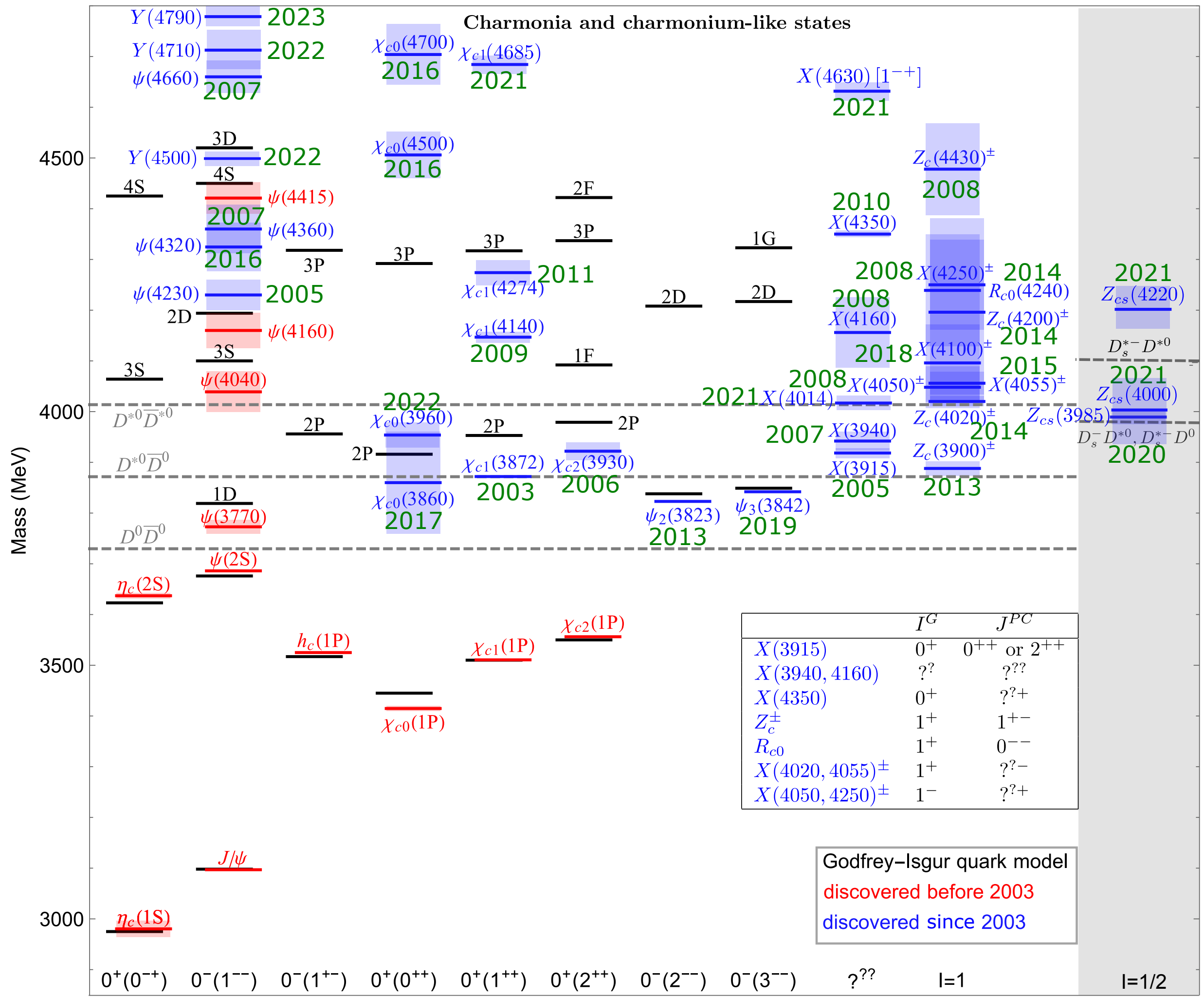
Charmonium states



Samuel C.C.Ting

[F.-K. Guo (郭奉坤), PoS LATTICE 2022 (2023) 232]

Charmonium(like) states



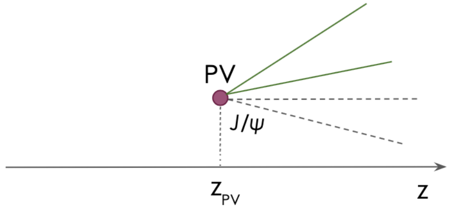
[F.-K. Guo (郭奉坤), PoS LATTICE 2022 (2023) 232]

$X(3872)$?

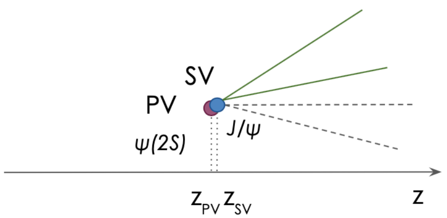
- Tetraquark
- $\chi_{c1}(2P)$
- Molecule
- Mixture

J/ψ production

- **Hadroproduction**

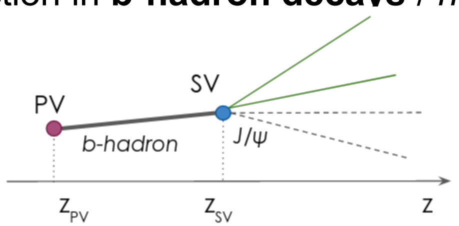


- Decays of **higher resonances**



prompt production

- Production in **b-hadron decays** / *non-prompt*



- **Prompt J/ψ production** and **production in b-hadron decays** distinguished from the fit to pseudo-lifetime distribution

distinguished via pseudo-proper decay time

$$t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{q\bar{q}} \text{ or } \tau = \frac{L_{xy}}{p_T} M_{q\bar{q}}$$

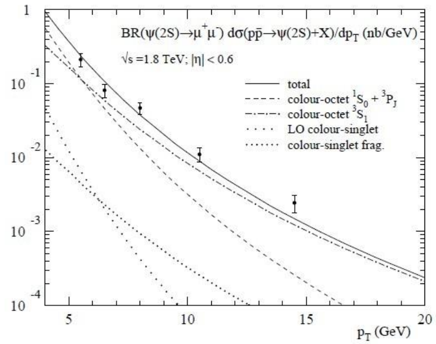
PV – primary vertex
SV – secondary vertex

J/ψ hadroproduction

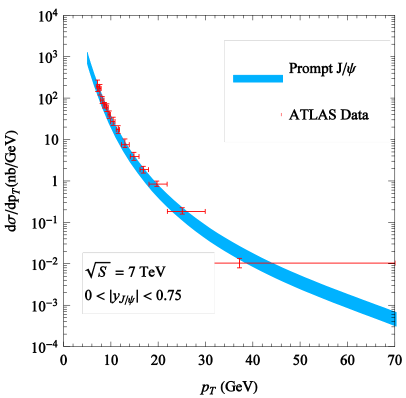
CO mechanism

- **Nicely explain ψ' surplus by CO contributions**

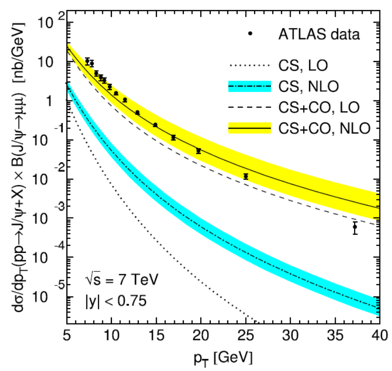
States	p_T behavior at LO
$^3S_1^{[1]}$	p_T^{-8}
$^3S_1^{[8]}$	p_T^{-4}
$^1S_0^{[8]}$	p_T^{-6}
$^3P_J^{[8]}$	p_T^{-6}



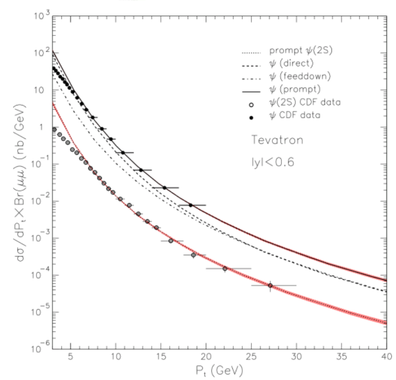
Kramer, 0106120



YQM, Wang, Chao, 1012.1030



Butenschoen, Kniehl, 1105.0820



Gong, Wan, Wang, Zhang, 1205.6682

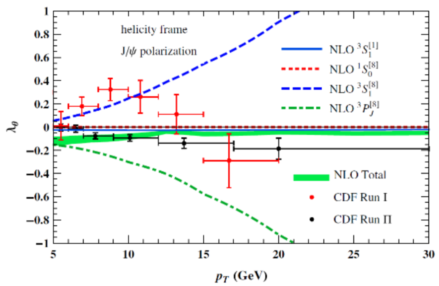
马滟青

Credit: Y.-Q. Ma

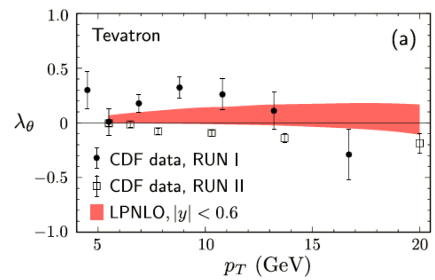
Polarisation?

Polarization puzzle at NLO

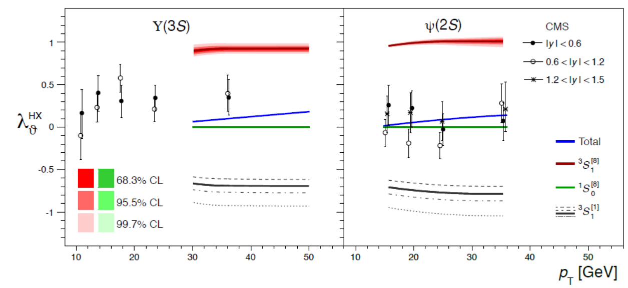
- J/ψ: transverse polarization canceled (*why?*) in $^3S_1^{[8]}$ and $^3P_J^{[8]}$



Chao,YQM,Shao,Wang, Zhang,1201.2675

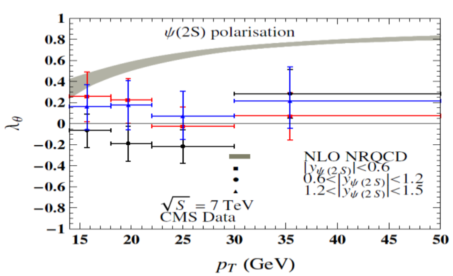


Bodwin, Chung, Kim, Lee, 1403.3612

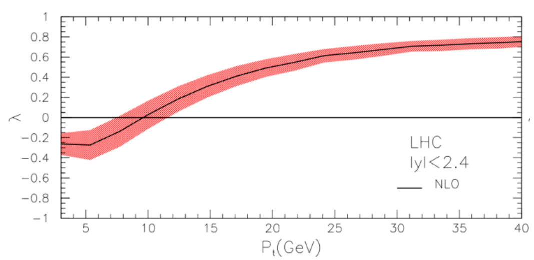


Faccioli,Knunz,Lourenco, Seixas,Wohri,1403.3970

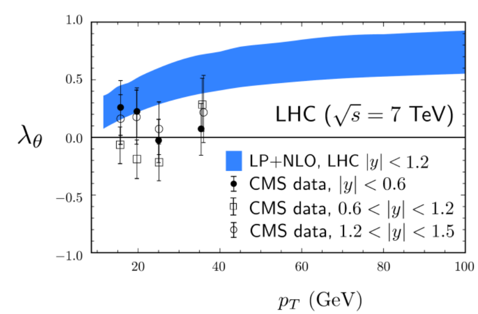
- $\psi(2S)$: cancelation weak, **hard to understand data**



Shao, Han, YQM, Meng, Zhang, Chao, 1411.3300



Gong, Wan, Wang, Zhang, 1205.6682



Bodwin et al., 1509.07904

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Credit: Y.-Q. Ma

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Hadronic decays

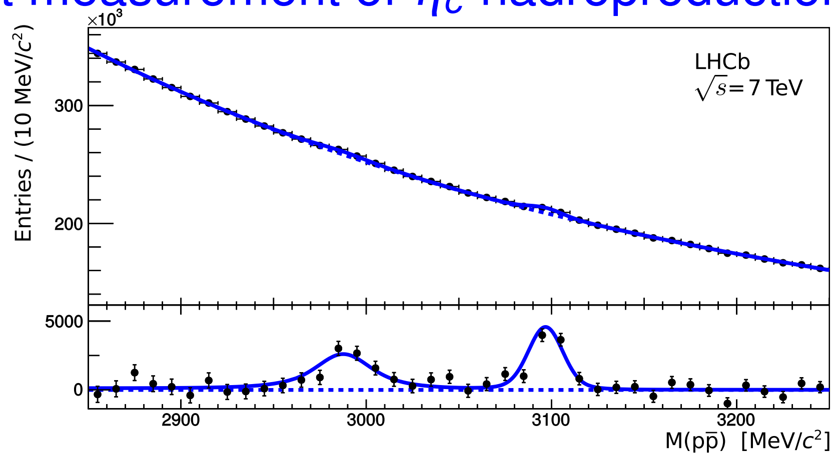
- Sizable branching fractions

	$\mathcal{B} \times 10^3$								
	$p\bar{p}$	$\phi\phi$	ϕK^+K^-	$\phi\pi^+\pi^-$	$\Lambda\bar{\Lambda}$	$\Xi^+\Xi^-$	$\Lambda(1520)\bar{\Lambda}(1520)$	$\eta_c\gamma$	$p\bar{p}\pi^+\pi^-$
η_c	1.35 ± 0.13	1.58 ± 0.19	2.9 ± 1.4	unknown	1.02 ± 0.23	0.90 ± 0.26	-	-	5.5 ± 1.9
J/ψ	2.12 ± 0.03	forbidden	0.83 ± 0.11	0.94 ± 0.15	1.89 ± 0.09	0.97 ± 0.08	unknown	17 ± 4	6.0 ± 0.5
χ_{c0}	0.22 ± 0.01	0.80 ± 0.07	0.97 ± 0.25	unknown	0.36 ± 0.02	0.45 ± 0.02	0.31 ± 0.12	forbidden	2.1 ± 0.7
h_c	< 0.17	forbidden	unknown	unknown	unknown	unknown	unknown	570 ± 50	3.3 ± 0.6
χ_{c1}	0.076 ± 0.003	0.42 ± 0.05	0.41 ± 0.15	unknown	0.13 ± 0.01	0.06 ± 0.01	< 0.09	forbidden	0.50 ± 0.19
χ_{c2}	0.073 ± 0.003	1.06 ± 0.09	1.42 ± 0.29	unknown	0.18 ± 0.02	0.14 ± 0.01	0.46 ± 0.15	forbidden	1.32 ± 0.34
η_c'	< 2.0	< 1.0	unknown	unknown	unknown	unknown	unknown	forbidden	seen
ψ'	0.29 ± 0.01	forbidden	0.07 ± 0.02	0.12 ± 0.03	0.38 ± 0.01	0.29 ± 0.01	unknown	3.4 ± 0.5	0.60 ± 0.04

- High multiplicity in *pp* collisions, high level of background due to too many combinations, chanllenging even for LHCb that has excellent hadron particle-identification

Charmonium $\to p\bar{p}$, the "history" in one slide

- Developed dedicated HLT2 trigger for prompt $p\bar{p}$ in 2010 [29/03/2010]
  - $\varepsilon_{\mathrm{trg}}$ improved by a factor of $\sim$5
  - First prompt $J/\psi \to p\bar{p}$ peak @ hadron collider
- Developed dedicated HLT1 trigger for prompt $p\bar{p}$ in 2011 [07/03/2011]
  - $\varepsilon_{\mathrm{trg}}$ improved by another factor of $\sim$3
- Provided first measurement of η_c hadroproduction [EPJC 75 (2015) 311]

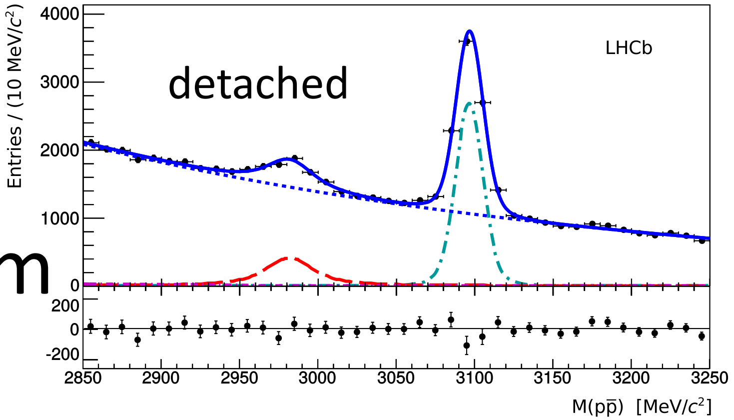


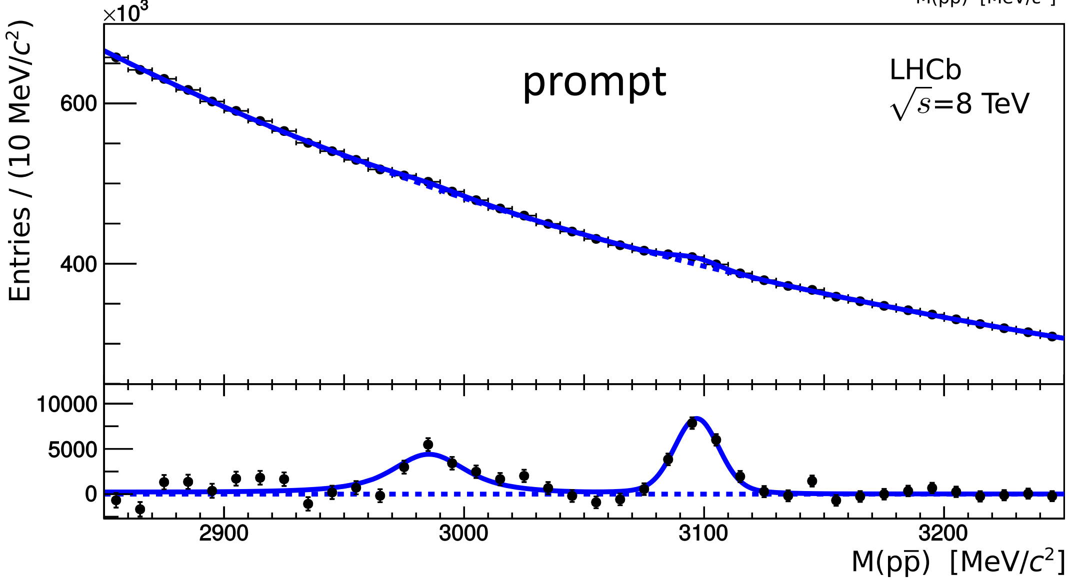
- However, the life of these trigger lines was never easy, trigger high-up kept asking to tighten and tighten cuts...

$\eta_c(1S)$ production at 7/8 TeV

[LHCb, EJPC 75 (2015) 311]

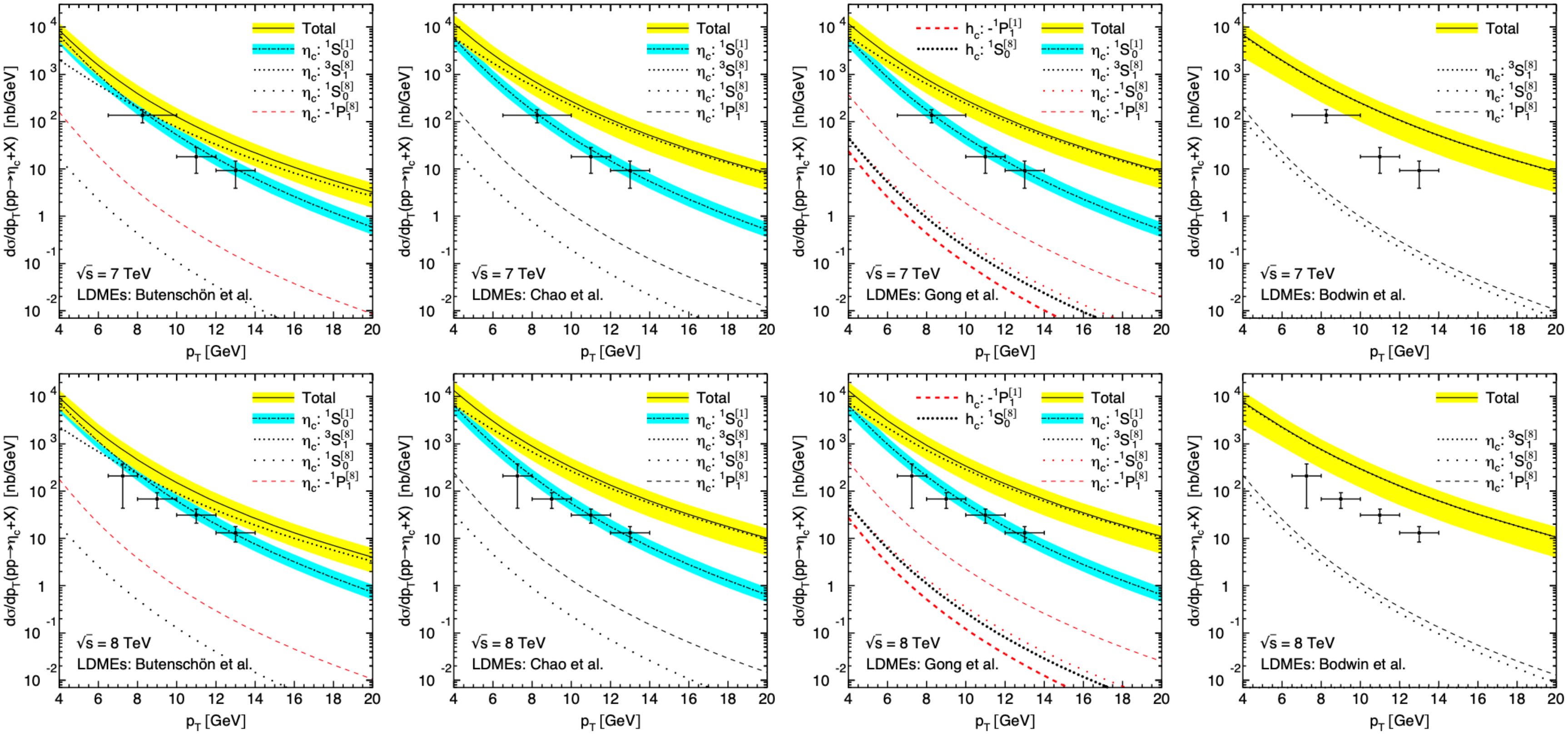
- $\eta_c(1S)$ hadroproduction firstly measured by LHCb
- Prompt signal suffers from high background





$\eta_c(1S)$ production at 7/8 TeV

- Results described by NLO CS?

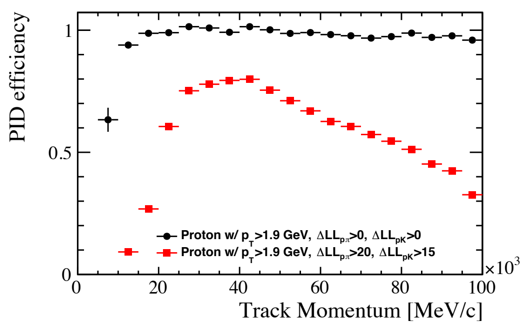


[M. Butenschoen, et al., PRL 114 (2015) 092004]

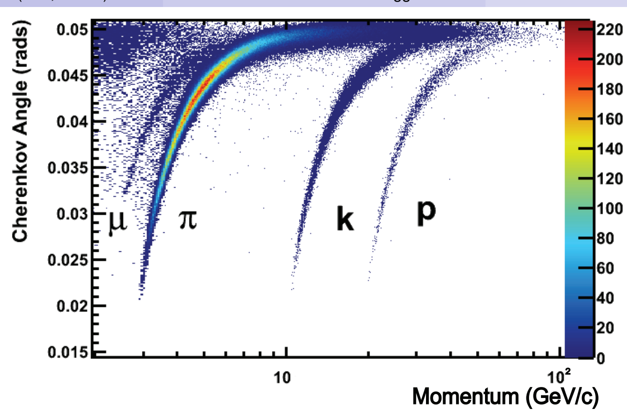
Made it possible for 13 TeV

Asked to reduce rate of Hlt1DiProton...

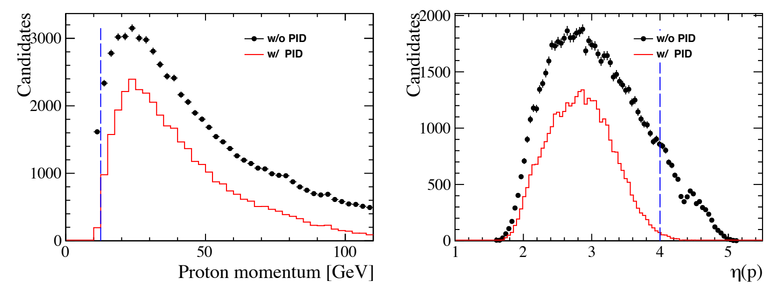
- As it is taking 12.5 kHz (?)...
- 10.9 kHz (8.8 kHz exclusive) after applying track chi2<4
- 6.5 kHz (5.1 kHz exclusive) after giving up 3.3-4.0 GeV, and only focus on η_c and J/ψ; & tightening track chi2<2.5
- $\sim$ 5 kHz after shaving the phase space, P>12.5 GeV, (PT/P)>0.0366, signal efficiency still high (>90%)



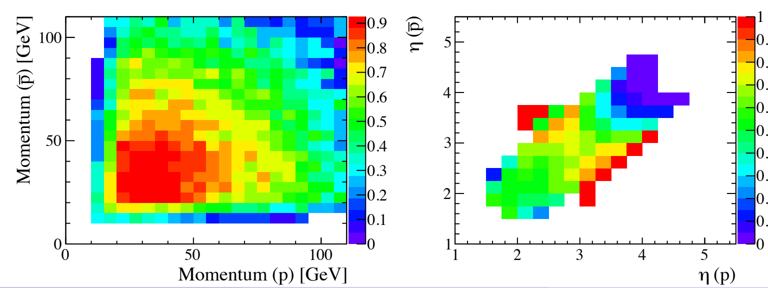
S. Barsuk, J. He (LAL, UCAS) Status of Hlt DiProton trigger February 24, 2016 6 / 9



- Cannot afford running RICH reconstruction at Hlt1 level
- Used 10% bandwidth!
- Non-PID cuts to redude bandwidth



PID efficiency as function of p/η



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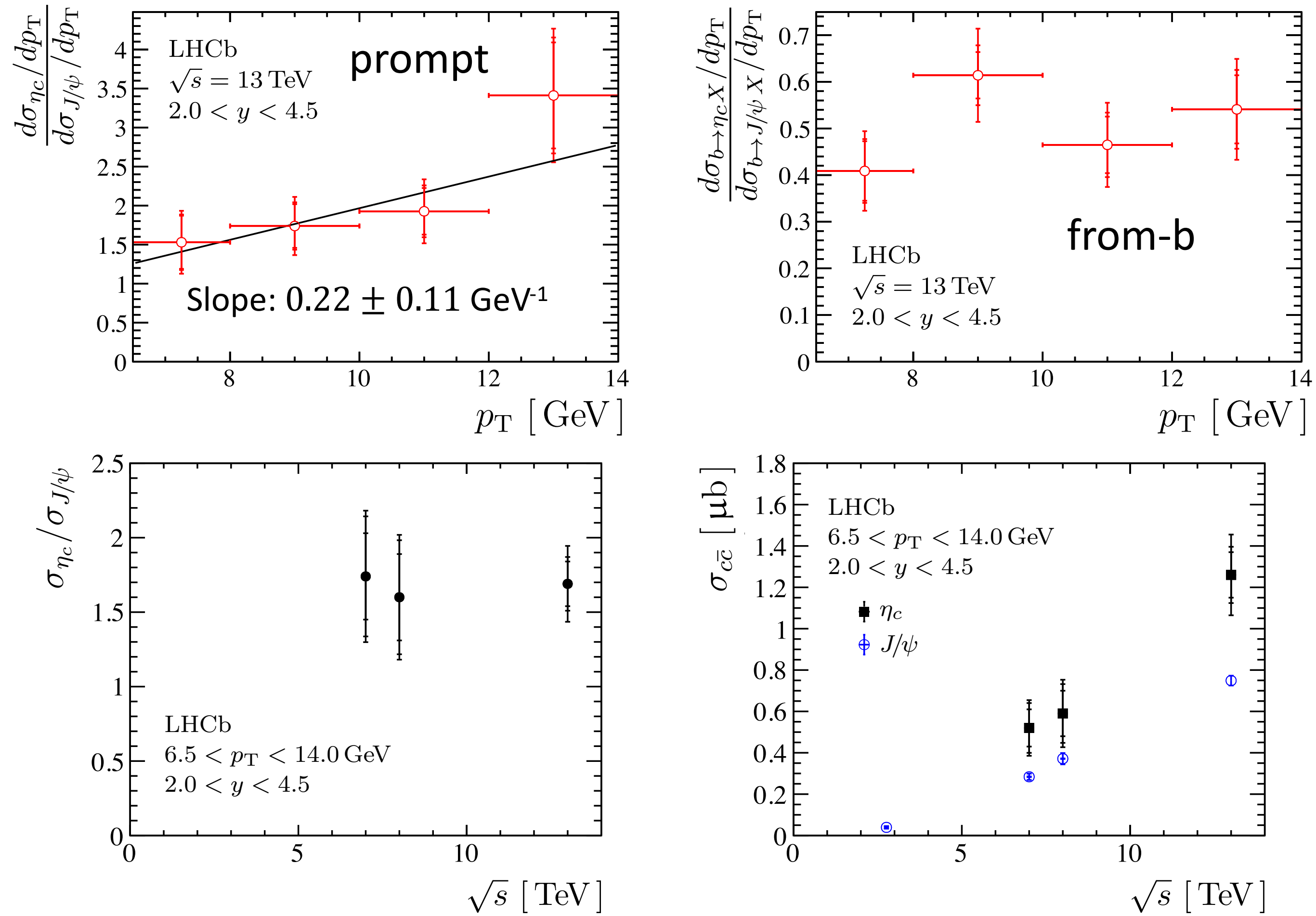
$\eta_c(1S)$ production at 13 TeV

[LHCb, EPJC 80 (2020) 191]

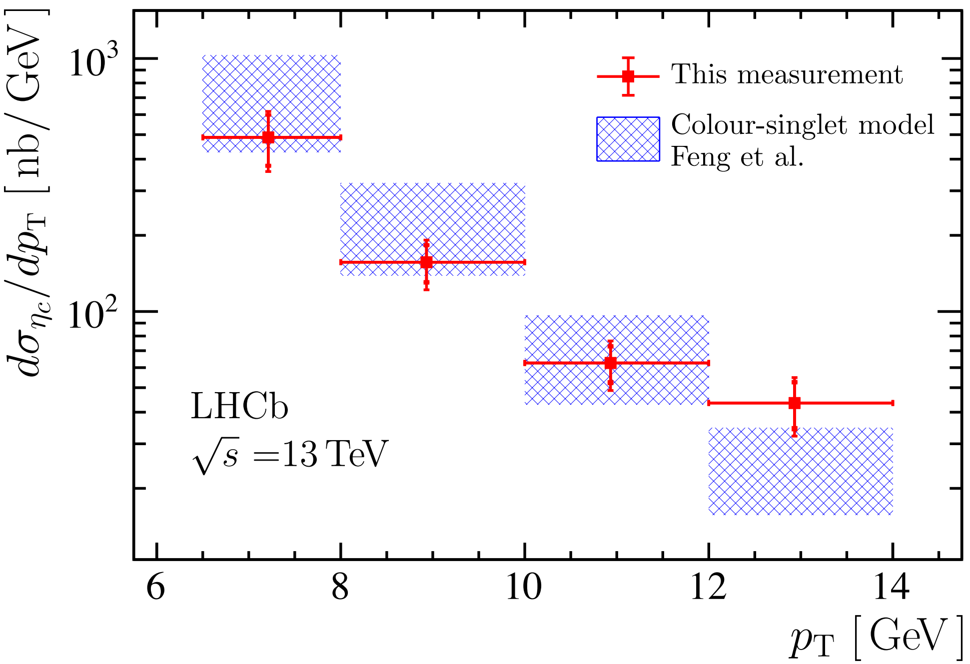
- Different p_{T} dependence for prompt $\eta_c(1S)$ and J/ψ?



$\eta_c(1S)$ production at 13 TeV

[LHCb, EPJC 80 (2020) 191]

- Comparison w/ CS, good agreement
- Theoretical precision limited by scale uncertainty



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

Prediction: $1.56^{+0.83}_{-0.49}$ (scale)$^{+0.38}_{-0.17}$ (CT14NLO) μb

[Y. Feng, et al., NPB 945 (2019) 114662]

Impact of $\eta_c(1S)$ production

- **LHCb data + HQSS helps to constrain $\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]}) \rangle$**

$$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]}) \rangle = \langle \mathcal{O}^{\eta_c}(^3S_1^{[8]}) \rangle$$

- **A conservative upper limit was set via**

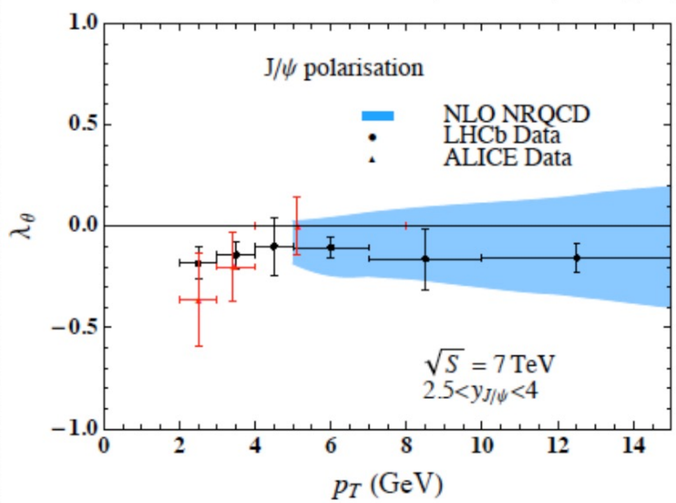
$$\langle \mathcal{O}^{\eta_c}(^3S_1^{[8]}) \rangle \hat{\sigma}(c\bar{c}\left[^3S_1^{[8]}\right]) = \sigma_{\mathrm{LHCb\ data}}$$

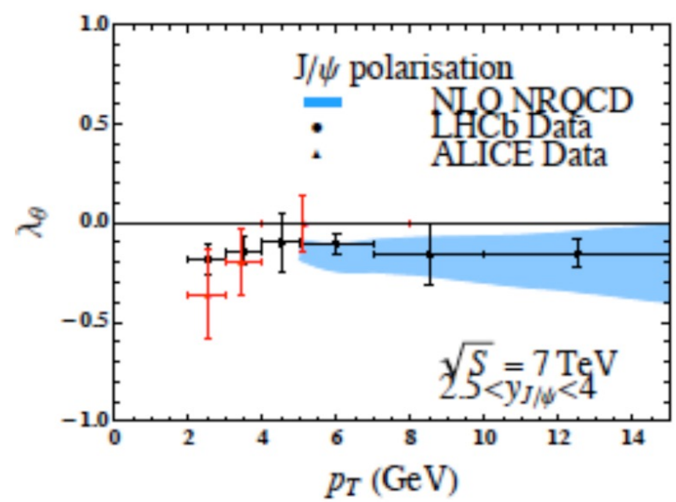
Before

After

Han et al. (2014)

$$0 < \langle \mathcal{O}^{\eta_c}(^3S_1^{[8]}) \rangle < 1.46 \times 10^{-2}\ \mathrm{GeV}^3$$



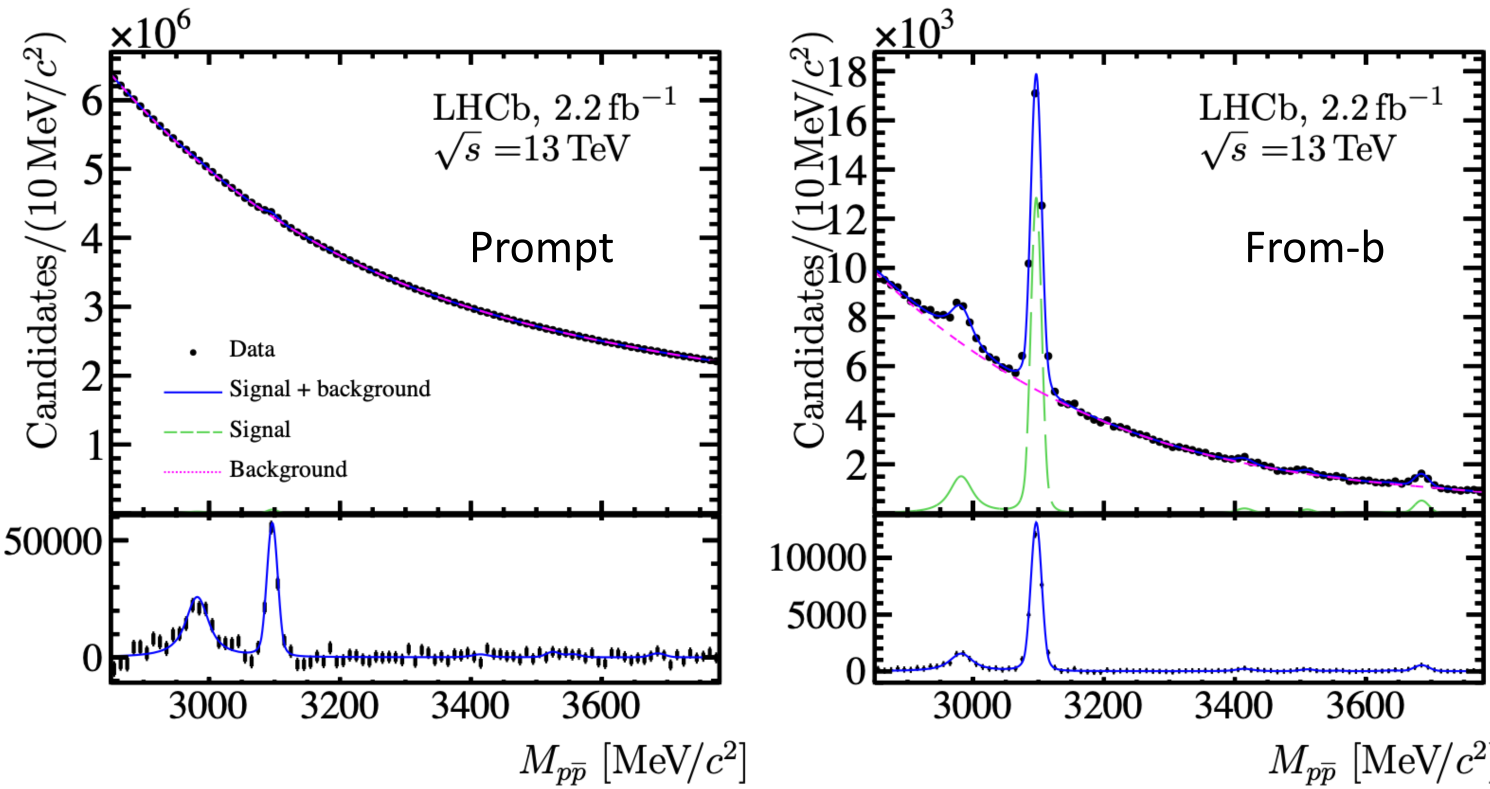


New

[LHCb-Paper-2024-004, in preparation]

η_c production in 2018

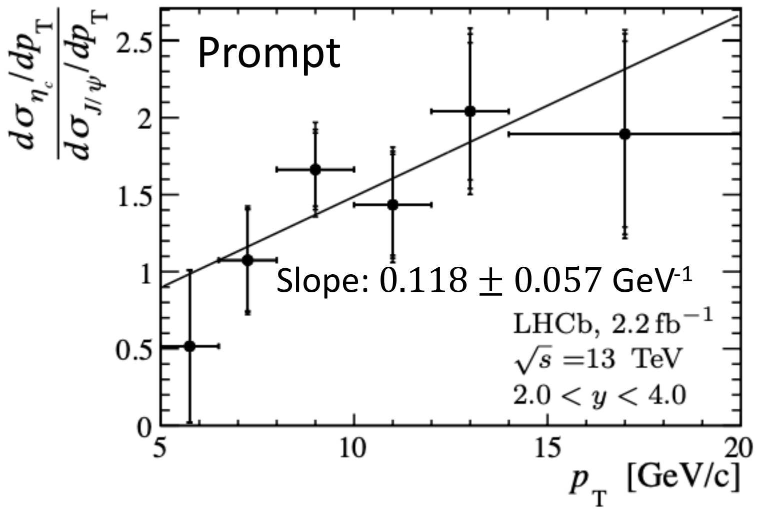
- Dedicated trigger added in 2018 to cover $\eta_c(2S)$, thanks to theoreticla work, [J.P. Lansberg, H.-S. Shao, H.-F. Zhang, PLB 10 (2018) 009]

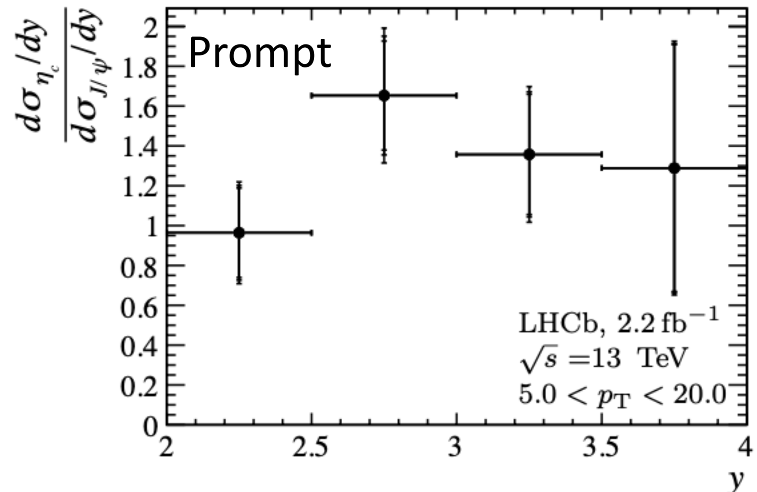


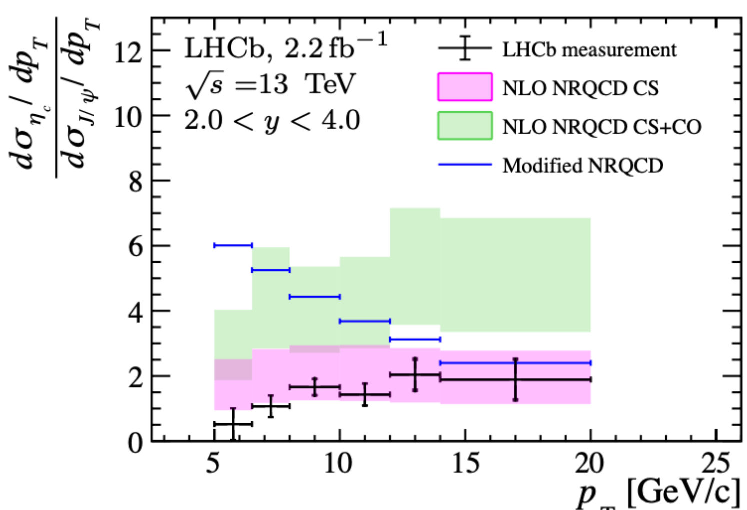
New

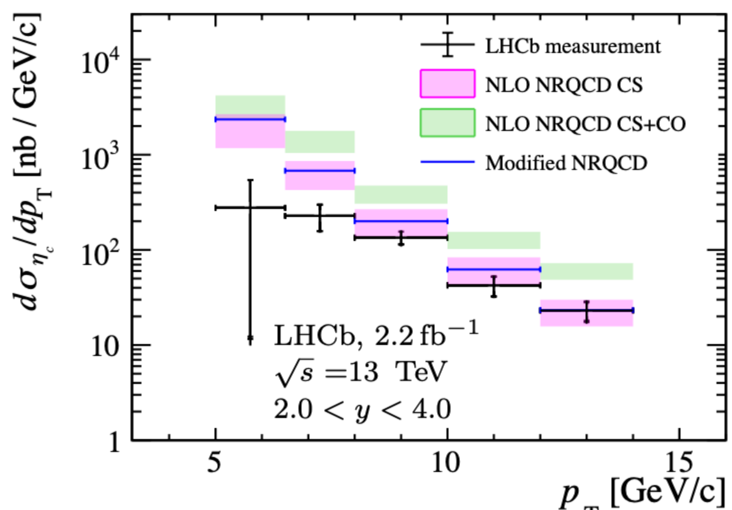
[LHCb-Paper-2024-004, in preparation]

- Different p_{T} dependence for prompt $\eta_c(1S)$ and J/ψ persists









New

[LHCb-Paper-2024-004, in preparation]

- First upper limits at 95% CL on $h_c(1P)$ and $\eta_c(2S)$ hadroproduction for $5 < p_T < 20$ GeV, $2 < y < 4$

$$\frac{(\sigma_{\eta_c(2S)} \times \mathcal{B}_{\eta_c(2S)\to p\bar{p}})}{(\sigma_{J/\psi} \times \mathcal{B}_{J/\psi\to p\bar{p}})} < 0.14,$$

$$\frac{(\sigma_{h_c(1P)} \times \mathcal{B}_{h_c(1P)\to p\bar{p}})}{(\sigma_{J/\psi} \times \mathcal{B}_{J/\psi\to p\bar{p}})} < 0.13.$$

- Most precise measurements:

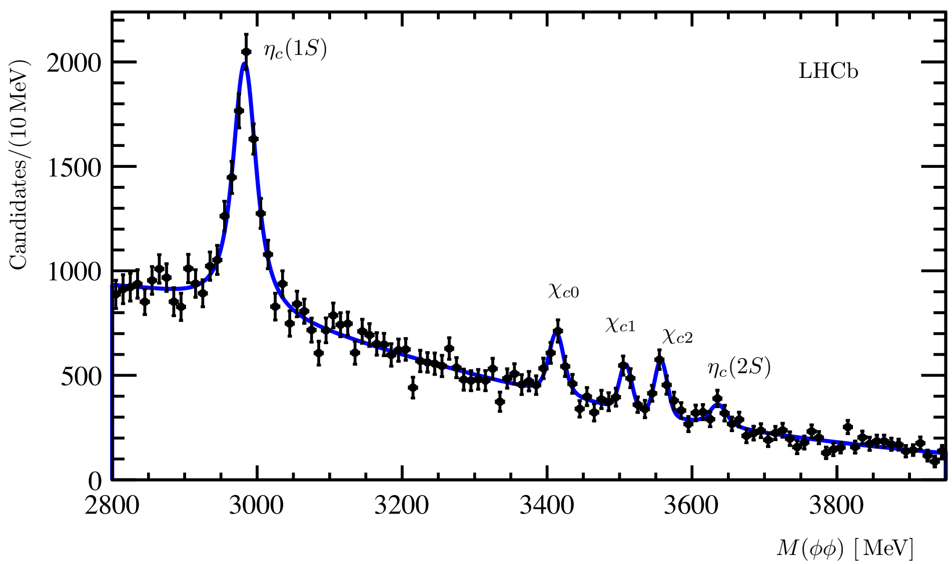
$$\mathcal{B}_{b\to\chi_{c0}X} = (3.05 \pm 0.54 \pm 0.08 \pm 0.29) \times 10^{-3},$$
$$\mathcal{B}_{b\to\chi_{c1}X} = (5.11 \pm 1.20 \pm 0.14 \pm 0.50) \times 10^{-3}$$

third uncertainty due to $\mathcal{B}_{\chi_{c0,1}\to p\bar{p}}, \mathcal{B}_{J/\psi\to p\bar{p}}, \mathcal{B}_{b\to J/\psi X}$

Charmonium to $\phi\phi$

- Inclusive production from b-decay

[EPJC 77 (2017) 609]



Ratios of charmonium C production rates,

$$R^{C_1}_{C_2} \equiv \frac{\mathcal{B}(b \to C_1 X) \times \mathcal{B}(C_1 \to \phi\,\phi)}{\mathcal{B}(b \to C_2 X) \times \mathcal{B}(C_2 \to \phi\,\phi)},$$

are measured to be

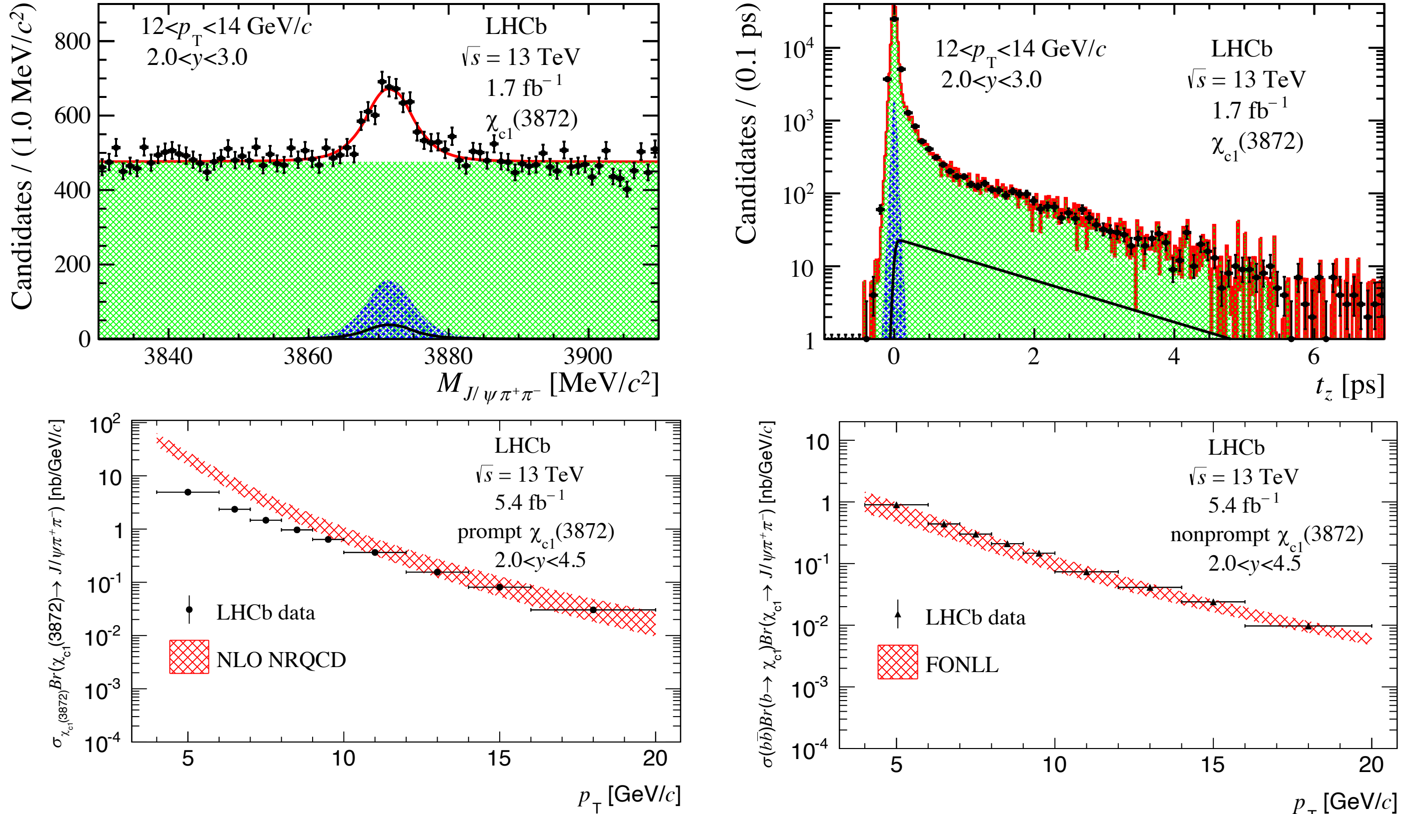
$$R^{\chi_{c0}}_{\eta_c(1S)} = 0.147 \pm 0.023 \pm 0.011,$$
$$R^{\chi_{c1}}_{\eta_c(1S)} = 0.073 \pm 0.016 \pm 0.006,$$
$$R^{\chi_{c2}}_{\eta_c(1S)} = 0.081 \pm 0.013 \pm 0.005,$$
$$R^{\chi_{c1}}_{\chi_{c0}} = 0.50 \pm 0.11 \pm 0.01,$$
$$R^{\chi_{c2}}_{\chi_{c0}} = 0.56 \pm 0.10 \pm 0.01,$$
$$R^{\eta_c(2S)}_{\eta_c(1S)} = 0.040 \pm 0.011 \pm 0.004,$$

$$\mathcal{B}(b \to X(3872)X) \times \mathcal{B}(X(3872) \to \phi\phi) < 4.5(3.9) \times 10^{-7},$$
$$\mathcal{B}(b \to X(3915)X) \times \mathcal{B}(X(3915) \to \phi\phi) < 3.1(2.7) \times 10^{-7},$$
$$\mathcal{B}(b \to \chi_{c2}(2P)X) \times \mathcal{B}(\chi_{c2}(2P) \to \phi\phi) < 2.8(2.3) \times 10^{-7}.$$

$X(3872)$ production

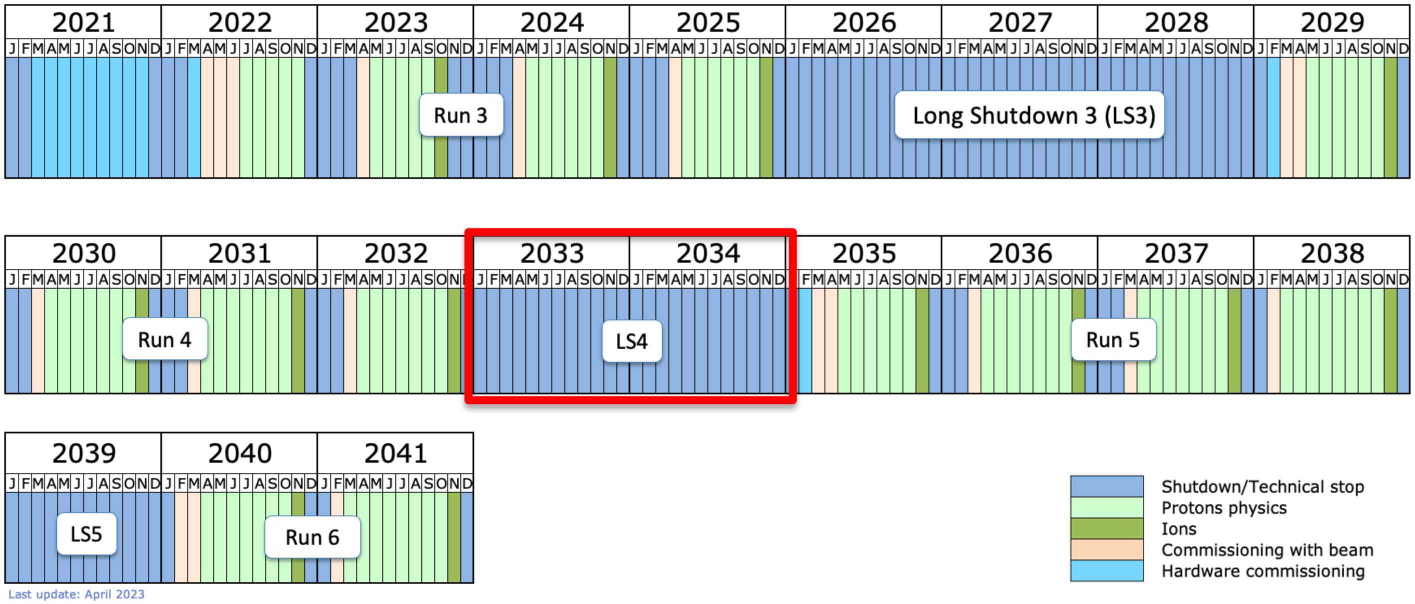
- First double-differential cross-section
- Consistent with $\chi_{c1}(2P) + D^0\overline{D}^{*0}$ mixture

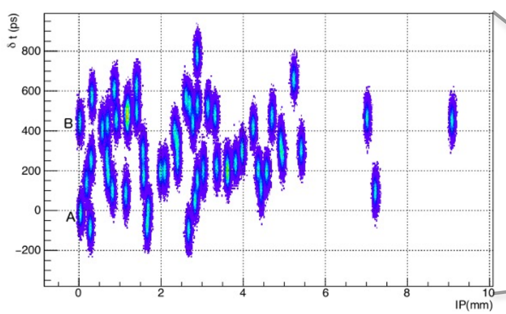
[JHEP 01 (2022) 131]

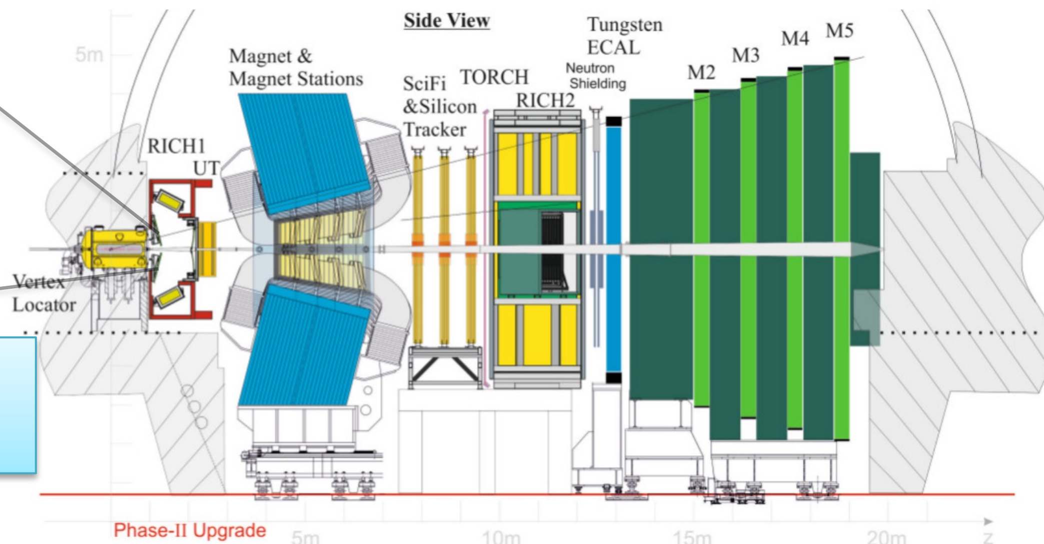


In pipeline: $J/\psi p$, $J/\psi\Lambda$, $J/\psi\phi$, $J/\psi\pi^+$...

The LHCb upgrades



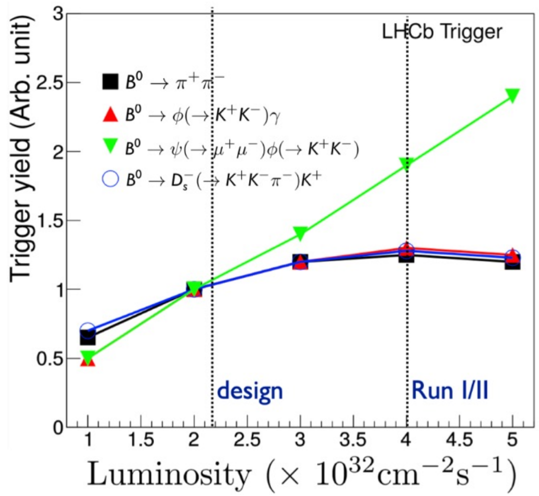




[CERN-LHCC-2018-027, 2021-012]

Upgrade II, 4D detector
Timing, $\mathcal{O}(10\text{ ps})$, is essential

The LHCb trigger (Run3)



Software High Level Trigger

- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

- Full event reconstruction, inclusive and exclusive kinematic/geometric selections
- Buffer events to disk, perform online detector calibration and alignment
- Add offline precision particle identification and track quality information to selections

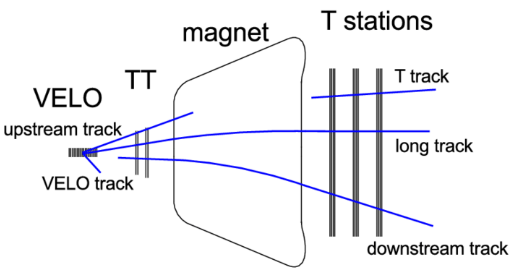
  Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage

Prospects at LHCb

	$\mathcal{B}\times 10^3$								
	$p\bar{p}$	$\phi\phi$	ϕK^+K^-	$\phi\pi^+\pi^-$	$\Lambda\bar{\Lambda}$	$\Xi^+\Xi^-$	$\Lambda(1520)\bar{\Lambda}(1520)$	$\eta_c\gamma$	$p\bar{p}\pi^+\pi^-$
η_c	1.35 ± 0.13	1.58 ± 0.19	2.9 ± 1.4	unknown	1.02 ± 0.23	0.90 ± 0.26	-	-	5.5 ± 1.9
J/ψ	2.12 ± 0.03	forbidden	0.83 ± 0.11	0.94 ± 0.15	1.89 ± 0.09	0.97 ± 0.08	unknown	17 ± 4	6.0 ± 0.5
χ_{c0}	0.22 ± 0.01	0.80 ± 0.07	0.97 ± 0.25	unknown	0.36 ± 0.02	0.45 ± 0.02	0.31 ± 0.12	forbidden	2.1 ± 0.7
h_c	< 0.17	forbidden	unknown	unknown	unknown	unknown	unknown	570 ± 50	3.3 ± 0.6
χ_{c1}	0.076 ± 0.003	0.42 ± 0.05	0.41 ± 0.15	unknown	0.13 ± 0.01	0.06 ± 0.01	< 0.09	forbidden	0.50 ± 0.19
χ_{c2}	0.073 ± 0.003	1.06 ± 0.09	1.42 ± 0.29	unknown	0.18 ± 0.02	0.14 ± 0.01	0.46 ± 0.15	forbidden	1.32 ± 0.34
η_c'	< 2.0	< 1.0	unknown	unknown	unknown	unknown	unknown	forbidden	seen
ψ'	0.29 ± 0.01	forbidden	0.07 ± 0.02	0.12 ± 0.03	0.38 ± 0.01	0.29 ± 0.01	unknown	3.4 ± 0.5	0.60 ± 0.04

- Charmonia to $p\bar{p}$ in Run-3
  - Hlt1 for hadroproduction still challenging, GPU/FPGA and AI to accelerate RICH reconstruction?
- Charmonia to $p\bar{p}\pi^+\pi^-$, as $\phi\phi, \phi KK$
  - No trigger (and challenging) for hadroproduction, first $\mathcal{B}(b \to h_c X)$ ongoing
- Λ reconstruction not very efficient, improved in Run-3



Summary

- 50 years after the discovery of J/ψ particle, its hadroproduction still not fully understood
- Thanks to the support of FCPPL, continued efforts on studying charmonium(like) production in LHCb, providing unique inputs!
  - $\eta_c(1S)$ hadroproduction, $b \to \chi_c X$
  - $b \to h_c(1P)X$ in pipeline
- Trigger still the bottleneck for Run-3
  - GPU/FPGA, AI to accerelate, wider collaboration