Study of charmonium production using decays to hadronic final states with the LHCb experiment

Andrii Usachov
Laboratoire de l'Accélérateur Linéaire

Peking University
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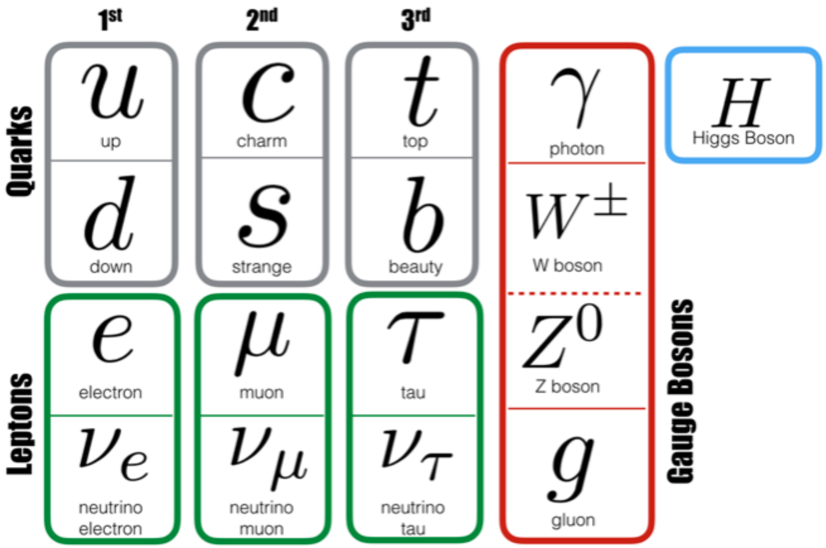
Outline

- Charmonium
- NRQCD tests via charmonium production
- LHCb experiment
- Measurement of $\boldsymbol{\eta_c}$ **production at** $\sqrt{\boldsymbol{s}} = \mathbf{13}\ \boldsymbol{TeV}$ **via the decay** $\boldsymbol{\eta_c \to p\bar{p}}$
- Measurement of **charmonium production in b-hadron inclusive decays using charmonia decays to** $\boldsymbol{\phi\phi}$
- **Phenomenological analysis** of charmonium production
- Measurement of $\boldsymbol{\eta_c(1S)}$ **mass and width**
- $\boldsymbol{B_s^0}$ **decays to** $\boldsymbol{\phi}$ **mesons**
- Main results and prospects

Charmonium

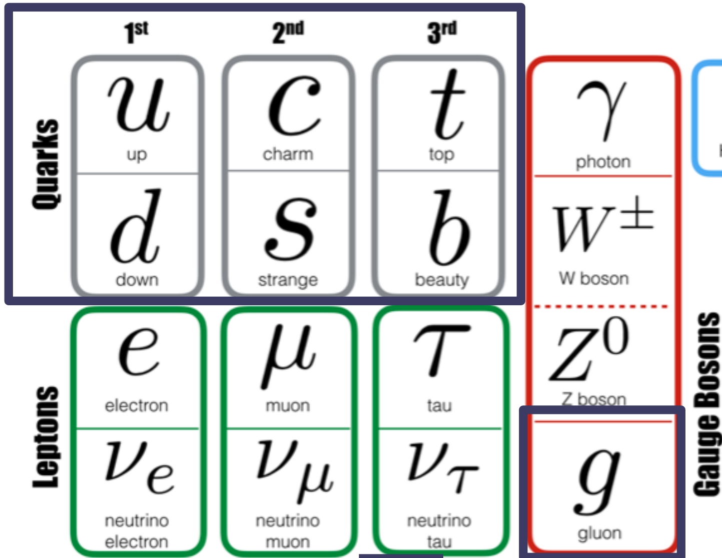
Standard Model and strong interaction



Fundamental interactions:

- **Strong → QCD**
- Weak
- Electromagnetic
- Gravitation

Standard Model and strong interaction



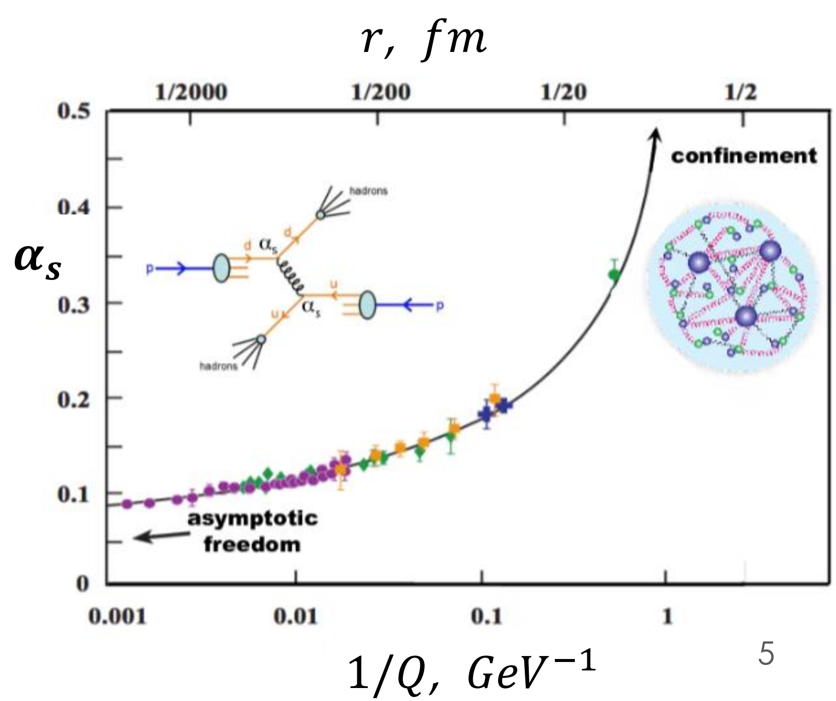
Fundamental interactions:

- **Strong → QCD**
- Weak
- Electromagnetic
- Gravitation

QCD: interactions of quarks and gluons

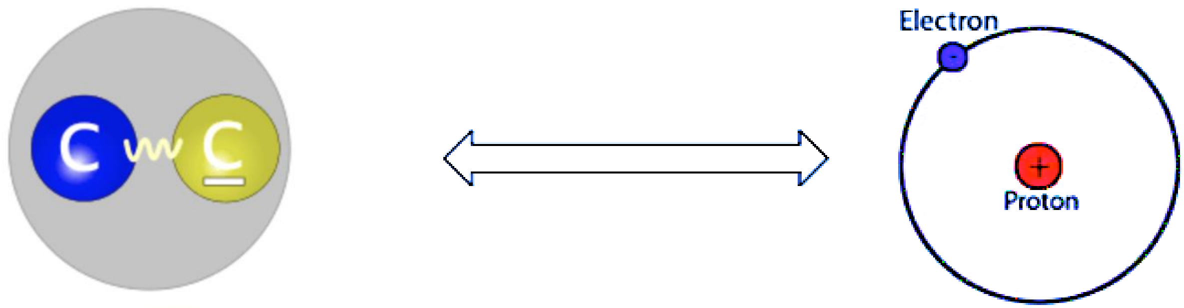
- Color charge : SU(3) symmetry
- Coupling constant $\boldsymbol{\alpha_s}$:
  - Asymptotic freedom and confinement
  - No free quarks, form hadrons
- Intrinsic scale $\boldsymbol{\Lambda_{QCD} \sim 200\ MeV}$

$$\alpha_s(r) = \frac{2\pi}{9\, ln\frac{1}{r\Lambda_{QCD}}}$$



Charmonium

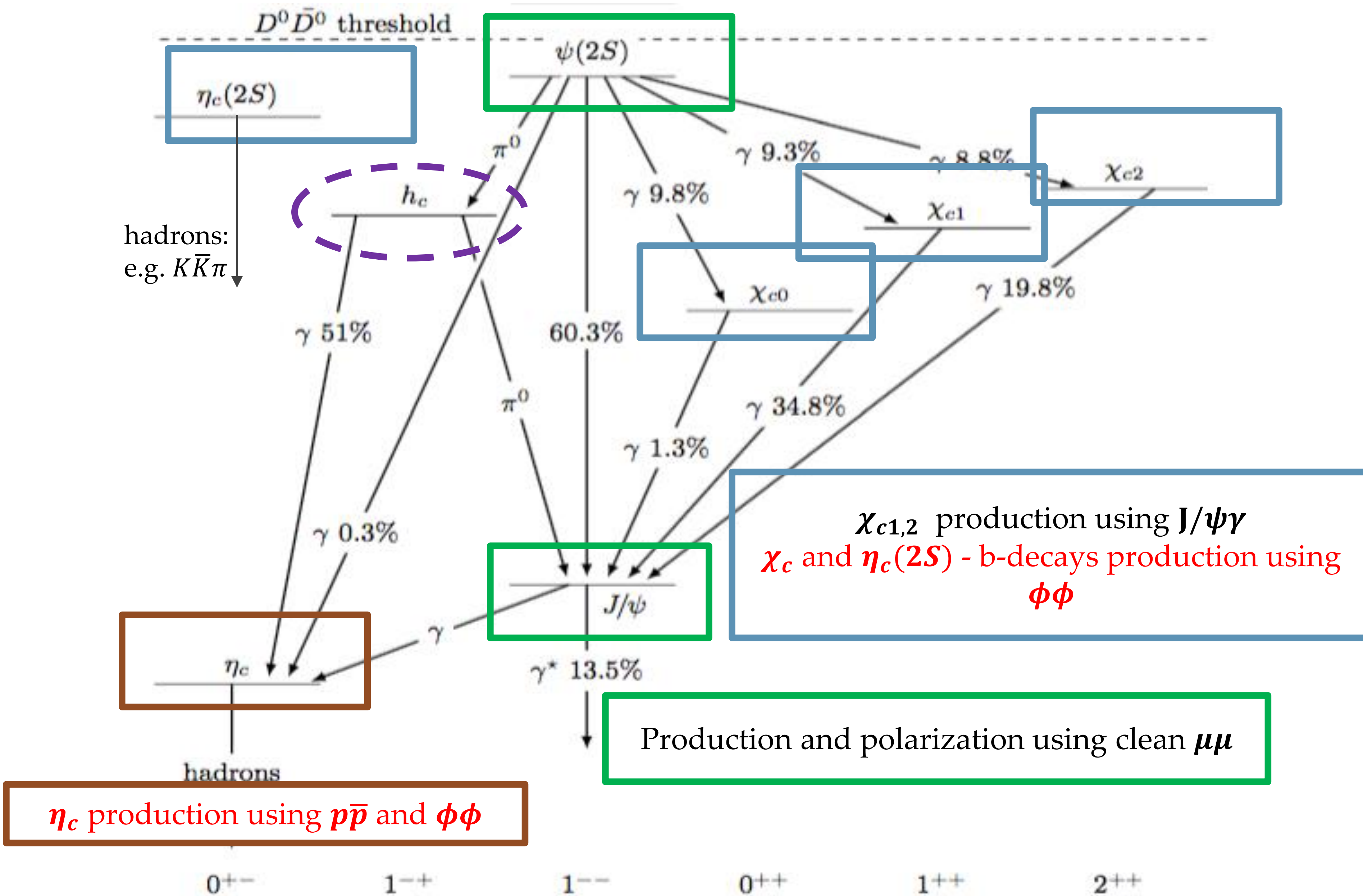
- $c\bar{c}$ states bound by strong interaction
- Hydrogen atom of QCD



- Non-relativistic QCD object: **charmonium: $v^2 \approx 0.3$,** bottomonium: $v^2 \approx 0.1$

- Charmonium ideal to probe QCD driven processes:
  hadroproduction,
  photoproduction,
  production in b-decays,
  central exclusive production (CEP),
  charmonium decays,
  production in medium (QGP), etc.

Charmonium family



Charmonium production processes: powerful QCD probes

Hard processes

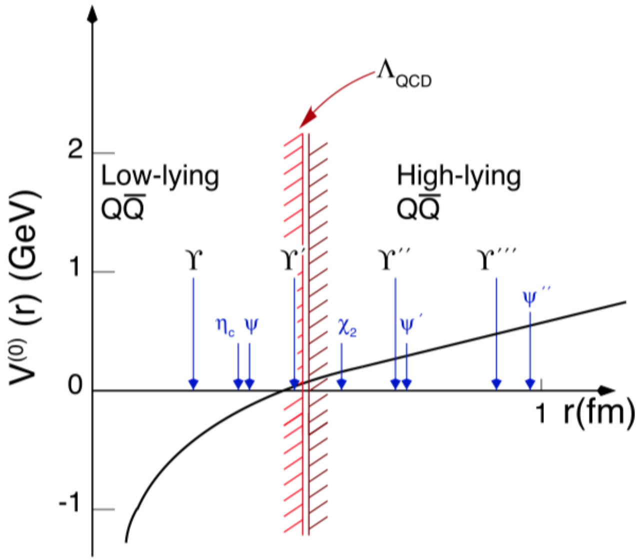
- e^+e^- production (B-factories)
- Photoproduction
- **Hadroproduction (hadron colliders)**

Production in decays:

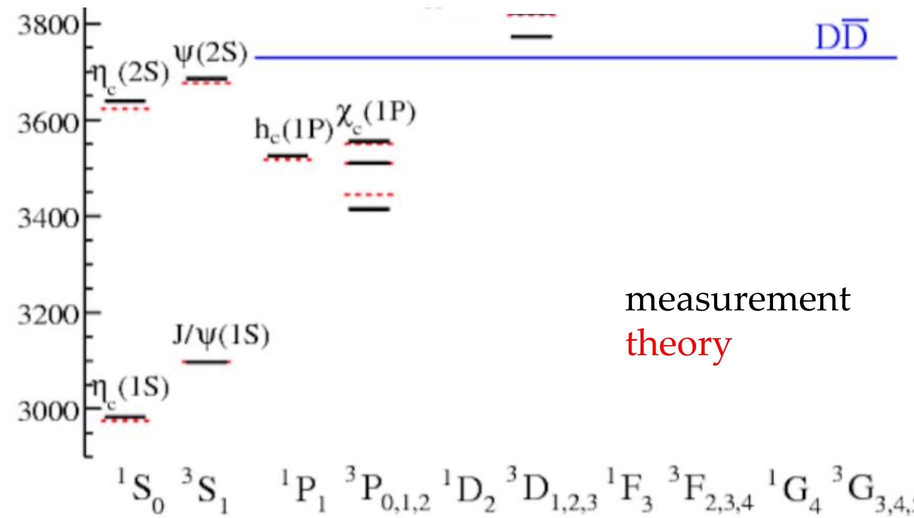
- Higher charmonium states
- b-decays **(~5 GeV)**
  – accessible at B-factories and hadron colliders
- Bottomonium decays **(~11 GeV)**
  – accessible at B-factories and hadron colliders, not many decays observed so far
- Z, W decays **(~80-90 GeV)**
- Higgs decays **(~120 GeV)**
  – not observed so far

Theory: spectroscopy, production and decays

- Potential models: **spectroscopy** with Schroedinger picture
- Charmonium states below $\boldsymbol{D\bar{D}}$ threshold are well interpreted by theory



$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + b\,r$$



- Lattice QCD
- Phenomenological models for **charmonium production**
  - **Color Singlet** model (part of Non Relativistic QCD)
  - **Color Evaporation model** $\sigma_{A+B\to H+X} = F_H \int_{4m_Q^2}^{4M^2} dm_{Q\bar{Q}}^2 \frac{d\sigma_{A+B\to H+X}}{dm_{Q\bar{Q}}^2}$

Effective Field Theories (EFTs)

- Make use of **intrinsic charmonium scales** ($m \gg mv \gg mv^2$)
- Derived from QCD

- Non-Relativistic QCD (**NRQCD**) - EFT at $\boldsymbol{mv}$ and $\boldsymbol{mv^2}$
  Bodwin, Braaten, Lepage, PRD 55 (1997) 5853
  - Not unique power counting

$$\mathcal{L}_{NRQCD} = \mathcal{L}_g + \mathcal{L}_l + \mathcal{L}_\psi + \mathcal{L}_\chi + \boxed{\mathcal{L}_{\psi\chi}}$$

$$\boxed{\mathcal{L}_{\psi\chi} = \frac{f_1(^1S_0)}{m_Q^2} O_1(^1S_0) + \frac{f_1(^3S_1)}{m_Q^2} O_1(^3S_1) + \frac{f_8(^1S_0)}{m_Q^2} O_8(^1S_0) + \frac{f_8(^3S_1)}{m_Q^2} O_8(^3S_1)}$$

- Potential NRQCD (**pNRQCD**) - EFT at $\boldsymbol{mv^2}$
  Brambilla, Pineda, Soto, Vairo, Nucl.PB 566 (2000) 275
  - Contains **potential-like terms**
  - To describe quarkonium states far from the threshold

Charmonium hadroproduction in the NRQCD

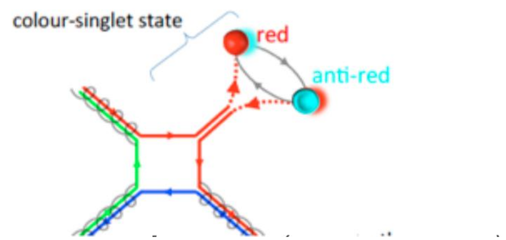
Cross section factorizes:

$$d\sigma_{A+B\to H+X} = \sum_n \boxed{d\sigma_{A+B\to Q\bar{Q}(n)+X}} \times \langle O^H(n)\rangle$$

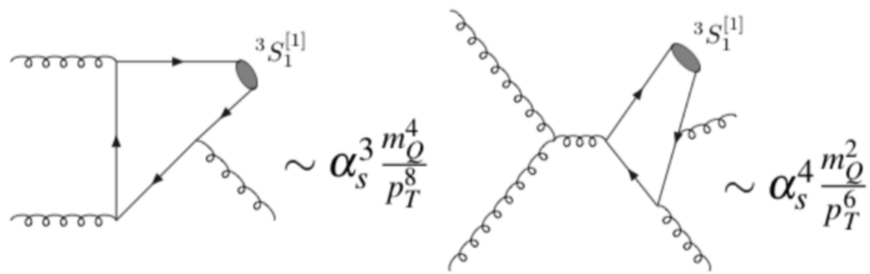
short distance, perturbative

Production mechanisms:

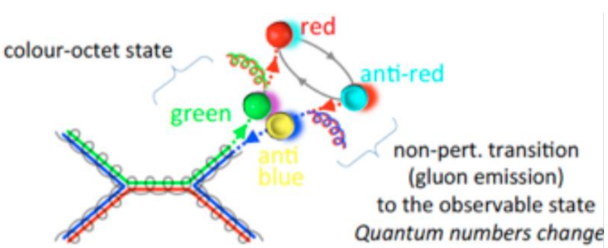
Color Singlet (CS): quantum numbers of $c\bar{c}$ pair and charmonium match



H. Woehri



Color Octet (CO): quantum numbers of $c\bar{c}$ pair are different from charmonium



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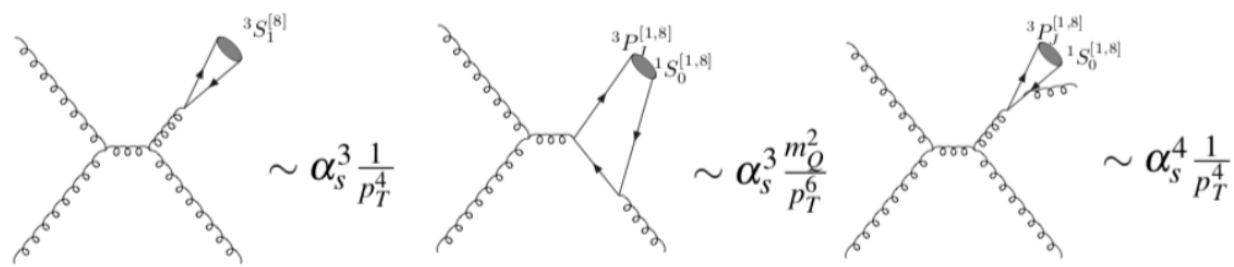

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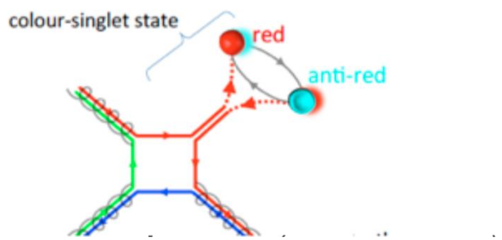

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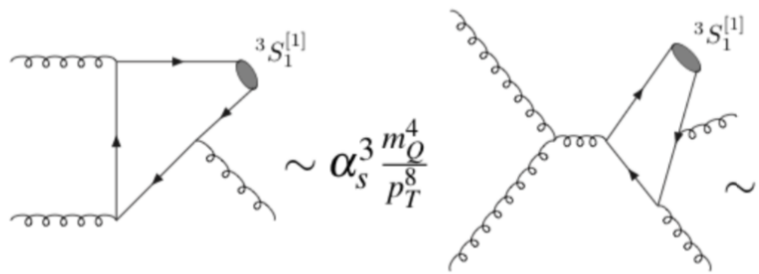

$\sim \alpha_s^3 \frac{m_Q^4}{p_T^8}$ $\sim \alpha_s^4 \frac{m_Q^2}{p_T^6}$

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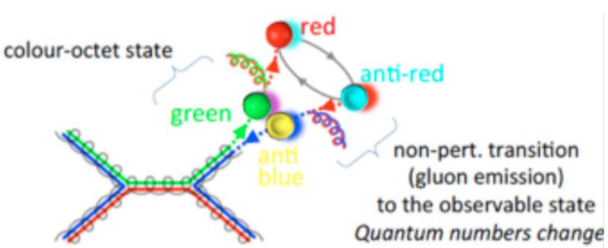

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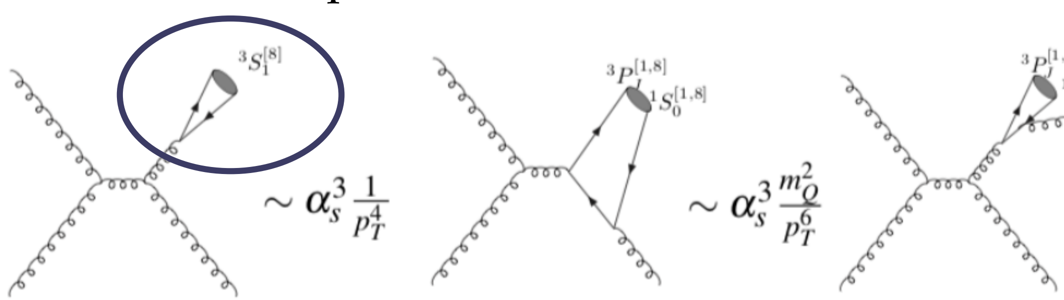


$\sim \alpha_s^3 \frac{1}{p_T^4}$ $\sim \alpha_s^3 \frac{m_Q^2}{p_T^6}$ $\sim \alpha_s^4 \frac{1}{p_T^4}$

strong J/ψ polarization at large p_T

Charmonium hadroproduction in the NRQCD

- **Cross section factorizes:**

$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \times \langle O^H(n)\rangle$$

long distance matrix elements (LDMEs), non-perturbative

- **Universality:** same LDMEs for different production processes (e.g. hadroproduction and b-decays)

- **Heavy quark spin-symmetry (HQSS) for LDMEs**:
Links between the CS and CO LDMEs
of **different charmonia states**

Simultaneous study of J/ψ and η_c →

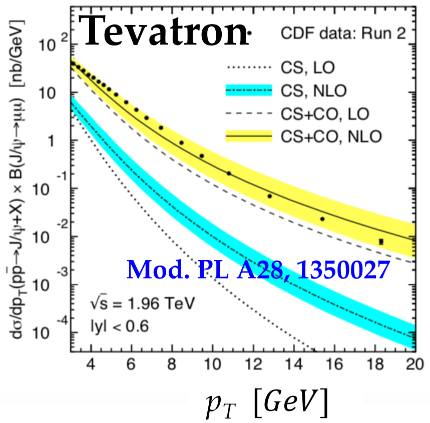
Simultaneous study of P-wave charmonia

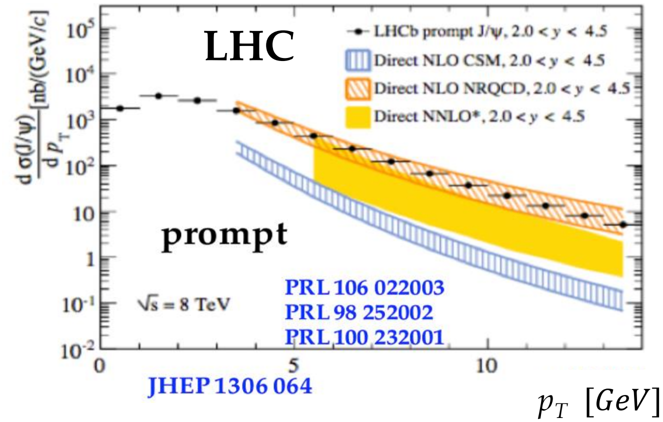
$$\langle O_1^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_1^{J/\psi}(^3S_1)\rangle$$
$$\langle O_8^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_8^{J/\psi}(^3S_1)\rangle$$
$$\langle O_8^{\eta_c}(^3S_1)\rangle = \langle O_8^{J/\psi}(^1S_0)\rangle$$
$$\langle O_8^{\eta_c}(^1P_1)\rangle = 3\langle O_8^{J/\psi}(^3P_0)\rangle$$

*other contributions are small according to the **expansion on** v

NRQCD vs experiment: J/ψ hadroproduction and polarization

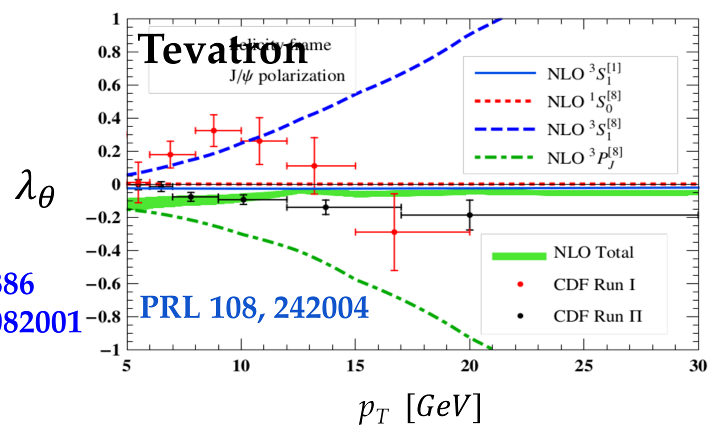
Production:



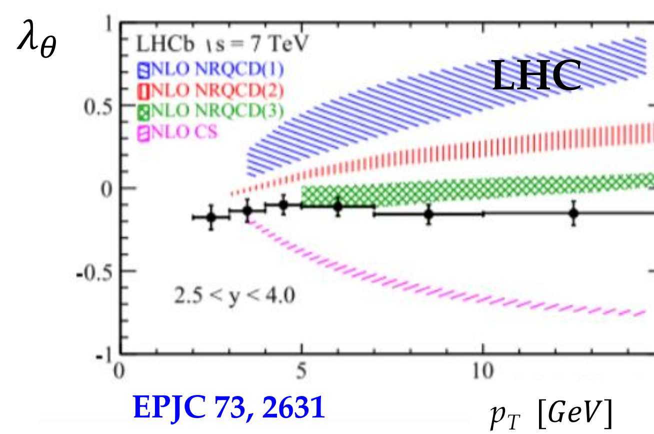


- *CS* NLO and NNLO* cannot describe prompt production at both LHC and Tevatron
- *NRQCD* description with dominating *CO* contribution
  → great success by NRQCD

Polarization:



PRL 85, 2886
PRL 108, 082001



PRL 108, 172002
PRL 110, 042002
PRL 108, 242004

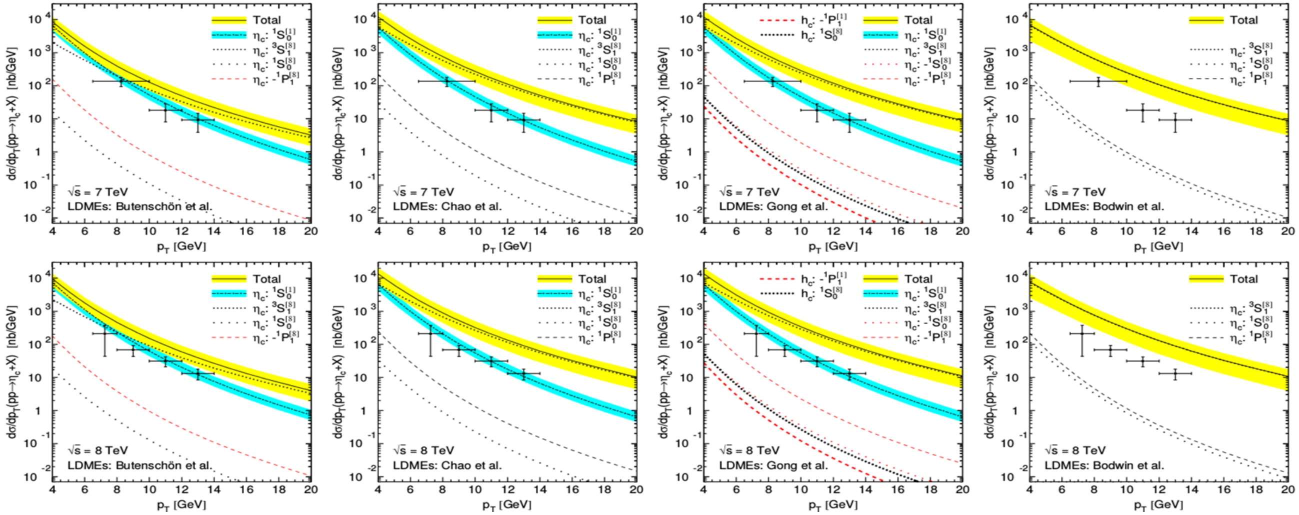
- *CO* predicts strong polarization
- *CS* contribution / feed-down effect from χ_c to describe small observed polarization ?

η_c hadroproduction challenges NRQCD

First measurement by LHCb **EPJC 75 (2015) 311** triggered important theory progress

η_c LDMEs determined from J/ψ production using HQSS relation

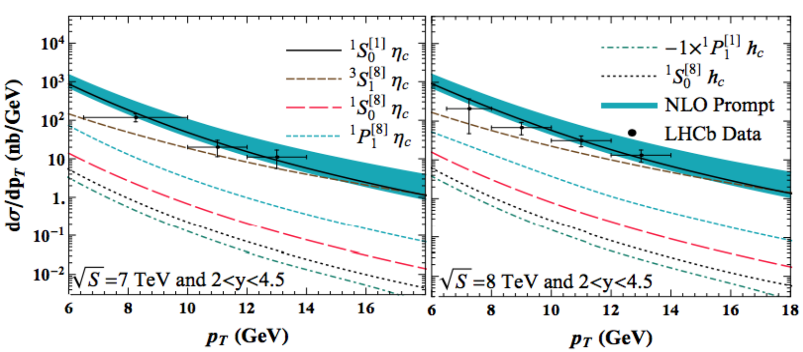
PRD 84(2011),051501 (R) | PRL 108(2012),242004 | PRL 110(2013),042002 | PRL 113(2014),022001



$$\langle O_1^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_1^{J/\psi}(^3S_1)\rangle$$
$$\langle O_8^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_8^{J/\psi}(^3S_1)\rangle$$
$$\langle O_8^{\eta_c}(^3S_1)\rangle = \langle O_8^{J/\psi}(^1S_0)\rangle$$
$$\langle O_8^{\eta_c}(^1P_1)\rangle = 3\langle O_8^{J/\psi}(^3P_0)\rangle$$

LHCb data entirely described by CS contribution, no room for predicted CO contribution

- Recent progress in theoretical description: **Han, Ma, Chao, Shao, Meng PRL 114 (2015) 092005**



Using constraints from **J/ψ and η_c production measurements**, upper limit on CO LDME extracted:

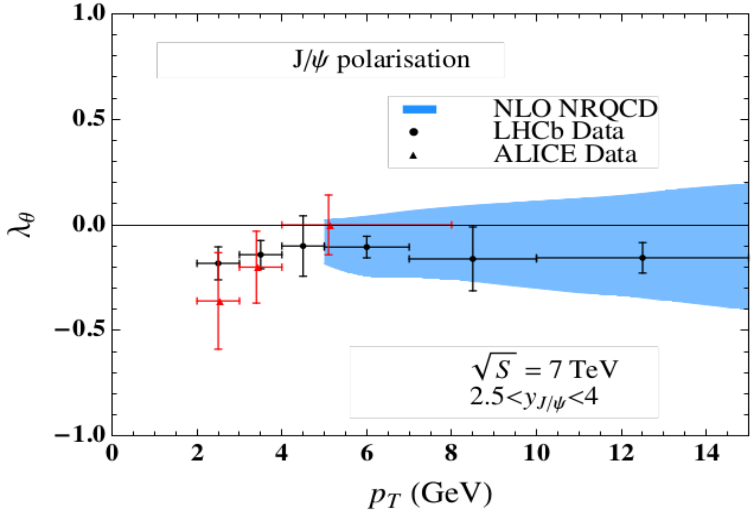
$$0 < O_8^{\eta_c}(\,^3S_1) < 1.46\times10^{-3}\mathrm{GeV}^3$$

η_c hadroproduction challenges NRQCD

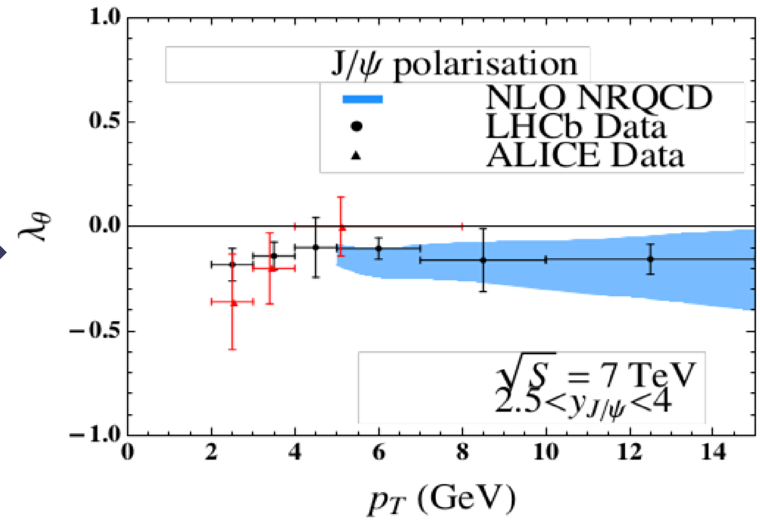
Upper limit on $O^{\eta_c}(^3S_1^{[8]})$ ⇒ new powerful constraint on J/ψ polarization

PRL 114(2015), 092005

Without η_c measurements



With η_c measurements



Outcome:

- *Progress in data* description but tension with CDF data
- Two large CO contributions cancel each other ⇒ Hierarchy problem
  - **Recent global fit with another factorization scheme**
    S. P. Baranov, A. V. Lipatov arXiv:1906.07182

Motivations:

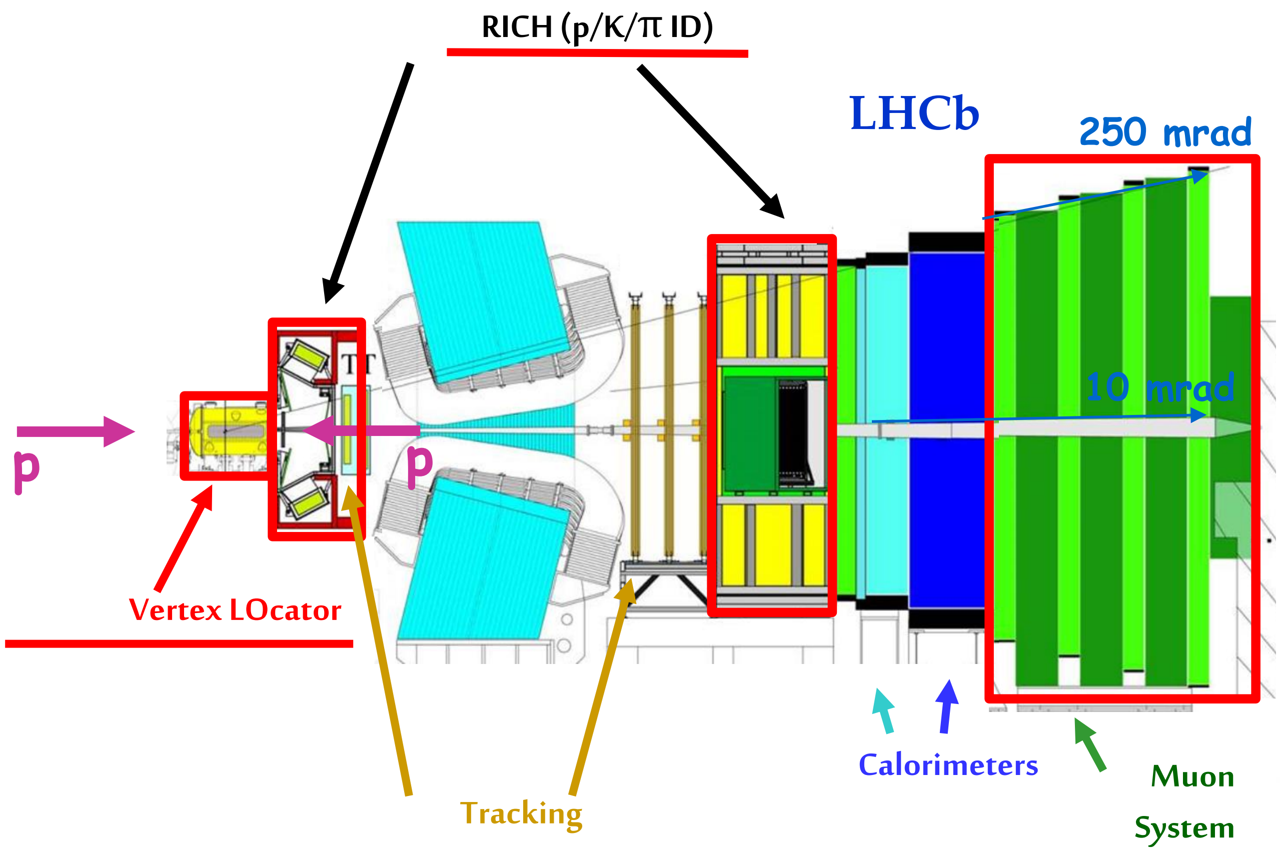
- Simultaneous study of hadroproduction and production in inclusive *b*-decays
- Measurement to be updated with larger sample and larger $\sqrt{s}$ at LHCb
- Similarly study **η_c(2S) and ψ(2S) hadroproduction**

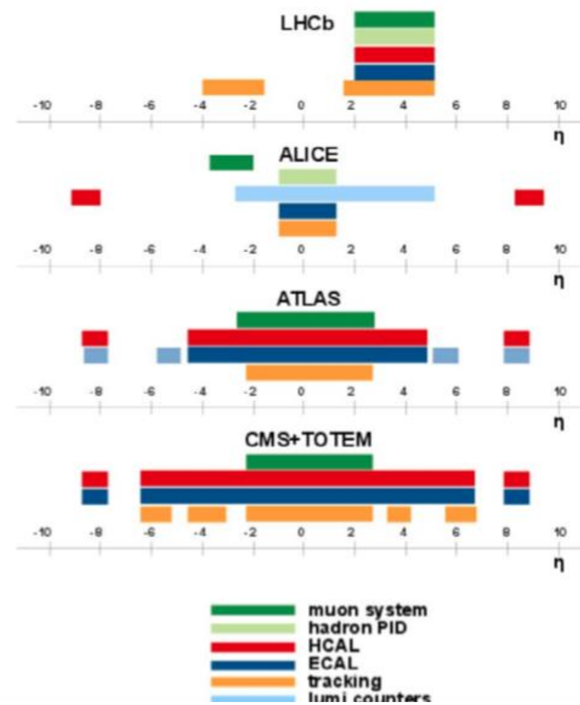
LHCb experiment

LHCb : single arm forward spectrometer

JINST 8 (2013) P08002, INT.J.MOD.PHYS.A30 (2015) 1530022

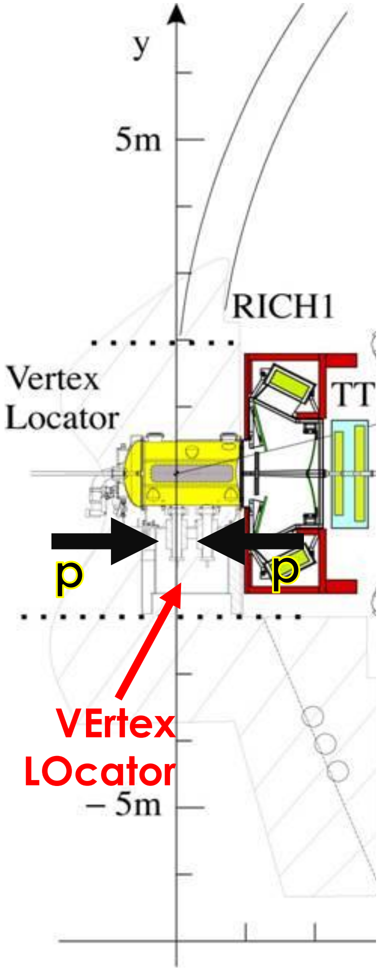
- **Forward peaked HQ production** at the LHC, second b in acceptance once the first b is in
- Forward region $1.9 < \eta < 4.9$, **~4% of solid angle**, but **~40% of HQ production x-section**





- **Complementary cross-section measurements** and overlap in terms of rapidity and p_T
- Key detector systems for production measurements: **vertex reconstruction (VELO), particle identification (Muon detector, Ring Imaging CHerenkov detectors - RICHs), Trigger**
- **Reconstruction of charmonia via hadronic decays possible**

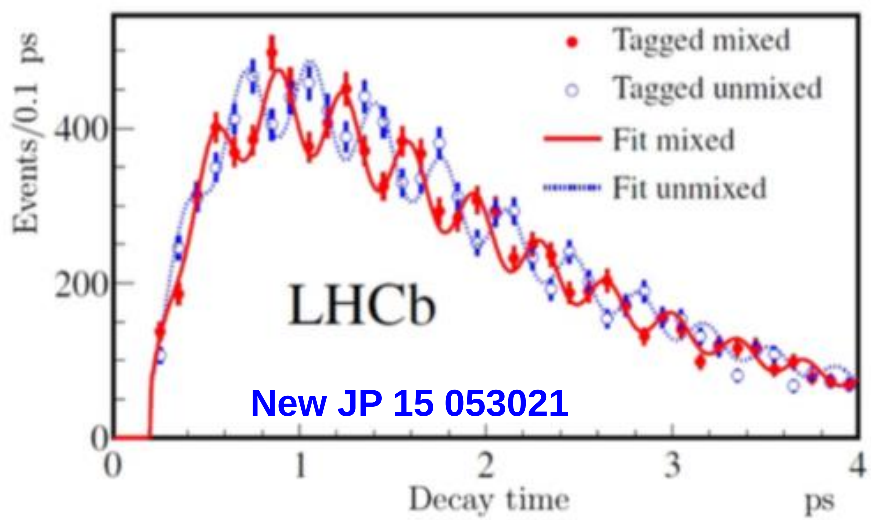
LHCb: VErtex LOcator



- 88 semi-circular **microstrip Si sensors, sensitive area at 8mm from the beam axis**
- **R and φ** measurements

- **Spatial resolution**, down to 4μ for single tracks
- **Impact parameter** measurement, $\sigma_{IP} = 11.6 + 23.4/pT$ [μ]
- **Primary vertex** reconstruction,
  $\sigma_x = \sigma_x = 13\mu$, $\sigma_z = 69\mu$ for a vertex of 25 tracks

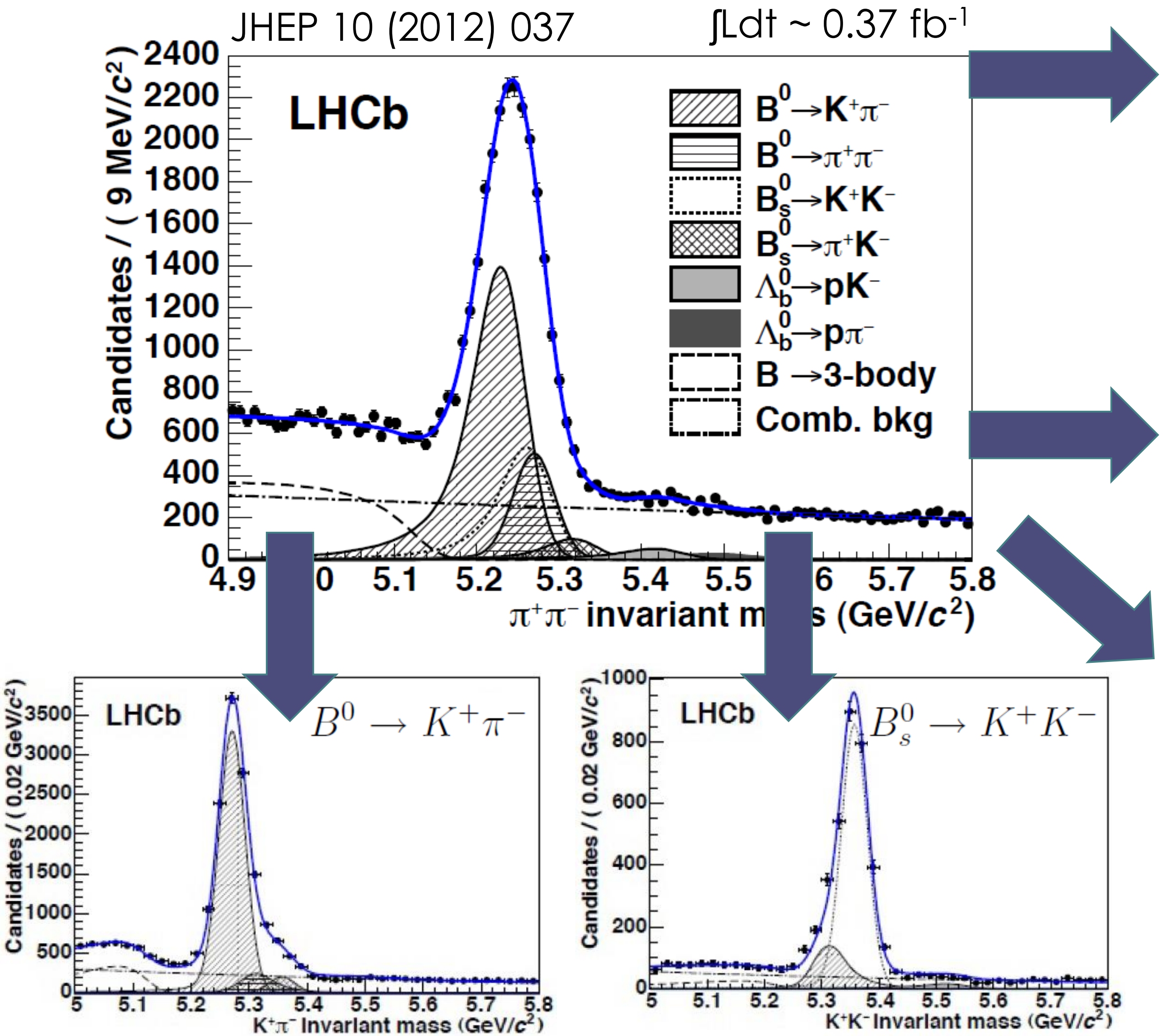
- B-meson travels on average ~1 cm

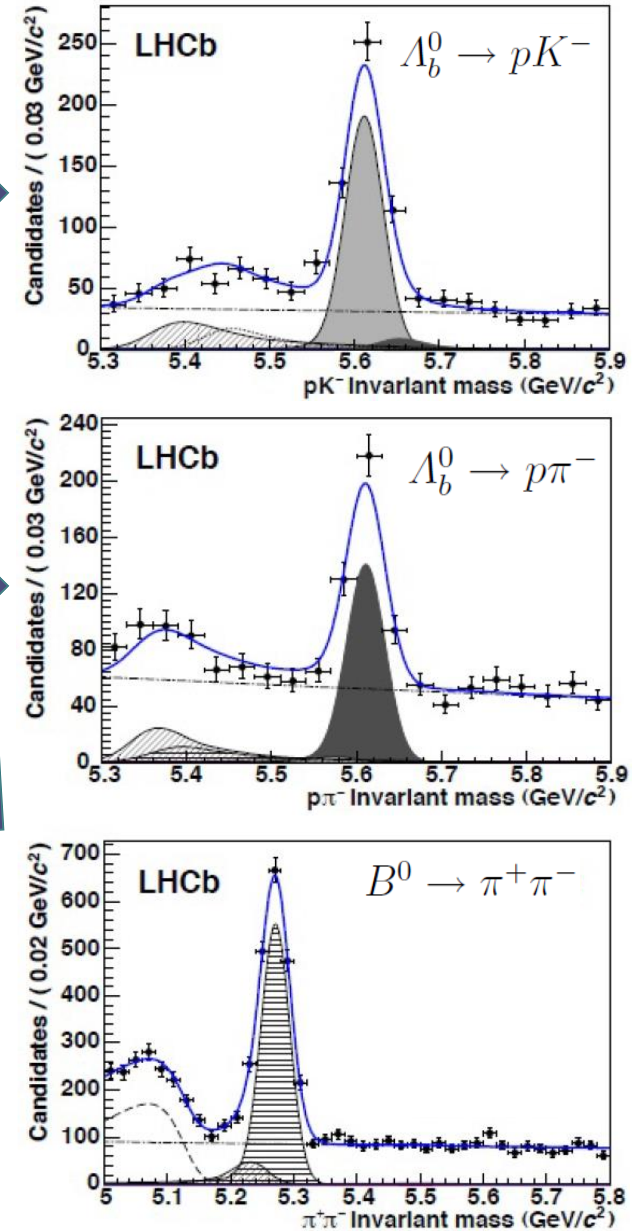


Measure coordinates of collision and b-decay vertices

Charged hadron identification with RICH at LHCb

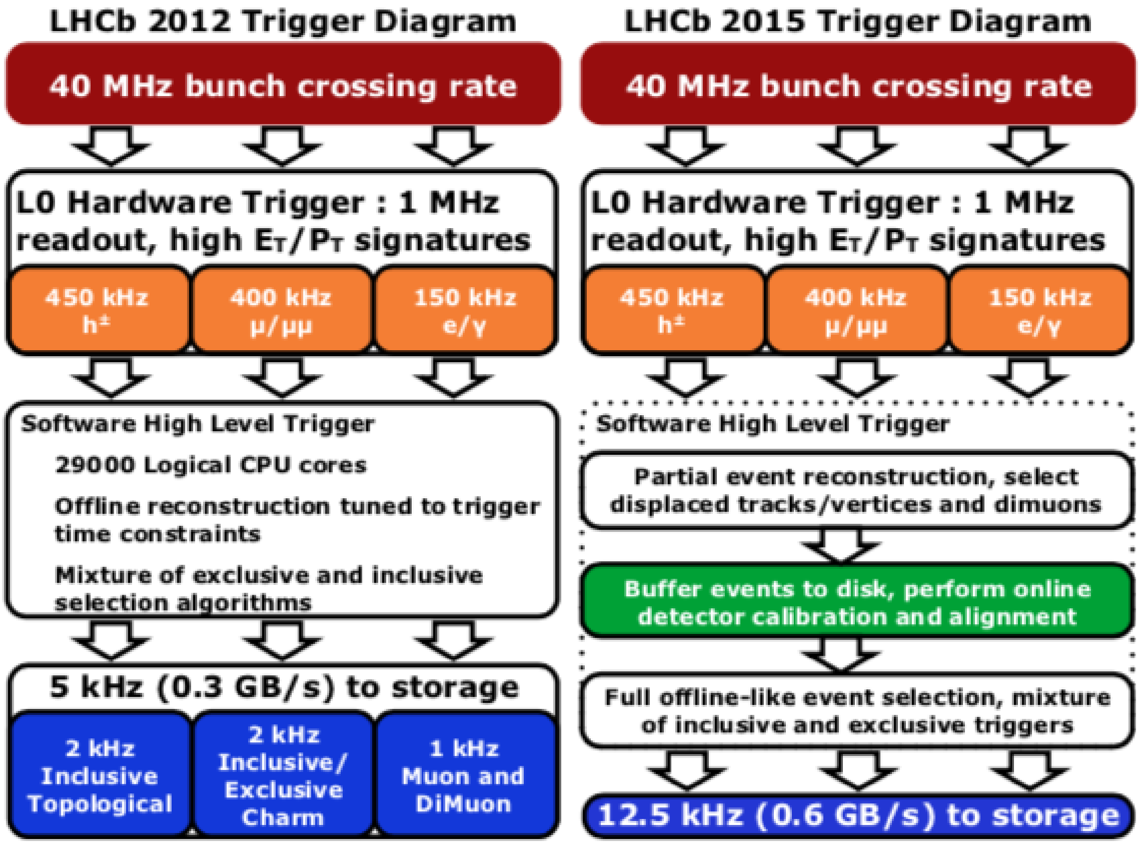
- RICH: 2 detectors, 3(2) radiators
- Performance: two-body b-hadron decays





Provides ID of protons and kaons

Trigger and stripping



$\phi\phi$ analysis, Run I $\qquad$ $p\bar{p}$ analysis, Run II

- Flexible trigger : **hardware L0, online software (HLT1), offline software (HLT2)** stages
- Specific offline selection (**Stripping**) on triggered events
- Stripped data stored on disk
- **Dedicated trigger and stripping selections for prompt charmonium via $p\bar{p}$ and $\phi\phi$**

Measurement of $\boldsymbol{\eta_c}$ production at $\sqrt{s} = 13\ TeV$ via the decay $\eta_c \to p\bar{p}$

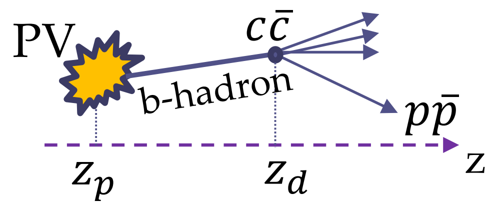
Data sample : Run II 2015-2016, $\int \mathcal{L}dt = 2.0\ fb^{-1}$

LHCb-PAPER-2019-024, in collaboration wide review

Cross-section determination

Two production processes:

- Prompt (PV, pp collision vertex): **hadroproduction** + feed-down from higher states
- **Production in b-decays** (b-decay vertex)



$$t_z = \frac{(z_d - z_p) M_{p\bar{p}}}{p_z}$$

Event selection: high-p_T proton tracks, proton ID using RICH, high-p_T $p\bar{p}$ pair forming good quality vertex

Selection is essentially performed at trigger level

$$\frac{\sigma(\eta_c(1S))}{\sigma(J/\psi)} = \frac{N^p_{\eta_c(1S)}}{N^p_{J/\psi}} \times \frac{\mathcal{B}_{J/\psi\to p\bar{p}}}{\mathcal{B}_{\eta_c(1S)\to p\bar{p}}} \times \frac{\epsilon_{J/\psi\to p\bar{p}}}{\epsilon_{\eta_c(1S)\to p\bar{p}}}$$

Absolute scale from J/ψ production

$$\frac{\mathcal{B}_{b\to\eta_c(1S)X}}{\mathcal{B}_{b\to J/\psi X}} = \frac{N^b_{\eta_c(1S)}}{N^b_{J/\psi}} \times \frac{\mathcal{B}_{J/\psi\to p\bar{p}}}{\mathcal{B}_{\eta_c(1S)\to p\bar{p}}} \times \frac{\epsilon_{J/\psi\to p\bar{p}}}{\epsilon_{\eta_c(1S)\to p\bar{p}}}$$

Data **PDG or LHCb** **MC simulation** $=1.00\pm0.02$

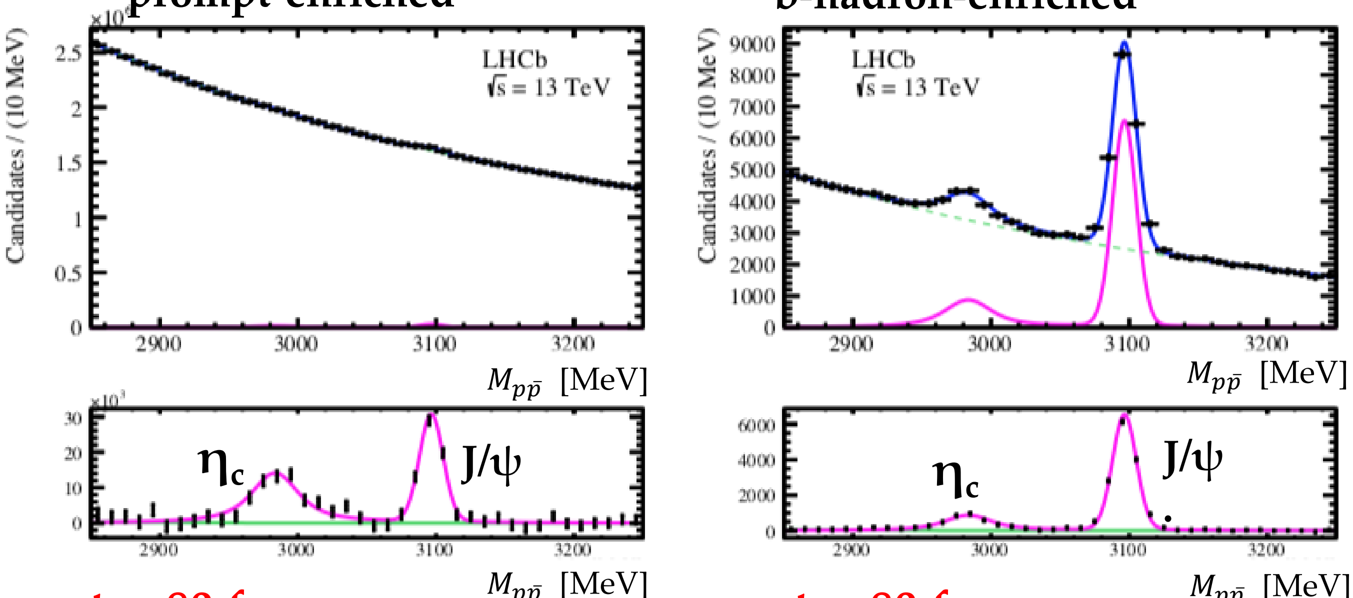
Yields extraction:

Separation technique or t_z *-fit* in p_T bins **to distinguish prompt and from *b*-decays charmonia**

Separation technique

- Split data to two samples and fit them **simultaneously** in p_T-bins
- Example: first bin, $6.5 < p_T < 8$ GeV

prompt-enriched **b-hadron-enriched**



$t_z < 80$ fs

$t_z > 80$ fs
IP $\chi^2 > 16$

Signals
- From J/ψ and η_c
- η_c natural width is taken into account

Background
- Combinatorial
- $J/\psi \to p\bar{p}\pi^0$

By taking into account cross-talk between samples, **prompt** and **from b-decays** yields are extracted

Separation technique : systematic uncertainties

Example: first bin, $6.5 < p_T < 8$ GeV

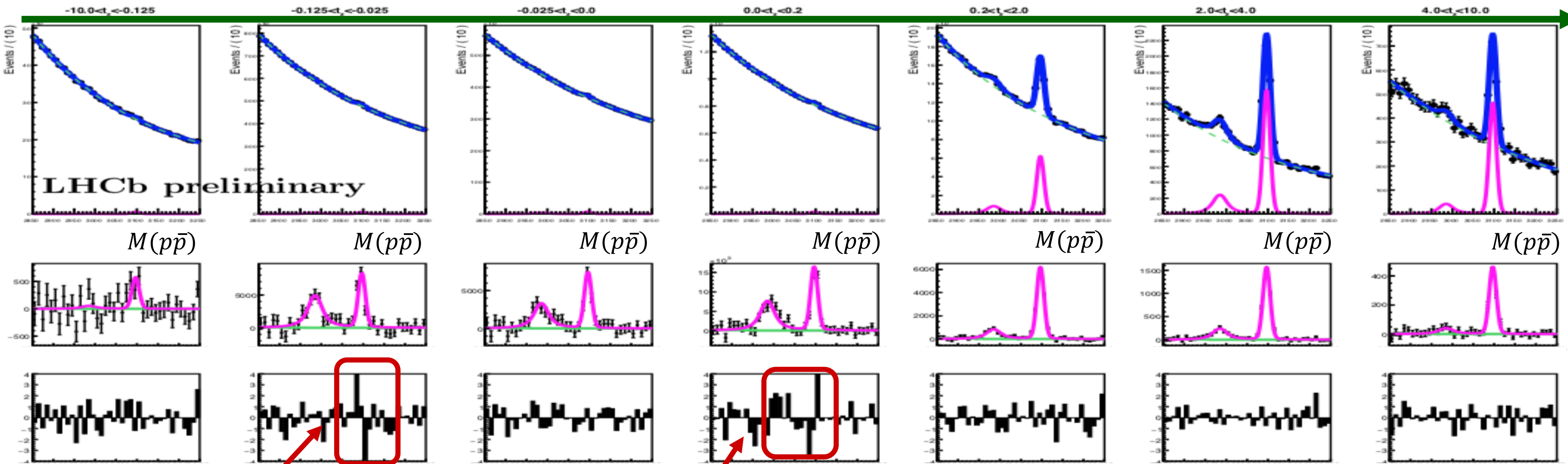
	$N^p_{\eta_c}/N^p_{J/\psi}$	$N^b_{\eta_c}/N^b_{J/\psi}$	
Mean value	0.984	0.263	
Stat. uncertainty	22.7	15.4	
p_T-dependence of $\sigma_{\eta_c}/\sigma_{J/\psi}$	0.4	0.2	**uncorrelated uncertainties**
Comb. bkg. description	2.1	2.5	
Contribution from $J/\psi \to p\bar{p}\pi^0$	0.2	0.7	
Cross-talk	1.9	1.4	
Tot Syst Uncorr	2.9	3.0	
Mass resolution model	2.7	3.1	**correlated uncertainties**
Variation of Γ_{η_c}	4.8	3.6	
J/ψ polarisation	2.1	–	
Tot Syst Corr	5.8	4.8	
Tot Syst	6.5	5.6	

- Total systematic uncertainties are **smaller** than statistical ones
- Uncorrelated syst. uncertainties are smoothed between p_T-bins

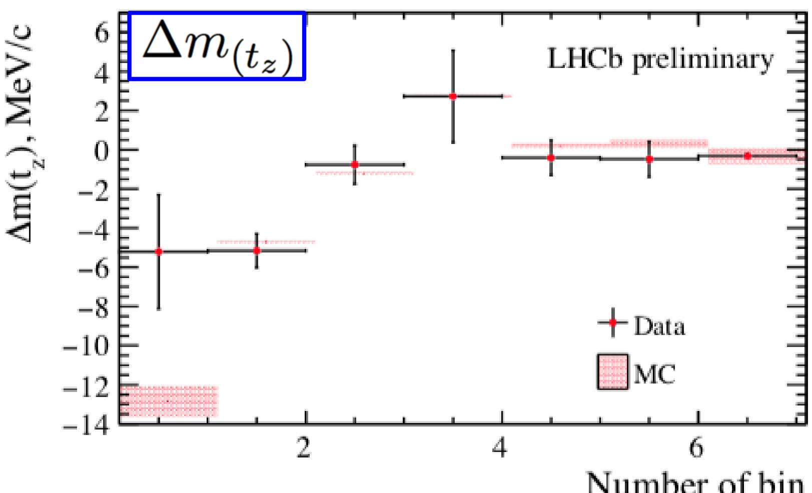
Uncertainty on production due to $BR(J/\psi \to p\bar{p})$ and $BR(\eta_c \to p\bar{p}) \approxeq 10\%$

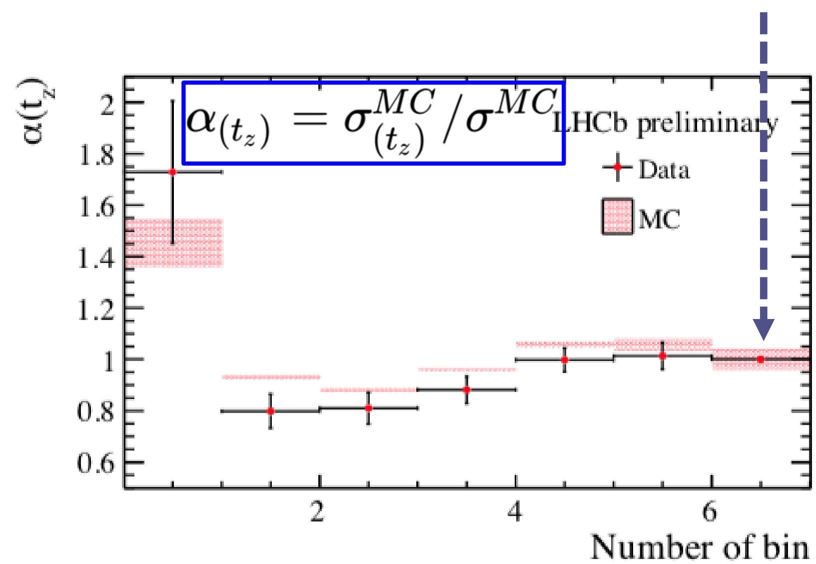
t_z-fit : corrections on peak positions and resolution

Simultaneous fit (to tz bins) to inv. mass in t_z -bins, **no peak shifts assumed**



Mass shift in t_z bins is required



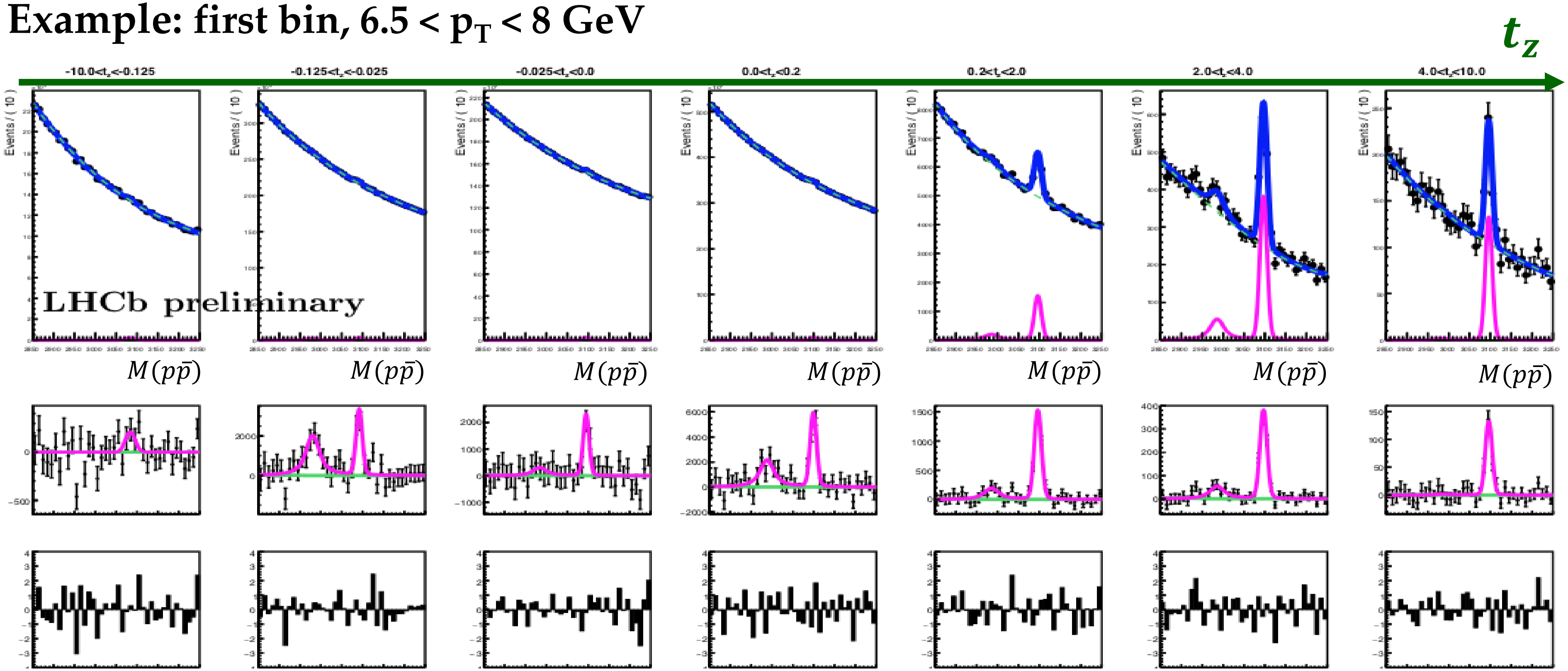


⇒ **MC well reproduces shifts**

⇒ Corrections extracted using simultaneous MC fit for η_c and J/ψ

Simultaneous fit to M($p\bar{p}$) in tz bins after corrections

Example: first bin, 6.5 < p_T < 8 GeV



Consistency check

	Fit result [MeV]	PDG [MeV]
$m_{J/\psi}$	3096.6 ± 0.1	3096.900 ±0.006
$m_{J/\psi}$-$m_{\eta c}$	111.2 ± 1.1	113.5 ± 0.5

tz fit to data

$$F(t_z) = \left(N_p \delta(t_z) + \frac{N_b}{\tau_b} \exp\left(-\frac{t_z}{\tau_b}\right) \right) \otimes Resolution + N_t f_{tail}(t_z)$$

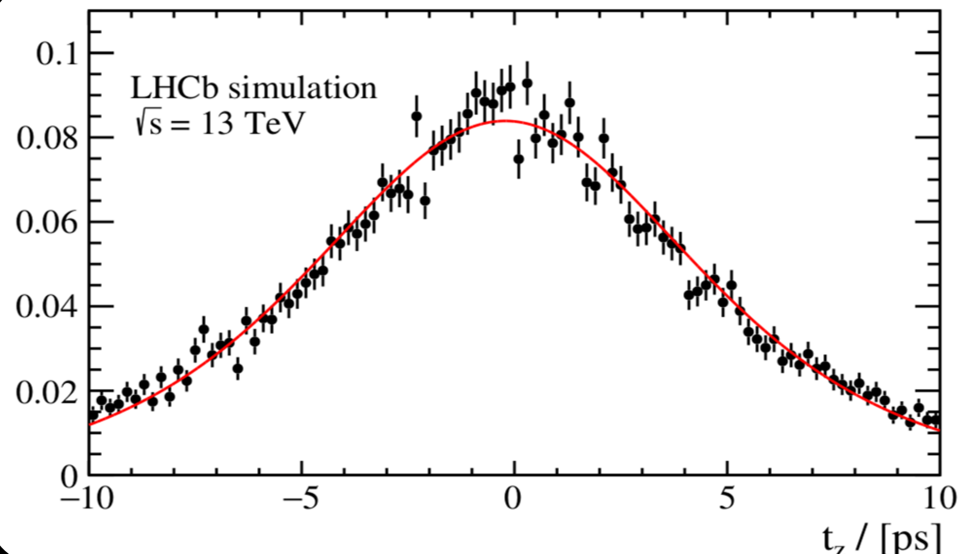
prompt

from b-decays

tz – resolution
(extracted from MC)

events with
mismatched PV

$$t_z^{next} = \frac{(z_{p\bar{p}} - z_{PV}^{next}) \times M_{p\bar{p}}}{p_z}$$

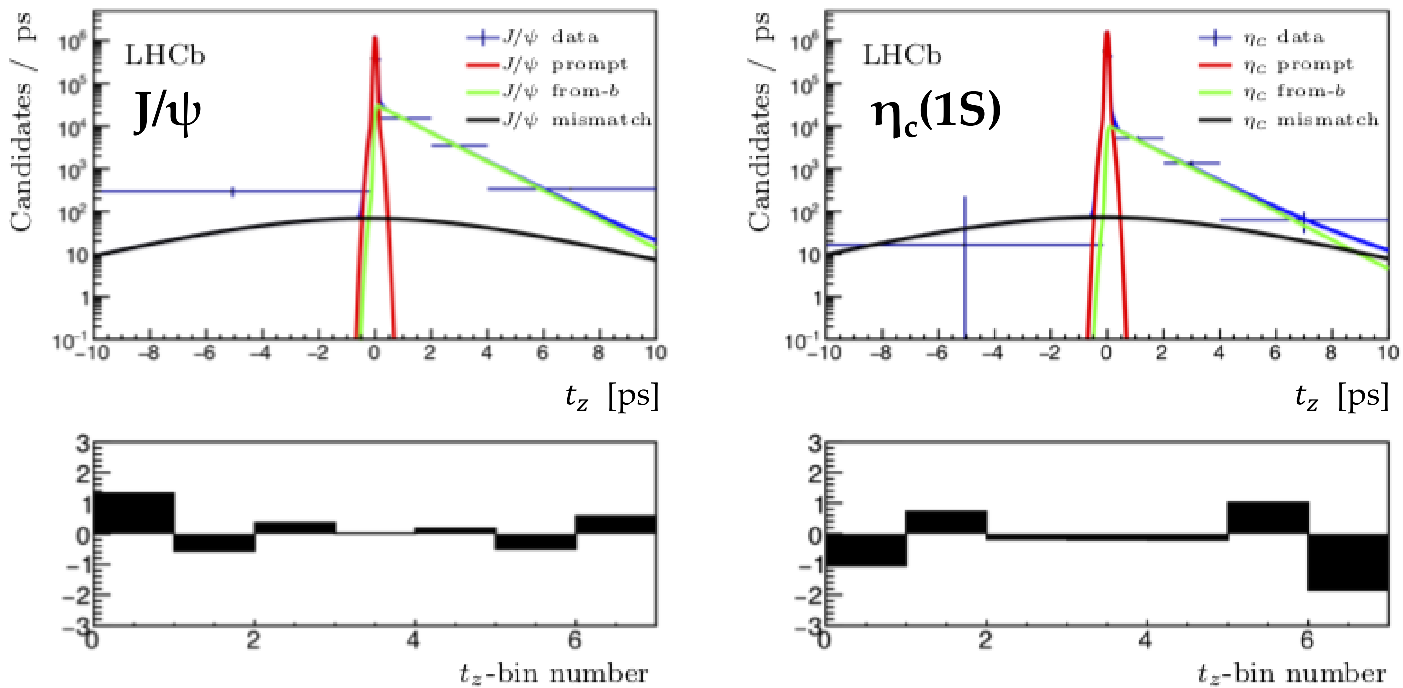


Described by kernel-estimated distribution in bins of p_T

t_z fit to data

$$F(t_z) = \left(N_p \delta(t_z) + \frac{N_b}{\tau_b} \exp\left(-\frac{t_z}{\tau_b}\right) \right) \otimes Resolution + N_t f_{tail}(t_z)$$

Simultaneous χ^2 fit to t_z distributions of J/ψ and η_c obtained from mass fit in t_z bins



$$\frac{N^{tail}}{N^{prompt} + N^{from-b}} < 2\%$$

Prompt $N^{prompt}_{\eta_c} / N^{prompt}_{J/\psi}$ and from b-decays $N^{b}_{\eta_c} / N^{b}_{J/\psi}$ extracted in p_T bins

t_z-fit : systematic uncertainties

Example: first bin, $6.5 < p_T < 8$ GeV

	$N^{prompt}_{\eta_c} / N^{prompt}_{J/\psi}$	$N^{b-decays}_{\eta_c} / N^{b-decays}_{J/\psi}$
Mean value	1.082	0.281
Stat. uncertainty	19.6	25.4
α_{t_z} corrections	1.8	1.0
p_T-dependence of $\sigma_{\eta_c}/\sigma_{J/\psi}$	0.1	0.8
Comb. bkg. description	2.3	3.2
Contribution from $J/\psi \to p\bar{p}\pi^0$	< 0.1	0.3
p_T-dependence of t_z resolution	0.7	0.4
p_T-dependence of τ_B	0.2	0.3
Bias μ	0.3	0.2
t_z-resolution model	0.2	0.3
Total systematic uncorrelated	3.0	3.6
J/ψ polarisation	2.1	–
Mass resolution model	3.0	3.8
Variation of Γ_{η_c}	5.2	5.1
Total systematic correlated	6.4	6.4
Total systematic	7.0	7.3

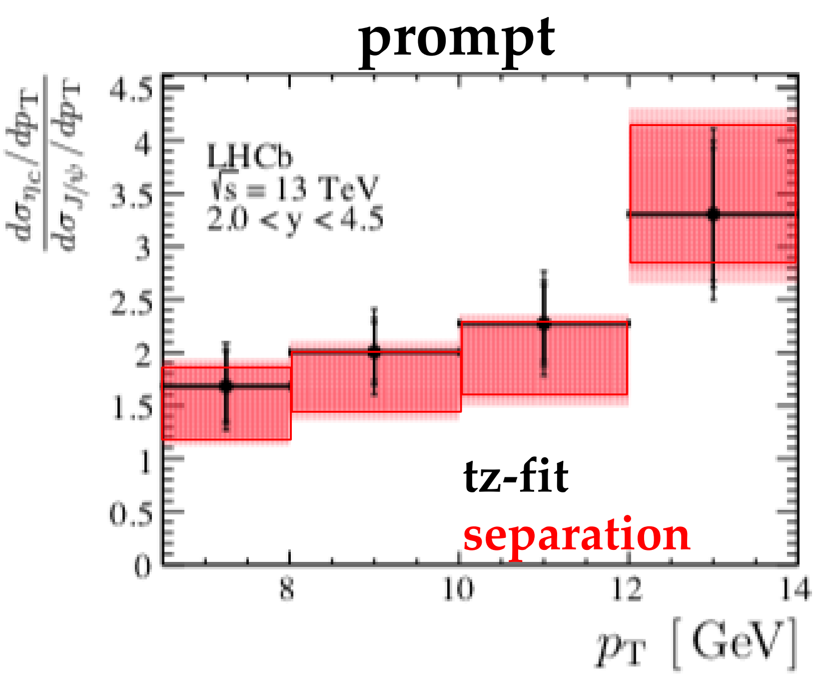
uncorrelated uncertainties

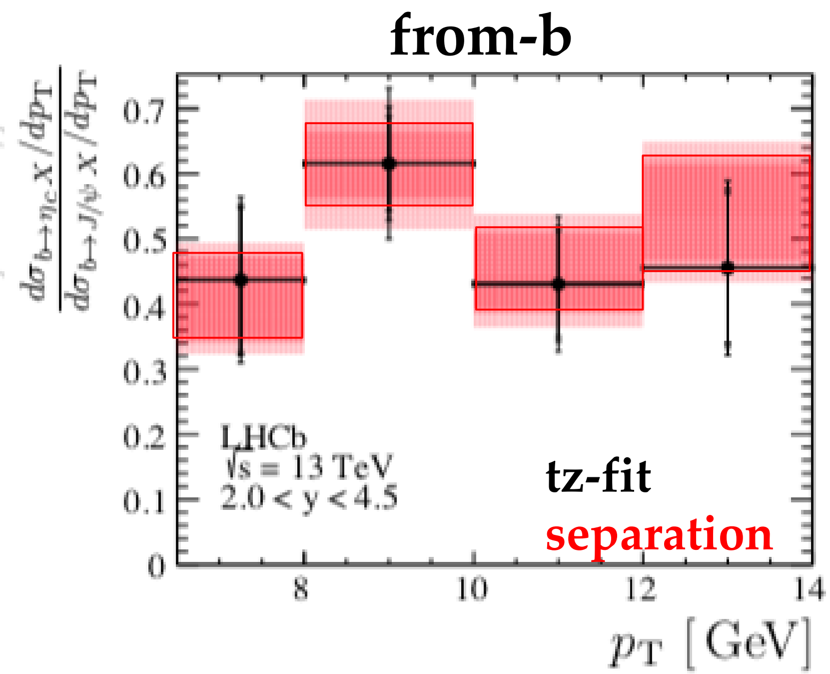
correlated uncertainties

- Total systematic uncertainties are **smaller** than statistical ones
- Uncorrelated syst. uncertainties are smoothed between p_T-bins

Uncertainty on production due to BR($J/\psi \to p\bar{p}$) and BR($\eta_c \to p\bar{p}$) $\approxeq$ 10%

η_c production : comparison between the two techniques





- Methods are **consistent**
- **Similar precision** for both methods
- Small gain in statistical precision with t_z-fit method

- Methods are **consistent**
- Separation method is **more precise**

$\eta_c(1S)$ **prompt** production

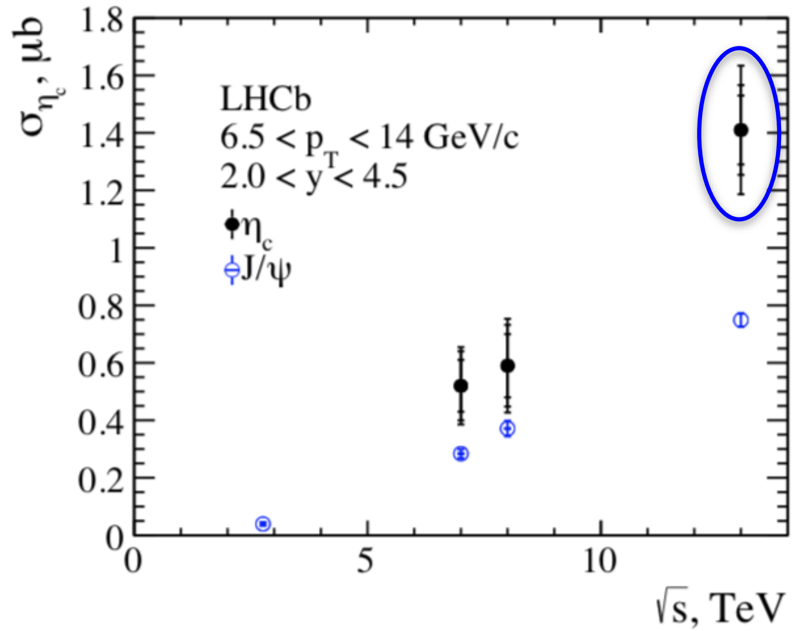
	$\sigma_{\eta c}/\sigma_{J/\psi}$
√s=7 TeV	$1.74 \pm 0.29_{stat} \pm 0.28_{syst} \pm 0.18_{BR}$
√s=8 TeV	$1.60 \pm 0.29_{stat} \pm 0.25_{syst} \pm 0.17_{BR}$
√s=13 TeV	$\mathbf{1.69 \pm 0.15_{stat} \pm 0.10_{syst} \pm 0.18_{BR}}$

Using measured J/ψ production
[JHEP 1705 063]:

$\sigma_{\eta c} = 1.26 \pm 0.11_{stat} \pm 0.08_{syst} \pm 0.14_{BR}$ μb

Color Singlet model prediction:
Feng, Shao, Lansberg, Zhang, Usachov, He
NP B945 (2019) 114662

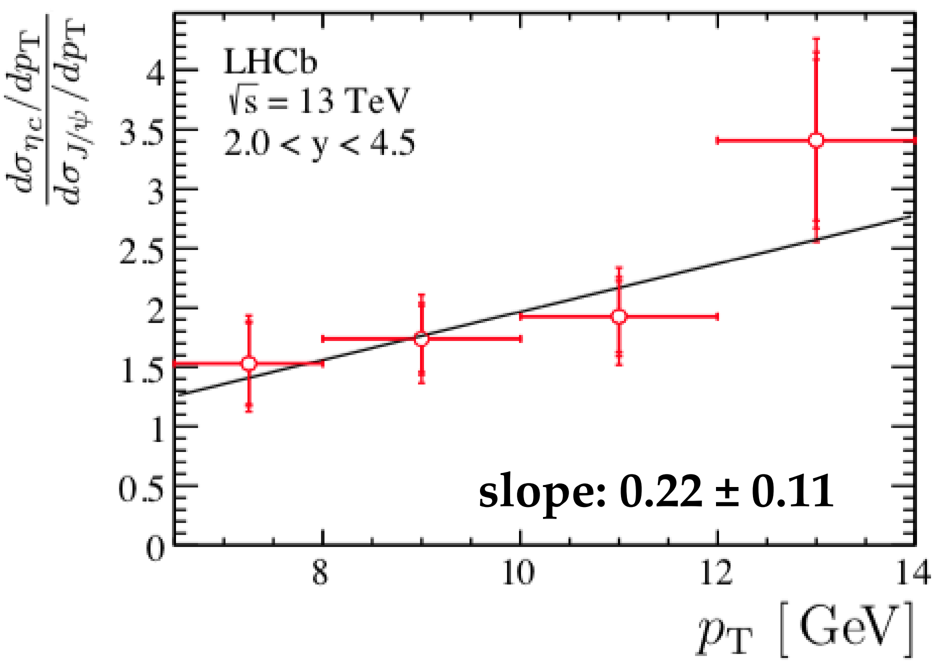
$1.56^{+0.83}_{-0.49}\ ^{+0.38}_{-0.17}$ μb

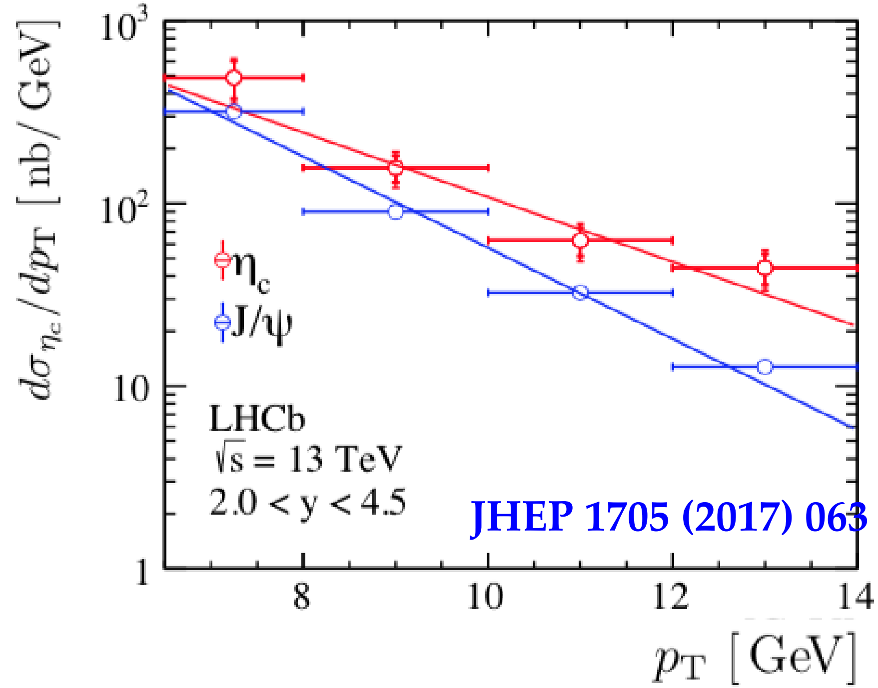


- **First $\eta_c(1S)$ prompt production measurement at 13 TeV**
- **More precise** than Run I measurement
- Consistent with CS model prediction

$\eta_c(1S)$ **prompt** production

p_T -differential **prompt production**



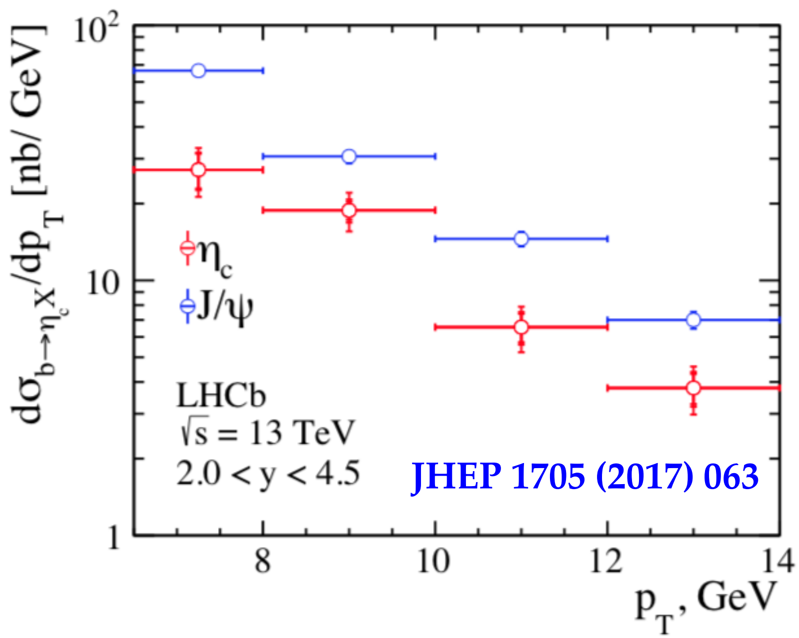


Indication of possible CO contribution ?

η_c(1S) production **in inclusive *b*-decays**

	$BR_{b\to\eta_c X}/BR_{b\to J/\psi X}$	$BR_{b\to\eta_c X}$
√s=7 and √s=8 TeV, average	$0.421 \pm 0.055_{stat} \pm 0.022_{syst} \pm 0.045_{BR}$	$(4.88 \pm 0.64_{stat} \pm 0.25_{syst} \pm 0.67_{BR})\times 10^{-3}$
√s=13 TeV	$\mathbf{0.48 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.05_{BR}}$	$\mathbf{(5.51 \pm 0.32_{stat} \pm 0.29_{syst} \pm 0.77_{BR})\times 10^{-3}}$

p_T -differential production **in inclusive *b*-decays**



- Result **consistent** with Run I measurement and **more precise**
- Precision limited by systematic uncertainties on branching fractions

Measurement of **charmonium production in b-hadron inclusive decays** using charmonia decays to $\phi\phi$

Data sample : Run I 2011-2012, $\int \mathcal{L}dt = 3.0\ fb^{-1}$

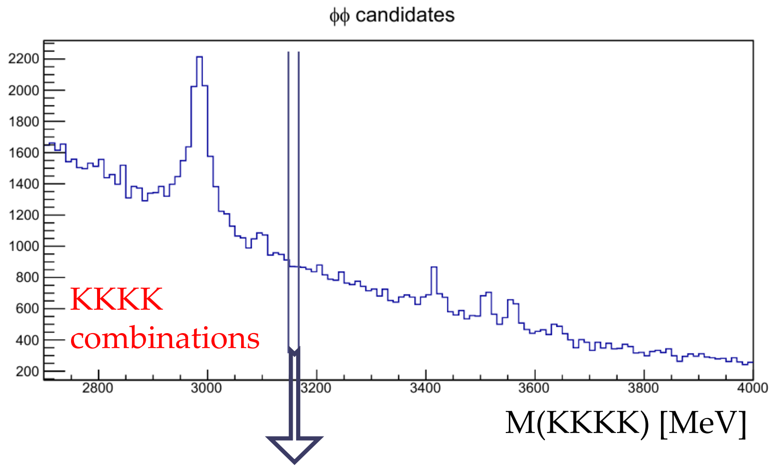
EPJC 77 (2017) 609

Charmonium production in inclusive b-decays using $\phi\phi$

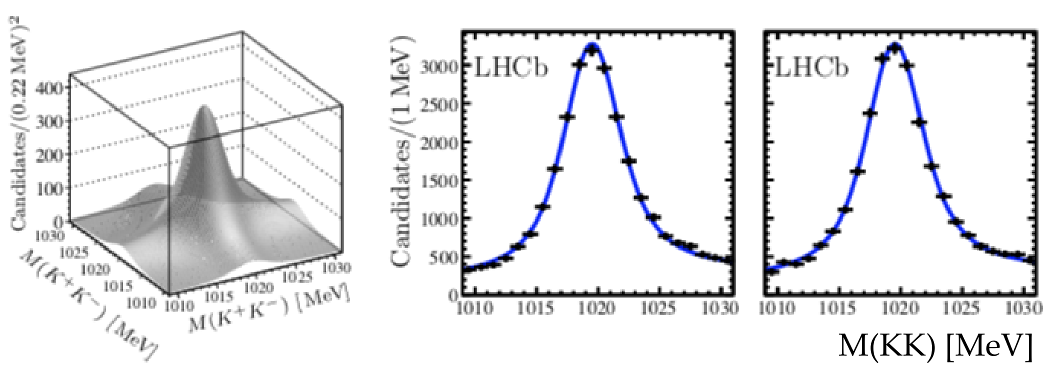
Event selection: high-p_T kaon tracks, kaon ID using RICH, kaon pairs invariant mass close to ϕ resonance, good quality *KKKK* vertex significantly displaced from PV

Selection is essentially performed at trigger and stripping levels

- True φφ combinations using **2D fit technique in bins of *M(KKKK)***



Spectrum comprises $\phi\phi$, ϕKK and $KKKK$ contributions
+ possible contributions from other resonances

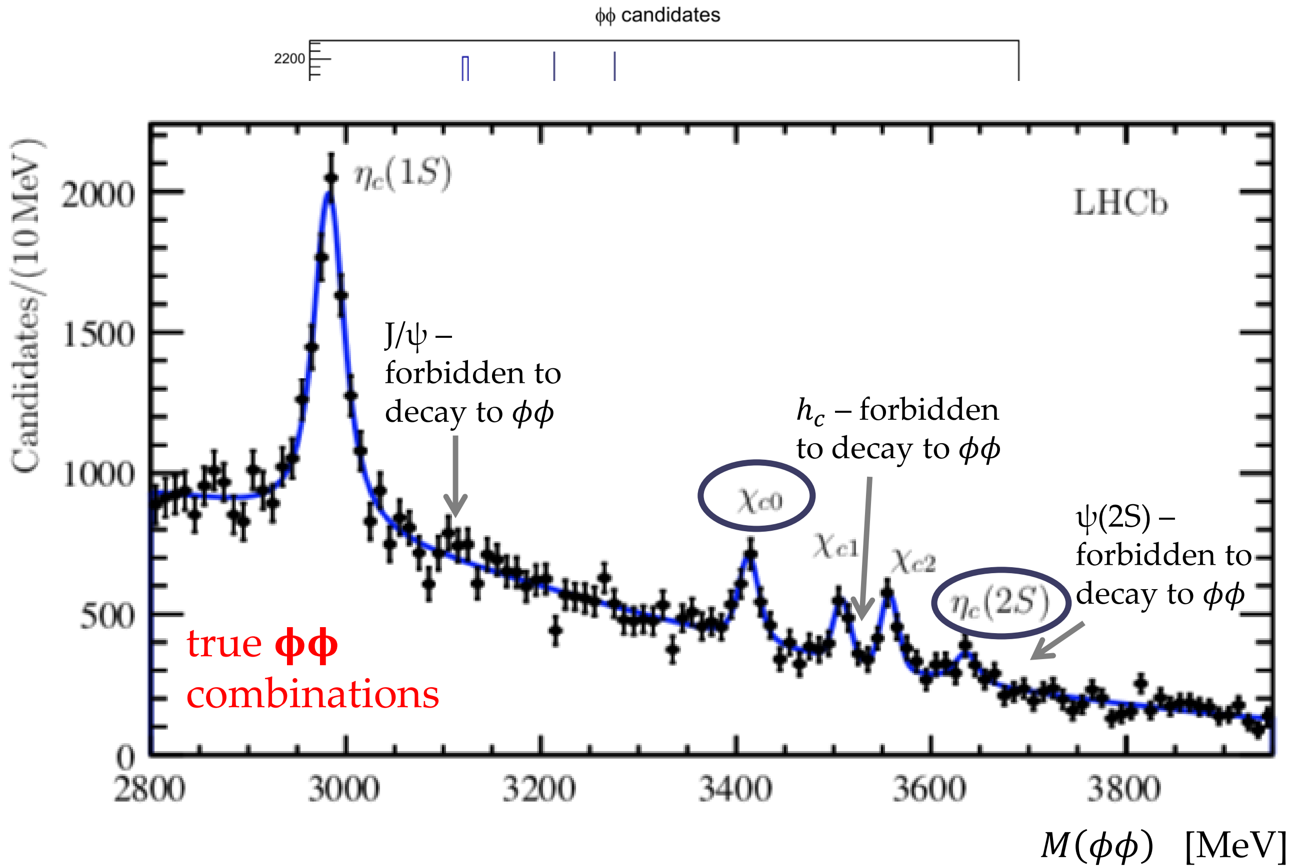


Charmonium production in inclusive b-decays using $\phi\phi$

Event selection: high-p_T kaon tracks, kaon ID using RICH, kaon pairs invariant mass close to ϕ resonance, good quality *KKKK* vertex significantly displaced from PV

Selection is essentially performed at trigger and stripping levels

- True φφ combinations using **2D fit technique in bins of *M(KKKK)***



Extract relative yields from the fit

Systematic uncertainties

	$N_{\chi_{c1}}/N_{\chi_{c0}}$	$N_{\chi_{c2}}/N_{\chi_{c0}}$	$N_{\eta_c(2S)}/N_{\eta_c(1S)}$
Including $X(3872)$, $X(3915)$, $\chi_{c2}(3930)$	0.006	0.008	0.003
Fix $\eta_c(1S)$ resolution to MC value	0.001	0.001	< 0.001
Resolution described with a single Gaussian	< 0.001	< 0.001	-0.002
Varying r parameter between 0.5 and 3 GeV^{-1}	< 0.001	< 0.001	< 0.001
Varying $\Gamma_{\eta_c(2S)}$	< 0.001	0.001	-0.003
Fit χ_c and $\eta_c(2S)$ region only	0.001	-0.004	-
Alternative bgrd parametrization	0.002	0.011	< 0.001
Accounting for $f_0(980)$ in 2D fit	0.005	0.005	0.001
Fix χ_c masses at nominal values	-0.010	-0.002	< 0.001
Fix resolution in 2D fit at MC value	< 0.001	-0.001	< 0.001
Add slope parameter for the ϕK^+K^- component in 2D fit	< 0.001	0.001	< 0.001
Add slope parameter for the $K^+K^-K^+K^-$ component in 2D fit	< 0.001	< 0.001	< 0.001
Combined systematic uncertainty	0.012	0.015	0.005

- Total systematic uncertainties are **smaller** than statistical ones

$\chi_{c0,1,2}$ production in inclusive b-decays

- **First measurement** of $BR(b \to \chi_{c0}X)$ production in inclusive b-decays
- **Most precise** measurements of $BR(b \to \chi_{c1}X)$ and $BR(b \to \chi_{c2}X)$

$$\frac{\mathcal{B}(b \to \chi_{c0}X)}{\mathcal{B}(b \to \eta_c X)} = 0.615 \pm 0.095 \pm 0.047 \pm 0.149$$

$$\frac{\mathcal{B}(b \to \chi_{c1}X)}{\mathcal{B}(b \to \eta_c X)} = 0.562 \pm 0.119 \pm 0.047 \pm 0.131$$

$$\frac{\mathcal{B}(b \to \chi_{c2}X)}{\mathcal{B}(b \to \eta_c X)} = 0.234 \pm 0.038 \pm 0.015 \pm 0.057$$

$$\frac{\mathcal{B}(b \to \chi_{c1}X)}{\mathcal{B}(b \to \chi_{c0}X)} = 0.92 \pm 0.20 \pm 0.02 \pm 0.14$$

$$\frac{\mathcal{B}(b \to \chi_{c2}X)}{\mathcal{B}(b \to \chi_{c0}X)} = 0.38 \pm 0.07 \pm 0.01 \pm 0.05$$

Naïve expectation: $\chi_{c2}:\chi_{c1}:\chi_{c0} = 5:3:1$

$$\mathcal{B}(b \to \chi_{c0}X) = (3.02 \pm 0.47 \pm 0.23 \pm 0.94) \times 10^{-3}$$

$$\mathcal{B}(b \to \chi_{c1}X) = (2.76 \pm 0.59 \pm 0.23 \pm 0.89) \times 10^{-3}$$

$$\mathcal{B}(b \to \chi_{c2}X) = (1.15 \pm 0.20 \pm 0.07 \pm 0.36) \times 10^{-3}$$

Prediction **Beneke, Maltoni, Rothstein, PRD 59 (1999) 054003**

$$BR(b \to \chi_{c0}X) = (0.17 \pm 0.56) \times 10^{-3}$$

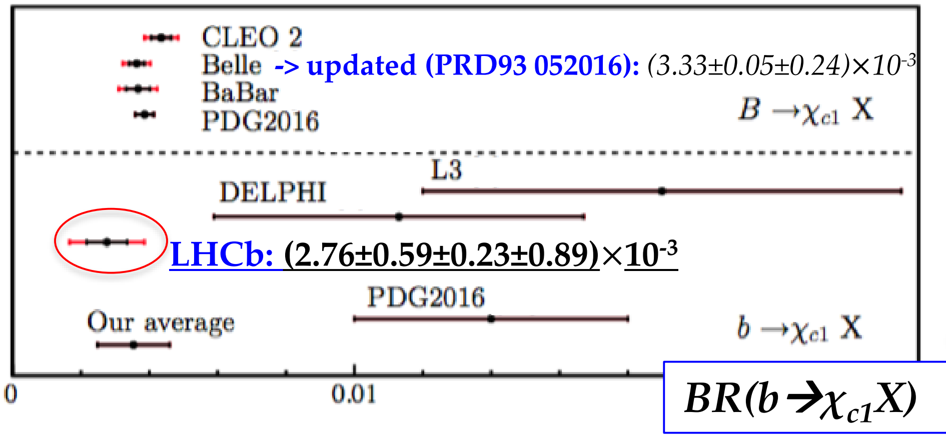
$$BR(b \to \chi_{c1}X) = (0.89 \pm 2.06) \times 10^{-3}$$

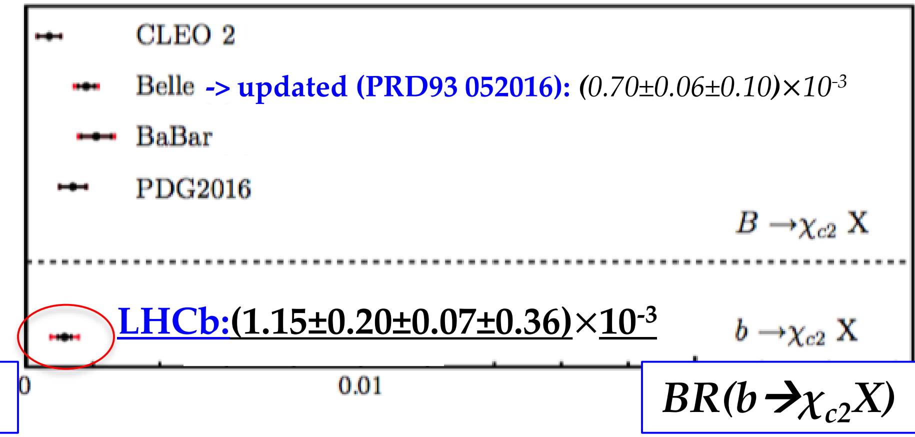
$$BR(b \to \chi_{c2}X) = (1.51 \pm 3.46) \times 10^{-3}$$

- **Results not described by NLO NRQCD prediction**
- **Negative short-distance factors for CS -> higher order calculations needed**

$\chi_{c0,1,2}$ production in inclusive b-decays

- **First measurement** of $BR(b\rightarrow\chi_{c0}X)$ production in inclusive b-decays
- **Most precise** measurements of $BR(b\rightarrow\chi_{c1}X)$ and $BR(b\rightarrow\chi_{c2}X)$





- Feed down contributions are not subtracted
- $BR(b\rightarrow\chi_{c1}X)$ and $BR(b\rightarrow\chi_{c2}X)$ are in agreement with measurements at B-factories (where only $B^{0,+}$ measons contribute)

$\eta_c(2S)$ production in inclusive b-decays

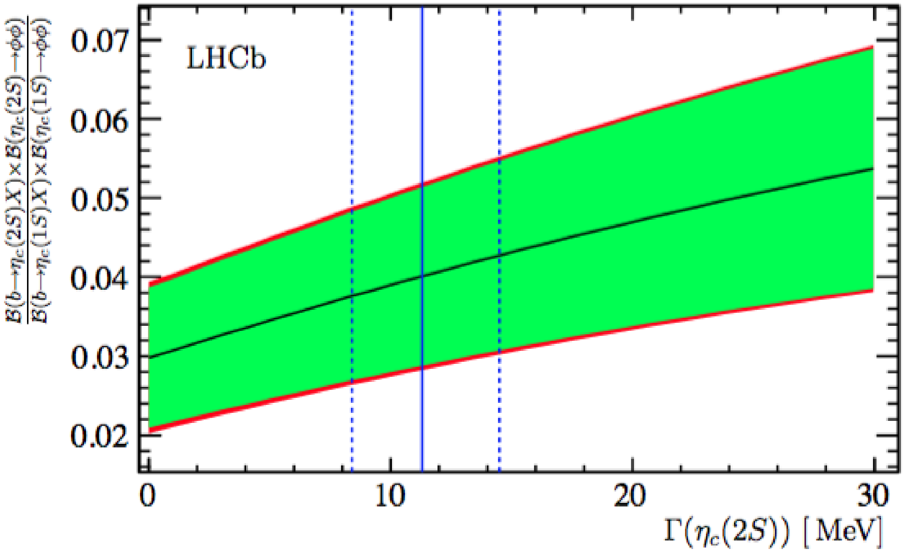
- **Double ratio of branching fractions**

$$\frac{\mathcal{B}(b \to \eta_c(2S)X) \times \mathcal{B}(\eta_c(2S) \to \phi\phi)}{\mathcal{B}(b \to \eta_c(1S)X) \times \mathcal{B}(\eta_c(1S) \to \phi\phi)} = 0.040 \pm 0.011 \pm 0.004$$

- **Product of branching fractions**

$$\mathcal{B}(b \to \eta_c(2S)X) \times \mathcal{B}(\eta_c(2S) \to \phi\phi) = (6.34 \pm 1.81 \pm 0.57 \pm 1.89) \times 10^{-7}$$

$\eta_c(2S)$ production as a function of assumed natural width:



- **First measurement of $\eta_c(2S)$** production in inclusive *b*-decays
- **First evidence of $\eta_c(2S)\to\phi\phi$ (3.7σ *significance)***

➜ **First step to measure $\eta_c(2S)$ prompt production**

Search for charmonium-like states in inclusive b-decays

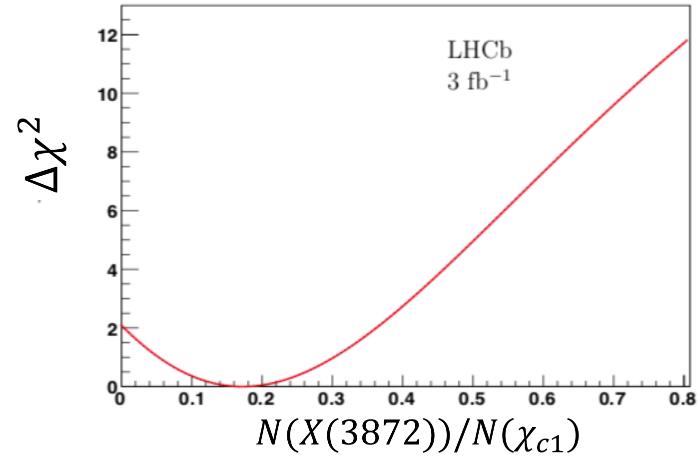
Limits with respect to states with similar quantum numbers:

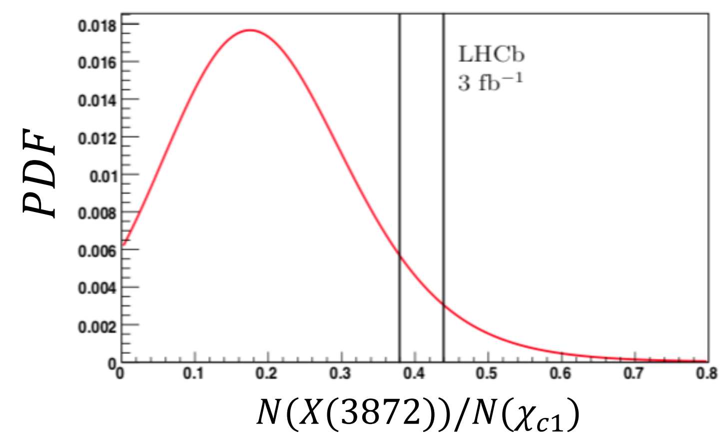
at 90 (95) % CL

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

$$\frac{BR(b \to X(3915)X) \times BR(X(3915) \to \phi\phi)}{BR(b \to \chi_{c0}X) \times BR(\chi_{c0} \to \phi\phi)} < 0.14\ (0.12)$$

$$\frac{BR(b \to \chi_{c2}(3930)X) \times BR(\chi_{c2}(3930) \to \phi\phi)}{BR(b \to \chi_{c2}X) \times BR(\chi_{c2} \to \phi\phi)} < 0.20\ (0.16)$$





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

- **First search of charmonium-like states in b-decays using their decays to $\phi\phi$**
- **Typical sensitivity for product of BRs is $O(10^{-7})$**

Phenomenological analysis of charmonium production

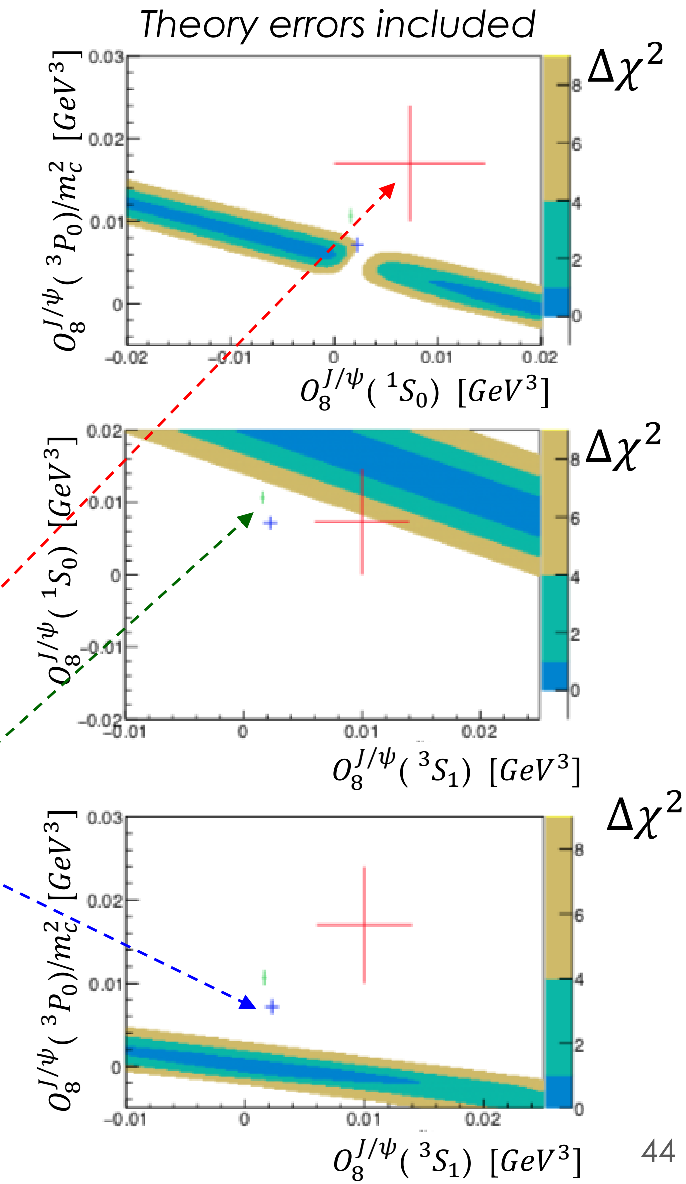
LAL-17-051 and updates

Simultaneous fits to J/ψ and η_c production

- **First** simultaneous study of **J/ψ** and **η_c b-decays production**

$$\frac{\mathcal{B}(b \to \eta_c(1S)^{direct} X)}{\mathcal{B}(b \to J/\psi^{direct} X)} = 0.691 \pm 0.090 \pm 0.024 \pm 0.103$$

- Data from **EPJC 75 (2015) 311** and **PDG**
- Relation between LDMEs from HQSS
- Branching fractions calculated in **Beneke, Maltoni, Rothstein, PRD 59 (1999) 054003**
- Fix CS LDME according to potential model $O_1^{J/\psi}({}^3S_1)$=1.16 GeV^3
- **Fit three LDMEs to two measurements**
- LDMEs compared to Shao, Ma, Chao et al. PRL 114 092005; Baranov. Lipatov arXiv:1904.00400; Butenschoen, Kniehl PRD84 051501
- Two independent measurements $\mathcal{B}(b \to J/\psi X)$ and $\mathcal{B}(b \to \eta_c X)/\mathcal{B}(b \to J/\psi X)$ (constraints) important
- **Theory calculations** should be revisited, higher order corrections maybe needed



Simultaneous fits to J/ψ and η_c production

- Compare determination of LDMEs **from hadroproduction and from b-decays**
- Short distance coefficients for prompt production provided by H.-S. Shao

$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \times \langle O^H(n)\rangle$$

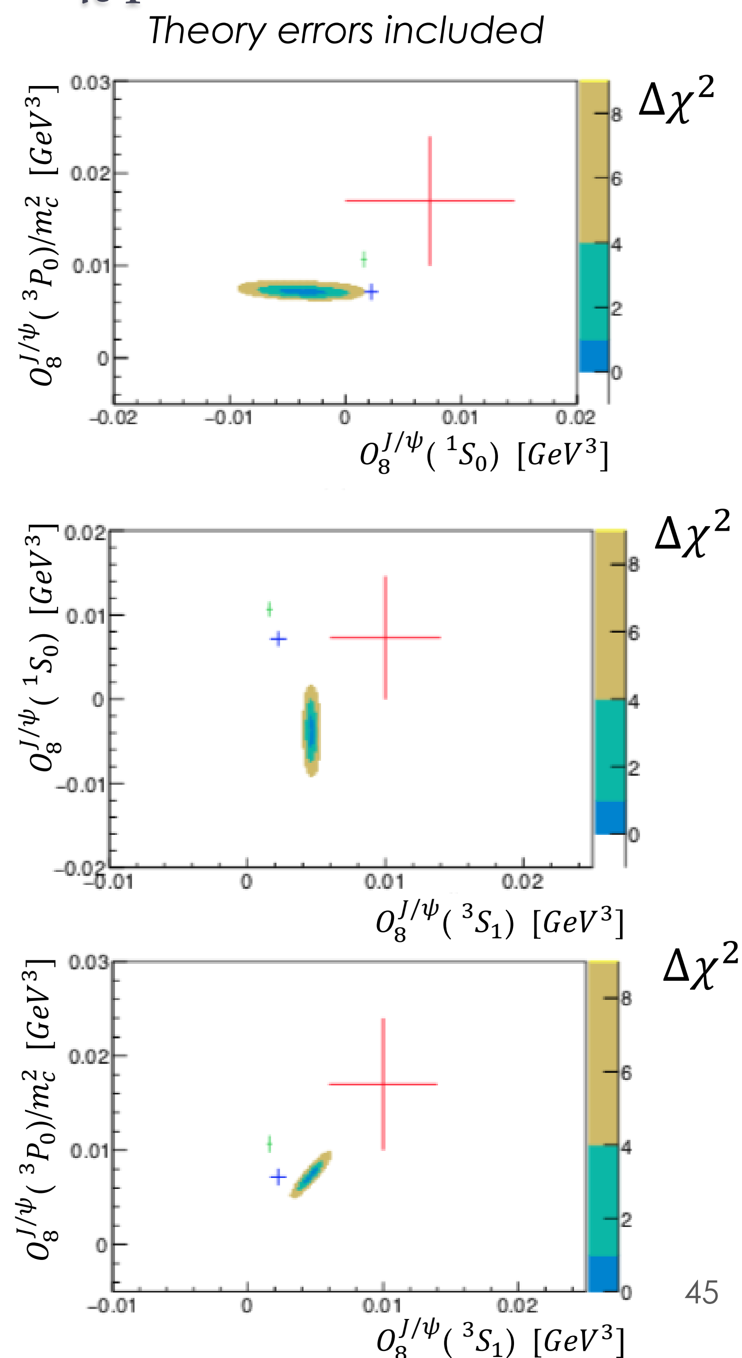
- Understanding of theoretical uncertainties crucial to make a comparison
- LDMEs compared to

Shao, Ma, Chao et al PRL 114 092005

Baranov. Lipatov arXiv:1904.00400

Butenschoen, Kniehl PRD84 051501

- **First simultaneous study of b-decays and prompt production**
- Alternatively, once hadroproduction and production in b-decays measured for charmonium states with linked LDMEs, the **factorization, universality and HQSS can be tested quantitatively**



$\chi_{c0,1,2}$ production in inclusive b-decays

Usachov, Kou, Barsuk, LAL-17-051

- From **Eur.Phys.J. C77 (2017) 609** and **Chin. Phys. C40 (2016) 100001:**

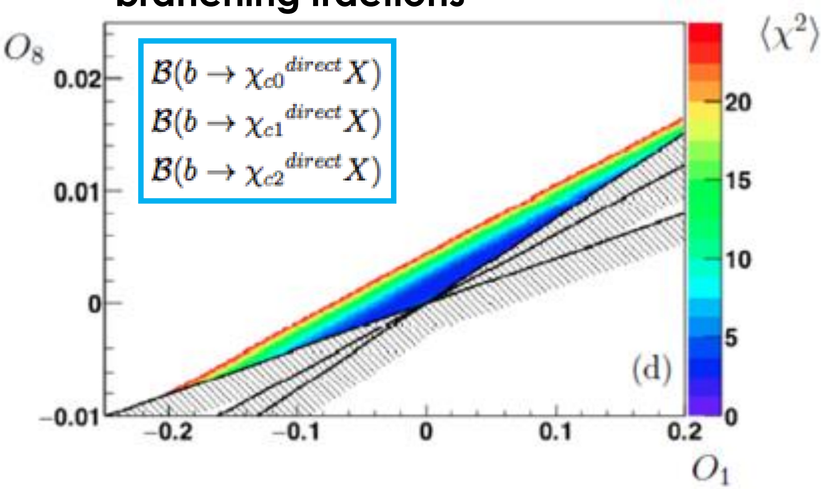
$$\mathcal{B}(b \to \chi_{c0}{}^{direct} X) = (2.74 \pm 0.47 \pm 0.23 \pm 0.94_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c1}{}^{direct} X) = (2.49 \pm 0.59 \pm 0.23 \pm 0.89_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c2}{}^{direct} X) = (0.89 \pm 0.20 \pm 0.07 \pm 0.36_{\mathcal{B}}) \times 10^{-3}$$

- Relation between LDMEs from HQSS:

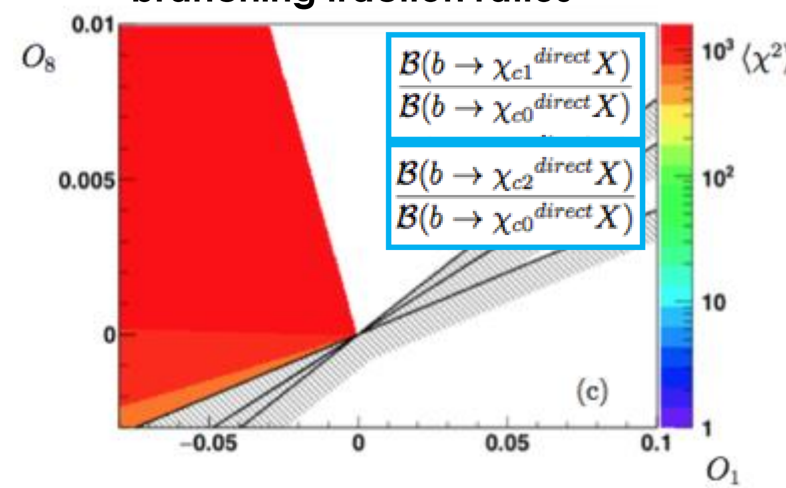
$$O_1 \equiv \langle O_1^{\chi_{c0}}(^3P_0)\rangle / m_c^2,$$
$$O_8 \equiv \langle O_8^{\chi_{c0}}(^3S_1)\rangle,$$
$$\langle O_1^{\chi_{cJ}}(^3P_J)\rangle / m_c^2 = (2J+1) O_1,$$
$$\langle O_8^{\chi_{cJ}}(^3S_1)\rangle = (2J+1) O_8.$$

- Branching fractions calculated in **Beneke, Maltoni, Rothstein, PRD 59 (1999) 054003**

Fit to three measurements of branching fractions



Fit to two measurements of branching fraction ratios



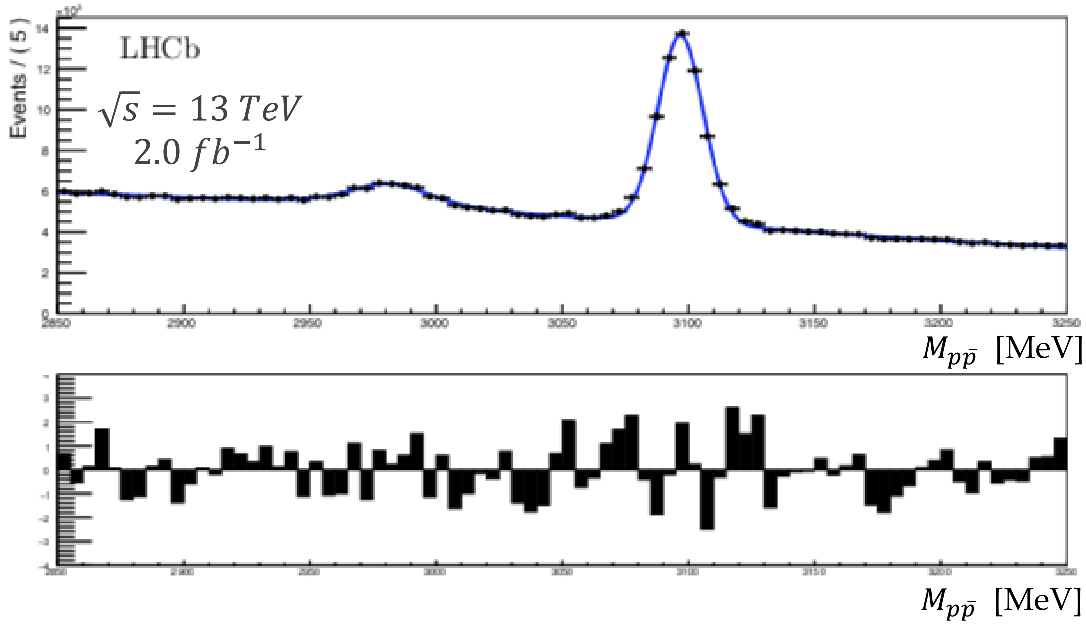
- Relative production is not described by theory
- Higher order calculations needed?

$\eta_c(1S)$ resonance parameters

EPJC 77 (2017) 609
LHCb-PAPER-2019-024, in collaboration wide review

Measurement of η_c mass using $\eta_c \to p\bar{p}$

Looser selection of $b \to \eta_c X$ decays than for production measurements



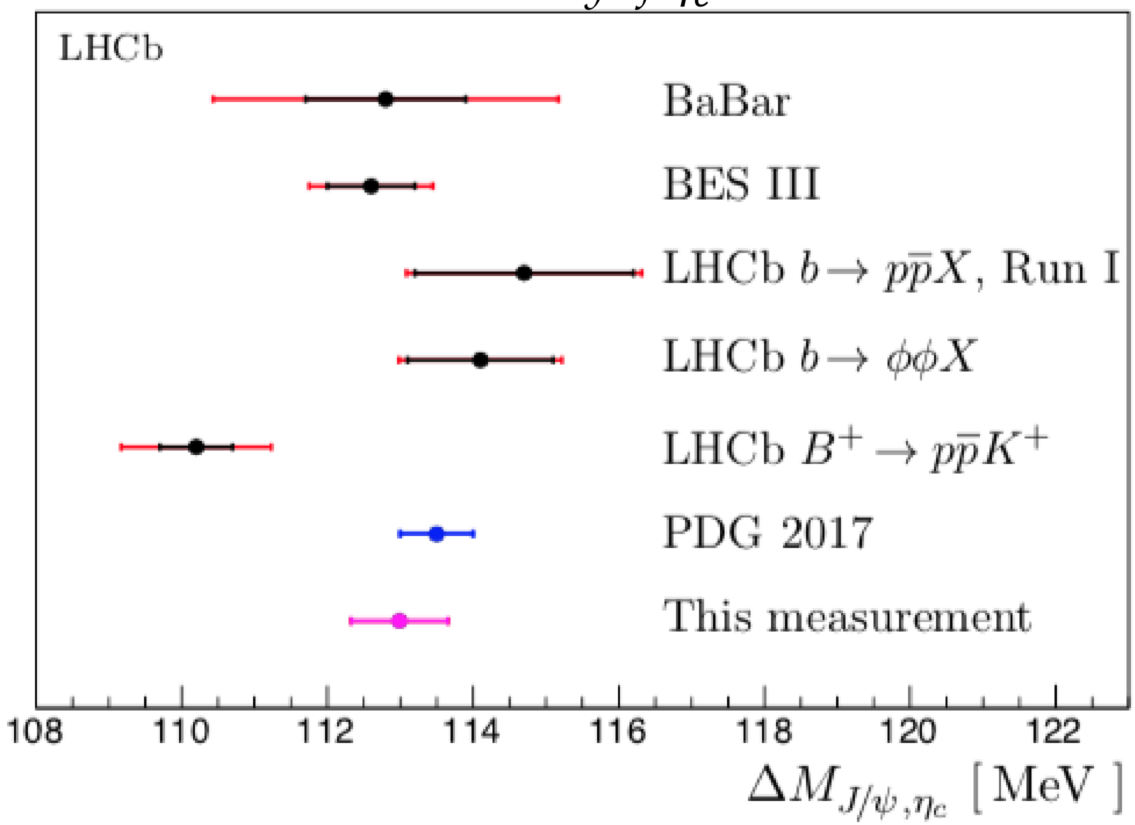
	$M_{J/\psi} - M_{\eta_c}$, MeV
Mean value	112.99
Stat. uncertainty	0.67
Mass resolution model	0.08
Variation of $\sigma_{\eta_c}/\sigma_{J/\psi}$	0.01
Variation of $\Gamma(\eta_c)$	0.04
Comb. bkg. description	0.03
Contribution from $J/\psi \to p\bar{p}\pi^0$	< 0.01
Momentum scale	0.05
Total systematic uncertainty	0.11
Total uncertainty	0.68

systematic uncertainties (Mass resolution model … Momentum scale)

- Precision limited by stat. uncertainty

Measurement of η_c mass using $\eta_c \to p\bar{p}$

Summary of η_c mass measurements

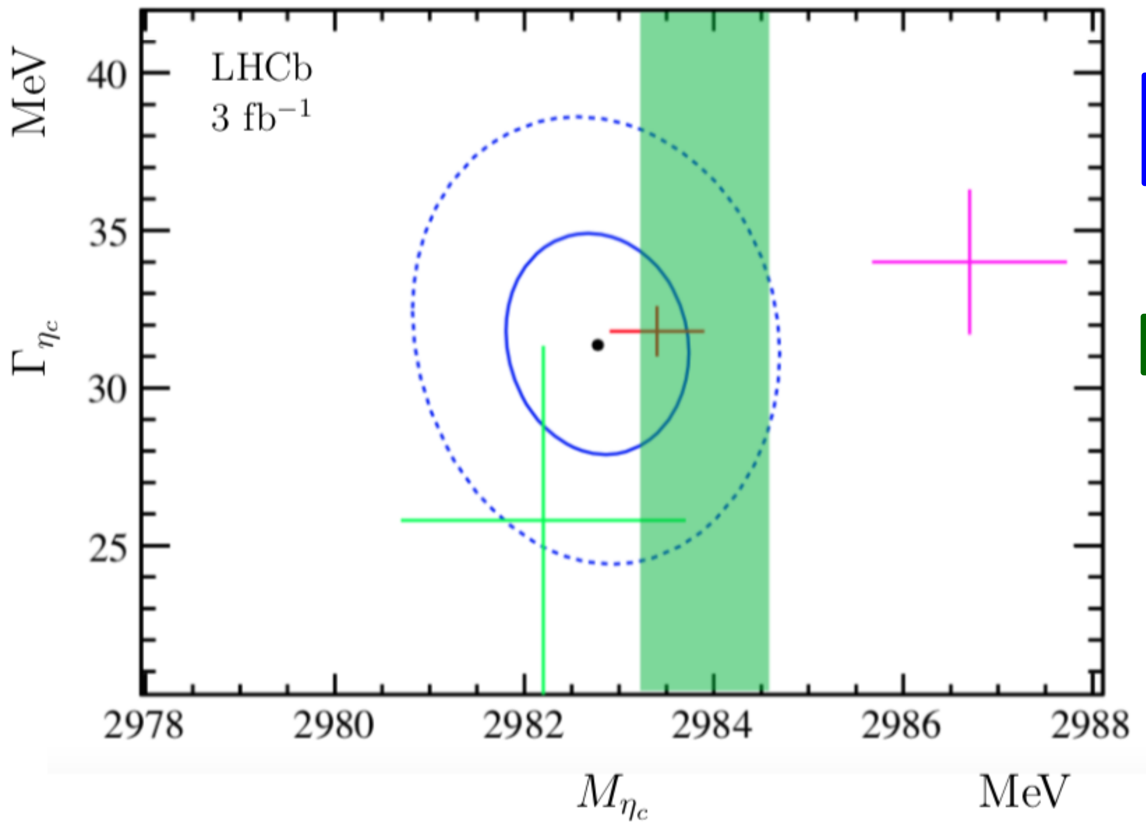


This measurement:	**112.99**	**± 0.67**	**± 0.11**
PDG average:	**113.5**	**± 0.5**	
BES III:	**112.6**	**± 0.6**	**± 0.6**
Run I result	**114.7**	**± 1.5**	**± 0.1**
New average:	***113.3***	**± 0.4**	

- The most precise measurement from a single experiment

Mass and natural width of η_c via decays to $p\overline{p}$ and ϕϕ

Summary of η_c mass and natural width measurements



PDG

$b \to (\eta_c \to \boldsymbol{\phi\phi})X$
EPJC 77, 609

$b \to (\eta_c \to \boldsymbol{p\overline{p}})X$
EPJC 75, 311
LHCb-ANA-2018-035

$B^+ \to (\eta_c \to \boldsymbol{p\overline{p}})K^+$
PLB 769, 305

- **General agreement between the measurements**
- **Mass precision of 0.4 MeV achieved**

Study of B_s^0 decays to ϕ mesons

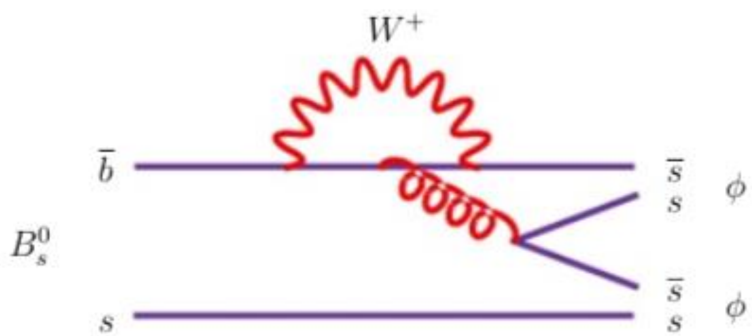
Data sample : Run I 2011-2012, $\int \mathcal{L}dt = 3.0\ fb^{-1}$

EPJC 77 (2017) 609

B_s^0 decays to ϕ mesons

- **Rare penguin processes**
- Look for New Physics contributions to loops

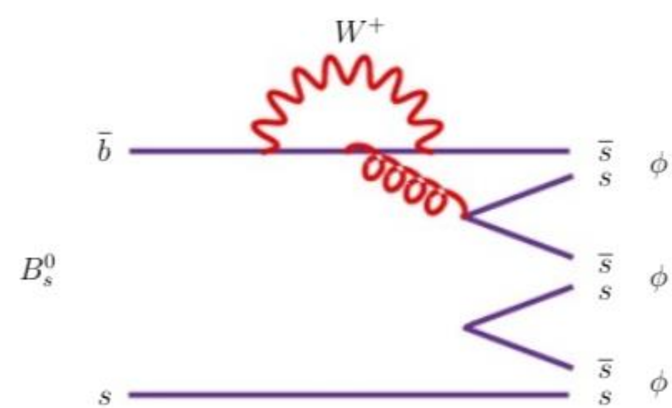
$B_s^0 \to \phi\phi$



Precision branching fraction and CP violation measurements

$B_s^0 \to \phi\phi\phi$

Can proceed via **three—body transition or via intermediate resonances** (e.g. $\boldsymbol{B_s^0 \to \eta_c \phi}$)



$$\mathcal{B}(B_s^0 \to \phi\phi) = (1.84 \pm 0.05 \pm 0.07 \pm 0.11_{f_s/f_d} \pm 0.12_{norm}) \times 10^{-5}$$

JHEP 10 (2015) 053 (LHCb)

Ratio of branching fractions for η_c decays to $\phi\phi$ and to $p\bar{p}$

- $\boldsymbol{BR(\eta_c \to \phi\phi)}$: PDG fit and PDG average values differ
- Tension between existing measurements
- Ratio $\frac{BR(\eta_c \to \phi\phi)}{BR(\eta_c \to p\bar{p})}$ extracted using $B_s^0 \to \phi\phi$ as a reference using LHCb measurement

$\Gamma(\phi\phi)/\Gamma_{total}$

VALUE (units 10^{-4})		EVTS
17.9± 2.0	**OUR FIT**	
28 ± 4	**OUR AVERAGE**	

$$\frac{BR(b \to \eta_c X) \times BR(\eta_c \to \phi\phi)}{\underbrace{BR(\bar{b} \to B_s^0)}_{\text{JHEP 04 (2013) 001 (LHCb)}} \times \underbrace{BR(B_s^0 \to \phi\phi)}_{\text{JHEP 10 (2015) 053 (LHCb)}}} = \overbrace{\frac{N(\eta_c \to \phi\phi)}{N(B_s^0 \to \phi\phi)}}^{\text{Data}} \overbrace{\frac{\epsilon(B_s^0)}{\epsilon(\eta_c)}}^{\text{MC}}$$

$$BR(b \to \eta_c X) = \underbrace{\frac{BR(b \to \eta_c X) \cdot BR(\eta_c \to p\bar{p})}{BR(b \to J/\psi X) \cdot BR(J/\psi \to p\bar{p})}}_{\text{EPJC 75 (2015) 311 (LHCb)}} \times \underbrace{[BR(b \to J/\psi X) \cdot BR(J/\psi \to p\bar{p})] \times [BR(\eta_c \to p\bar{p})]^{-1}}_{\text{PDG}}$$

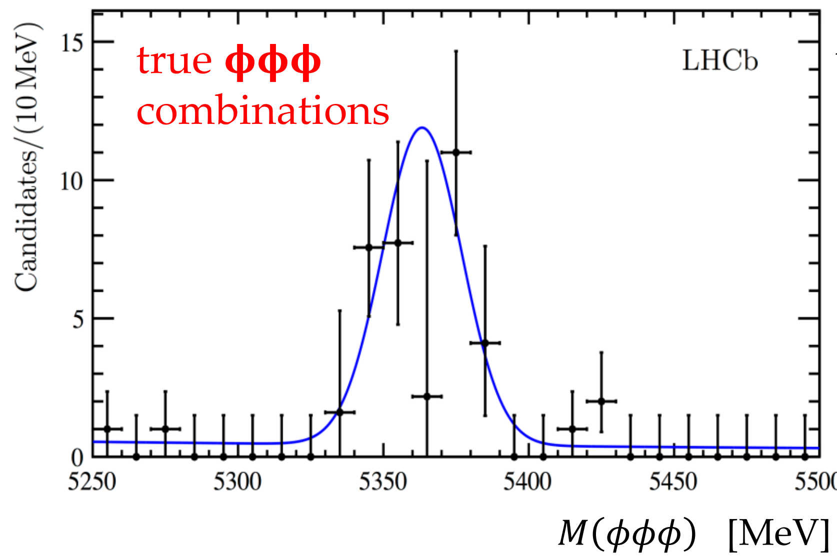
$$\boxed{\frac{BR(\eta_c \to \phi\phi)}{BR(\eta_c \to p\bar{p})} = 1.79 \pm 0.14 \pm 0.09 \pm 0.31_{BR}}$$

value extracted using PDG fit: ***1.17 ± 0.18***

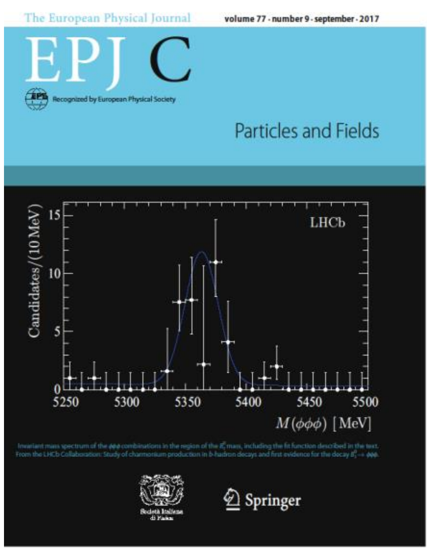
- This result disfavours the measurement performed via $\gamma\gamma \to \eta_c$

First evidence of $B_s^0 \to \phi\phi\phi$

- **3D fit** of $M(K^+K^-)_1)M(K^+K^-)_2 \times M(K^+K^-)_3$ in bins of $M(KKKKKK)$
  to select true $\phi\phi\phi$ combinations
  similarly to 2D fit in charmonium production analysis via decays to $\phi\phi$



$B_s^0 \to \phi\phi\phi$ signal:
4.9σ significance



$B_s^0 \to \phi\phi$ used as a reference:

$$\frac{BR(B_s^0 \to \phi\phi\phi)}{BR(B_s^0 \to \phi\phi)} = 0.117 \pm 0.030 \pm 0.015$$

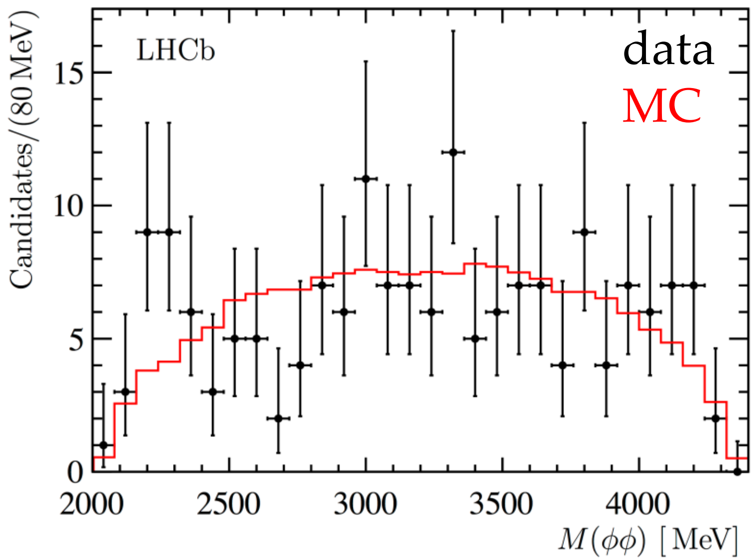
using $BR(B_s^0 \to \phi\phi)$ from *JHEP 10 (2015) 053* :

$$\boldsymbol{BR\left(B_s^0 \to \phi\phi\phi\right) = (2.15 \pm 0.54 \pm 0.28 \pm 0.21_{BR}) \times 10^{-6}}$$

- First evidence of $B_s^0 \to \phi\phi\phi$

First evidence of $B_s^0 \to \phi\phi\phi$

- Search for **resonant contributions**

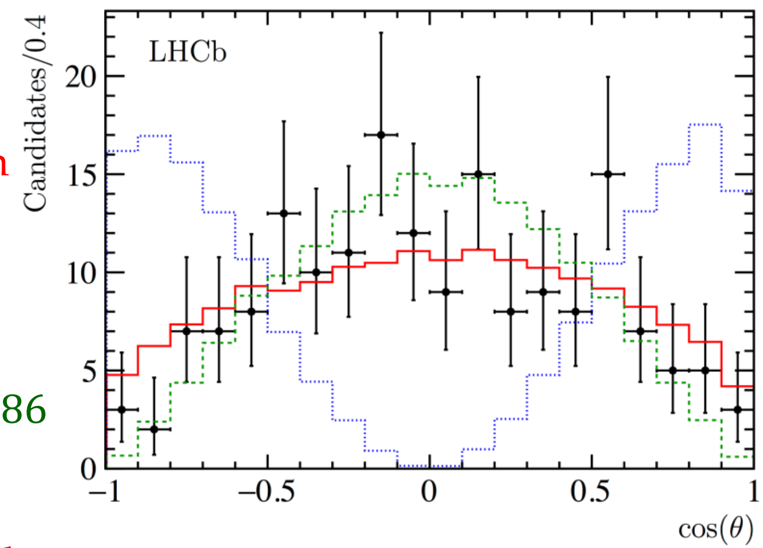


- *Symmetrized Dalitz plots not conclusive*

$$\boldsymbol{BR(B_s^0 \to \phi\phi\phi)}$$
$$= \mathbf{(2.15 \pm 0.54 \pm 0.28 \pm 0.21_{BR}) \times 10^{-6}}$$

- Study **of $\boldsymbol{\phi}$ polarization**

$\boldsymbol{\theta}$: angle of ϕ in the B_s^0 rest frame with respect to B_s^0 boost



- **No significant resonant contributions observed**
- **Data inconsistent with longitudinal $\boldsymbol{\phi}$ polarization**

Main results

Physics measurements:

- First measurement of **prompt** $\boldsymbol{\eta_c(1S)}$ production at $\sqrt{s} = 13\ TeV$
  - Validation of Run I results
  - More precise than theory prediction ⇒ stronger constraint on theory
- First or most precise measurements of production of $\boldsymbol{\eta_c(1S)}$**,** $\boldsymbol{\chi_{c0,1,2}}$ **and** $\boldsymbol{\eta_c(2S)}$ **in** $\boldsymbol{b}$**-hadron inclusive decays**
  - First stringent constaint on theory using production of all $\chi_{c0,1,2}$ states
  - First step to measure $\eta_c(2S)$ prompt production
- Search for charmonium-like states in b-hadron inclusive decays
  - Important to understand their nature
- Measurement of $\boldsymbol{\eta_c(1S)}$ **resonance** parameters
  - Important to solve tensions between measurements
- Measurement of branching fraction of $\boldsymbol{\eta_c(1S) \to \phi\phi}$ decay
  - Important input to resolve PDG tension
- First evidence for $\boldsymbol{B_s^0 \to \phi\phi\phi}$ decay and its resonance structure

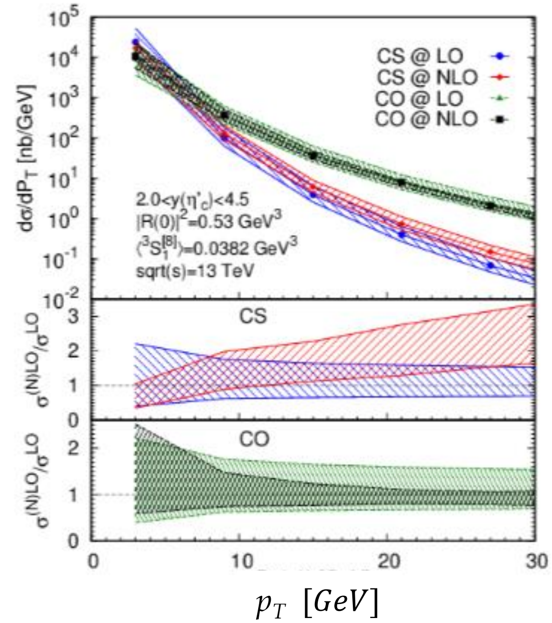
Main results

Phenomenological studies:

- First simultaneous study of η_c and J/ψ, prompt and *b*-decay production
  - Strong constraint on theory
  - New consistency checks of NRQCD
  - Reasonable description of data points

- First simultaneous study of $\chi_{c0,1,2}$ production in *b*-decays
  - NRQCD fails to describe relative $\chi_{c0,1,2}$ production

Experimental prospects



At LHCb

- **Polarisation of $\psi(2S)$**
- **Prompt $\eta_c(2S)$** production with 2018 data
- Investigate other hadronic decays with Run II (and Run I) data samples
  - $K_s^0 K\pi$
  - $\Lambda\bar{\Lambda}$
  - $\Lambda(1520)\bar{\Lambda}$, $\Lambda(1520)\bar{\Lambda}(1520)$
- h_c study using $p\bar{p}\pi\pi$
- **Prompt η_b production**
- η_c production in CEP, heavy ion collisions
- B_c and hadron exotics studies involving η_c reconstruction

+ *Lower-p_T and higher-p_T production studies*

At BES III and future super tau-charm factories

- Improve precision of **BR** for $\eta_c(1S) \to \phi\phi$ and $\eta_c(1S) \to p\bar{p}$ and their ratio
- **BR** measurements for $\eta_c(2S)$ decays to hadrons

At Belle II

- Update on $BR(B \to c\bar{c}\, X)$ and $BR(B^+ \to c\bar{c}\, K^+)$
- Update charmonium production measurements

謝謝　！

$p\bar{p}$: data sample and event selection

Data sample : Run II 2015-2016 2.0 fb^{-1} integrated luminosity

-> *momentum scale calibration is applied*

	Variable	Hlt1	Hlt2	Stripping	Offline selection
Trigger		L0Hadron	Hlt1DiProton	–	L0Hadron_TOS Hlt1DiProton_TOS Hlt2DiProton_TOS
Protons	p_T, GeV/c	> 1.9	> 1.9	> 1.95	> 2.0
	p, GeV/c	> 12.5		> 10.0	> 12.5
	p_T/p	> 0.0366			> 0.0366
	Track χ^2/NDF	< 2.5	< 3.0	< 4.0	< 2.5
	Ghost probability	< 0.2			< 0.2
	$\Delta \log \mathcal{L}^{p-\pi}$	–	> 20	> 20	> 20
	$\Delta \log \mathcal{L}^{p-K}$	–	> 10	> 15	> 15
$p\bar{p}$	p_T, GeV/c	> 6.5	> 6.5	> 6.0	> 6.5
	Vertex χ^2/ndf	< 4	< 9		< 4.0
	Vertex DOCA, mm	< 0.1			< 0.1
	Mass, GeV/c^2	$2.8 - 3.3$	$2.8 - 4.0$	$2.8 - 4.0$	$2.85 - 3.25$
	SPD multiplicity	< 300	< 300	< 300	< 300

Selection is essentially performed at the trigger level

$\phi\phi$: data sample and event selection

Data sample : Run I 2011-2012 3.0 fb^{-1} integrated luminosity

-> *momentum scale calibration is applied*

	Variable	Denotion	Requirement
Kaons	Track quality	χ^2/ndf	< 3
	Impact parameter to primary vertex	χ^2_{IP}	> 4
	Transverse momentum	p_{T}, GeV	> 0.5
	Identification	ProbNNk	> 0.1
ϕ	Vertex quality	χ^2	< 25
	Invariant mass	$\lvert M_{K^+K^-} - M_\phi \rvert$, MeV	< 12
$\phi\phi$	Vertex quality	χ^2/ndf	< 9
	Distance between the decay vertex and the primary vertex	χ^2	> 100

Selection is essentially performed at the trigger and stripping level

Separation technique

From PDG:

$$\mathcal{B}_{J/\psi\to p\bar{p}} = (2.120 \pm 0.029) \times 10^{-3}$$
$$\mathcal{B}_{\eta_c\to p\bar{p}} = (1.50 \pm 0.16) \times 10^{-3}$$
$$\mathcal{B}_{b\to J/\psi X} = (1.16 \pm 0.1)\%$$

yield in prompt-enriched sample:
yield in b-hadron-enriched sample:

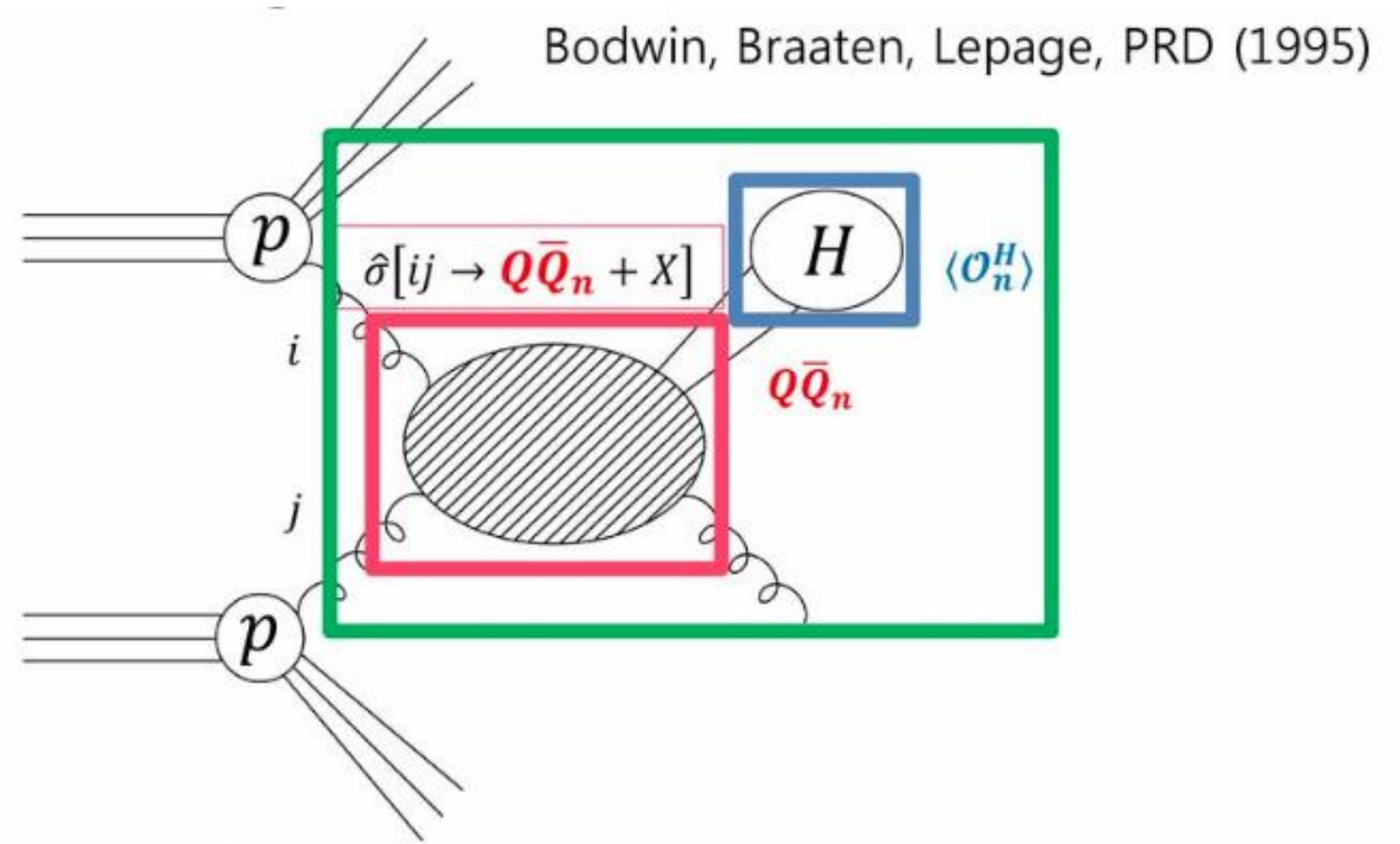
$$\begin{cases} n^p_{\eta_c} = \epsilon^{P\to P} \boldsymbol{N^P_{\eta_c}} + \epsilon^{b\to P} \boldsymbol{N^b_{\eta_c}} \\ n^b_{\eta_c} = \epsilon^{b\to b} \boldsymbol{N^b_{\eta_c}} + \epsilon^{P\to b} \boldsymbol{N^P_{\eta_c}}, \end{cases}$$

from fit

from MC

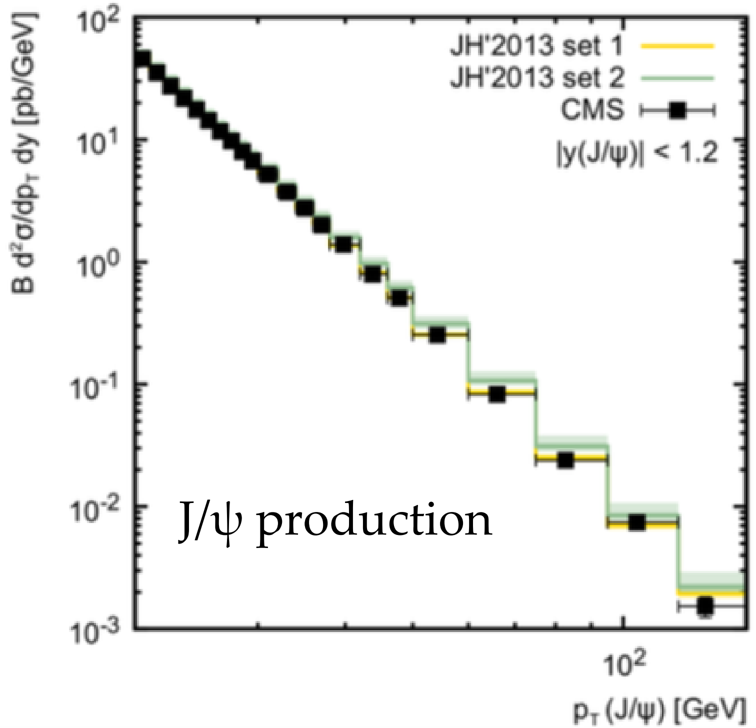
Extracted from DATA

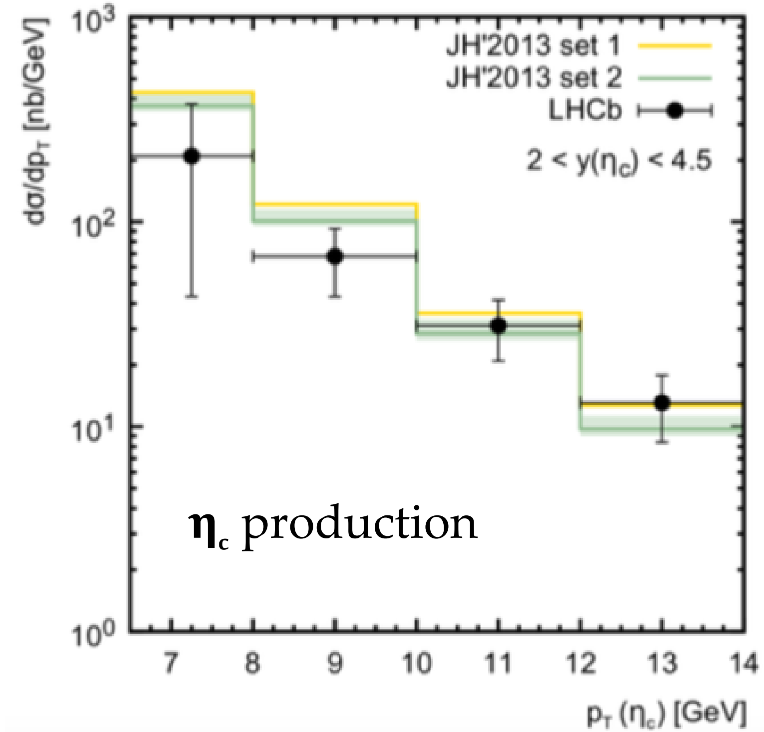
Factorization



η_c hadroproduction: k_T-factorization

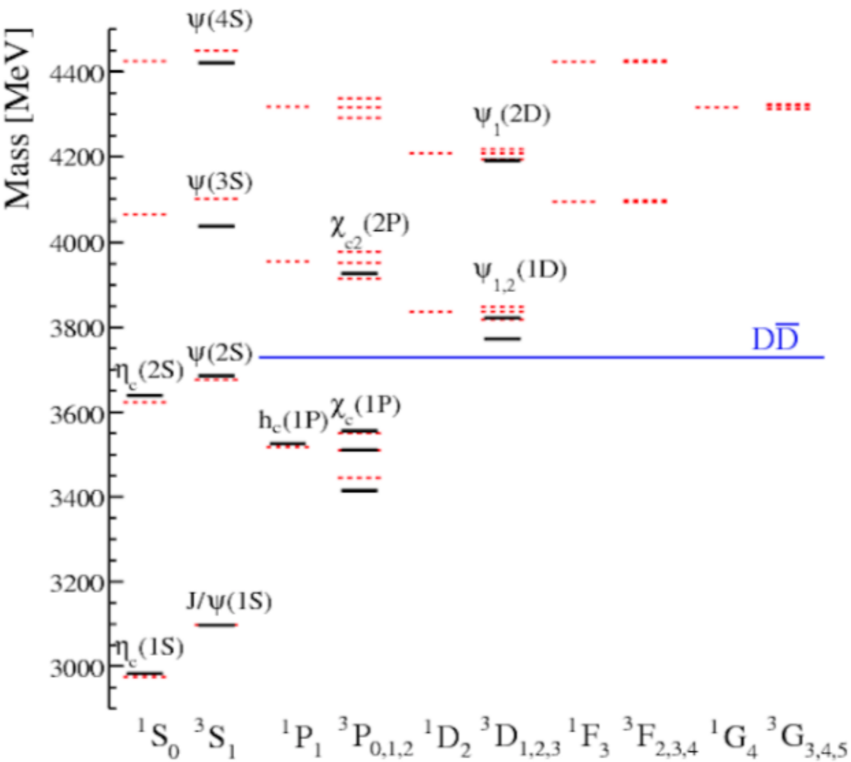
S. P. Baranov, A. V. Lipatov arXiv:1904.00400

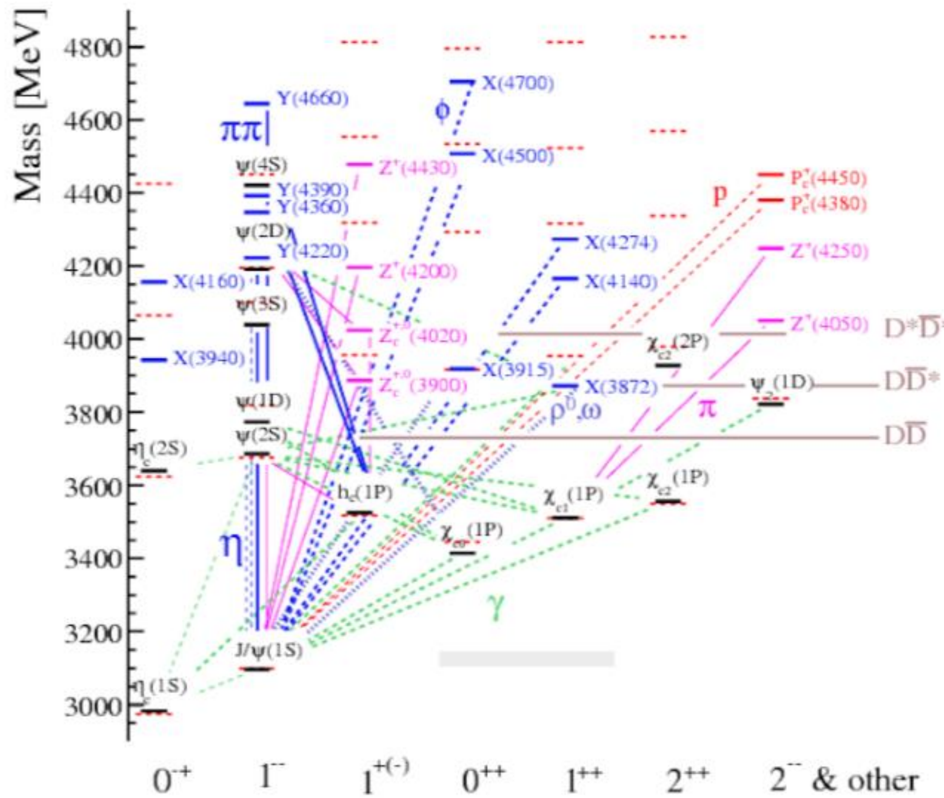




- Transverse momentum dependent distributions of gluons
- LO accuracy
- Good description of data points
- Global fit of all hadroproduction observables

S. P. Baranov, A. V. Lipatov arXiv:1906.07182


Mass [MeV]
4400
4200
4000
3800
3600
3400
3200
3000
ψ(4S)
ψ(3S)
ψ(2S)
J/ψ(1S)
η_c(2S)
η_c(1S)
h_c(1P)
χ_c(1P)
χ_c2(2P)
ψ_1(2D)
ψ_1,2(1D)
DD̄
¹S₀ ³S₁ ¹P₁ ³P₀,₁,₂ ¹D₂ ³D₁,₂,₃ ¹F₃ ³F₂,₃,₄ ¹G₄ ³G₃,₄,₅


Mass [MeV]
4800
4600
4400
4200
4000
3800
3600
3400
3200
3000
Y(4660)
ππ
ψ(4S)
Y(4390)
Y(4360)
ψ(2D)
Y(4220)
X(4160)
ψ(3S)
X(3940)
ψ(1D)
ψ(2S)
η_c(2S)
η
J/ψ(1S)
η_c(1S)
Z⁺(4430)
Z⁺(4200)
Z_c^{+,0}(4020)
Z_c^{+,0}(3900)
h_c(1P)
X(4700)
ϕ
X(4500)
X(3915)
χ_c0(1P)
X(4274)
X(4140)
X(3872)
ρ⁰,ω
χ_c1(1P)
χ_c2(2P)
χ_c2(1P)
γ
p
P_c⁺(4450)
P_c⁺(4380)
Z⁺(4250)
Z⁺(4050)
ψ_2(1D)
π
D*D̄*
DD̄*
DD̄
0⁻⁺ 1⁻⁻ 1⁺⁽⁻⁾ 0⁺⁺ 1⁺⁺ 2⁺⁺ 2⁻⁻ & other

Charmonia decay channels for production measurements at LHCb

	$\mu\mu$ (ll)	$J/\psi\ \gamma$	$p\bar{p}$	$\phi\phi$	baryons
$\eta_c(1S)$	forbidden	-	~ 0.15 %	~ 0.2 %	~ 0.1 %
$J/\psi(1S)$	~ 6 %	-	~ 0.2 %	forbidden	~ 0.1 %
$\chi_{c0}(1P)$	forbidden	~ 1.3 %	~ 0.02 %	~ 0.08 %	~ 0.04 %
$h_c(1P)$	forbidden	forbidden	?	forbidden	~ 0.01 %
$\chi_{c1}(1P)$	forbidden	34 %	~ 0.01 %	~ 0.04 %	~ 0.01 %
$\chi_{c2}(1P)$	forbidden	19 %	~ 0.1 %	~ 0.01 %	~ 0.01 %
$\eta_c(2S)$	forbidden	-	~ 0.01 %	?	?
$\psi(2S)$	~ 1 %	-	~ 0.03 %	forbidden	~ 0.02 %

seen in prompt production

seen in b-decays, promising channels

- Decays to hadrons (can) give access to $\eta_c(1S)$, $\chi_{c0}(1P)$, $\eta_c(2S)$ and $h_c(1P)$ (?), whose production can't be measured using $\mu\mu$ or $J/\psi\gamma$

$\eta_c(1S)$ branching fractions

- Indirect determination:

Eur.Phys.J. C77 (2017) 609

from known B^0_s and η_c yields Λ^0_b fragmentation fraction $f_{\Lambda^0_b}$ momentum dependence and

$$\mathcal{B}(B_s^0 \to \phi\phi) = (1.84 \pm 0.05 \pm 0.07 \pm 0.11_{f_s/f_d} \pm 0.12_{\text{norm}}) \times 10^{-5}$$
$$\mathcal{B}(b \to J/\psi X) = (1.16 \pm 0.10)\%$$
$$\frac{\mathcal{B}(b \to \eta_c(1S)X) \times \mathcal{B}(\eta_c(1S) \to p\overline{p})}{\mathcal{B}(b \to J/\psi X) \times \mathcal{B}(J/\psi \to p\overline{p})} = 0.302 \pm 0.042$$
$$\mathcal{B}(J/\psi \to p\overline{p}) = (2.120 \pm 0.029) \times 10^{-3}$$
$$f_s/f_d = 0.259 \pm 0.015$$

estimated branching fractions ratio

$$\frac{\mathcal{B}(\eta_c(1S) \to \phi\phi)}{\mathcal{B}(\eta_c(1S) \to p\overline{p})} = 1.79 \pm 0.14 \pm 0.09 \pm 0.10_{f_s/f_d} \pm 0.03_{f_{\Lambda_b^0}} \pm 0.29_{\mathcal{B}}$$

significantly larger than the value determined from PDG:

$$\frac{\mathcal{B}(\eta_c(1S) \to \phi\phi)}{\mathcal{B}(\eta_c(1S) \to p\bar{p})} = 1.17 \pm 0.18$$

Observation of $\eta_c(2S) \to p\bar{p}$ and search for $X(3872) \to p\bar{p}$

PLB 769, 305

- Only few decay modes of $\eta_c(2S)$ were observed
- $BR(\eta_c(2S) \to p\bar{p})$ – important knowledge for **further prompt production** studies

J.-P. Lansberg, H.-S. Shao, H.-F. Zhang arXiv:1711.00265

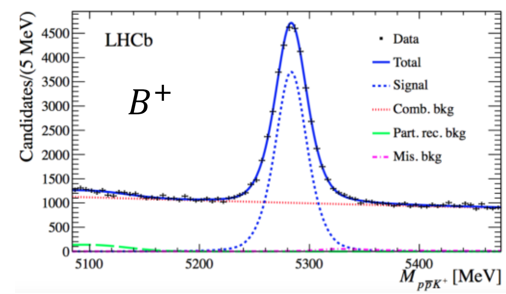
➞ only upper limit on $\boldsymbol{BR(\psi(2S) \to \eta_c(2S)\gamma) \times BR(\eta_c(2S) \to p\bar{p})}$ by BESIII

- Spectroscopy studies for $\eta_c(1S)$

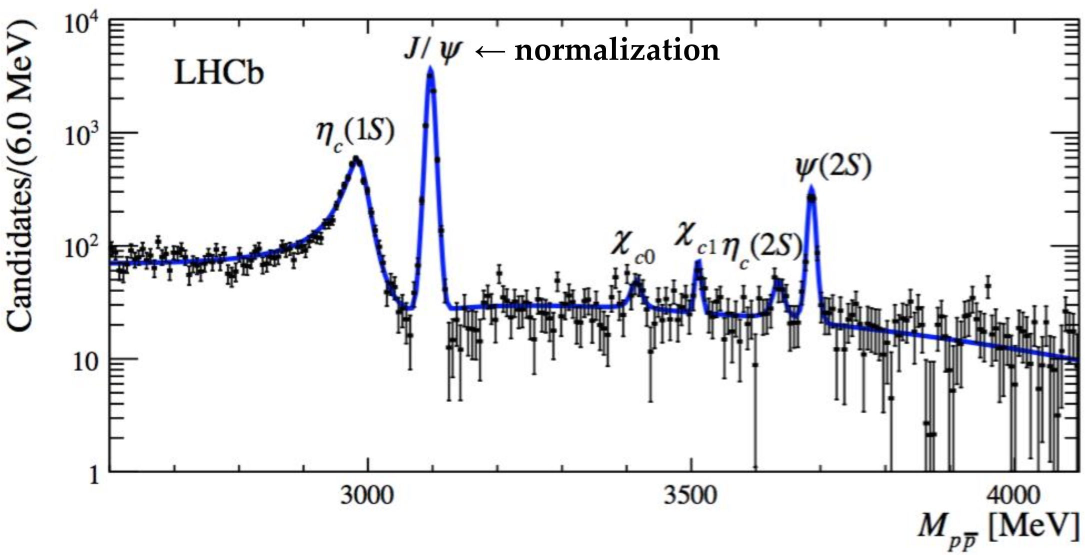
➞ tensions in mass and width measurements performed using different $\eta_c(1S)$ production processes

➞ *complications in line shape when using* $\boldsymbol{\eta_c(1S)\gamma}$ *radiative decays*

- Spectroscopy studies for $\eta_c(2S)$: lack of measurements
- Search for $X(3872) \to p\bar{p}$ and $\psi(3770) \to p\bar{p}$
  - $\boldsymbol{B^+ \to p\bar{p}K^+}$: clean environment to study $(c\bar{c}) \to p\bar{p}$

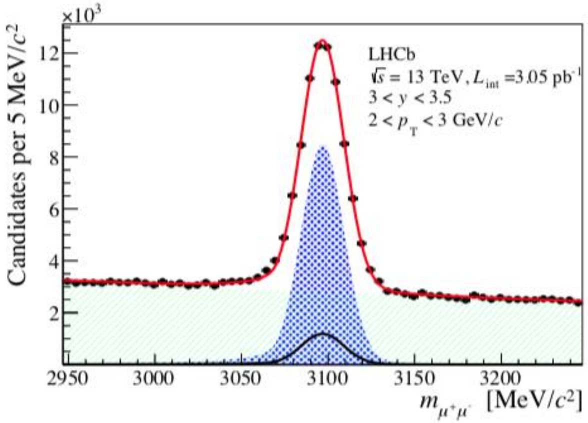


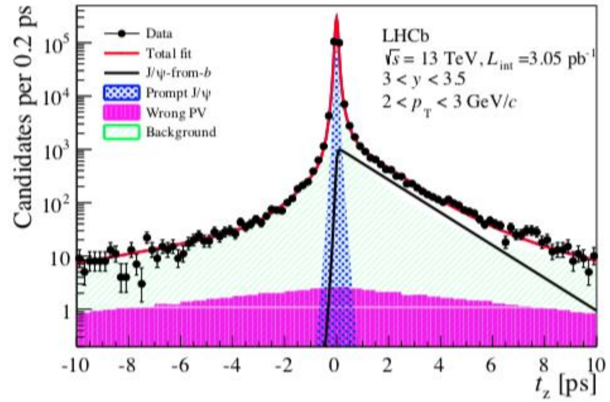
- **Background subtracted $\boldsymbol{M(p\bar{p})}$ distribution:**



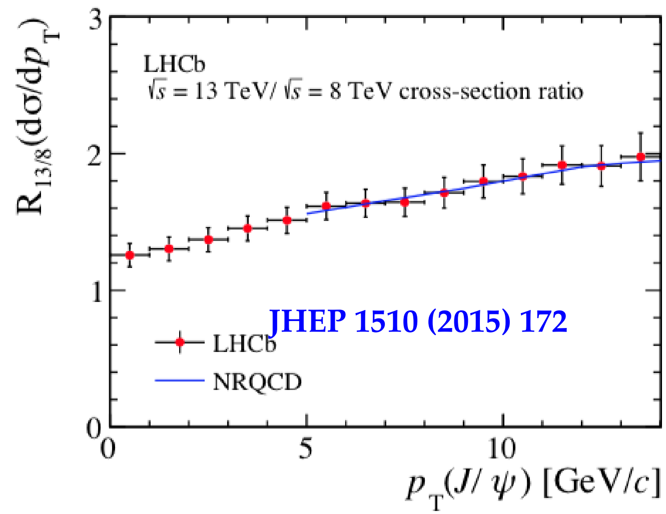
State	Signal Yield
$\eta_c(1S)$+non res.	11246 ± 119
J/ψ	6721 ± 93
χ_{c0}	84 ± 22
χ_{c1}	95 ± 16
$\eta_c(2S)$	106 ± 22
$\psi(2S)$	588 ± 30
$\psi(3770)$	-6 ± 9
$X(3872)$	-14 ± 8

J/ψ hadroproduction at LHCb using J/ψ → $\mu\mu$





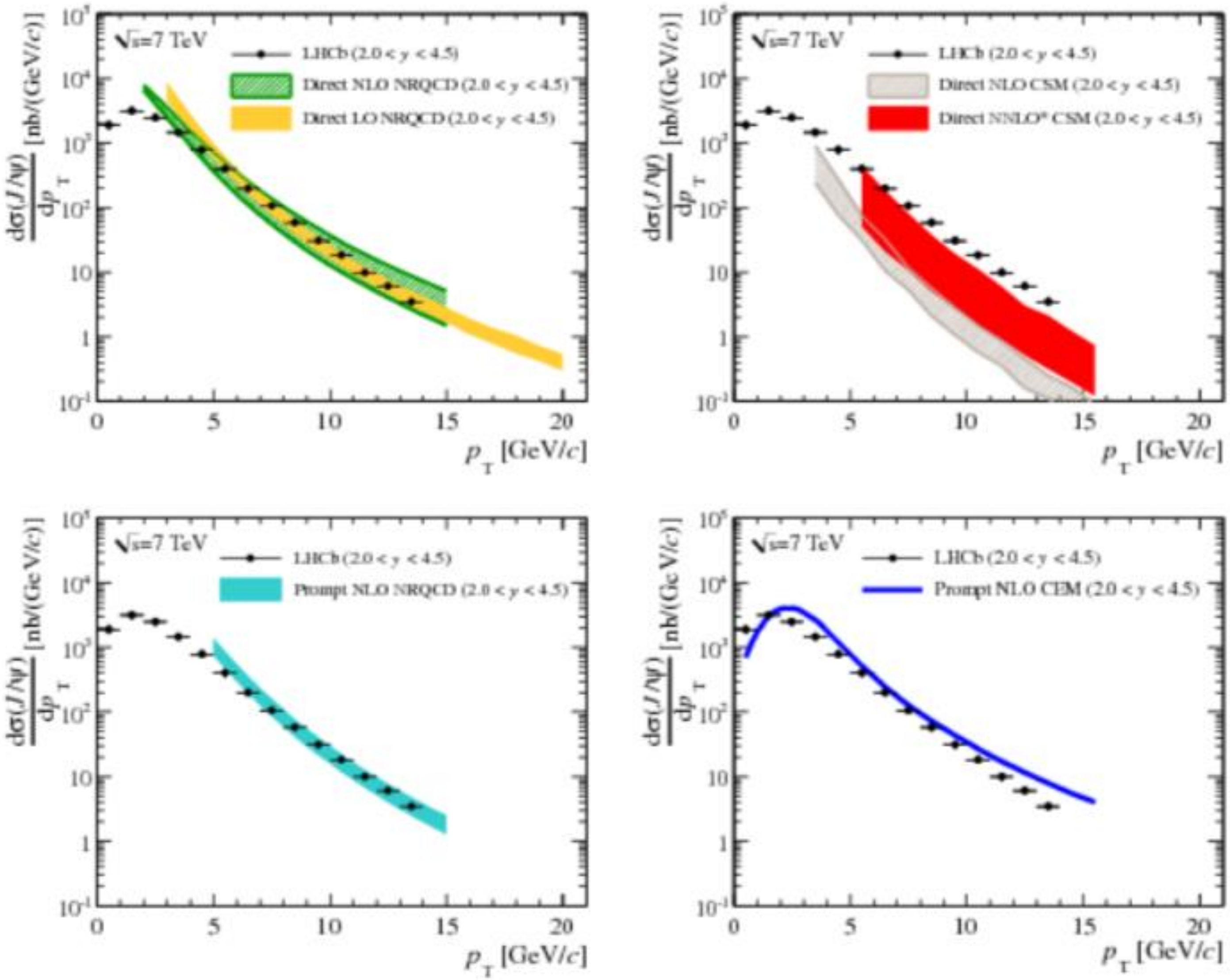
- clean signal from **J/ψ → $\mu\mu$**
- separate prompt production and production b-decays by fitting pseudo-proper lifetime



Ratio of 13 TeV/ 8 TeV production:

- **Many systematic uncertainties cancelled**
- **Ultimane theory precision**

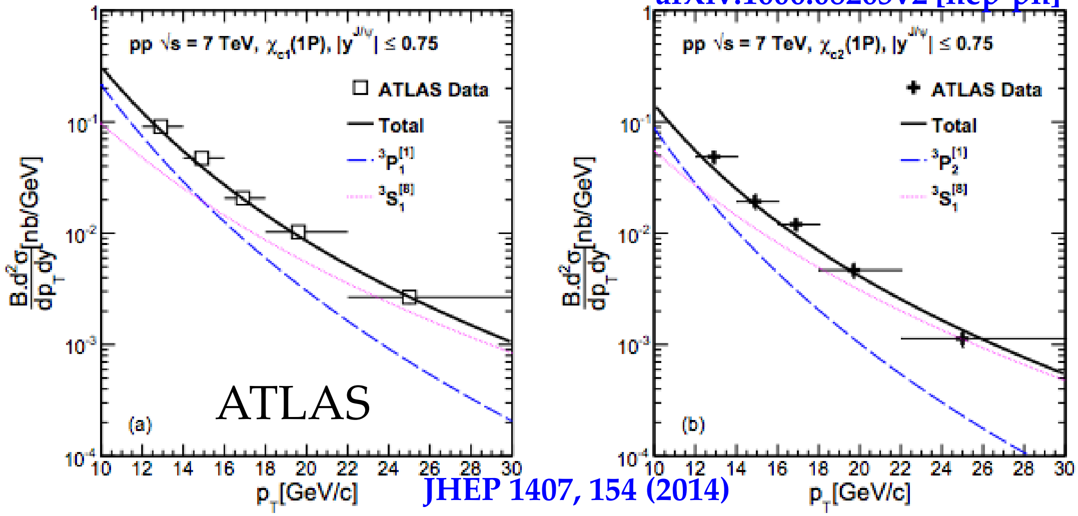
J/ψ prompt production compared to theory



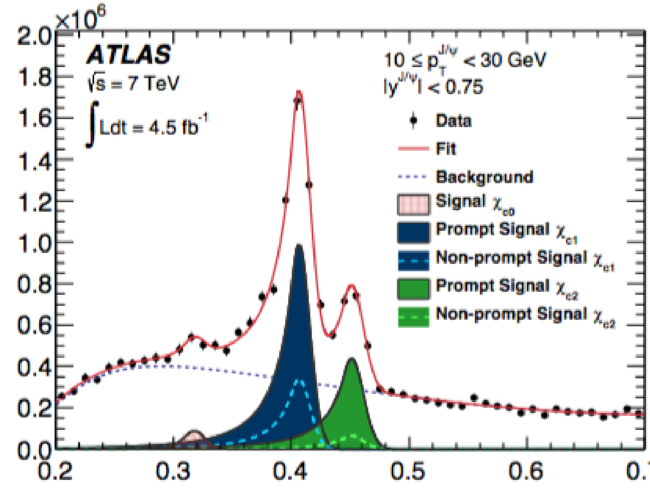
$\chi_{c1,2}$ prompt production using $\chi_{c1,2} \rightarrow J/\psi\ \gamma$

NRQCD fit for absolute production:

arXiv:1606.08265v2 [hep-ph]

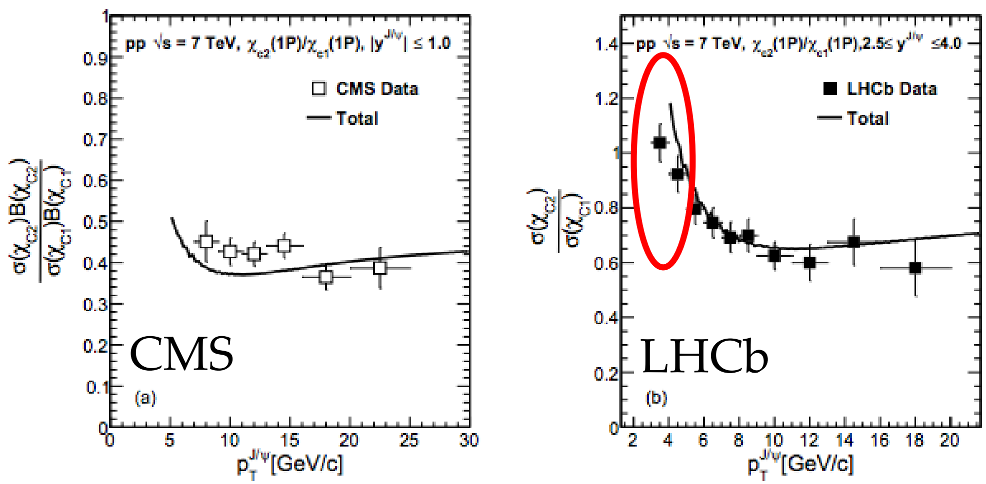


JHEP 1407, 154 (2014)



JHEP 1407, 154 (2014)

More precise when looking for ratio:

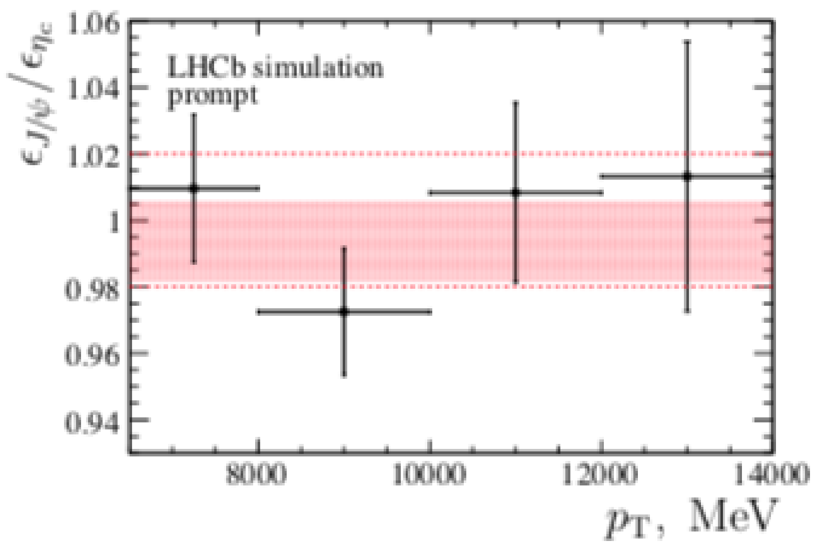


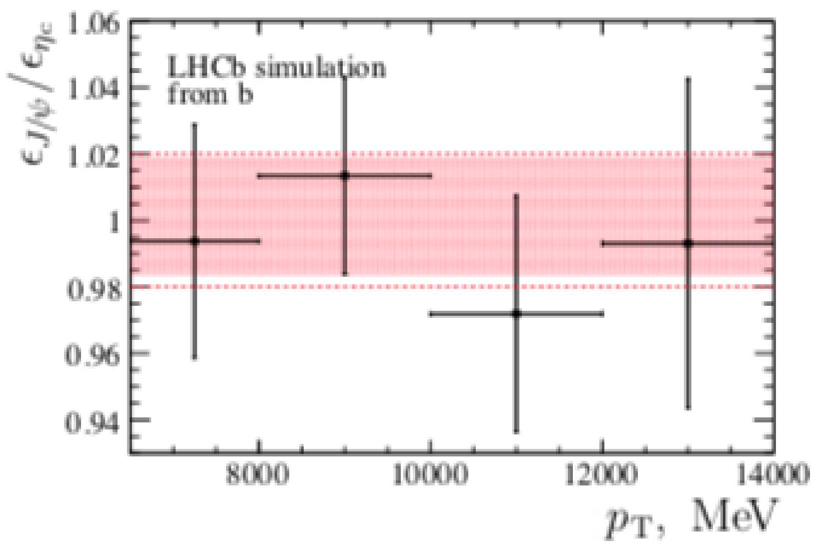
Eur. Phys. J. C 72, 2251 (2012)

JHEP 1310, 115 (2013)

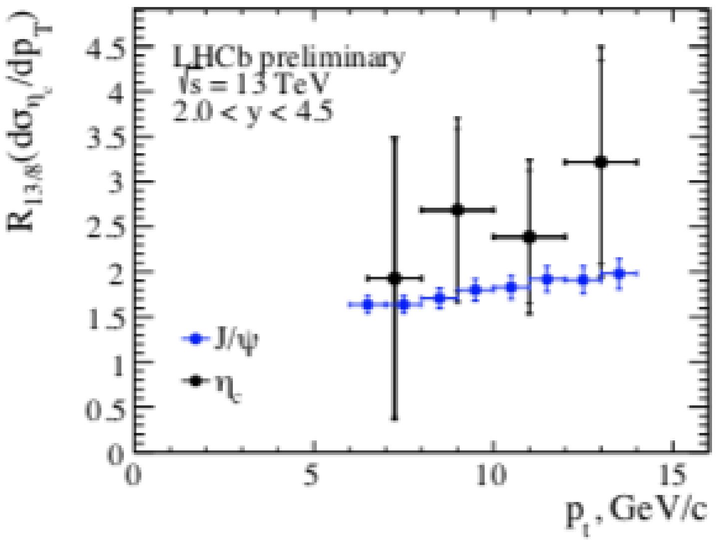
- **color Octet LDME extracted from fit**
- small p_T region has to be explored

Efficiency ratio

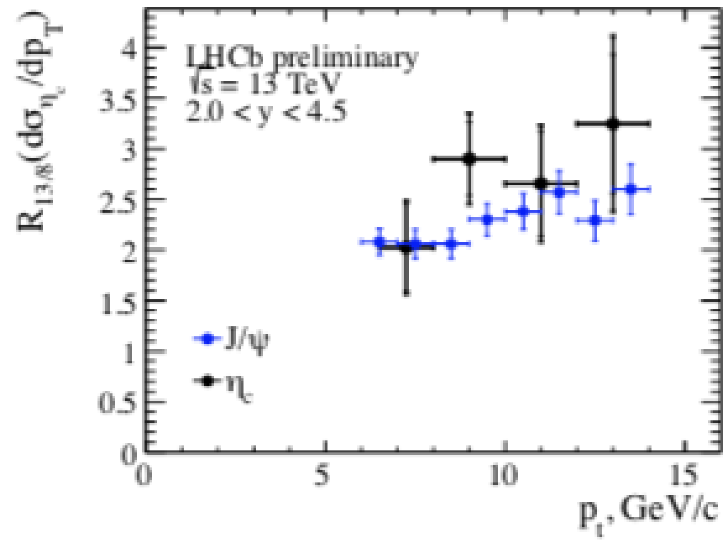




13/8 ratios

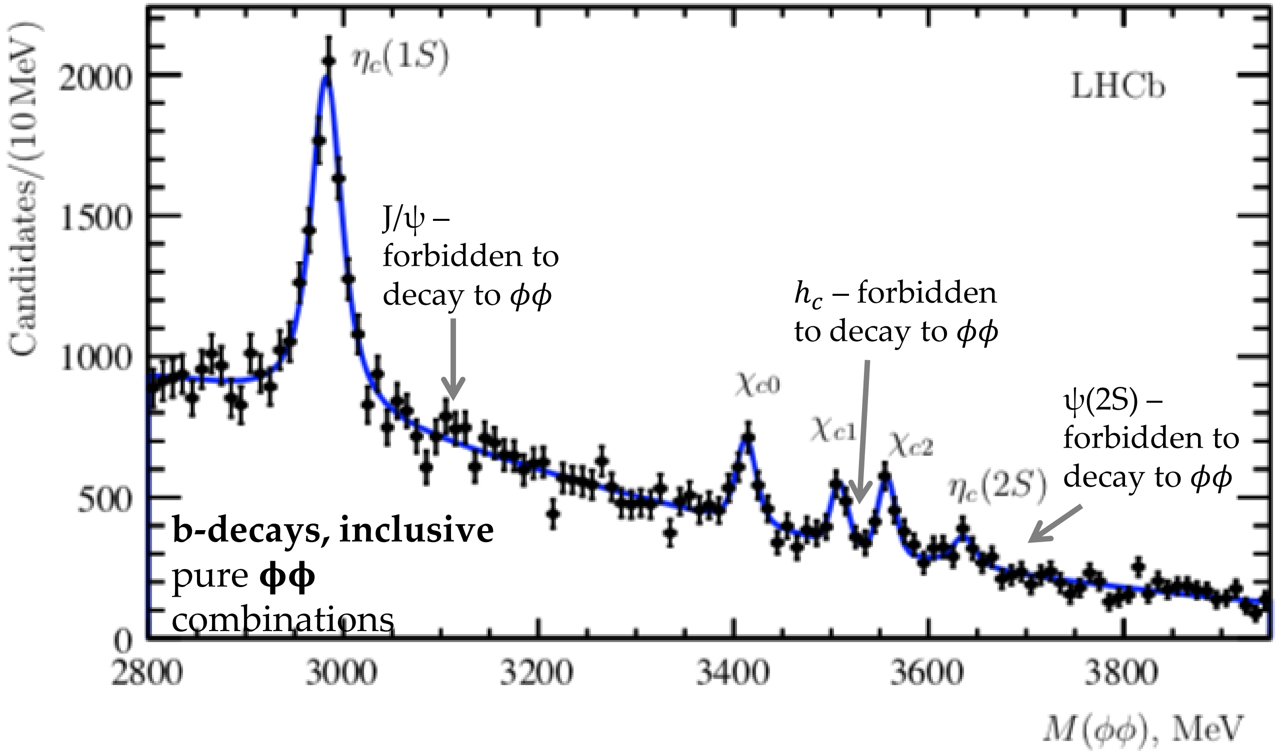


LHCb preliminary
√s = 13 TeV
2.0 < y < 4.5
J/ψ
η_c
$R_{13/8}(d\sigma_{\eta_c}/dp_T)$
p_t, GeV/c



LHCb preliminary
√s = 13 TeV
2.0 < y < 4.5
J/ψ
η_c
$R_{13/8}(d\sigma_{\eta_c}/dp_T)$
p_t, GeV/c

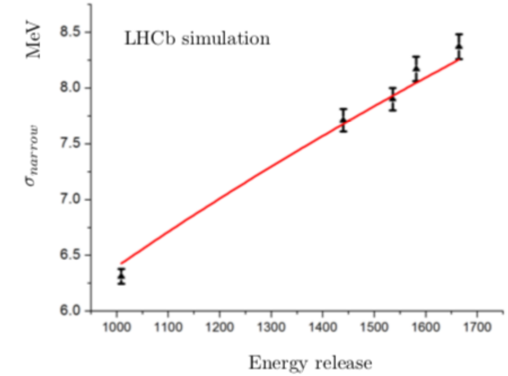
Charmonia production **in b-decays** study using $\phi\phi$ at LHCb at $\sqrt{s} = 7{,}8\ TeV$



Signals:

double Gaussian (x) RBW;

Resolution is scaled according MC:

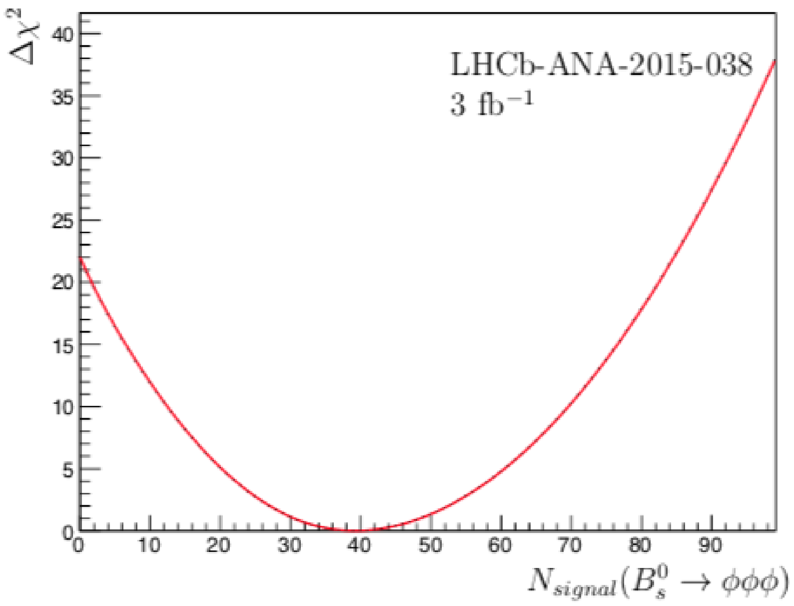


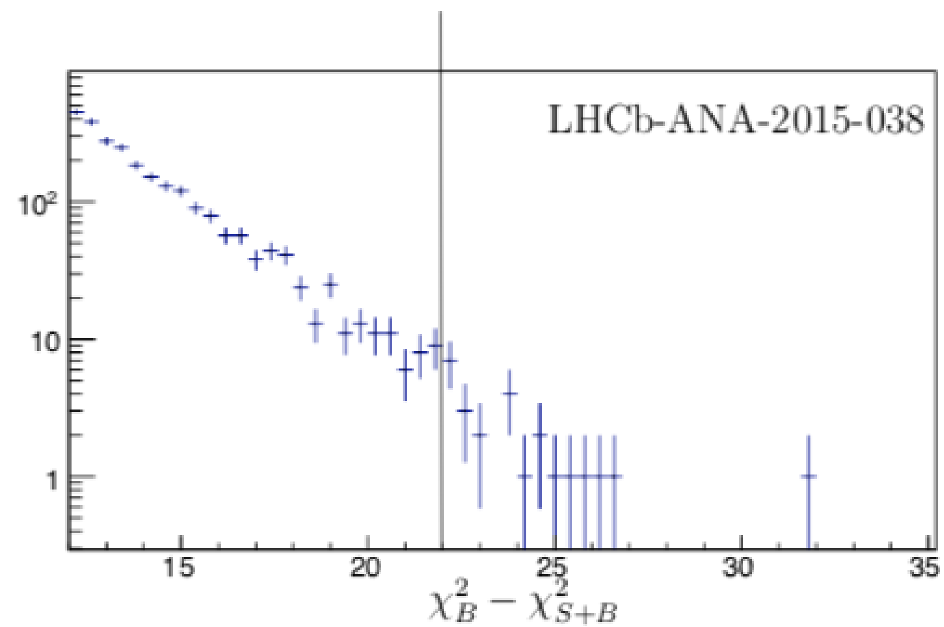
Fit results:

Resonance	Event yield ratio
$N_{\chi_{c1}}/N_{\chi_{c0}}$	$0.494 \pm 0.107 \pm 0.012$
$N_{\chi_{c2}}/N_{\chi_{c0}}$	$0.656 \pm 0.121 \pm 0.015$
$N_{\eta_c(2S)}/N_{\eta_c(1S)}$	$0.056 \pm 0.016 \pm 0.005$

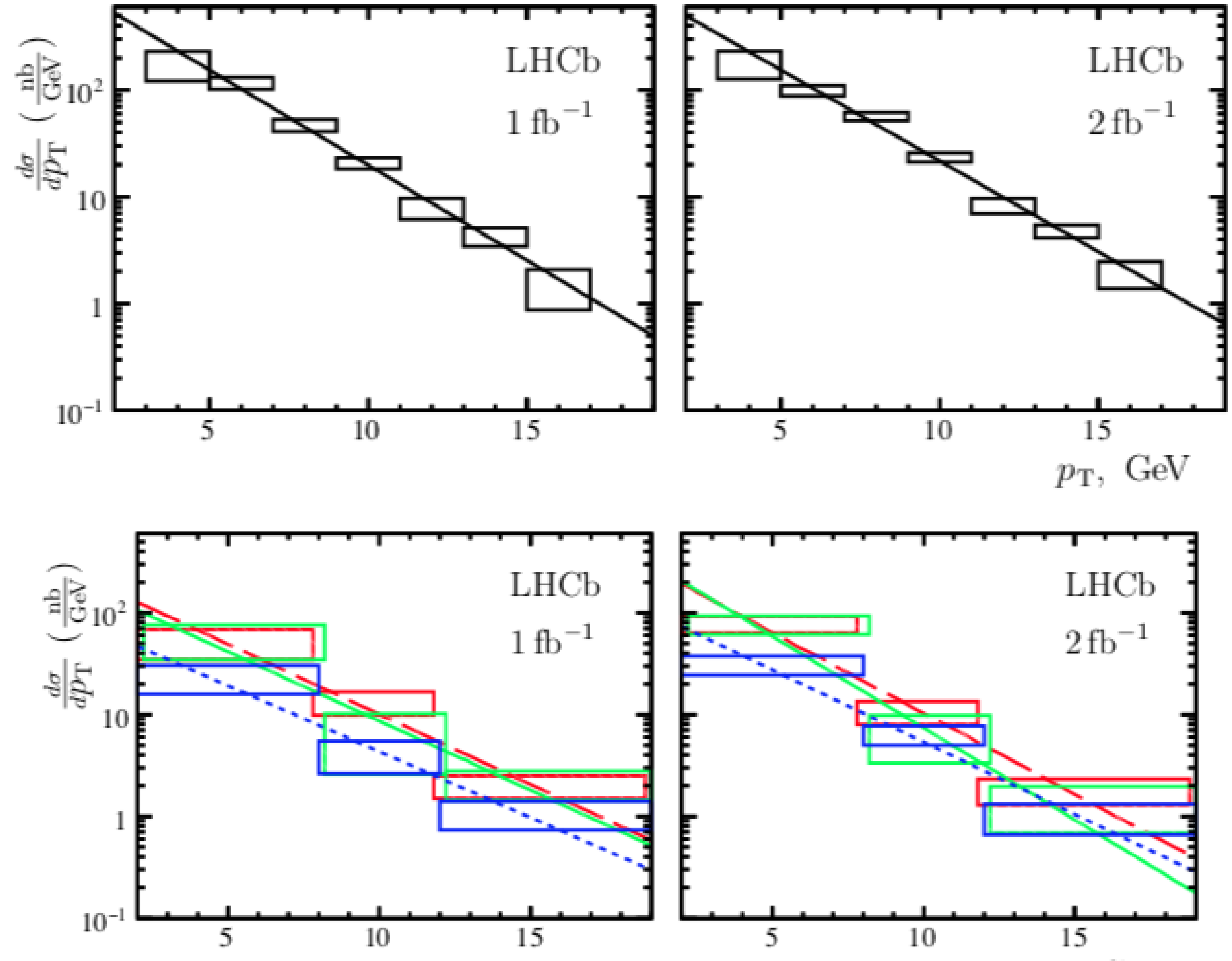
Resonance	Event yield ratio
$N_{\chi_{c0}}/N_{\eta_c(1S)}$	$0.144 \pm 0.022 \pm 0.011$
$N_{\chi_{c1}}/N_{\eta_c(1S)}$	$0.071 \pm 0.015 \pm 0.006$
$N_{\chi_{c2}}/N_{\eta_c(1S)}$	$0.094 \pm 0.016 \pm 0.006$

$\eta_c(2S)$ significance





p_T - spectra



	$\eta_c(1S)$	χ_{c0}	χ_{c1}	χ_{c2}
$\sqrt{s} = 7\,\text{TeV}$	0.41 ± 0.02	0.32 ± 0.04	0.31 ± 0.06	0.30 ± 0.05
$\sqrt{s} = 8\,\text{TeV}$	0.39 ± 0.02	0.37 ± 0.04	0.41 ± 0.06	0.33 ± 0.04

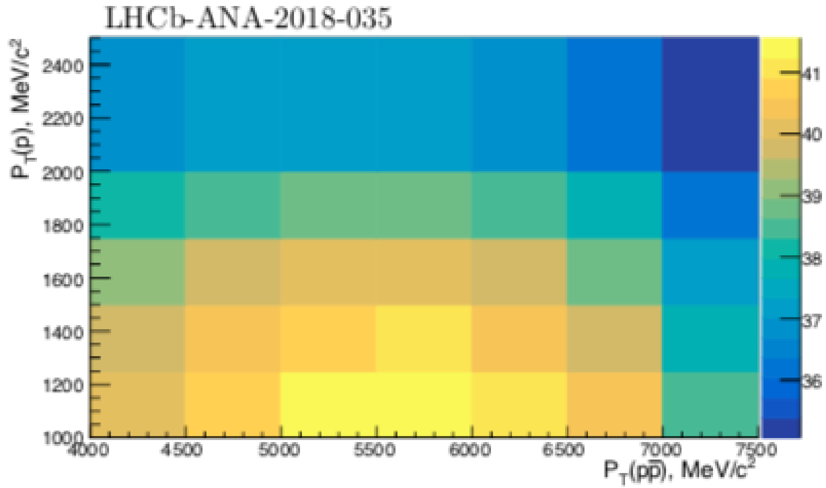
Measurement of η_c mass using $\eta_c \to p\bar{p}$

Looser selection of $b \to \eta_c X$ decays than for production measurements

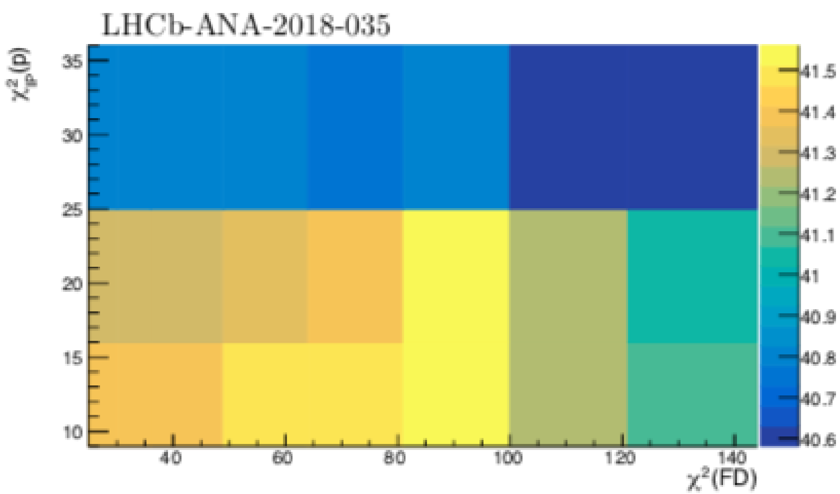
	Variable	Selection criteria
Trigger		L0_Hadron_TOS Hlt1(Two)TrackMVADecision_TOS Hlt2Topo(2,3,4)BodyDecision_TOS
Proton candidates	p_{T}, GeV/c Track χ^2/NDF Impact parameter χ^2 $\Delta \log \mathcal{L}^{p-\pi}$ $\Delta \log \mathcal{L}^{p-K}$	$> 1.0\,\mathrm{GeV}/c^2$ < 5.0 > 9 > 15 > 10
Charmonium candidates	p_{T}, GeV/c Vertex χ^2 Flight distance χ^2 Rapidity y	**>5.5 - optimised** < 9 **>81 - optimised** $2 < y < 4.5$
Multiplicity	SPD multiplicity	< 600

MC: contamination by prompt $\eta_c(1S)$ is below 1%

Measurement of η_c mass : optimization

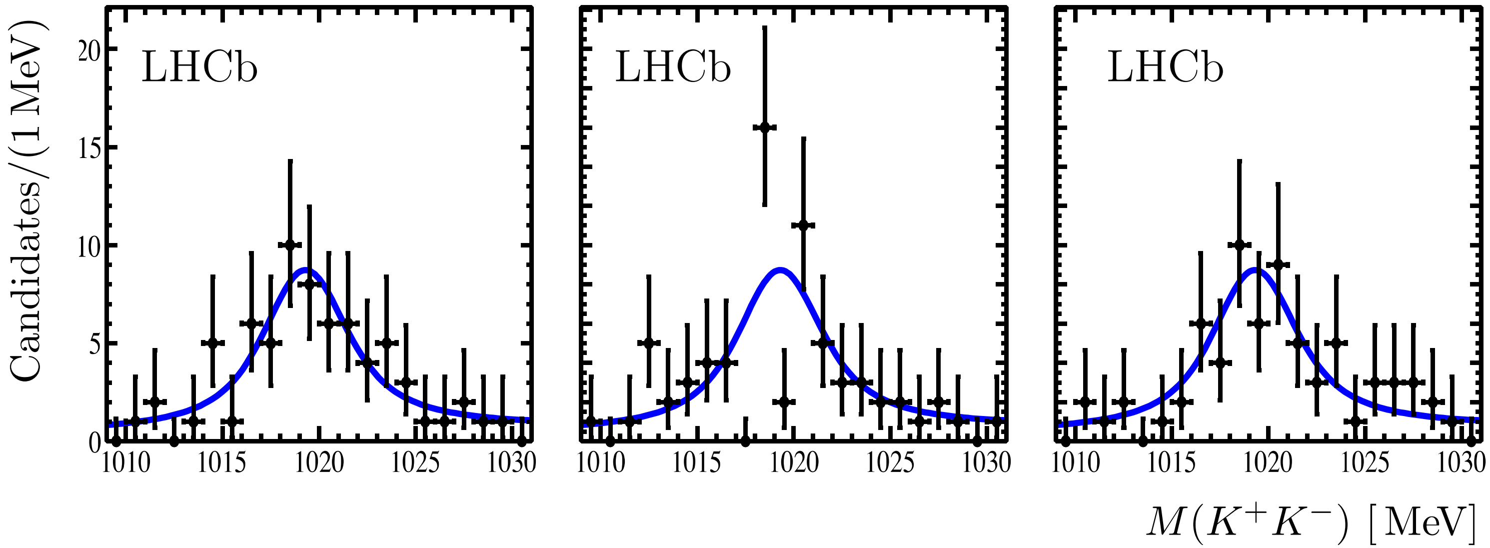


(a)



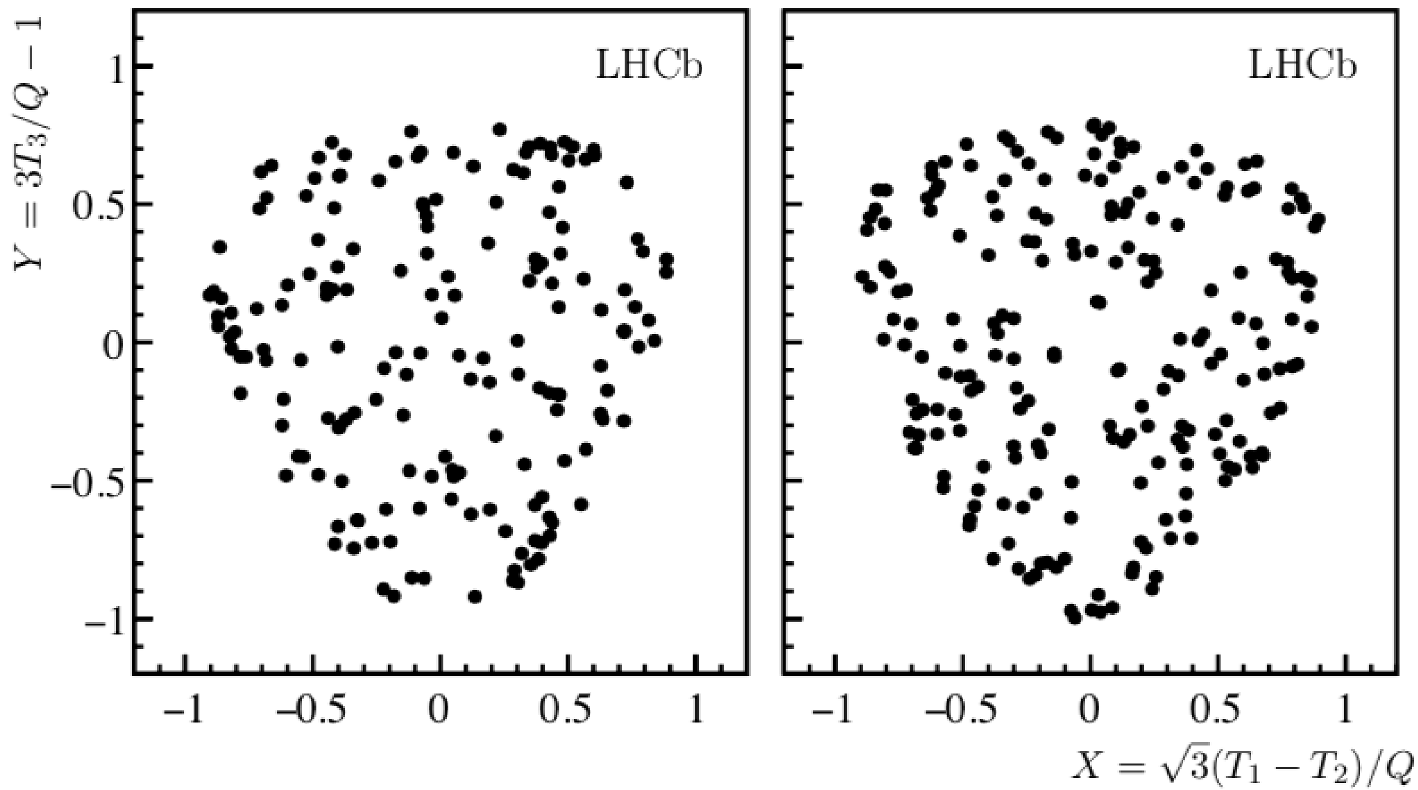
(b)

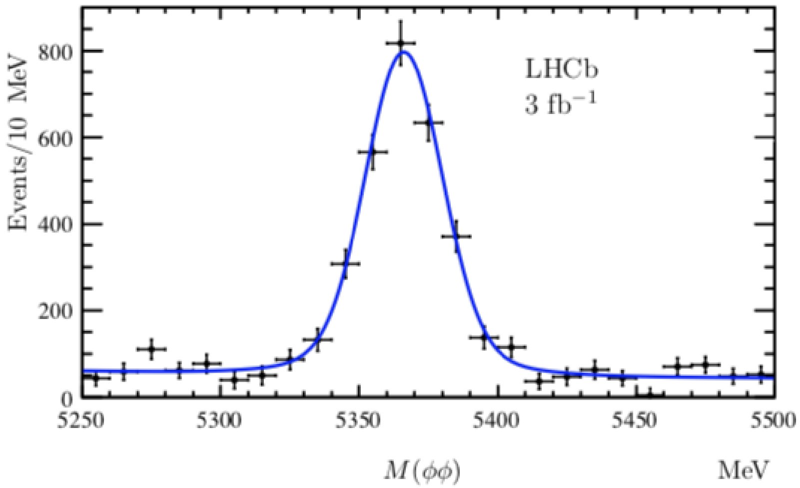
3D fit example



$B_s^0 \to \phi\phi\phi$ systematics

	$N(B_s^0)$
Background shape variation, $\phi\phi\phi$	< 1
Resolution at MC value in 3D fit	-1
Resolution of B_s^0 described by a single Gaussian	-2
$f_0(980)$ in the 3D fit	1
Decay model	4
Combined	5

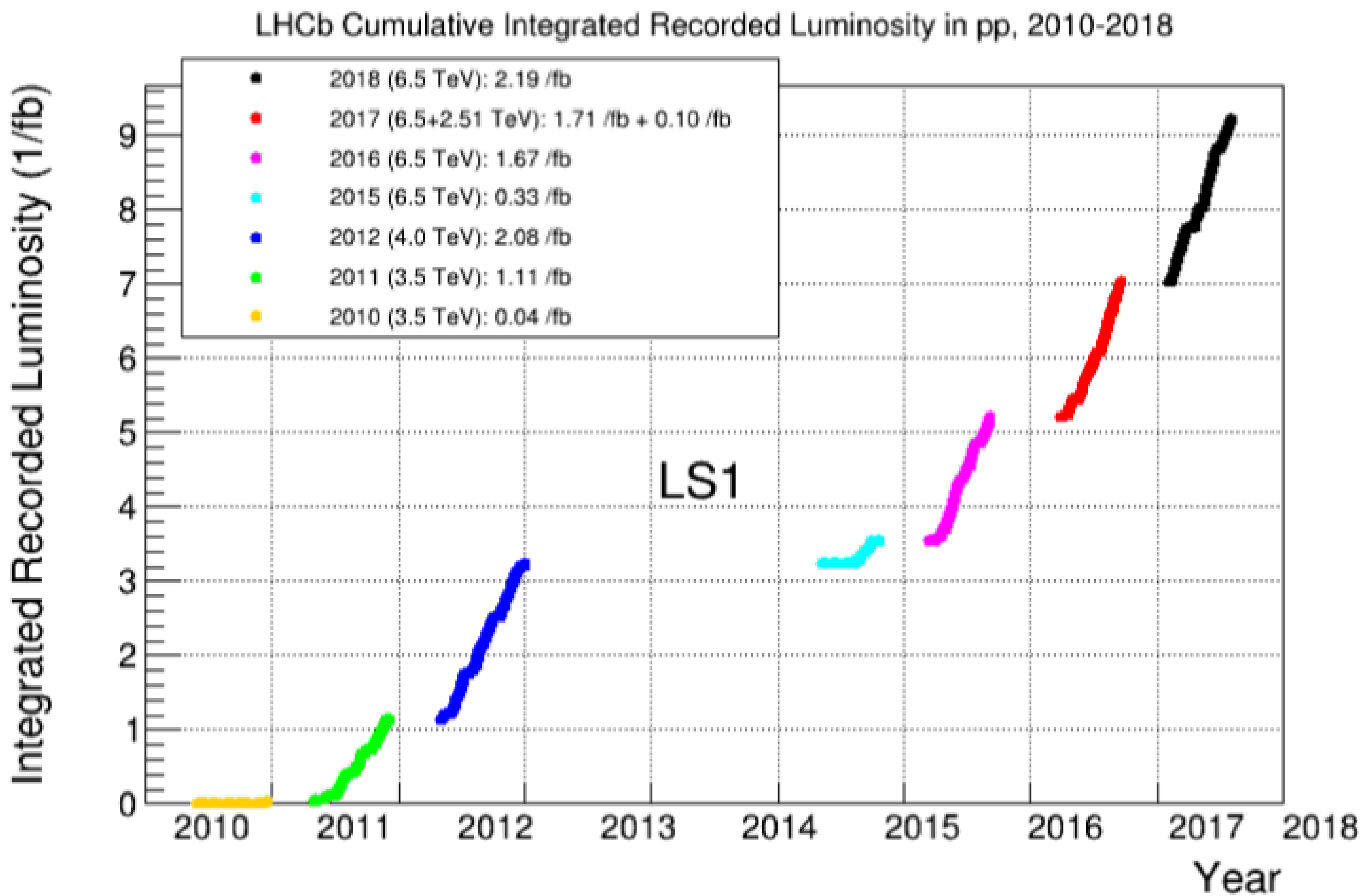

LHCb
LHCb
$Y = 3T_3/Q - 1$
$X = \sqrt{3}(T_1 - T_2)/Q$
1
0.5
0
−0.5
−1
−1
−0.5
0
0.5
1
−1
−0.5
0
0.5
1

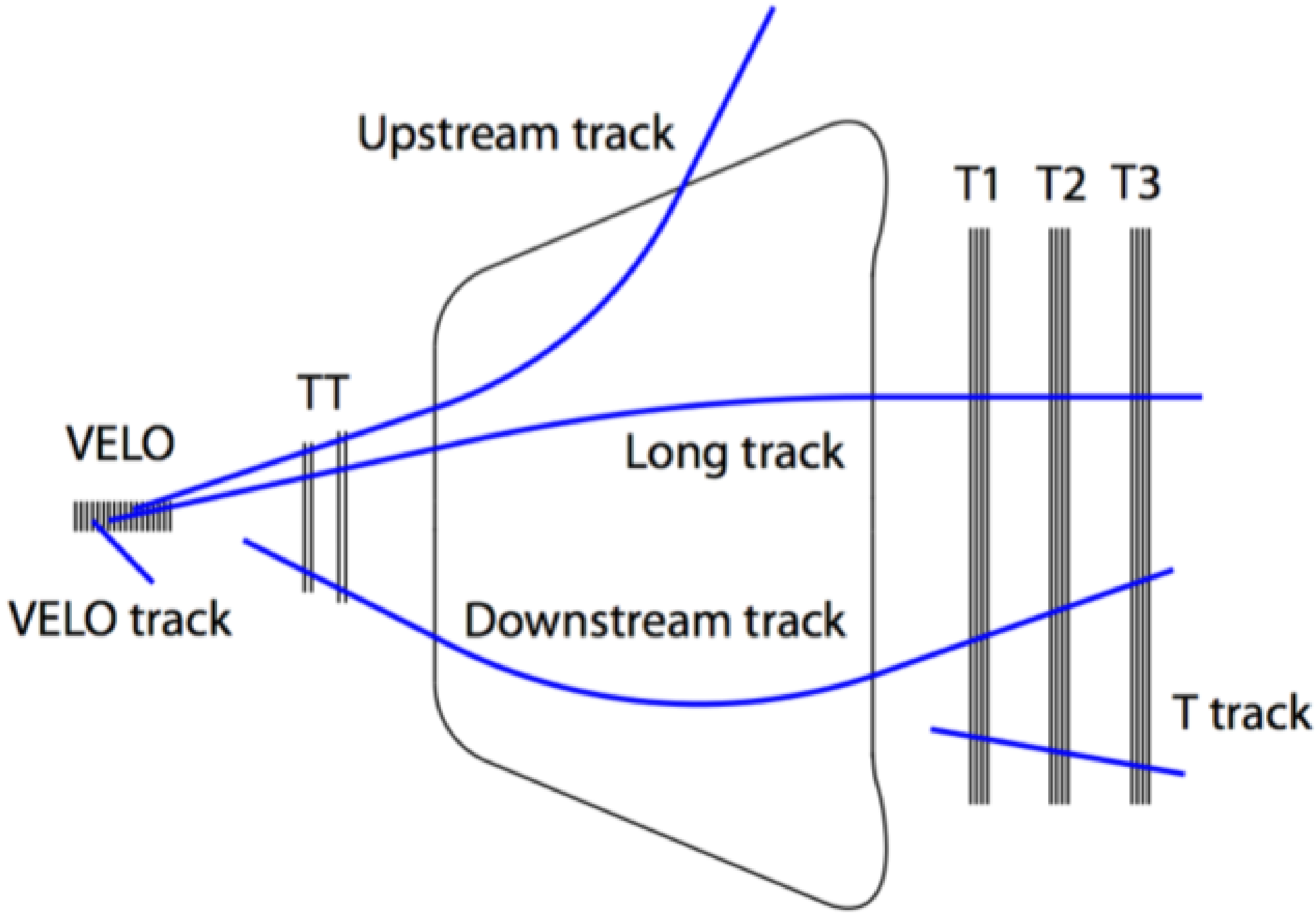


$$\frac{\mathcal{B}(\bar{b} \to B_s^0) \times \mathcal{B}(B_s^0 \to \phi\phi)}{\mathcal{B}(b \to \eta_c X) \times \mathcal{B}(\eta_c \to \phi\phi)} = 0.128 \pm 0.010 \pm 0.007$$

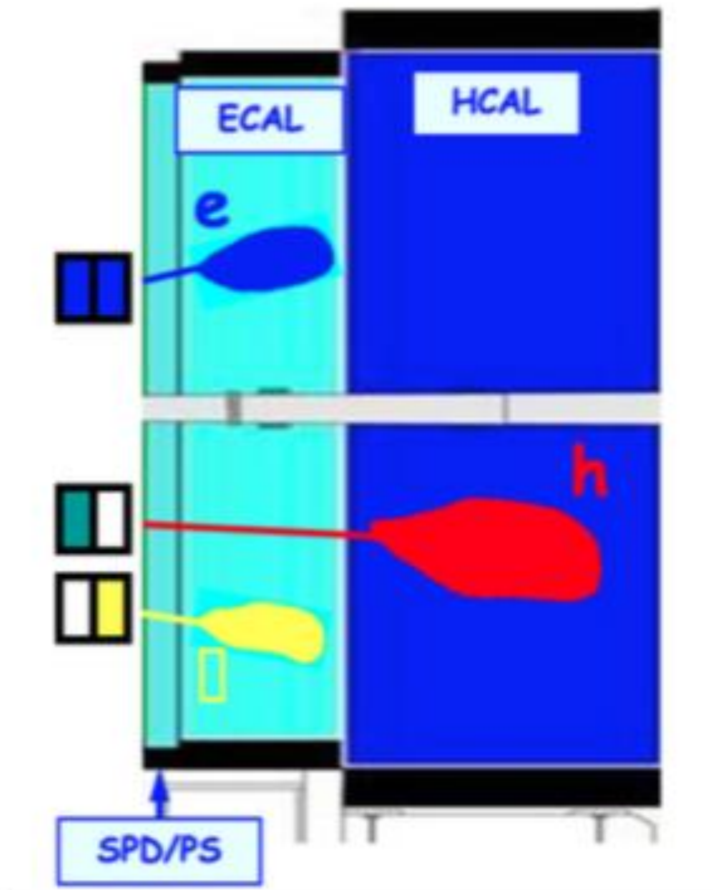
$$\mathcal{B}(B_s^0 \to \phi\phi) = (2.18 \pm 0.17 \pm 0.11 \pm 0.14_{f_s} \pm 0.65_{\mathcal{B}}) \times 10^{-5}$$

	$N(B_s^0)$
Background shape variation, $\phi\phi$	-2
Resolution in 2D fit at MC value	-23
$f_0(980)$ in the 2D fit	2
Resolution for B_s^0 described by a single Gaussian	-81
Combined	84


LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
LS1
Integrated Recorded Luminosity (1/fb)
0
1
2
3
4
5
6
7
8
9
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year


Upstream track
T1
T2
T3
TT
VELO
Long track
VELO track
Downstream track
T track

Calorimeters



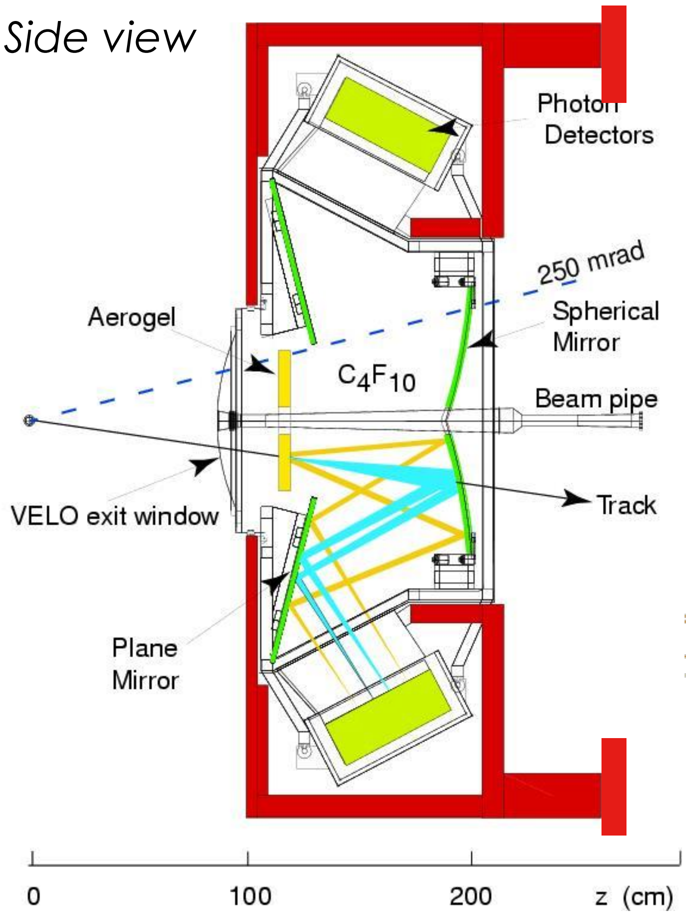
Charged hadron identification with RICH at LHCb

***2 Ring Imaging Cherenkov Detectors (RICH)**: **3 Radiators**, photons from Cerenkov cone focused onto rings recorded by **Hybrid Photon Detector** (HPD) arrays, out of acceptance*

RICH 1

Acceptance 25-300 mrad

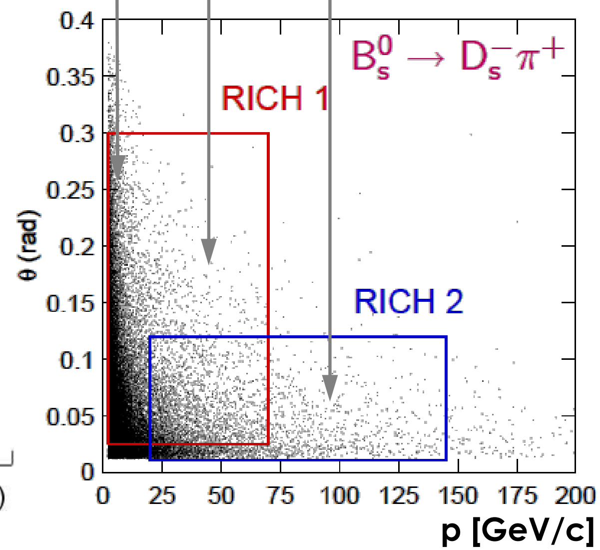
Side view



Silica Aerogel:
n=1.03
1-10 GeV/c

C_4F_{10}:
n=1.0014
Up to ~70 GeV/c

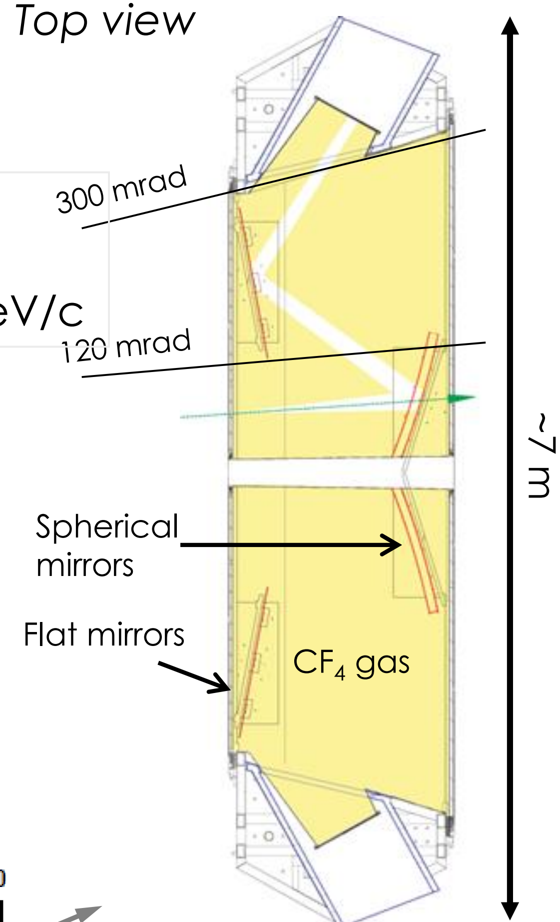
CF_4:
n=1.0005
Up to ~100 GeV/c



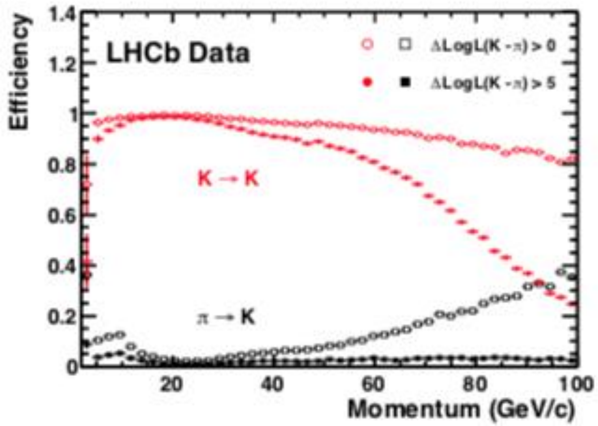
RICH 2

Acceptance 15-120 mrad

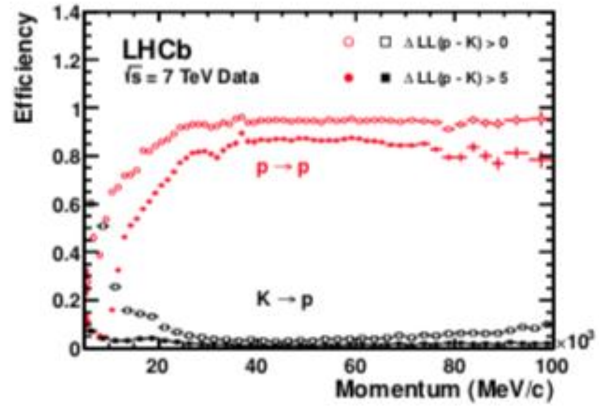
Top view



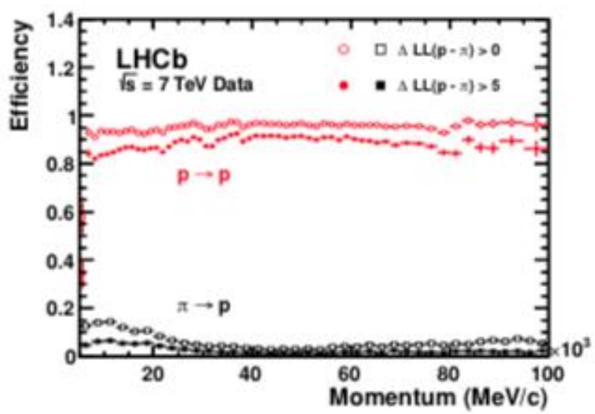
Note scale difference



(a) Kaon PID efficieny (red) and $\pi \to K$ misidentification (black).



(b) Proton PID efficieny (red) and $K \to p$ misidentification (black).



(c) Proton PID efficieny (red) and $\pi \to p$ misidentification (black).