Charmonium production using decays to hadronic final states at LHCb

vs Non-Relativistic QCD (NRQCD)

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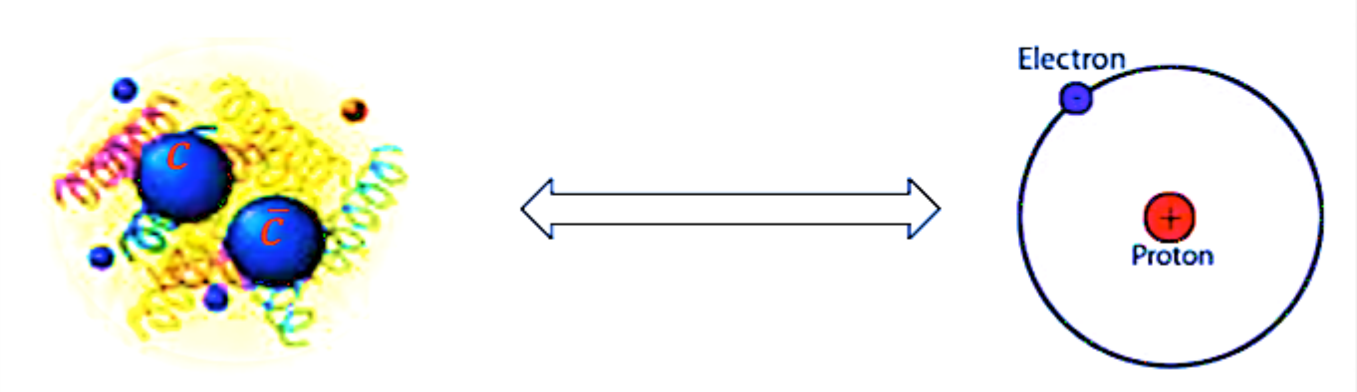
PHENIICS Fest 2018

Charmonium

- Bound state of ***ccbar*** under strong interaction

  e.g **$\eta_c(1S)$, χ_c, J/ψ, $\eta_c(2S)$, $\psi(2S)$**
- "Hydrogen atom in QCD"



- Non-relativistic QCD object:
  - Charmonium: $v^2 \approx 0.3$
  - Bottomonium: $v^2 \approx 0.1$

- Charmonium states below DDbar threshold are well identified by spectroscopy (potential models, lattice)

- **Production: multiple well-separated scales (both perturb. and non-perturbative aspects)**

  →charmonium ideal to understand hadronization, to study QGP

Charmonia production in the NRQCD

NRQCD assumptions:

➔ **Factorization**

$$\mathcal{L}_{NRQCD} = \sum_n \boxed{\frac{c_n(\alpha_s(m),\mu)}{m^n}} \times \boxed{O_n(\mu, mv, mv^2, ..)}$$

- ccbar pair production - **short-distance elements,** calculated perturbatively
- hadronisation - **long-distance matrix elements (LDMEs),** non-perturbative

(*expansion on quark velocity v*)

(can be extracted from fits to data as free parameters)

➔ **Universality**

LDMEs does not depend from ccbar pair creation process

Alternative theoretical approaches:

- Color evaporation model (CEM)
- kt – factorization
- …

NRQCD is the most powerful tool to predict charmonia production

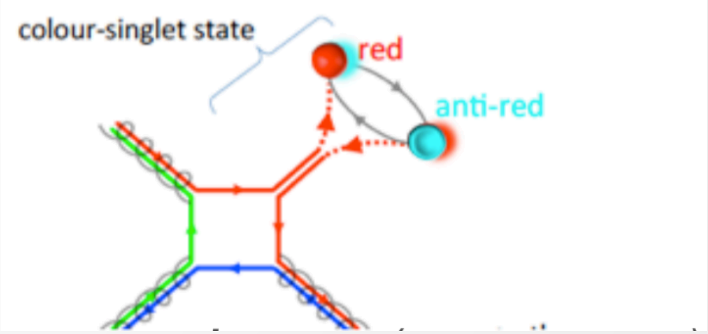
Charmonia production in the NRQCD

Cross section factorizes:

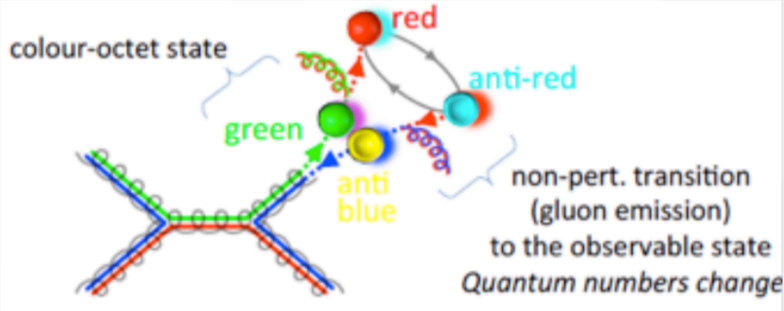
$$d\sigma_{A+B\to H+X} = \sum_n \boxed{d\sigma_{A+B\to Q\bar{Q}(n)+X}} \times \boxed{\langle O^H(n)\rangle}$$

Production mechanisms:

- Color Singlet (CS):
  quantum numbers ccbar pair and charmonium match



- Color Octet (CO):
  quantum numbers ccbar pair in CO state are different from charmonium



Spin-symmetry for LDMEs:

Links between the CS and CO matrix elements of **different charmonia states**

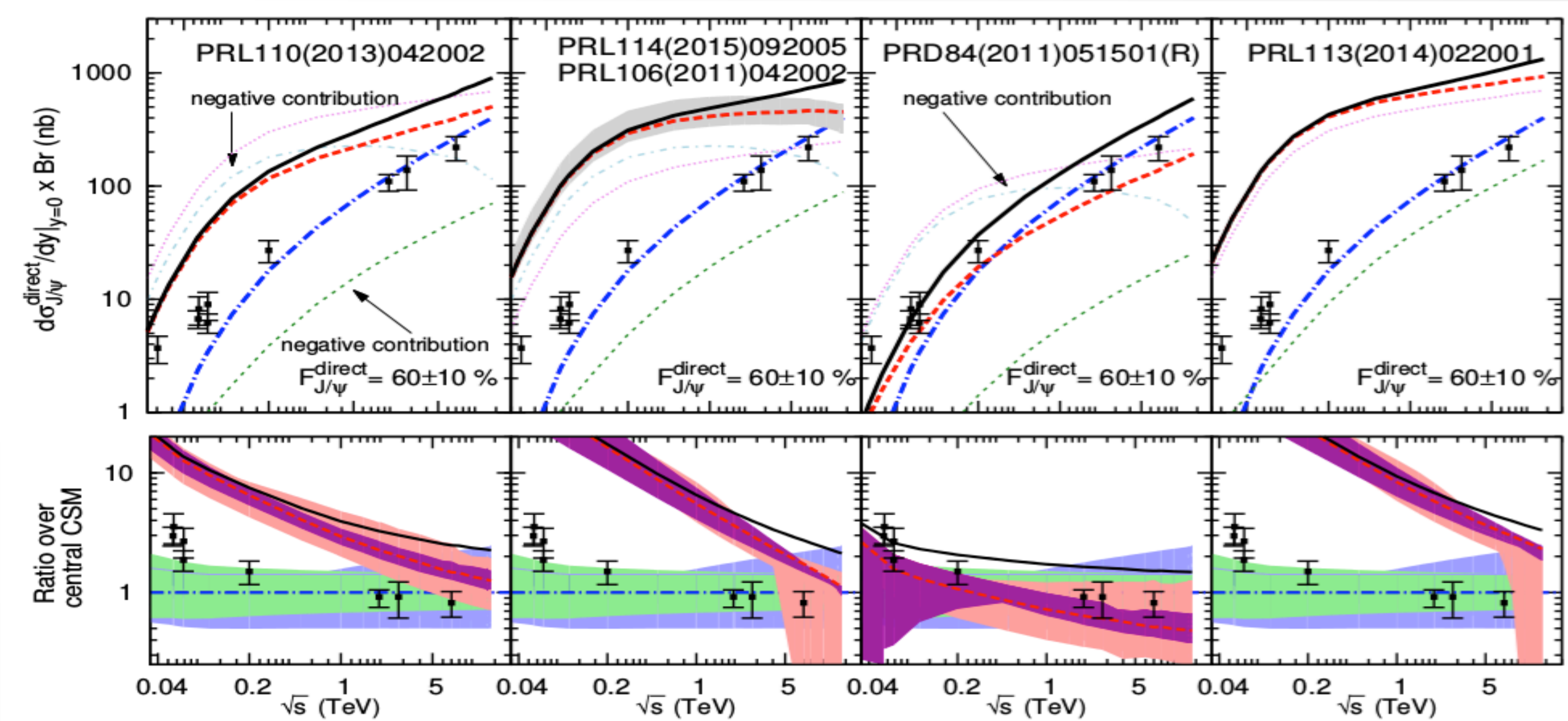
$$\langle O_1^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_1^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_8^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^3S_1)\rangle = \langle O_8^{J/\psi}(^1S_0)\rangle,$$
$$\langle O_8^{\eta_c}(^1P_1)\rangle = 3\langle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

Simultaneous studying of J/ψ and η_c

√s dependence of J/psi **hadro**production vs NRQCD at NLO

Eur.Phys.J. C75(2015) 7, 313

Available data from 4π experiments at ISR, RHIC, Tevatron and LHC

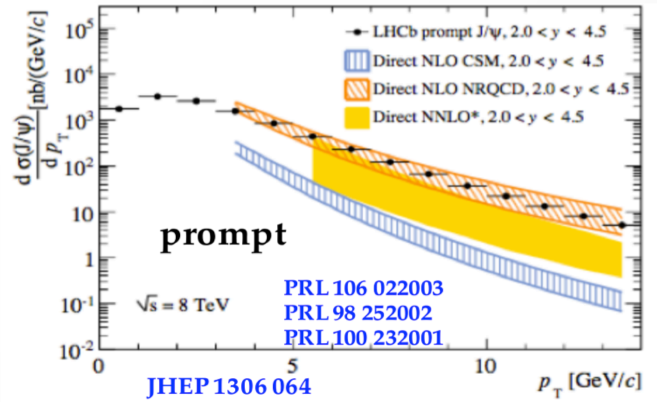


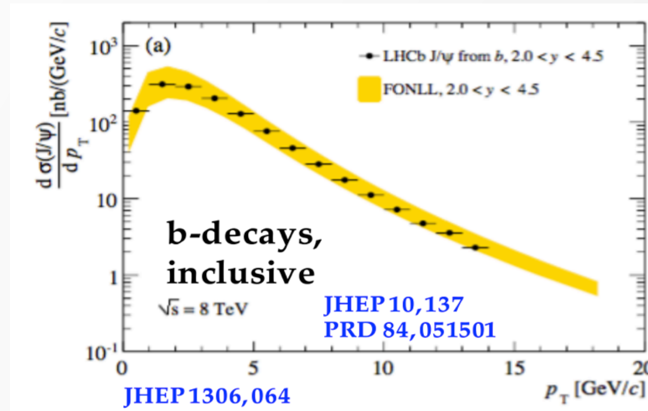
Four groups of theorists are in the game

NRQCD description of J/ψ production and polarization at LHCb

Production:

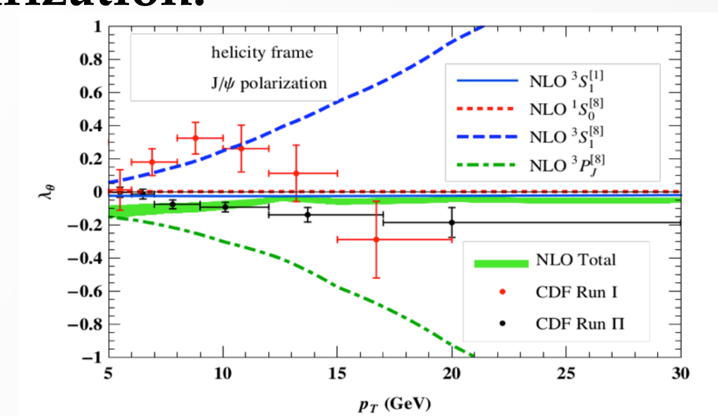
PRL 108, 172002
PRL 110, 042002
PRL 108, 242004

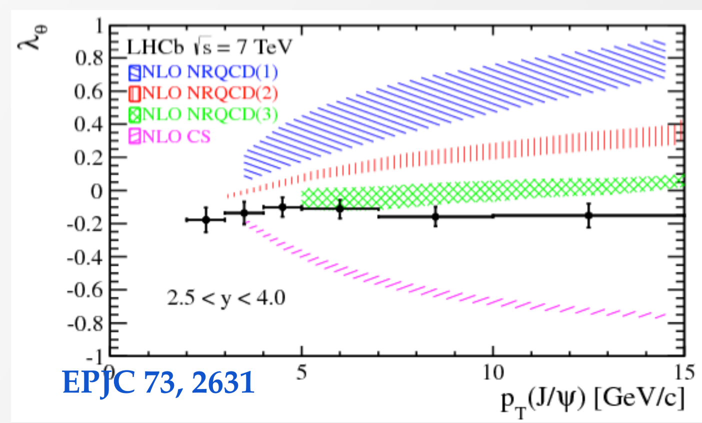




- Measurements of LHC and Tevatron are in agreement
- *CS* NLO and NNLO* could not describe prompt production
- *NRQCD* description dominates by *CO* contribution

Polarization:





- *CO* predicts strong polarization
- Large *CS* contribution is required

Charmonium production via decays to hadronic final states at LHCb

Charmonia decay channels for production measurements at LHCb

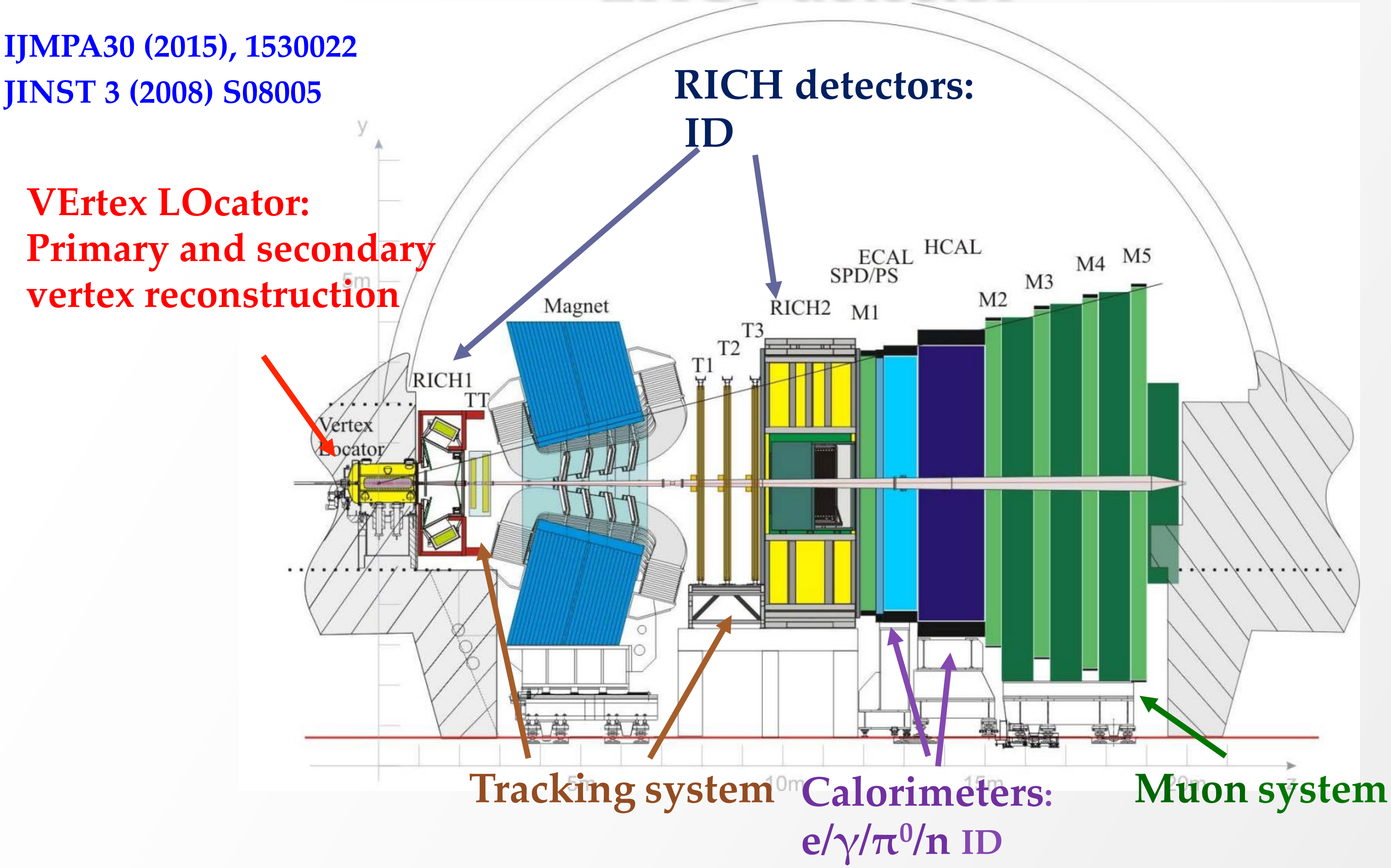
	$\mu\mu$ (ll)	$J/\psi\ \gamma$	ppbar	$\varphi\varphi$	baryons
η_c(1S)	forbidden	-	~ 0.15 %	~ 0.2 %	~ 0.1 %
J/ψ(1S)	~ 6 %	-	~ 0.2 %	forbidden	~ 0.1 %
χ_{c0}(1P)	forbidden	~ 1.3 %	~ 0.02 %	~ 0.08 %	~ 0.04 %
h_c(1P)	forbidden	forbidden	?	forbidden	~ 0.01 %
χ_{c1}(1P)	forbidden	34 %	~ 0.01 %	~ 0.04 %	~ 0.01 %
χ_{c2}(1P)	forbidden	19 %	~ 0.1 %	~ 0.01 %	~ 0.01 %
η_c(2S)	forbidden	-	~ 0.01 %	?	?
ψ(2S)	~ 1 %	-	~ 0.03 %	forbidden	~ 0.02 %

seen in prompt production
seen in b-decays, promising channels

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

LHCb detector

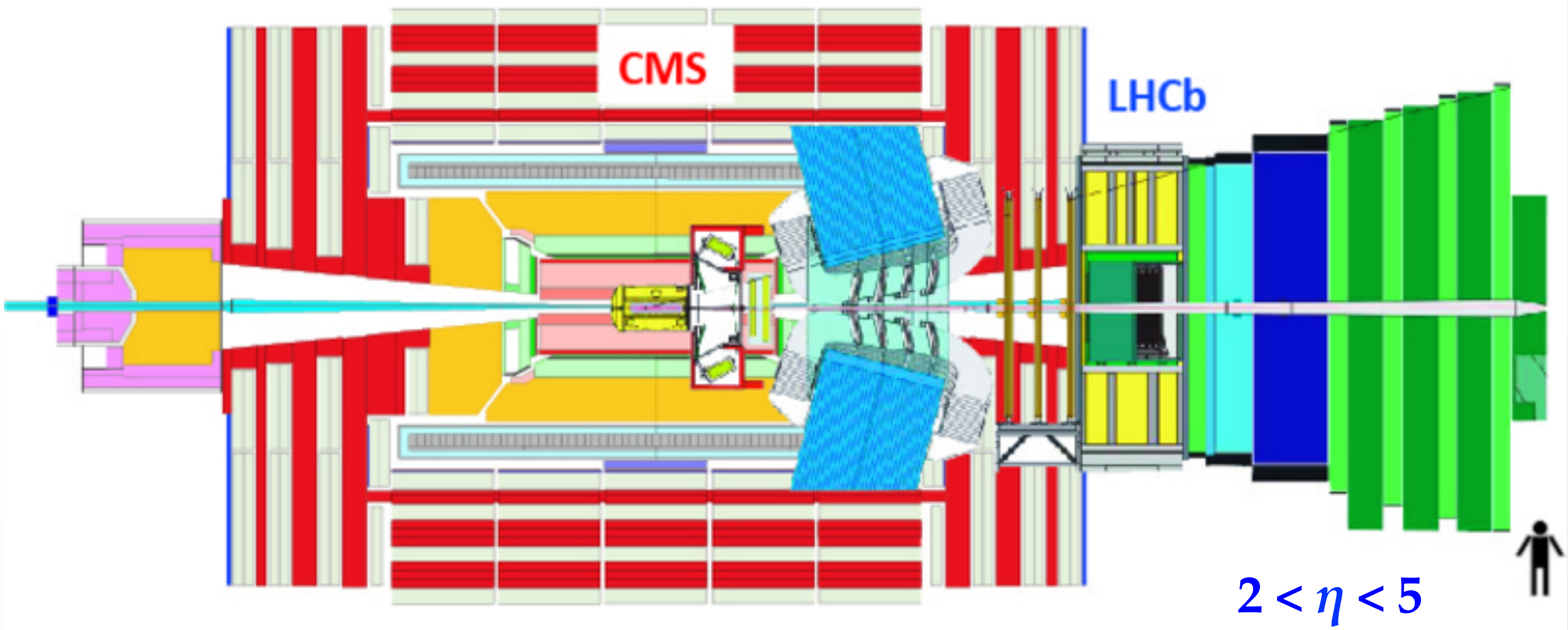
IJMPA30 (2015), 1530022
JINST 3 (2008) S08005



- Precise vertex reconstruction with VELO
- Powerful charge particle ID by RICH detectors
- Robust trigger

LHCb detector

IJMPA30 (2015), 1530022
JINST 3 (2008) S08005



- Precise vertex reconstruction with VELO
- Powerful charge particle ID by RICH detectors
- Robust trigger
  - **Coverage complementary to ATLAS and CMS in p_T and η**

$\eta_c(1S)$ production using $\eta_c(1S) \rightarrow$ ppbar decay at $\sqrt{s}$ = 7,8 TeV

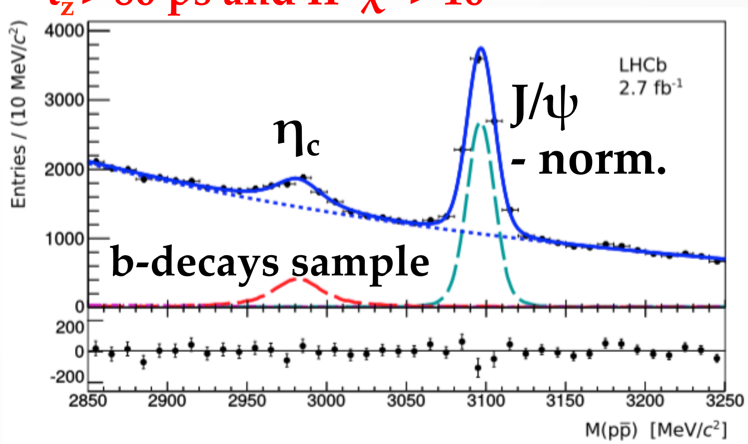
charmonia origins

- prompt hadroproduction
- b-decays production, inclusive

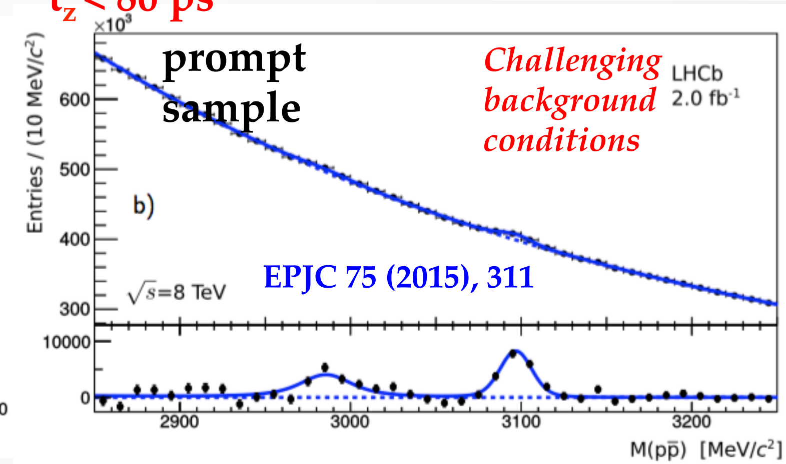
Experimentally can be separated by **pseudo-proper decay time**:

$$t_z = \frac{(z_{SV} - z_{PV}) M_{c\bar{c}}}{p_z}$$

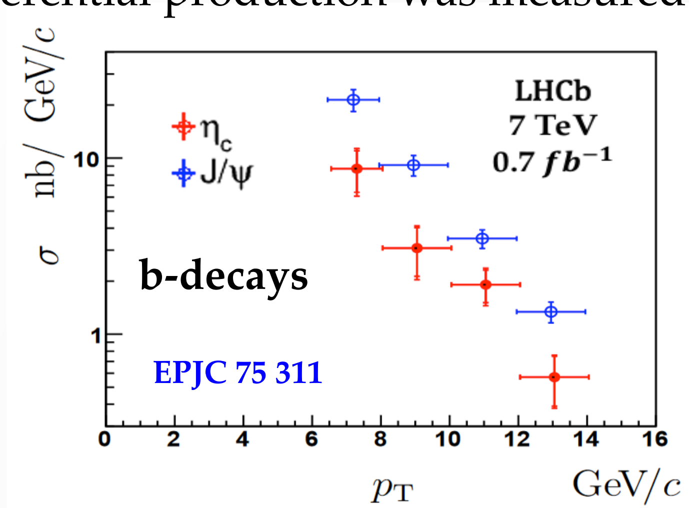
$t_z > 80$ ps and IP $\chi^2 > 16$

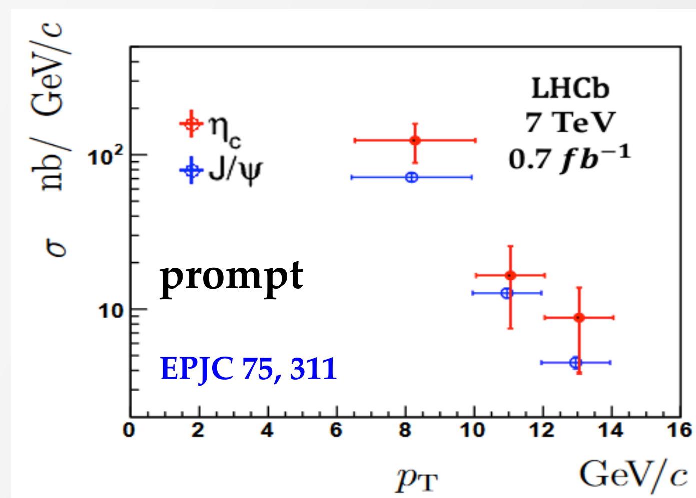


$t_z < 80$ ps



- Knowing yields in two samples from fit, efficiencies and cross-talk from MC, differential production was measured:





First η_c prompt and from inclusive b-decays production measurement

η_c(1S) production at the LHC challenges NRQCD factorization

η_c LDMEs determination:

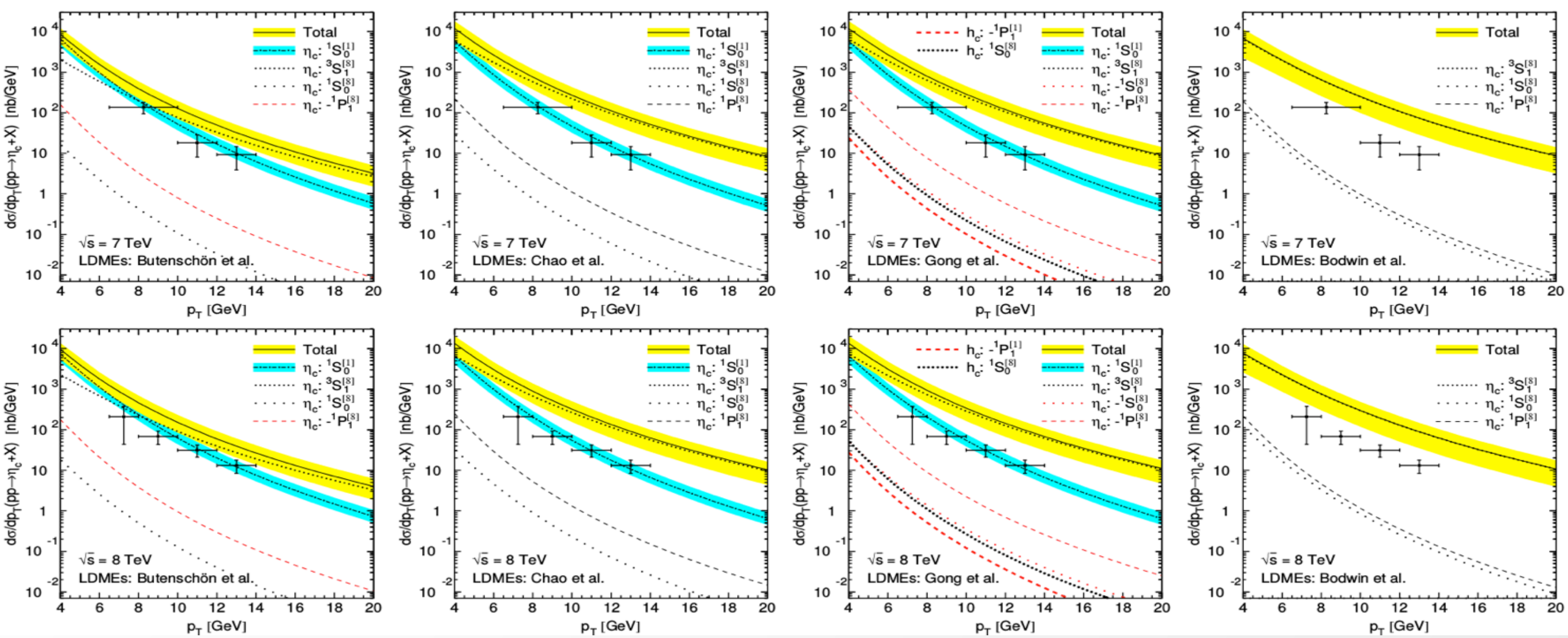
PRL 114(2015), 092004

- determined from known HQSS relation for J/ψ

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

- direct projection to LHCb data

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



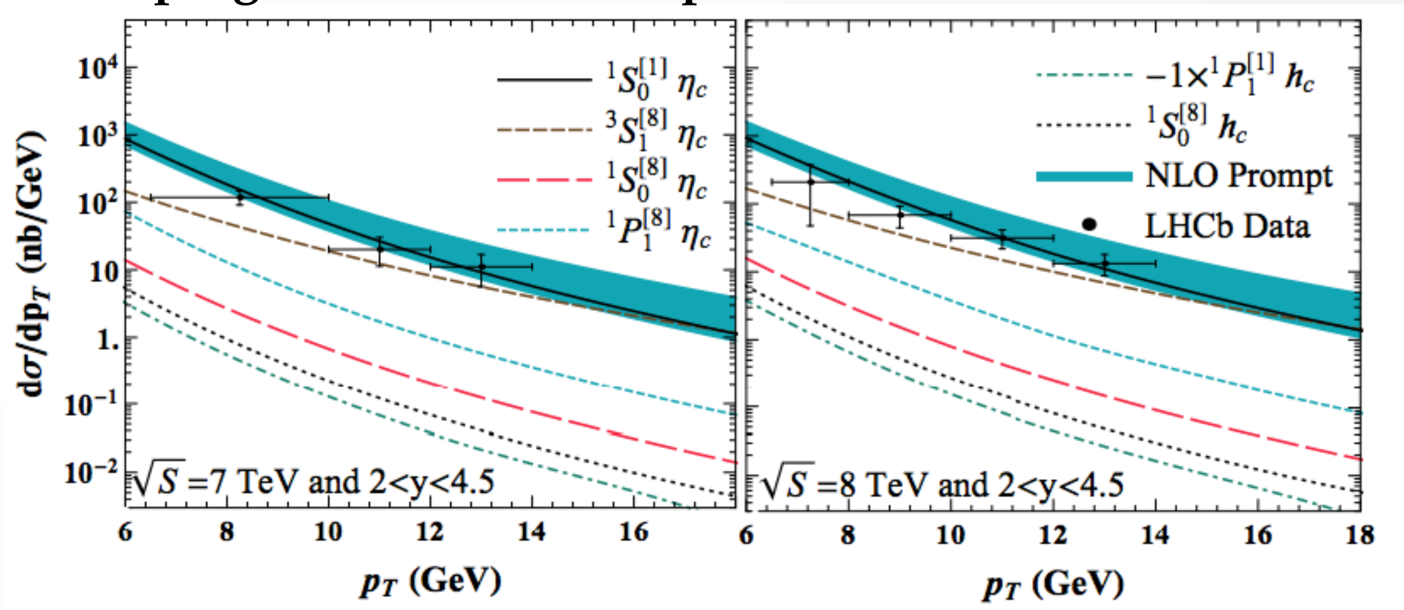
Results:

- **LHCb data saturated by CS contribution**

η_c(1S) production at the LHC challenges NRQCD factorization

PRL 114(2015), 092005

Recent nice progress in theoretical prediction:



using constraints from **fits to J/ψ production measurements and fit to η_c production measurement**, upper limit on CO LMDE extracted

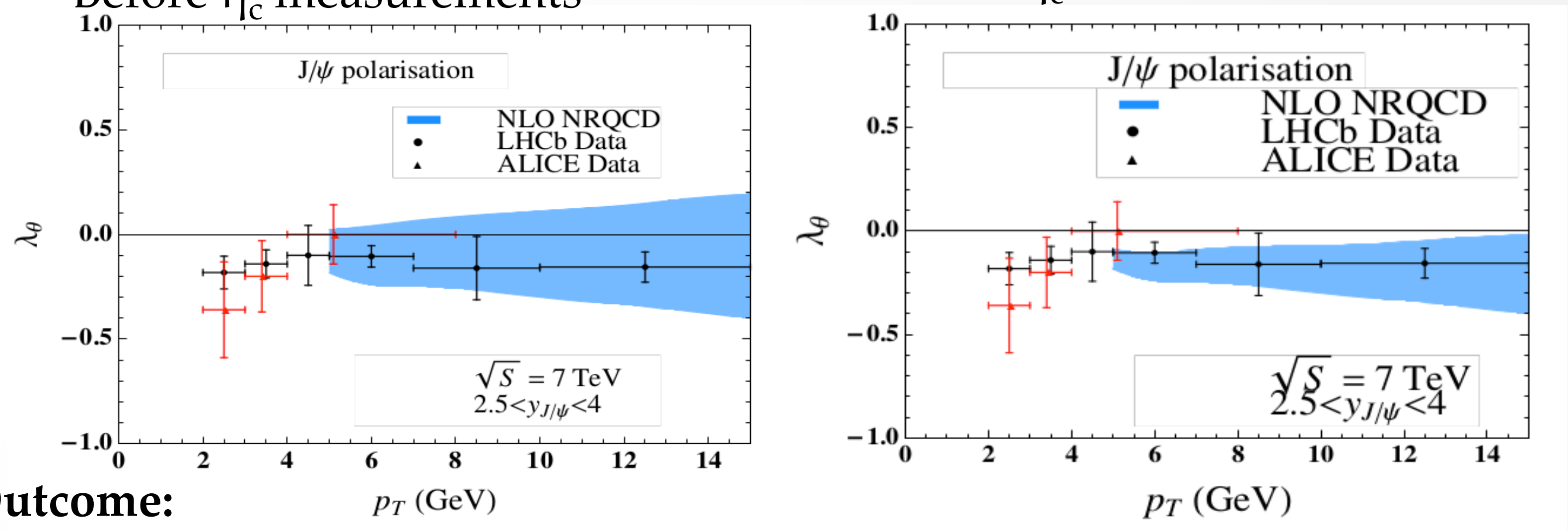
The only resonable description of data points

$\eta_c(1S)$ production at the LHC challenges NRQCD factorization

PRL 114(2015), 092005

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

Before η_c measurements | After η_c measurements



Outcome:

- *reasonable* (****) description of data achieved
- tension with CDF data
- two large CO contributions cancel each other ⇒ hierarchy problem ⇒ Soft Gluon Fragmentation, etc.?
- joint study of hadroproduction and production in inclusive *b*-decays?

Prospects:

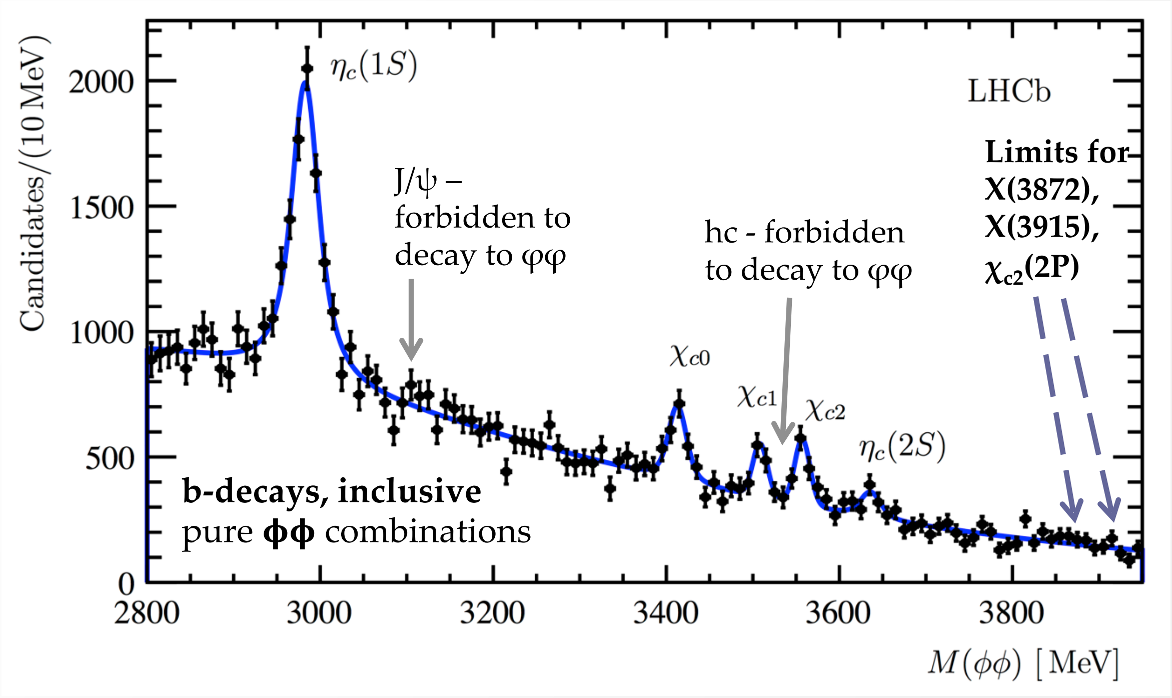
- Measure $\eta_c(1S)$ more precisely using Run II data (ongoing)

- Same links for $\eta_c(2S)$ and $\psi(2S)$ are expected⇒ powerful test of NRQCD

- **measure prompt $\eta_c(2S)\to$ppbar or $\eta_c(2S)\to\phi\phi$** } 2018 Data

χ_c and $\eta_c(2S)$ production in inclusive b-decays using φφ as √s = 7,8 TeV
EPJC 77 (2017), 609

- Powerful test of NRQCD factorization, universality of LDME and heavy quark spin symmetry assumptions
- Aiming at constraining LDMEs simultaneously by prompt and *b*-decays measurements

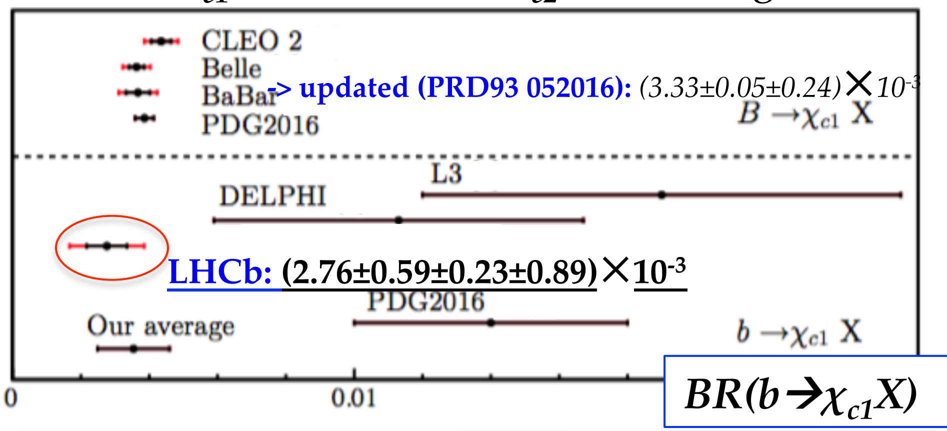


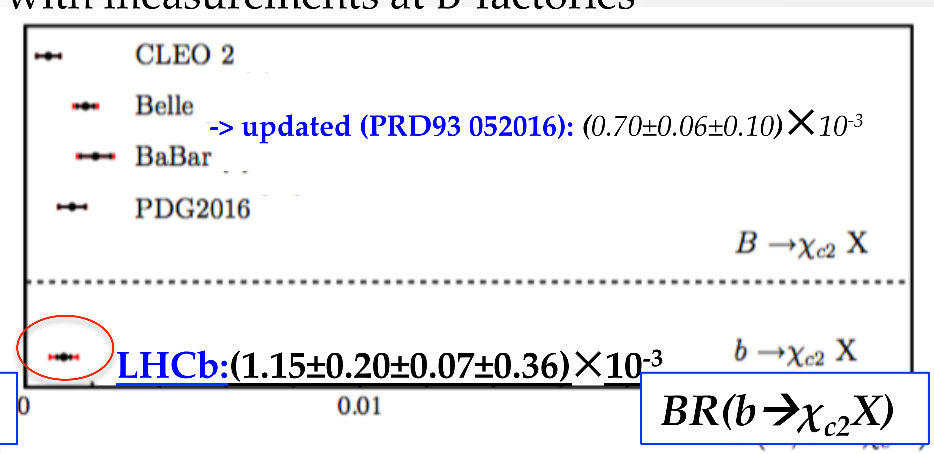
- χ_c and $\eta_c(2S)$ production rates measured using measurement of ***BR(b→η_c(1S)X)***
EPJC 75, 311

χ_c and $\eta_c(2S)$ production in inclusive b-decays using $\varphi\varphi$ as $\sqrt{s}$ = 7,8 TeV

EPJC 77 (2017), 609

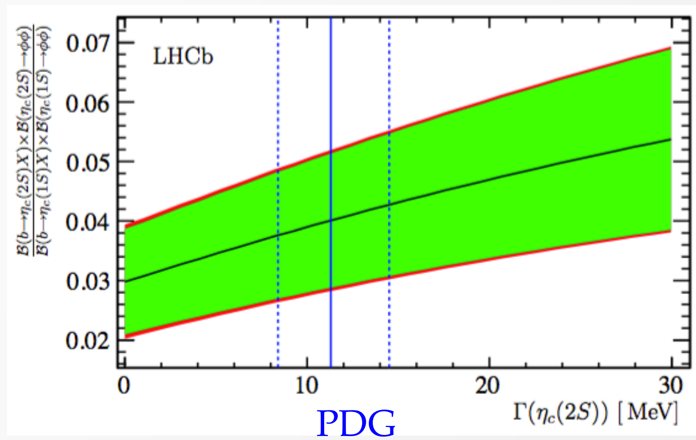
- First measurement of $BR(b\rightarrow\chi_{c0}X)$ production in inclusive b-decays
  $BR(b\rightarrow\chi_{c0}X)$
- The most precise measurements of $BR(b\rightarrow\chi_{c1}X)$ and $BR(b\rightarrow\chi_{c2}X)$
- $BR(b\rightarrow\chi_{c1}X)$ and $BR(b\rightarrow\chi_{c2}X)$ are in agreement with measurements at B-factories





- First measurement of $\eta_c(2S)$ production in inclusive b-decays; first evidence of $\eta_c(2S)\rightarrow\varphi\varphi$ (**3.7σ significance**)

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



➜ first step to measure $\eta_c(2S)$ prompt production, waiting for 2018 data !

χ_c and $\eta_c(2S)$ production in inclusive b-decays: test of NRQCD

Barsuk, Kou, Usachov LAL-17-051

- From **EPJC 77 (2017), 609** and **PDG:**

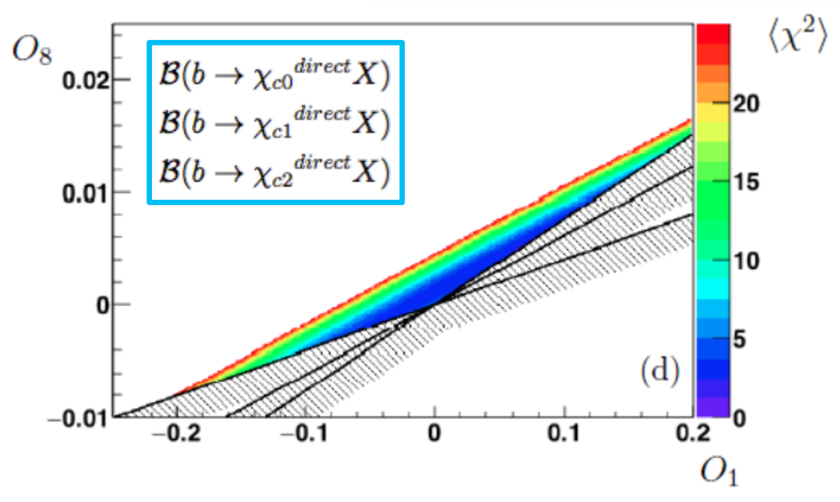
$$\mathcal{B}(b \to \chi_{c0}{}^{direct} X) = (2.74 \pm 0.47 \pm 0.23 \pm 0.94_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c1}{}^{direct} X) = (2.49 \pm 0.59 \pm 0.23 \pm 0.89_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c2}{}^{direct} X) = (0.89 \pm 0.20 \pm 0.07 \pm 0.36_{\mathcal{B}})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

- Relation between LDME from HQSS:

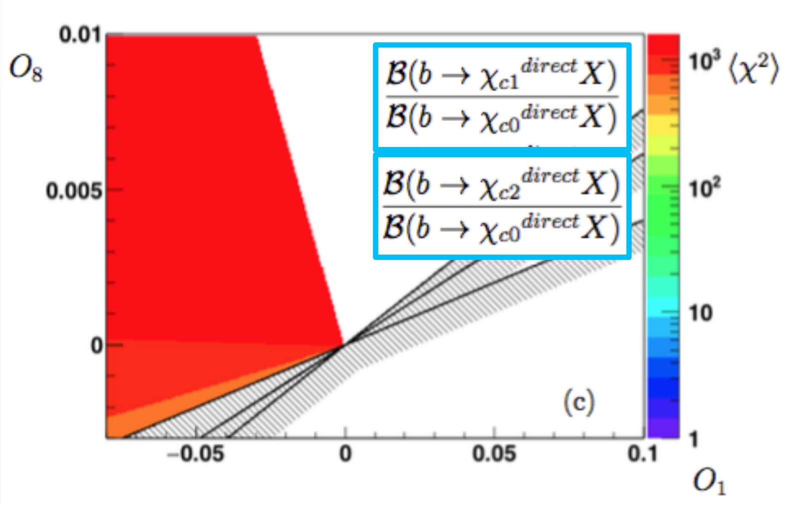
$$O_1 \equiv \langle O_1^{\chi_{c0}}(^3P_0)\rangle / m_c^2,$$
$$O_8 \equiv \langle O_8^{\chi_{c0}}(^3S_1)\rangle,$$
$$\langle O_1^{\chi_{cJ}}(^3P_J)\rangle / m_c^2 = (2J+1) O_1,$$
$$\langle O_8^{\chi_{cJ}}(^3S_1)\rangle = (2J+1) O_8.$$

- Short-distance coefficients calculated within NRQCD NLO
Beneke, Maltoni, Rothstein, PRD 59, 054003

1. Fit two LDMEs to three measurements:



2. Discrepancy when fitting two LDMEs to two relative production measurements:



Conclusions

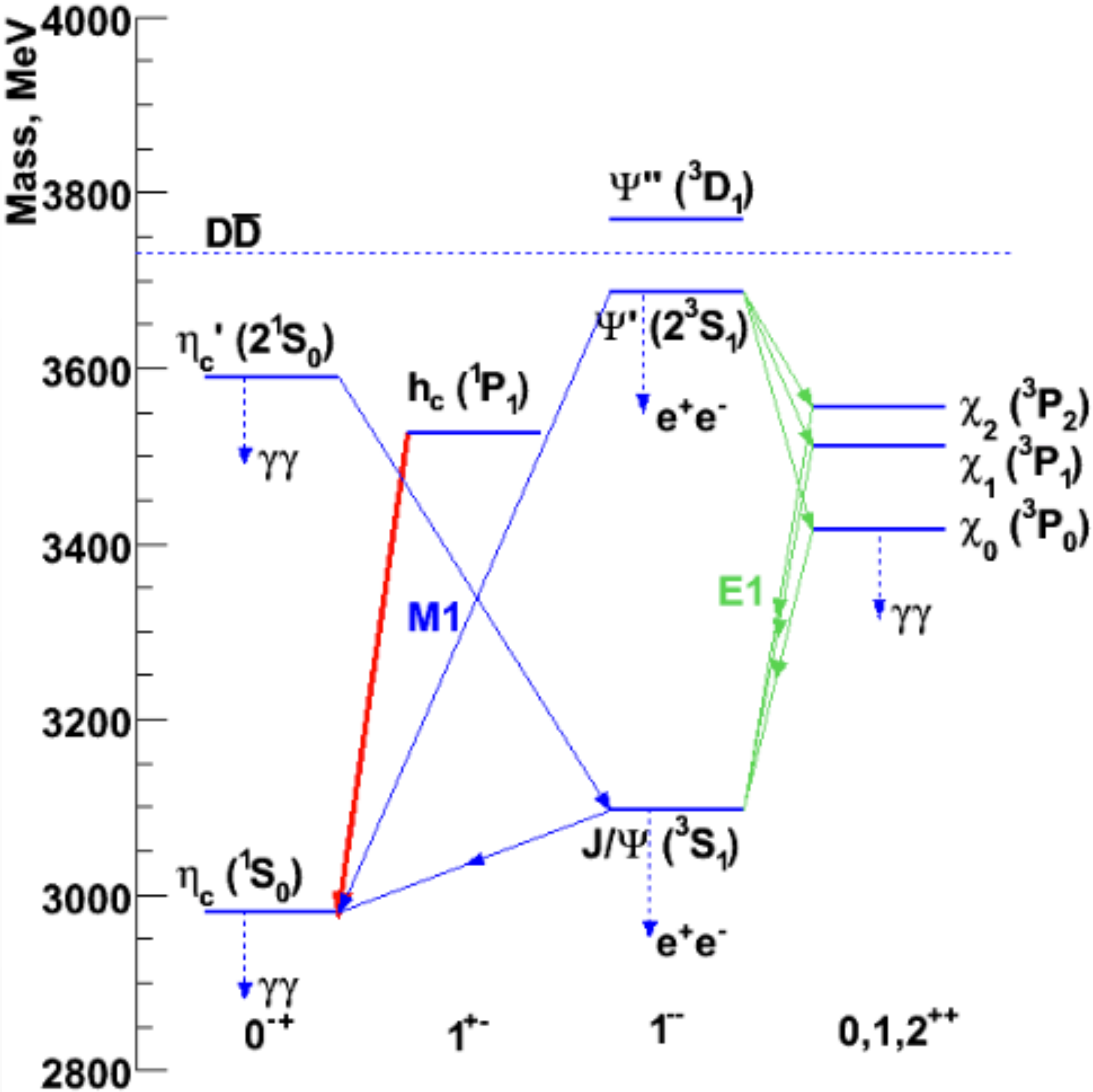
- Description of charmonium production at LHC is a challenge for QCD

- Decays to hadrons give access to **η_c(1S), χ_{c0}(1P), η_c(2S) and h_c(1P)** states
- LHCb is well suited to measure charmonia decays to hadrons

- **First measurement of η_c(1S) prompt production** using its decay to **ppbar at LHCb** is saturated by CS contribution
- The only reasonable theoretical description of **η_c(1S) prompt production** in the market**, hierarchy problem in CO contributions**

- **First measurement of χ_c production in inclusive b-decays using $\varphi\varphi$**
- χ_c production in inclusive b-decays is in disagreement with theory

Prospects
- new more precise measurement of **η_c(1S)** production using Run II data on the way
- strong request for **prompt η_c(2S) production measurement:**
hunting for prompt η_c(2S) using ppbar and/or $\varphi\varphi$ using 2018 data

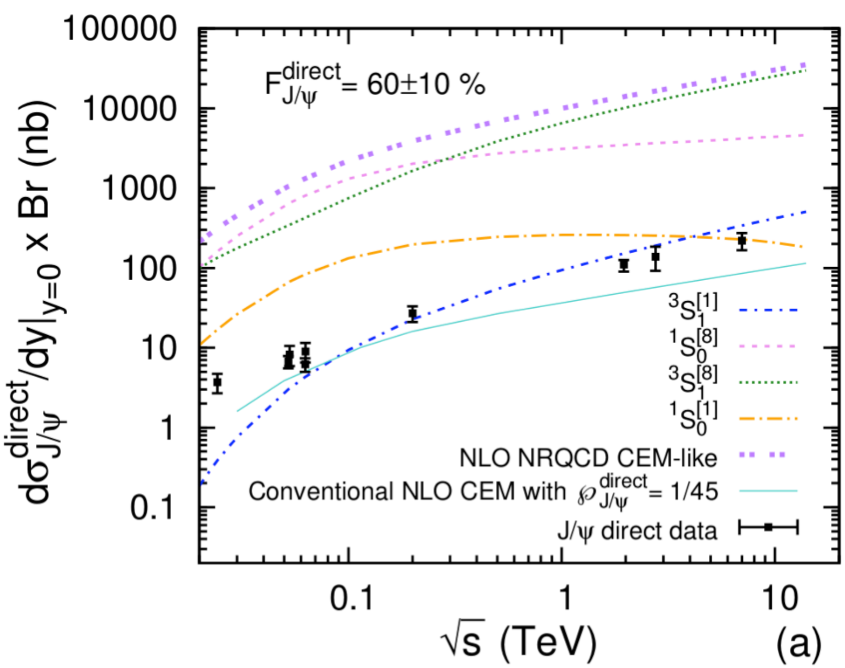

Mass, MeV
4000
3800
3600
3400
3200
3000
2800
DD̄
Ψ'' (³D₁)
Ψ' (2³S₁)
e⁺e⁻
ηc' (2¹S₀)
γγ
hc (¹P₁)
χ₂ (³P₂)
χ₁ (³P₁)
χ₀ (³P₀)
γγ
M1
E1
J/Ψ (³S₁)
e⁺e⁻
ηc (¹S₀)
γγ
0⁻⁺
1⁺⁻
1⁻⁻
0,1,2⁺⁺

√s dependence of J/psi production vs CEM and CSM

Eur.Phys.J. C75(2015) 7, 313

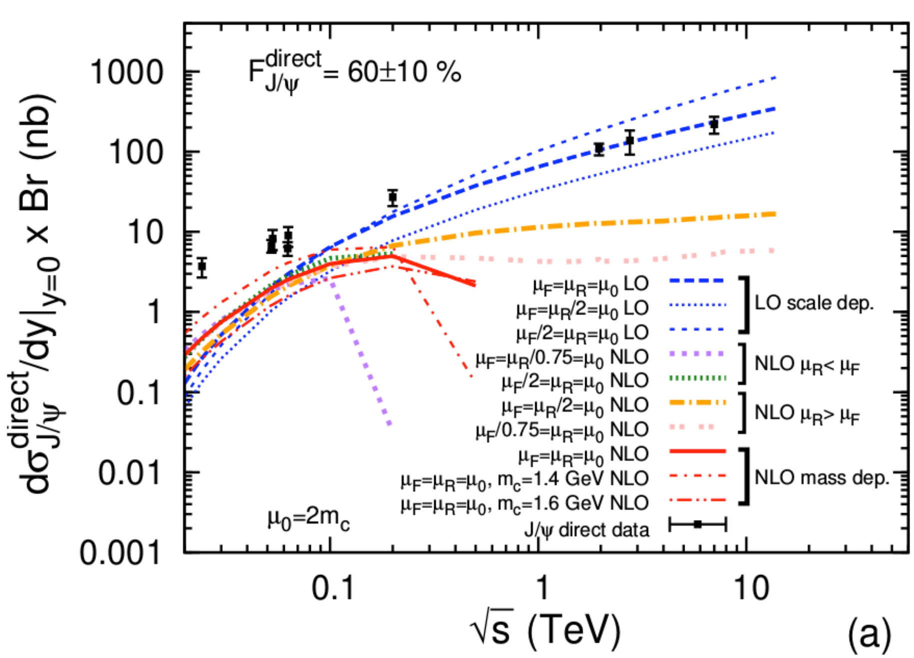
- **CEM cross section determination:**

$$\sigma_Q^{(N)LO,\ direct} = \mathcal{P}_Q^{direct} \int_{2m_Q}^{2m_H} \frac{d\sigma_{Q\bar{Q}}^{(N)LO}}{dm_{Q\bar{Q}}} dm_{Q\bar{Q}}$$



- **CSM:**

gives negative total cross section



Results:

- The total CEM-like contribution overshoots the data, by a factor >100.

Possible solutions:

- Large NNLO corrections are expected(?)
- Resume initial state radiation (?)

√s dependence of J/psi production vs NRQCD at NLO

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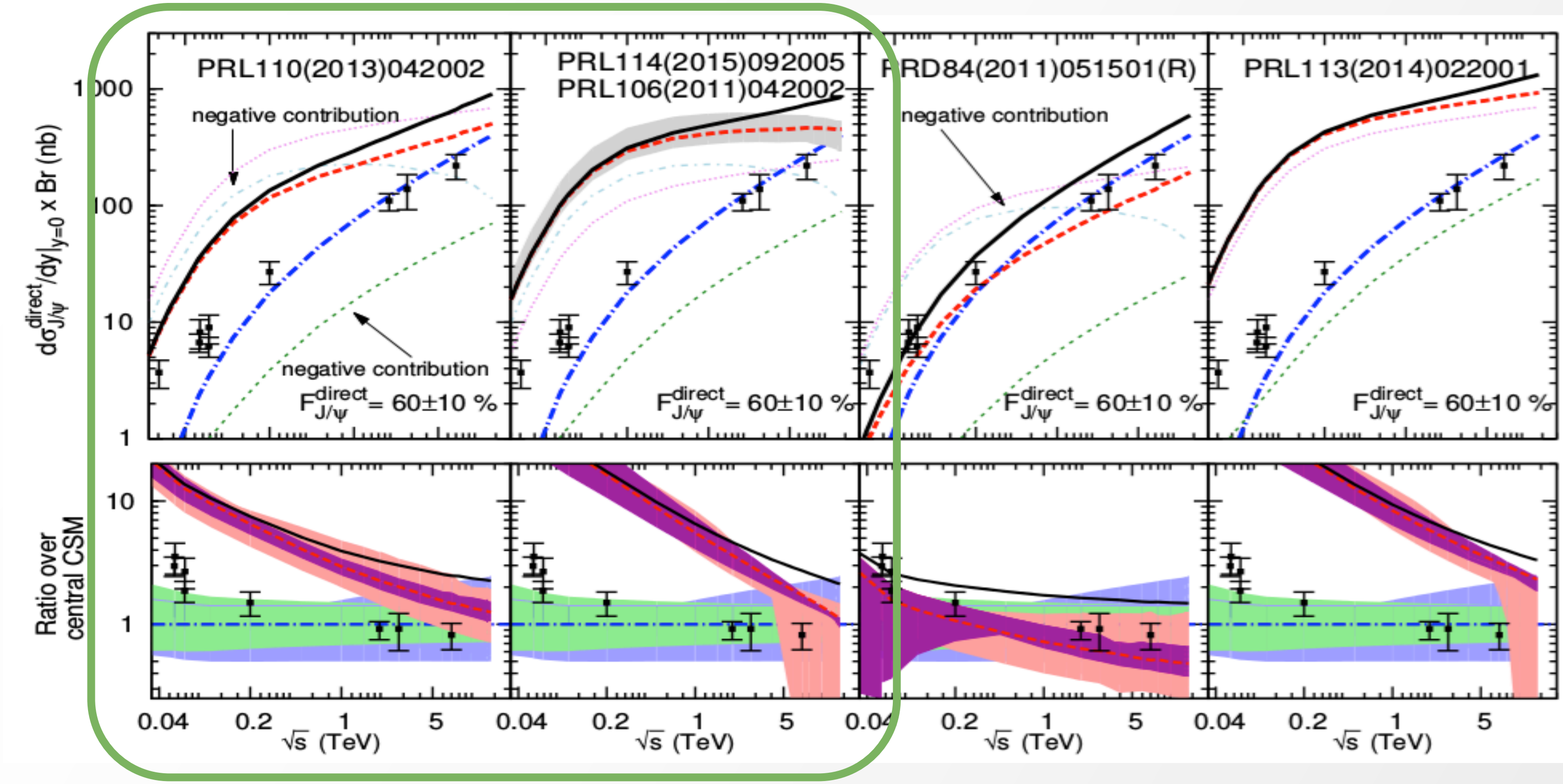
Available data from 4π experiments at ISR, RHIC, Tevatron and LHC



- Driven by medium- and large-p_T data:

$$7\ GeV < p_T < 20\ GeV \Rightarrow pp$$

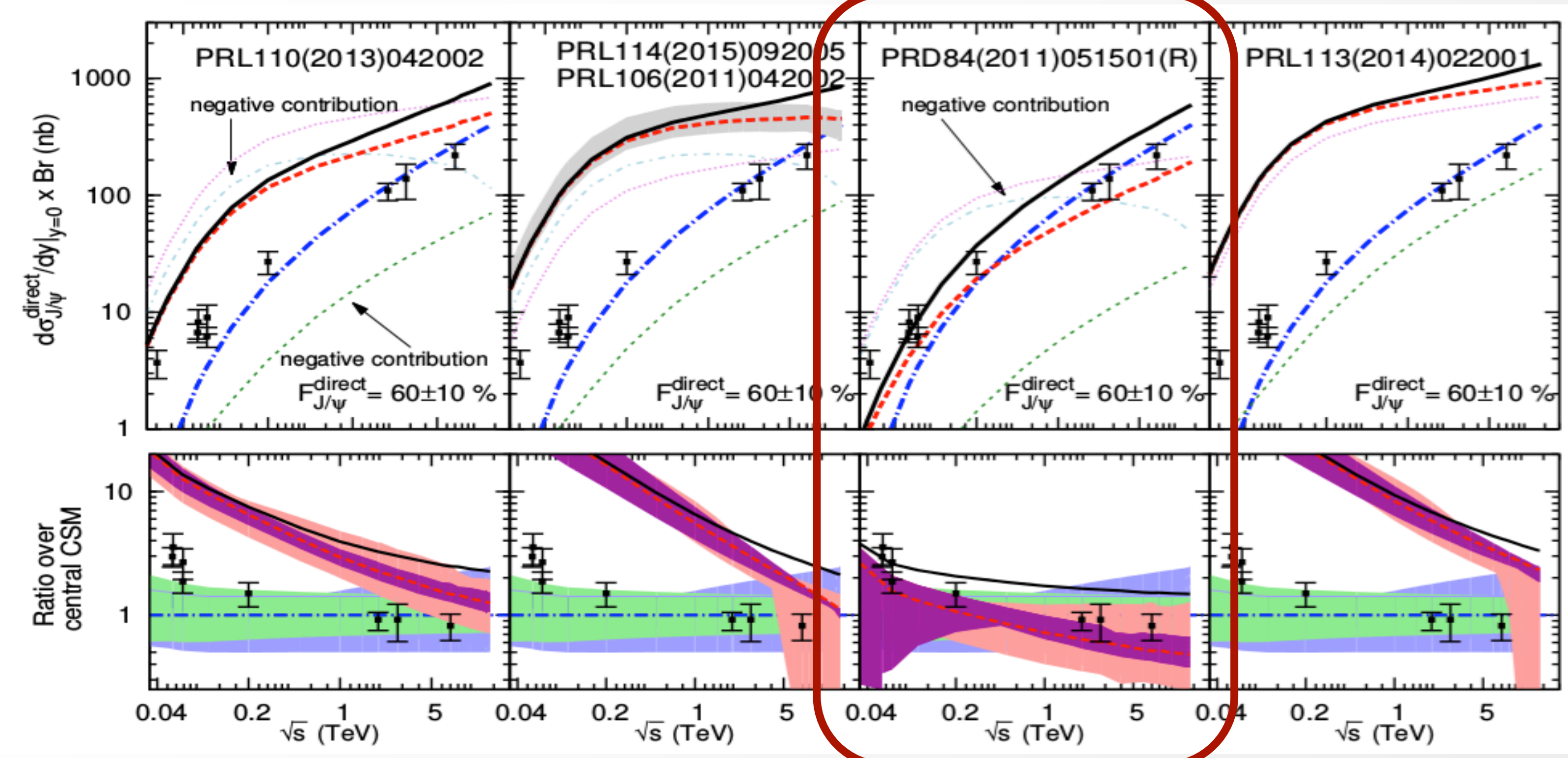
collisions

- Good description of large-p_T data
- Contradiction with low-p_T data

√s dependence of J/psi production vs NRQCD at NLO

Eur.Phys.J. C75(2015) 7, 313

Available data from 4π experiments at ISR, RHIC, Tevatron and LHC



- Driven by low- and medium-p_T data:

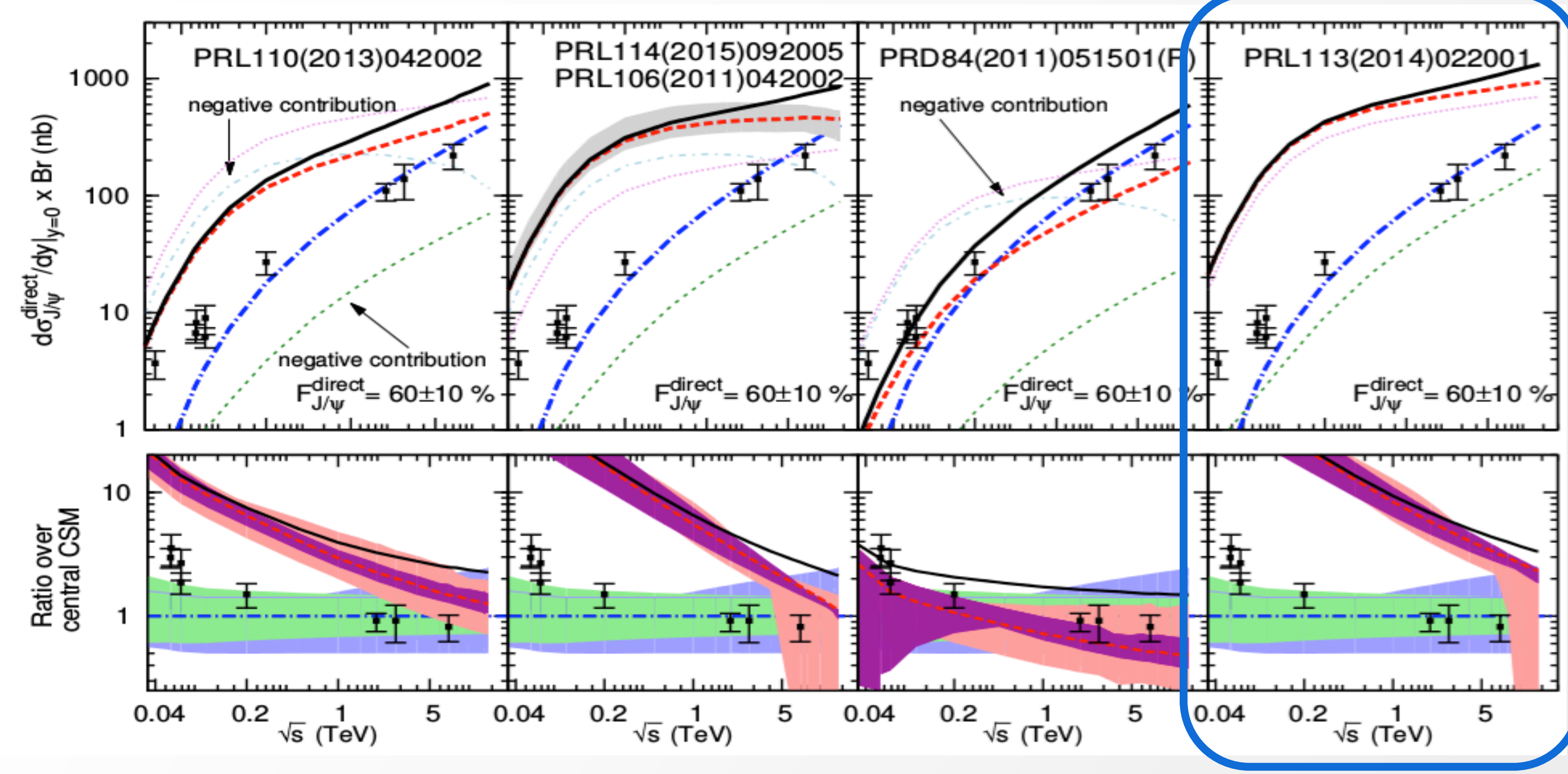
  $3\ GeV < p_T < 20\ GeV \Rightarrow pp$

  $1\ GeV < p_T < 10\ GeV \Rightarrow \gamma\gamma,\ ep$
- Agreement with e^+e^- and p_T-integrated
- Contradiction with polarization data
- Tension with $\gamma\gamma$ data

√s dependence of J/psi production vs NRQCD at NLO

Eur.Phys.J. C75(2015) 7, 313

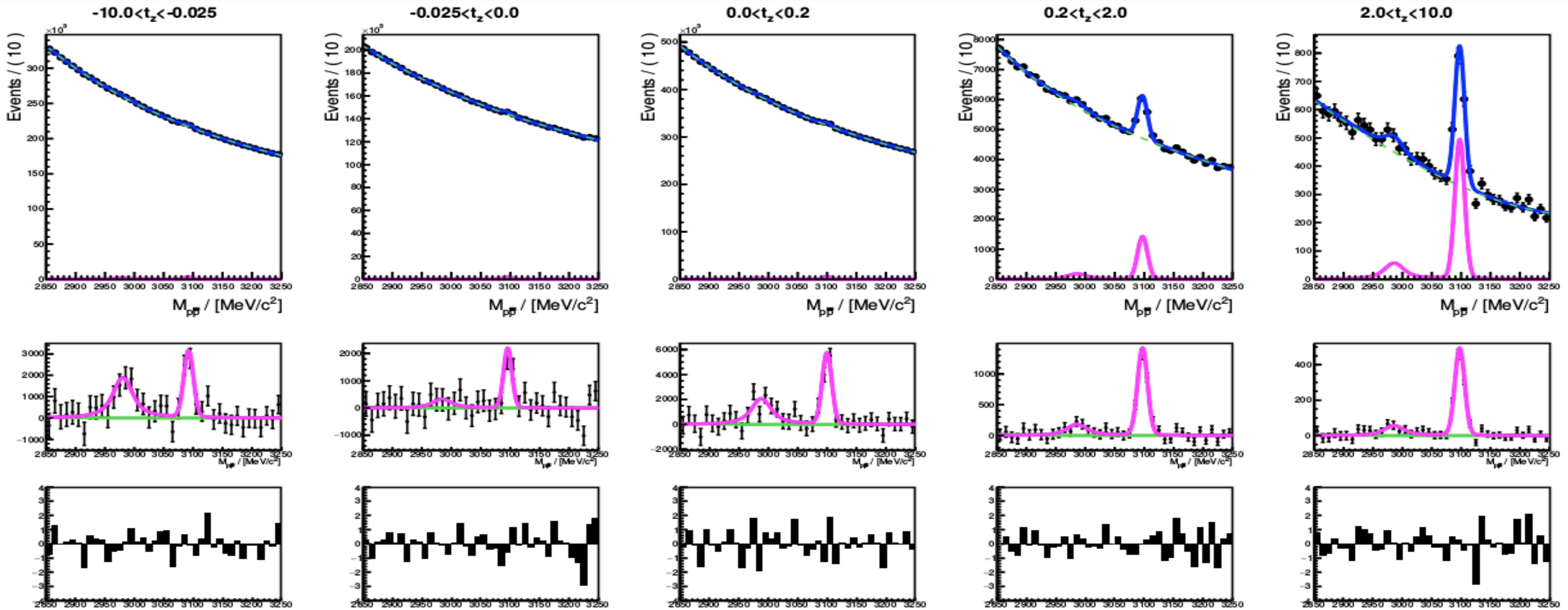
Available data from 4π experiments at RHIC, Tevatron and LHC



- Driven by medium- and large-p_T data:
  $7\ GeV < p_T < 20\ GeV \Rightarrow pp$ collisions
- Good description of large-p_T data
- Worse p_T-integrated description

Simultaneous fit to M(pp)

Example: first bin of PT (6.5 < p_T < 8 GeV/c) :



	Fit result, [MeV/ c^2]	PDG, [MeV/c^2]
$\sigma_{\eta c}$	8.24 ± 0.14	-
$m_{J/\psi}$	3097.1 ± 0.1	3096.900 ±0.006
$m_{J/\psi}$-$m_{\eta c}$	111.6 ± 1.1	113.5 ± 0.5

Mass values are consistent with PDG

t_z simultaneous fit model

$$F(t_z) = \boxed{(N_p\delta(t_z)} + \boxed{\frac{N_b}{\tau_b}\exp -t_z/\tau_b)} * \boxed{DG(\mu, S_{J/\psi}, S_n/S_w, \beta)} + \boxed{N_t f_{tail}(t_z)}$$

prompt ccbar

ccbar from b-decays

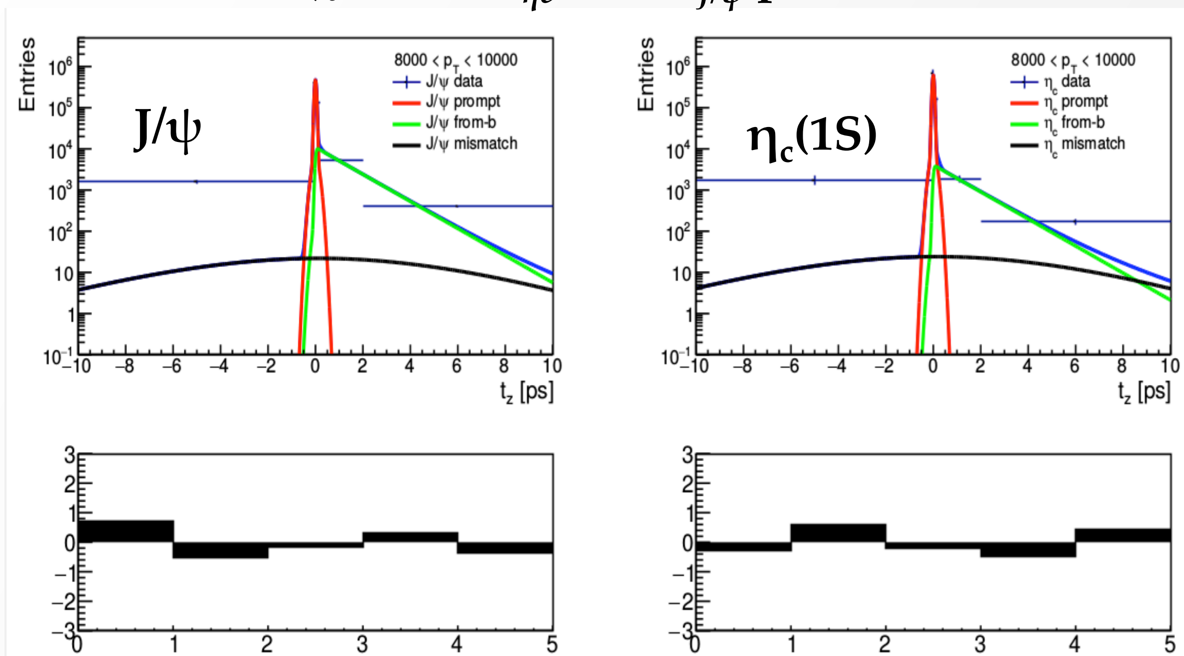
tz - resolution

events with mismatched PV

tz fit to data

$$F^{\eta_c}(t_z) = \boxed{(N_p\delta(t_z)} + \boxed{\frac{N_b}{\tau_b}\exp -t_z/\tau_b)} * DG(\mu, S_{J/\psi}, S_n/S_w, \beta) + \boxed{N_t f_{tail}(t_z)}$$

Simultaneous χ^2 fit to $N_{\eta c}$ and $N_{J/\psi}$ points from mass fit



tz bin

tz bin

$$\mu = (-0.5 \pm 1.8) \times 10^{-3}\ ps$$

$$S_{\eta_c, J/\psi} = (4.10 \pm 0.26) \times 10^{-2}\ ps$$

$$\tau_b = 1.269 \pm 0.040\ ps$$

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

Prompt $N^p{}_{\eta c}/N^p{}_{J/\psi}$ and from b-decays $N^b{}_{\eta c}/N^b{}_{J/\psi}$ exctracted in PT bins

and production in inclusive b-decays

Barsuk, Kou, Usachov LAL-17-051

- From **EPJC 75 (2015) 311** and **PDG:**

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

- Relation between LDME from HQSS:

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

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

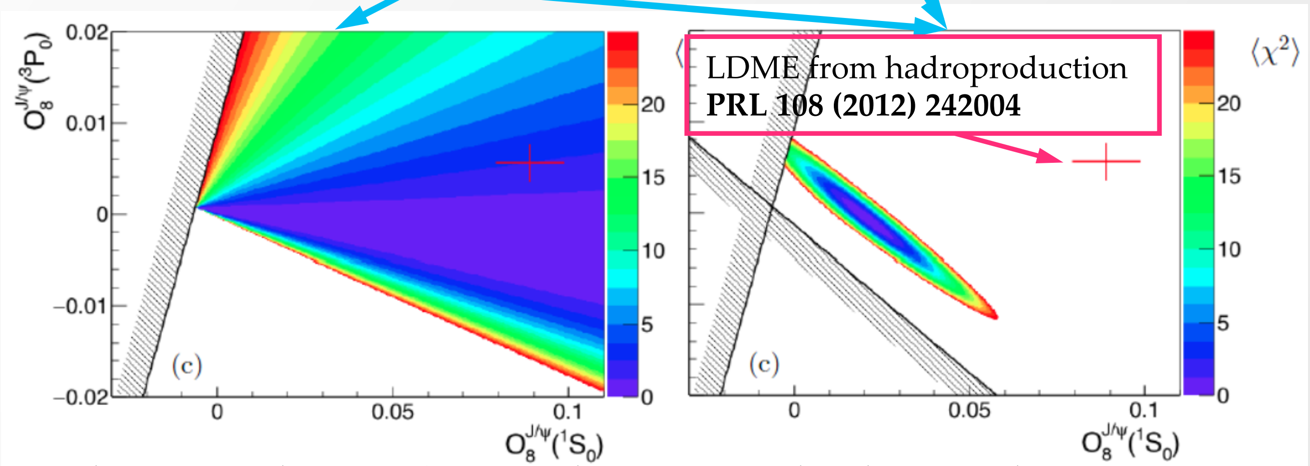
- **Fit two LDMEs to measurements**

- Consecutively fix two remaining LDME from **Chao et al., PRL 108 (2012) 242004**

$$\langle O_8^{J/\psi}(^3S_1)\rangle = 0.003\,\mathrm{GeV}^3$$
$$\langle O_8^{J/\psi}(^3S_1)\rangle = 1.16\,\mathrm{GeV}^3$$

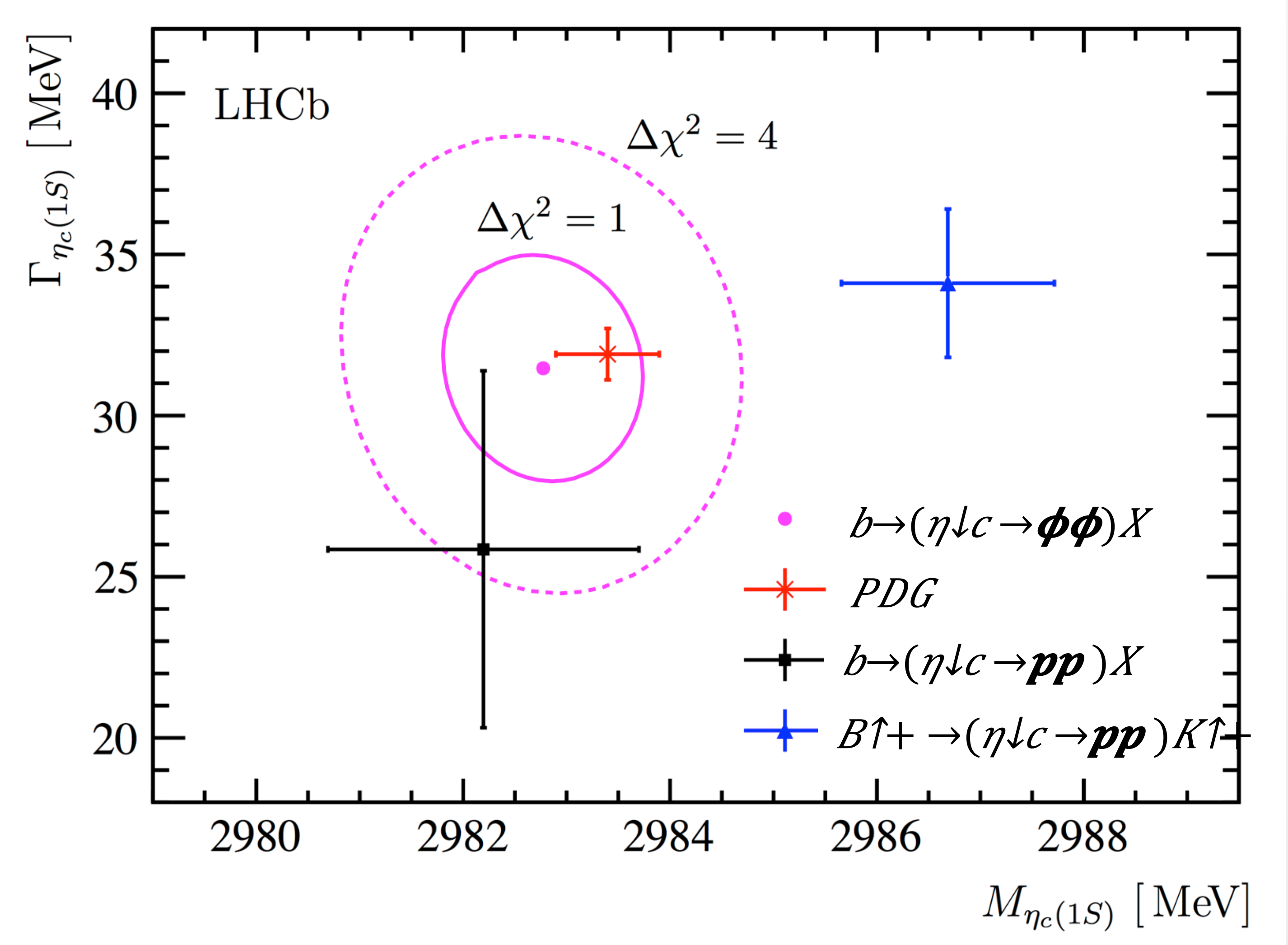
$$\frac{\mathcal{B}(b \to \eta_c(1S)^{direct} X)}{\mathcal{B}(b \to J/\psi^{direct} X)}$$

$$\mathcal{B}(b \to J/\psi^{direct} X)$$



- Constrain theory using **simultaneously** results on **charmonia hadroproduction and** on **charmonia from b-inclusive decays**

Spectroscopy with $\eta_c(1S)$ decays to hadrons at LHCb



EPJC 77, 609
EPJC 75, 311
PLB 769, 305

- General agreement with world average
- Similar to PDG precision expected for η_c mass with Run II data