Production of heavy quarks and quarkonia at LHC(b)

Vanya Belyaev (ITEP/Moscow)

Outline

- Heavy quark and quarkonia production
  - Why?
- LHCb experiment
- Open charm D^0 D^+ D_s Λ_c
- Hidden charm J/ψ ψ' χ_c
- Associative charm $2\times J/\psi$ $J/\psi+C$ $2\times C$ Z^0+C
- Bottomonia Υ
- Next steps and conclusion

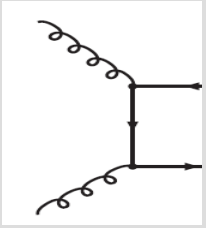
Heavy quarks & QCD

- HQ is likely the most powerful tool for quantitative study of QCD: $\alpha_s(m_Q)$, Λ_{QCD}/m_Q, ….
- Why one needs to know QCD ?
  - All mass of visible Universe is due to QCD
    - Higgs takes care only on O(1%) of proton mass
  - All fundamental quantities are affected by QCD corrections.

  The precise extraction is not possible without deep understanding of QCD
    - Dominant source of systematic for Higgs properties
  - strong *CP*-problem
  - QCD effects could nicely mimic New Physics: DPS
  - ….

HQ and quarkonia production

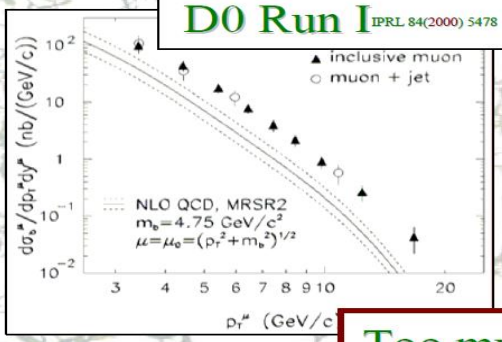
- For high energy proton-proton collision (LHC)
  - Mainly gluon–gluon fusion
  - Contribution for other sources is small
  - Simple?
  - Long and rich history, experimental and theoretical
    - End of XX-century @ Tevatron:
      - DATA/theory >> 10
  - Some improvements around mid 2000
  - Becomes clear that the pattern is not so simple….



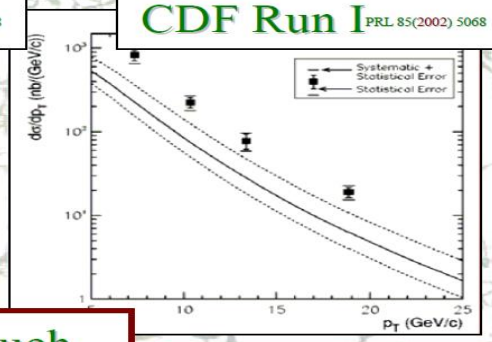
Some old slide: 2005

Beauty production at High Energy

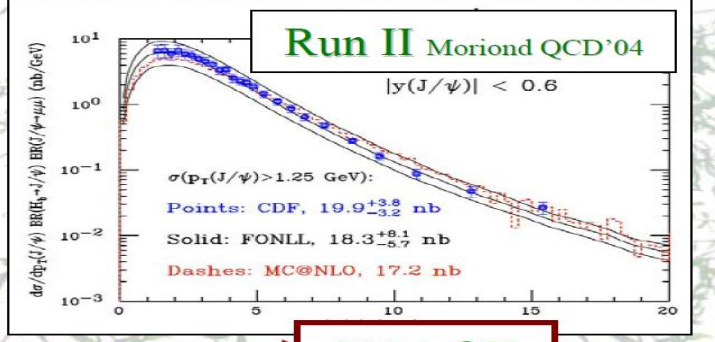
D0 Run I [PRL 84(2000) 5478]



CDF Run I [PRL 85(2002) 5068]

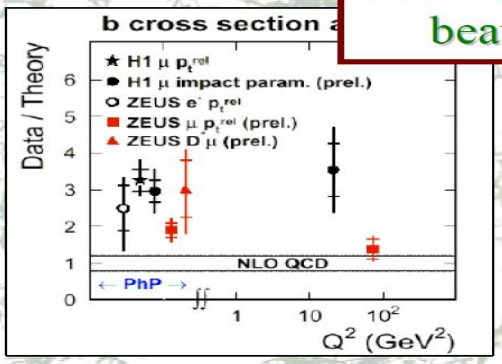


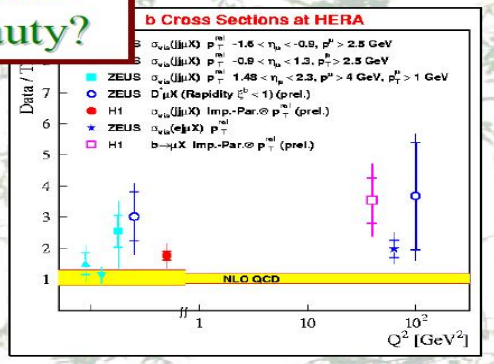
Run II Moriond QCD'04

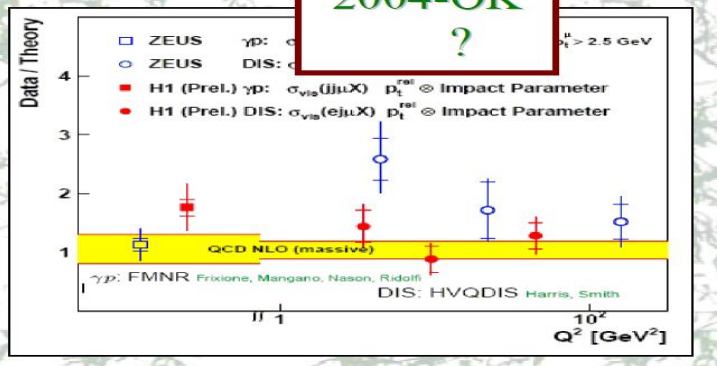


Too much beauty?

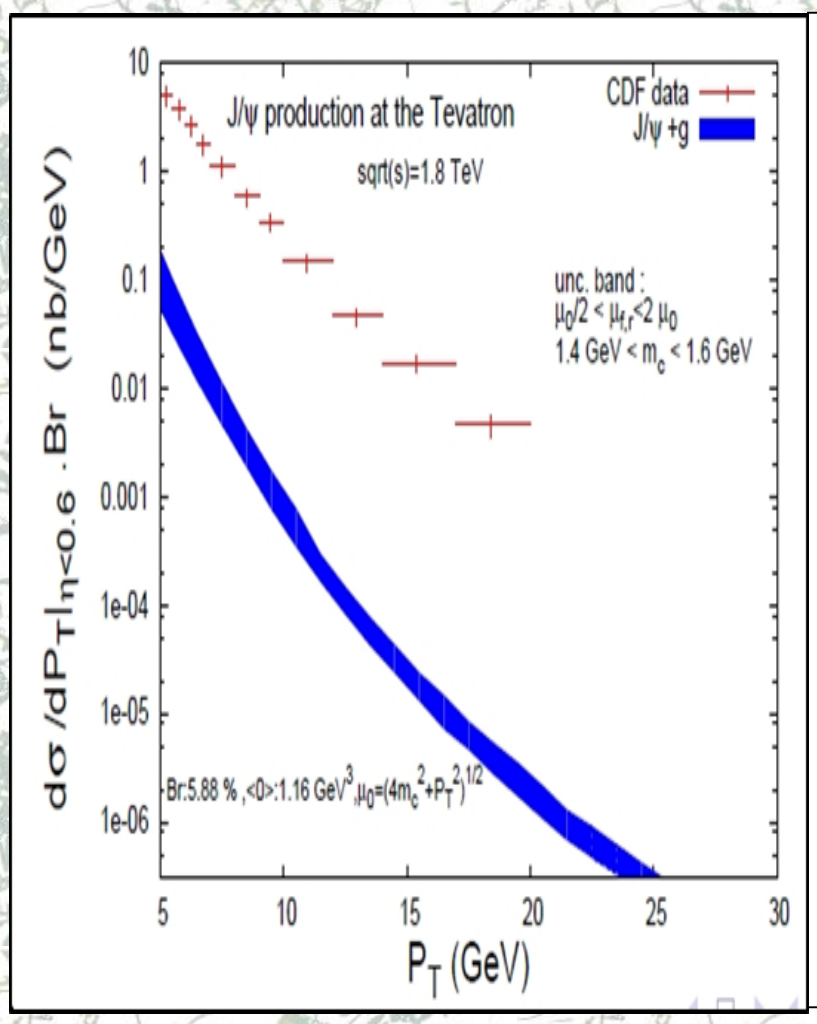
2004-OK ?



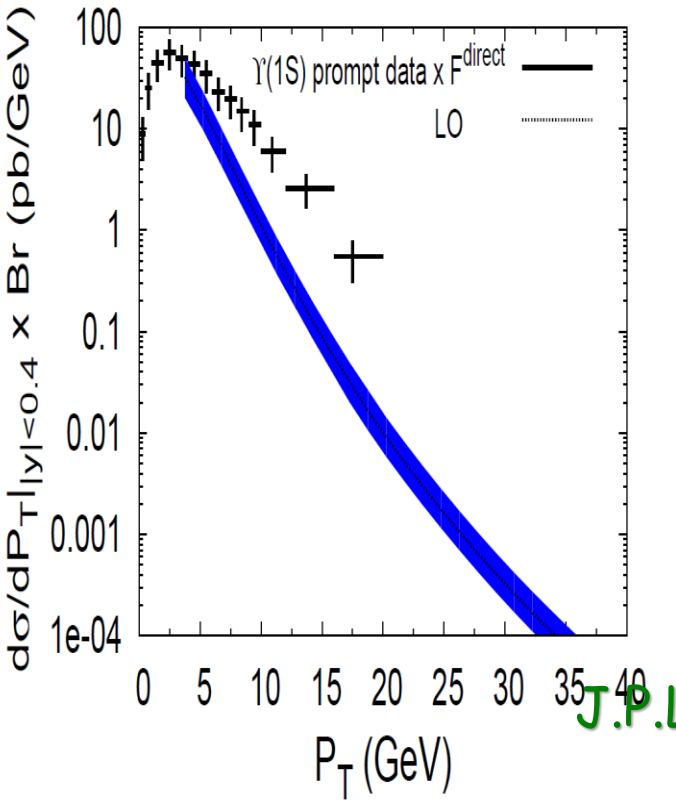


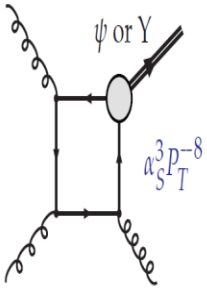


Another example J/ψ&ϒ @Tevatron



J.Campbell, F. Maltoni, F. Tramontano, Phys.Rev.Lett. 98:252002,2007
P.Artoisenet, J.Campbell, JPL, F.Maltoni, F. Tramontano, Phys. Rev. Lett. 101, 152001 (2008)
CDF PRL 88 (2002) 161802;PRD 87, 052004 (2013)



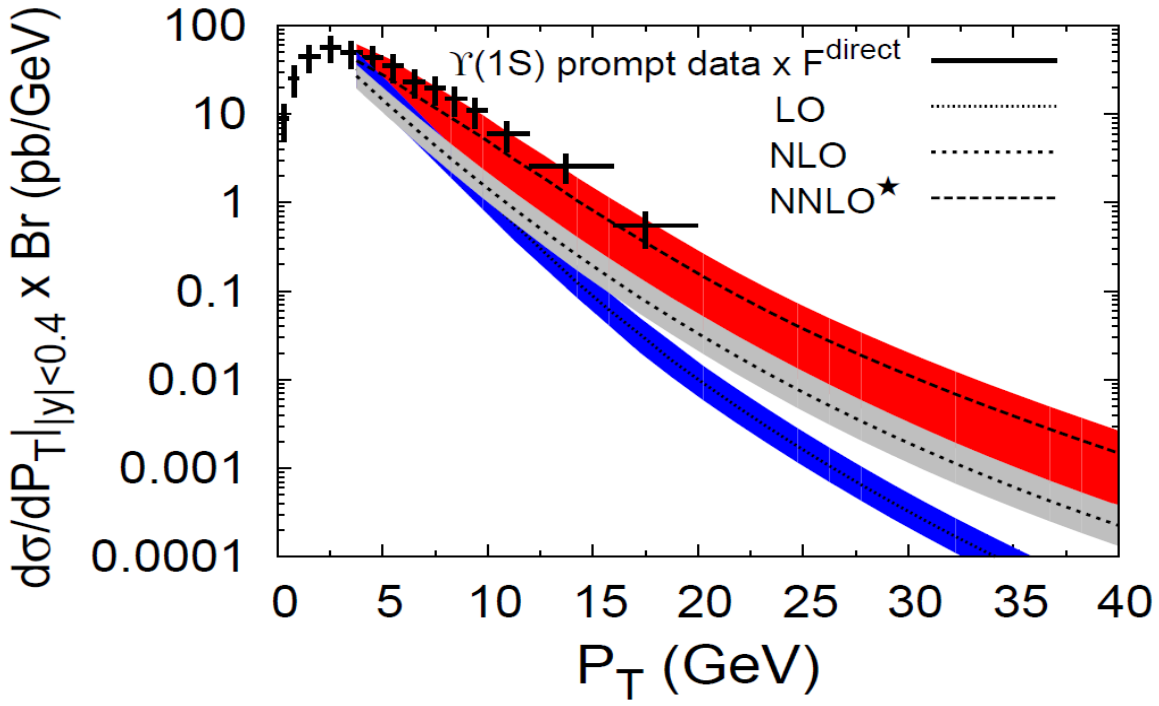


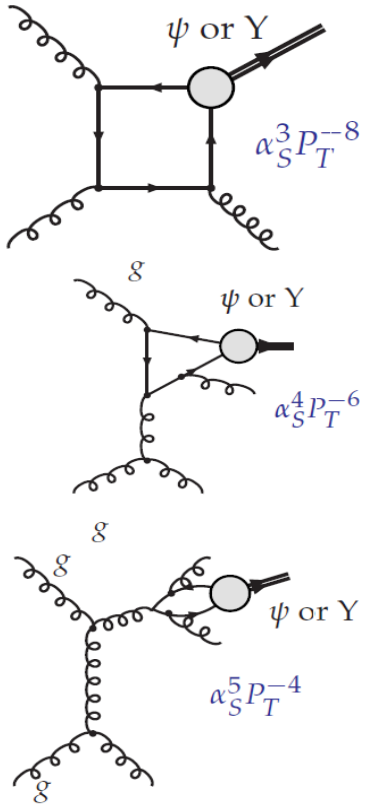
J.P.Lansberg

Progress with theory

J.P.Lansberg

J.Campbell, F. Maltoni, F. Tramontano, Phys.Rev.Lett. 98:252002,2007
P.Artoisenet, J.Campbell, JPL, F.Maltoni, F. Tramontano, Phys. Rev. Lett. 101, 152001 (2008)
CDF PRL 88 (2002) 161802;PRD 87, 052004 (2013)





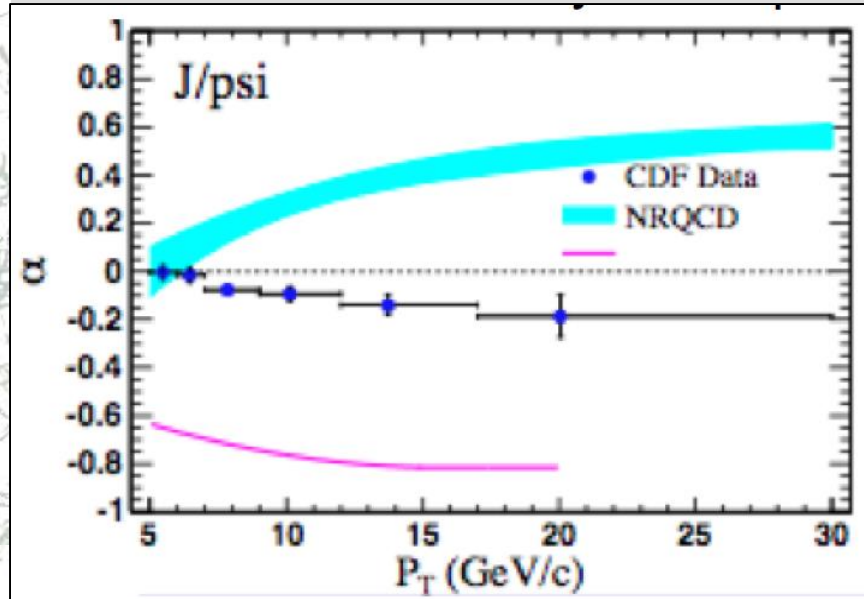
+ double t-channel gluon exchange at α_S^5

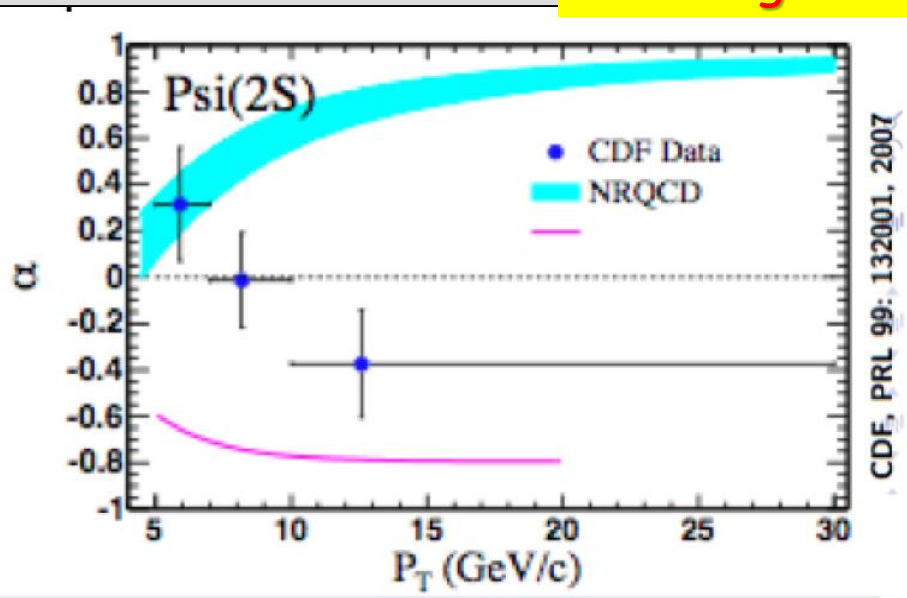
Attention: the NNLO* is not a complete NNLO

And what now?

- Almost 20 years of continuous progress
  - Great improvement between experiment and theory for cross-sections.
  - Everything understood?

Warning bell!



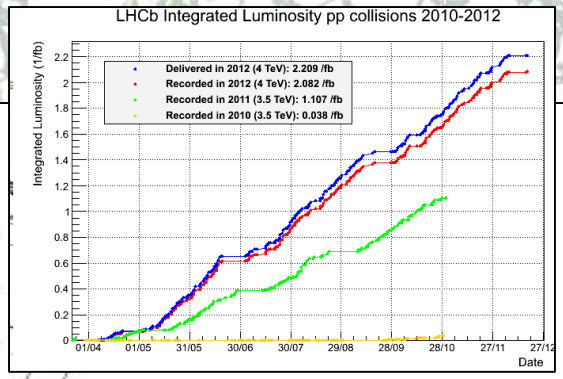


Polarization fiasco

- Reconsider the role of various mechanisms?
  - k_T-factorization?
- Importance of feed-down ?
  - Important to compare J/ψ and ψ'
  - Important to know production of P-wave states
- More data needed
- Other observables: $2\times J/\psi$, quarkonia in pPb, $J/\psi+C$, $J/\psi+\Upsilon$,..... may shed light on the problem

LHCb is trying to attack all these targets..

LHCb Experiment



- 1057 members
- 67 institutes
- 16 counties

2 groups from PRC
- Tsinghua
- CCNU

- 2<η<5
- 4% of solid angle
- 40% of HQ

pp-collisions
√s = 0.9, 2.76, 7 & 8
(13++ in 2015)
pA and Ap

Trigger & Selection

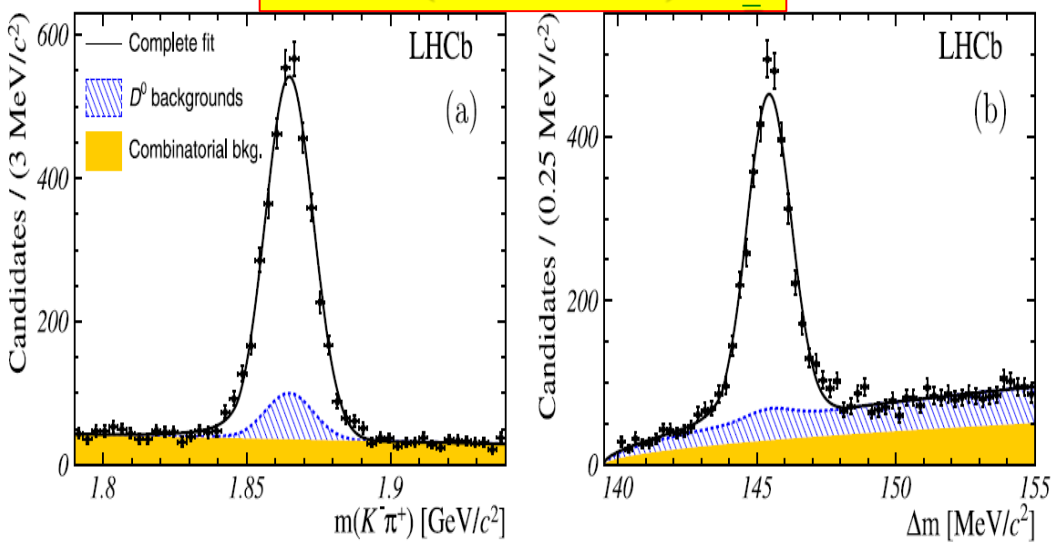
- Very flexible trigger, down to low-p_T particles
  - Hardware: energetic (di)muon, hadron, $e^{\pm}$ or γ
  - Software: full reconstruction & particle ID
  - Typical efficiency for 2μ states >70%, for hadronic states ~30%
- Offline:
  - Refine reconstruction, track quality, particle ID, good common vertices,
  - For open charm and beauty exploit finite lifetime and require vertex separation

Prompt open charm D^0, D^{*+}, D^+

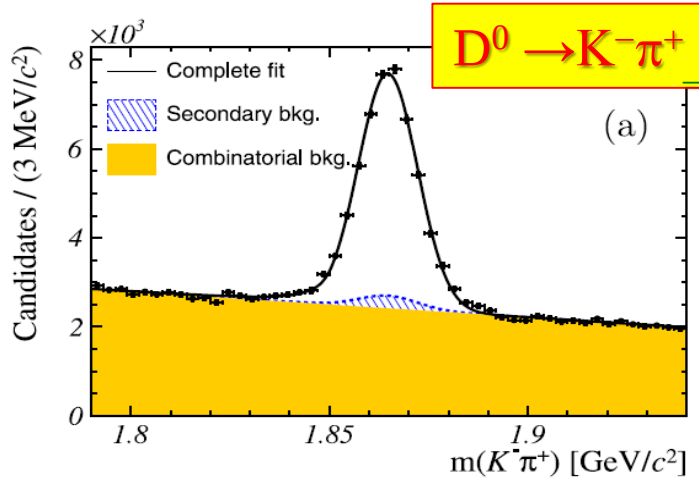
NPB 871(2013) 1

- "Early" measurement
  - only $15 nb^{-1}$
  - 5×10^{-6} from full dataset
- Contribution from b→c decays

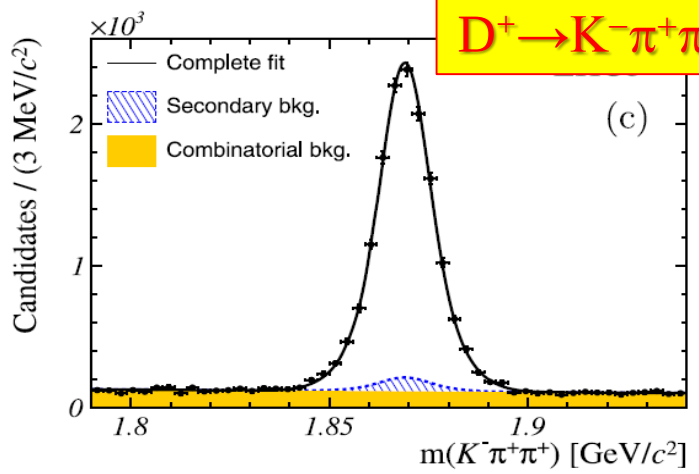
$D^{*+} \to (D^0 \to K^- \pi^+)\, \pi^+$



$D^0 \to K^- \pi^+$



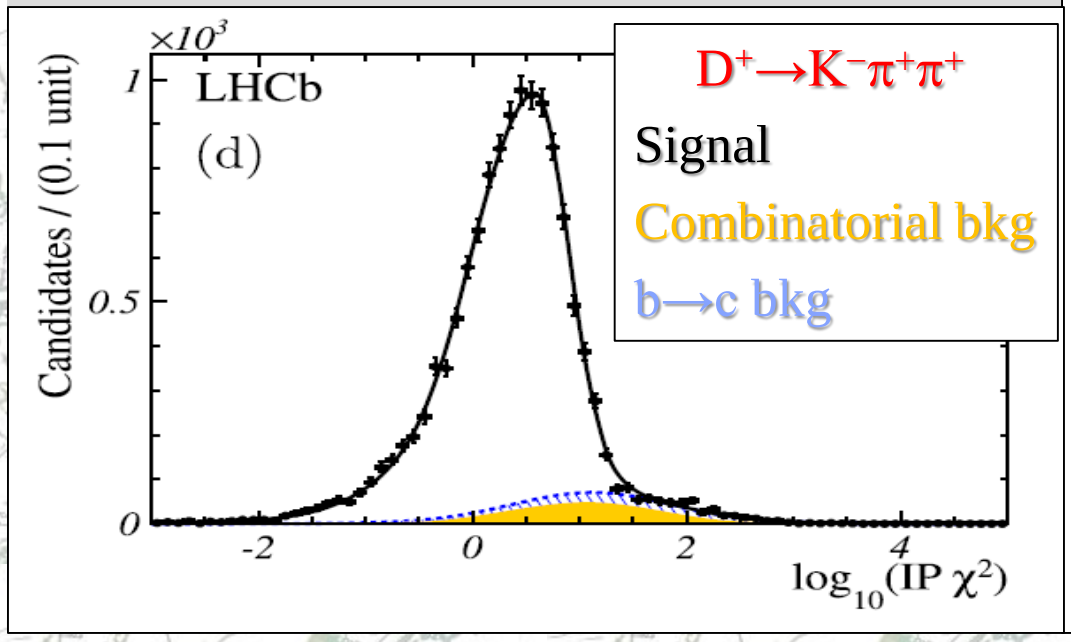
$D^+ \to K^- \pi^+ \pi^+$

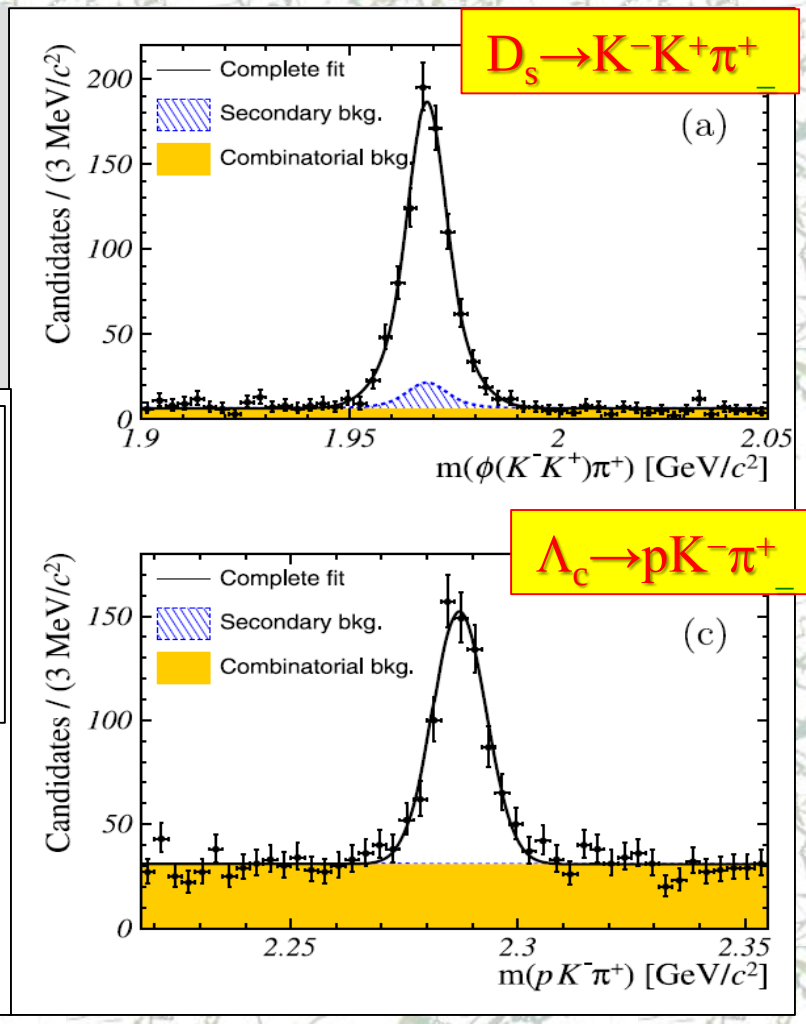


Prompt open charm D_s,Λ_c

NPB 871(2013) 1

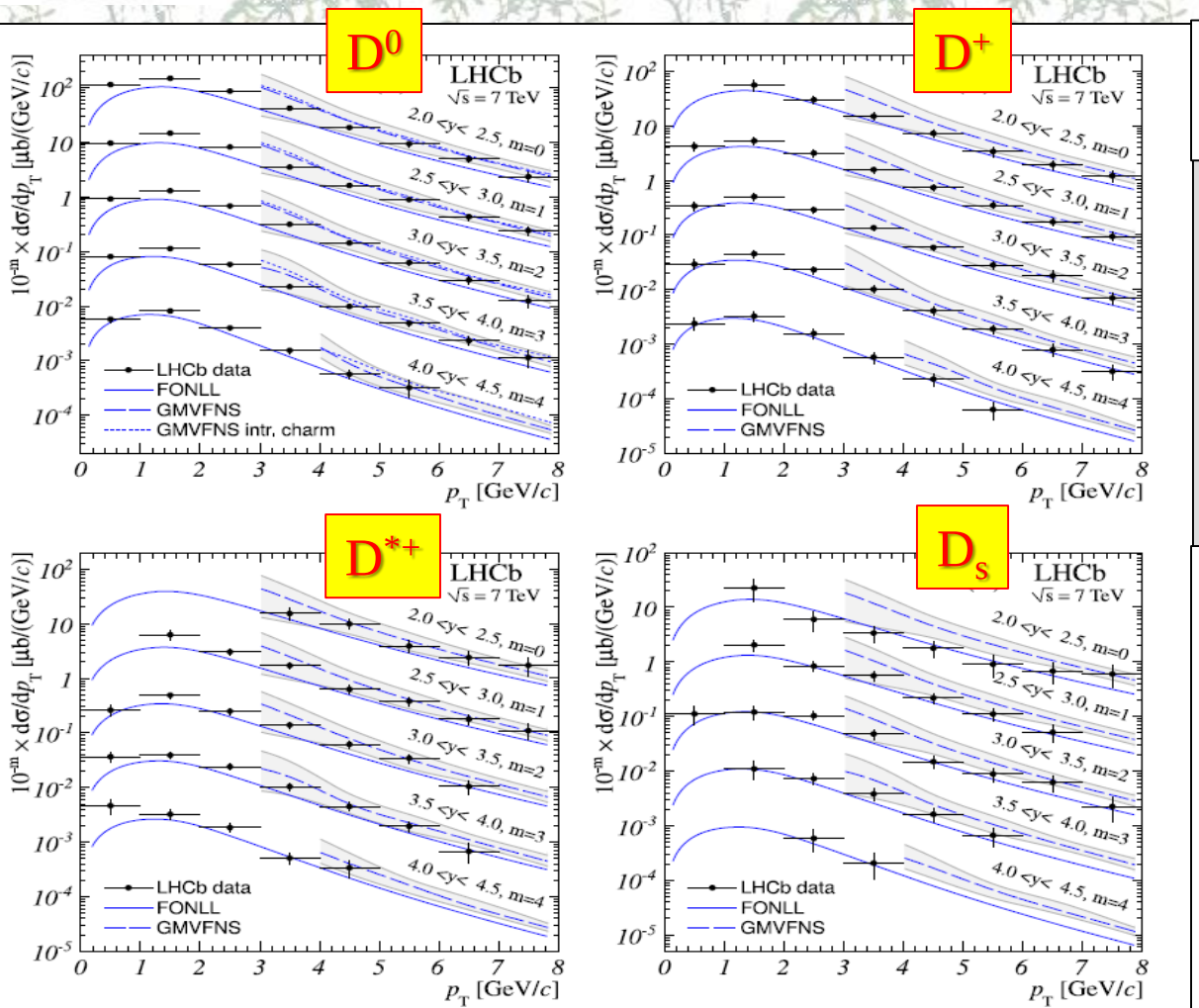
- All efficiencies were validated using data-driven techniques
- Major background has been extracted *directly from data*





Cross-sections vs theory

$$\sigma(c\bar{c})_{p_T<8\ \mathrm{GeV}/c,\ 2.0<y<4.5} = 1419 \pm 12\,(\mathrm{stat}) \pm 116\,(\mathrm{syst}) \pm 65\,(\mathrm{frag})\ \mu\mathrm{b}.$$



$$\frac{d\sigma_i(H_c)}{dp_T} = \frac{1}{\Delta p_T} \cdot \frac{N_i(H_c \to f + \mathrm{c.c.})}{\varepsilon_{i,\mathrm{tot}}(H_c \to f) \cdot \mathcal{B}(H_c \to f) \cdot \mathcal{L}_{\mathrm{int}}},$$

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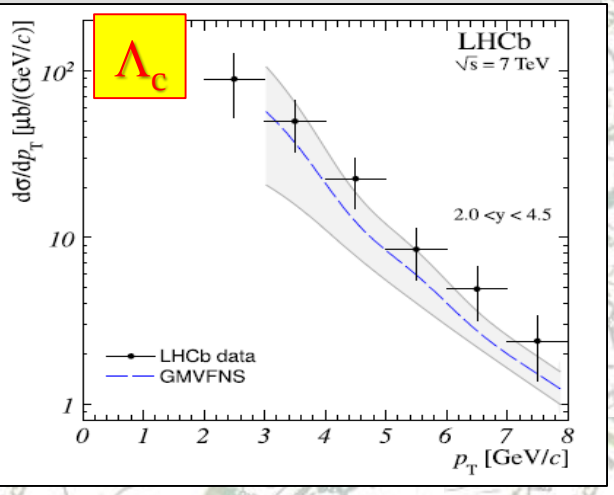
Good agreement with GMVFNS Kniehl *et al.* FONLL Cacciari *et al.*



Hidden charm J/ψ

EPJ C71 (2011) 1675

$J/\psi \rightarrow \mu^+\mu^-$ very nice signature, easy to trigger, low background

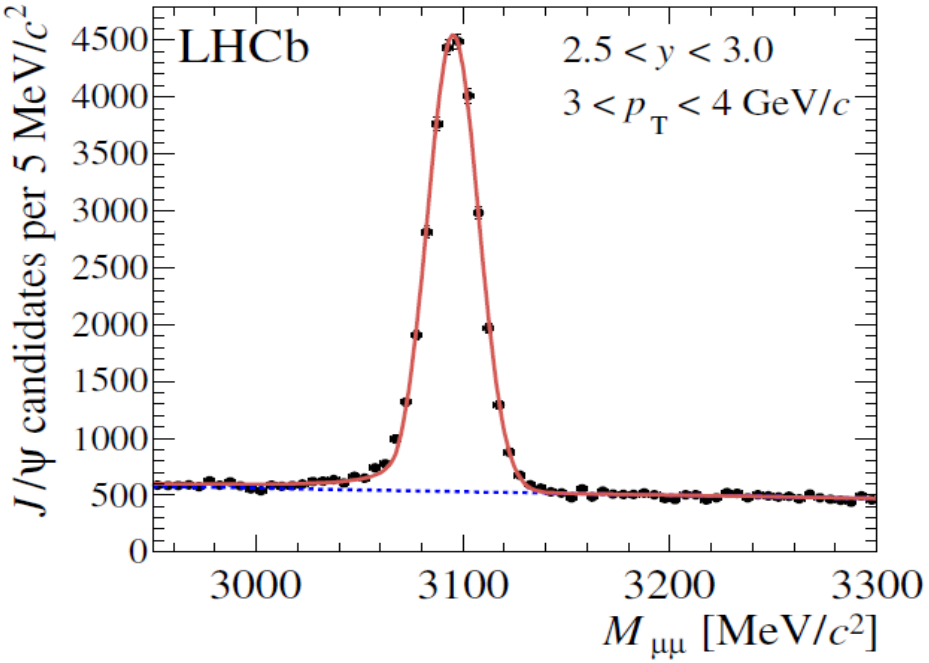
- Measure double differential cross-section

$$\frac{d^2\sigma}{dy\,dp_T} = \frac{N(J/\psi \rightarrow \mu^+\mu^-)}{\mathcal{L} \times \varepsilon_{tot} \times \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-) \times \Delta y \times \Delta p_T},$$

$2<y(J/\psi)<4.5$

$p_T(J/\psi)<14$ GeV/c

Efficiencies are validated on data



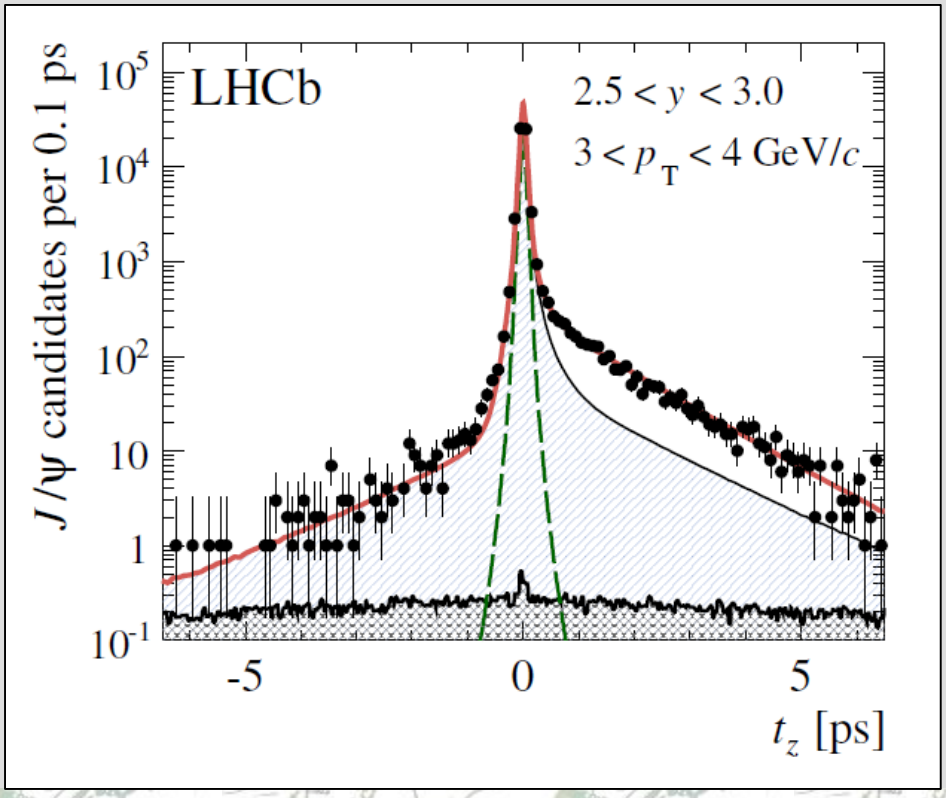
Contribution from B-decays

EPJ C71 (2011) 1675

- There is large contribution from decays of long-lived B-hadrons, $\beta\gamma c\tau \approx O(1\text{cm})$
- Use "pseudo-lifetime"

$$t_z = \frac{(z_{J/\psi} - z_{\mathrm{PV}}) \times M_{J/\psi}}{p_z},$$

- Simultaneous 2D-fit
  - $m(\mu^+\mu^-)$
  - t_z

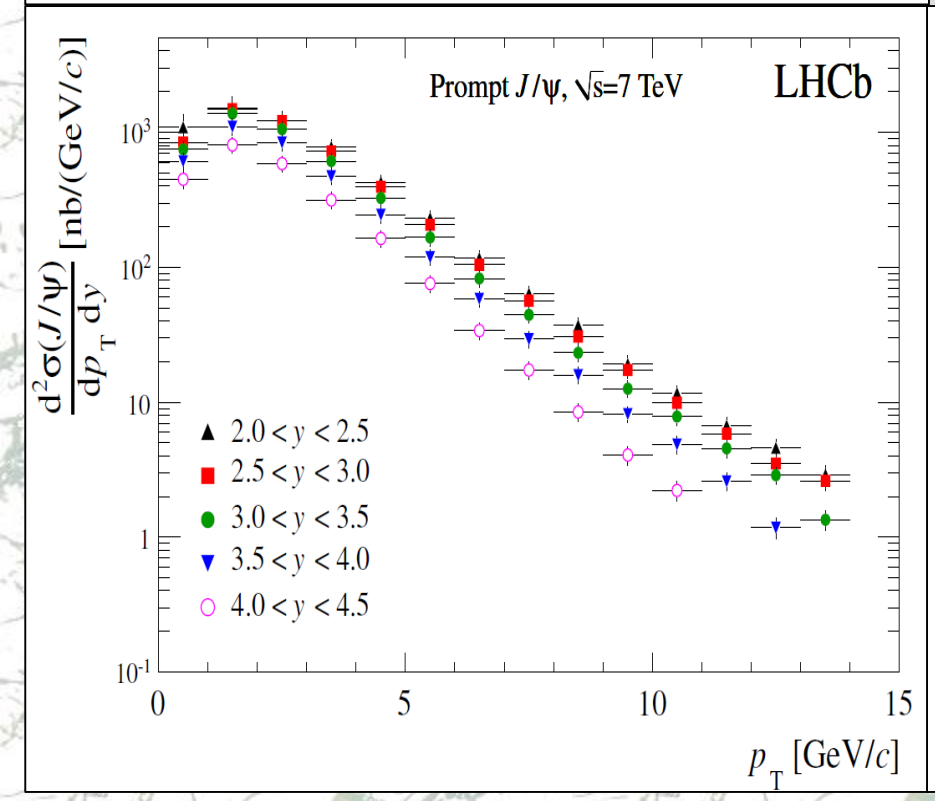


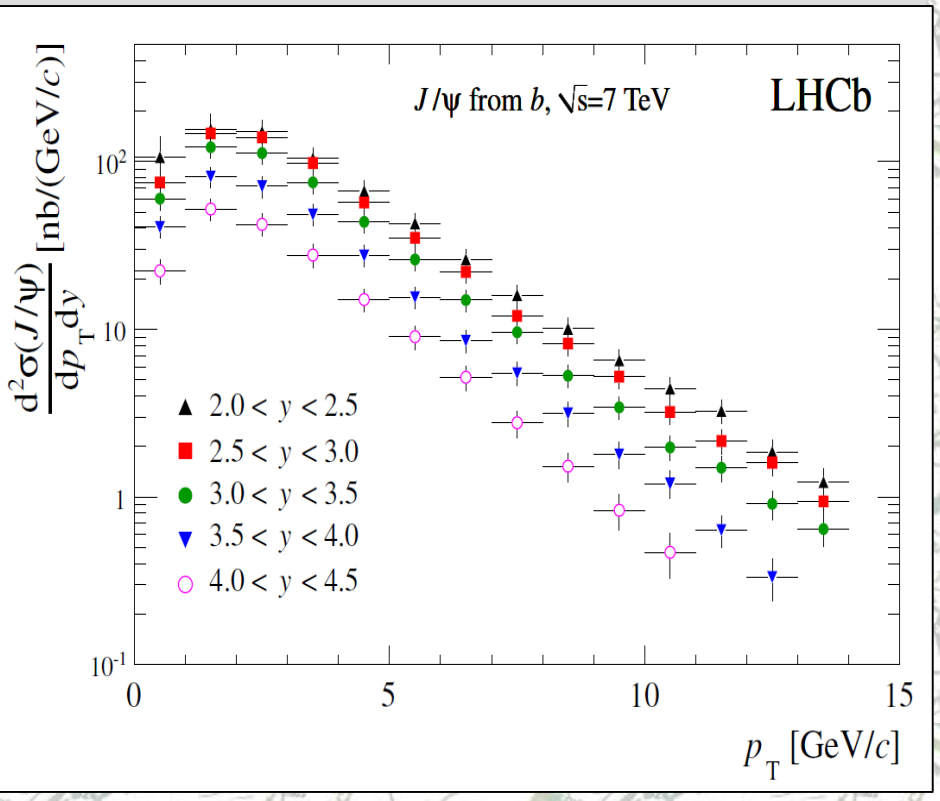
Differential cross-sections

EPJ C71 (2011) 1675

$$\frac{d^2\sigma}{dy\,dp_T} = \frac{N(J/\psi \to \mu^+\mu^-)}{\mathcal{L} \times \varepsilon_{tot} \times \mathcal{B}(J/\psi \to \mu^+\mu^-) \times \Delta y \times \Delta p_T},$$

The slopes are different!





Fraction of J/ψ from B-decays

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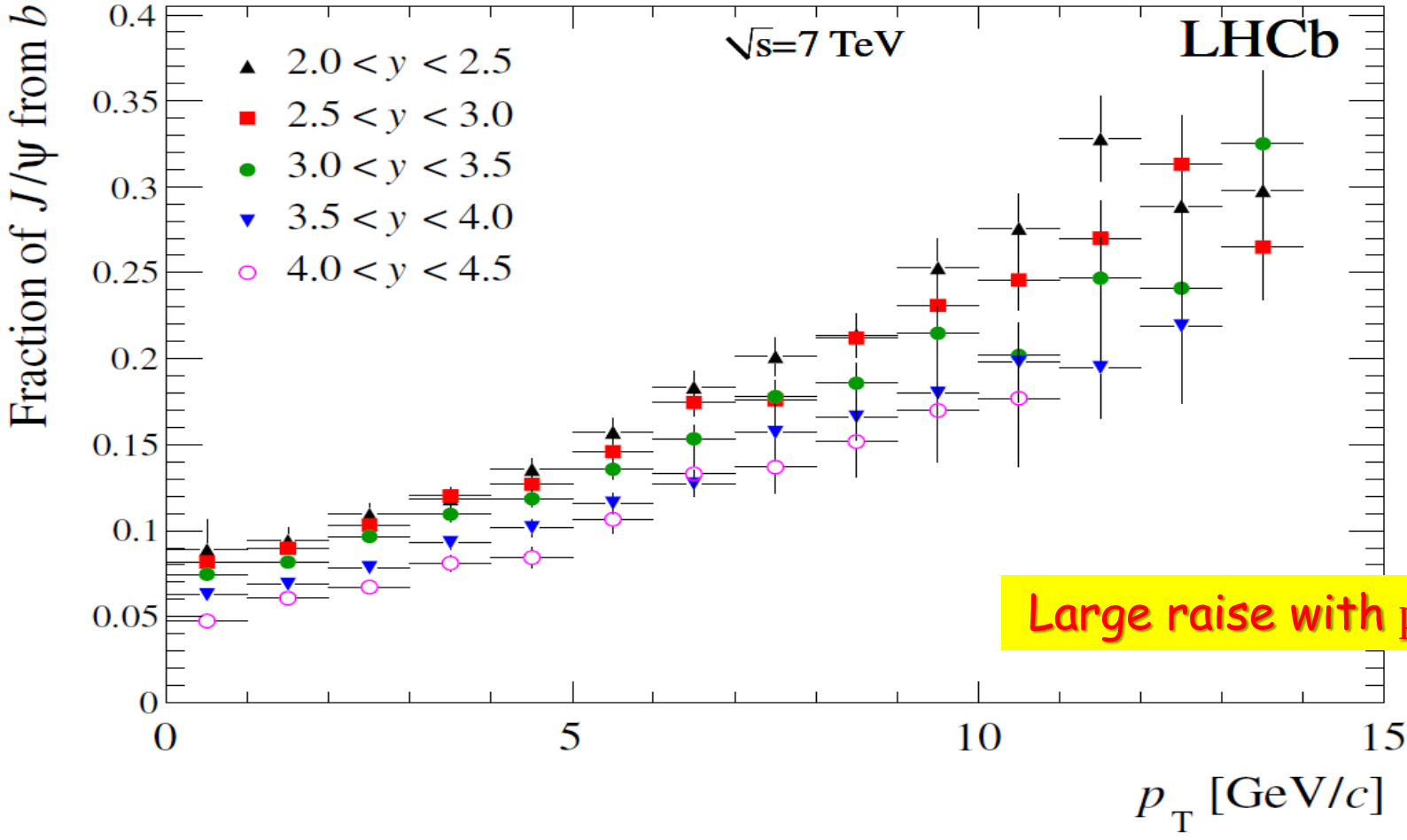

Prompt J/ψ DATA vs theory

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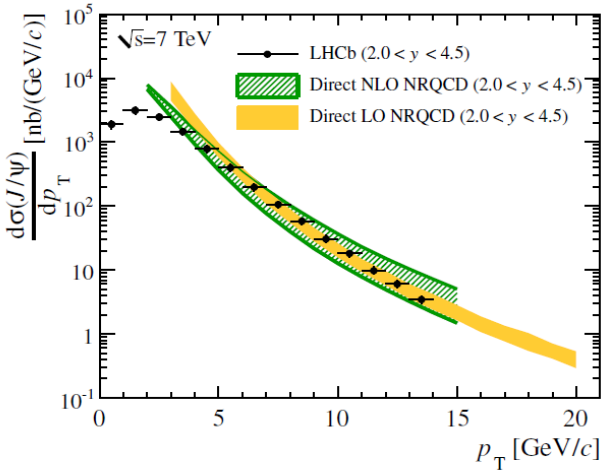
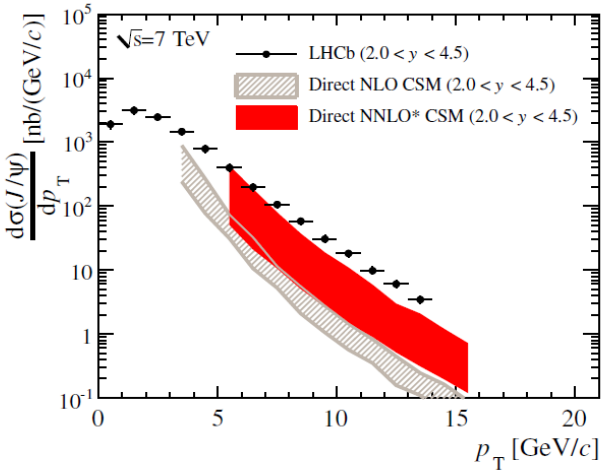
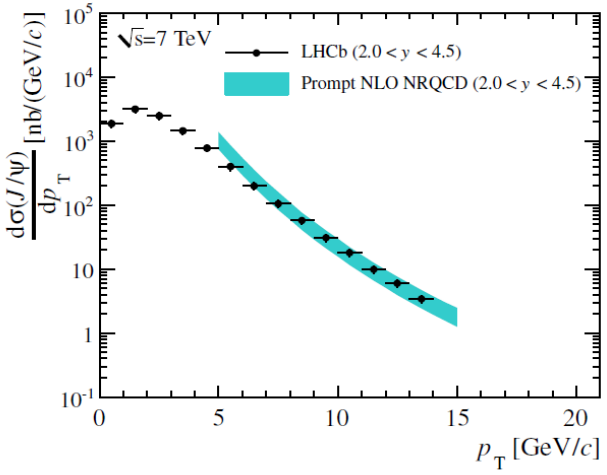
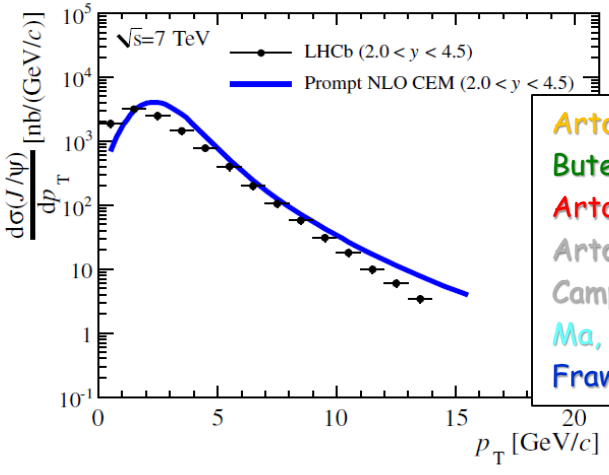




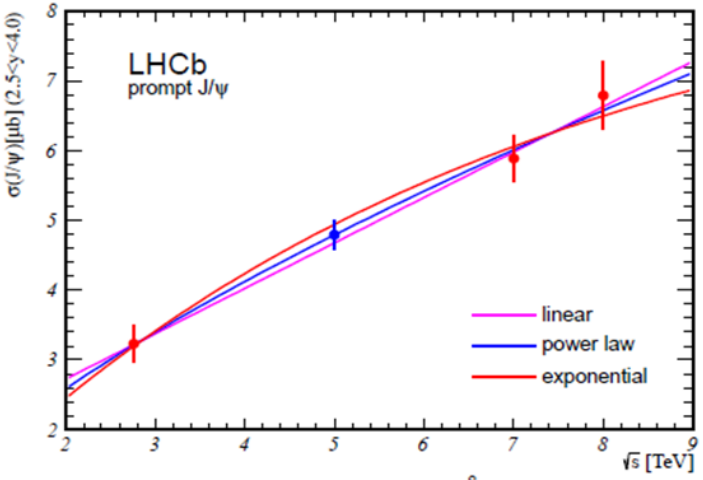


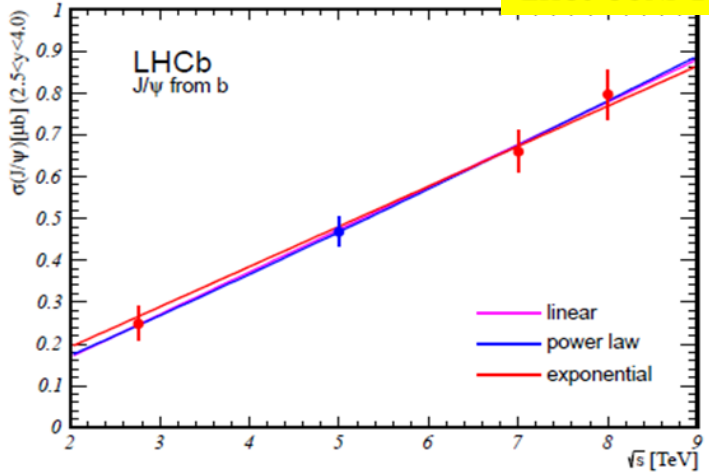


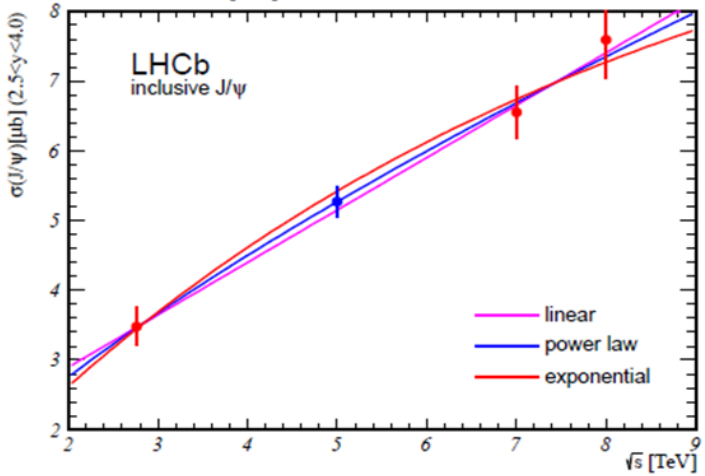
Artoisenet LO
Butenshoen & Kniehl NLO
Artoisenet et al, Lansberg, NNLO*
Artoisenet, Lansberg, Maltoni;
Campbell, Maltoni, Tramontano NLO CSM
Ma, Wang, Chao NLO CS+CO
Frawley, Ulrich, Vogt NLO CEM

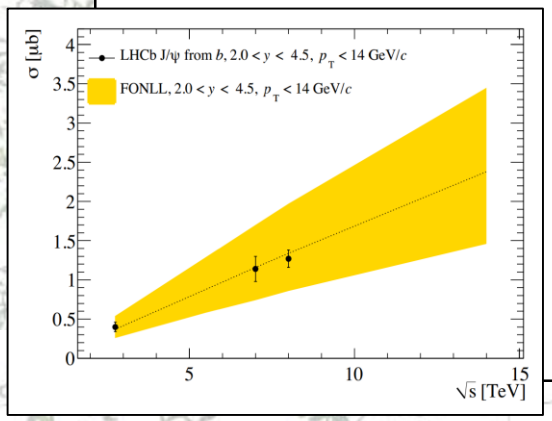
J/ψ at √s=2.76 & 8 TeV

ALICE-PUBLIC-2013-002
LHCb-CONF-2013-013







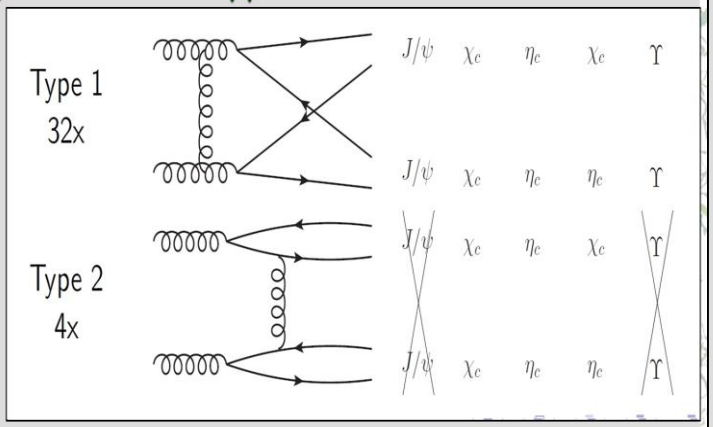


EPJ C71 (2011) 1675
JHEP 02 (2013) 041
JHEP 06 (2013) 064

Interesting case $2\times J/\psi$

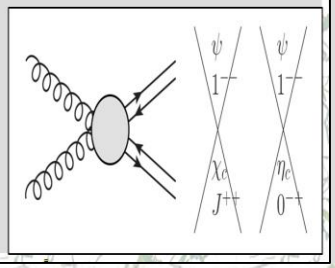
- Valuable information for CS vs CO discrimination

- 36 diagrams of two types

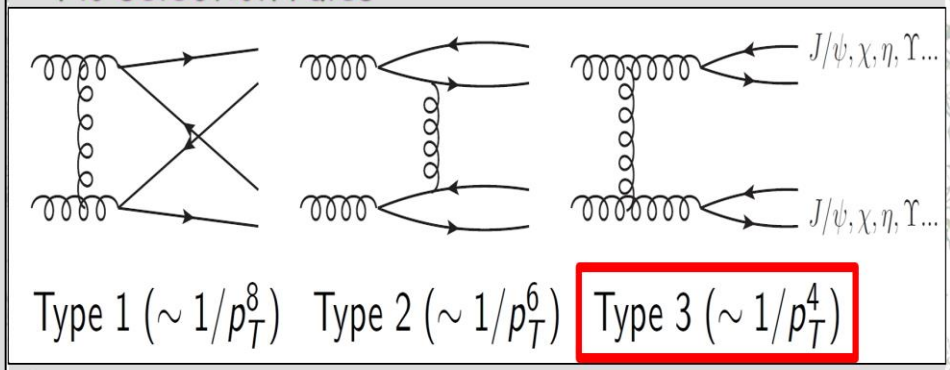


- *Intrinsically it can't be small!*
- Selection rules:

  (go off at (N)NLO)



- No selection rules



- "Small" $\sim 10^{-2...-3}$ color-octet contribution to wave function of quarkonium
- However could be dominating:
  - For high p^T-region due to gluon fragmentation graph
  - For final states, suppressed for CS scenario

2×J/ψ at (π,p)*Pt* collisions

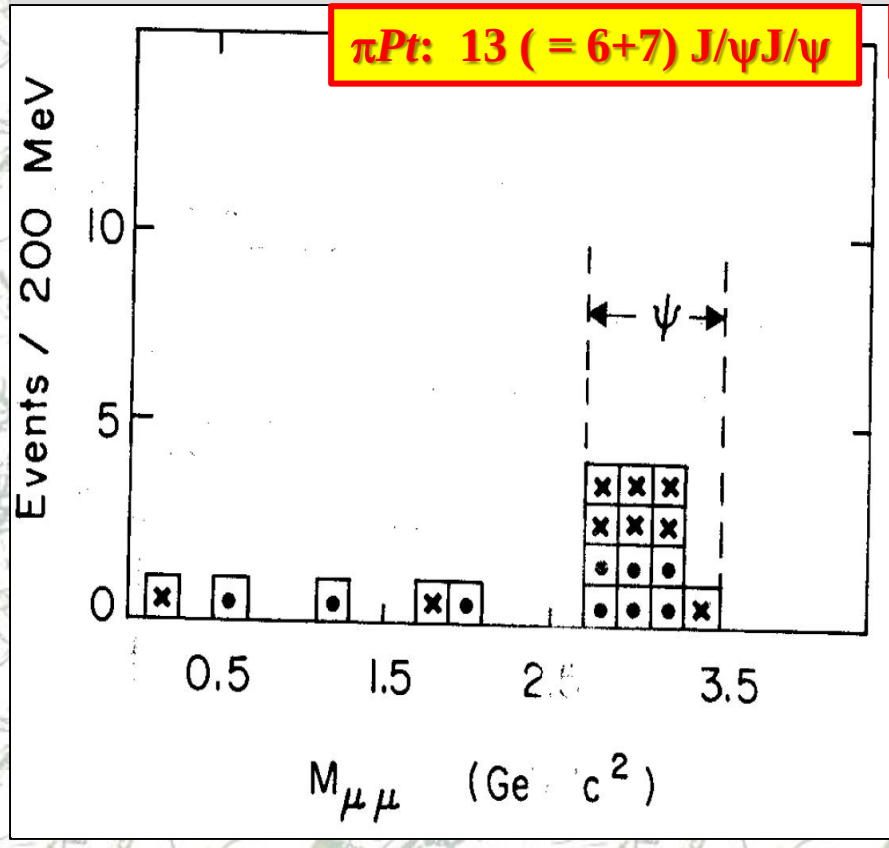
$\sigma^{J/\psi J/\psi}/\sigma^{J/\psi} = (3\pm1)\times10^{-4}$

NA3, 1982

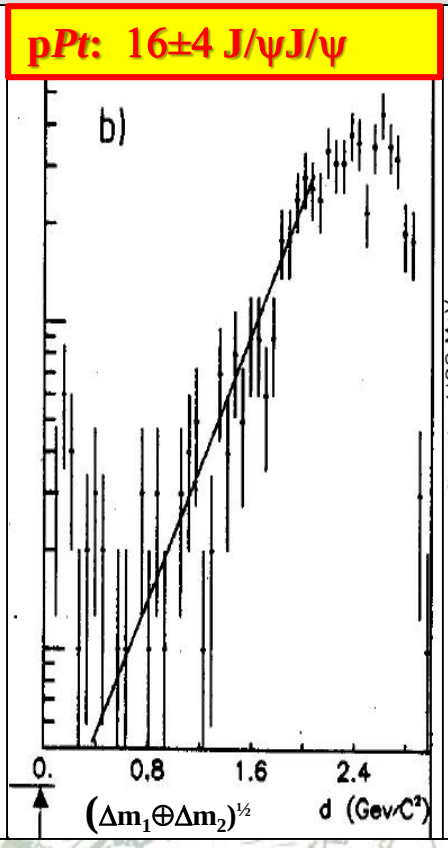
J. Badier *et al.*, "Evidence for ψψ production in π⁻ interactions at 150 and 280 GeV/*c*", Phys. Lett. B 114, 457 (1982).

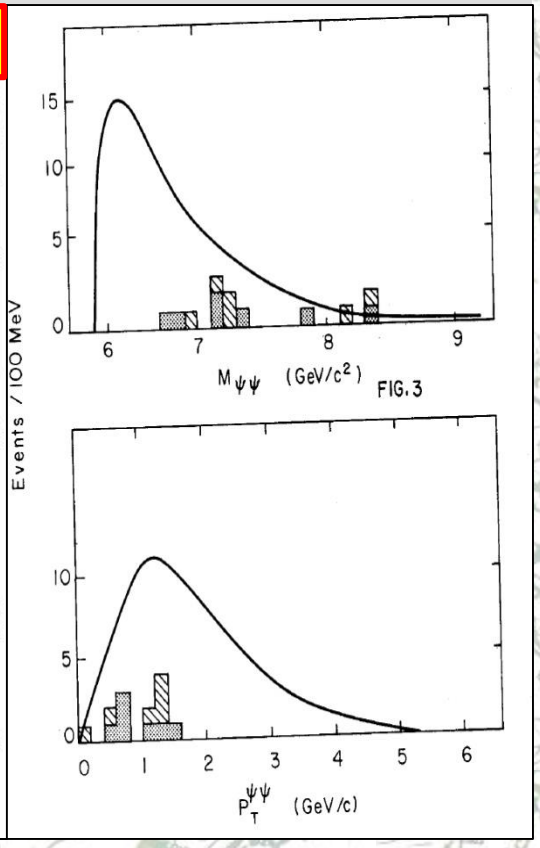
J.Badier *et al.*, "ψψ production and limits on beauty meson production from 400 GeV/*c* protons", Phys Lett B 158, 85 (1985)

π*Pt*: 13 (= 6+7) J/ψJ/ψ



p*Pt*: 16±4 J/ψJ/ψ

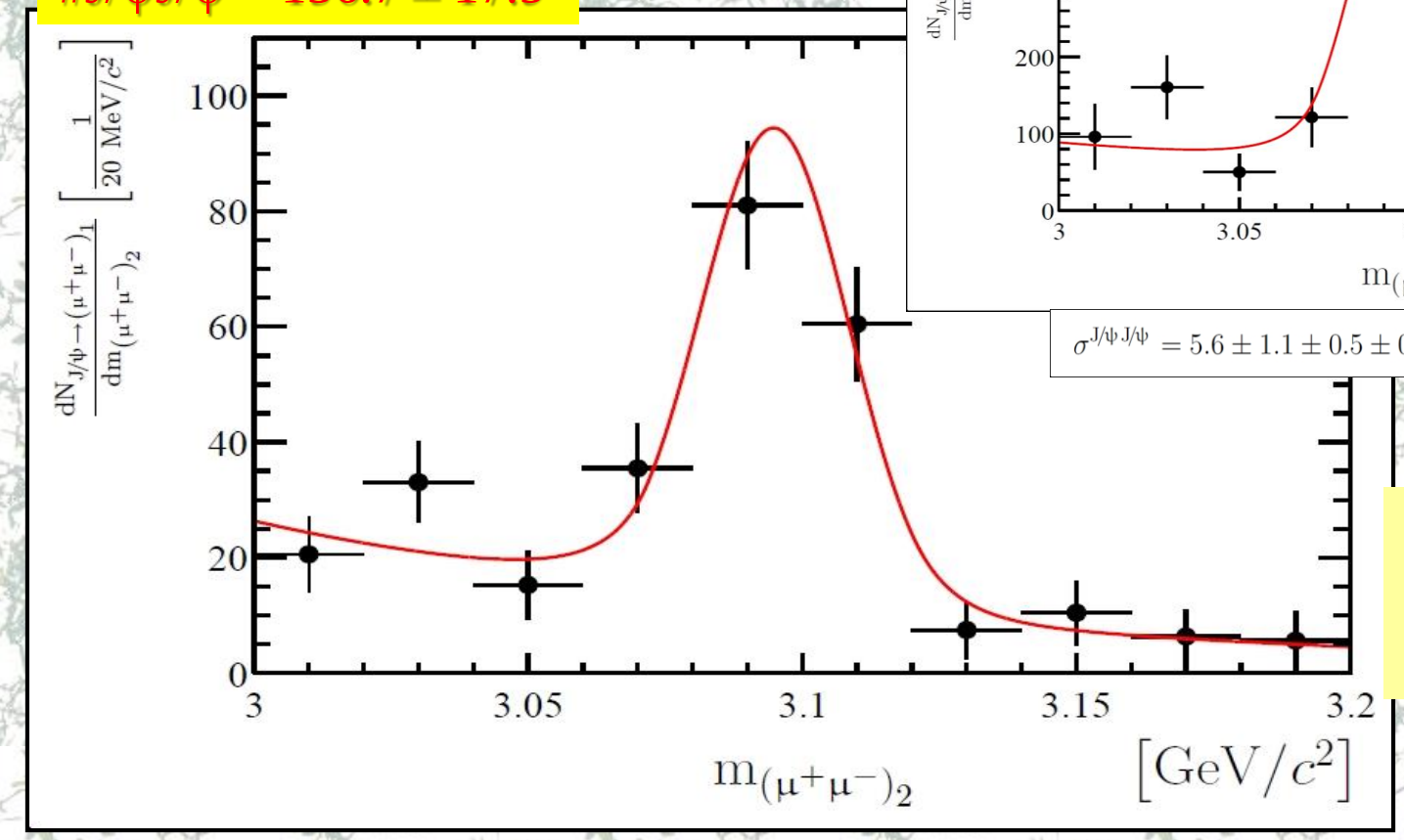


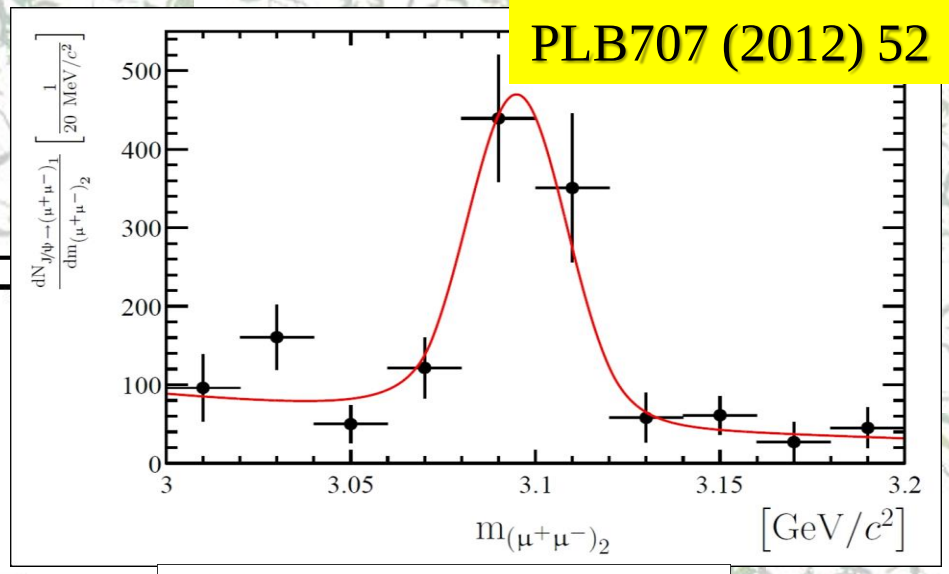


2×J/ψ at LHCb

PLB707 (2012) 52

#J/ψJ/ψ = 136.7 ± 17.5





$\sigma^{J/\psi J/\psi} = 5.6 \pm 1.1 \pm 0.5 \pm 0.9|_{\mathrm{tr}} \pm 0.6|_{\mathcal{L}}$ nb,

Theory: CS ~4nb
- Qiao, Sun, Sun
- Berezhnoy et al.

Double Parton Scattering

Google >300k documents

Double-Parton Scattering is Not Rare « Collider Blog
muon.wordpress.com/.../**double-parton-scatt**... - Перевести эту страницу
29 Dec 2009 – The thrust of the Berger, Jackson and Shaughnessy paper is a study showing that clear evidence for **double-parton scattering** can be obtained ...

[PDF] **Double Parton Scattering** at the LHC –
moriond.in2p3.fr/QCD/2011/.../Berger.pdf - Перевести эту страницу
Формат файлов: PDF/Adobe Acrobat - Быстрый просмотр
Double Parton Scattering at the LHC –. Dynamic and Kinematic Characteristics. Example: pp → b¯b jet jet X. Edmond L Berger. Argonne National Laboratory ...

Phys. Rev. D 56, 3811 (1997): **Double parton scattering** in p[over ¯]p ...
link.aps.org › ... › Volume 56 › Issue 7 - Перевести эту страницу
The process-independent parameter of **double parton scattering**, σeff, is obtained without reference to theoretical calculations by comparing observed DP events ...

Fresh look at **double parton scattering** - APS Link Manager
link.aps.org › ... › Volume 83 › Issue 11 - Перевести эту страницу
24 Jun 2011 – A revised formula for the inclusive cross section of a **double parton scattering** process in a hadron collision is suggested basing on the modified ...

Double Parton Scattering
www-cdf.fnal.gov/.../**double_parton**_summ... - Перевести эту страницу
Double Parton Scattering in pbar-p Collisions at root s = 1.8 TeV In a paper submitted to Physical Review Letters, the CDF collaboration announced the first ...

Signals for **Double Parton Scattering** at the Fermilab Tevatron
arxiv.org › hep-ph - Перевести эту страницу
29 May 1996 – Abstract: Four **double-parton scattering** processes are examined at the Fermilab Tevatron energy. With optimized kinematical cuts and realistic ...

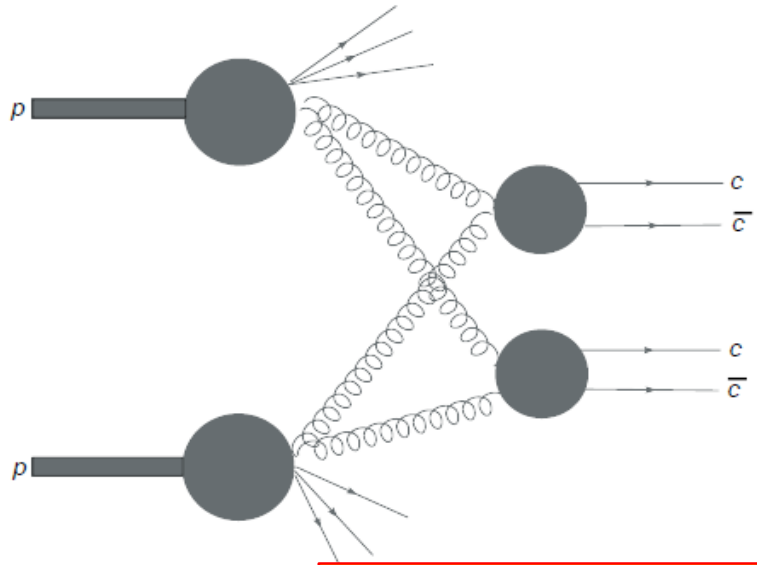
Double parton scattering of hadron-hadron interaction and its ...
arxiv.org › hep-ph - Перевести эту страницу
25 Apr 1997 – Title: **Double parton scattering** of hadron-hadron interaction and its gluonic contribution. Authors: Hung Hsiang Liu (Inst. of Phys, Academia ...

[PDF] Signals for **Double Parton**
www.phys.psu.edu/~cteq/.../flaugher.pdf - Перевести эту страницу
Формат файлов: PDF/Adobe Acrobat - Быстрый просмотр
Double Parton Scattering (DPS). Two parton-parton hard scatters in one pp collision. Extend knowledge of proton structure. 0 spatial distribution of partonsinside ...

High Energy Physics Group - **Double Parton Scattering**
www.hep.phy.cam.ac.uk/theory/.../dps.html - Перевести эту страницу
Cavendish High Energy Physics Group Research Theory **Double Parton Scattering**.

Is **double parton scattering** useful?
www.physicsforums.com/showthread.php?t... - Перевести эту страницу
Заблокировать все результаты с www.physicsforums.com
Сообщений: 2 - Авторов: 2 - 19 июл 2011
Is **double parton scattering** useful? High Energy, Nuclear, Particle Physics discussion.

DPS: simple paradigm



Two independent scattering processes

Relations through (unknown) $_2$PDFs

$$\Gamma_{ij}(x_1,x_2;\mathbf{b_1},\mathbf{b_2};Q_1^2,Q_2^2) = D_h^{ij}(x_1,x_2;Q_1^2,Q_2^2)f(\mathbf{b_1})f(\mathbf{b_2}),$$

Assume factorization of $_2$PDFs

$$D_h^{ij}(x_1,x_2;Q_1^2,Q_2^2) = D_h^i(x_1;Q_1^2)D_h^j(x_2;Q_2^2).$$

(Can't be true for all x,Q^2)

Easy to make predictions!
And the predictions are easy to test

$$\sigma_{\rm DPS}^{AB} = \frac{m}{2}\frac{\sigma_{\rm SPS}^{A}\sigma_{\rm SPS}^{B}}{\sigma_{\rm eff}}.$$

Universal (energy and process independent) factor)

$$1/\sigma_{eff} = \int d^2b F^2(b)$$

$$\sigma_{\rm eff}^{\rm DPS} = 14.5 \pm 1.7^{+1.7}_{-2.3}\ {\rm mb}$$

CDF, F.Abe *et al.*, PDR 56 3811 (1997)

How to test DPS ?

- For two species **A** and **B** one need to measure associative production **σ(A+B)** as well as their inclusive productions **σ(A)**, **σ(B)**
  - DPS contribution follows from identity:
  - Look for the correlations:

    p_T spectra, $\Delta\phi$ & Δy correlations, mass spectra, polarization effects, …. ?

$$\sigma^{AB}_{\rm DPS} = \frac{m}{2}\frac{\sigma^{A}_{\rm SPS}\sigma^{B}_{\rm SPS}}{\sigma_{\rm eff}}.$$

- Inclusive production is well measured at **LHCb** for many species

  J/ψ — EJPC 71(2011) 1645

  Z^0 — arXiv:1204.1620

  Open charm: D^0, D^+, D_s, Λ_c — CERN-LHCb-PAPER-2012-041

  jets — CERN-LHCb-CONF-2011-015

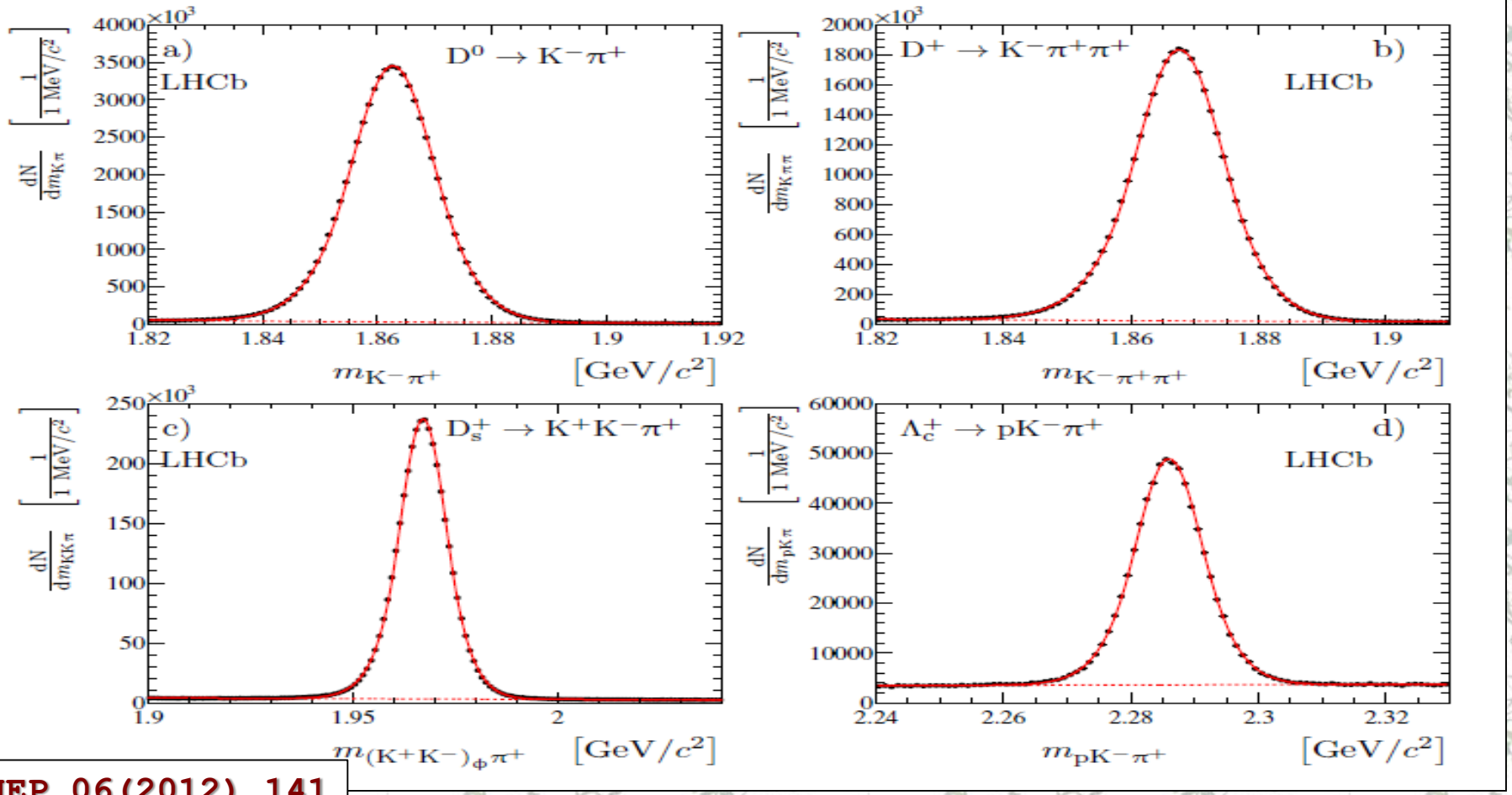
  and many-many others: ψ', Y(nS), $W^{\pm}$, χ_c, χ_b, B-hadrons, …

Today 26 pairs:

2×J/ψ (1) J/ψ+open charm (4) 2×open charm (6+10) Z^0+jets (1)

Open charm signals

$N(D^0) \approx 2\times10^8/fb^{-1}$ $N(D^+) \approx 1\times10^8/fb^{-1}$ $N(D_s) \approx 1\times10^7/fb^{-1}$ $N(\Lambda_c) \approx 2\times10^6/fb^{-1}$



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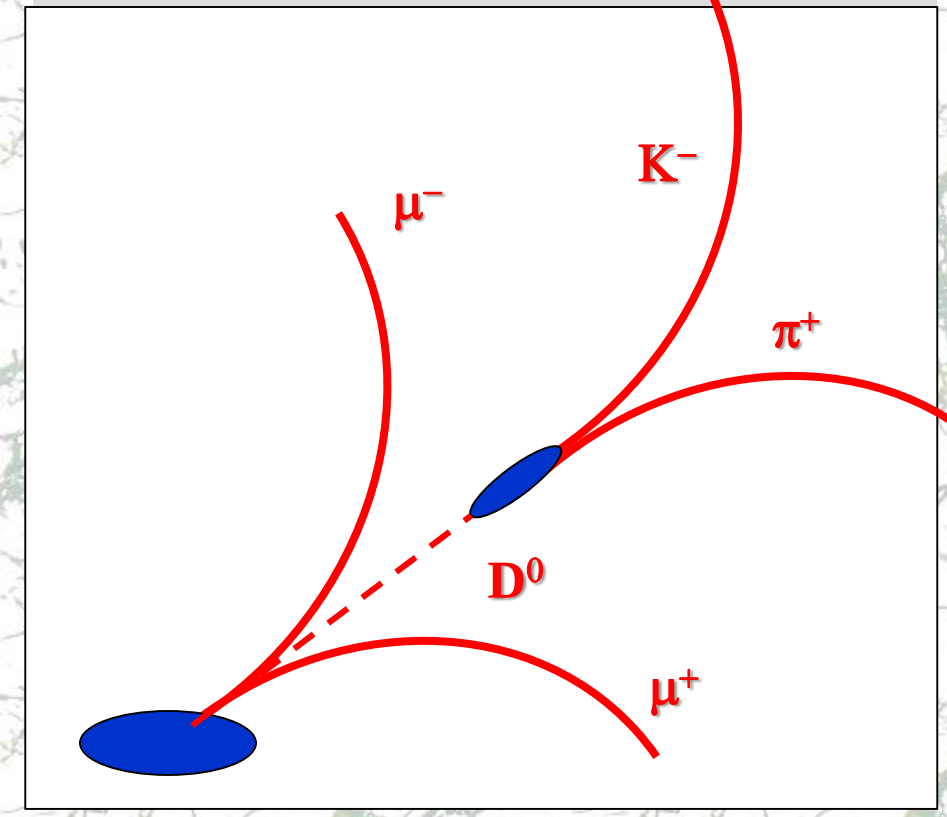
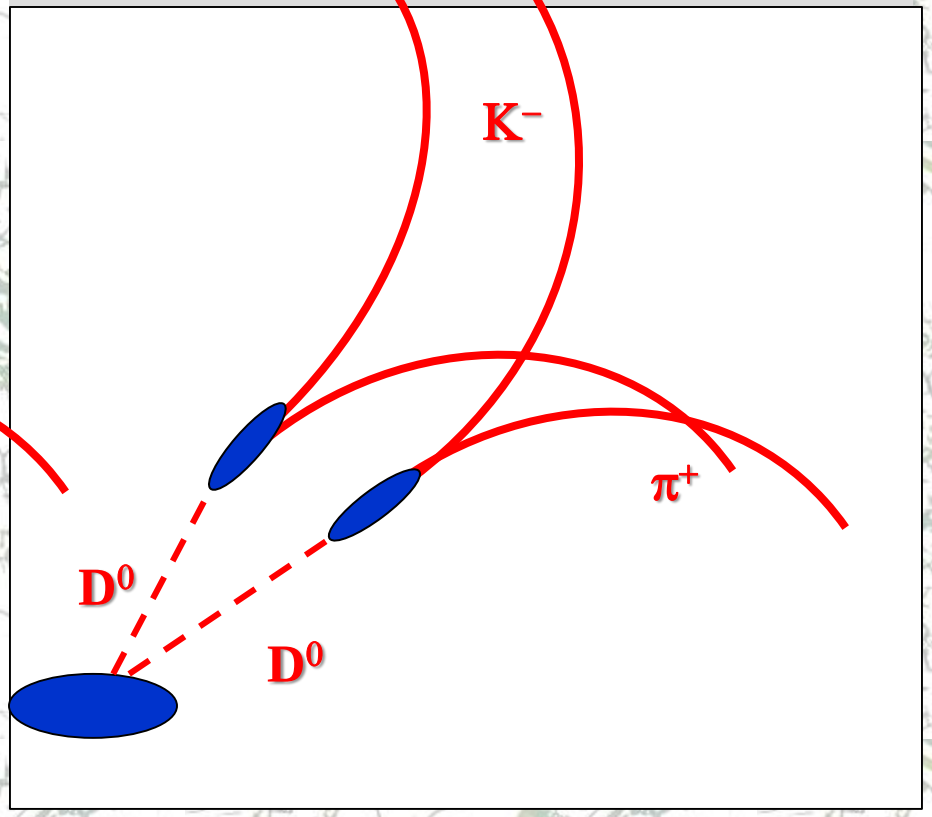
Event Selection

J/ψC two charm with common vertex

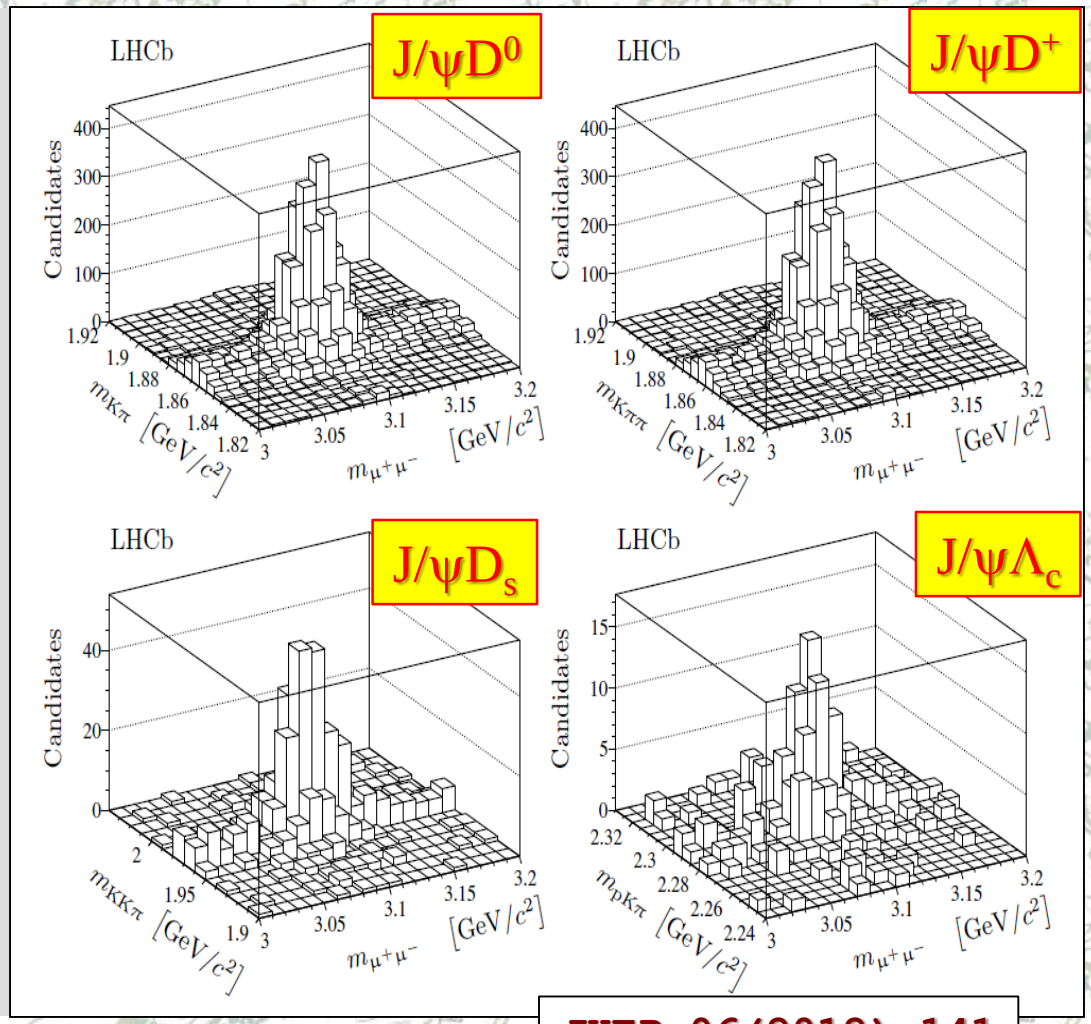


2×Open charm hadrons



Signal extraction

- J/ψ + open charm
- clear signals for all four modes
- Significances > 7σ



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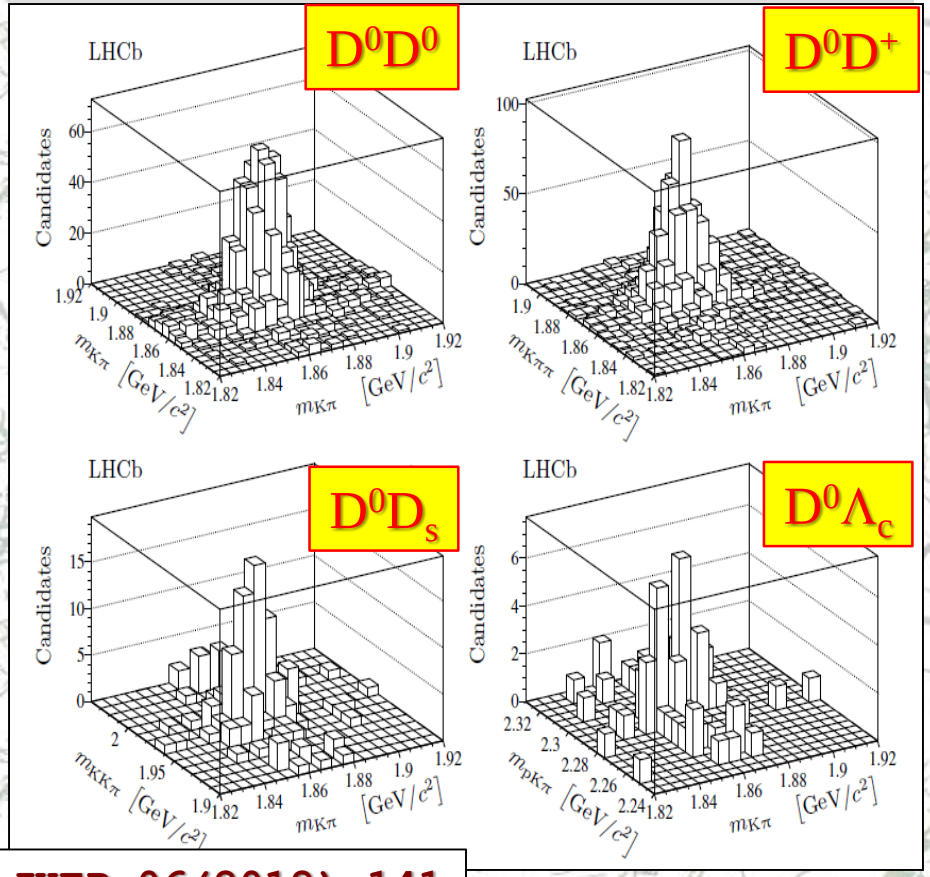
(open charm)^2

D^0 & open charm



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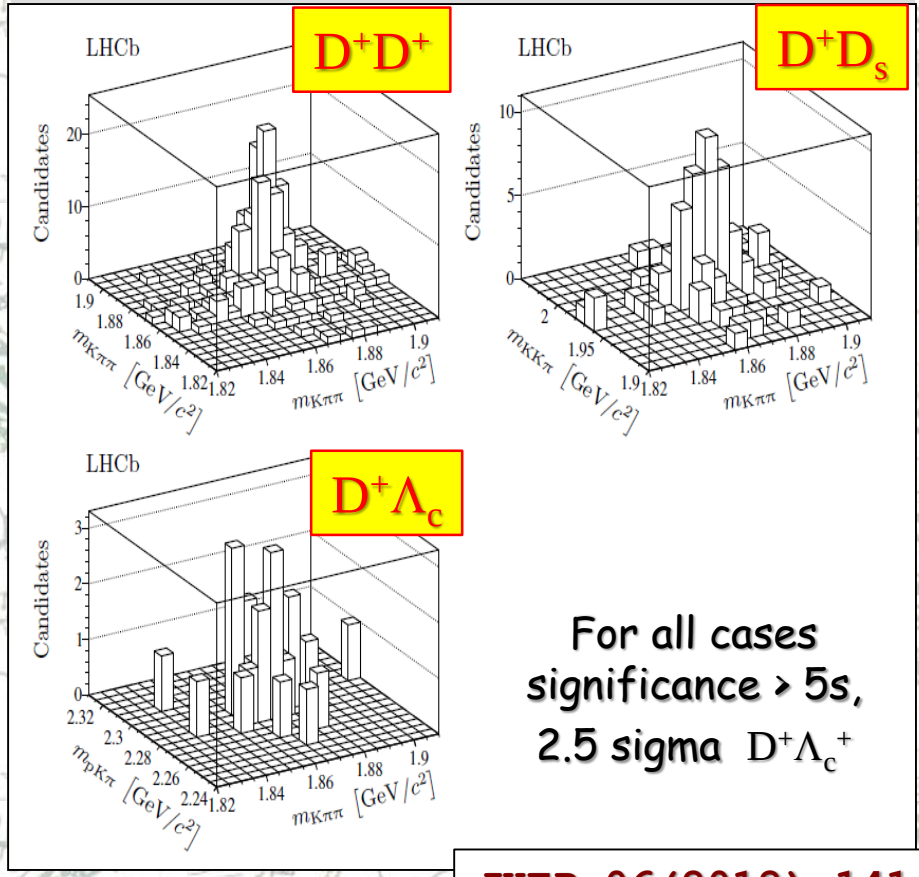
D^+ & open charm



For all cases significance > 5s, 2.5 sigma $D^+\Lambda_c^+$

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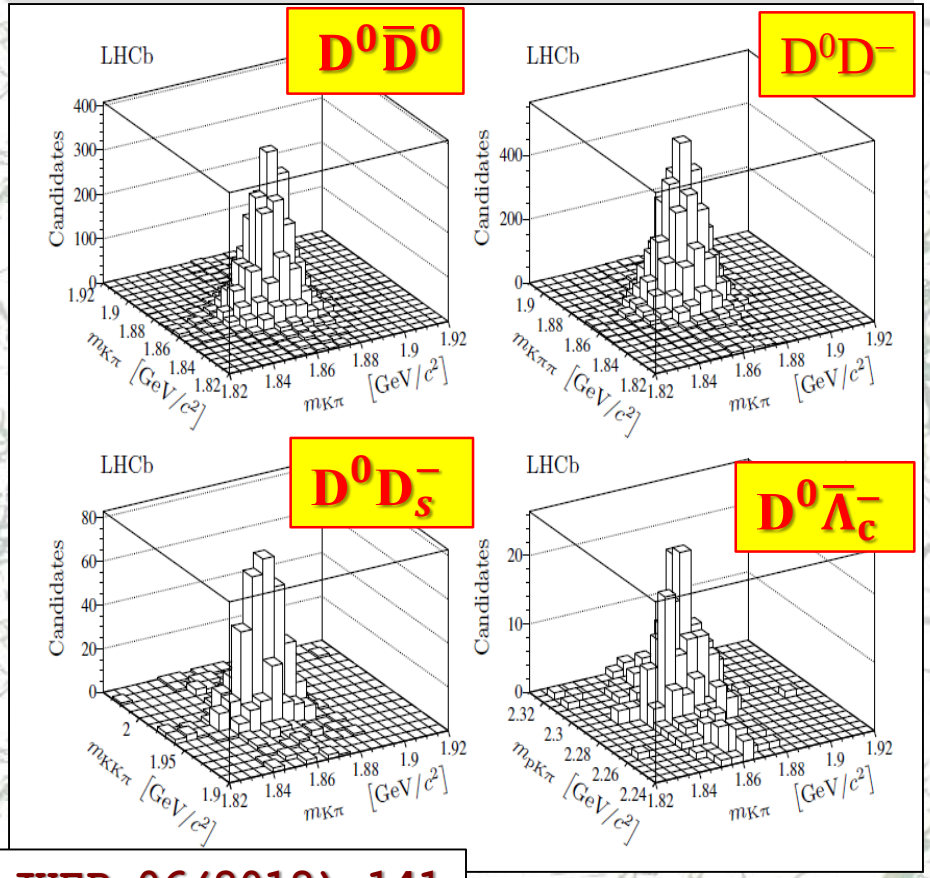
Open charm + open anti-charm

D^0 & open anti-charm



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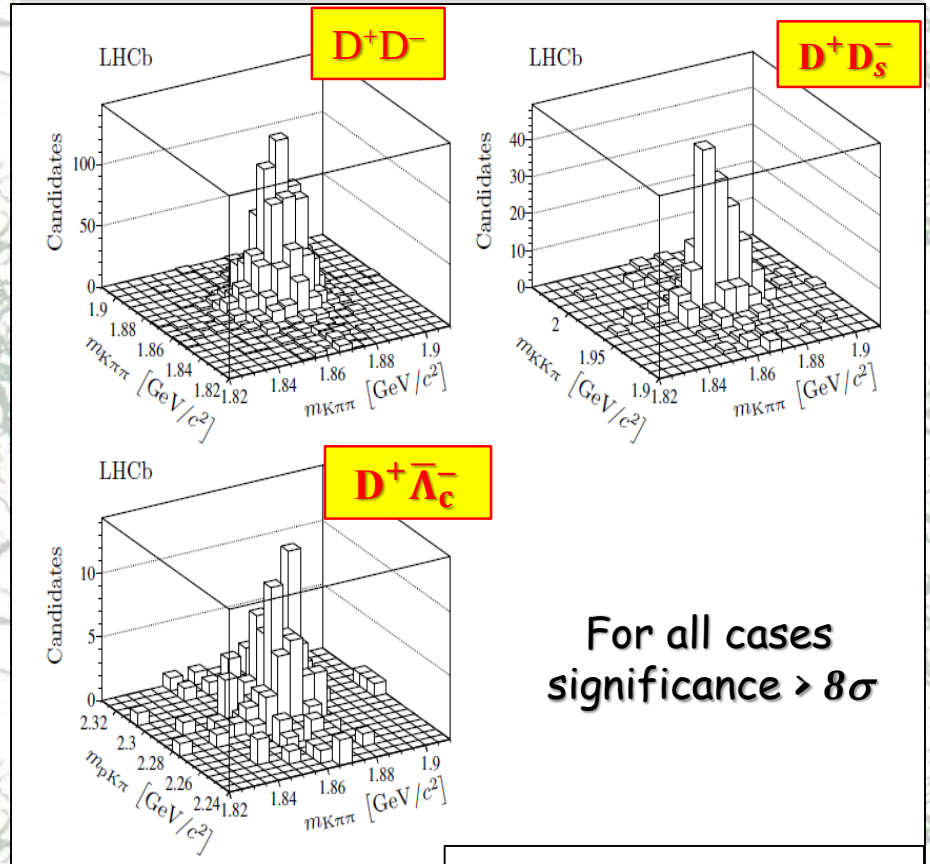
D^+ & open anti-charm



For all cases significance > 8σ

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Cross-sections

- Use per-event efficiency, mainly from DATA: trigger, particle ID, background etc.

$$\sigma^{J/\psi\, J/\psi} = 5.1 \pm 1.0 \pm 1.1 \text{ nb},$$

- Major systematic:
  tracking (reducible)
  Br(Λ_c), *Br*(D_s), ….

Mode	σ [nb]
$J/\psi\, D^0$	$161.0 \pm 3.7 \pm 12.2$
$J/\psi\, D^+$	$56.6 \pm 1.7 \pm 5.9$
$J/\psi\, D_s^+$	$30.5 \pm 2.6 \pm 3.4$
$J/\psi\, \Lambda_c^+$	$43.2 \pm 7.0 \pm 12.0$

Mode	$\sigma_{J/\psi C}/\sigma_{J/\psi}$ $[10^{-3}]$	$\sigma_{J/\psi C}/\sigma_C$ $[10^{-4}]$	$\sigma_{J/\psi}\sigma_C/\sigma_{J/\psi C}$ [mb]
$J/\psi\, D^0$	$16.2 \pm 0.4 \pm 1.3^{+3.4}_{-2.5}$	$6.7 \pm 0.2 \pm 0.5$	$14.9 \pm 0.4 \pm 1.1^{+2.3}_{-3.1}$
$J/\psi\, D^+$	$5.7 \pm 0.2 \pm 0.6^{+1.2}_{-0.9}$	$5.7 \pm 0.2 \pm 0.4$	$17.6 \pm 0.6 \pm 1.3^{+2.8}_{-3.7}$
$J/\psi\, D_s^+$	$3.1 \pm 0.3 \pm 0.4^{+0.6}_{-0.5}$	$7.8 \pm 0.8 \pm 0.6$	$12.8 \pm 1.3 \pm 1.1^{+2.0}_{-2.7}$
$J/\psi\, \Lambda_c^+$	$4.3 \pm 0.7 \pm 1.2^{+0.9}_{-0.7}$	$5.5 \pm 1.0 \pm 0.6$	$18.0 \pm 3.3 \pm 2.1^{+2.8}_{-3.8}$

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Cross-sections

Mode	σ [nb]	$\sigma_{CC}/\sigma_{C\overline{C}}$ [%]	$\sigma_{C_1}\sigma_{C_2}/\sigma_{C_1C_2}$ [mb]
D^0D^0	$690 \pm 40 \pm 70$	10.9 ± 0.8	$2 \times (42 \pm 3 \pm 4)$
$D^0\overline{D}^0$	$6230 \pm 120 \pm 630$		$2 \times (4.7 \pm 0.1 \pm 0.4)$
D^0D^+	$520 \pm 80 \pm 70$	12.8 ± 2.1	$47 \pm 7 \pm 4$
D^0D^-	$3990 \pm 90 \pm 500$		$6.0 \pm 0.2 \pm 0.5$
$D^0D_s^+$	$270 \pm 50 \pm 40$	15.7 ± 3.4	$36 \pm 8 \pm 4$
$D^0D_s^-$	$1680 \pm 110 \pm 240$		$5.6 \pm 0.5 \pm 0.6$
$D^0\bar{\Lambda}_c^-$	$2010 \pm 280 \pm 600$	—	$9 \pm 2 \pm 1$
D^+D^+	$80 \pm 10 \pm 10$	9.6 ± 1.6	$2 \times (66 \pm 11 \pm 7)$
D^+D^-	$780 \pm 40 \pm 130$		$2 \times (6.4 \pm 0.4 \pm 0.7)$
$D^+D_s^+$	$70 \pm 15 \pm 10$	12.1 ± 3.3	$59 \pm 15 \pm 6$
$D^+D_s^-$	$550 \pm 60 \pm 90$		$7 \pm 1 \pm 1$
$D^+\Lambda_c^+$	$60 \pm 30 \pm 20$	10.7 ± 5.9	$140 \pm 70 \pm 20$
$D^+\bar{\Lambda}_c^-$	$530 \pm 130 \pm 170$		$15 \pm 4 \pm 2$

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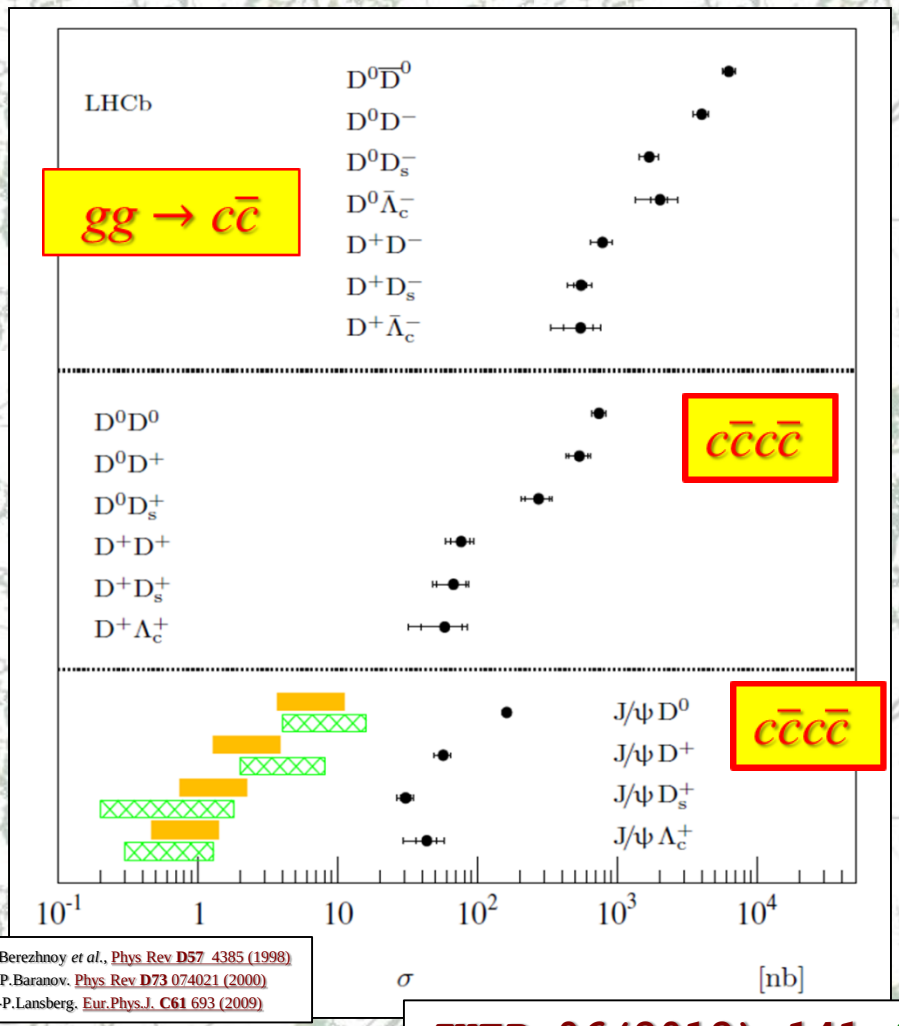
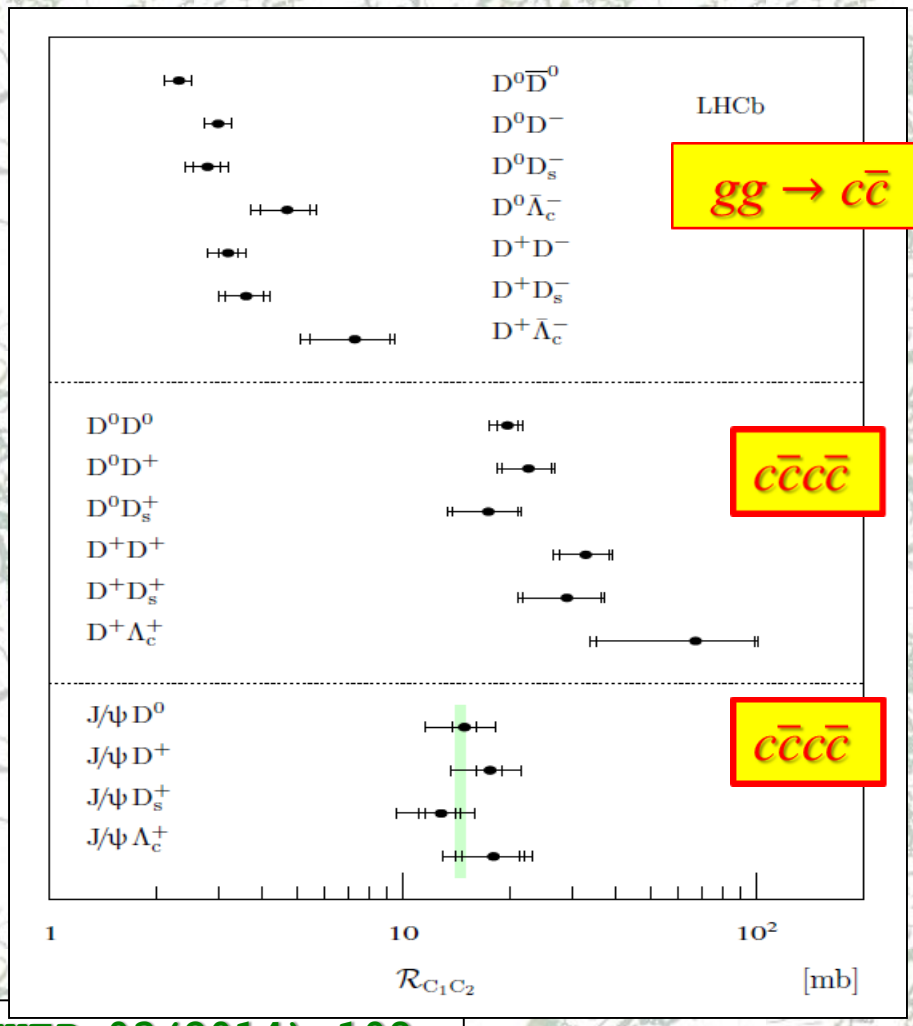
Cross-sections





A.Berezhnoy *et al.*, Phys Rev **D57** 4385 (1998)
S.P.Baranov. Phys Rev **D73** 074021 (2000)
J.-P.Lansberg. Eur.Phys.J. **C61** 693 (2009)

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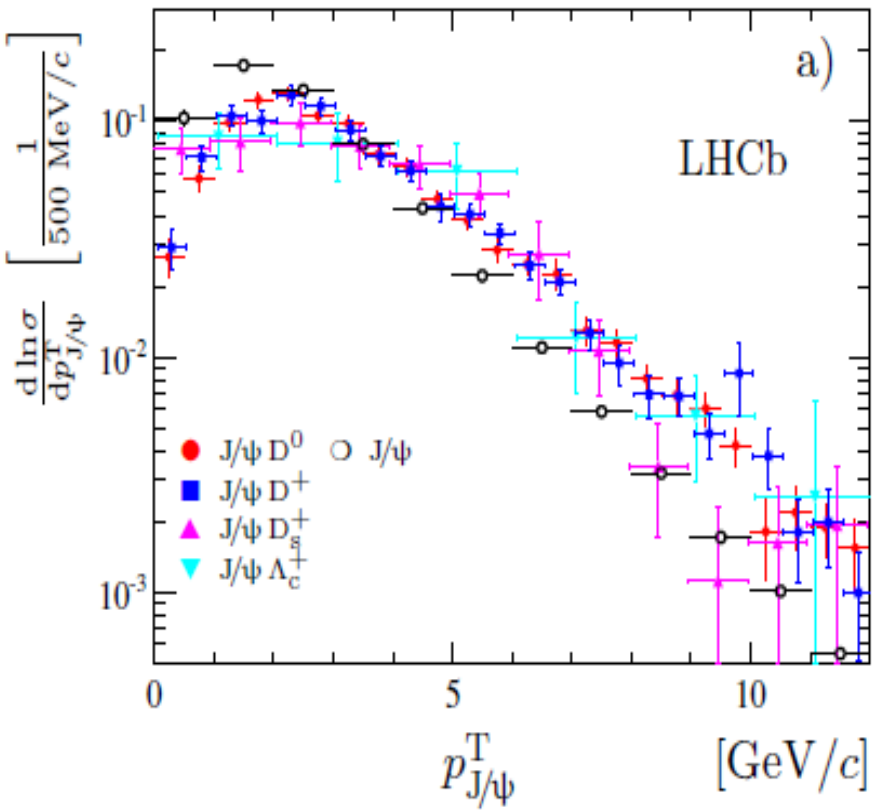
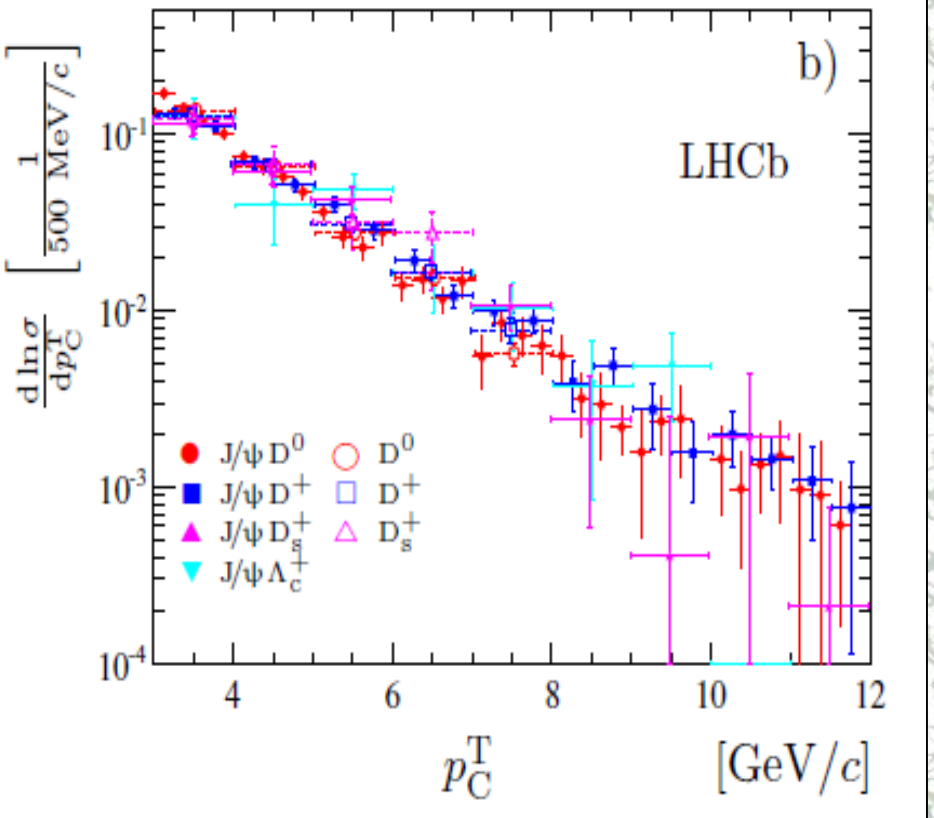
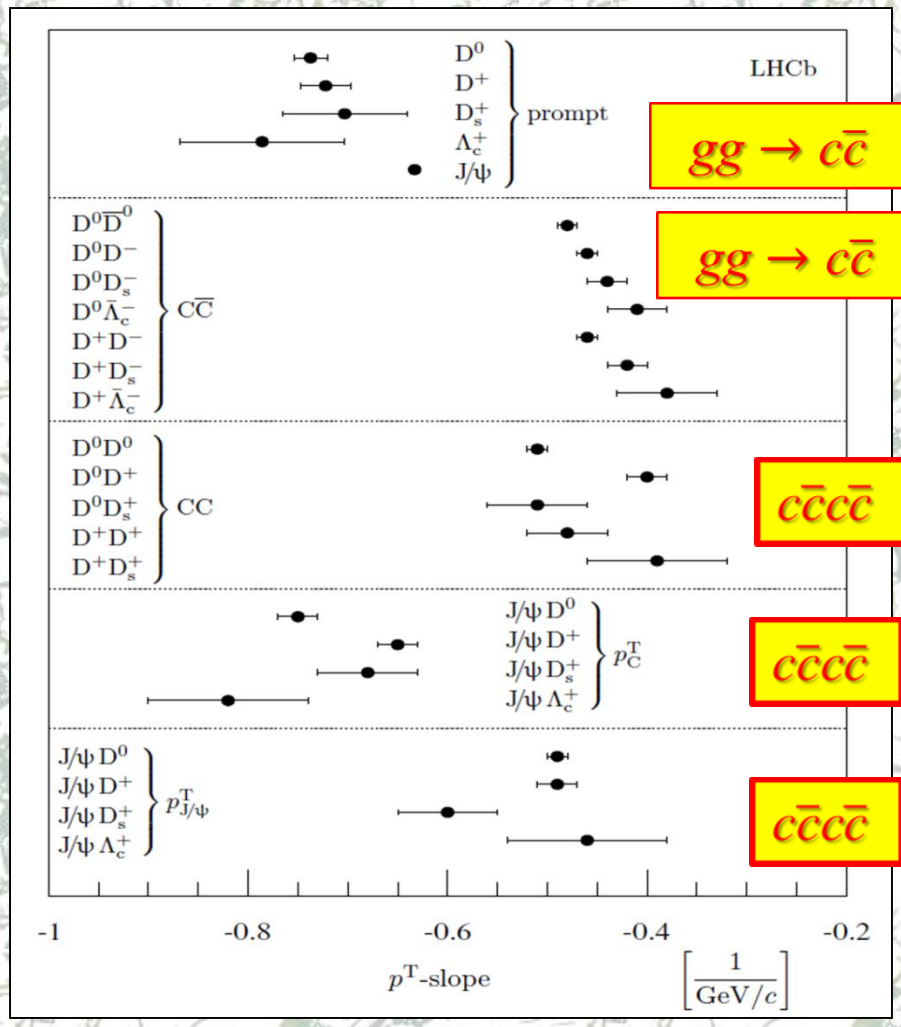
Event Properties: p_T

J/ψ + open charm:





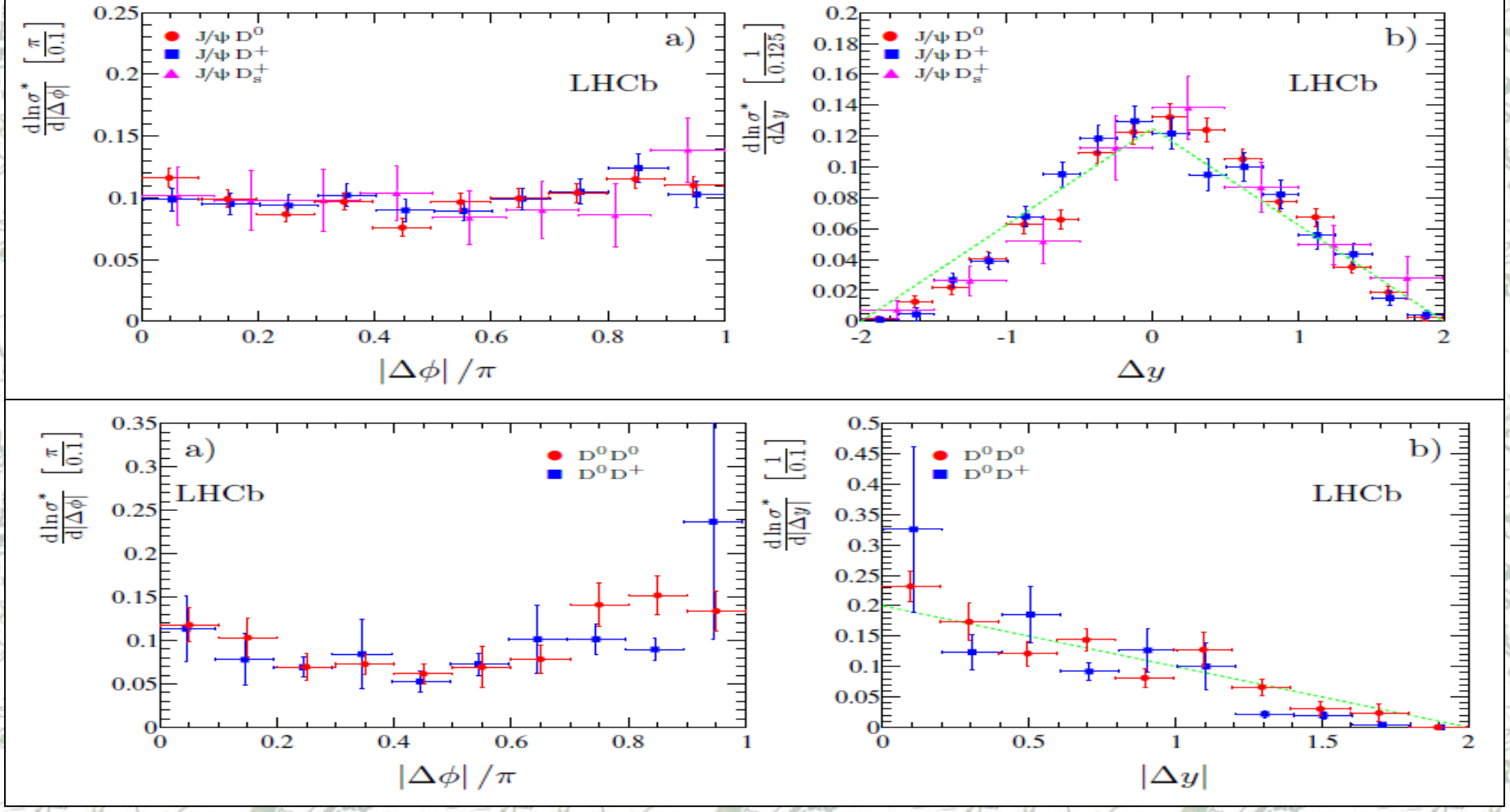
Slope parameter for p_T-spectra



- Fit p_T-spectra with exponential function:
  ~ exp ($\beta \times p_T$)
- DPS: expected similarity between *inclusive* and $c\bar{c}c\bar{c}$
- Expected to be similar between $J/\psi C$ and CC
- No reason to be the same for $J/\psi C$ and *inclusive*
- Expected to be similar between $c\bar{c}$ and *inclusive*

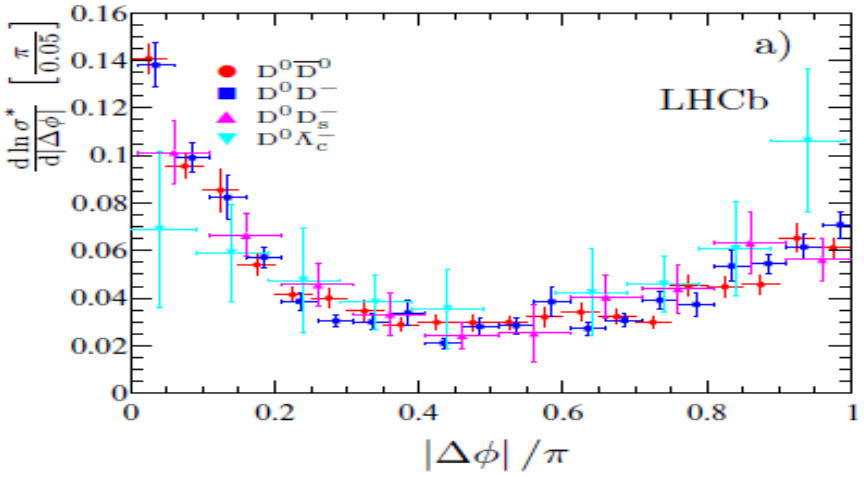
Δϕ & Δy correlations

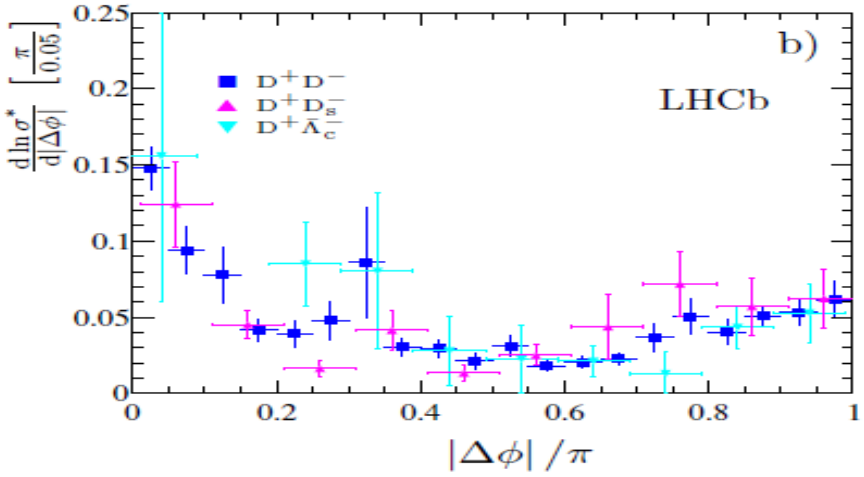
No evident correlations

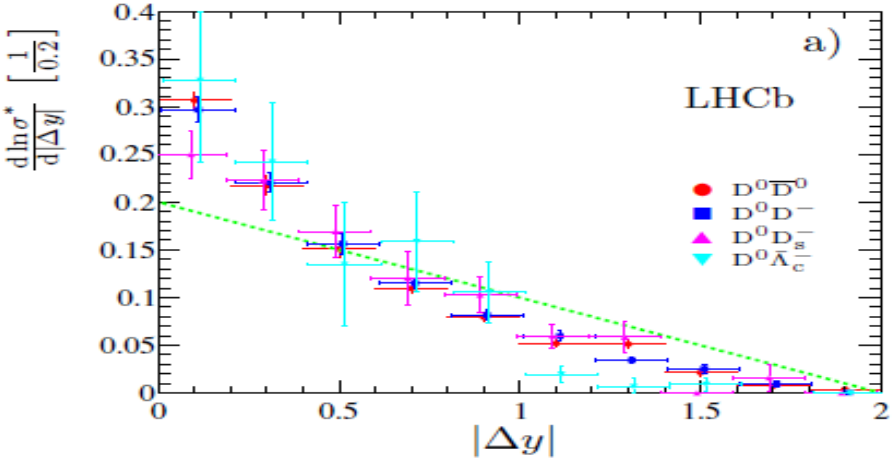


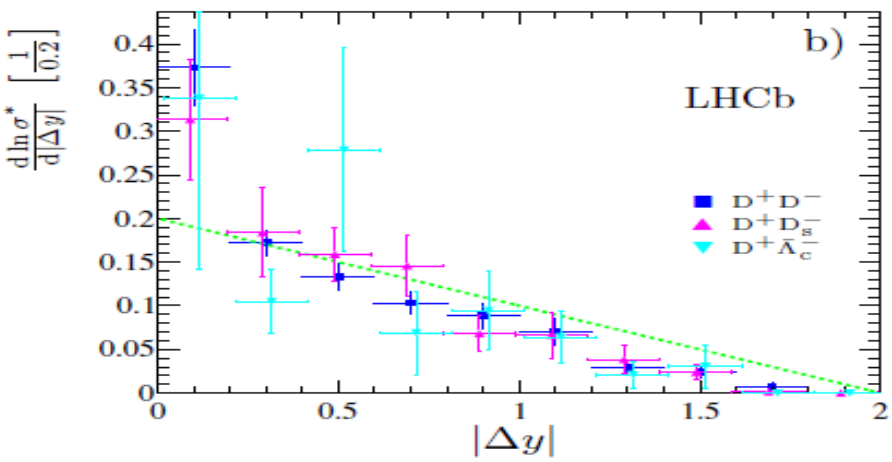
Δϕ & Δy correlations

Clear correlations!







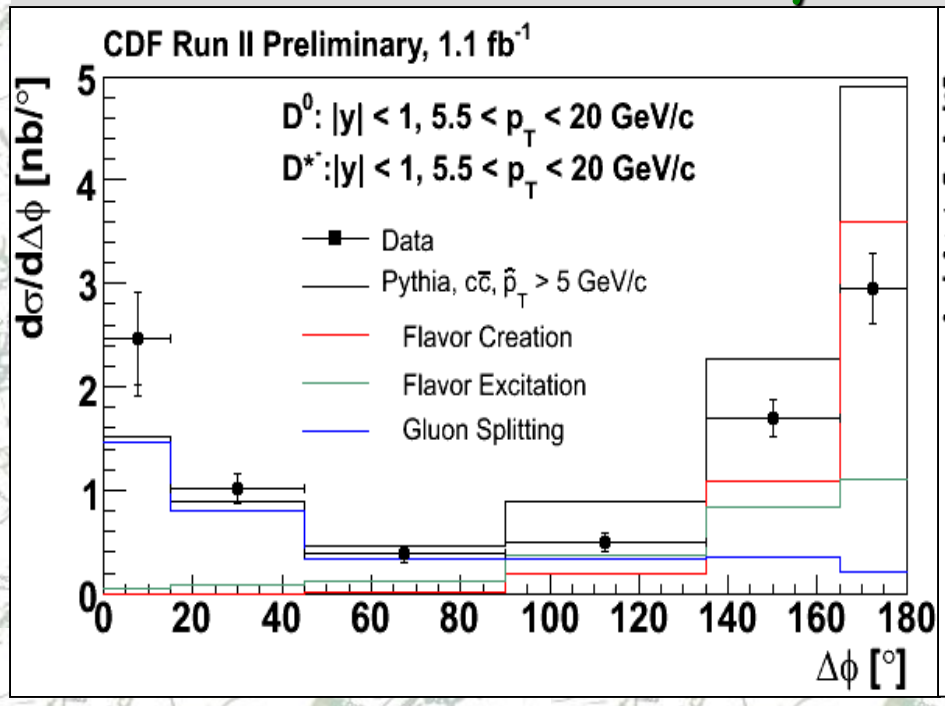


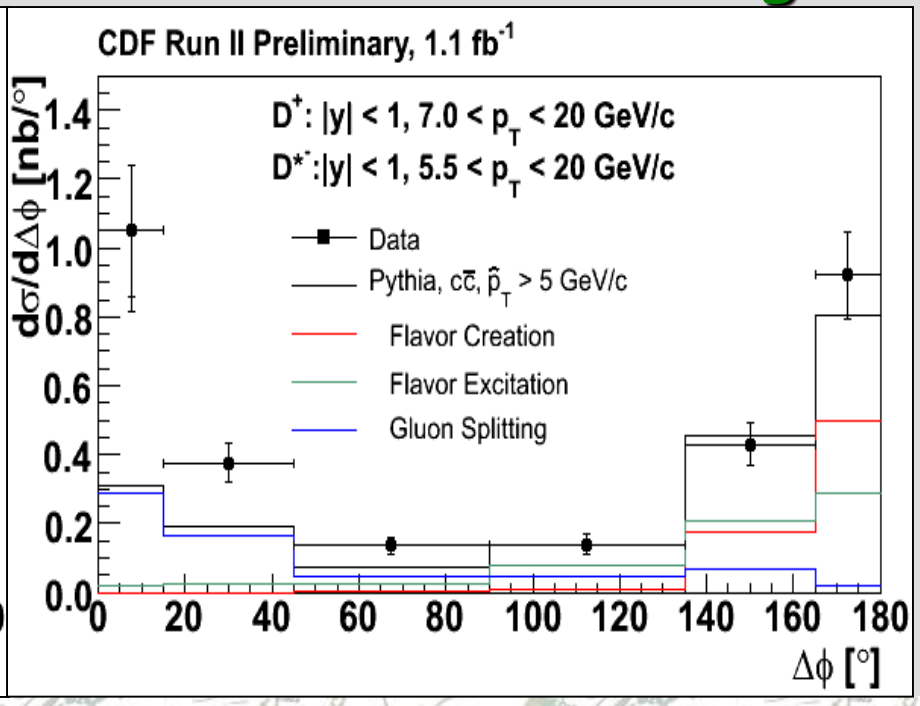
Compare with CDF'2k+6

http://www-cdf.fnal.gov/physics/new/bottom/060921.blessed-double-charm-corr/

- CDF: azimuthal correlations for $D^{(0,+)}\,D^{*-}$
- Large gluon splitting contribution

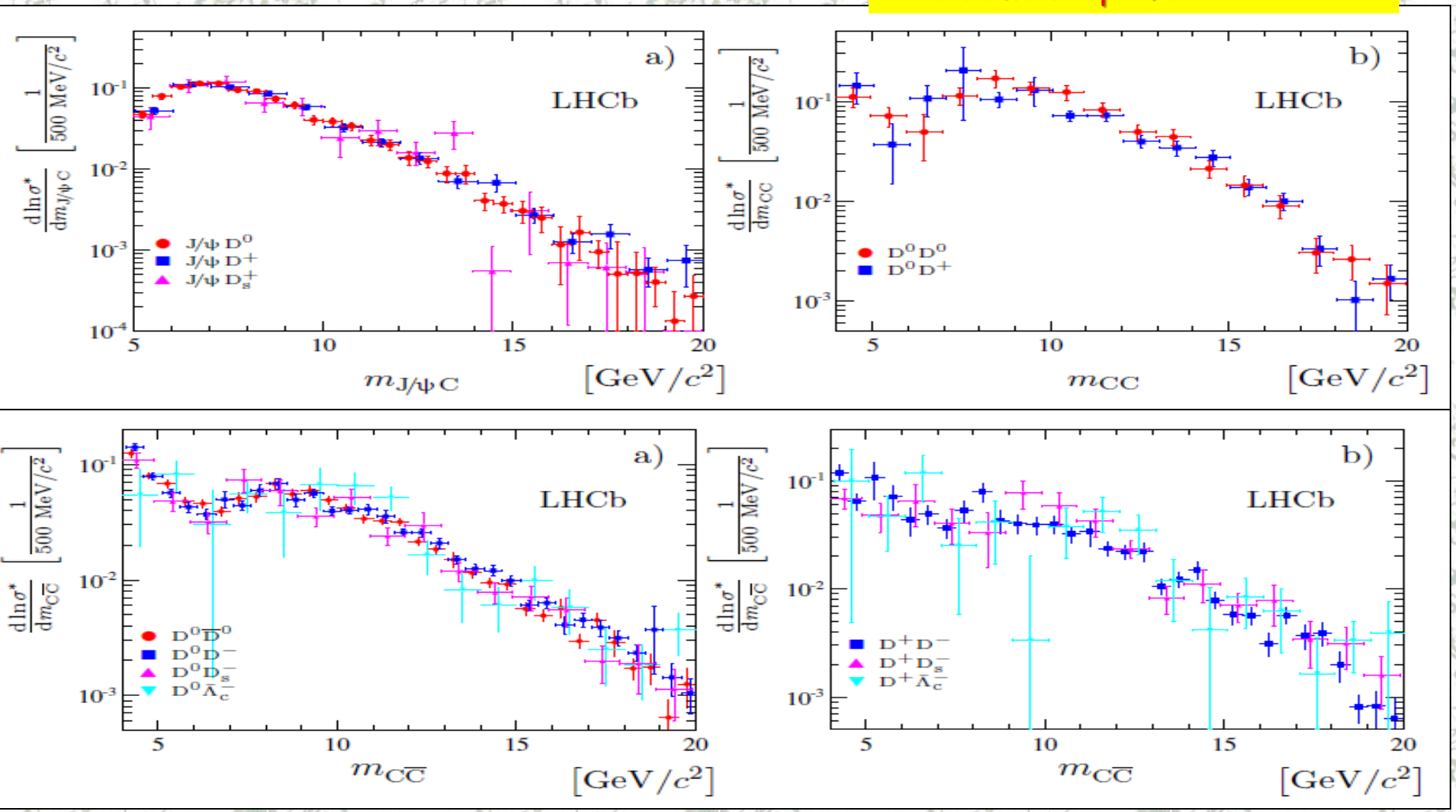
Very different kinematical region





Mass distributions

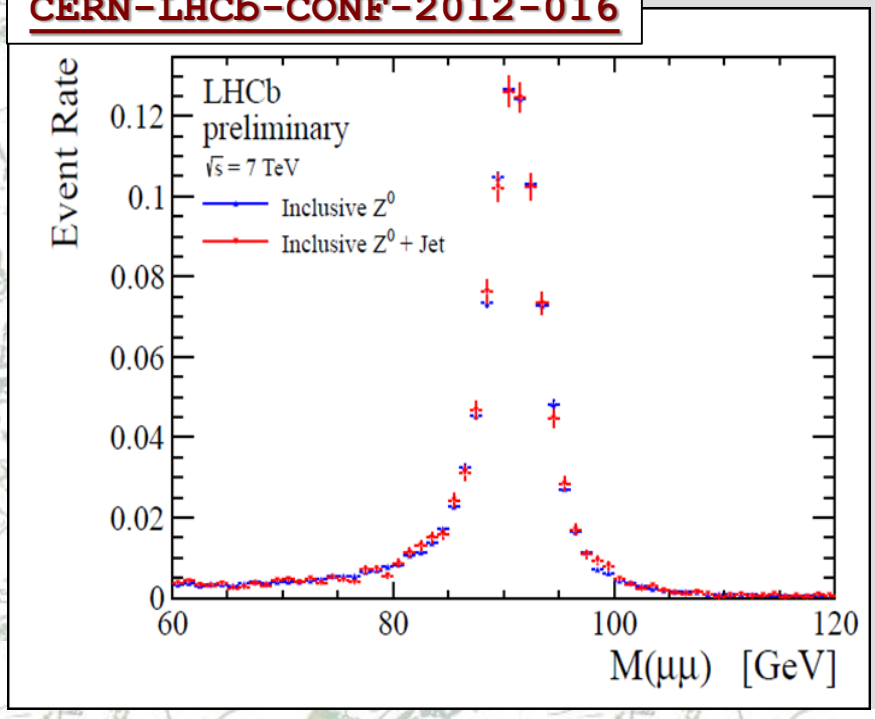
The same shape for m>7 GeV/c^2



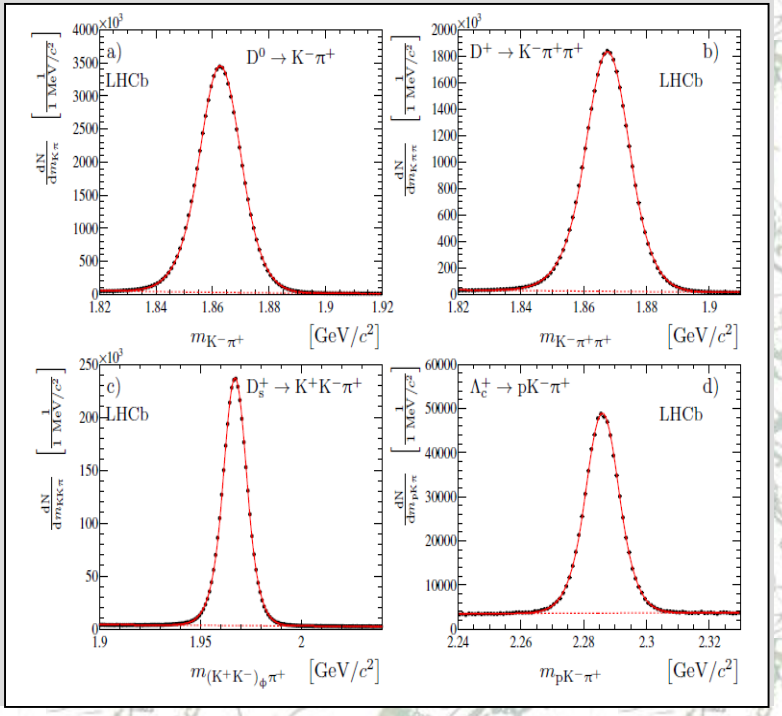
Z^0 + charm meson

- We have clear D-signals, we have clear $Z^0 \to \mu^+\mu^-$ signals: try to merge them together

CERN-LHCb-CONF-2012-016

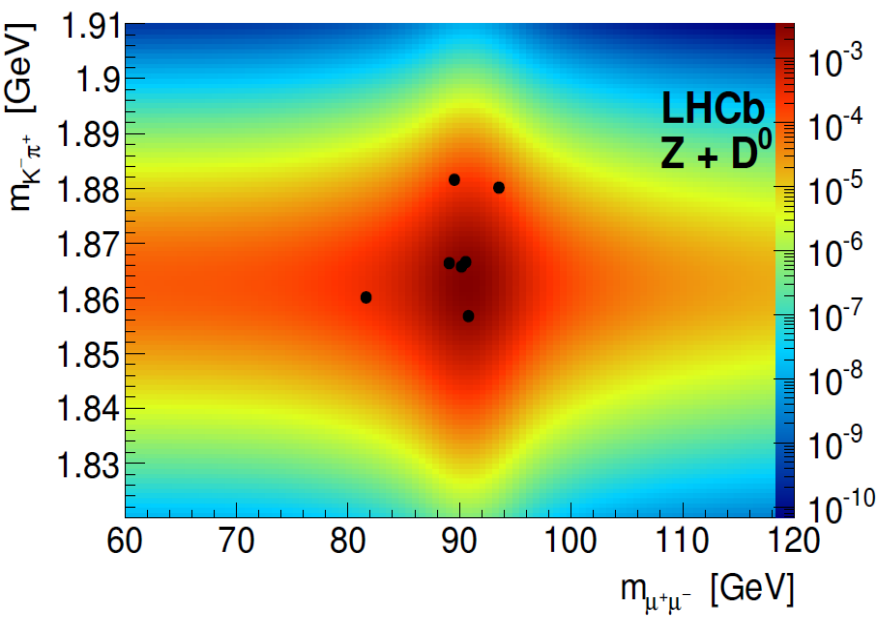


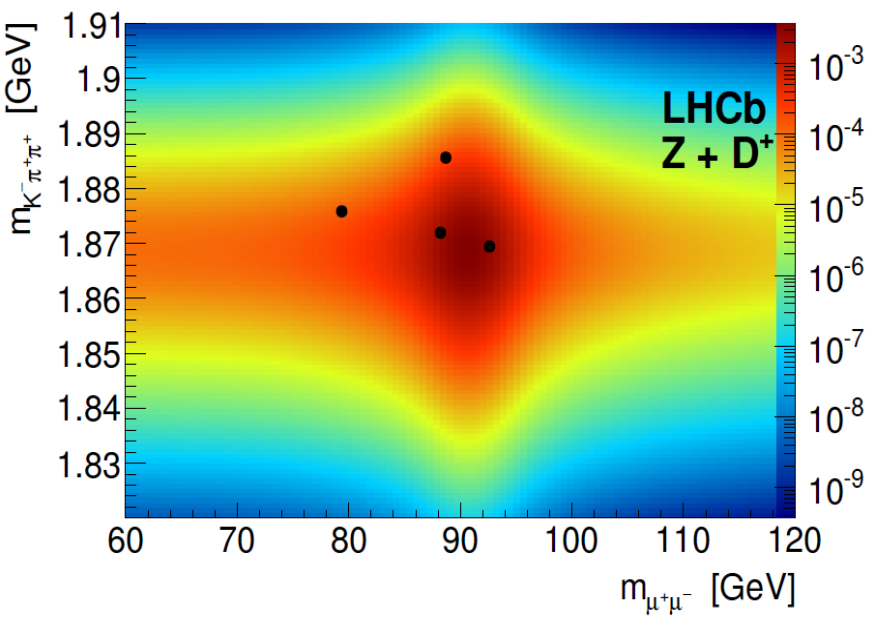
+



Z^0 + charm mesons

- 11 signal events: 7 Z^0&D^0 and 4 Z^0&D^+
- Statistical significance >5σ





Z^0 + charm meson

- Cross-section: sum of SPS and DPS

	Measured	MCFM massless [1]	MCFM massive [17]	DPS (Eq. (6.1))
$Z + D^0$	$2.50 \pm 1.12 \pm 0.22$	$0.85^{+0.12\ +0.11}_{-0.07\ -0.17} \pm 0.05$	$0.64^{+0.01\ +0.08}_{-0.01\ -0.13} \pm 0.04$	$3.28^{+0.68}_{-0.58}$
$Z + D^+$	$0.44 \pm 0.23 \pm 0.03$	$0.37^{+0.05\ +0.05}_{-0.03\ -0.07} \pm 0.03$	$0.28^{+0.01\ +0.04}_{-0.01\ -0.06} \pm 0.02$	$1.29^{+0.27}_{-0.23}$

- For Z^0+D^0 case: in agreement, for Z^0+D^+ case too small
- More data needed to make conclusions
  - Only ~1/3 of data is used in this analysis

P-wave charmonia: χ_c states

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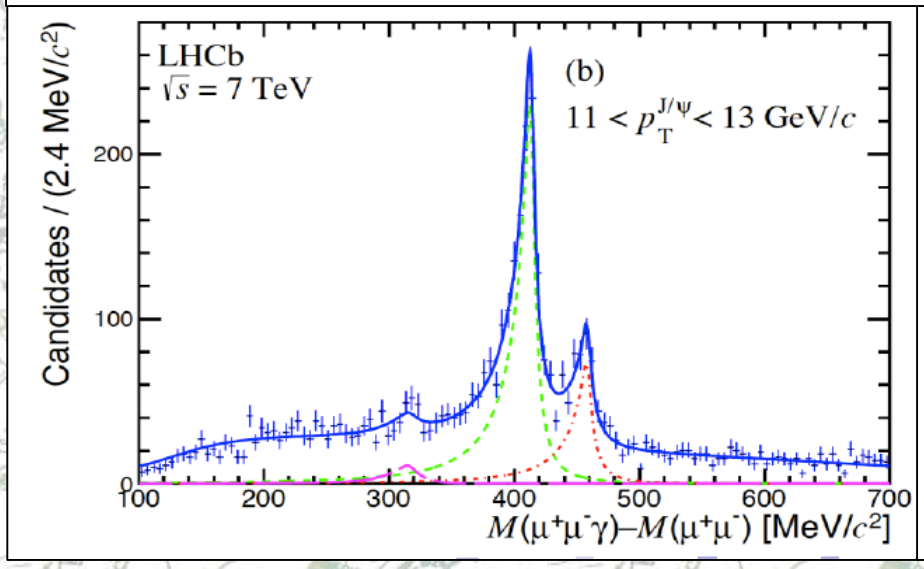
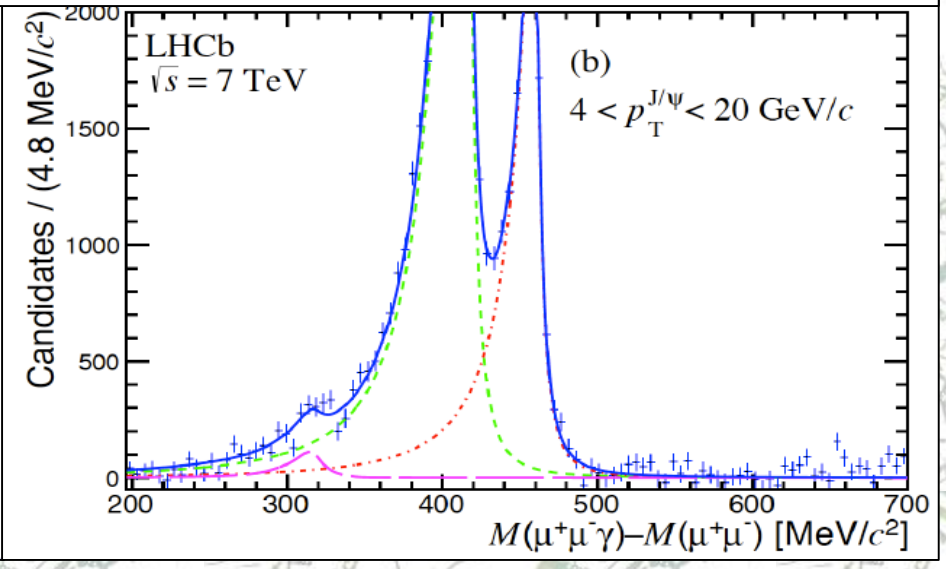
$\chi_c \to (J/\psi \to \mu^+\mu^-)\gamma$ with γ-conversions

- Excellent mass resolution: resolve χ_{c1} and χ_{c2} !
  - First evidence of χ_{c0} at hadron machines!

$$\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 1.19 \pm 0.27(stat) \pm 0.29(sys) \pm 0.16(p_T model) \pm 0.09(\mathcal{B})$$
$$\sigma(\chi_{c2})/\sigma(\chi_{c1}) = 0.787 \pm 0.014(stat) \pm 0.034(sys) \pm 0.051(p_T model) \pm 0.047(\mathcal{B})$$





χ_{c2}/χ_{c1} ratio

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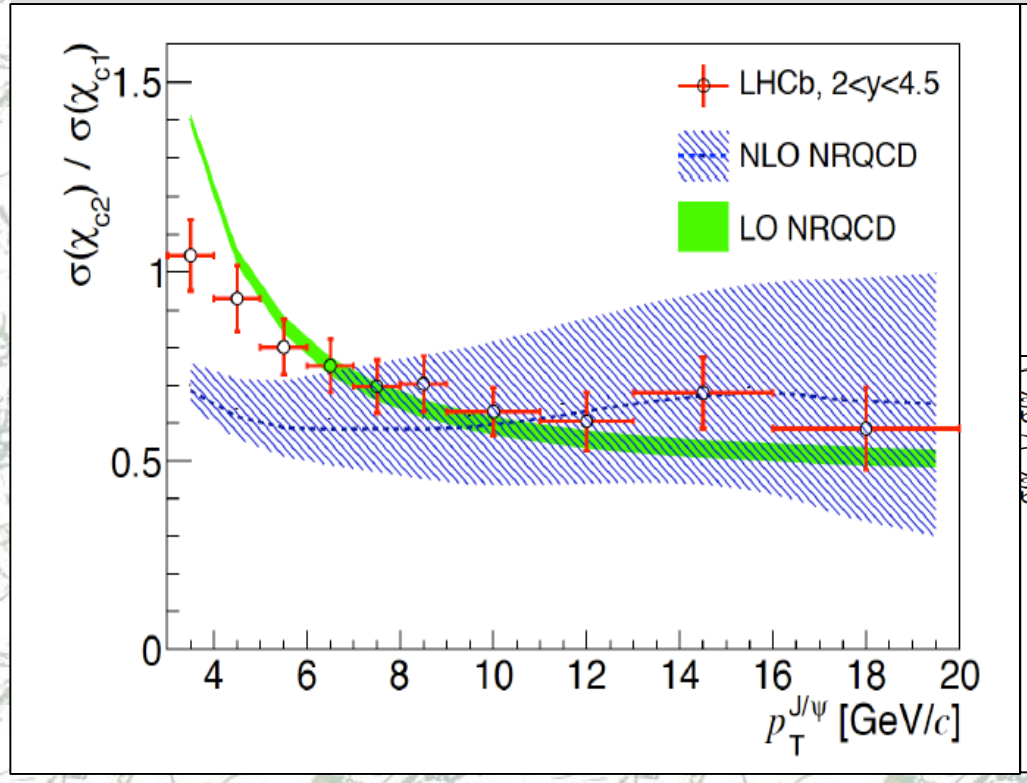
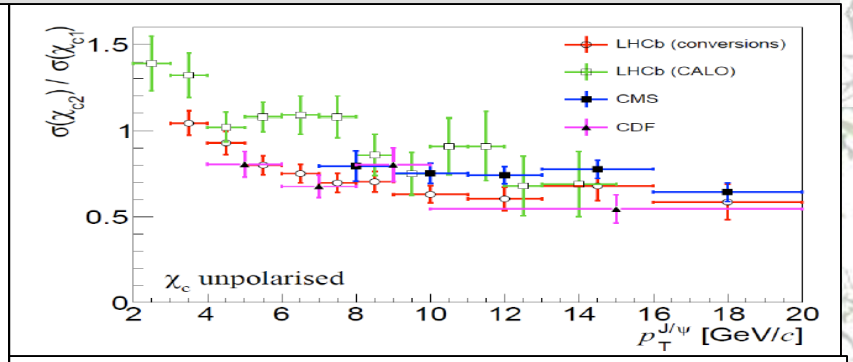
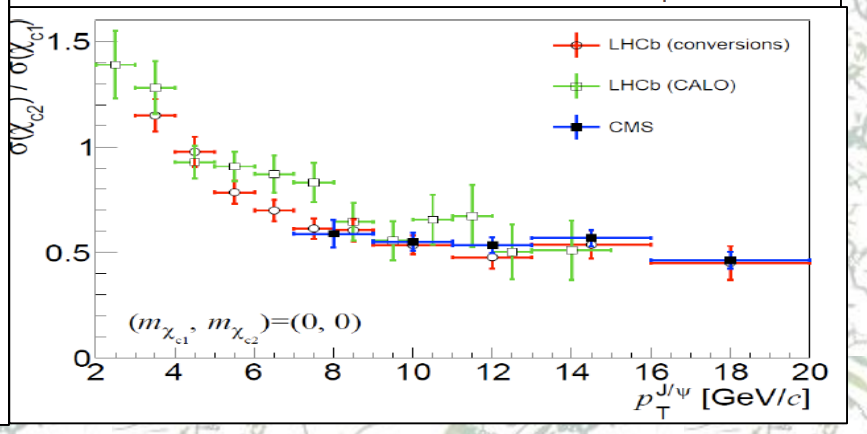
- for on-shell gluons $\sigma(gg \to \chi_{c1}) = 0$
- Important ingredient for S &P-wave CO



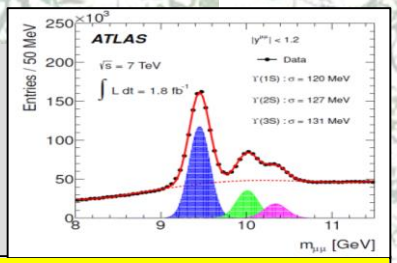




Υ production @2.76,7&8TeV

Υ →μ⁺μ⁻ excellent mass resolution!

EPJ C72 (2012) 2025



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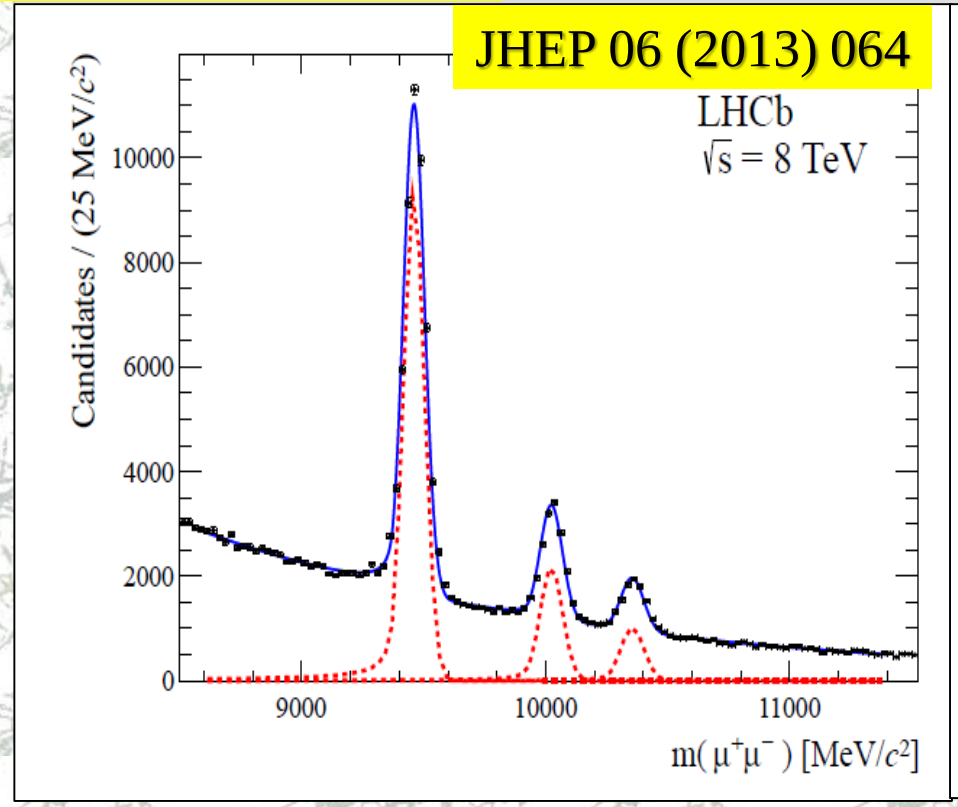

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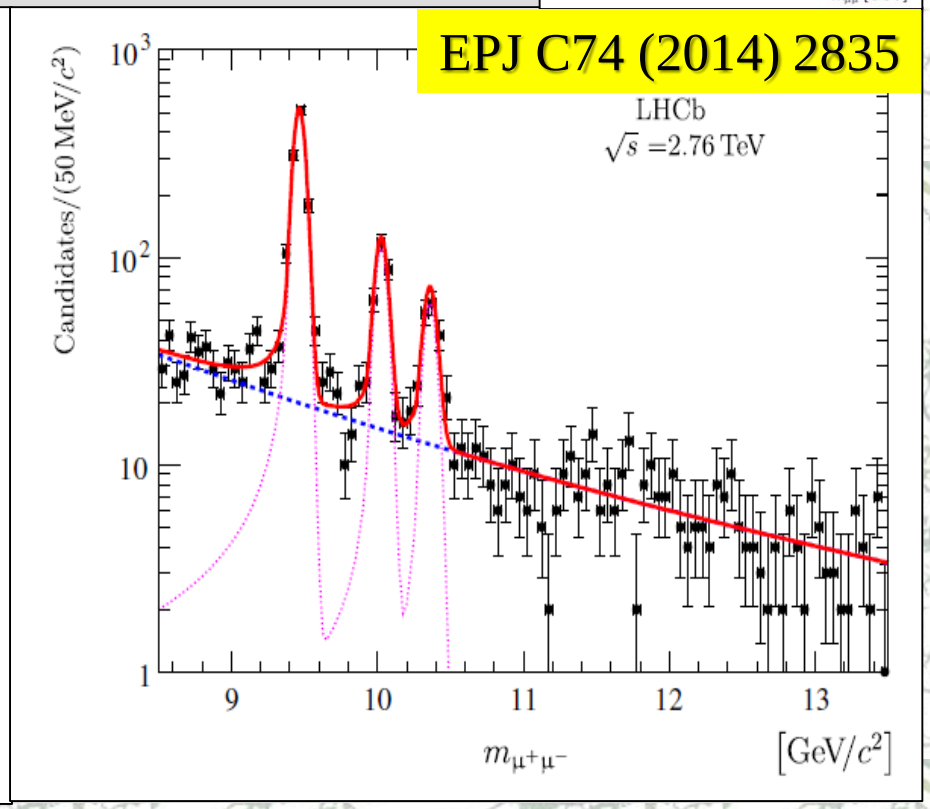

Υ production

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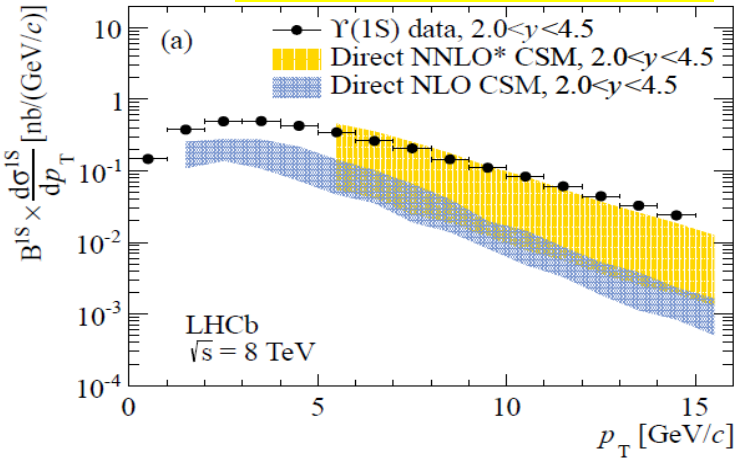

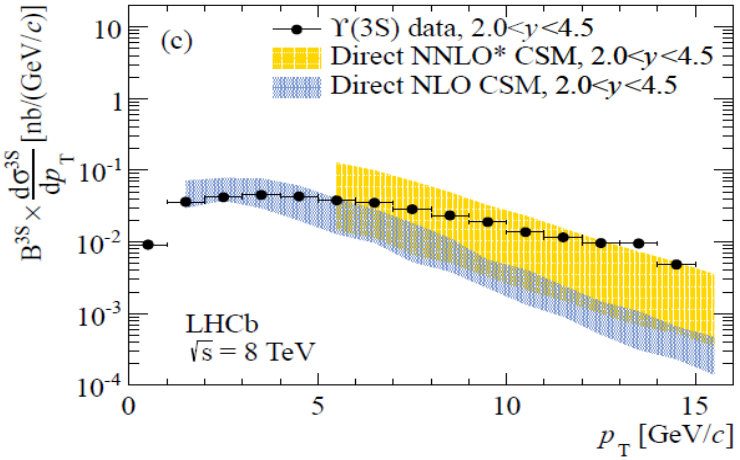

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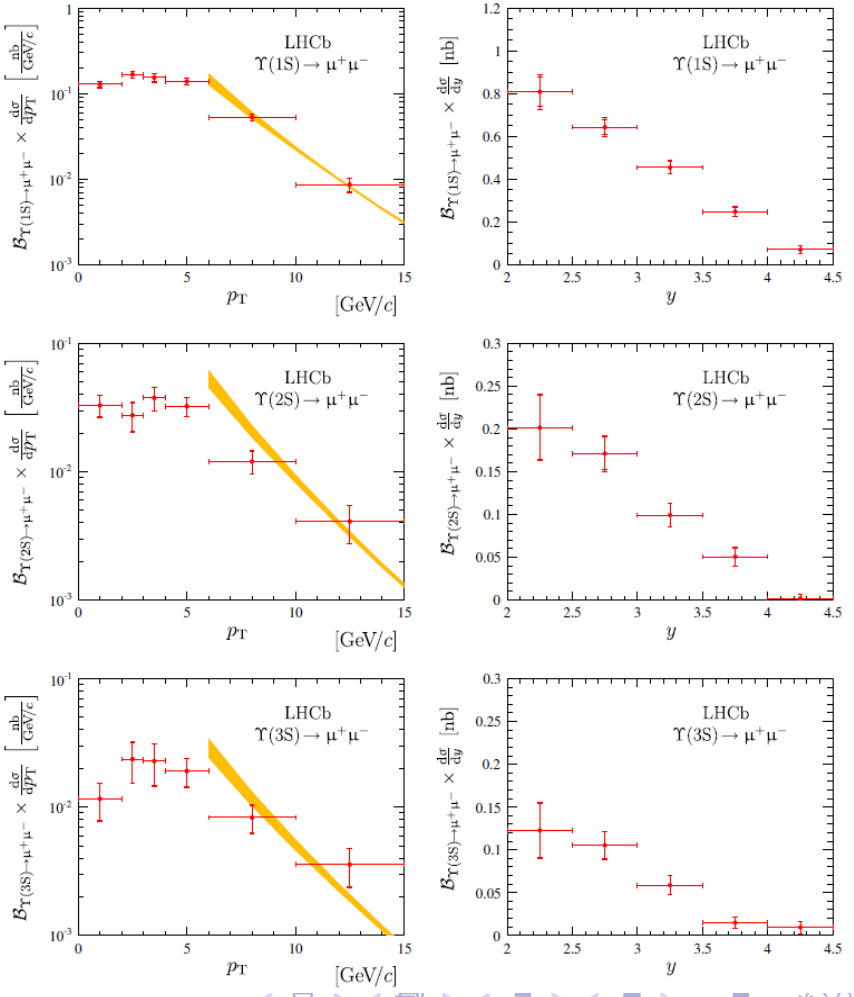
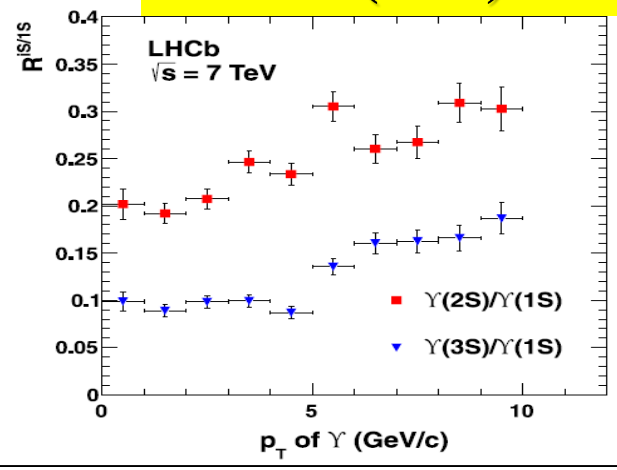
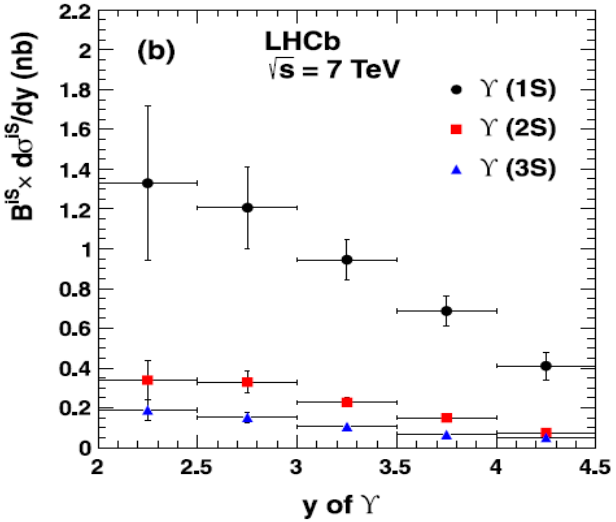


Υ(nS)/Υ(1S) ratios

EPJ C72 (2012) 2025





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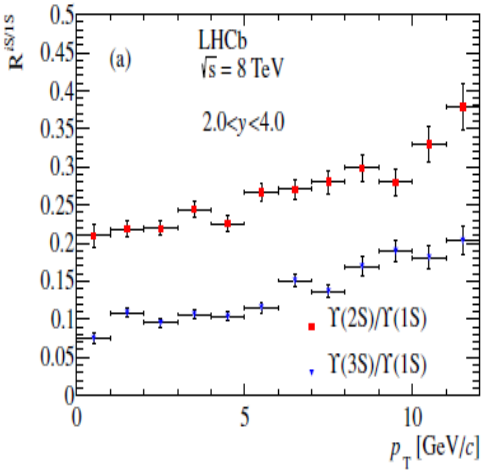

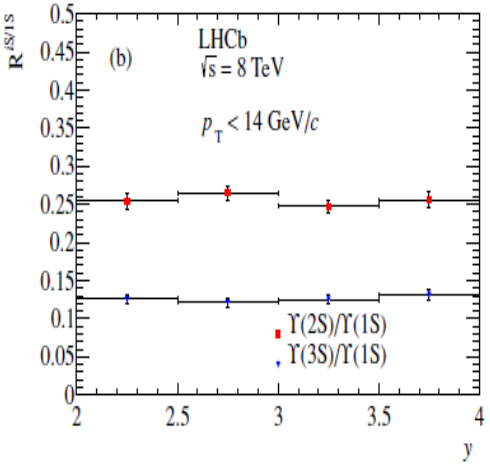

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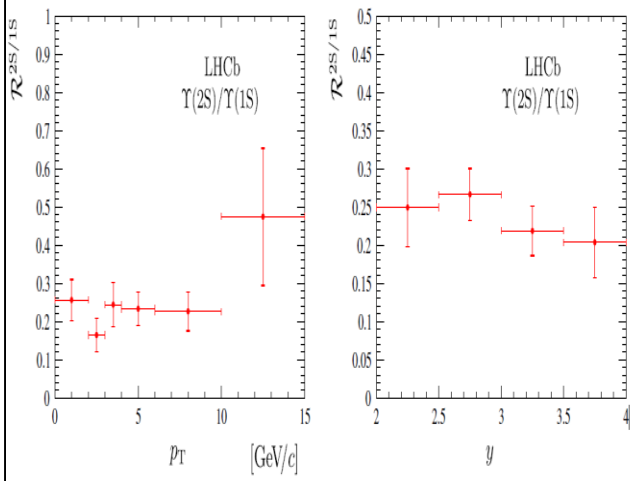
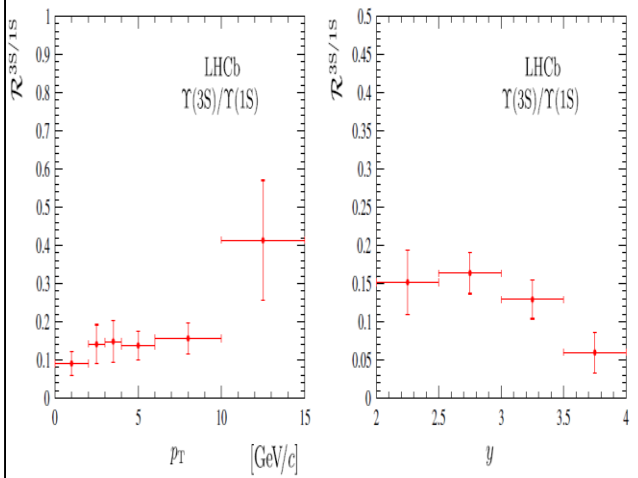




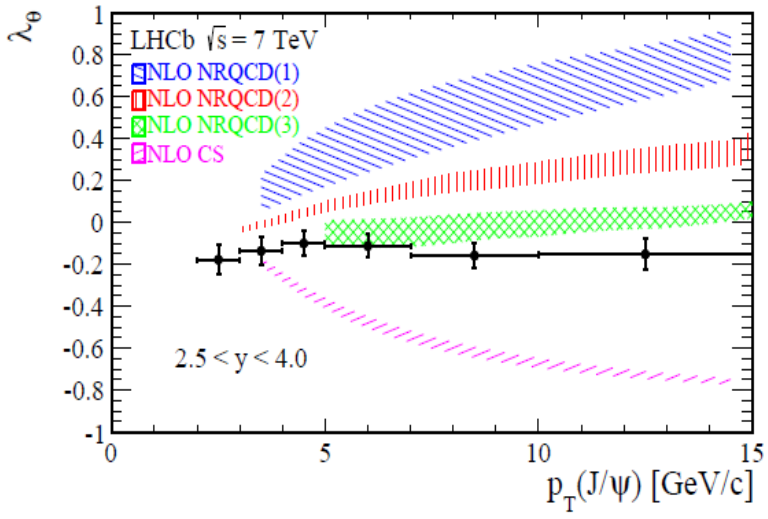
Other interesting topics

- Production in pA & Ap collisions
  - JHEP 02 (2014) 074 LHCb-PAPER-2014-015, arXiv:1405.5151
- B-hadron production
  - JHEP 08 (2013) 117
- B_c production PRL 109 (2012) 231001
- Search for double charmed baryons
  - JHEP 12 (2013) 090

Leading role of Tsinghua group

Polarisation fiasco (again)

EPJ C73 (2013) 2631



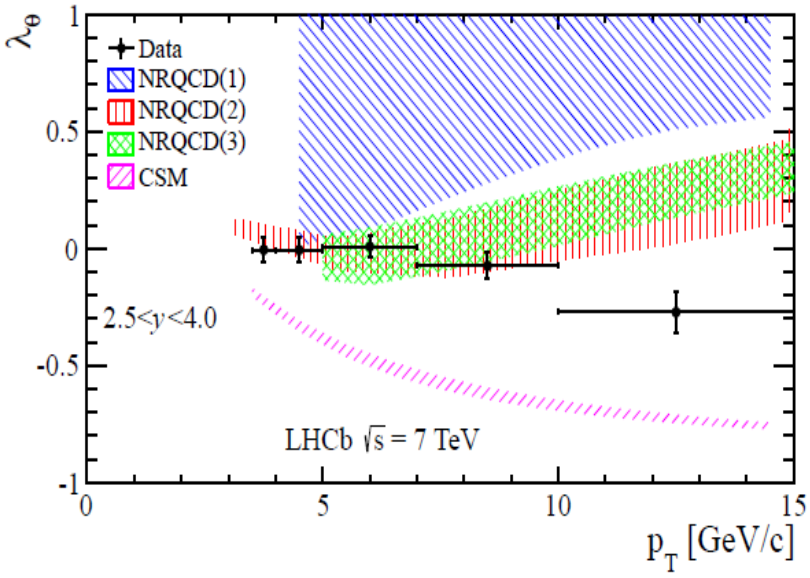
HX frame

- CSM no feed down: Nucl. Phys. Proc. Suppl. B222-224 (2012) 151
- NRQCD: no feed-down: Nucl. Phys. Proc. Suppl. B222-224 (2012) 151
- NRQCD: feed-down from $\chi_c(^3P_J^1, ^3S_J^8)$ and $\psi(2S)$ Phys. Rev. Lett. 110 (2013) 042002
- NRQCD: feed-down from $^3P^{[8]}$ Phys.Rev. Lett. 108 (2012) 242004

ψ' was expected to be easier:

- Free from feeddown

LHCb-PAPER-2013-067, arXiv:1403.1339



Summary

- HQ production is interesting & hot topic
  - Many active players, including LHCb
- There is great theory progress
  - .. and nice collaboration
- Some "old" puzzles are still with us
  - Polarization, role of CO
- Interesting data appears from LHC that need to be explained: challenge for theory
  - At high collision energies/large gluon densities new effects appears, e.g. DPS