Observation of double charm production at LHCb

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On behalf of LHCb Collaboration

LHCb-PAPER-2012-003 (in preparation)

Outline

- 2×Charm
- LHCb Detector & Data sample
- Event Selection
- 2×Charm signals
- Efficiency corrections
- Systematics
- Cross-sections & ratios
- Properties of 2×Charm events
- Conclusions

Heavy quark production in pp(gg)-collisions

LHC is LgC

- Open beauty & open charm :
  - *"well known"*
  - The measurements are in a reasonable agreement with *state-of-art* pQCD calculations
- Charmonium & bottomonium:
  - few open questions and puzzles
  - Polarization?
  - Color Singlet/CS vs Color Octet/CO
  - Recently very good progress with theory **NLLO***

- Double (charm)onia
  - Test for CO vs CS
  - 2×J/ψ is measured by

    NA3 in 1982 [PLB **114** 457, PLB **158**, 85]

    LHCb in 2011 [PLB **707** 52]
  - LHCb measurement is in excellent agreement with pQCD calculations for

$$gg \rightarrow 2\times J/\psi$$

$$\sigma_{LHCb} = 5.1 \pm 1.0 \pm 1.1\ \mathrm{nb}$$

$$\sigma_{gg} = 4\ \mathrm{nb}$$

How to get 2xCharm?

- pQCD matrix elements $gg \to 2\times J/\psi$ and to $gg \to c\bar{c}J/\psi$ and $gg \to c\bar{c}c\bar{c}$
  - Agrees well for $2\times J/\psi$

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)

- Intrinsic Charm:
  - Charm from (badly known) charm PDF
  - Lack of predictive power

- Double Parton Scattering
  - Simple paradigm with raising popularity

Double Parton Scattering

Google 240k 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 ...

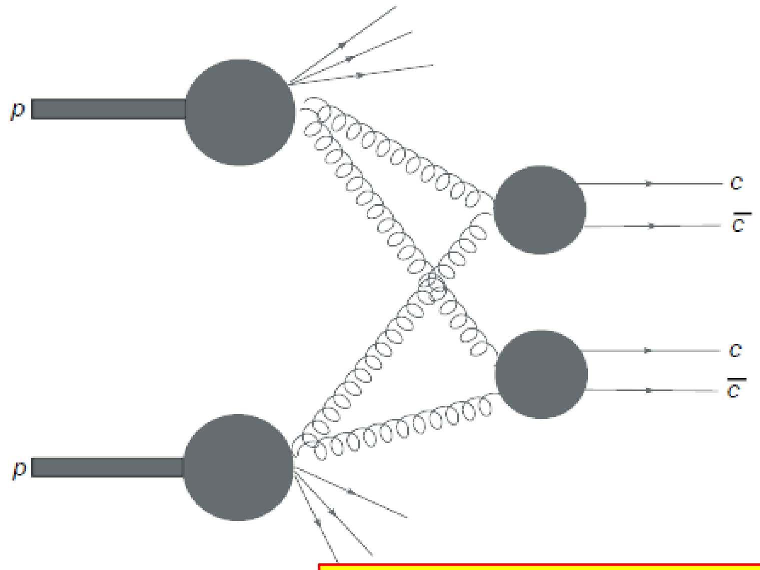
Double parton scattering of hadron-hadron interaction and its ...
arxiv.org › hep-ph - Перевести эту страницу
25 Apr 1997 – Title: **Double parton scattering** of hadron-hadron interaction and its gluonic contribution. Authors: Hung Hsiang Liu (Inst. of Phys, Academia ...

[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

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

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

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

2×Charm as proton probe

- Intrinsic Charm Model:
  - we are testing/constraining (badly known) charm **PDF**s – typical uncertainties ×2
- Double Parton Scattering
  - Provide $_2$**PDF**s
  - Measure σ_{eff} – ***universal*** proton property

2×Charm @ LHCb

$C = D^0, D^+, D_s, \Lambda_c$

$2 < y_{J/\psi, C} < 4$

$3 < p^T_C < 12$ GeV/c

$p^T_{J/\psi} < 12$ GeV/c

- We want to measure $c\bar{c}c\bar{c}$
  - $J/\psi C$ and CC
- As bonus $C\bar{C}$
  - Dominated by the regular $gg \rightarrow c\bar{c}$
    - More information useful from correlations
      - Gluon splitting , flavour creation, etc.
    - Similar to CDF'2k+6
- In total 25 possible modes:

$c\bar{c}c\bar{c}$ (1 $J/\psi J/\psi$) + 4 $J/\psi C$ + 10 CC

$gg \rightarrow c\bar{c}$ 10 $C\bar{C}$

Predictions for LHCb

Mode	σ_{gg}		σ_{DPS}	σ_{IC}
		[nb]		
$J/\psi D^0$	10 ± 6	7.4 ± 3.7	146 ± 39	220
$J/\psi D^+$	5 ± 3	2.6 ± 1.3	60 ± 17	100
$J/\psi D_s^+$	1.0 ± 0.8	1.5 ± 0.7	24 ± 7	30
$J/\psi \Lambda_c^+$	0.8 ± 0.5	0.9 ± 0.5	56 ± 22	—
		[μb]		
$D^0 D^0$			2.0 ± 0.5	1.5
$D^0 D^+$			1.7 ± 0.4	1.4
$D^0 D_s^+$	$\Sigma = 0.1\mu b$		0.65 ± 0.15	0.4
$D^0 \Lambda_c^+$			1.5 ± 0.5	1.4
$D^+ D^+$			0.34 ± 0.09	0.3
$D^+ D_s^+$			0.27 ± 0.07	0.2
$D^+ \Lambda_c^+$			0.64 ± 0.23	

σ_{gg}

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)

σ_{DPS}

based on LHCb measurements of

$\sigma_{J/\psi}$ [EPJ C71 1645]
σ_C [LHCb-CONF-2010-013]

C.H.Kom, A.Kulesza & J.W.Stirling, Phys.Rev.Lett, 107 082002 (2011)
S.P.Baranov, A.M.Snigirev and N.P.Zotov, Phys.Lett. B705 116 (2011)
A.Novoselov, arXiv:1105.62076
M.Luszczak, R.Maciula, A.Szczurek, arXiv:1111.3255

σ_{IC}

based on Alekhin's PDFs
S.Alekhin, PRD68 014002

2×Charm

LHCb Detector & Data sample

Event Selection

2×Charm signals

Efficiency corrections

Systematics

Cross-sections & ratios

Properties of 2×Charm events

Conclusions

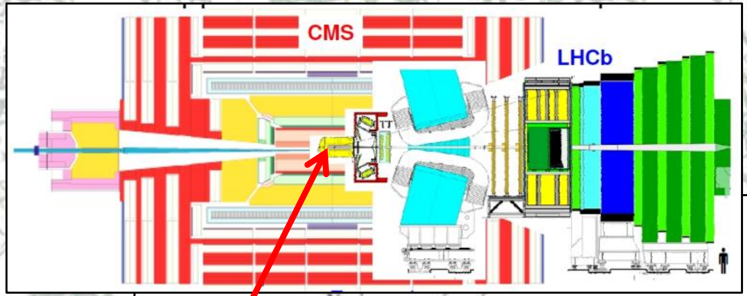
How to measure 2×Charm?

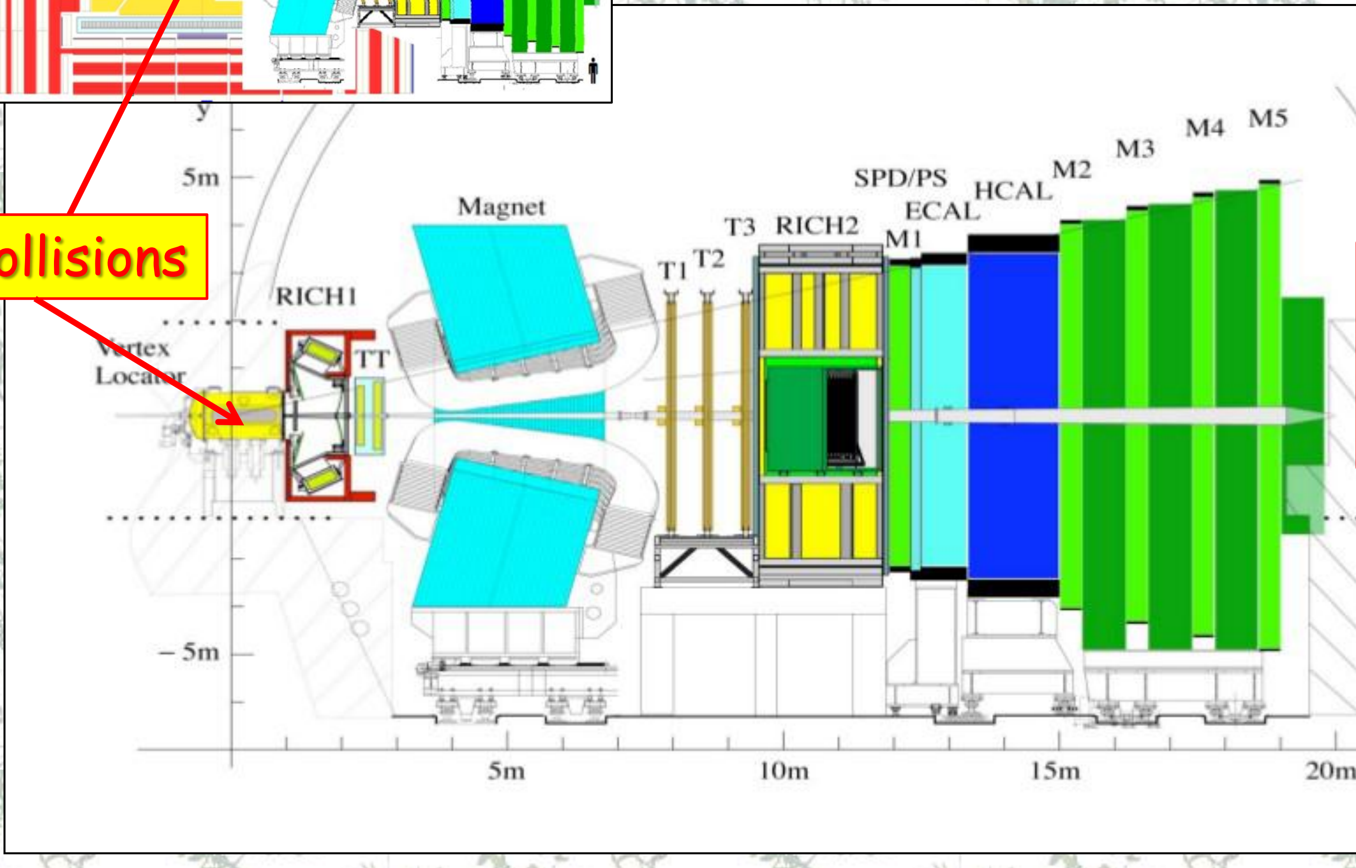
- Need excellent detector:
  - Track reconstruction and momentum resolution
  - Hadron identification
  - Muon identification
  - Vertex/lifetime/impact parameter resolution
  - Efficient trigger for muons and hadrons
- Need high statistics…

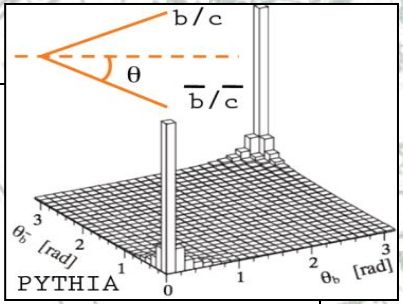
Natural choice: LHCb at LHC

LHCb: beauty detector

General purpose universal detector in forward region







pp-collisions

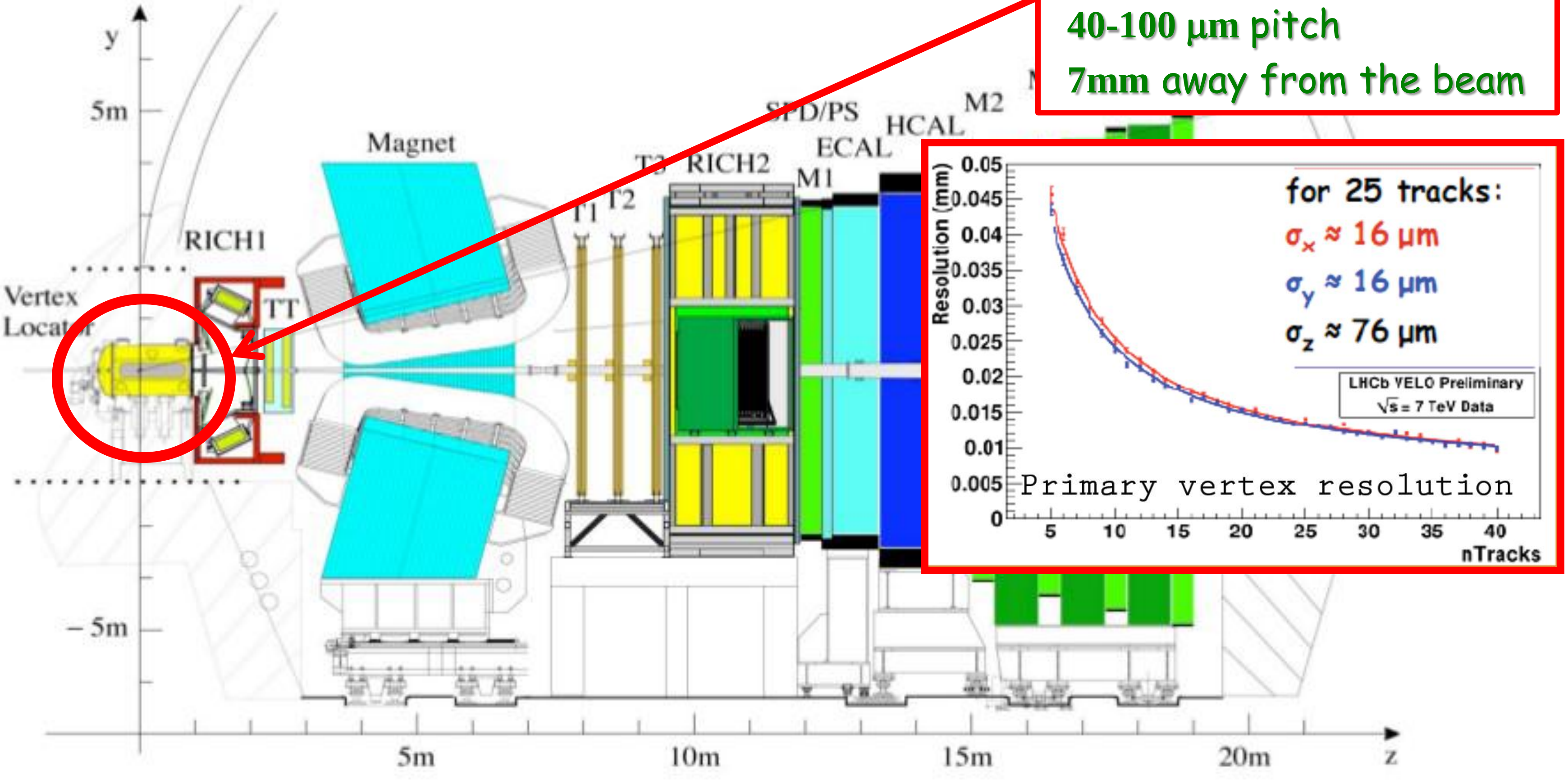
$2<\eta<5$

4% of solid angle

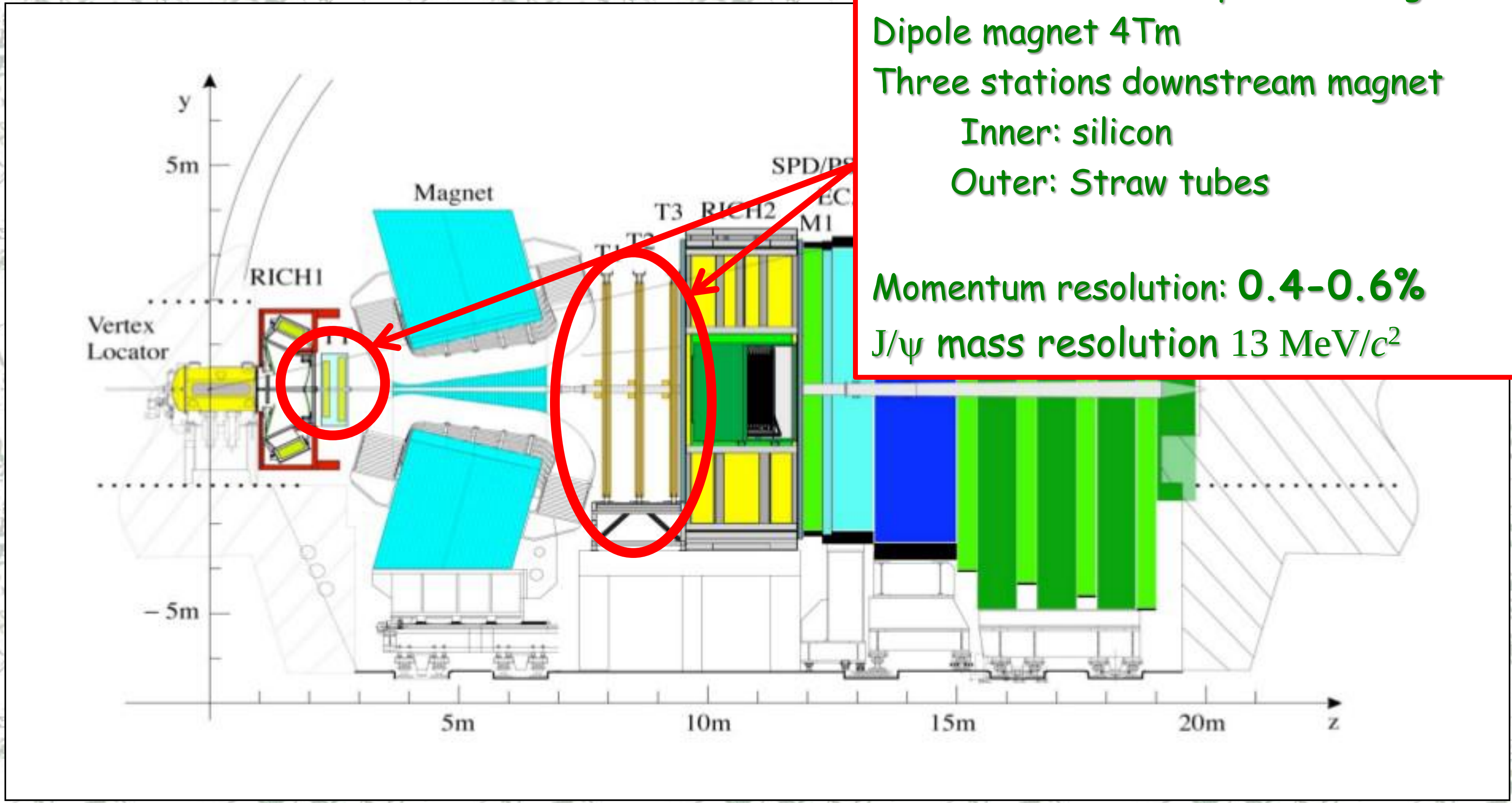
40% of heavy quarks

VELO

- 42×2 silicon strip planes
- r-ϕ geometry
- 40-100 μm pitch
- 7mm away from the beam



Tracking system

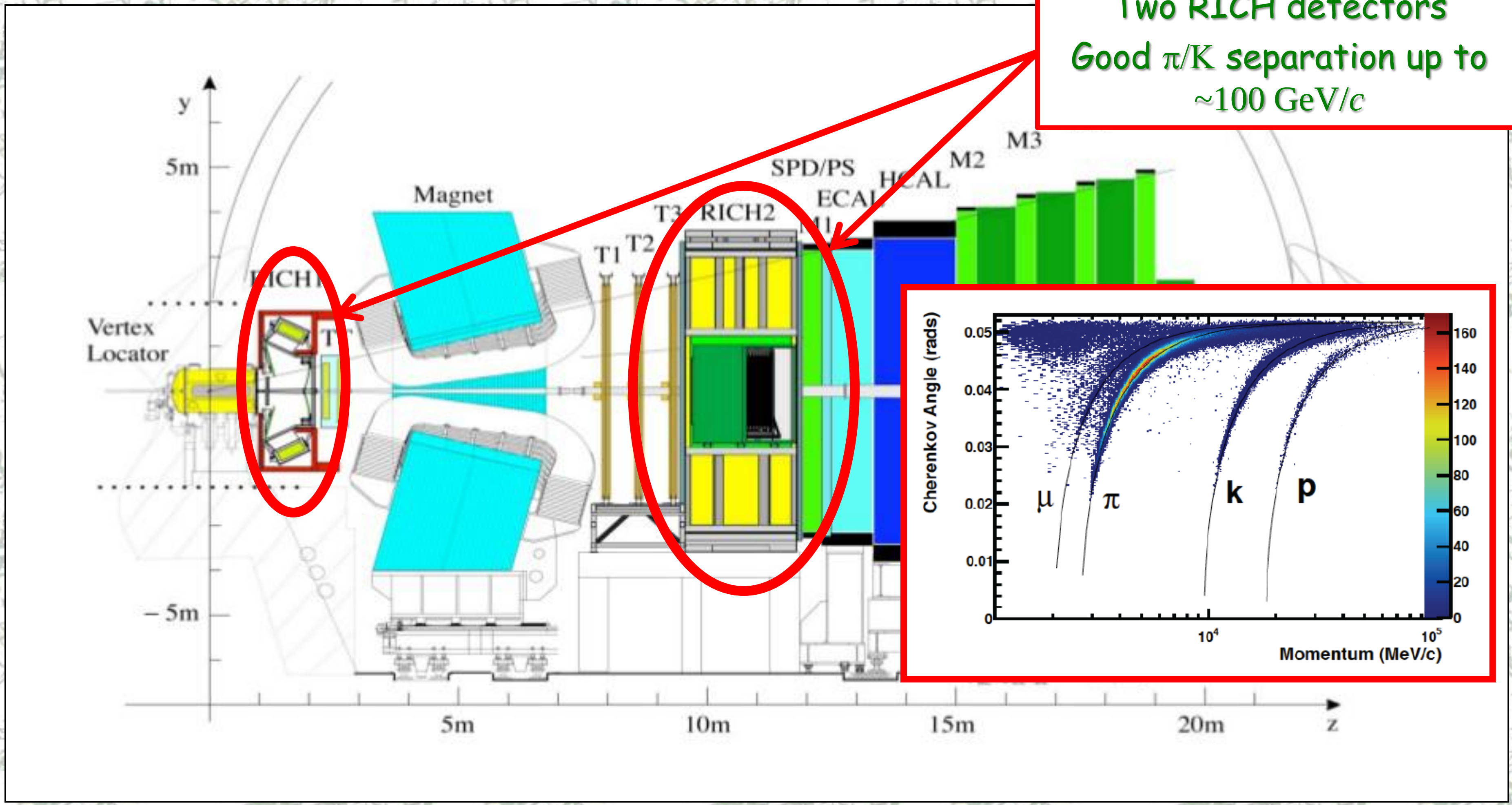


Two silicon stations upstream magnet
Dipole magnet 4Tm
Three stations downstream magnet
Inner: silicon
Outer: Straw tubes

Momentum resolution: **0.4-0.6%**
J/ψ mass resolution 13 MeV/c^2

Hadron ID

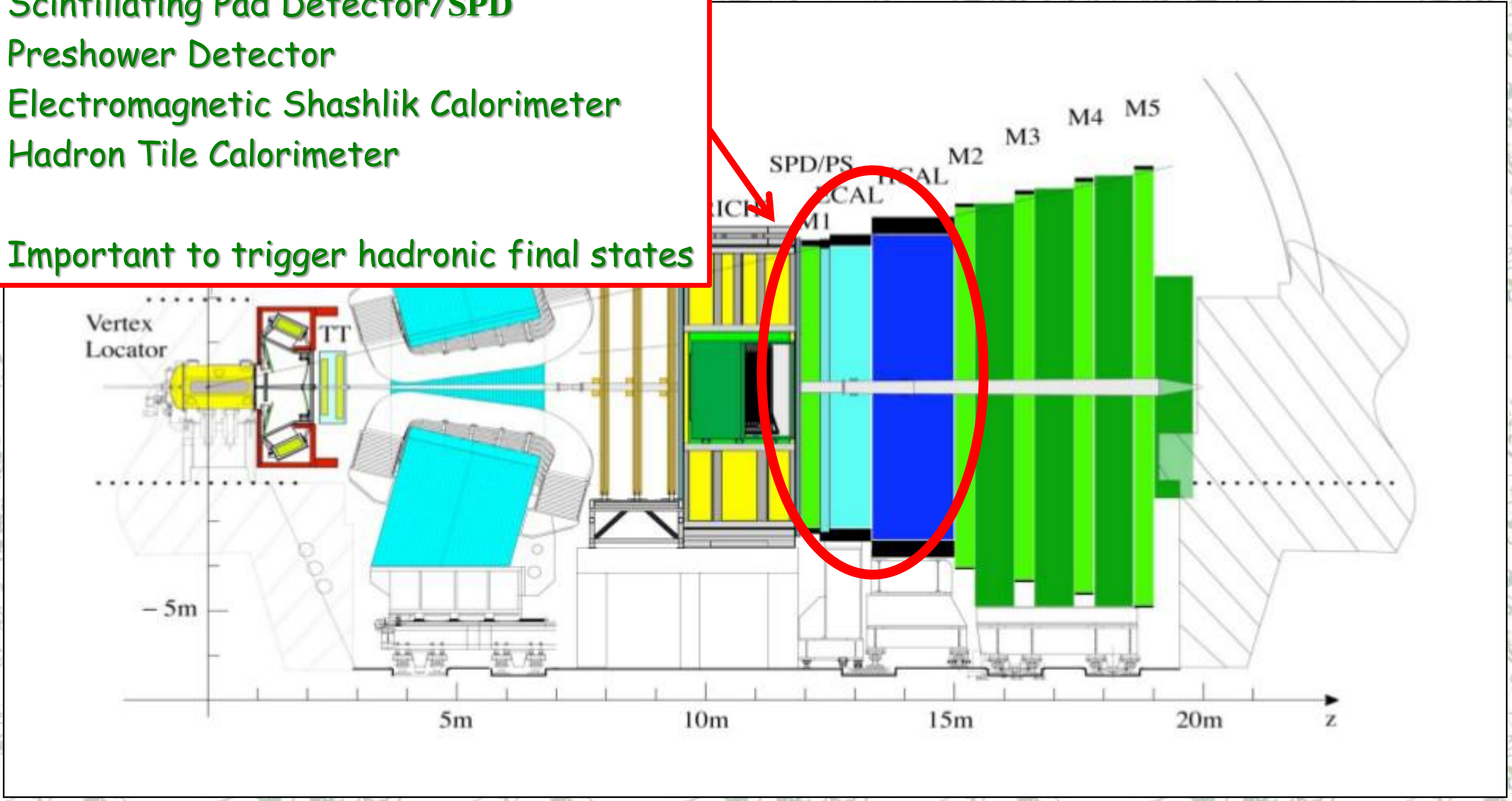
Two RICH detectors
Good π/K separation up to ~100 GeV/c



Calorimeter system

Scintillating Pad Detector/SPD
Preshower Detector
Electromagnetic Shashlik Calorimeter
Hadron Tile Calorimeter

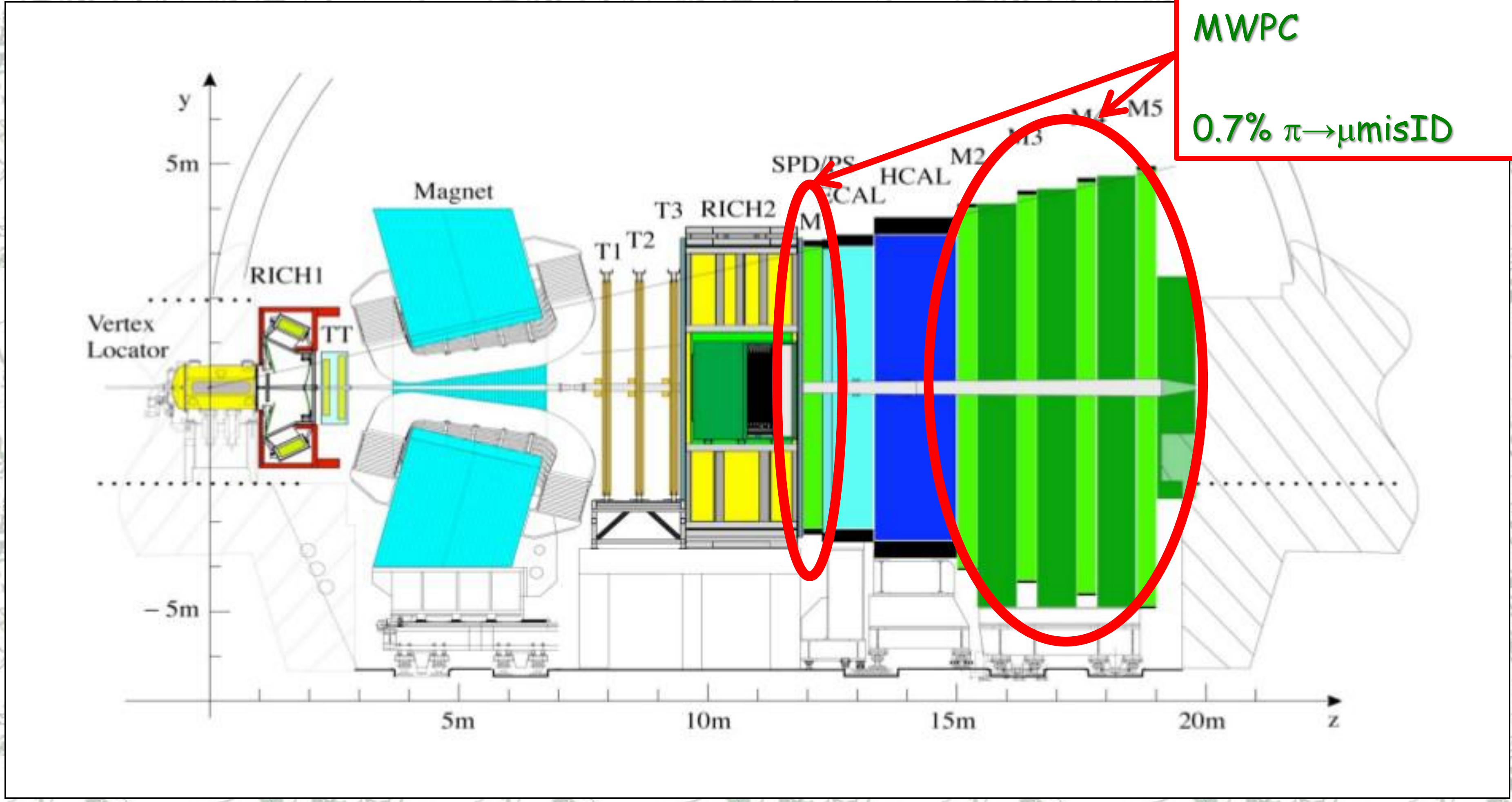
Important to trigger hadronic final states



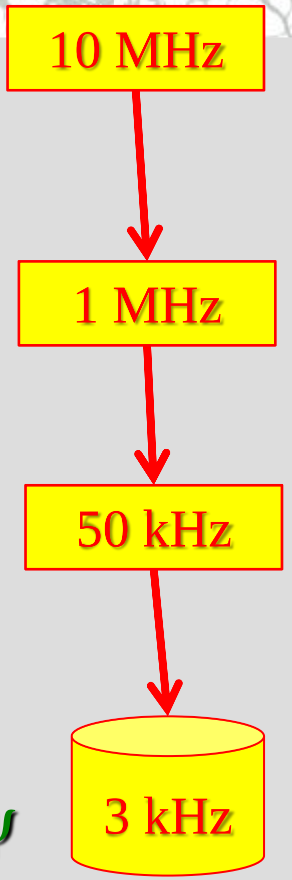
Muon system

4(+1) stations
MWPC

0.7% $\pi \to \mu$ misID



Trigger



L0 hardware

- high-p_T μ, 2μ, h, $e^{\pm}$, γ

Software Hlt1

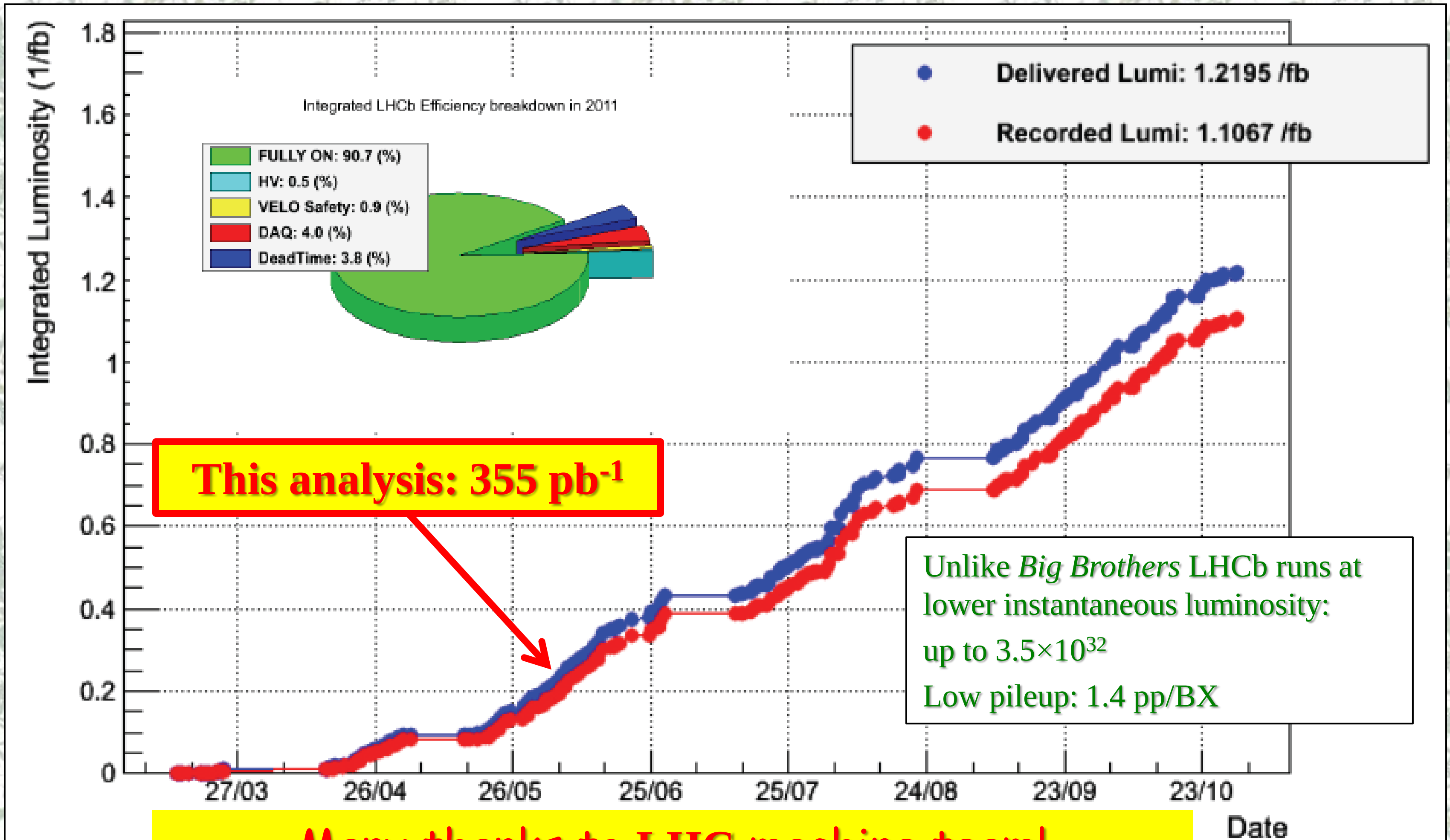
- Reconstruct μ, 2μ, h
- cut on IP, p_T, mass

Software Hlt2

- Full reconstruction of J/ψ
- Full reconstruction of open charm hadrons

DAQ records information needed for off-line trigger matching, allowing determination of trigger efficiency directly from data

Lumi'2k+11 1.1fb^{-1} recorded at$\sqrt{s}$=7TeV



Many thanks to LHC machine team!

2×Charm

LHCb Detector & Data sample

Event Selection

2×Charm signals

Efficiency corrections

Systematics

Cross-sections & ratios

Properties of 2×Charm events

Conclusions

Analysis strategy

- Determine the *model independent* cross-sections in **LHCb** fiducial volume

$2<y<4$

$3< p^{T}_{C} <12$ GeV/c

$p^{T}_{J/\psi} < 12$ GeV/c

- Reconstruct prompt charm hadrons:

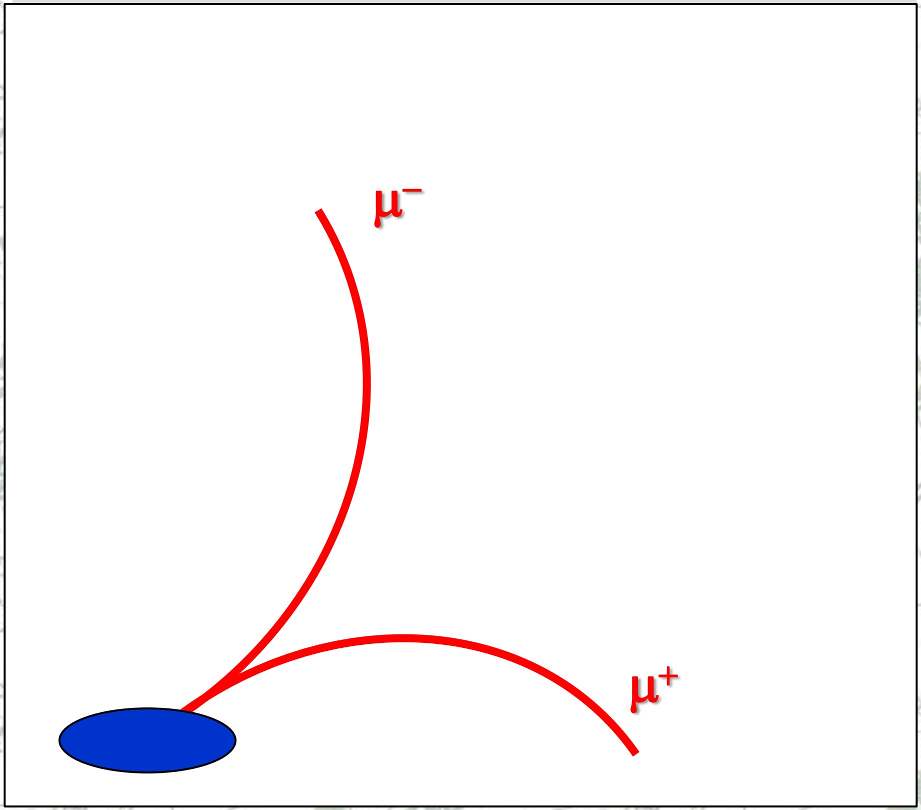
  $J/\psi \to \mu^+\mu^-$

  $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s \to (K^+K^-)_\phi\pi^+$, $\Lambda_c \to p^+K^-\pi^+$

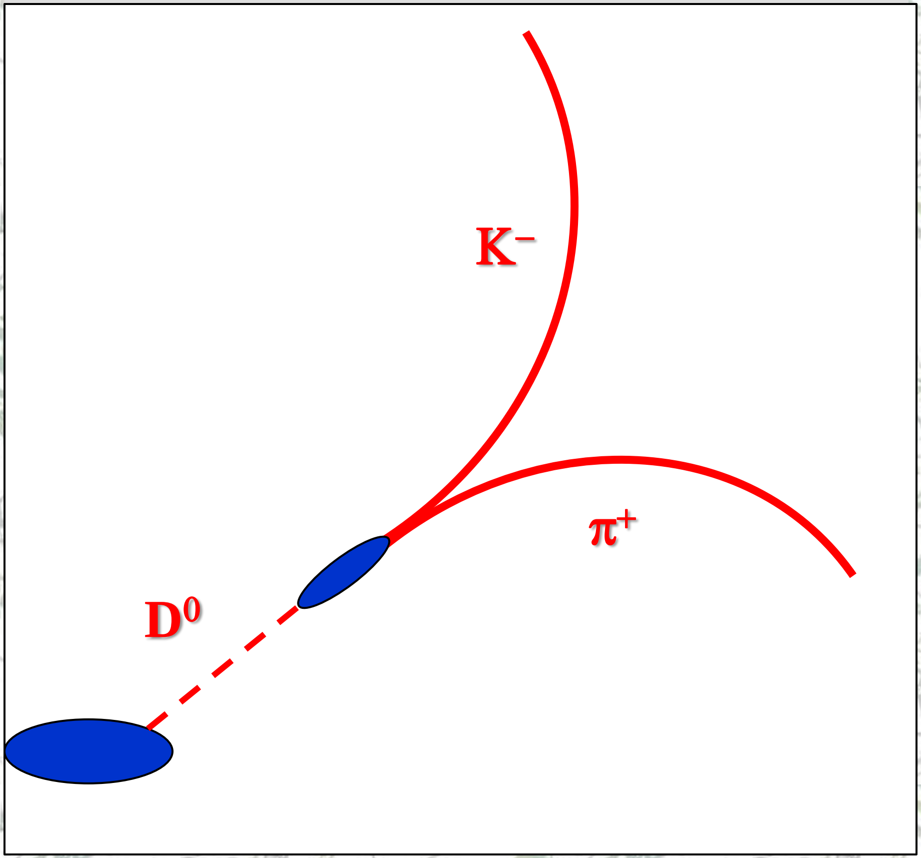
- Take care about background and keep track on efficiency determination
  - Use *sPlot* technique for background subtraction
  - Use *per-event* efficiency correction
  - Extract efficiencies from data (when possible)

Event Selection

J/ψ two muons in common PV vertex

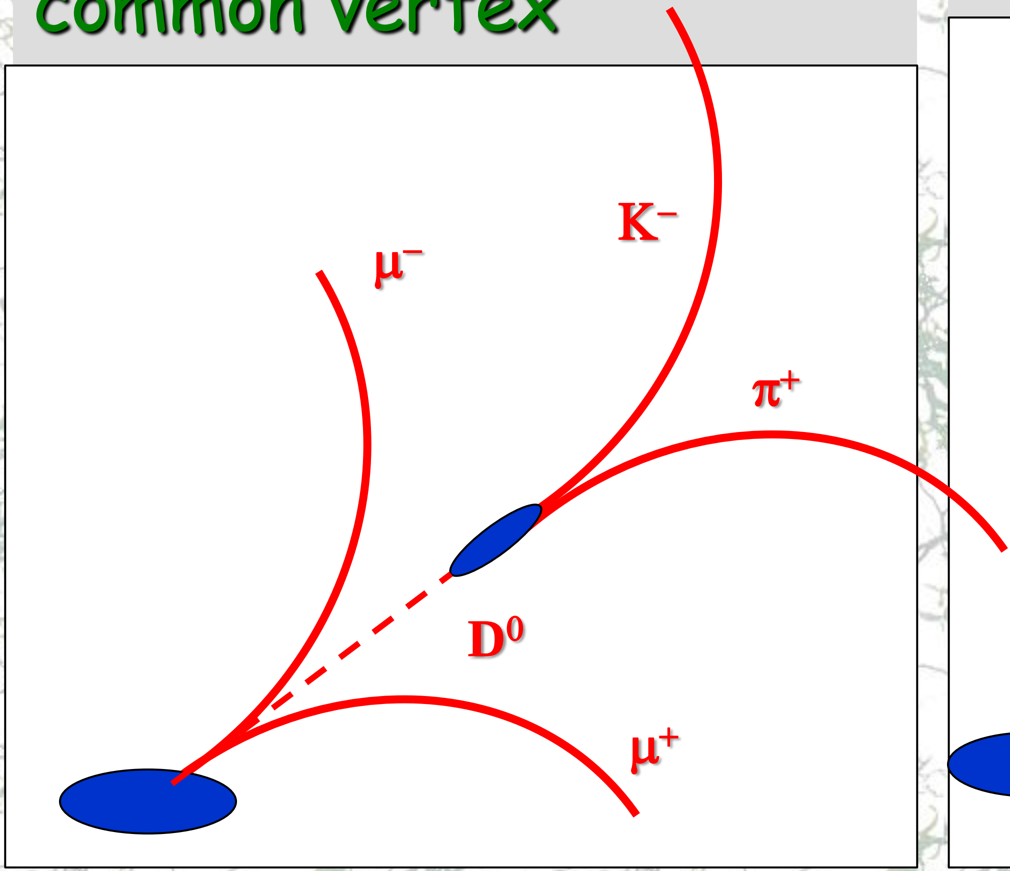


Open charm hadrons

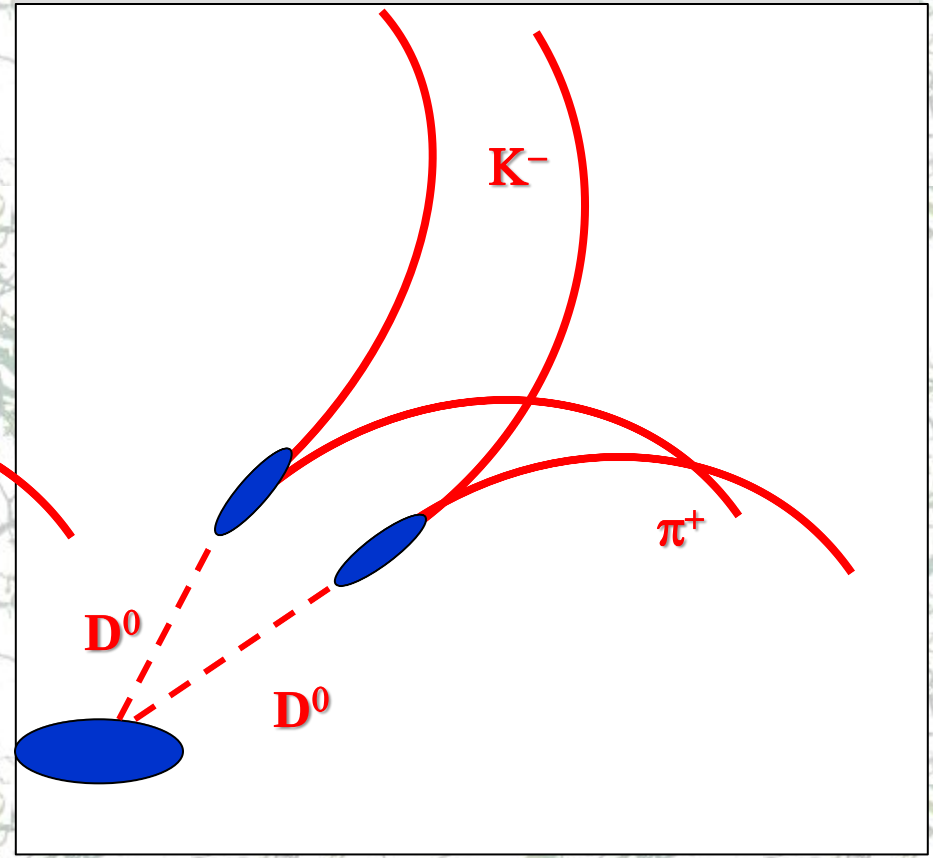


Event Selection

J/ψC two charm with common vertex



2×Open charm hadrons



Charm hadron reconstruction

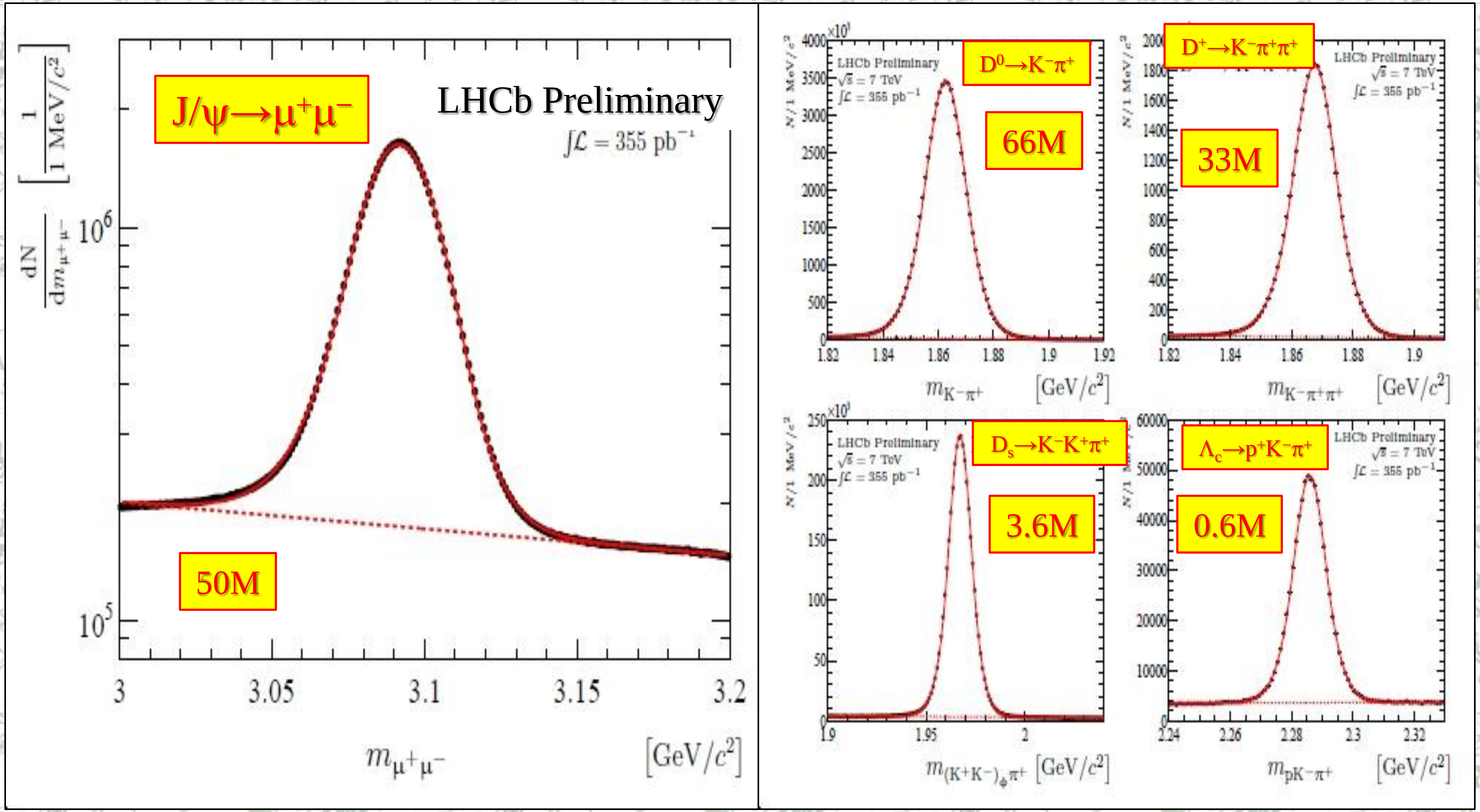
- Start from good quality tracks
- Apply positive PID
  μ,K,π,p
- Vertex quality cuts
- PV & *decay consistency*
- $c\tau$ cut for open charm hadrons

"3σ mantra"

- Daughter particles do not point to PV (>3σ)
- Mother particle does point to PV (<3σ)
- Mother particle has non-zero lifetime (except J/ψ)
- The decay structure is self-consistent

- As similar as possible (a bit tighter for Λ_c)

Charm hadrons



2×Charm

- Require both hadrons consistent with the same **PV** – the only one cut $\chi^2_{fit}(C_1C_2)/ndf < 5$
- <u>By construction:</u> 100% efficiency for signal:
  - $\chi^2_{fit}(C_1C_2) = \chi^2_{fit}(C_1)+\chi^2_{fit}(C_2)$
  - $\chi^2_{fit}(C_1)/ndf < 5$ & $\chi^2_{fit}(C_2)/ndf < 5$
  - Remove particles from different **PV** (pileup)
- Apply trigger matching:

  J/ψC require the event is triggered by **J/ψ**

  CC and $\mathbf{C\overline{C}}$: either of open charm hadrons triggers event

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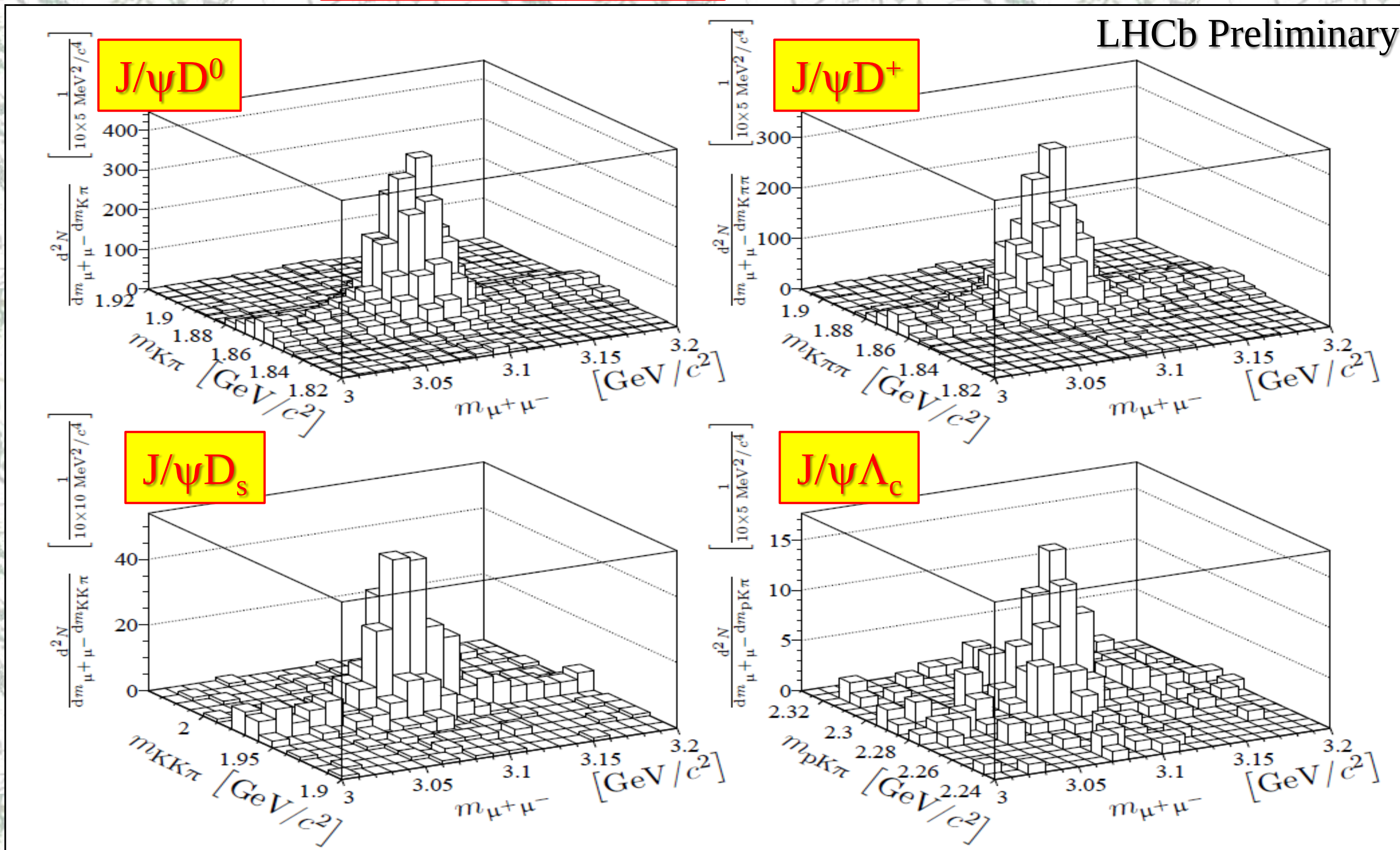
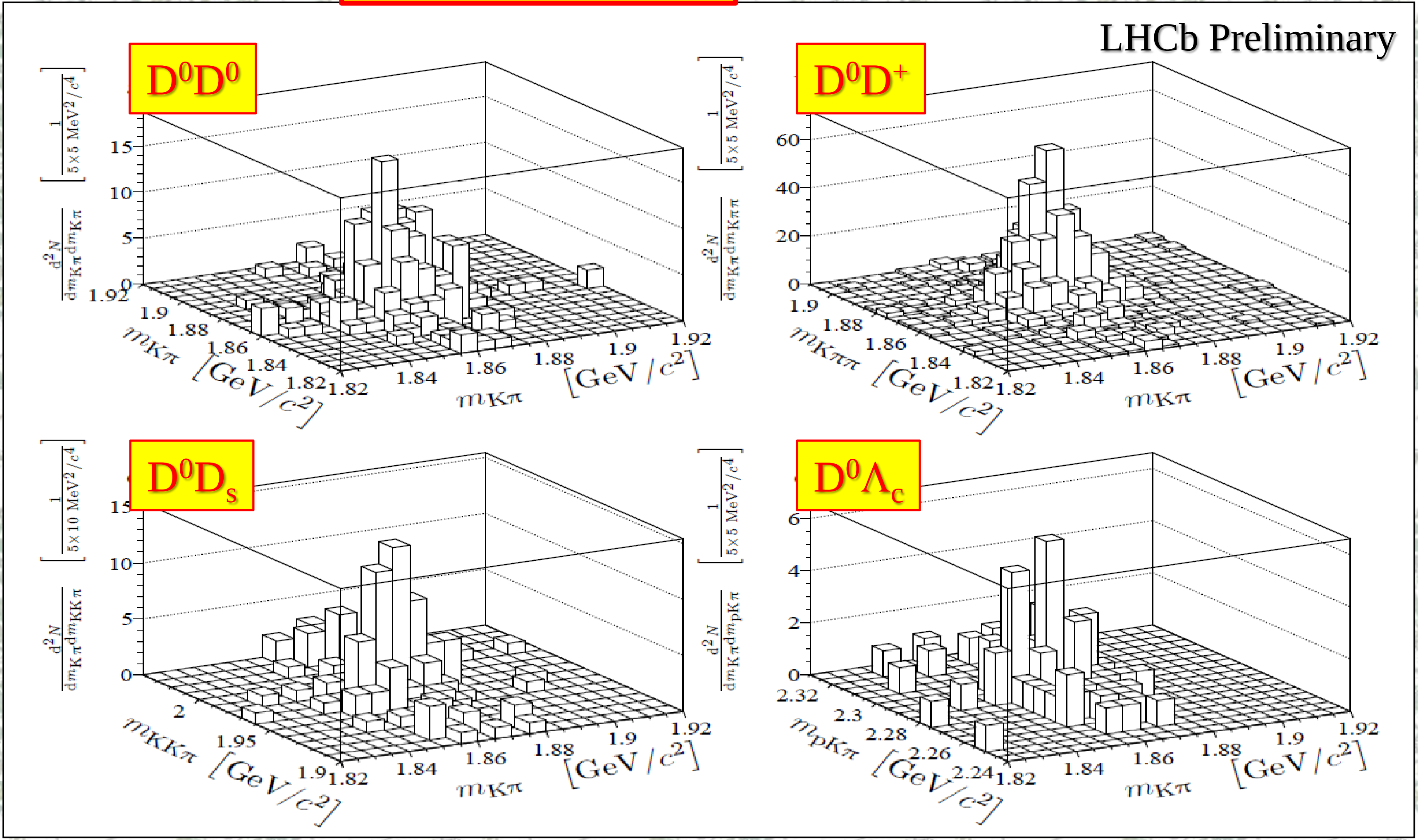
$J/\psi C$ 2D-mass spectra

Clear $c\bar{c}c\bar{c}$ signals!



D^0C 2D-mass spectra

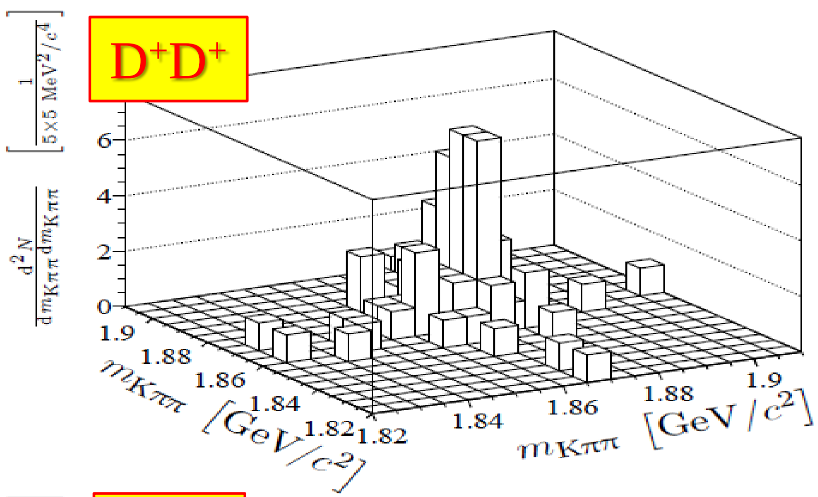
Clear $c\bar{c}c\bar{c}$ signals!

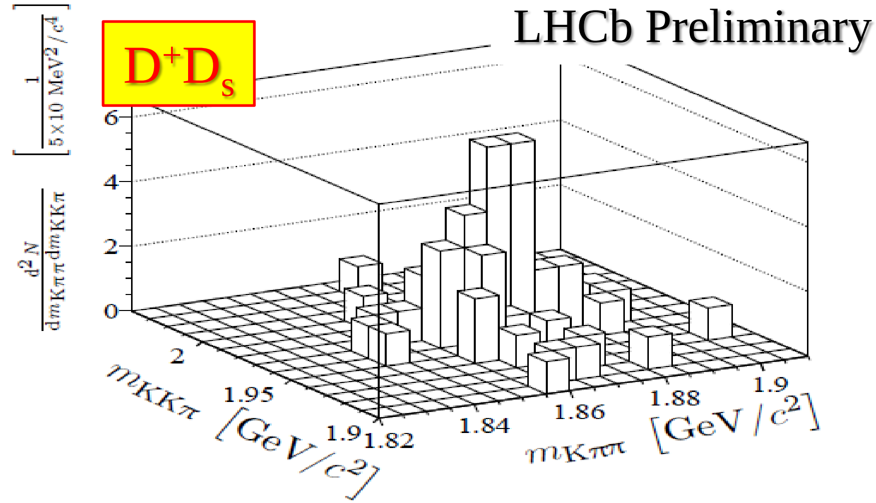


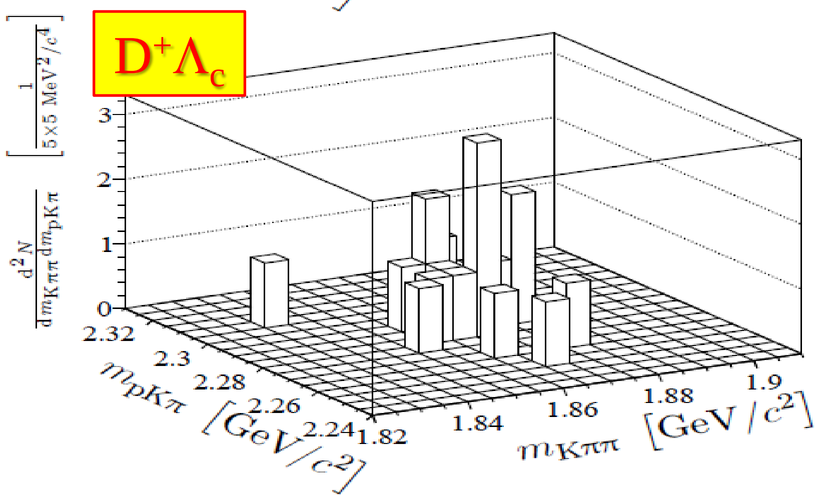
D^+C 2D-mass spectra

$c\bar{c}c\bar{c}$

LHCb Preliminary





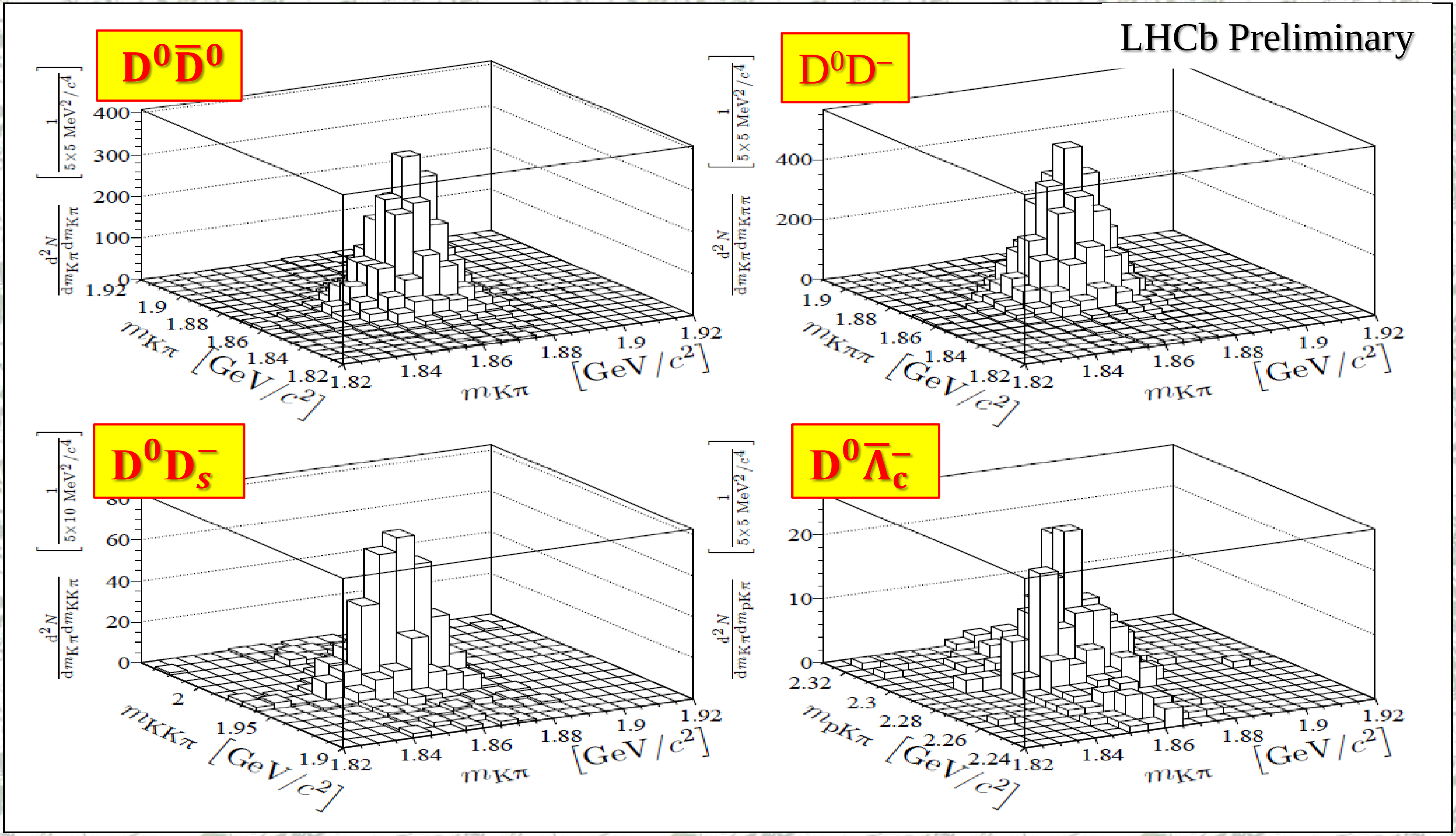


Not enough statistics (yet)

for D_sD_s, $D_s\Lambda_c$ & $\Lambda_c\Lambda_c$

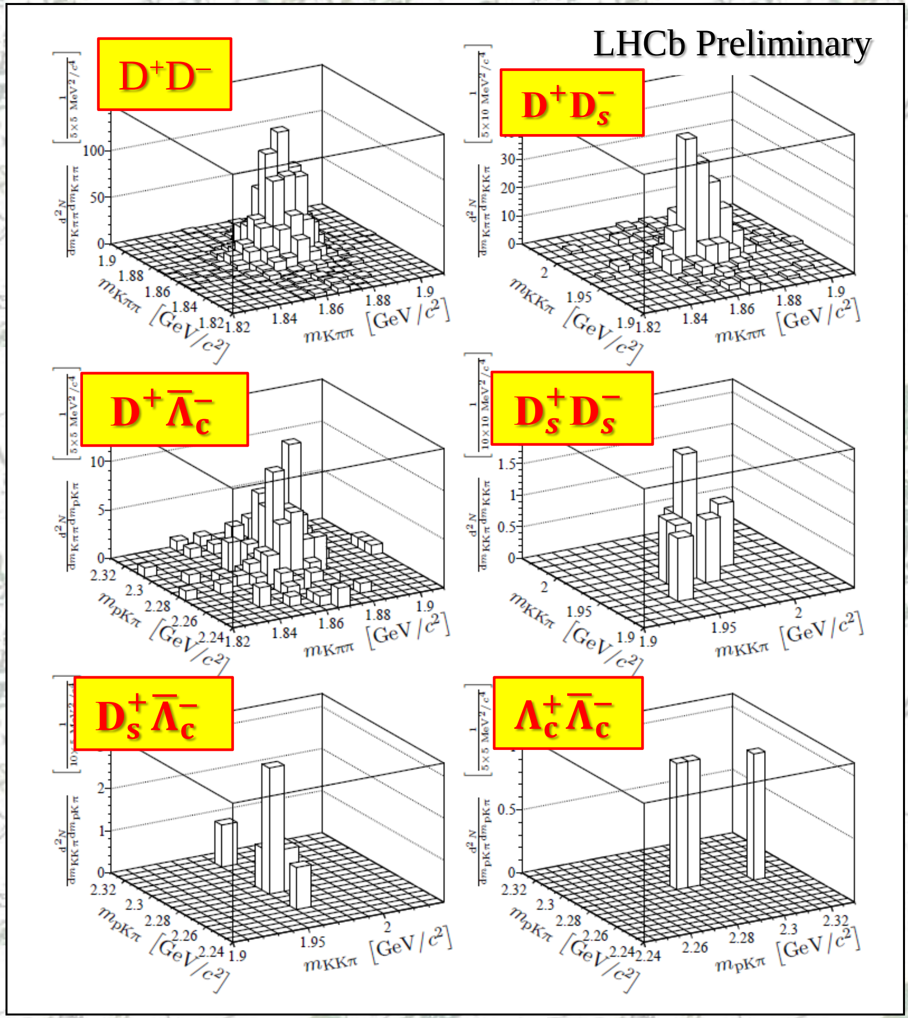
$D^0\bar{C}$ 2D-mass spectra

$gg \to c\bar{c}$



$c\bar{c}$ 2D-mass spectra

$gg \to c\bar{c}$



Signal Extraction

- 2D- unbinned maximum likelihood fit

$$F(m_i m_j) \propto N^{S_i \times S_j} \times S_i(m_i)S_j(m_j) + N^{S_i \times B_j} \times S_i(m_i)B_j(m_j) + N^{B_i \times S_j} \times B_i(m_i)S_j(m_j) + N^{B_i \times B_j} \times B_i(m_i)B_j(m_j)$$

Signal

J/ψ: *double-sided Crystal Ball*

Open Charm: *«Bukin»*

Background: *exponential*

Extensive *goodness-of-fit* tests

Cross-check *(binned) fit-in-slices*

Significance

Yields & Significances

Mode	Yield	Significance	Goodness-of-fit[%]
$J/\psi D^0$	4875 ± 86	$> 30\sigma$	59
$J/\psi D^+$	3323 ± 71	$> 30\sigma$	26
$J/\psi D_s^+$	328 ± 22	13.6σ	65
$J/\psi \Lambda_c^+$	116 ± 14	7.3σ	98

Mode	$\mathcal{Y}$	$\mathcal{S}_\sigma$	$\mathcal{P}$ [%]
D^0D^0	1087 ± 37	27σ	4.5
$D^0\bar{D}^0$	10080 ± 105	$> 30\sigma$	33
D^0D^+	1177 ± 39	29σ	24
D^0D^-	11224 ± 112	$> 30\sigma$	36
$D^0D_s^+$	111 ± 12	8σ	10
$D^0D_s^-$	859 ± 31	26σ	13
$D^0\Lambda_c^+$	41 ± 8	5σ	9
$D^0\bar{\Lambda}_c^-$	308 ± 19	14σ	35
D^+D^+	249 ± 19	12σ	15
D^+D^-	3236 ± 61	$> 30\sigma$	67
$D^+D_s^+$	52 ± 9	5σ	54
$D^+D_s^-$	419 ± 22	18σ	59
$D^+\Lambda_c^+$	21 ± 5	2.5σ	36
$D^+\bar{\Lambda}_c^-$	137 ± 14	8σ	7

>5σ

4 J/ψC

6 CC

7 $C\bar{C}$

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Per-event efficiencies:
as much as possible from data

$$\varepsilon^{tot} = \varepsilon^{acc\&rec\&sel} \times \varepsilon^{pid} \times \varepsilon^{trg} \times \varepsilon^{*track}$$

$$\varepsilon^{acc\&rec\&sel} = \varepsilon_1^{acc\&rec\&sel} \times \varepsilon_2^{acc\&rec\&sel}$$

$$\varepsilon^{pid} = \prod \varepsilon^{K} \times \prod \varepsilon^{\pi} \times \prod \varepsilon^{p} \quad [\quad \times \varepsilon^{2\mu, J/\psi}]$$

$$\varepsilon^{*track} = \prod \varepsilon^{*track}$$

$$\varepsilon^{trg}(J/\psi C) = \varepsilon^{trg}(J/\psi)$$

$$\varepsilon^{trg}(CC, C\overline{C}) = 1 - (1 - \varepsilon_1^{trg})(1 - \varepsilon_2^{trg})$$

MC
DATA
Diff

Efficiencies II

- $\varepsilon_i^{acc\&rec\&sel}$ from (single charm) Monte Carlo Simulation
  - As function of p^T & y for D^0, D^+, D_s, Λ_c
  - As function of p^T,y & $\cos\theta^*$ for J/ψ
- ε^K, ε^π and ε^p from **DATA** using $\Lambda^0 \to p^+\pi^-$ and $D^{*+} \to (D^0 \to K^-\pi^+)\,\pi^+$
  - As function of p&η and **#Tracks**
- $\varepsilon^{2\mu,J/\psi}$ from **DATA**, using inclusive J/ψ peak
  - As function of J/ψ p^T&y
- $\varepsilon^{trg}(J/\psi)$ & ε_i^{trg} from **DATA** using inclusive J/ψ, D^0, D^+, D_s^+, Λ_c^+
  - As function of p^T&y
- ε^{*track} from detailed **DATA/MC** comparison
  - As function of track p^T&η

Cross-section

- Use *sWeight/sPlot* technique:
  - Each event i has *weight* ω_i from *sWeight*
    - *Probability event to be signal*
  - This *weight* is corrected by $1/\varepsilon^{TOT}$

$$N^{\mathrm{corr}} = \sum_i \frac{\omega_i}{\varepsilon_i^{\mathrm{tot}}}.$$

$$\sigma = \frac{N^{\mathrm{corr}}}{\mathcal{L} \times \mathcal{B}_1 \times \mathcal{B}_2 \times \varepsilon^{\mathrm{GEC}}}$$

The price:
The inflation of "*statistical*" error
Need good control over efficiency!

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Systematic uncertainties

- Dominant:
  - hadron track reconstruction uncertainty related to hadron interactions in detector:
    - *2% per hadron track*
- For modes with Λ_c and D_s large uncertainties due to uncertainties in branching fractions
  - cancelled in ratios
- Uncertainties related to signal extraction and efficiency corrections are small (1-3-5%)

2×Charm

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$J/\psi C$ cross-sections and ratios

LHCb Preliminary

Mode	σ [nb]
$J/\psi D^0$	$161.0 \pm 3.7 \pm 10.3 \pm 6.5$
$J/\psi D^+$	$56.6 \pm 1.7 \pm 4.9 \pm 3.3$
$J/\psi D_s^+$	$30.5 \pm 2.6 \pm 2.6 \pm 2.2$
$J/\psi \Lambda_c^+$	$43.2 \pm 7.0 \pm 4.0 \pm 11.3$

Using LHCb measurements for $\sigma_{J/\psi}$ [EPJ C71, 1645] and σ_C [LHCb-CONF-2010-013]

LHCb Preliminary

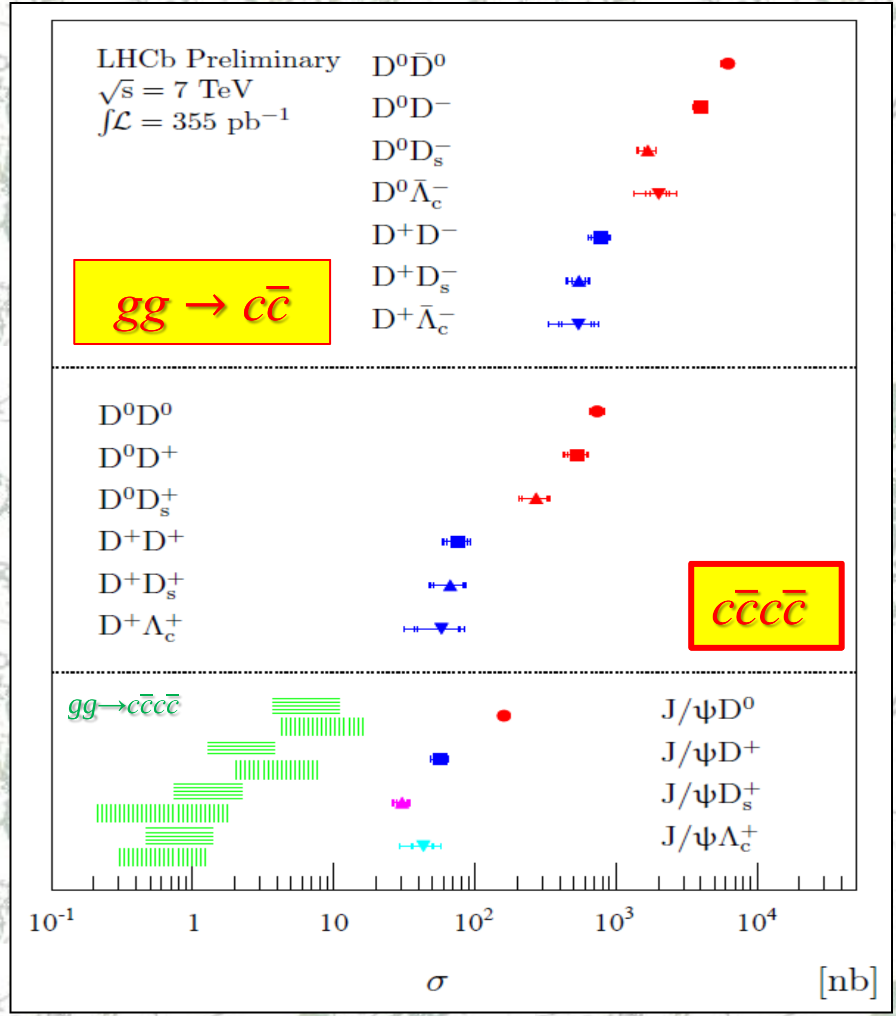
Mode	$\sigma_{J/\psi C}/\sigma_{J/\psi}$ $[10^{-3}]$	$\sigma_{J/\psi C}/\sigma_C$ $[10^{-4}]$	$\sigma_{J/\psi}\sigma_C/\sigma_{J/\psi C}$ [mb]
$J/\psi D^0$	$16.18 \pm 0.38 \pm 1.31^{+3.38}_{-2.52}$	$6.69 \pm 0.18 \pm 0.46$	$14.9 \pm 0.4 \pm 1.1^{+2.3}_{-3.1}$
$J/\psi D^+$	$5.69 \pm 0.17 \pm 0.62^{+1.19}_{-0.89}$	$5.67 \pm 0.20 \pm 0.40$	$17.6 \pm 0.6 \pm 1.3^{+2.8}_{-3.7}$
$J/\psi D_s^+$	$3.07 \pm 0.26 \pm 0.35^{+0.64}_{-0.48}$	$7.76 \pm 0.81 \pm 0.63$	$12.8 \pm 1.3 \pm 1.1^{+2.0}_{-2.7}$
$J/\psi \Lambda_c^+$	$4.34 \pm 0.70 \pm 1.21^{+0.91}_{-0.68}$	$5.52 \pm 1.00 \pm 0.62$	$18.0 \pm 3.3 \pm 2.1^{+2.8}_{-3.8}$

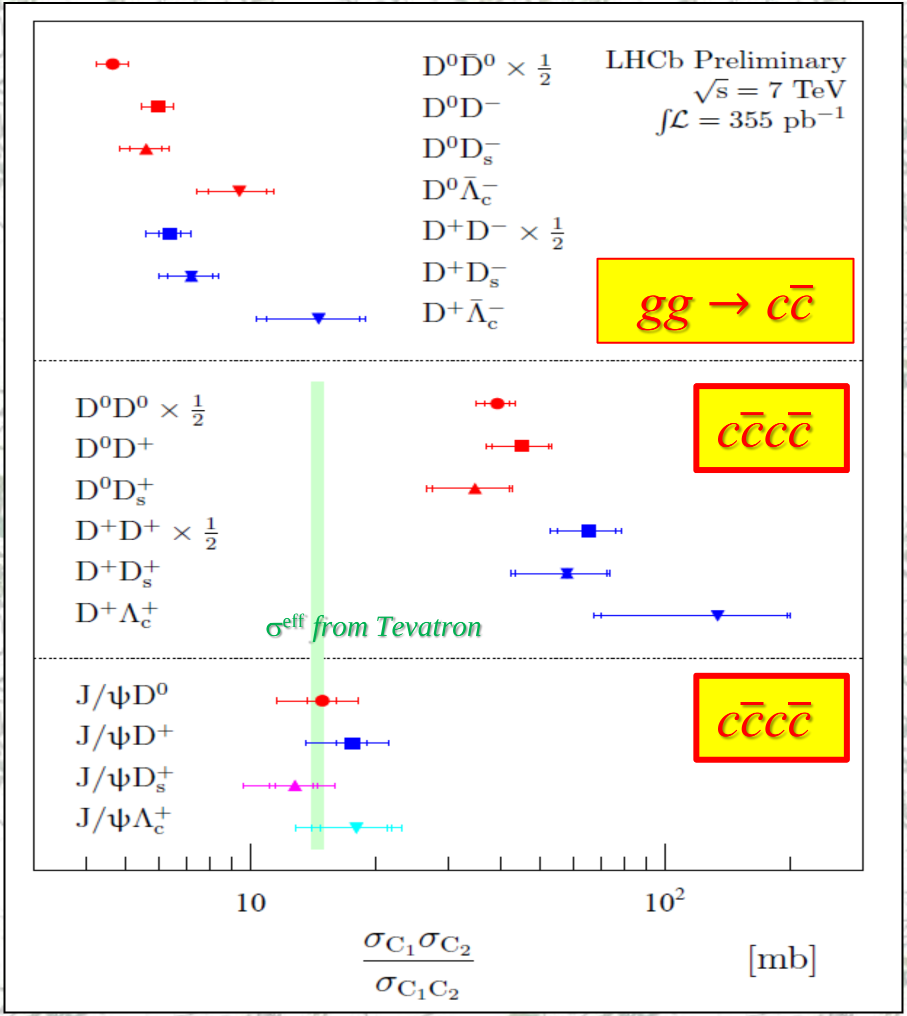
CC & C$\bar{C}$ cross-sections

LHCb Preliminary

Mode	σ [nb]	$\sigma_{CC}/\sigma_{C\bar{C}}$ [%]	$\sigma_{C_1}\sigma_{C_2}/\sigma_{C_1C_2}$ [mb]
D^0D^0	$687 \pm 43 \pm 66 \pm 33$	10.9 ± 0.8	$2 \times (42.2 \pm 2.8 \pm 3.6)$
$D^0\bar{D}^0$	$6225 \pm 123 \pm 561 \pm 280$		$2 \times (4.65 \pm 0.13 \pm 0.40)$
D^0D^+	$516 \pm 81 \pm 59 \pm 31$	12.8 ± 2.1	$46.6 \pm 7.3 \pm 4.2$
D^0D^-	$3985 \pm 91 \pm 439 \pm 231$		$6.02 \pm 0.19 \pm 0.54$
$D^0D_s^+$	$266 \pm 53 \pm 33 \pm 20$	15.7 ± 3.4	$35.6 \pm 7.5 \pm 3.8$
$D^0D_s^-$	$1680 \pm 107 \pm 202 \pm 121$		$5.6 \pm 0.5 \pm 0.6$
$D^0\bar{\Lambda}_c^-$	$2010 \pm 279 \pm 261 \pm 543$	—	$9.4 \pm 1.5 \pm 1.3$
D^+D^+	$76 \pm 12 \pm 11 \pm 7$	9.6 ± 1.6	$2 \times (65.6 \pm 10.5 \pm 7.3)$
D^+D^-	$779 \pm 43 \pm 109 \pm 73$		$2 \times (6.4 \pm 0.4 \pm 0.7)$
$D^+D_s^+$	$67 \pm 16 \pm 9 \pm 6$	12.1 ± 3.3	$58.6 \pm 14.5 \pm 5.9$
$D^+D_s^-$	$547 \pm 57 \pm 77 \pm 45$		$7.2 \pm 0.9 \pm 0.8$
$D^+\Lambda_c^+$	$58 \pm 29 \pm 9 \pm 16$	10.7 ± 5.9	$134.8 \pm 68.3 \pm 19.8$
$D^+\bar{\Lambda}_c^-$	$534 \pm 130 \pm 80 \pm 144$		$14.6 \pm 3.7 \pm 2.1$

Cross-sections & ratios





2×Charm

LHCb Detector & Data sample

Event Selection

2×Charm signals

Efficiency corrections

Systematics

Cross-sections & ratios

Properties of 2×Charm events

Conclusions

Properties of $J/\psi C, CC$ & $C\bar{C}$ events

- Background subtracted & efficiency corrected distributions:

$J/\psi C$ & CC

pQCD *some* correlations

DPS the production is essentially uncorrelated

$C\bar{C}$

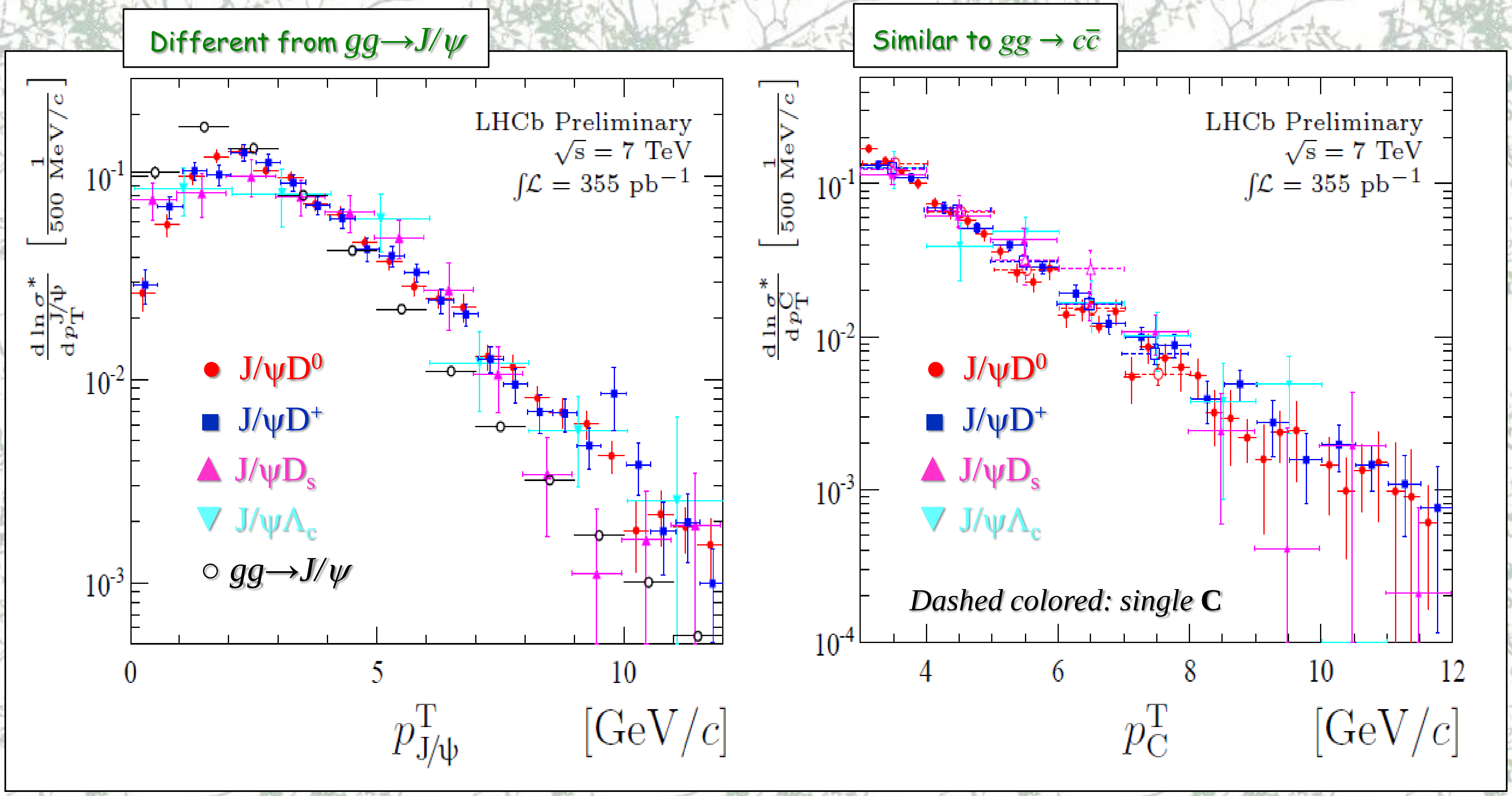
Gluon splitting, flavour creation flavour excitation, etc…

$p^T(C_1)$, $p^T(C_2)$

$\Delta\phi$ and Δy

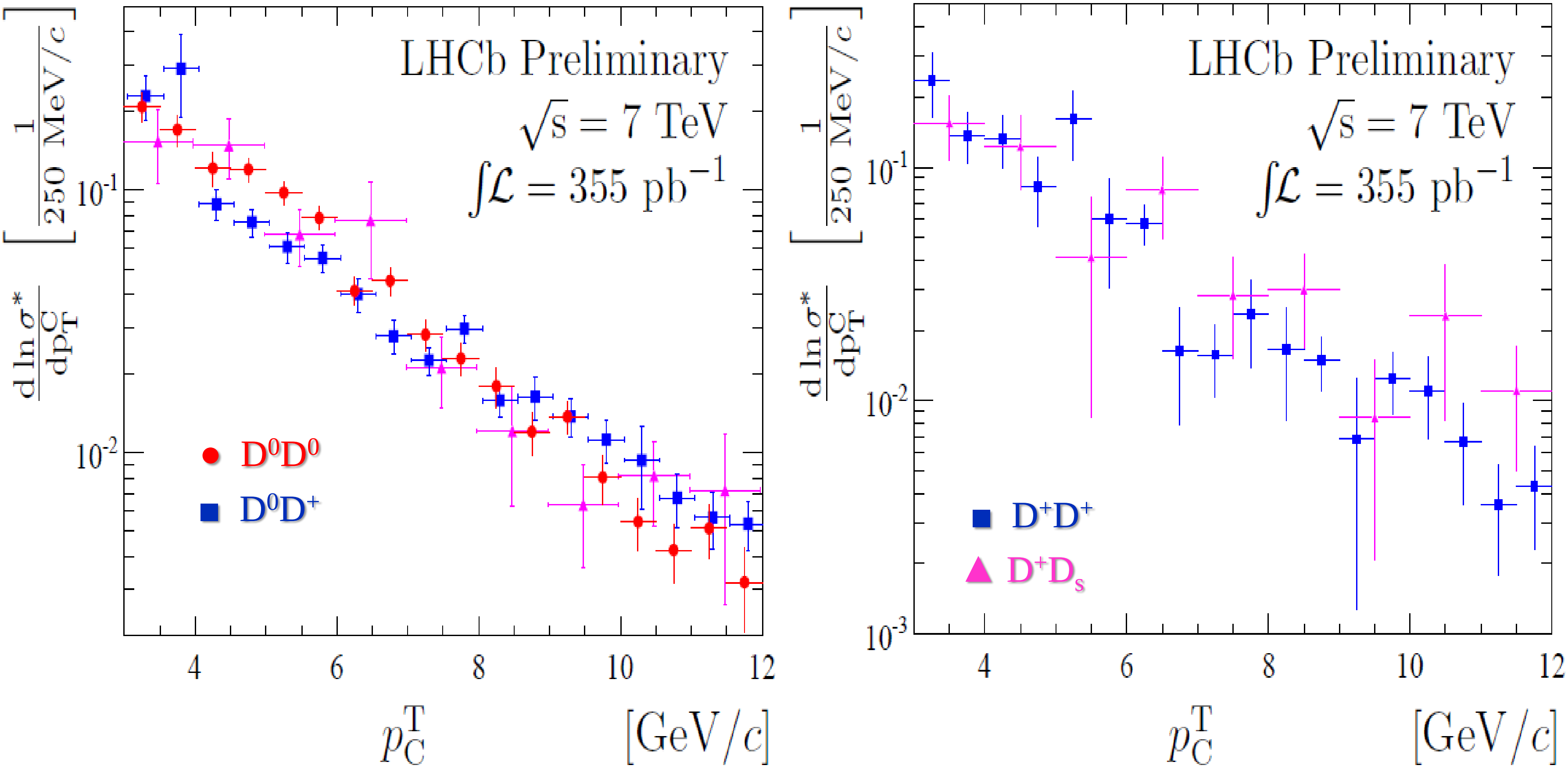
$m(C_1,C_2)$

J/ψC p^T-spectra



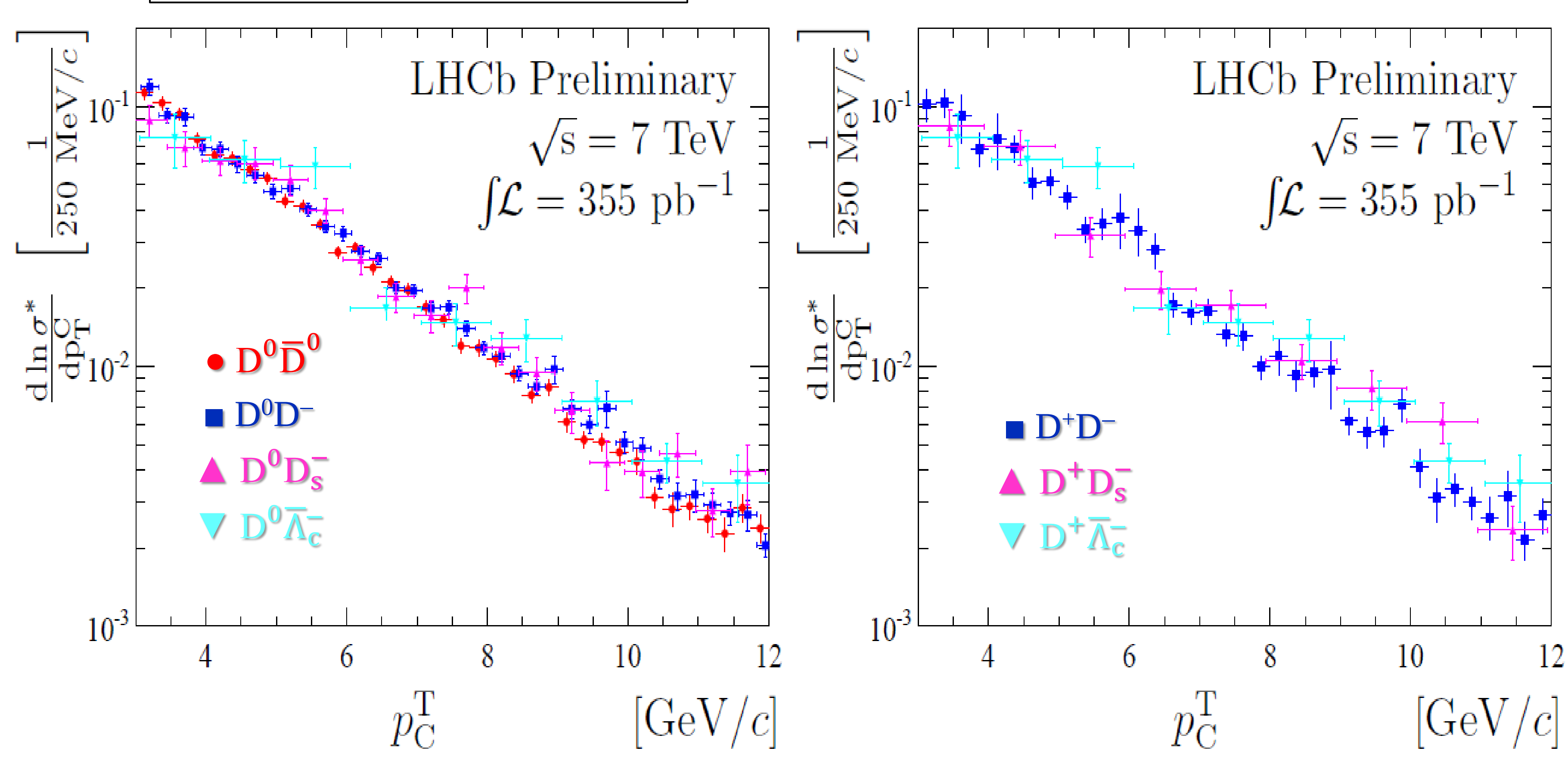
CC p^T-spectra

Spectra are flavour independent

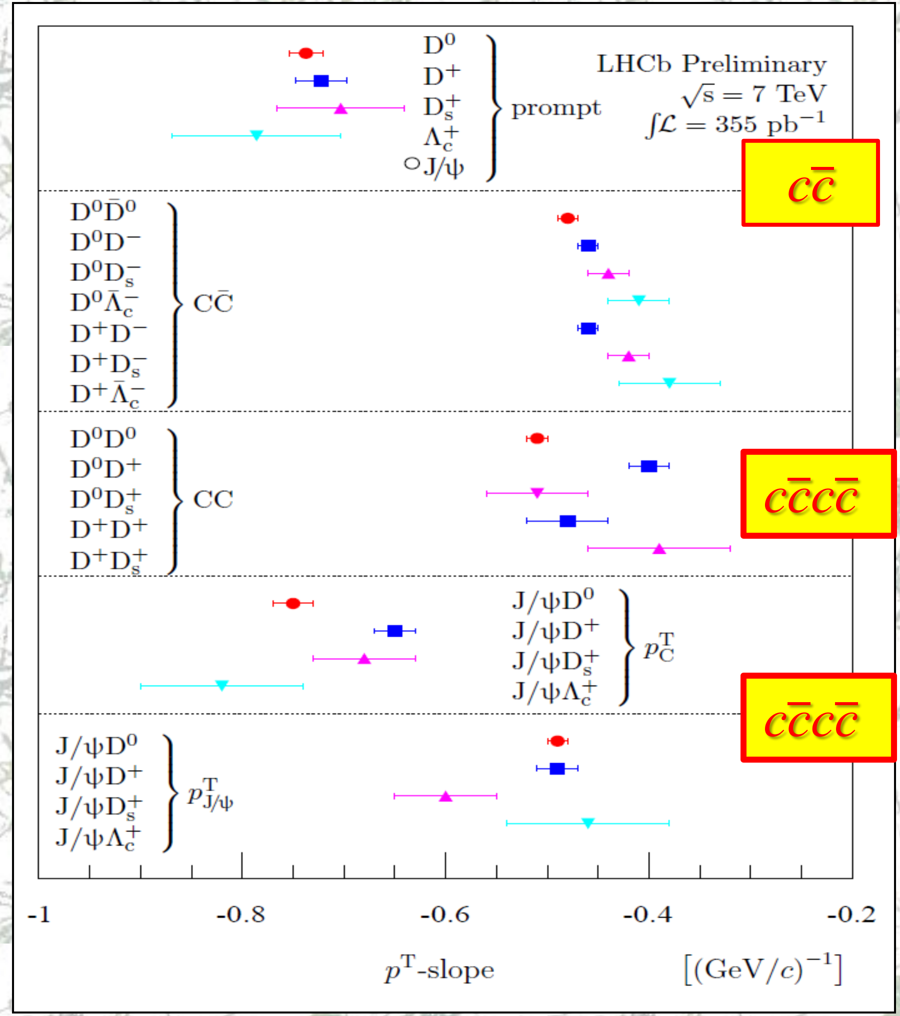


$c\bar{c}$ p^T-spectra

Spectra are flavour independent



p^{T}-slopes: $3<p^{\mathrm{T}}<12$ GeV/c

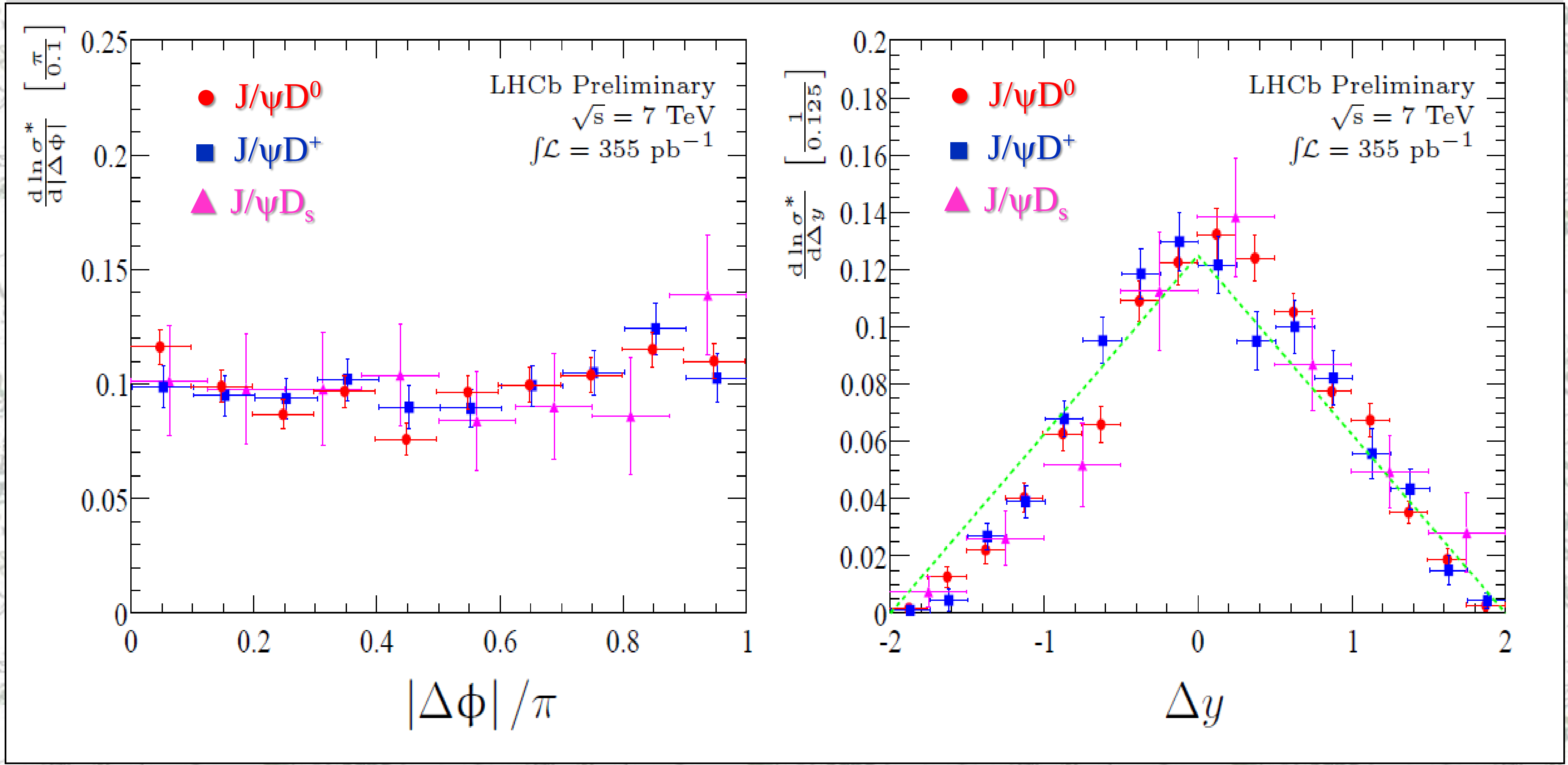


Fit with *exponential*

- "Similar" within each category
- C from J/ψC is similar to single C
- J/ψ from J/ψC is very different from single J/ψ
- CC and $C\bar{C}$ are similar and both are very different from single C

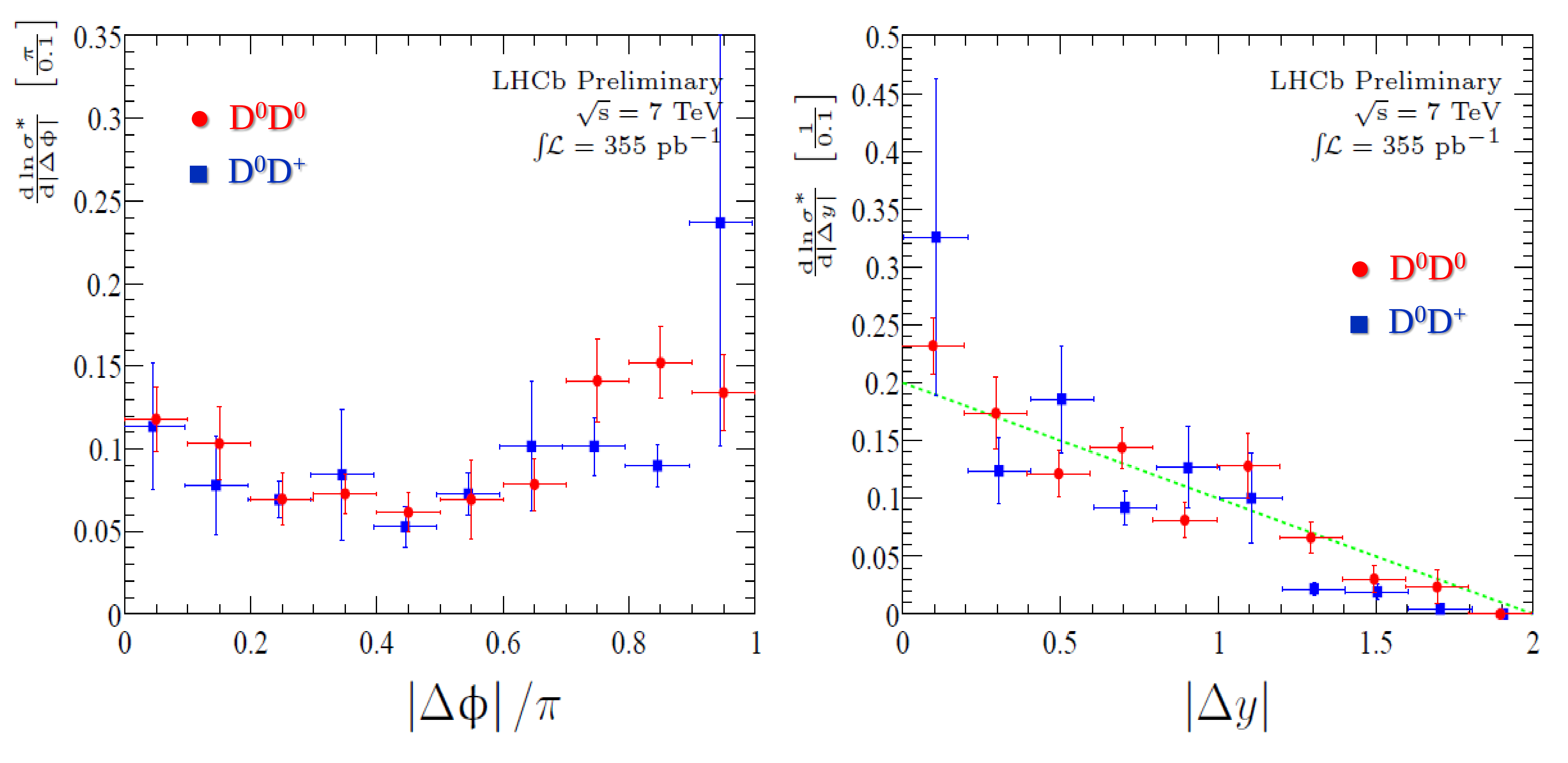
J/ψC Δϕ and Δy

Support for non-correlated production

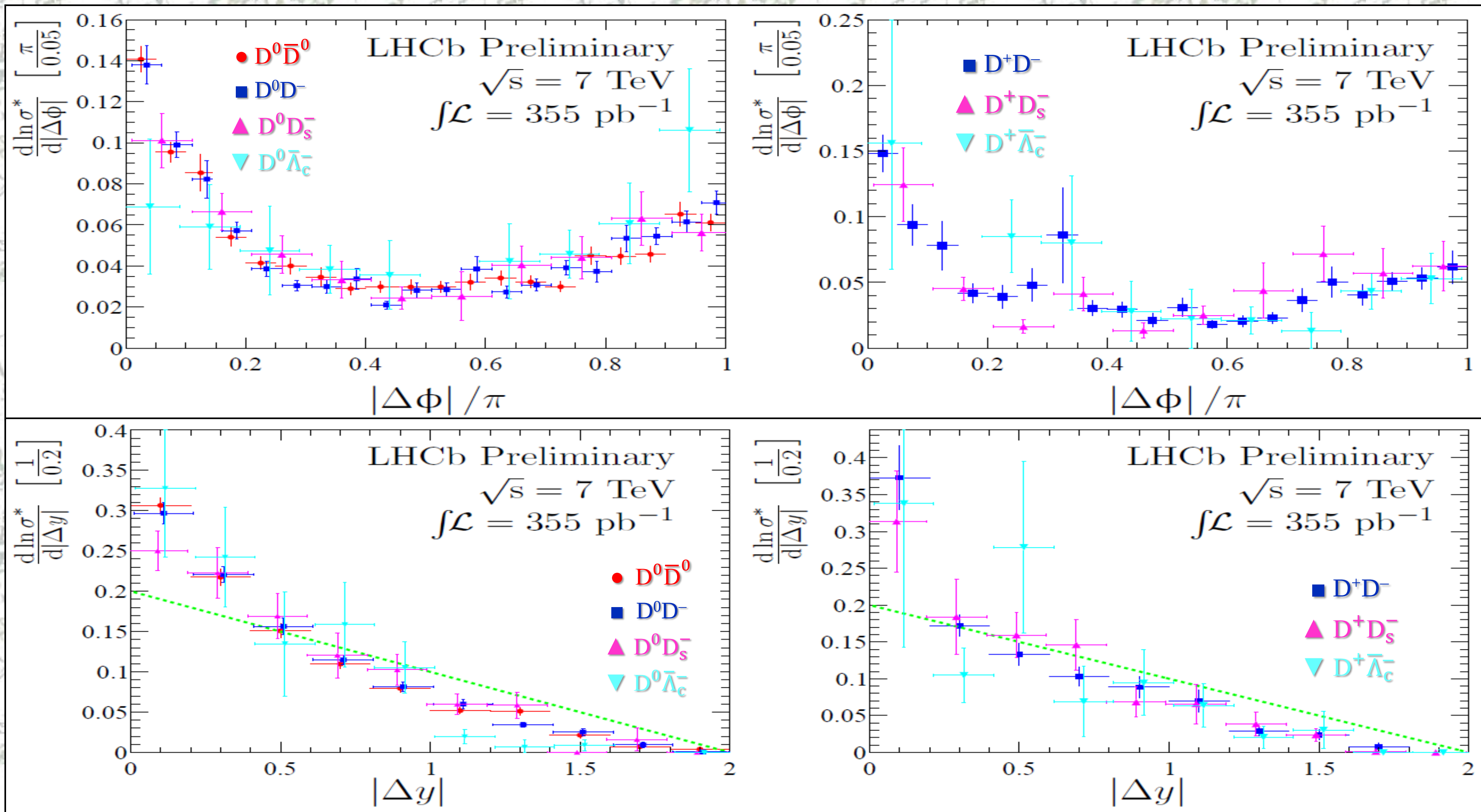


CC Δϕ and Δy

No prominent correlations?



$c\bar{c}$ $\Delta\phi$ and Δy

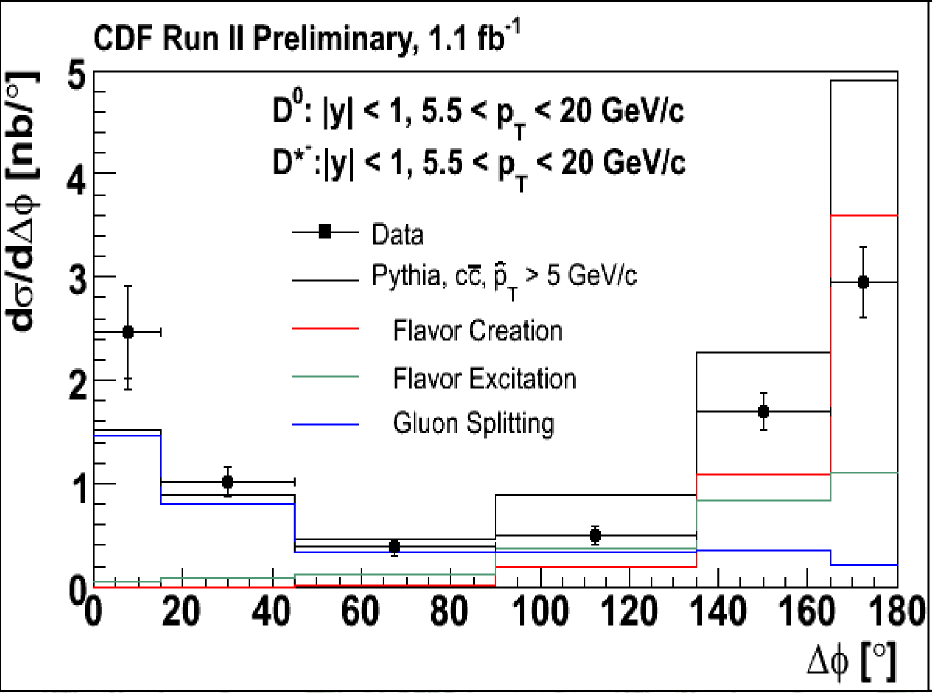


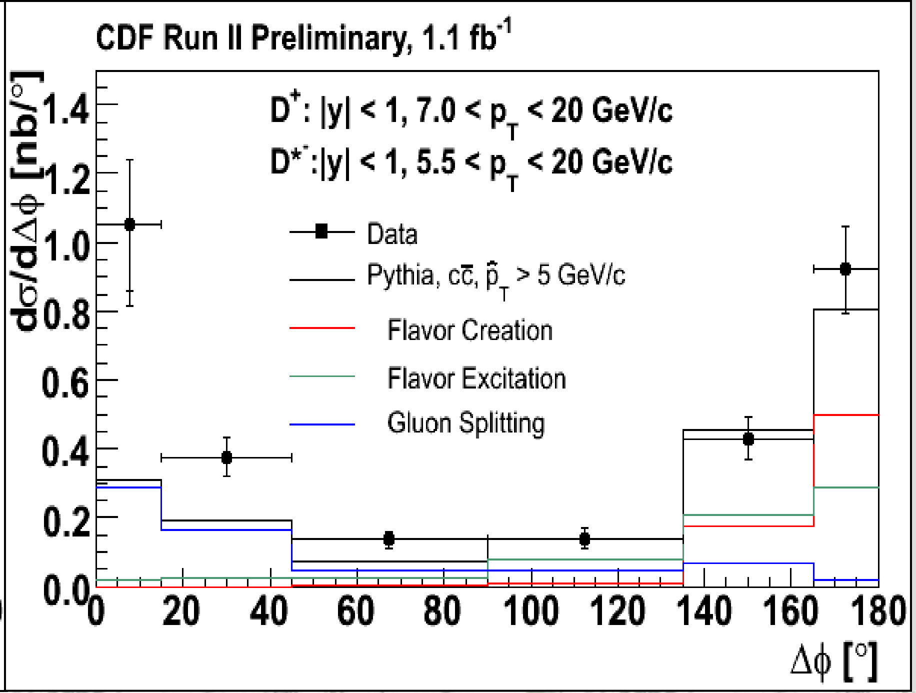
Compare with CDF'2k+6

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

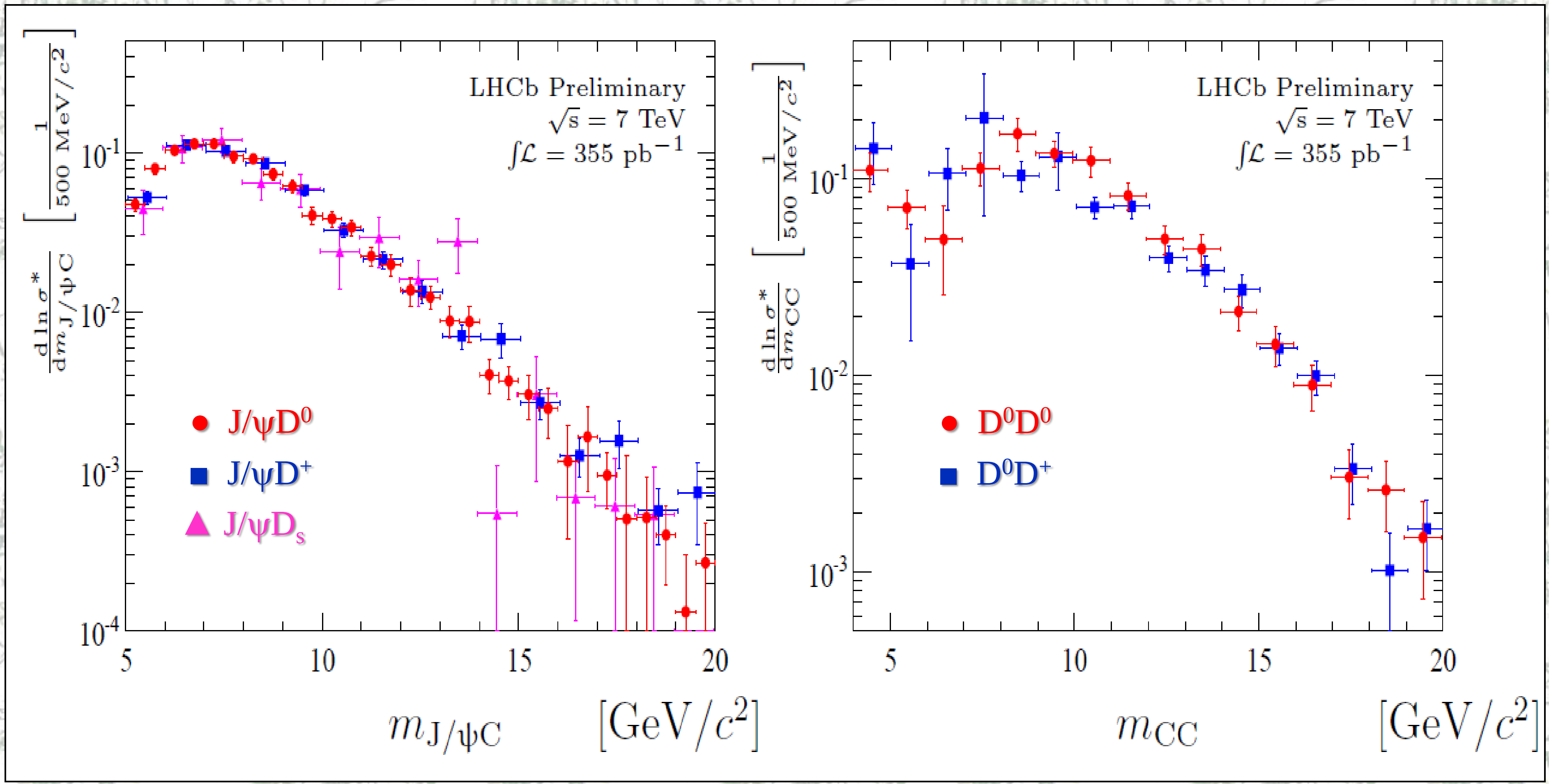
- CDF: azimuthal correlations for $D^{(0,+)} D^{*-}$
- Large gluon splitting contribution

Very different kinematical region



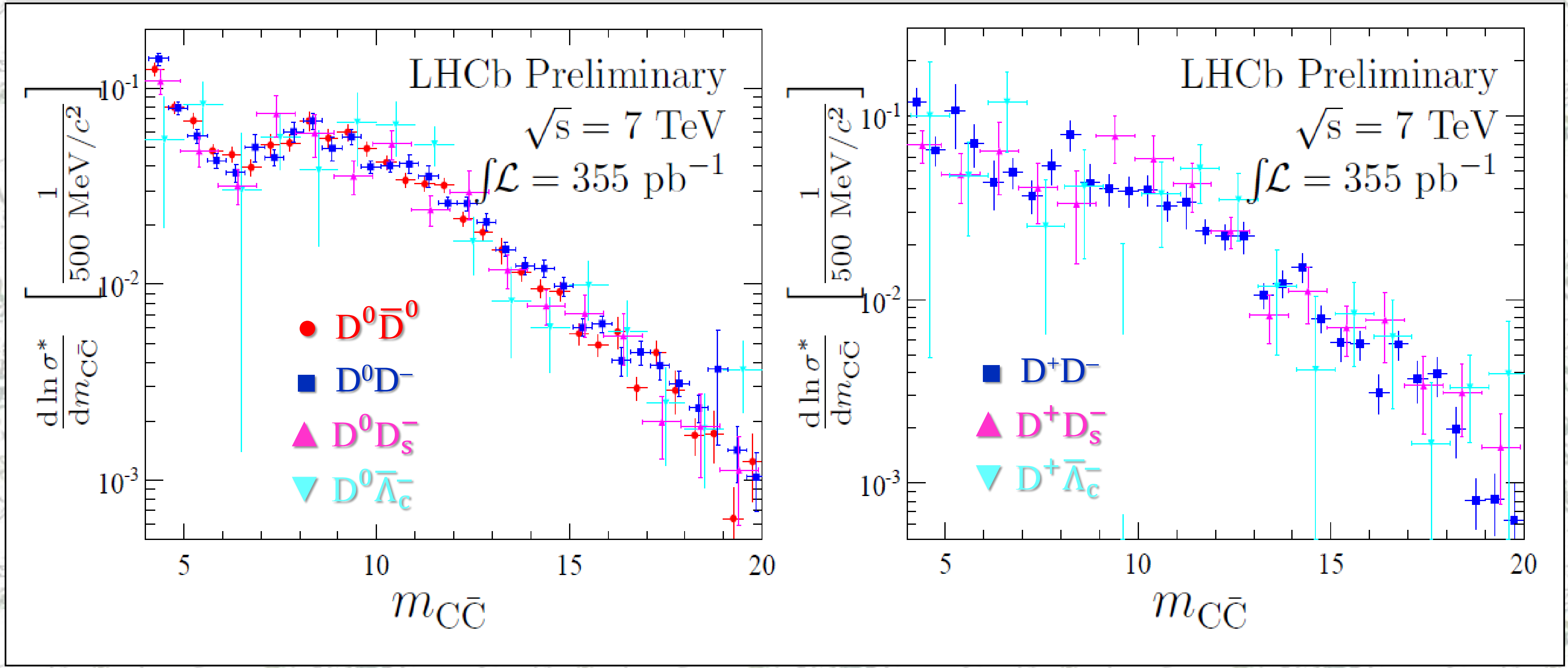


$J/\psi C$ and CC invariant mass



$\mathrm{C\bar{C}}$ invariant mass

- "Flavour" independent
- for m>7 GeV/c^2: very similar to CC



Global Event Activity

- Compare number of primary vertices, tracks, hits in subdetectors, ….
- No clear pattern has been observed
- No significant difference with respect to the single charm events with same selection

- (One more indirect argument against pileup)
  - decrease number of PVs (-1)
  - increase multiplicity (x1.5-2.0)

2×Charm

LHCb Detector & Data sample

Event Selection

2×Charm signals

Efficiency corrections

Systematics

Cross-sections & ratios

Properties of 2×Charm events

Conclusions & Summary

Comparison with models

pQCD ($gg \rightarrow c\bar{c}c\bar{c}$)/**MadOnia**, **DPS**, **Pythia**, **IC**

- pQCD is off by the factor ~20
- Support for (factorization) DPS
  - excellent agreement for **J/ψC**
  - factor ~3 off for **CC**
  - general support for "*uncorrelated*" production
- **Pythia** fails to reproduce all the cross-section ratios and spectra.
- **IC** agrees on cross-section, but lack of well-defined predictions on spectra, correlations, …

Summary

- $J/\psi C$ production has been measured (>7σ) for the first time at hadron machines

  All *four modes*: $J/\psi D^0$, $J/\psi D^+$, $J/\psi D_s$, $J/\psi \Lambda_c$
- CC production has been observed for the first time for *six modes* with >5σ significance:

  D^0D^0, D^0D^+, D^0D_s, $D^0\Lambda_c$, D^+D^+, D^+D_s
- $C\overline{C}$ production have been measured for *seven modes*
- Cross-sections and ratios have been obtained
- p^T-spectra, $\Delta\phi$, Δy and $m(C_1C_2)$ have been studied

In total LHCb measured 1 + 4 + 6 + 7 = 18 modes from 25

Stay tuned: LHCb-PAPER-2012-003 in preparation

THANK YOU

thanks

- *Anatoly Likhoded* for inspiring efforts and stimulating discussions
- *Antoni Szczurek* for useful discussions on **DPS**
- *Jean-Philippe Lansberg* for the great help with **MadOnia**

BACK UP

Theory: double charm at LHCb

Table 1.1: Predictions for the production cross-sections of the $J/\psi C$ and CC modes in the LHCb fiducial range given by the leading order $gg \to J/\psi c\bar{c}$ matrix element [12, 13, 16] σ_{gg}, the double parton scattering approach, σ_{DPS} and the intrinsic charm model, σ_{IC}.

Mode	σ_{gg} State-of-art pQCD		σ_{DPS}	σ_{IC}
		[nb]		
$J/\psi D^0$	10 ± 6	7.4 ± 3.7	146 ± 39	220
$J/\psi D^+$	5 ± 3	2.6 ± 1.3	60 ± 17	100
$J/\psi D_s^+$	1.0 ± 0.8	1.5 ± 0.7	24 ± 7	30
$J/\psi \Lambda_c^+$	0.8 ± 0.5	0.9 ± 0.5	56 ± 22	—
		[μb]		
$D^0 D^0$			2.0 ± 0.5	1.5
$D^0 D^+$			1.7 ± 0.4	1.4
$D^0 D_s^+$			0.65 ± 0.15	0.4
$D^0 \Lambda_c^+$			1.5 ± 0.5	1.4
$D^+ D^+$			0.34 ± 0.09	0.3
$D^+ D_s^+$			0.27 ± 0.07	0.2
$D^+ \Lambda_c^+$			0.64 ± 0.23	

PYTHIA

Mode	$\sigma^{\star}_{J/\psi C}$ [nb]
$J/\psi D^0$	160
$J/\psi D^+$	58
$J/\psi D_s^+$	33
$J/\psi \Lambda_c^+$	23

Mode	$\sigma^{\star}_{CC, C\bar{C}}$ [nb]
$D^0 D^0$	1.0×10^3
$D^0 \bar{D}^0$	17.4×10^3
$D^0 D^+$	680
$D^0 D^-$	12.6×10^3
$D^0 D_s^+$	370
$D^0 D_s^-$	6.8×10^3
$D^0 \Lambda_c^+$	253
$D^0 \bar{\Lambda}_c^-$	4.8×10^3
$D^+ D^+$	120
$D^+ D^-$	2.3×10^3
$D^+ D_s^+$	140
$D^+ D_s^-$	2.5×10^3
$D^+ \Lambda_c^+$	100
$D^+ \bar{\Lambda}_c^-$	1.8×10^3
$D_s^+ D_s^+$	39
$D_s^+ D_s^-$	670
$D_s^+ \Lambda_c^+$	50
$D_s^+ \bar{\Lambda}_c^-$	0.9×10^3
$\Lambda_c^+ \Lambda_c^+$	20
$\Lambda_c^+ \bar{\Lambda}_c^-$	370

Do we have pileup?

- 3 approaches:
  - Generator level MC with applied efficiency factors
    - Cross-check with inclusive J/ψ, D^0,D^+,D_s and Λ_c MC samples
    - Good statistics, but some assumptions
  - Full simulation:
    - Low statistics, need some assumptions
  - Real data: vary χ^2_{fit}/ndf cut
- All three methods: *pileup is totally negligible*
    - A tiny fraction of the statistical error

Pileup from data

pileup is totally negligible

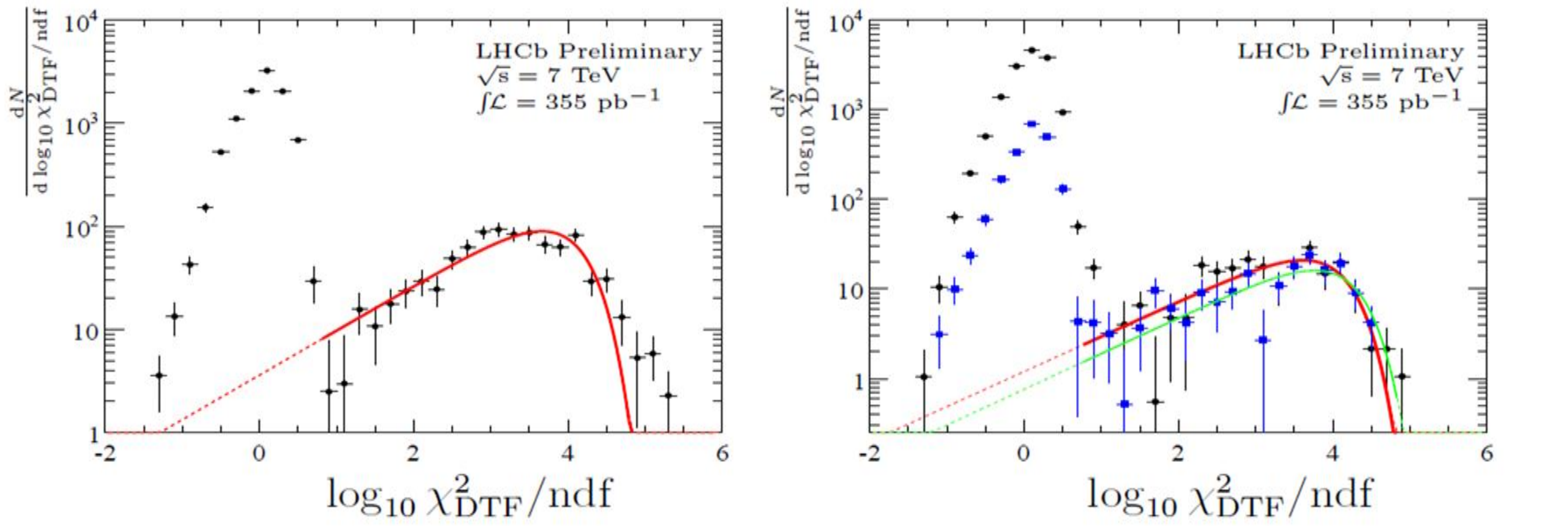
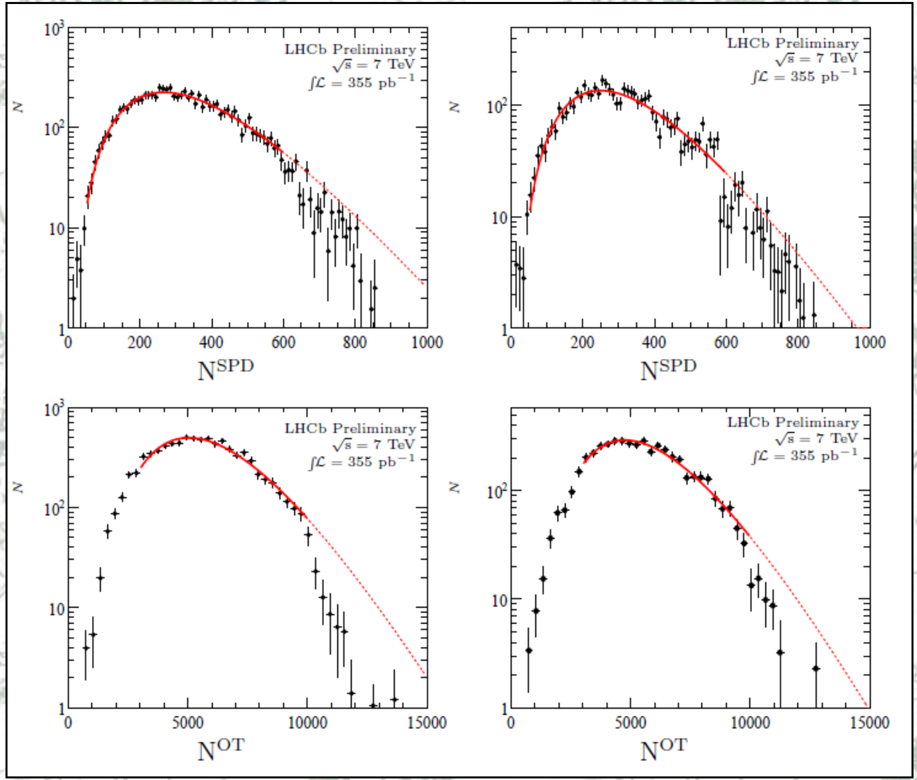


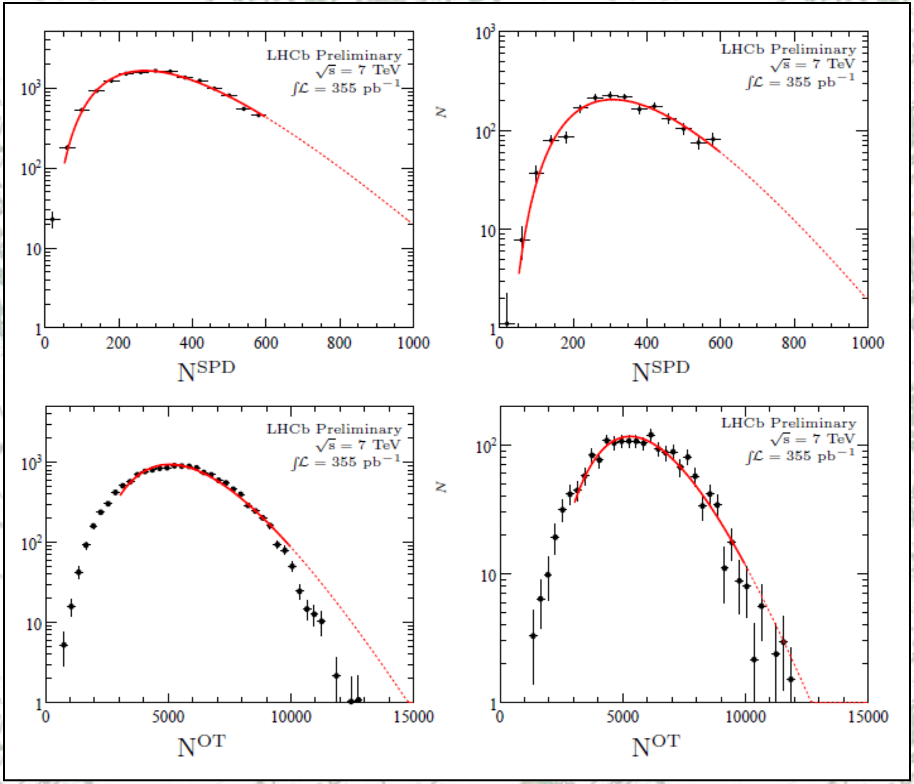
Figure 6.1: The background subtracted distributions of χ^2_{DTF}/ndf. a) For $J/\psi D^0$ events. The solid red line corresponds to the fit result in region $\chi^2_{DTF}/ndf > 5$ by function described in text, the dashed line corresponds to the extrapolation of fit results to $\chi^2_{DTF}/ndf < 5$ region. (b) D^0D^0 events (black circles corresponds to CC and blue rectangles corresponds to $C\bar{C}$ case). The solid red (green) line corresponds to the fit result in region $\chi^2_{DTF}/ndf > 5$ by function described in text, the dashed red (green) line corresponds to the extrapolation of fit results to $\chi^2_{DTF}/ndf < 5$ region for CC and $C\bar{C}$ cases respectively.

Global Event Cuts

Global Event Cuts (activity in subdetectors, namely #hits in **Outer Tracker** and #hits in SPD detector) are applied during data taking to suppress few very busy events.

The effect is studied on the data itself. Efficiency ε^{GEC} is extracted through extrapolation





DPS: a rather simple paradigm

LHC is LgC

$$\sigma^{AB}_{\rm DPS} = \frac{m}{2}\sum_{i,j,k,l}\int \Gamma_{ij}(x_1,x_2,\mathrm{b}_1,\mathrm{b}_2,Q_1^2,Q_2^2)\times\hat{\sigma}^A_{ik}(x_1,x_1',Q_1^2)\hat{\sigma}^B_{jl}(x_2,x_2',Q_2^2)$$
$$\times\ \Gamma_{kl}(x_1',x_2',\mathrm{b}_1-\mathrm{b},\mathrm{b}_2-\mathrm{b},Q_1^2,Q_2^2)\times dx_1dx_2dx_1'dx_2'd^2b_1d^2b_2d^2b,$$

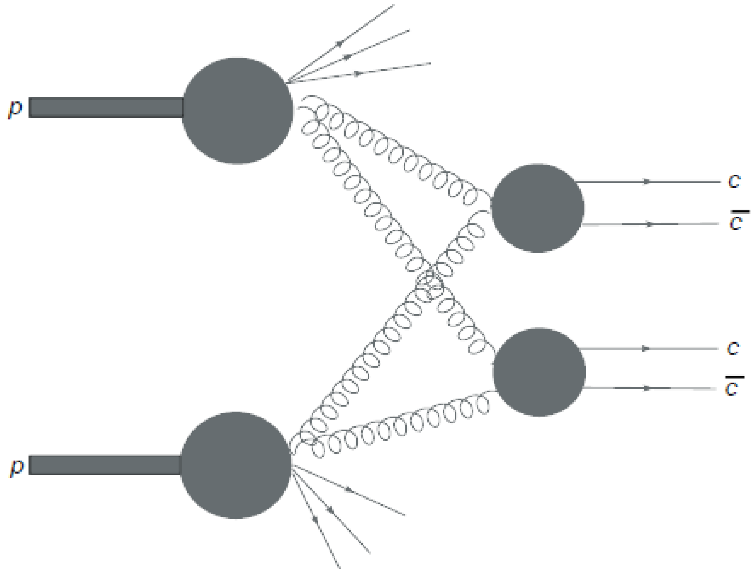
Single partonic x-section

$_2$PDF (unknown)

$$\Gamma_{ij}(x_1,x_2;\mathrm{b}_1,\mathrm{b}_2;Q_1^2,Q_2^2) = D_h^{ij}(x_1,x_2;Q_1^2,Q_2^2)f(\mathrm{b}_1)f(\mathrm{b}_2),$$

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

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



Both for total and (double) differential

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

Easy to make predications!
And the predicitons are easy to test

Universal (energy and process independent) factor)

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

Analysis strategy

- To measure:
  - Model independent cross-section in signal window
  - Various ratios (with minimal error)
- Rely on *per-event efficiency*

The price:
The *enormous* inflation of "*statistical*" error

- Evaluate various techniques for signal extraction
  - Choose $_s$*Plot*/$_s$*Weight*
  - Correct *weight* from $_s$*Weight* by $1/\varepsilon$
  - Careful check for biases and correlations

Event Selection

- Start from good tracks:
  - Minimal p^T, good track fit quality, remove clones
- For hadrons: fiducial cuts for good PID
- (μ,K,p,π) PID cuts are imposed

	Track Selection
$\mu^\pm, \mathrm{h}^\pm$	$\chi^2_{\mathrm{tr}}/\mathrm{ndf} < 5$ & $\Delta^{\mathrm{KL}} > 5000$
$\mu^\pm$	$p^{\mathrm{T}} > 650$ MeV/c
$\mathrm{h}^\pm$	$p^{\mathrm{T}} > 250$ MeV/c & $2.0 < \eta < 5$ & $\chi^2_{\mathrm{IP}} > 9$
$\pi^\pm, \mathrm{K}^\pm$	3.2 GeV/$c < p <$ 100 GeV/c
$\mathrm{p}_\pm$	10 GeV/$c < p <$ 100 GeV/c
	Particle Identification
$\mu^\pm$	$\Delta^{\mu/\mathrm{h}} \log \mathcal{L} > 0$
$\pi^\pm$	$\Delta^{\pi/\mathrm{K}} \log \mathcal{L} > 2$
$\mathrm{K}^\pm$	$\Delta^{\mathrm{K}/\pi} \log \mathcal{L} > 2$
$\mathrm{p}^\pm$	$\Delta^{\mathrm{p/K}} \log \mathcal{L} > 10$ & $\Delta^{\mathrm{p}/\pi} \log \mathcal{L} > 10$

Charm hadron reconstruction

- Vertex quality cuts
- PV & *decay consistency*
- $c\tau$ cut
- As similar as possible (a bit tighter for Λ_c)

"3σ mantra"

- Daughter particles do not point to PV (>3σ)
- Mother particle does point to PV (<3σ)
- Mother particle has non-zero lifetime (except J/ψ)
- The decay structure is self-consistent

		J/ψ $\mu^+\mu^-$	D^0 $K^-\pi^+$	D^+ $K^-\pi^+\pi^+$	D_s^+ $(K^+K^-)_\phi\,\pi^+$	Λ_c^+ $pK^-\pi^+$
y				$2 < y < 4$		
p^T	[GeV/c]	< 12			$3 < p^T < 12$	
χ^2_{VX}		< 20	< 9	< 25	< 25	< 25
χ^2_{IP}		—			< 9	
χ^2_{fit}/ndf				< 5		
$c\tau$	[μm]	—		$c\tau \geq 100$		$c\tau \geq 100$ $c\tau < 500$
$\lvert\cos\theta^*\rvert$		—	< 0.9	—	—	—
$m_{K^+K^-}$	[GeV/c^2]	—	—	—	< 1.04	—
min $p_T^{h\pm}$	[GeV/c]	—	—	—	—	≥ 0.5

Systematic uncertainties

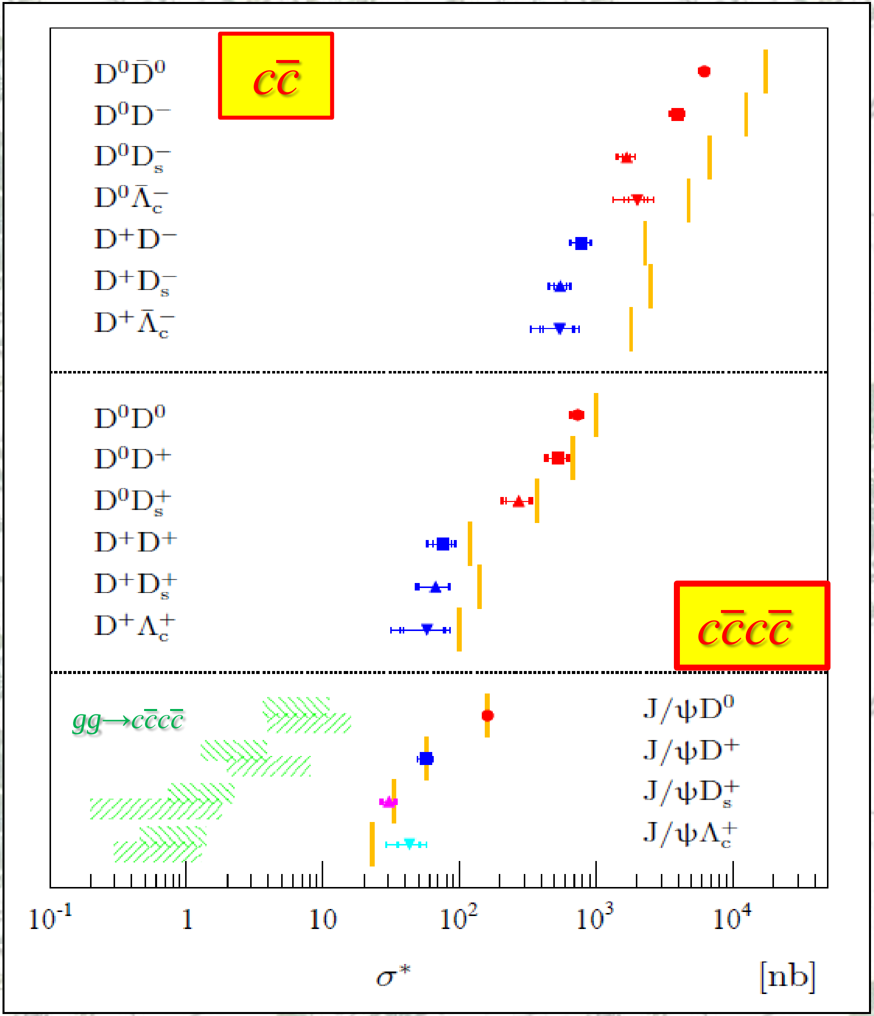
- **Dominant:**
  hadron track reconstruction uncertainty related to hadron interactions in detector:
  2% per hadron track

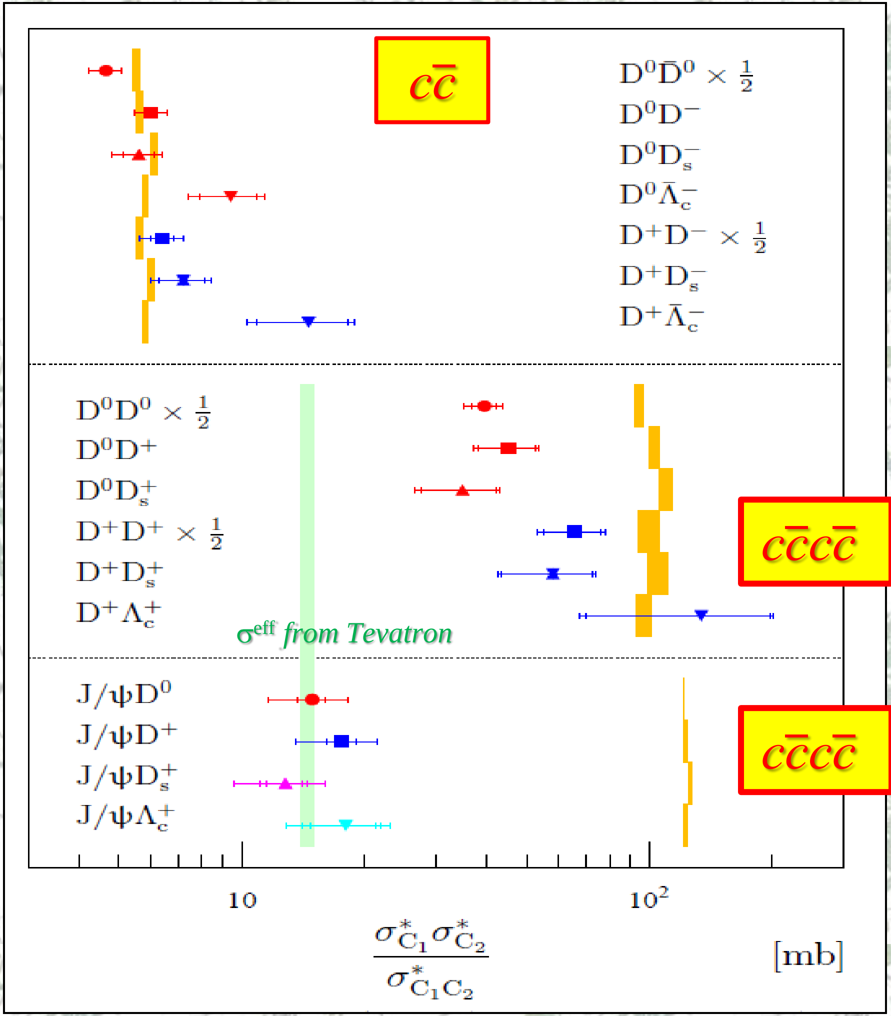
Source		J/ψD^0	J/ψD$^+$	J/ψD$_s^+$	J/ψΛ$_c^+$
J/ψ reconstruction	$\varepsilon_1^{\rm reco}$		1.3		
C reconstruction	$\varepsilon_2^{\rm reco}$	0.7	0.8	1.7	3.3
Muon ID	$\varepsilon_{\rm J/\psi}^{\rm ID}$		1.1		
Hadron ID	$\varepsilon_{\rm had}^{\rm ID}$	1.1	1.9	1.1	1.5
Tracking	$\xi^{\rm trk}$	4.9	7.0	7.0	7.0
Trigger	$\varepsilon_{\rm J/\psi C}^{\rm trg}$		3.0		
J/ψ polarization	$\varepsilon_{\rm J/\psi}^{\rm reco}$		3.0		
Global event cuts	$\varepsilon^{\rm GEC}$		0.7		
Luminosity	$\mathcal{L}$		3.7		
$\mathcal{B}(\rm J/\psi \to \mu^+\mu^-)$	$\mathcal{B}_1$		1.0		
C branching ratios	$\mathcal{B}_2$	1.3	4.3	6.0	26
Total		8	10	11	28

Source		D^{0}D^0	D^{0}D$^+$	D^{0}D$_s^+$	D^{0}Λ$_c^+$
D^{0}C reconstruction	$\varepsilon_2^{\rm reco}\times\varepsilon_2^{\rm reco}$	1.4	1.4	2.3	3.6
Hadron ID	$\varepsilon_{\rm had}^{\rm ID}$	1.2	1.8	1.6	2.4
Tracking	$\xi^{\rm trk}$	8.5	10.7	10.6	10.6
Trigger	$\varepsilon_{\rm C}^{\rm trg}$	1.8	2.5	3.9	5.2
Global event cuts	$\varepsilon^{\rm GEC}$		1.0		
Luminosity	$\mathcal{L}$		3.7		
$\mathcal{B}(\rm D^0 \to K^-\pi^+)$	$\mathcal{B}_1$		1.3		
C branching ratios	$\mathcal{B}_2$	1.3	4.3	6.0	26
Total		10	12	14	30

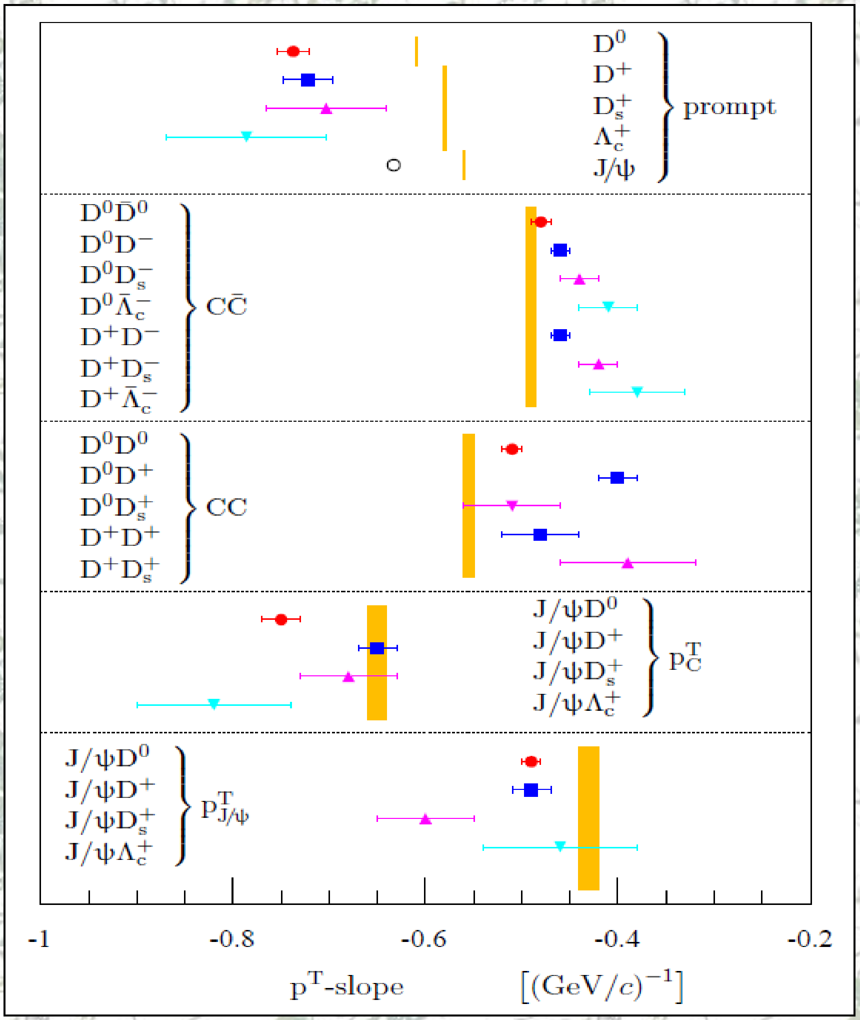
Source		D$^+$D$^+$	D$^+$D$_s^+$	D$^+$Λ$_c^+$
D$^+$C reconstruction	$\varepsilon_2^{\rm reco}\times\varepsilon_2^{\rm reco}$	1.4	2.2	4.0
Hadron ID	$\varepsilon_{\rm had}^{\rm ID}$	2.3	2.4	3.0
Tracking	$\xi^{\rm trk}$		12.8	
Trigger	$\varepsilon_{\rm C}^{\rm trg}$	3.7	5.8	5.0
Global event cuts	$\varepsilon^{\rm GEC}$		1.0	
Luminosity	$\mathcal{L}$		3.7	
$\mathcal{B}(\rm D^+ \to K^-\pi^+\pi^+)$	$\mathcal{B}_1$		4.3	
C branching ratios	$\mathcal{B}_2$	4.3	6.0	26
Total		17	17	31

Cross-sections & ratios





p^T-slopes: $3<p^T< 12$ GeV/c



Fit with *exponential*

- "Similar" within each category
- C from J/ψC is similar to single prompt C
- J/ψ from J/ψC is very different from prompt J/ψ
- CC and C$\bar{\text{C}}$ are similar and both are very different from single prompt C