Physics with multiple heavy quarks

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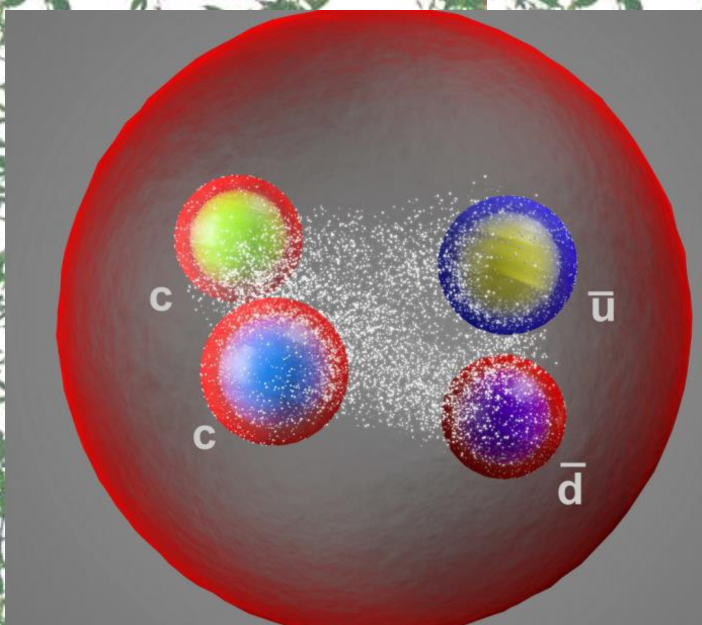
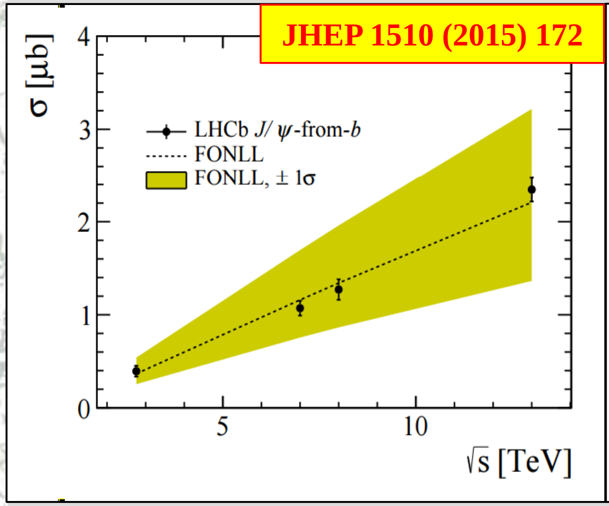


Multiple Heavy Quarks

- Multiple Heavy Quarks in high-energy hadron collisions
  Single **P**arton **S**cattering vs **D**ouble **P**arton **S**cattering
- $c\bar{c}c\bar{c}$
  - DPS: J/ψJ/ψ, J/ψD, DD, ….,
  - SPS: Ξ_{cc}^{++} , X(6900) , T_{cc}^{+}
- $c\bar{c}b\bar{b}$
  - DPS: ϒD, ϒJ/ψ, ….
  - SPS: B_c^+
- $b\bar{b}b\bar{b}$
  - DPS: ϒ ϒ
- (**T**riple **P**arton **S**cattering $c\bar{c}c\bar{c}c\bar{c}$)
  - J/ψJ/ψJ/ψ

High energy ~~hadron~~ gluon collisions

- Heavy flavour production at LHC is dominated by gg-fusion process
- Quarkonia: reasonably (rapidly improving) agreement with NR QCD
  - J/ψ, ψ', η_c, $\chi_{c1,2}$, $\chi_{b1,2}(nP)$, ….
- Open flavour: FONLL does good job



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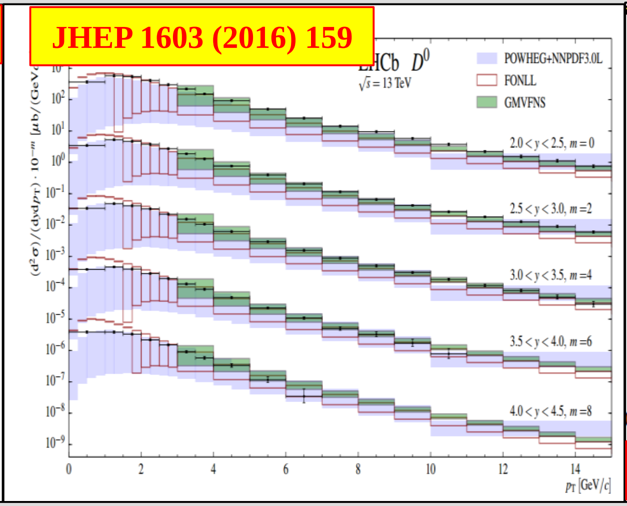

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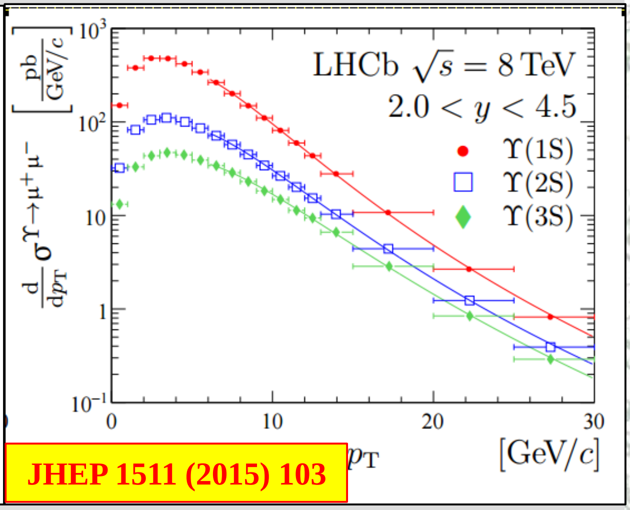

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- Heavy flavour production cross-section in forward region is large

$\sigma(c\bar{c})_{p_T<8\,\mathrm{GeV}/c,\,2.0<y<4.5} = 1419 \pm 12\,(\mathrm{stat}) \pm 116\,(\mathrm{syst}) \pm 65\,(\mathrm{frag})\,\mu\mathrm{b}$, vs $\sigma^{\mathrm{acc}}_{\mathrm{inel}}(p_T > 0.2\,\mathrm{GeV}/c,\ 2.0 < \eta < 4.5) = 55.0 \pm 2.4\,\mathrm{mb}$,

Nucl.Phys. B871 (2013) 1

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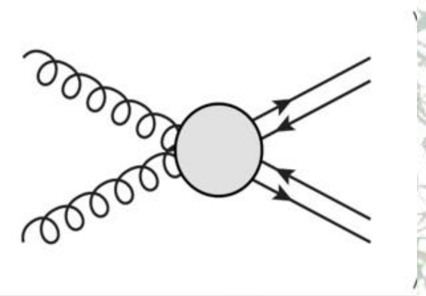
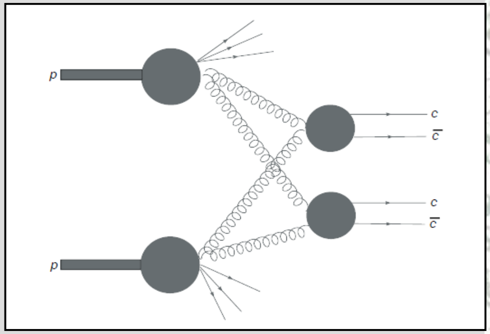
$Q_1\overline{Q}_1Q_2\overline{Q}_2$ production: 3 possible ways

- ***S**ingle **P**arton **S**cattering* $gg \rightarrow (Q_1\overline{Q}_1)(Q_2\overline{Q}_2)$
  - State-of-art theory calculations
  - Many theory approaches
  - Typically large theory uncertainty



- ***D**ouble **P**arton **S**cattering* $gg \rightarrow (Q_1\overline{Q}_1)$ $gg \rightarrow (Q_2\overline{Q}_2)$
  - Two idependent gg fusion processes
  - Very large parton flux
  - Simple approach
  - Large predictive power

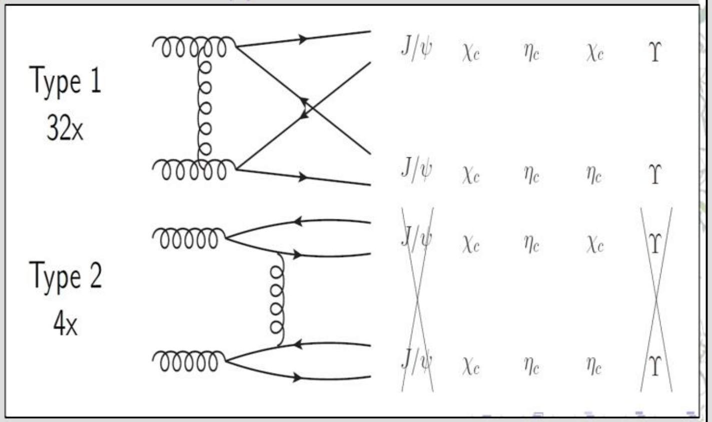


- (Intrinsic charm: if there is some intrinsic charm in proton, one needs to produce only one $Q_1\overline{Q}_1$ cc is already here…)

SPS e.g. for J/ψJ/ψ

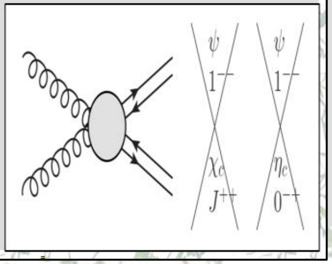
- Typically large set of diagrams
  - Many approaches, CS/CO, large uncertainties, …

- 36 diagrams of two types

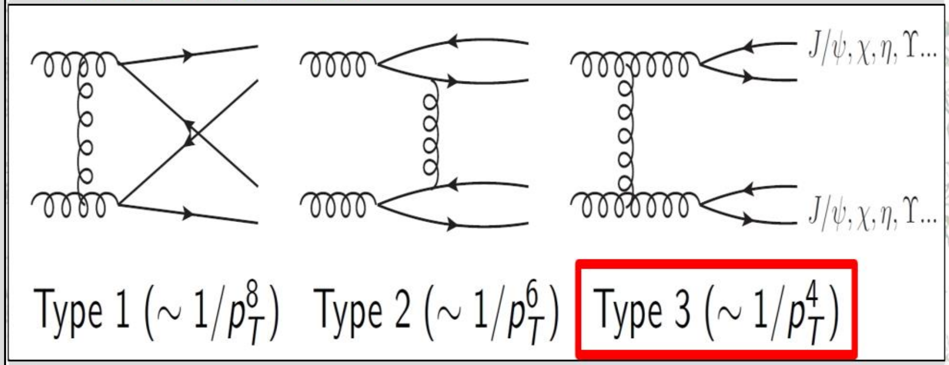


- *Intrinsically it can't be small!*
- Selection rules:

  (go off at (N)NLO)

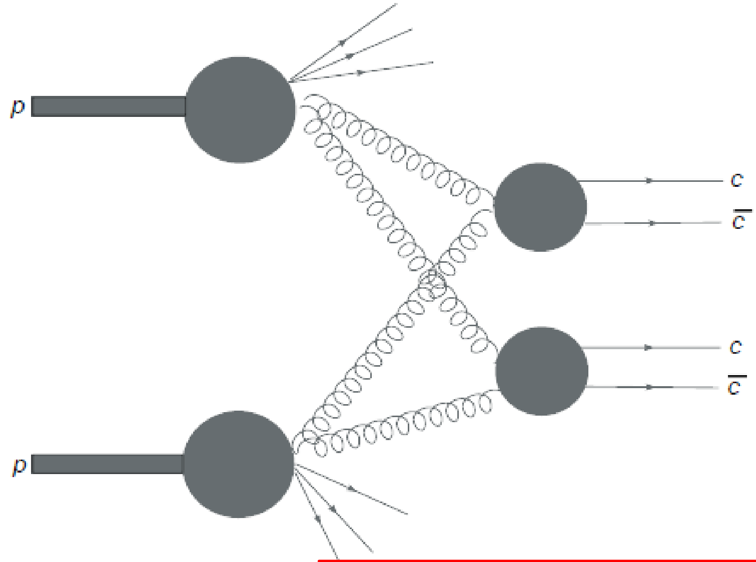


- No selection rules



- "Small" ~$10^{-2..-3}$ 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

DPS: simple paradigm



Two ***independent*** scattering processes

Relations through (unknown) $_2$PDFs

$$\Gamma_{ij}(x_1, x_2; \mathrm{b}_1, \mathrm{b}_2; Q_1^2, Q_2^2) = D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2) f(\mathrm{b_1}) f(\mathrm{b_2}),$$

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

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

Universal (energy and process independent) factor

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

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

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

$Q_1\overline{Q}_1Q_2\overline{Q}_2$ production

- Large theory uncertainty
  - Low predictive power
- ***Correlated final state***
- Moderate dependency on $\sqrt{s}$
- Kinematics:
  - Can have large p_T
  - Smaller masses
  - Angular/rapidity correlations

Possible to produce and study particles with Q_1Q_2 or $Q_1\overline{Q}_2$

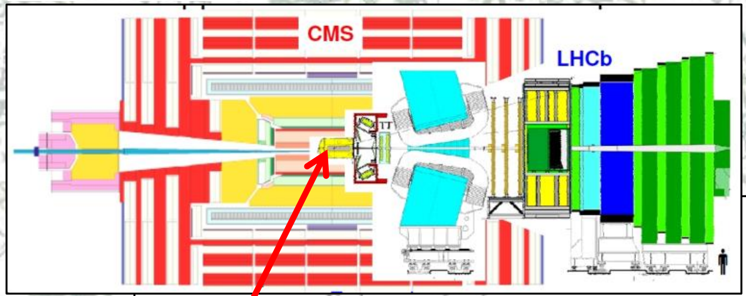
- Single parameter:
  - data-driven predictions
- ***No correlations***
- Large (~quadratic) dependency on $\sqrt{s}$
- Kinematics:
  - Smaller p_T
  - Larger masses
  - No correlations
- (Can be largely violated in certain kinematic regions)

No particles with Q_1Q_2 or $Q_1\overline{Q}_2$

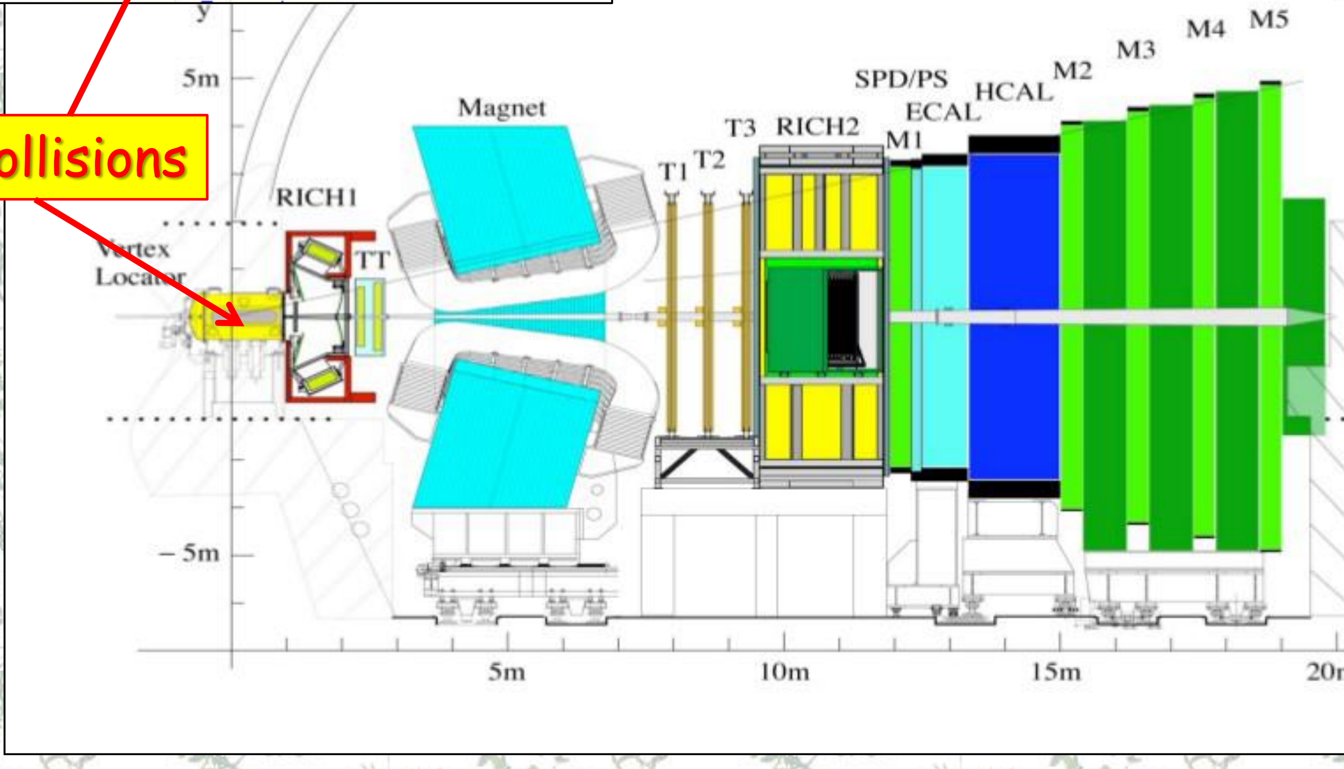
$Q_1\bar{Q}_1Q_2\bar{Q}_2$ studies at LHCb

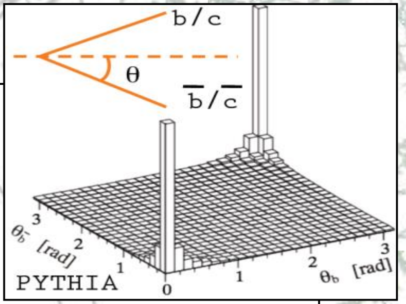
LHCb: beauty detector

General purpose universal detector in forward region



pp-collisions





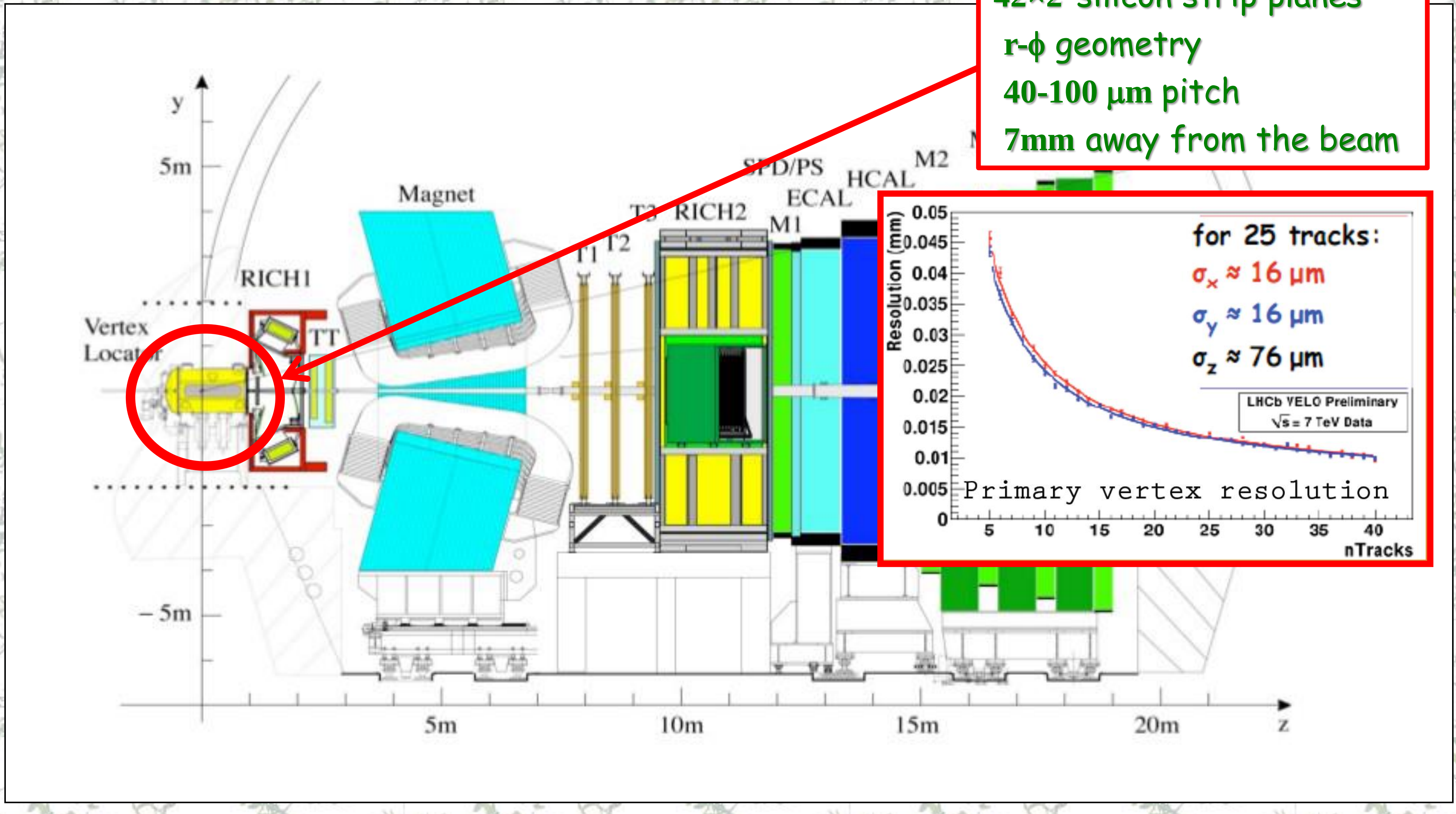
$2<\eta<5$

4% of solid angle

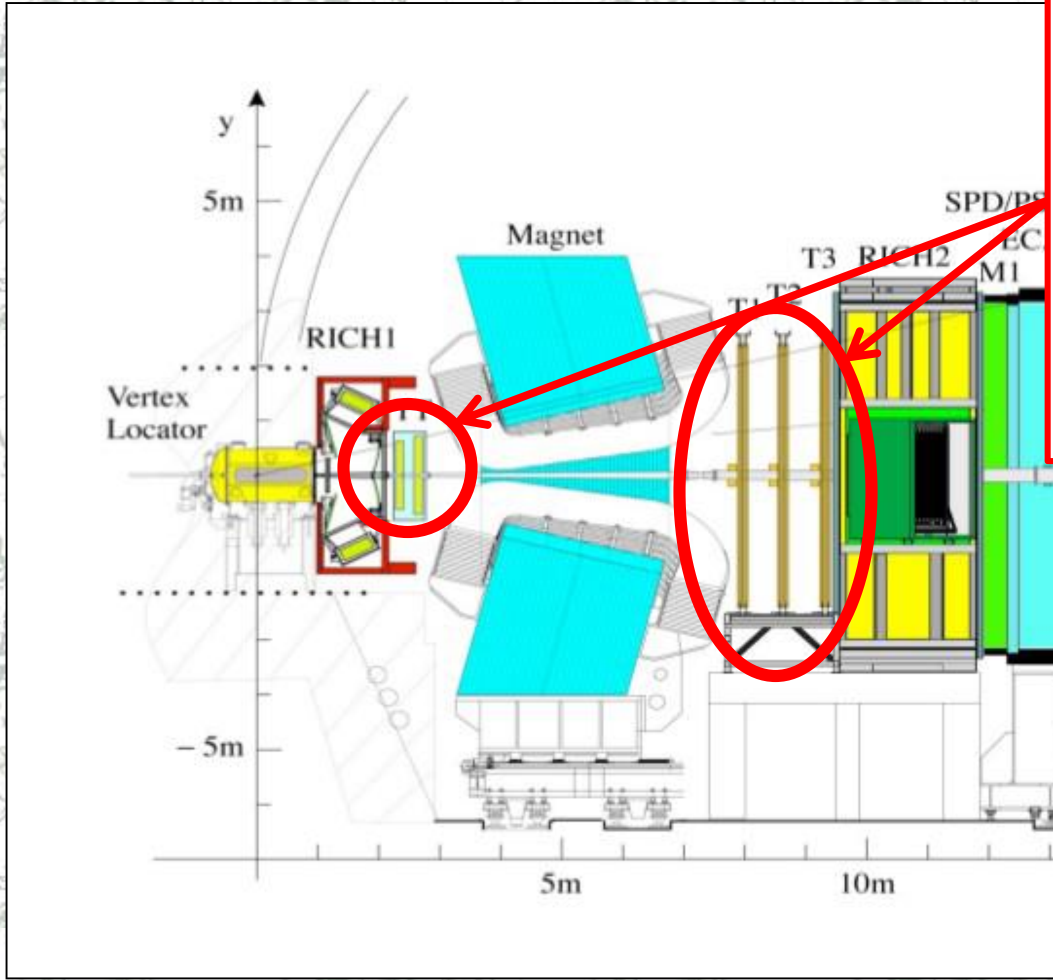
40% of heavy quarks

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

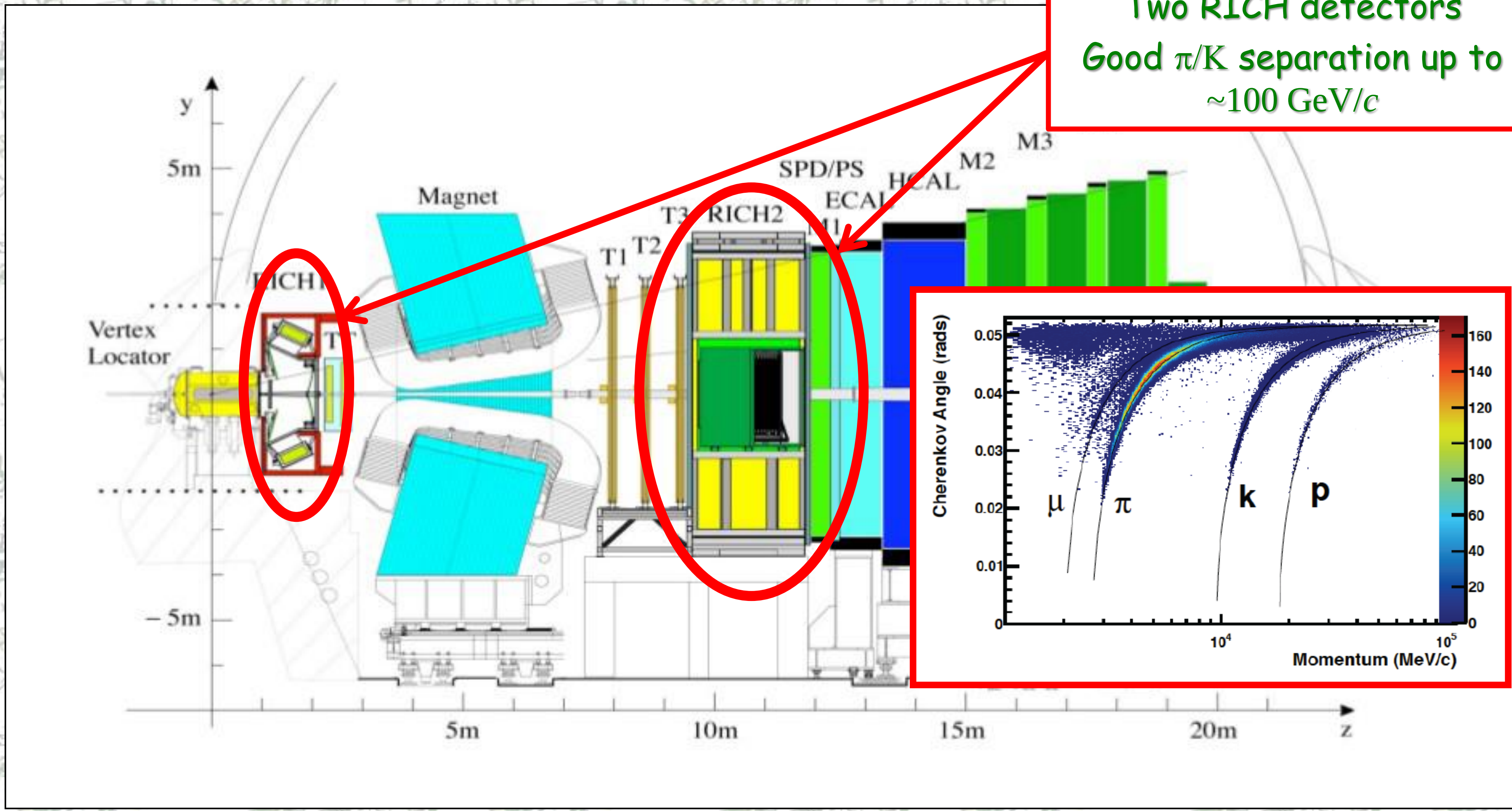
Momentum resolution: **0.4-0.6%**

J/ψ mass resolution 13 MeV/c^2

Hadron ID

Two RICH detectors

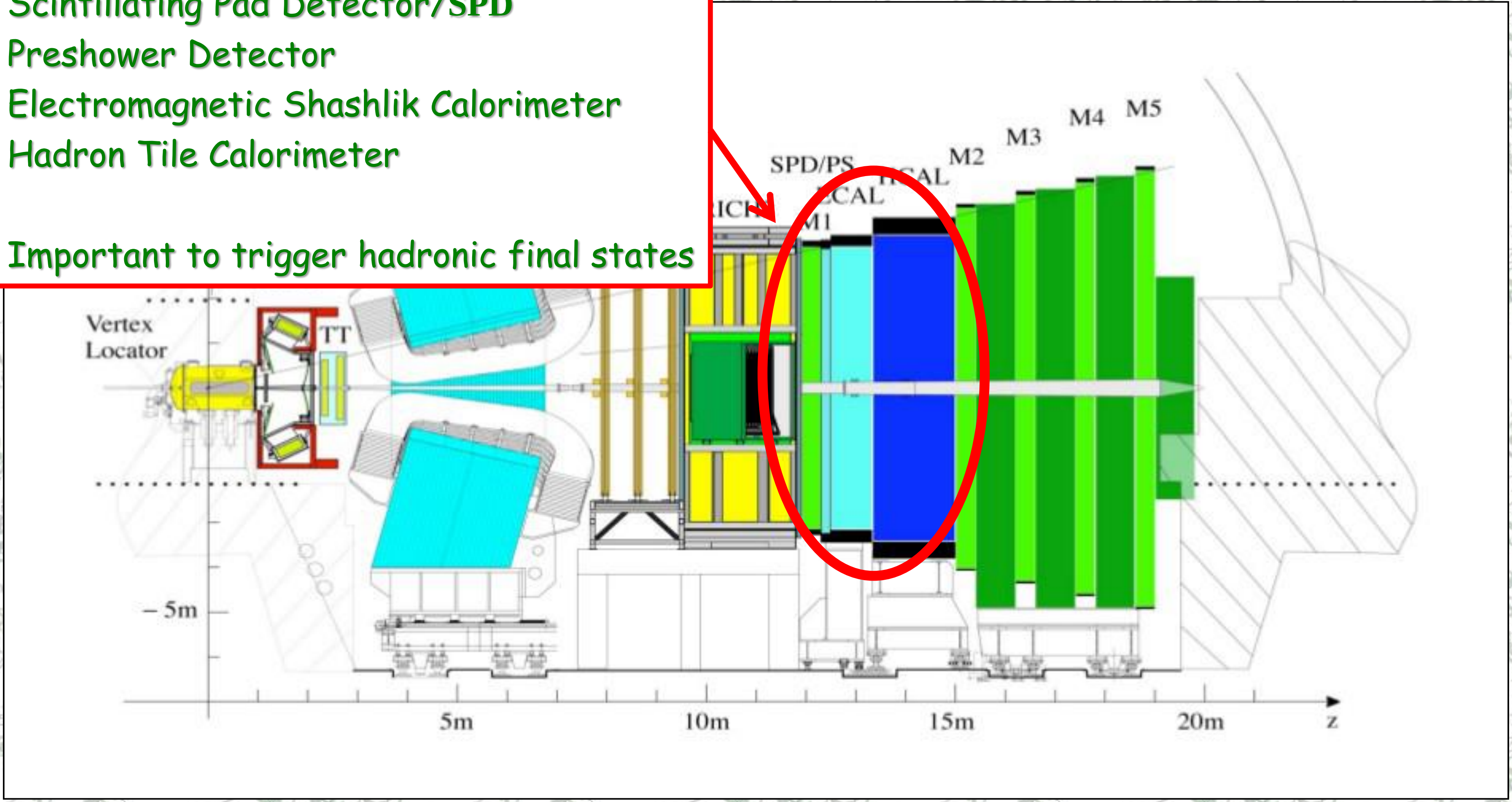
Good π/K separation up to ~100 GeV/c



Calorimeter system

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

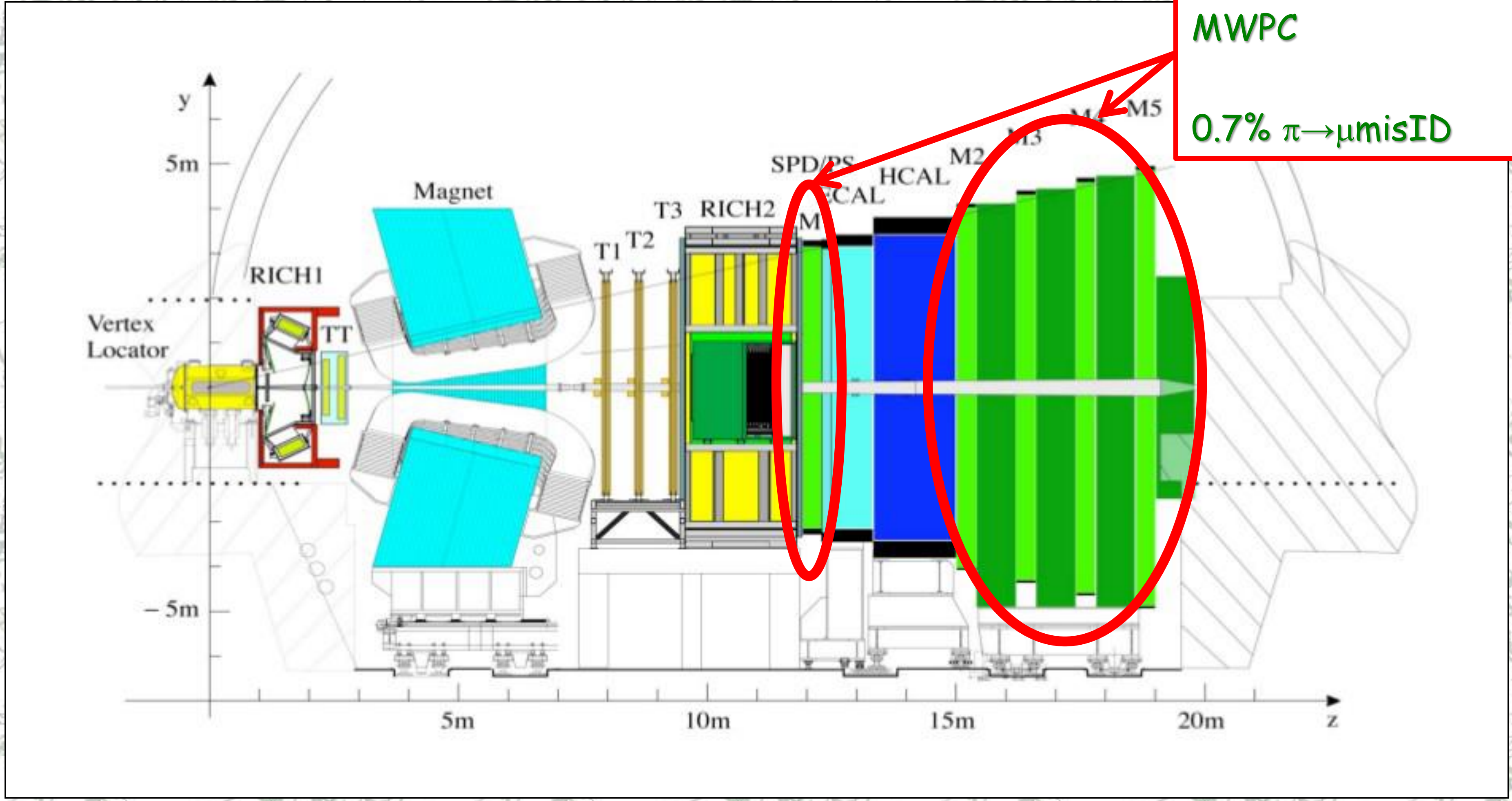
Important to trigger hadronic final states



Muon system

4(+1) stations
MWPC

0.7% $\pi\to\mu$ misID



$cc\bar{c}\bar{c}$: $J/\psi J/\psi$

Four-act play

$J/\psi J/\psi$ at $(\pi,p)Pt$ collisions

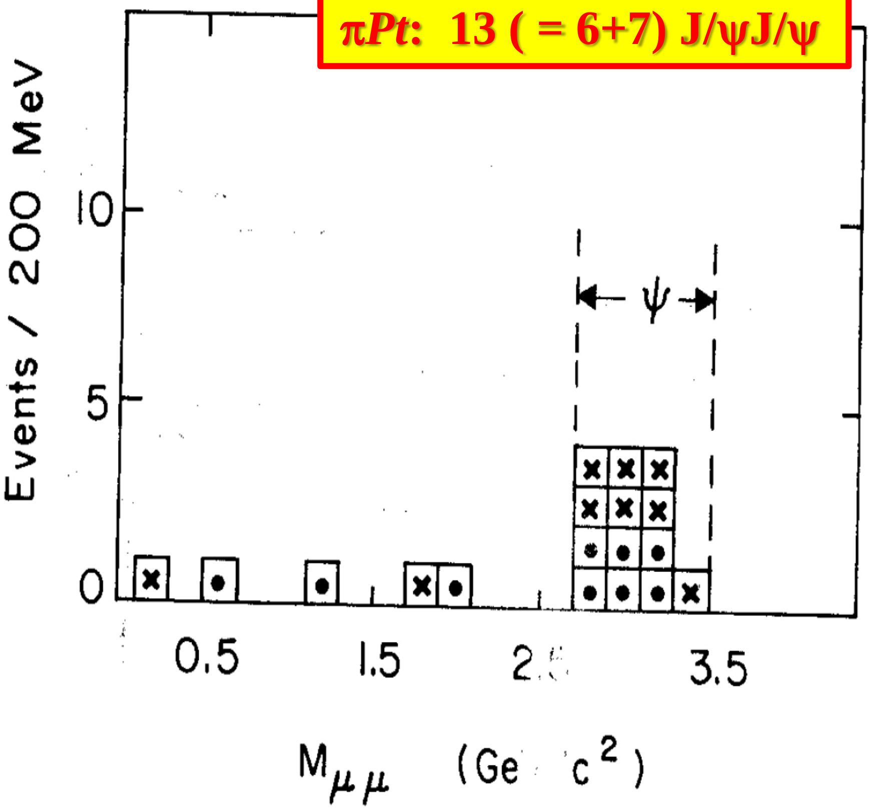
NA3, 1982

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

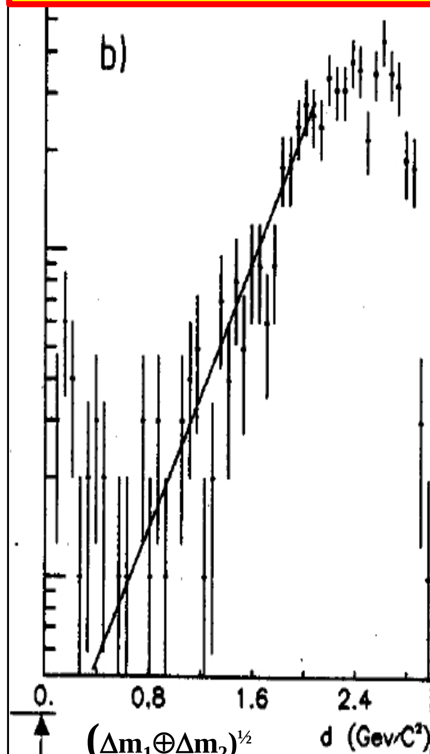
J. Badier *et al*., "Evidence for $\psi\psi$ production in π^- interactions at 150 and 280 GeV/*c*", Phys. Lett. B 114, 457 (1982).

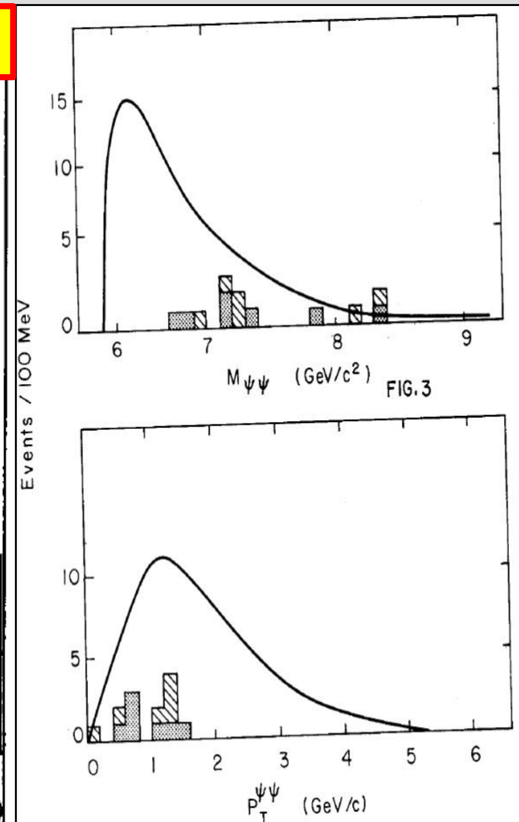
J.Badier *et al*., "$\psi\psi$ production and limits on beauty meson production from 400 GeV/*c* protons", Phys Lett B 158, 85 (1985)

πPt: 13 (= 6+7) $J/\psi J/\psi$



pPt: 16±4 $J/\psi J/\psi$





J/ψJ/ψ at √s=7TeV pp-collisions LHCb

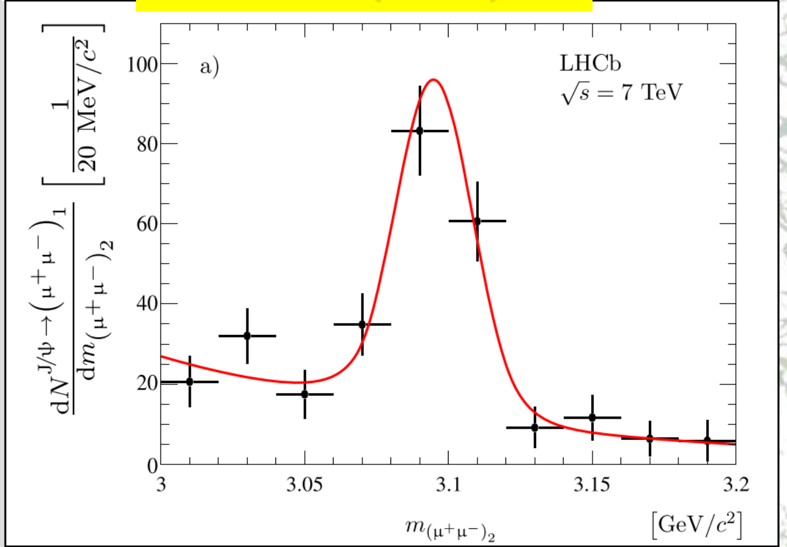
PLB 707 (2012) 52

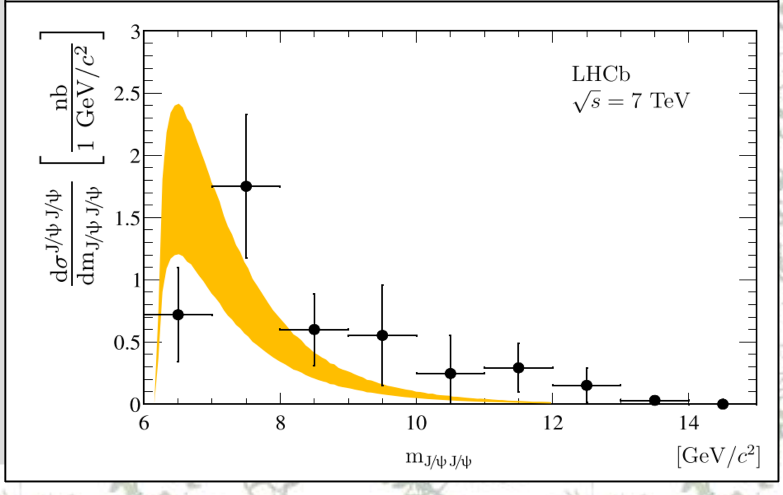
- First observation
  - 141±19 events, >6σ

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

  - SPS: 4.2nb (±30%)
  - DPS: 7nb (±30%)
- Compatible with SPS, DPS
  - … and their sum

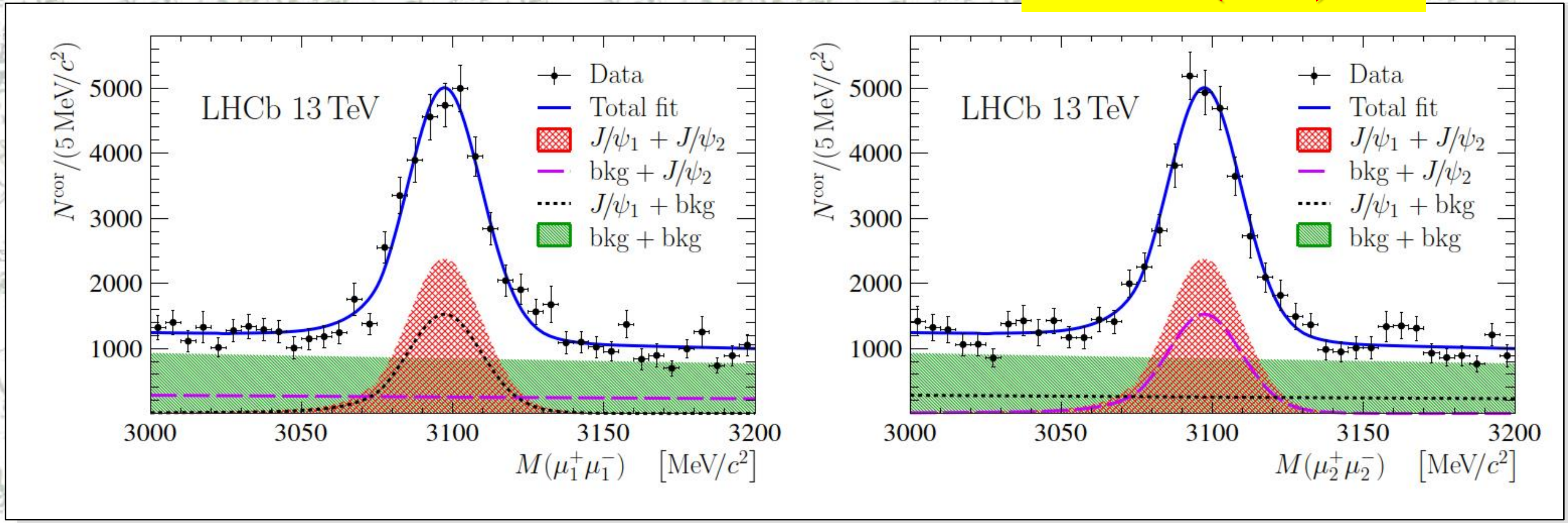
$$\sigma^{J/\psi J/\psi}/\sigma^{J/\psi} = \left(5.1 \pm 1.0 \pm 0.6^{+1.2}_{-1.0}\right) \times 10^{-4},$$





J/ψJ/ψ at √s=13TeV pp-collisions LHCb

JHEP 06 (2017) 047



- Signal of $(1.05\pm0.05)\times10^3$ events

$$\sigma(J/\psi\, J/\psi) = 15.2 \pm 1.0\,(\mathrm{stat}) \pm 0.9\,(\mathrm{syst})\ \mathrm{nb},$$

$$\frac{\sigma(J/\psi\, J/\psi)}{\sigma(J/\psi)} = (10.2 \pm 0.7\,(\mathrm{stat}) \pm 0.9\,(\mathrm{syst})) \times 10^{-4},$$

- SPS: (1-12)nb (±30%)
- DPS : 8.1nb (±25%)

Neither SPS nor DPS can be excluded

J/ψJ/ψ at √s=13TeV pp-collisions LHCb

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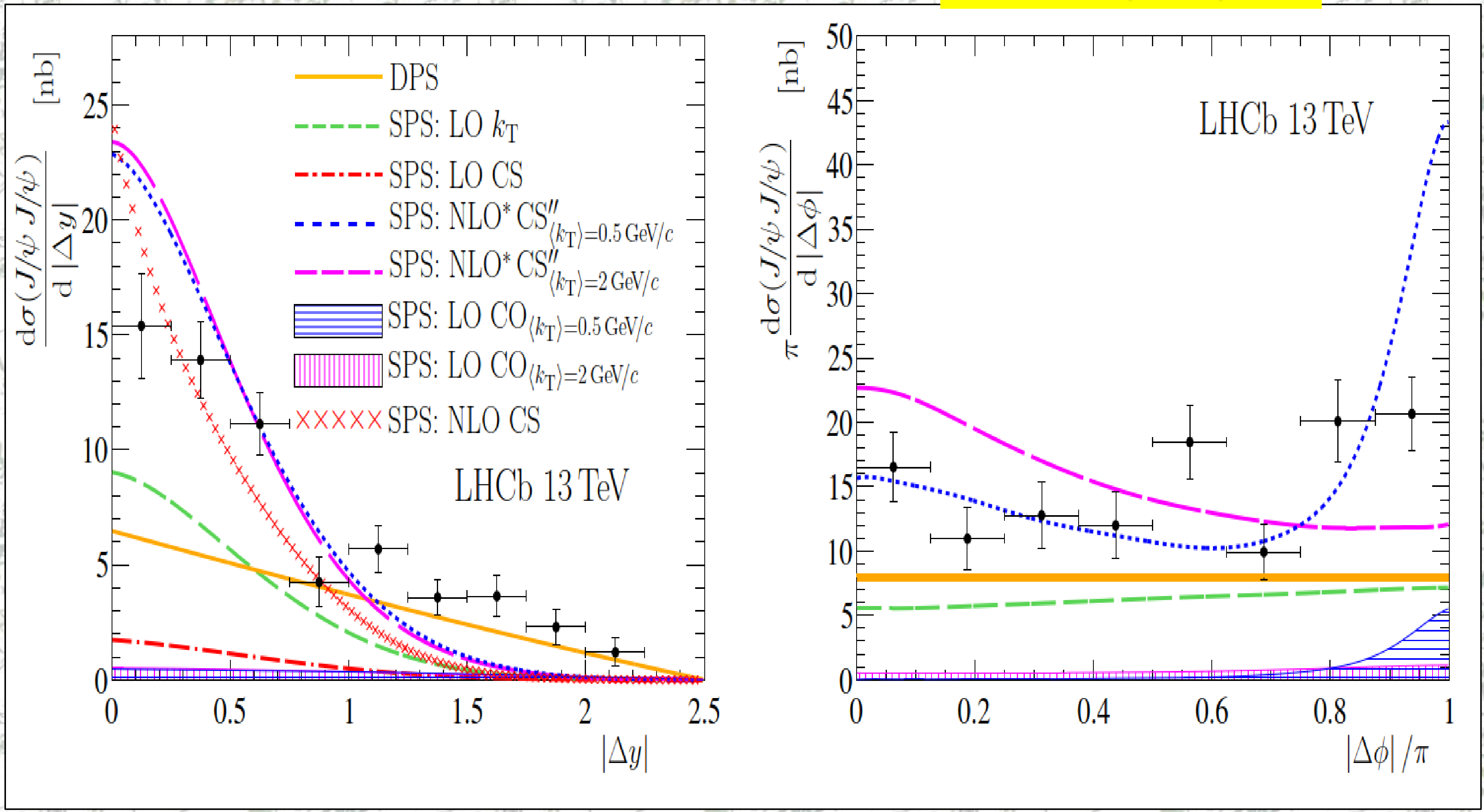

J/ψJ/ψ at √s=13TeV pp-collisions LHCb

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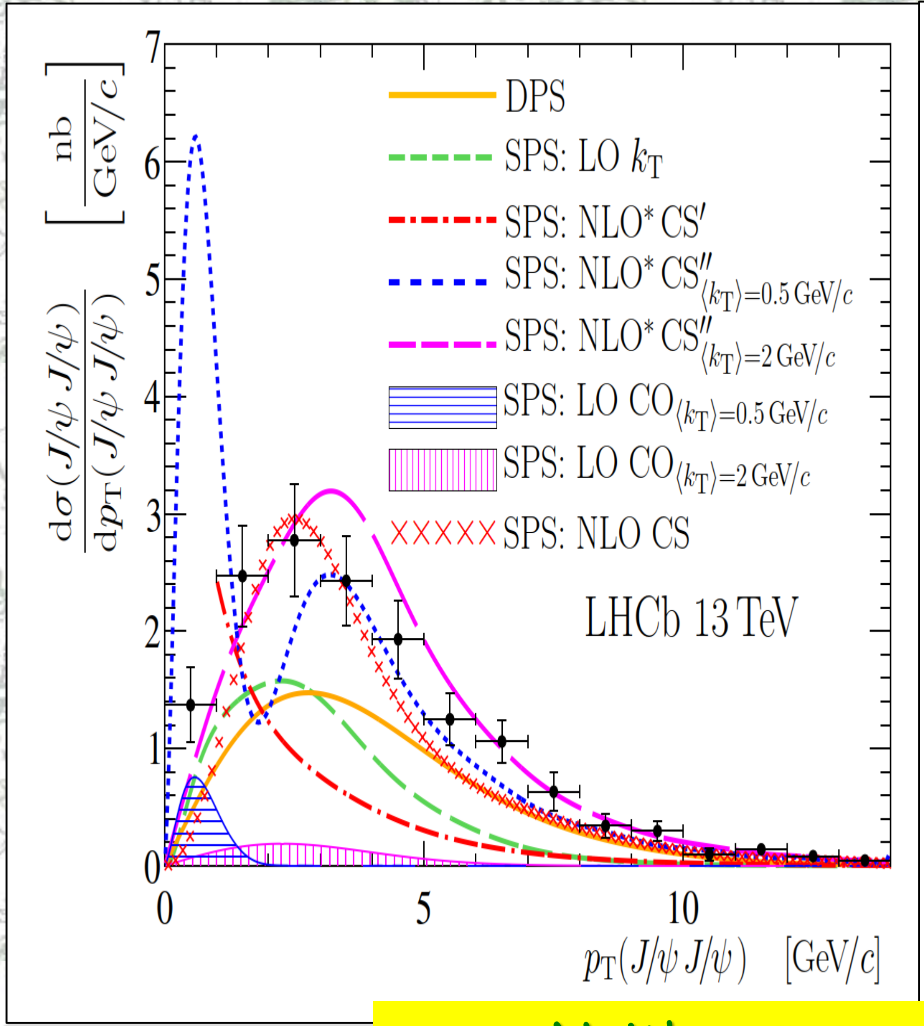

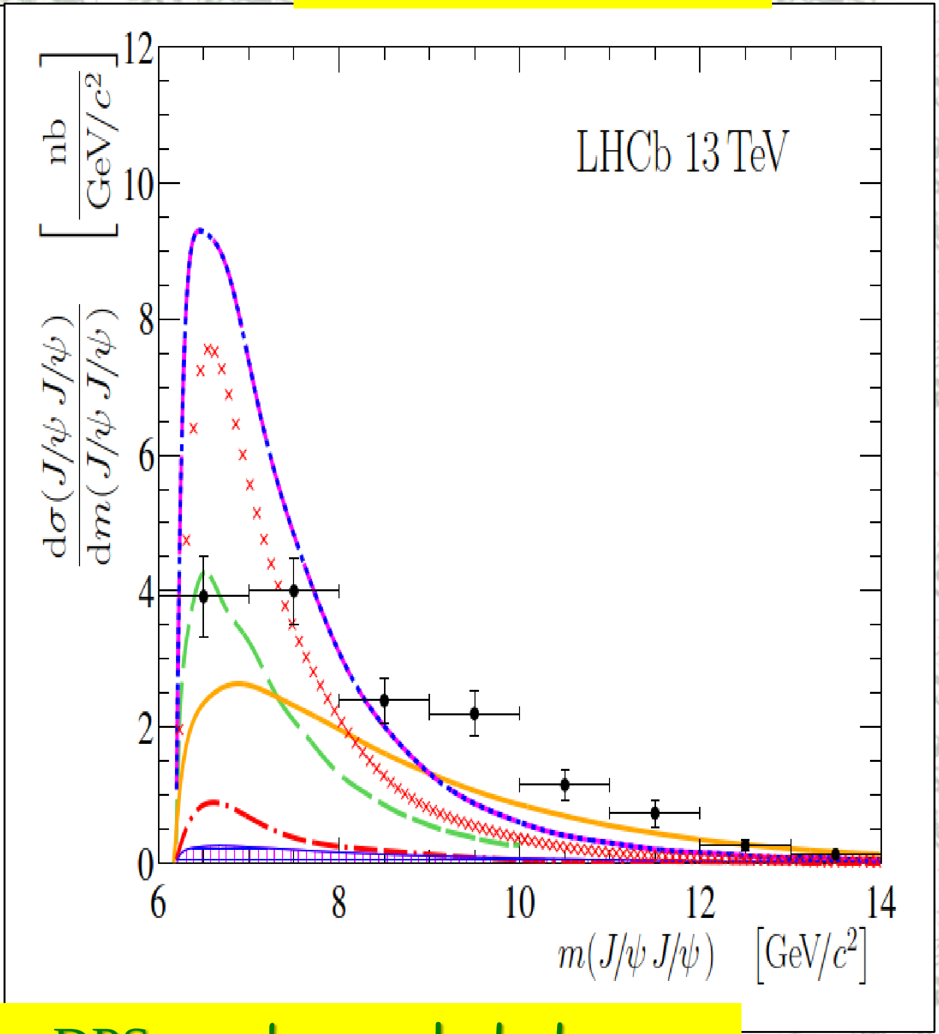

Neither SPS nor DPS can be excluded

$cc\overline{cc}$: $J/\psi D\bar{c}$

Other $cc\bar{c}\bar{c}$ processes : $J/\psi D\bar{c}$

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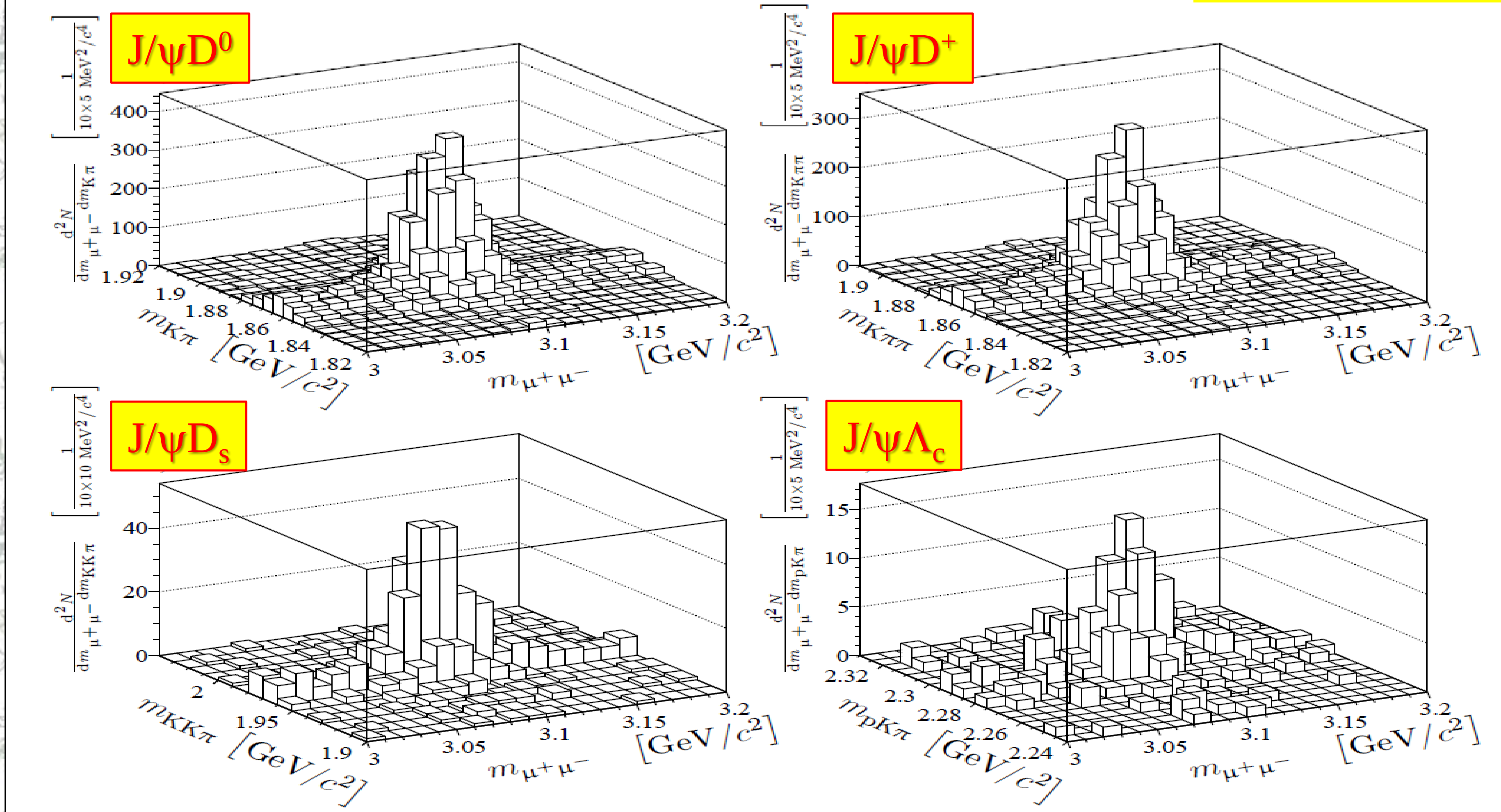

Cross-sections: $J/\psi D\bar{c}$

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LHCb measurement

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

Theory predictions: SPS << DPS

Mode	σ^{gg}		σ^{DPS}	σ^{sea}
		[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	

$J/\psi D\bar{c}$

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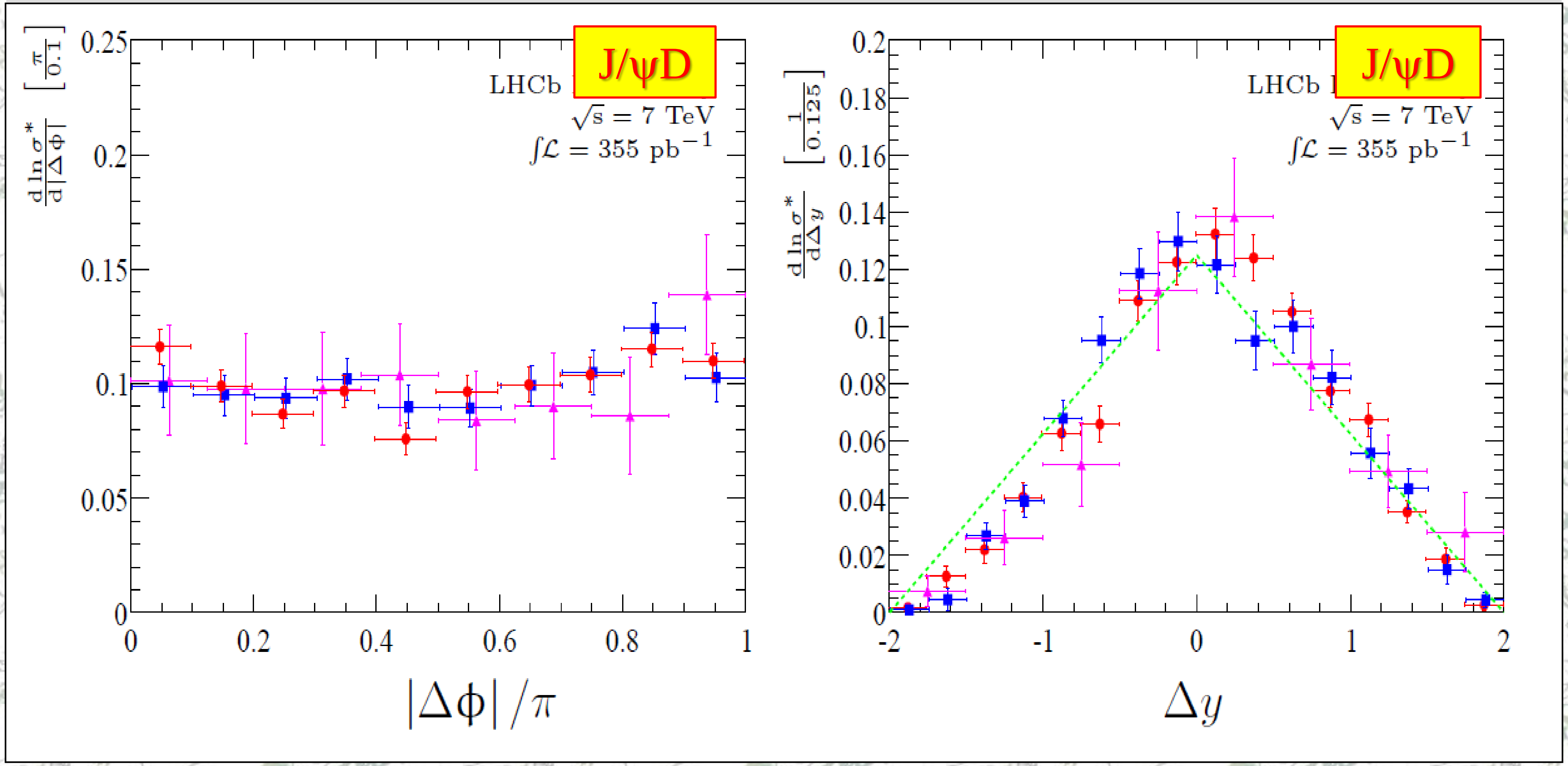
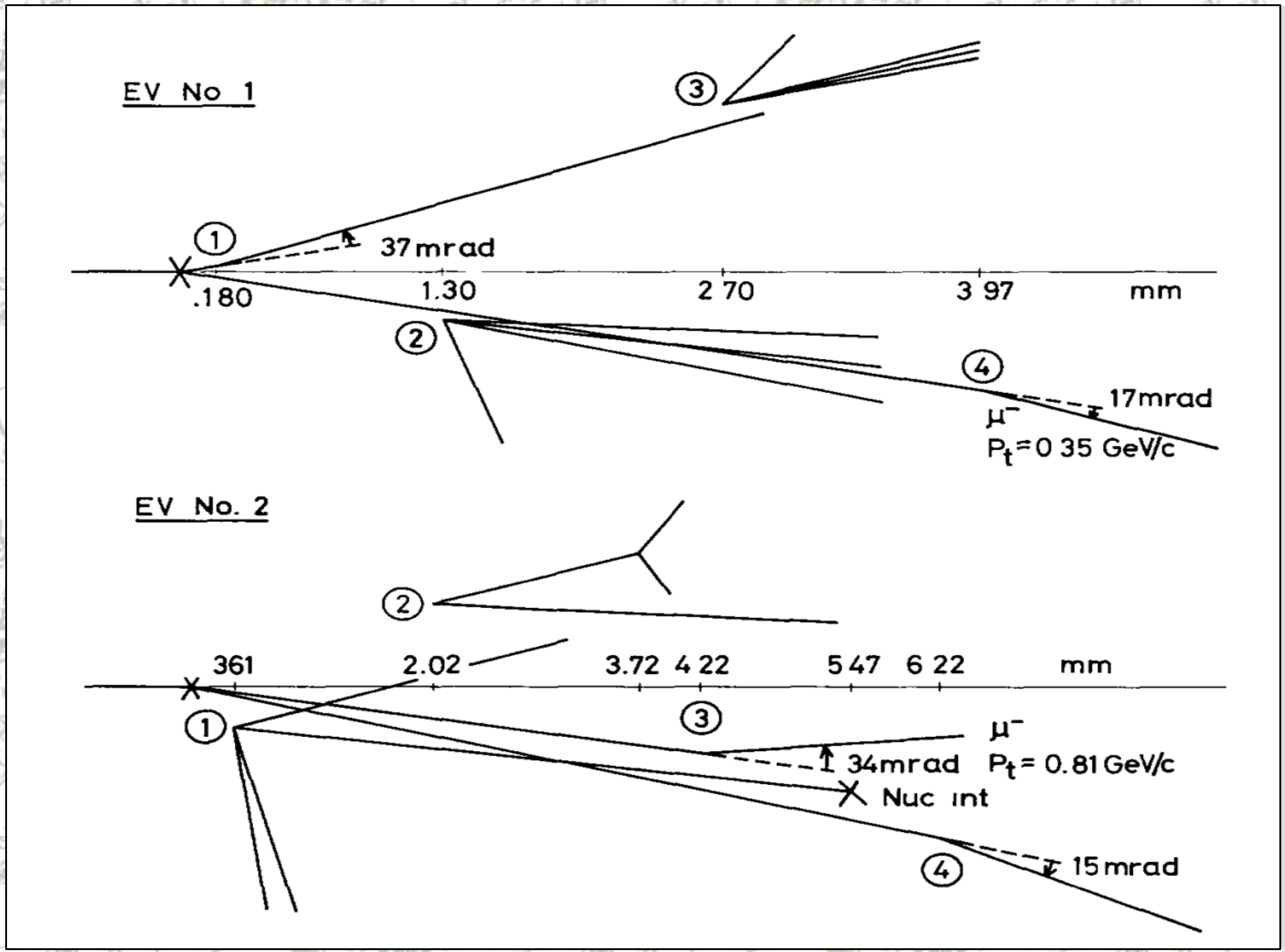
Largely uncorrelated: DPS dominance?



$cc\overline{cc}$: $DD\overline{cc}$

$cc\bar{c}\bar{c}$ in $\pi^{-}A$ by WA75



- 1987
- 350 GeV/c π^{-}
- 2 events

Other $cc\bar{c}\bar{c}$ processes : $DD\bar{c}\bar{c}$

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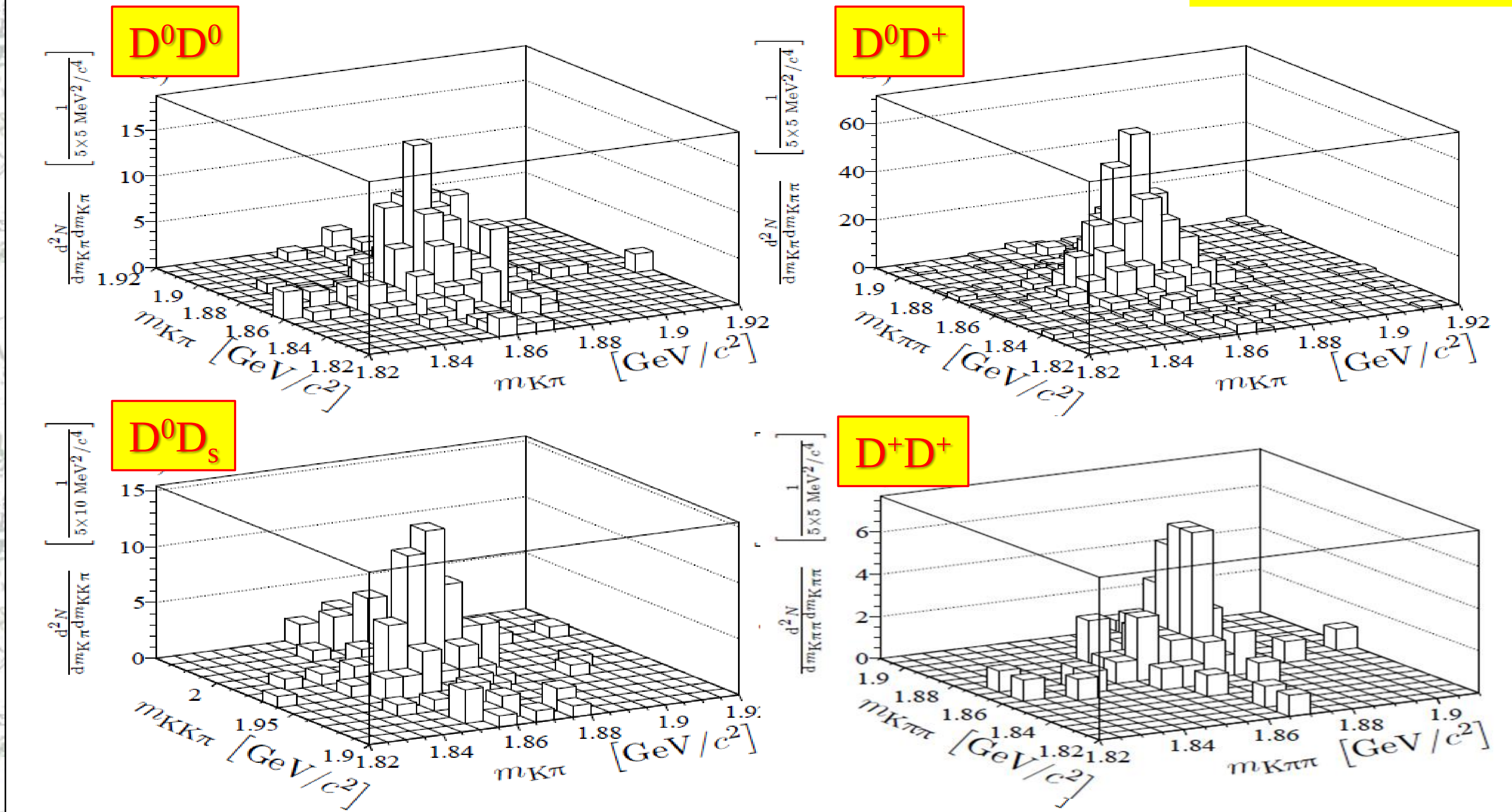

Cross-sections : $DD\overline{cc}$

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LHCb measurement

Mode	σ [nb]	$\sigma_{CC}/\sigma_{C\overline{C}}$ [%]
D^0D^0	$690 \pm 40 \pm 70$	10.9 ± 0.8
$D^0\overline{D}^0$	$6230 \pm 120 \pm 630$	
D^0D^+	$520 \pm 80 \pm 70$	12.8 ± 2.1
D^0D^-	$3990 \pm 90 \pm 500$	
$D^0D_s^+$	$270 \pm 50 \pm 40$	15.7 ± 3.4
$D^0D_s^-$	$1680 \pm 110 \pm 240$	
$D^0\overline{\Lambda}_c^-$	$2010 \pm 280 \pm 600$	—
D^+D^+	$80 \pm 10 \pm 10$	9.6 ± 1.6
D^+D^-	$780 \pm 40 \pm 130$	
$D^+D_s^+$	$70 \pm 15 \pm 10$	12.1 ± 3.3
$D^+D_s^-$	$550 \pm 60 \pm 90$	
$D^+\Lambda_c^+$	$60 \pm 30 \pm 20$	10.7 ± 5.9
$D^+\overline{\Lambda}_c^-$	$530 \pm 130 \pm 170$	

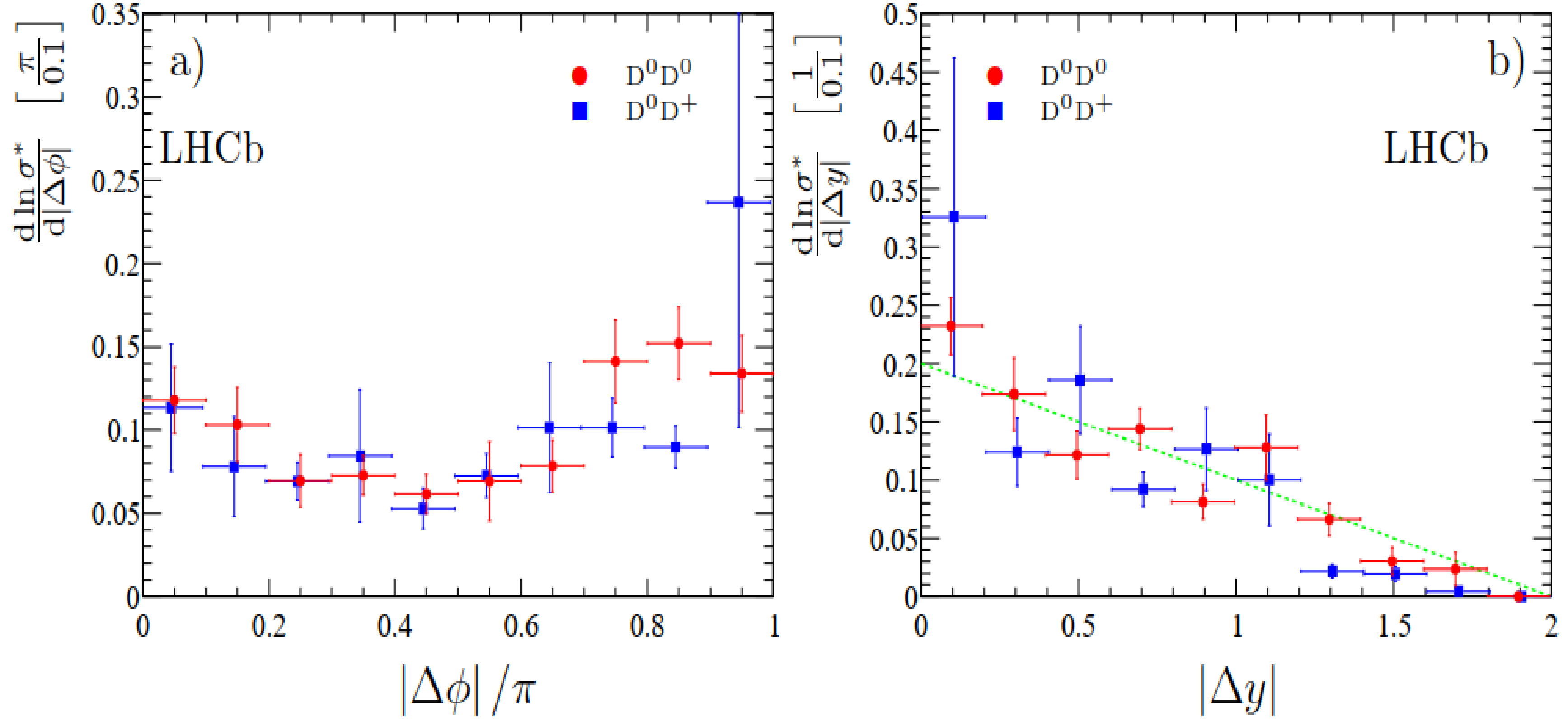
Theory predictions

	σ^{DPS} [μb]
D^0D^0	1.0 ± 0.25
D^0D^+	0.85 ± 0.2
$D^0D_s^+$	0.33 ± 0.07
$D^0\Lambda_c^+$	0.75 ± 0.25
D^+D^+	0.17 ± 0.05
$D^+D_s^+$	0.14 ± 0.03
$D^+\Lambda_c^+$	0.32 ± 0.12

data ~ DPS

$DD\overline{c}\overline{c}$

Largely uncorrelated: DPS dominance?



$c b \bar{c} \bar{b}$: $\Upsilon D \bar{c}$

$b\bar{c}b\bar{c}$ process: $\Upsilon D\bar{c}$

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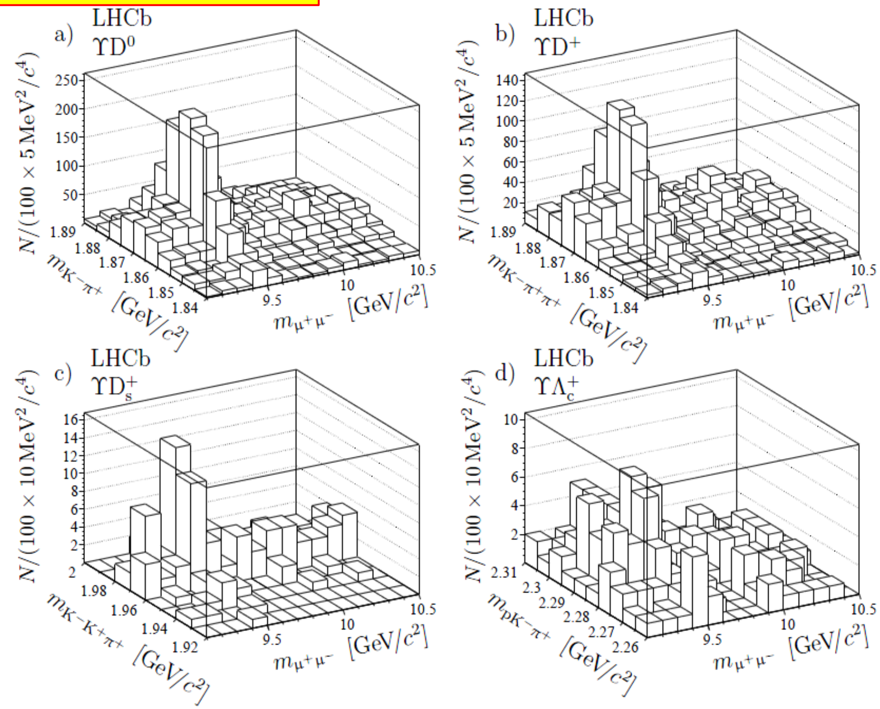

Signals	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
D^0	980 ± 50	184 ± 27	60 ± 22
D^+	556 ± 35	116 ± 20	55 ± 17
D_s^+	31 ± 7	9 ± 5	6 ± 4
Λ_c^+	11 ± 6	1 ± 4	1 ± 3

$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=7\,\mathrm{TeV}} = 155 \pm 21\,(\mathrm{stat}) \pm 7\,(\mathrm{syst})\,\mathrm{pb},$$
$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=7\,\mathrm{TeV}} = 82 \pm 19\,(\mathrm{stat}) \pm 5\,(\mathrm{syst})\,\mathrm{pb},$$
$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=8\,\mathrm{TeV}} = 250 \pm 28\,(\mathrm{stat}) \pm 11\,(\mathrm{syst})\,\mathrm{pb},$$
$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=8\,\mathrm{TeV}} = 80 \pm 16\,(\mathrm{stat}) \pm 5\,(\mathrm{syst})\,\mathrm{pb},$$

$$\left.\frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=7\,\mathrm{TeV}} = (7.7 \pm 1.0)\,\%,$$
$$\left.\frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=8\,\mathrm{TeV}} = (8.0 \pm 0.9)\,\%,$$

Predictions:
SPS: (0.1-0.6)%
DPS O(10%)

$$\mathcal{B}_{2/1} \times \frac{\sigma^{\Upsilon(2S)D^0}_{\sqrt{s}=7\,\mathrm{TeV}}}{\sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=7\,\mathrm{TeV}}} = (13 \pm 5)\%,$$
$$\mathcal{B}_{2/1} \times \frac{\sigma^{\Upsilon(2S)D^0}_{\sqrt{s}=8\,\mathrm{TeV}}}{\sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=8\,\mathrm{TeV}}} = (20 \pm 4)\%,$$

$$\mathcal{B}_{2/1} \times \frac{\sigma^{\Upsilon(2S)D^+}_{\sqrt{s}=7\,\mathrm{TeV}}}{\sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=7\,\mathrm{TeV}}} = (22 \pm 7)\%,$$
$$\mathcal{B}_{2/1} \times \frac{\sigma^{\Upsilon(2S)D^+}_{\sqrt{s}=8\,\mathrm{TeV}}}{\sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=8\,\mathrm{TeV}}} = (22 \pm 6)\%,$$

Expected:
DPS: 25%

data agree with DPS

$\Upsilon D\bar{c}$

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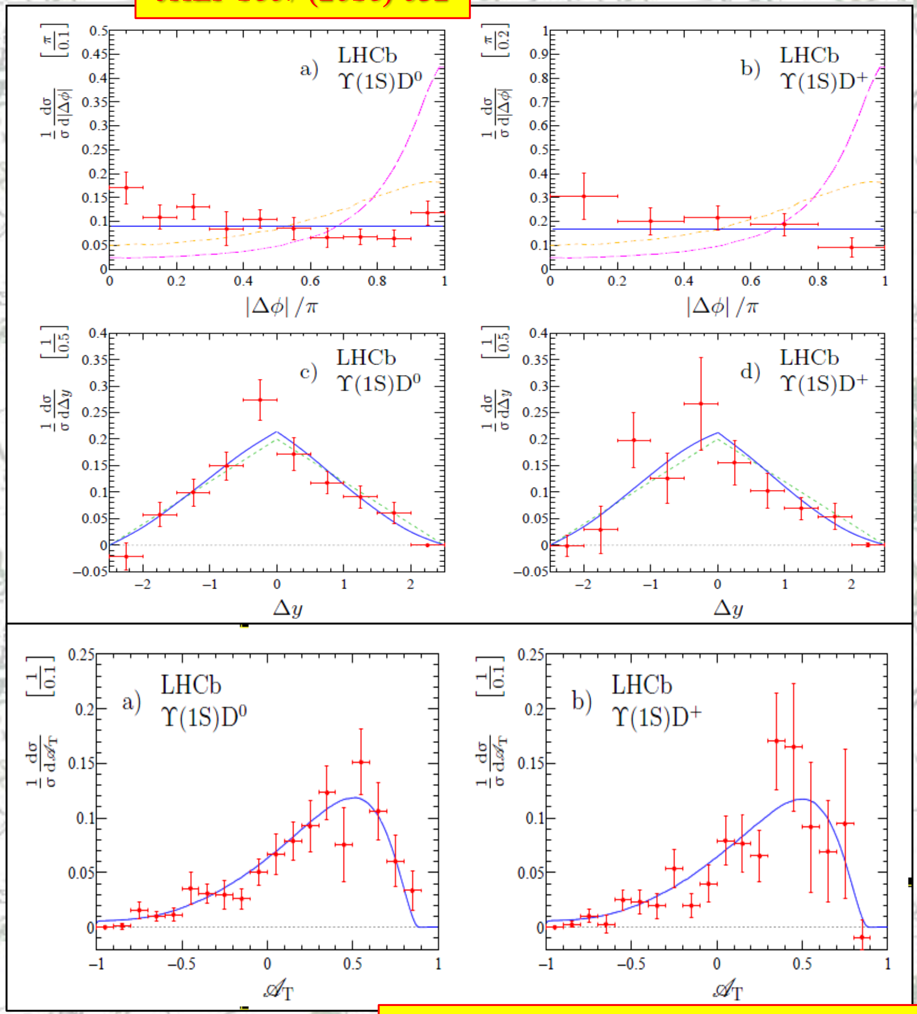
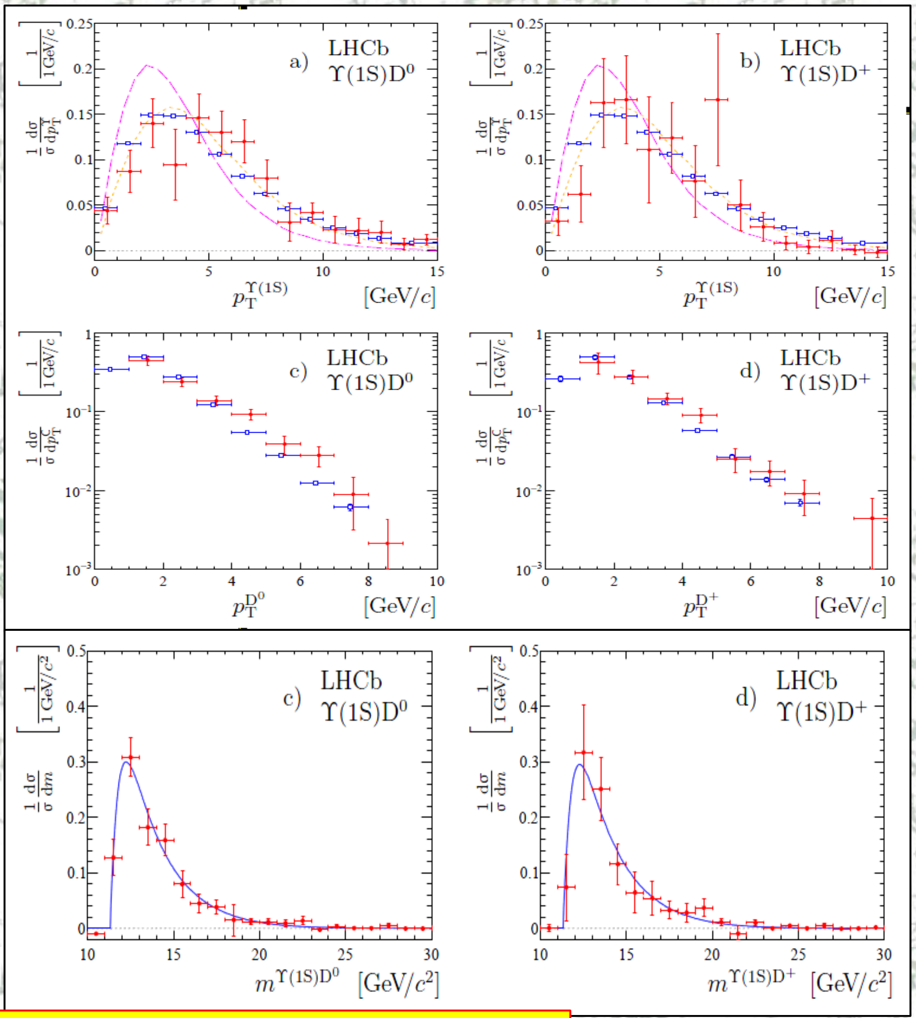




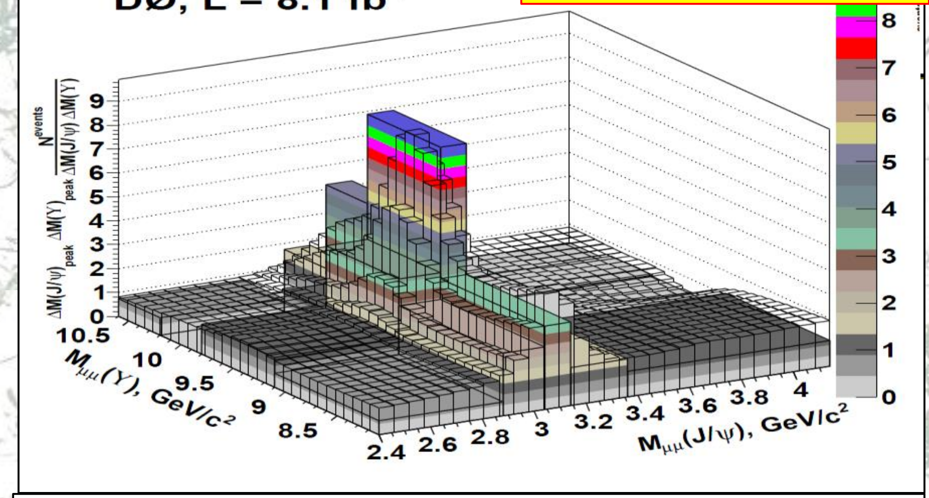
ALL differential distributions in excellent agreement with DPS

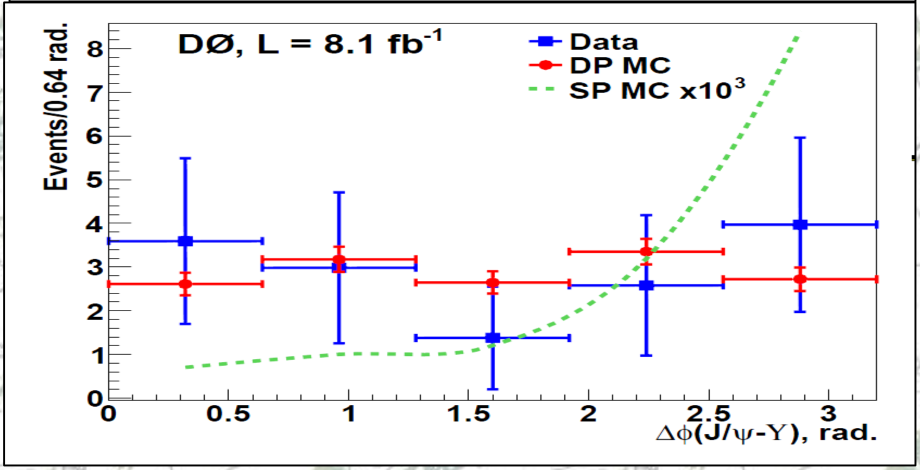
$c\bar{c}b\bar{b}$: $\Upsilon J/\psi$ (by D0)

J/ψ+ϒ   D0 @ 1.96TeV

Signal: 12.0 ±3.8±2.8

PRL 116(2016) no8, 082002





- Very interesting final state: no SPS LO CS diagrams!

$$\sigma(J/\psi+\Upsilon) = 27\pm9\pm7\ \text{nb}$$

- Uniform Δϕ suggest DPS dominance

$$\sigma_{\text{eff}} = 2.2\pm0.7\pm0.9\text{mb}$$

$Q_1\overline{Q}_1Q_2\overline{Q}_2$ production

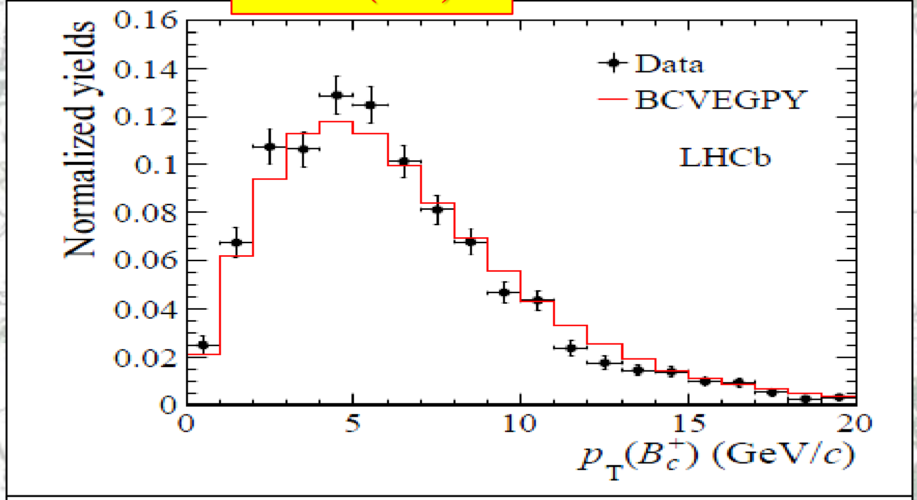
- $J/\psi J/\psi$: neither SPS nor DPS can be excluded
  - cross-sections
  - correlations
- $J/\psi D\overline{c}$: DPS
- $DD\overline{cc}$: (likely) DPS dominance
- $\Upsilon D\overline{c}$: DPS
- ($J/\psi\Upsilon$ by D0: DPS)

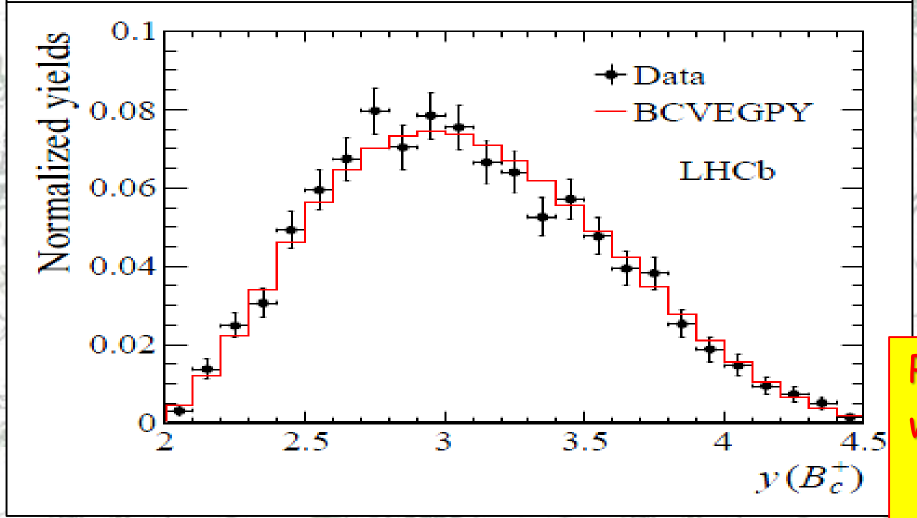
- One can conclude that SPS is not so important…
  - Is there an evidence for SPS processes?

$c\bar{c}b\bar{b}$: $B_c^+ X$

B_c^+ pure SPS $c\bar{c}b\bar{b}$

PLB742 (2015) 29





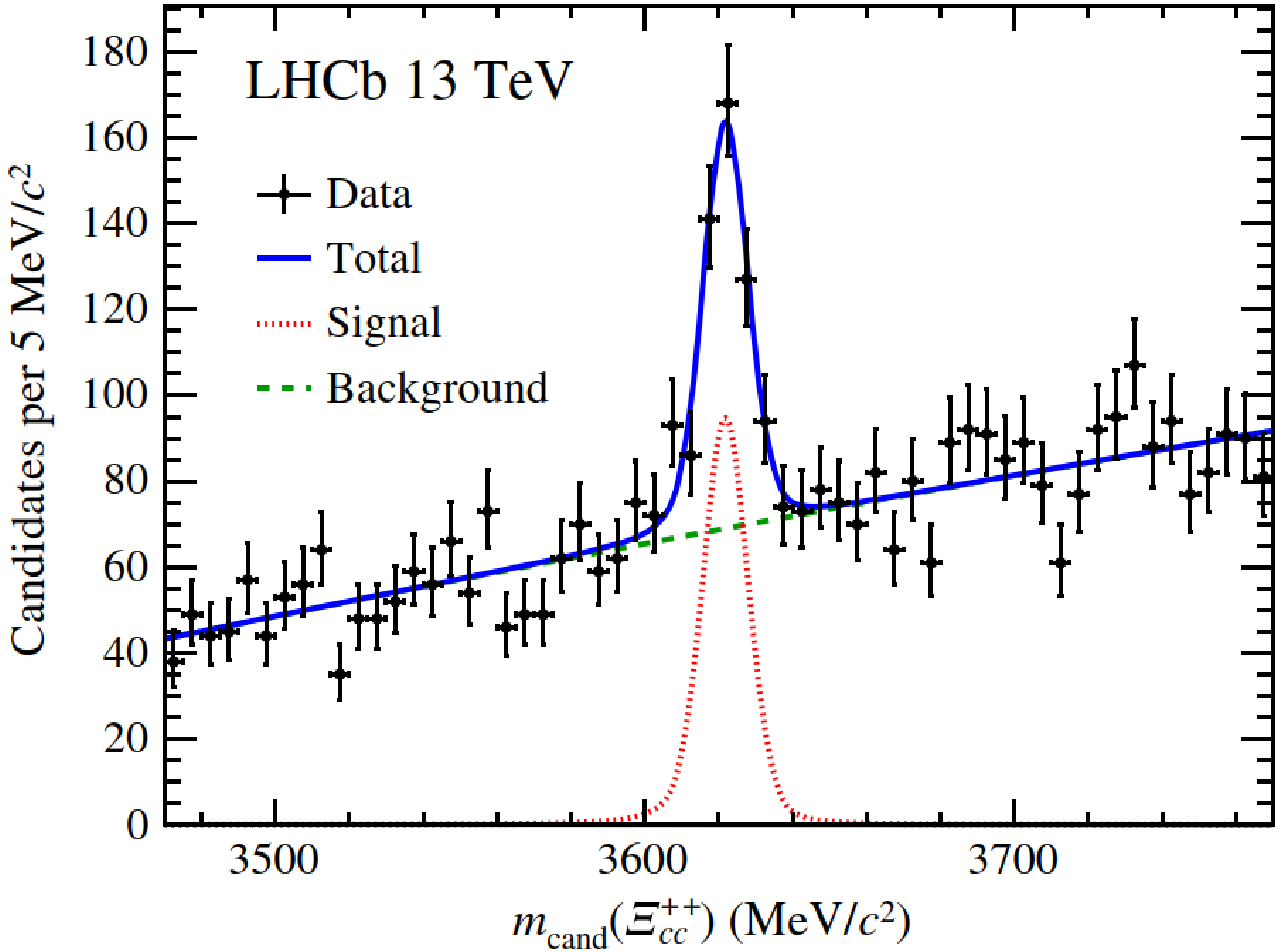
- Very special case:
  - ☺ Large signals, properties are well measured :
    - Mass , lifetime,
    - Ratios of Brs
  - ☺ differential rates in excellent $O(1\text{-}5\%)$ agreement with α_s^4 calculations
  - ☹ Overall rate is largely "unknown": no measured Br

Puzzle:
where are double heavy baryons Ξ_{cc} & Ξ_{bc}?
- also pure SPS
- essentially the same matrix element

$c c \overline{c c}: \Xi_{cc}^{++} X$

Ξ_{cc}^{++} : $cc\overline{c}\overline{c}$ pure SPS process

PRL 119 (2017) 11, 112001



N=313 ±33

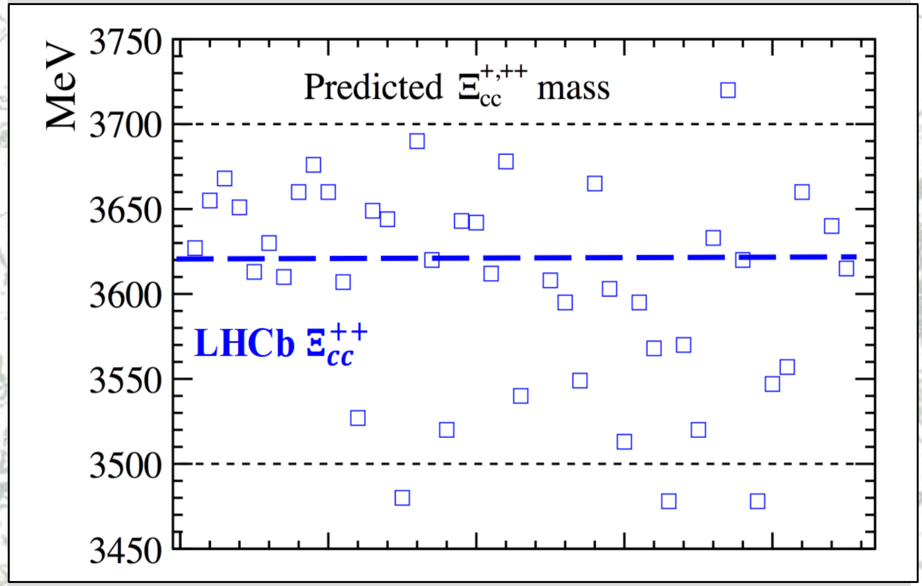
>12σ

- Long-waited

- Need more data to study the production

Ξ_{cc}^{++}

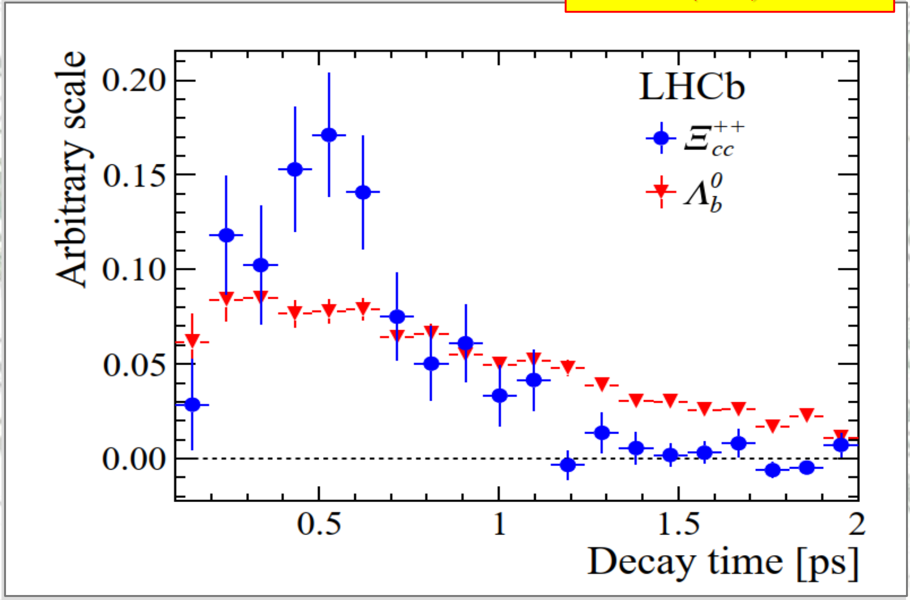
- Numerous theory predictions (wide range)



- Measured mass allows predict the T_{cc}^{+} mass!

- Lifetime from theory is rather uncertain
  - 200-700 fs

PRL 121 (2018) 5. 052002



$256^{+24}_{-22}\ 24\ fs$

$cc\overline{cc}$: X(6900)

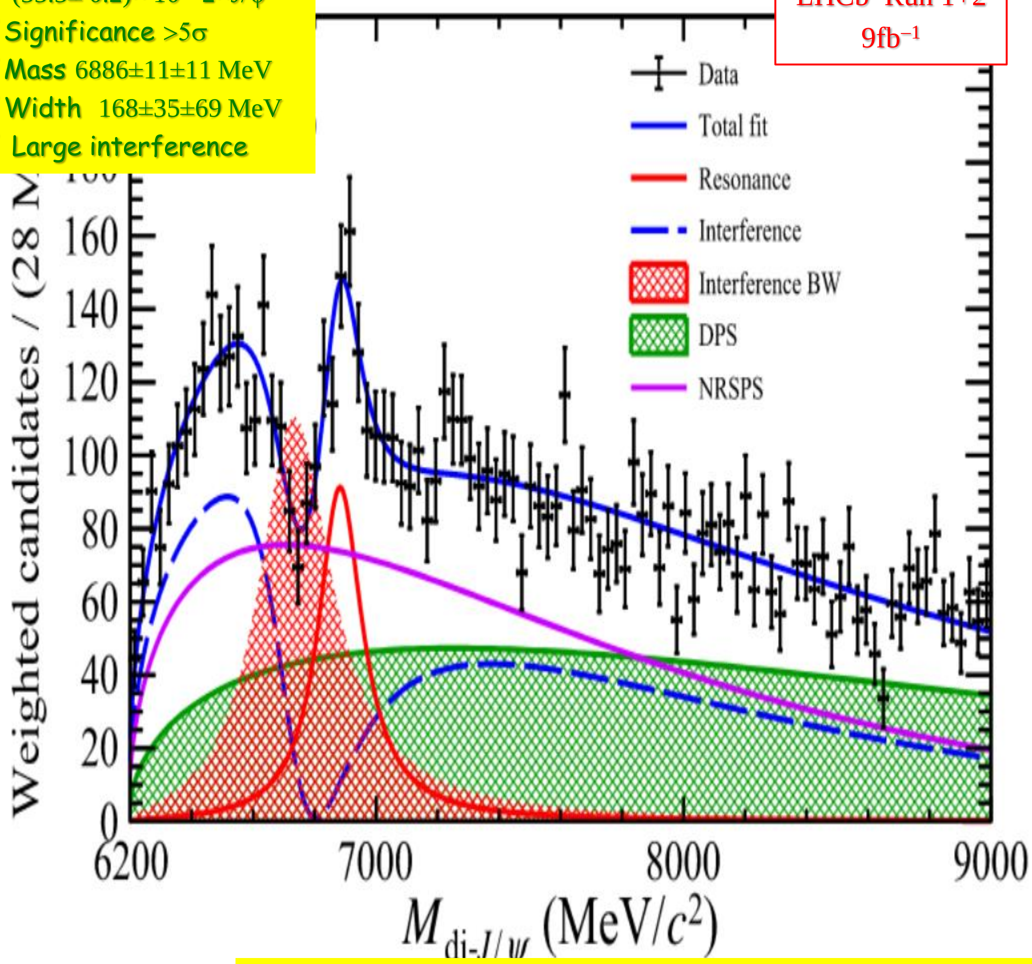
Fully charmed tetraquark $cc\bar{c}\bar{c}$

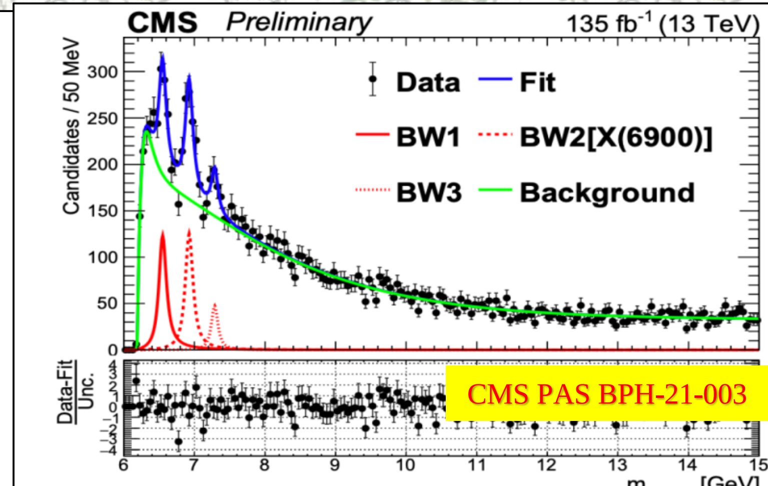
LHCb: Science Bulletin 65 (2020) 23 1983

$(33.3\pm 0.2)\times 10^3$ $2\times J/\psi$

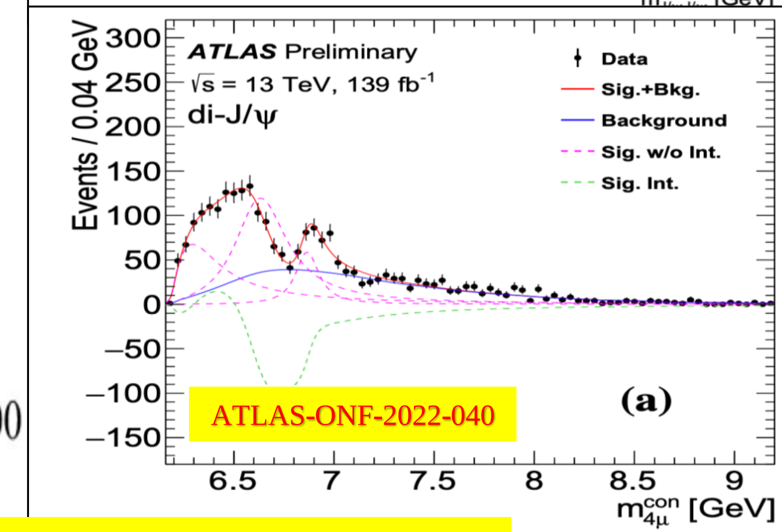
- Significance $>5\sigma$
- Mass $6886\pm11\pm11$ MeV
- Width $168\pm35\pm69$ MeV
- Large interference

LHCb Run 1+2
9fb^{-1}





CMS PAS BPH-21-003

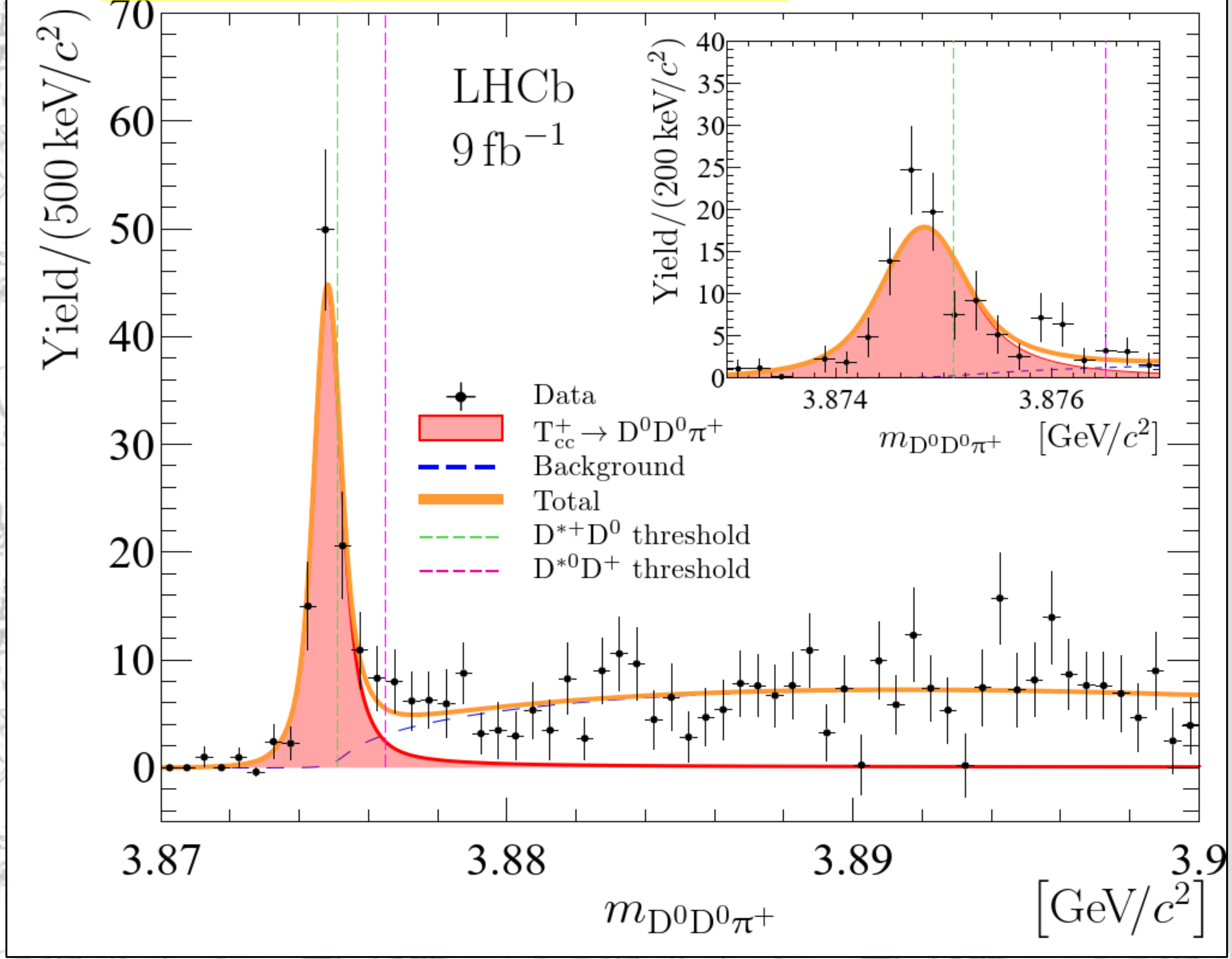


ATLAS-ONF-2022-040

There exist sizeable SPS contribution!

T_{cc}^{+} : $cc\overline{cc}$ pure SPS process $D^0D^0\pi^+$

LHCb: Nature Phys. 18 (2022) 7 751



Peak is stable

- Data taking periods
- Data taking conditions
- Dipole magnet polarity
- Charge

~~Reflections~~

~~Fake D^0~~

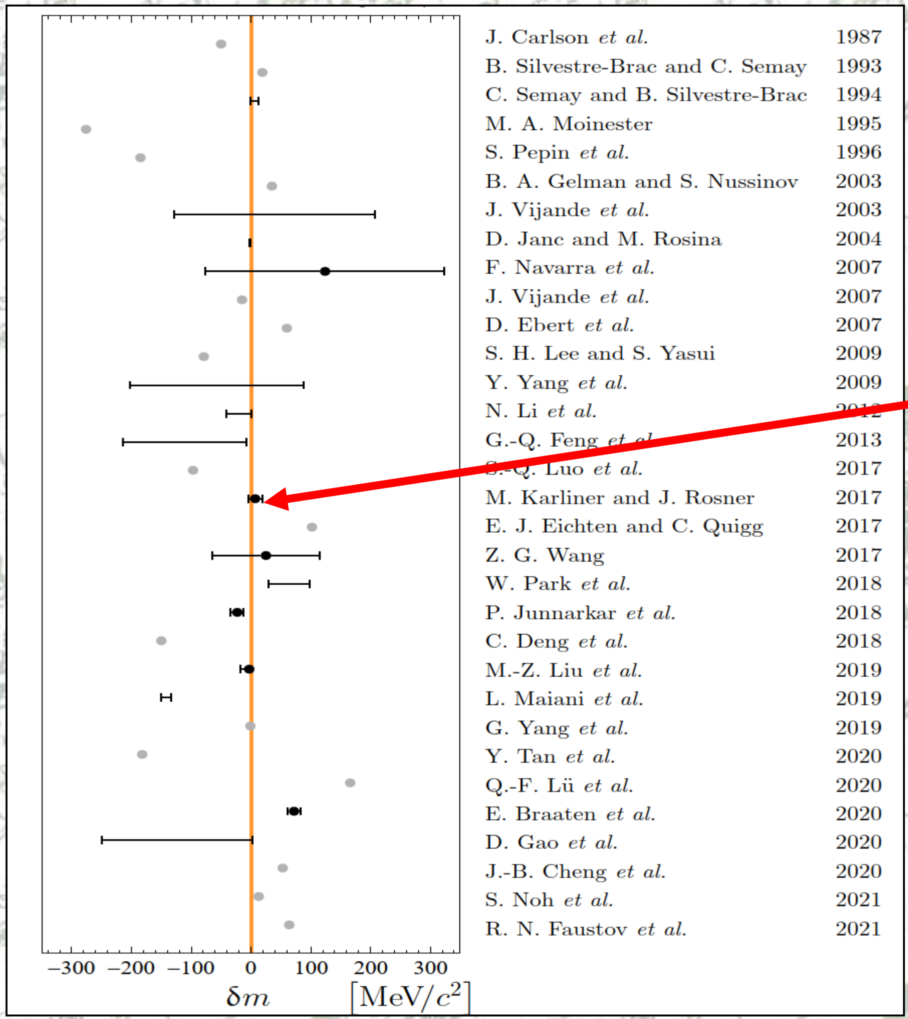
~~Duplicates~~

Breit-Wigner fit

Parameter	Value
N	117 ± 16
δm_{BW}	-273 ± 61 keV/c^2
Γ_{BW}	410 ± 165 keV

- Significance 22σ
- m_{BW} below $D^{*+}D^0$ threshold 4.3σ

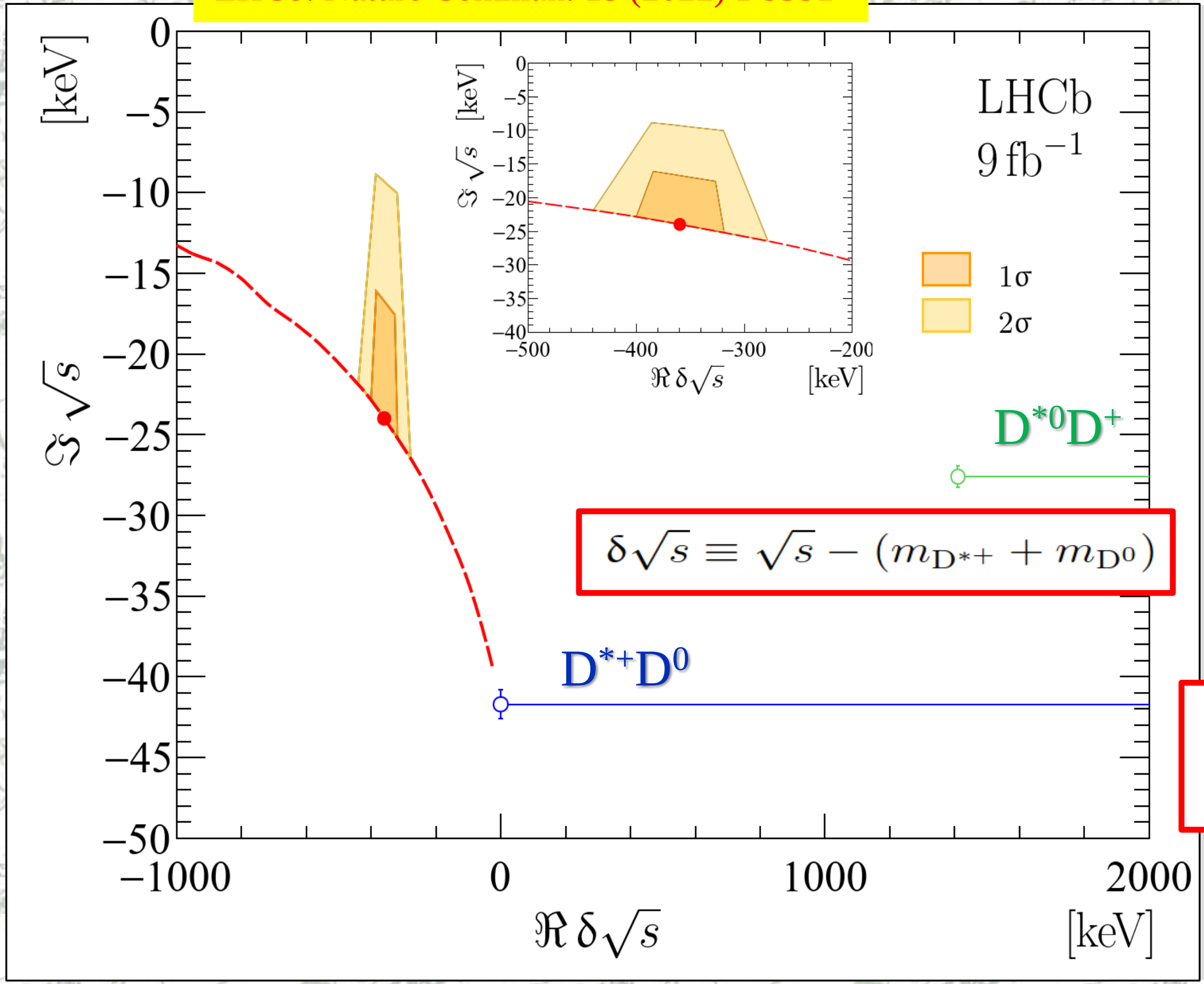
T_{cc}^{+} double charm tetraquark $cc\bar{u}\bar{d}$



- Active theory discussions
- Consensus:
  - isoscalar, $J^P=1^+$, not too far from the DD^* threshold
- Close relation with Ξ_{cc}^{++} baryon
- Very interesting perspective for $bb\bar{u}\bar{d}$
  - It can be stable!

Amplitude pole

LHCb: Nature Commun. 13 (2022) 1 3351



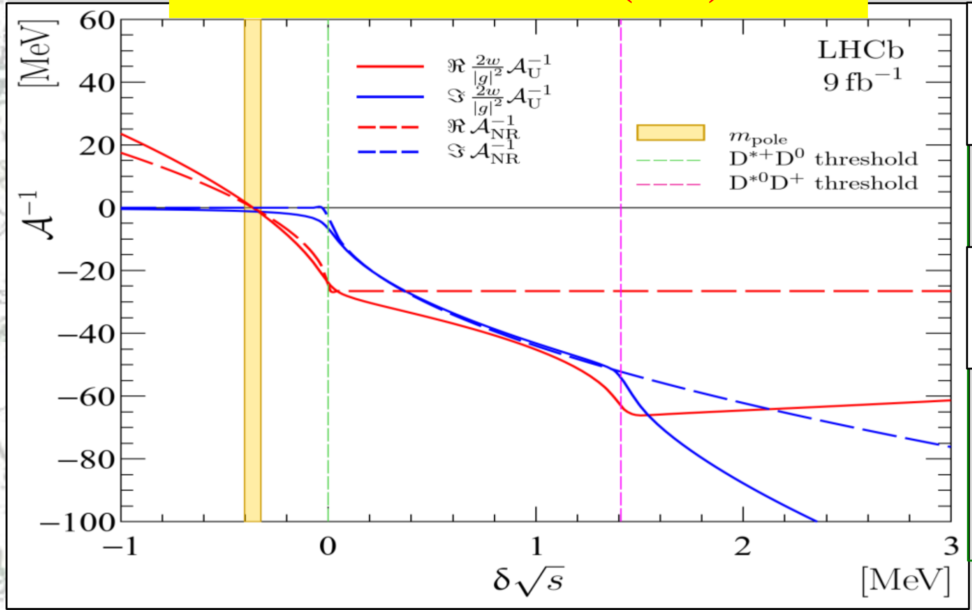
Analytic continuation of the amplitude to the second Riemann sheet

$$\sqrt{\hat{s}} \equiv m_{\mathrm{pole}} - \frac{i}{2}\Gamma_{\mathrm{pole}}$$

$$\begin{aligned} \delta m_{\mathrm{pole}} &= -360 \pm 40\,^{+4}_{-0}\ \mathrm{keV}/c^2 \\ \Gamma_{\mathrm{pole}} &= 48 \pm 2\,^{+0}_{-14}\ \mathrm{keV}\,, \end{aligned}$$

Low energy scattering parameters

LHCb: Nature Commun. 13 (2022) 1 3351



$$\mathcal{A}_{NR}^{-1} = \frac{1}{a} + r\frac{k^2}{2} - ik + \mathcal{O}(k^4)$$

- Scattering length

$$a = \left[-(7.16 \pm 0.51) + i\,(1.85 \pm 0.28)\right]\ \mathrm{fm}$$

- Real part is negative
  - → attraction

- Effective range $r = -\frac{1}{w}\frac{16}{|g|^2}$

$$0 \le -r < 11.9\,(16.9)\ \mathrm{fm\ at}\ 90\,(95)\%\ \mathrm{CL}$$

Non-positive ← "feature" of our model

- Compositeness $Z = 1 - \sqrt{\frac{1}{1+2\,|r/\Re\,a|}}$

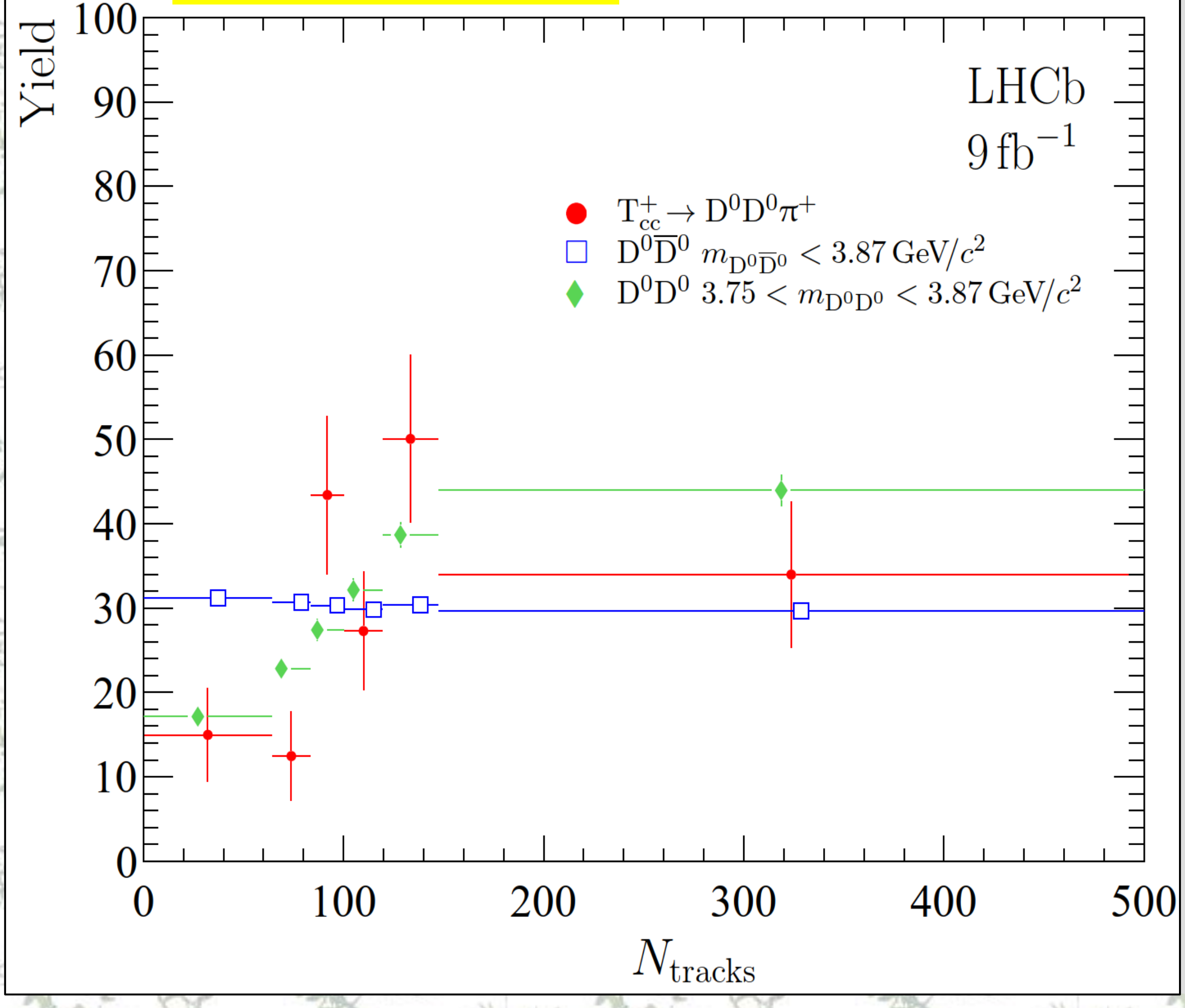
$$Z \propto |g|^{-2}$$

$$Z < 0.52\,(0.58)\ \mathrm{at}\ 90\,(95)\%\ \mathrm{CL}$$

Weinberg 1965,
Matuschek,Baru,Guo&Hanhart 2021

Event activity/Track multiplicity

arXiv:2109:01056



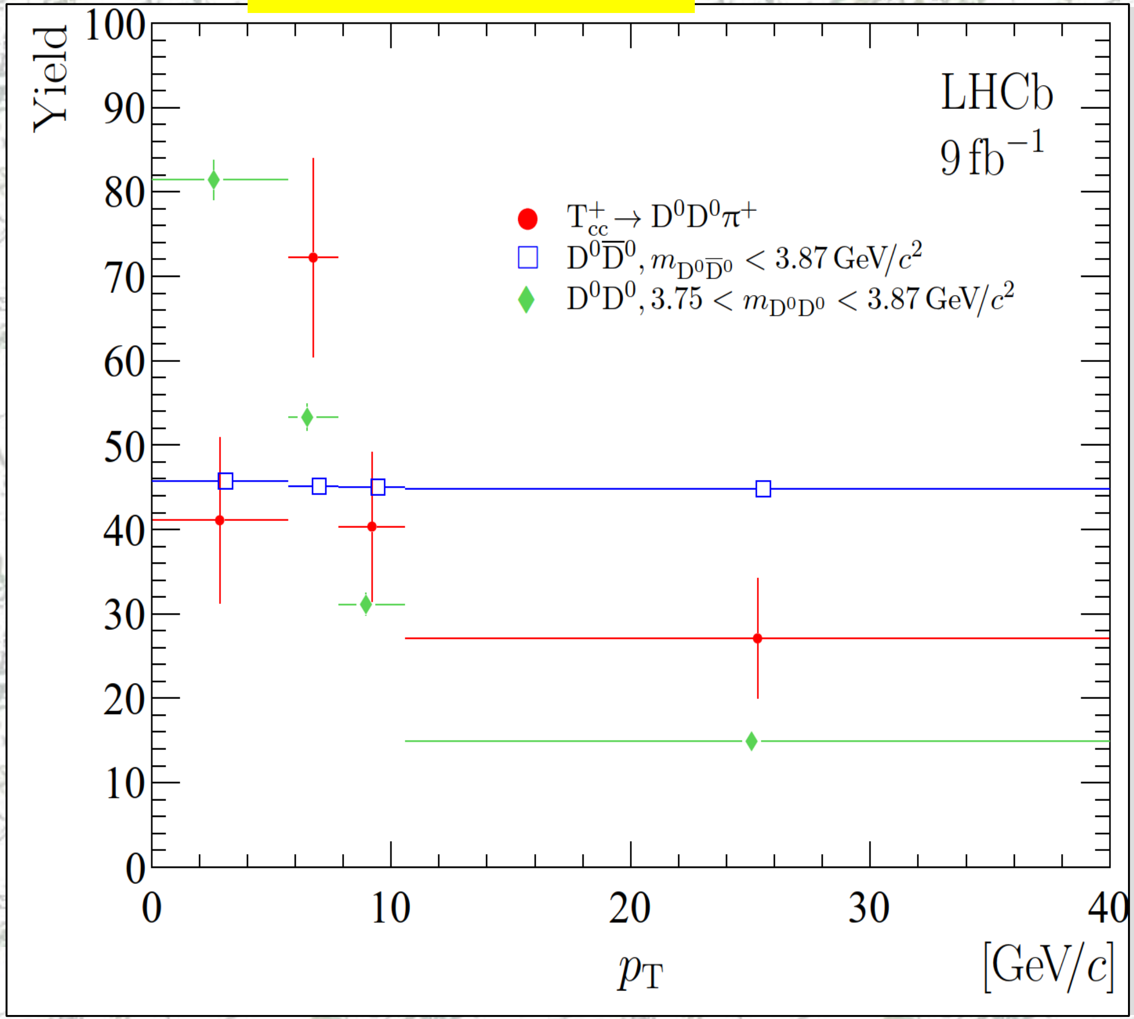
- Track multiplicity
- low-mass $D\bar{D}$ and DD

p-value: T_{cc}^{+} vs $D\bar{D}$ = 0.1%
p-value: T_{cc}^{+} vs DD = 12%

- Similar to DD
  - DPS process
  - … unexpected
- Different from $D\bar{D}$
  - Expected ***but*** ***totally different***!

p_T spectrum

arXiv:2109:01056



p-value: T_{cc}^+ vs $D\overline{D}$ = 1.4%

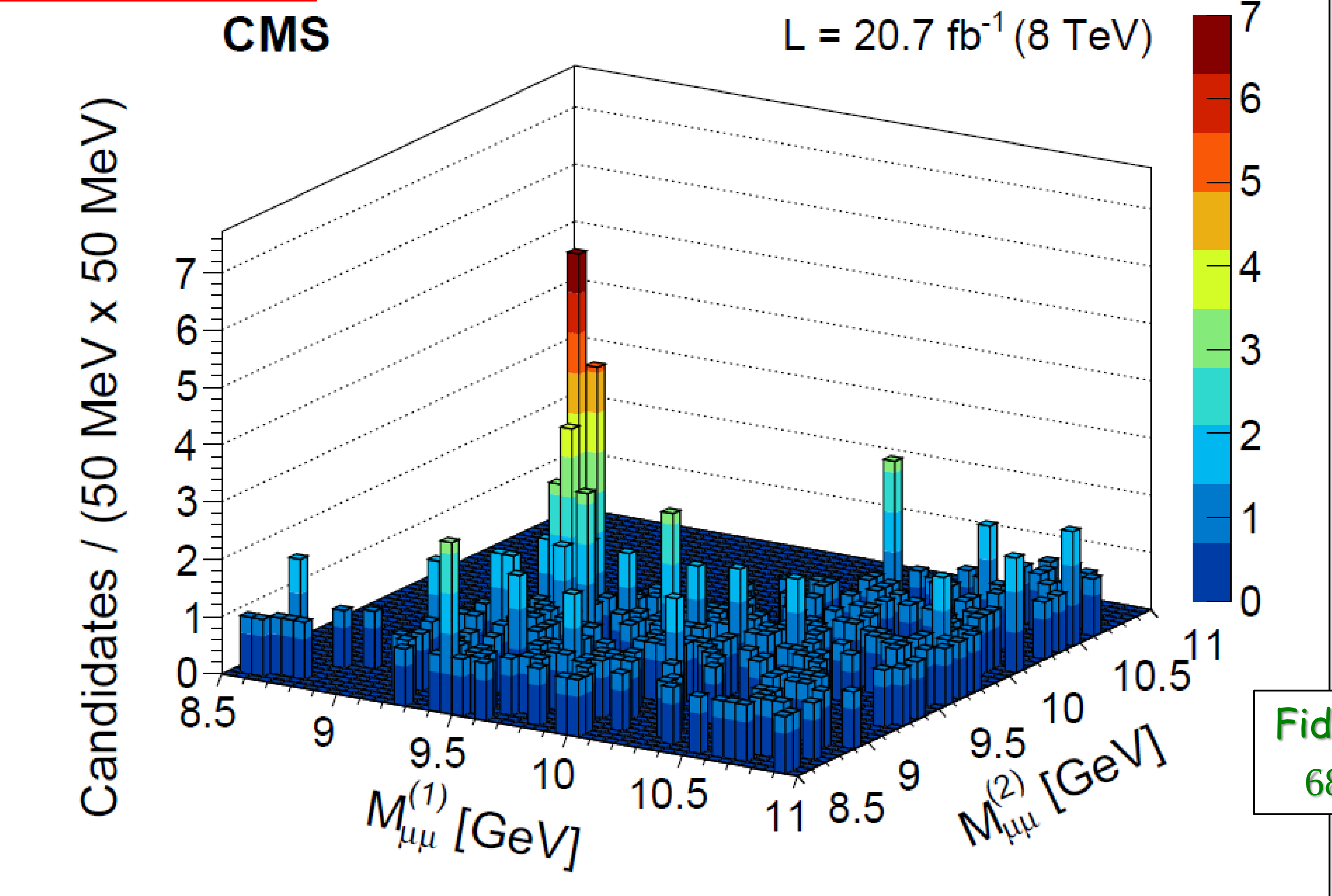
p-value: T_{cc}^+ vs DD = 0.02%

- *A bit inconclusive*
- *More data is needed*

Other $Q_1\bar{Q}_1Q_2\bar{Q}_2$ studies

$2\times\Upsilon$ CMS @ 8TeV

JHEP 1705 (2017) 013



Fiducial cross-section:

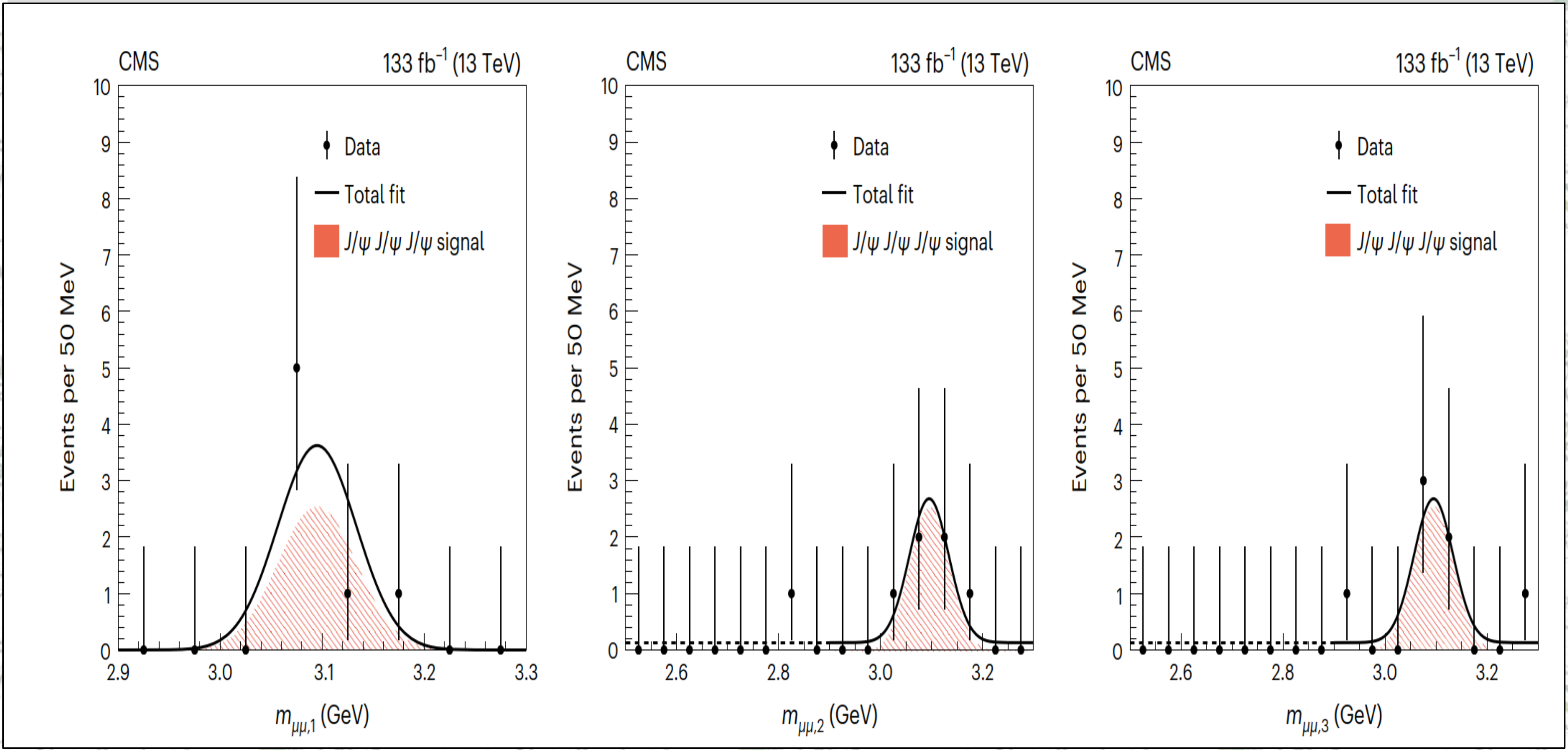
$68.8\pm12.7\pm7.4\pm2.8$ pb

σ_{eff} = 2.2–6.6mb

$cc\overline{c}\overline{c}\overline{c}$: $J/\psi J/\psi J/\psi$ by CMS

Nature Phys. (2013)

$5.0^{+2.6}_{-1.9}$ signal events, significance 6.7σ

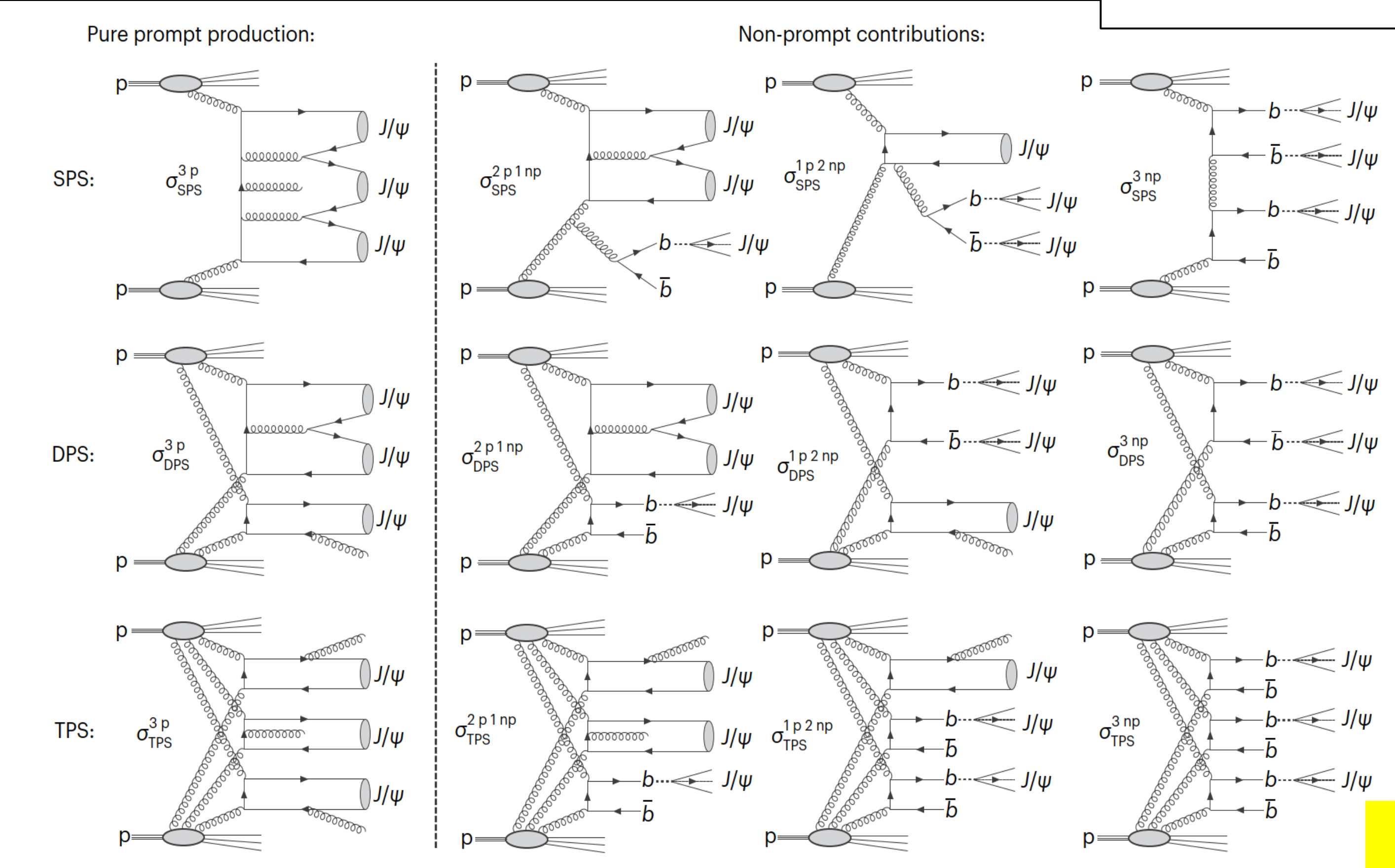


$ccc\overline{ccc}$: J/ψJ/ψJ/ψ by CMS

Nature Phys. (2013)

- Interpretation is *not* simple

$$\sigma_{\rm TPS}^{pp\to\psi_1\psi_2\psi_3+X} = \left(\frac{\mathfrak{m}}{3!}\right)\frac{\sigma_{\rm SPS}^{pp\to\psi_1+X}\,\sigma_{\rm SPS}^{pp\to\psi_2+X}\,\sigma_{\rm SPS}^{pp\to\psi_3+X}}{\sigma^2_{\rm eff,TPS}},$$

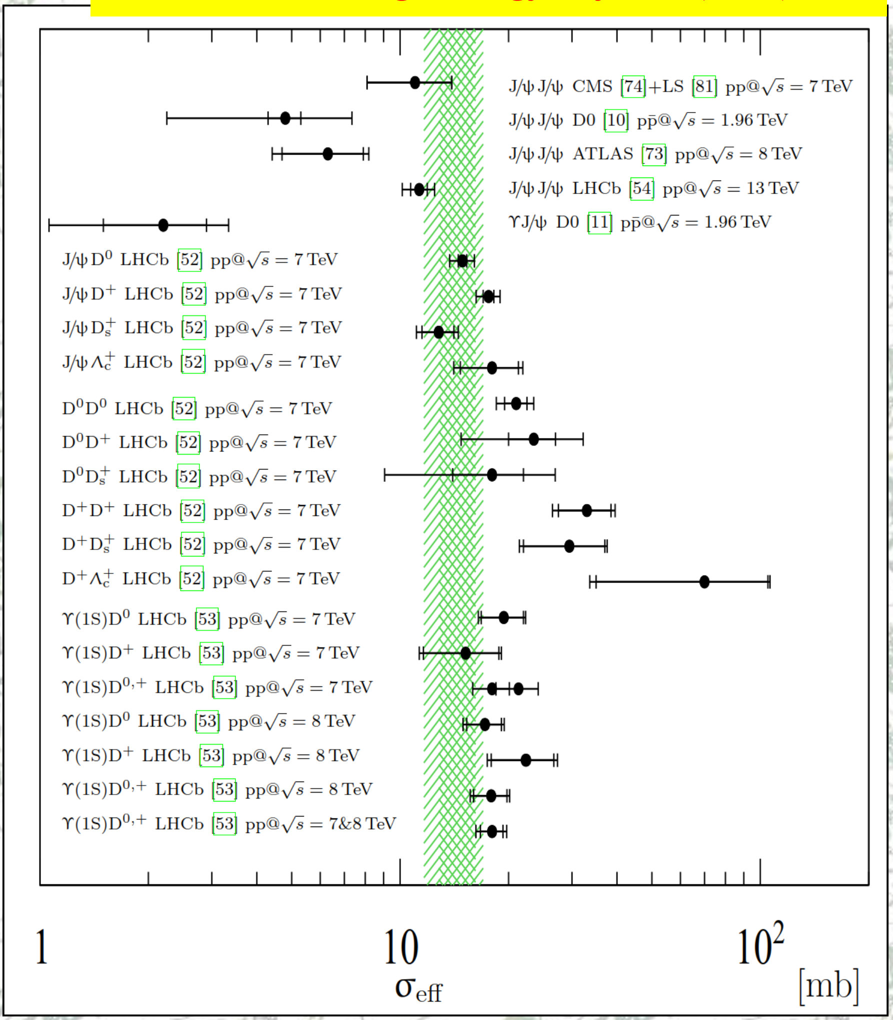


Sum of DPS and TPS

$Q_1\bar{Q}_1Q_2\bar{Q}_2$ conclusions

- Multiple production of heavy quarks in high energy hadron collisions is studied in many final states
- Some final states unambiguously DPS dominated
- Bright examples of pure SPS: B_c^+, Ξ_{cc}^{++}, T_{cc}^+, X(6900) show that for certain final states& kinematic regions SPS can play important role

Adv.Ser.Direct.High Energy Phys. 29 (2018) 141



$Q_1\overline{Q}_1Q_2\overline{Q}_2$ conclusions

- Multiple production of heavy quarks in high energy hadron collisions is studied in many final states
- Allows test of various QCD approaches:
  - color octet/color singlet, k_T-factorization …
- Important for understanding of proton structure
  - DPS, universality of σ_{eff}, violation of factorization, parton correlations
  - TPS – expected many results at LHC Run3
- Multiple production of heavy quarks in pA and AA interactions, where can be even more interesting!

Thank you!