RESOLVING THE SELEX-LHCB DOUBLE-CHARM BARYON CONFLICT: THE IMPACT OF INTRINSIC HEAVY-QUARK HADROPRODUCTION AND SUPERSYMMETRIC LIGHT-FRONT HOLOGRAPHIC QCD

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(most of results obtained in collaboration with
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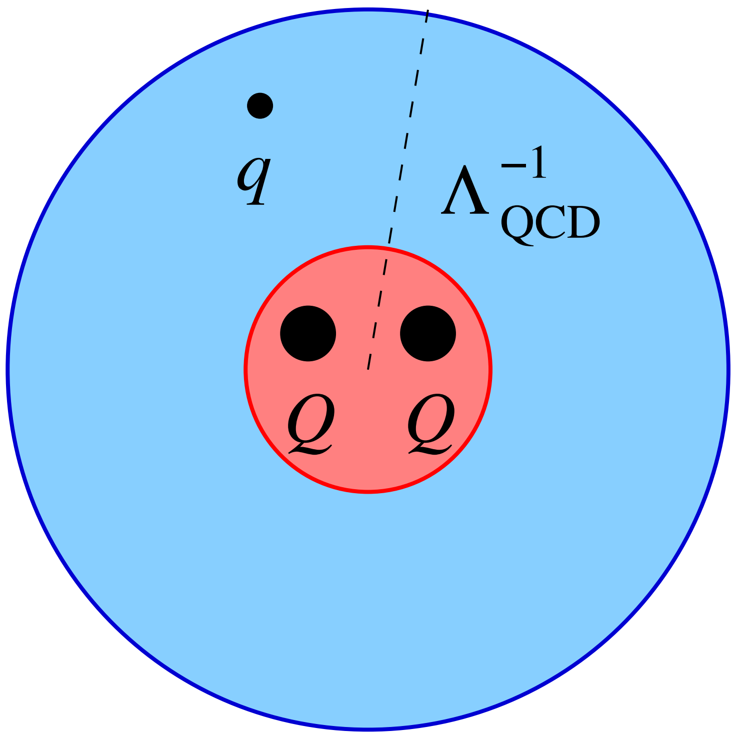
Production of the double charm-baryons in pQCD

The quark-antiquark annihilation and gluon-gluon fusion are the leading production mechanisms.



$$J^P = \frac{1}{2}^+$$

$$m(\Xi_{cc}^{+(+)}) \approx 3620\, MeV/c^2$$

A compact heavy diquark allows us to split production of the double charm baryon into two steps:

1) production of cc-diquark

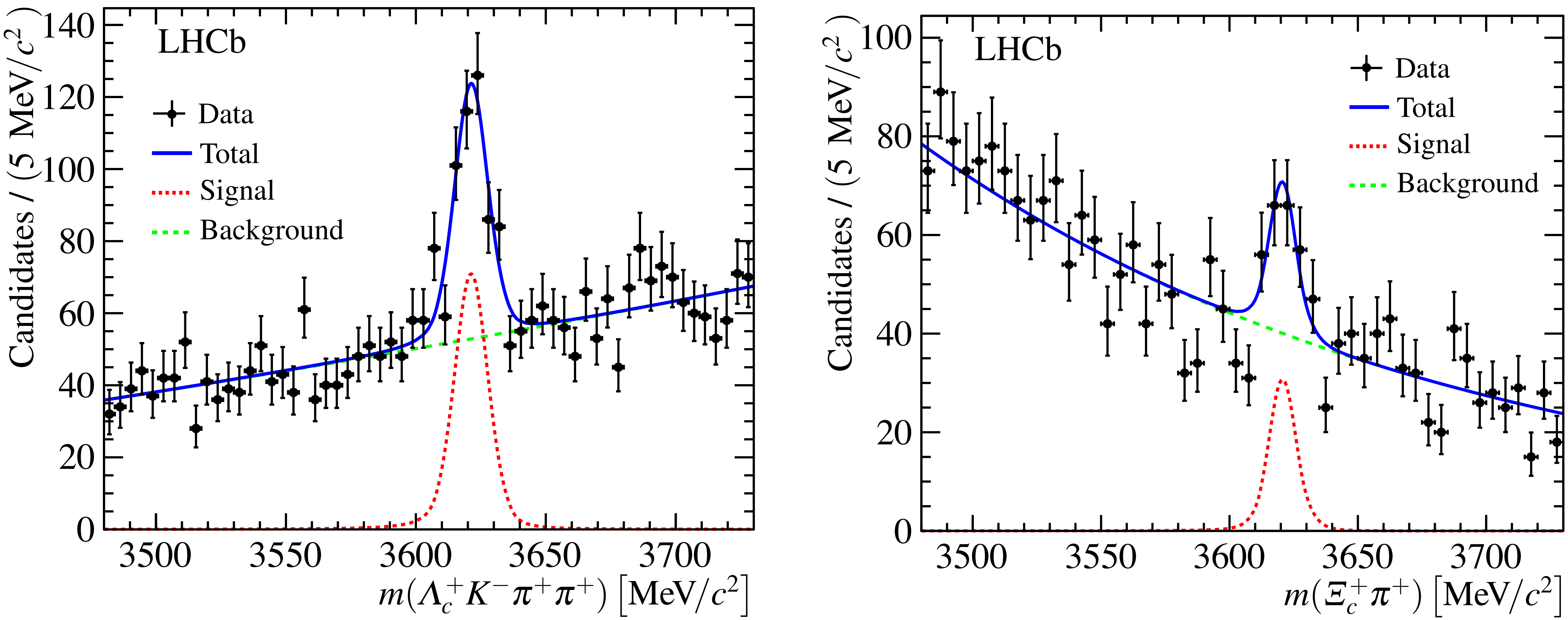
2) fragmentation of this diquark to a baryon.

$$g + g \to (cc) \to |(cc)u\rangle$$

$$|(cc)u\rangle \to r_{cc} : r_{QCD} \approx 0.39 : 1$$

The double charm-baryons at LHCb

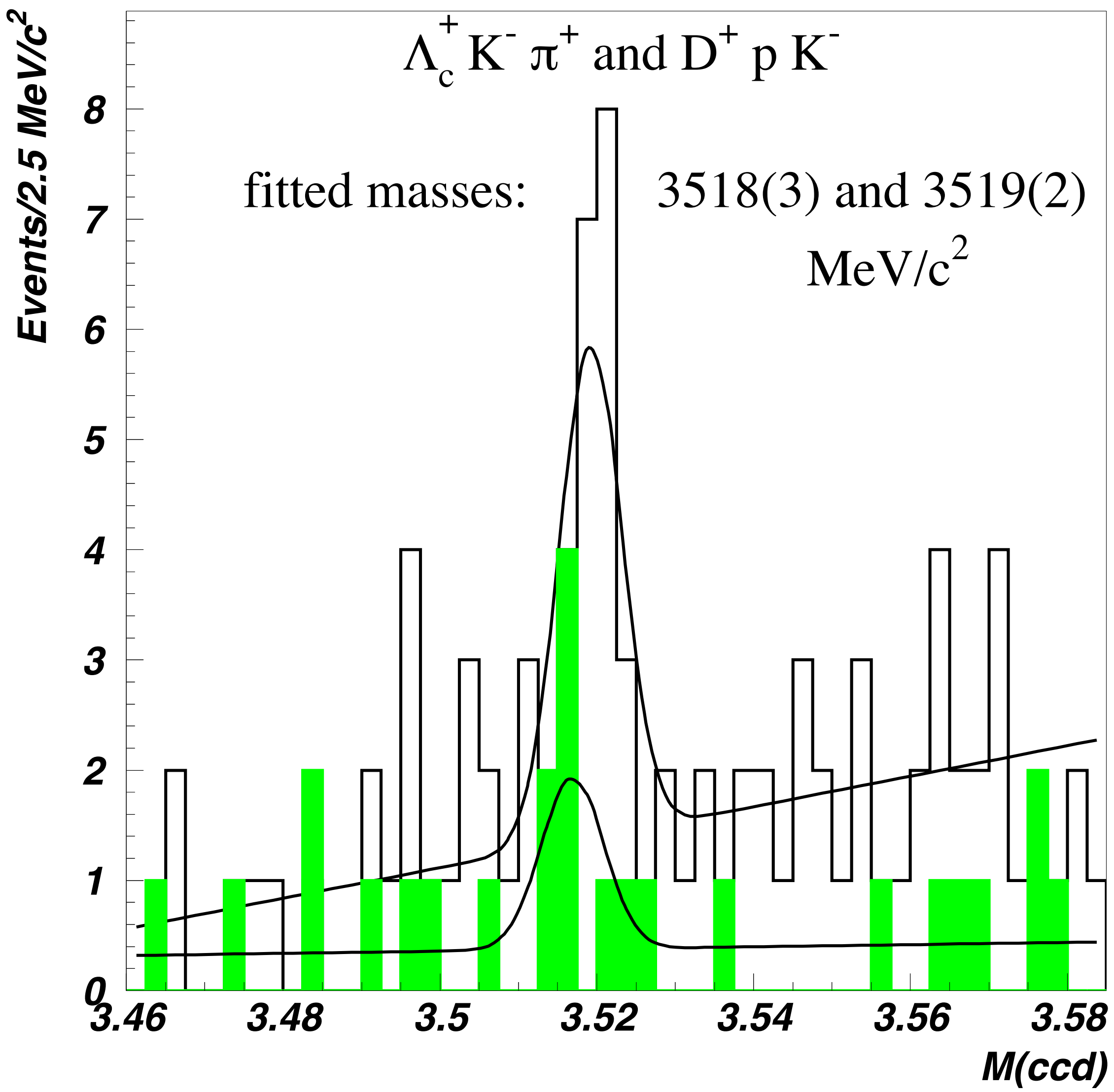
The LHCb collaboration recently published observation of $\Xi_{cc}^{++}(3620)$



$$m(\Xi_{cc}^{++})3621.40 \pm 0.72(stat) \pm 0.27(syst) \pm 0.14(\Lambda_c^+)$$

The double-charm baryons at SELEX

The first observation of the double-charm baryons was published by the SELEX collaboration fifteen years ago.



$$\Xi_{cc}^+(3519 \pm 2) \to \Lambda_c^+ K^- \pi^+$$

$$\Xi_{cc}^+(3518 \pm 3) \to p D^+ \pi^-$$

with statistical significances of 6.3σ and 4.8σ, respectively.

The mass difference with the LHCb state is 103 MeV, so LHCb and SELEX states canNOT be interpreted as an isospin doublet since one would expect a mass difference of isospin partners of only a few MeV.

The double-charm baryons at SELEX

The SELEX experiment was a fixed-target experiment utilizing the Fermilab negative charged beam and positive beam at 600 GeV/c to produce charm particles in a set of thin foil of Cu or in a diamond and operated in the kinetic region $x_F > 0.1$ (x_F : Feynman-x). The negative beam composition was about 50% Σ^- and 50% π^-. The positive beam was 90% protons.

Production rate:

SELEX: $$R^{\text{SELEX}}_{\Lambda_c^+} = \frac{\sigma(\Xi_{cc}^+) \cdot Br(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} = \frac{N_{\Xi_{cc}^+}}{\epsilon_+} \cdot \frac{\epsilon_{\Lambda_c^+}}{N_{\Lambda_c^+}} = (1.2 - 1.4) \times 10^{-2}$$

pQCD: $$R^{\text{pQCD}}_{\Lambda_c^+} \sim 10^{-4} - 10^{-5}$$

Kinematics fiatures:

$$\langle x_F \rangle \sim 0.33 \quad ; \quad \langle p_T \rangle \approx 1\,\text{GeV/c}$$

Such features are NOT amenable to perturbative QCD analysis

Production of J/ψ-pair at NA3

The NA3 experiment was a beam dump experiment at CERN utilizing pion beams at 150 GeV/c and 280 GeV/c and a 400 GeV/c proton beam to produce charm particles with incident on hydrogen and platinum targets in the kinematic region $x_F > 0$.

It is quite rare for two charmonium states to be produced in the same hadronic collision. However, the relative double to single rate measured by NA3 is

$$\frac{\sigma_{\psi\psi}}{\sigma_{\psi}} = (3 \pm 1) \times 10^{-4}$$

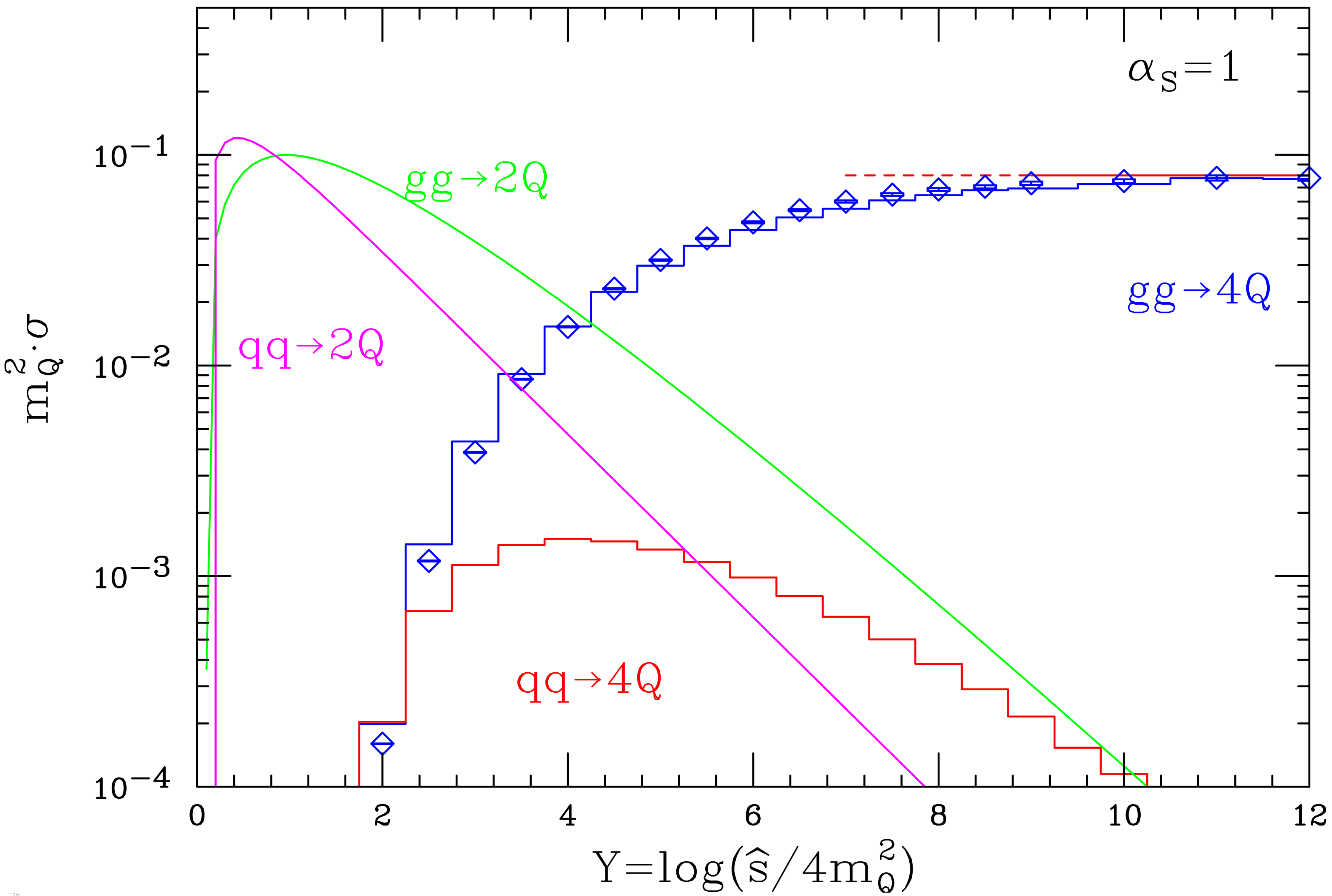
Another surprising feature are that the quarkonium pairs carried always very large fraction of the beam momentum:

$$x_{\psi\psi} > 0.6 \text{ at } 150 \text{ GeV/c}$$
$$x_{\psi\psi} > 0.4 \text{ at } 280 \text{ GeV/c}$$

Production rate of J/ψ-pair: NA3 vs LHCb

NA3: $\sigma(J/\psi + J/\psi)/\sigma(J/\psi) = (3 \pm 1) \times 10^{-4}$ $\quad Y_{\mathrm{NA3}} < 2.7$

LHCb: $\sigma(J/\psi + J/\psi)/\sigma(J/\psi) = (5.1 \pm 1.0 \pm 0.6^{+1.2}_{-1.0}) \times 10^{-4}$ $\quad Y_{\mathrm{LHCb}} < 14$



Partonic cross section for the production of two or four heavy quarks

Production ratio: The SELEX vs NA3

It is not possible to compare the SELEX and the NA3 data directly but we are able to compare the production ratios of four to two heavy quarks

$$R^{\mathrm{SELEX}} = R^{\mathrm{SELEX}}_{\Lambda_c^+} \times \frac{f(c \to \Lambda_c^+)}{f_{\Xi_{cc}}} \sim 10^{-3} - 10^{-2}$$

$$R^{\mathrm{NA3}} = \frac{\sigma(\psi\psi)}{\sigma(\psi)} \times \frac{f_{J/\psi}}{f^2_{\psi/\pi}} \sim 2 \times 10^{-2}$$

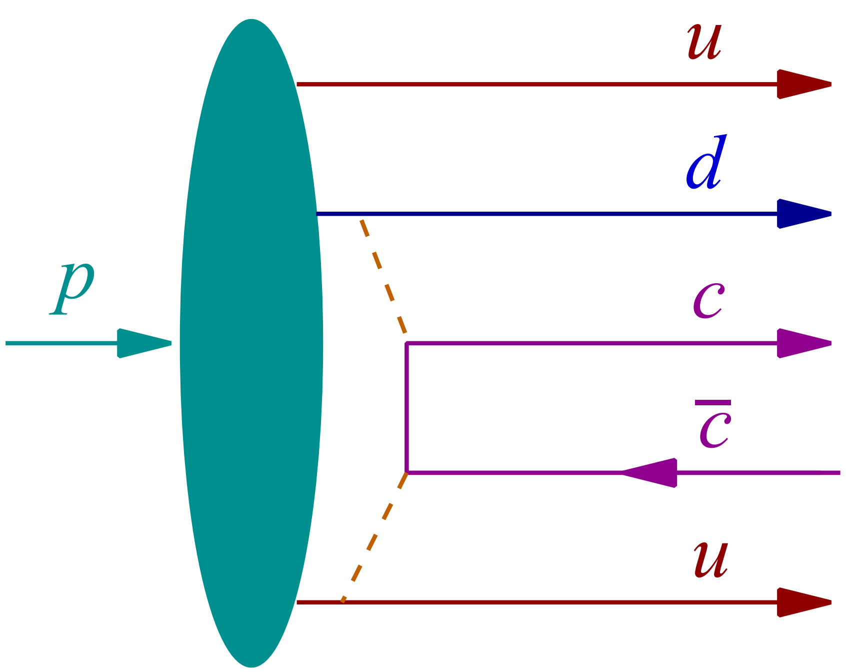
The ratio for the SELEX is comparable to the NA3 one or even less!

Intrinsic charm mechanism (BHPS model)

In the BHPS model the wavefunction of a hadron in QCD can be represented as a superposition of the Fock state fluctuations, e.g.

$$|p\rangle \propto |uud\rangle + |uudg\rangle + |uudQ\bar{Q}\rangle \ldots \qquad x_Q \propto (m_Q^2 + k_{T,Q}^2)^{1/2}$$

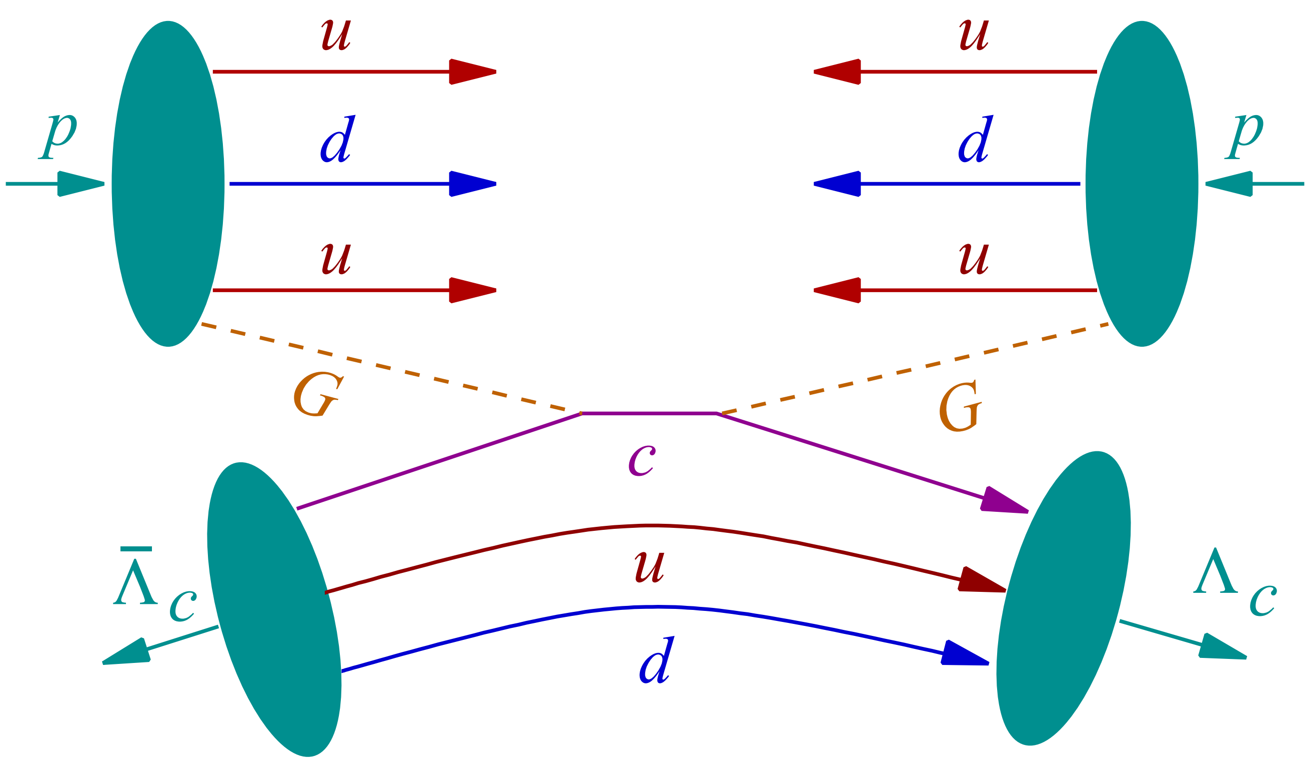
$$\frac{dP_{iQ}}{\prod_{i=1}^{n} dx_i d^2k_{T,i}} \propto \alpha_s^4(M_{Q\bar{Q}}) \frac{\delta\left(\sum_{i=1}^{n} \vec{k}_{T,i}\right)\delta\left(1-\sum_{i=1}^{n} x_i\right)}{\left(m_p^2 - \sum_{i=1}^{n} m_{T,i}^2/x_i\right)^2}$$



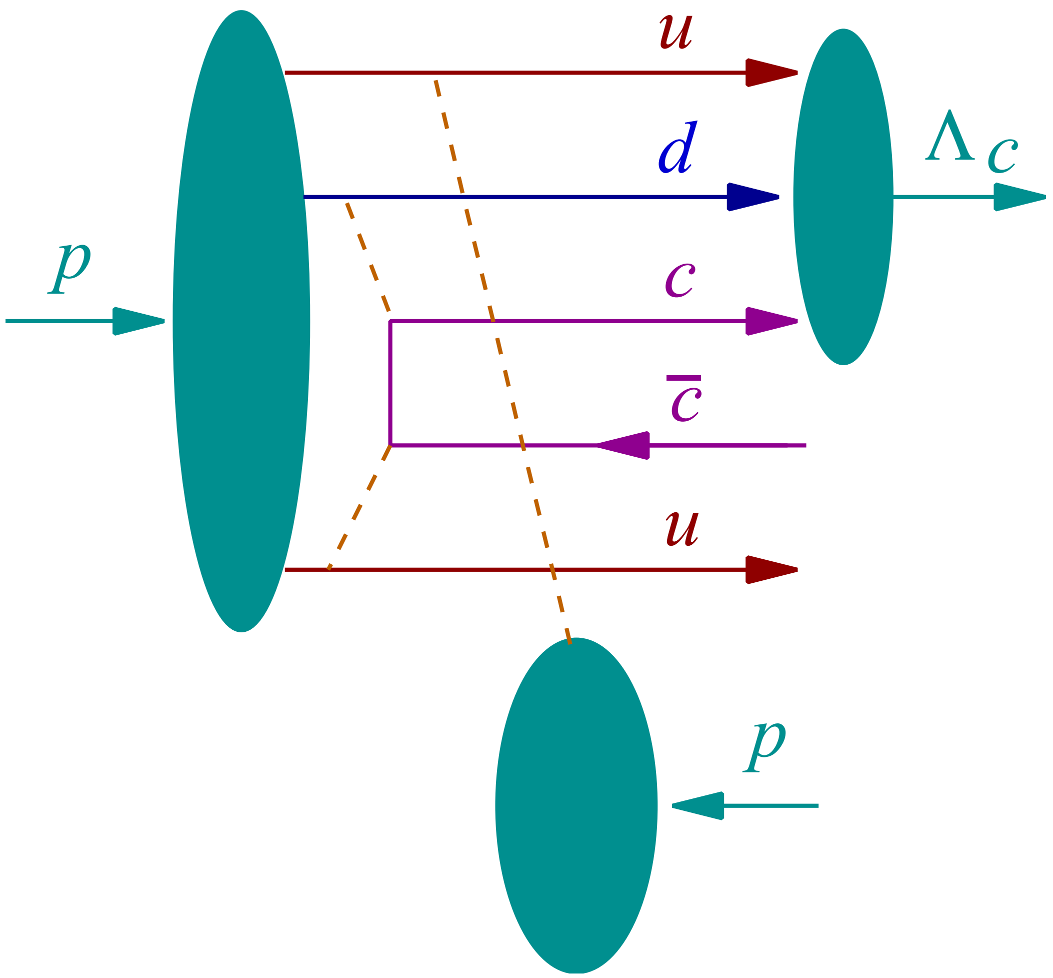
$$\sigma_{ic} = P_{ic} \cdot \sigma_{inel}$$

The existence of a non-perturbative intrinsic heavy quark component in the nucleon is a rigorous prediction of QCD!

Hadroproduction: pQCD vs intrinsic charm

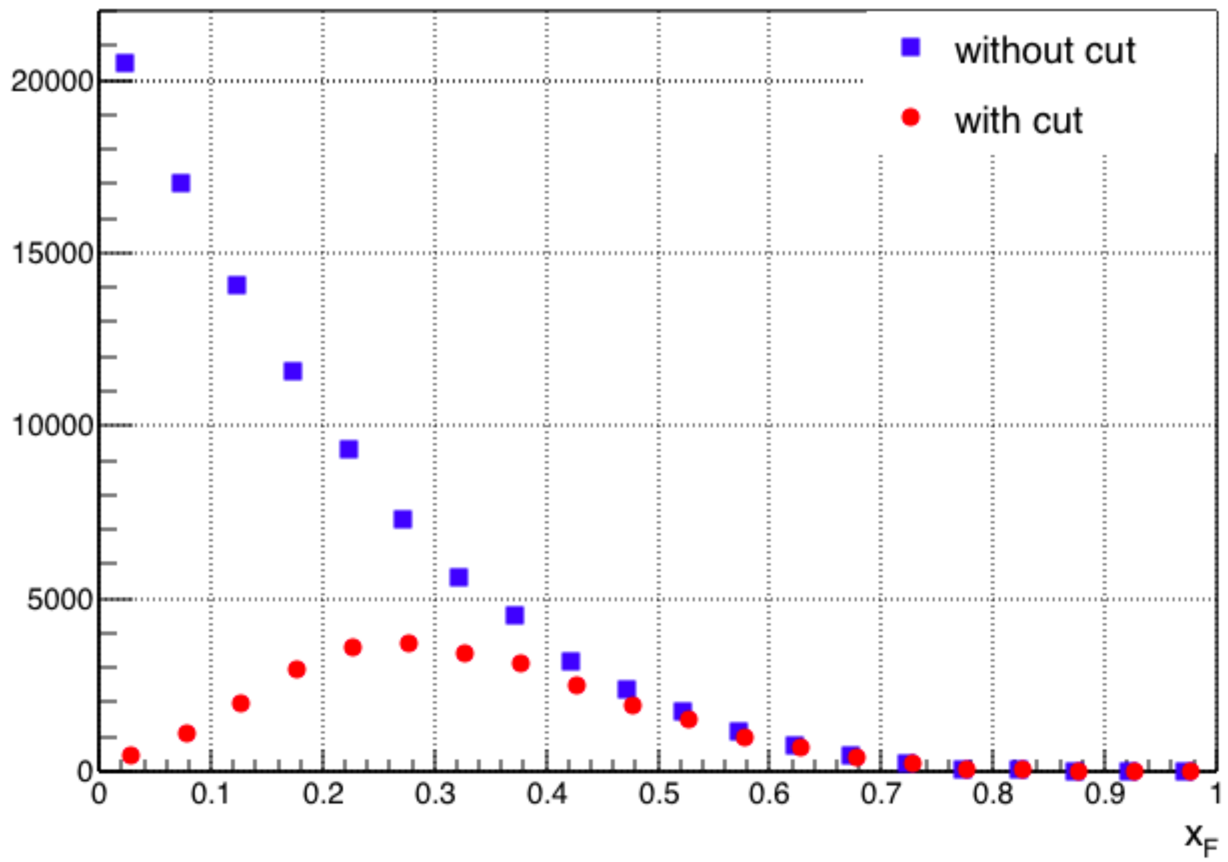


pQCD: gluon-gluon fusion

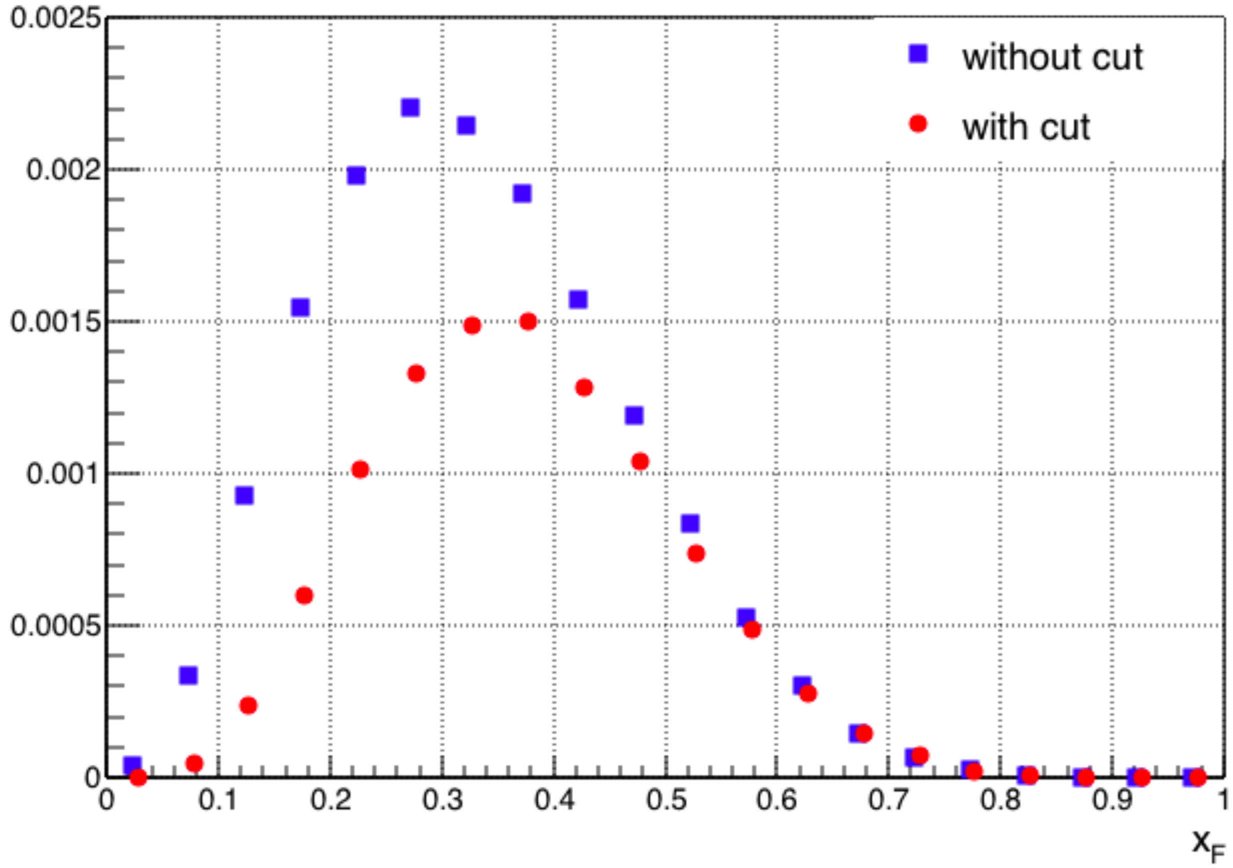


recoalescence

SELEX acceptance: pQCD vs Intrinsic Charm



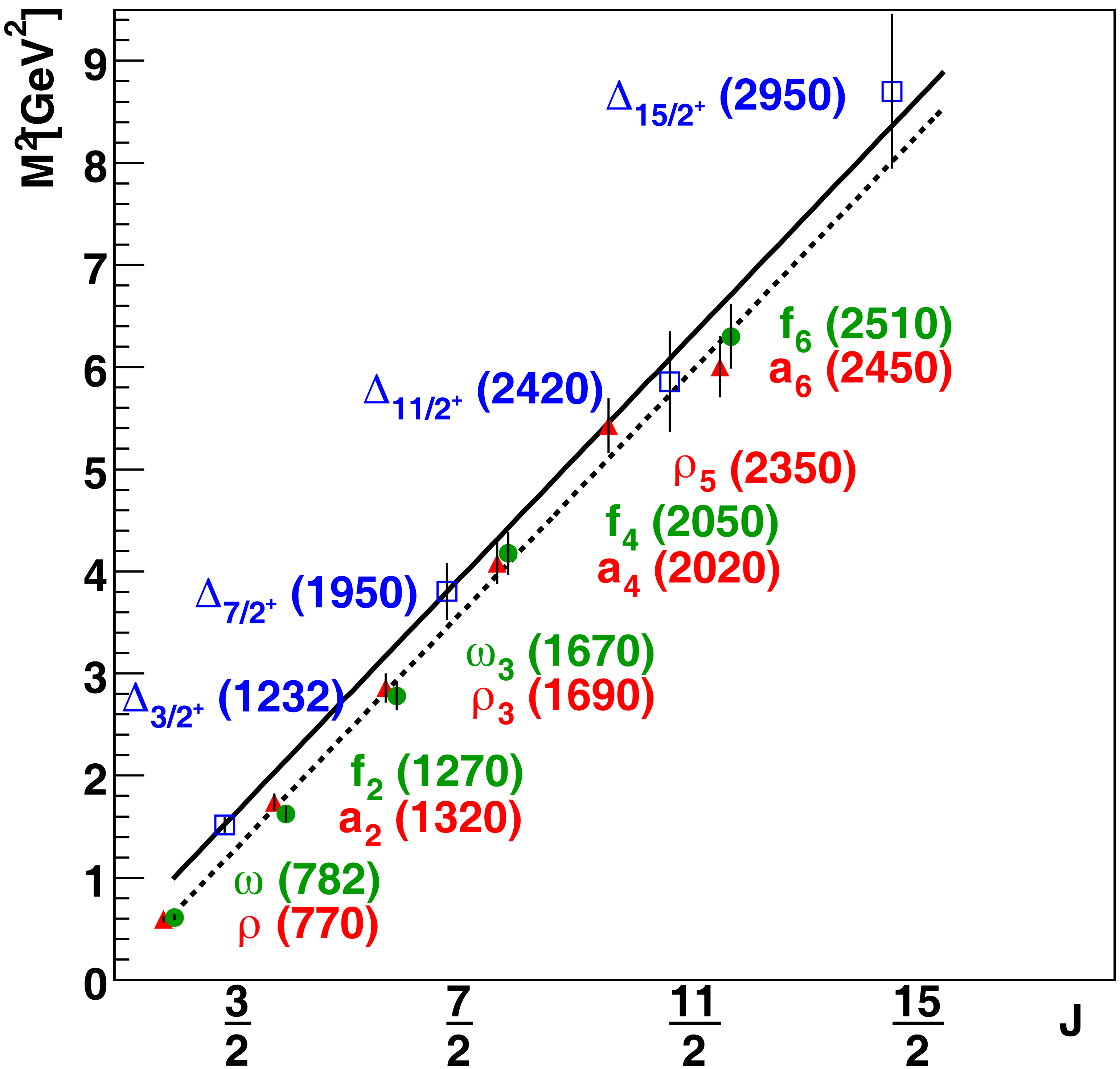
pQCD



Intrinsic Charm

Mesons and Baryons: Same Regge Slope $M^2 \propto J$!

M²[GeV²]

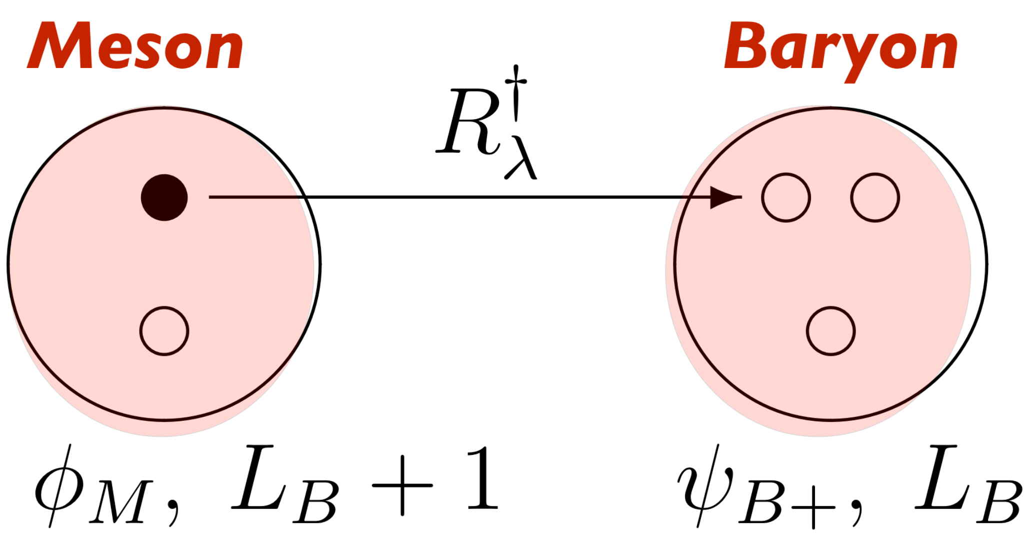


The leading Regge trajectory: Δ resonances with maximal J in a given mass range. Also shown is the Regge trajectory for mesons with J = L+S.

E. Klempt and B. Ch. Metsch

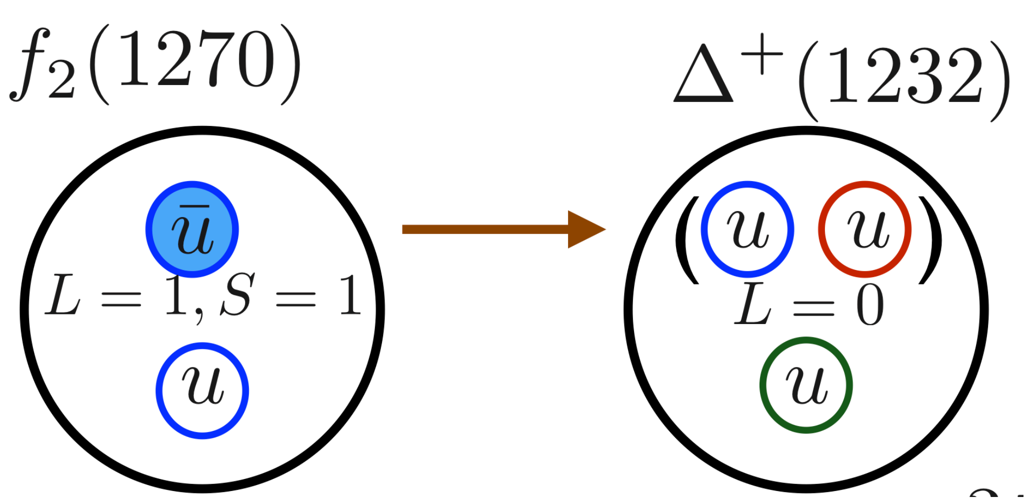
Mass of Ξ_{cc}^{+} in LFHQCD

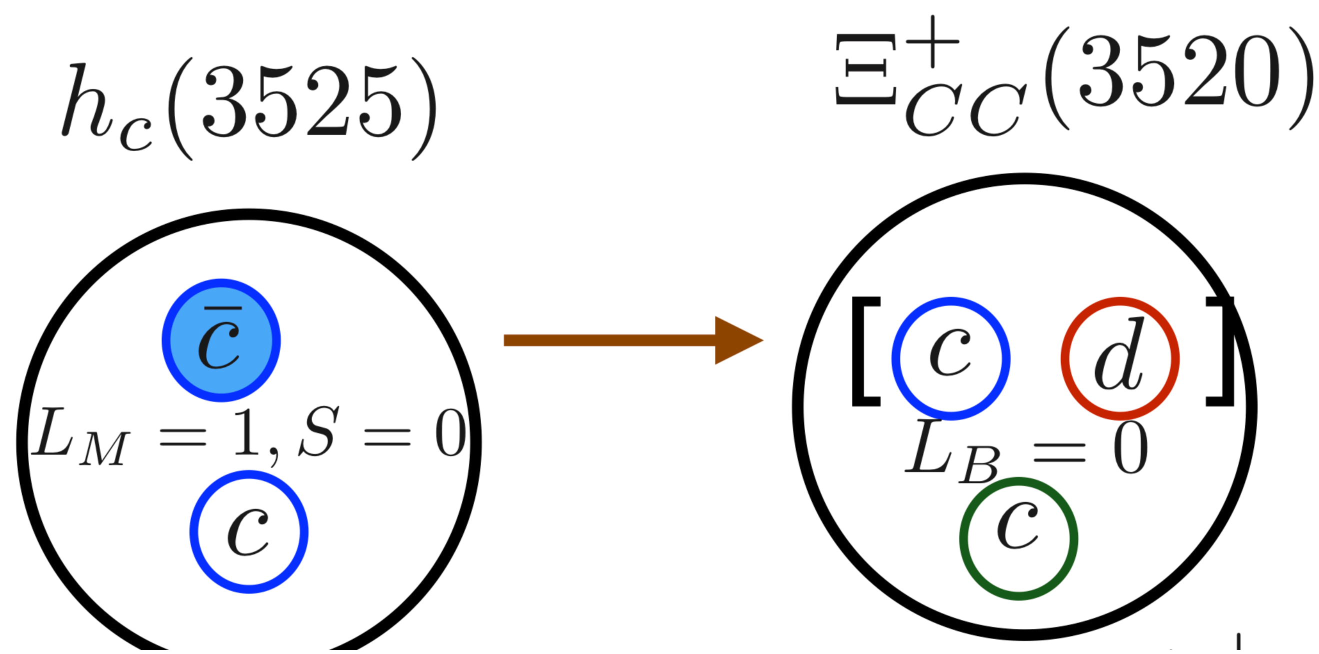
LFHQCD — light front holographic QCD



The LFHQCD is based on the idea of representation, for example, a pair of quarks as an anti-diquark.

$$R_\lambda^\dagger \quad \bar{q} \to (qq) \quad S=1$$
$$\bar{3}_C \to \bar{3}_C$$





[Brodsky, Dosch, Nielsen, de Teramond]

Meson			Baryon			Tetraquark		
q-cont	$J^{P(C)}$	Name	*q*-cont	J^P	Name	*q*-cont	$J^{P(C)}$	Name
$\bar{q}q$	0^{-+}	$\pi(140)$	—	—	—	—	—	—
$\bar{q}q$	1^{+-}	$h_1(1170)$	$[ud]q$	$(1/2)^+$	$N(940)$	$[ud][\bar{u}\bar{d}]$	0^{++}	$\sigma(500)$
$\bar{q}q$	2^{-+}	$\eta_2(1645)$	$[ud]q$	$(3/2)^-$	$N_{\frac{3}{2}^-}(1520)$	$[ud][\bar{u}\bar{d}]$	1^{-+}	—
$\bar{q}q$	1^{--}	$\rho(770),\ \omega(780)$	—	—	—	—	—	—
$\bar{q}q$	2^{++}	$a_2(1320),\ f_2(1270)$	$(qq)q$	$(3/2)^+$	$\Delta(1232)$	$(qq)[\bar{u}\bar{d}]$	1^{++}	$a_1(1260)$
$\bar{q}q$	3^{--}	$\rho_3(1690),\ \omega_3(1670)$	$(qq)q$	$(3/2)^-$	$\Delta_{\frac{3}{2}^-}(1700)$	$(qq)[\bar{u}\bar{d}]$	1^{-+}	$\pi_1(1600)$
$\bar{q}q$	4^{++}	$a_4(2040),\ f_4(2050)$	$(qq)q$	$(7/2)^+$	$\Delta_{\frac{7}{2}^+}(1950)$	$(qq)[\bar{u}\bar{d}]$	—	—
$\bar{q}s$	0^-	$K(495)$	—	—	—	—	—	—
$\bar{q}s$	1^+	$\bar{K}_1(1270)$	$[ud]s$	$(1/2)^+$	$\Lambda(1115)$	$[ud][\bar{s}\bar{q}]$	0^+	$K_0^*(1430)$
$\bar{q}s$	2^-	$K_2(1770)$	$[ud]s$	$(3/2)^-$	$\Lambda(1520)$	$[ud][\bar{s}\bar{q}]$	1^-	—
$\bar{s}q$	0^-	$K(495)$	—	—	—	—	—	—
$\bar{s}q$	1^+	$K_1(1270)$	$[sq]q$	$(1/2)^+$	$\Sigma(1190)$	$[sq][\bar{s}\bar{q}]$	0^{++}	$a_0(980)$
								$f_0(980)$
$\bar{s}q$	1^-	$K^*(890)$	—	—	—	—	—	—
$\bar{s}q$	2^+	$K_2^*(1430)$	$(sq)q$	$(3/2)^+$	$\Sigma(1385)$	$(sq)[\bar{u}\bar{d}]$	1^+	$K_1(1400)$
$\bar{s}q$	3^-	$K_3^*(1780)$	$(sq)q$	$(3/2)^-$	$\Sigma(1670)$	$(sq)[\bar{u}\bar{d}]$	2^-	$K_2(1820)$
$\bar{s}q$	4^+	$K_4^*(2045)$	$(sq)q$	$(7/2)^+$	$\Sigma(2030)$	$(sq)[\bar{u}\bar{d}]$	—	—
$\bar{s}s$	0^{-+}	$\eta'(958)$	—	—	—	—	—	—
$\bar{s}s$	1^{+-}	$h_1(1380)$	$[sq]s$	$(1/2)^+$	$\Xi(1320)$	$[sq][\bar{s}\bar{q}]$	0^{++}	$f_0(1370)$
								$a_0(1450)$
$\bar{s}s$	2^{-+}	$\eta_2(1870)$	$[sq]s$	$(3/2)^-$	$\Xi(1620)$	$[sq][\bar{s}\bar{q}]$	1^{-+}	—
$\bar{s}s$	1^{--}	$\Phi(1020)$	—	—	—	—	—	—
$\bar{s}s$	2^{++}	$f_2'(1525)$	$(sq)s$	$(3/2)^+$	$\Xi^*(1530)$	$(sq)[\bar{s}\bar{q}]$	1^{++}	$f_1(1420)$
								$a_1(1420)$
$\bar{s}s$	3^{--}	$\Phi_3(1850)$	$(sq)s$	$(3/2)^-$	$\Xi(1820)$	$(sq)[\bar{s}\bar{q}]$	—	—
$\bar{s}s$	2^{++}	$f_2(1640)$	$(ss)s$	$(3/2)^+$	$\Omega(1672)$	$(ss)[\bar{s}\bar{q}]$	1^+	$K_1(1650)$

Meson Baryon Tetraquark

New Organization of the Hadron Spectrum

M. Nielsen, sjb

Superpartners for states with one c quark

Meson			Baryon			Tetraquark		
q-cont	$J^{P(C)}$	Name	q-cont	J^P	Name	q-cont	$J^{P(C)}$	Name
$\bar{q}c$	0^-	$D(1870)$	—	—	—	—	—	—
$\bar{q}c$	1^+	$D_1(2420)$	$[ud]c$	$(1/2)^+$	$\Lambda_c(2290)$	$[ud][\bar{c}\bar{q}]$	0^+	$\bar{D}_0^*(2400)$
$\bar{q}c$	2^-	$D_J(2600)$	$[ud]c$	$(3/2)^-$	$\Lambda_c(2625)$	$[ud][\bar{c}\bar{q}]$	1^-	—
$\bar{c}q$	0^-	$\bar{D}(1870)$	—	—	—	—	—	—
$\bar{c}q$	1^+	$\bar{D}_1(2420)$	$[cq]q$	$(1/2)^+$	$\Sigma_c(2455)$	$[cq][\bar{u}\bar{d}]$	0^+	$D_0^*(2400)$
$\bar{q}c$	1^-	$D^*(2010)$	—	—	—	—	—	—
$\bar{q}c$	2^+	$D_2^*(2460)$	$(qq)c$	$(3/2)^+$	$\Sigma_c^*(2520)$	$(qq)[\bar{c}\bar{q}]$	1^+	$D(2550)$
$\bar{q}c$	3^-	$D_3^*(2750)$	$(qq)c$	$(3/2)^-$	$\Sigma_c(2800)$	$(qq)[\bar{c}\bar{q}]$	—	—
$\bar{s}c$	0^-	$D_s(1968)$	—	—	—	—	—	—
$\bar{s}c$	1^+	$D_{s1}(2460)$	$[qs]c$	$(1/2)^+$	$\Xi_c(2470)$	$[qs][\bar{c}\bar{q}]$	0^+	$\bar{D}_{s0}^*(2317)$
$\bar{s}c$	2^-	$D_{s2}(\sim 2860)?$	$[qs]c$	$(3/2)^-$	$\Xi_c(2815)$	$[sq][\bar{c}\bar{q}]$	1^-	—
$\bar{s}c$	1^-	$D_s^*(2110)$	—	—	—	—	—	—
$\bar{s}c$	2^+	$D_{s2}^*(2573)$	$(sq)c$	$(3/2)^+$	$\Xi_c^*(2645)$	$(sq)[\bar{c}\bar{q}]$	1^+	$D_{s1}(2536)$
$\bar{c}s$	1^+	$D_{s1}(\sim 2700)?$	$[cs]s$	$(1/2)^+$	$\Omega_c(2695)$	$[cs][\bar{s}\bar{q}]$	0^+	??
$\bar{s}c$	2^+	$D_{s2}^*(\sim 2750)?$	$(ss)c$	$(3/2)^+$	$\Omega_c(2770)$	$(ss)[\bar{c}\bar{s}]$	1^+	??

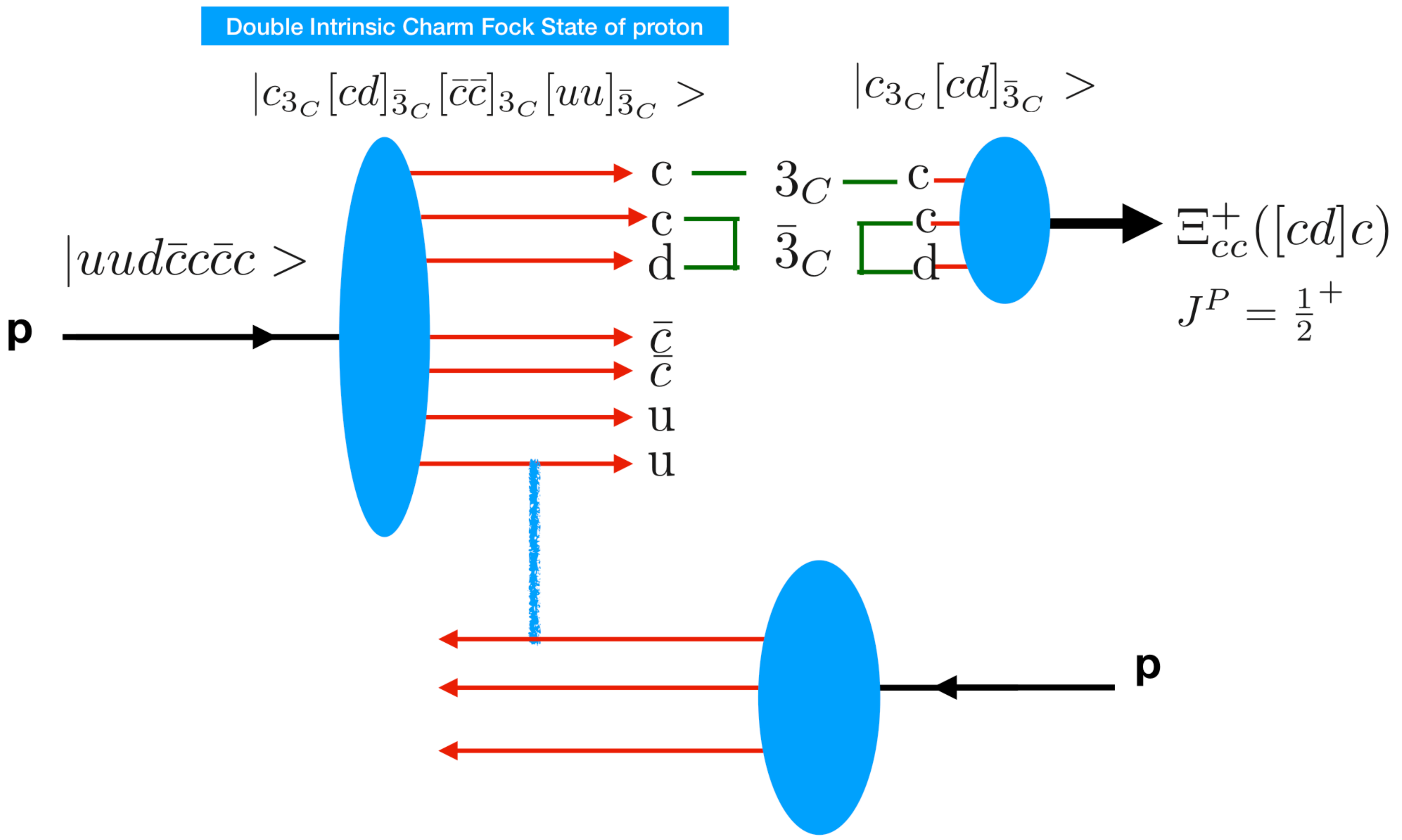
predictions

beautiful agreement!

M. Nielsen, sjb

Production of Ξ_{cc}^{+} baryon with Intrinsic charm

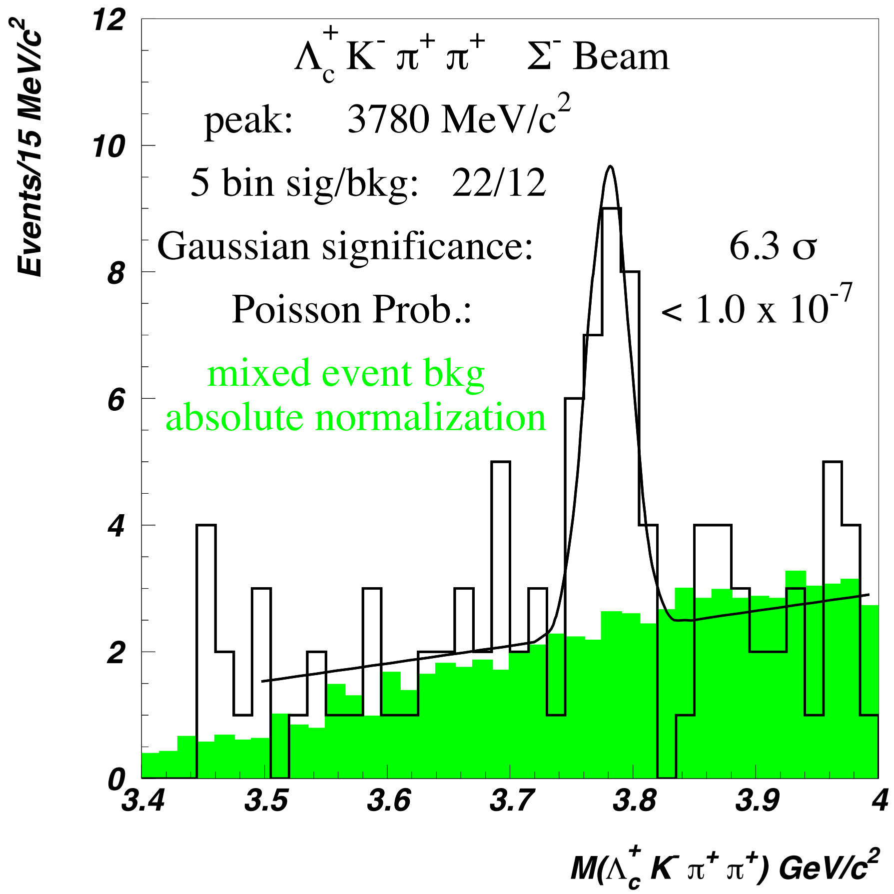
$$p + A \to \Xi(ccd)^{+} + X$$



[Stanley Brodsky's presentation, NSTAR-2107]

The $\Xi_{cc}^{++}(3780)$ SELEX state

At a few conferences the SELEX collaboration presented observation of $\Xi_{cc}^{++}(3780)$ state with statistical significance of 6.3σ.



By removing the slower part of the pion's, SELEX observed that roughly 50 % of the signal events above background decay weakly and 50 % decay strongly to $\Xi_{cc}^{++}(3780) \to \Xi_{cc}^{+}(3520) + \pi^{+}$. However, this is NOT possible for a single state.

$$\Xi_{cc}^{++}(3780) \to \Lambda_c^{+} K^{-} \pi^{+} \pi^{+}$$

Masses and decay properties of $\Xi_{cc}^{++}(3780)$ state

The SUSY LFHQCD prediction for the baryon mass spectra is given by the simple formula: $M^2 \propto \lambda(n + L + 1)$; $\sqrt{\lambda} \approx 0.52 GeV$

Assuming $\Xi_{cc}^{++}(3780)$ to be an excited state of $\Xi_{cc}^{+}(3520)$:

State (n,L)	Mass (MeV/c^2)
$\lvert[uc]c\rangle_{3/2}(1,0)$	3730 ± 100
$\lvert(uc)c\rangle_{3/2}(0,1)$	3730 ± 100

The $\lvert[uc]c\rangle_{3/2}(1,0)$ state is more preferable for the weak decay.

In contrast to that $\lvert(uc)c\rangle_{3/2}(0,1)$ includes a D^*-meson-like state leading to the strong decay.

SELEX Double Charm Isospin splitting problem

The SELEX Collaboration has reported a very large isospin splitting of double-charm baryons. The mass splittings were reported to be up to 21 MeV.

The theoretical analysis of the isospin splitting of the SELEX states implies that double charm baryons are very compact, i.e. the light quark must be very close to the two heavy quarks .

[Brodsky, Guo, Hanhart and Meissner, 2012]

The pQCD processes lead us to the following internal scale structure:

$$|(cc)u\rangle \to r_{cc} : r_{QCD} \approx 0.39 : 1$$

In contrast to that the intrinsic charm and LFHQCD lead us to the following:

$$|[dc]c\rangle \to \lambda_{[qc]} \sim 1/m_{[qc]} \approx 0.5$$

Lifetime: SELEX vs LHCb

The LHCb measurements of the lifetime lighted up significant discrepancy with the SELEX result:

Experiment	State	lifetime (fs)
LHCb	Ξ_{cc}^{++}	$256^{+24}_{-22} \pm 14$
SELEX	Ξ_{cc}^{+}	$< 33\,(\text{at } 90\ \%\ \text{C.L.})$

$$\tau(\Xi_{cc}^{++})/\tau(\Xi_{cc}^{+}) \approx 2.5 - 4$$

$$\tau(\Xi_{cc}^{+}) \approx 60 - 100\,\text{fs}$$

Ω_c^0 lifetime: fixed-target experiments vs LHCb

There is also a huge discrepancy between LHCb and fixed-target experiments:

LHCb:

$$\tau(\Omega_c^0) = 268 \pm 24 \pm 10 \pm 2\,\text{fs}$$

Fixed-target experiments:

Experiment	lifetime (fs)	Number of events
FOCUS	$72 \pm 11 \pm 11$	64
WA89	$55^{+13}_{-11}{}^{+18}_{-23}$	86
E687	$86^{+27}_{-20} \pm 28$	25
SELEX	$65 \pm 13 \pm 9$	83

Summary

- Using both theoretical and experimental arguments, we can see that the SELEX and the LHCb results for the production of doubly charmed baryons can both be correct.
  - The data for the double J/psi production observed by the NA3 experiment strongly complement the SELEX production rate for $\Xi_{cc}^{+}(3520)$ state.
  - The LFHQCD predicts the correct masses for the SELEX states
    - As well as the decay properties of $\Xi_{cc}^{++}(3780)$

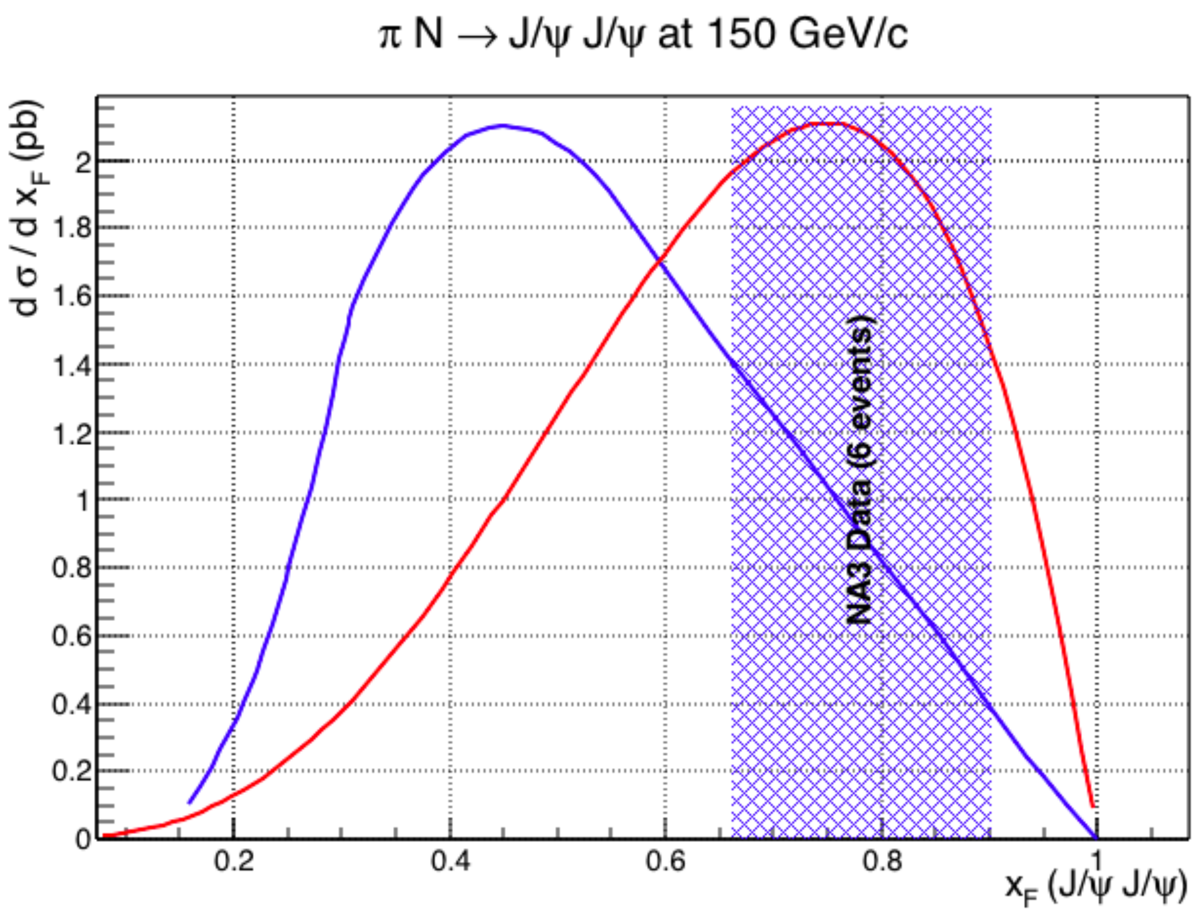
- At this moment there are NO theoretical or experimental results against the SELEX double-charm data.

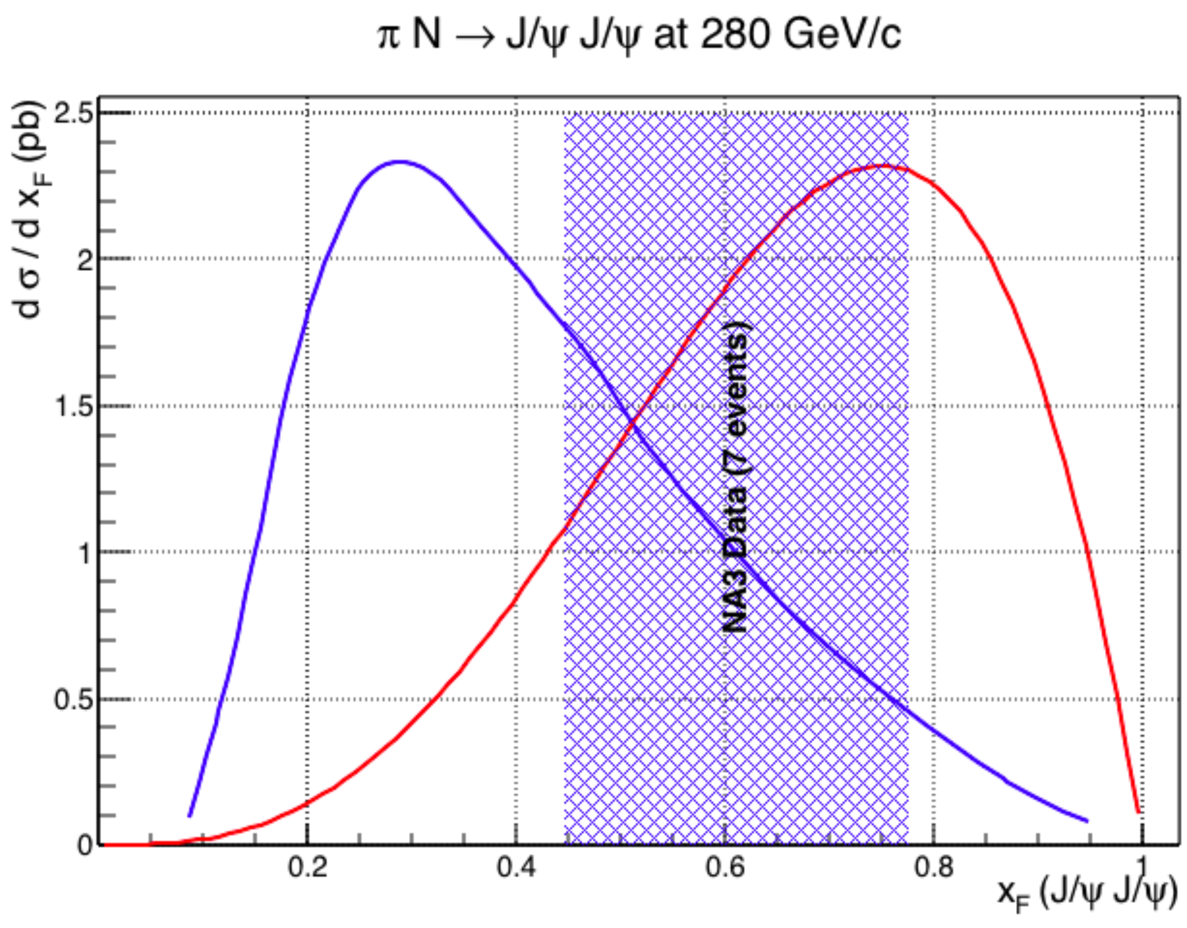
Thank you for the invitation!

Back Up

back up

Kinematics of J/ψ-pair at NA3





The blue curve presents the pQCD motivated x_F distribution (Ecclestone and Scott, 1983).
The red curve shows this distribution from the Intrinsic charm.