Hadron decays

- **QCD** respects quark flavors
- **QED** respects strangeness, charm, beauty, and the third component of strong isospin (I_3)
- **WI** violate all quark flavors:

— «Ground state» hadrons (low mass pseudoscalar mesons and spin 1/2 baryons) decay mostly by weak or (in a few cases) electromagnetic interactions

—Excited states (vector mesons, spin 3/2 baryon, higher radial or orbital exictations) decay strongly to lower mass hadrons

- Isospin relations help predicting their decay rates. Examples:
  - the Δ(1230) baryon
  - the D*(2010) meson

The Δ(1230) Baryon

Strong Isospin

	Composition	J^P	I	I_3	
Δ^+	uud	$3/2^+$	3/2	+1/2	
p	uud	$1/2^+$	1/2	1/2	} N doublet partners
n	udd	$1/2^+$	1/2	-1/2	
π^+	$u\bar{d}$	0^-	1	+1	} π triplet partners
π^0	$\frac{1}{\sqrt{2}}(-u\bar{u}+d\bar{d})$	0^-	1	0	

Let's use Strong Isospin I to compare the transition rates

$$R = \Gamma(\Delta^+ \to n\pi^+)/\Gamma(\Delta^+ \to p\pi^0)$$

$$|n\pi^+\rangle = |\tfrac{1}{2}, -\tfrac{1}{2}\rangle \otimes |1, 1\rangle = -\sqrt{\tfrac{1}{3}}\,|\tfrac{3}{2}, \tfrac{1}{2}\rangle + \sqrt{\tfrac{2}{3}}\,|\tfrac{1}{2}, \tfrac{1}{2}\rangle$$

Clebsch-Gordan coefficients

(see last page)

$$|p\pi^0\rangle = |\tfrac{1}{2}, \tfrac{1}{2}\rangle \otimes |1, 0\rangle = \sqrt{\tfrac{2}{3}}\,|\tfrac{3}{2}, \tfrac{1}{2}\rangle + \sqrt{\tfrac{1}{3}}\,|\tfrac{1}{2}, \tfrac{1}{2}\rangle$$

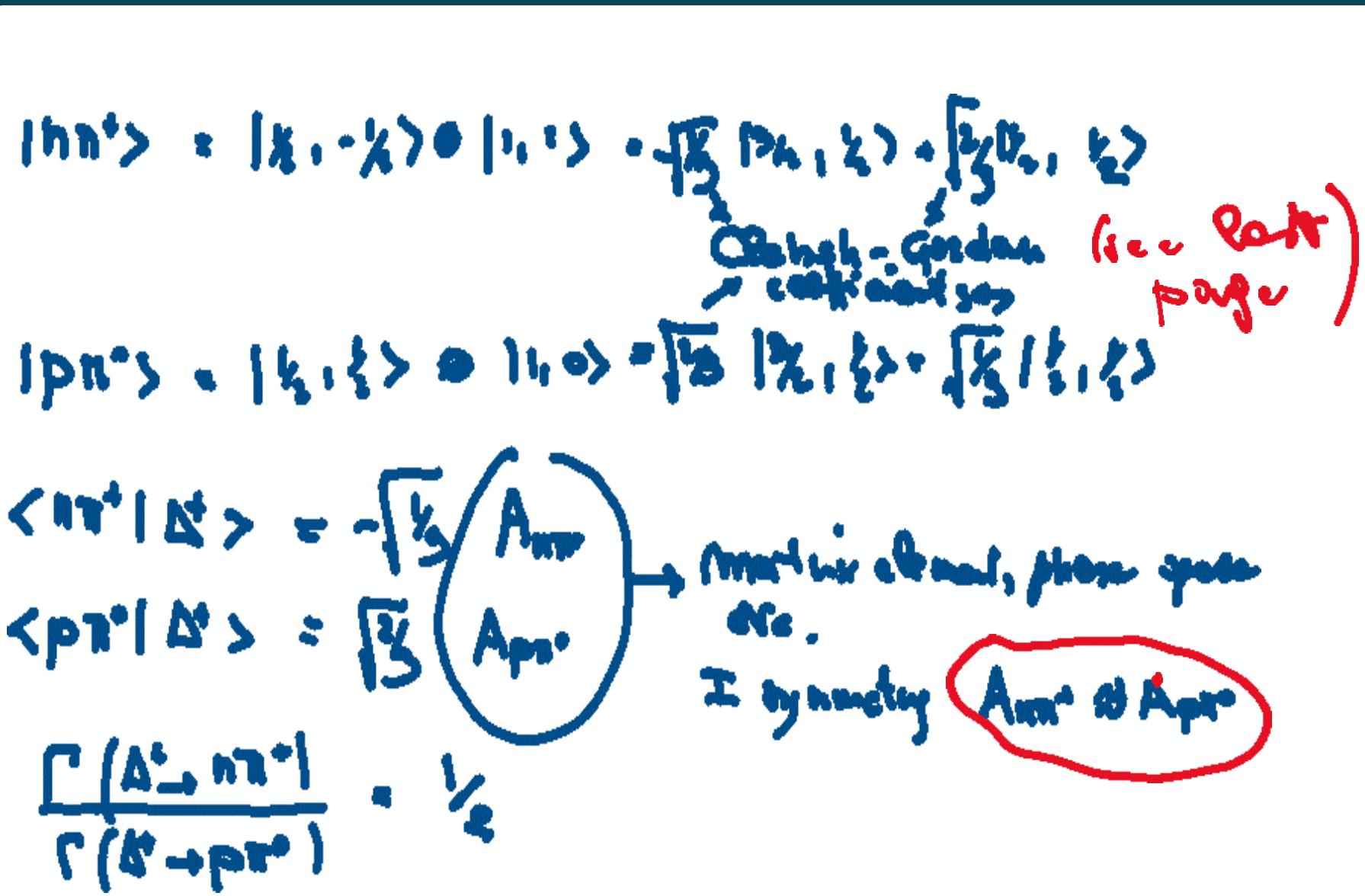
$$\langle n\pi^+|\Delta^+\rangle = -\sqrt{\tfrac{1}{3}}\,A_{n\pi^+}$$

$$\langle p\pi^0|\Delta^+\rangle = \sqrt{\tfrac{2}{3}}\,A_{p\pi^0}$$

→ matrix element, phase space etc.

I symmetry $A_{n\pi^+} \approx A_{p\pi^0}$

$$\frac{\Gamma(\Delta^+ \to n\pi^+)}{\Gamma(\Delta^+ \to p\pi^0)} = \frac{1}{2}$$



The D* mesons

D^{*+}	2010	$c\bar{d}$ ↑↑	1^-	½	½	I Partners
D^{*0}	2007	$c\bar{u}$ ↑↑	1^-	½	-½	
D^+	1870	$c\bar{d}$ ↑↓	0^-	½	½	I Partners
D^0	1864	$c\bar{u}$ ↑↓	0^-	½	-½	

$$R^+ = \Gamma(D^{*+} \to D^+ \pi^0) / \Gamma(D^{*+} \to D^0 \pi^+)$$

$$R^0 = \Gamma(D^{*0} \to D^+ \pi^-) / \Gamma(D^{*0} \to D^0 \pi^0)$$

R1

$$|D^+\pi^0\rangle = \sqrt{2/3}\,|3/2,\ 1/2\rangle - \sqrt{1/3}\,|1/2,\ 1/2\rangle$$

$$|D^0\pi^+\rangle = \sqrt{1/3}\,|3/2,\ 1/2\rangle + \sqrt{2/3}\,|1/2,\ 1/2\rangle$$

$$\left.\begin{aligned} A(D^+\pi^0) &\propto -\sqrt{1/3} \\ A(D^0\pi^+) &\propto \sqrt{2/3} \end{aligned}\right\} \quad \boxed{R_1 = 1/2}$$

$D^0\pi^+$	(67.7 ±0.5) %
$D^+\pi^0$	(30.7 ±0.5) %
$D^+\gamma$	(1.6 ±0.4) %

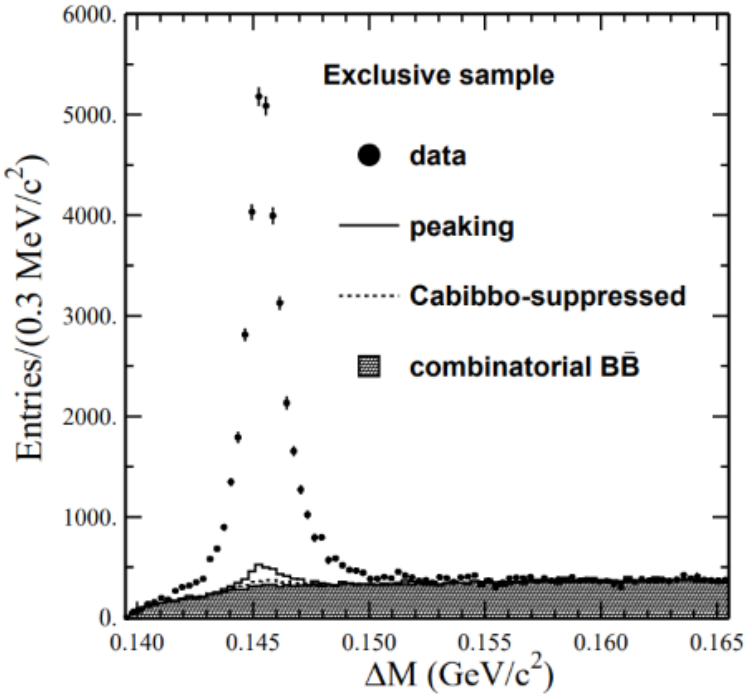
Good agreement. Deviations due to differences in kinematics, Coulomb scattering

A note on Phase Space

$$Q = M(D^*) - M(D) - M(\pi) \simeq 6\ MeV$$

Very small Phase Space:

- D and π are almost at rest in the D* rest frame
- Events are tagged by $\Delta M = M(D^*) - M(D)$ (plot)



R2

We would expect a similar relation to hold for R_2. However

$M(\pi^-) + M(D^+) = 2010\ \text{MeV} > M(D^{*0})$

$M(\pi^0) + M(D^0) = 2000\ \text{MeV} < M(D^{*0})$

$D^{*0} \to D^+ \pi^-$ is forbidden by kinematics!

$Q(D^{*0} \to D^0 \pi^0) = 7\ \text{MeV}$

Significant contribution from the e.m. decay

$D^{*0} \to D^0 \gamma$

PDG

$Br(D^0 \pi^0) = 64.7 \pm 0.9$

$Br(D^0 \gamma) = 35.3 \pm 0.9$

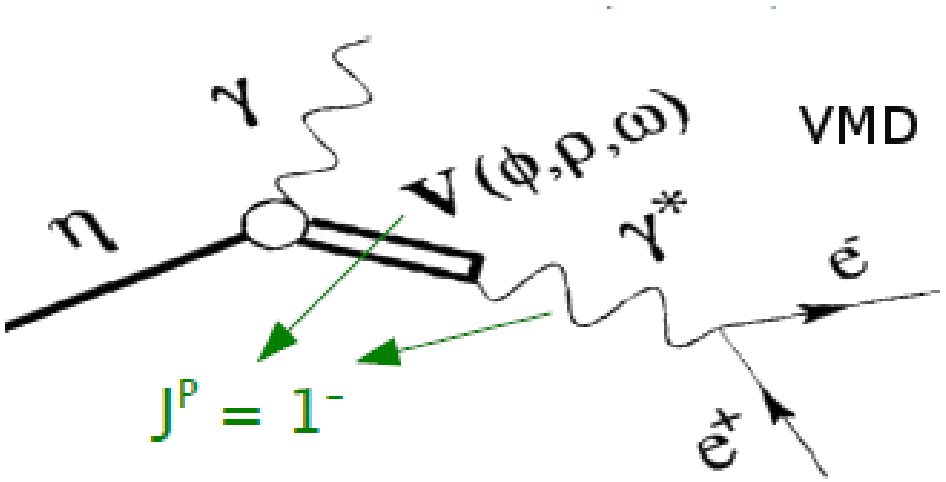
Resonances in e^+e^- collisions

- Vector mesons, CP eigenstates
  - V= (ρ,ω,Φ, ψ, Υ), $\mathbf{J^{CP} = 1^{--}}$ (same as γ)
- In e^+e^- colliders they can be directly produced :
  - observed as resonances in formation
- Focus on :
  -

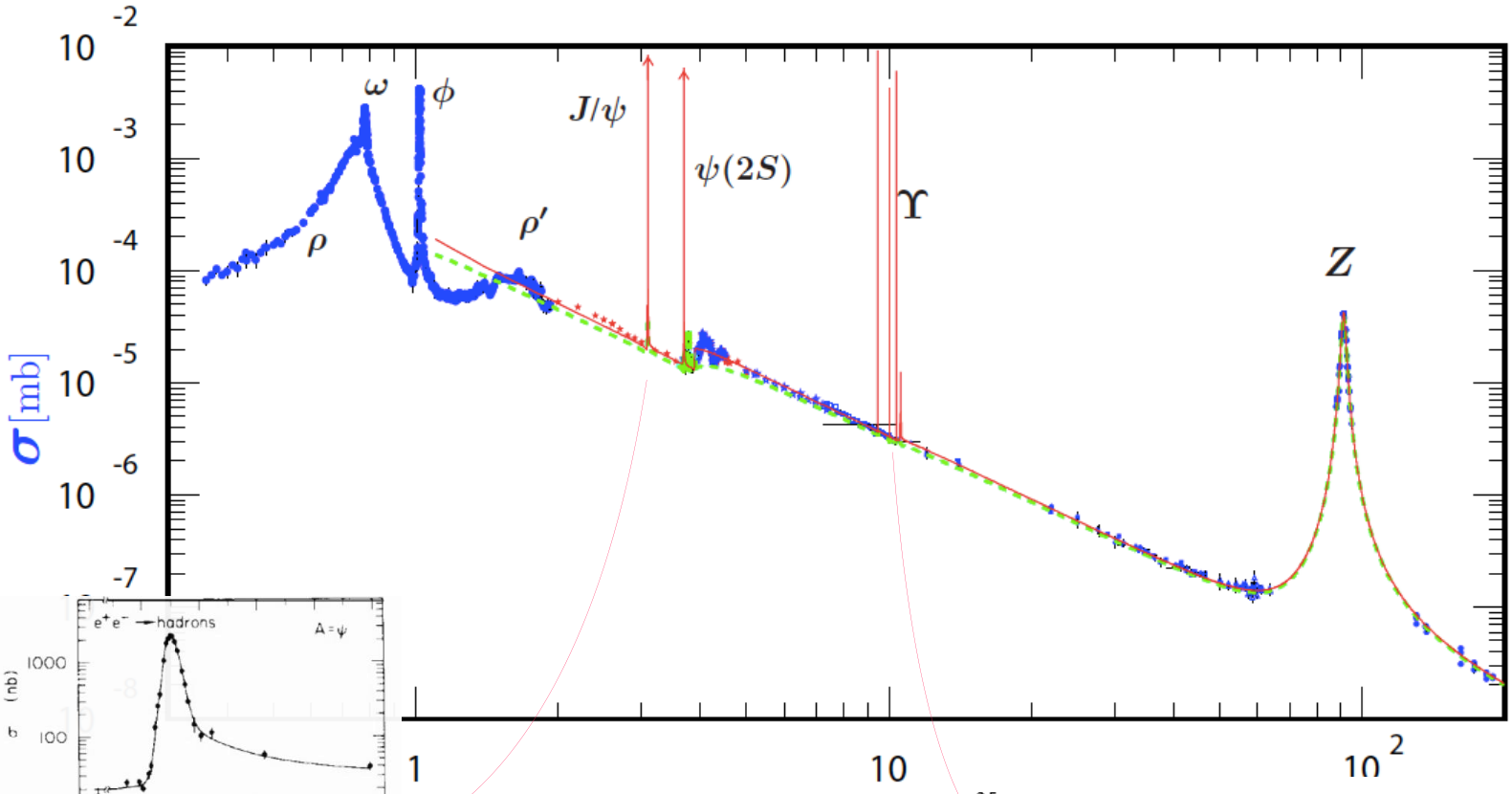
$$|\Upsilon(nS)> \; = \; |b\bar{b}>$$

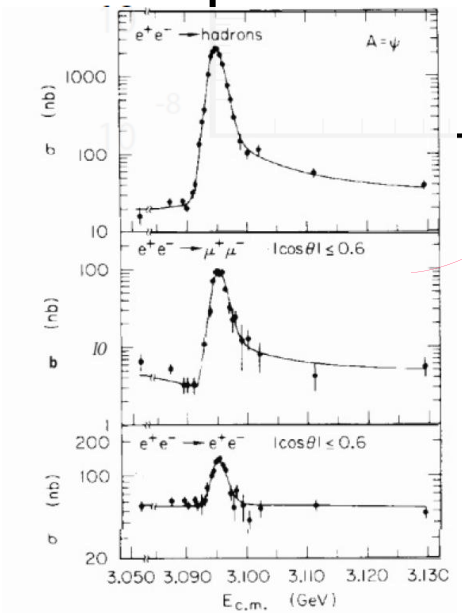
$$|\Phi> \; = \; |s\bar{s}>$$

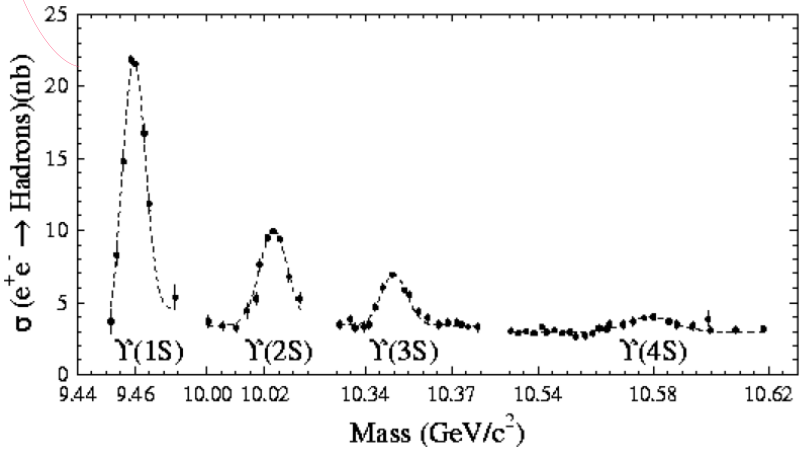
$$|\psi(nS)> \; = \; |c\bar{c}>$$



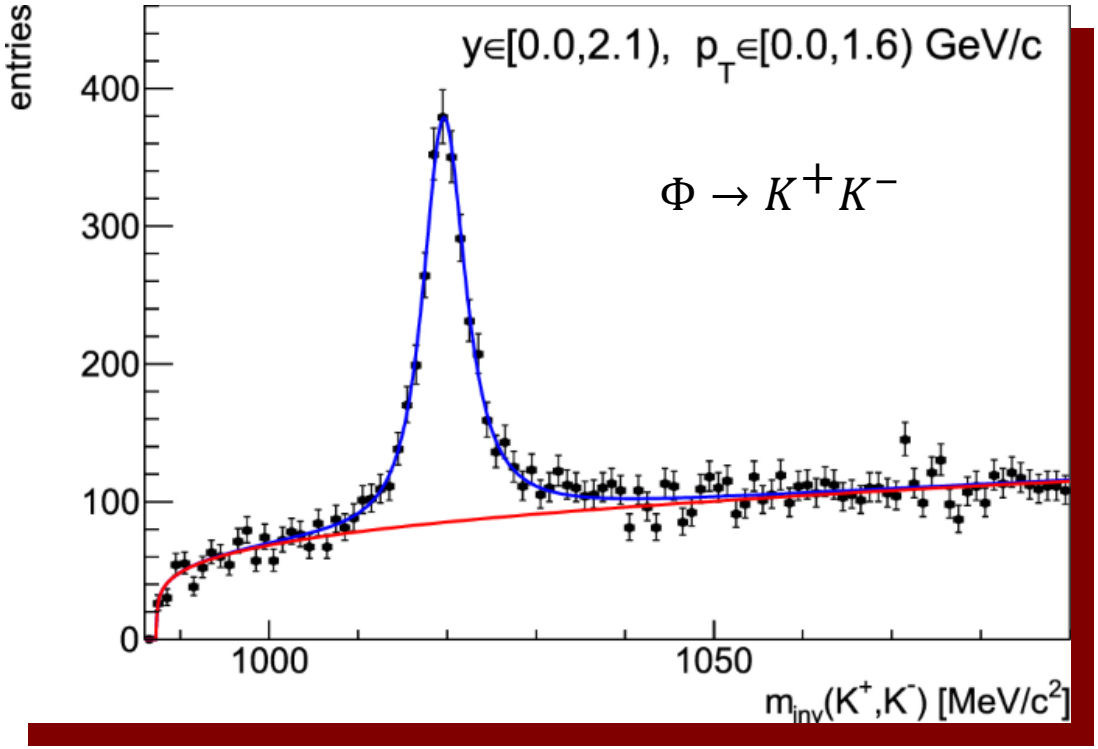
Resonances in e^+e^- collisions







Φ(1020)



Mass $M = 1020\text{MeV}$

Width $\Gamma = 4.26\text{MeV}$

$\text{Br}(\Phi \to K^+ K^-) = 50.1 \pm 0.6\%$

$\text{Br}(\Phi \to K^0 \overline{K^0}) = 33.6 \pm 0.4\%$

$\text{Br}(\Phi \to \pi^+ \pi^- \pi^0) = 14.7 \pm 0.4\%$

Strong decay

m(KK) = 990 MeV Q = M(Φ)-m(KK) = 30 MeV

m(πππ) = 420 MeV Q = M(Φ)-m(πππ) = 600 MeV

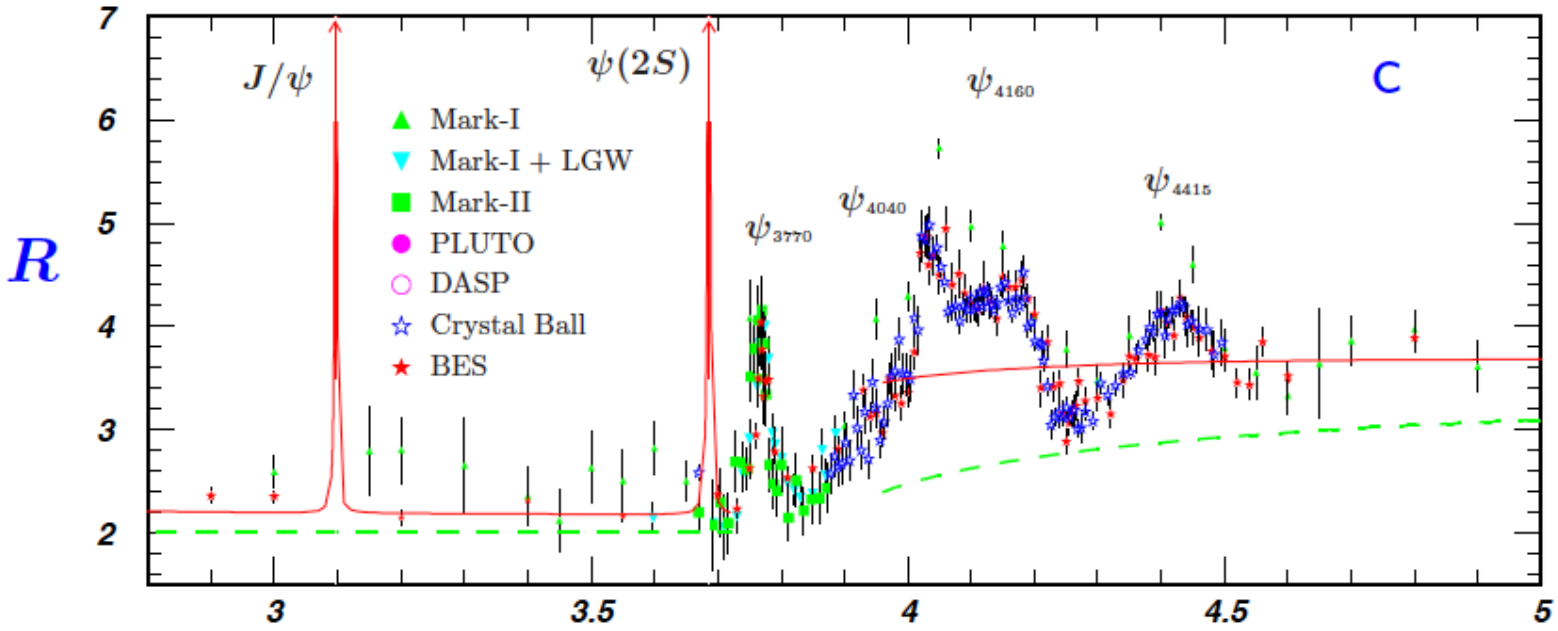
Why is KK favored over 3p ?

Charmonium

- Two narrow resonances

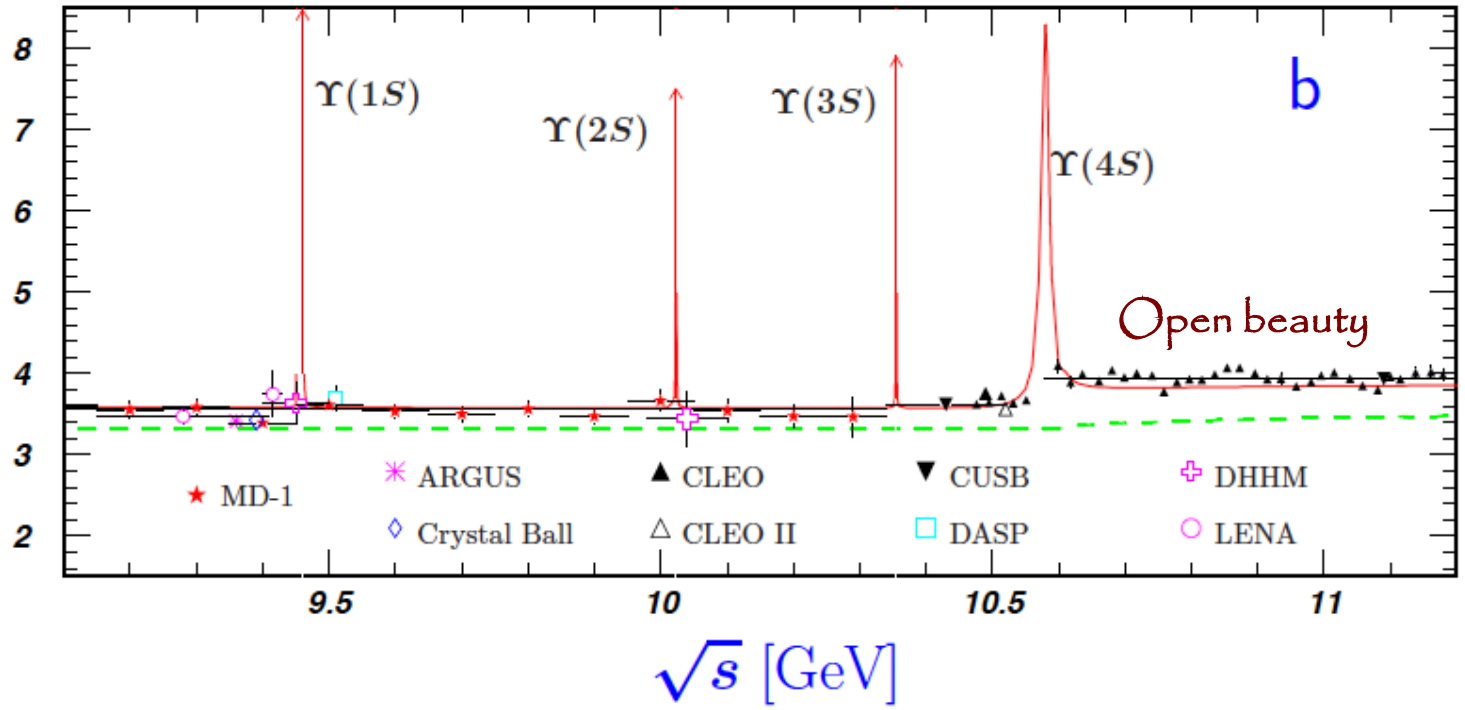
—ψ(1S) m~3100 MeV , ψ(2S) m~3600, Γ ~ o(KeV)

- Several large resonances Γ~MeV
- Why ?



Bottomomium

- Three narrow and two wide resonances



Summary of Vector Meson Properties

	ρ	ω	ϕ	ψ(1S)	ψ(3S)	Y(1S)	Y(4S)
Mass	770	782	1020	3100	3770	9460	10579
Width	150	8.7	4.2	0.09	86	0.05	20
Main decay mode	ππ	$\pi^+\pi^-\pi^0$	KK (ππ)	ggg	$D\bar{D}$	ggg	$B\bar{B}$
(%)	> 99		84 (15)	88	94	82	> 99
Br($\ell^+\ell^-$)	4.5×10^{-5}	7.4×10^{-5}	3×10^{-4}	6%	10^{-5}	2.5	10^{-5}

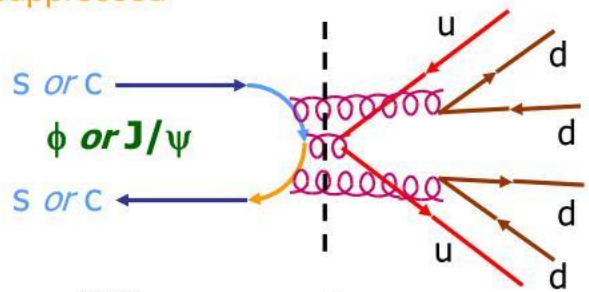
The OZI Rule

What is the OZI Rule?

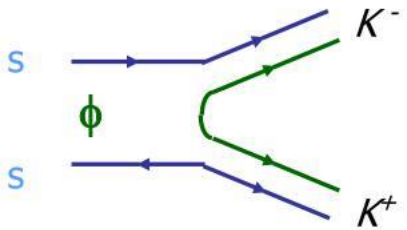
- Named after its inventors (Okubo, Zweig and Iizuka) based on observation rather than sound logic:

  If you can cut a diagram in half by cutting only gluon lines, then it is *suppressed* (but *NOT forbidden*).

e.g. $\phi \rightarrow \pi^-\pi^+\pi^0$ is OZI suppressed relative to K^-K^+ that is kinematically suppressed



OZI suppressed



Not OZI suppressed

Physics 841, U. Cincinnati, Oct, 2004

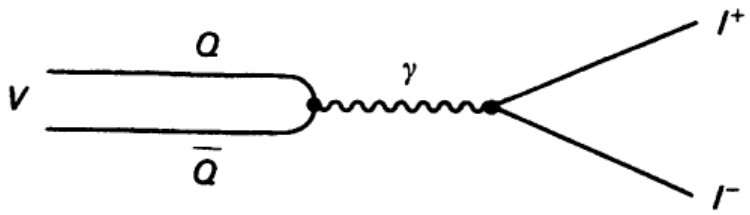
Brian Meadows, U. Cincinnati

$A(3\pi) \propto \alpha_s^3 \sim 0.2^3 = 8\times10^{-3}$

$A(2K) \propto \alpha_s \sim 0.2$

Leptonic decay of onia

- Several vector mesons do decay to lepton pairs through quark-antiquark annihilation



$$|\rho^0> = \frac{1}{\sqrt{2}}|u\bar{u} - d\bar{d}>$$

$$|\omega^0> = \frac{1}{\sqrt{2}}|u\bar{u} + d\bar{d}>$$

$$|\phi> = |s\bar{s}>$$

$$|\psi(nS)> = |c\bar{c}>(n, = 12)$$

$$|\Upsilon(nS)> = |b\bar{b}>(n, =, 123)$$

Leptonic "ONIA" decays

$$\Gamma(V \to e^+ e^-) = 16\pi\alpha^2 \frac{|\psi(0)^2|}{M_V^2} Q^2$$

$$Q = \Sigma_i w_i z_i, z_i = \begin{cases} 2/3 & i = u, c \\ -1/3 & i = d, s, b \end{cases}$$

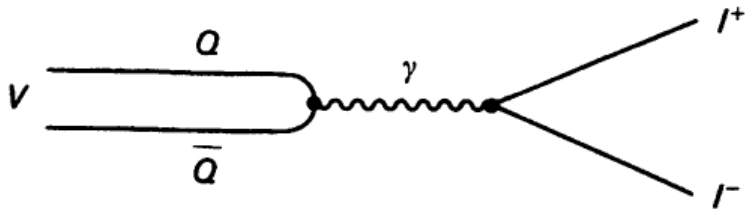
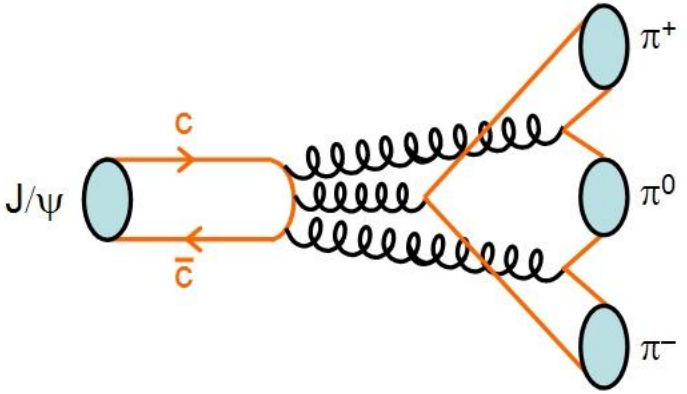
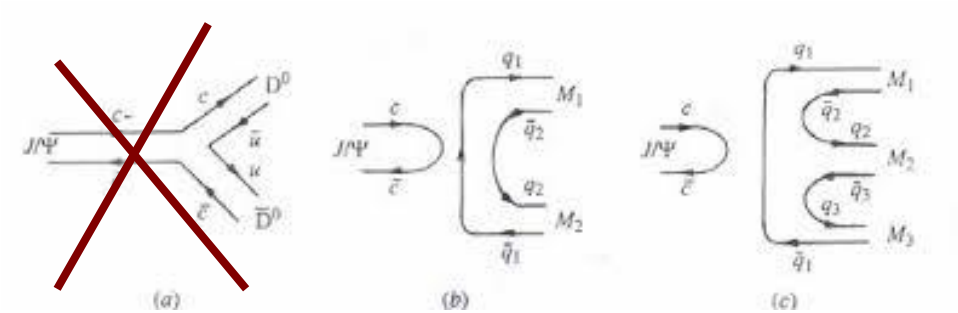


Table 4.10. *Leptonic widths of vector mesons*

Meson	Quark wavefunction	$\Sigma_i w_i z_i$	$\Gamma_{e^+e^-}$, keV	$\Gamma_{e^+e^-} \cdot \Sigma_i w_i z_i^2$	
ρ	$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$	$\frac{1}{2}$	6.8 ± 0.3	13.6 ± 0.6	150 MeV
ω	$\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$	$\frac{1}{18}$	0.60 ± 0.02	10.8 ± 0.4	8.7 MeV
ϕ	$s\bar{s}$	$\frac{1}{9}$	1.37 ± 0.05	12.3 ± 0.5	4.2 MeV
ψ	$c\bar{c}$	$\frac{4}{9}$	5.3 ± 0.4	11.9 ± 0.9	90 keV
Υ	$b\bar{b}$	$\frac{1}{9}$	1.32 ± 0.05	11.9 ± 0.5	50 keV

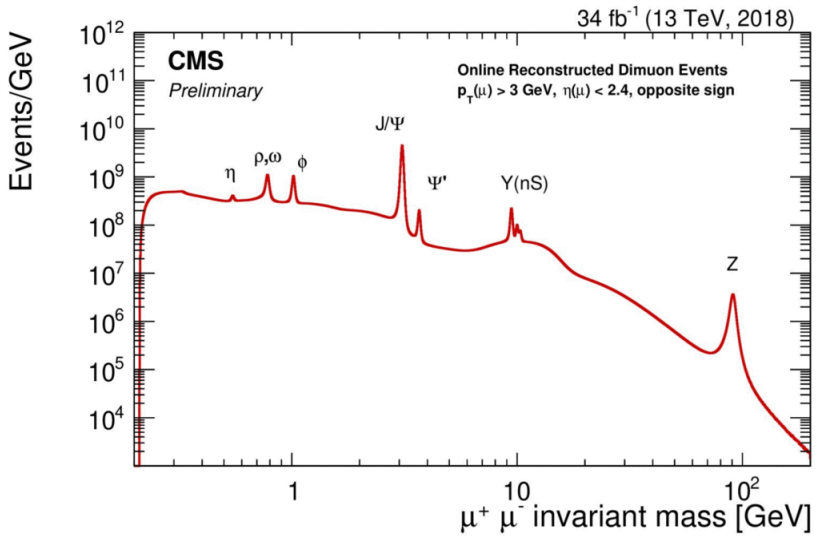
OZI rule: ψ(1S,2S), Υ(1S,2S,3S)





The particle masses are smaller than that of *DD* /*BB* open states.
They mostly decays to hadrons, but with narrow width

Electromagnetic decays to lepton pairs are therefore competitive, their Br o(few%): as they are much easier to tag, these particles are usually reconstructed in high energy collisions only through their decays to lepton pairs.



Shown: $m(\mu^+\mu^-)$reconstructed by the CMS online software. In addition to a few vector meson resonances, also the Z gauge boson and the pseudoscalar state $\eta = \frac{1}{\sqrt{2}} |u\,\bar{u} + d\,\bar{d}>$ are observed

"Large" resonances: ψ(3S), Υ(4S)

- Their mass is just larger than the threshold to produce "open" states:

$$M(\psi(3S)) - 2M(D) = 3770 - 2\text{x}1870 = 30MeV$$

$$M(\Upsilon(4S)) - 2M(B) = 10580 - 2\text{x}5280 = 20MeV$$

- **Small available energy:**
  - **Few MeV width => large enough cross section**
  - **Mesons pairs are produced almost at rest**
- **Flavor factories**
  - **Charm: BES3 operating at the ψ(3S)**
  - **Beauty: *BABAR, Belle, Belle2* operating at the Υ(4S)**

Flavor Factory properties

Collider	Detector	Resonance	C.M. energy	σ (nb)	L (fb^{-1})	N($D\bar{D}/B\bar{B}$)
BESIII	BES3	ψ(3S)	3770	6.4	20	130 x 10^6
PEP2	*BABAR*	Υ(4S)	10580	1.1	424	471 x 10^6
KEK	*Belle*	Υ(4S)	10580	1.1	711	772 x 10^6
SuperKEK	*Belle2*	Υ(4S)	10580	1.1	757	830 x 10^6

D meson mass reconstructed at BES3

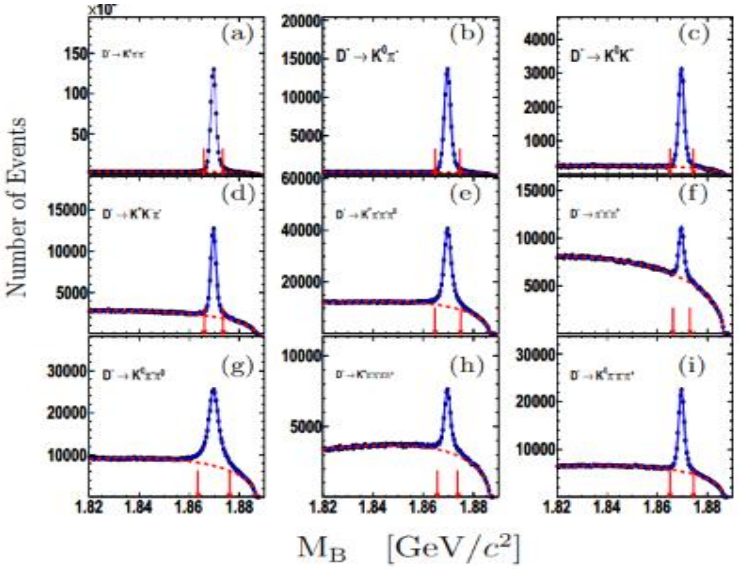
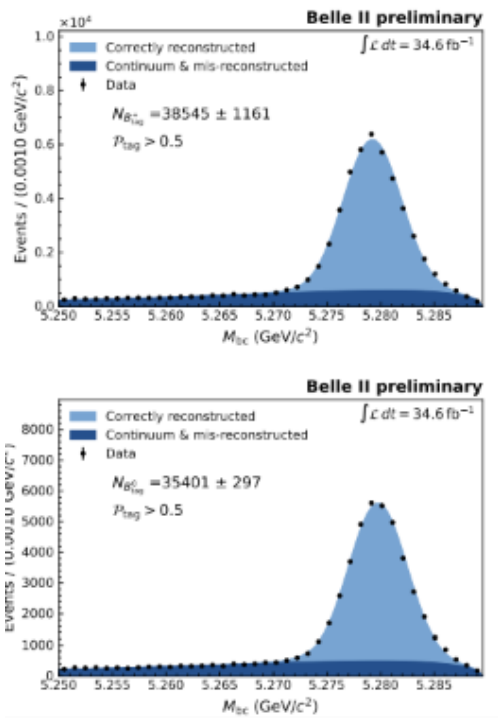


Figure 1: Distributions of the beam energy constraint masses for D^- hadronic tags used for the $D^+ \to \mu^+\nu$ analysis. Modes in panels (a)-(i) are $D^- \to K^+\pi^-\pi^-$, $K_s\pi^-$, K_sK^-, $K^+K^-\pi^-$, $K^+\pi^-\pi^-\pi^0$, $\pi^+\pi^-\pi^-$, $K_s\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^-\pi^+$, and $K_s\pi^-\pi^-\pi^+$.

B meson mass reconstructed at Belle2



Clebsh Gordan coefficients

PDG

34. CLEBSCH-GORDAN COEFFICIENTS, SPHERICAL HARMONICS, AND d FUNCTIONS

Note: A square-root sign is to be understood over *every* coefficient, *e.g.*, for $-8/15$ read $-\sqrt{8/15}$.

Notation:

J	J	...
M	M	...

m_1	m_2	
m_1	m_2	Coefficients
.	.	
.	.	
.	.	

$$Y_1^0 = \sqrt{\frac{3}{4\pi}}\cos\theta$$

$$Y_1^1 = -\sqrt{\frac{3}{8\pi}}\sin\theta\, e^{i\phi}$$

$$Y_2^0 = \sqrt{\frac{5}{4\pi}}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$$

$$Y_2^1 = -\sqrt{\frac{15}{8\pi}}\sin\theta\cos\theta\, e^{i\phi}$$

$$Y_2^2 = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\sin^2\theta\, e^{2i\phi}$$

1/2×1/2

+1/2 +1/2	1	1	0
		0	0
+1/2 −1/2	1/2	1/2	1
−1/2 +1/2	1/2	−1/2	−1
−1/2 −1/2			1

1×1/2

+1 +1/2	3/2	3/2	1/2	
	1	+1/2	+1/2	
+1 −1/2	1/3	2/3	3/2	1/2
0 +1/2	2/3	−1/3	−1/2	−1/2
0 −1/2	2/3	1/3	3/2	
−1 +1/2	1/3	−2/3	−3/2	
−1 −1/2			1	

2×1

+2 +1	3	3	2		
	1	+2	+2		
+2 0	1/3	2/3	3	2	1
+1 +1	2/3	−1/3	+1	+1	+1
+2 −1	1/15	1/3	3/5		
+1 0	8/15	1/6	−3/10		
0 +1	2/5	−1/2	1/10		

1×1

+1 +1	2	2	1			
	1	+1	+1			
+1 0	1/2	1/2	2	1	0	
0 +1	1/2	−1/2	0	0	0	
+1 −1	1/6	1/2	1/3			
0 0	2/3		0	−1/3		
−1 +1	1/6	−1/2	1/3			
0 −1	1/2	1/2	2			
−1 0	1/2	−1/2	−2			
−1 −1	1					

	3	2	1			
	0	0	0			
+1 −1	1/5	1/2	3/10			
0 0	3/5		0	−2/5		
−1 +1	1/5	−1/2	3/10			

3/2×1

+3/2 +1	5/2	5/2	3/2			
	1	+3/2	+3/2			
+3/2 0	2/5	3/5	5/2	3/2	1/2	
+1/2 +1	3/5	−2/5	+1/2	+1/2	+1/2	
+3/2 −1	1/10	2/5	1/2			
+1/2 0	3/5	1/15	−1/3			
−1/2 +1	3/10	−8/15	1/6			
+1/2 −1	3/10	8/15	1/6			
−1/2 0	3/5	−1/15	−1/3			
−3/2 +1	1/10	−2/5	1/2			
0 −1	2/5	1/2	1/10			
−1 0	8/15	−1/6	−3/10			
−2 +1	1/15	−1/3	3/5			
−1 −1	2/3	1/3	3			
−2 0	1/3	−2/3	−3			
−2 −1	1					

2×1/2

+2 +1/2	5/2	5/2	3/2			
	1	+3/2	+3/2			
+2 −1/2	1/5	4/5	5/2	3/2		
+1 +1/2	4/5	−1/5	+1/2	+1/2		
+1 −1/2	2/5	3/5	5/2	3/2		
0 +1/2	3/5	−2/5	−1/2	−1/2		
0 −1/2	3/5	2/5	5/2	3/2		
−1 +1/2	2/5	−3/5	−3/2	−3/2		
−1 −1/2	4/5	1/5	5/2			
−2 +1/2	1/5	−4/5	−5/2			
−2 −1/2			1			

3/2×1/2

+3/2 +1/2	2	2	1			
	1	+1	+1			
+3/2 −1/2	1/4	3/4	2	1		
+1/2 +1/2	3/4	−1/4	0	0		
+1/2 −1/2	1/2	1/2	2	1		
−1/2 +1/2	1/2	−1/2	−1	−1		
−1/2 −1/2	3/4	1/4	2			
−3/2 +1/2	1/4	−3/4	−2			
−3/2 −1/2	1					

	5/2	3/2	1/2			
	−1/2	−1/2	−1/2			
+1/2 −1	3/10	8/15	1/6			
−1/2 0	3/5	−1/15	−1/3			
−3/2 +1	1/10	−2/5	1/2			
−1/2 −1	3/5	2/5	5/2			
−3/2 0	2/5	−3/5	−5/2			
−3/2 −1	1					