# Charm physics, selected topics

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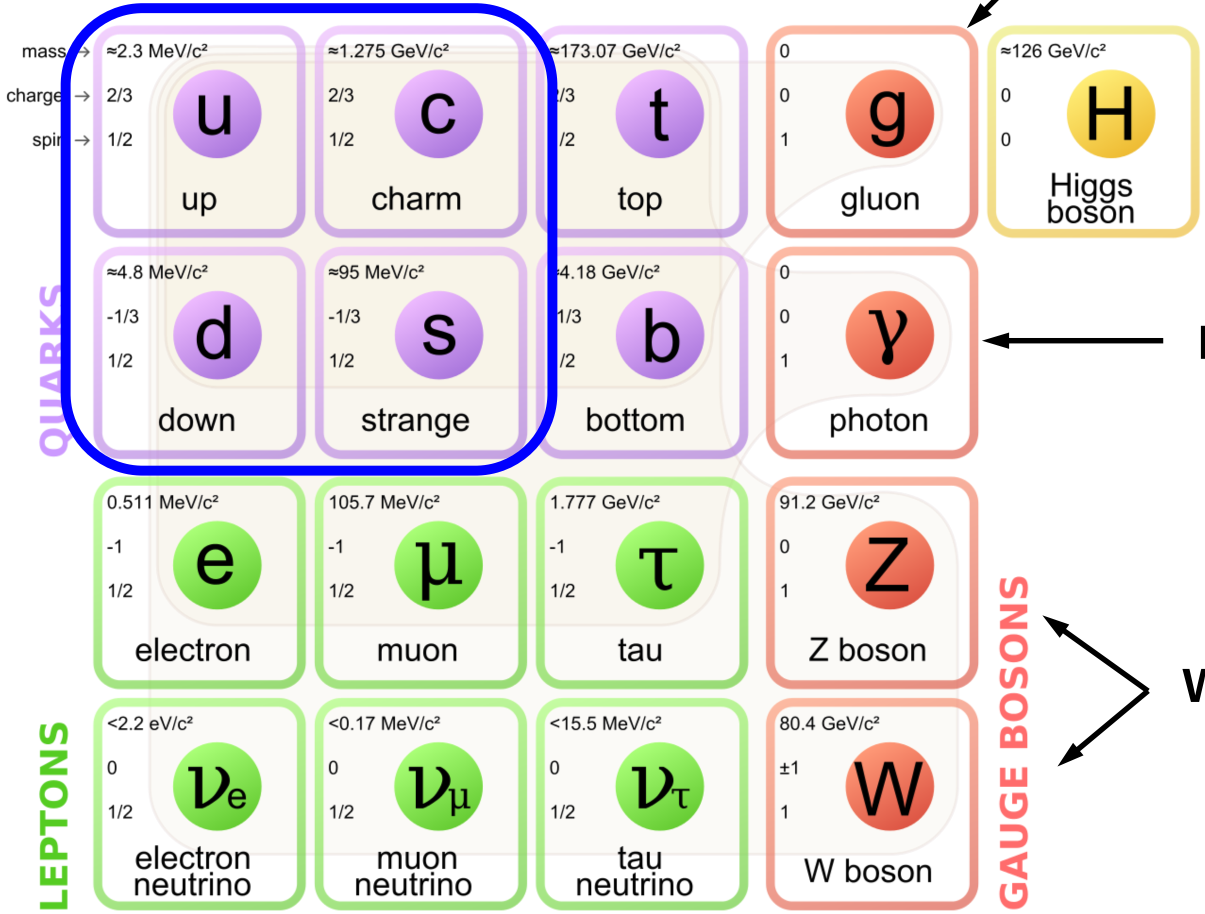
- ❑ **Introduction : charm discovery**
- ❑ **Charm decays and charm puzzles**
- ❑ **Mixing and CP parity violation**

*Usual disclaimers:*
*Selective and biased introduction*
*Many simplifications, avoid formalism*
*Slides from other presentations are sometimes used without a proper reference*

Bezmiechowa Górna, 11-20/07/2024

# Reminder : leptons, quarks, gauge bosons & interactions

- «Truly » elementary particles: **fermions** (leptons and quarks) and **gauge bosons**
- Up-type quark of the second generation : **charm**



**Strong interaction**

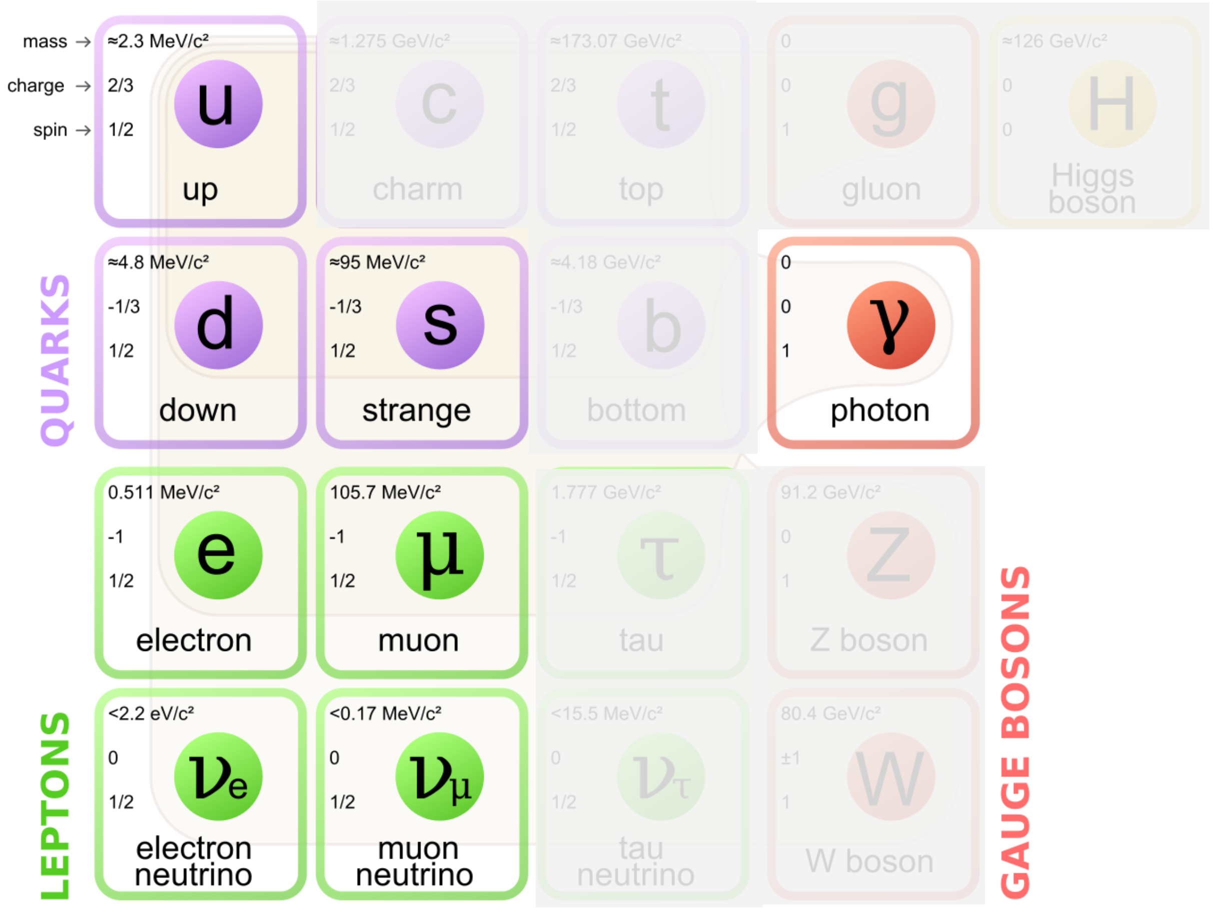
**EM interaction**

**Weak interaction**

## Discovery of c-quark

*November revolution*

# Reminder : leptons, quarks, gauge bosons & interactions



Nikola Cabibbo, 1963 : mix down-type quarks

Couplings :

Cabibbo angle $\theta_c \sim 13^o$

Glashow, Iliopoulos et Maiani (GIM) proposed, 1970
a fourth quark : the quark *c* (of charge 2/3)

to explain the absence of FCNC
prediction of the quark mass, $m_c \sim 1.5$ GeV

# Nikola Cabibbo, 1963

- First building block of Flavour physics, well before many of the SM ingredients were clear
- Cabibbo theory of semileptonic decays provided the first step towards a unified description of hadronic and leptonic weak interactions by reconciling strange-particle decays with the universality of weak interaction

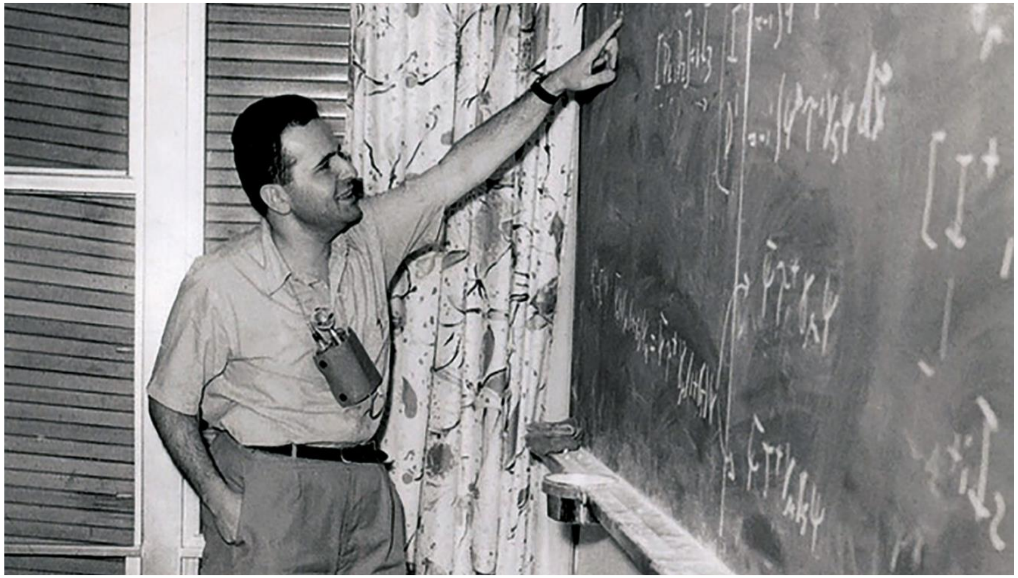
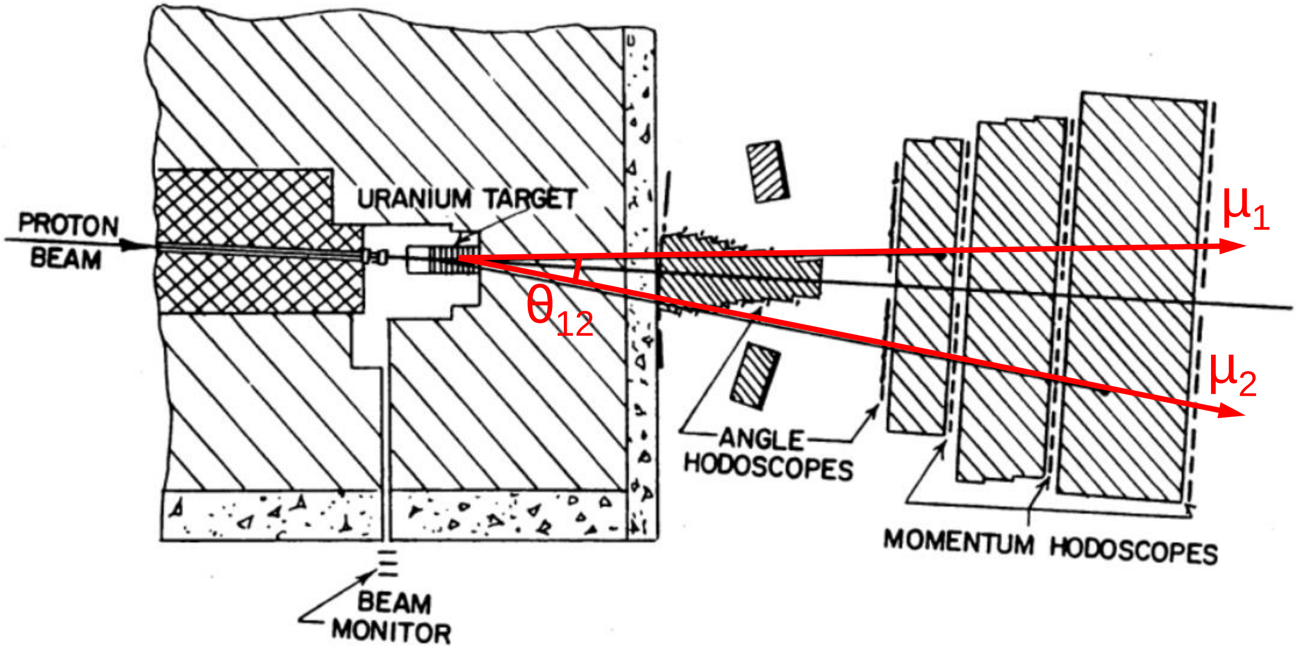


*Photo credit: Monica Pepe-Altarelli, Cabibbo's family*

# Precursors: dimuon measurements at AGS/BNL

- Fixed target experiment (no B field)

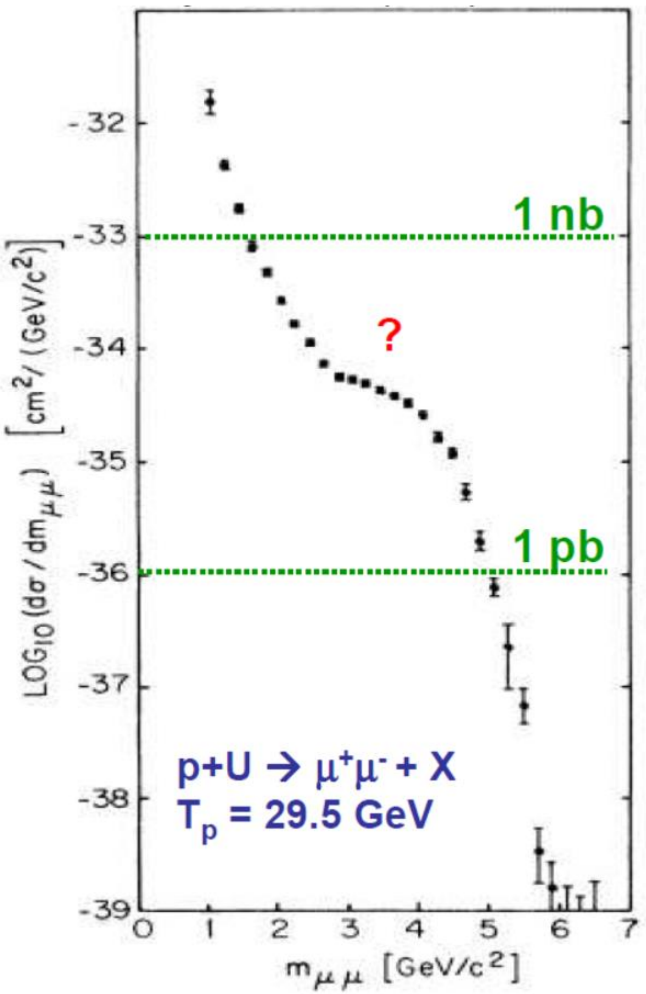
**$p + U \rightarrow \mu^+ \mu^- + X$, $T_p$ = 22, 25, 28.5, 29.5 GeV**



- Dense U target
- Pion/Kaon absorbtion, steal/concrete absorbers
- Angle hodoscopes
- Momentum hodoscopes
- Dimuon signal – difference between in-time and delayed coincidences

$$M_{\mu\mu} = \sqrt{2 \cdot p_1 p_2 [1 - \cos\theta_{12}]}$$

**J.H. Christenson et al., Phys. Rev. D8 (1973) 2016**



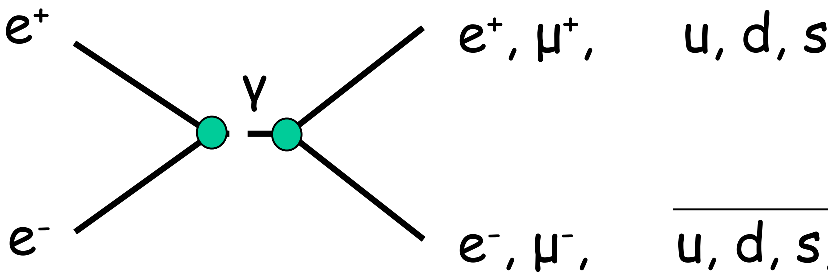
**Observation of Muon Pairs in High-Energy Hadron Collisions, J.H. Christenson et al., Phys. Rev. D8 (1973) 2016**

Abstract: Muon pairs with effective masses between 1 GeV/c2 and 6.5 GeV/c2 have been observed in the collisions of 30-GeV protons with a uranium target. **The production cross section was seen to vary smoothly with mass exhibiting no resonant structure.**

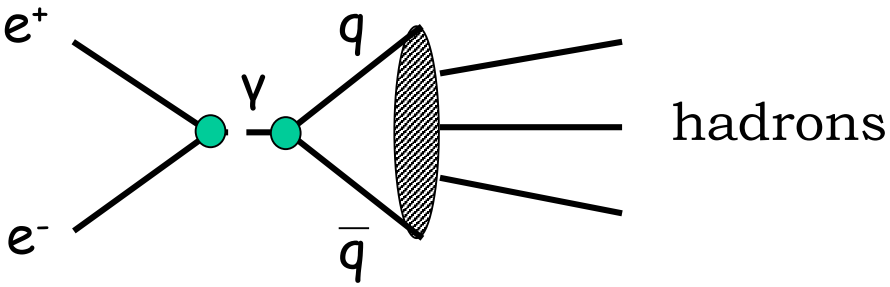
- Inspiration to construct e+e- spectrometer at AGS/BNL

# Precursors: the R ratio

Studying number of players via $e^+e^-$ cross-section

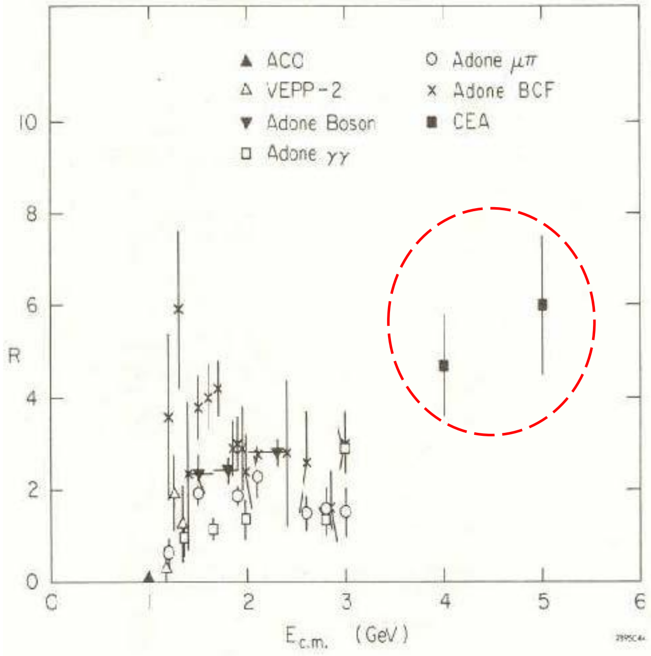


The $e^+e^- \to q\bar{q}$ detected via decays to stables hadrons.



$$\boxed{R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_C \sum_i q_i^2}$$

The R ratio (July 1974), from J. Otwinowski

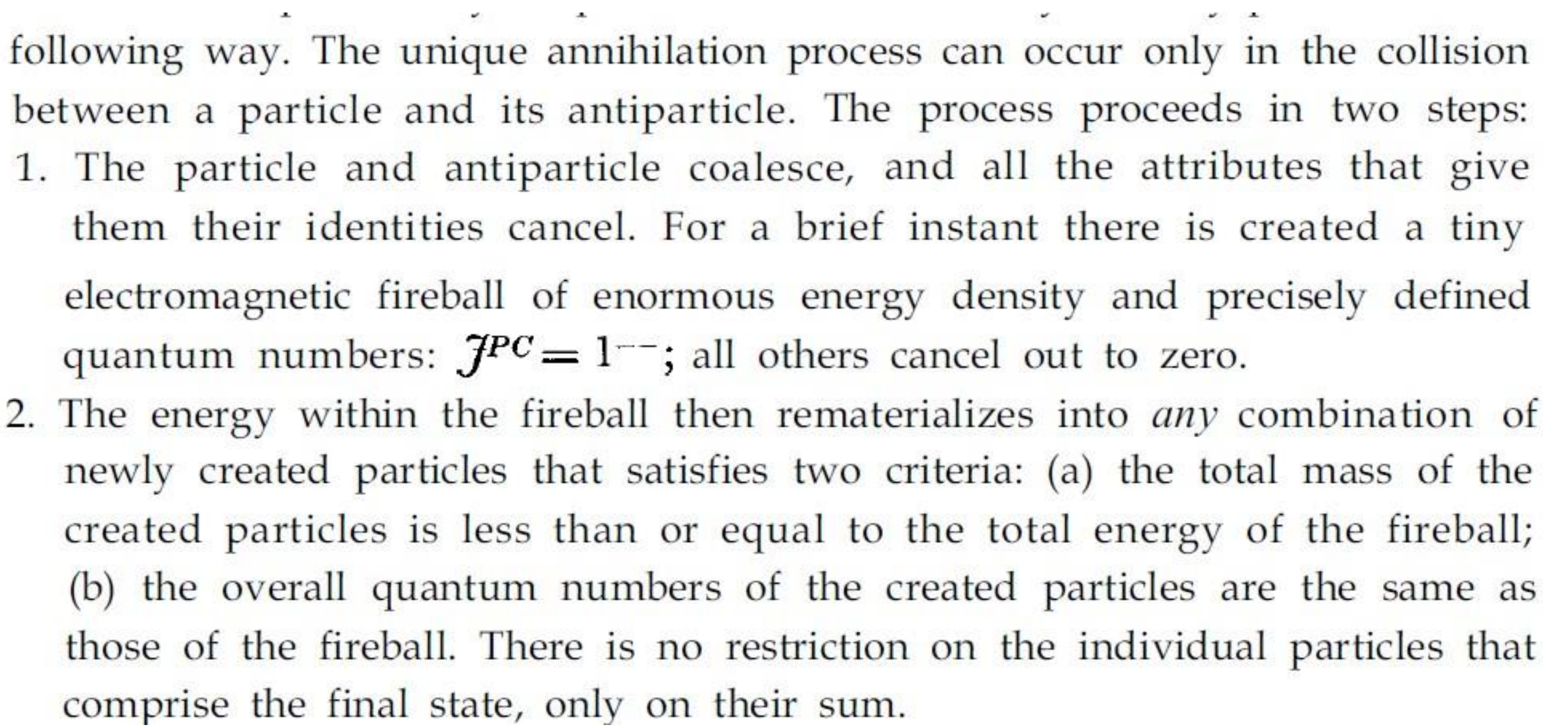


- ❑ Inspiration for the charm quark discovery scan at SLAC

# Discovery of charm quark

- ψ at SLAC: arguments to choose e+e- collider

*From Nobel lecture of B. Richter, 1976*



following way. The unique annihilation process can occur only in the collision between a particle and its antiparticle. The process proceeds in two steps:

1. The particle and antiparticle coalesce, and all the attributes that give them their identities cancel. For a brief instant there is created a tiny electromagnetic fireball of enormous energy density and precisely defined quantum numbers: $J^{PC} = 1^{--}$; all others cancel out to zero.
2. The energy within the fireball then rematerializes into *any* combination of newly created particles that satisfies two criteria: (a) the total mass of the created particles is less than or equal to the total energy of the fireball; (b) the overall quantum numbers of the created particles are the same as those of the fireball. There is no restriction on the individual particles that comprise the final state, only on their sum.

# Discovery of charm quark

- Energy scan and R ratio

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

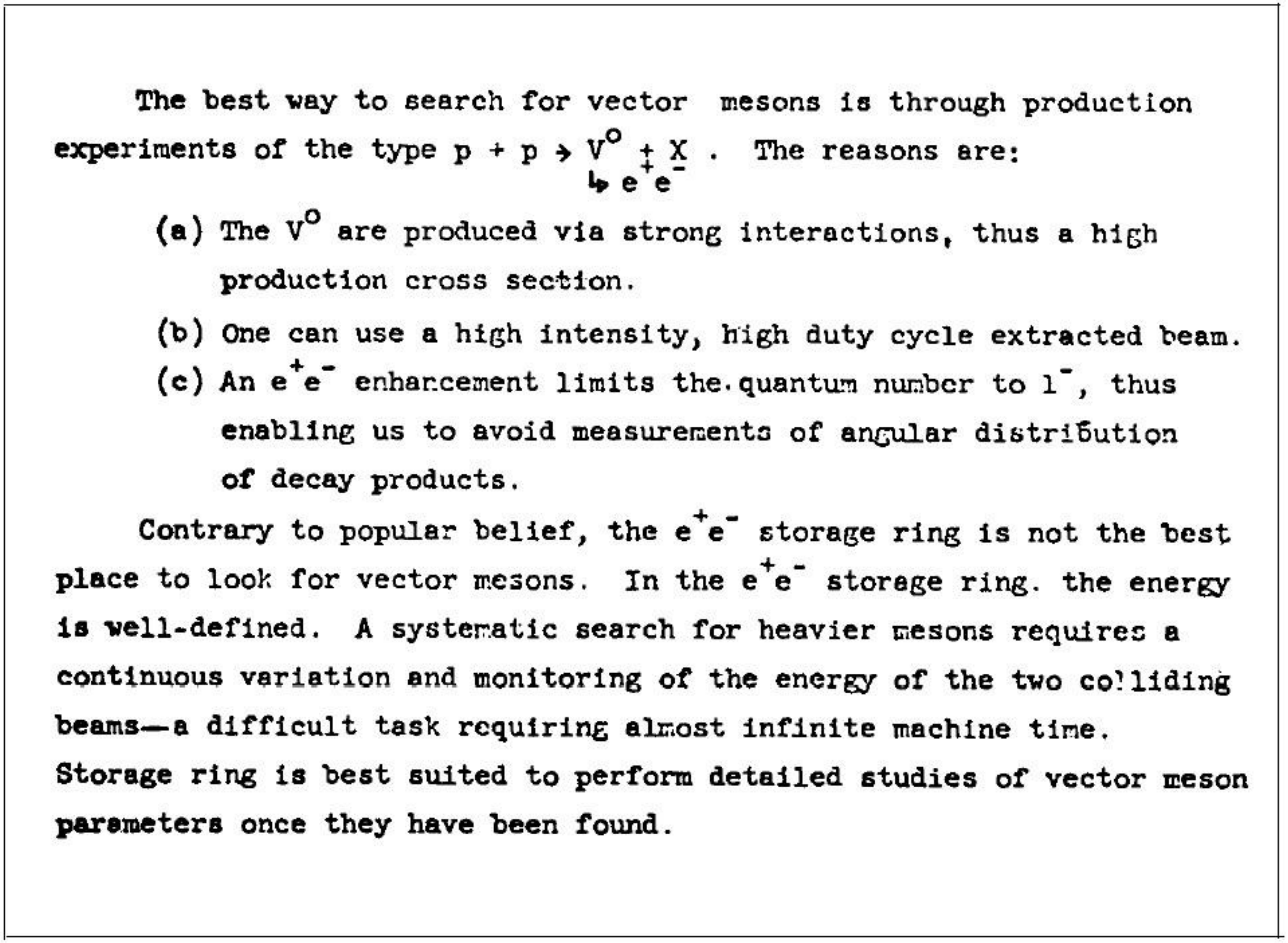
- ψ at SLAC: R value predictions, summary by J. Ellis 1974

Table I. Table of Values of R from the Talk by J. Ellis at the 1974 London Conference [8] (references in table from Ellis's talk)

| *Value* | *Model* | |
|---|---|---|
| *0.36* | Bethe-Salpeter bound quarks | Bohm et al., Ref .42 |
| *2/3* | Gell-Mann-Zweig quarks | |
| *0.69* | Generalized vector meson dominance | Renard, Ref. 49 |
| ~ 1 | Composite quarks | Raitio, Ref. 43 |
| 10/9 | Gell-Mann-Zweig with charm | Glashow et al., Ref. 31 |
| *2* | Colored quarks | |
| *2.5* to 3 | Generalized vector meson dominance | Greco, Ref. 30 |
| *2 to 5* | Generalized vector meson dominance | Sakurai, Gounaris, Ref, *47* |
| 3-1/3 | Colored charmed quarks | Glashow et al., Ref. 31 |
| 4 | Han-Nambu quarks | Han and Nambu. Ref. 32 |
| 5.7±0.9 | Trace anomaly and ρ dominance | Terazawa, Ref. 27 |
| $5.8^{+3.2}_{-3.5}$ | Trace anomaly and ε dominance | Orito et al., Ref. 25 |
| 6 | Han-Nambu with charm | Han and Nambu, Ref. 32 |
| 6.69 to 7.77 | Broken scale invariance | Choudhury, Ref. 18 |
| 8 | Tati quarks | Han and Nambu, Ref. 32 |
| 8 ± 2 | Trace anomaly, and ε dominance | Eliezer, Ref. 26 |
| 9 | Gravitational cut-off, Universality | Parisi, Ref. 40 |
| 9 | Broken scale invariance | Yachtmann. Ref. 39 |
| 16 | $SU_{12} \times SU_2$) gauge models | Fritzsch & Minkowski. Ref. 34 |
| 35-1/3 | $SU_{16} \times SU_{16}$) | |
| ~ 5000 | High $Z$ quarks | Yock. Ref. 73 |
| 70,383 | Schwinger's quarks ) | |
| ∞ | ∞ of partons | Cabibbo and Karl, Ref. 9<br>Matveev and Tolkachev, Ref. 35<br>Rozenblit. Ref. 36 |

# Discovery of charm quark

- J at BNL: arguments to choose proton beam on target



The best way to search for vector mesons is through production experiments of the type $p + p \rightarrow V^{O} + X$ , $V^{O} \rightarrow e^{+}e^{-}$. The reasons are:

(a) The $V^{O}$ are produced via strong interactions, thus a high production cross section.

(b) One can use a high intensity, high duty cycle extracted beam.

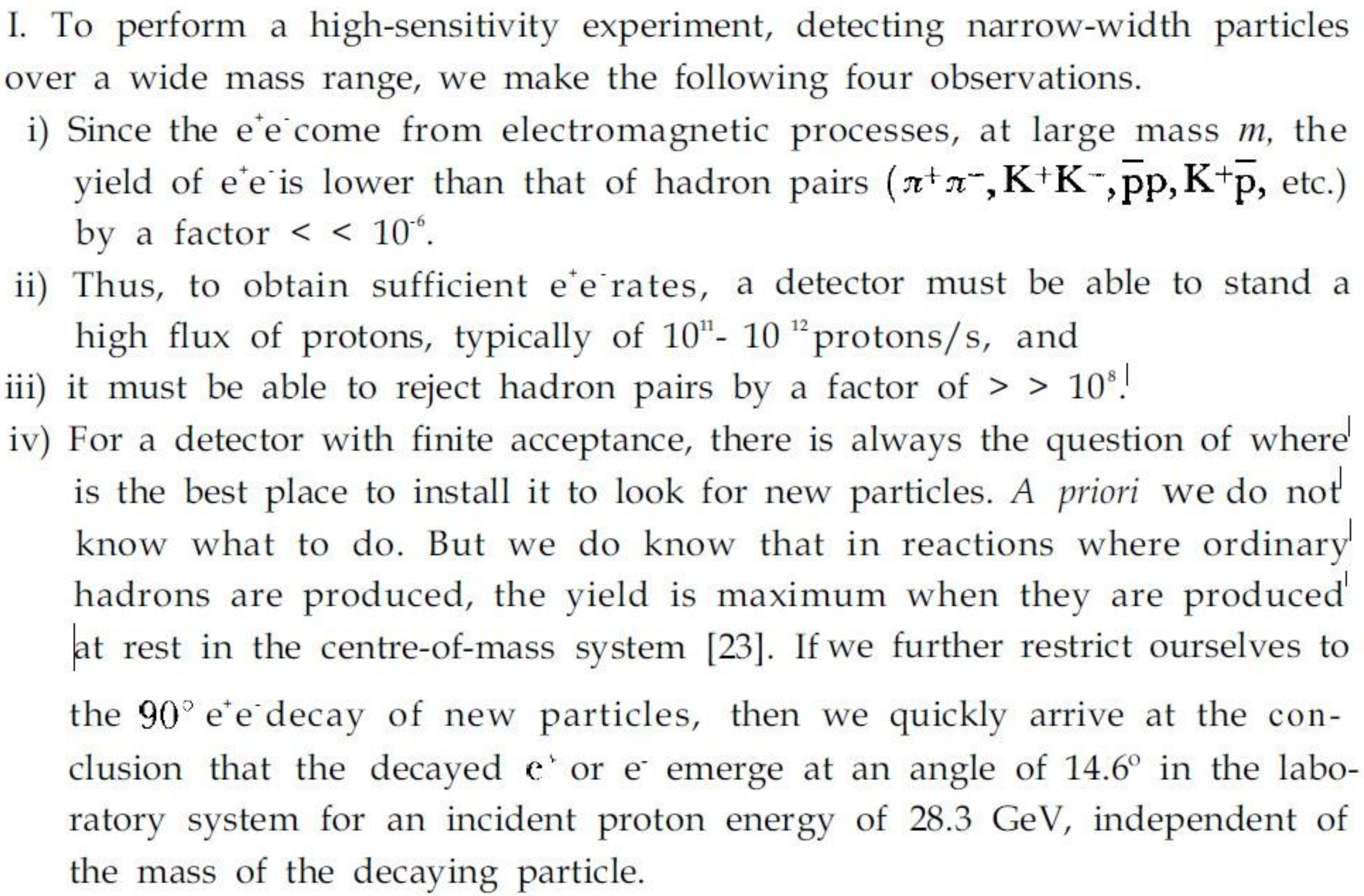
(c) An $e^{+}e^{-}$ enhancement limits the quantum number to $1^{-}$, thus enabling us to avoid measurements of angular distribution of decay products.

Contrary to popular belief, the $e^{+}e^{-}$ storage ring is not the best place to look for vector mesons. In the $e^{+}e^{-}$ storage ring. the energy is well-defined. A systematic search for heavier mesons requires a continuous variation and monitoring of the energy of the two colliding beams—a difficult task requiring almost infinite machine time. Storage ring is best suited to perform detailed studies of vector meson parameters once they have been found.

Fig. 3. Page 4 of proposal 598 submitted to Brookhaven National Laboratory early in 1972 and approved in May of the same year, giving some of the reasons for performing this experiment in a slow extracted proton beam.

# Discovery of charm quark

- J at BNL: detector arguments



I. To perform a high-sensitivity experiment, detecting narrow-width particles over a wide mass range, we make the following four observations.

i) Since the $e^+e^-$ come from electromagnetic processes, at large mass *m*, the yield of $e^+e^-$ is lower than that of hadron pairs ($\pi^+\pi^-$, $K^+K^-$, $\bar{p}p$, $K^+\bar{p}$, etc.) by a factor $<<10^{-6}$.

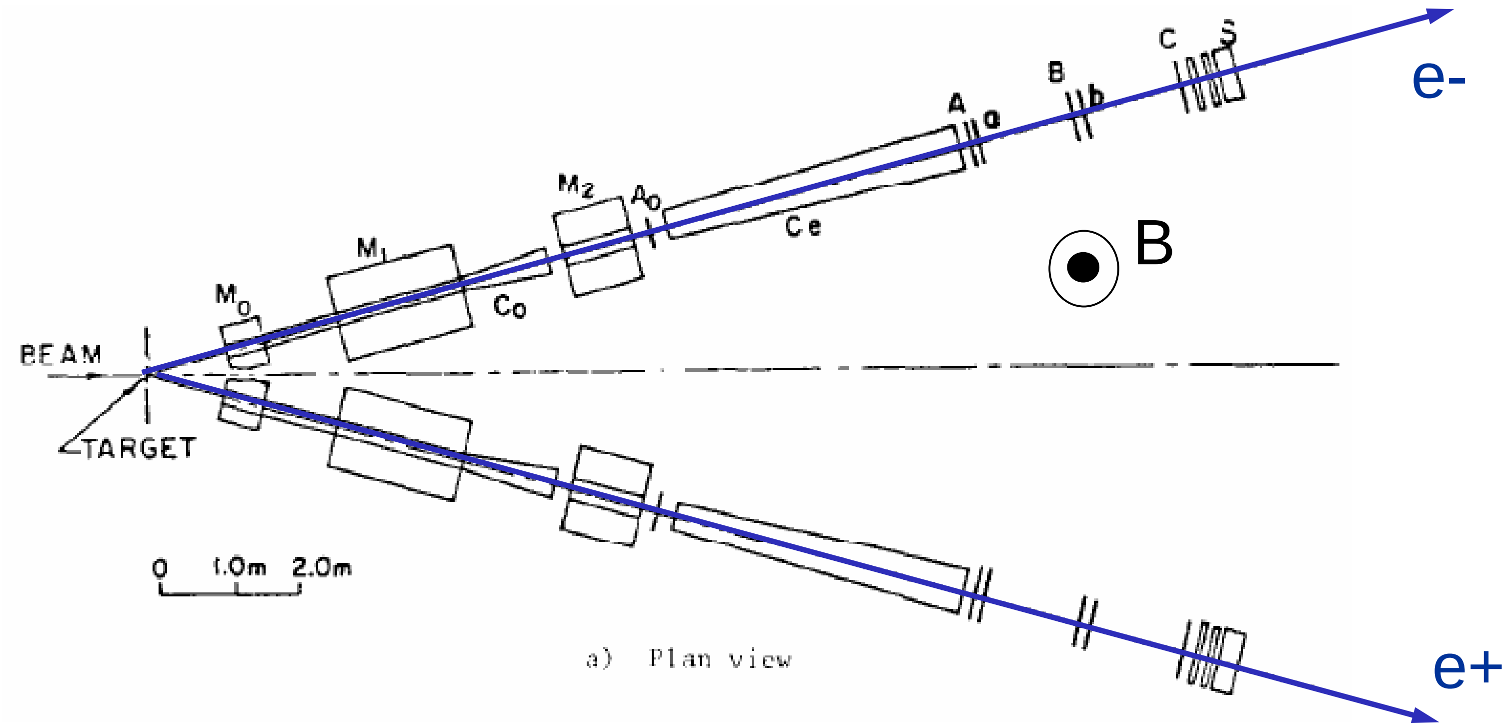
ii) Thus, to obtain sufficient $e^+e^-$ rates, a detector must be able to stand a high flux of protons, typically of $10^{11}$- $10^{12}$ protons/s, and

iii) it must be able to reject hadron pairs by a factor of $>>10^{8}$.

iv) For a detector with finite acceptance, there is always the question of where is the best place to install it to look for new particles. *A priori* we do not know what to do. But we do know that in reactions where ordinary hadrons are produced, the yield is maximum when they are produced at rest in the centre-of-mass system [23]. If we further restrict ourselves to the 90° $e^+e^-$ decay of new particles, then we quickly arrive at the conclusion that the decayed $e^+$ or $e^-$ emerge at an angle of 14.6° in the laboratory system for an incident proton energy of 28.3 GeV, independent of the mass of the decaying particle.

# Discovery of charm quark

- J at BNL: proton beam on target, look at invariant mass of the e+e- pairs

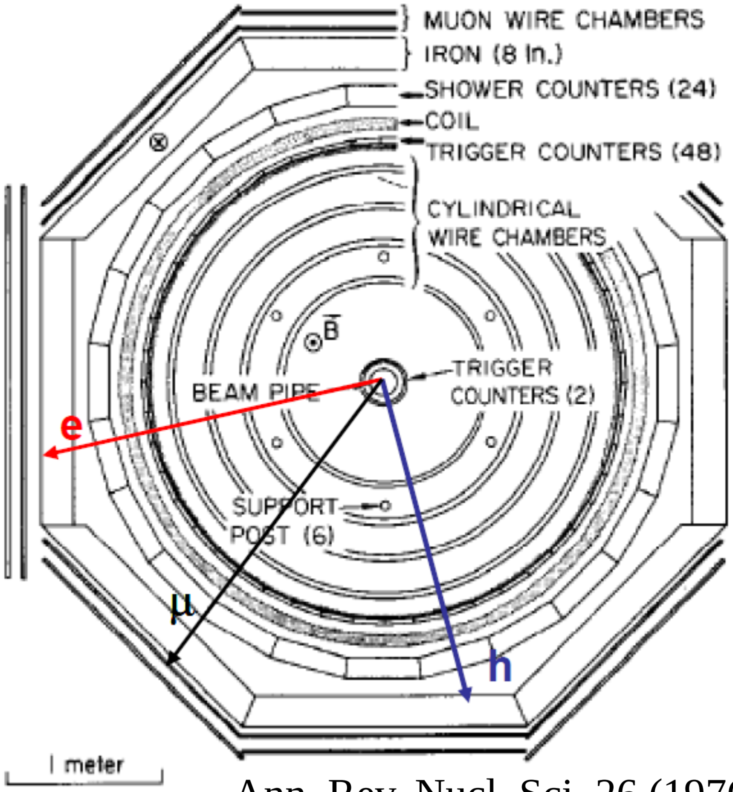


Two arms e+e- spectrometer :

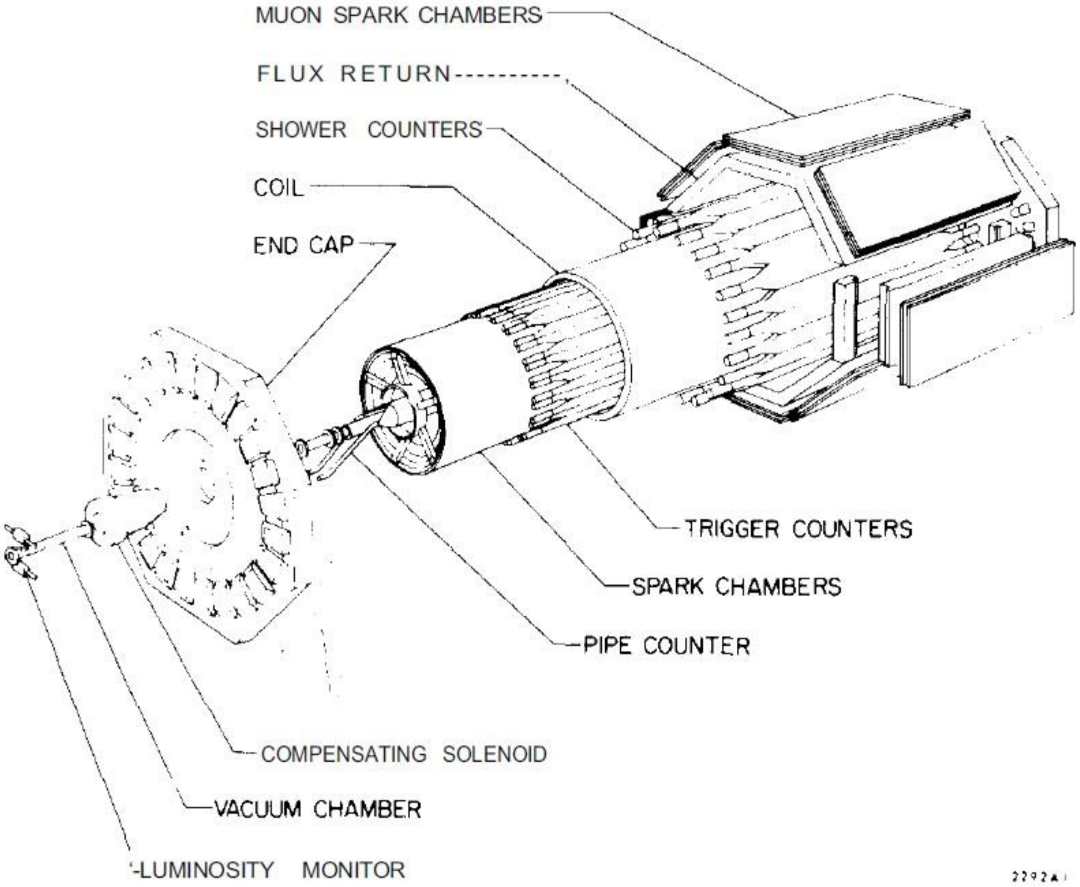
Tracking (dipole magnets + MWPCs)
PID detectors: Hodoscopes (TOF)
EM shower counters, e/h separation from shower development
Ĉerenkov counters (charged hadron ID)

# Discovery of charm quark

- $\psi$ at SLAC: scan particle yields (cross-section) over the center of mass energy of the e+e- colliding beams



Ann. Rev. Nucl. Sci. 26 (1976) 89

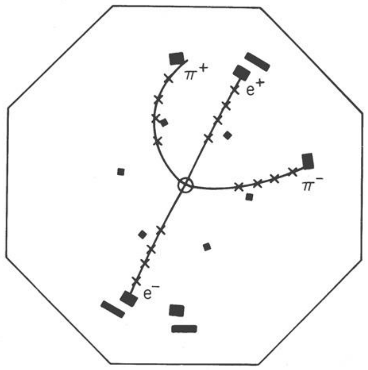


Mark I detector at SLAC :
Tracking (cylindrical magnet + cylindrical wire chambers
PID detectors:
Trigger chambers (TOF)
Shower counters (e identification)
Muon wire chambers

# The November revolution

**J.J. Augustin et al., PRL 33 (1974) 1406**

- $\psi$ at SLAC: scan particle yields (cross-section) over the center of mass energy of the e+e- colliding beams



Computer reconstruction of a psi-prime decay in the SLAC Mark I detector

$\boxed{J/\psi = c\bar{c},\ J^{PC} = 1^{--}}$

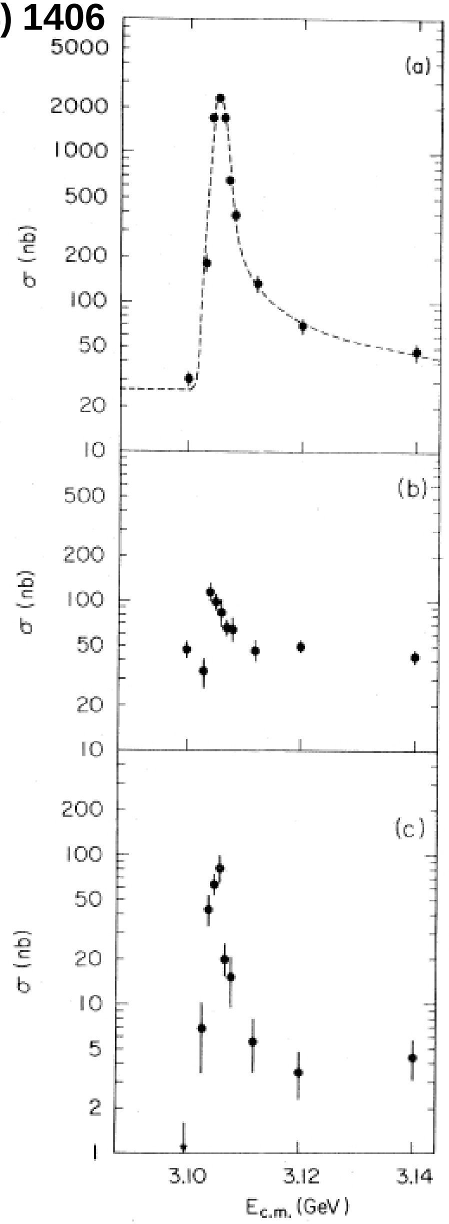


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) $e^+e^-$ final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and $K^+K^-$ final states. The curve in (a) is the expected shape of a $\delta$-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b) and (c) are integrated over the detector acceptance. The total hadron cross section, (a), has been corrected for detection efficiency.

**J.J. Auber et al., PRL 33 (1974) 1404**

- J at BNL: proton beam on target, look at invariant mass of the e+e- pairs

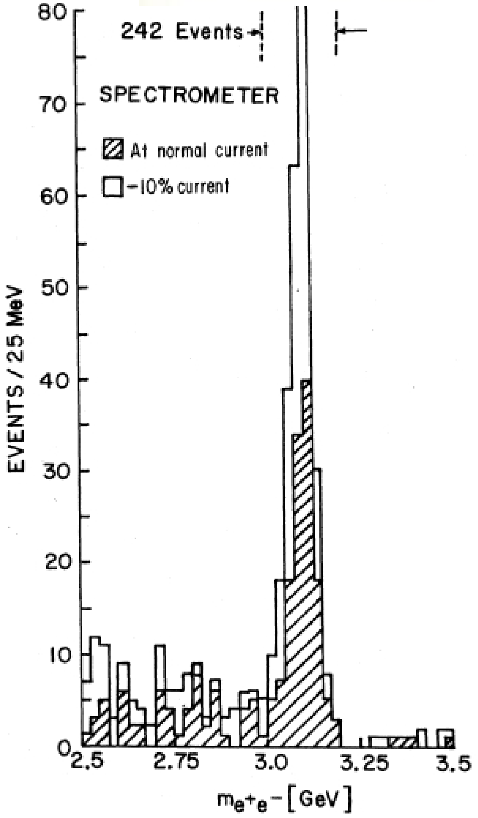
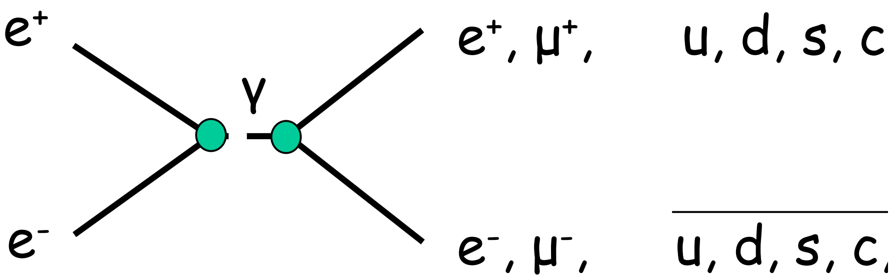


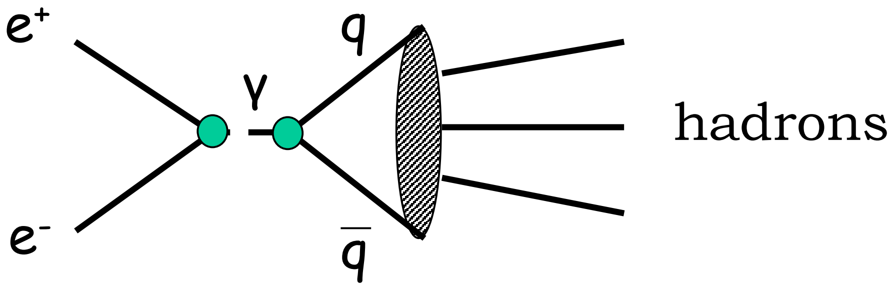
FIG. 2. Mass spectrum showing the existence of $J$. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

# Discovery of charm quark

Studying number of players via $e^+e^-$ cross-section

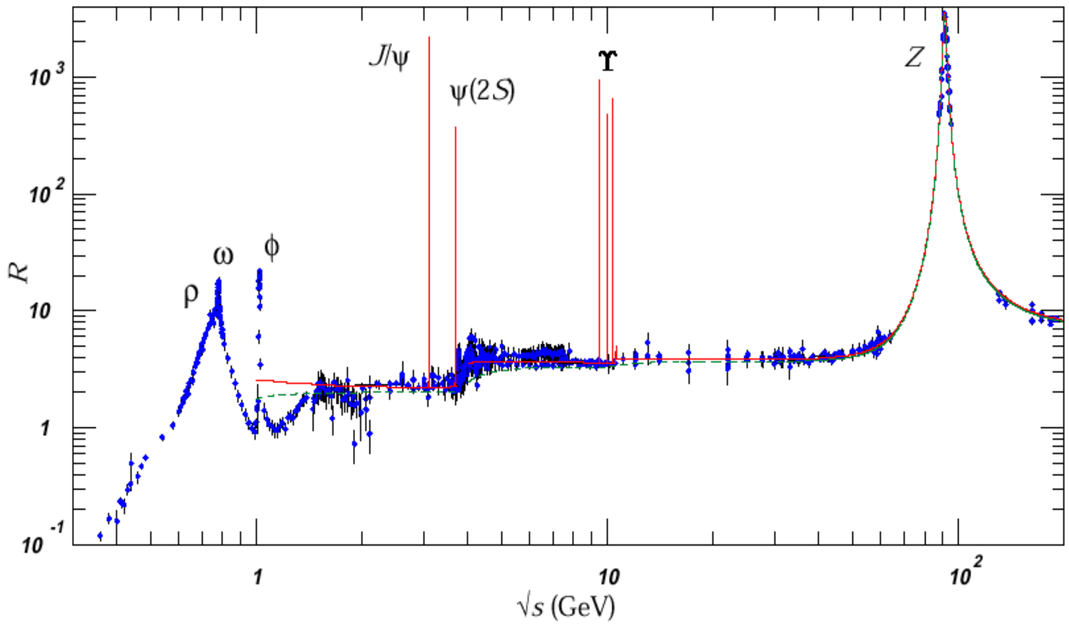


The $e^+e^- \to q\bar{q}$ detected via decays to stables hadrons.



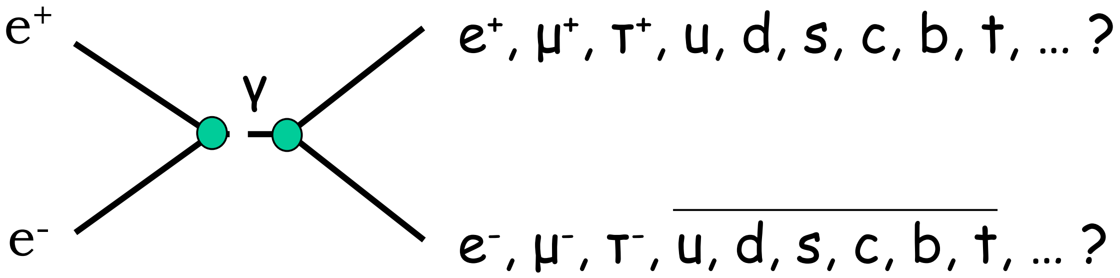
$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_C \sum_i q_i^2$$

- Guess on the mass
- Guess on the charge

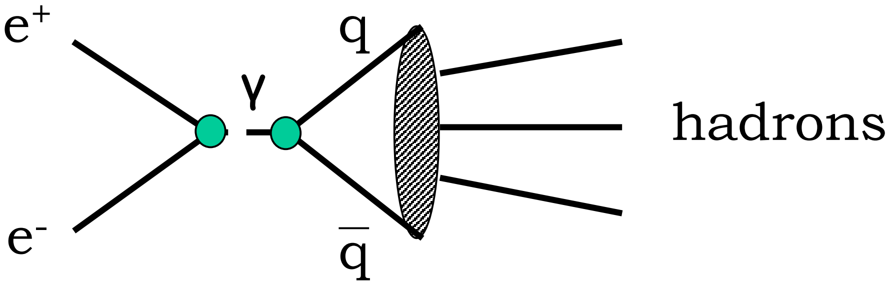


# Discovery of charm quark

Studying number of players
via $e^+e^-$ cross-section



The $e^+e^-$ → qq detected via decays
to stables hadrons.

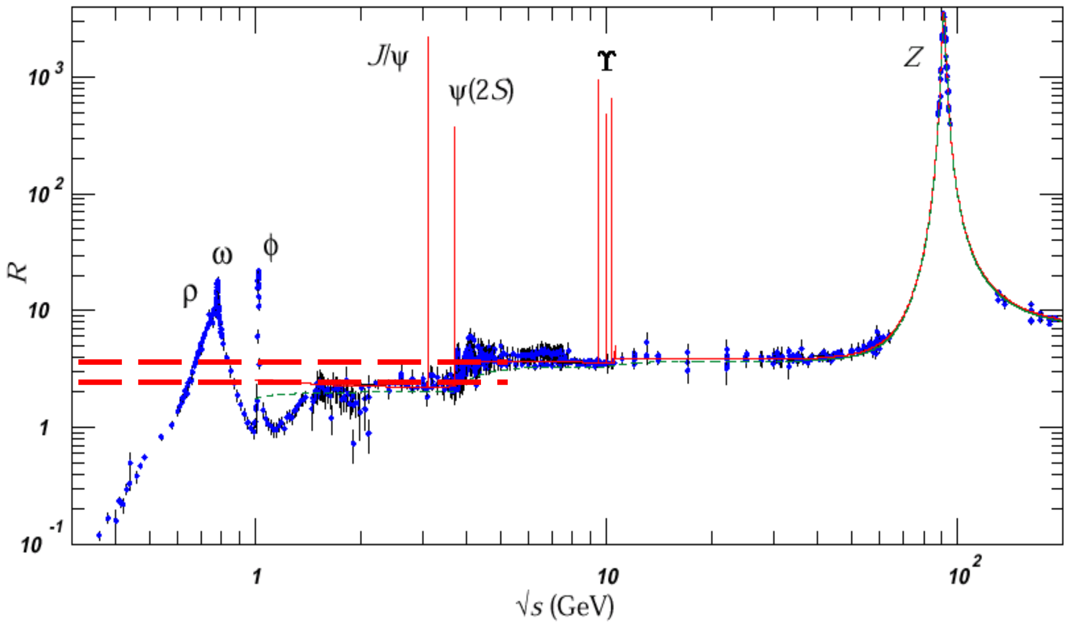


$$\boxed{R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_C \sum_i q_i^2}$$

- With u,d,s R = Nc x [6/9]
- With u,d,s,c R = Nc x [$6/9 + q_c^2$]

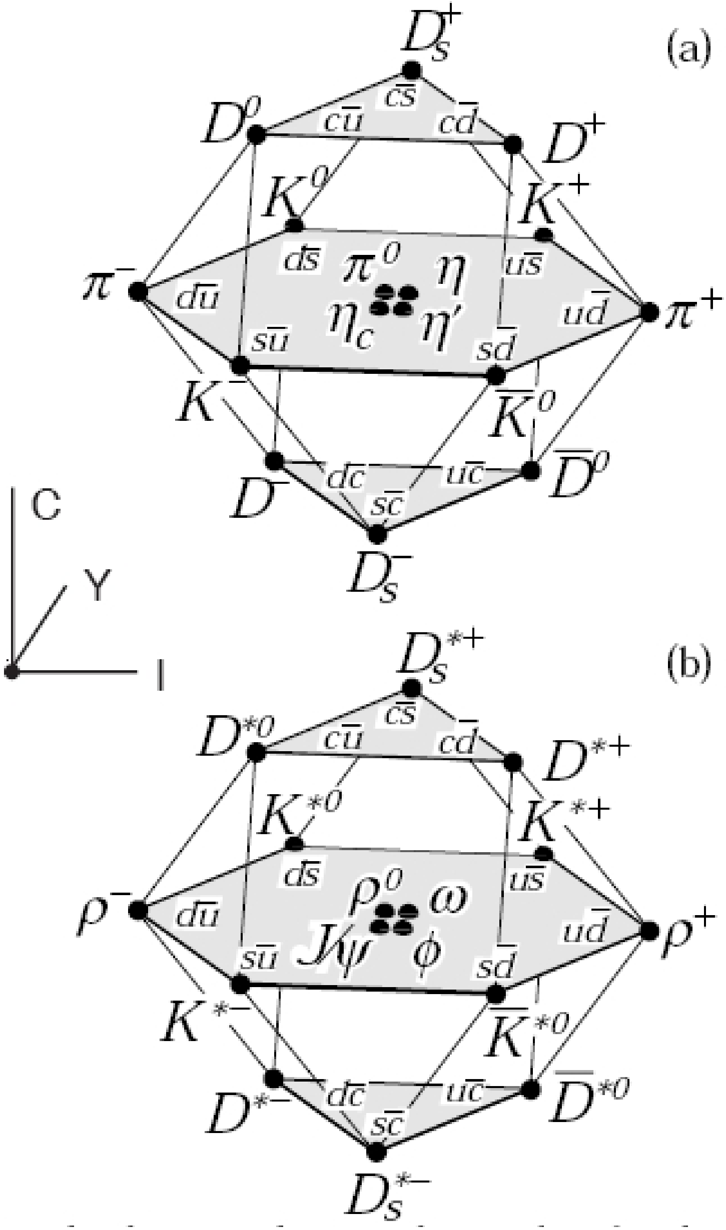
Nc = 3 – number of QCD colours

$q_c = + 2/3$ ; ($c\bar{c}$) state "J/ψ" of ~3.1 GeV

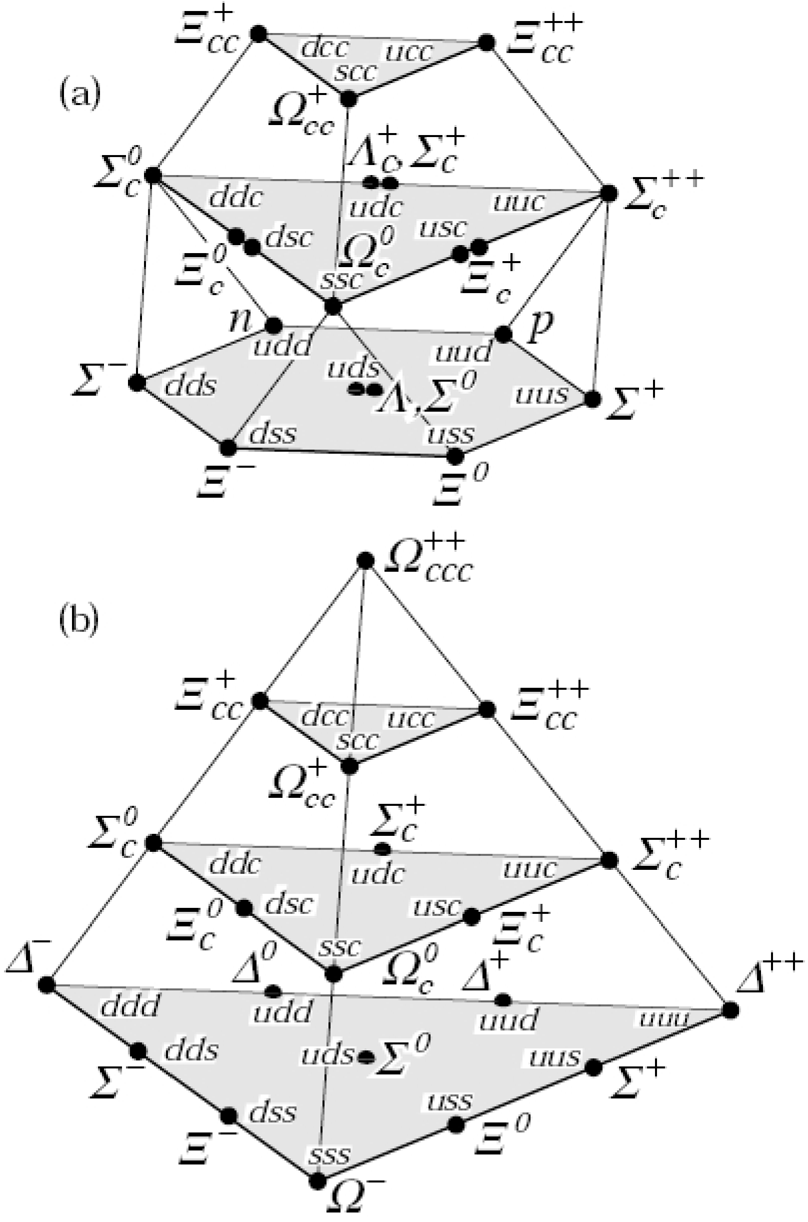


# Charmed hadrons

SU(4) weight diagrams for mesons composed of u,d,s,c quarks



SU(4) multiplets of baryons composed of u,d,s,c quarks



Hyper-charge $Y = S + C + B + T + B'$, Gell-Mann&Nishijima: $Y = 2(Q - I3)$

# Discovery of charm quark

*From Nobel lecture of S. Ting, 1976*

4. CONCLUSION

In conclusion, we can ask ourselves some further questions:

1) We know that the photon transforms itself into p, w, and with a mass of about 1 GeV. It can transform into J and its various associated states with a mass of about 3 - 5 GeV. What happens when we go to higher and higher energies? It seems very unlikely that there should not be many more new series of photon-like particles.

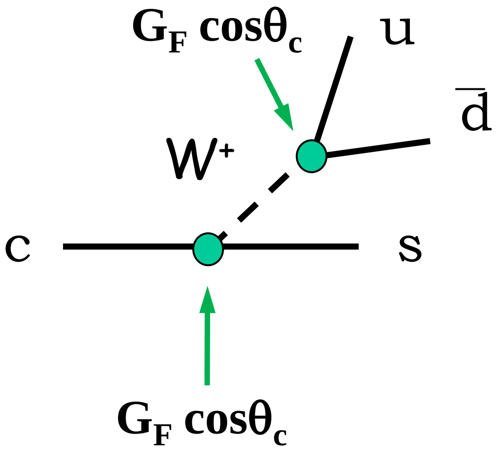
2) The existence of J implies that we need at least four quarks to explain the phenomena observed so far. How many more quarks will we need if we find a new series of particles in higher energy regions?

3) If we need a large family of quarks, are they the real fundamental blocks of nature? Why has none of them been found?

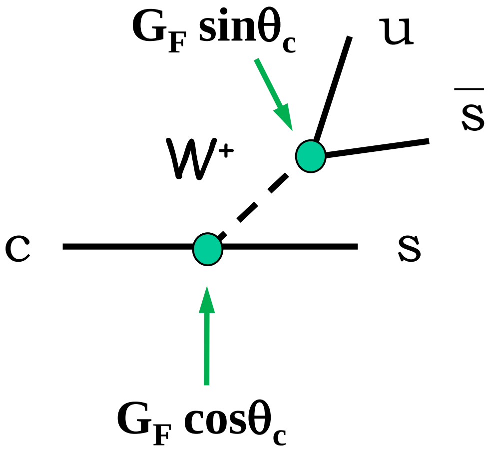
# Charm decays

# Charm weak decays, Cabibbo vocabulary :

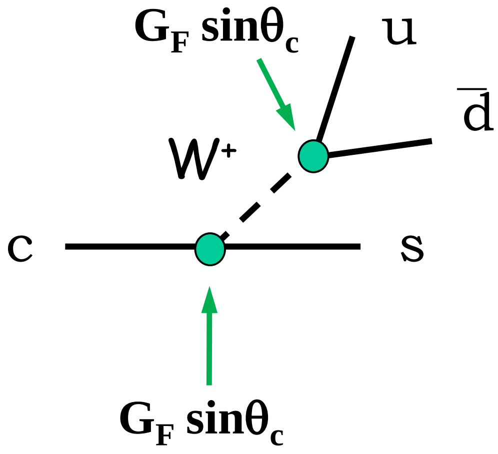
CFD

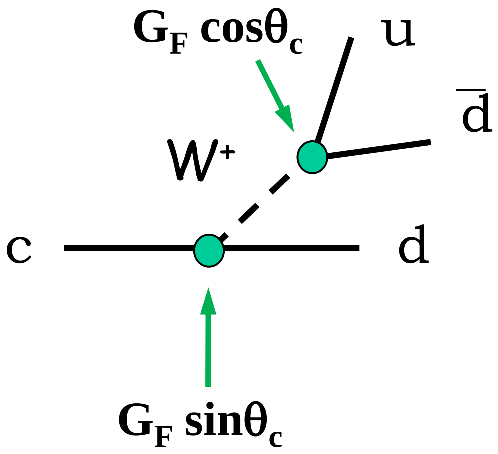


CSD



DCSD



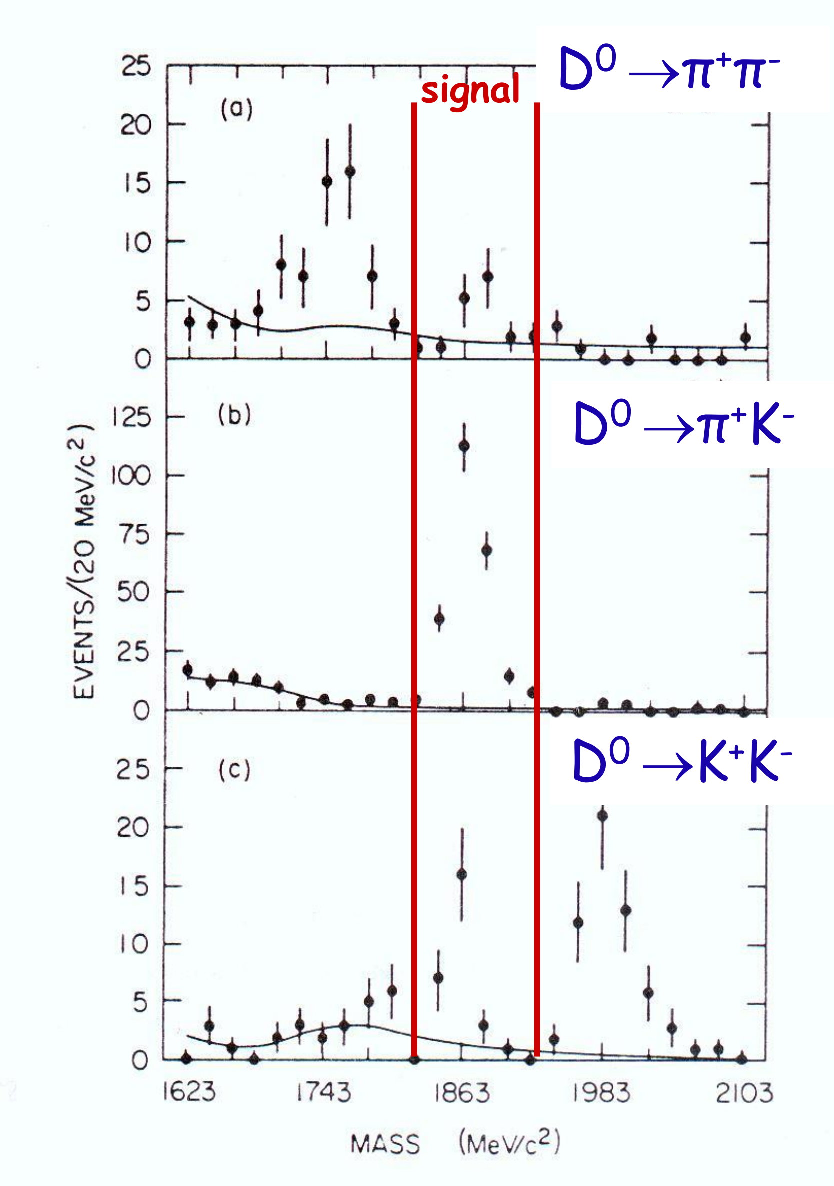


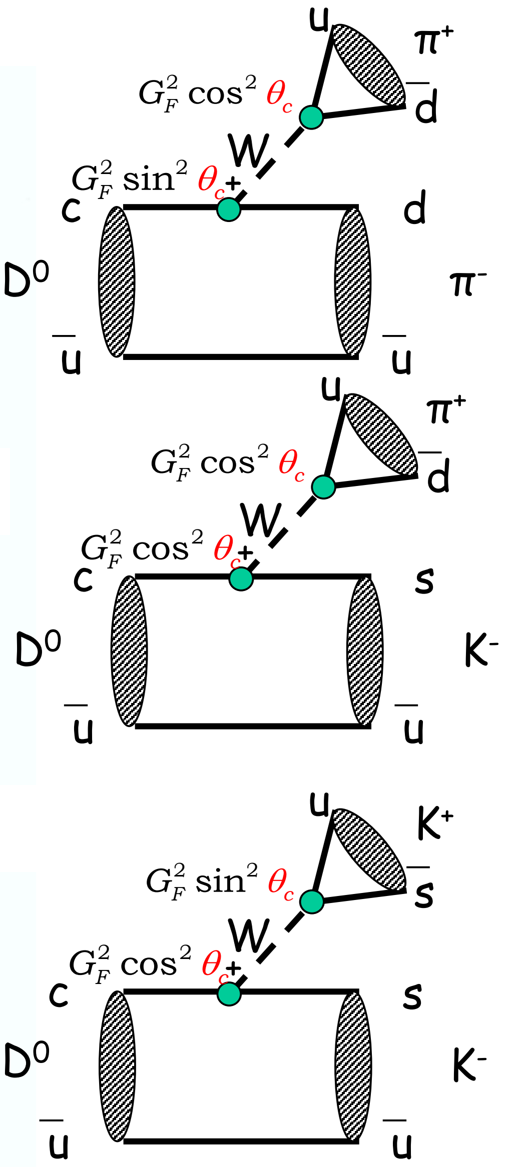
Q: is Cabibbo angle always present at the weak vertex ?

From the lecture of Achille

# D mesons (=mesons with open charm)

$$\begin{pmatrix} c \\ s_c \end{pmatrix} = \begin{pmatrix} c \\ s\cos\theta_c - d\sin\theta_c \end{pmatrix}$$





$$u\bar{d} \quad \sim G_F^2\cos^2\theta_c \sim G_F^2$$

$$u\bar{s} \quad \sim G_F^2\sin^2\theta_c$$

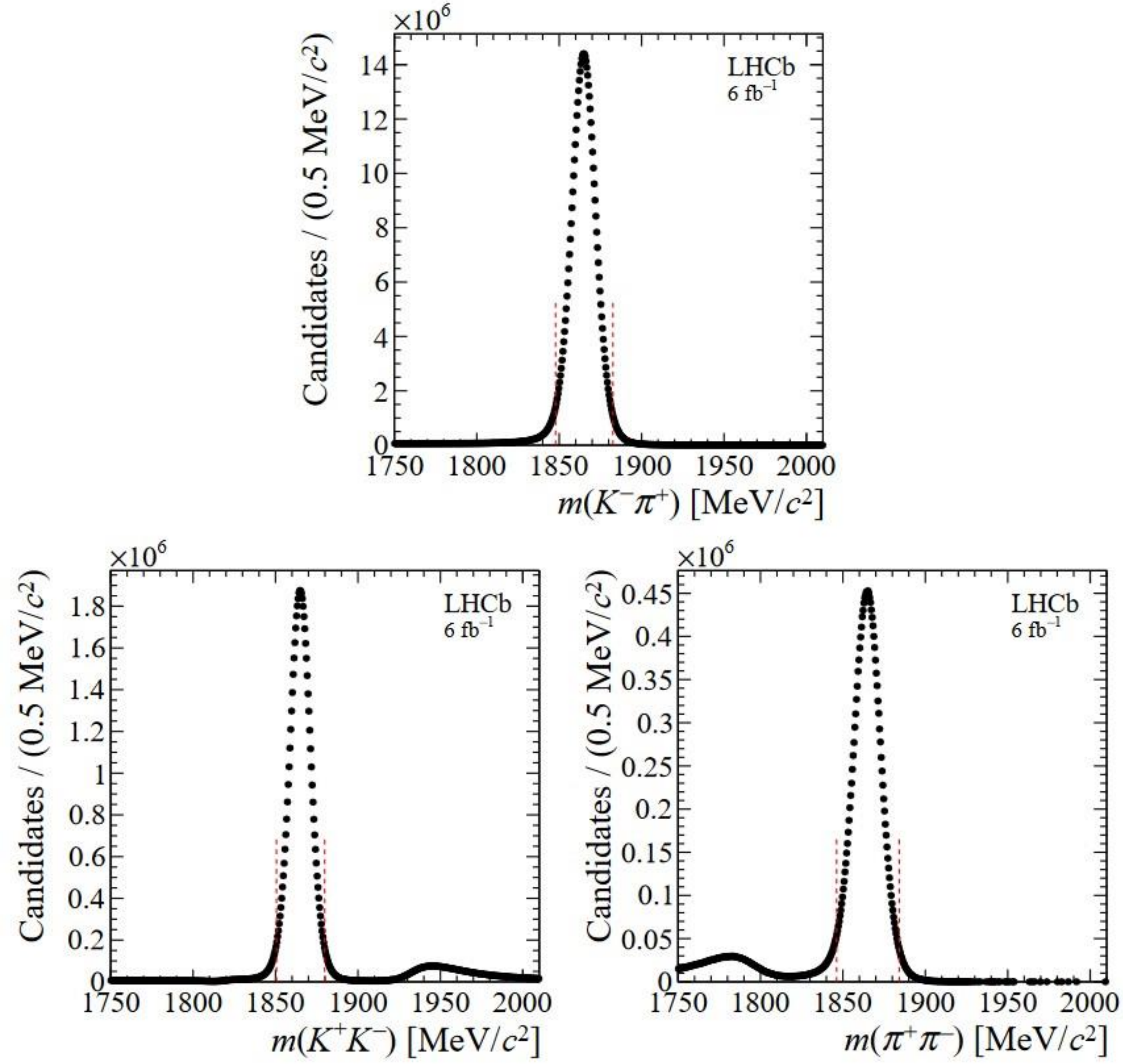
$$c\bar{d} \quad \sim G_F^2\sin^2\theta_c$$

$$c\bar{s} \quad \sim G_F^2\cos^2\theta_c \sim G_F^2$$

# $D\rightarrow hh$ decays

$(D^{*+}\rightarrow\pi^{+})D^{o}\rightarrow h^{+}h^{-}$ decays at LHCb

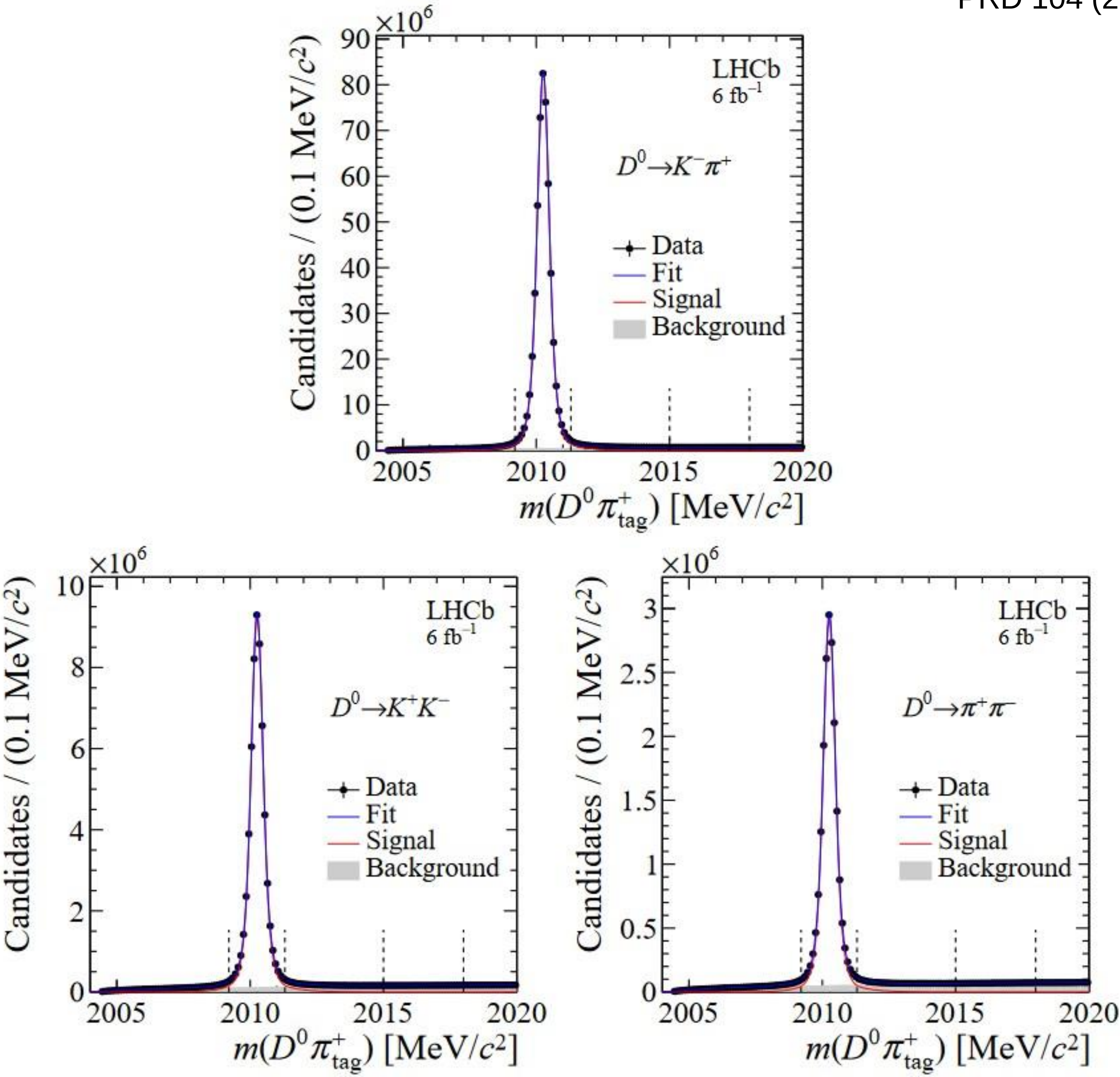
PRD 104 (2021) 072010



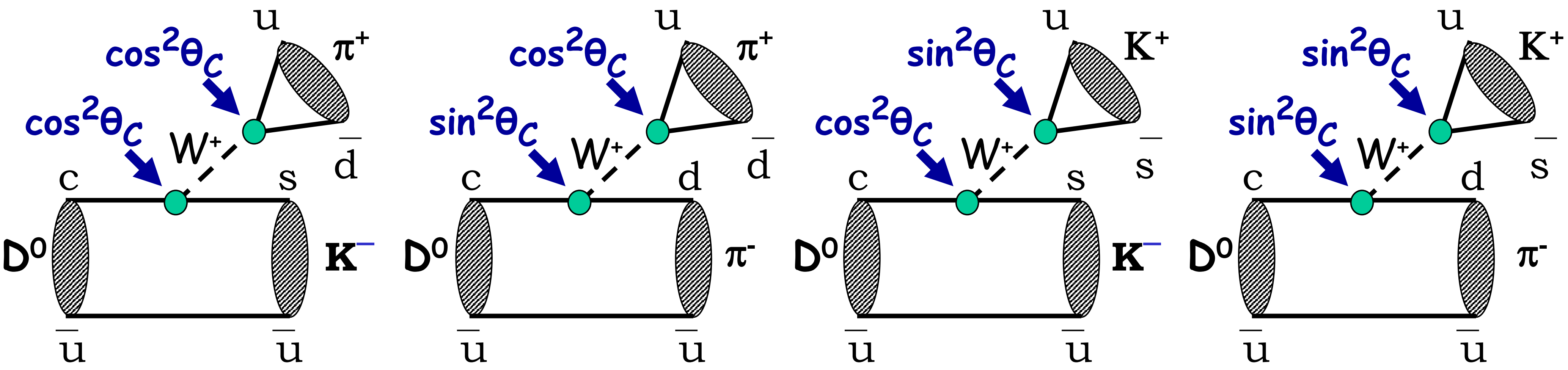
# D→hh decays

(D*+→π+)Do→ h+h- decays at LHCb

PRD 104 (2021) 072010



- ➔ explanation of many measurements :

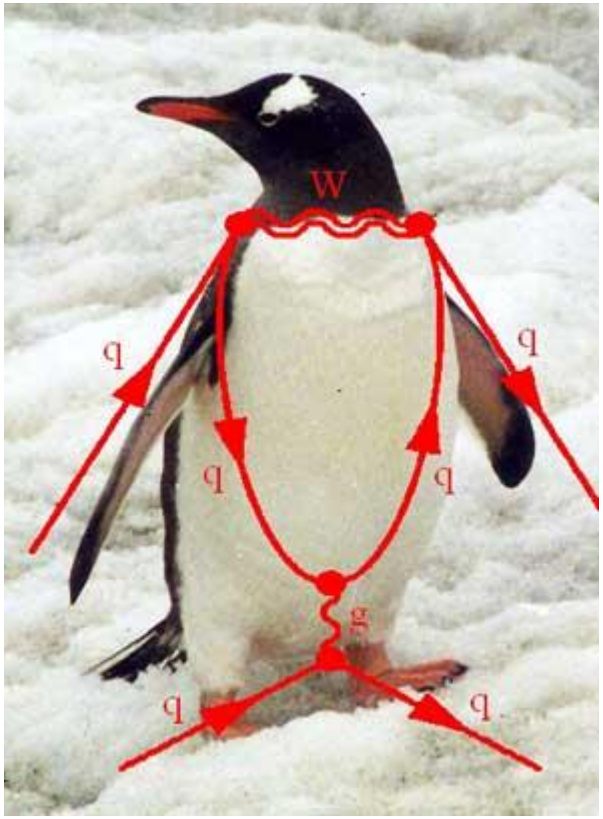


**$BR(D^0 \rightarrow K^- \pi^+) \gg BR(D^0 \rightarrow K^- K^+, \pi^- \pi^+) \gg BR(D^0 \rightarrow K^+ \pi^-)$**

**1 : 20 : 400**

Q: do we need to consider third generation for charm decays ?

# onic D-decays



$^+$

$\overline{s}$

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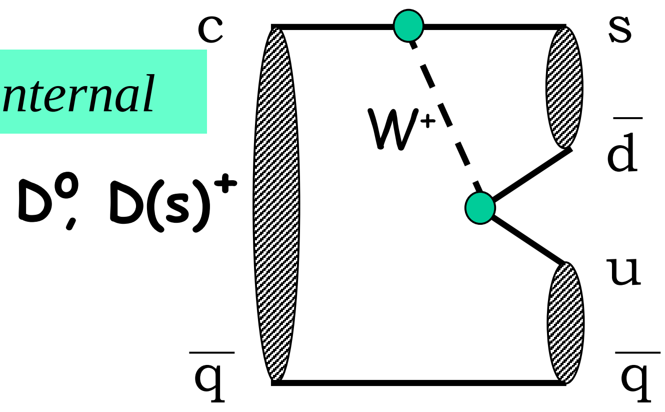
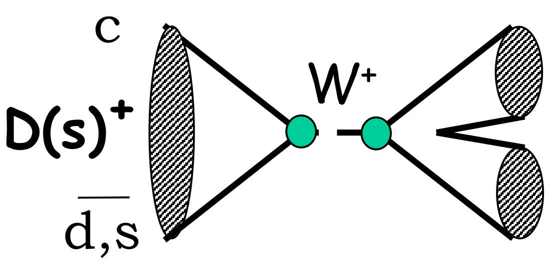
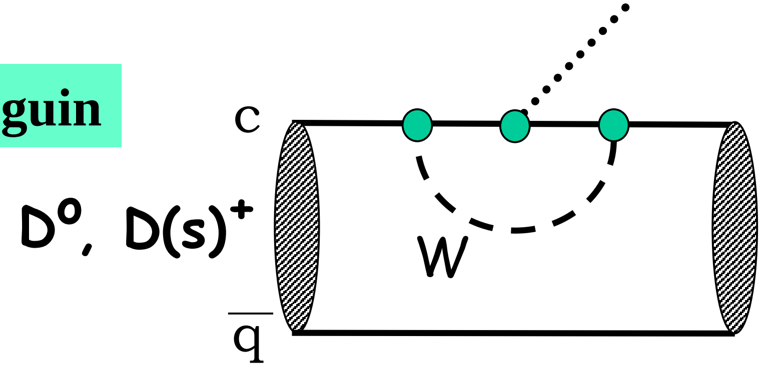
*internal*



**hilation**

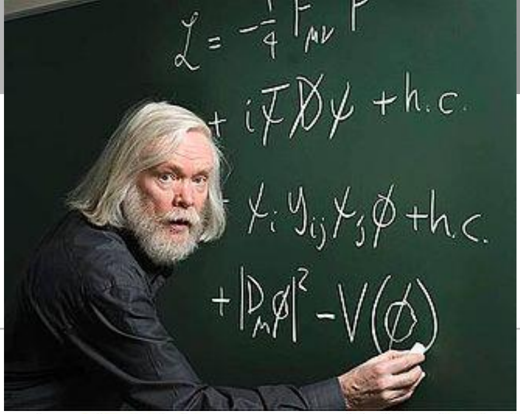


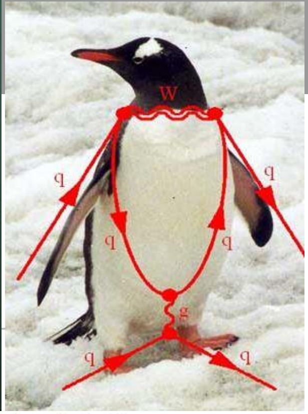
**Penguin**



☐ ***Every line, vertex and loop can contain NP contribution***

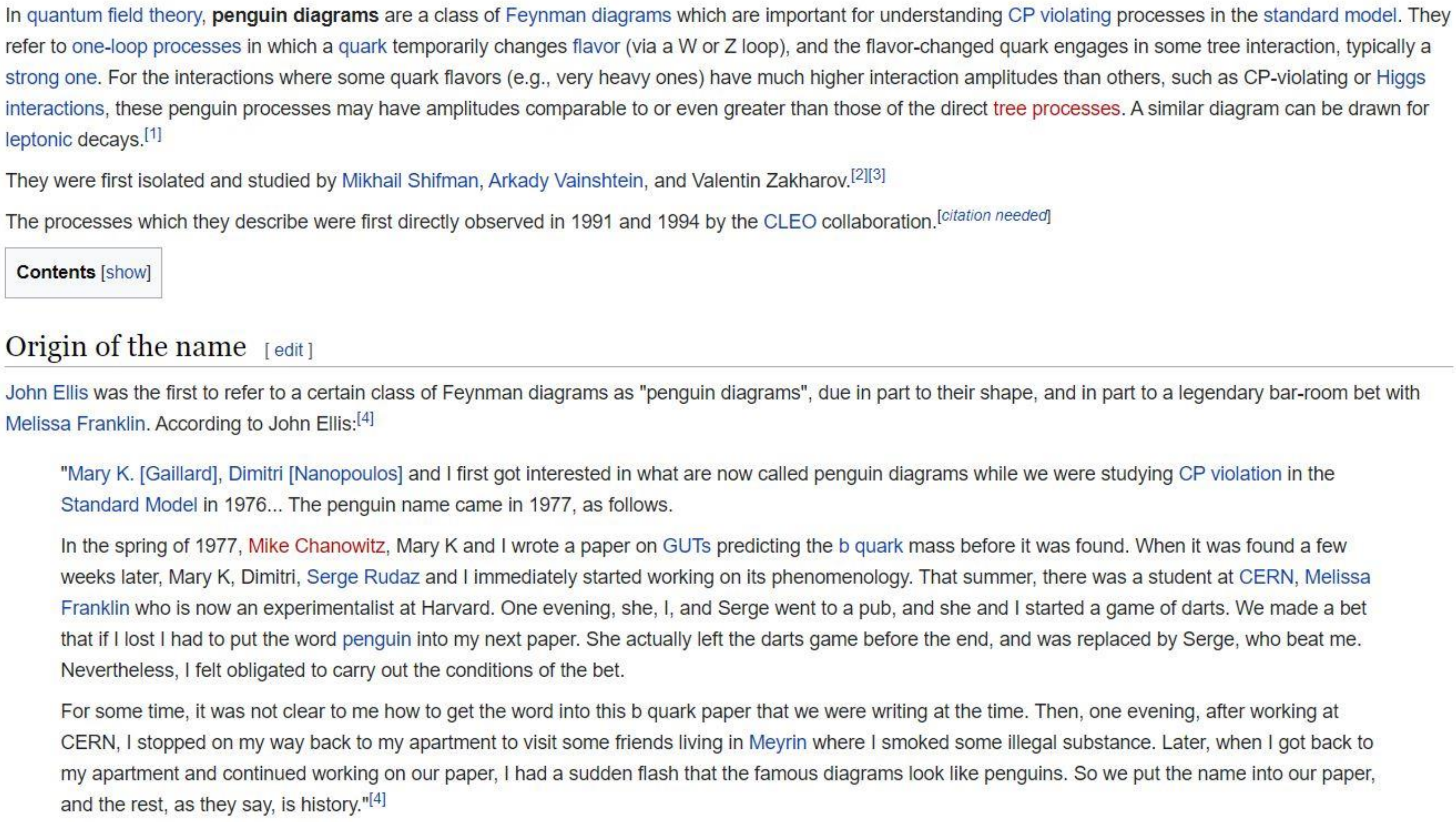
# Penguin ???





## Penguin diagram

From Wikipedia, the free encyclopedia



In quantum field theory, **penguin diagrams** are a class of Feynman diagrams which are important for understanding CP violating processes in the standard model. They refer to one-loop processes in which a quark temporarily changes flavor (via a W or Z loop), and the flavor-changed quark engages in some tree interaction, typically a strong one. For the interactions where some quark flavors (e.g., very heavy ones) have much higher interaction amplitudes than others, such as CP-violating or Higgs interactions, these penguin processes may have amplitudes comparable to or even greater than those of the direct tree processes. A similar diagram can be drawn for leptonic decays.[1]

They were first isolated and studied by Mikhail Shifman, Arkady Vainshtein, and Valentin Zakharov.[2][3]

The processes which they describe were first directly observed in 1991 and 1994 by the CLEO collaboration.[*citation needed*]

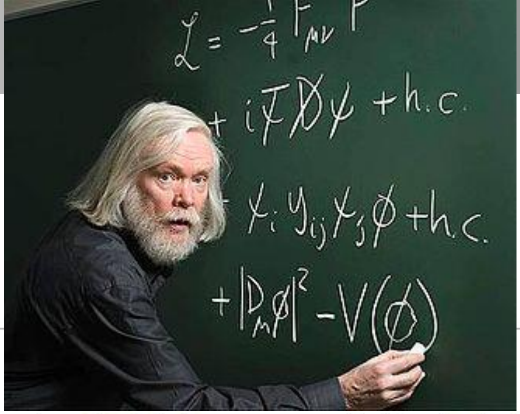
**Contents** [show]

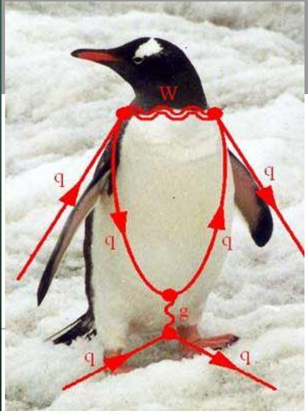
### Origin of the name [ edit ]

John Ellis was the first to refer to a certain class of Feynman diagrams as "penguin diagrams", due in part to their shape, and in part to a legendary bar-room bet with Melissa Franklin. According to John Ellis:[4]

> "Mary K. [Gaillard], Dimitri [Nanopoulos] and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976... The penguin name came in 1977, as follows.
>
> In the spring of 1977, Mike Chanowitz, Mary K and I wrote a paper on GUTs predicting the b quark mass before it was found. When it was found a few weeks later, Mary K, Dimitri, Serge Rudaz and I immediately started working on its phenomenology. That summer, there was a student at CERN, Melissa Franklin who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.
>
> For some time, it was not clear to me how to get the word into this b quark paper that we were writing at the time. Then, one evening, after working at CERN, I stopped on my way back to my apartment to visit some friends living in Meyrin where I smoked some illegal substance. Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history."[4]

# Penguin ???





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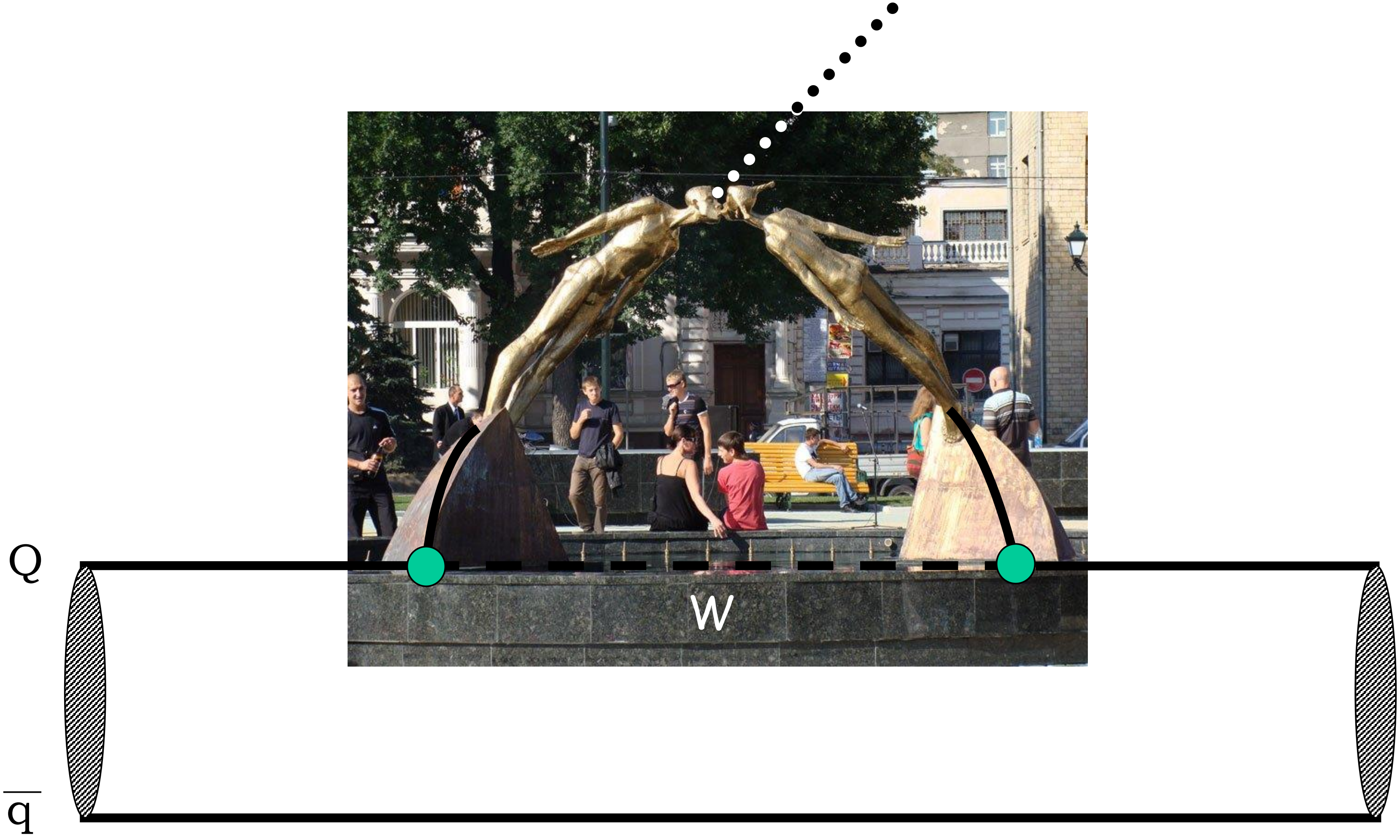
**« Drugs are bad ! »**
**Tim Gershon**

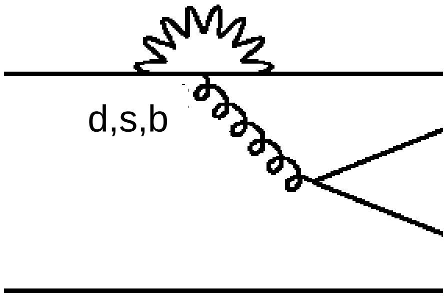
# Penguin ???

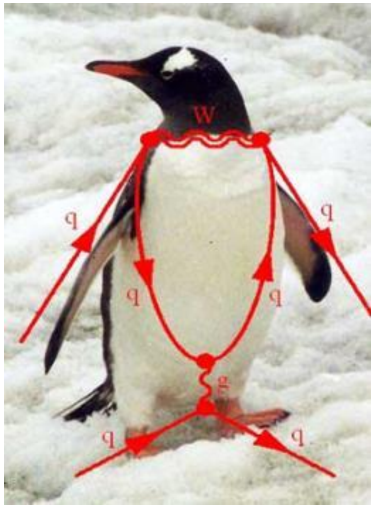


*Kharkiv, Lovers fountain, before the war*

# Standard Model penguins

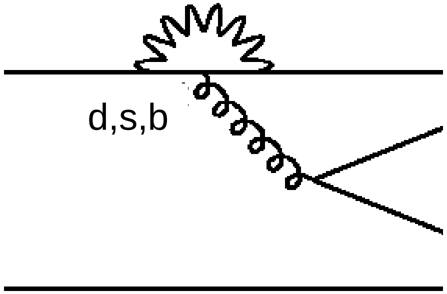
**SM penguin**



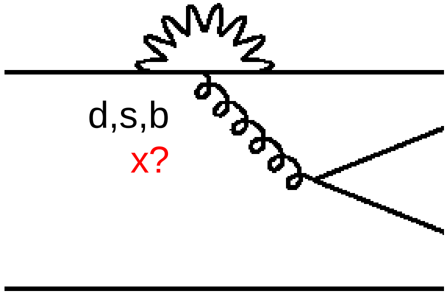


# Standard Model penguins and others

**Penguin :**

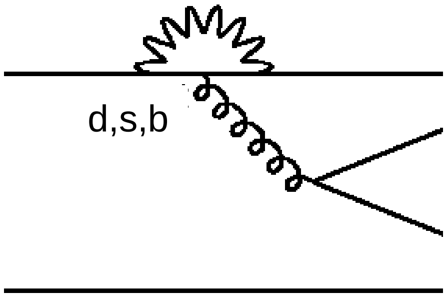


**Penguin :**

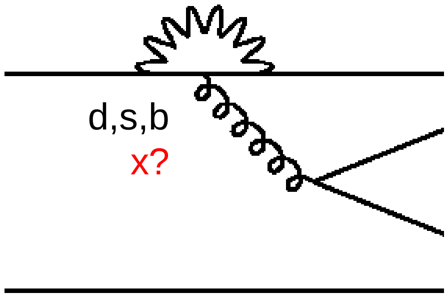


# Standard Model penguins and others

**Penguin :**

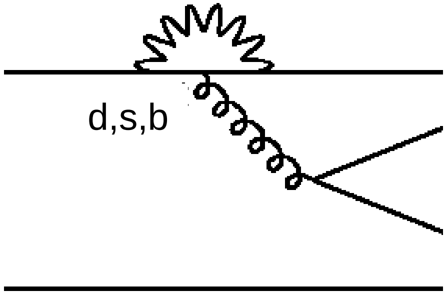


**Penguin :**

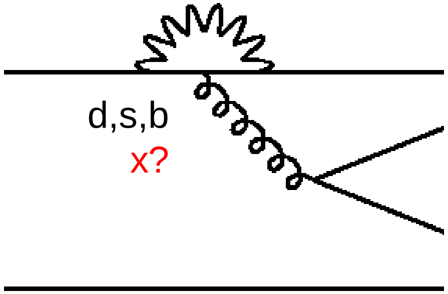


# Standard Model penguins and others

**Penguin :**



**Penguin :**



… with my compliments to the old Microsoft/Linux battle …

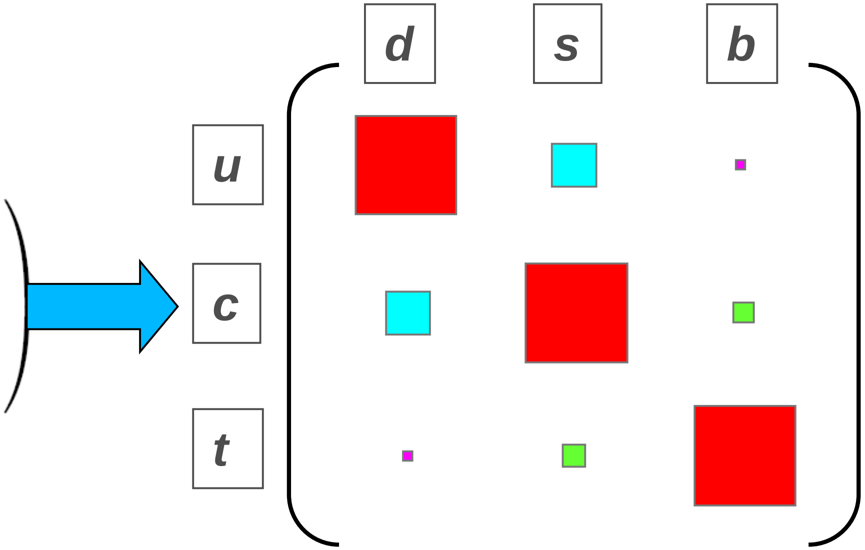
From the lecture of Achille

Weak interaction eigenstates ≠ Mass eigenstates (≡ flavour or strong interaction eigenstates)

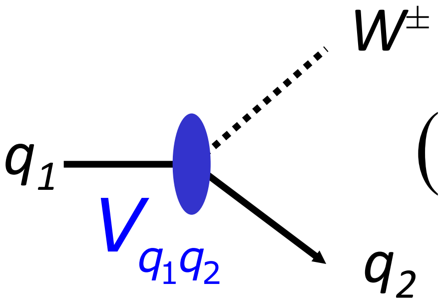
$$\boxed{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \boxed{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}$$

**$V_{CKM}$** 3X3 unitary (complex) matrix describing the **quarks mixing**: the **CKM matrix**

$$\begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$



As a consequence, the charged currents couplings are given through:



$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} \boxed{\begin{matrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{matrix}} & \begin{matrix} V_{ub} \\ V_{cb} \end{matrix} \\ \begin{matrix} V_{td} & V_{ts} \end{matrix} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

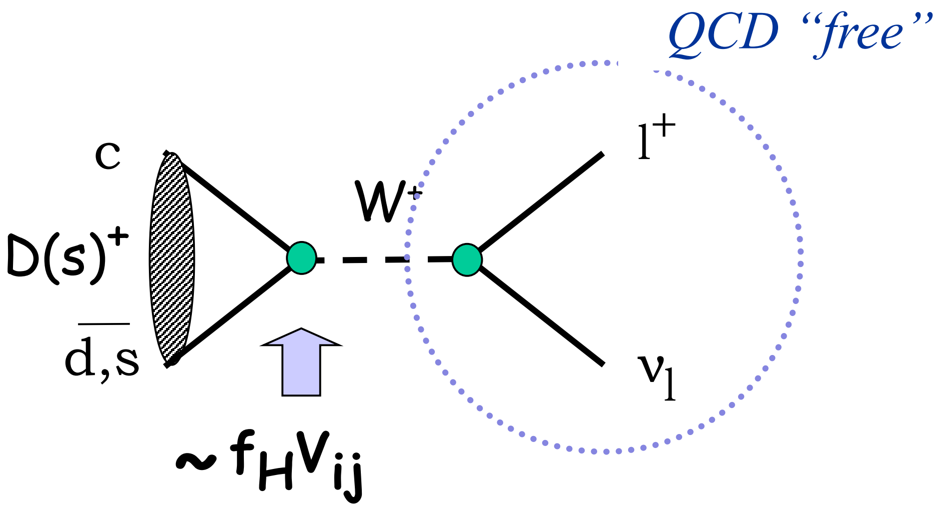
| **1** | $\lambda$ | $\lambda^2$ | $\lambda^3$ |
|---|---|---|---|
| **same** | **1-2** | **2-3** | **1-3** |

**family**

**$\lambda = \sin\theta_c \sim 0.22$**

# How to calculate charm decays

## Take into account QCD contribution

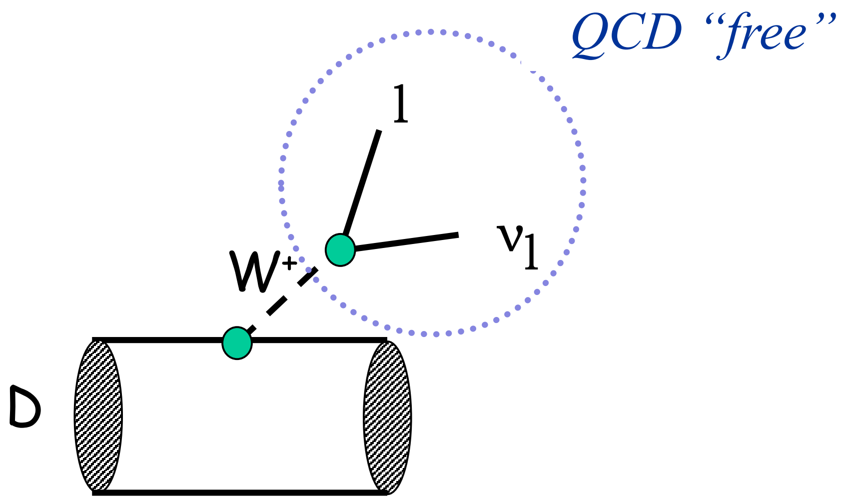


**Leptonic decay, weak annihilation**

$|V_{ij}| \sim \lambda$ or 1 for D-decays

$|V_{ij}| \sim \lambda^3$ or $\lambda^2$ for B-decays

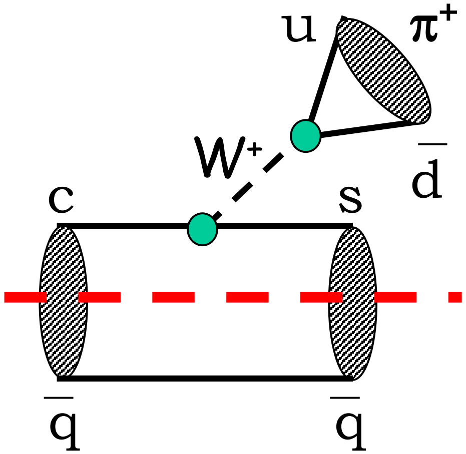
Helicity suppressed

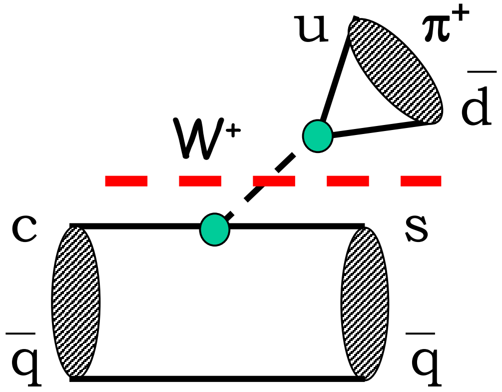


**SL decay, W emission**

## First aid tools

**“Spectator” assumption** “Factorization” approach





# Historical charm puzzles

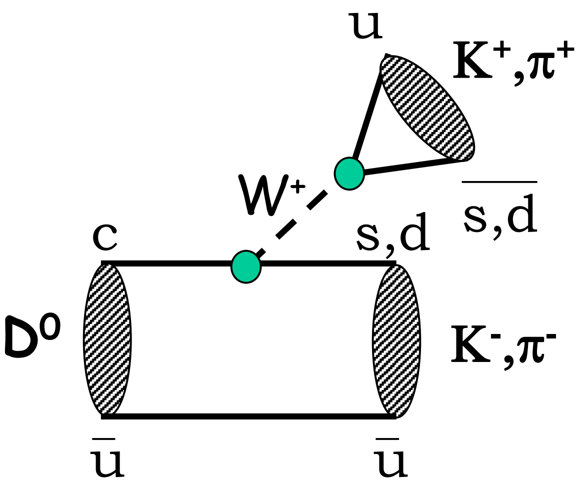
$D^0 = (c\bar{u})$
$D^+ = (c\bar{d})$
$D_s^+ = (c\bar{s})$

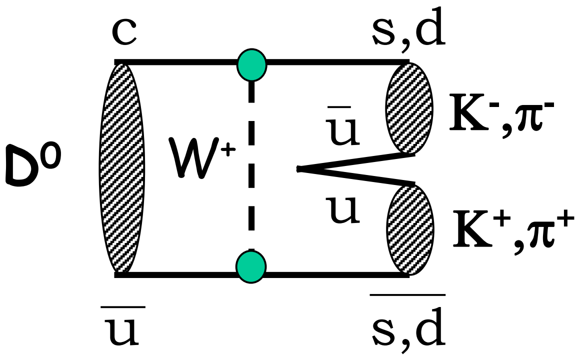
- Lifetime spread

$$\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+) < \tau(D^0) < \tau(D_S^+) < \tau(D^+)$$

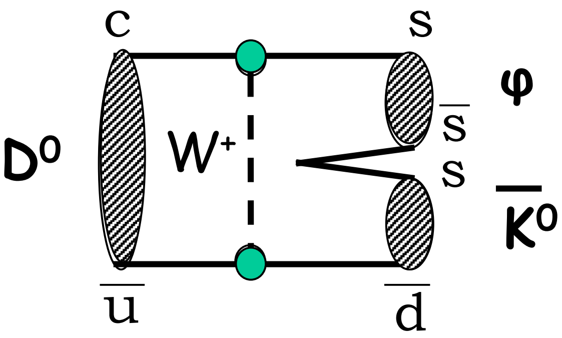
**$\tau(D+)/\tau(D0)$ ~2.54 ; $\tau(D+)/\tau(\Omega c)$ ~15**

- $D^o \rightarrow K^-K^+$ vs. $D^o \rightarrow \pi^-\pi^+$ puzzle, BR($D^o \rightarrow K^-K^+$) / BR($D^o \rightarrow \pi^-\pi^+$) ~2.5





- $D^o \rightarrow \varphi K^o$ puzzle, BR($D^o \rightarrow \varphi K^o$) ~ 0.8%



# Lifetime spread

## Beauty lifetimes

$B^- = (b\bar{u})$
$\bar{B}^0 = (b\bar{d})$
$\bar{B}_s{}^0 = (b\bar{s})$

τ(Λb)<τ(Ξb) <τ(Bs)<τ(B0) <τ(B+)

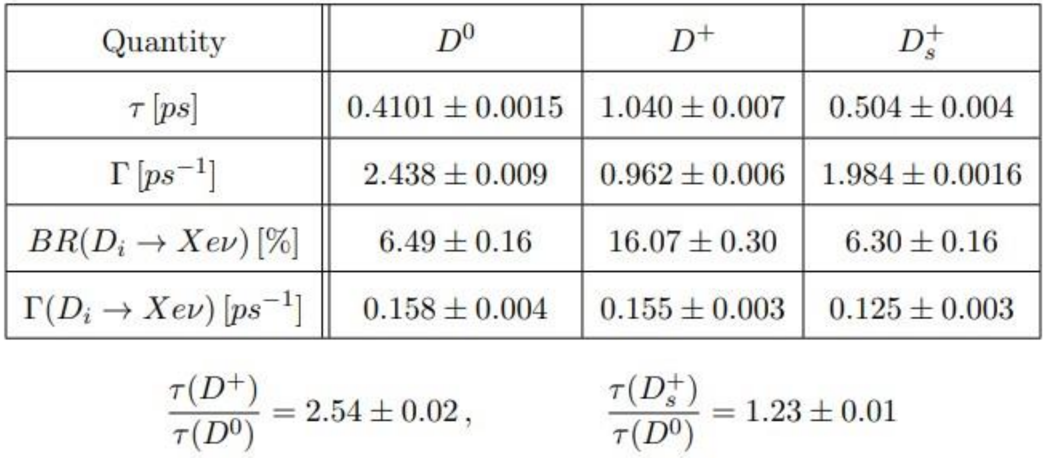
τ(B+)/τ(Bs) ~1.1, τ(B+)/τ(Λb) ~1.2

## Charm lifetimes

$$\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+) < \tau(D^0) < \tau(D_S^+) < \tau(D^+)$$

τ(D+)/τ(D0) ~2.54 ; τ(D+)/τ(Ωc) ~15

$D^0 = (c\bar{u})$
$D^+ = (c\bar{d})$
$D_s{}^+ = (c\bar{s})$



| Quantity | $D^0$ | $D^+$ | $D_s^+$ |
|---|---|---|---|
| $\tau\ [ps]$ | $0.4101 \pm 0.0015$ | $1.040 \pm 0.007$ | $0.504 \pm 0.004$ |
| $\Gamma\ [ps^{-1}]$ | $2.438 \pm 0.009$ | $0.962 \pm 0.006$ | $1.984 \pm 0.0016$ |
| $BR(D_i \to Xe\nu)\ [\%]$ | $6.49 \pm 0.16$ | $16.07 \pm 0.30$ | $6.30 \pm 0.16$ |
| $\Gamma(D_i \to Xe\nu)\ [ps^{-1}]$ | $0.158 \pm 0.004$ | $0.155 \pm 0.003$ | $0.125 \pm 0.003$ |

$$\frac{\tau(D^+)}{\tau(D^0)} = 2.54 \pm 0.02\,, \qquad \frac{\tau(D_s^+)}{\tau(D^0)} = 1.23 \pm 0.01$$

# Phenomenological game with charm meson lifetimes

**$D^0$ = $(c\bar{u})$**
**$D^+$ = $(c\bar{d})$**
**$D_s^+$ = $(c\bar{s})$**

$$\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+) < \tau(D^0) < \tau(D_S^+) < \tau(D^+)$$

**τ(D+)/τ(D0) ~2.54 ; τ(D+)/τ(Ωc) ~15**

*DCSD vs. CAD* $D^+ \to K^\pm\pi^\mp\pi^+$ ⇒ **Pauli interference effect**

⊕ $\tau(D^+)$ *vs.* $\tau(D^0)$ ⇒ $W$ – **exchange contribution**

⊕ $\tau(D_S^+)$ *vs.* $\tau(D^0)$ ⇒ $W$ – **annihilation contribution**

$$\frac{\mathcal{B}(D^+\to K^+\pi^+\pi^-)}{\mathcal{B}(D^+\to K^-\pi^+\pi^+)} \approx \frac{\Gamma_{SP}}{\Gamma_{PI}} \times \tan^4\theta_C$$

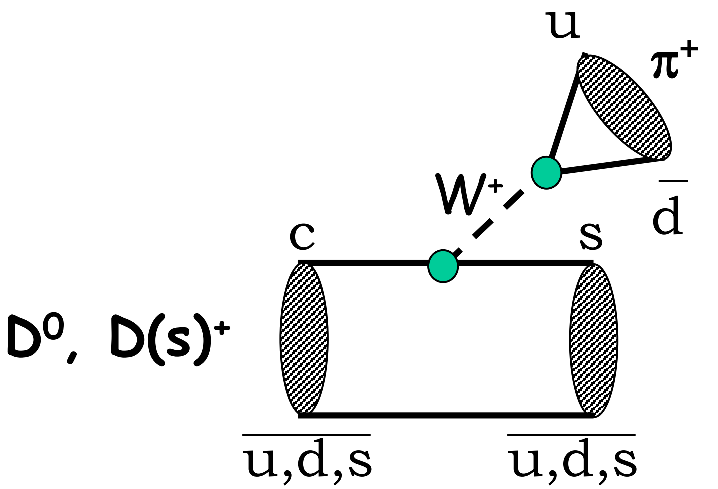
$$\Rightarrow \quad \frac{\Gamma_{PI}}{\Gamma_{SP}} \approx 0.4$$

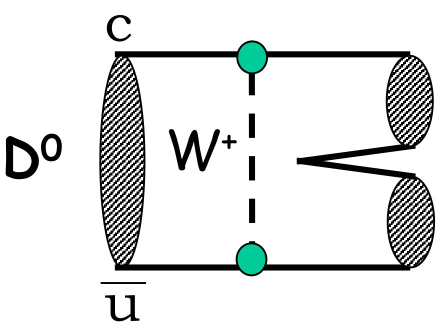
$$\frac{\tau_{D^+}}{\tau_{D^0}} = \frac{\Gamma_{SP} + \Gamma_{WX} + \Gamma_{SL}}{\Gamma_{PI} + \Gamma_{SL}}$$

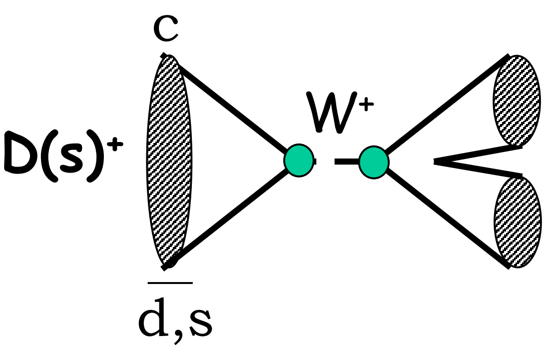
$$\Rightarrow \quad \frac{\Gamma_{WX}}{\Gamma_{SP}} \approx 0.3$$

$$\frac{\tau_{D_S^+}}{\tau_{D^0}} = 1.05 \times \frac{\Gamma_{SP} + \Gamma_{WX} + \Gamma_{SL}}{\Gamma_{SP} + \Gamma_{WA} + \Gamma_{SL}}$$

$$\Rightarrow \quad \frac{\Gamma_{WA}}{\Gamma_{SP}} \approx 0.1$$







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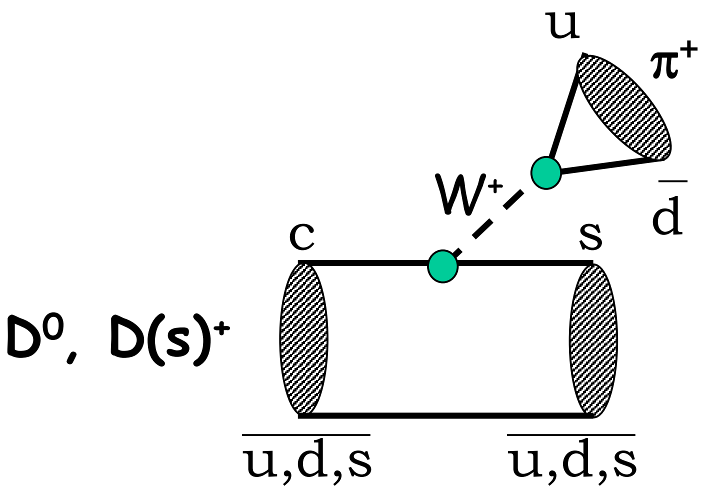
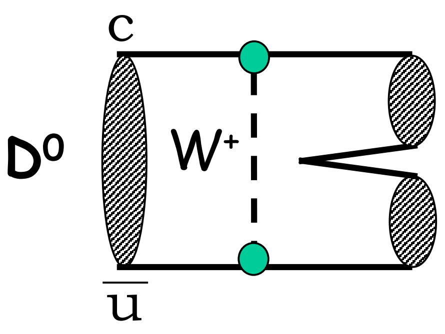
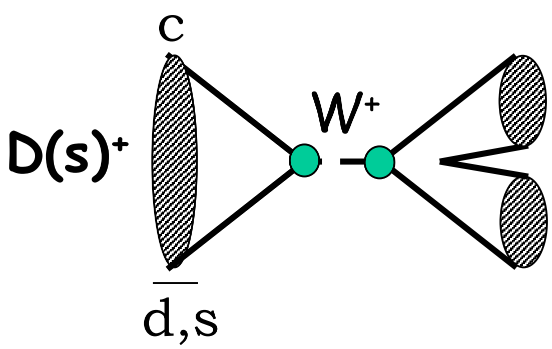


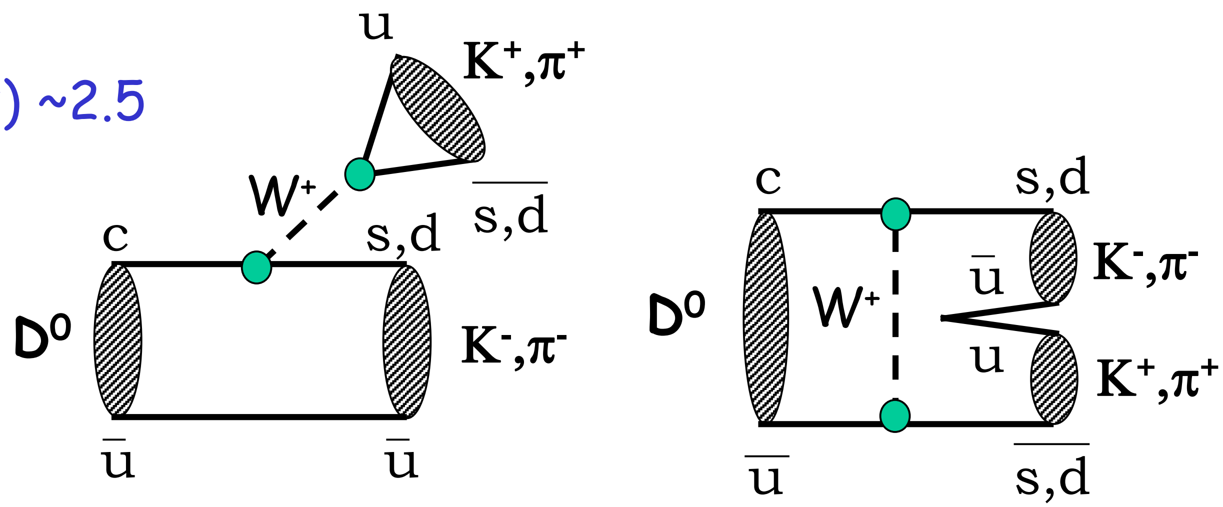




**Well done ... however, new LHCb measurements of charmed baryon lifetimes cannot be explained**

# $D^o \rightarrow K^-K^+$ vs. $D^o \rightarrow \pi^-\pi^+$ puzzle

- ❑ Experimental value :
  $BR(D^o \rightarrow K^-K^+) / BR(D^o \rightarrow \pi^-\pi^+) \sim 2.5$
- ❑ Similar diagrams :

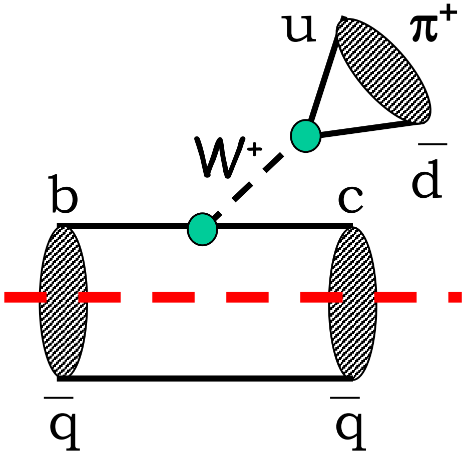


- ❑ Naively (SU(3) flavour symmetry): $BR(D^o \rightarrow K^-K^+) / BR(D^o \rightarrow \pi^-\pi^+) = 1.$
- ❑ Phase space difference: × 0.89
- ❑ Different decay constants for K and π: $\times (f_K / f_\pi)^2 \sim 1.49$
- ❑ Finally expected: $BR(D^o \rightarrow K^-K^+) / BR(D^o \rightarrow \pi^-\pi^+) \sim 1.29$
- ❑ SU(3) breaking effects: ~1.29 → ~1.4 « 2.5
- ❑ Contribution from final state interactions ?

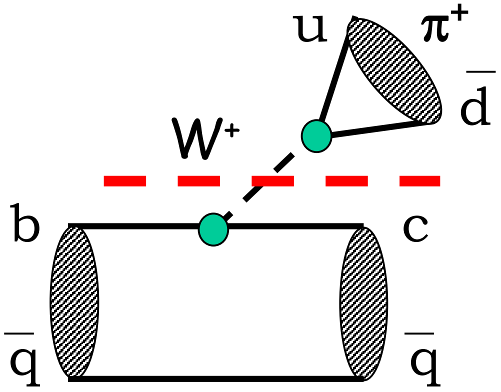
# How to calculate charm hadronic decays

## First aid tools

“Spectator” assumption

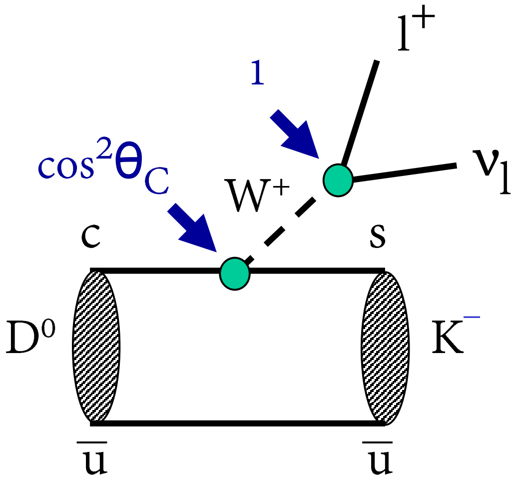


**“Factorization” approach**



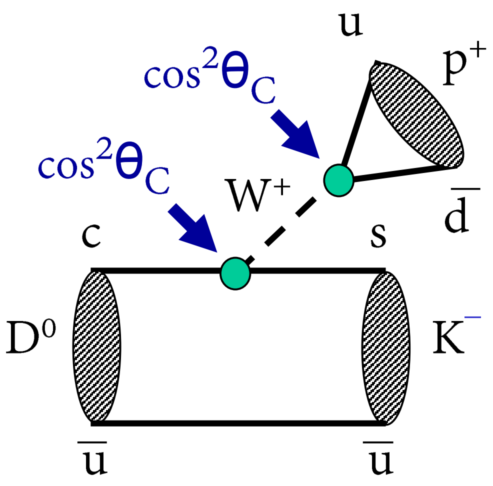
# Factorization : treat QCD contribution

*Bauer, Stech, Wirbel*



**Easy: SL decay**

ū – purely spectator quark



**Difficult: hadronic decay**

"For one of the currents use only asymptotic part of the hadronic field"

$$
\begin{aligned}
A(D^0 \to K^-\pi^+) &= \frac{G_F}{\sqrt{2}} \cos^2\theta \cdot a_1 < \pi|(\bar{u}d)_\mu|0 >< K^-|(\bar{s}c)^\mu|D^0 > \\
&= \frac{G_F}{\sqrt{2}} \cos^2\theta \cdot a_1(-if_\pi)p^\pi_\mu < K^-|(\bar{s}c)^\mu|D^0 > |_{q^2=m^2_\pi} .
\end{aligned}
$$

# Factorization : treat QCD contribution

Beyond factorization : treat QCD contribution

*Bauer, Stech, Wirbel*

Very difficult:
→ Final state interactions, etc.

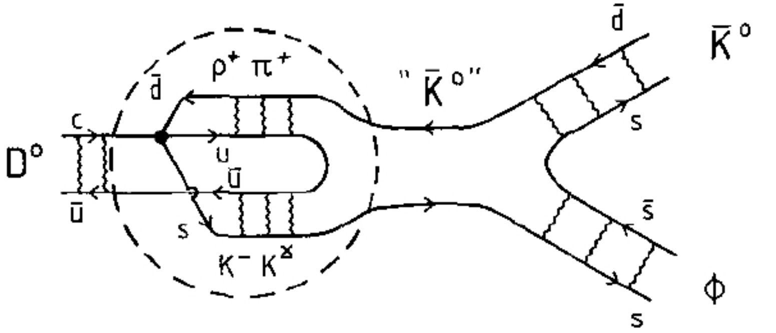


**Fig. 2.** "Quark annihilation" from "quark decay" and subsequent final state interaction in the process $D^0 \to \bar{K}^0 \phi$. The dotted region describes the subprocess $D^0 \to$ "$\bar{K}^0$" where the "$\bar{K}^0$" states carry the quantum numbers of a $\bar{K}^0$-meson

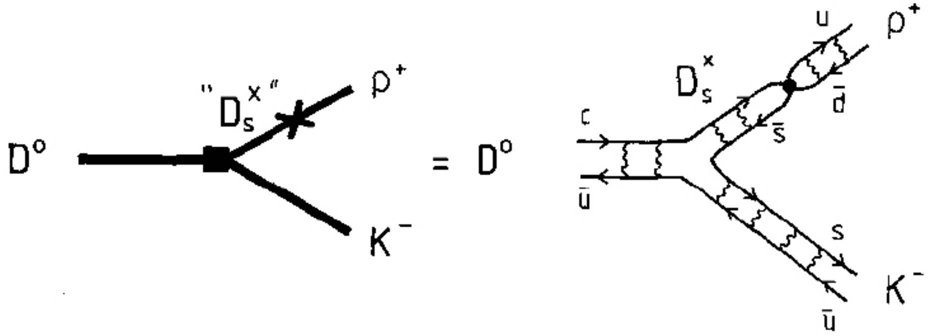
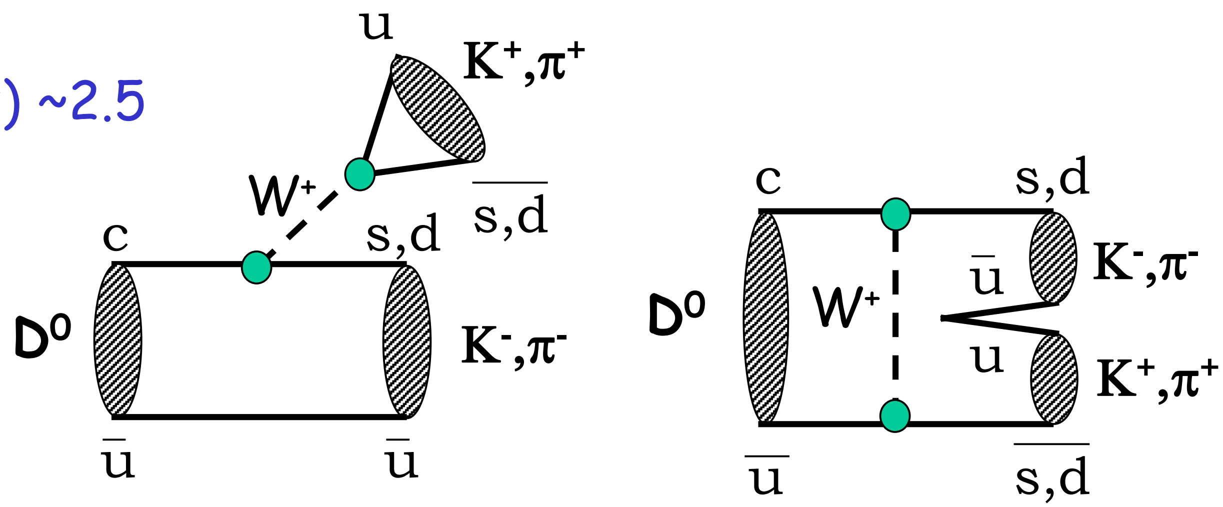


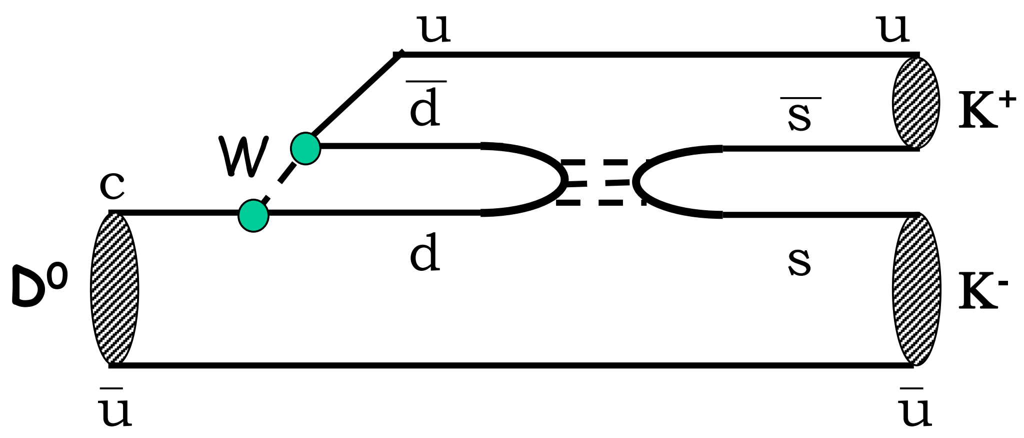
**Fig. 4.** Decay graph on the level of hadrons. The strong vertex ■ proceeds the weak transition. The cross denotes the subsequent weak vertex. The flavour flow has quark decay topology (the $\bar{u}$ quark acts as a spectator)

# $D^0 \rightarrow K^-K^+$ vs. $D^0 \rightarrow \pi^-\pi^+$ puzzle

- ❑ Experimental value :
  $BR(D^0 \rightarrow K^-K^+) / BR(D^0 \rightarrow \pi^-\pi^+) \sim 2.5$
- ❑ Similar diagrams :

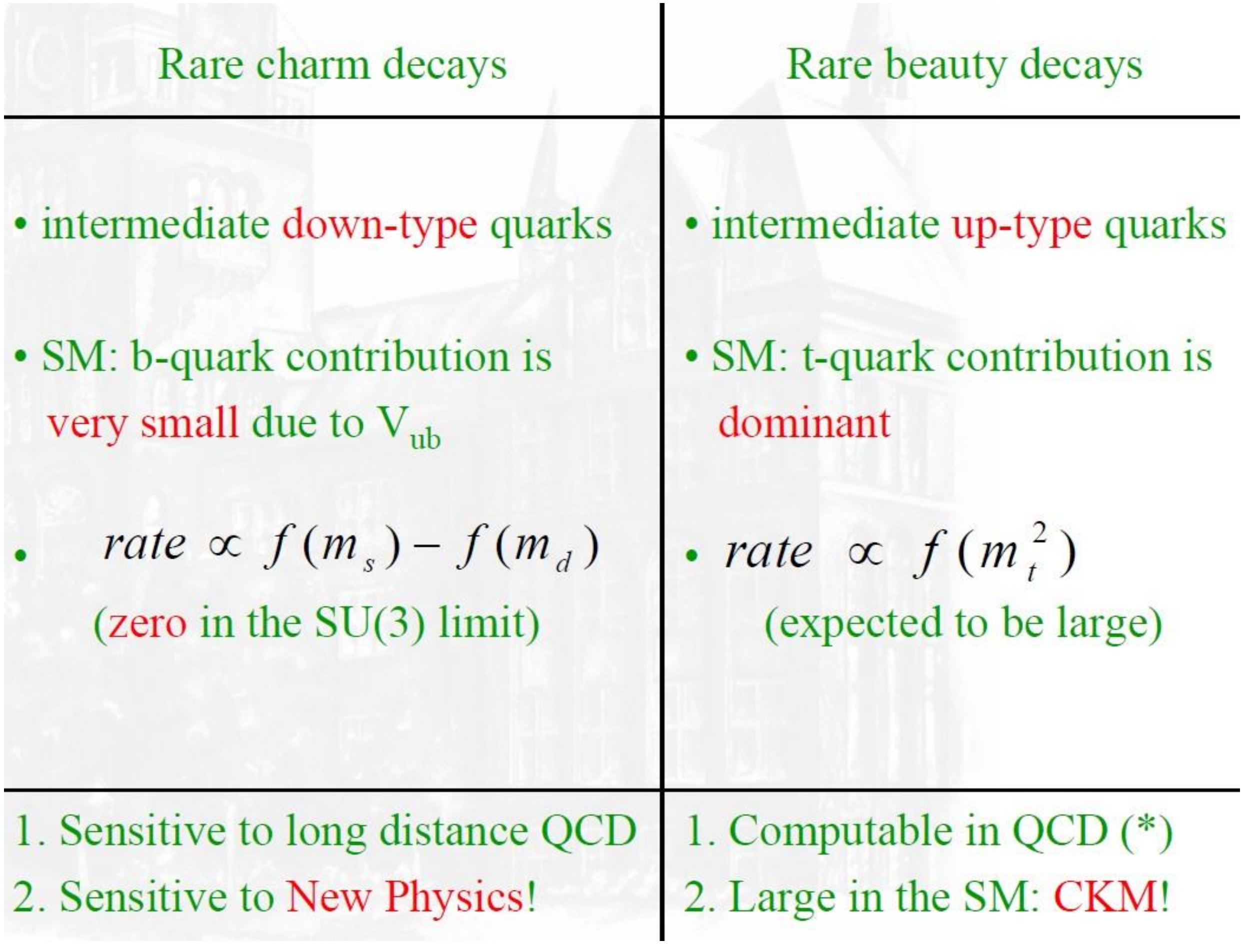


- ❑ Naively (SU(3) flavour symmetry): $BR(D^0 \rightarrow K^-K^+) / BR(D^0 \rightarrow \pi^-\pi^+) = 1.$
- ❑ Phase space difference: × 0.89
- ❑ Different decay constants for K and π: $\times (f_K / f_\pi)^2 \sim 1.49$
- ❑ Finally expected: $BR(D^0 \rightarrow K^-K^+) / BR(D^0 \rightarrow \pi^-\pi^+) \sim 1.29$
- ❑ SU(3) breaking effects: ~1.29 → ~1.4 « 2.5
- ❑ Contribution from **final state interactions** ?
  E.g. "K" <-> "π" transitions ?



# Rare decays

- ❑ Rare decays ... usually, processes involving FCNC
- ❑ Why interesting in charm sector ?

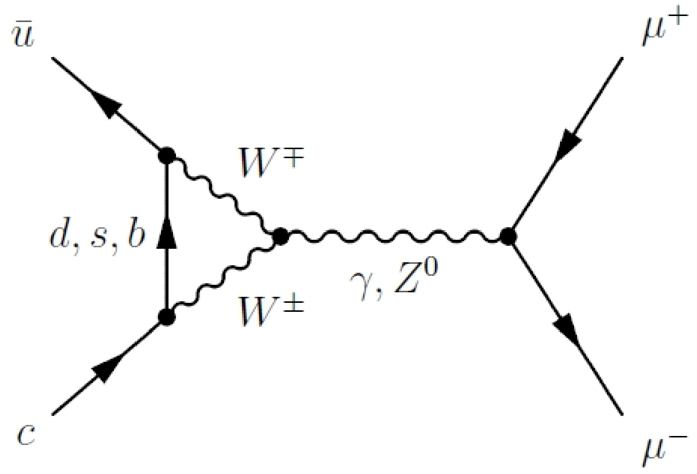


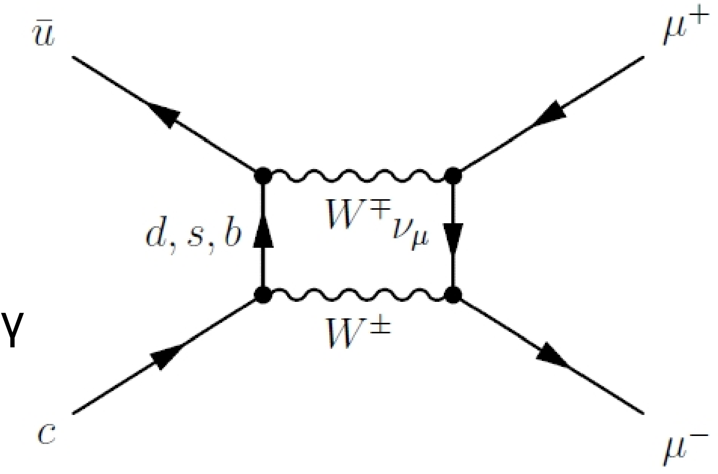
| Rare charm decays | Rare beauty decays |
|---|---|
| • intermediate down-type quarks | • intermediate up-type quarks |
| • SM: b-quark contribution is very small due to $V_{ub}$ | • SM: t-quark contribution is dominant |
| • $rate \propto f(m_s) - f(m_d)$<br>(zero in the SU(3) limit) | • $rate \propto f(m_t^2)$<br>(expected to be large) |
| 1. Sensitive to long distance QCD<br>2. Sensitive to New Physics! | 1. Computable in QCD (*)<br>2. Large in the SM: CKM! |

From A Petrov

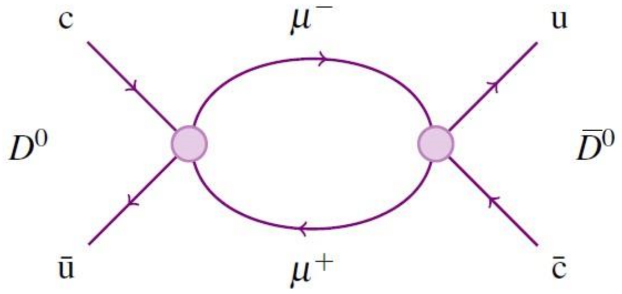
# Rare decays

- E.g. : D→ee, **D→μμ,** FCNC decay, helicity suppression
- Standard Model, BR ~ $10^{-13}$ – $10^{-11}$





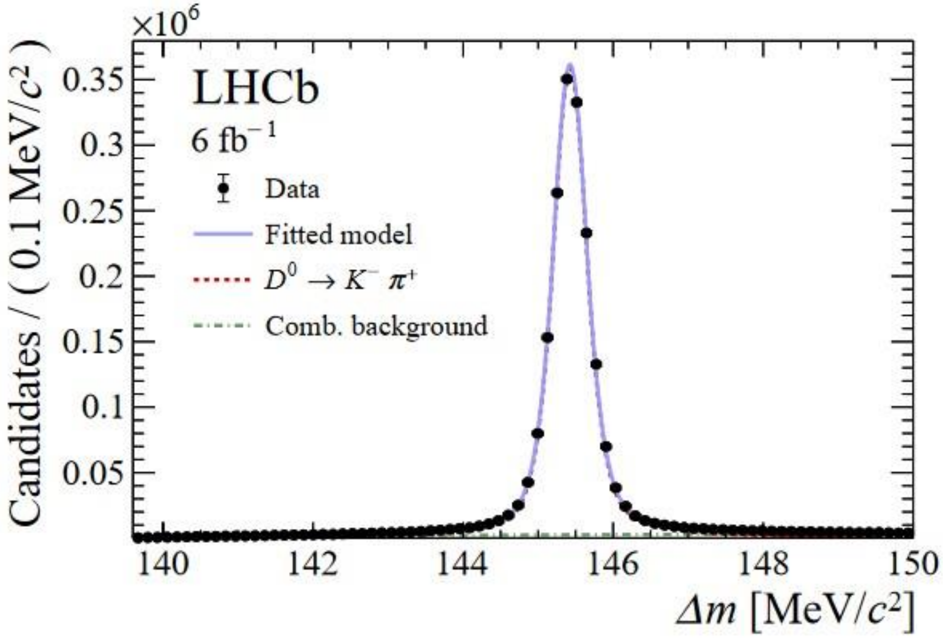
- Lined to charm flavor mixing (lecture of Guillaume) and D→γγ

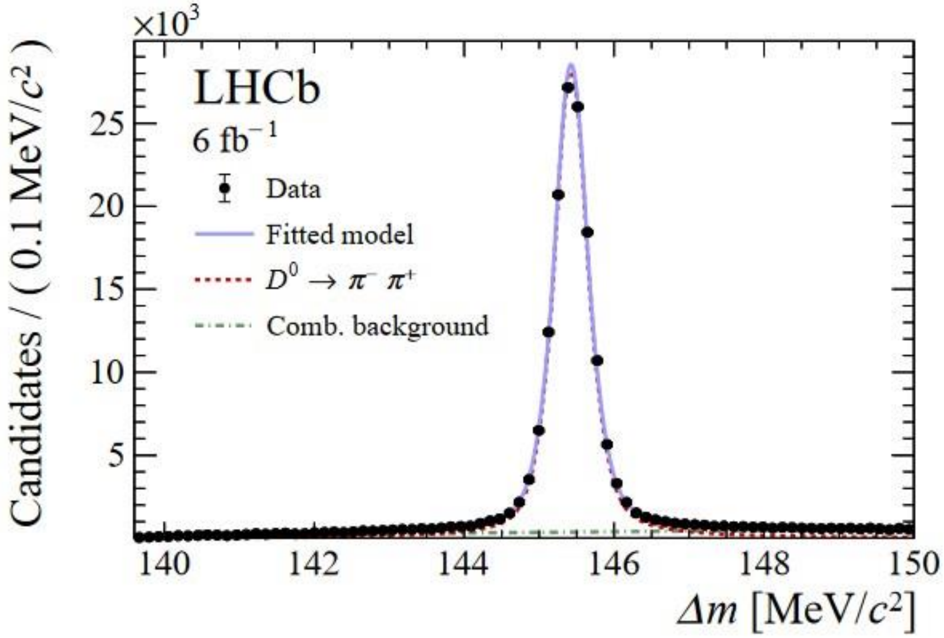


- Sentitive to BSM, e.g. at tree level to Z-like boson with non-zero flavour-changing couplings

# Rare decays

- Search for **D→μμ**
- LHCb analysis, PRL 131 (2023) 041804
- $D^o$ from $D^{*+}$ decays $D^{*+} \to D^0\pi^+$
- Normalization by and background from $D^o$→hh decays $D^0 \to K^-\pi^+$ $D^0 \to \pi^+\pi^-$

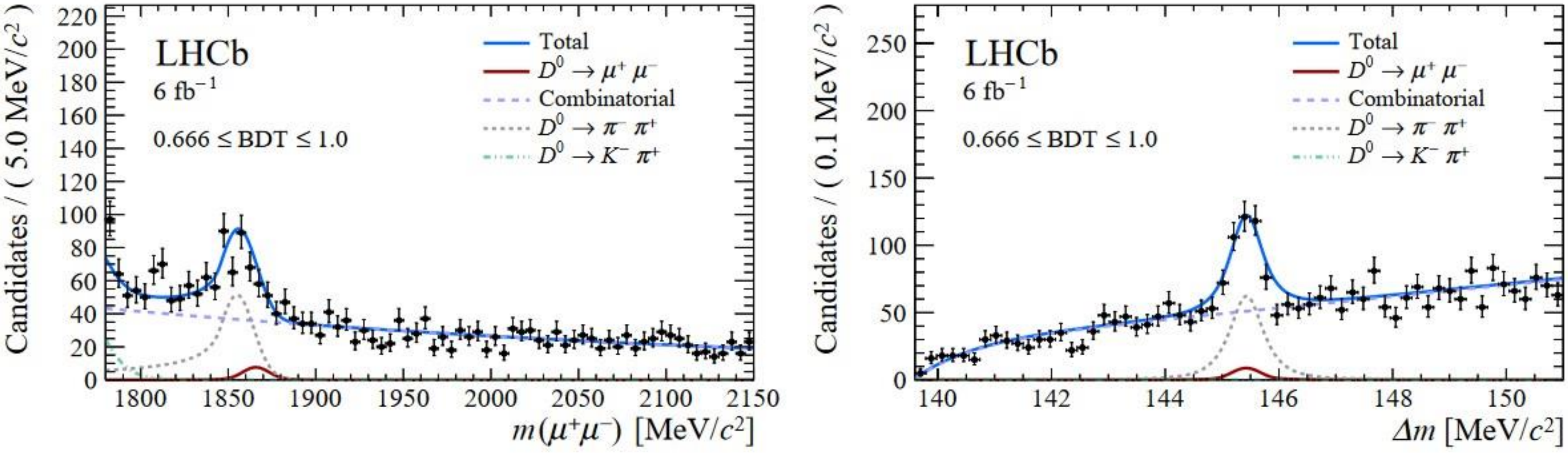




$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \frac{N_{D^0 \to \mu^+\mu^-}}{N_{D^0 \to h^+h^-}} \cdot \frac{\varepsilon_{h^+h^-}}{\varepsilon_{\mu^+\mu^-}} \cdot s \cdot \mathcal{B}(D^0 \to h^+h^-)$$

# Rare decays

- ☐ Search for **D→μμ**
- ☐ $79 \pm 45$ signal candidates



$$\mathcal{B}(D^0 \to \mu^+\mu^-) = (1.7 \pm 1.0) \times 10^{-9}$$

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1 \times 10^{-9}$$ @90% CL

- ☐ Lowest UL to date
- ☐ Exceeds SM values

# Rare decays

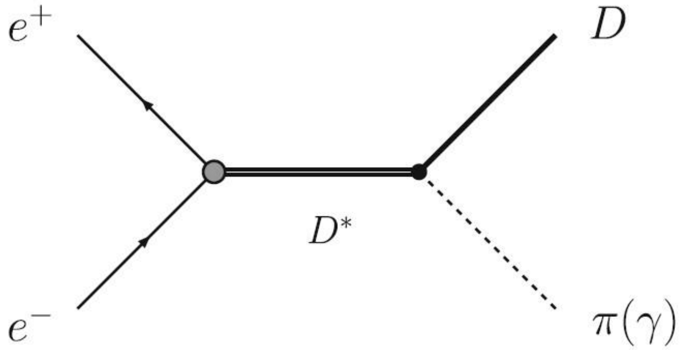
- E.g. : **D→ee**, D→μμ, FCNC decay, helicity suppression

- Alternative search for c→uee

JHEP 11 (2015) 142

- Reverse the diagram, and search for a **production of D* mesons**

$$e^+e^- \to D^*(2007)$$



- No helicity suppression
- Similar SD and LD SM contributions expected
- **Production mode**, CMD3 search

$$B(D^{0*}(2007) \to e^+e^-) < 1.7 \times 10^{-6}$$

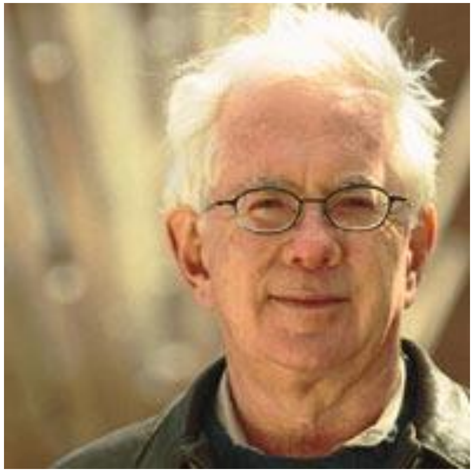
Phys. Atom. Nucl. **83**(6) (2020) 954

- **Decay mode**, LHCb search

$$B(D^{0*}(2007) \to \mu^+\mu^-) < 2.6 \times 10^{-8}$$

EPJC 83 (2023) 666

# As an outlook / introduction to Guillaume’s lecture



*Sheldon Glashow*

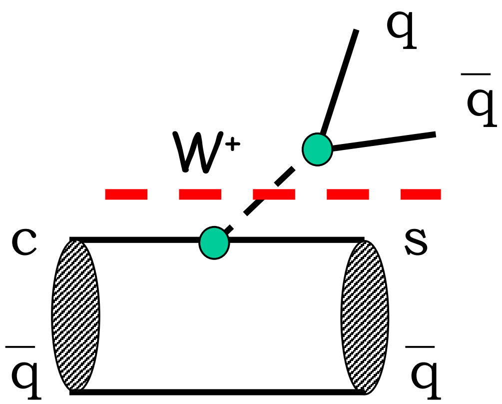
This is not the place to describe our views in detail. They are very speculative and probably false. The point I wish to make is simply that it is too early to convince ourselves that we know the future of particle physics.
There are too many points at which the conventional picture may be wrong or incomplete. The SU(3)xSU(2)xU(1) gauge theory with three families is certainly a good beginning, not to accept but to attack, extend, and exploit.
We are far from the end.

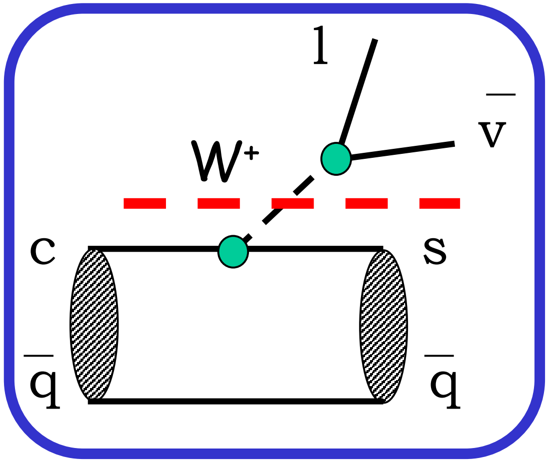
*Sheldon Glashow, Nobel lecture, 1979*

# Questions : factorization

- For which decay “factorization” is equivalent to precise calculations ?

**“Factorization” approach**





# Questions : diagram game

- Which penguin is stronger ?

$|V_{cd}^*\ V_{ud}| \sim \lambda$

$|V_{cs}^*\ V_{us}| \sim \lambda$

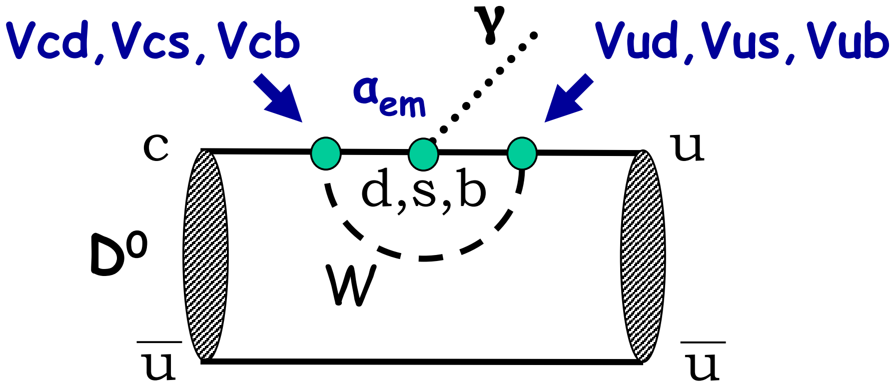
$|V_{cb}^*\ V_{ub}| \sim \lambda^5$

$|V_{ub}^*\ V_{us}| \sim \lambda^4$

$|V_{cb}^*\ V_{cs}| \sim \lambda^2$

$|V_{tb}^*\ V_{ts}| \sim \lambda^2$

$M_{u,d} < M_s < M_c < M_b << M_t$



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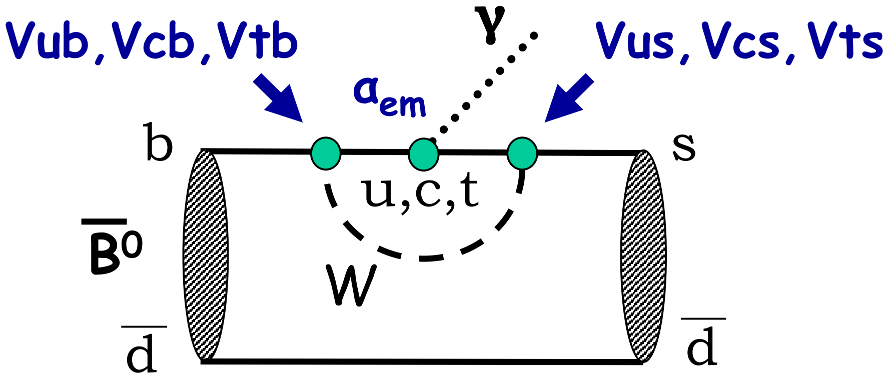

$\sim 10^{-8..9}$

$BR(B^0 \rightarrow K^{*0}\gamma) = (4.01 \pm 0.20) \times 10^{-5}$

$$\sim \frac{M_{q1}^2 - M_{q2}^2}{M_W^2}$$