The questions

- Do quark exist ?
  - Are they truly fermions?
  - Is their charge a fraction of the electron charge ?
  - How many are they ?
- How about color ?
- Do gluons exist ?
  - Are they truly vectors ?
  - Do gluons interact one with the other ?
- Test perturabtive QCD
  - measure running of α_S

The answers

1) Discovery of the Ω

2) Vector mesons decay to leptons

3) continuum in $e^+e^- \rightarrow$ hadrons

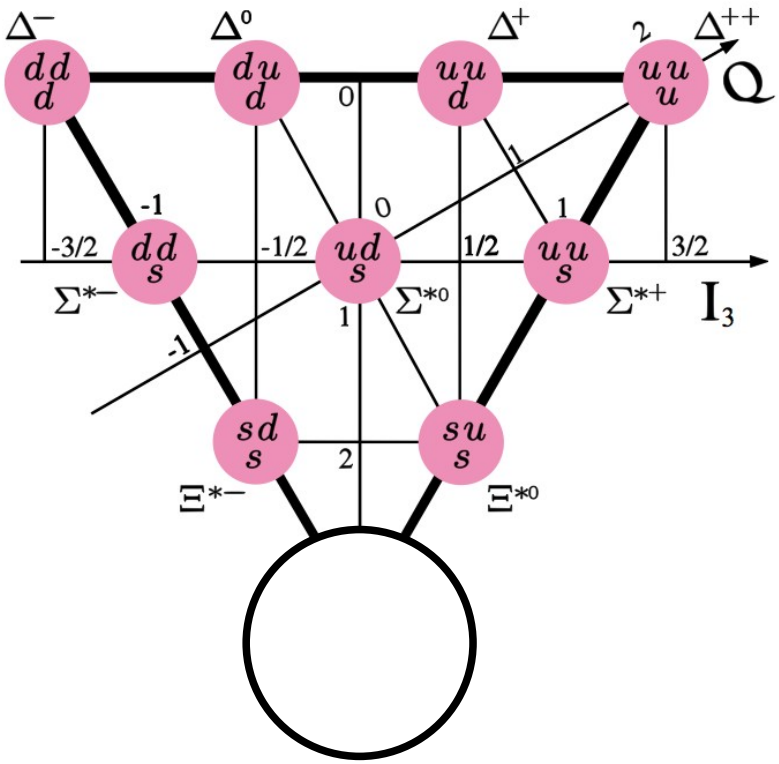
4) resonances in $e^+e^- \rightarrow$ hadrons

5) jet production in $e^+e^- \rightarrow$ hadrons

6) measurements of α_S

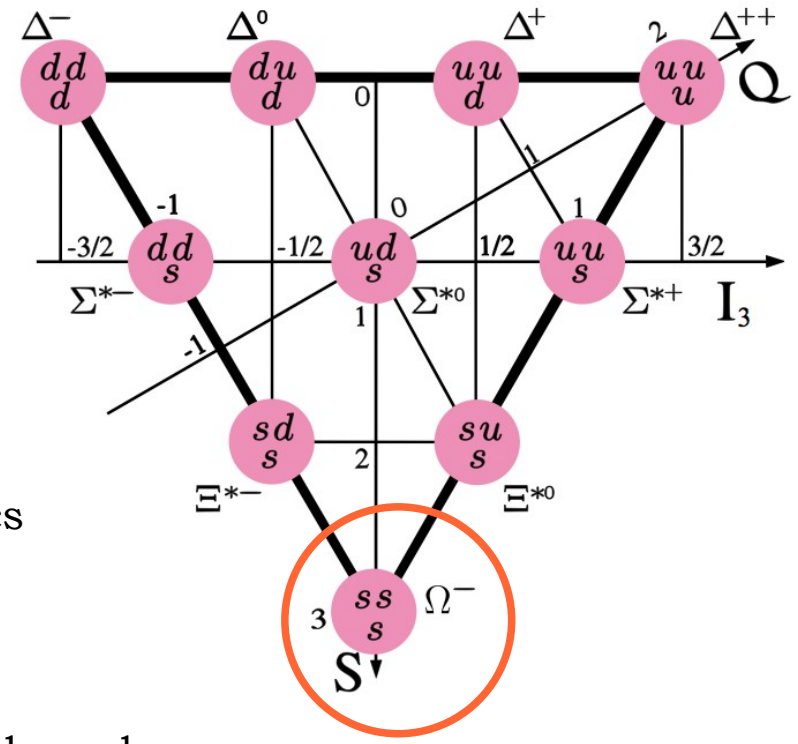
The baryon decuplet

- Nine states where observed
- The quark model predicted 10
- Let's assess
  - Quantum numbers
  - Mass ?
  - Constituent quarks
  - Decay modes
  - Lifetime (short/long)



The Omega

- **$\Omega^- = sss$**
  - S=-3, Q=-1, B=1
  - M ~1700 MeV
  - Metastable:



$\Omega^-(1680) \rightarrow \Xi^0 K^-(1809)$

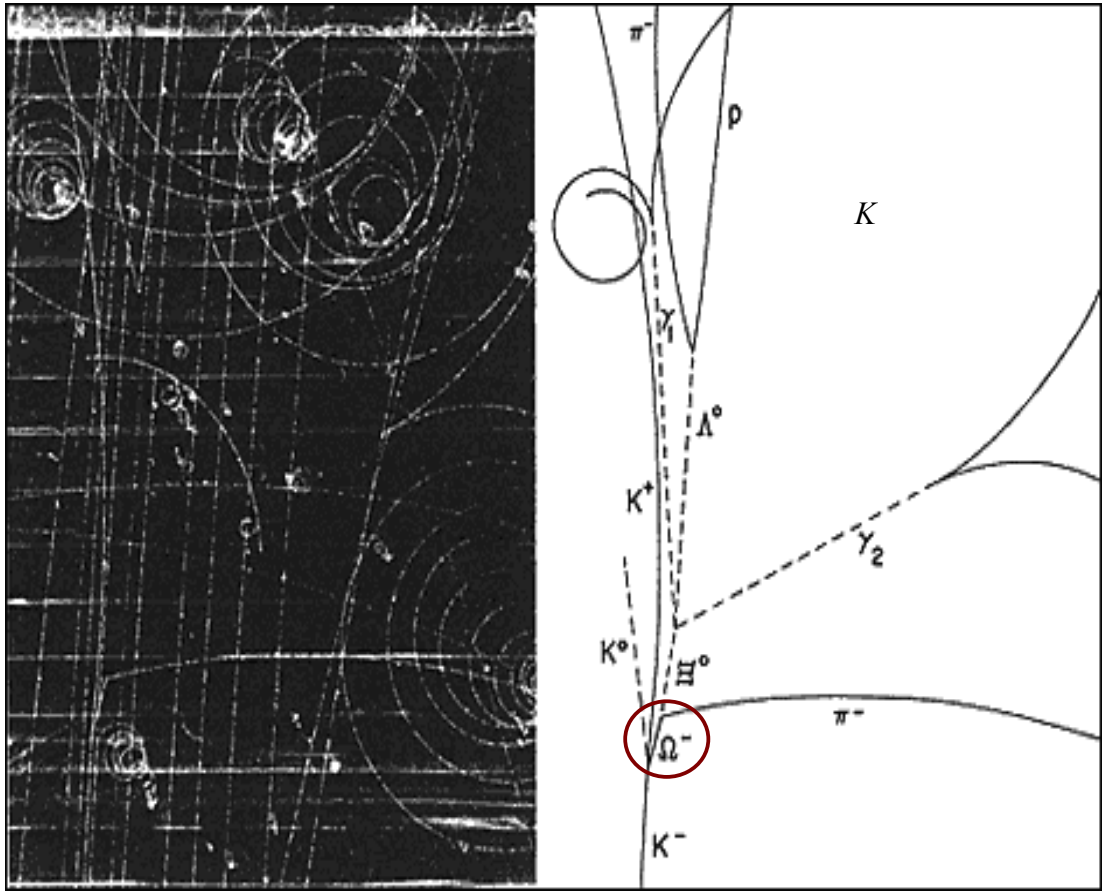
forbidden by kinematics

$\Omega^-(1680) \rightarrow \Xi^0 \pi^-(1560)$

ΔS=1: weak decay, it's the only long lived particle in the decuplet

La scoperta dell'Omega

- BNL 1964: Barnes et al. send a 5 GeV K^- beam on a liquid H_2 bubble chamber
- Observe ONE event, m=1672 MeV, τ=82 ps



$$K^- p \rightarrow \Omega^- K^+ K^0$$

$$\Omega^- \rightarrow \Xi^0 \pi^-$$

$$\Xi^0 \rightarrow \Lambda(p\pi^-)\pi^0(\gamma_1\gamma_2)$$

$$\gamma_1 \rightarrow e^- e^+$$

$$\gamma_2 \rightarrow e^- e^+$$

!



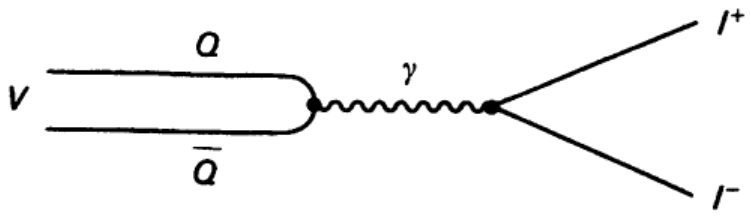
1968 Alvarez
(discovery of new states and development of bubble chamber and analysis techniques)



1969 Gell-Mann

Leptonic decay of onia

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



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

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

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

$$|\psi(nS)> = |c\bar{c}> \ (n=1,2)$$

$$|\Upsilon(nS)> = |b\bar{b}> \ (n=1,2,3)$$

Leptonic "ONIA" decays

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

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

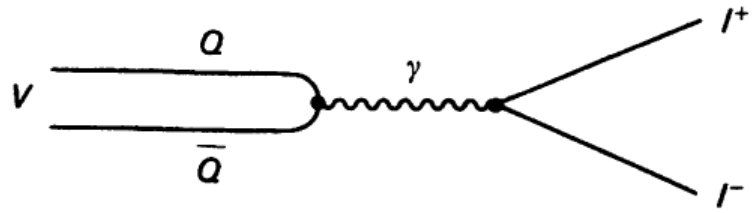


Table 4.10. *Leptonic widths of vector mesons*

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

$\sigma(e^+e^- \to q\bar{q})$

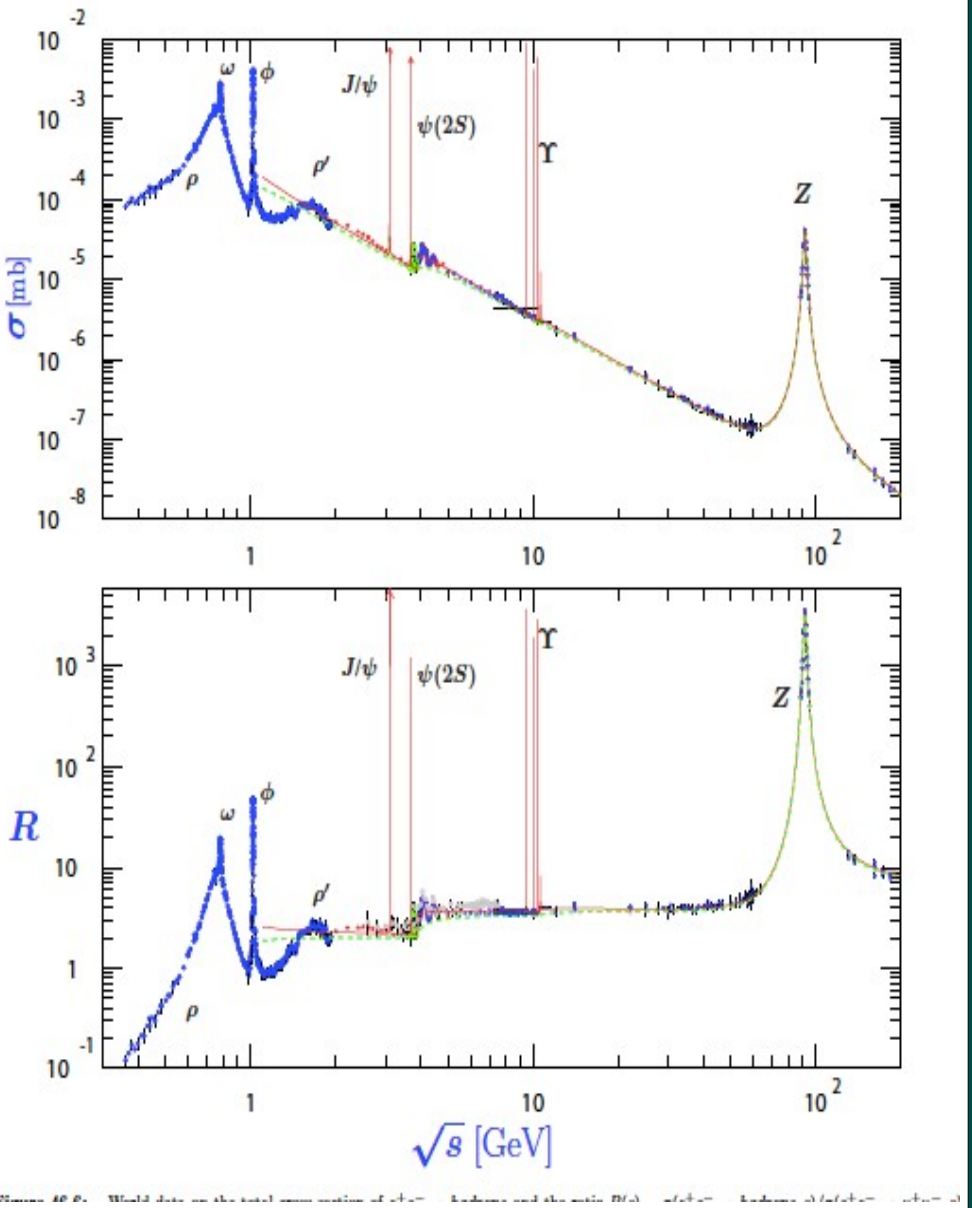
$$\sigma(e^+ e^- \to f\bar{f}) = \frac{4\pi}{3}\frac{\alpha^2}{s}\cdot N_c \cdot q_f^2$$

$$\sigma(e^+ e^- \to had) = \frac{4\pi}{3}\frac{\alpha^2}{s}\cdot N_c \cdot \Sigma q_f^2$$

$$R = \frac{\sigma(e^+ e^- \to had)}{\sigma(e^+ e^- \to \mu^+ \mu^-)} = N_c \cdot \Sigma q_f^2$$

$$N_c = \begin{cases} 1 & \text{leptoni} \\ 3 & \text{quarks} \end{cases}$$

$$q_f = \begin{cases} -1 & \text{leptoni} \\ 2/3 & u, c, (t) \\ -1/3 & d, s, b \end{cases}$$

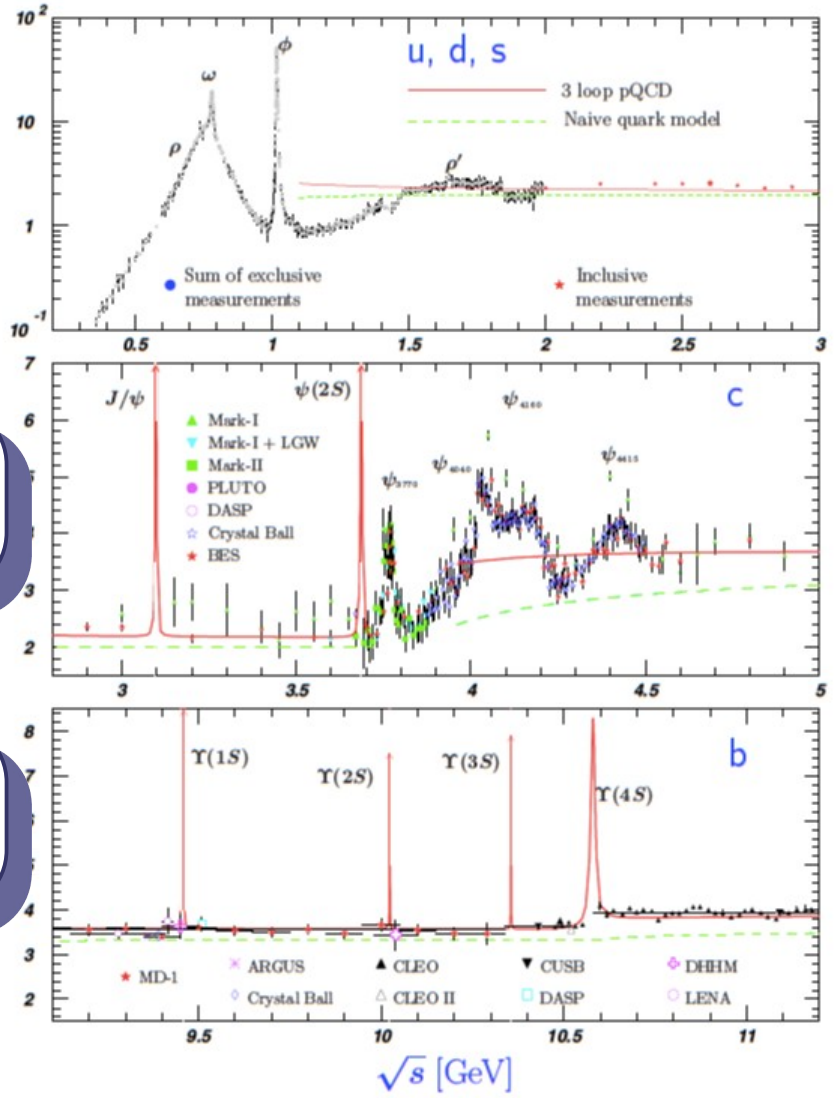


$R(s) = N_c \Sigma_i q^2_i$

$\sqrt{s}<3$: $R=3\times(\frac{4}{9}+2\times\frac{1}{9})=2$

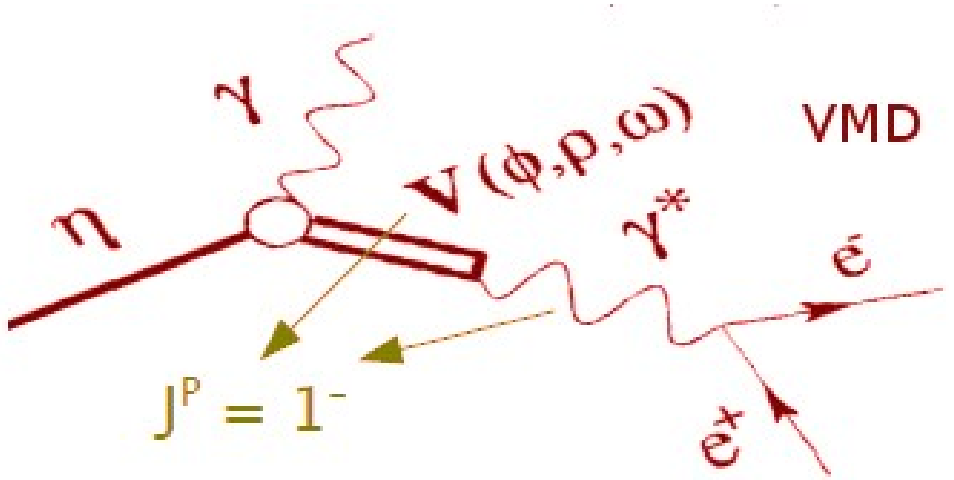
$4.5<\sqrt{s}<9$: $R=3\times(2\times\frac{4}{9}+2\times\frac{1}{9})=\frac{10}{3}$

$11<\sqrt{s}<70$: $R=3\times(2\times\frac{4}{9}+3\times\frac{1}{9})=\frac{11}{3}$

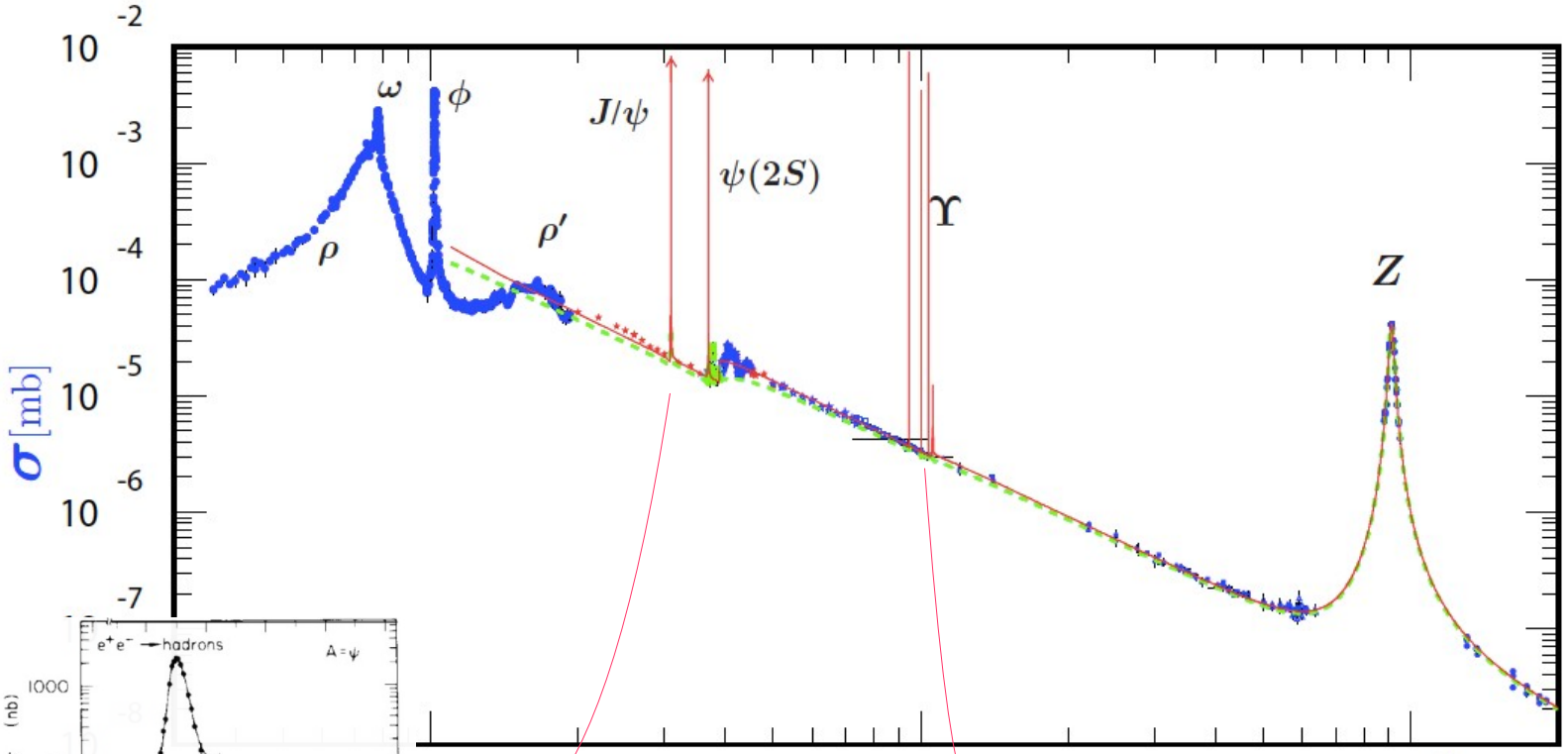


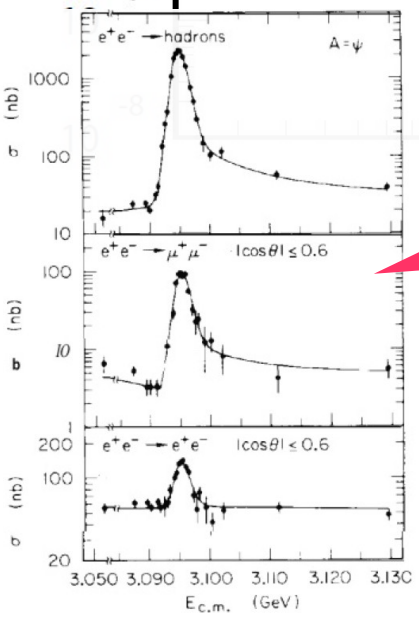
Resonances in e^+e^- collisions

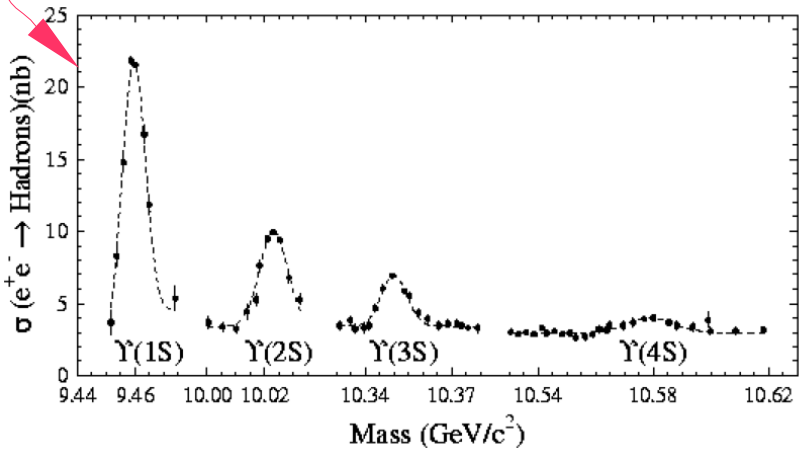
- Vector mesons, CP eigenstates
  - $V = (\rho, \omega, \Phi, \psi, \Upsilon)$, $\mathbf{J^{CP} = 1^{--}}$ (same as γ)
- In e^+e^- colliders they can be directly produced :
  - observed as resonances in formation
- Focus on :
  - $|\Upsilon(nS)> = |b\bar{b}>$
  - $|\Phi> = |s\bar{s}>$
  - $|\psi(nS)> = |c\bar{c}>$



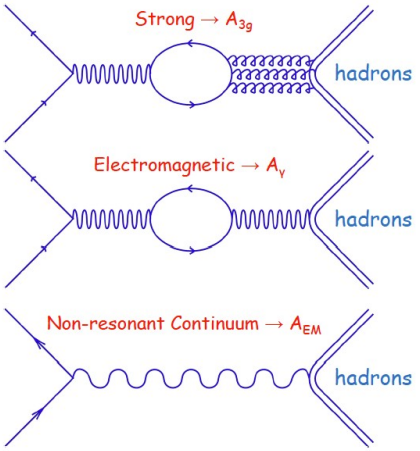
Resonances in e^+e^- collisions

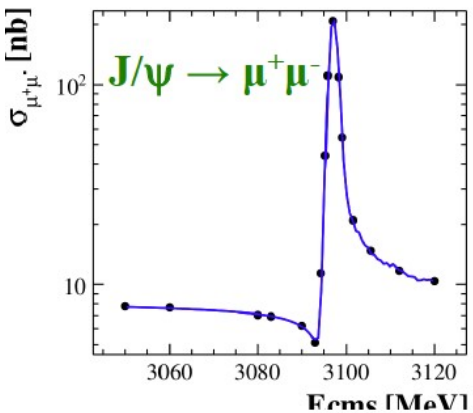






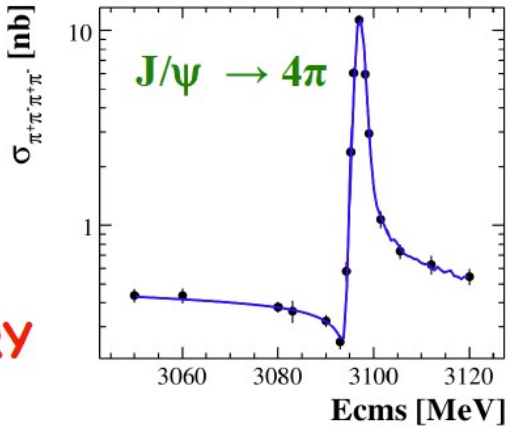
BES3





$\Delta\Phi = \pi$

PRELIMINARY



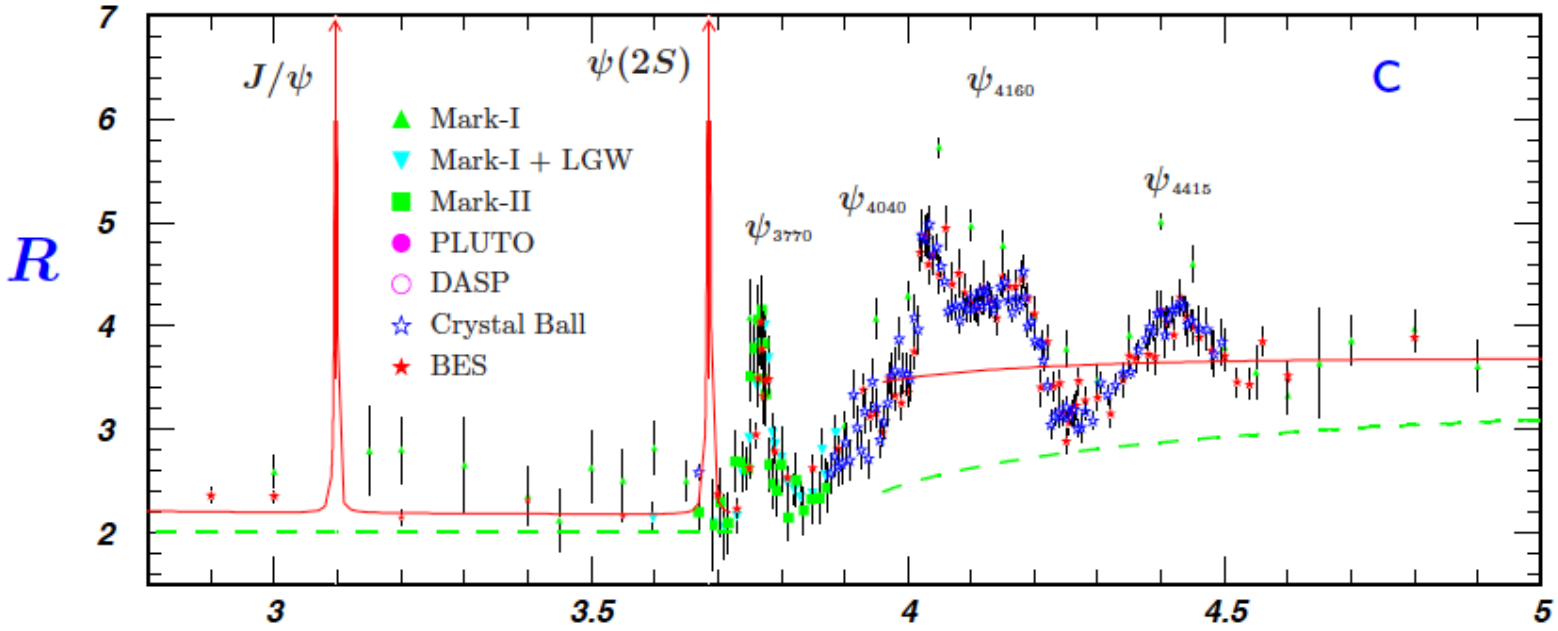
A dip before the peak :

destructive interference between continuum and the resonance → J/ψ has the same quantum numbers as the photon

change of phase across the resonance as in forced RCL circuit

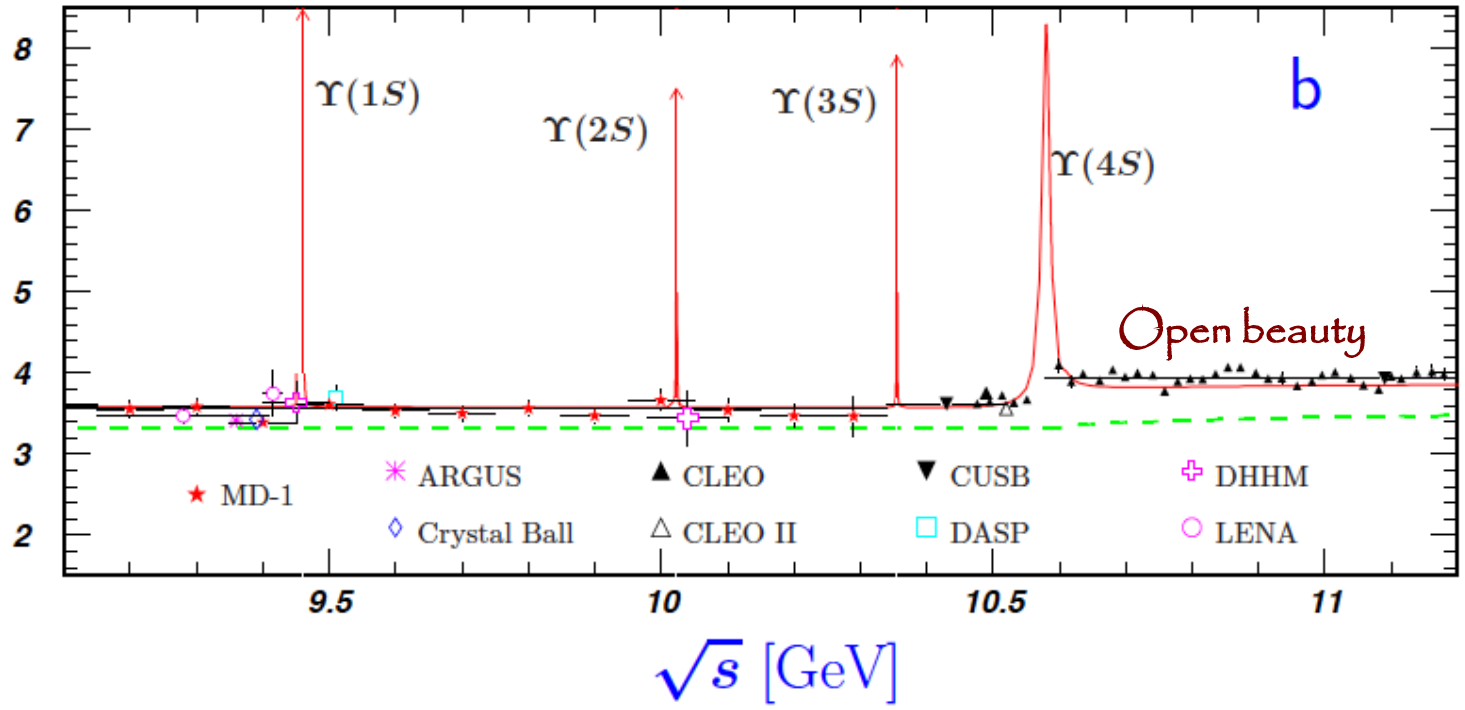
Charmonium

- Two narrow resonances
  - $\psi(1S)$ m~3100 MeV , $\psi(2S)$ m~3600, $\Gamma \sim$ o(KeV)
- Several large resonances Γ~MeV
- Why ?

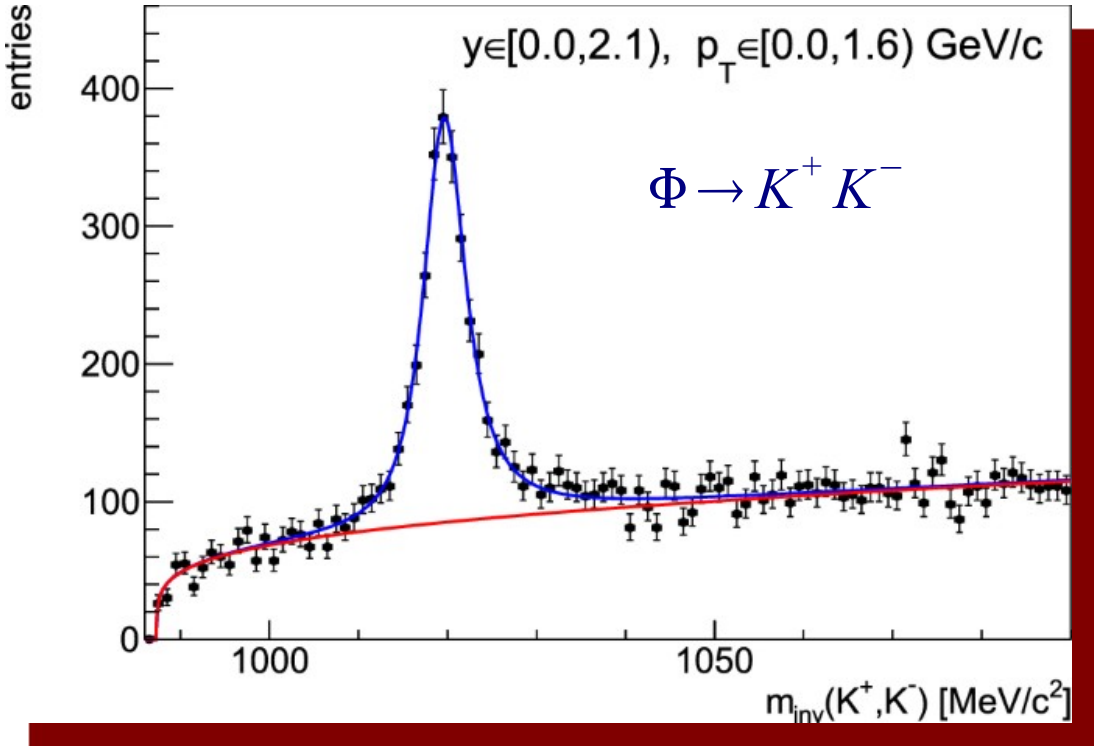


Bottomomium

- Three narrow and two wide resonances



Φ(1020)



Mass $M = 1020$ MeV

Width $\Gamma = 4.26$ MeV

$Br(\Phi \to K^+ K^-) = 48.9\%$

$Br(\Phi \to K^0 \bar{K}^0) = 34.2\%$

$Br(\Phi \to \pi^+ \pi^- \pi^0) = 15.2\%$

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 3π ?

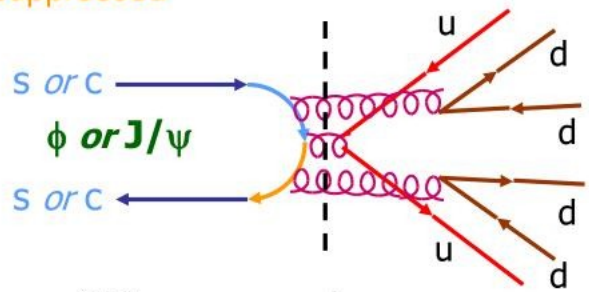
The OZI Rule

What is the OZI Rule?

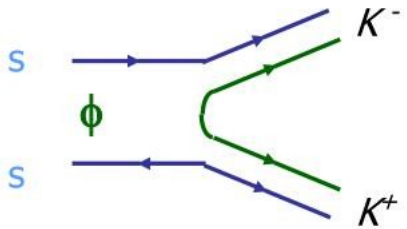
- Named after its inventors (Okubo, Zweig and Iizuka) based on observation rather than sound logic:

  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

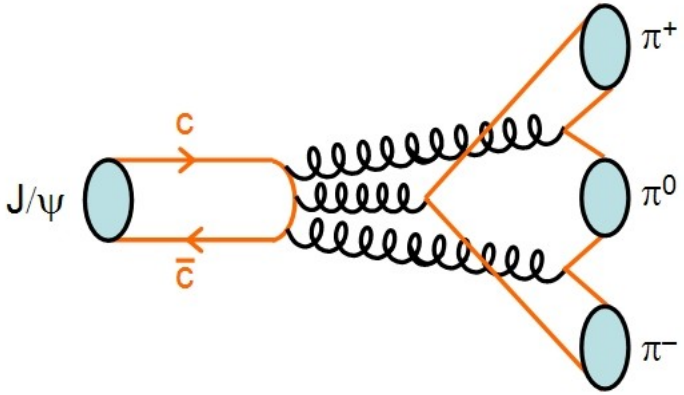
Physics 841, U. Cincinnati, Oct, 2004

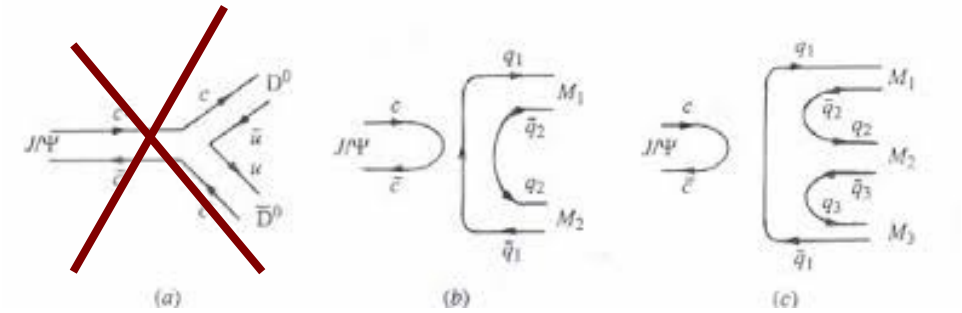
Brian Meadows, U. Cincinnati

$$A(3\pi) \propto \alpha_s^3 \sim 0.2^3 = 8 \times 10^{-3} \qquad A(2K) \propto \alpha_s \sim 0.2$$

OZI rule: charmonium (and bottomomium)

Narrow resonances are too light to decay to "open" states



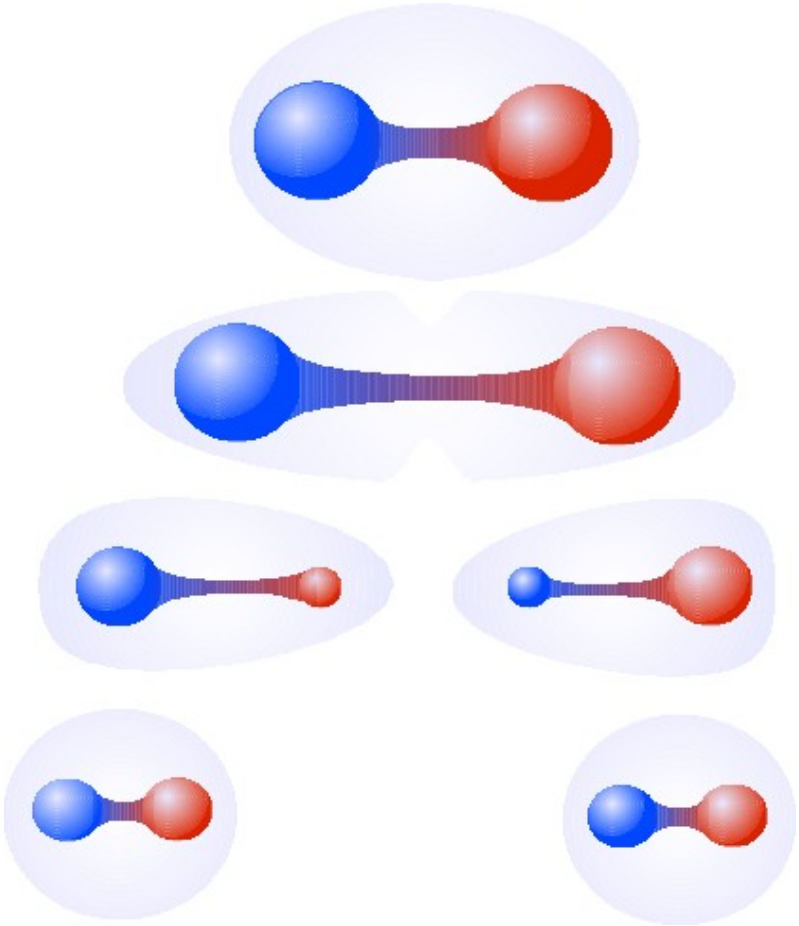


High energy QCD: jets

- In high energy collisions, hadron production shows up as emission of collimated showers of particles, called Jets
- Their formation can be understood as a consequence of QCD confinement

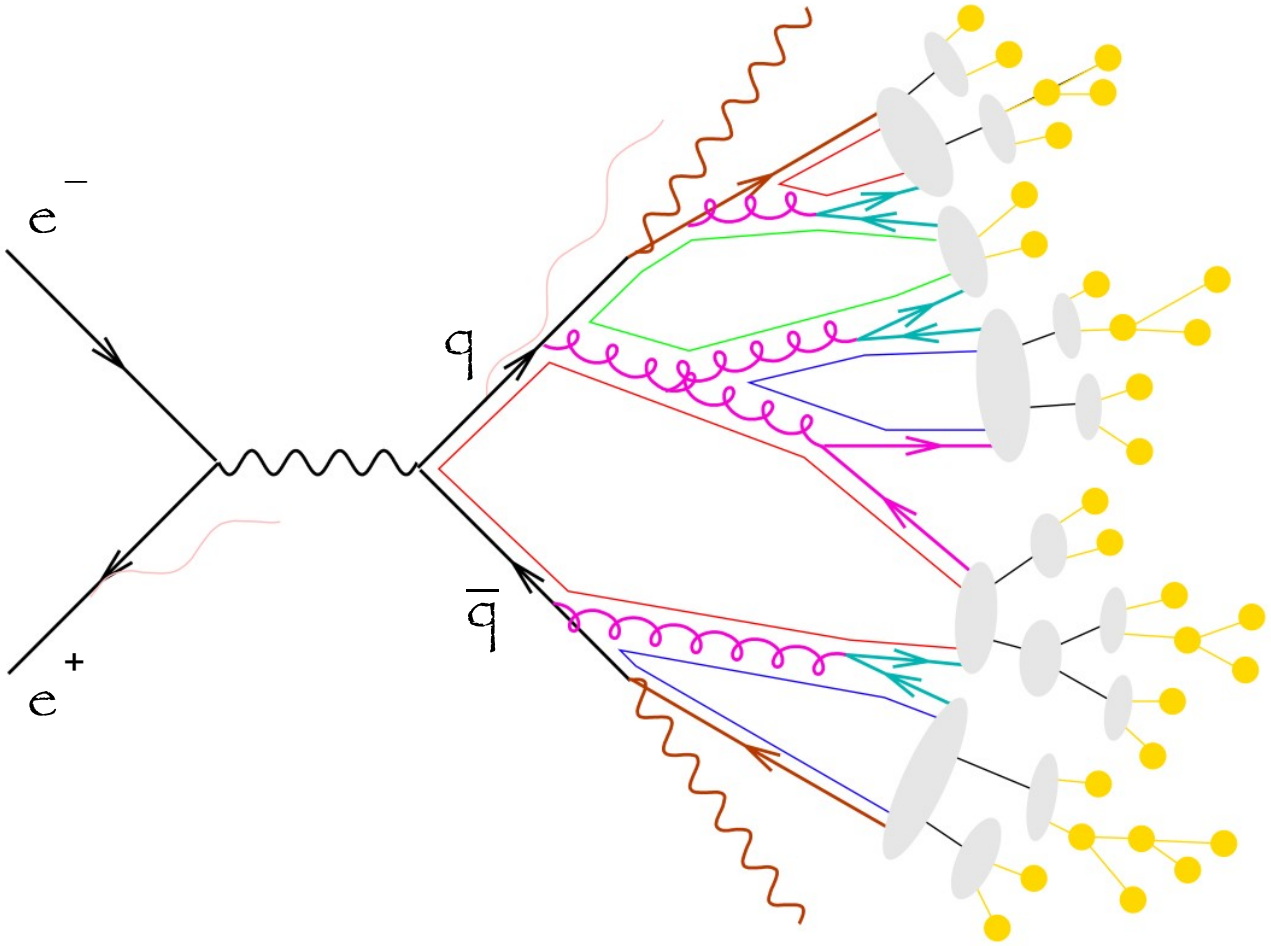
Reminder: the confinement hypothesis

- A quark and an anti-quark move in opposite direction
- The potential energy grows (linearly)
- A color string stretches ...
- ... until it breaks to produce a new quark-antiquark pair
- The process continues until energy is not sufficient anymore to create new hadrons



An easy piece

$e^+ e^- \rightarrow q\bar{q} \rightarrow$ hadrons

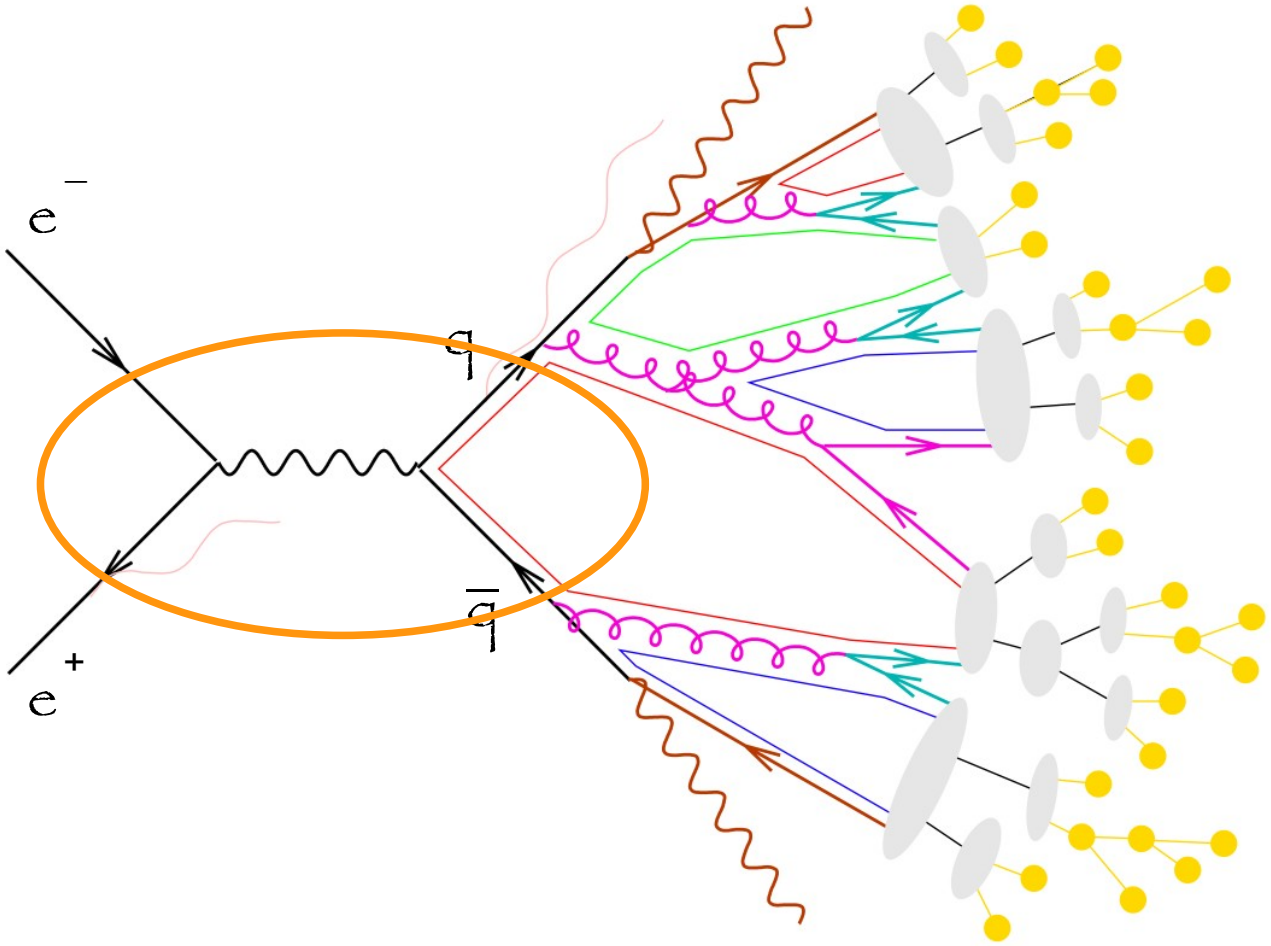


- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\rightarrow$ hadrons
- hadronic decays

The procees is computed in four stages

An easy piece

$e^+ e^- \rightarrow q\bar{q} \rightarrow$ hadrons



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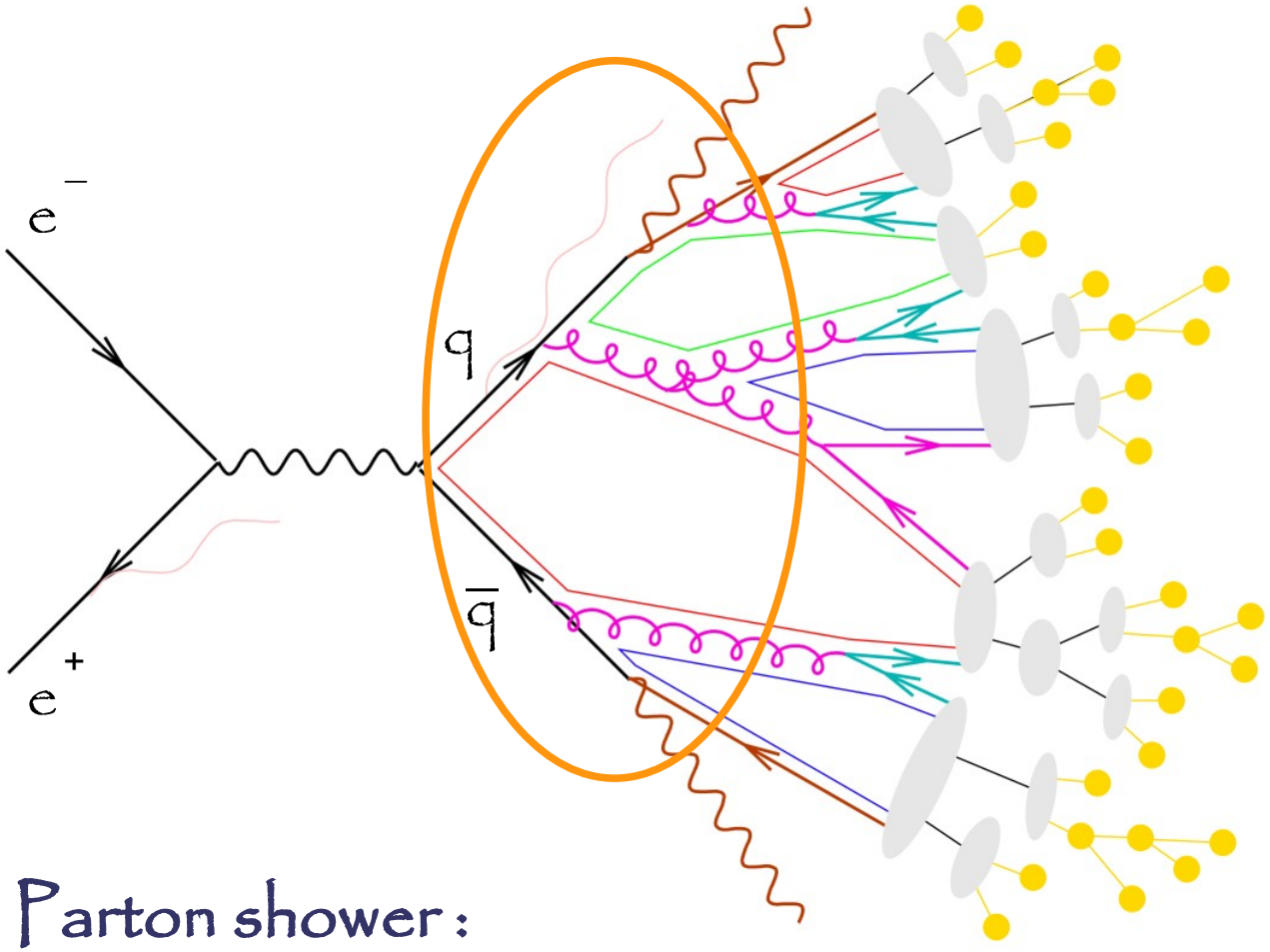
- hadronic decays

Hard process, QED

An easy piece

$e^+ e^- \rightarrow q\bar{q} \rightarrow$ adroni



- hard scattering
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- cluster $\rightarrow$ hadrons
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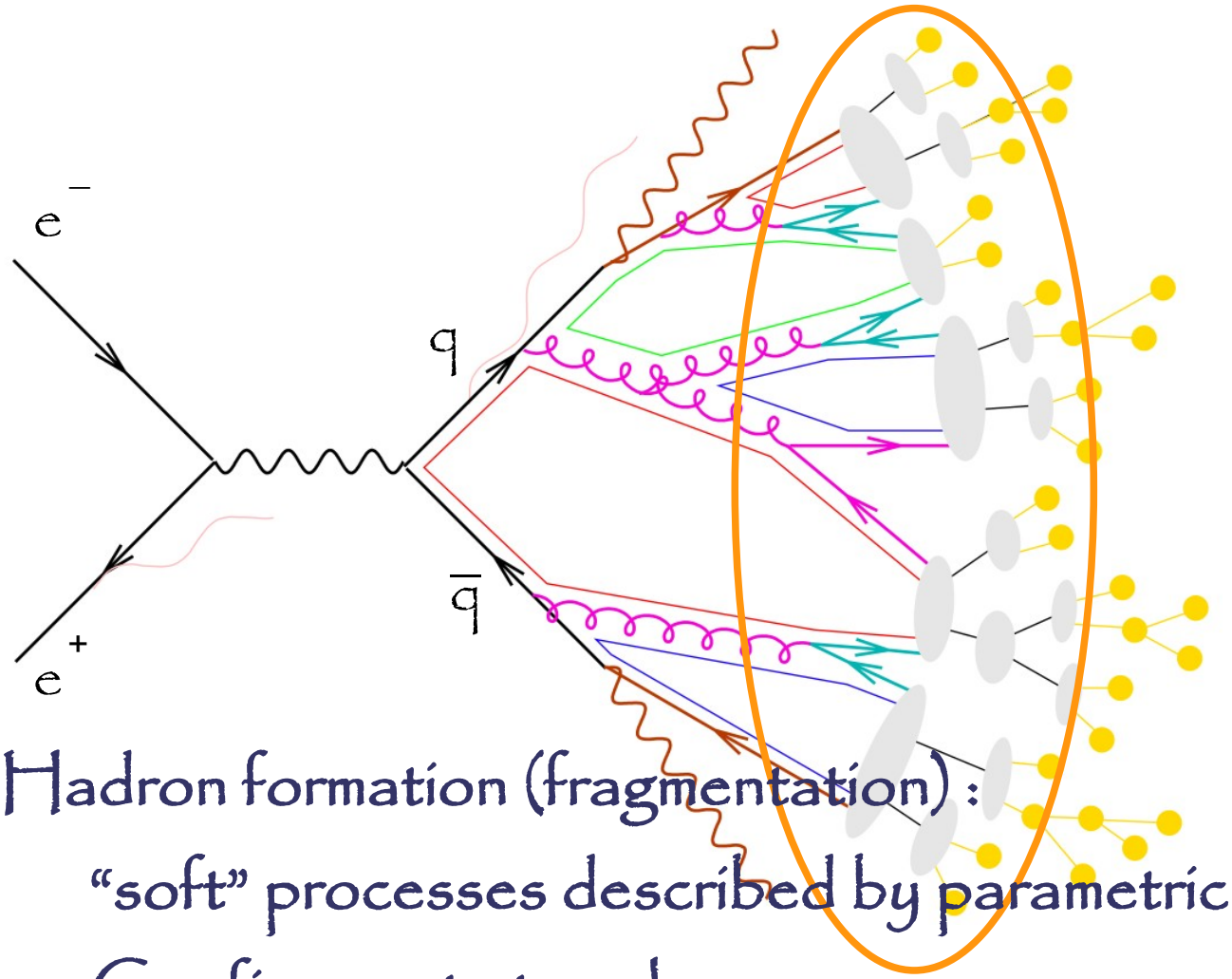
Parton shower :

gluon radiation, pair formation, perturbative QCD

An easy piece

$e^+ e^- \rightarrow q\bar{q} \rightarrow$ hadrons



- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \rightarrow bW$
- parton shower evolution
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- colour singlets
- colourless clusters
- cluster fission
- cluster → hadrons
- hadronic decays

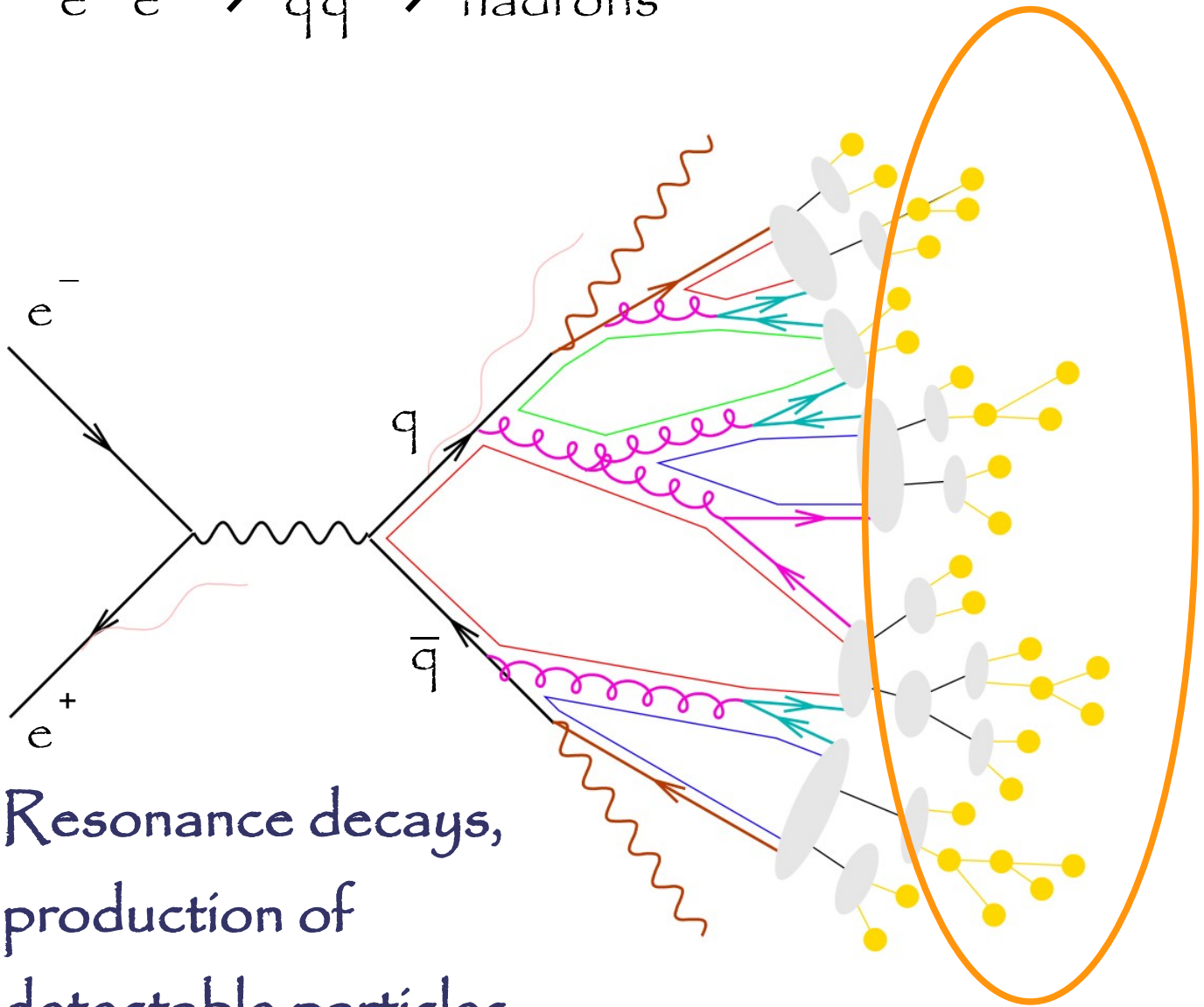
Hadron formation (fragmentation) :

"soft" processes described by parametric models

Confinement at work

An easy piece

$e^+ e^- \rightarrow q\bar{q} \rightarrow$ hadrons

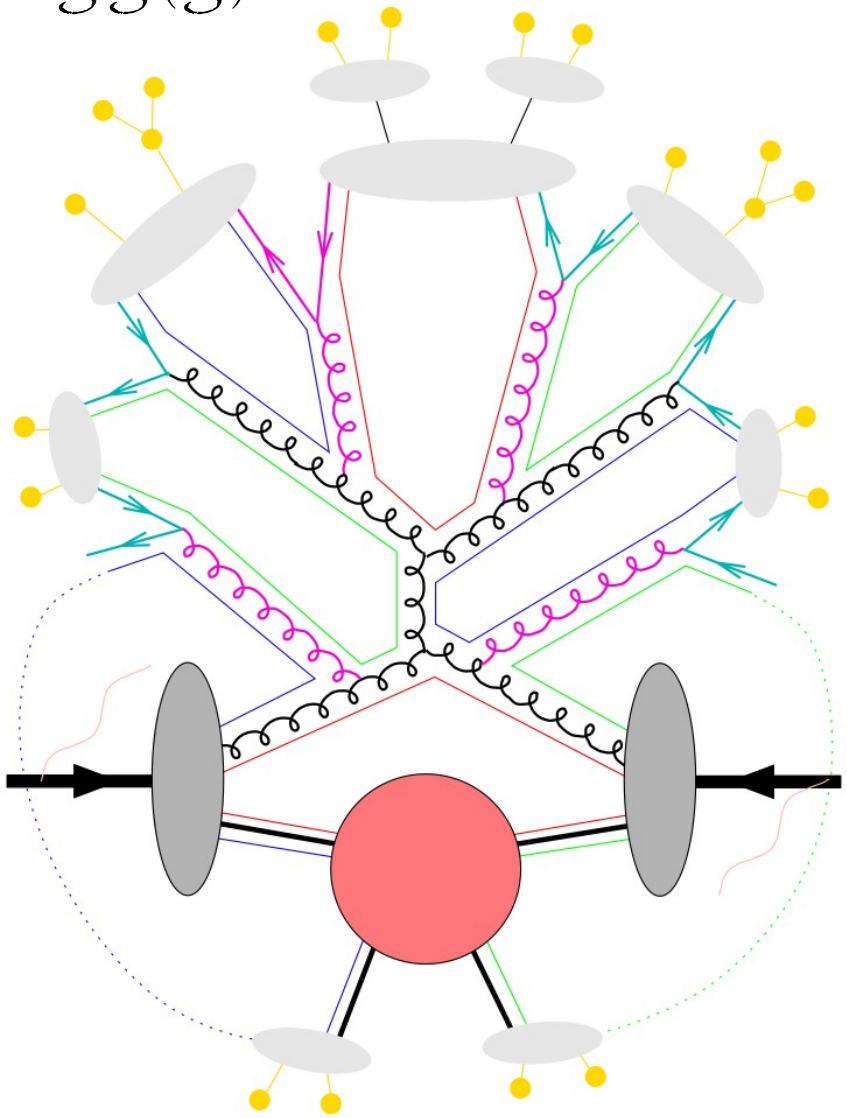


- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster → hadrons
- hadronic decays

Resonance decays, production of detectable particles

A tough piece (LHC)

pp → g g (g) → hadrons



- hard scattering
- (QED) initial/final state radiation
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster → hadrons
- hadronic decays

and in addition

+ backward parton evolution
+ soft (possibly not–so–soft) underlying event

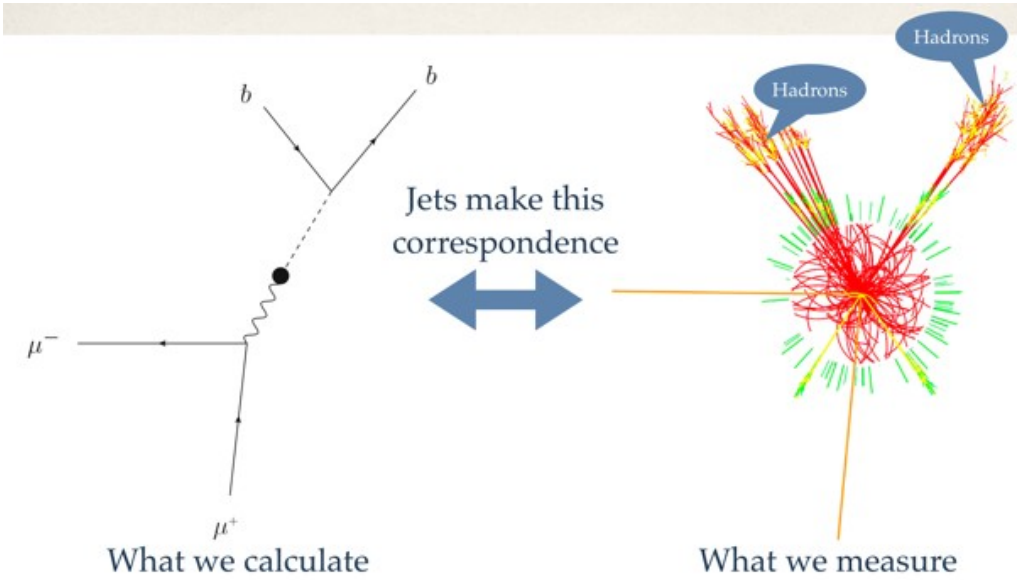
Factorization

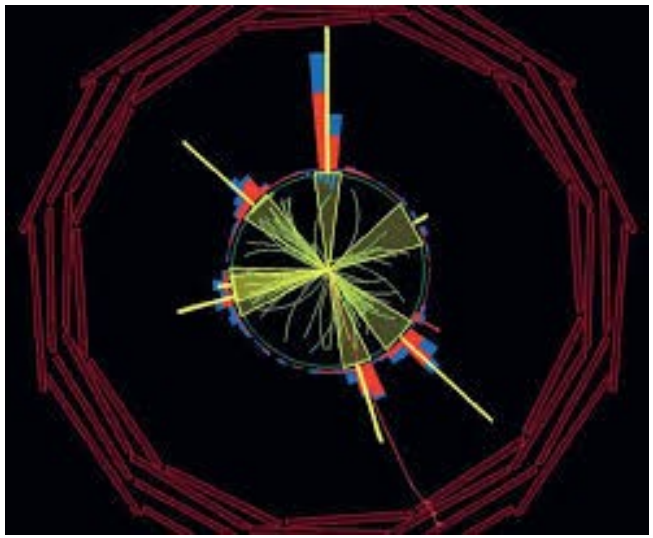
Two energy scales :

- Hard (parton shower):
  - evolution of colored objects
  - parton: a colored object, euther a gloun or a quark
- Soft
  - production and evolution of color singlets (hadrons)
- Factorization :
  - Hard and soft processes are two independent phases, use ad hoc models developed in e^+e^- , ep collisions to model hadron formation in more complex pp interactions
  - Needs to be tested

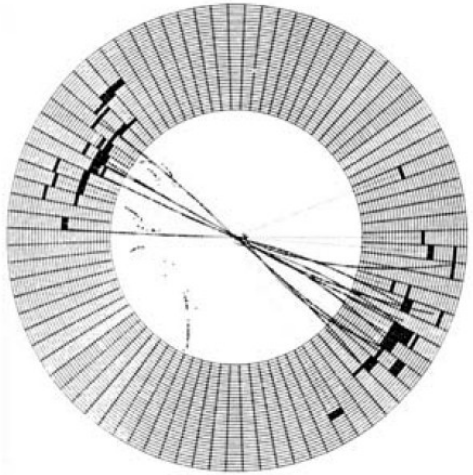
Hadronization and jet formation

- Hadron multiplicity increases with ~ log($\mathbf{E_{HARD}}$)
- Transverse momentum does not increase (p_T) ~ Λ_{QCD} ~ 300 MeV
- Final state hadrons are collected in jets with : $\Theta \simeq \frac{p_T}{E_{HARD}} \simeq \frac{300\,MeV}{E_{HARD}}$
- We identify the observed jet with the original parton
  - ambiguity due to jet algorythm



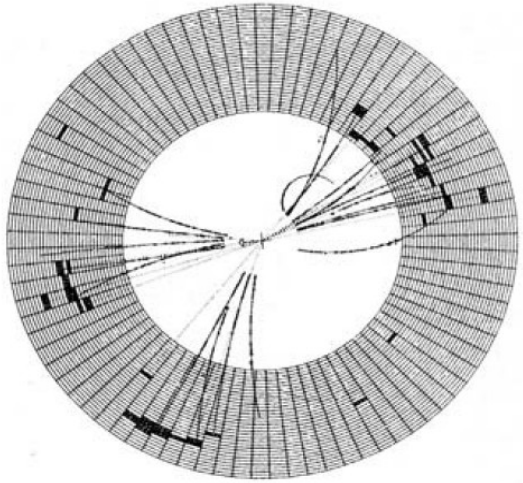


ee -> jets and gluon discovery



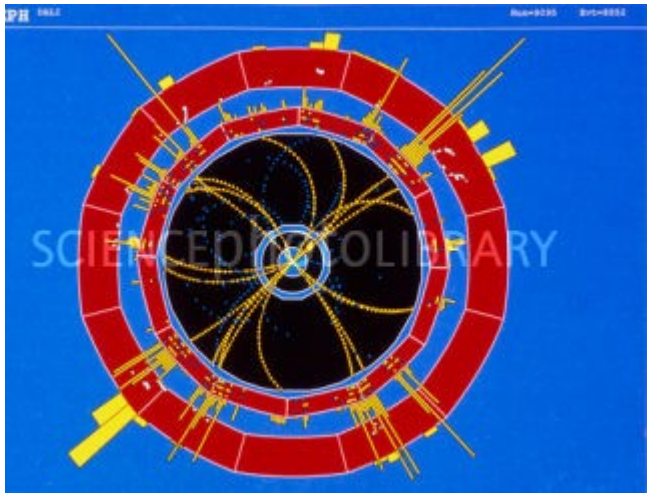
$e^+ e^- \rightarrow 2\ jets$

JADE, $\sqrt{s} \simeq 30\ GeV$



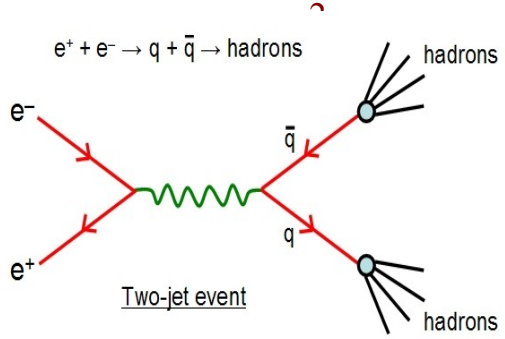
$e^+ e^- \rightarrow 3\ jets$

JADE, $\sqrt{s} \simeq 30\ GeV$

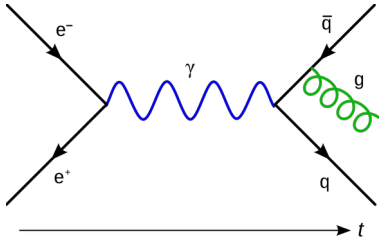


$e^+ e^- \rightarrow 4\ jets$

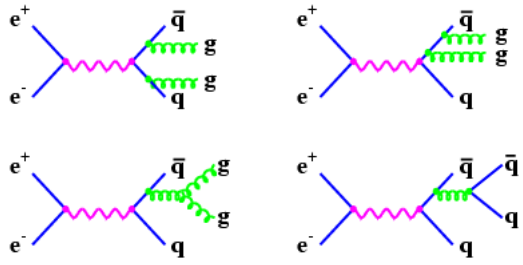
$\aleph$, $\sqrt{s} \simeq 90\ GeV$



$\sigma \propto \alpha_s \cdot \alpha^2$



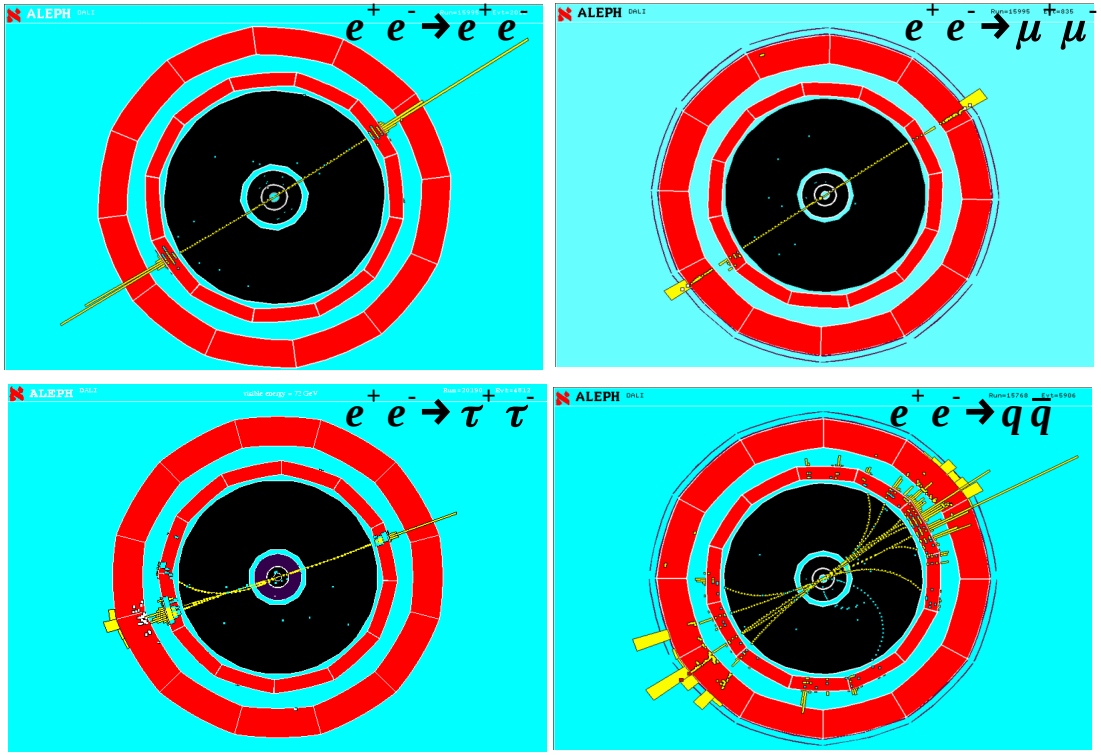
$\sigma \propto \alpha_s^2 \cdot \alpha^2$

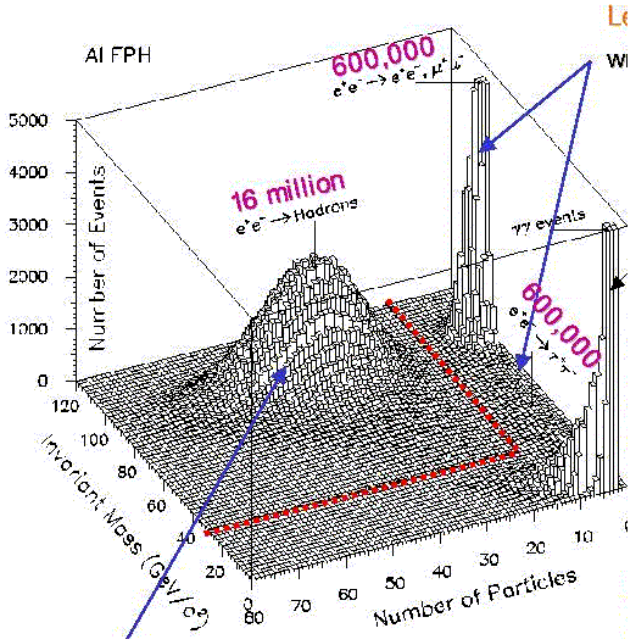


$e^+e^- \rightarrow$ adroni

- Nelle annichilazioni elettrone positrone è
  - facile distinguere adroni da leptoni
  - molto difficile, talvolta impossibile, identificare quale coppia di quark sia stata prodotta nella collisione

topologia
segnale nei rivelatori

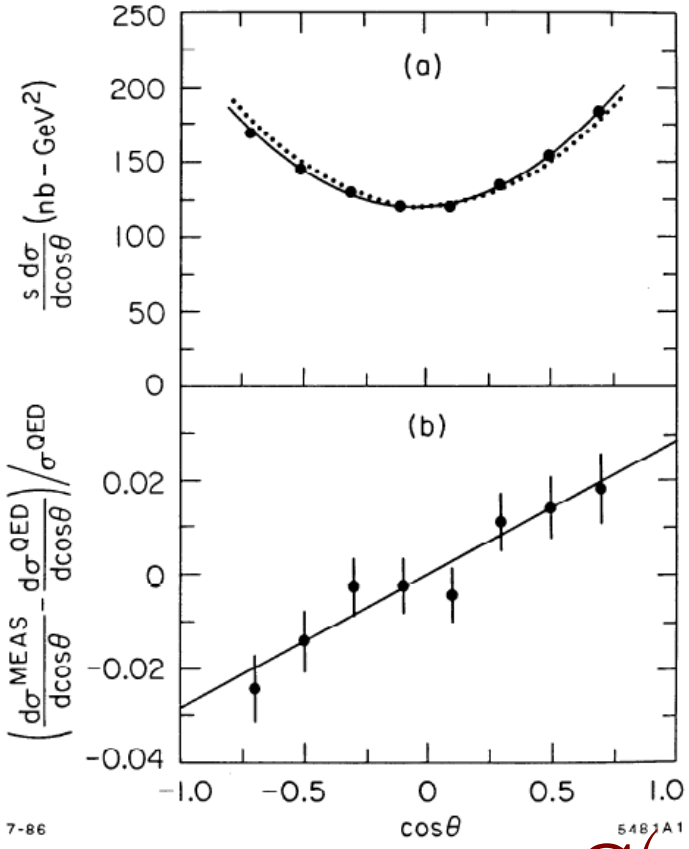




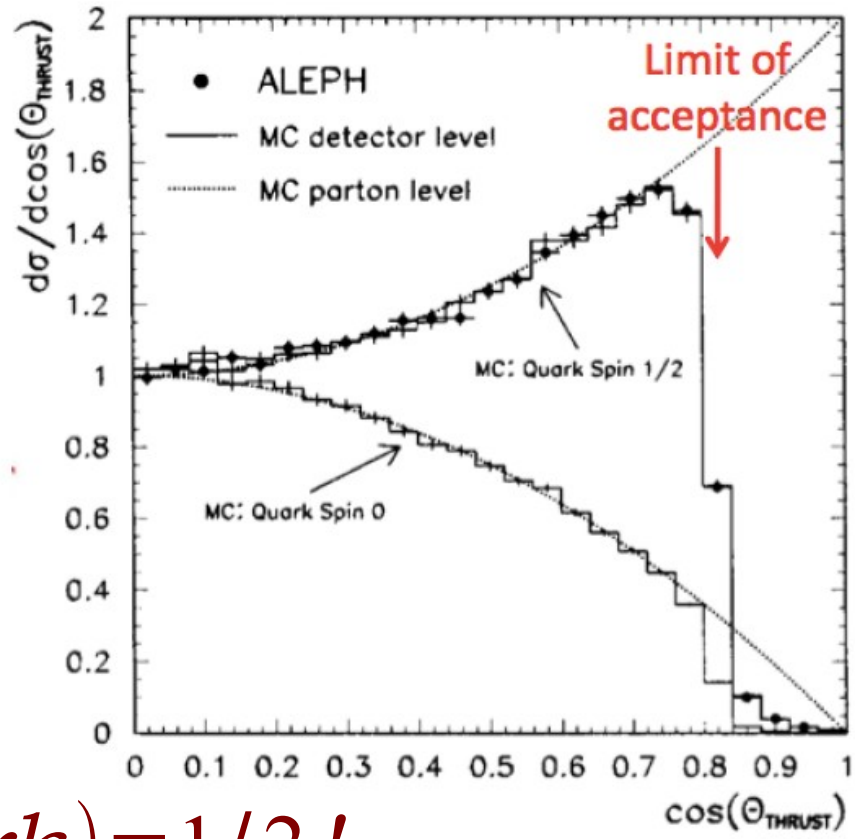
Fermion spin

- Indirect way : measurement of the absolute cross section
- Direct way : measure the differential cross section $\frac{d\sigma}{d\cos\theta}(Jets)$

$SLAC: \sqrt{s} = 29\,GeV$



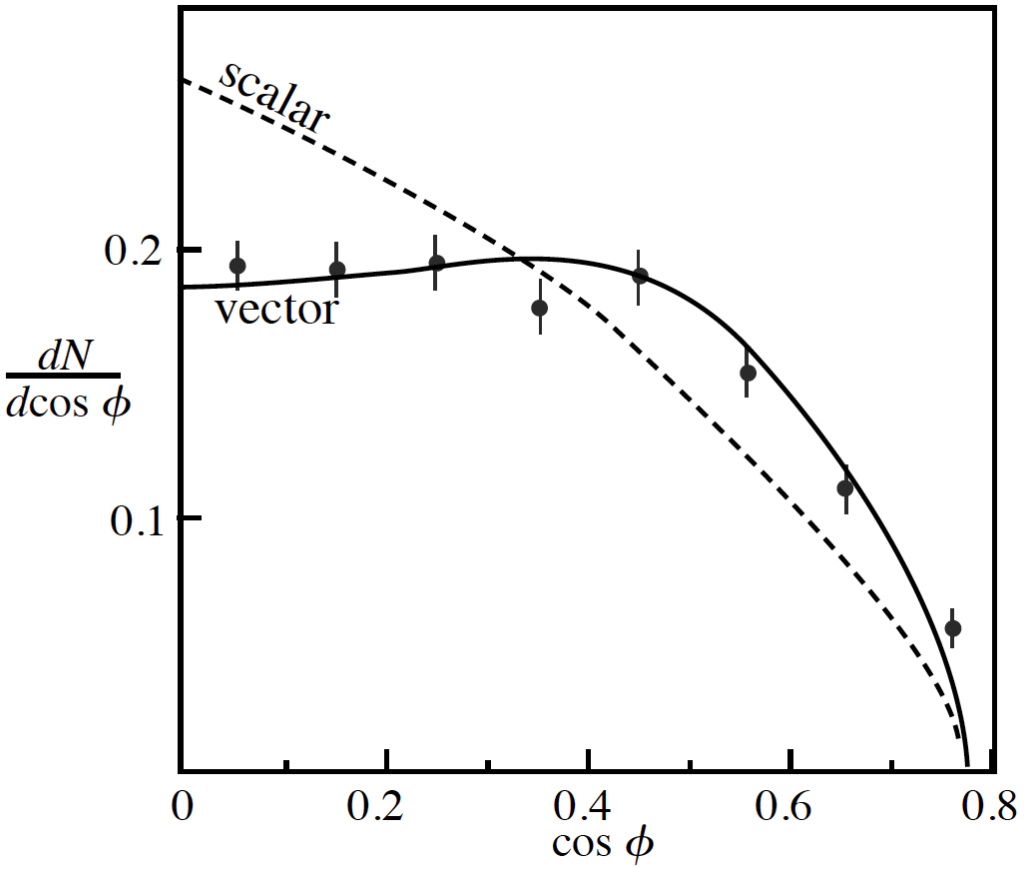
$LEP: \sqrt{s} = 91\,GeV$

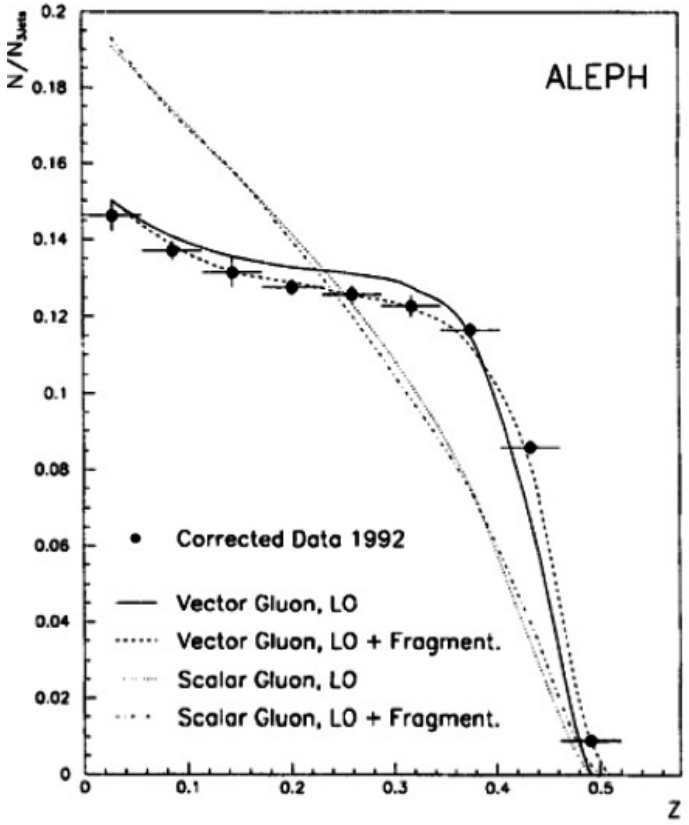


$S(quark) = 1/2\,!$

Gluon spin

- Φ :is the angle between the momentum sum of the two hardest jets and the softest one (the gluon)





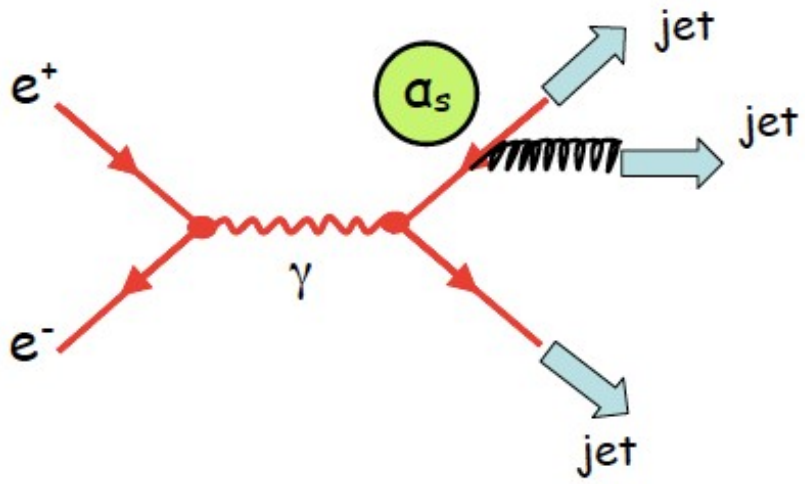
$$S(gluon)=1\ !$$

Measurements of α_s

Determination of α_s

Using jets in e^+e^--collisions

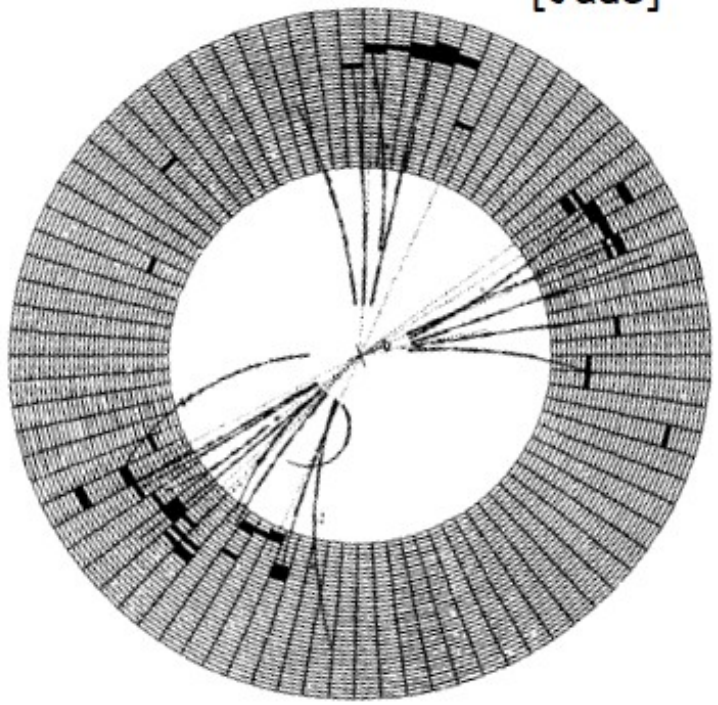
Measurement using
Simple jet rates:



$$\frac{\#3-\text{jet events}}{\#2-\text{jet events}} \sim \alpha_s(s)$$

... can also use 4-jets ...

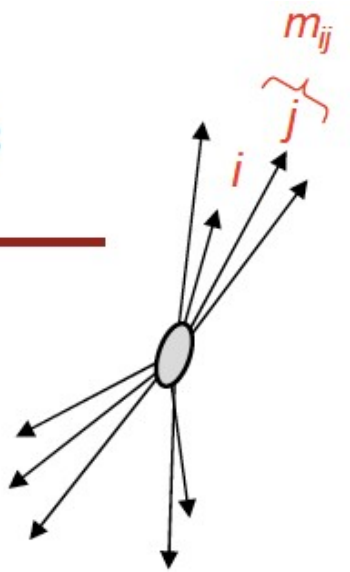
3-jet event
[Jade]



What's a jet ?

Determination of α_s

Jet finding algorithms



Question: How is a jet defined?

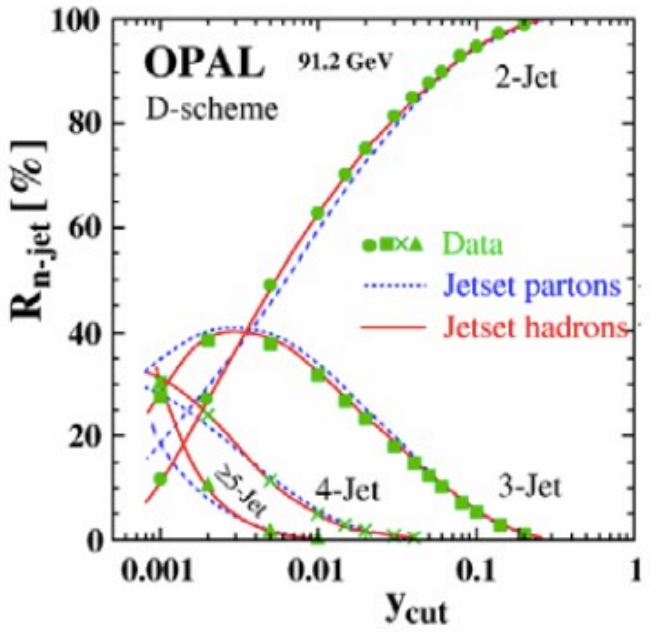
Jet Algorithm:
[Here: Jade-Algorithm]

Hadronic particles i and j are grouped to a pseudo-particle k as long as the invariant mass is smaller than a jet resolution parameter:

$$\frac{m_{ij}^2}{s} < y_{\mathrm{cut}}$$

where m_{ij} is the invariant mass of i and j.
All remaining pseudo-particles are the jets.

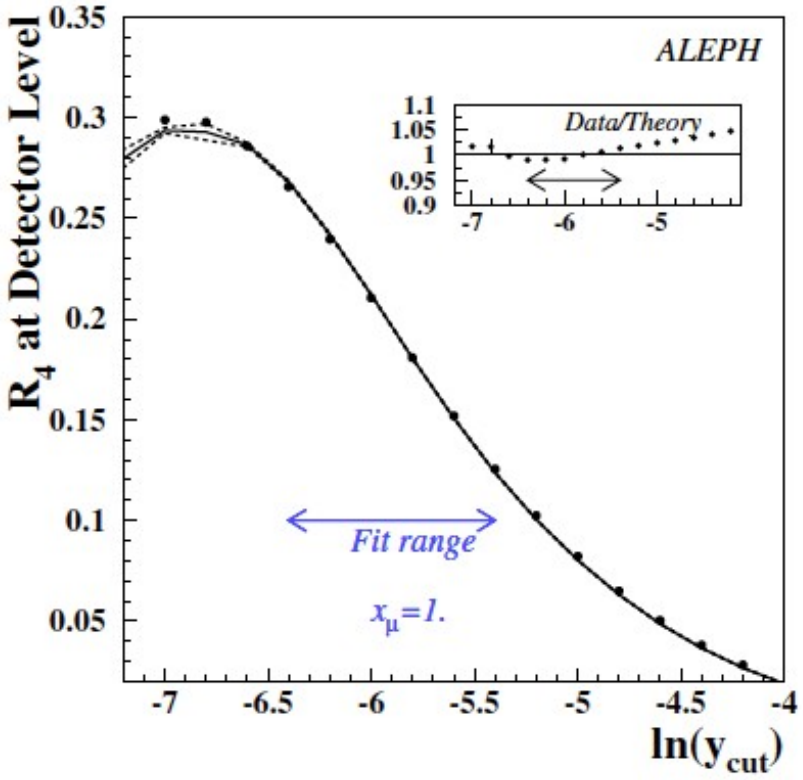
Number of jets depends on choise of y_{cut} !

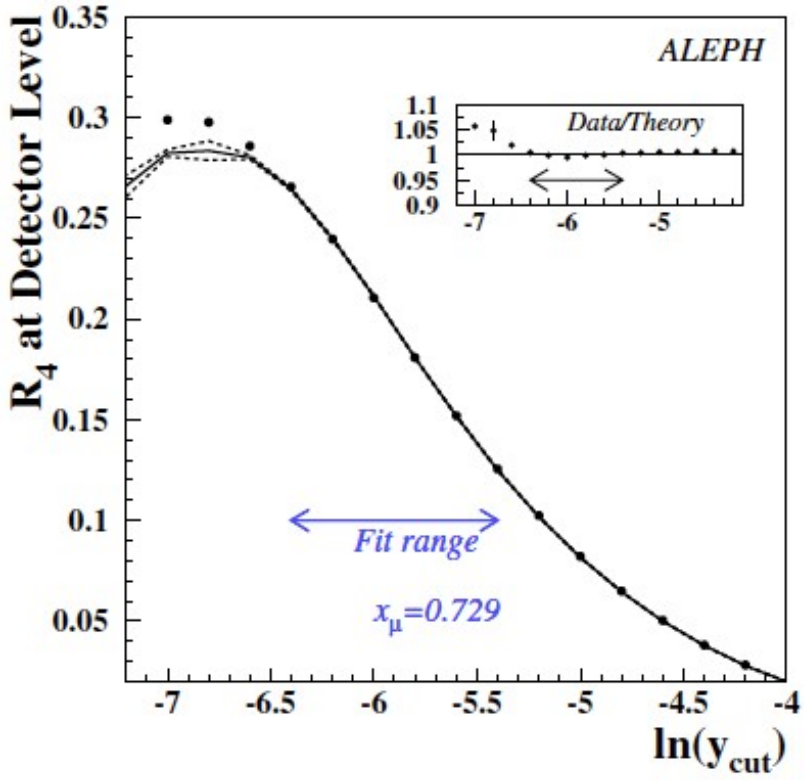


α_s from 4 jets fractions

$$R_4(y_{\rm cut}) = \frac{\sigma_{\text{4-jet}}(y_{\rm cut})}{\sigma_{\rm tot}} = \eta^2 B_4(y_{\rm cut}) + \ ...$$
$$... + \eta^3 [C_4(y_{\rm cut}) + 3/2(\beta_0 \log x_\mu - 1)\ B_4(y_{\rm cut})]$$

$$\eta \propto \frac{\alpha_s}{4\pi}$$

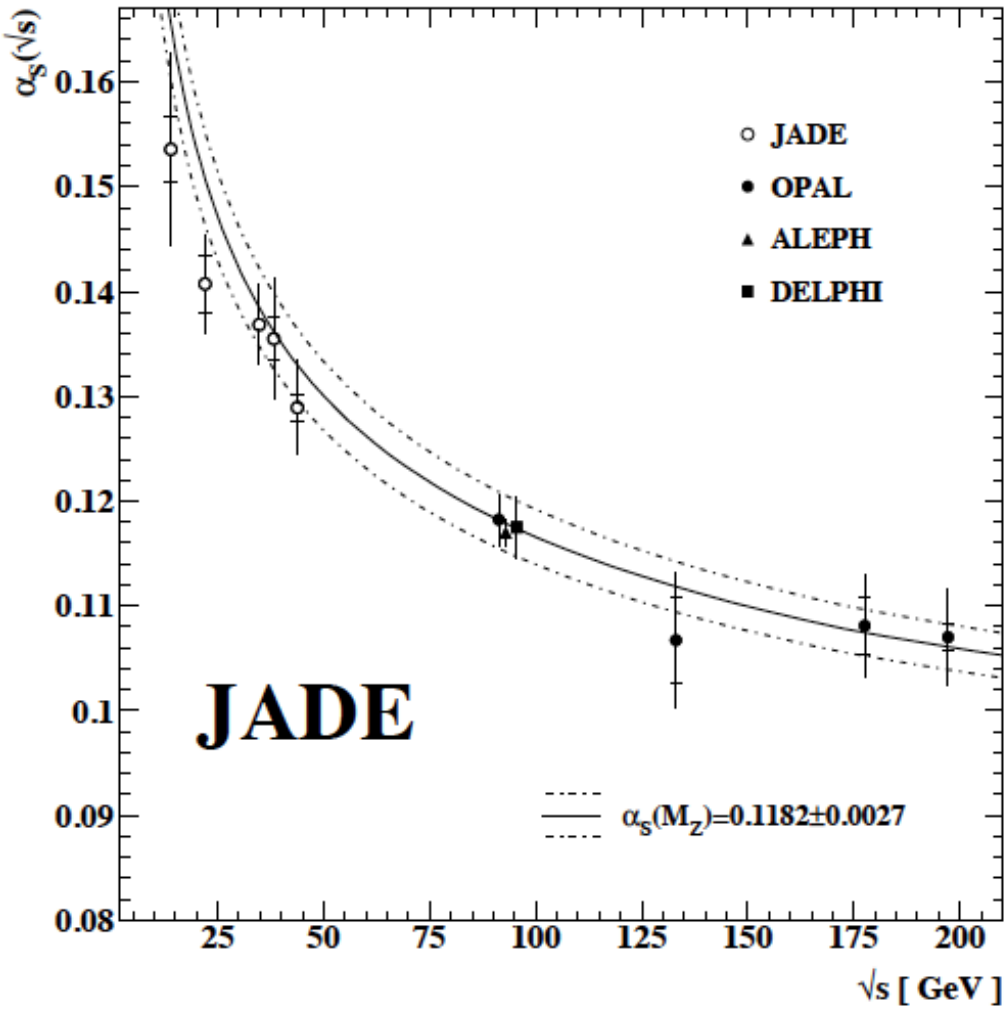




Running of α_s from 4 jets rate

Determination of α_s

Using jets in e^+e^--collisions



α_s-Results from 4-jet rates

New JADE results from 2007 [Schieck et. al]

Measurement of α_s for E ~ m(τ)

Determination of α_s

Using hadronic τ decays

→ $\alpha_s(m_\tau)$

$$R^{\tau}_{had} = \frac{\Gamma(\tau \to \nu_\tau + Hadrons)}{\Gamma(\tau \to \nu_\tau + e\bar{\upsilon}_e)} \sim f(\alpha_s)$$

$\sqrt{s} = m_\tau \simeq 1.7\ GeV$

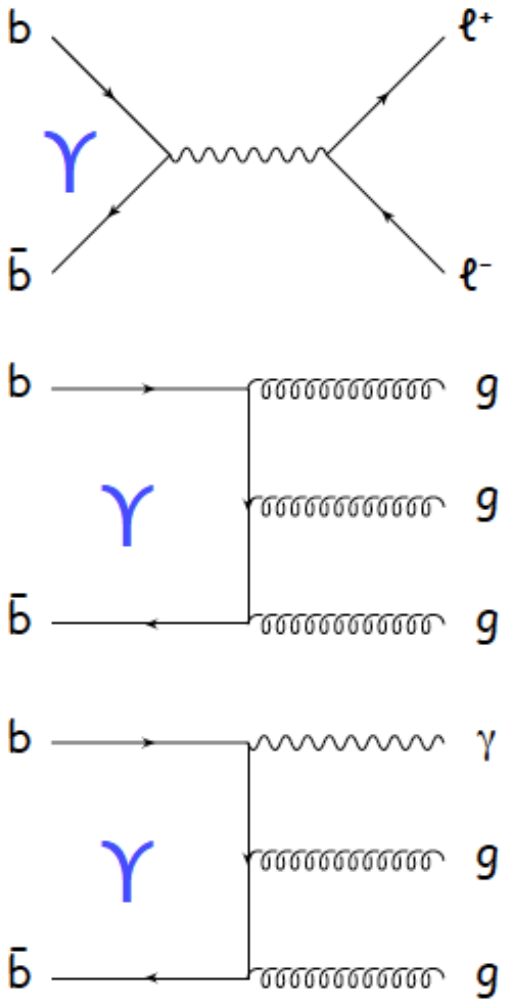
$$R^{\tau}_{had} = \frac{\left|\tau^- \to \nu_\tau\ q\ \bar{q}\ (W^-)\right|^2 + \left|\tau^- \to \nu_\tau\ q\ \bar{q}\ (W^-, \text{gluon})\right|^2 + \ldots}{\left|\tau^- \to \nu_\tau\ e^-\ (W^-)\right|^2}$$

$$R^{\tau}_{had} = R^{\tau,0}_{had}\left(1 + \frac{\alpha_s(m_\tau^2)}{\pi} + \ldots\right)$$

Measurementof α_s at E = m(Y)

Determination of α_s

Using hadronic Υ decays



$$\sqrt{s} = m_\Upsilon \simeq 10 \ GeV$$

Determine decay ratios:

(I) $$\frac{\Gamma(\Upsilon \to \text{hadrons})}{\Gamma(\Upsilon \to \ell\ell)}$$

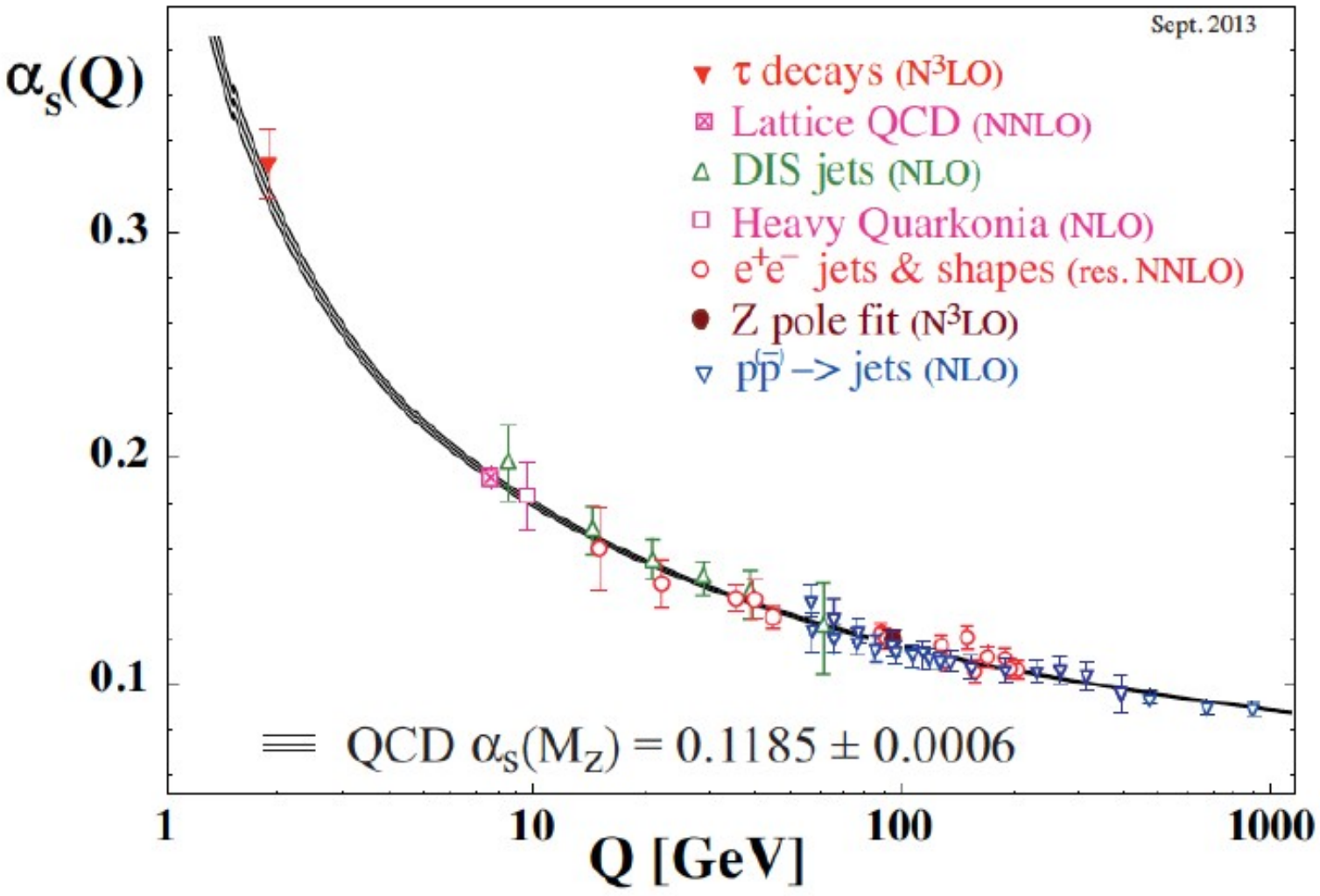
(II) $$\frac{\Gamma(\Upsilon \to \gamma + \text{hadrons})}{\Gamma(\Upsilon \to \text{hadrons})}$$

Using PDG:
[Hinchcliff & Manohar, 2000]

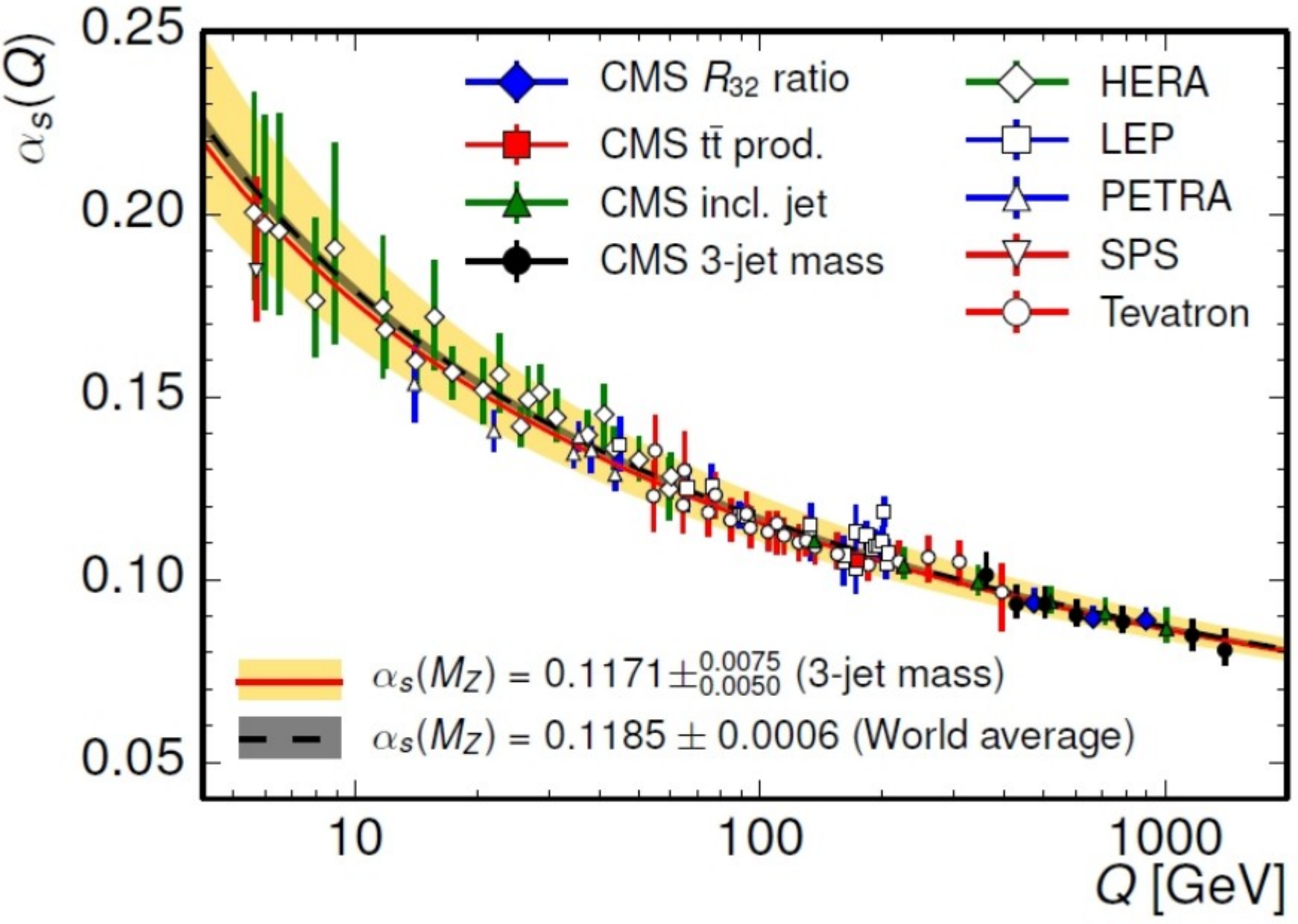
I. → $\alpha_s = 0.177 \pm 0.01$

II. → $\alpha_s = 0.189 \pm 0.01$

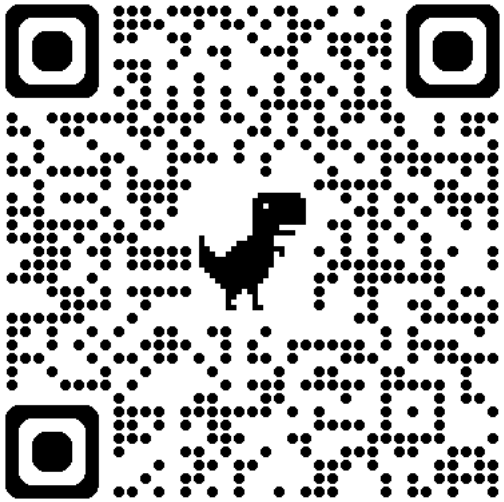
Summary :running of α_s



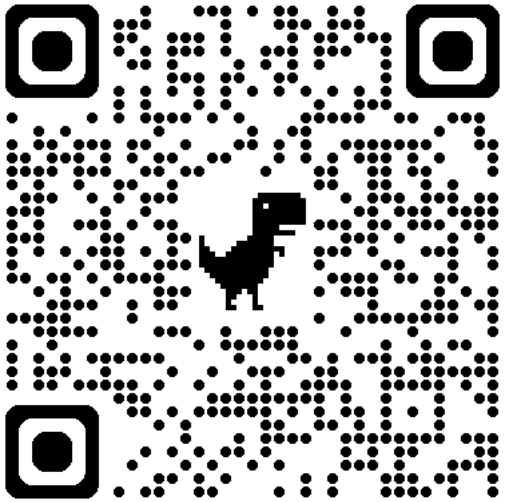
Summary :running of α_s



Sondaggio: conoscenze acquisite



Sondaggio: valutazione del corso



Sondaggio: vota il nickname

OFFLINE:

- Votazioni in moodle entro domani sera
- Il premio sara' consegnato Venerdi' al termine del party

Unification of interactions ?

- Is there a value of q^2 for which $\alpha(q^2) = \alpha_s(q^2) = \alpha_{WI}(q^2)$?
  - Standard Model : no !
  - MS + SUSY : $\sqrt{q^2} = 10^{16}$ GeV (G.U.T.)

