QCD, Jets, & Gluons

- Quantum Chromodynamics (QCD)
- $e^+ e^- \rightarrow \mu^+ \mu^-$
- $e^+ e^-$ annihilation to hadrons ($e^+ e^- \rightarrow Q\overline{Q}$)

Quantum Chromodynamics

- Another gauge theory, as QED
- Interactions described by exchange of massless, spin-1 bosons – so-called "gauge bosons"
- Force is long range, due to massless gluons – but long range force is cancelled by combinations of color in mesons and baryons

The color quantum number

- Color was invented to explain:
  - Δ^{++} = uuu
  - e+e- → hadrons
  - Also explains $\pi^0 \rightarrow \gamma\,\gamma$
- Color of a quark has three possible values
  - say red, blue, green
- Antiquarks carry anticolor
  - Anti-red, anti-blue, anti-green
- Bosons mediating the quark-quark interaction are called <u>gluons</u>
  - Gluons are to the strong force what the photon is to the EM force
  - Gluons carry a color and an anticolor
    - 9 possible combinations of color and anticolor
    - $r\bar{r}+g\bar{g}+b\bar{b}$ is color neutral, leaving 8 effective color combinations
- Results in potential $V = -\frac{4}{3}\,\alpha_s\,/r + kr$

Color

- 3 different color states
  - x_C = r, g, b
- Color hypercharge
  - Y^C
- Color isospin
  - I_3^C

Hadrons are combinations of quarks with $Y^C = 0$ and $I_3^C = 0$

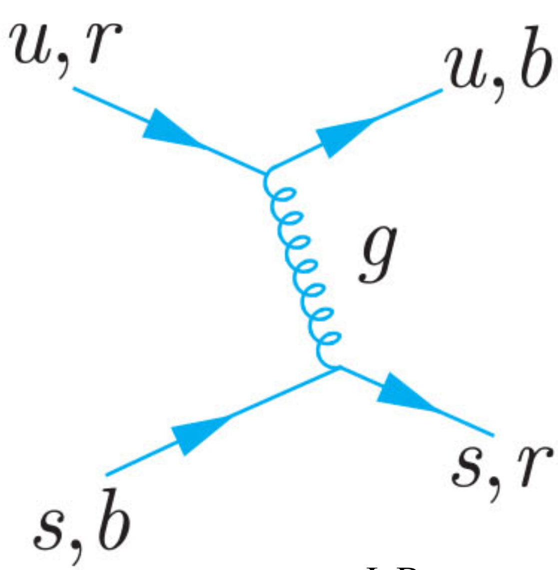
so baryons = r g b

& mesons = r anti-r, etc.

(a) Quarks			(b) Antiquarks		
	I_3^C	Y^C		I_3^C	Y^C
r	1/2	1/3	$\bar{r}$	−1/2	−1/3
g	−1/2	1/3	$\bar{g}$	1/2	−1/3
b	0	−2/3	$\bar{b}$	0	2/3

Color

- In this diagram, the gluon has the color quantum numbers:
  - $I^C_3 = I^C_3(r) - I^C_3(b) = \frac{1}{2}$
  - $Y^C = Y^C(r) - Y^C(b) = 1$
- So gluon exists in color state

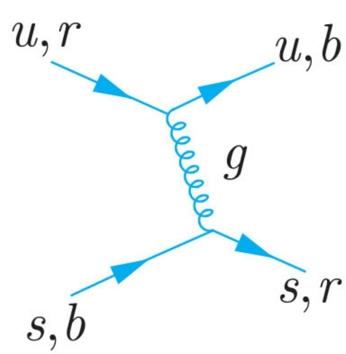


(a) Quarks

	I^C_3	Y^C
r	1/2	1/3
g	−1/2	1/3
b	0	−2/3

Quantum Chromodynamics

- Important properties of strong interactions distinguishing it from QED:
  - Color confinement
    - Observed states have zero color charges.
  - Asymptotic freedom
    - Interaction gets weaker at short distances.
    - At 0.1 fm the lowest order diagrams dominate and one gluon exchange approximates quark-quark scattering.

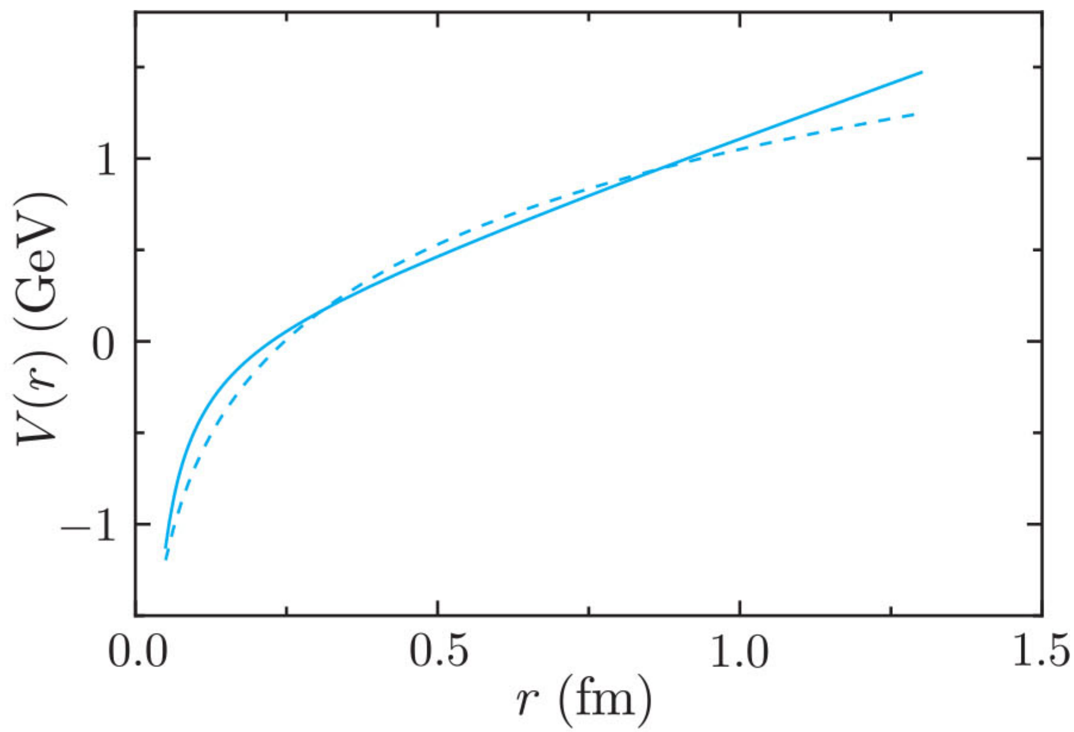


Quantum Chromodynamics

- QCD potential:

  $V = -(4/3)\,\alpha_s / r \quad (r \leq 0.1\ \text{fm})$

  $V = kr \quad (r \geq 1\ \text{fm})$

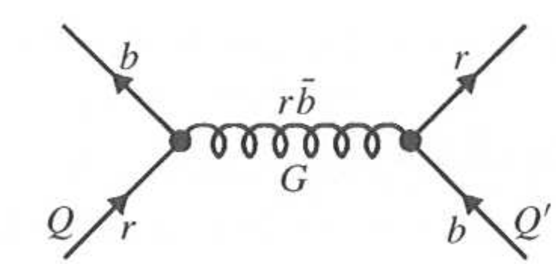


The color quantum number

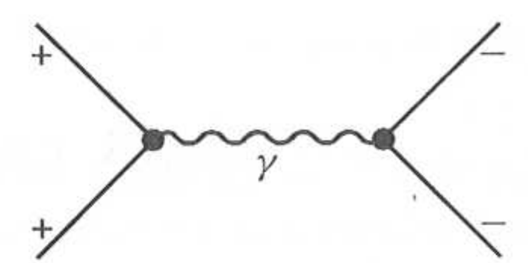
- A possible basis for the gluons:
  - $r\bar{b}$, $r\bar{g}$, $b\bar{g}$, $b\bar{r}$, $g\bar{r}$, $g\bar{b}$, $^1/_{\sqrt{2}}(r\bar{r}-b\bar{b})$, $^1/_{\sqrt{6}}(r\bar{r}+b\bar{b}-2g\bar{g})$

    (color singlet – no color – excluded: $^1/_{\sqrt{3}}(r\bar{r}+b\bar{b}+g\bar{g})$

- Gluon exhanges are analogous to photon exchanges, but different



gluons carry color charge

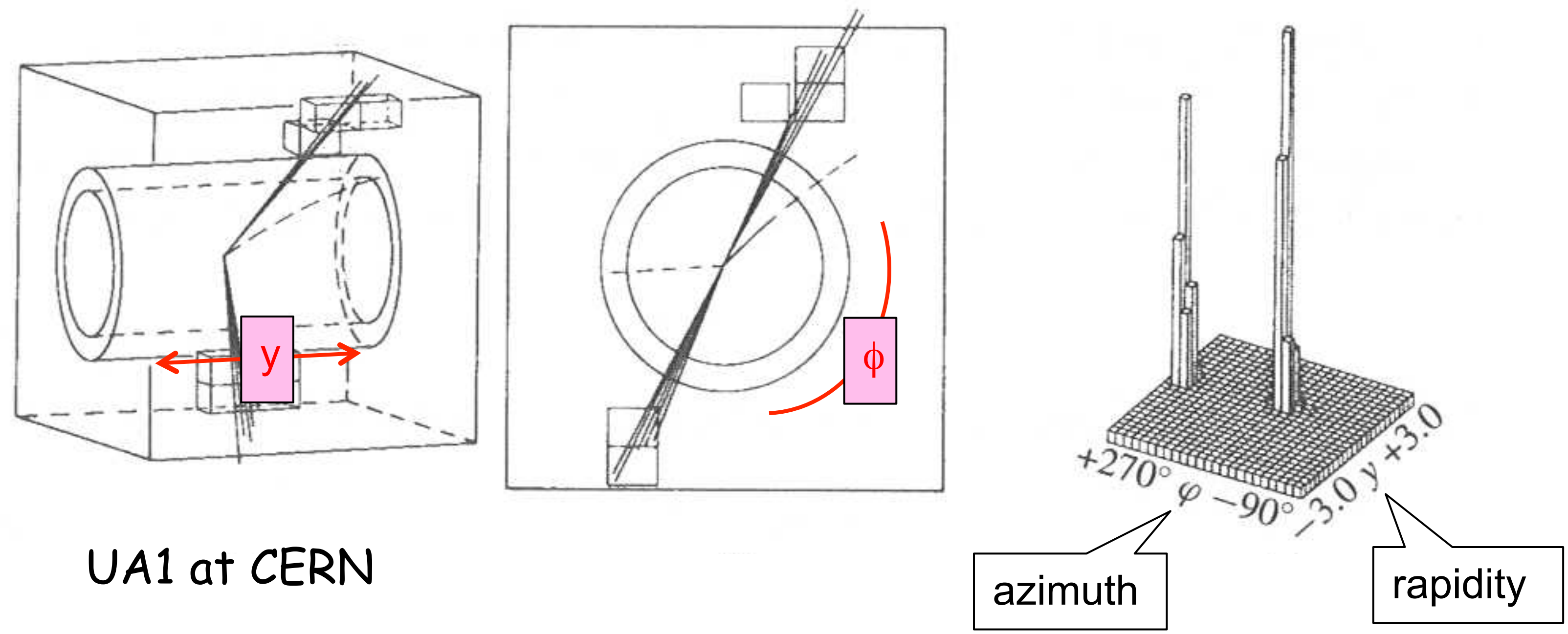


Photons **do not** carry electric charge

- Hadrons are always color neutral (or color-singlets)
  - eg. $Q_r\bar{Q}_r$, $Q_rQ_bQ_g$
  - Note – quark combinations such as QQ or $QQ\bar{Q}\bar{Q}$ are not (normally) bound

The QCD Potential at Short Distance

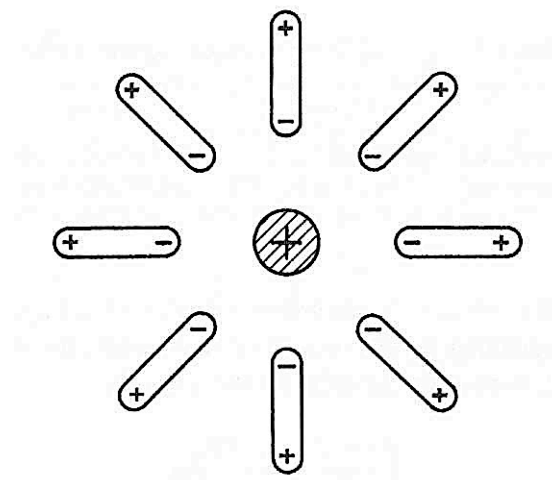
- Jets produced in high energy collisions are direct support for the short range behavior



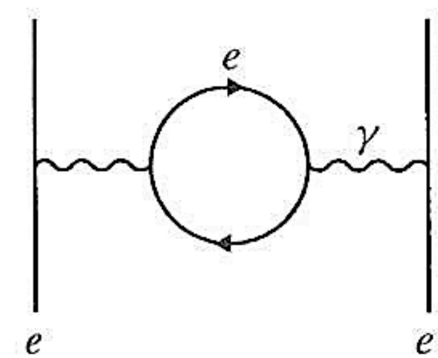
UA1 at CERN

Running Couplings in QED

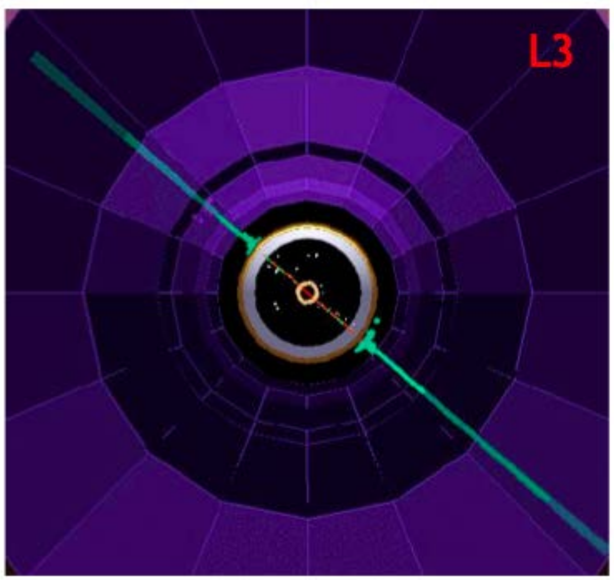
- Shielding effect is created around a charge, effectively changing the strength of coupling

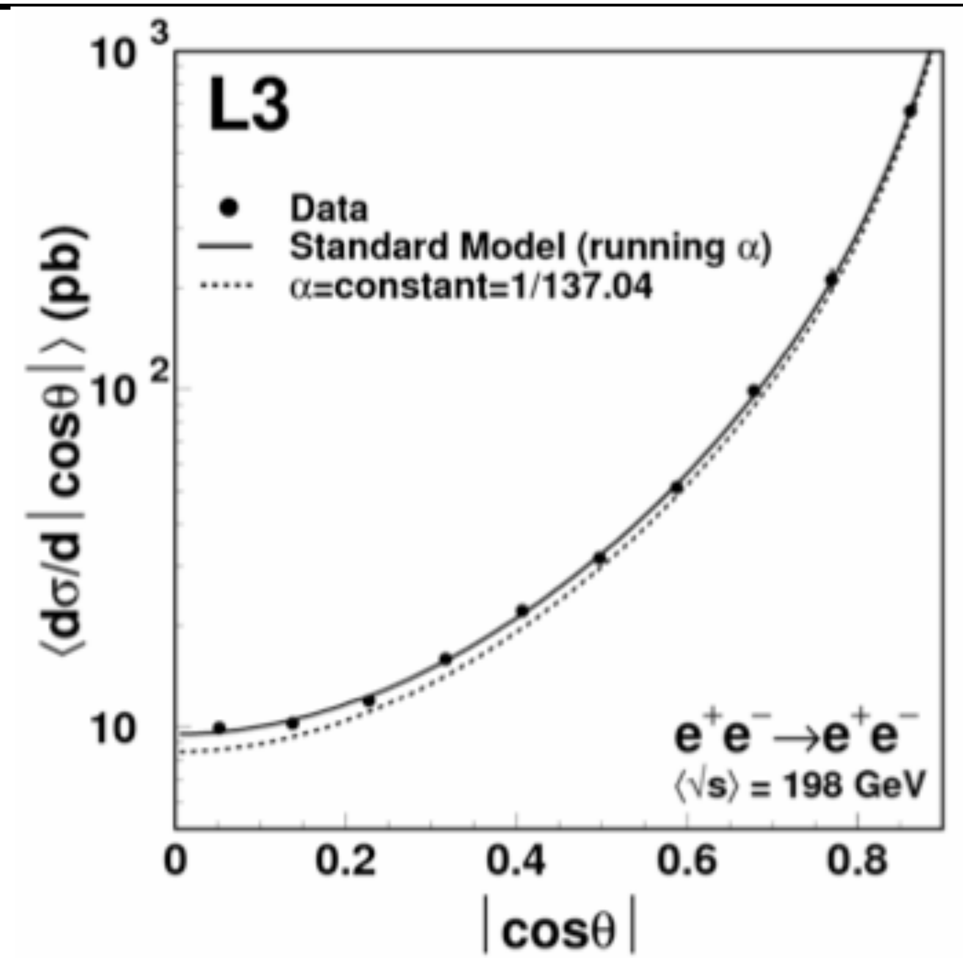


- Pairs of charge will be created and reabsorbed, producing shielding effect ("vacuum polarization")

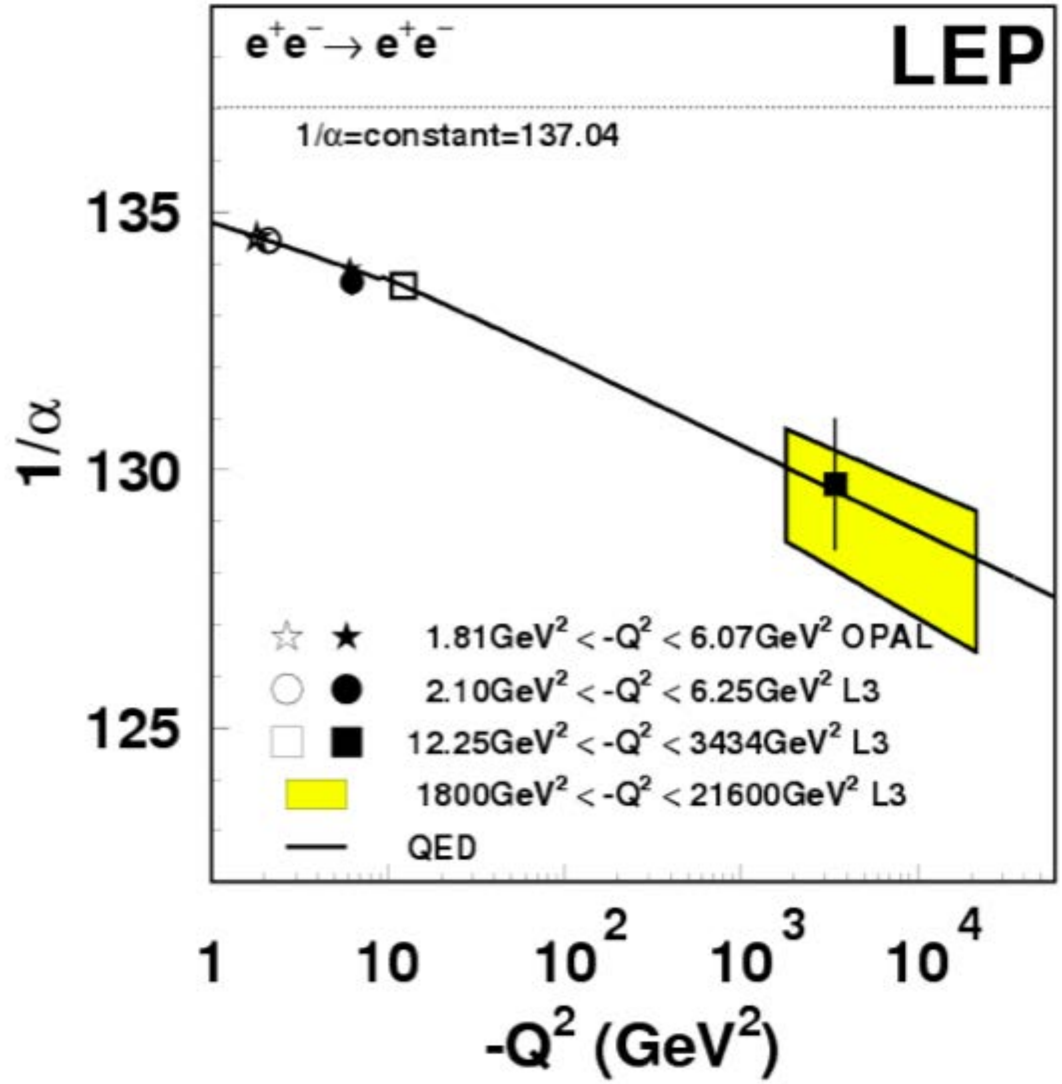


Bhabha measurement at large momentum-transfer (L3)





Running Couplings in QED



S.Mele

QED predictions from Burkhardt&Pietrzyk PLB **513(2001)46**

Running Couplings

- Dependence of coupling on momentum transfer (and therefore mass scale) follows the renormalization group equation:

$$\frac{1}{\alpha(\mu^2)} = \frac{1}{\alpha(q^2)} + \beta_0 \ln\left(\frac{q^2}{\mu^2}\right) + \cdots$$

- β_0 depends on the number of degrees of freedom

$$\beta_0 = \frac{1}{12\pi}(4n_f - 11n_b)$$

- where n_b are bosons degrees of freedom and n_f are fermions degrees of freedom in the vacuum loops
- In QED there are no bosons in the loops, so at high energy

  $n_b = 0$, $n_f = 3$ (where all three families are active)

  consequently, $\alpha(M_Z = 91\ \text{GeV}) = 1/129$

Running Couplings

$$\frac{1}{\alpha(\mu^2)} = \frac{1}{\alpha(q^2)} + \beta_0 \ln\left(\frac{q^2}{\mu^2}\right) + \cdots$$

$\beta_0 = \frac{1}{12\pi}(4n_f - 11n_b)$ $=1/12\pi(4x3 - 0) = 1/\pi$

- $q^2 = m_e^2 = (5.1 \times 10^{-4}\ \text{GeV})^2$
- $1/\alpha(m_Z^2) = 137 + 1/\pi \ln(2.5 \times 10^{-7}/91^2)$

$\alpha(m_Z^2) = 1/129$

Running Couplings in QCD

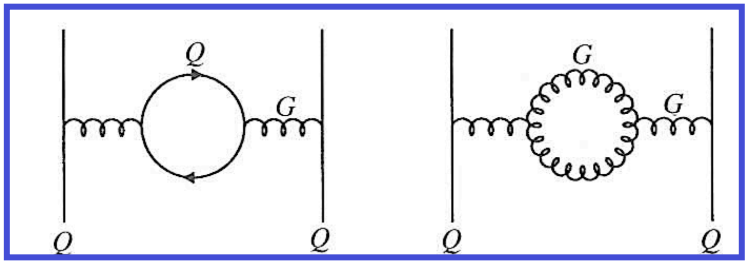
- In QCD there are three degrees of freedom (3 colors)

  $n_b = 3$

  $n_f = 3$ (where all three families are active)

$$\beta_0 = \frac{1}{12\pi}(4n_f - 11n_b) = (12-33)/12\pi = -7/4\pi$$

$$\alpha_s(q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{7}{4\pi}\alpha_s(\mu^2)\ln\left(\frac{q^2}{\mu^2}\right)}$$



or $$\alpha_s(q^2) = \frac{1}{B\ln(q^2/\Lambda^2)}$$

where $B = -\beta$ $\quad \Lambda^2 = \mu^2 \exp\{-1/B\ \alpha_s(\mu^2)\}$

Running Couplings in QCD

$$\alpha_s(q^2) = \frac{1}{B \ln(q^2/\Lambda^2)}$$

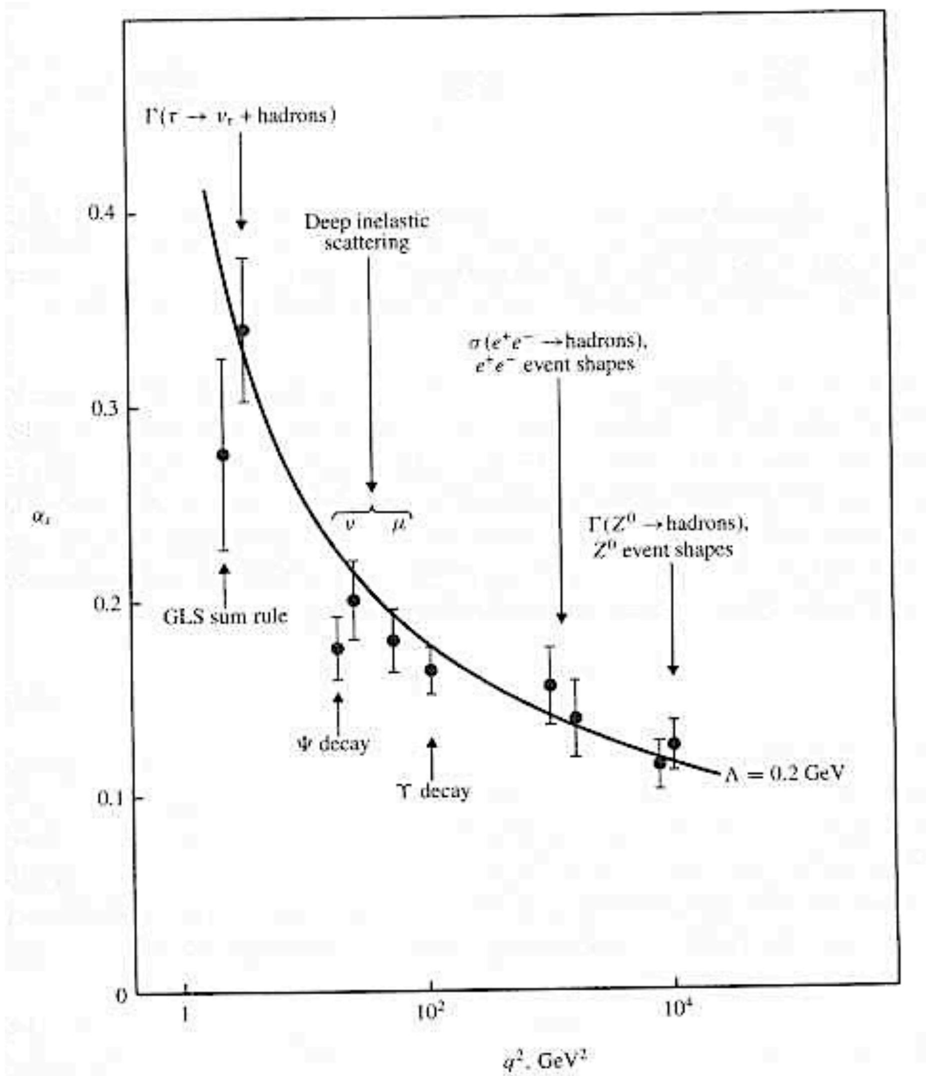
- α_s decreases with increasing q^2
  - this is the opposite dependence from QED
  - it is typical of non-Abelian field, where the field particles carry charge and are self-coupling
  - the longitudinal gluons have an antishielding effect, spread out the color charge, weakening the interaction

- Large q^2 $\alpha_s \rightarrow 0$
  - asymptotic freedom

- Small q^2 $\alpha_s \rightarrow$ oo
  - confinement

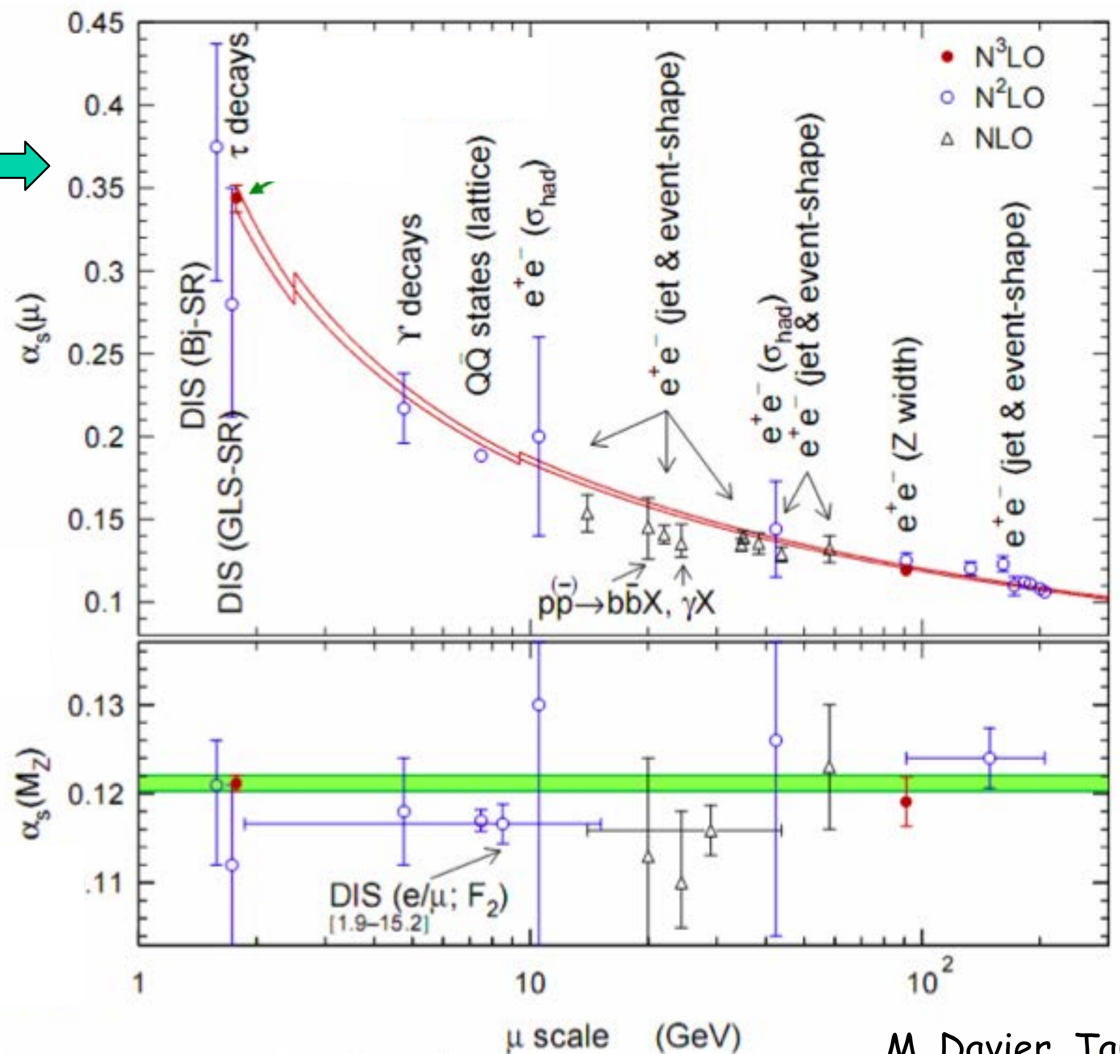
Perturbation theory applies for q^2 >> L

Running Couplings in QCD



Running of Strong Coupling

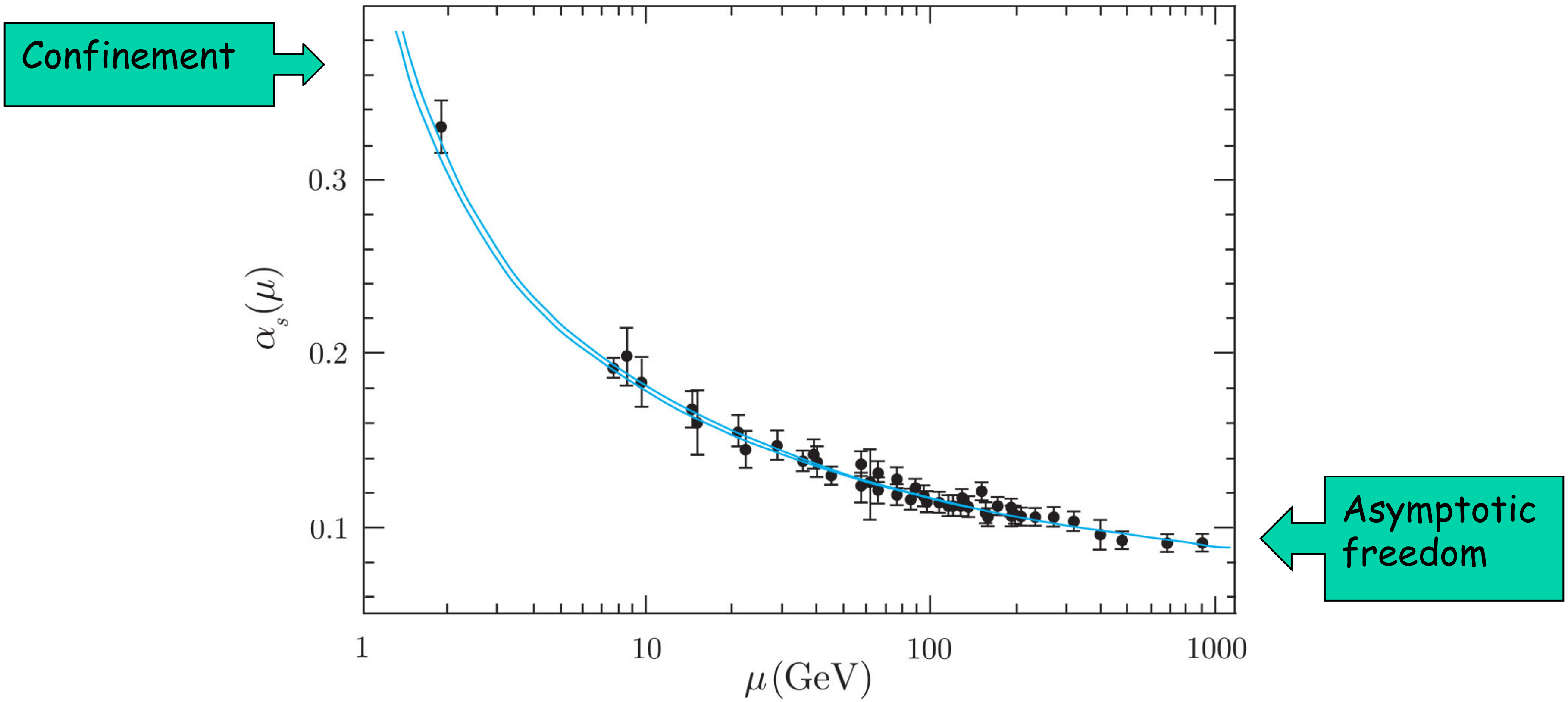
Confinement



Asymptotic freedom

M. Davier, Tau2010

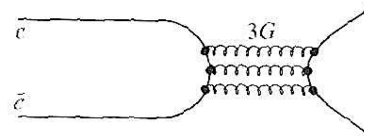
Running of Strong Coupling



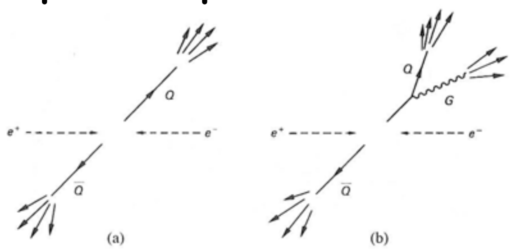
Running Couplings in QCD

Many observables are sensitive to the value of α_s

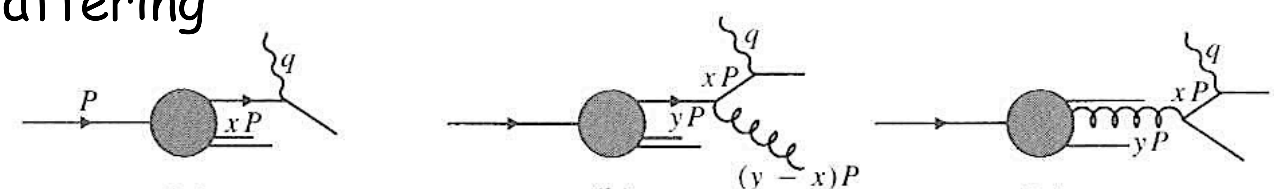
- Widths of bounds state of cc and bb



- R = $\sigma(e^+e^- \to \text{hadrons})/\sigma(\text{point})$ requires factor $(1 + \alpha_s/\pi)$
- Event shapes depend on fraction of 3 jets



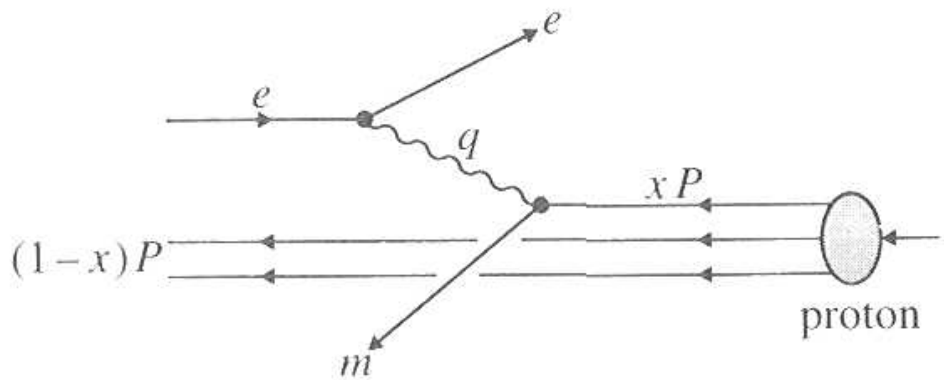
- Scaling deviations in deep inelastic lepton-nucleon scattering



- Hadronic width of the Z

The "discovery" of quarks

- deep inelastic lepton-nucleon scattering revealed dynamical understanding of quark substructure

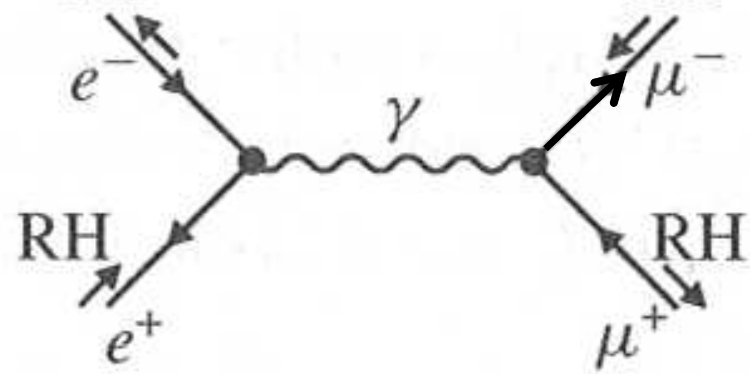


- leptoproduction of hadrons could be interpreted as elastic scattering of the lepton by a pointlike constituent of the nucleon, the quark
- theory of scattering of two spin-1/2, pointlike particles required

$e^+ e^- \rightarrow \mu^+ \mu^-$

- The electromagnetic process is dominated by single-photon exchange
- $M_{if} = e^2/q^2 = 4\pi\alpha/q^2$
- $$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s} f(\theta)$$

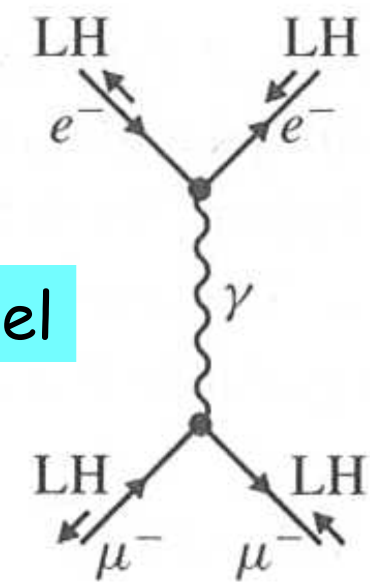
  (neglecting the muon mass)
- What about spins?
  - The conservation of helicity at high energy for the EM interaction means only LR and RL states will interact



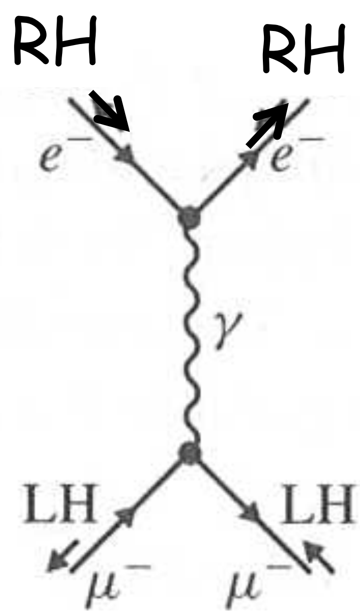
$e^+ e^- \rightarrow \mu^+ \mu^-$

- Conservation of helicity
  - consider conservation of helicity at high energy in scattering of electron

t channel

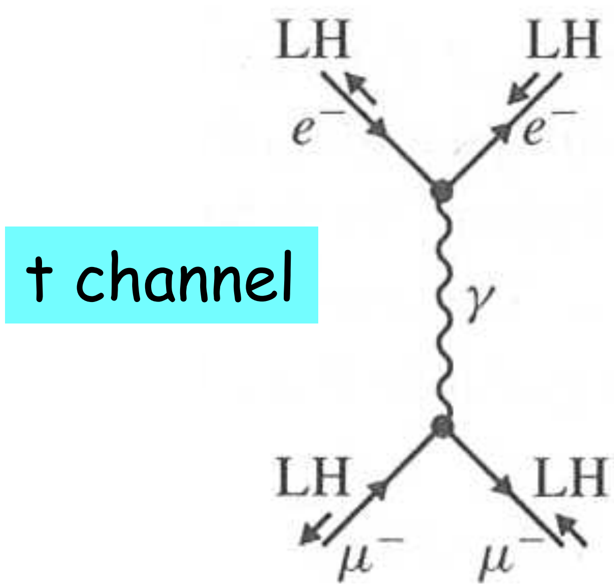


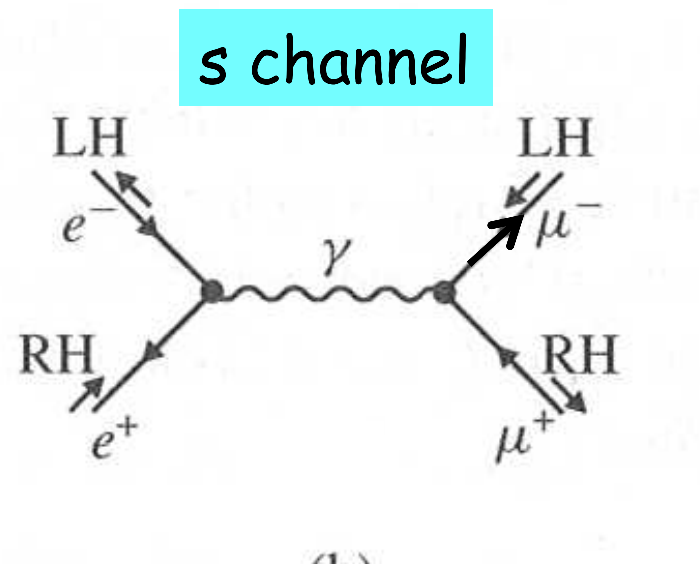
$e^-_R \rightarrow e^-_R$
and
$e^-_L \rightarrow e^-_L$



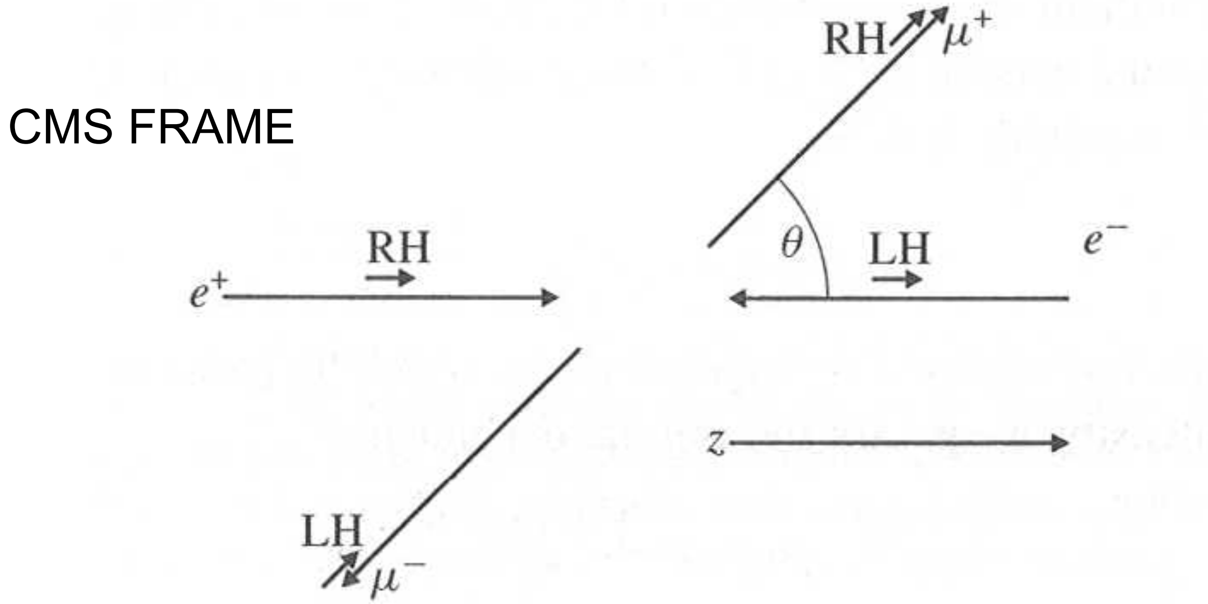
$e^+ e^- \rightarrow \mu^+ \mu^-$

- Conservation of helicity
  - consider crossed diagrams
  - $e^-_L \rightarrow e^-_L$ t-channel, and e^-_L only couples with e^+_R in s-channel (e^-_R only couples with e^+_L)





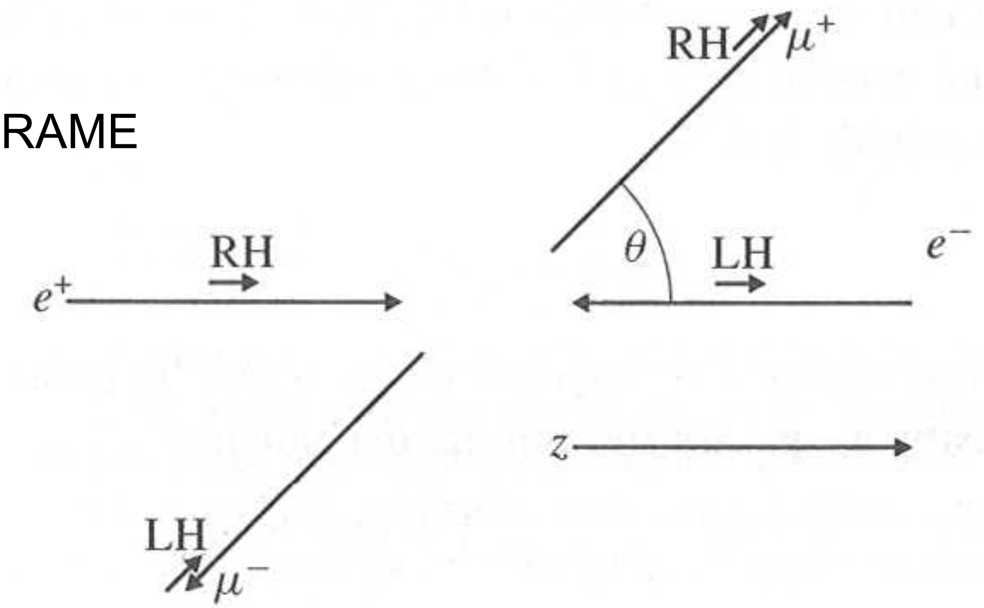
$e^+ e^- \rightarrow \mu^+ \mu^-$



- Amplitude is $d^J_{mm'}(\theta) = d^1_{1,1}(\theta) = (1+\cos\theta)/2$
  - if RL $\rightarrow$ RL
- Amplitude is $d^J_{mm'}(\theta) = d^1_{1,-1}(\theta) = (1-\cos\theta)/2$
  - If LR $\rightarrow$ RL
- $M^2 = [(1+\cos\theta)/2]^2 + [(1-\cos\theta)/2]^2 = (1+\cos^2\theta)/2$

$e^+ e^- \rightarrow \mu^+ \mu^-$

CMS FRAME



- Now, for RL → RL and LR → RL we have

  $M^2 \sim [(1+\cos\theta)/2]^2 + [(1-\cos\theta)/2]^2 = (1+\cos^2\theta)/2$

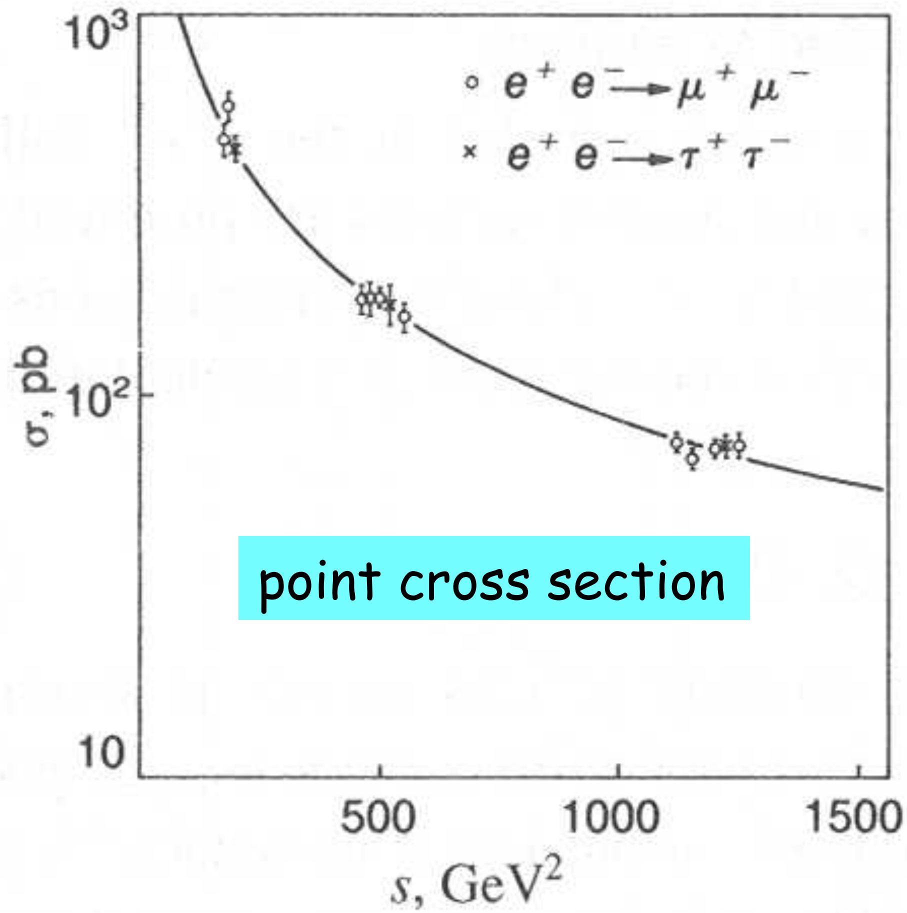
- Sum over final states, adding RL → LR and LR → LR, to double M^2

  $M^2 = (1+\cos^2\theta)$

$e^+ e^- \rightarrow \mu^+ \mu^-$

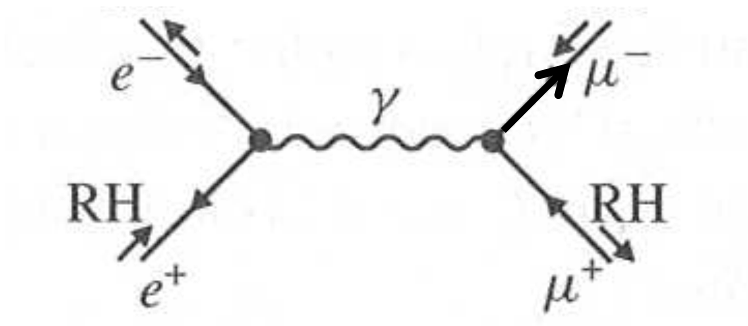
- $$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}(1+\cos^2\theta)$$

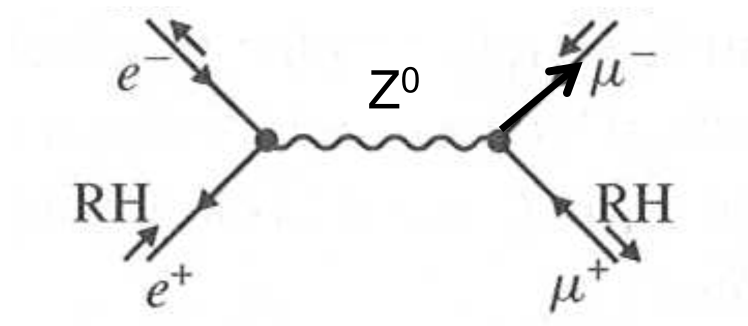
- $\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)$
  $= 4\pi\alpha^2 / 3s$
  $= 87\text{nb} / s(\text{GeV}^2)$
  (point cross section)



$e^+ e^- \to \mu^+ \mu^-$ at higher energy

- At higher energy, the Z^0 exchange diagram becomes important





$a_{em} \sim 4\pi\alpha/s$ $\quad$ $a_{wk} \sim G$ (Fermi const.)

interference $\sim a_{wk}a_{em}/a_{em}^2 \sim Gs/(4\pi\alpha) \sim 10^{-4}s$

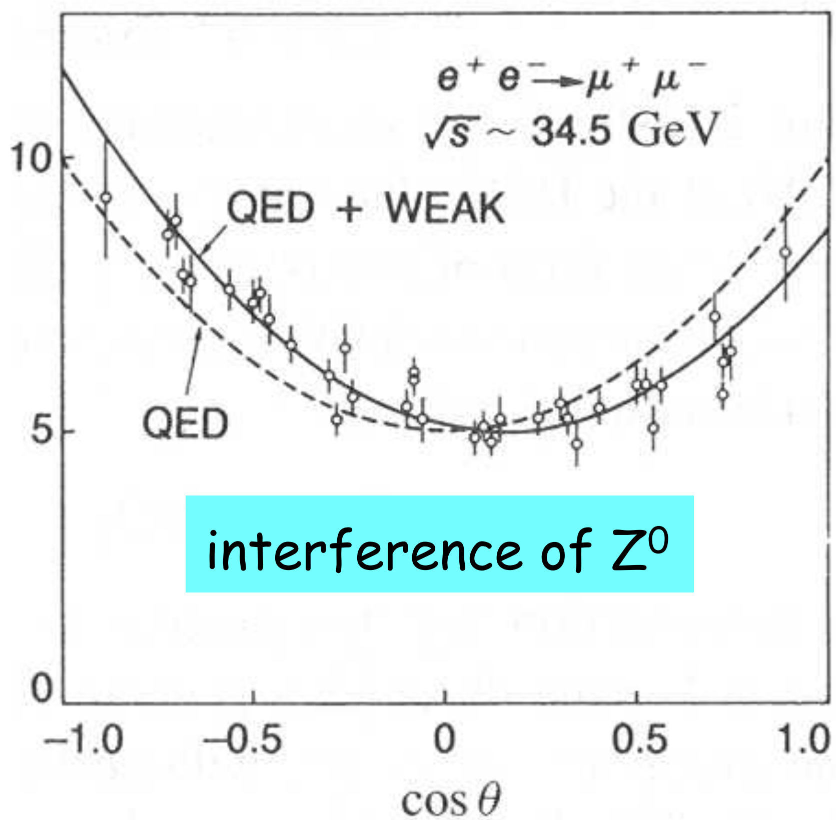
$e^+ e^- \rightarrow \mu^+ \mu^-$

$f \sim a_{wk} a_{em} / a_{em}^2 \sim Gs/(4\pi\alpha)$
$\sim 10^{-4} s$ (interference)

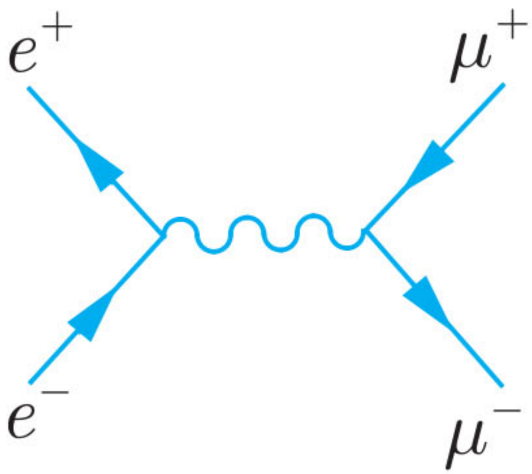
Asymmetry

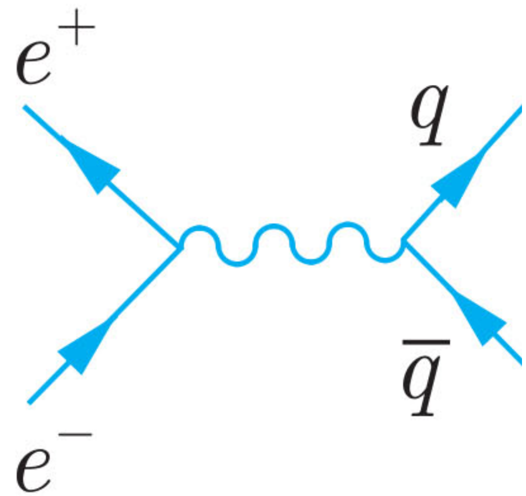
$(B-F)/(F+B) = f$

$\simeq 10\%$ at $s=1000\ GeV^2$



$e^+ e^-$ annihilation to hadrons





- $\frac{d\sigma}{d\Omega} \quad \frac{\alpha^2}{4s}(1+\cos^2\theta)$

- $\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)$

  $= 4\pi\alpha^2 / 3s$

  $= 87\text{nb} / s(\text{GeV}^2)$

  (point cross section)

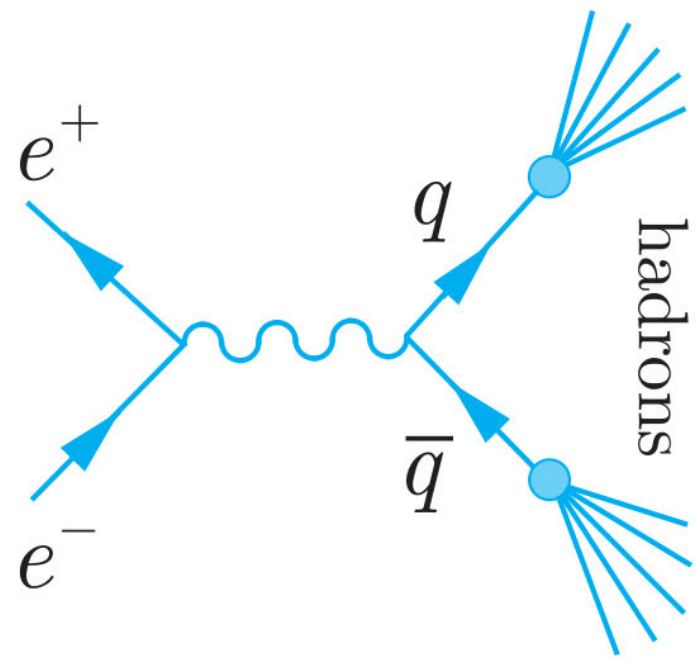
$e^+ e^-$ annihilation to hadrons

- $$\frac{d\sigma}{d\Omega} \quad \frac{\alpha^2}{4s}(1+\cos^2\theta)$$

- $\sigma(e^+ e^- \rightarrow q^+ q^-)$

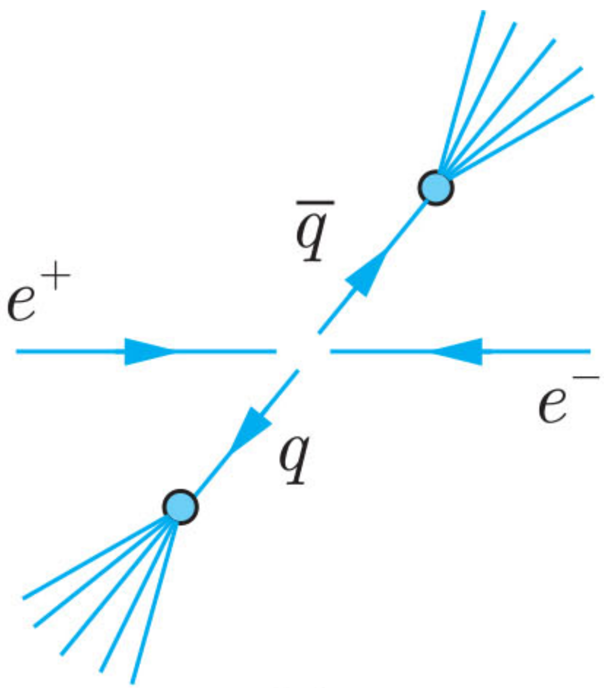
  $= 4\pi\alpha^2 Q^2_q N_c / 3s$

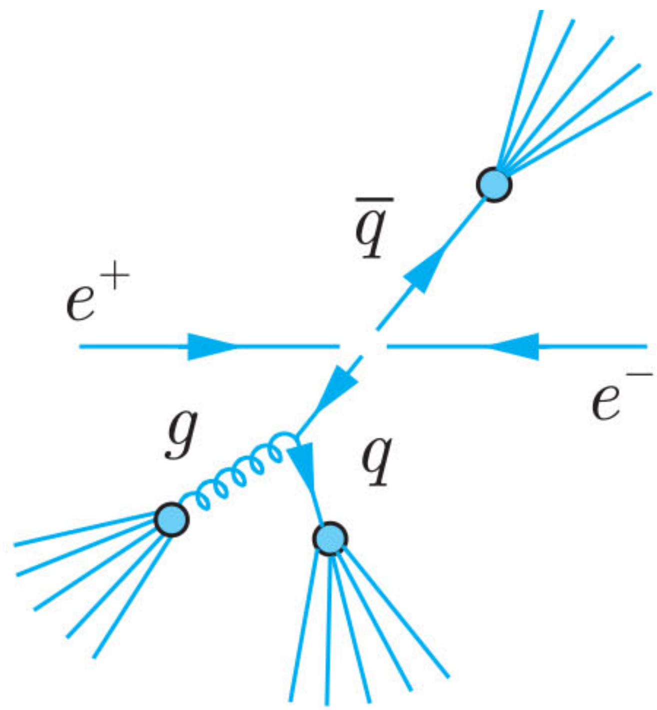
  $= 87\text{nb}\ Q^2_q N_c / s(\text{GeV}^2)$



Fragmentation

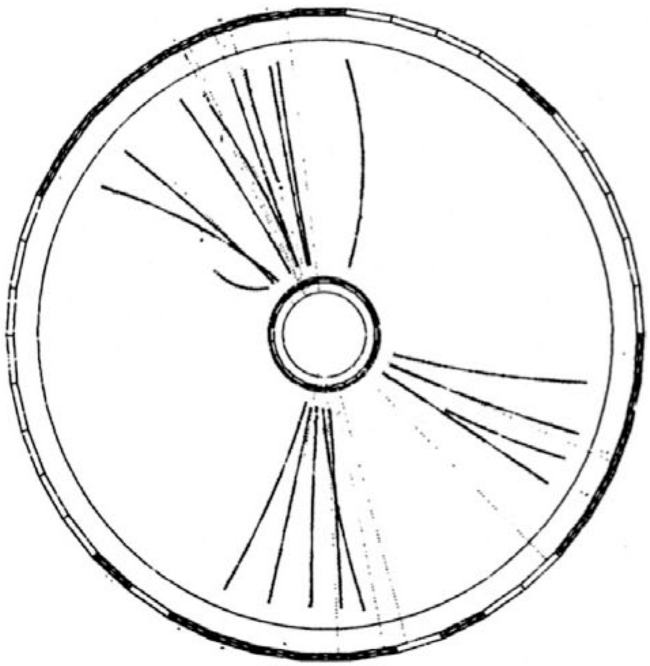
Three-jet events

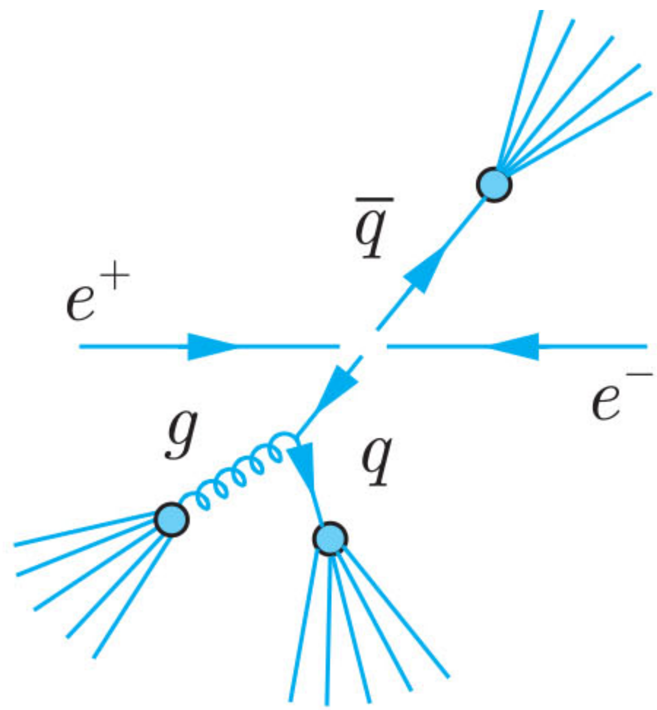




Three-jet events

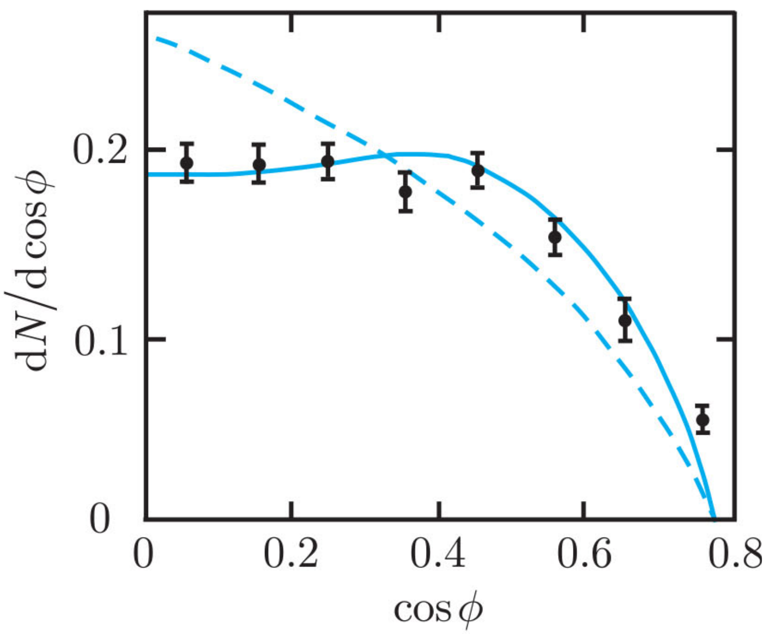
- Three-jet event observed by JADE Collaboration at DESY



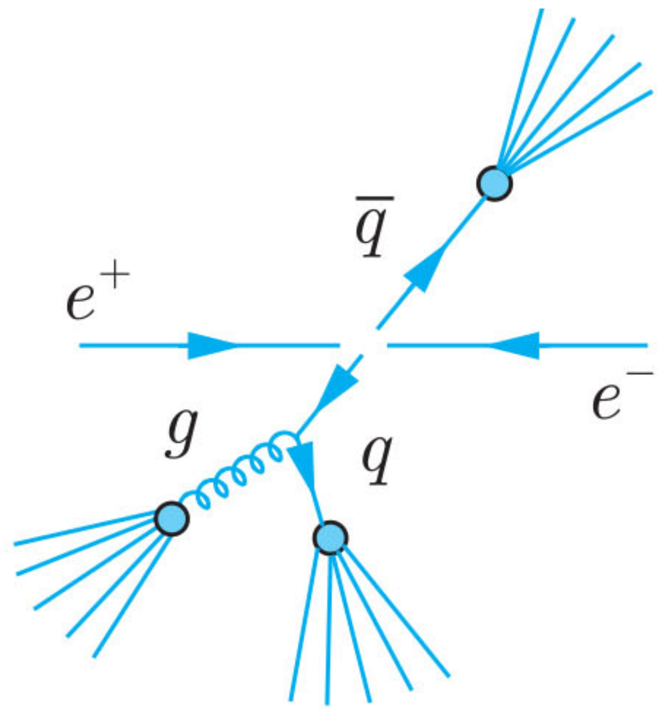


Three-jet events

- Three-jet event angular distribution observed by TASSO Collaboration at DESY



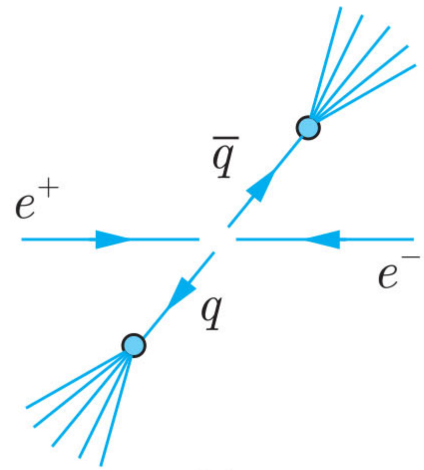
- Dashed line – spin 0 gluon
- Solid line – spin 1 gluon



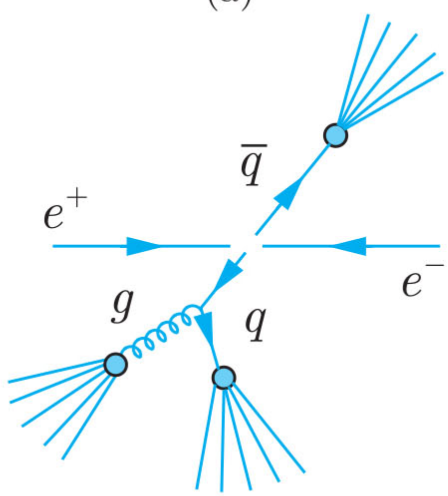
Correction for three-jet events

- Multiply by $(1 + \alpha_s/\pi)$

- $\sigma(e^+ e^- \rightarrow q^+ q^-)$
  $= 4\pi\alpha^2 Q^2_q N_c / 3s$
  $(1 + \alpha_s/\pi)$
  $= 87\text{nb}\, Q^2_q N_c / s(\text{GeV}^2)$
  $(1 + \alpha_s/\pi)$

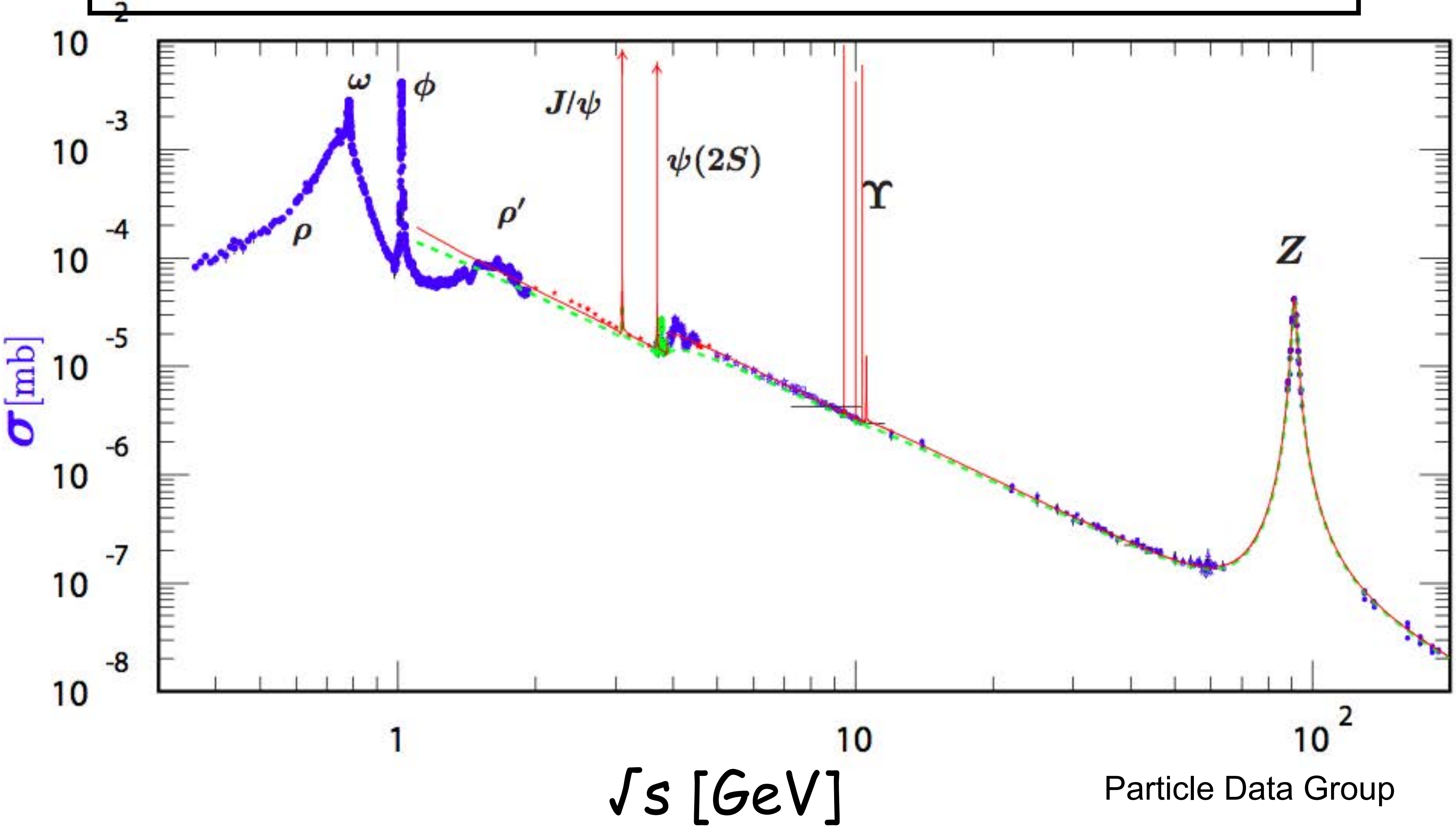


(a)



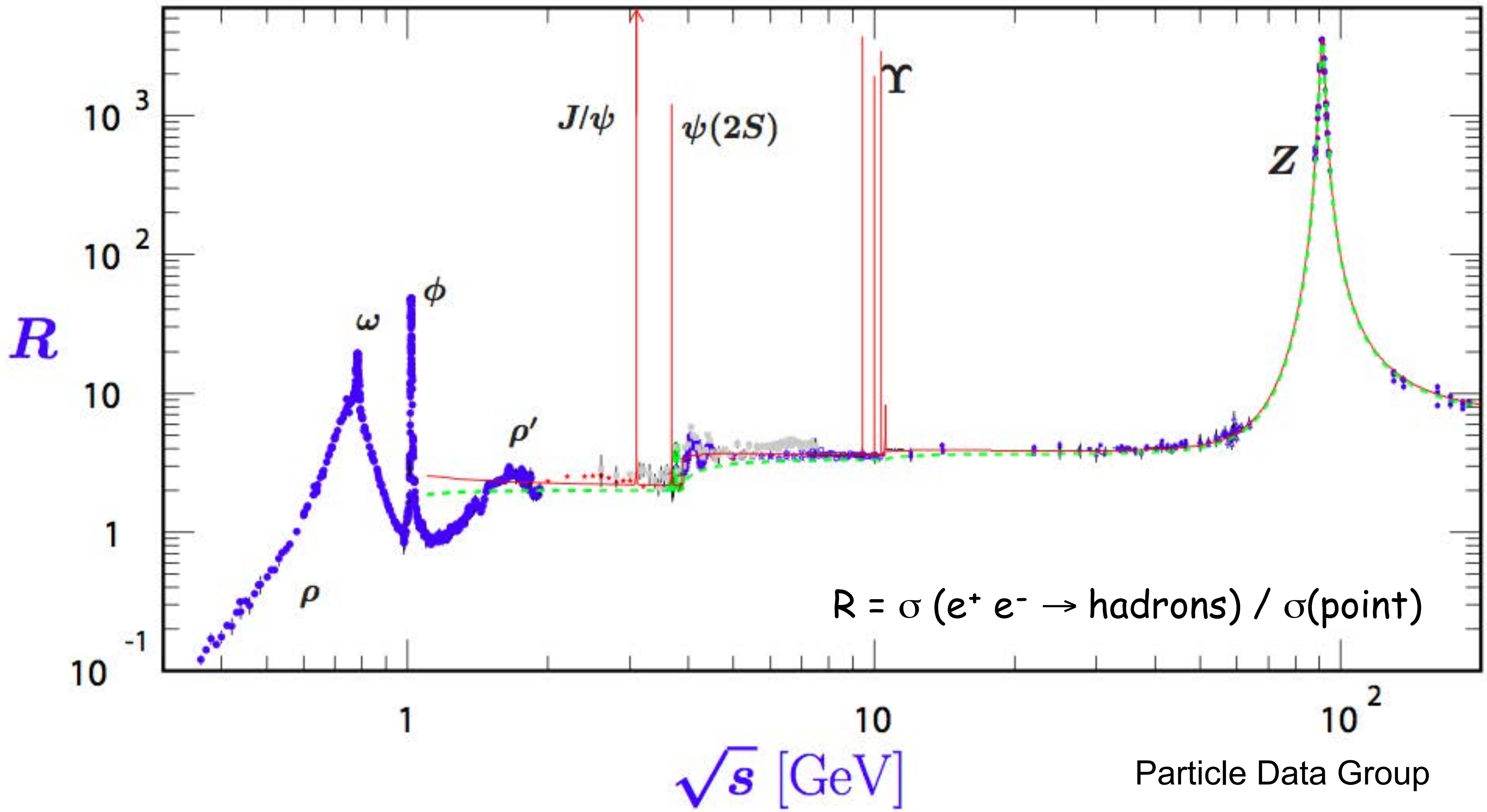
$e^+ e^-$ annihilation to hadrons

$e^+ e^-$ annihilation to hadrons



Particle Data Group

$e^+ e^-$ annihilation to hadrons



Particle Data Group

$e^+ e^-$ annihilation to hadrons

- $R = \sigma(e^+ e^- \to \text{hadrons}) / \sigma(\text{point})$
  - consider $e^+ e^- \to$ hadrons as $e^+ e^- \to Q\bar{Q}$, summed over all quarks

- $R = \Sigma e_i^2 (1 + \alpha_s/\pi)/ e^2$

  $= N_c ((1/3)^2 + (2/3)^2 + (1/3)^2 + (2/3)^2 + (1/3)^2 + \ldots.) (1 + \alpha_s/\pi)$

  d u s c b

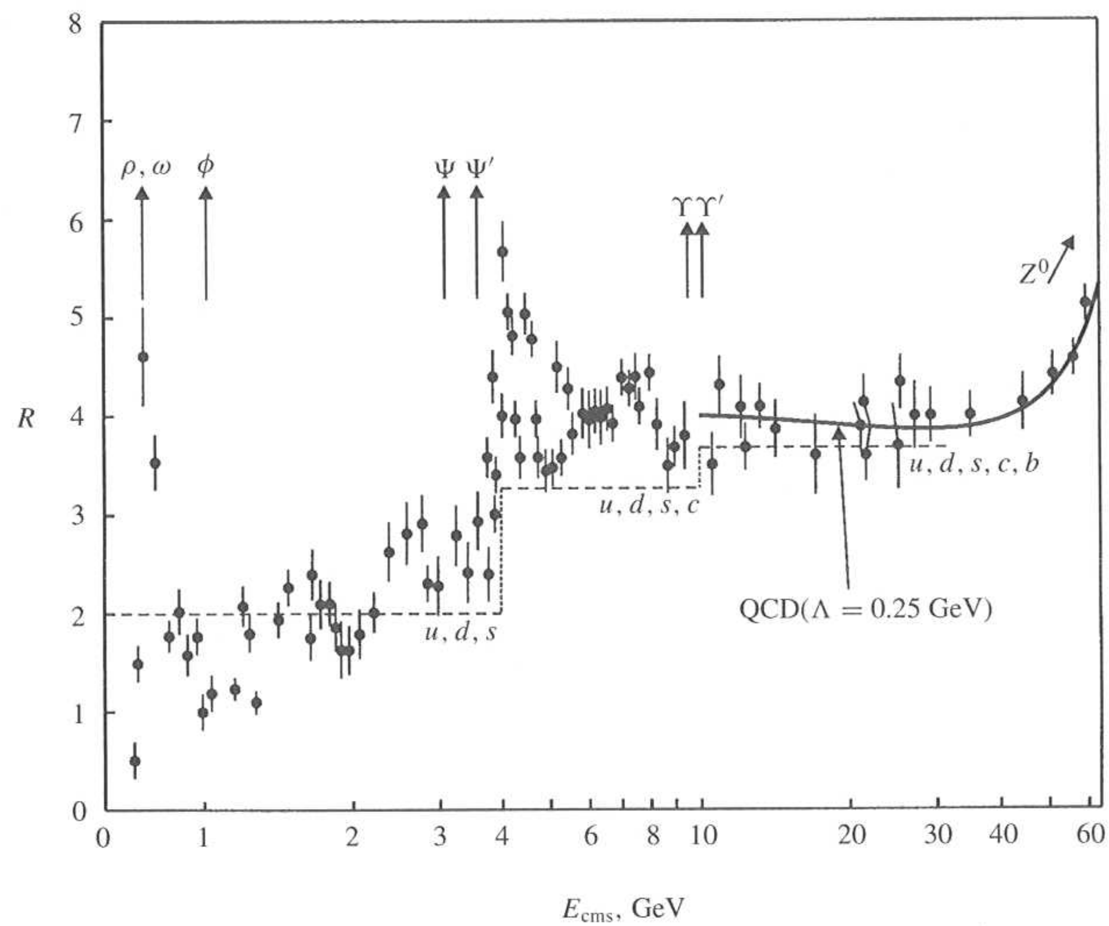
  - $N_c=3$

- Therefore, R should increase by a well defined value as each flavor threshold is crossed

$e^+ e^-$ annihilation to hadrons

Threshold	R
below c	2
charm	3 1/3
bottom	3 2/3

times $(1 + \alpha_s/\pi)$



$e^+ e^-$ annihilation to hadrons

Threshold	R
below c	2
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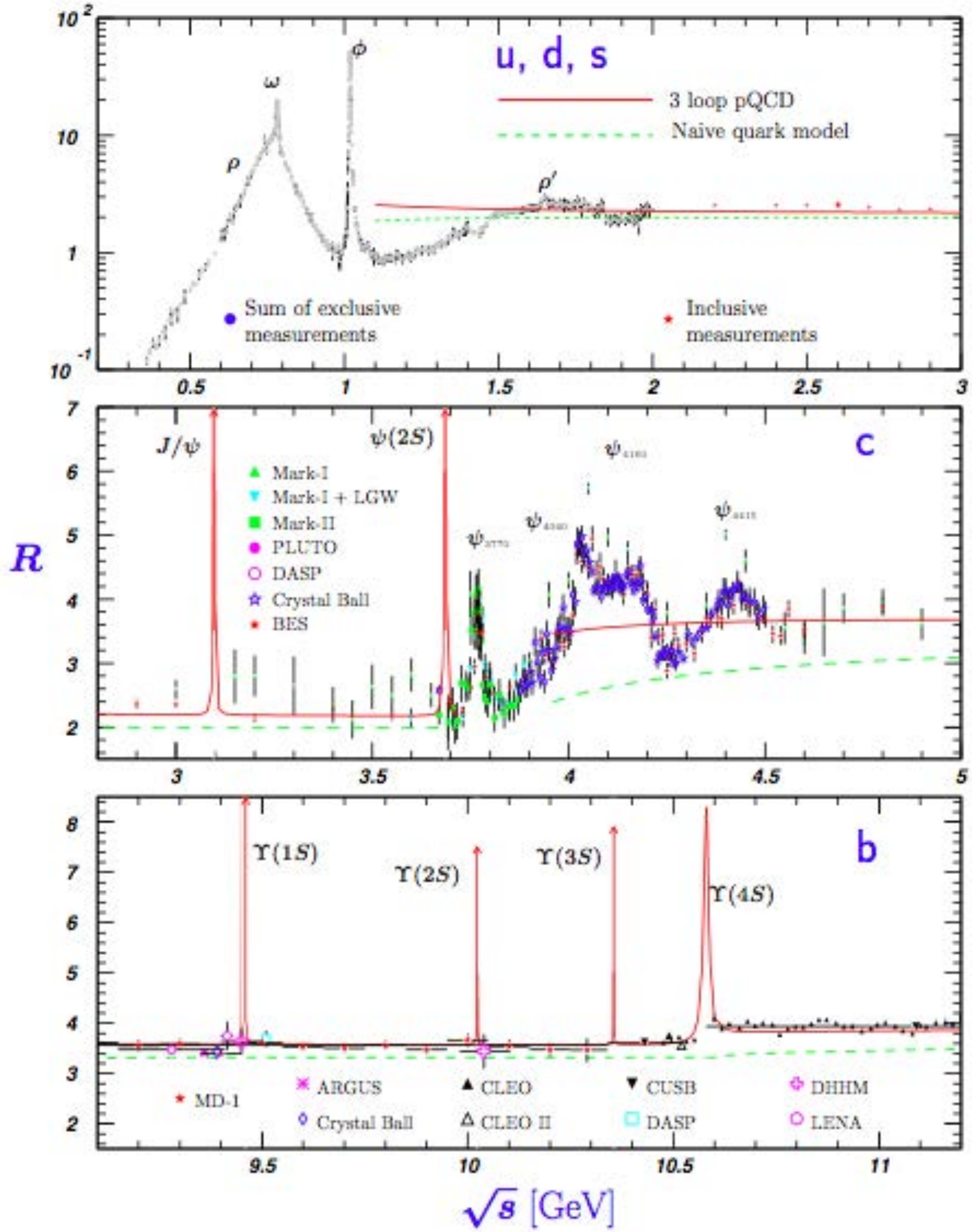
times $(1 + \alpha_s/\pi)$



Particle Data Group

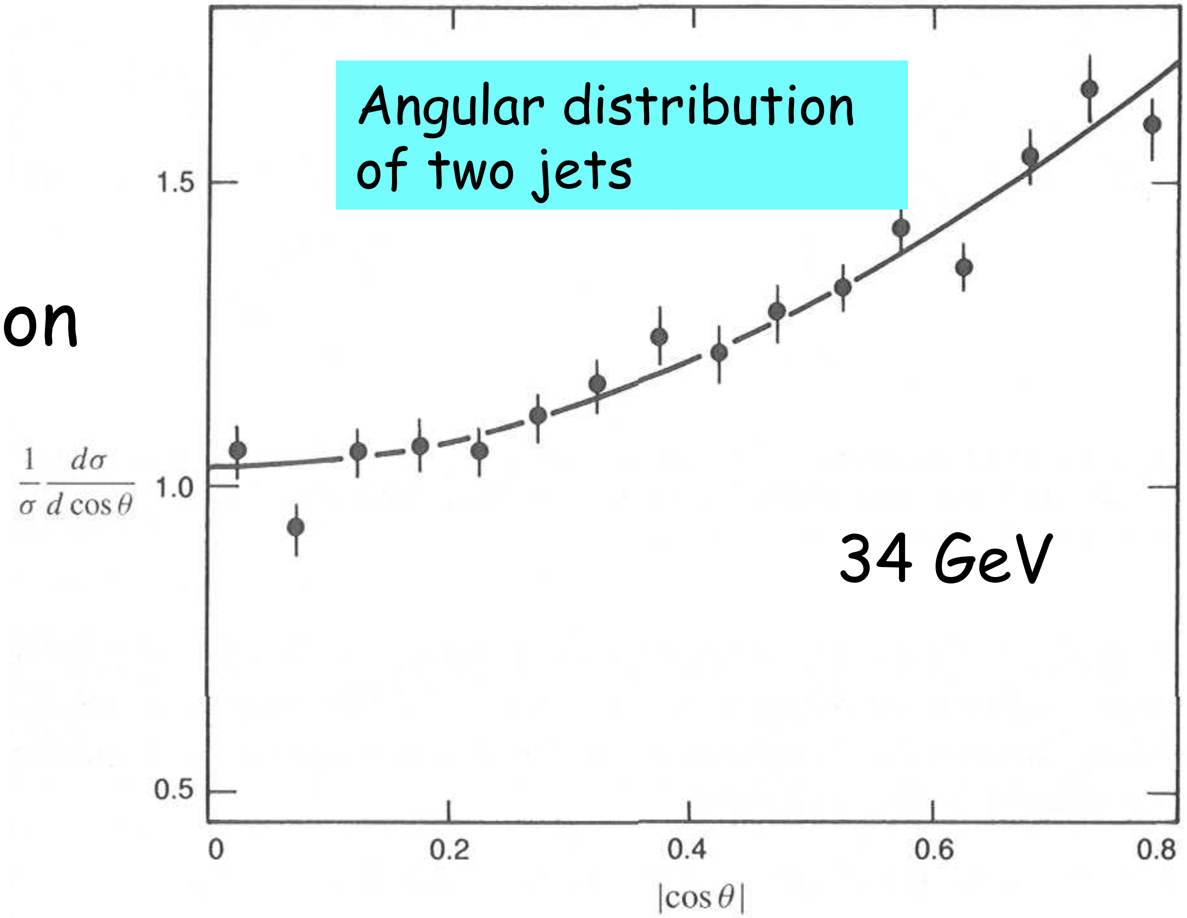
J. Brau

$e^+ e^-$ annihilation to hadrons

$e^+ e^- \rightarrow Q\bar{Q}$

If Q is spin ½, this distribution should be

$(1+\cos^2\theta)$



$e^+ e^-$ annihilation to hadrons

- Constancy of R indicates pointlike constituents
- Angular distributions of hadron jets prove spin 1/2 partons
- Values of R consistent with partons of quarks with expected charge and color quantum number

Exotic Hadrons

- Exotic hadrons are not within the simple quark model as either q q-bar, or q q q
- They are theoretically possible, not being inconsistent with QCD
- The known low mass states are dominated by hadrons composed of the simple quark model configurations, q q-bar and q q q

Exotic Hadrons: Glueballs

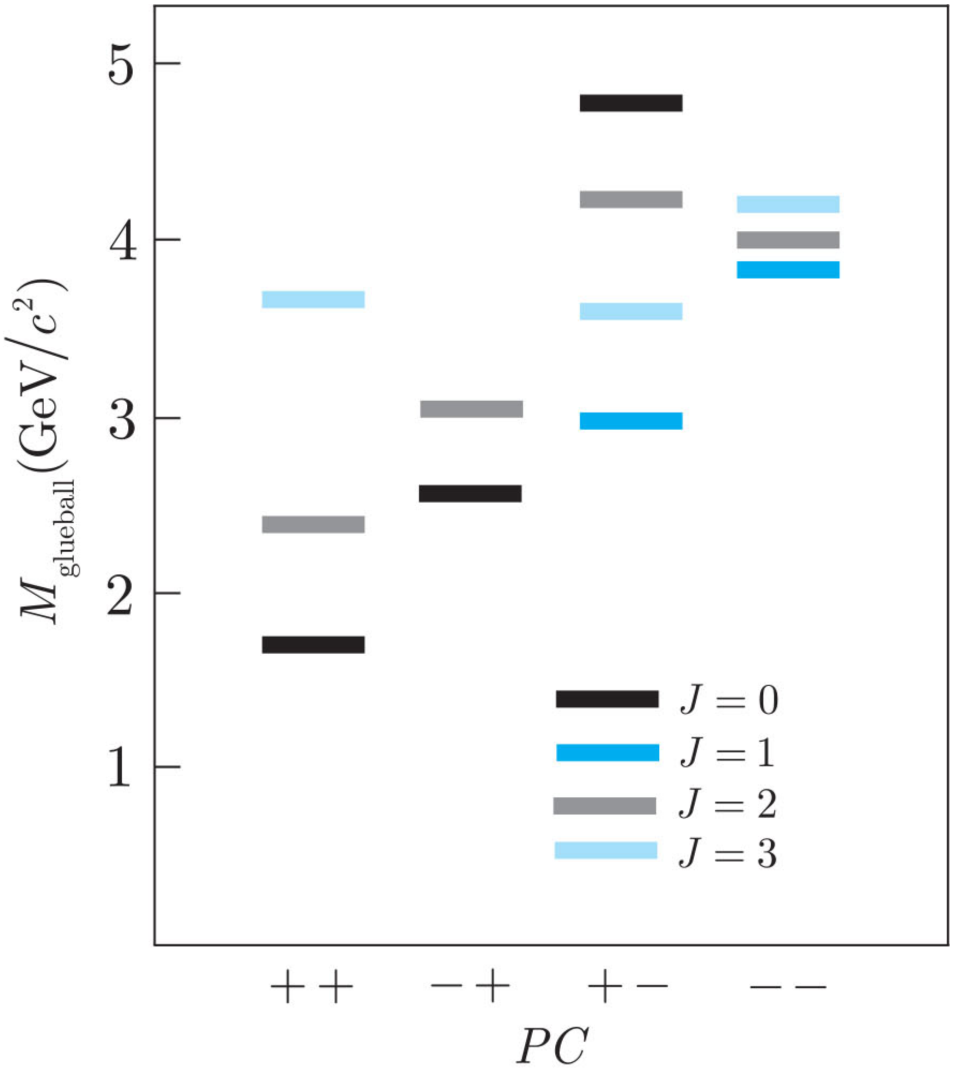
- Composed of gluons alone
- Strongly interaction with

  $$B = Q = S = C = \widetilde{B} = 0$$

- Approximate lattice gauge theory calculations yield quark-less states with mass around 1.5-1.7 GeV/c^2

Exotic Hadrons: Glueballs

- Example predicted glueball mass spectrum



Exotic Hadrons: Glueballs

- Quark anti-quark pairs will mix with the pure gluon state
- To find an exotic particle that we can be sure is not explained by quark anti-quark we look for quantum numbers that are not possible from quark anti-quark
- These are $P=(-1)^J$ $C=(-1)^{J+1}$
- Which means 0^{+-} , 1^{-+} , 2^{+-} , 3^{-+} ....
- The lightest glueball on the spectrum is 2^{+-} at about 4 GeV, too heavy to be very stable

Exotic Hadrons: Hybrids

- There is evidence for hybrids:
  - $\pi_1(1400)$ and $\pi_1(1600)$
  - Both $J^{PC} = 1^{-+}$
  - These may be hybrids, or 4 quark states
  - Hybrid is most likely

  - There are also many states in 1-2 GeV range with

    $I = S = C = \tilde{B} = 0$ and $J^{PC} = 0^{++}$

    Quark model does not predict so many

    Are these hybrids?

Exotic Hadrons: Heavy Quarkonia

$$e^+ + e^- \rightarrow \gamma + \pi^+ + \pi^- + J/\psi$$

and

$$e^+ + e^- \rightarrow X(4260) \rightarrow \pi^+ + \pi^- + J/\psi,$$

$$M = 4251 \pm 9\,\mathrm{MeV/c^2}, \quad \Gamma = 120 \pm 12\,\mathrm{MeV}.$$

Why doesn't it decay to charm pairs?

Is this a four quark state?

Exotic Hadrons: Exotic baryons

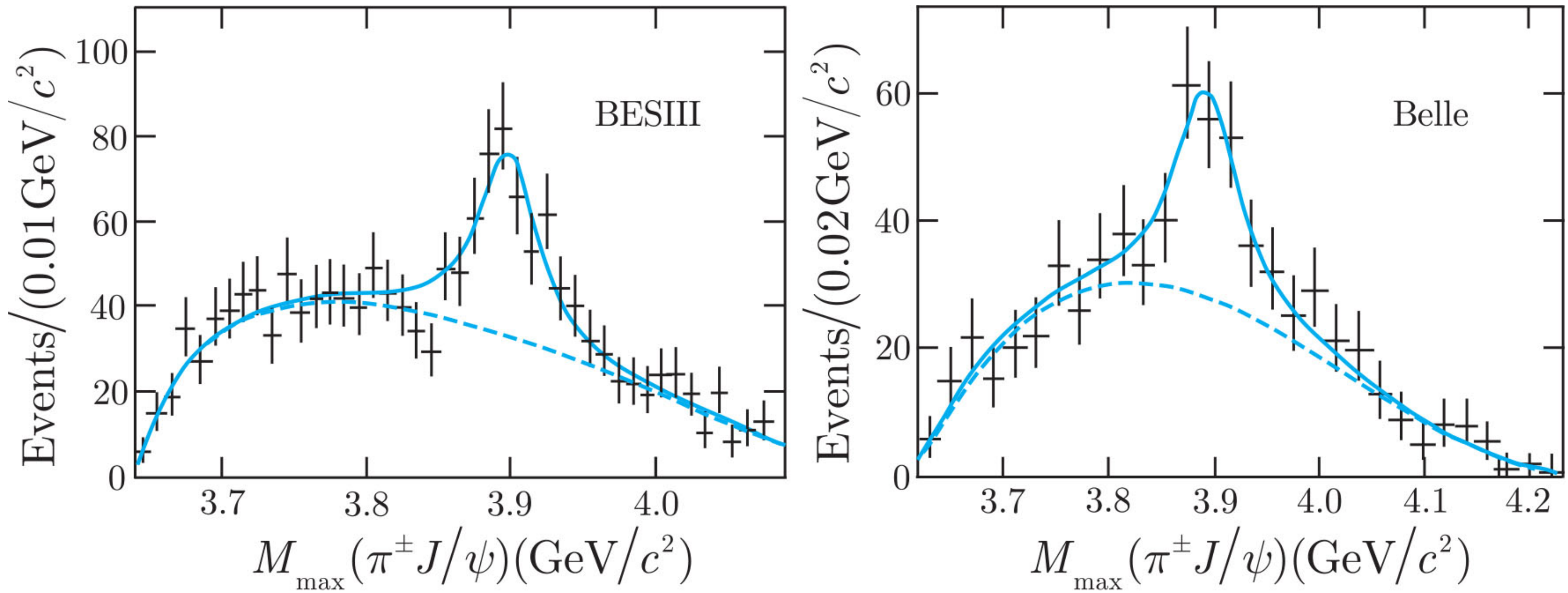
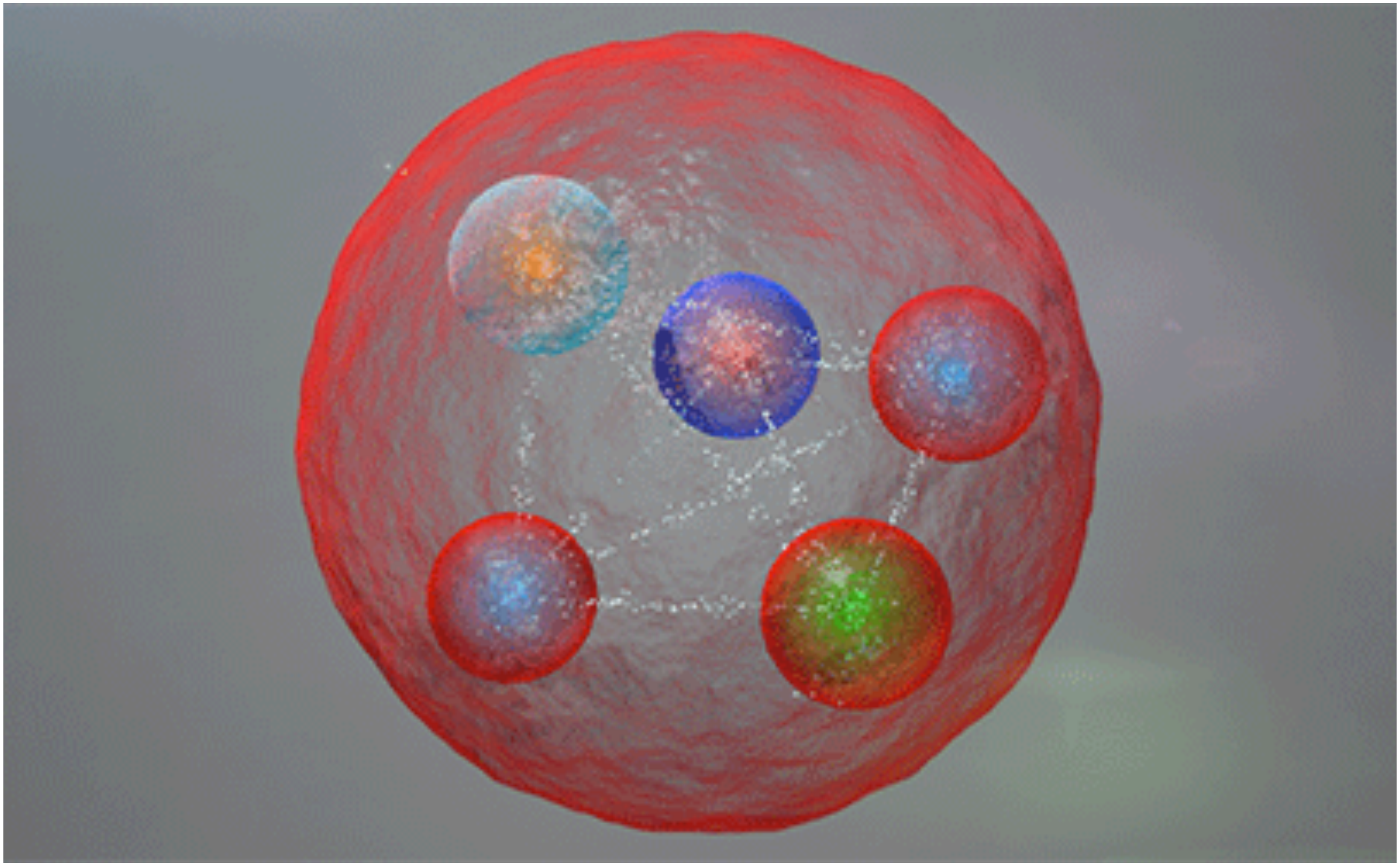


Figure 7.10 Invariant mass distribution of the heaviest $J/\psi\pi^-$ and $J/\psi\pi^-$ pairs observed in the reaction $e^+e^- \to \pi^+\pi^- J/\psi$ by the BESIII Collaboration (adapted from Ablikin *et al.*, 2013) and the Belle Collaboration (adapted from Liu *et al.*, 2013). (Copyright, American Physical Society, reproduced with permission.)

Likely c cbar u dbar and c cbar d ubar

Pentaquarks



Pentaquarks

$$\Lambda_b^0 \rightarrow K^- + p + J/\psi.$$

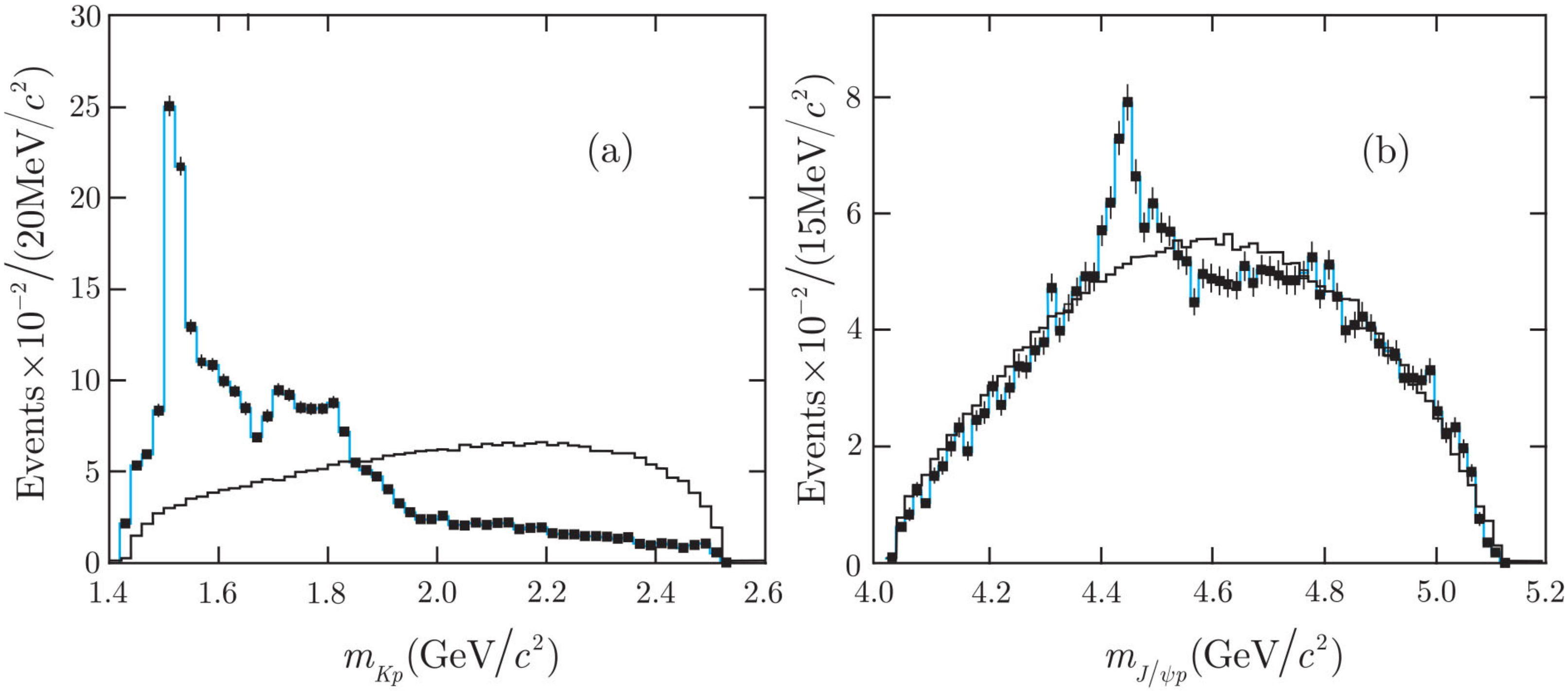


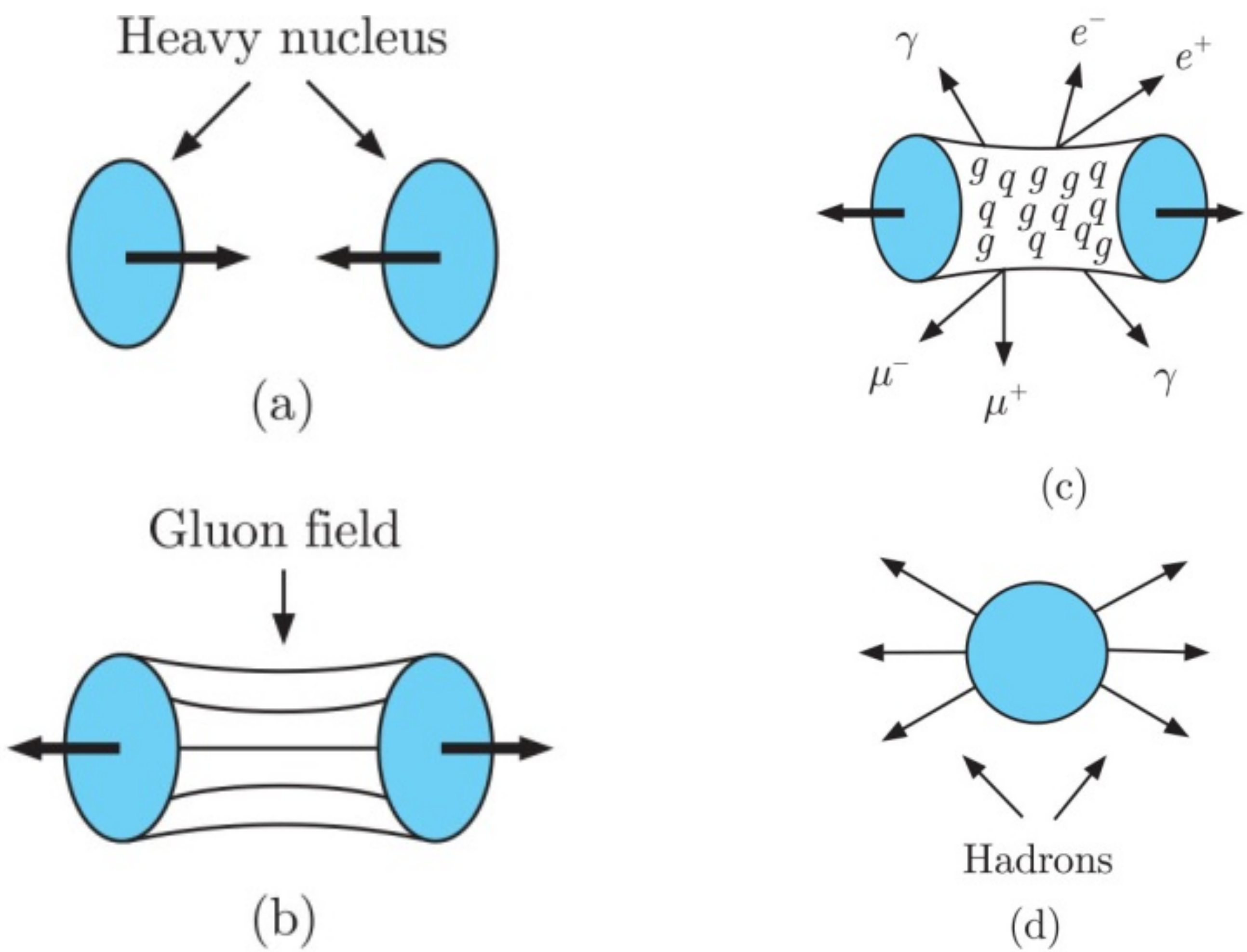
Figure 7.11 Invariant mass of (a) K^-p and (b) $J/\psi p$ combinations from $\Lambda_b^0 \rightarrow J/\psi K^- p$ decays. The black line is the expectation from phase space; the blue line is the data. (Adapted from Aaij *et al.* 2015, with permission from the American Physical Society.)

Pentaquarks

$$\Lambda_b^0 \to K^- + P_c^+ ; \quad P_c^+ \to J/\psi + p$$

P^+_c = u u d c cbar

The quark-gluon plasma



The quark-gluon plasma

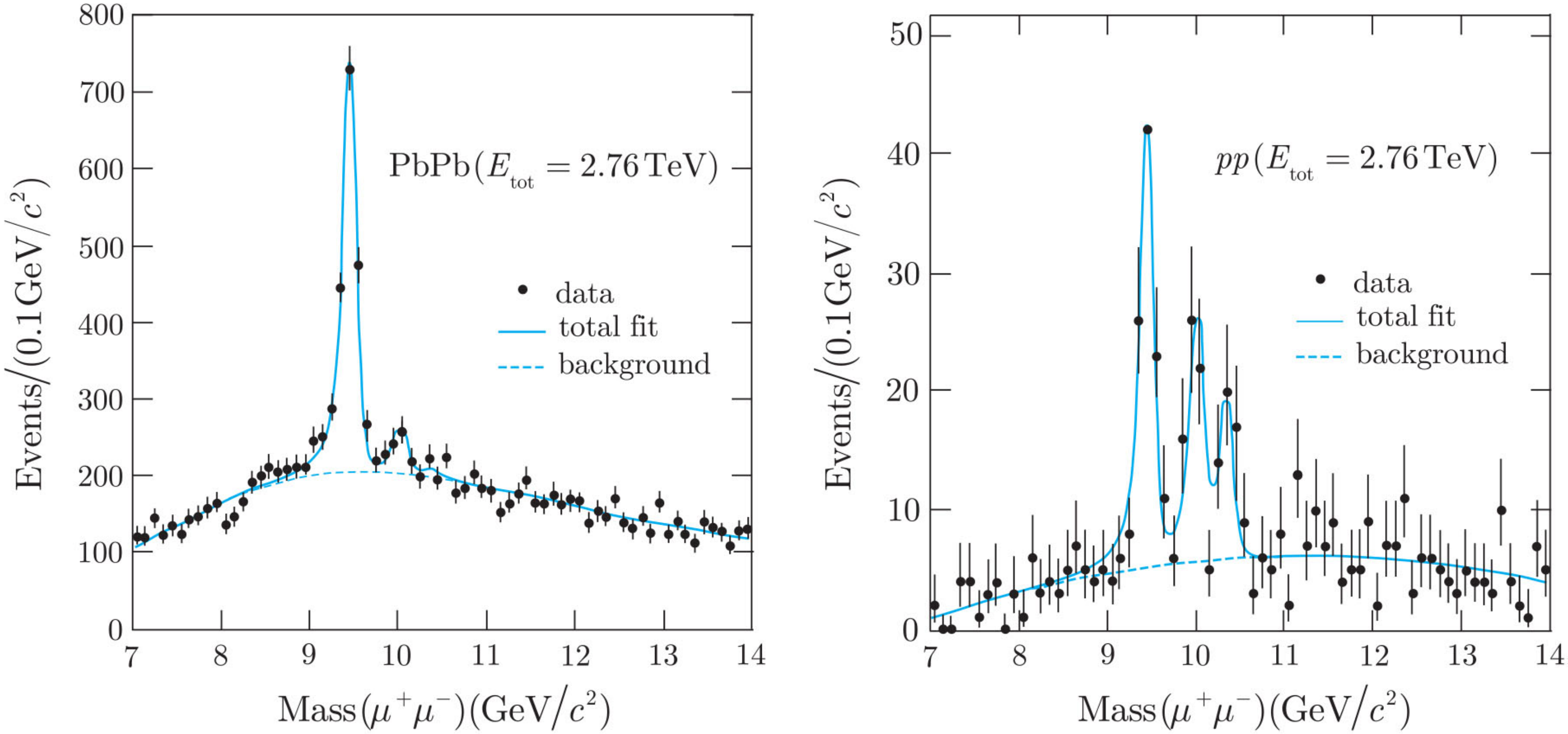


Figure 7.13 Dimuon invariant-mass distributions in PbPb (left) and pp (right) data at a total centre-of-mass energy of 2.76 TeV. (Adapted from S. Chatrchyan *et al.* 2012, with permission from the American Physical Society.) The same reconstruction and analysis selection criteria are applied to both datasets. The solid (signal + background) and dashed (background) curves show the results of the simultaneous fit to the two datasets.