QCD Studies in Low Energy e^+e^- Annihilation

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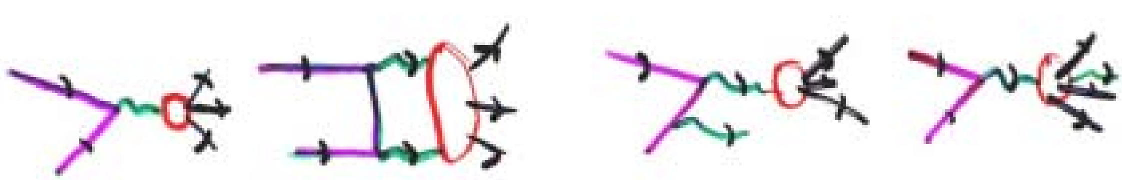
SLAC

Workshop on e^+e^- in the 1-2 GeV Range

Physics and Accelerator Issues

Alghero, Sardinia, Italy

Sept 10-13, 2003



$$\boxed{\text{New Physics Opportunities in Low Energy } e^+e^- \text{ Annihilation}}$$

High $\mathcal{L}$: Small σ
asymmetries
new states

Photon Detection: $\boxed{\gamma^* \to \gamma X}$ New physics regime
Timelike DVCS
Exotica: $(q\bar{q}\,q\bar{q})_{I=2}$ ...

Polarization: polarized beams
final state P, ..

Non-zero crossing angle, moving cm

Atomic Baryonium .

- $e^+e^- \to$ hadrons / leptons

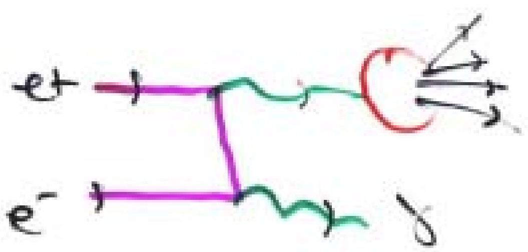
- Illustrious History : Adone!

CEA, SPEAR, Novosibirsk, Adone, BES
Orsay, PEP, BABAR, BELLE ...
SLC, LEP

- Low energy regime

  - high luminosity machines like Adone

  - radiative return at Babar, Belle

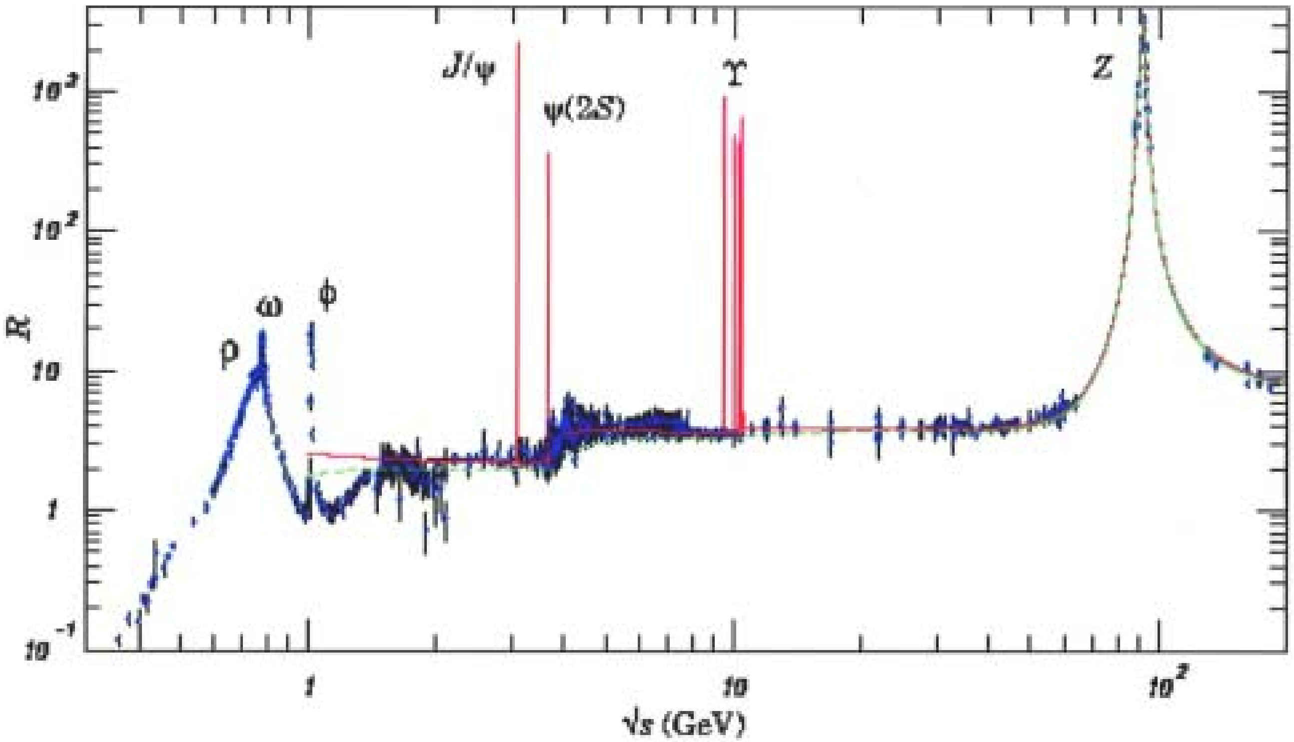


$$\hat{s} = z s < s = E_{cm}^2$$

Much remains to do:

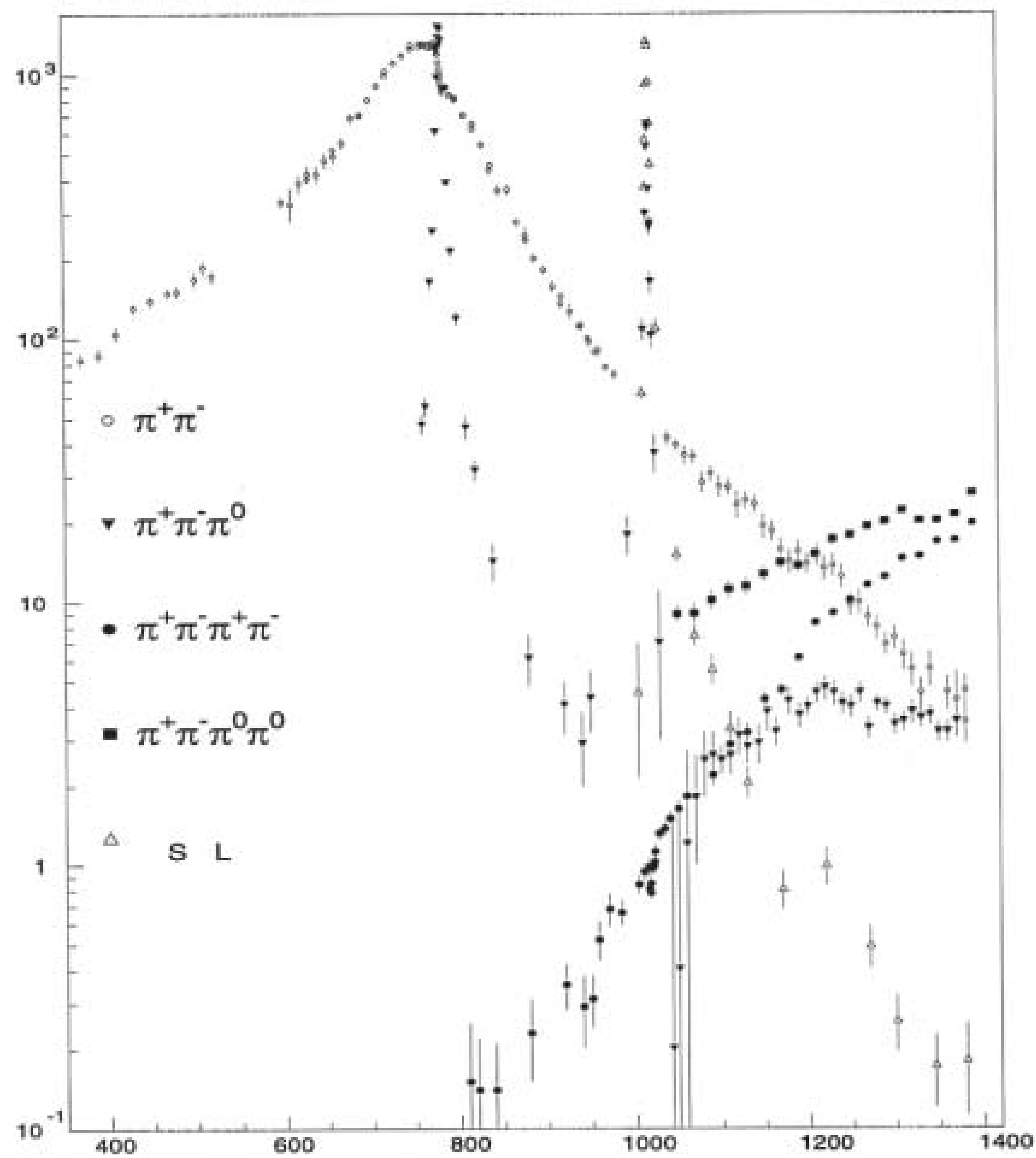
- Exclusive channels
- Polarization
- Asymmetries
- Resonances
- Rare-(s) : Discrepancy with $\tau \to \nu X$

R measurements



$$R = \sigma(e^+e^- \rightarrow \text{Hadrons}) / \sigma_0(e^+e^- \rightarrow \mu^+\mu^-)$$

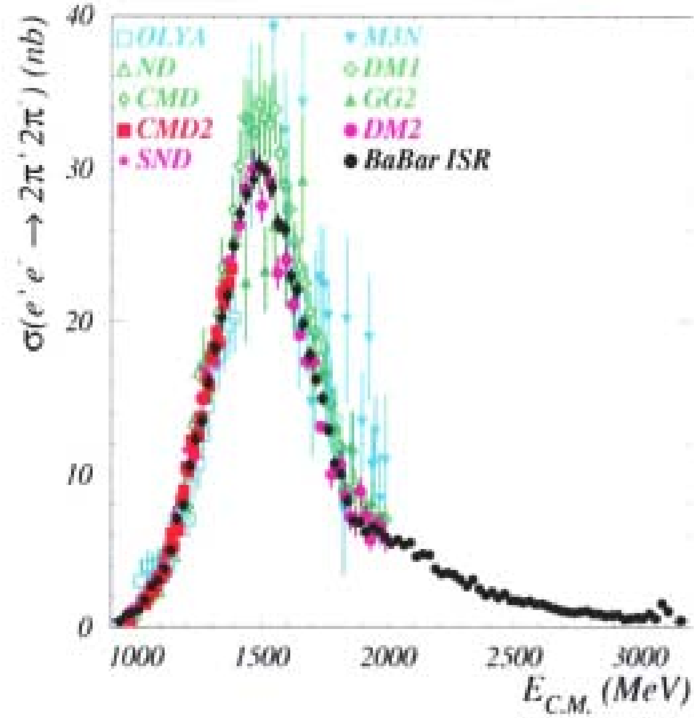
A large number of measurements scattered at various energy ranges, over the last 3 decades.



$e^+e^- \rightarrow$ hadrons for $E_{CM} < 1400$ MeV; recent data from Novosibirsk VEPP-2M collider [27].

$\pi^+\pi^-\pi^+\pi^-$ cross section

Systematic Errors can be under control



- $\mu\mu\gamma$ ISR luminosity 3%
- background subtraction 1%
  (10-15% for $M_{4\pi}$<1.0 GeV)
- χ^2 MC-DATA cut difference 2%
- radiative corr. accuracy 1%
- MC-DATA track losses diff. 2%
- model dependent acceptance 2%

Estimated total systematic error 5%

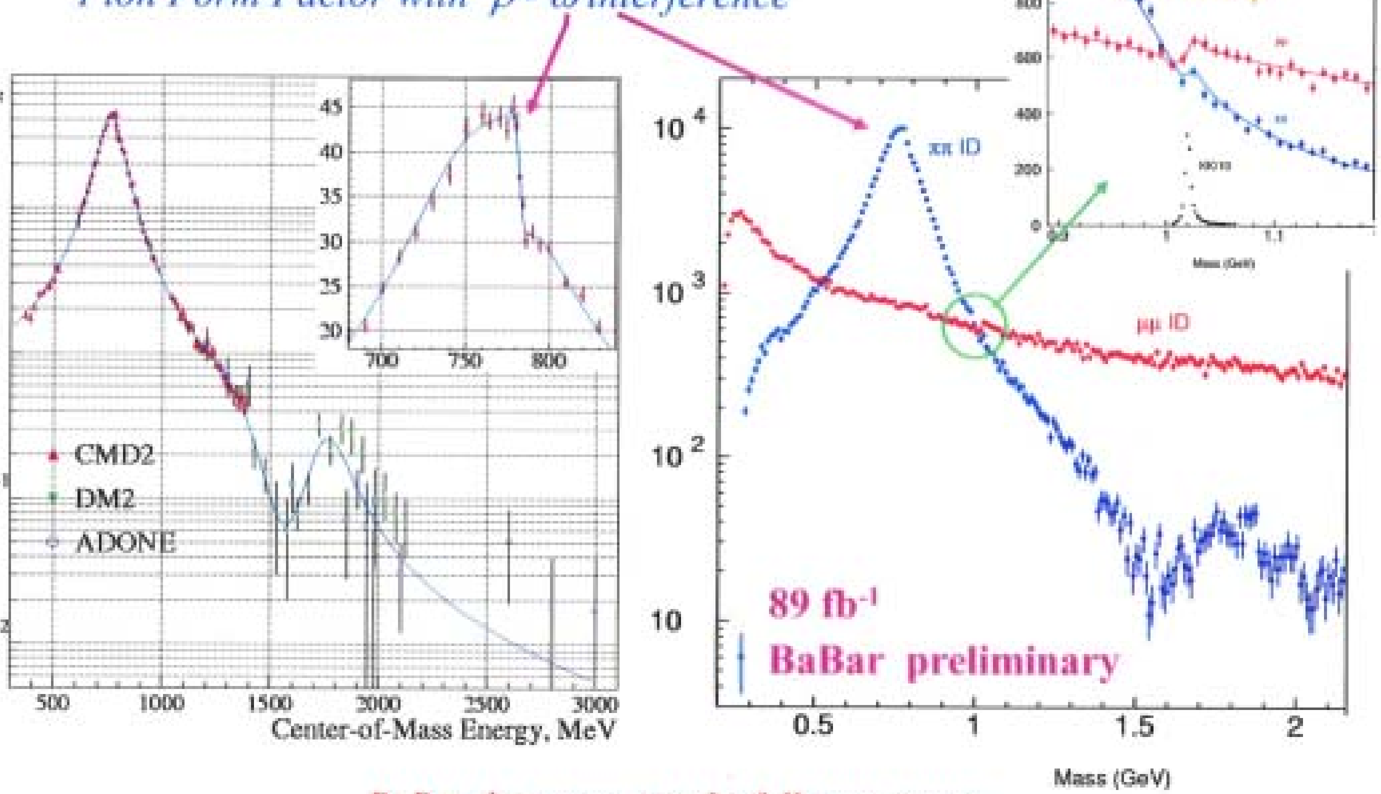
- **Very competitive statistical uncertainties**
- **Babar is the only experiment which covers whole range**

→ no point-to-point normalization problem

Details are in dedicated talk by Roberto Stroili

$\pi^+\pi^- \gamma$

Pion Form Factor with ρ - ω interference



BaBar data covering the full mass range

ISR Cross Section

$$\frac{d\sigma(s,x)}{dx} = W(s,x)\sigma_f\left[s(1-x)\right]; \qquad x = \frac{2E_\gamma^*}{\sqrt{s}}$$

In Born approximation:

M. Benayoun *et.al.* Mod.Phys.Lett. A Vol.14, No. 37(1999)2605.

$$W(s,x) = \frac{2\alpha}{\pi \cdot x} \cdot (2ln\frac{\sqrt{s}}{m_e} - 1) \cdot (1 - x + \frac{x^2}{2})$$

W(s,x) can be calculated with < 1% accuracy

Cross Section for final state f (normalized to radiative dimuons)

"effective c.m. energy squared" $=M^{2f}_{inv}= s(1-x)$

$$\sigma_f(s') = \frac{dN_{f\gamma} \cdot \varepsilon_{\mu\mu} \cdot (1+\delta^{\mu\mu}_{FSR})}{dN_{\mu\mu\gamma} \cdot \varepsilon_f \cdot (1+\delta^{f}_{FSR})} \cdot \sigma_{e^+e^- \to \mu^+\mu^-}(s') \rightarrow dL(s')$$

Detection efficiencies

Corrections for final state radiation

ISR luminosity

ISR statistics compared to low energy e^+e^-

BaBar integrated $\mathcal{L}$ = 125 fb^{-1}
+ folding in estimated event selection and photon/muon efficiencies

E_{cm}= 0.61—0.96 GeV:

	Luminosity	Hadrons	
CMD2 (published)	180K Bhabha	114K	(more stat on ρ peak)
BaBar $\lvert\cos\theta_\gamma^*\rvert<0.80$	176K $\mu\mu\gamma$	970K	

(comparable overall statistics, but BaBar statistics stronger off ρ peak – specially at $s^{1/2}$=0.8-1 GeV where CMD-2 & τ data most discrepant CMD-2 also has x5 more data now being analyzed)

E_{cm}= 2—5 GeV:

	Hadrons
BES	~85K
BaBar $\lvert\cos\theta_\gamma^*\rvert<0.80$	1760K

(the large sample from BaBar ISR is equivalent to 30 points in $s^{1/2}$ at 100 MeV step with 0.4% stat. precision each)

Inclusive R Measurements

What about using the ISR photon energy + hadrons opposite to it? Resolution enough ? Efficiency under control? Does it matter ?

Hadronic contributions to α_{em} :

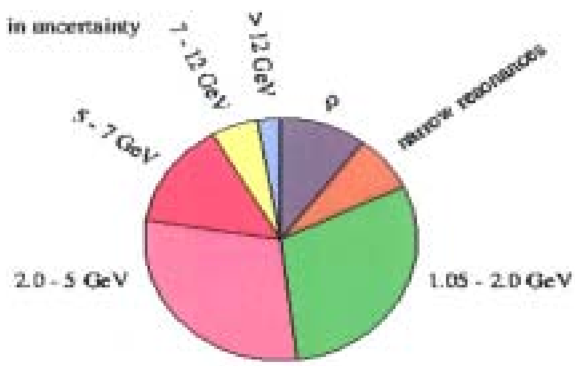
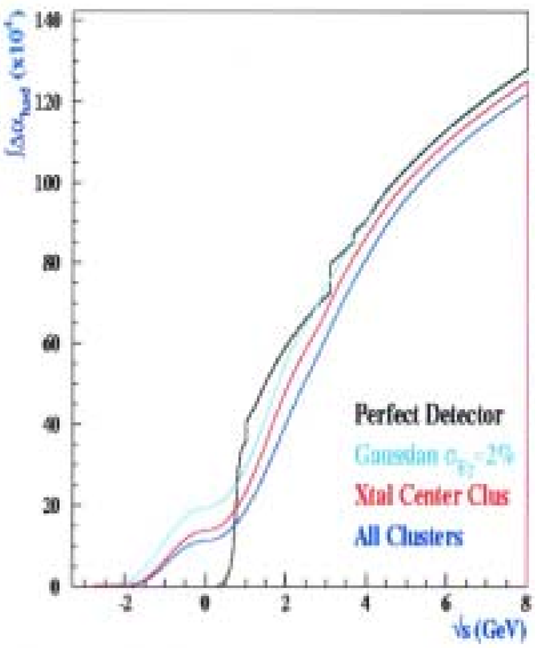


Fig. 2. Relative contributions to $\Delta\alpha^{(5)}_{had}(m_Z^2)$ in magnitude and uncertainty.



The absolute total effect of integral at 7 GeV Compared to perfect detector:

Gaussian ~0.5%

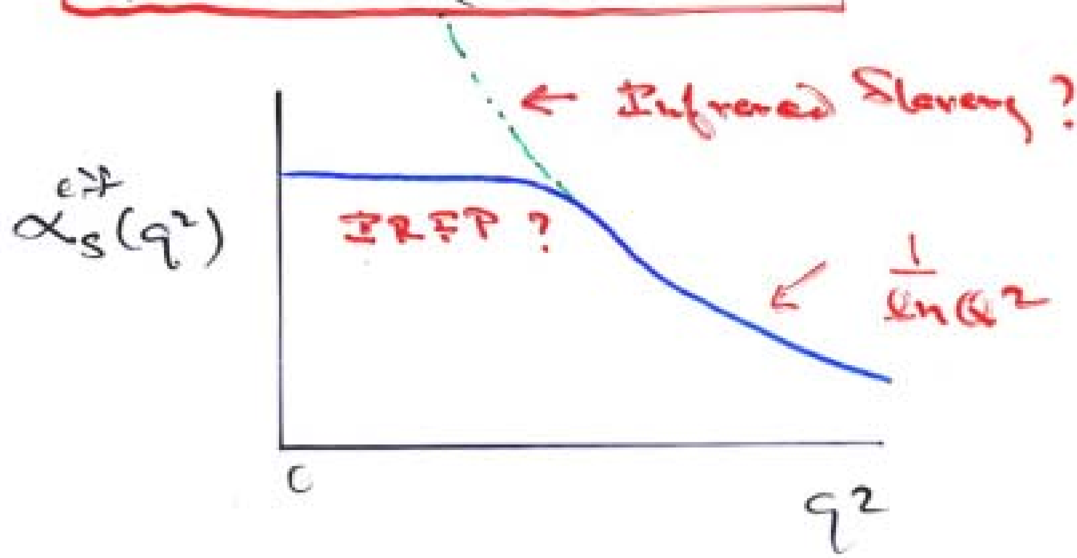
Crystal center ~3%

All clusters ~7%

We can surely calibrate From data to a small fraction of the 3% ! Looks very promising.

Can work for $\Delta\alpha_{had}$ up to $\sqrt{S'}$~ 7-8 GeV before photon background from normal non-radiative hadronic events becoming significant.

QCD in the Infrared



$\beta = 0$ in IR ?

Cornwall — Near conformal behavior of QCD

Petronzio, Parisi — ADS_5/CFT Correspondence — Polchinski, Strassler

Alkofer — Avoids renormalon resummation

Roberts

Maxwell — Counting Rules for Exclusive Processes — BF, MAT

Mattingly — Phenomenological evidence

Stevenson — Peter

Menke Merino — $\tau \to H \nu$

Rathsman SJB

Why study $R_{e^+e^-}(s)$ at low energies?

* 1. Evidence for IR-Fixed Point of Effective coupling

$$R_{e^+e^-}(s) = \frac{\sigma_{e^+e^- \to \text{hadrons}}}{\sigma_{e^+e^- \to \mu^+\mu^-}}$$

$$= \sum_q e_q^2 \left[1 + \frac{\alpha_R(s)}{\pi} \right]$$

$\alpha_R(s) \sim$ constant at low energies

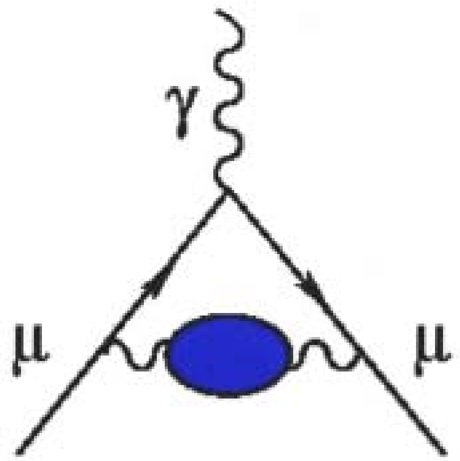
Mattingly + Stevenson

Compare with $\alpha_\tau(m_\tau^2)$ Near conformal interactions

* 2. Generalized Crewther Relation

* 3. a_μ^{had}

The Need for R in Muon g-2



$a_\mu = (g-2)/2$

	a_μ x10^{11}
QED	11658406 ± 3
Hadronic (LO)	~7000 ± ~60
Hadronic (NLO)	101 ± 6
Hadronic (light-by-light)	80 ± 40
Weak	152 ± 4

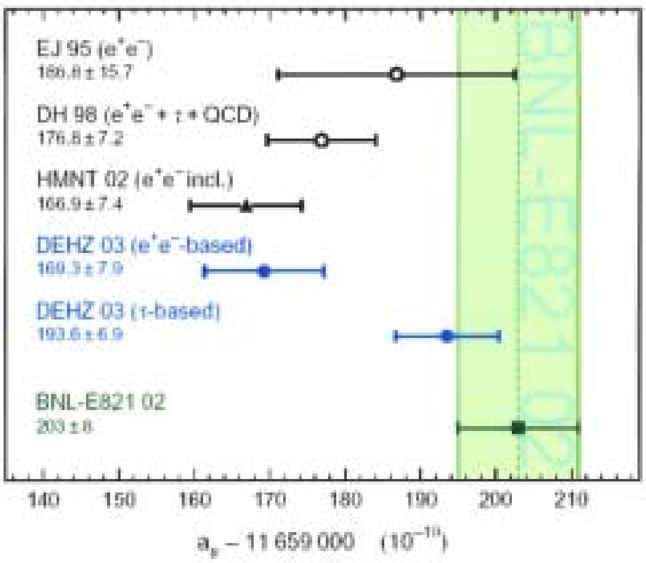
The leading order hadronic correction cannot be calculated from perturbative QCD => Need experimental R(s) measurement.

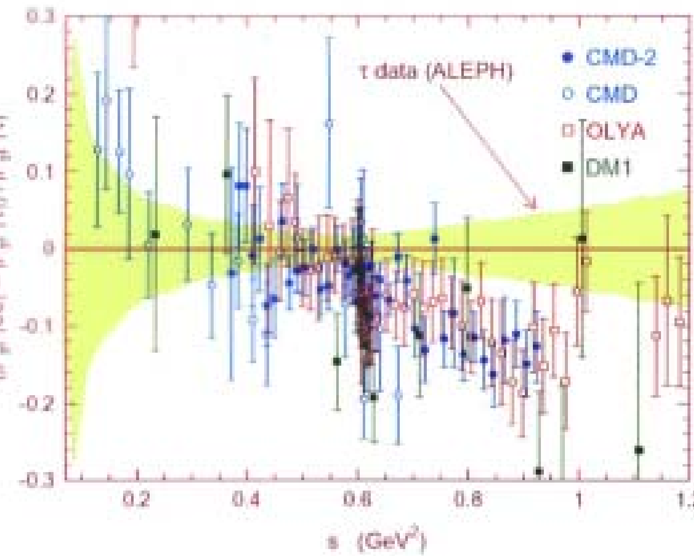
$$\Delta a_\mu^{had} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{R_{had}(s')K(s')}{s'^2} ds'$$

Most contributions and uncertainty come from s'< 3 GeV^2. Low energy measurements traditionally done by summing exclusive modes, dominated by $\pi^+\pi^-$ mode contribution.

The status of a_μ

Aug/02 review by: Davier, Eidelman, Hoecker, Zhang hep-ph/0208177

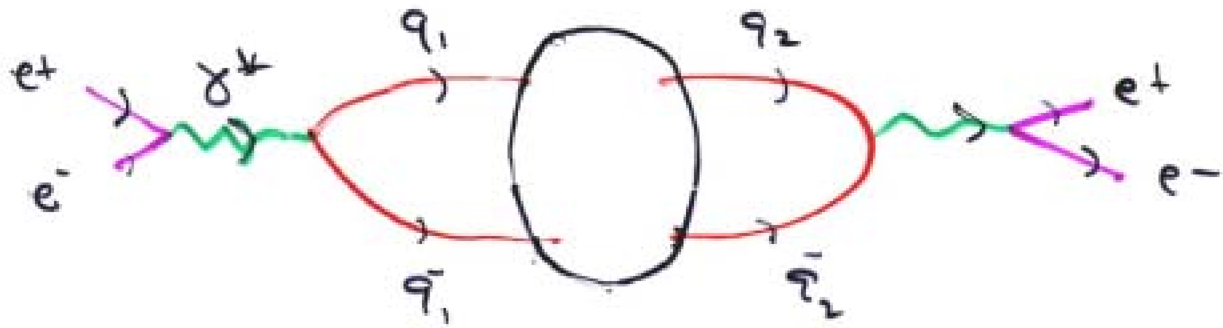




At least one conclusion can be drawn:

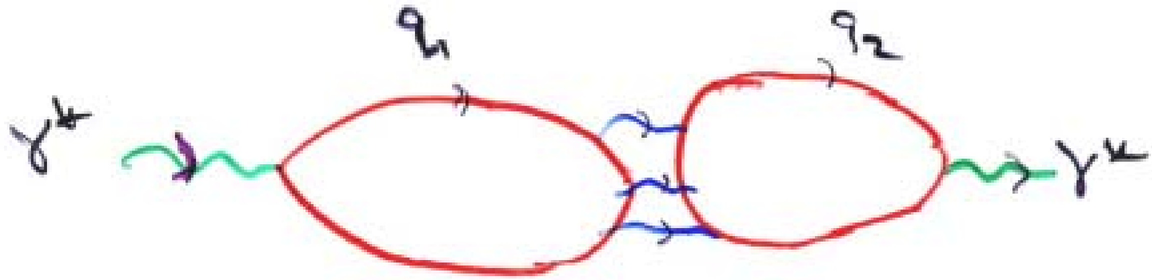
New e^+e^- R measurements would be very desirable !

Interference between different quark currents



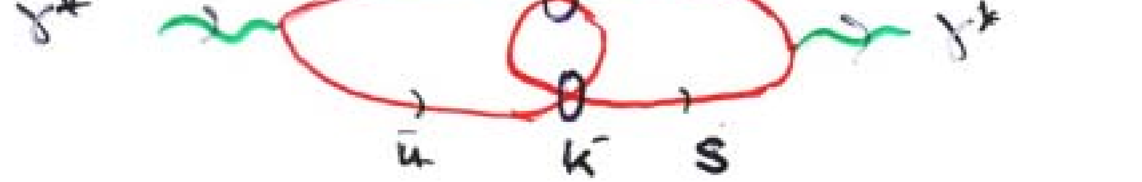
u, s interference: $\gamma^* \to K^+K^-$

$R_{e^+e^-}(s)$ at leading twist:



$$\left(\sum_i e_{q_i}\right)^2 \alpha_s^3$$

Channel by Channel



$$R(Q) \equiv 3 \sum_f Q_f^2 \left[1 + \frac{\alpha_R(Q)}{\pi} \right]$$

$\mu \to Q$

$$\frac{\alpha_R(Q)}{\pi} = \frac{\alpha_{\overline{\rm MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^2 \left[\left(\frac{41}{8} - \frac{11}{3}\zeta_3 \right) C_A - \frac{1}{8} C_F + \left(-\frac{11}{12} + \frac{2}{3}\zeta_3 \right) f \right]$$
$$+ \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^3 \left\{ \left(\frac{90445}{2592} - \frac{2737}{108}\zeta_3 - \frac{55}{18}\zeta_5 - \frac{121}{432}\pi^2 \right) C_A^2 \right.$$
$$+ \left(-\frac{127}{48} - \frac{143}{12}\zeta_3 + \frac{55}{3}\zeta_5 \right) C_A C_F - \frac{23}{32} C_F^2$$
$$+ \left[\left(-\frac{970}{81} + \frac{224}{27}\zeta_3 + \frac{5}{9}\zeta_5 + \frac{11}{108}\pi^2 \right) C_A \right.$$
$$\left. + \left(-\frac{29}{96} + \frac{19}{6}\zeta_3 - \frac{10}{3}\zeta_5 \right) C_F \right] f$$
$$+ \left(\frac{151}{162} - \frac{19}{27}\zeta_3 - \frac{1}{108}\pi^2 \right) f^2$$
$$\left. + \left(\frac{11}{144} - \frac{1}{6}\zeta_3 \right) \frac{d^{abc} d^{abc}}{C_F d(R)} \frac{\left(\sum_f Q_f\right)^2}{\sum_f Q_f^2} \right\}$$

assumes
$\mu = Q$

light-by-light

$d(R) = N$

$C_A = N$

$d_{abc} d^{abc} = \frac{40}{3}$

$C_F = \frac{N^2-1}{2N}$

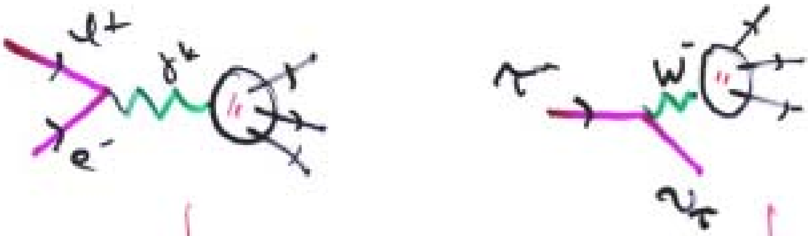
$\sum_f Q_f = 2/3 - 1/3 - 1/3 = 0$

$T = 1/2$

Gorishny
Kataev
Larin

Surguladze
Samuel

$\boxed{\text{Compare } \quad e^+e^- \to X \quad \text{and} \quad \tau \to \nu_\tau X^-}$



$\langle 0 | J^\mu_\gamma | H^0 \rangle$ $\qquad\qquad$ $\langle 0 | J^\mu_{W^-} | H^- \rangle$

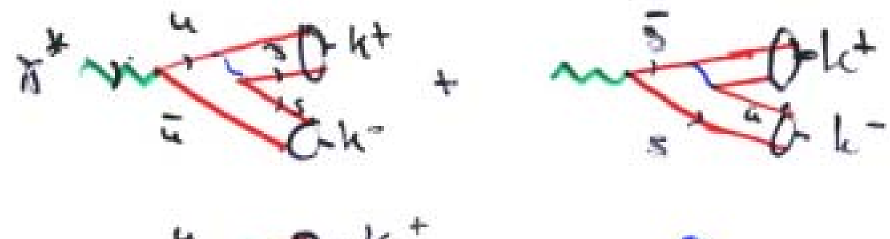
$I = 0, 1$ $\qquad\qquad$ $I = 1$

$I_z = 0$ $\qquad\qquad$ $I_z = -1$

– $I = 1$ Vector currents related by isospin

* Davier, Hocker : Fails at $s > 0.6 \text{ GeV}^2$

Possible source of difference

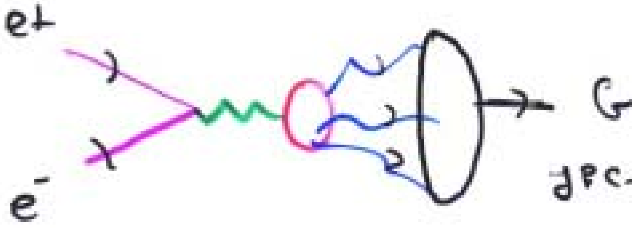


Interfere!

no analog

Need analysis channel by channel

Search for glueballs in e^+e^-, $\gamma\gamma$



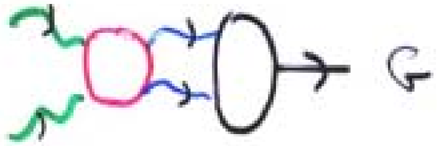
$J^{PC} = 1^{--}$

resonance at $s = M_G^2$

Lattice: $M_G^{1^{--}} \sim 3.6$ GeV

$$\int_{s \sim m_G^2} d\sqrt{s}\ \sigma_{e^+e^- \to f} = 2\pi^2 (2J+1) \frac{\Gamma_{e^+e^-} \Gamma_f}{\Gamma_{TOT}}$$

α_s^3 suppressed



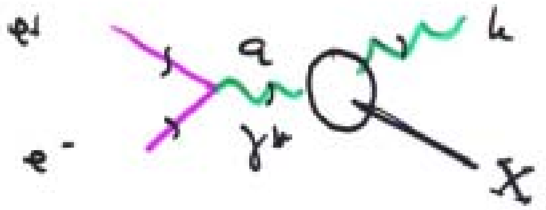
$J^{PC} = 0^{++}, 2^{++}$

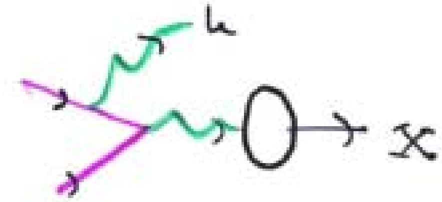
$$\int_{s \sim m_G^2} d\sqrt{s}\ \sigma_{\gamma\gamma \to f} = \frac{2\pi^2 (2J+1)\ \Gamma_{\gamma\gamma}\ \Gamma_f}{\Gamma_{TOT}}$$

α_s^2 suppressed

Search for Exotic C=+ States

$e^+e^- \to \gamma X$ $\qquad M_X^2 = s - 2\omega_k\sqrt{s}$ (cm)

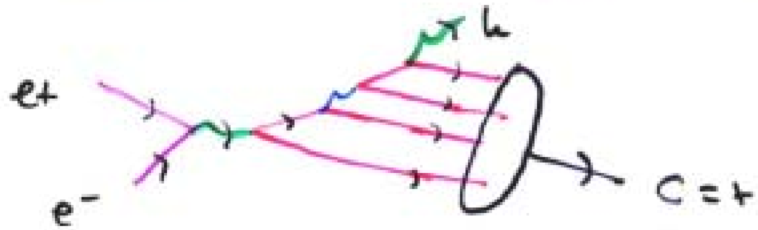




$(q\bar{q}), (q\bar{q}g), (gg)$ $\qquad C=+$ $\qquad C=-$

$(q\bar{q})(q\bar{q})$ $\qquad I=0,1,2$ $\qquad I=0,1$

Example: $C=+$, $I=2$, $4q$ state



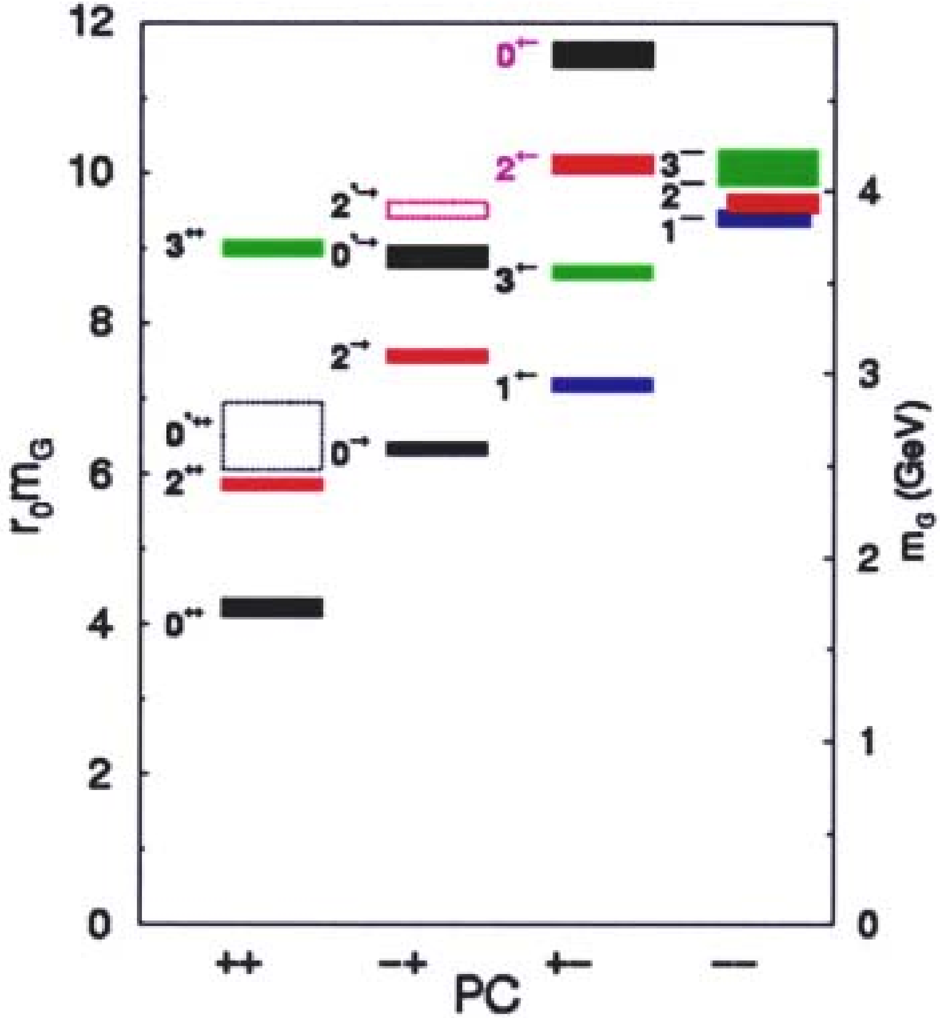
$8_C \times 8_C = 1_C$

Avoid ISR: θ_k^{cm} large angle photon

Interfere with ISR

Charge asymmetry $\quad \mathrm{Re}\, T^{\dagger}_{\mu\nu} F$

Single-spin asymmetry $\quad \mathrm{Im}\, T^{\dagger}_{\mu\nu} F$



Morningstar et al

$$\boxed{e^+ e^- \to \phi\, G_J}$$

Polarized e^- Beam

More observables

$$e^-_\uparrow\, e^+ \to \phi_\uparrow\, G_J$$

Beam polarization

$$\left\{ \begin{array}{ll} \vec{S}_e \cdot (\vec{P}_\phi \times \vec{P}_e) & \text{SSA} \\ \vec{S}_e \cdot \vec{S}_\phi & \text{Spin Transfer} \end{array} \right.$$

$*\quad \vec{S}_\phi \cdot (\vec{P}_\phi \times \vec{P}_e) \qquad$ SSA

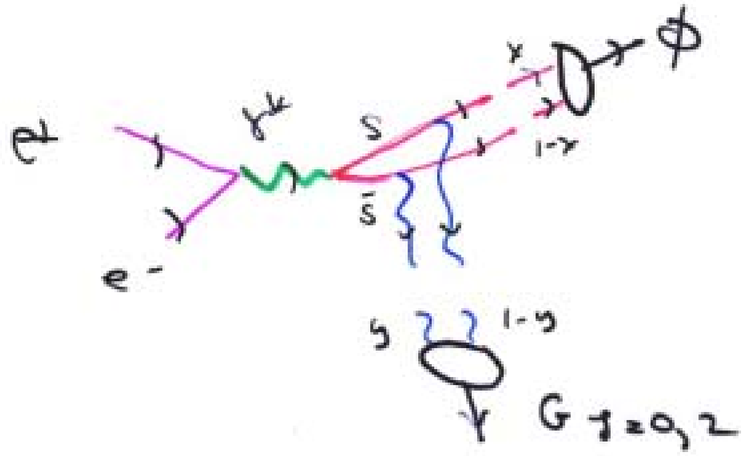
$*\quad (\vec{P}_{e^-} \times \vec{P}_{e^+}) \cdot (\vec{P}_\phi \times \vec{P}_G) \qquad$ non-zero crossing angle

SSA needs FSI $\sim \phi, G_J$

$$\frac{d\Omega}{d\cos\theta_{cm}}(e^+ e^- \to \phi\, G_J) \sim \left\{ \begin{array}{ll} \frac{1}{s^2} \sin^2\theta & J=0 \\ \frac{1}{s^3}(1+\cos^2\theta) & J=2 \end{array} \right.$$

Search for glueballs in $e^+e^- \to \phi\, G$

J. Lee
F. Goldhaber
SJB



Glue Rich
High "Strangeness"
Chomonts

$$\mathcal{M} = \int_0^1 dx \int_0^1 dy \; T_H(e^+e^- \to s\bar{s}\, g\, \bar{g})\, \phi_\phi^{(x)} \phi_{G_J}^{(y)}$$

$$\phi_\phi(x) = \int d^2k_\perp \, \psi^{LF}_{s\bar{s}/\phi}(x, k_\perp)$$

$$\phi_G(y) = \int d^2k_\perp \, \psi^{LF}_{gg/G}(y, k_\perp)$$

$$\uparrow$$

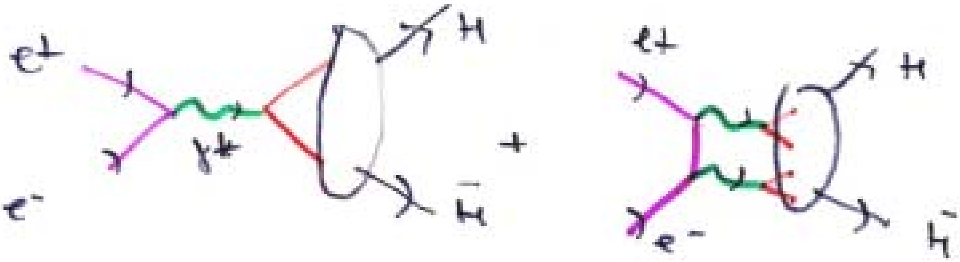
$$\langle 0 | G_{\mu\nu} G^{\mu\nu} | G_J \rangle$$

$$dR(e^+e^- \to \phi\, G_0) \sim \alpha_s^2 \left(\frac{m_s^2}{s}\right)^2 \, q \; \frac{e_s^2}{N_c^2}$$

$$\left[\frac{3}{4}(1-\cos^2\theta) + \frac{8 m_s^2}{s} \cdot \frac{3}{8}(1+\cos^2\theta)\right]$$

$$\uparrow \quad J_z^\phi = 0$$

$\boxed{\text{Charge asymmetry in } e^+e^- \to H\bar{H}}$



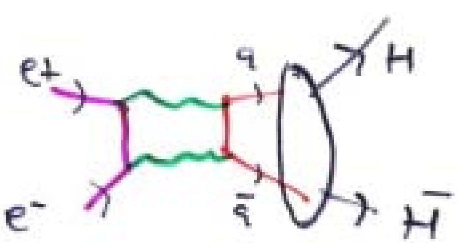
+ bremsstrahlung

Compare to asymmetry in QED

dom by ext line radiation for $\Delta E/E \to 0$

$$R_A = \frac{A_{e^+e^-\to H\bar{H}}}{A_{e^+e^-\to \mu^+\mu^-}} = R_A(\theta_{cm}, \phi, s)$$

Simplest model:
(J=0 fixed pole)



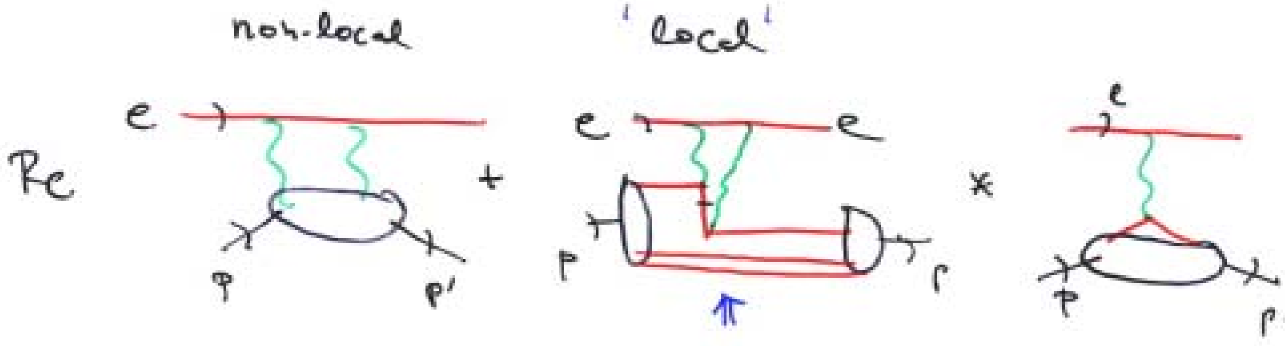
$$R_A = \sum_{q\in H} e_q^2 \left\langle \frac{1}{x_q} \right\rangle$$ indep of θ, ϕ, s

Afanasev
Carlson
SJB

Guidon Vanderhaegen

Blunden, Melnitchouk, et al

$\boxed{e^\pm p \to e^\pm p \quad \text{Asymmetry}}$



$$\sum_{q \in p} e_q^2 \left\langle \frac{1}{x_q} \right\rangle$$

" $J=0$ " Fixed Pole

$M \sim s^0 F(t)$

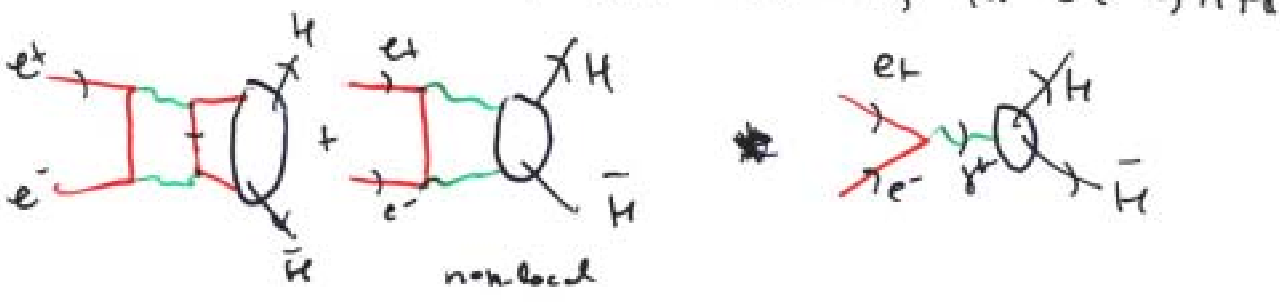
π^2 enhancement in space-like scattering

$$\delta M_p^2 = \delta M_q^2 \left\langle \frac{1}{x_q} \right\rangle \qquad \text{Same moment.}$$

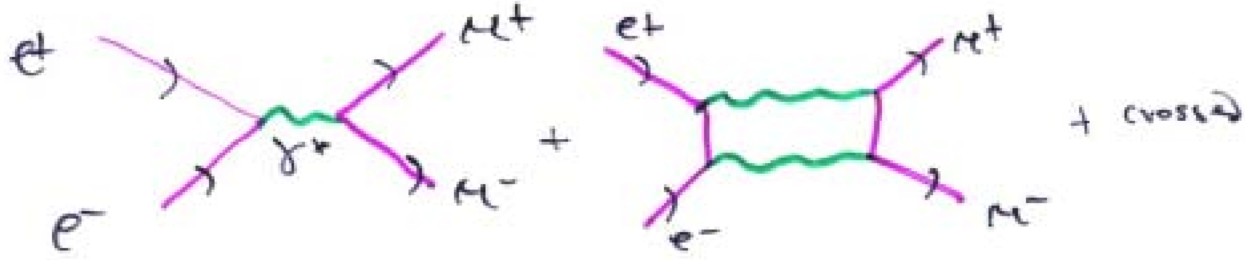
Afanasev

Carlson

Test in front-back asymmetry in $e^+e^- \to H\bar{H}$



Charge asymmetry in $e^+e^- \to \mu^+\mu^-$, $\tau^+\tau^-$



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}(1+\cos^2\theta)\left[1+\delta\right]$$

$$A = \frac{d\sigma(\theta,\phi) - d\sigma(\pi-\theta,\phi)}{d\sigma(\theta,\phi) + d\sigma(\pi-\theta,\phi)}$$

$$= \delta^{\gamma\gamma}_{\mu e} + \delta^{B}_{\mu e}$$

Meister + Yennie PR 130, 1210 (1963)
R.W. Brown, et al PLB 43, 403 (1973)