Electron-positron and electron-electron colliders

D. Babusci, F. Bossi, C. Gatti, G. Venanzoni

INFN- LNF

Giornate di studio su IRIDE, 14-15 marzo 2013

e^+e^- collider

Physics opportunities with an e^+e^- collider with c.o.m. energy tunable within [~ 0.5, ~ 3.0] GeV

- ✓ the hadronic contribution to muon anomalous magnetic moment a_μ
- ✓ the hadronic contribution to α_{em}
- ✓ spectroscopy and $\gamma\gamma$ physics
- ✓ exotics (dark forces)

e^+e^- collider

LNF-10/17(P)

see also Eur. Phys. J. C **50** (2007) 729

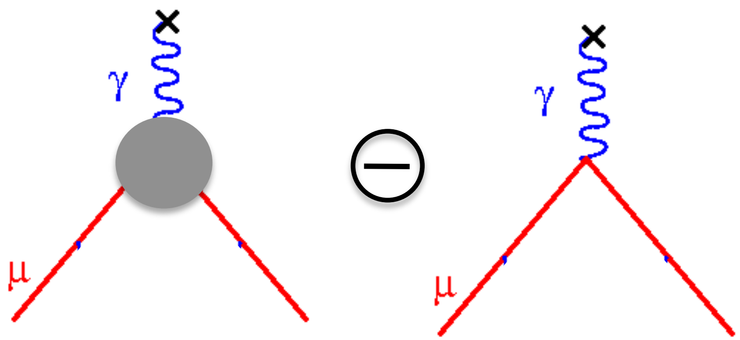
Proposal for taking data with the KLOE-2 detector at the DAΦNE collider upgraded in energy

D. Babusci[a], C. Bini[b], F. Bossi[a], G. Isidori[a], D. Moricciani[c], F. Nguyen[d], P. Raimondi[a], G. Venanzoni[a], D. Alesini[a], F. Archilli[c], D. Badoni[a], R. Baldini-Ferroli[a,r], M. Bellaveglia[a], G. Bencivenni[a], M. Bertani[a], M. Biagini[a], C. Biscari[a], C. Bloise[a], V. Bocci[d], R. Boni[a], M. Boscolo[a], P. Branchini[d], A. Budano[d], S.A. Bulychjev[e], B. Buonomo[a], P. Campana[a], G. Capon[a], M. Castellano[a], F. Ceradini[d], E. Chiadroni[a], P. Ciambrone[a], L. Cultrera[a], E. Czerwinski[a], E. Dané[a], G. Delle Monache[a], E. De Lucia[a], T. Demma[a], G. De Robertis[f], A. De Santis[b], G. De Zorzi[b], A. Di Domenico[b], C. Di Donato[g], B. Di Micco[d], E. Di Pasquale[a], G. Di Pirro[a], R. Di Salvo[c], D. Domenici[a], A. Drago[a], M. Esposito[a], O. Erriquez[f], G. Felici[a], M. Ferrario[a], L. Ficcadenti[a], D. Filippetto[a], S. Fiore[b], P. Franzini[b], G. Franzini[a], A. Gallo[a], G. Gatti[a], P. Gauzzi[b], S. Giovannella[a], A. Ghigo[a], F. Gonnella[c], E. Graziani[d], S. Guiducci[a], F. Happacher[a], B. Höistad[h], E. Iarocci[a,i], M. Jacewicz[h], T. Johansson[h], W. Kluge[j], V.V. Kulikov[e], A. Kupsc[h], J. Lee Franzini[a], C. Ligi[a], F. Loddo[f], P. Lukin[k], F. Marcellini[a], C. Marchetti[a], M.A. Martemianov[e], M. Martini[a], M.A. Matsyuk[e], G. Mazzitelli[a], R. Messi[c], C. Milardi[a], M. Mirazzita[a], S. Miscetti[a], G. Morello[l], P. Moskal[m], S. Müeller[n], S. Pacetti[a,r], G. Pancheri[a], E. Pasqualucci[b], M. Passera[o], A. Passeri[d], V. Patera[a,i], A.D. Polosa[b], M. Preger[a], L. Quintieri[a], A. Ranieri[f], P. Rossi[a], C. Sanelli[a], P. Santangelo[a], I. Sarra[a], M. Schioppa[l], B. Sciascia[a], M. Serio[a], F. Sgamma[a], M. Silarski[m], B. Spataro[a], A. Stecchi[a], A. Stella[a], S. Stucci[l], C. Taccini[d], S. Tomassini[a], L. Tortora[d], C. Vaccarezza[a], R. Versaci[p], W. Wislicki[q], M. Wolke[h], J. Zdebik[m], M. Zobov[a]

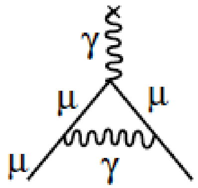
a_μ

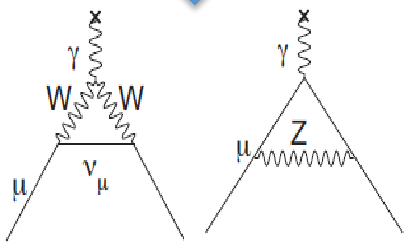
one of the most (if not the most) significant low-energy constraint on a wide class of new-physics models

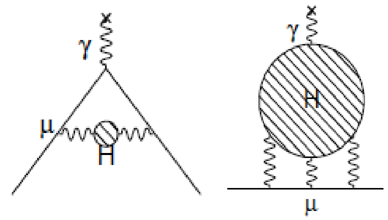
$$a_\mu = \frac{g_\mu - 2}{2}$$



$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm Weak} + a_\mu^{\rm Had}$$







HLO **HHO** (LbL)

a_μ

QED & Weak → precisely known

Had → large uncertainty (significant work ongoing)

Contribution	Result ($\times 10^{-11}$) Units
QED (leptons)	$116\,584\,718.09 \pm 0.14 \pm 0.4_\alpha$
Weak	$154 \pm 2_{\mathrm{Higgs}} \pm 1_{\mathrm{had}}$
HLO (vac. pol.)	$6\,923 \pm 42$
HHO (vac. pol.)	-97.9 ± 0.9
HHO (LbL)	105 ± 26
Total SM	$116\,591\,802 \pm 42 \pm 26 \pm 2\ (49)_{\mathrm{tot}}$

a_μ

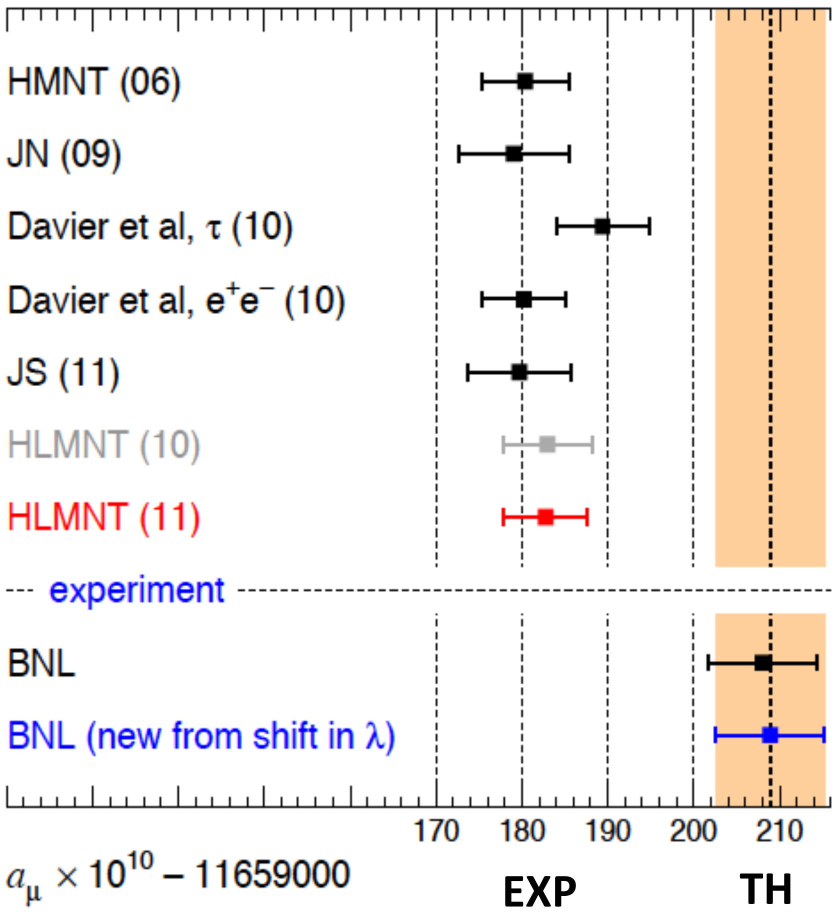
Experimental result → E821 @ BNL (1997- 2001)

$$a_\mu = 116\,592\,089\,(54)_{\rm stat}\,(33)_{\rm sys}\,(63)_{\rm tot}\;\times\;10^{-11}$$

(0.54 ppm !)

a_μ

$$\mathrm{EXP} - \mathrm{TH} = (28.7 \pm 8.4) \times 10^{-10}$$

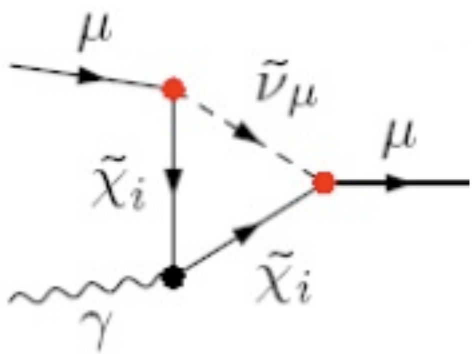


$\sim 3.4\,\sigma$

NB - the discrepancy is large compared to Weak contribution

new physics ?

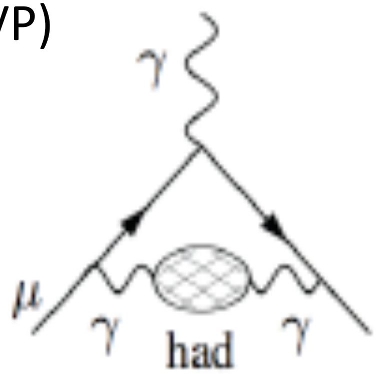
SUSY



a_μ: hadronic contribution

theoretical error (5 ÷ 6) x 10^{-10} dominated by hadronic contributions (HLO and LbL)

HLO (VP)



$$a_\mu^{\rm HLO} = (690.9 \pm 4.4) \times 10^{-10}$$

~ 0.6 %

↓

$$\gamma^* \rightarrow \text{hadrons}$$

HHO (LbL)

$$a_\mu^{\rm LbL} = (11 \pm 4) \times 10^{-10}$$

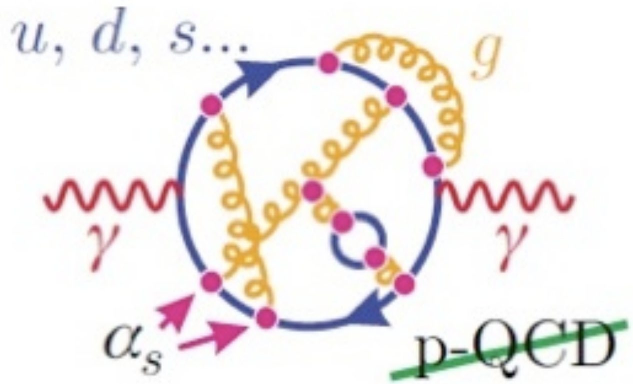
~ 40 %

↓

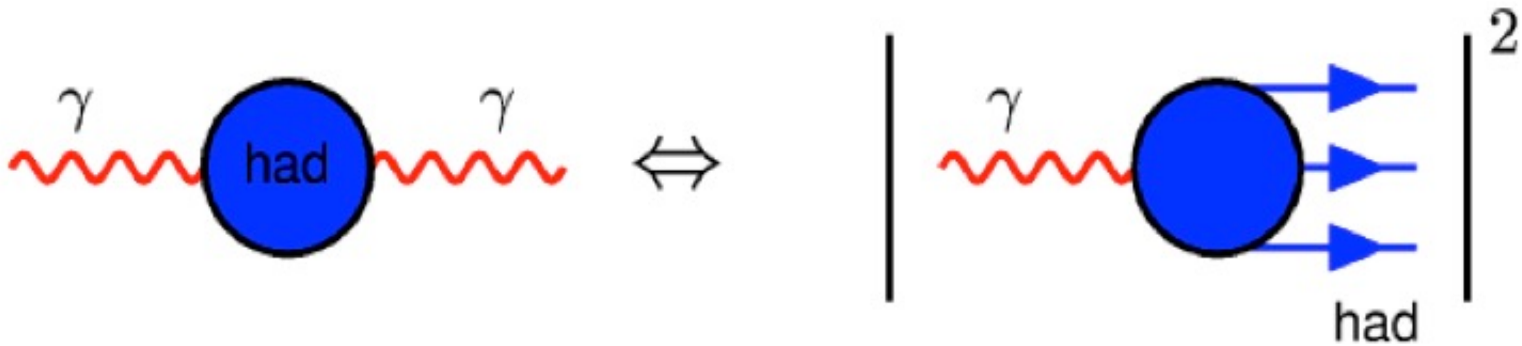
$$\gamma^* \gamma^* \rightarrow \text{hadrons}$$

a_μ: hadronic contribution

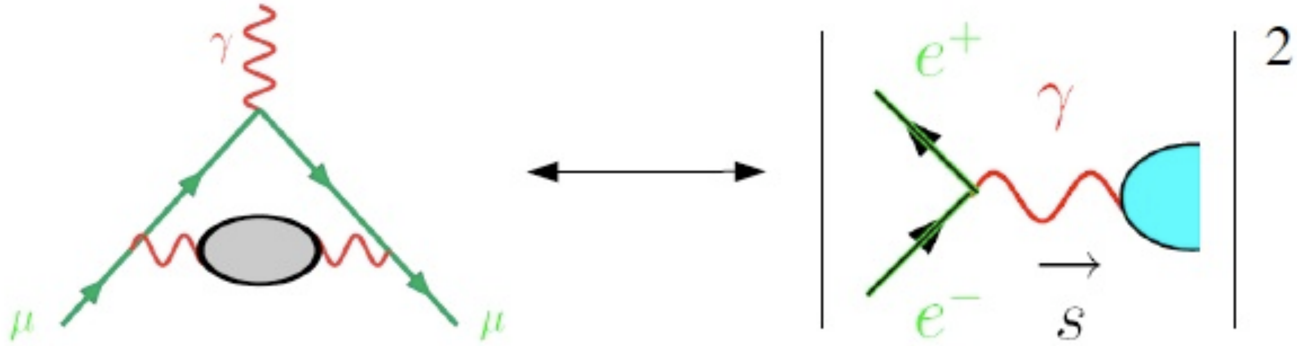
hadronic contribution to vacuum polarization



not calculable at low q^2 … optical theorem



a_μ: hadronic contribution



$$a_\mu^{\mathrm{HLO}} = \frac{1}{3}\left(\frac{\alpha\, m_\mu}{\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{\mathrm{d}\,s}{s^2}\,\hat{K}(s)\,R(s)$$

makes important low energy contribution

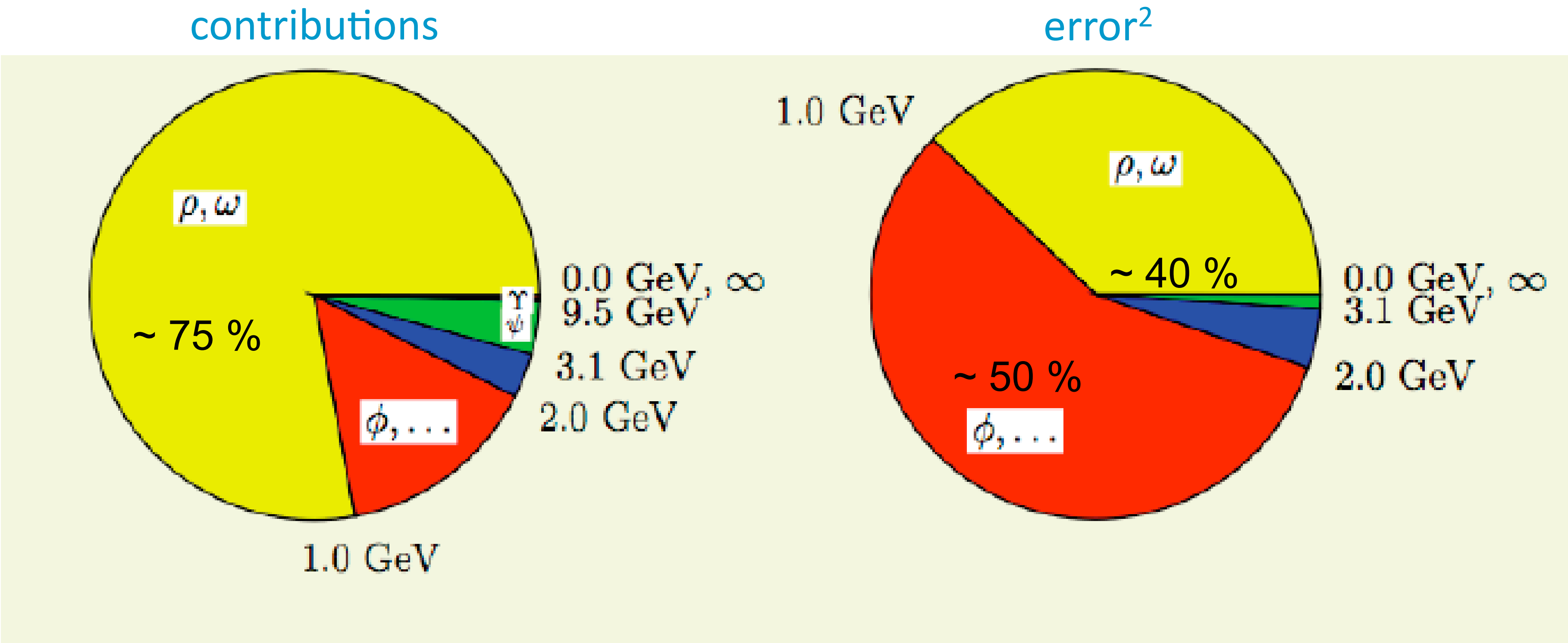
↓

$$e^+e^- \to \pi^+\pi^-$$

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

a_μ: hadronic contribution

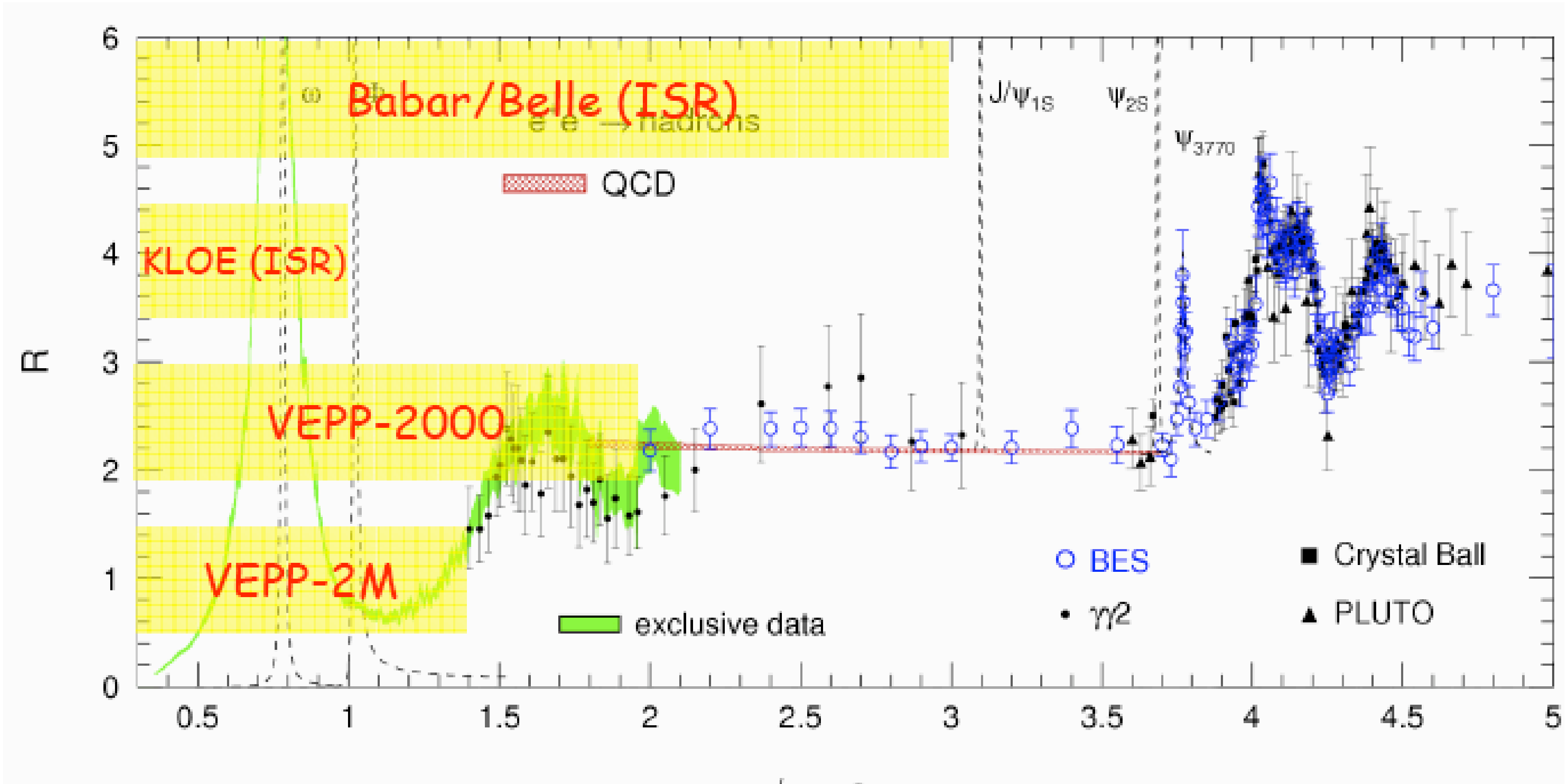
experimental errors on σ^{had} translate into theoretical uncertainty of a_μ^{HLO}



region < 3 GeV exhausts dispersion integral

a_μ: hadronic contribution

e^+e^- data: present situation



$\delta\sigma^{had}$ ~ 1% ~ (3 - 5)% ~ (7 - 15)% ~ 6%

a_μ: hadronic contribution

$$\text{EXP} - \text{TH} = (28.7 \pm 8.4) \times 10^{-10}$$

$$8.4 = \sim 5\,(\text{HLO}) \oplus \sim 3\,(\text{LbL}) \oplus \sim 6\,(\text{E821})$$

↓ **4.0**

↓ **2.5** — new meas. $e^+e^- \to$ had.

↓ **2.5** — $\gamma\gamma$-physics

↓ **1.6** — new (g - 2) meas. @ FNAL

4.0 → **(7 - 8) σ** (if 28.7 will remain the same)

this means: $\delta\sigma^{\text{had}} \begin{cases} \sim 0.4\% & \sqrt{s} < 1\,\text{GeV} \\ \sim 2\% & \sqrt{s} \in (1,2)\,\text{GeV} \end{cases}$

0.7 % now

6 % now

α_{em}: hadronic contribution

fine-structrure constant at the scale M_Z plays a crucial role in basic EW radiative corrections to SM

$$\alpha(M_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha(M_Z^2)}$$

(u, d, s, c, b quarks only)

$$\Delta\alpha(M_Z^2) \to \Delta\alpha_{\text{lept}} + \Delta\alpha_{\text{had}}^{(5)}$$

✓ $\Delta\alpha_{\text{lept}}$ $\longrightarrow$ perturbation theory: known up to 3-loop

✓ $\Delta\alpha_{\text{had}}^{(5)}$ $\longrightarrow$ dispersion relation:

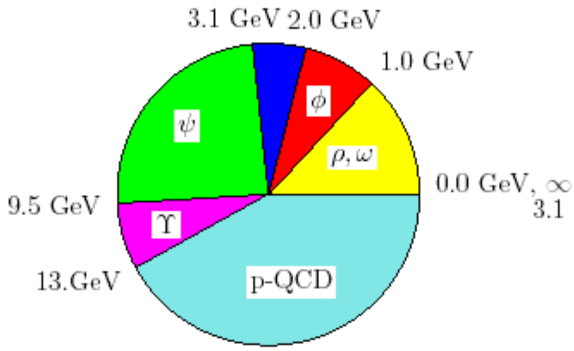
$$\Delta\alpha_{\text{had}}^{(5)} = -\frac{\alpha\, M_Z^2}{3\,\pi}\,\text{Re}\int_{4\,m_\pi^2}^{\infty} \text{d}\,s\,\frac{R(s)}{s\,(s - M_Z^2 - i\,\epsilon)}$$

α_{em}: hadronic contribution

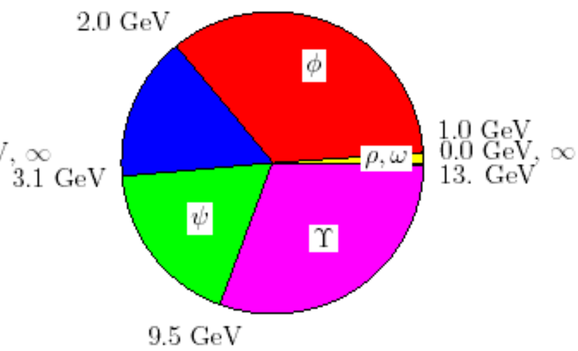
current data: $\Delta\alpha^{(5)}_{\text{had}}(M_Z^2) = 0.027607 \pm 0.000225$

→ $\alpha^{-1}(M_Z^2) = 128.947 \pm 0.035$ i.e. $\dfrac{\delta\alpha(M_Z^2)}{\alpha(M_Z^2)} = 2.7 \times 10^{-4}$

~ one order of magnitude worse than that of M_Z and G_μ → limiting factor in calculation of precise SM predictions



$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$



$\delta^2\, \Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$

high-energy region is not a problem: error reduction by theory; the key problem is the E < 2.5 GeV region

ILC with GigaZ

A future linear collider would tremendously improve the precision of electroweak observables

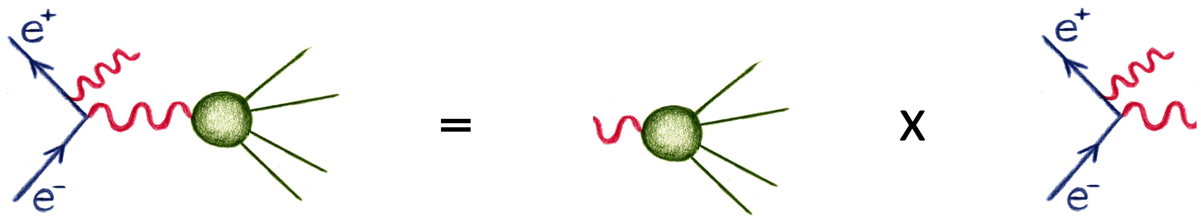
- $t\bar{t}$ threshold
  - obtain m_t indirectly from production cross section: δm_t = 1 → 0.1 GeV
- Z peak measurements
  - polarised beams, uncertainty $\delta A^{0,f}{}_{LR}$: $10^{-3} \rightarrow 10^{-4}$
    translates to $\delta\sin^2\theta^l{}_{\rm eff}$: $10^{-4} \rightarrow 1.3 \cdot 10^{-5}$
  - high statistics: 10^9 Z decays: $\delta R^0{}_{\rm lep}$: $2.5 \cdot 10^{-2} \rightarrow 4 \cdot 10^{-3}$
- WW threshold
  - from threshold scan: δM_W = 15 → 6 MeV
- Low energy data
  - $\Delta\alpha_{\rm had}$: more precise cross section data for low energy ($\sqrt{s}$ < 1.8 GeV) and around $c\bar{c}$ resonance (BES-III), improved α_s, improvements in theory: $10^{-4} \rightarrow 5 \cdot 10^{-5}$

σ^{had} measurement

at low energies ($\lesssim$ 2 GeV) only measurements of exclusive chs. are feasible $\longrightarrow$ two approaches:

✓ Radiative return (KLOE, BABAR, BELLE)

- runs at fixed-energy machines (meson factories)
- use initial state radiation (ISR) to access lower energies



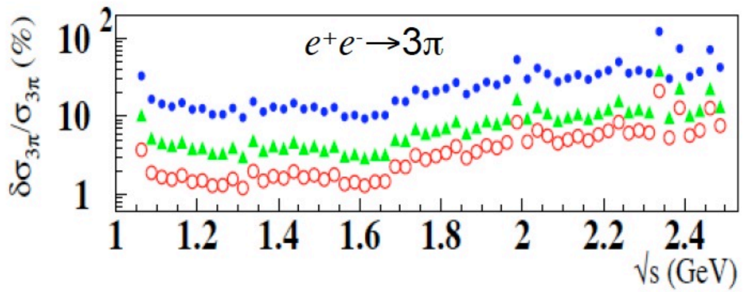
measured X-section = resulting X-section x radiator function

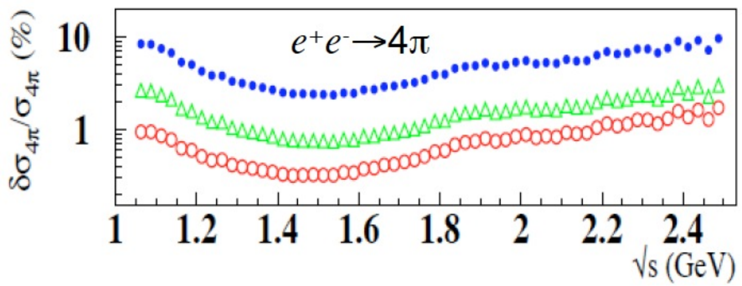
- data as by-product of standard physics program
- requires precise theoretical calculation of radiator function
- luminosity and beam energy enter only once for all energy points

σ^{had} measurement

✓ Energy scan (CMD2, SND)

- energy of colliding beams is tuned to desidered value
- "direct" measurement of X-sections
- needs dedicated accelerator/physics program
- needs to measure luminosity and beam energy for every data point

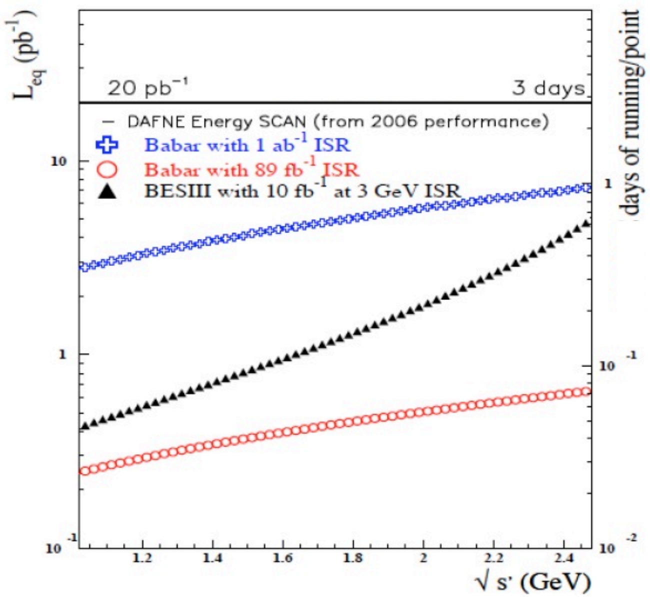




- Published BaBar results: 89 fb^{-1} (ISR)

▲ "BaBar" × 10 (890 fb^{-1})

○ energy scan: 20 pb^{-1}/point @ L = 10^{32} $cm^{-2}s^{-1}$, 25 MeV bin → 1 year data-taking

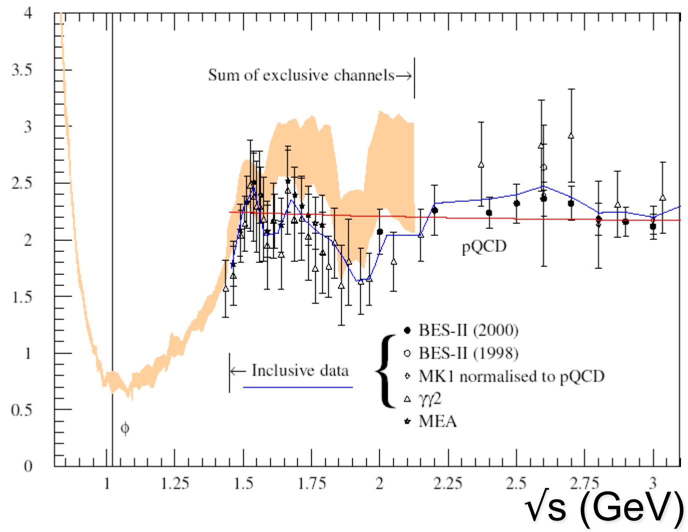


statistically better than a O(1 ab^{-1}) @ B-factories

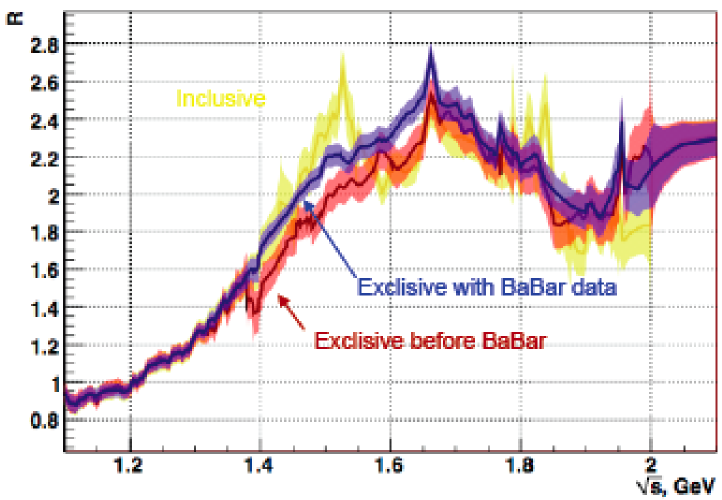
σ^{had} measurement

Exclusive vs inclusive measurements

most recent incl. meas.: MEA and B-antiB → L_{int} = 200 nb^{-1} (1 hour @ 10^{32} cm^{-2} s^{-1}): error = 10% (stat.) + 15% (sys.)



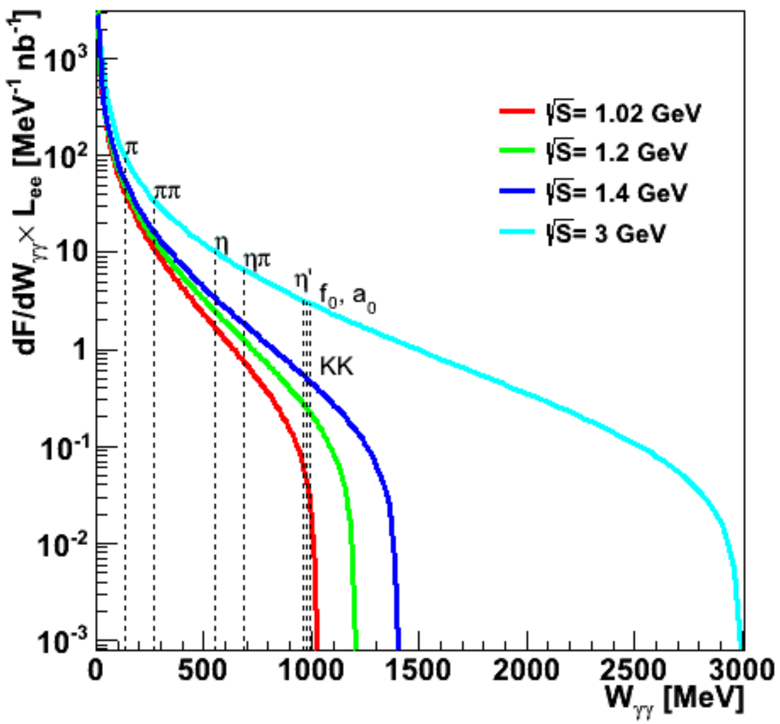
new BaBar data is improving a lot this region, however still remains the question on the completeness of excl. data vs systematics of old incl. meas.



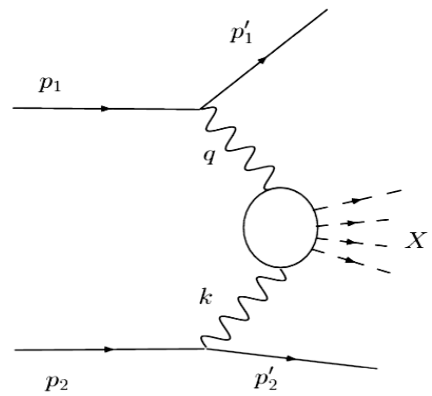
Spectroscopy and γγ-physics

Interesting open issues in low-energy spectroscopy (4q states, glueballs, …) which would strongly benefit from high-precision measurements of

$e^+e^- \rightarrow \gamma^* \rightarrow$ X & $e^+e^- \rightarrow e^+e^- \gamma^*\gamma^* \rightarrow e^+e^-$ X



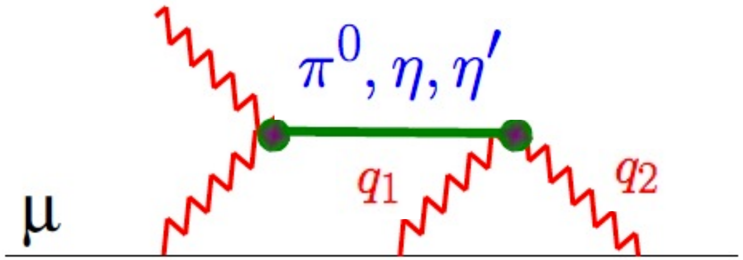
γγ-physics



$$\frac{\mathrm{d}N_X}{\mathrm{d}W_{\gamma\gamma}} = L_{\mathrm{int}} \frac{\mathrm{d}F}{\mathrm{d}W_{\gamma\gamma}} \sigma(\gamma^*\gamma^* \rightarrow X)$$

γγ-physics

Hadronic LbL contribution to a_μ ⟶ largely dominated by term



● ⟶ Transition Form Factor $F_{\pi^0(\eta,\eta')\,\gamma^*\gamma^*}$

uncertainty due to our ignorance about $F(q_1^2, q_2^2)$ ($q^2 < 0.5$ GeV^2)

what we really miss is the function $\dfrac{\mathrm{d}^2 F(q_1^2, q_2^2)}{\mathrm{d}q_1^2\,\mathrm{d}q_2^2}$ ⟶ $\gamma^*\gamma^* \to PS$, $\gamma^* \to PS\,\gamma^*$

also O(%)-level measurements of Γ (PS ⟶ γγ) are necessary to constrain *F(0, 0)* (⟶ Venanzoni's talk)

NB – γγ-physics program can also be carried out at an (same luminosity) e^-e^- collider ⟶ no bckg from annihalation channel

Dark Forces

(more details in Venanzoni's talk)

Recent astrophysical puzzles:

- ✓ the positron excess observed by the PAMELA satellite within a kpc, without observing an excess of antiprotons
- ✓ the 511 keV line from the galactic core observed by INTEGRAL
- ✓ the annual modulation observed by the DAMA/LIBRA together with the absence of a similar signal from silicon based detectors
- ✓ the low energy spectrum of nuclear recoil events observed by CoGent

and the long-standing Dark Matter problem $\longrightarrow$ construction of various exotic extensions of the SM characterized by

- new light states (vectors & scalars w/ masses $\in$ (0.1, 1) GeV)
- weakly coupled to γ, or directly coupled to μ and/or e

Dark Forces

→ precision differential measurements of

- $e^+e^- \longrightarrow e^+e^- + \gamma$
- and/or $e^+e^- \longrightarrow \mu^+\mu^- + \gamma$
- and/or $e^+e^- \longrightarrow E_{miss} + \gamma$

at low energies are the best way to constrain (or find evidencies of …) such model

NB – different option: fixed target experiment, e.g.

$$e^- p \to e^- pU \to e^- p\mu^+\mu^-$$

(see Venanzoni's talk)

e^+e- collider: conclusion

There is a rich physics program both below and above 1 GeV:

- ✓ Low-energy program (0.6 ÷ 1.4) GeV is really unique → NO competition from other facilities
- ✓ High-energy region (1.4 ÷ 3.0) GeV is still poorly known: fractional accuracy of σ^{had}~ 6% → reduction to 2% would have strong impact on precision tests of SM via a_μ and α_{em} (M_Z)
- ✓ Interesting $\gamma\gamma$-physics program → improvement in accuracy of LbL contribution to a_μ + spectroscopy
- ✓ Searches for an hidden "parallel" world with potential manifestations at ~ 1 GeV

e^+e^- collider: conclusion

This physics program, to be completed in a reasonable time (2-3 years of data-taking), requires a collider with:

✓ Luminosity ~ $(2 – 3) \times 10^{32}$ cm^{-2} s^{-1}

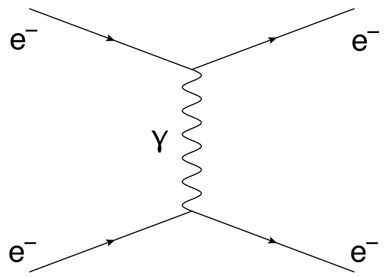
and, for σ^{had} measurement,

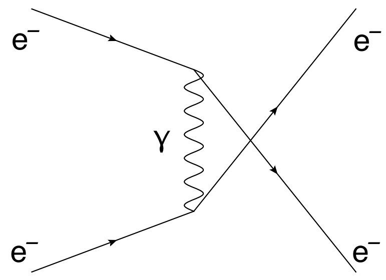
✓ variable energy in the range $\sqrt{s} = (0.6 \div 3.0)$ GeV
(in steps of ~25 MeV)

e^-e^- collider

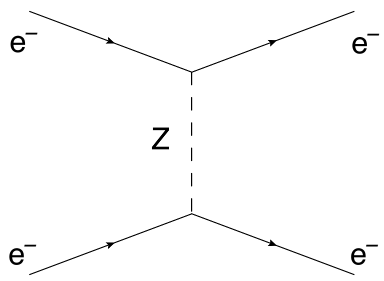
Physics opportunities with an e^-e^- collider have also been explored

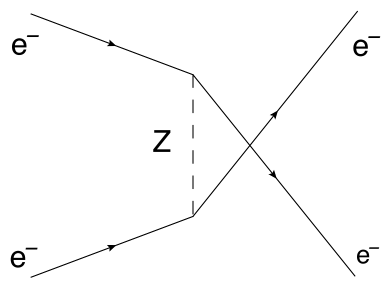
- ✓ $\gamma\gamma$ physics $\longrightarrow$ as for e^+e^- but w/out the bckg associated to the annihilation channel





- ✓ weak mixing angle θ_W $\longrightarrow$ Moller scattering: γ-Z^0 interference



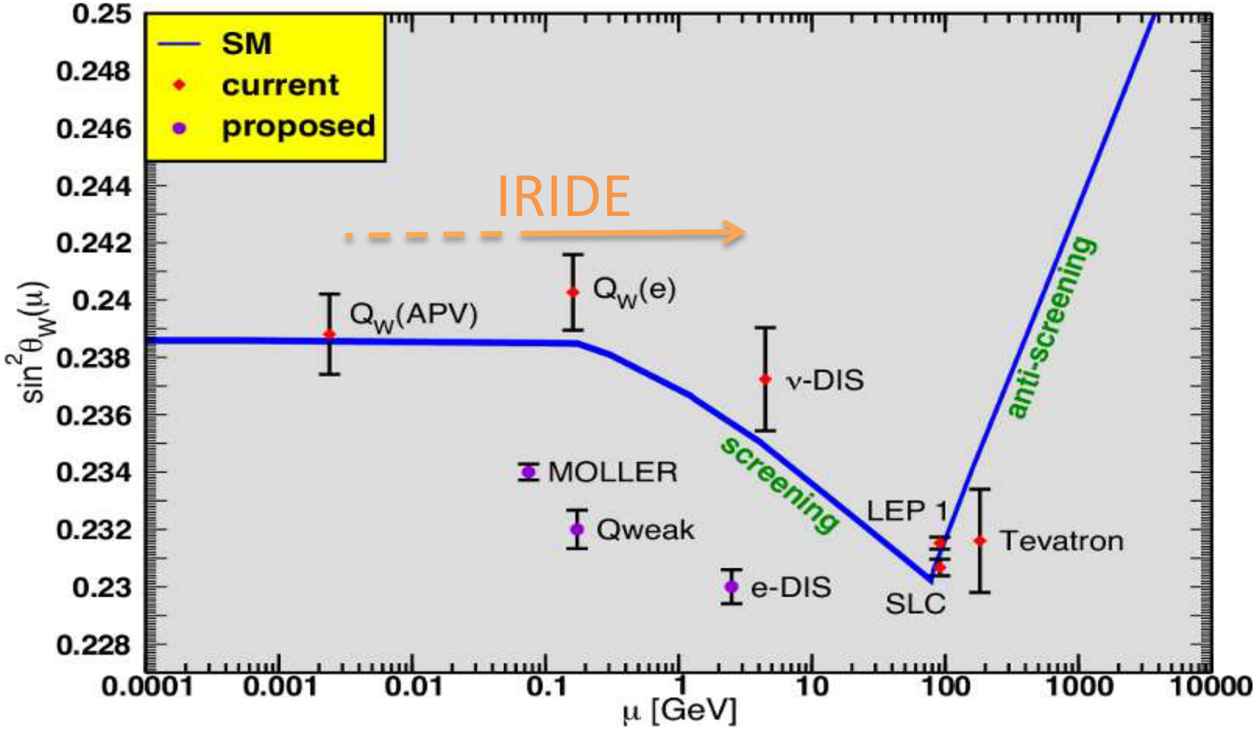


e^-e^- collider

→ measurement of parity violating asymmetry

$$A_{\rm PV}^{(2)} = \frac{\sigma_{RR} - \sigma_{LL}}{\sigma_{RR} + \sigma_{LL}}$$

(subscripts denote initial e^-e^- states' polarization)

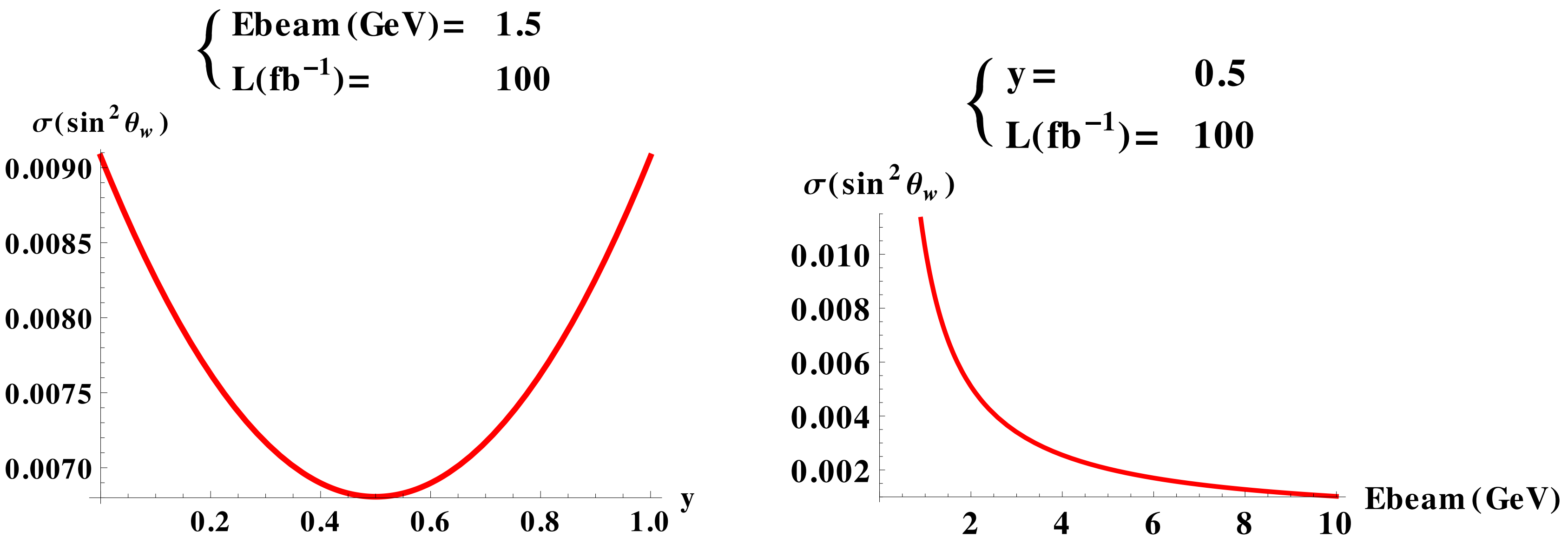


$$= Q = \sqrt{y\,s} \qquad \left(y = \frac{1-\cos\theta_{\rm cm}}{2}\right)$$

$e^- e^-$ collider

required accuracy: $\sigma(\sin^2\theta_W) \leq 4 \times 10^{-3}$

→ MOLLER@JLAB

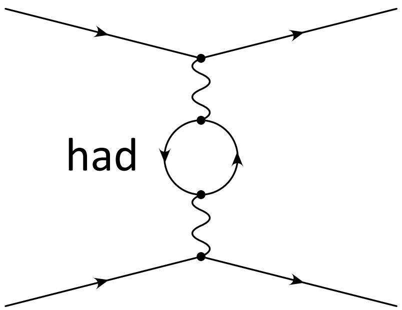


→ at least 100 fb^{-1} in the μ-region covered by IRIDE (!!)

e^-e^- collider

… but the measurement of $\sin^2 \theta_W$ can also be done with an e^- beam against a fixed target (e.g., Qweak @ JLAB, P2 @ Mainz), were effective luminosity compensate for the low asimmetry (see Venanzoni's talk)

✓ vacuum polarization → possibility to obtain a_μ^{had} from t-channel diagram in Moller scattering



(M. Passera, L. 32, G. Venanzoni in progress)