ISR Hadron Production in e+e− and Meson-γ Transition Form Factors

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- **Introduction to BaBar**

- **Initial State Radiation**
  - **the KK$\pi\pi$ final states and the Y(2175)**
  - **the $\pi^+\pi^-$ final state**
  - **effect on g$_\mu$−2**

- **Summary**

- **Transition Form Factors**
  - **timelike η, η'**
  - **spacelike π^0, η, η', η_c**
  - **discussion**

The BaBar Experiment

- e^+e^- collisions at $E_{CM}=$10.6 GeV, designed for CP violation in B decays

- Different beam energies
  - → E_{e^-} = 9.0 GeV
  - → E_{e^+} = 3.1 GeV
  - → c.m.-lab boost, $\beta\gamma$=0.55

- Asymmetric detector
  - → c.m. frame acceptance
    $-0.9 \sim \cos\theta^* \sim 0.85$
    wrt e^- beam

- with excellent performance
  - → good tracking, mass resolution
  - → good γ, π^0 recon.
  - → full e,μ,π,K,p ID

- High luminosity
  - → ~520 fb^{-1} accumulated
  - ↔1.7 billion $e^+e^- \rightarrow q\bar{q}$ events
  - ↔12 million $e^+e^- \rightarrow \gamma_{ISR}\rho^0$
  - ↔ 1 million $e^+e^- \rightarrow e^+e^-\pi^0$
  - → 232-480 fb^{-1} used
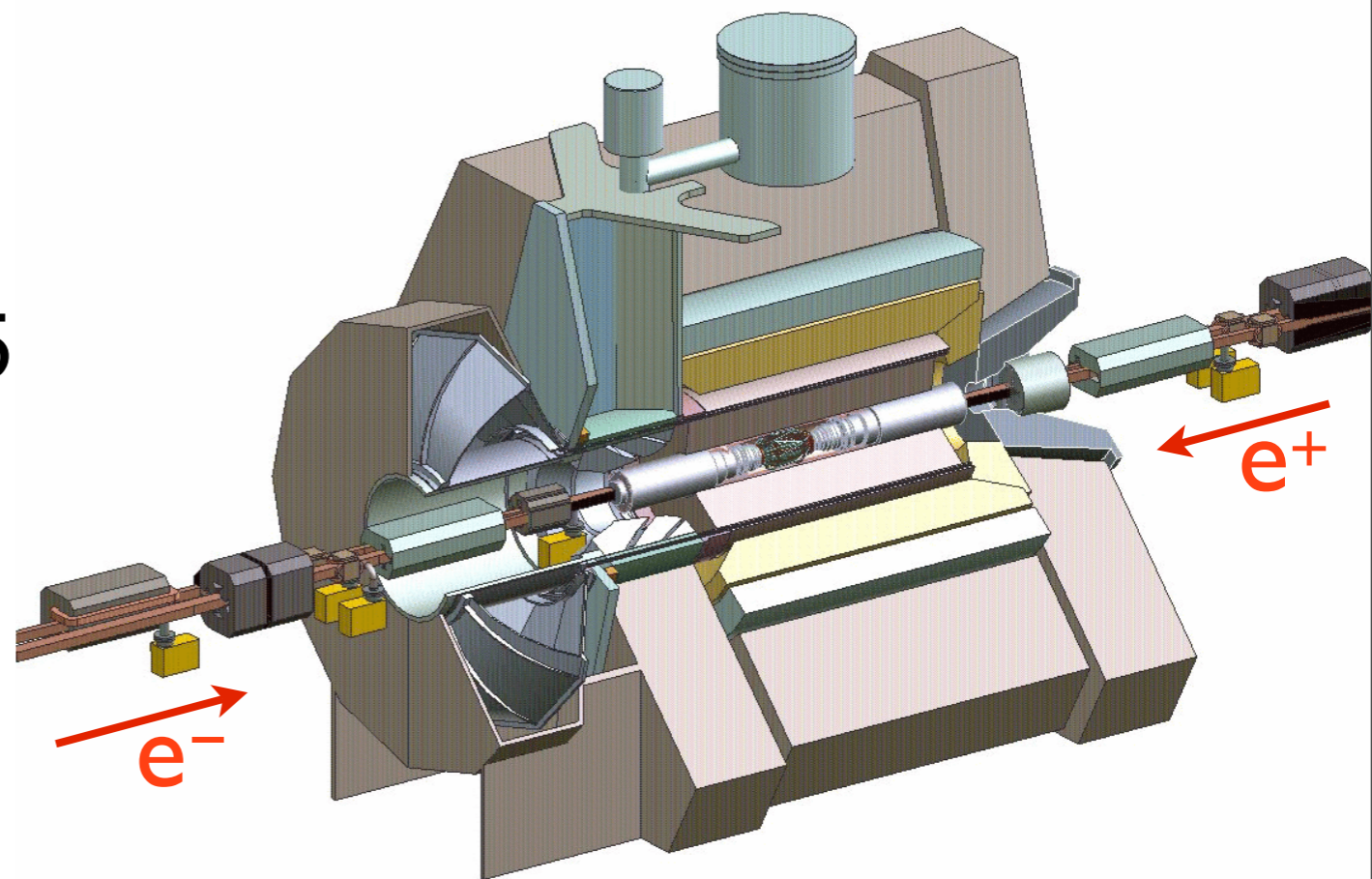
Initial State Radiation in e⁺e⁻ Annihilations
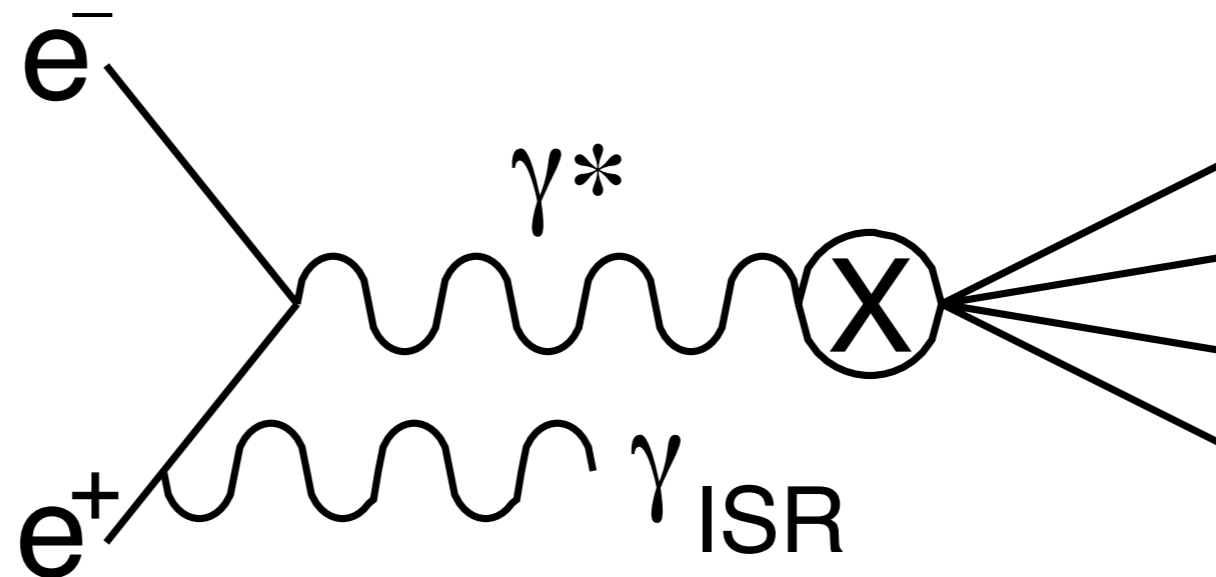
- $e^+e^- \to \gamma_{ISR}e^+e^- \to \gamma_{ISR}\gamma^* \to \gamma_{ISR}X$

- X is any allowed (hadronic) system, e.g.,
  - → a resonance with $J^{PC}=1^{--}$
  - → two particles with compatible quantum numbers
  - → 3, 4, ... particles
  - → 2 or more jets

- the cross section: $d\sigma(s,s',\theta_\gamma)/ds'd\cos\theta_\gamma = W(s,s',\theta_\gamma)\sigma(s')$

- the radiator function W is known to ~1%

- measure $\sigma(e^+e^- \to X)$ vs. $m = m_{\gamma^*} = m_X = E_{CM} = \sqrt{s'}$

- ISR gives simultaneous access to a continuous, wide s' range in a single experiment
  → very small point-to-point systematic errors

- if the γ_{ISR} is detected then the system X is also well contained in the detector
  → minimal acceptance issues
  → measure the full angular distribution and other event structure variables

- the hadronic system X is boosted
  → can measure all the way down to threshold with good efficiency
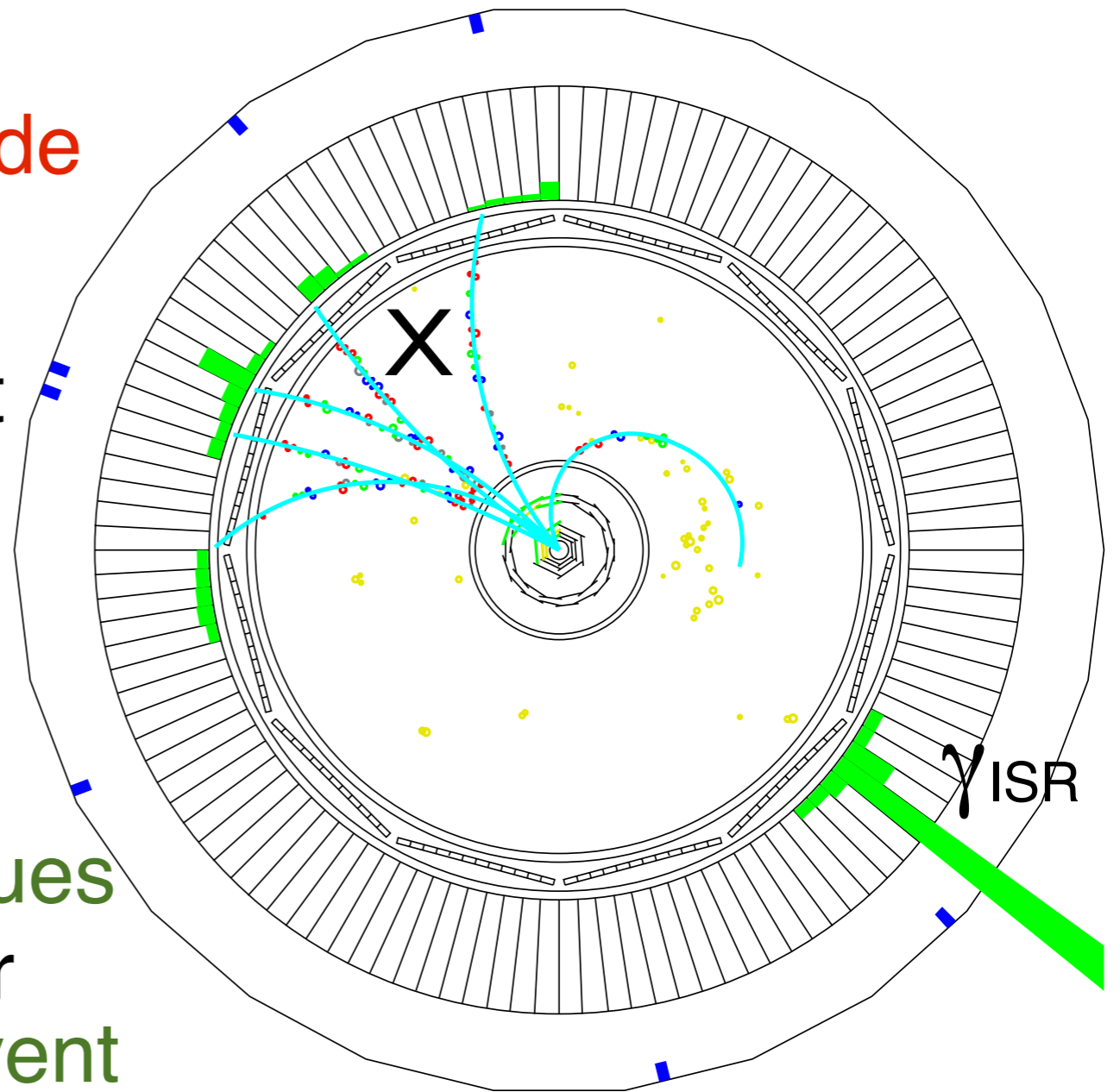
- also
  → mass resolution worse than collider E_{CM} spread
  → need very high luminosity at the nominal E_{CM}

The K$^+$K$^-\pi^+\pi^-$ and K$^+$K$^-\pi^0\pi^0$ Final States

- event selection:
  - → require: a hard γ;
    identified K$^+$ and K$^-$;
    identified π^+, π^- or 2 π^0

  - → perform kinematic fits
    to various hypotheses

  - → select if $\chi^2_{KK\pi\pi\gamma}$ <30 for
    the signal hypothesis,
    other χ^2 are poor
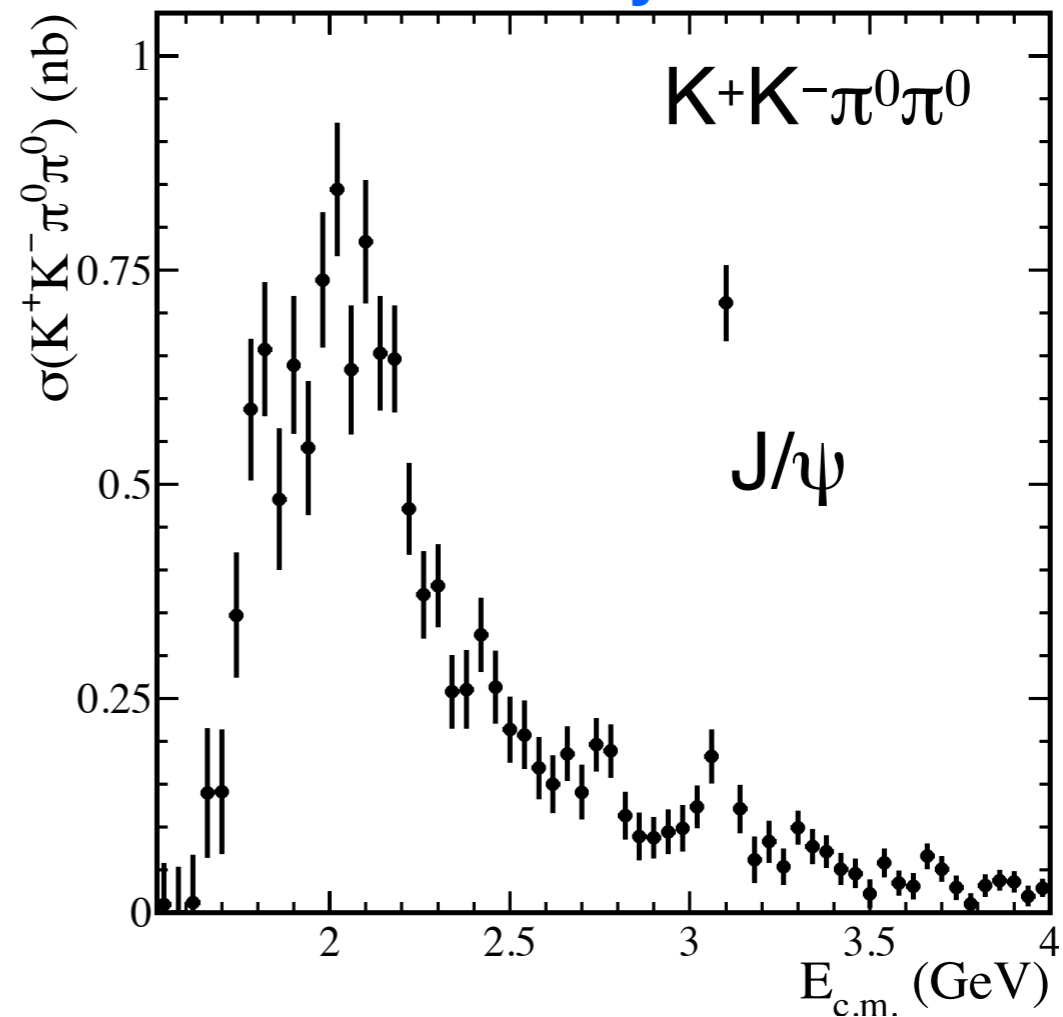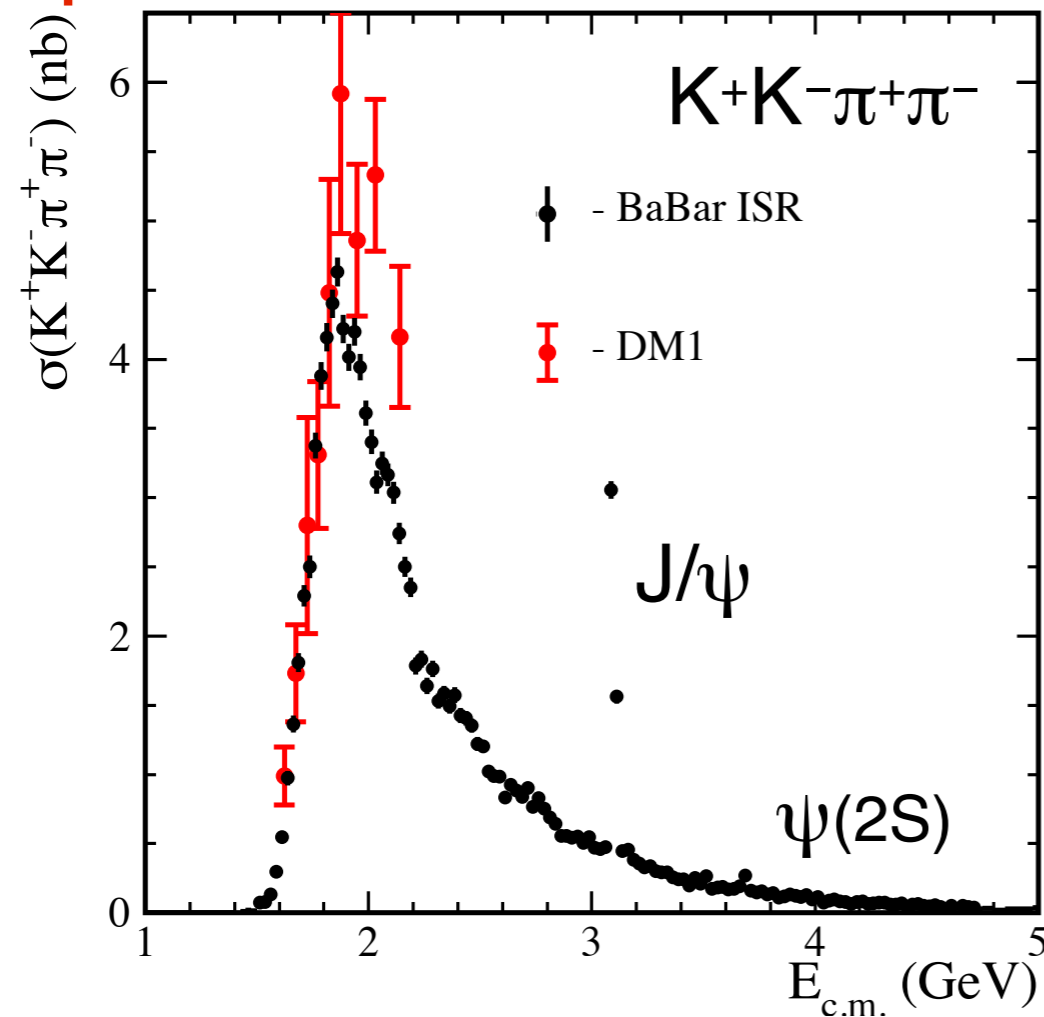
- measure backgrounds from
  the data and subtract
  - → previous/quick msmts. of
    $e^+e^- \to q\bar{q} \to \pi^0 KK\pi\pi$, $e^+e^- \to$
    $\gamma_{ISR} K_S K\pi$, $\gamma_{ISR} 4\pi$
  - → others from χ^2 control regions

- measure efficiencies from the data
  - → events with missing particles

232 fb^{-1}, PRD-RC 74, 091103, (06)
454 fb^{-1}, submitted to PRD
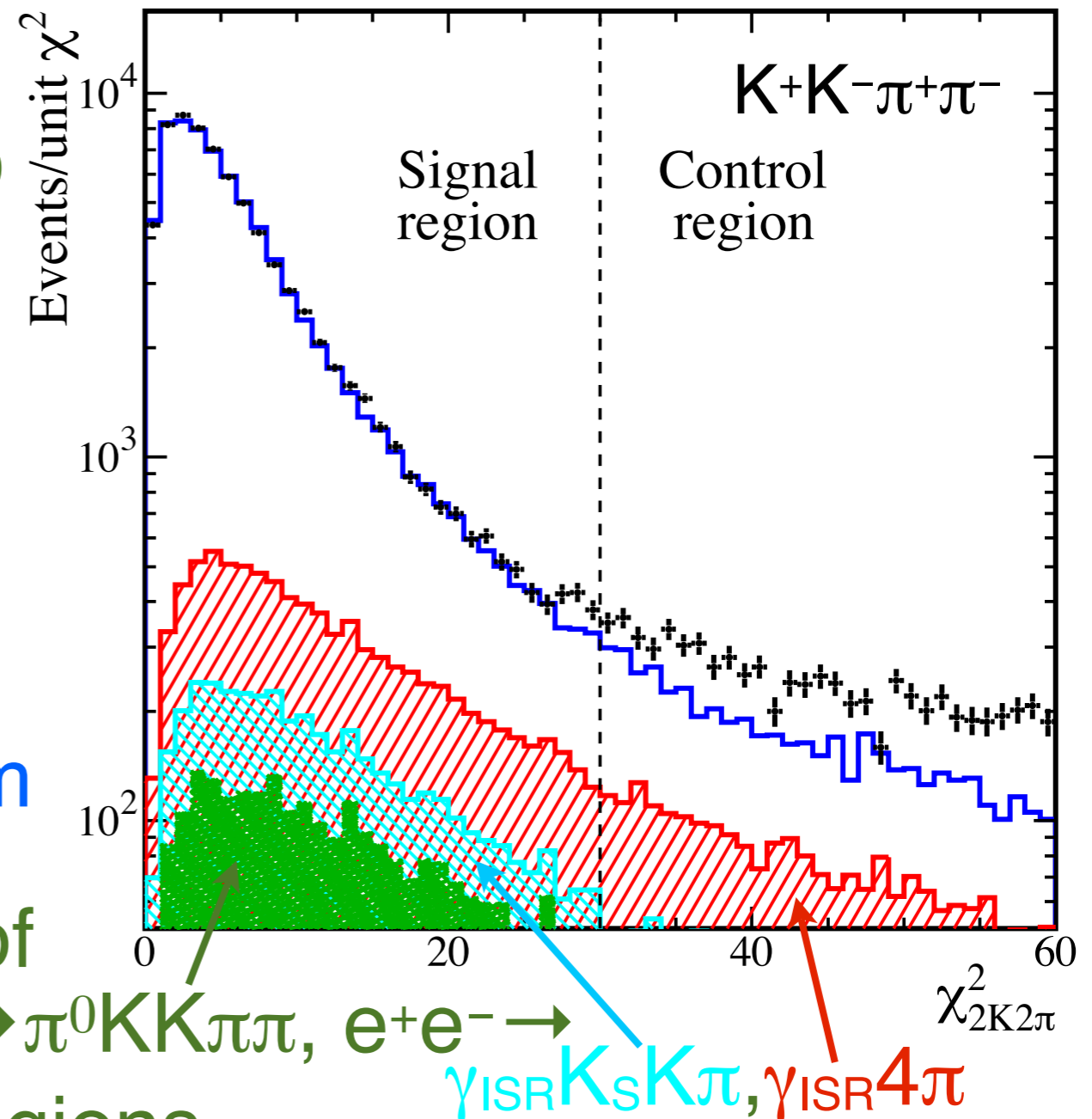
- **updated** cross sections: 5%, 7% overall systematic

→ improved world best K⁺K⁻π⁺π⁻, only K⁺K⁻π⁰π⁰ msmt.

→ several hints of structure in the 2-3 GeV range

→ clear signals for J/ψ, ψ(2S) ↔ branching ratios

- observe considerable substructure

→ measure cross sections for e⁺e⁻→K*⁰(890)Kπ, K₂*(1430)⁰Kπ, K⁺K⁻ρ⁰(770), ...

→ see K*⁰(890)K*⁰(890), K*⁰(890)K₂*(1430)⁰, K₁(1270)K, ...

- **in particular, the $\phi\pi\pi$ cross sections:**
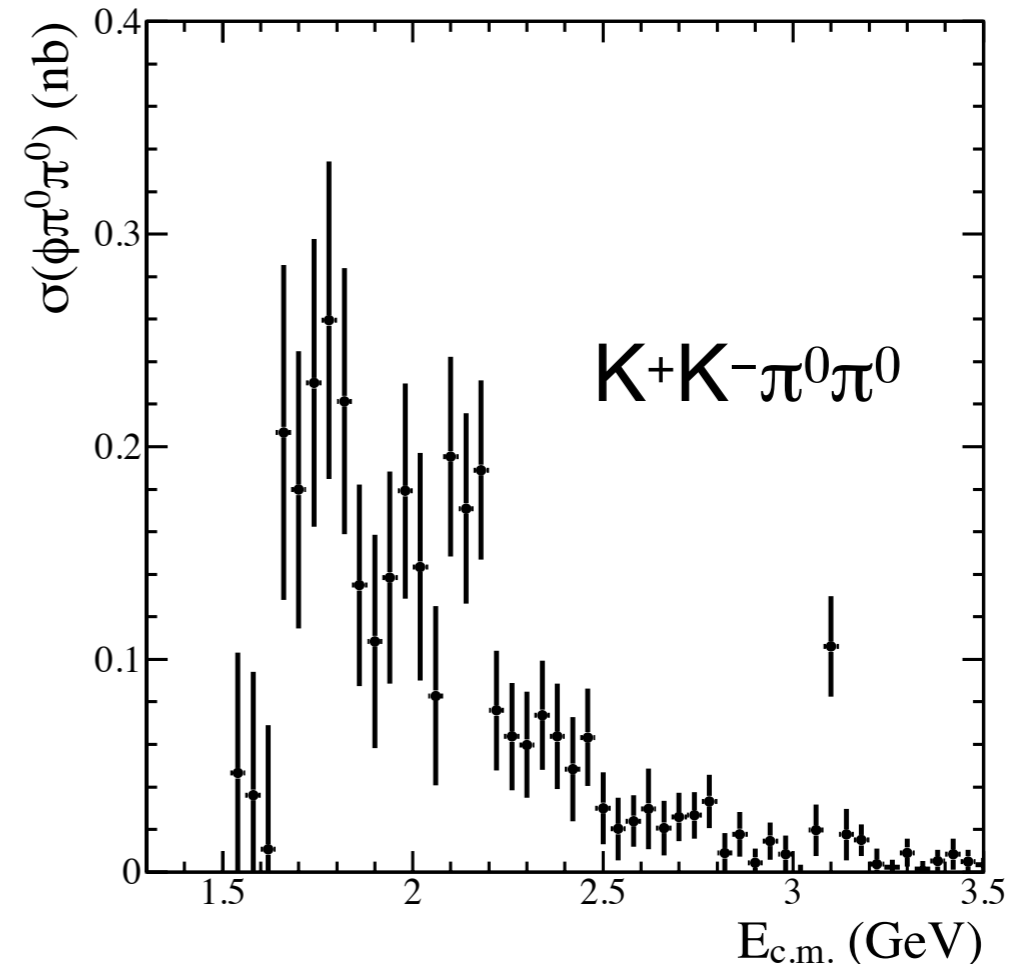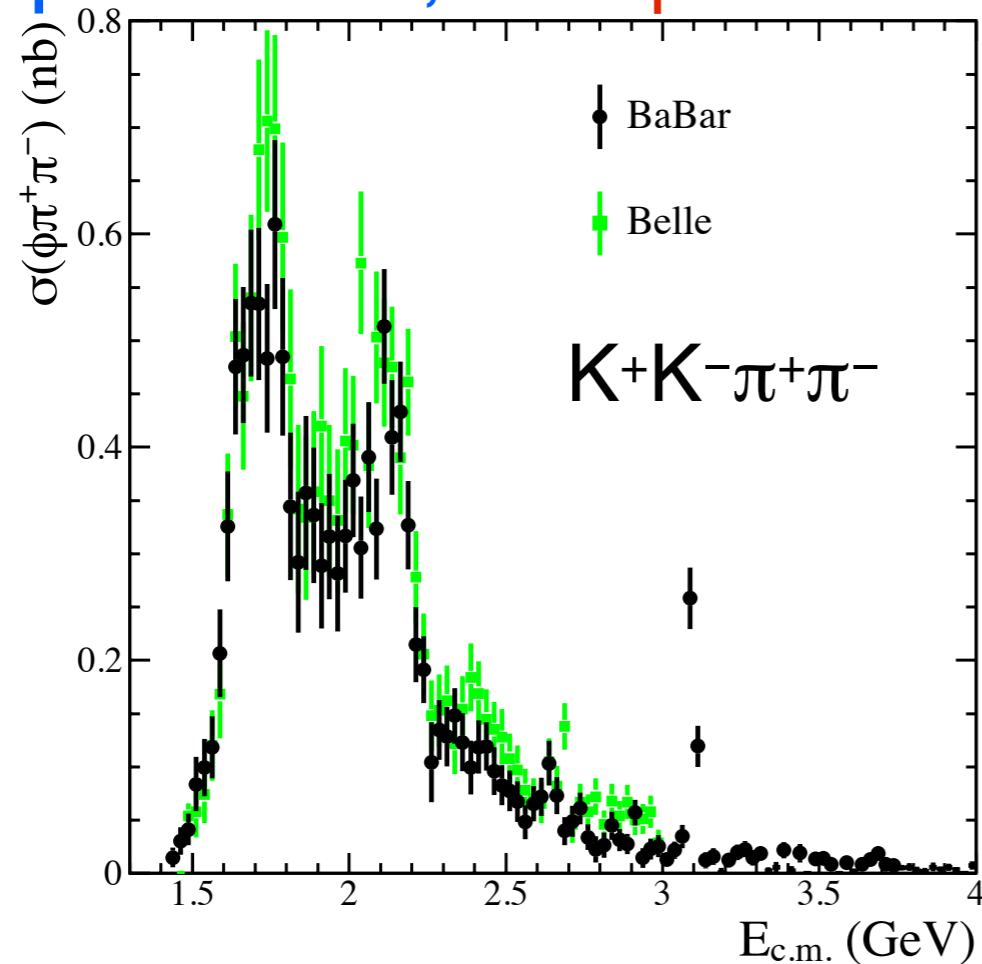
→ show 2-peak structure near threshold

→ lower-mass peak expected from $\phi(1680)$

- **the second peak is a new resonance, the Y(2175)**
  - → first reported by BaBar at 5.6σ PRD-RC 76, 012008 (07)
  - → confirmed by BES   PRL   100, 102003 (08)
  - → confirmed by Belle   PRD   80, 031101 (09)
  - → observed in this study at 9.3σ
  - → $K^+K^-\pi^+\pi^-$ and $K^+K^-\pi^0\pi^0$ modes consistent
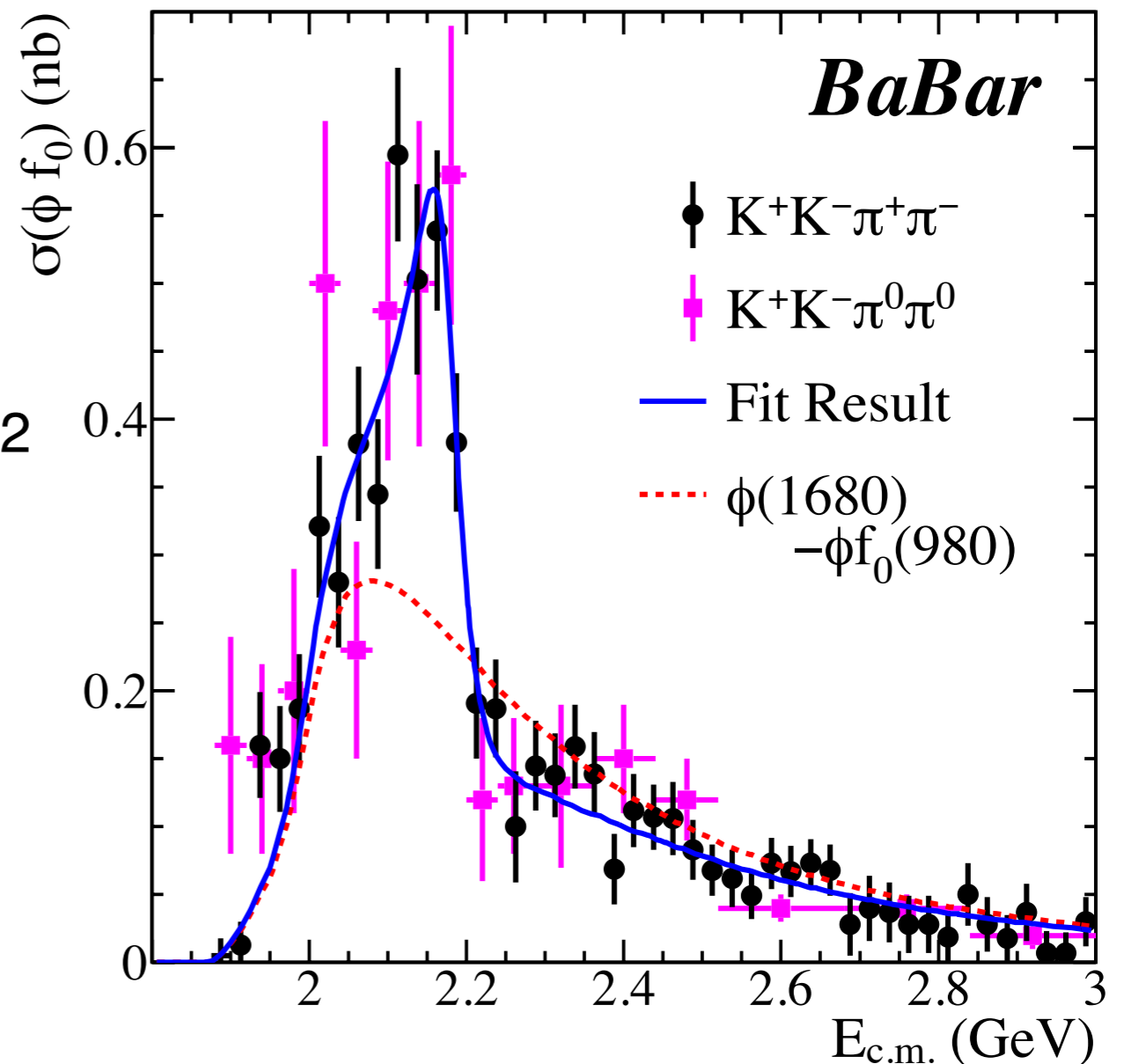
- **What is this new state?**
  → $J^{PC} = 1^{--}$

- **simultaneous fit to several mass distributions gives:**

  m_Y: 2180±   8±   8 MeV/c²
  Γ_Y: 77± 15± 15 MeV
  σ_Y: 93± 21± 10 pb
  ψ_Y: −2.11±0.24±0.12 rad
         wrt $\phi(1680)$

- **decay modes:**
  → $\phi f_0(980)$ dominant
  → hint of non-ϕ KKf₀
 → no evidence for $\phi\pi\pi$ or KK$\pi\pi$ outside ϕf_0 region
  ⇒ unlikely to be a ϕ''

- **mass is just below $\Lambda\bar{\Lambda}$ threshold**   → is it an $s\bar{s}s\bar{s}$ state?
  → is it analogous to the Y(4260), which is just below $\Lambda_c\bar{\Lambda}_c$ threshold and decays to J/$\psi\pi\pi$?
 → ...or some other charmonium-like state?

BaBar

- $K^+K^-\pi^+\pi^-$
- $K^+K^-\pi^0\pi^0$
- Fit Result
- $\phi(1680)$ $-\phi f_0(980)$

$\sigma(\phi f_0)$ (nb)

$E_{c.m.}$ (GeV)

The $\pi^+\pi^-$ Final State

- **extremely detailed analysis, aim for <1% precision:**
  - → require a hard γ, ID'd π^+ and π^- (or $\mu^+\mu^-$ or K$^+$K$^-$)
  - → measure effects of additional ISR and FSR

- **measure e$^+$e$^-$→$\gamma_{ISR}\mu^+\mu^-$, γ_{ISR}K$^+$K$^-$ simultaneously**
  - → particle ID efficiency, error from the data

- **measure other backgrounds from the data**
  - → e$^+$e$^-$→q$\bar{q}$→$\pi^0\pi^+\pi^-$, $\pi^0\mu^+\mu^-$, π^0K$^+$K$^-$: comb γ_{ISR}, other γ
  - → other ISR: previous or dedicated measurements

- **measure trigger and tracking efficiencies in the data**
  - → including correlations, dead regions, etc.

- **check: $\mu^+\mu^-$ x-section consistent with QED within 1.7%**
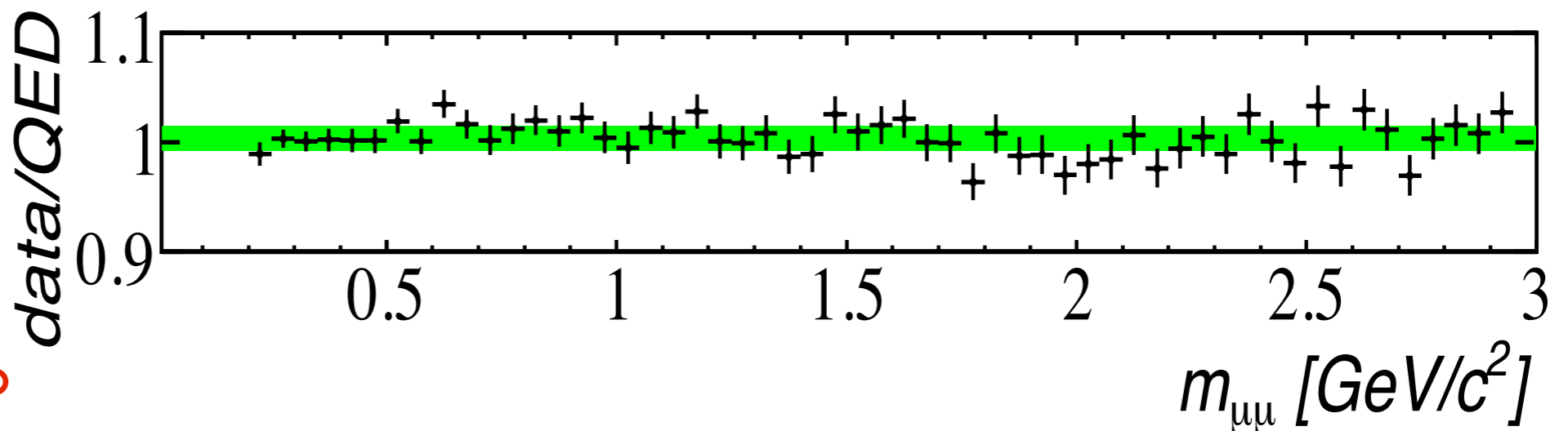
- use that to normalize the $\pi^+\pi^-$ cross section
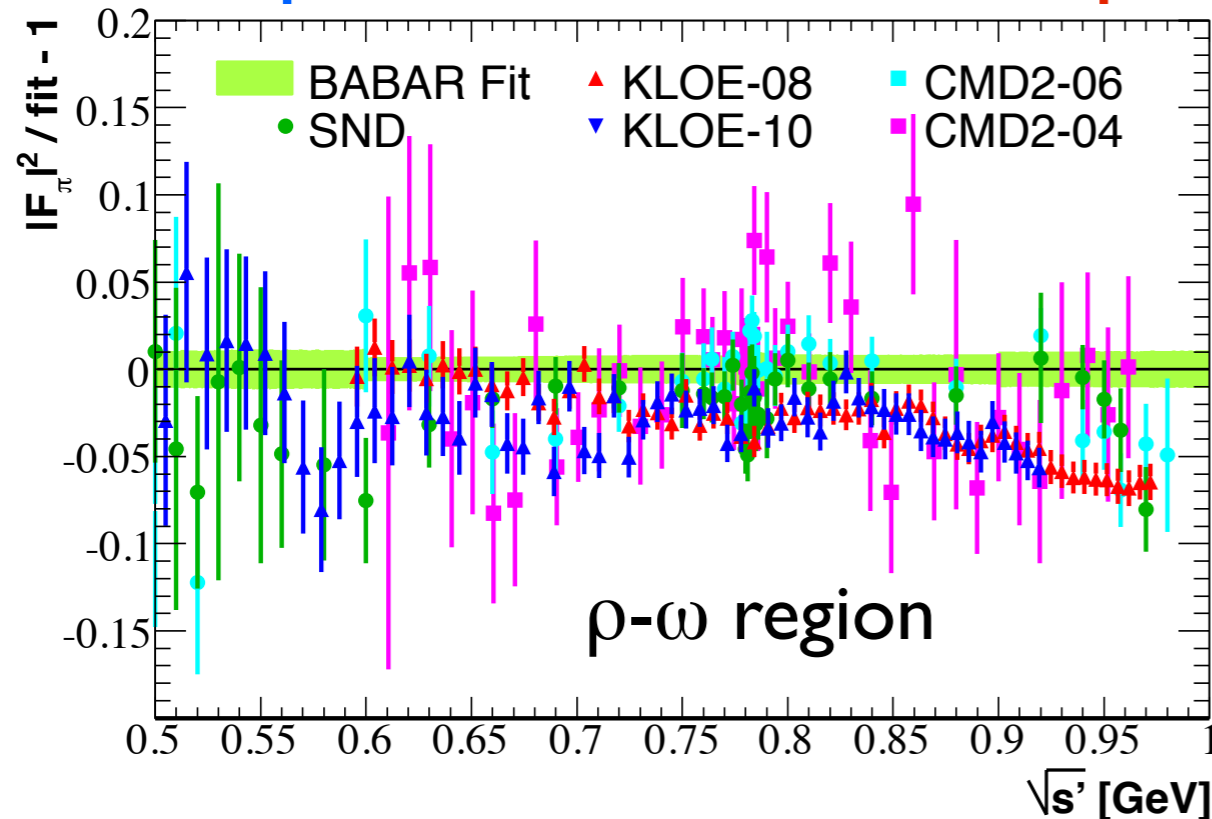 ➜ measurement unfolded for mass resolution
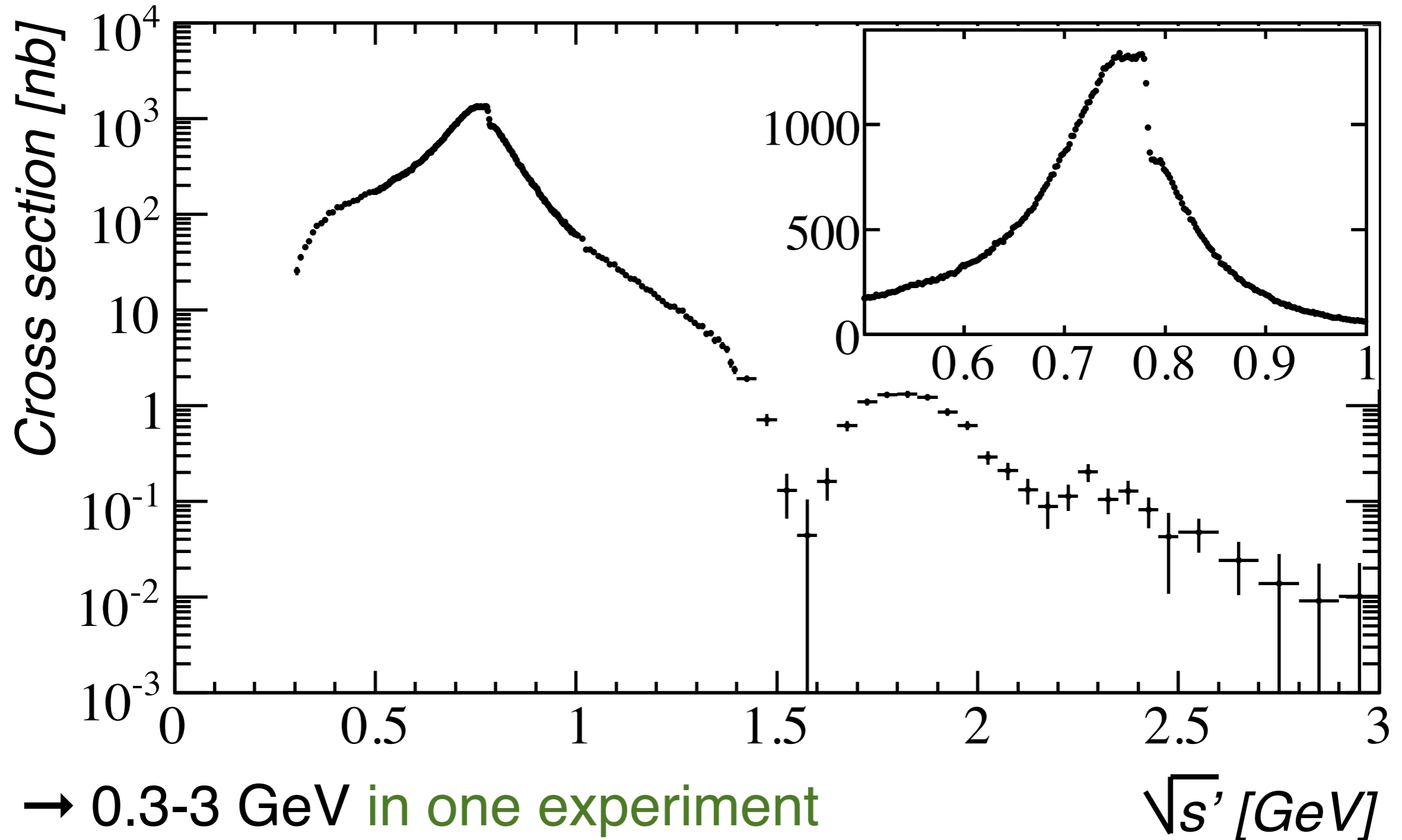
➜ 0.3-3 GeV in one experiment

➜ 0.5% systematic error near ρ peak

➜ see ρ-ω interference

➜ much structure above 1.2 GeV ↔ excited ρ states

- compare x-sec/FF with previous results

→ syst. errors:
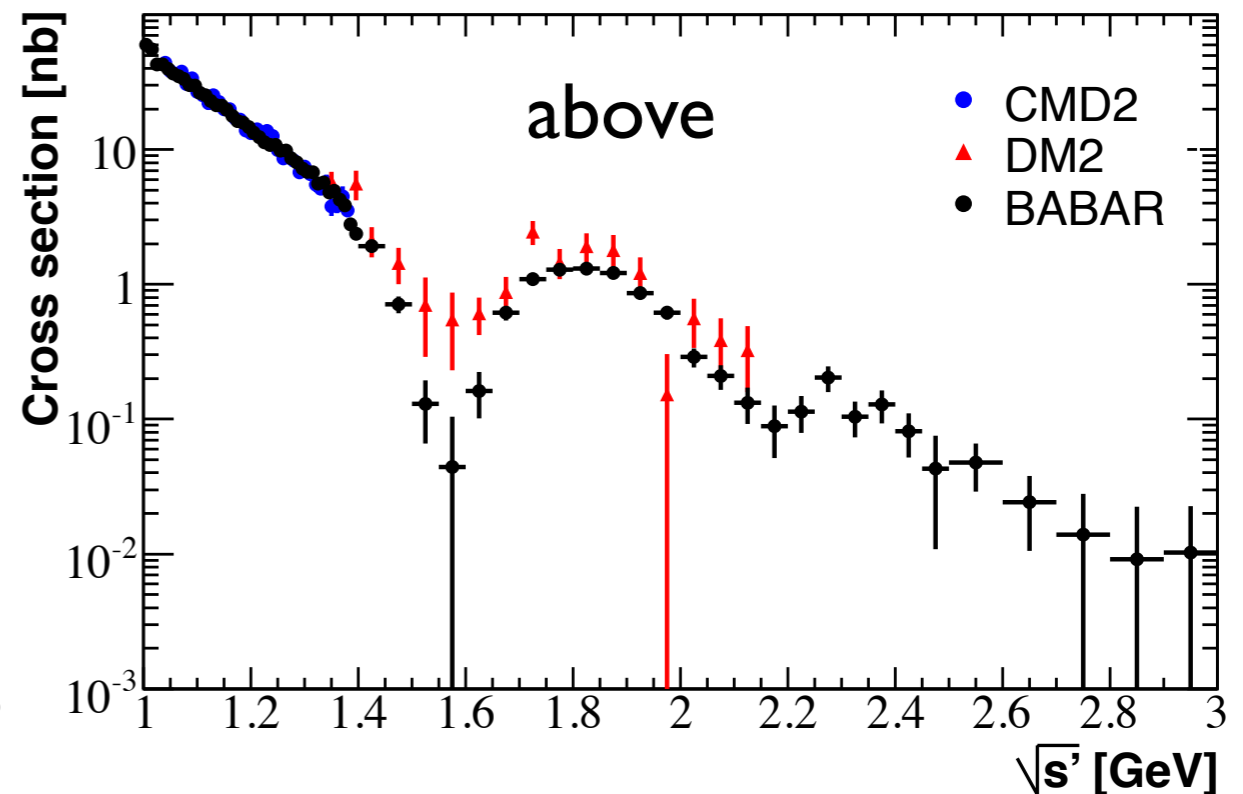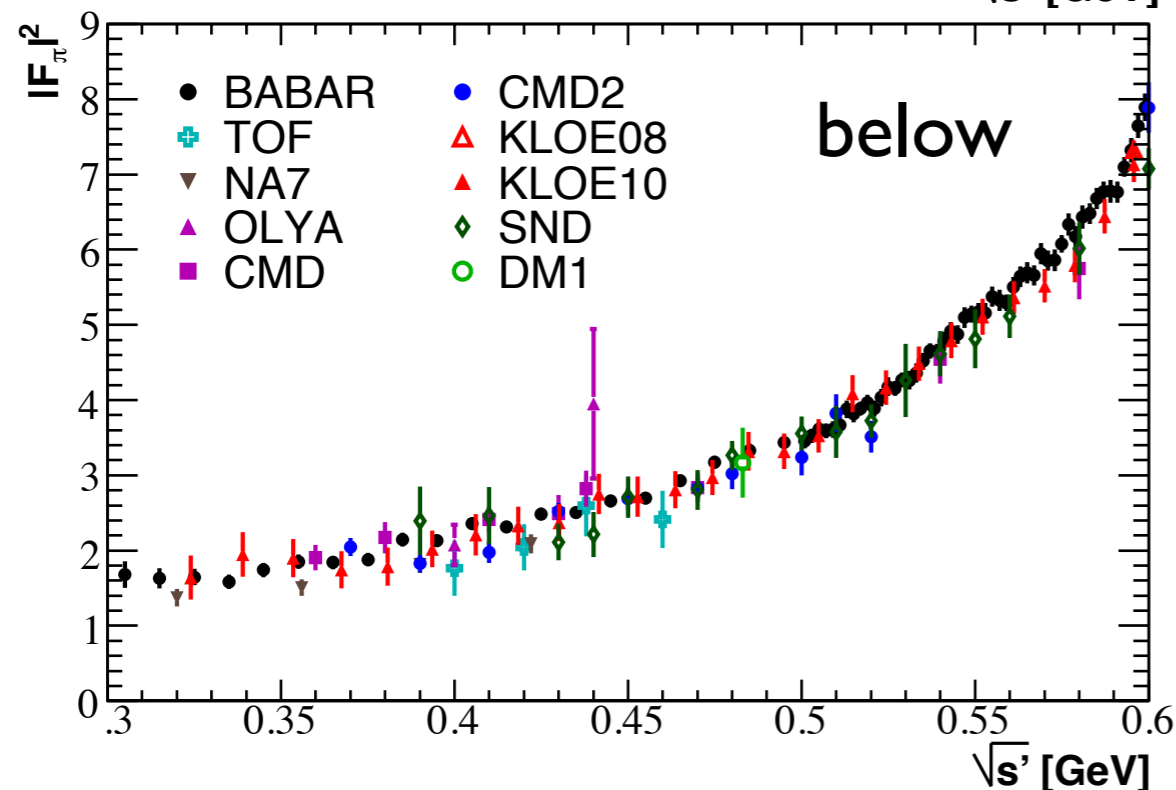
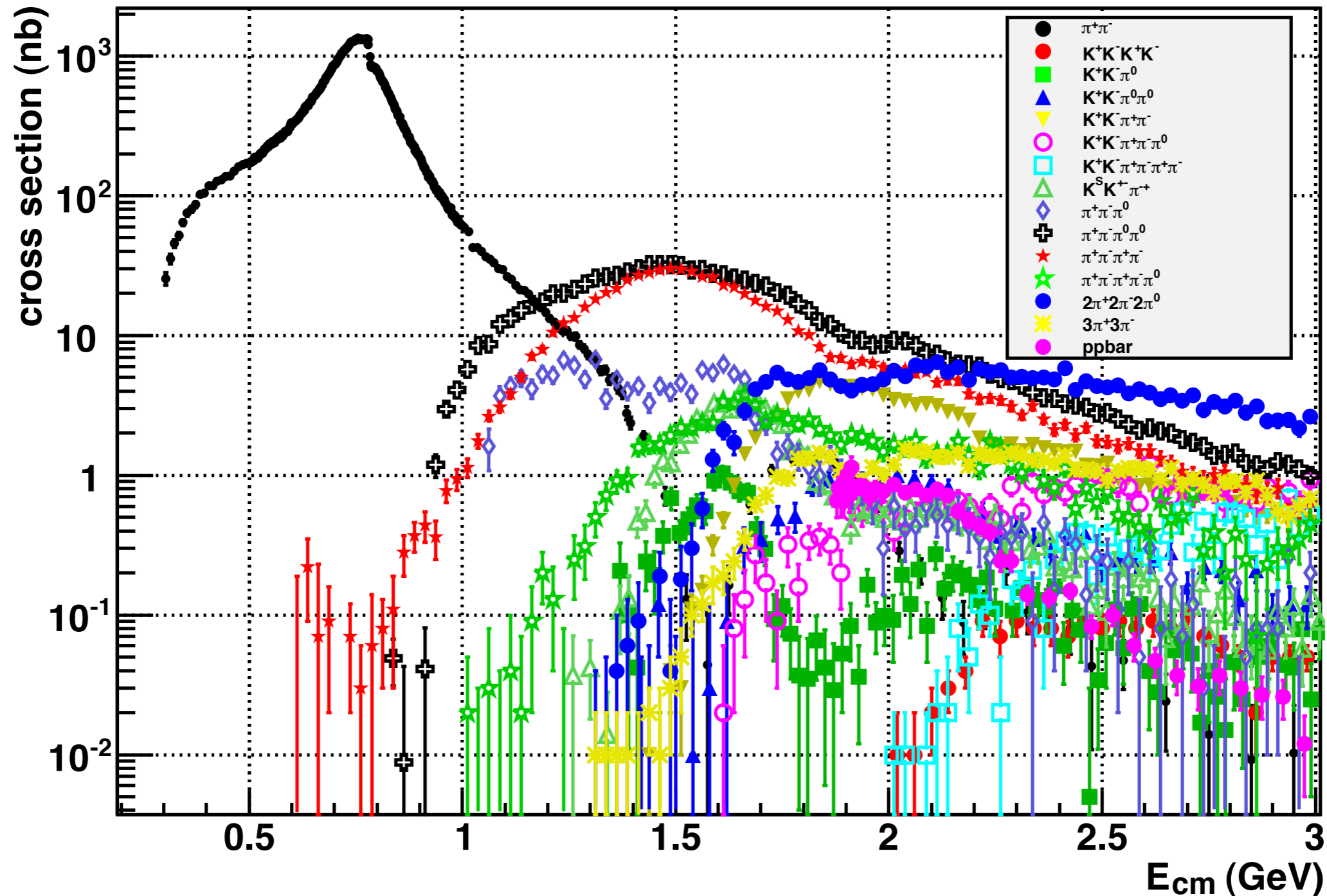|	
BaBar	0.5%
CMD-2	0.8%
SND	1.5%
KLOE	0.8%

→ scatter ~reasonable

→ measurements are hard!

→ similar comments at low E_{CM}, for 1-1.4 GeV

→ dominant (only) measurement above 1.4 (2.2) GeV

- **BaBar has also measured numerous other modes**

→ references in backup slides

→ typical systematic uncertainty ~1% / particle

→ need K^+K^-, K_SK_L, $K_SK_L\pi\pi$, $K_SK^+\pi^-\pi^0$, $\pi^+\pi^-3\pi^0$, $\pi^+\pi^-4\pi^0$

→ 1-2 GeV region is critical for g_μ-2, $\alpha(M_Z)$ calculations

The Anomalous Muon Magnetic Moment

- the theoretical calculation of $g_\mu - 2$ requires the integral

$$a_\mu^{had} = \frac{1}{4\pi^3} \int_{4m_{\pi^2}}^{\infty} K(s)\sigma_{had}(s)ds,$$

with $K(s) \sim 1/s$

- the $e^+e^- \rightarrow \pi^+\pi^-$ process dominates this integral
  - → our measurement is an important contribution

- next largest uncertainty is from the 1-2 GeV region
  - → many important contributions from BaBar here

- overall effect of BaBar measurements
  - → reduce error on global fits by ~20%
  - → move value slightly closer to the SM value

- currently, the theory and experimental values differ by $(28.7+8.0)\times 10^{-10}$, or 3.6σ

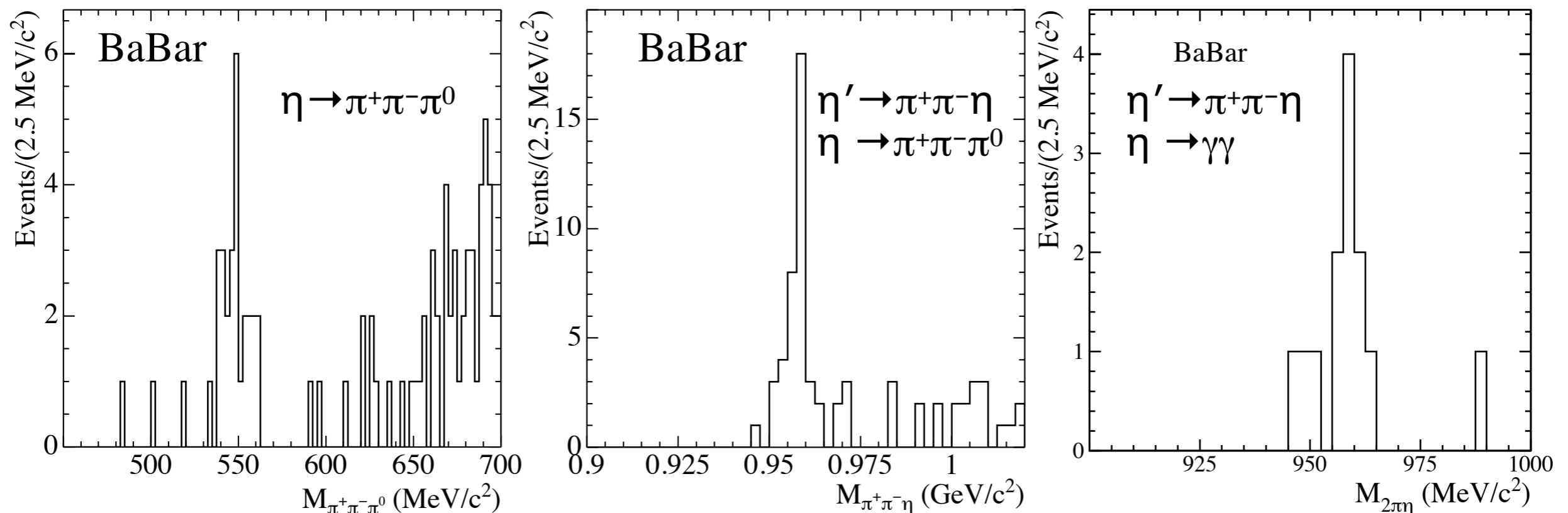M. Davier, et al., EPJC 71, 1515 (11)
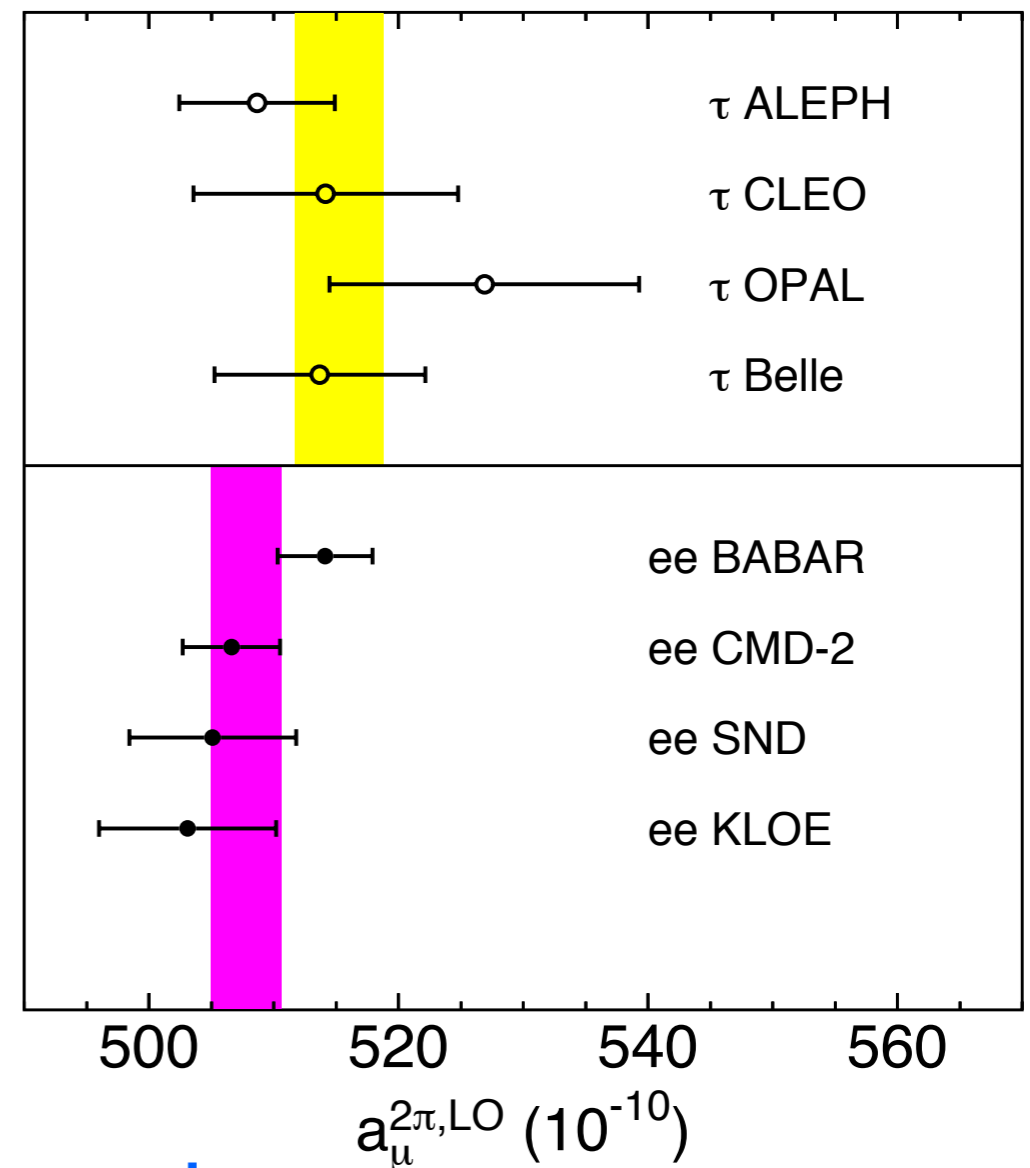
Timelike Transition Form Factors
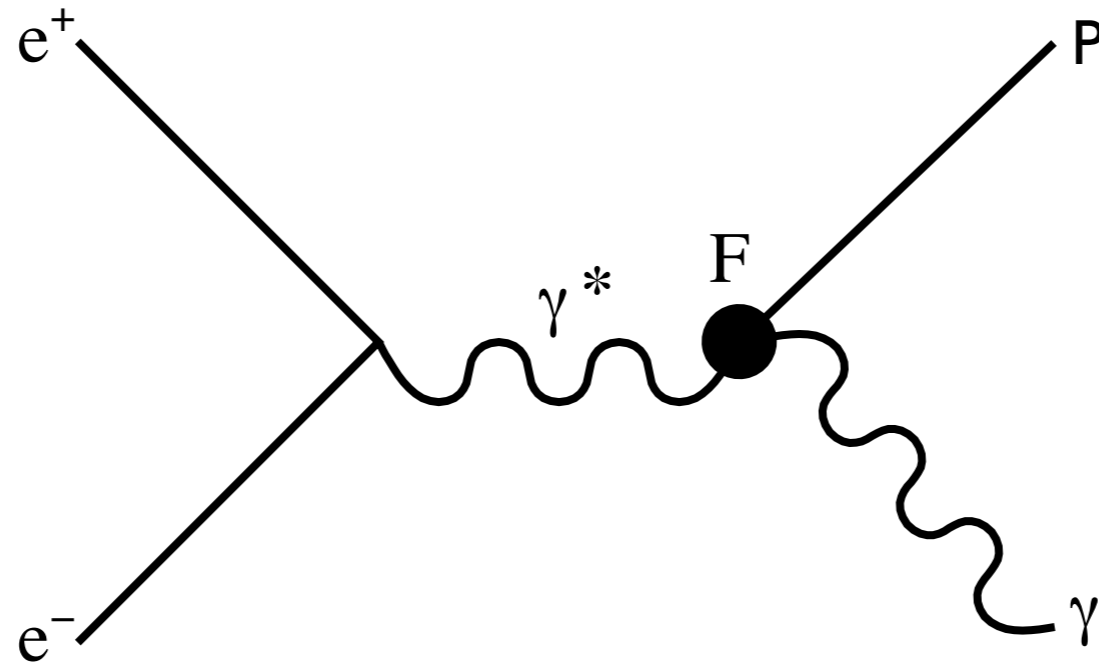
- $e^+e^- \to \gamma^* \to \gamma P$, where P is any pseudoscalar meson

- characterized by a transition form factor (TFF) $F(Q^2)$
  - ➜ Q^2 is the mass of the γ^*
  - ➜ timelike ↔ $Q^2 > 0$

- F can be related to the distribution amplitudes $\Phi(x, Q^2)$ of quarks in P carrying momentum fraction x
  - ➜ Q^2 dependence calculable from Φ ↔ model tests
  - ➜ asymptotic value of $Q^2 F(Q^2)$ can be related to the meson decay constant ↔ test of QCD
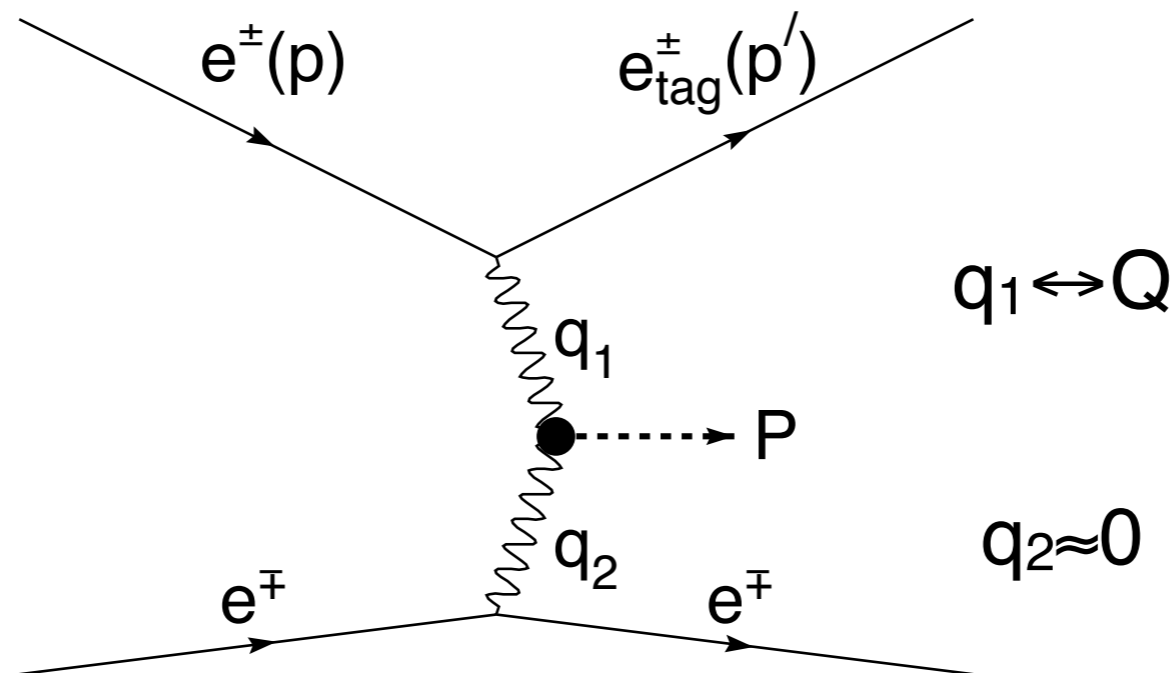
$e^+e^- \rightarrow \gamma\eta$ and $\gamma\eta'$

- **analysis very similar to ISR:**
  - → require: a hard γ; 2-4 charged tracks; 2 more γ
  - → reconstruct $\eta \rightarrow \pi^+\pi^-\pi^0$, $\pi^0 \rightarrow \gamma\gamma$;
    $\eta' \rightarrow \pi^+\pi^-\eta$, $\eta \rightarrow \pi^+\pi^-\pi^0$, $\gamma\gamma$
  - → select $\chi^2_{\eta^{(')}\gamma} < 30$, obtain clean signals

- **extract the cross sections**
  - → $\sigma(e^+e^- \rightarrow \eta\gamma) = 4.5 \pm 1.2 \pm 0.3$ fb
  - → $\sigma(e^+e^- \rightarrow \eta'\gamma) = 5.4 \pm 0.8 \pm 0.3$ fb

Spacelike Transition Form Factors

- $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-P$, P a pseudoscalar meson

- characterized by a TFF $F(q_1^2, q_2^2)$
  - ➜ q^2 is the mass of the γ^*

- consider the "single tag" case, where
  - ➜ q_1^2 is large, the e^+ or e^- is detected
  - ➜ q_2^2 is small, the e^- or e^+ is emitted along the beam and the second photon is quasi-real
  - ⇒ then $q_2^2 \approx 0$, and $F(q_1^2, q_2^2) \rightarrow F(-q_1^2) \equiv F(Q^2)$

$e^+e^- \to e^+e^-\pi^0, \eta/\eta', \eta_c$

- **analysis similar to ISR:**

  → require: a hard, ID'd $e^\pm$; 0-4 $\pi^\pm$; 0-1 $K^\pm$; 0-2 more γ

  → reconstruct $\pi^0 \to \gamma\gamma$; $\eta \to \pi^+\pi^-\pi^0$; $\eta' \to \pi^+\pi^-\eta$; $\eta_c \to K_S K\pi$

  → kinematic requirements yield clean signals
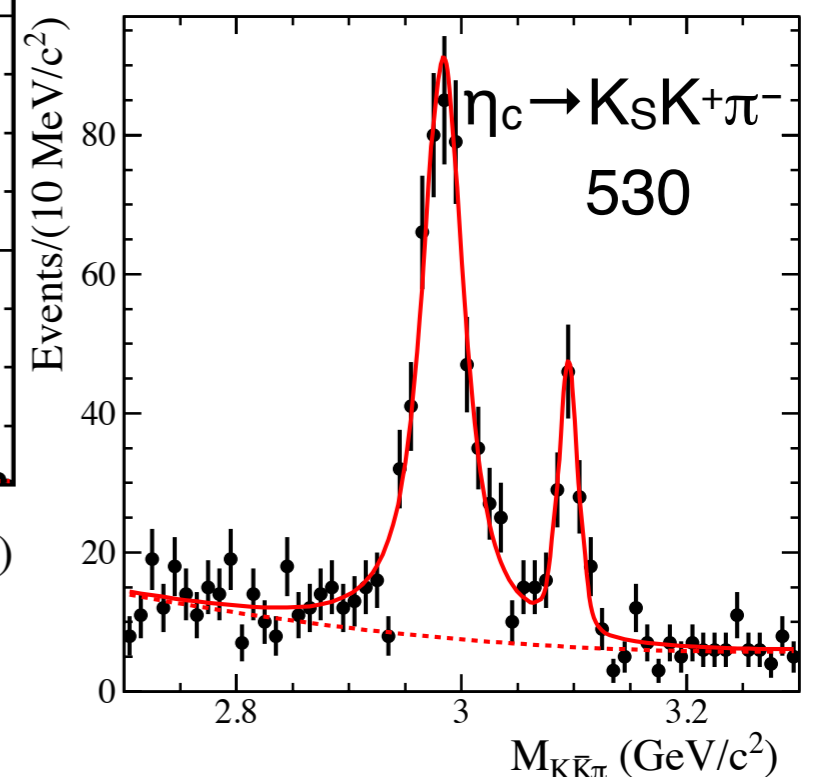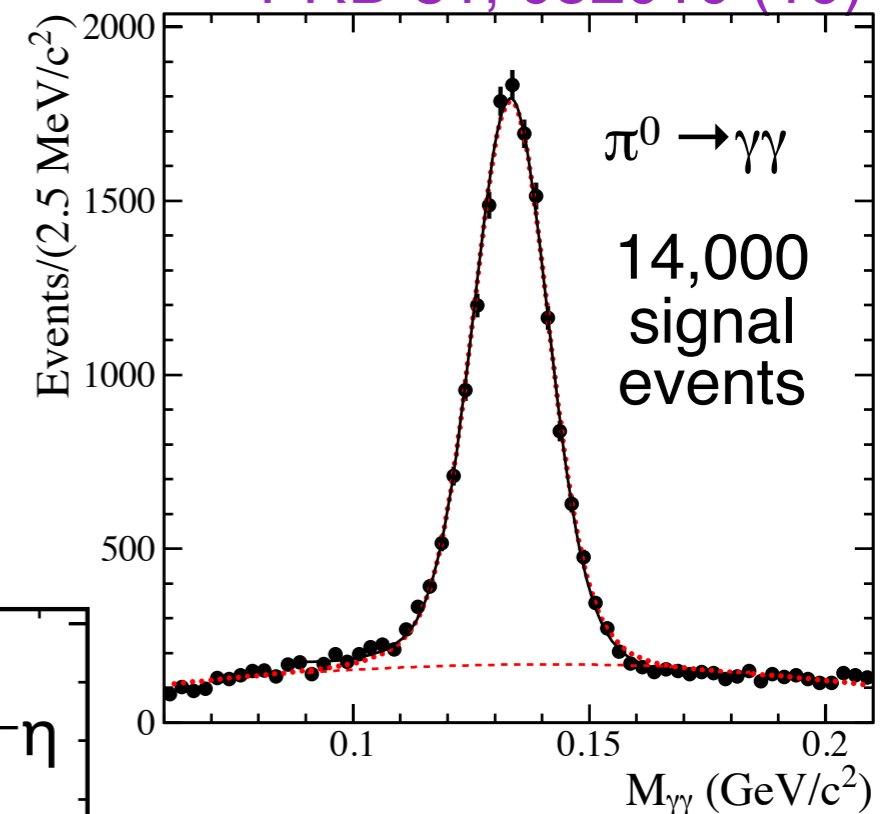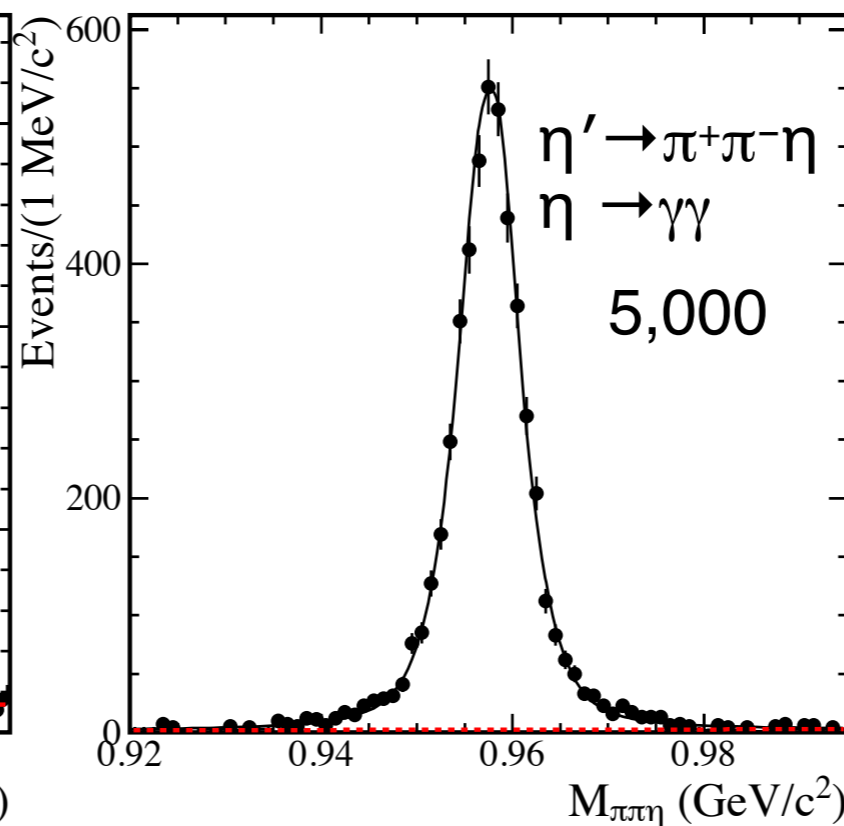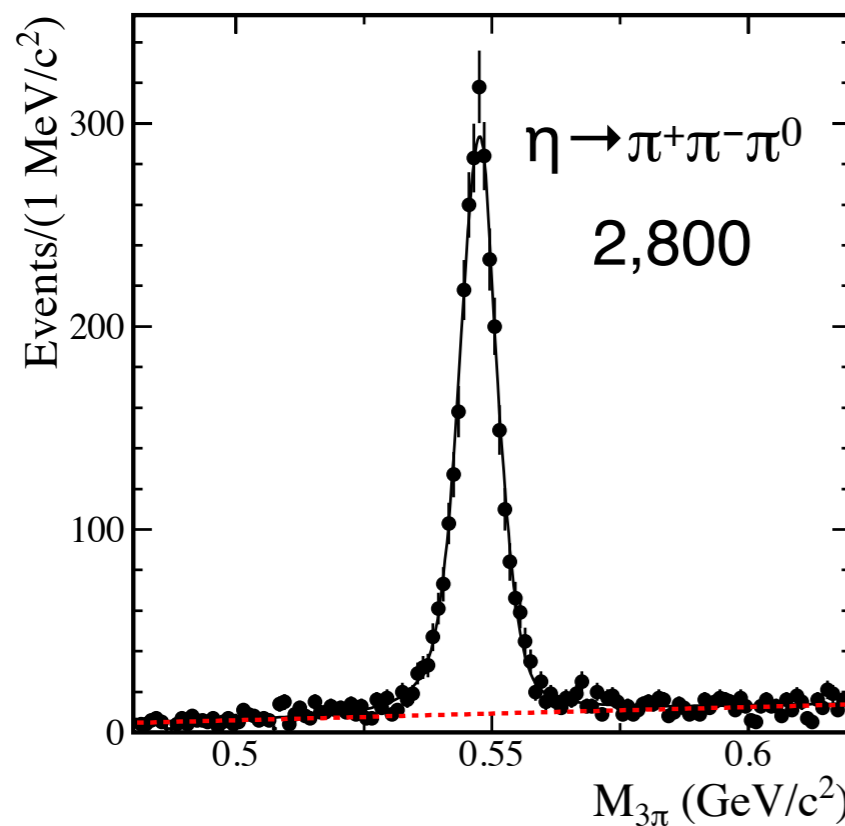
- **extract cross sections and TFFs as functions of Q^2**

$\pi^0 \to \gamma\gamma$

14,000 signal events

$\eta \to \pi^+\pi^-\pi^0$

2,800

$\eta' \to \pi^+\pi^-\eta$
$\eta \to \gamma\gamma$

5,000

$\eta_c \to K_S K^+\pi^-$

530

Results for the η_c

- measure untagged events also
  - → corresponds to F(0)
  - → also gives nice measurements of η_c mass, width
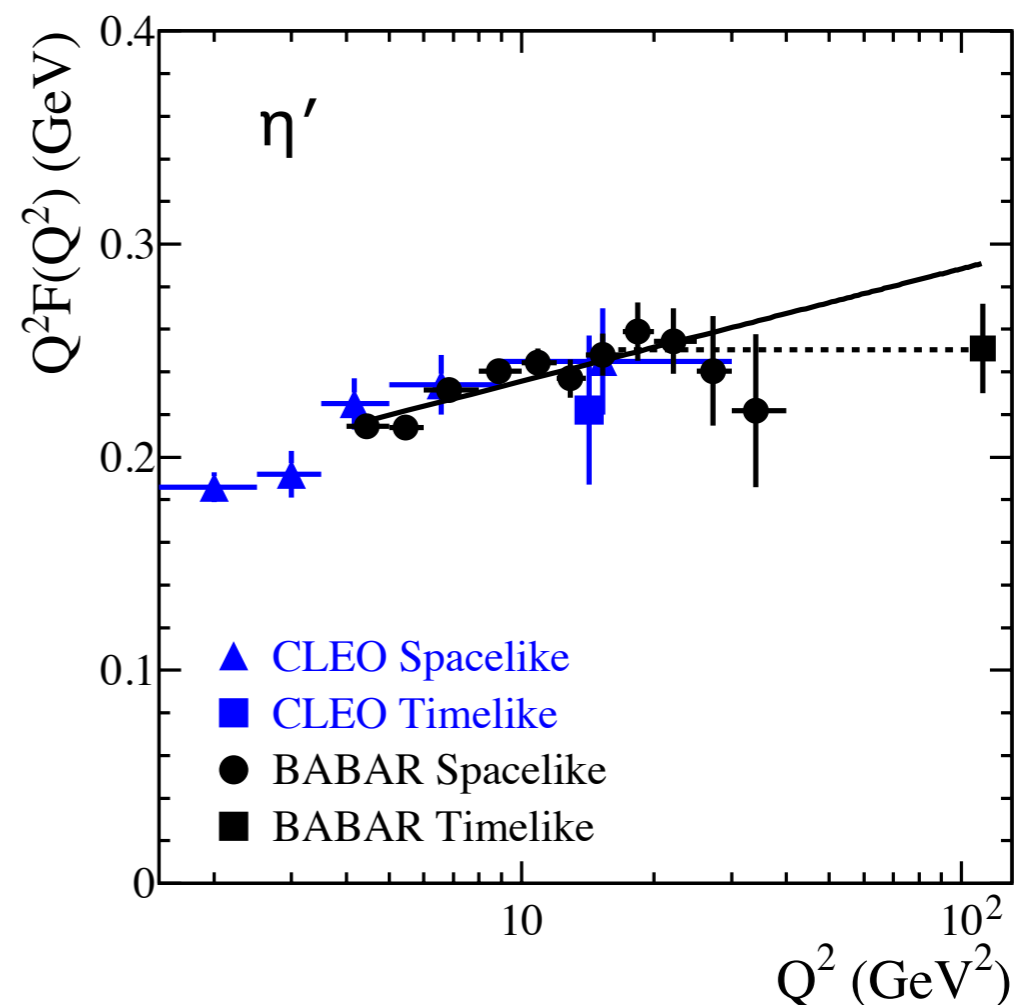
- normalize the η_c TFF to the value at $Q^2=0$
  - → slightly below the leading order QCD prediction
  - → described well by a monopole function,

    $F(Q^2)=F(0) / (1+Q^2/\Lambda)$, with

    $\Lambda = 8.5 \pm 0.6 \pm 0.7$ GeV^2/c^4
  - → vector dominance predicts

    $\Lambda = m^2_{J/\psi} = 9.6$ GeV^2/c^4

Plot axes: $|F(Q^2)/F(0)|$ versus Q^2 (GeV^2)

Legend:
- BaBar
- LO QCD
- Monopole fit

Results for η and η'
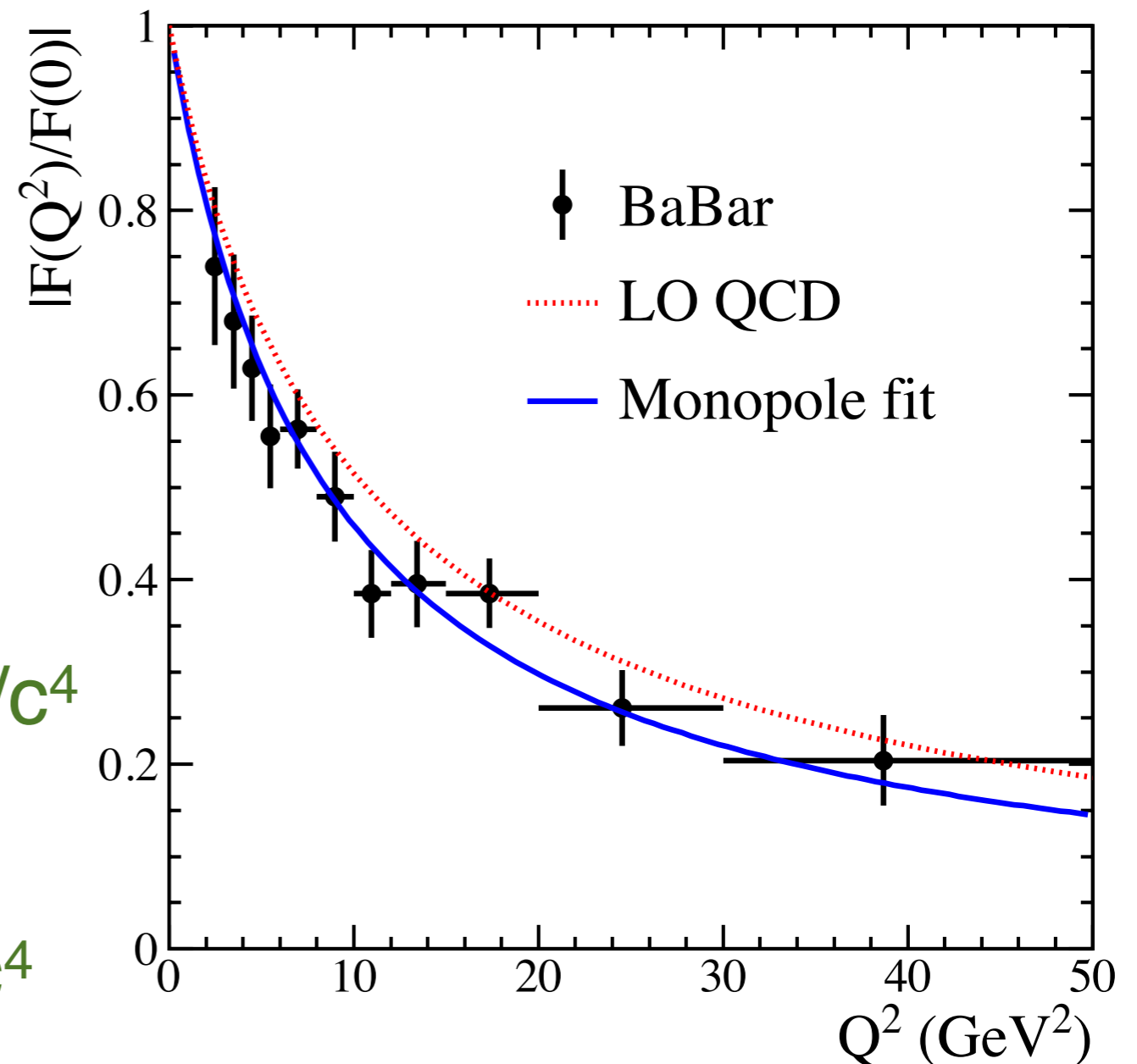
- the TFFs scaled by Q^2:
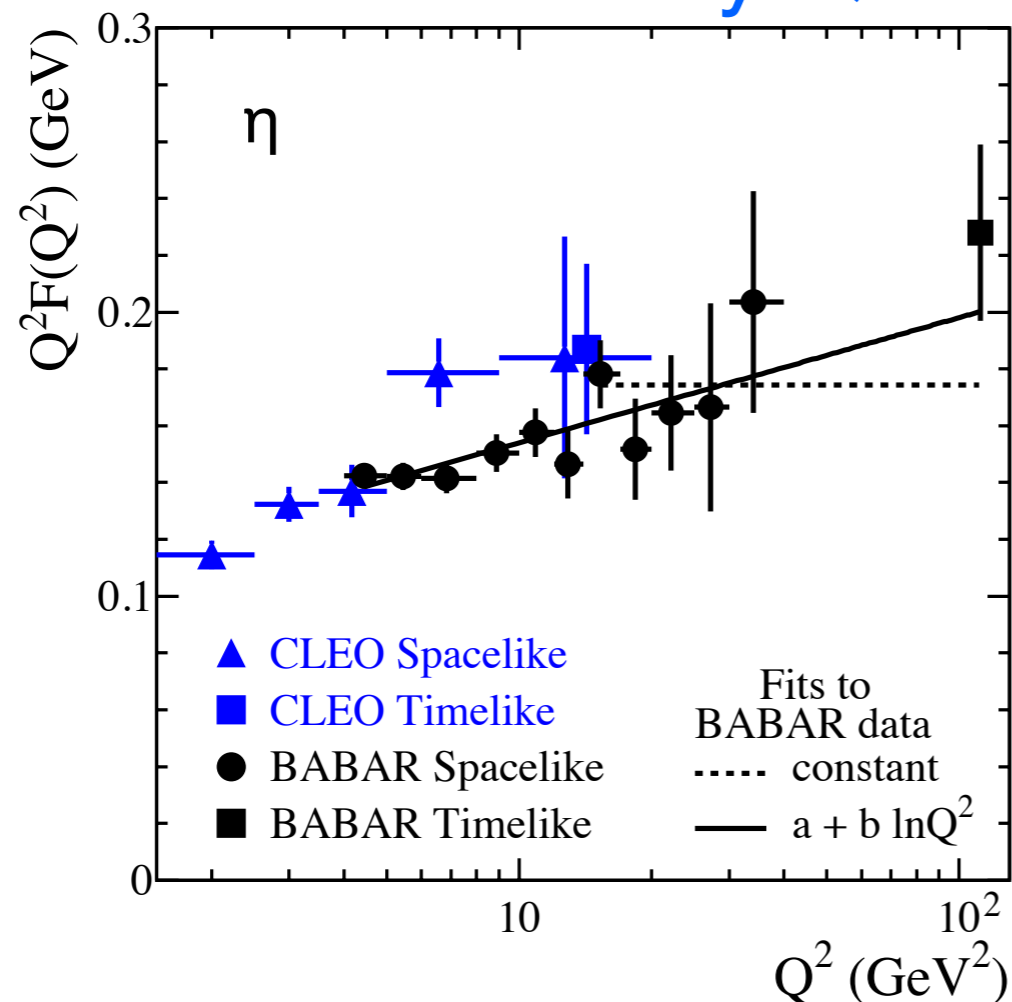
→ consistent with CLEO results

→ time- and spacelike points consistent

→ all consistent with ~logarithmic rise with Q^2 ...

→ toward an asymptotic value (- - - -)...

→ or a continued rise (———)....

- theoretical asymptotic values depend on η-η' mixing...

Results for π^0

- the scaled TFFs:
  - → consistent with CELLO and CLEO
  - → consistent with a rise over the full measured range
  - → exceed the predicted asymptotic value of $\sqrt{2}f_\pi = 0.185$ GeV for $Q^2 > 10$ GeV^2
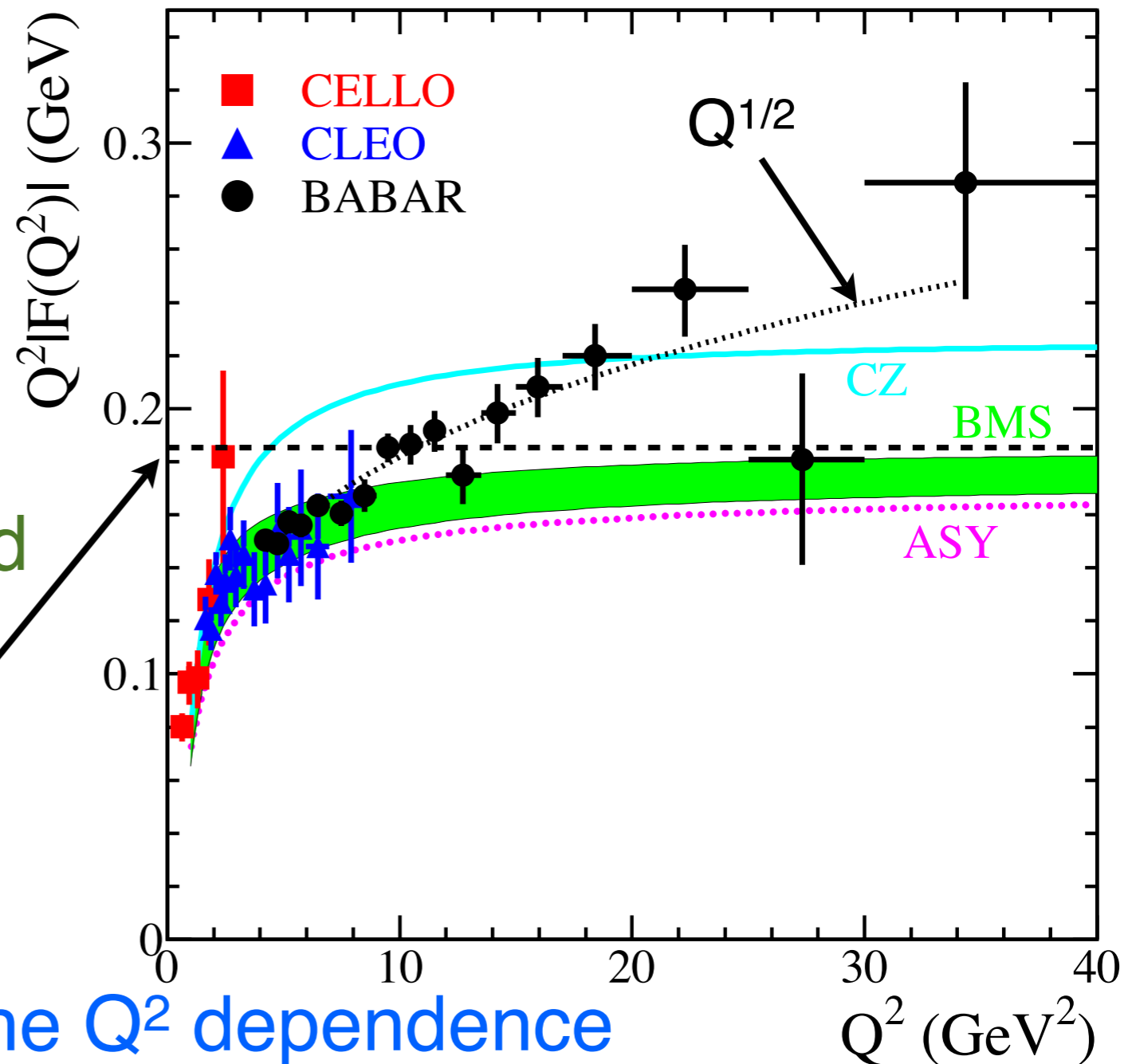
- theoretically predicted DAs did not describe the Q^2 dependence
  - → ASY = asymptotic
    CZ = Chernyak-Zhitnitsky
    BMS = Bakulev-Mikhailov-Stefanis
  - ⇒ need for higher order corrections?
  - ⇒ ...or new models for the distribution amplitudes?

e.g. Brodsky, Lepage, PLB 87, 359 (79)
NPB 201, 492 (82)
PLB 508, 279 (01)

- **since then, a flurry of theoretical activity:**
  - → **a few examples:**

Fit results: N=1.3±0.2, m=0.65±0.05GeV

M.V.Polyakov, JETPL 90, 228 (09)

H.N.Li & S.Mishima
PRD 80, 074024 (09)

- Asymptotic DA, LO
- Asymptotic DA, NLO
- Flat DA, LO
- Flat DA, NLO

Dorokhov, arXiv:1003.4693

- FFcello
- FFcleo
- FFbabar

$2f_\pi$
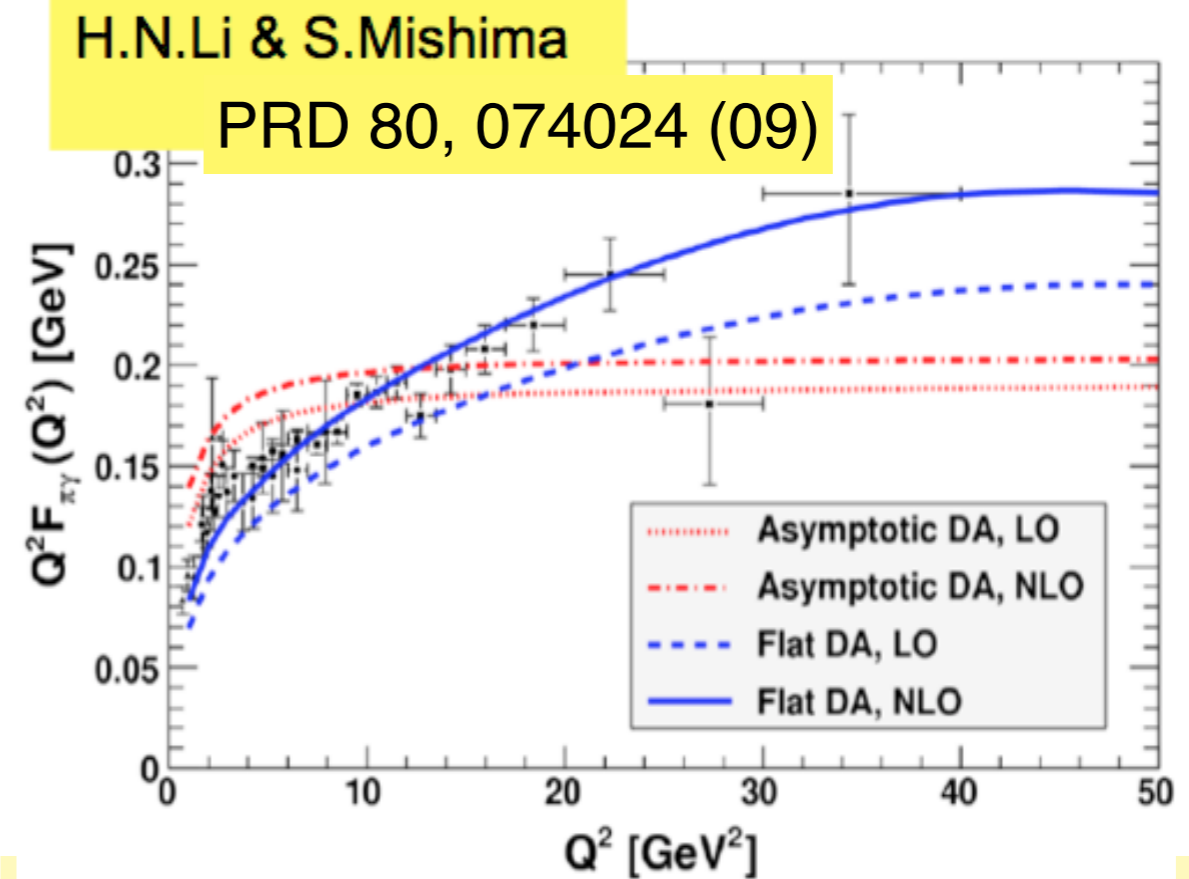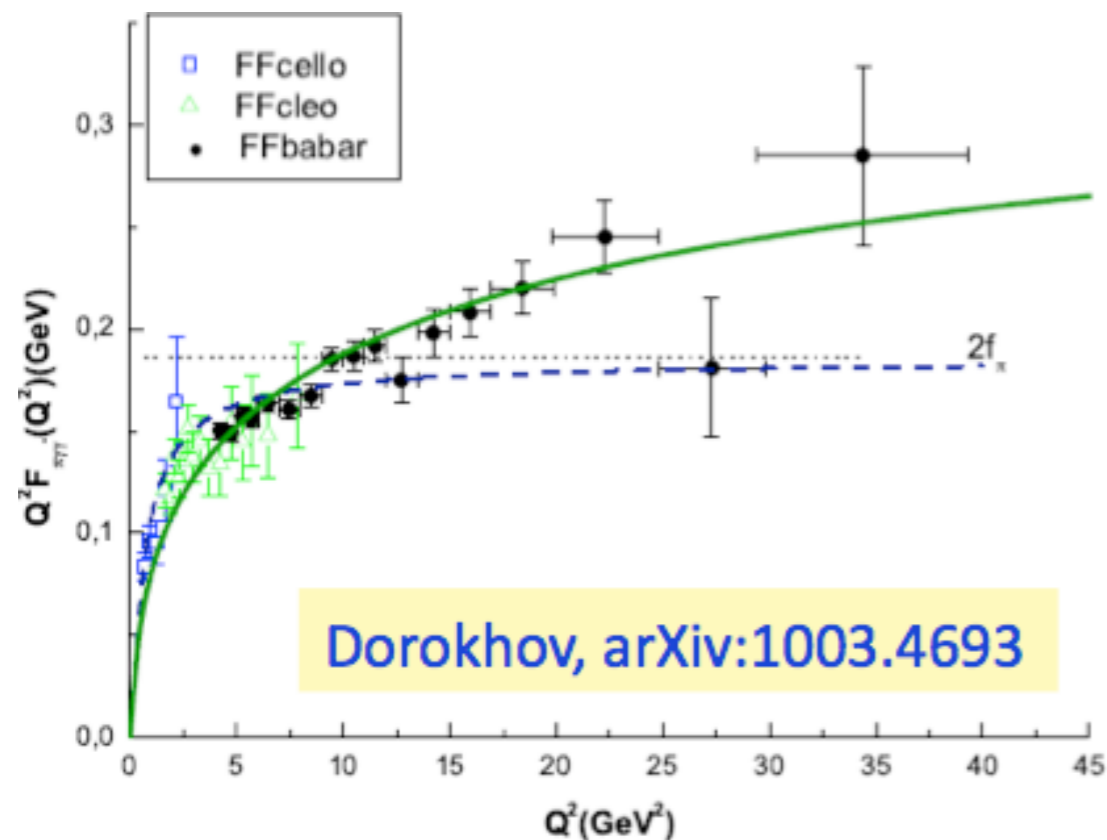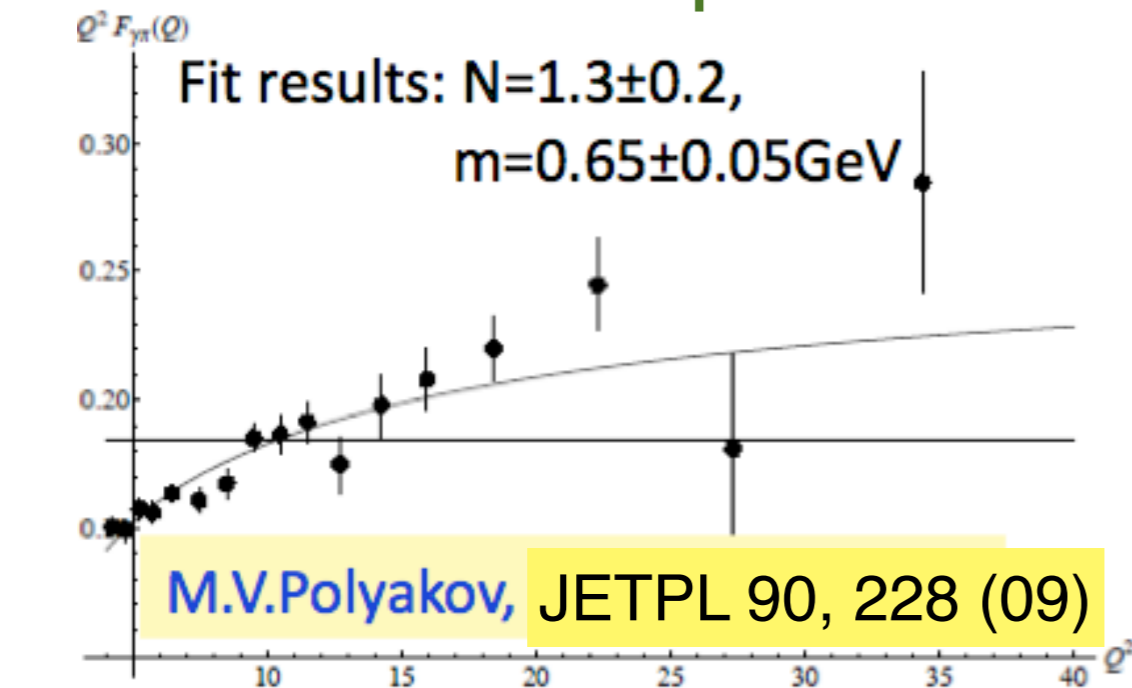
Agaev,Braun,Offen,Porkert, PRD 83, 054020 (11)

$Q^2 F_{\pi^0\gamma^*\gamma}(Q^2)$

Model I
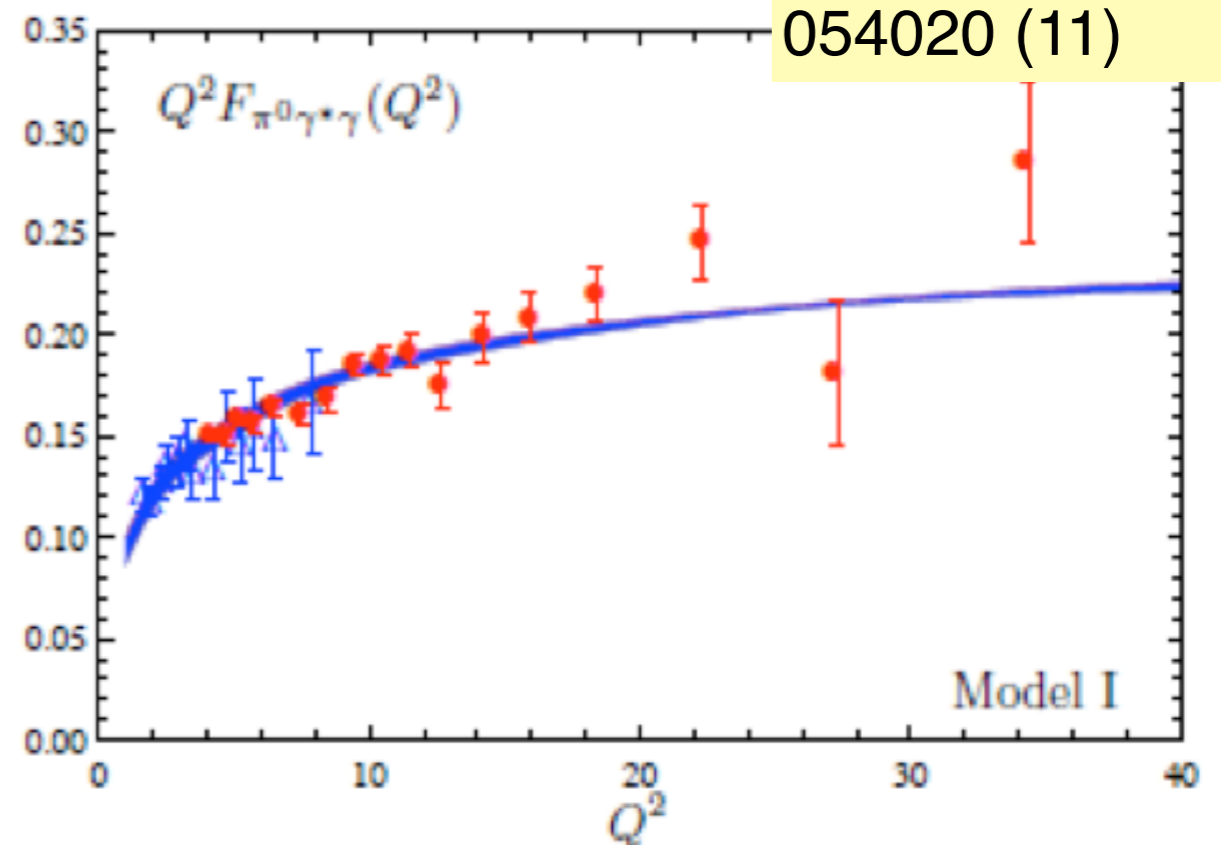
- **now need better, higher-Q^2 measurements**

- the η and η' have nonstrange and strange components:
  - $\rightarrow |n\rangle = (|u\bar{u}\rangle + |d\bar{d}\rangle) / \sqrt{2}$, $|s\rangle = |s\bar{s}\rangle$
  - $\rightarrow |\eta\rangle = \cos\phi|n\rangle + \sin\phi|s\rangle$, $|\eta'\rangle = \sin\phi|n\rangle + \cos\phi|s\rangle$

- expect $f_n \approx f_\pi$, $f_s \approx 1.34 f_\pi$, asymptotic TFF of $5\sqrt{2}f_n/3$, $2f_s/3$
  - $\rightarrow$ use $\phi = 41°$
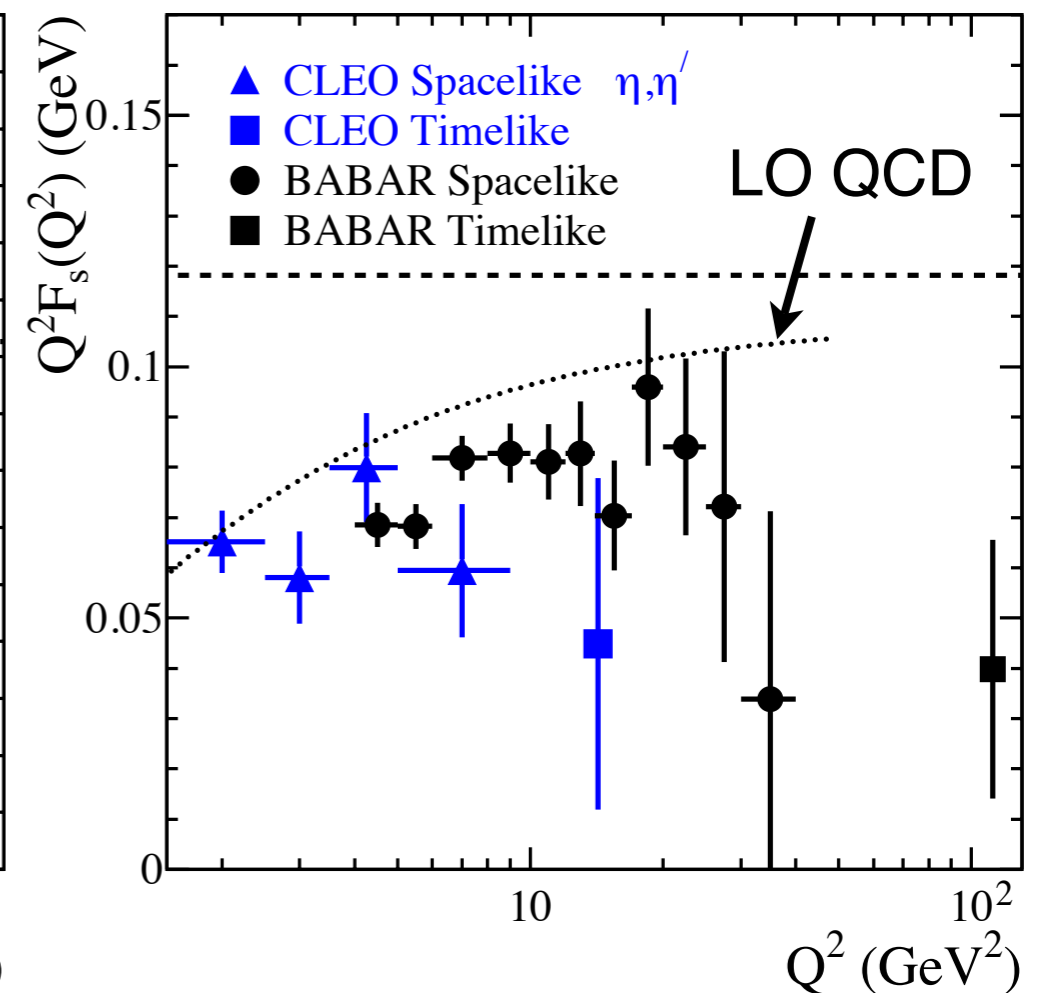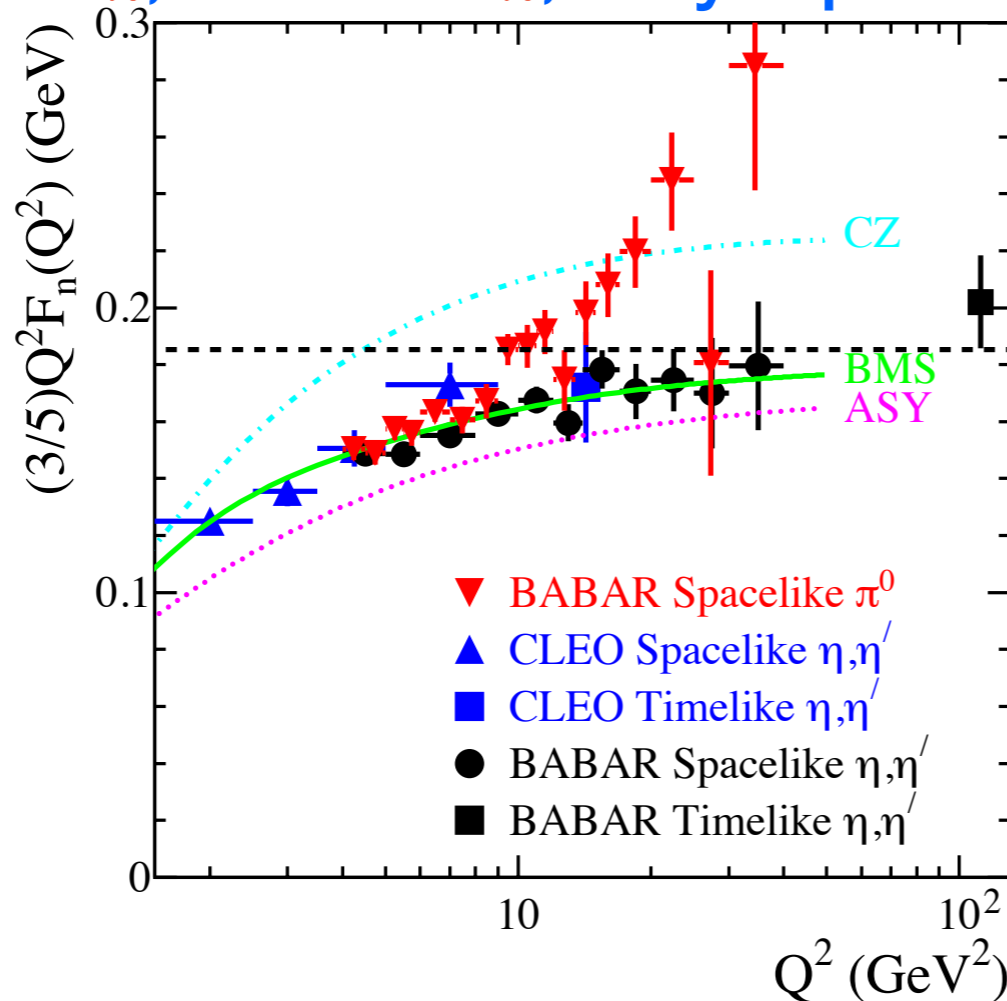
- $\rightarrow F_\pi$ inconsistent with F_n for $Q^2 > 10$ GeV^2
- $\rightarrow$ BSM describes F_n well; CZ, ASY describe Q^2 dep.
- $\rightarrow F_s$ lies below the QCD prediction
- $\rightarrow$ ...though F_s depends strongly on ϕ, ...

Summary

- BaBar has made huge contributions to hadron physics via initial state radiation
  - → e^+e^- annihilations at low energy
  - → meson and baryon form factors
  - → discovery of new states and spectroscopy of others
  - → improved understanding of R, $g_\mu - 2$, $\alpha(M_Z)$

- BaBar has made new/improved measurements of meson transition form factors
  - → η, η' at 10.6 GeV via $e^+e^- \to \gamma\eta, \gamma\eta'$
  - → $\pi^0, \eta, \eta', \eta_c$ via two photon collisions

- much more could be done!
  - → more measurements expected from BaBar, Belle
  - → limited by people, statistics
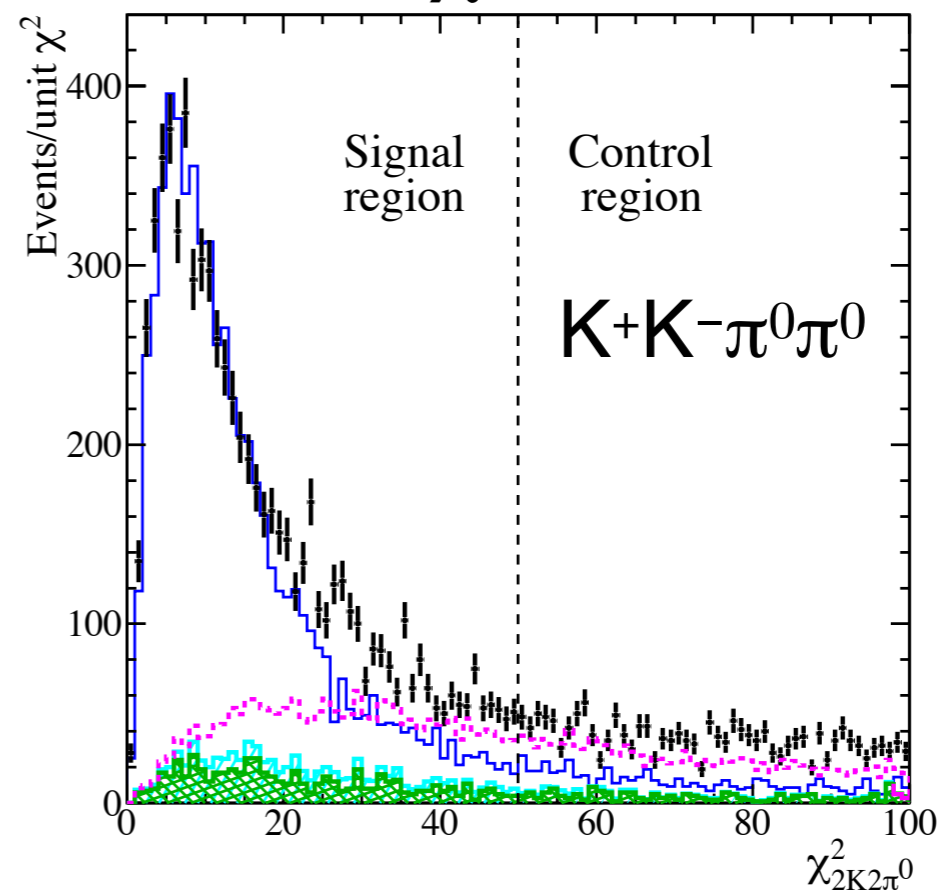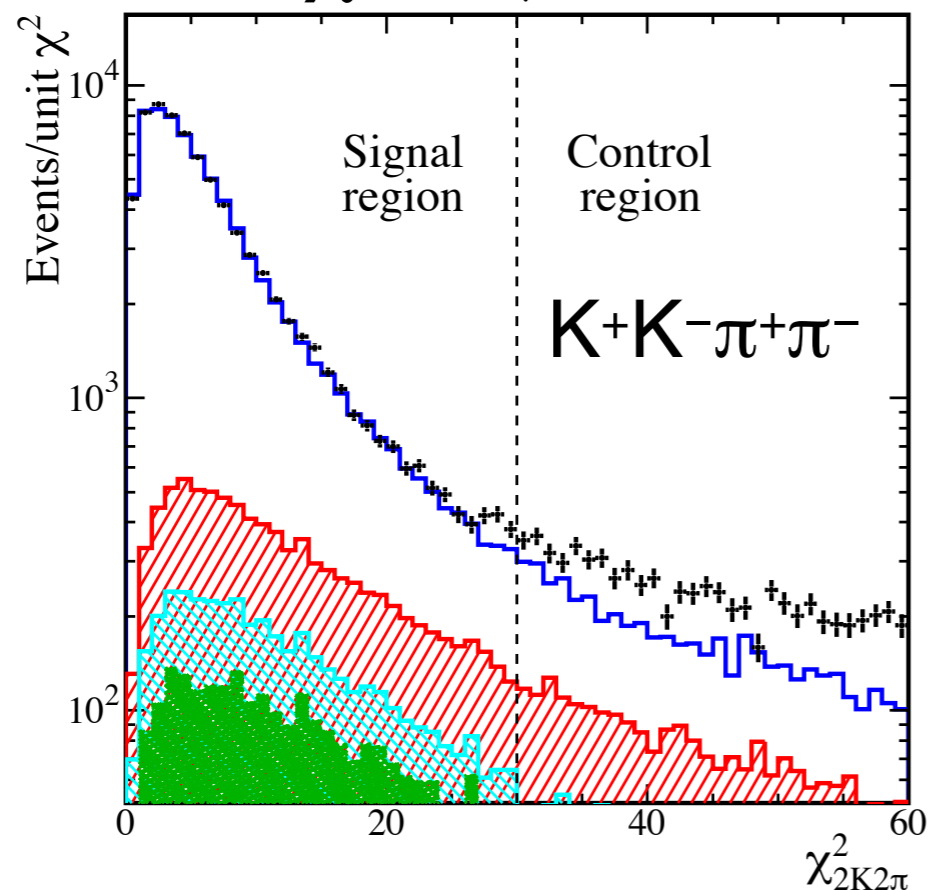 - → even better at a super B factory

Backup Slides

The $K^+K^-\pi^+\pi^-$ and $K^+K^-\pi^0\pi^0$ Final States

- event selection:

  → require: a hard γ; ID'd K^+ and K^-; ID'd π^+, π^- or 2 π^0

  → perform kinematic fits to various hypotheses

  → select $\chi^2_{KK\pi\pi\gamma}$ <30 or 50, use other χ^2 values

- measure backgrounds from the data and subtract

  → $e^+e^- \rightarrow q\bar{q} \rightarrow \underline{\pi^0 KK\pi\pi(n\pi^0)}$: form π^0 from γ_{ISR} + other γ

  → $e^+e^- \rightarrow \underline{\gamma_{ISR}K_SK\pi}$, $\underline{\gamma_{ISR}4\pi}$, $\underline{\gamma_{ISR}KK\pi^0/\eta/3\pi^0}$: prev. msmts.

  → others: from χ^2 control regions

The $\pi^+\pi^-$ Final State

- **extremely detailed analysis,** 232 fb^{-1}, PRL 103, 231801 (09)
  aim for sub-% precision; event selection:
  → require: a hard γ; ID'd π^+ and π^- (or $\mu^+\mu^-$ or K$^+$K$^-$)
  → kinematic fits, including with additional ISR or FSR γ
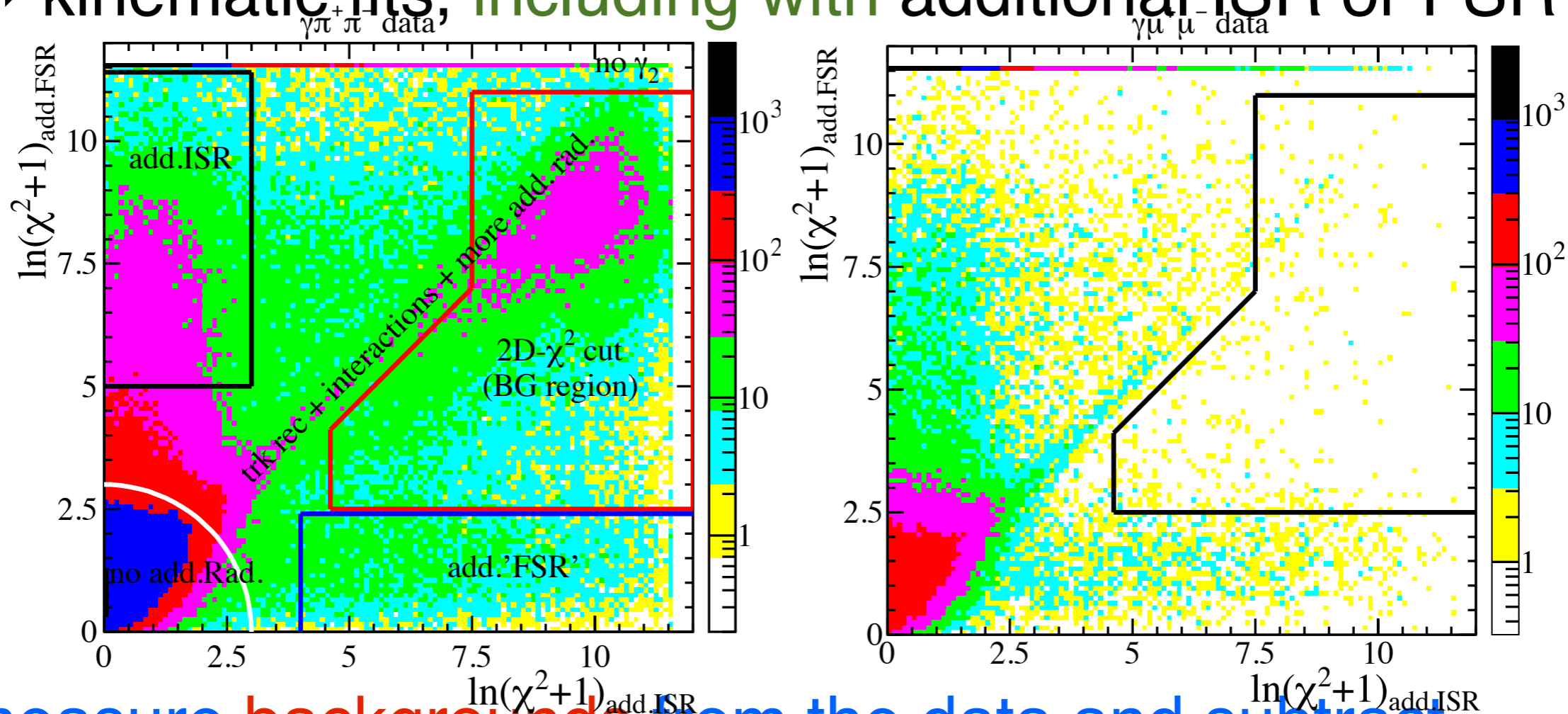
- **measure backgrounds from the data and subtract**
  → e$^+$e$^-$→qq→$\pi^0\pi^+\pi^-$, $\pi^0\mu^+\mu^-$, π^0K$^+$K$^-$: comb γ_{ISR}, other γ
  → e$^+$e$^-$→$\gamma_{ISR}\mu^+\mu^-$, γ_{ISR}K$^+$K$^-$: measured simultaneously,
  taking all cross feed into account

$\gamma\gamma^* \rightarrow \pi^0$ TFF: comparison with theory

$$Q^2 F(Q^2) = \frac{\sqrt{2} f_\pi}{3} \int_0^1 \frac{dx}{x} \varphi_\pi(x, Q^2) + O(\alpha_s) + O(\Lambda^2_{QCD}/Q^2)$$

Brodsky, Lepage PLB 87, 359 (1979)
Efremov, Radyushkin, PLB 94, 245 (1980)

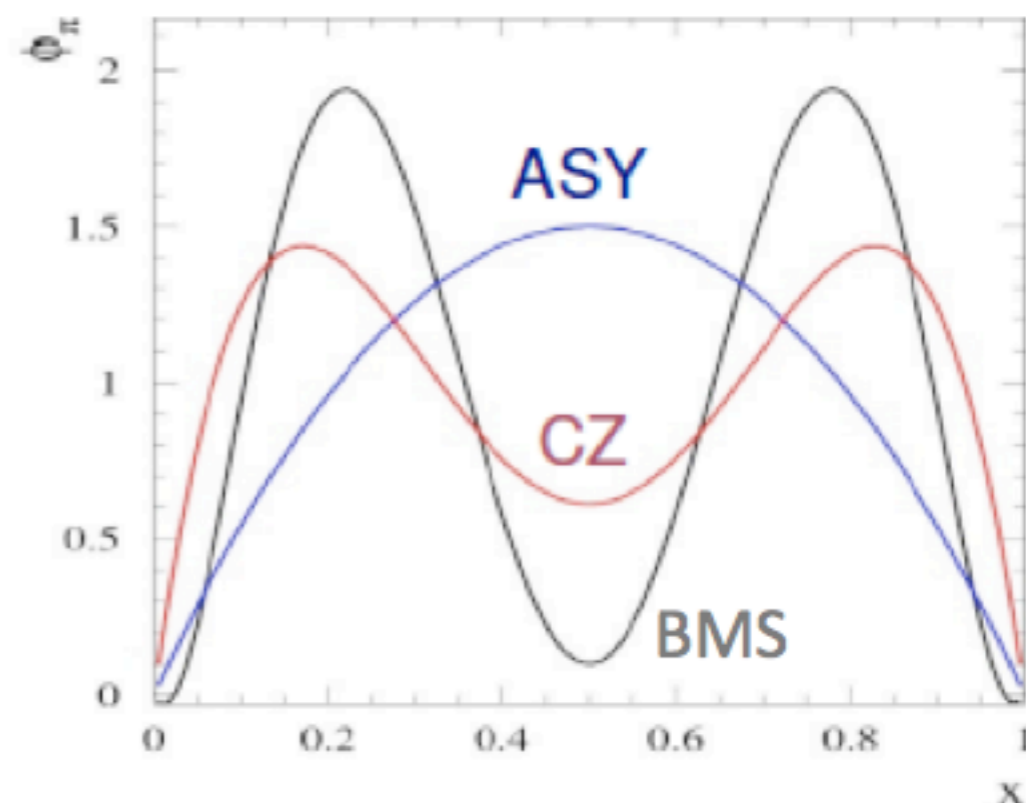Expansion of the DA in series of Gegenbauer polynomials:

$$\varphi(x, Q^2) = \varphi_{ASY} \left[1 + \sum_{n \geq 1} a_{2n}(Q^2) C_{2n}^{3/2}(2x-1) \right]$$

$\phi_{ASY} = 6x(1-x)$ is the asymptotic form of the pion DA

Tow of the most commonly used DA shapes:

CZ DA: V.L.Chernyak and A.R.Zhitnitsky,
Nucl.Phys. B201, 492 (1982).
BMS DA: A.P.Bakulev, S.V.Mikhailov and
N.G.Stefanis, Phys.Lett. B508, 279 (2001).

BaBar cross sections with ISR

$e^+e^- \rightarrow$:

$\pi^+\pi^-$	threshold-3.0 GeV	PRL 103, 231801 (2009)
$\pi^+\pi^-\pi^0$	1.05-3.0 GeV	PRD 70, 072004 (2004)
$\pi^+\pi^-\pi^0\pi^0$	threshold-4.5 GeV	Preliminary
$\pi^+\pi^-\pi^+\pi^-$	threshold-4.5 GeV	PRD 71, 052001 (2005)
$\pi^+\pi^-\pi^+\pi^-\pi^0/\eta$	threshold-4.5 GeV	PRD 76, 092005 (2007)
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$		
$K^+K^-\pi^+\pi^-\pi^+\pi^-$	threshold-4.5 GeV	PRD 73, 052003 (2006)
$K^+K^-\pi^0$, $K^+K_S\pi^-$,		
$K^+K^-\eta$	threshold-2.6 GeV	PRD 77, 092002 (2008)
$K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$,		
$K^+K^-K^+K^-$	threshold-4.5 GeV	submitted to PRD
$K^+K^-\pi^+\pi^-\pi^0/\eta$,	threshold-4.5 GeV	PRD 76, 092005 (2007)
pp	threshold-4.5 GeV	PRD 73, 012005 (2006)
$\Lambda^0\Lambda^0$, $\Lambda^0\Sigma^0$, $\Sigma^0\Sigma^0$	threshold-3.0 GeV	PRD 76, 092006 (2007)