Low-energy exclusive $e^+e^- \rightarrow$ hadrons cross sections and inclusive production of charged particles with Babar

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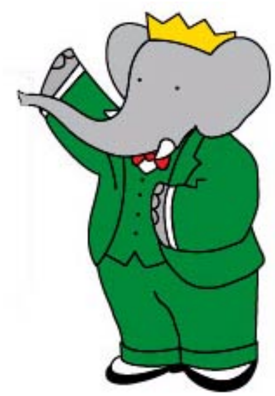
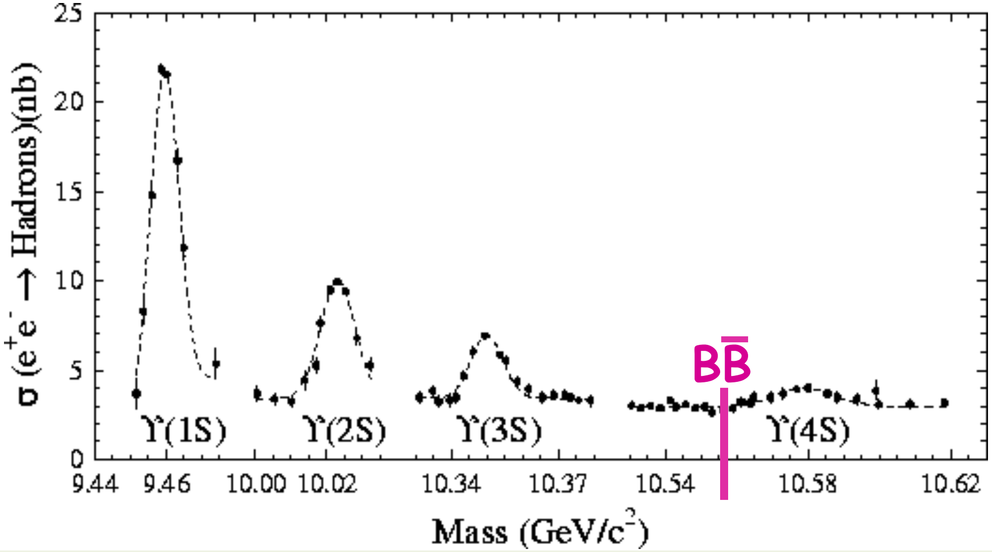


Babar experiment

- PEP-II rings: asymmetric e^+e^- collider @ SLAC
- Collected data 1999-2008; data analysis still very active (~30 pubs. In 2013)

Υ(4S)	430 fb^{-1}
Υ(3S)	30 fb^{-1}
Υ(2S)	14 fb^{-1}
Other (mostly off-resonant)	~60 fb^{-1}



- CPV in B decays, CKM physics ~465 x 10^6 $\Upsilon(4S) \rightarrow B\bar{B}$ events
- ~650 x 10^6 $e^+e^- \rightarrow c\bar{c}$ events: D^0-$\bar{D}^0$ mixing, charmonium states
- ~430 x 10^6 $e^+e^- \rightarrow \tau^+\tau^-$ events: lepton flavor violation
- Initial-state γ radiation (ISR) events: access to low-energy e^+e^- cross sections
- Other QCD topics: hadron form factors, light-hadron spectroscopy, inclusive particle production

Recent "QCD" Topics from Babar

(I) $e^+e^- \to K^+K^-(\gamma)$ cross section (ISR)
[PRD 88, 032013 (2013)]

(II) $e^+e^- \to p\bar{p}$ cross section (ISR, tagged γ)
[PRD 87, 092005 (2013)]

(III) $e^+e^- \to p\bar{p}$ cross section (ISR, untagged γ)
[arXiv:1308.1795, submitted to PRD; preliminary]

(IV) $e^+e^- \to K_SK_L(\pi^+\pi^-)$, $K_SK_s\pi^+\pi^-$, $K_SK_sK^+K^-$ cross sections (ISR)
[preliminary]

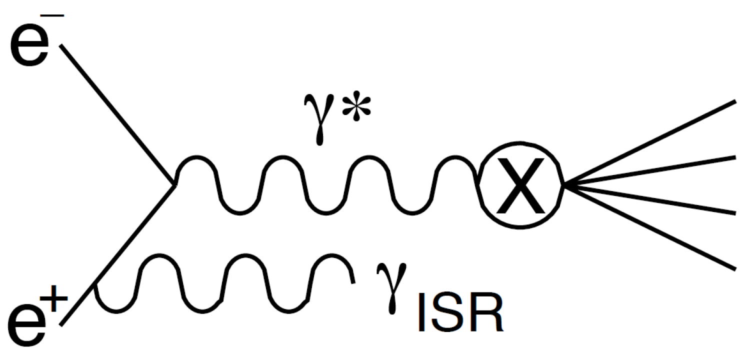
(V) Inclusive charged π, K, and p production at 10.54 GeV
[PRD 88, 032011 (2013)]

$e^+e^- \rightarrow K^+K^-(\gamma)$ cross section

[PRD 88, 032013 (2013)]

Babar: broad ISR program for a precise low-energy measurement of

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



$\pi^+\pi^-$
$\pi^+\pi^-\pi^0$
$\Phi\ f^0(980)$
$p\,\bar{p}$
$\Lambda\,\Lambda,\ \Lambda\,\Sigma^0,\ \Sigma^0\,\Sigma^0$
$2(\pi^+\pi^-),\ K^+K^-\pi^+\pi^-,\ K^+K^-2\pi^0,\ 2(K^+K^-)$
$K^0_S\,K^{+-}\pi^{-+},\ K^+K^-\pi^0,\ K^+K^-\eta$
$2(\pi^+\pi^-)\,\pi^0,\ 2(\pi^+\pi^-)\,\eta,\ K^+K^-\pi^+\pi^-\pi^0,\ K^+K^-\pi^+\pi^-\eta$
$3(\pi^+\pi^-),\ 2(\pi^+\pi^-\pi^0),\ 2(\pi^+\pi^-)\,K^+K^-$

Previously published Babar ISR channels

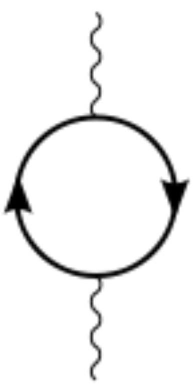
→ Now adding K^+K^-, K_SK_L, $K_SK_{S/L}\pi^+\pi^-$, $K_SK_SK^+K^-$ channels and updating $p\bar{p}$

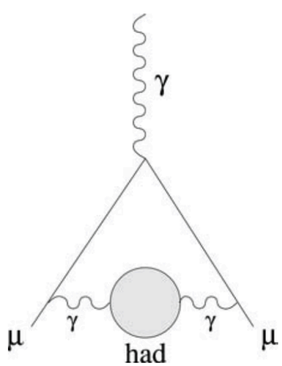
- Measure $\sigma\,(e^+e^- \rightarrow X)$ versus $m_{\gamma^*} = m_X = E_{CM} = \sqrt{s'}$
- Babar covers the complete set of significant exclusive channels
- Sum of exclusive channels more precise than an "inclusive" γ_{ISR}+hadrons measurement due to worse energy resolution for photons

$e^+e^- \to K^+K^-(\gamma)$ cross section

$R = \sigma(e^+e^- \to \text{hadrons}) / \sigma(e^+e^- \to \mu^+\mu^-)$ at low E_{CM}:

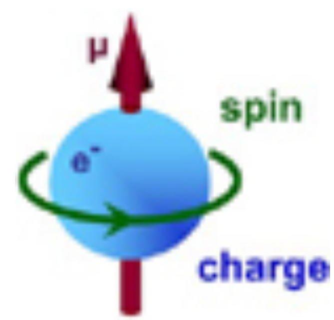
- Needed for calculation of hadronic corrections to vacuum polarization
- Uncertainties due to vacuum polarization a limiting factor in precise comparison between data and theory for muon magnetic anomaly a_μ





$$\vec{\mu}_\mu = \frac{-g_\mu e}{2m_\mu c}\vec{S} \qquad a_\mu = \frac{g_\mu - 2}{2}$$

$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm had}.$$



a_μ^{had} can't be calculated perturbatively:

→ Use measured low-E_{CM} $e^+e^- \to$ hadrons cross section & dispersion relations to calculate VP contribution to a_μ^{had}

$e^+e^- \rightarrow K^+K^-(\gamma)$ cross section

$$\frac{dN_{K^+K^-(\gamma)\gamma_{\rm ISR}}}{d\sqrt{s'}} = \frac{dL^{\rm eff}_{\rm ISR}}{d\sqrt{s'}}\ \varepsilon_{KK\gamma}(\sqrt{s'})\ \sigma^0_{KK(\gamma)}(\sqrt{s'})$$

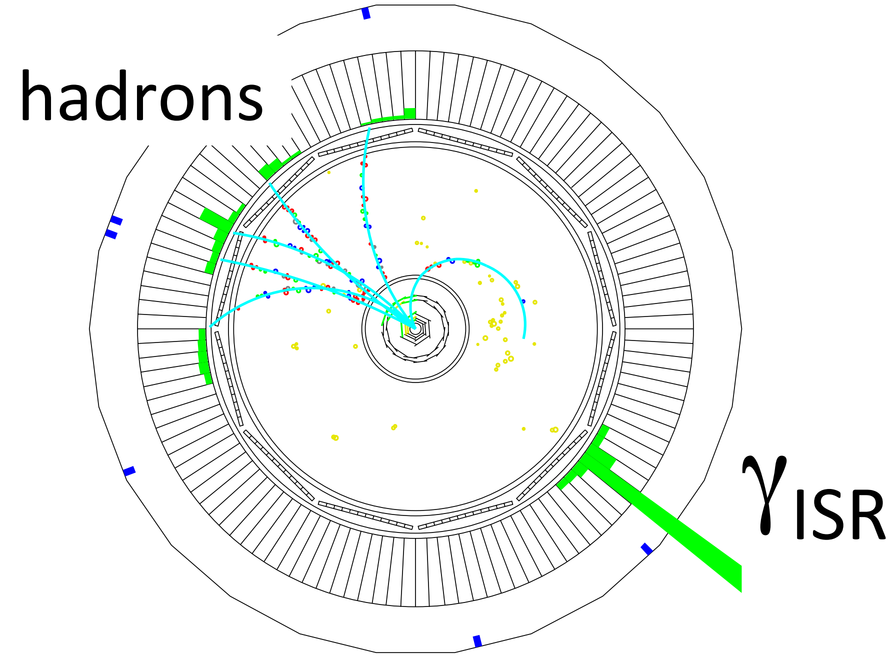
- Measured $K^+K^-(\gamma)$ event rate
- Measured from $\mu^+\mu^-(\gamma)$ event rate
- MC-based, data-corrected efficiency
- The result

- Higher-order radiation $K^+K^-\gamma$ events included so that the efficiency can be controlled to the 10^{-3} level
- Luminosity determined from $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ events in the same sample
  → reduced systematic uncertainties (no reliance on theoretical radiator function, which introduces uncertainties due to missing higher orders); no reliance on absolute luminosity measurement

$e^+e^- \rightarrow K^+K^-(\gamma)$ cross section

Data sample: 232 fb^{-1} at 10.54 GeV

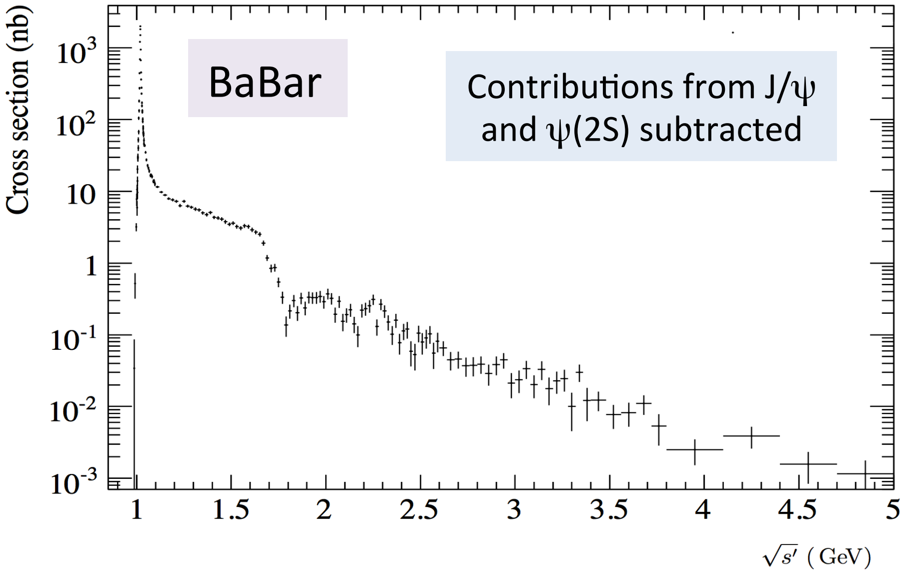
- 2 tracks, opposite charge, p > 1 GeV, identified as kaons (dE/dx and DIRC)
- ≥ 1 photon with E* > 3 GeV (* = CM frame)
- ISR photon = γ with highest E*

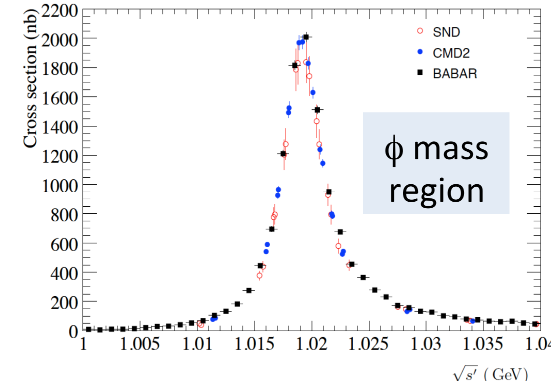


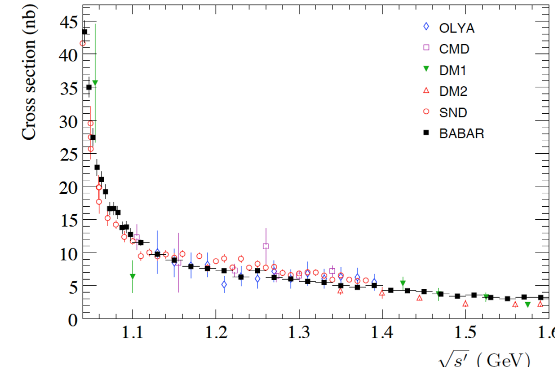
[event display courtesy of Dave Muller]

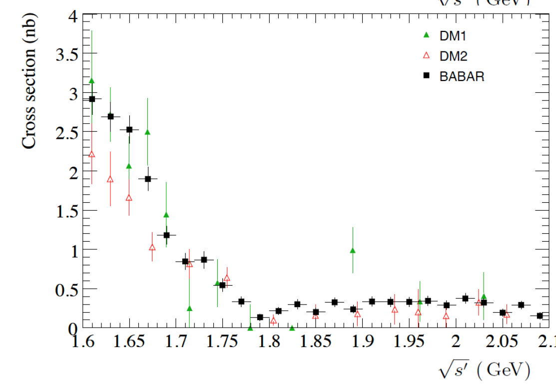
- γ_{ISR} must lie within 0.3 radians of p_{miss} vector formed from all other particles → strong background suppression against non-ISR events
- Background ($\pi^+\pi^-\gamma$, $\mu^+\mu^-\gamma$, $K^+K^-\pi^0\gamma$, etc.) < 20% in all $\sqrt{s'}$ regions (usually much less) is subtracted
- Cross section unfolded for detector resolution

$e^+e^- \to K^+K^-(\gamma)$ cross section









Babar results

- cover large energy range
- six orders of magnitude
- more precise than previous results

[DM1-2 = Orsay ; SND, CMD, OLYA

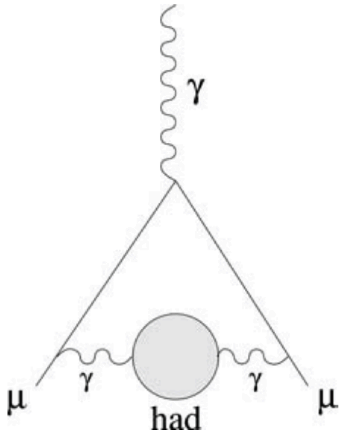
= Novosibirsk low fixed-energy energy e^+e^-]

$e^+e^- \to K^+K^-(\gamma)$ cross section

Impact on contribution to muon anomaly from K^+K^-:

$$a_\mu^{KK,LO} = [22.93 \pm 0.18_{stat} \pm 0.22_{syst} \pm 0.03_{VP(\phi\ params.)}] \times 10^{-10}$$

(1.2% precision)

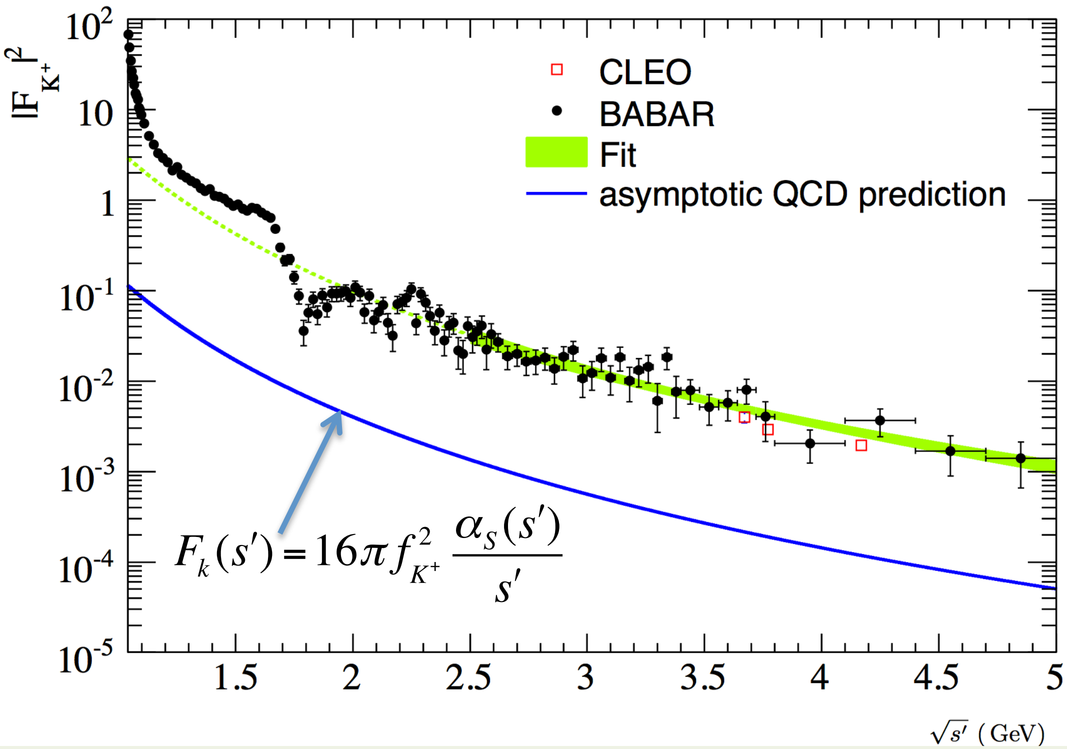


versus previous world average

$[21.63 \pm 0.27_{stat} \pm 0.68_{syst}] \times 10^{-10}$ (3.3% precision)

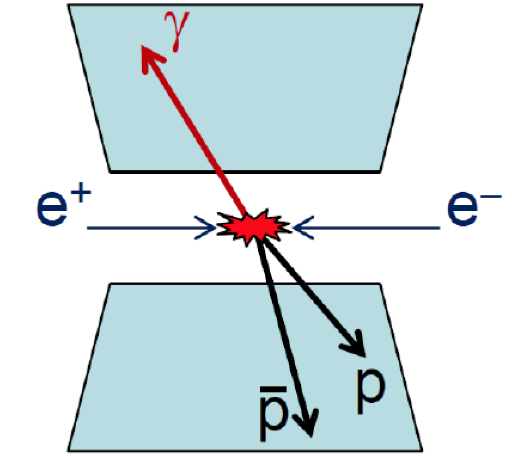
$e^+e^- \rightarrow K^+K^-(\gamma)$ cross section

Charged Kaon form factor:

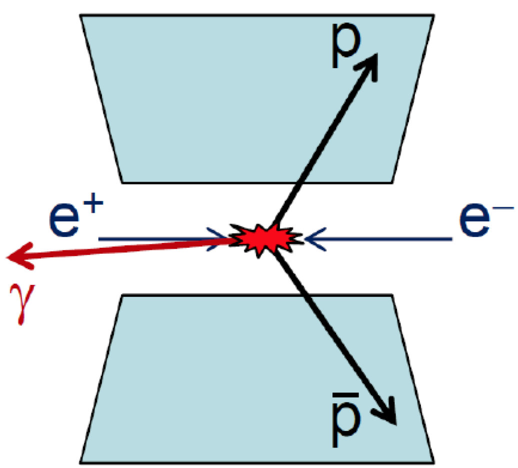


- Above hadron-resonance region, data agree with shape of the QCD $\alpha_S(s')/s'$ prediction
- Babar confirms discrepancy for predicted normalization seen by CLEO at fixed-E_{CM} points

$e^+e^- \rightarrow p\bar{p}$ cross section



Tagged analysis:
[PRD 87, 092005 (2013)]
[update of PRD 73, 012005 (2006) using twice as much data and improved techniques]

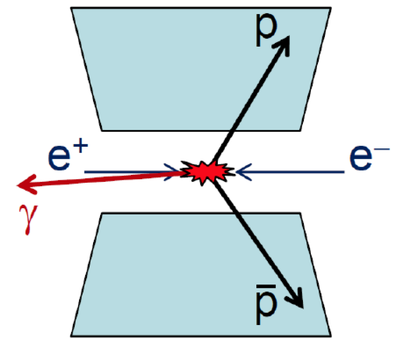


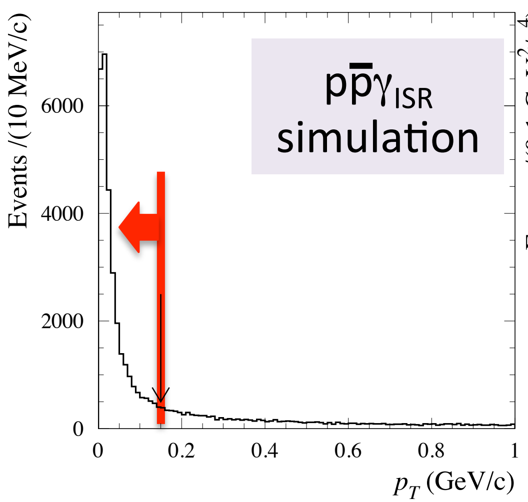
Untagged analysis:
[arXiv:1308.1795 ; preliminary]
[greatly Improves detection efficiency and precision of measurements for $m_{p\bar{p}} > 3$ GeV]

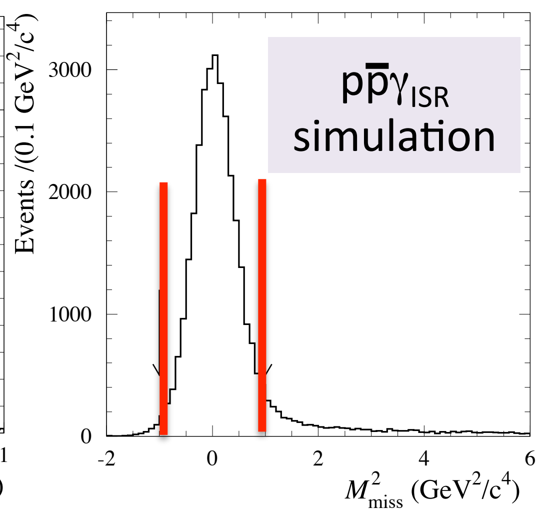
$e^+e^- \to p\bar{p}$ cross section

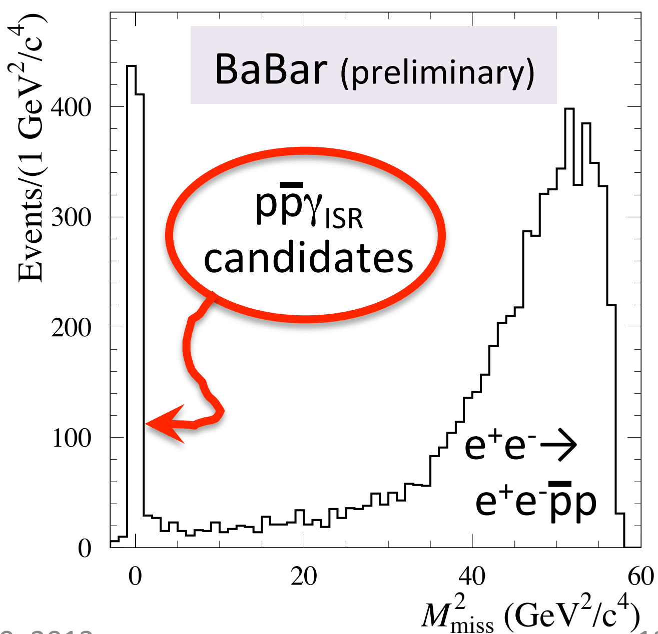
Untagged analysis: main selection variables

- p_T of $p\bar{p}$ pair ($p_T \approx 0$ for signal events)
- Missing mass-squared M^2_{miss} recoiling against $p\bar{p}$ pair (expect $M^2_{miss} \approx 0$ for signal events)



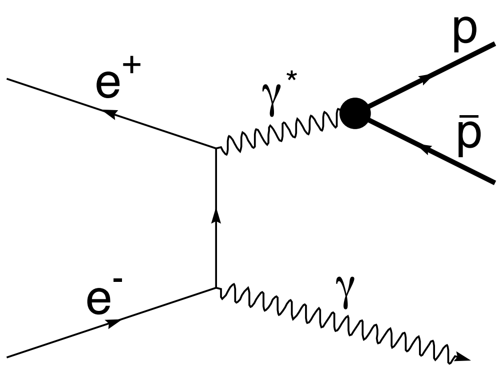


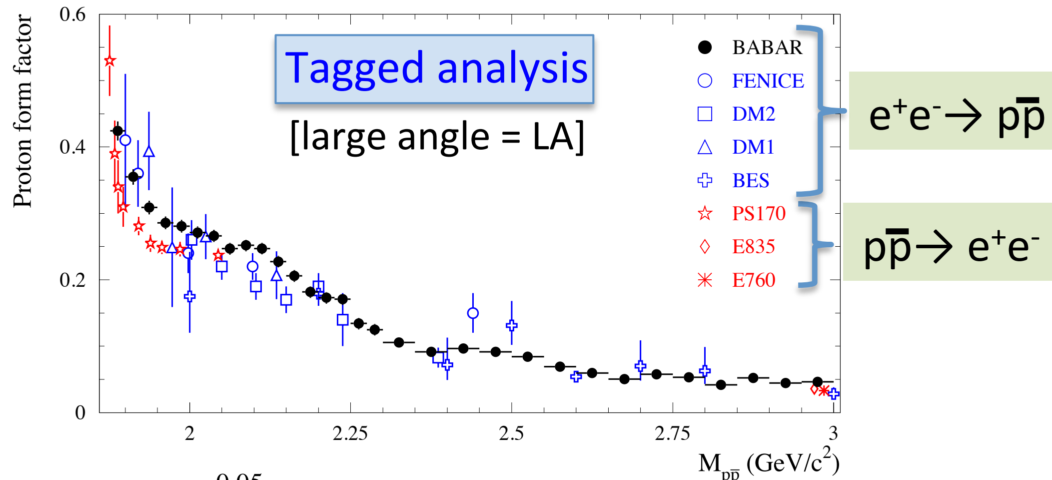




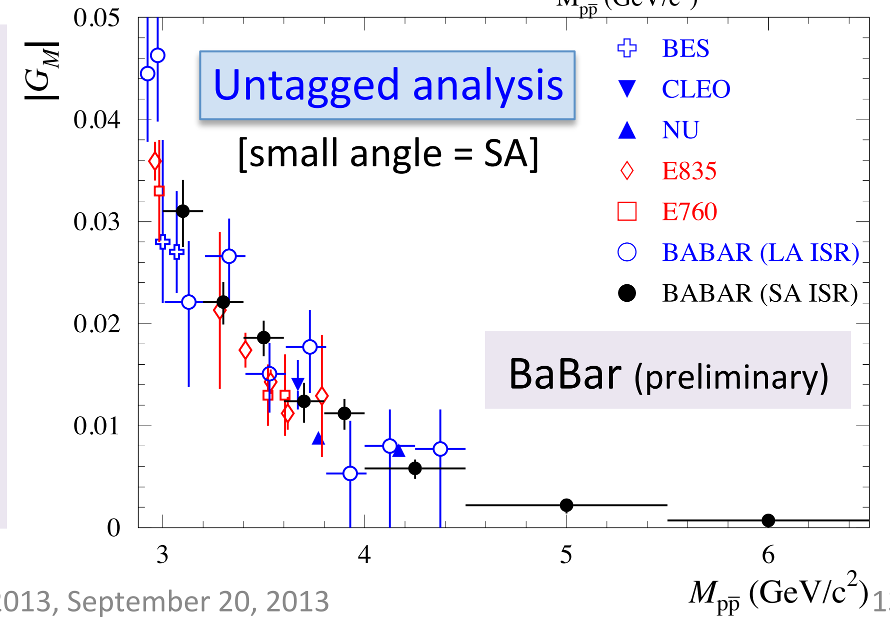
$e^+e^- \rightarrow p\bar{p}$ cross section

[PRD 87, 092005 (2013) and arXiv:1308.1795]





- Confirm enhancement in the threshold region
- Precise results over wide energy range
- Much increased precision at high mass values from the untagged events



$e^+e^- \to K_S K_L$ cross section

[preliminary (Sept. 2013)]

- Exactly one $K_S \to \pi^+\pi^-$ candidate consistent with interaction point (IP)
- No charged tracks consistent with IP

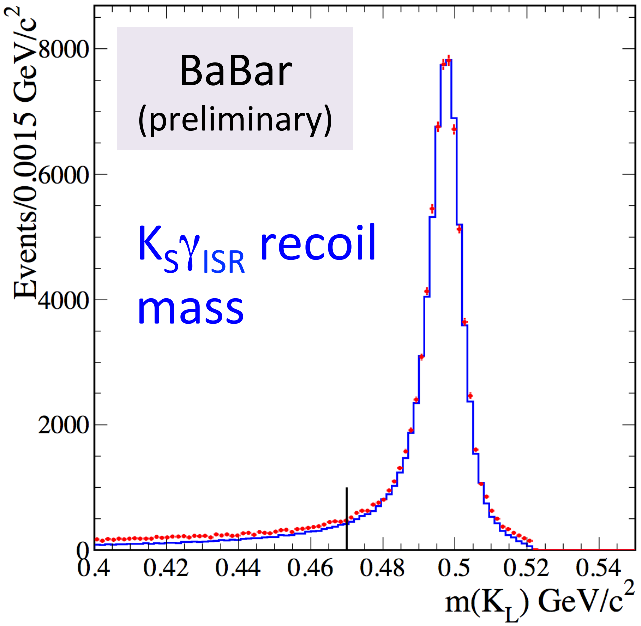
K_L detection efficiency measured using data:

- for dominant $e^+e^- \to \phi\gamma_{ISR} \to K_S K_L \gamma_{ISR}$ channel, plot recoil mass against the $K_S\gamma_{ISR}$ system

$$m^2_{rec} = (E^+ + E^- - E_\gamma - E_{K^0_S})^2 - (\bar{p}^+ + \bar{p}^- - \bar{p}_\gamma - \bar{p}_{K^0_S})^2$$

→ clean K_L signal, w.o. explicit K_L selection

- Apply K_L selection to this sample:
  → require an isolated EM cluster with
  - E > 0.2 GeV
  - < 0.5 rad. from expected K_L direction



→ K_L detection efficiency ≈ 48% (6% lower than simulation) determined as a function of K_L energy and direction

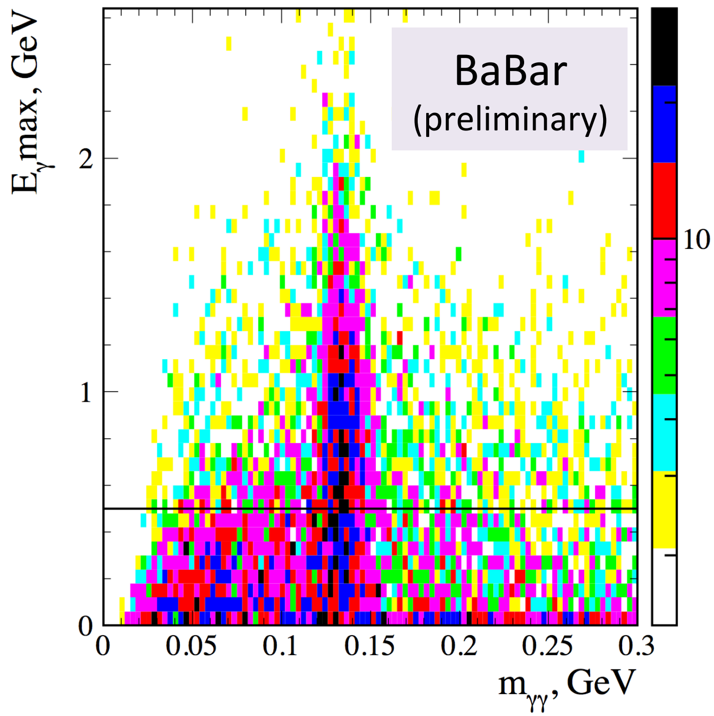
$e^+e^- \rightarrow K_S K_L$ cross section

[preliminary (Sept. 2013)]

$e^+e^- \rightarrow K_S K_L$ nonresonant channel [$m_{K_S K_L} = \sqrt{s'} > 1.06$ GeV]

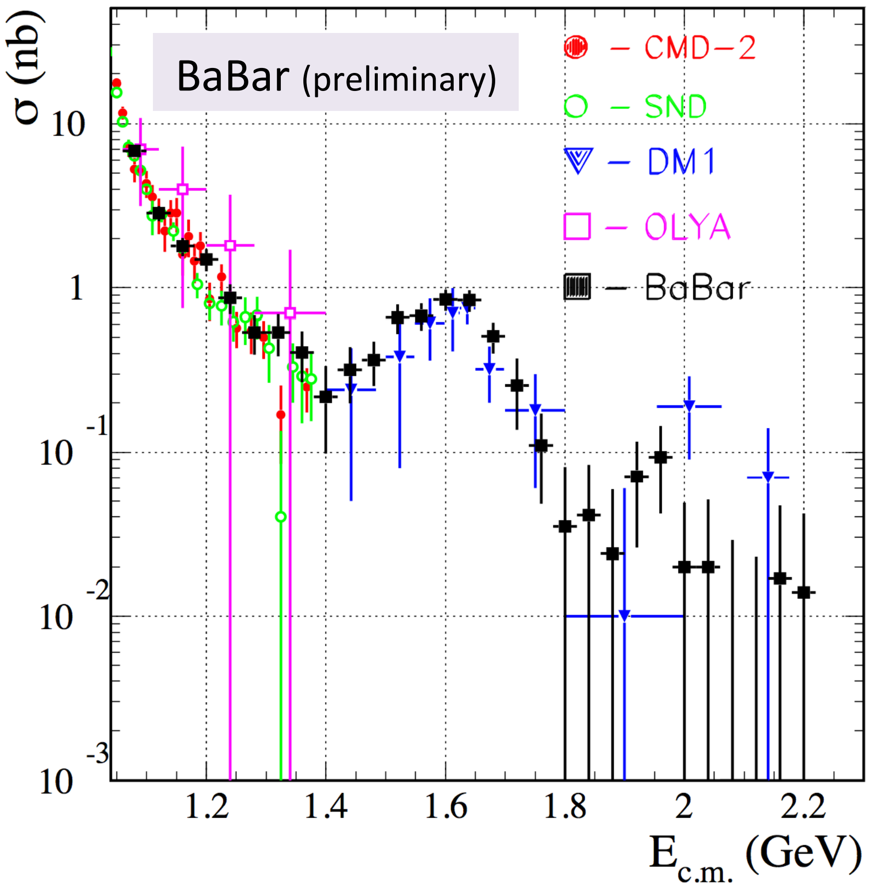
$\rightarrow$ significant background from $e^+e^- \rightarrow K_S K_L (n\pi^0)$; $n \geq 1$ ISR events

- Examine all EM clusters except those assigned to the K_L and γ_{ISR}, assume they are photons
- Plot $E_{\gamma,max}$ versus $m_{\gamma\gamma}$ for all $\gamma\gamma$ pairs
- Require $E_{\gamma,max} < 0.5$ GeV in order to reduce background from $n\pi^0$ events
- Data sidebands used to evaluate and subtract residual background



$e^+e^- \rightarrow K_S K_L$ cross section

[preliminary (Sept. 2013)]



Babar data

- cover larger energy range
- are more precise

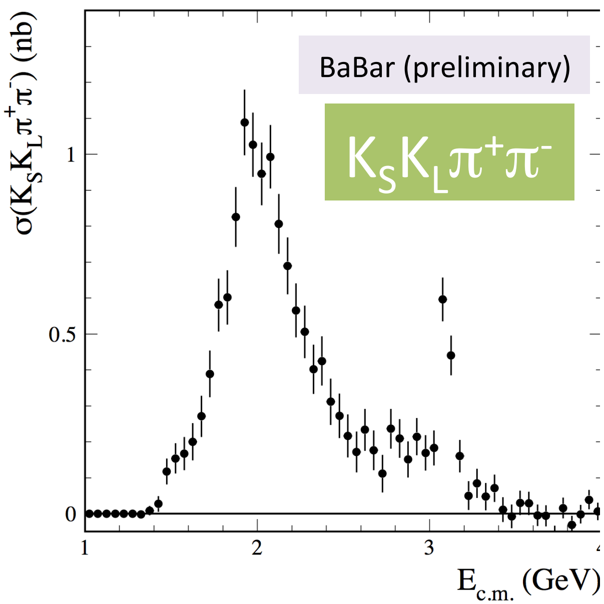
than previous results

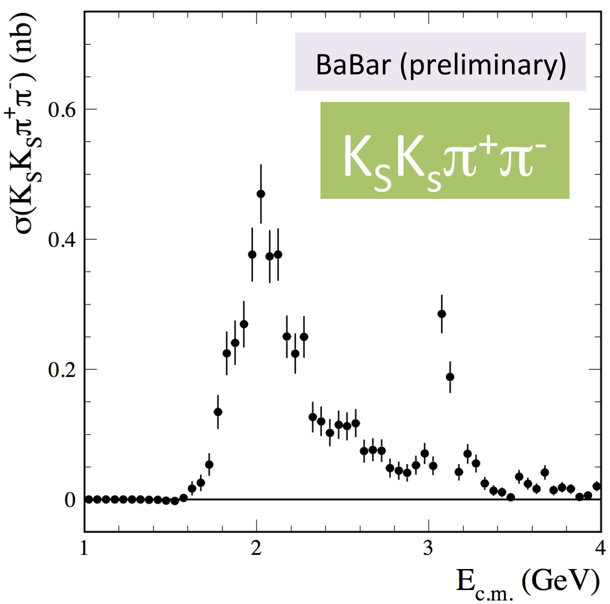
Clear evidence for the $\phi(1600)$

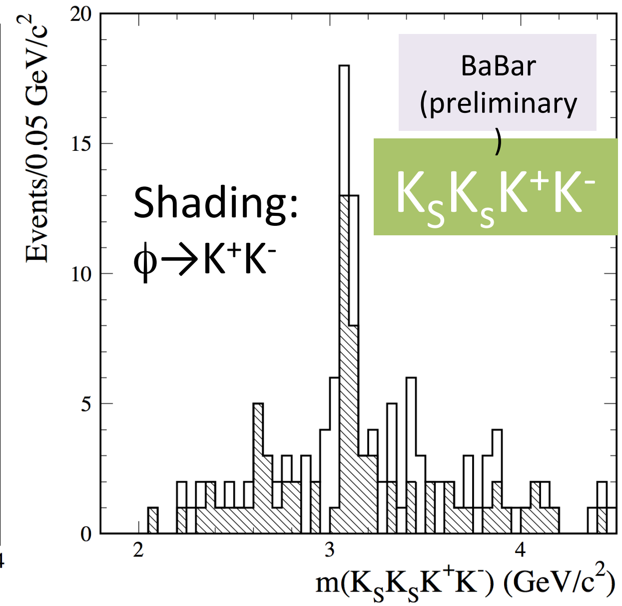
[≈1000 events in this region, compared to 58 for only previous measurement in this region: DM1 fixed energy e^+e^- expt. (Orsay): PLB99 (1981) 261]

First measurements ever of the $e^+e^- \to K_SK_L\pi^+\pi^-$, $K_SK_s\pi^+\pi^-$, $K_SK_sK^+K^-$ cross section

[preliminary (Sept. 2013)]







Measured Quantity	J/ψ Branching Fraction (10^{-3}) This work	PDG2012
$\mathcal{B}_{J/\psi\to K^0_S K^0_L \pi^+\pi^-}$	3. 7 ± 0.6 ± 0.4	no entry
$\mathcal{B}_{J/\psi\to K^0_S K^0_S \pi^+\pi^-}$	1. 68± 0.16± 0.08	no entry
$\mathcal{B}_{J/\psi\to K^0_S K^0_S K^+K^-}$	0. 42± 0.08± 0.02	no entry

First observations of $J/\psi \to K_SK_L\pi^+\pi^-$, $K_SK_s\pi^+\pi^-$, $K_SK_sK^+K^-$

Inclusive $\pi^{\pm}$, $K^{\pm}$, and p, $\bar{p}$ production

[PRD 88, 032011 (2013)]

- Multiplicity and momentum spectra of identified charged hadrons represent basic characteristics of multihadronic events
- Global information on the hadronization process; how it depends on hadron mass and quantum numbers
- Basic information used to tune Monte Carlo event generators
- Energy evolution provides a test of perturbative QCD

- Precise measurements at 91 GeV (LEP and SLC)
- Only previous results in 10 GeV region had been from ARGUS (1989)

  [Belle: charged $\pi^{\pm}$ and $K^{\pm}$ fragmentation functions; PRL 111 (2013) 062002]

- Babar analysis: 0.91 fb^{-1} of off-peak (continuum) data at 10.54 GeV

  ≈ 0.2% of data sample (results dominated by systematic uncertainties)

Inclusive $\pi^\pm$, $K^\pm$, and $p, \bar{p}$ production

Track selection: $p>200$ MeV, $d_0<1$mm, trajectory intersects DIRC

→ good momentum resolution and PID

→ Particle ID from dE/dx and DIRC: ~90% efficient, <5% mis-ID

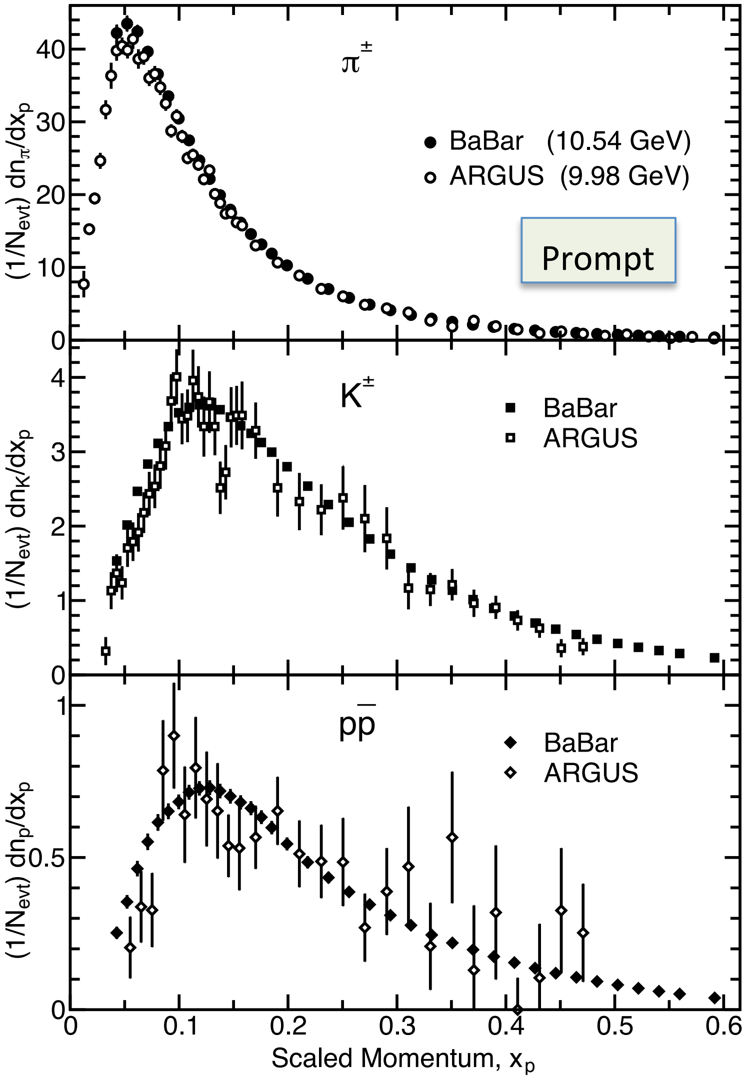
Event selection:

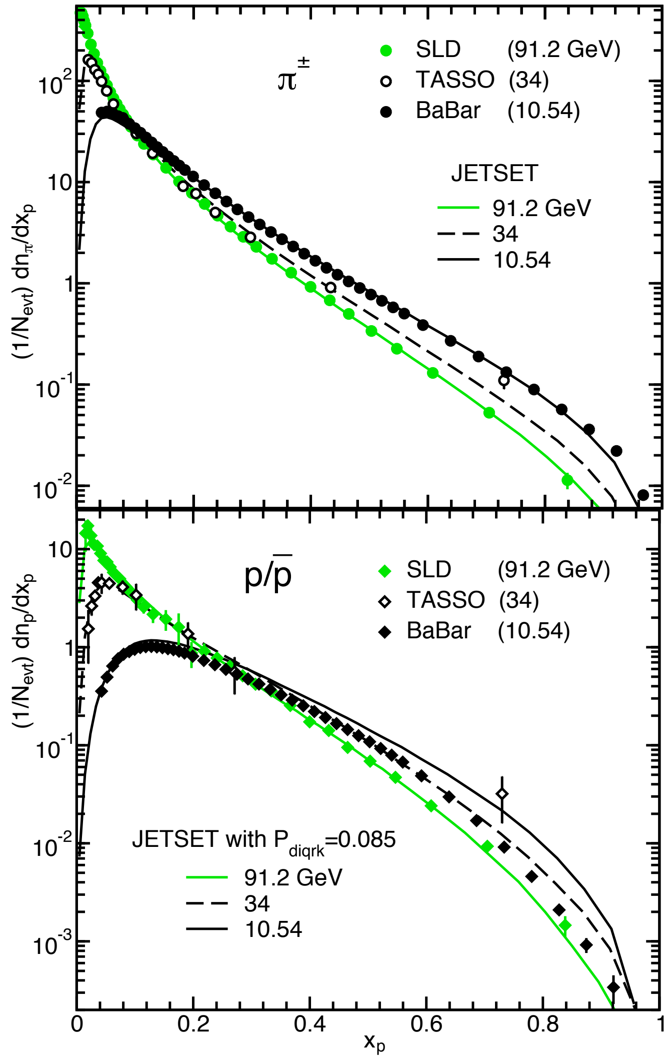
- Good vertex from ≥ 3 tracks
- Highest multiplicity vertex: $d_0<5$mm, $z_0<5$ cm
- 2nd Fox-Wolfram moment < 0.9 (event is not pencil-like)
- $5 < E_{tot} < 14$ GeV ; $|\cos\theta_{thrust}| < 0.8$

→ 2.2×10^6 events, purity 95.4%

- Data control samples used to correct track-selection & particle-ID efficiencies
- Background is subtracted (main background: well understood $\tau^+\tau^-$)
- "Prompt" particles: decay products of K_S, Λ, etc., NOT included

Inclusive $\pi^\pm$, $K^\pm$, and p, $\bar{p}$ production





$x_p = 2p^*/E_{CM}$

Precise low-E_{CM} data allow details of scaling behavior to be investigated

Scaling of $\pi^\pm$ well described by MC (Jetset); scaling of $p/\bar{p}$ overestimated

- large x_p : α_s
- small x_p : mass effect ($x_p \leq m_h/E_{CM}$)

Inclusive $\pi^{\pm}$, $K^{\pm}$, and p, $\bar{p}$ production

Modified leading-logarithm approximation (MLLA):

→ calculations to all orders in α_s

Local-parton-hadron duality (LPHD):

→ inclusive distributions of primary hadrons same as for partons up to normalization

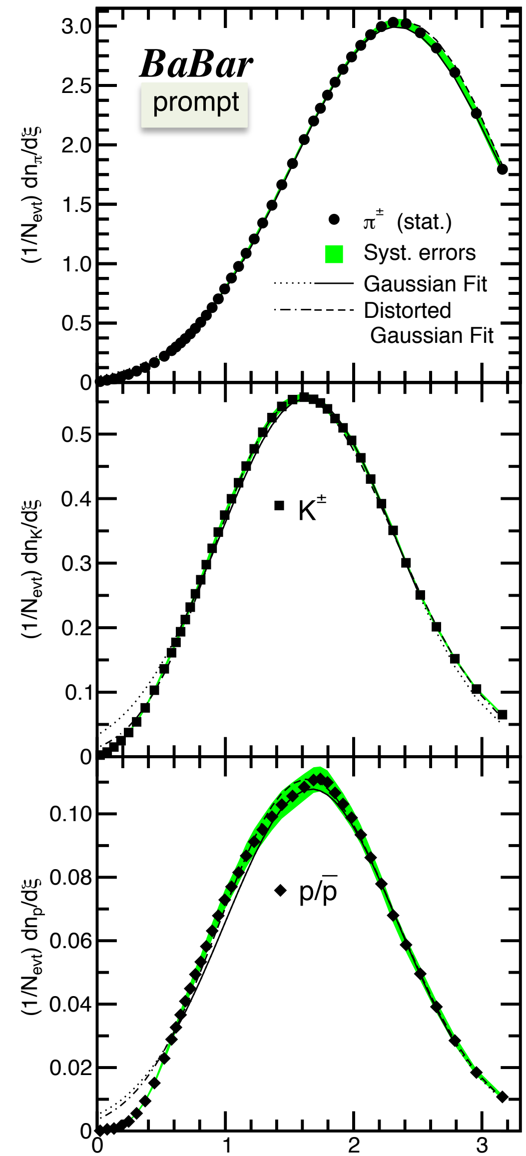
MLLA+LPHD predictions: $\xi = -\ln(x_p)$ spectra:

- Gaussian within one unit of peak
- Skewed Gaussian over wider range

Hadron	Gaussian	Distorted
$\pi^{\pm}$	0.92–3.27	0.22–3.27
$K^{\pm}$	0.63–2.58	0.34–3.05
$p/\bar{p}$	0.56–3.27	0.48–3.27

(require χ^2 probability > 0.01)

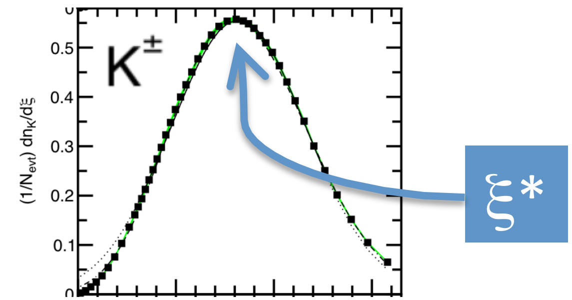
→ Data consistent with MLLA prediction, as also seen at higher energies



$\xi = -\ln(x_p) = -\ln(2p^*/E_{CM})$

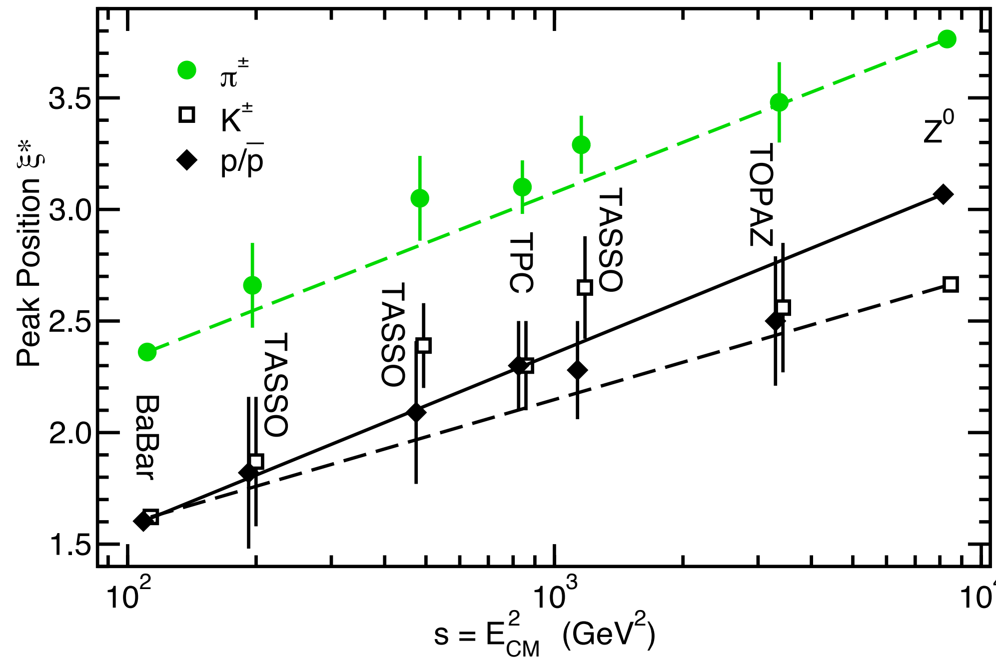
Inclusive $\pi^{\pm}$, $K^{\pm}$, and p,$\bar{p}$ production

Peak ξ^* of the ξ = - ln (x_p) distribution:



Predicted by MLLA to

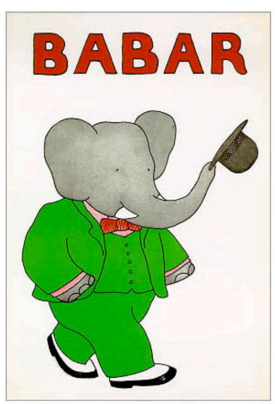
- Increase logarithmically with E_{cm} for a given hadron type:
  - → data consistent with this hypothesis
  - → BaBar adds a high-precision low-energy data point
  - → different slope for kaons due to changing flavor content ?
- Decrease exponentially with hadron mass (fixed E_{CM}):



→ but ξ^* for kaons and protons is about the same: prediction fails here (as also seen at higher energies)

Summary

- Comprehensive program for σ ($e^+e^- \rightarrow$ hadrons) at low E_{CM} from the sum of exclusive channels; important for the g-2 prediction
- First Babar results on $e^+e^- \rightarrow K^+K^-$, $K_SK_L(\pi^+\pi^-)$, $K_SK_S\pi^+\pi^-$, $K_SK_SK^+K^-$, and untagged $p\bar{p}$ (first results ever for the K_L, K_S channels)
- Updated results on tagged $e^+e^- \rightarrow p\bar{p}$
- Precise measurements of π^+, K^+, p, $\bar{p}$ production at 10.54 GeV allow new tests of QCD scaling predictions
- Babar conclusions for MLLA+LHPD similar to those from higher-energy experiments; add a high-precision, low-energy data point



EXTRA SLIDES

Form factor expressions

$$|F_K|^2(s') = \frac{3s'}{\pi\alpha^2(0)\beta_K^3} \frac{\sigma_{KK}(s')}{C_{\mathrm{FS}}}$$

$$\beta_K = \sqrt{1 - 4m_K^2/s'}$$

$$C_{\mathrm{FS}} = 1 + \frac{\alpha}{\pi}\eta_K(s')$$

(final-state Coulomb correction)

$$\sigma_{p\bar{p}}(M_{p\bar{p}}) = \frac{4\pi\alpha^2\beta C}{3M_{p\bar{p}}^2}\left[|G_M(M_{p\bar{p}})|^2 + \frac{2m_p^2}{M_{p\bar{p}}^2}|G_E(M_{p\bar{p}})|^2\right]$$

$$\beta = \sqrt{1 - 4m_p^2/M_{p\bar{p}}^2},\ C = y/(1 - e^{-y})$$

$$y = \pi\alpha(1 + \beta^2)/\beta$$

Hadronic contributions to a_μ^{had}

Channel	$a_\mu(\text{had})\ (10^{-11})$	
	BABAR	world average w/o *BABAR*
$\pi\pi(\gamma)$	$5141 \pm 22 \pm 31$	5056 ± 30
$\pi^+\pi^-\pi^+\pi^-$	$136.4 \pm 0.3 \pm 3.6$	139.5 ± 9.0
K^+K^-	$229.3 \pm 1.8 \pm 2.2$	$216.3 \pm 2.7 \pm 6.8$

From Frank Porter, APS 2013 meeting (UC Santa Cruz)

- Precision on $\pi^+\pi^-$ comparable with previous WA
- Precision on 4π factor 2.6 better than previous WA
- Precision on K^+K^- factor 3 better than previous WA

$\pi^+\pi^-\pi^+\pi^-$ PRD **85** 112009 (2012)

$\pi\pi(\gamma)$ PRD **86** 032013 (2012)

Measured value of a_μ ~3.6σ larger than SM prediction

Inclusive π±, K±, and p, p̄ production