Low-energy e^+e^- → hadrons cross sections and inclusive charged particle production with Babar

J. William Gary

University of California, Riverside

for the Babar Collaboration

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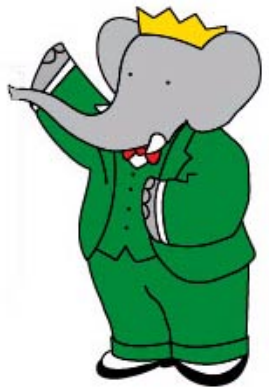
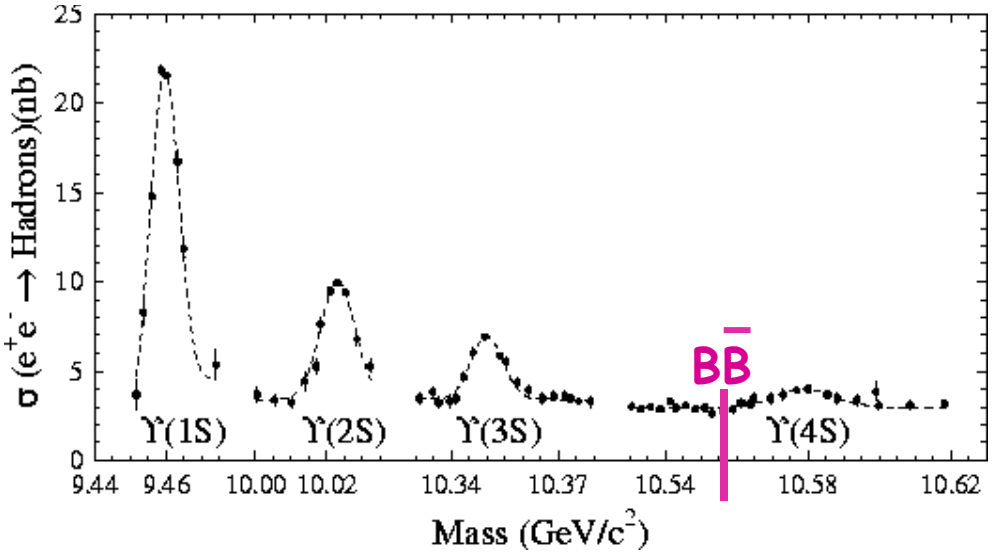


Babar experiment

- PEP-II rings: asymmetric e^+e^- collider @ SLAC
- Collected data 1999-2008; data analysis still very active

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 Υ(4S) → $B\bar{B}$ events
- ~650 x 10^6 e^+e^- → $c\bar{c}$ events: D^0-$\bar{D}^0$ mixing, charmonium states
- ~430 x 10^6 e^+e^- → $\tau^+\tau^-$ events: lepton flavor violation
- Initial-state radiation (ISR) events: access to low-energy e^+e^- cross sections

Recent "QCD" Topics from Babar

(I) $e^+e^- \rightarrow K^+K^-(\gamma)$ cross section (ISR)
[arXiv:1306.3600, submitted to PRD]

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

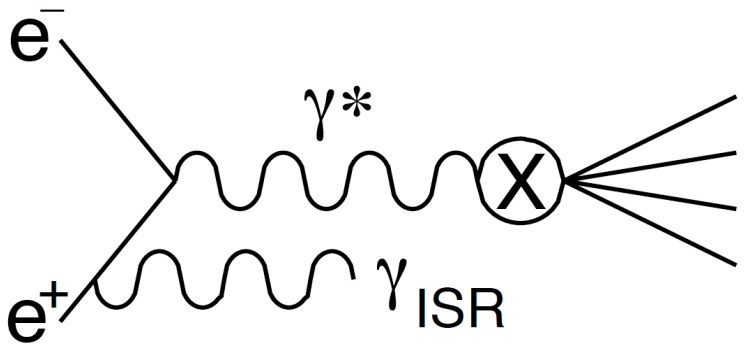
(III) Identified charged π, K, and p production at 10.54 GeV
[arXiv:1306.2895, submitted to PRD]

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

[arXiv:1306.3600 (2013), submitted to PRD]

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

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



Published Babar channels

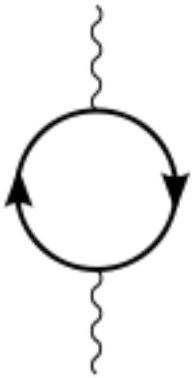
$\pi^+\pi^-$
$\pi^+\pi^-\pi^0$
$\Phi\, f^0(980)$
$p\,\bar{p}$
$\Lambda\,\Lambda,\ \Lambda\,\Sigma^0,\ \Sigma^0\,\Sigma^0$
$2(\pi^+\pi^-),\ K^+K^-\pi^+\pi^-,\ K^+K^-2\pi^0,\ 2(K^+K^-)$
$K^0_S\,K^{+-}\pi^{-+},\ K^+K^-\pi^0,\ K^+K^-\eta$
$2(\pi^+\pi^-)\,\pi^0,\ 2(\pi^+\pi^-)\,\eta,\ K^+K^-\pi^+\pi^-\pi^0,\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

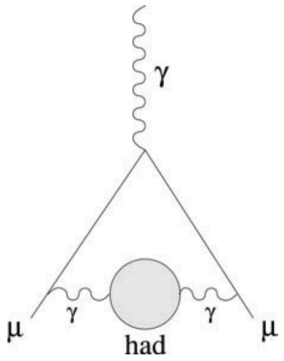
- Measure $\sigma(e^+e^- \to X)$ versus $m_{\gamma^*} = m_X = E_{CM} = \sqrt{s'}$
- Babar covers almost complete set of the significant exclusive channels
- Sum of exclusive channels more precise than an "inclusive" γ_{ISR}+hadrons measurement due to worse energy resolution for photons

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

R = σ ($e^+e^- \rightarrow$ hadrons) / σ ($e^+e^- \rightarrow \mu^+\mu^-$) 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





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

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

a_μ^{had} can't be calculated:

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

$e^+e^- \to K^+K^-(\gamma)$ 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 $e^+e^- \to \mu^+\mu^-(\gamma)$ events in the same sample

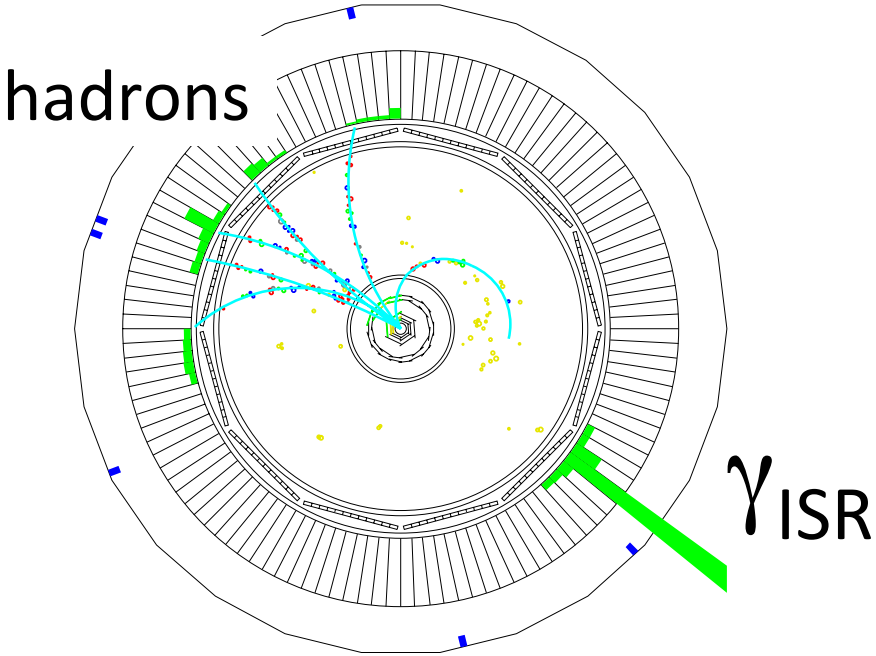
  → reduced systematic uncertainties (no reliance on theoretical radiator function, which introduces uncertainties due to missing higher orders); no reliance on absolute luminosity measurement

$e^+e^- \to K^+K^-(\gamma)$ 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*

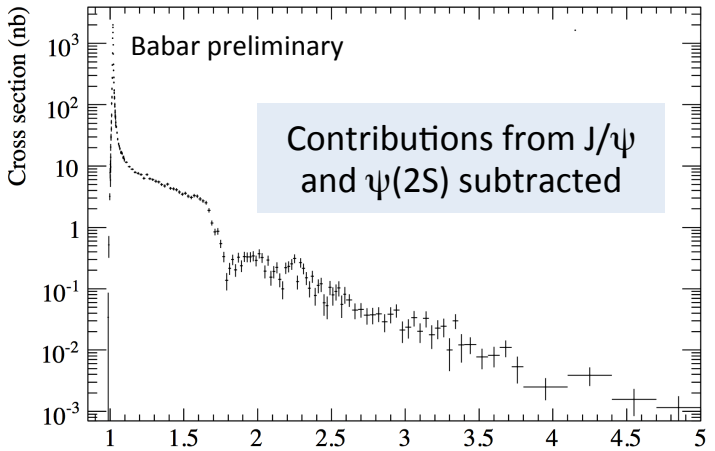
Skip details

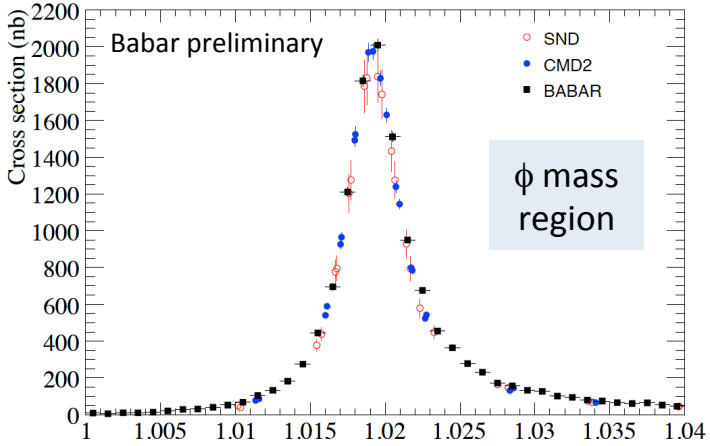


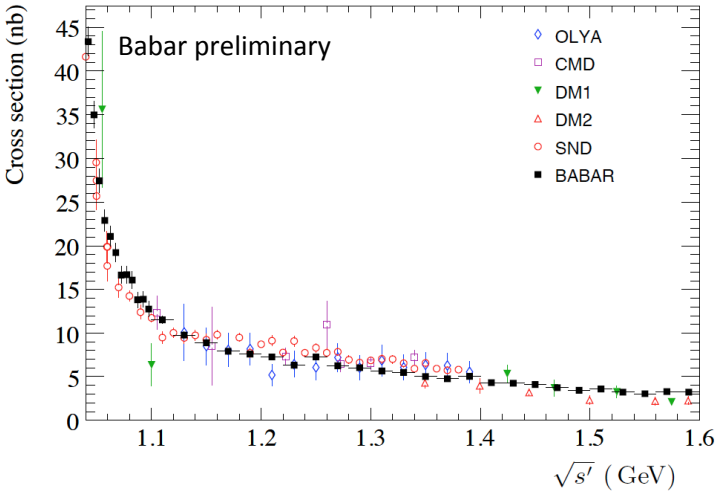
[ISR event display courtesy of Dave Muller]

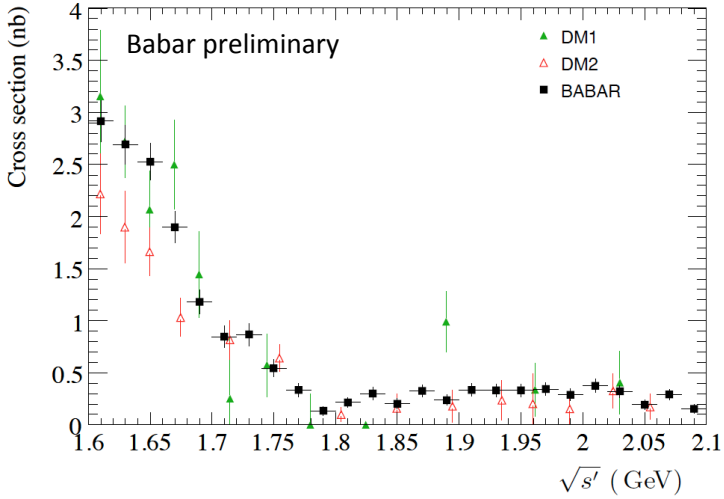
- γ_{ISR} must lie within 0.3 radians of p_{miss} vector formed from all other particles → strong background suppression against non-ISR events
- Background ($\pi^+\pi^-\gamma$, $\mu^+\mu^-\gamma$, $K^+K^-\pi^0\gamma$, etc.) < 20% in all √s' regions (usually much less) is subtracted
- Cross section unfolded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

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









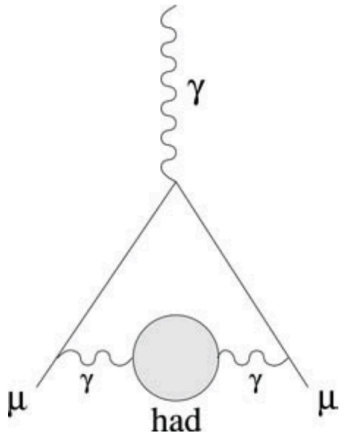
- Babar results cover large energy range and six orders of magnitude
- Are more precise than previous results

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

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

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

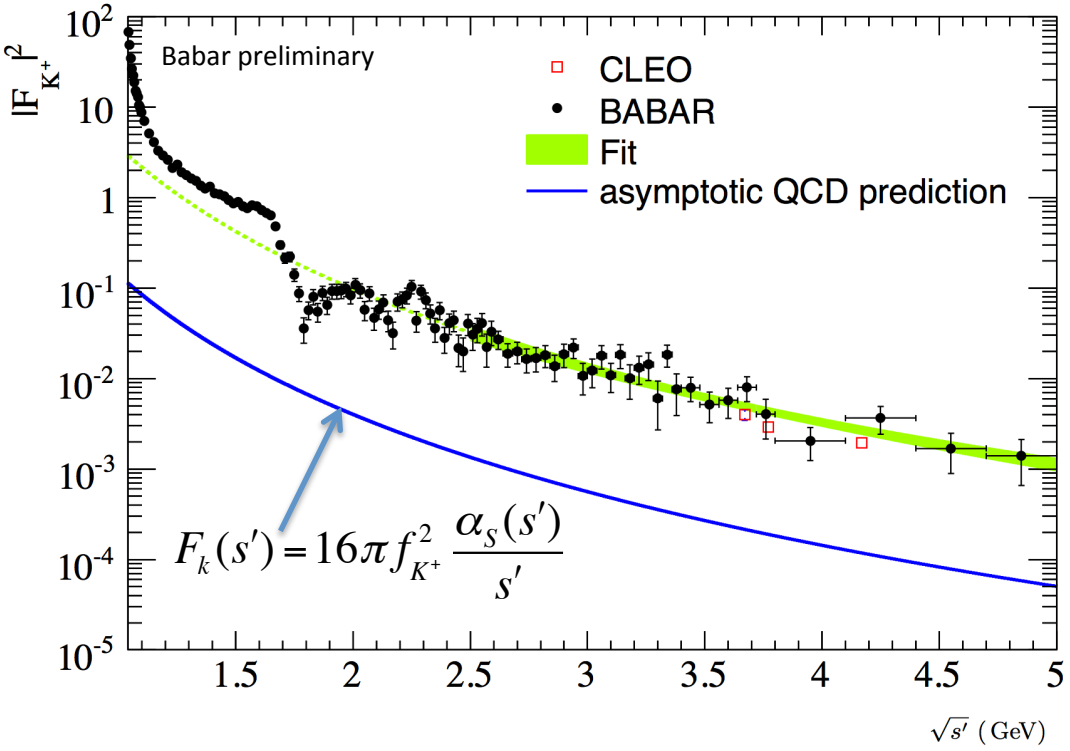
(1.2% precision, preliminary)



versus previous $[21.63 \pm 0.27_{stat} \pm 0.68_{syst}]$ (3.3% precision)

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

Charged Kaon form factor:

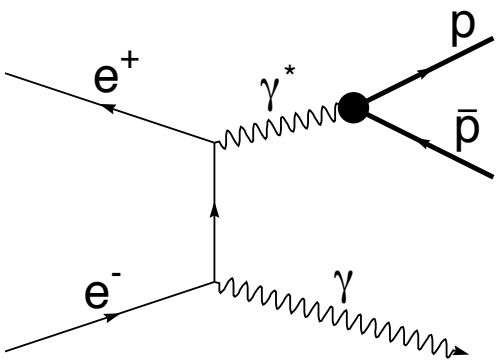


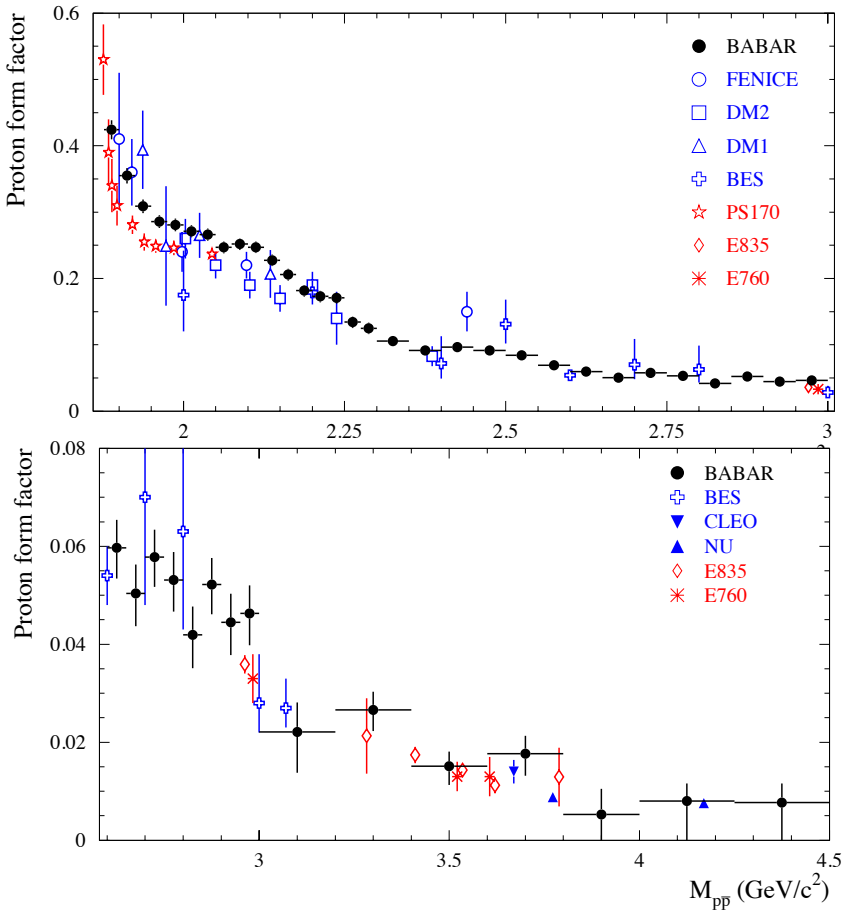
- Above hadron-resonance region, data agree with shape of the QCD $\alpha_S(s')/s'$ prediction but not with the predicted normalization
- BaBar results agree with fixed-E_{CM} CLEO results

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

[PRD 87, 092005 (2013)]

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





- Confirm enhancement in the threshold region
- Precise results over wide energy range
- Currently extending to higher energies using untagged data

Identified charged hadron production

[arXiv:1306.2895, submitted to PRD]

- Multiplicity and momentum spectra of identified particles provide a basic characterization of multihadronic events
- Measurements provide global information on the hadronization process; how it depends on hadron mass and quantum numbers
- Basic input used to tune Monte Carlo event generators
- Energy evolution can provide a test of perturbative QCD

- Precise measurements at 91 GeV (LEP and SLC)
- Only previous published results at ~10 GeV from ARGUS (1989)
  [Belle: arXiv:1301.6183; charged π and K fragmentation functions; submitted to PRL]

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

Identified charged hadron production

Track selection: p>200 MeV, d_0<1mm, 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<5mm, z_0<5 cm
- 2nd Fox-Wolfram moment < 0.9 (event is not pencil-like)
- $5 < E_{tot} < 14$ GeV ; $|\cos\theta_{thrust}| < 0.8$

Skip details

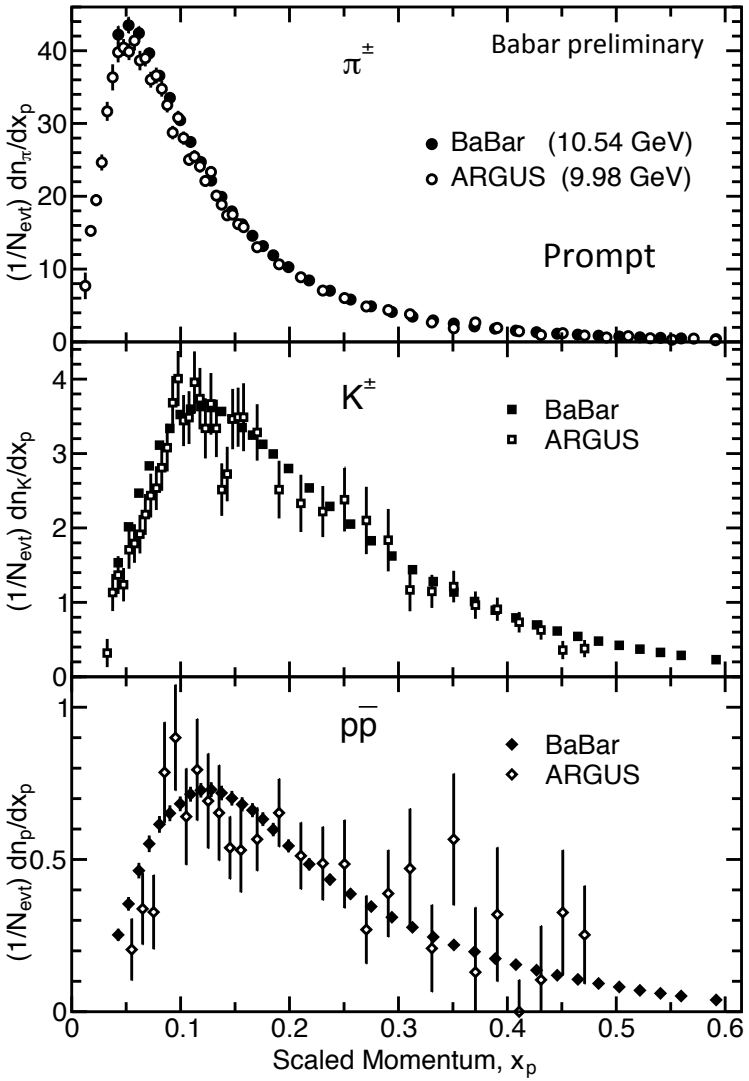
→ 2.2×10^6 events, purity 95.4%

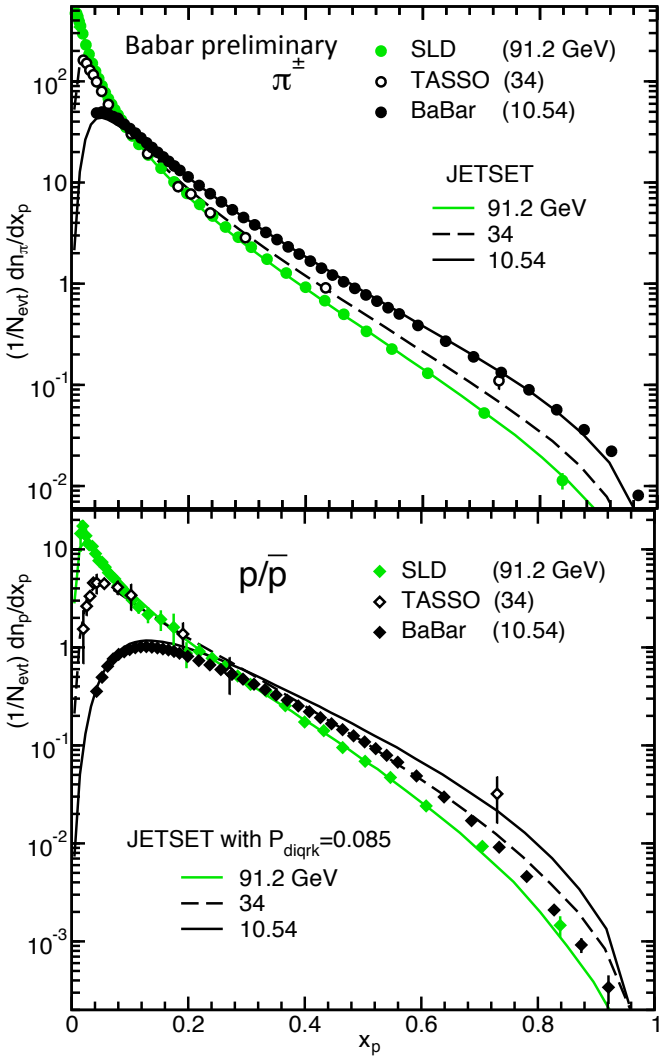
Correct MC track-selection & particle-ID efficiencies using data control samples

Background is subtracted (main background: well understood $\tau^+\tau^-$)

Decay products of weakly decaying strange particles NOT included → **"Prompt"**

Identified charged hadron production





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 $x_p \rightarrow \alpha_s$

small x_p → hadron mass effect ($x_p \leq m_h/E_{CM}$)

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

Identified charged hadron 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

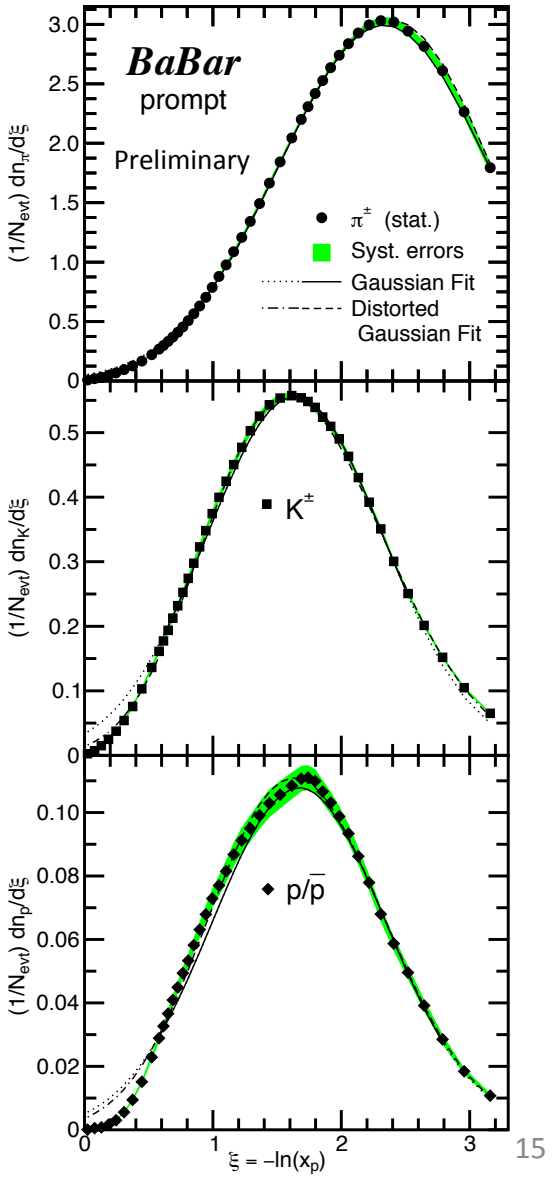
MLLA+LPHD predictions: $\xi = -\ln(x_p)$ spectra:

- 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
$p/\overline{p}$	0.56–3.27	0.48–3.27

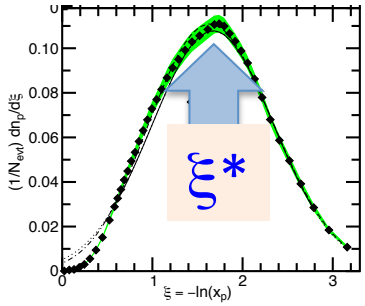
(require χ^2 probability > 0.01)

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



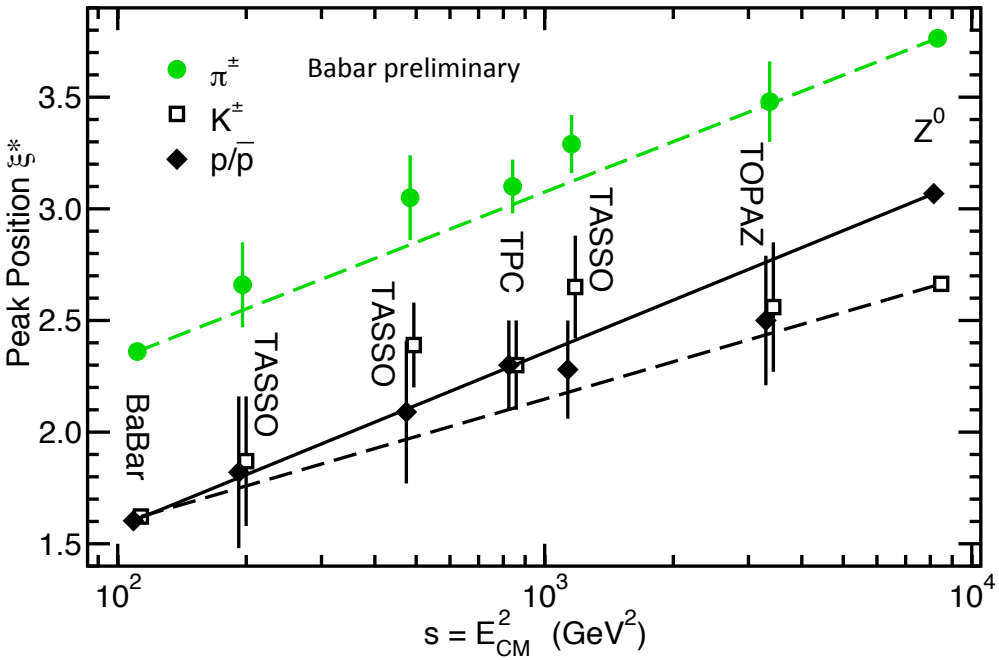
Identified charged hadron production

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



Predicted by MLLA to

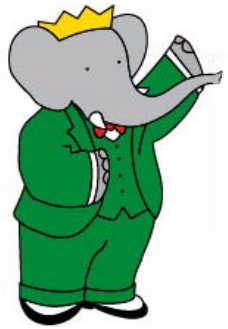
- Increase logarithmically with E_{cm} for a given hadron type:
  - → data consistent with this hypothesis
  - → BaBar adds a high-precision low-energy data point
  - → different slope for kaons due to changing flavor content ?
- Decrease exponentially with hadron mass (fixed E_{CM}):



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

Summary

- Strong and comprehensive program in σ ($e^+e^- \rightarrow$ hadrons) at low E_{CM} from sum of exclusive channels
- Major impact on the g-2 issue
- First results on σ ($e^+e^- \rightarrow K^+K^-$)
- Updated results on σ ($e^+e^- \rightarrow p\bar{p}$)
- Precise measurements of π^+, K^+, 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

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

√ s' obtained from kinematic fit assuming 4-momentum conservation:

- Extra photon "(γ)": assume there is an ISR γ along the beam axis in every event → χ^2_{ISR}
- Compare with fit using observed extra photons with E > 20 MeV → χ^2_{FSR}
- Use "ISR" solution if $\chi^2_{ISR} < \chi^2_{FSR}$, otherwise use "FSR" solution

Efficiency $\varepsilon_{KK\gamma}$ from MC with corrections for data-MC differences (trigger, tracking, particle ID, χ^2 selection)

$$\frac{dN_{\mu\mu(\gamma)\gamma_{\rm ISR}}}{d\sqrt{s'}} = \frac{dL^{\rm eff}_{\rm ISR}}{d\sqrt{s'}}\,\varepsilon_{\mu\mu\gamma}(\sqrt{s'})\,\sigma^0_{\mu\mu(\gamma)}(\sqrt{s'})\,(1+\delta^{\mu\mu}_{\rm FSR}(\sqrt{s'}))$$

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

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

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

(final-state Coulomb correction)