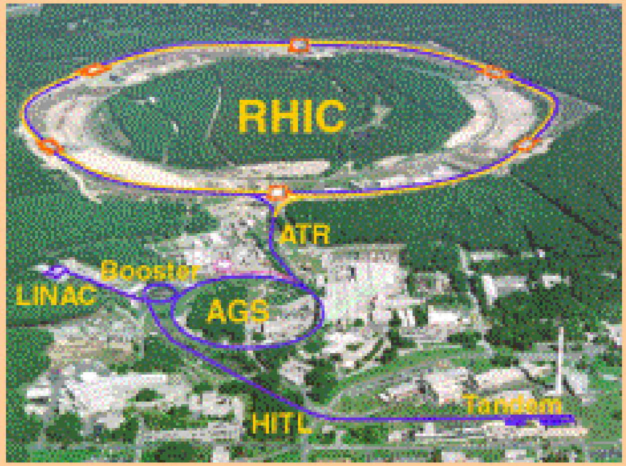
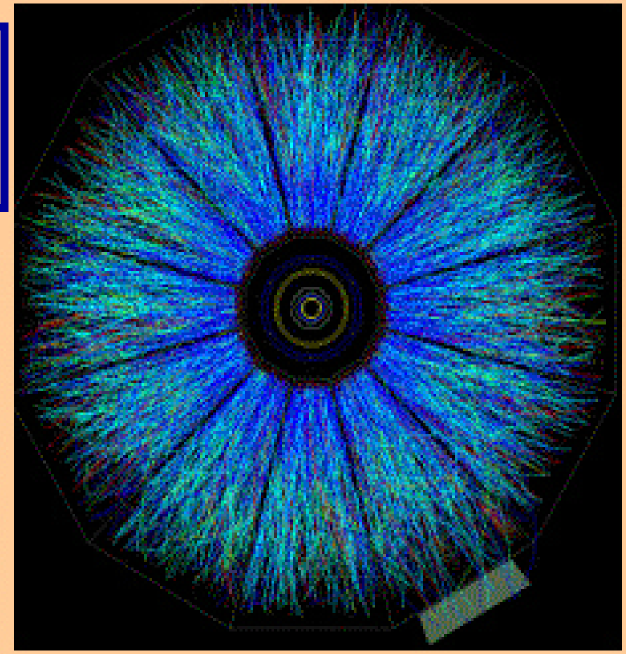
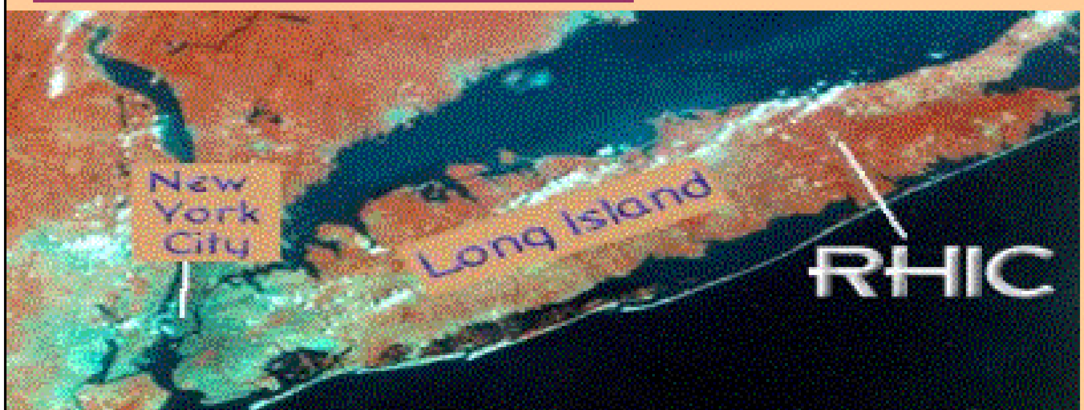
# *Overview of New Results and "Still-Puzzling" Results from STAR*

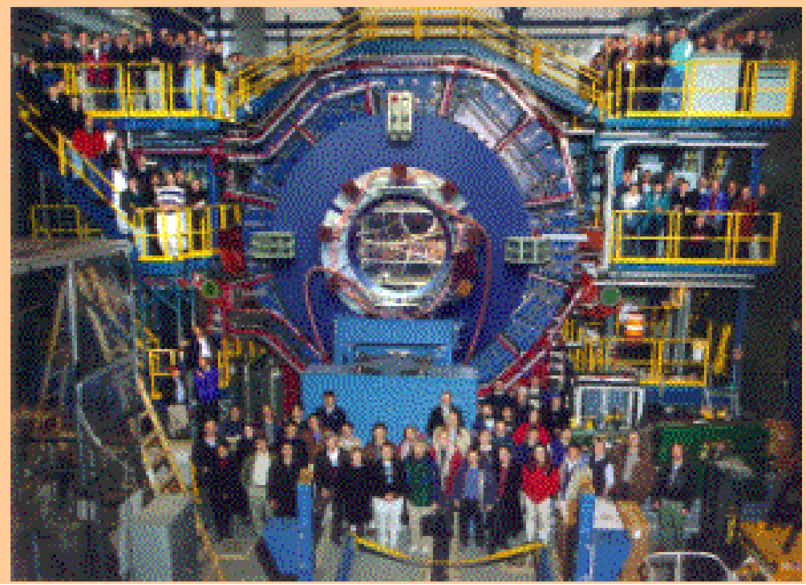
- *STAR*
- *STAR Physics Results*
- *Conclusions / Expectations*



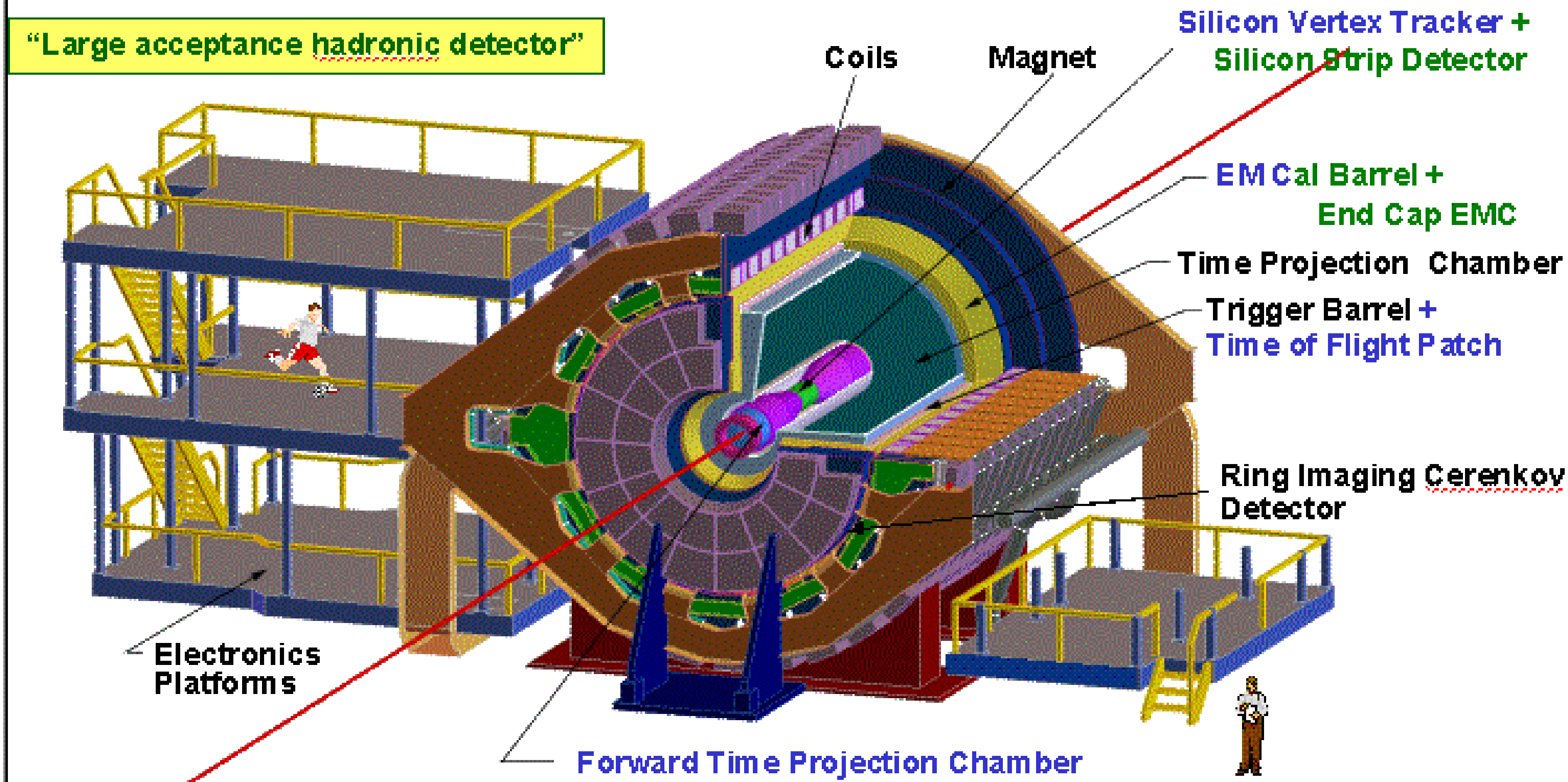
John Harris
(Yale University)
for the STAR Collaboration



ITP - Santa Barbara, April 8, 2002

# STAR Detector at RHIC




**Detectors Run 2000**

- TPC, Trigger Barrel, RICH

**New Detectors this Run (2001):**

- SVT, FTPC, ToF patch, partial EMC, FPD

**New Detectors in 2002:**

- SSD, PMD* (not shown)
- 1/2 Endcap EMC, more EMC (~1/2)

# STAR Collaboration

**419 collaborators**
**44 institutions**
**9 countries**

**Brazil**
Universidade de Sao Paolo

**China**
IHEP - Beijing
USTC - Hefei
IMP - Lanzhou
SINR - Shanghai
Tsinghua University
IPP - Wuhan

**England**
University of Birmingham

**France**
IReS Strasbourg
SUBATECH - Nantes

**Germany**
MPI – Munich
University of Frankfurt

**India**
IOP - Bhubaneswar
VECC - Calcutta
Panjab University
University of Rajasthan
Jammu University
IIT - Bombay

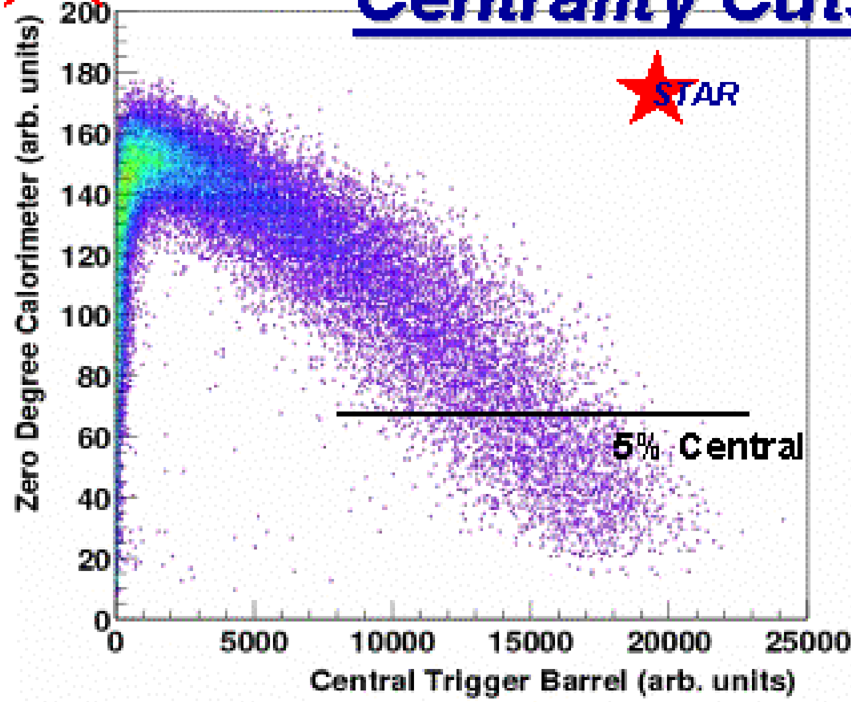
**Poland**
Warsaw University of Technology

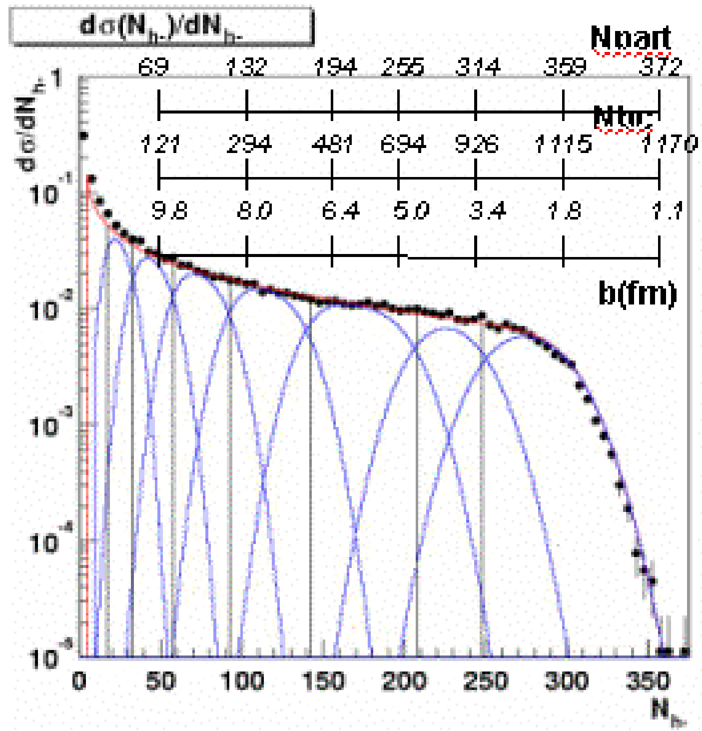
**Russia**
MEPHI – Moscow
LPP/LHE JINR - Dubna
IHEP-Protvino

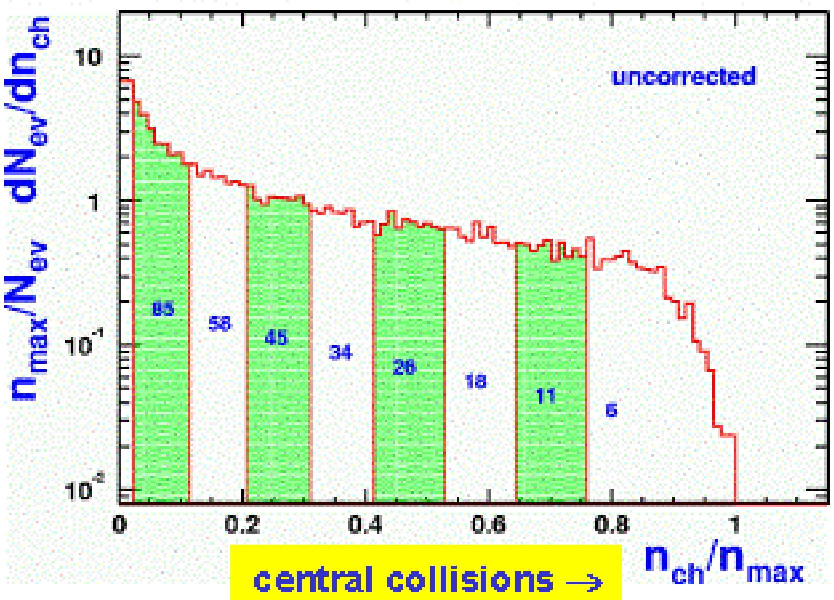
**U.S. Labs**
Argonne National Laboratory
Brookhaven National Laboratory
Lawrence Berkeley National Laboratory

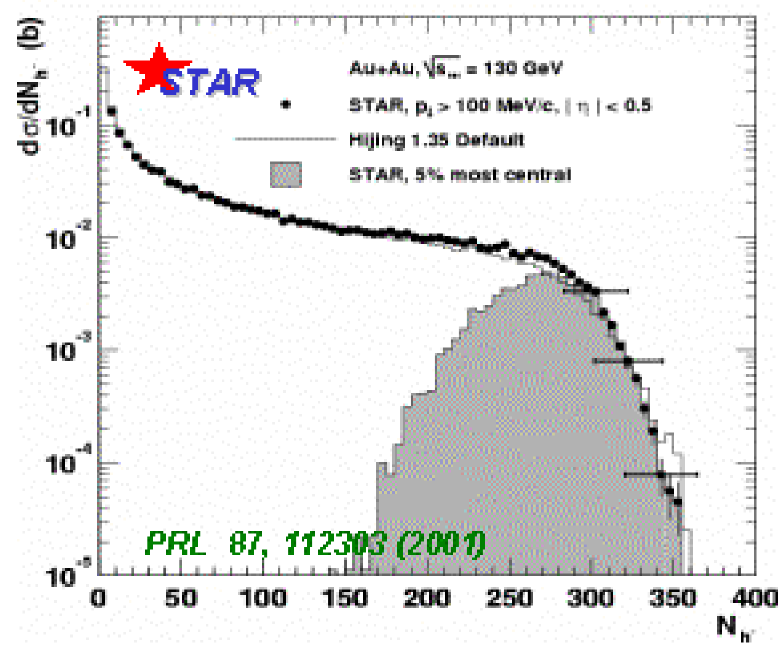
**U.S. Universities**
UC Berkeley / SSL
UC Davis
UC Los Angeles
Carnegie Mellon University
Creighton University
Indiana University
Kent State University
Michigan State University
City College of New York
Ohio State University
Penn. State University
Purdue University
Rice University
University of Texas - Austin
Texas A&M University
University of Washington
Wayne State University
Yale University

# Geometry Trigger & Centrality Cuts




$n_{ch}$ - number of primary tracks in |η| < 0.75

# ***Particle Production:***
# ***Non-Strange and Strange***

Particle Identification

Spectra, yields and ratios

# Particle ID Techniques in STAR

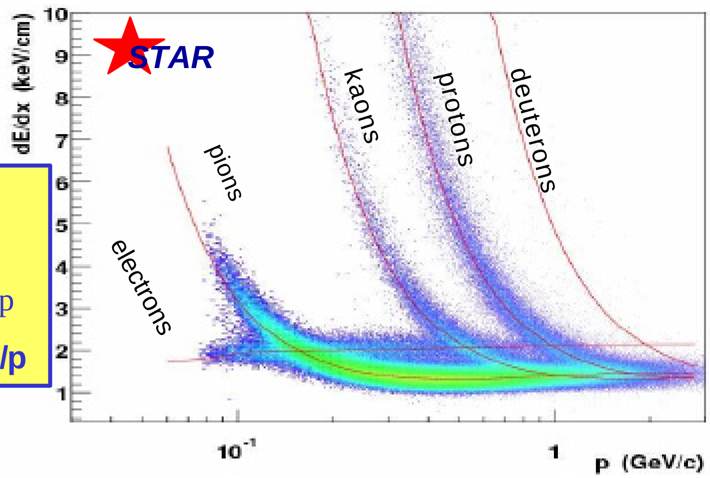
## dE/dx

dE/dx PID range:

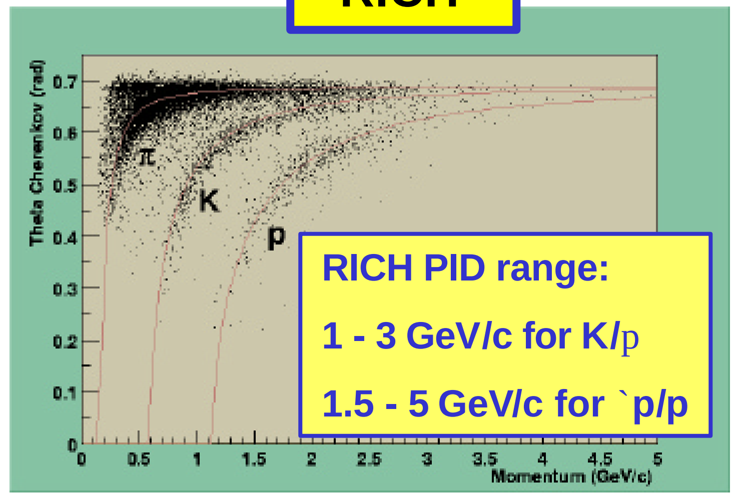
[s (dE/dx) = .08]

p ® ~ 0.7 GeV/c for K/p

® ~ 1.0 GeV/c for `p/p




## RICH




RICH PID range:

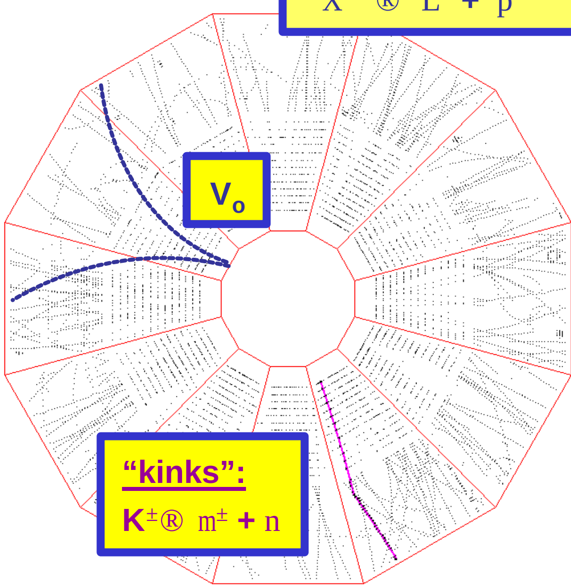
1 - 3 GeV/c for K/p

1.5 - 5 GeV/c for `p/p

## Topology

Decay vertices

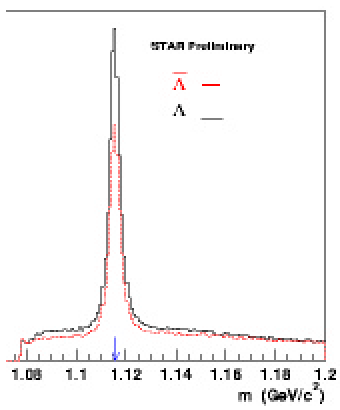
| | |
|---|---|
| $K_s$ ® p⁺ + p⁻ | L ® p + p⁻ |
| `L ® `p + p⁺ | X⁻ ® L + p⁻ |
| `X⁺ ® `L + p⁺ | W ® L + K⁻ |



$V_0$

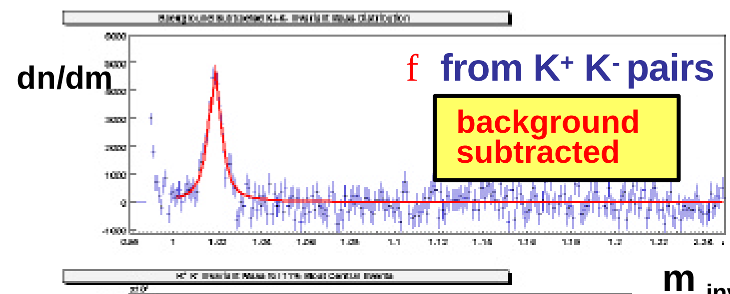
"kinks":

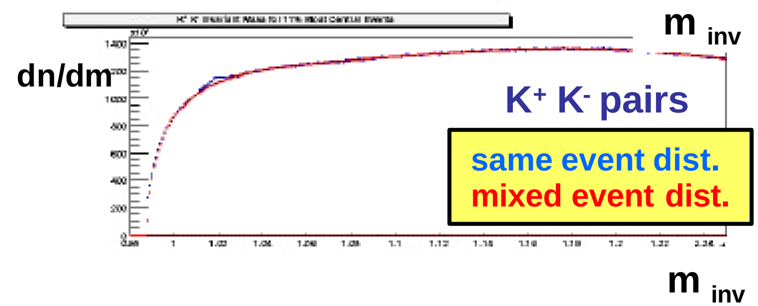
K± ® m± + n




## Combinatorics

| | |
|---|---|
| $K_s$ ® p⁺ + p⁻ | f ® K⁺ + K⁻ |
| L ® p + p⁻ | $\bar{L}$ ® `p + p⁺ |
| [ r ® p⁺ + p⁻] | [D ® p + p⁻] |



# $m_T$ Distributions

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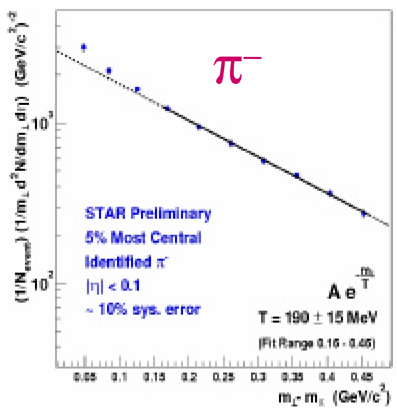
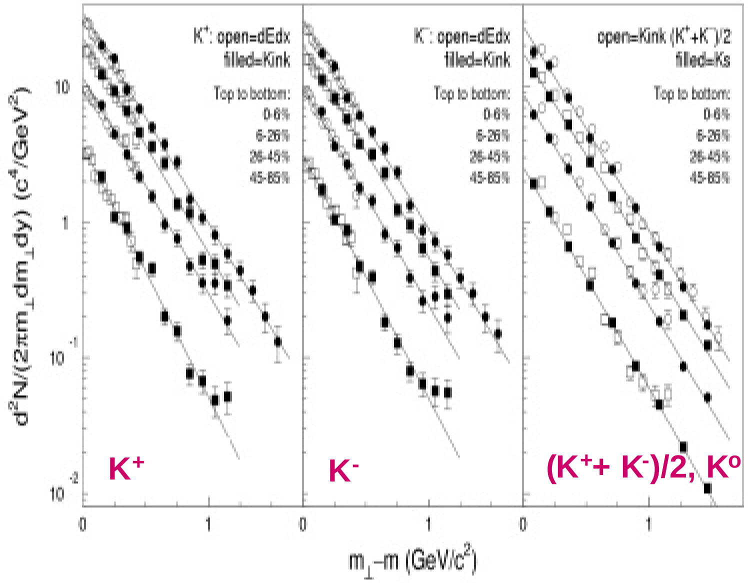
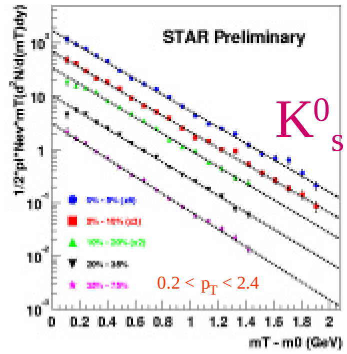
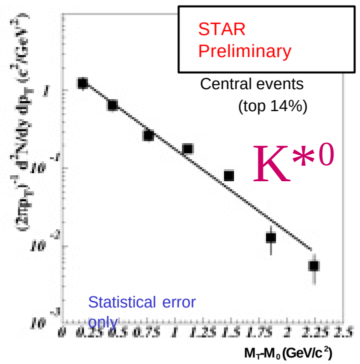
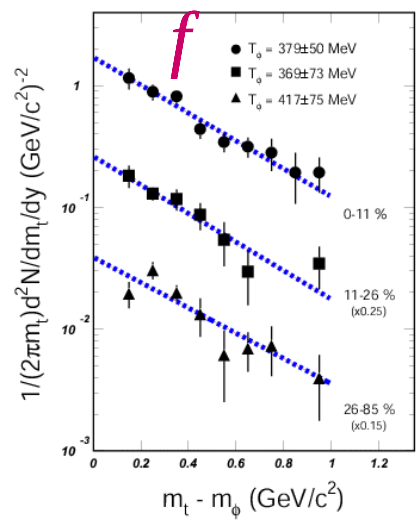
$$m_T = \sqrt{p_T^2 + m^2}$$

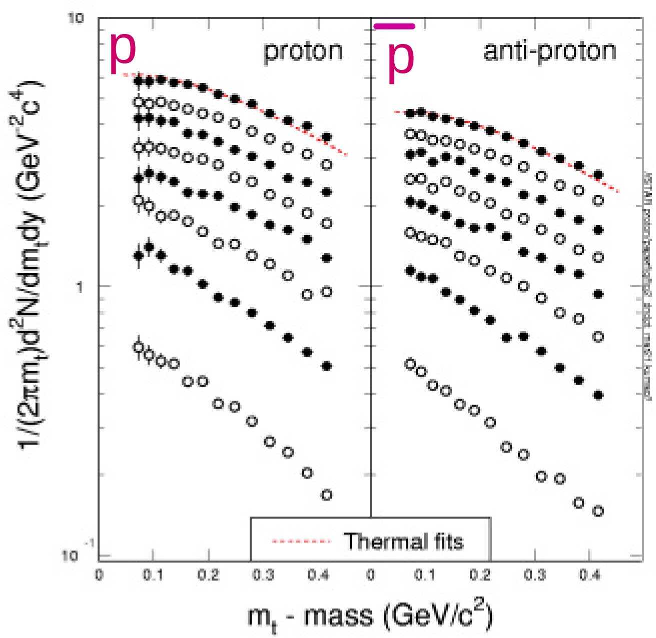


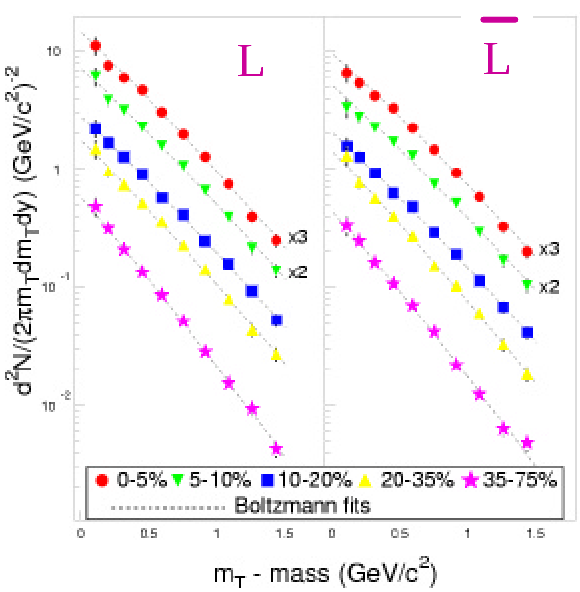



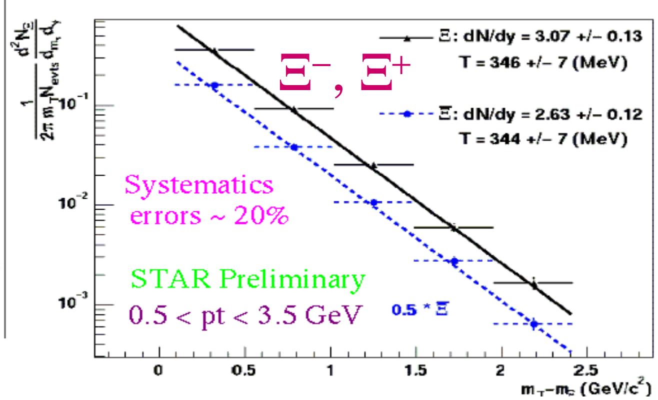



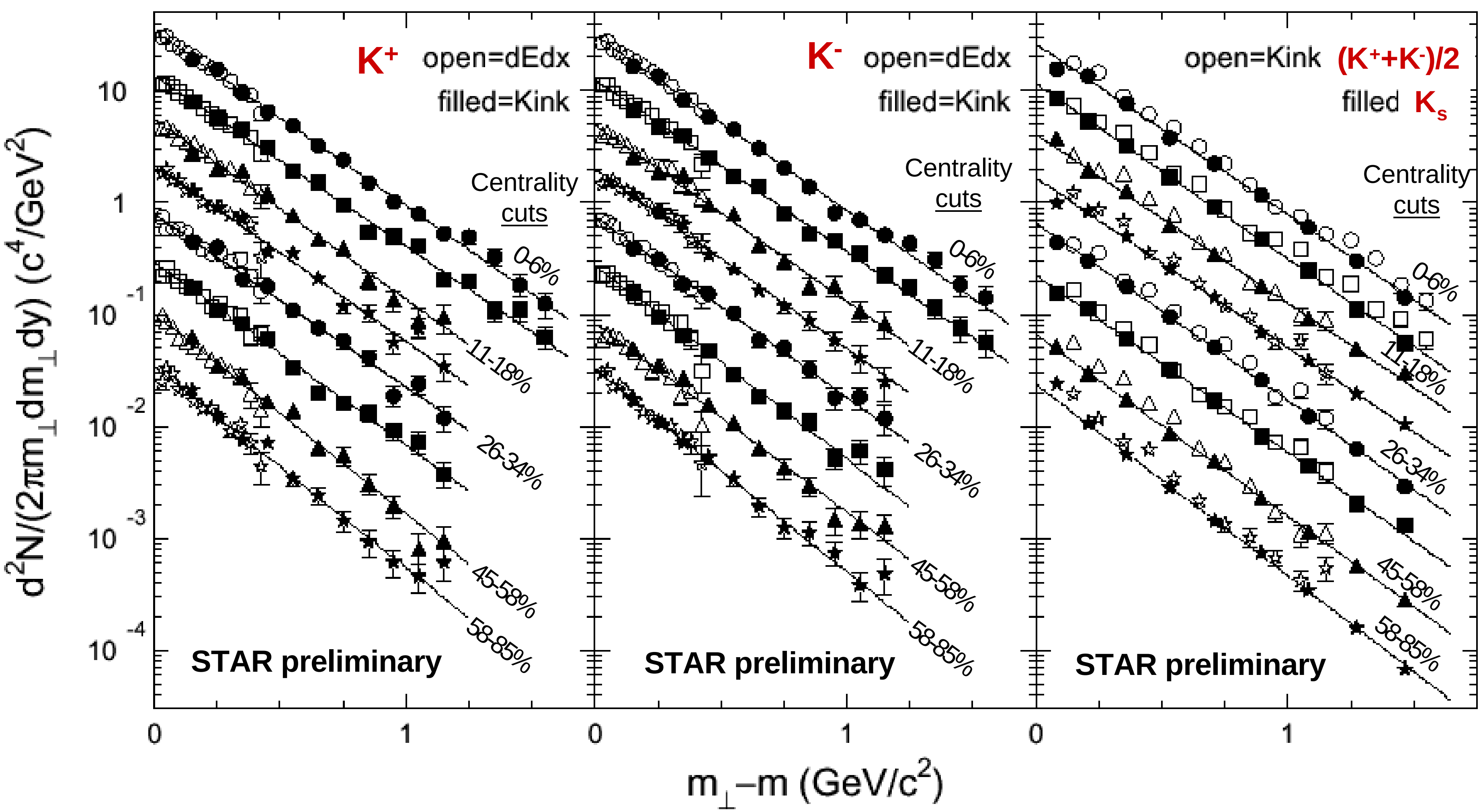



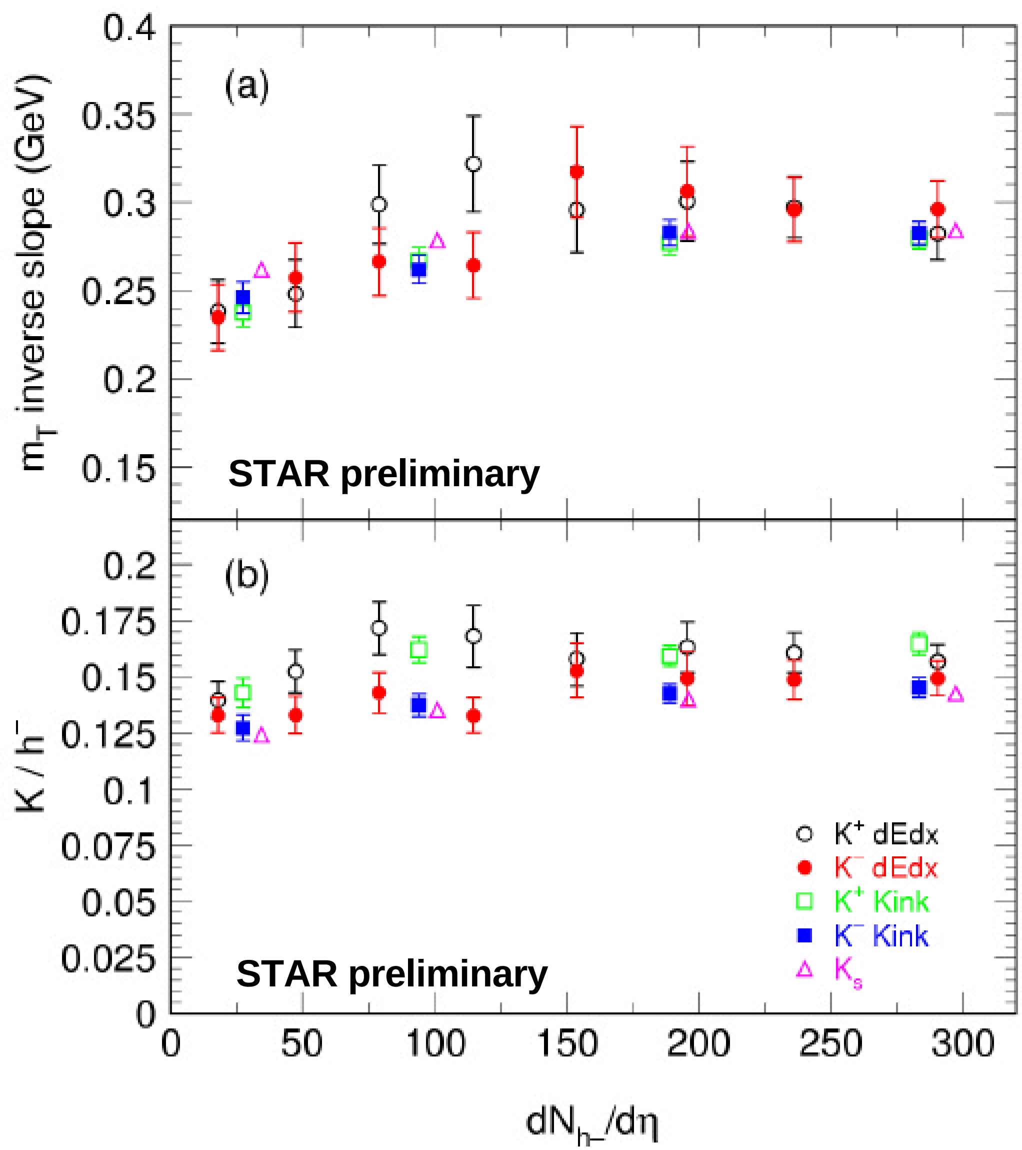
# Kaon Spectra at Mid-rapidity vs Centrality




Exponential fits to $m_T$ spectra: $\frac{1}{m_T}\frac{dN}{dm_T} \propto A \exp\left(-\frac{m_T}{T}\right)$

$m_\perp = m_t = \sqrt{(p_t^2 + m^2)}$

# Kaon $m_T$ Slopes and K/h- vs Centrality




Slight increase in inv. slope as get more central.

K/h$^-$

Peripheral ~ central!

Production mechanisms?

# Strange Particles per event in STAR

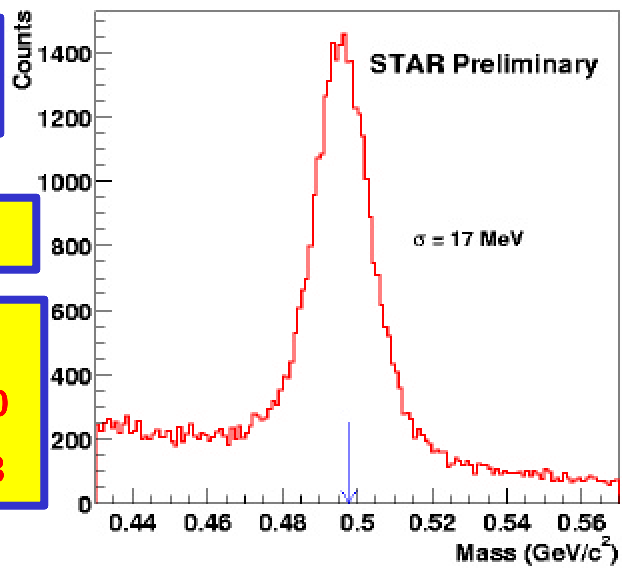
**# reconstructed in detector**

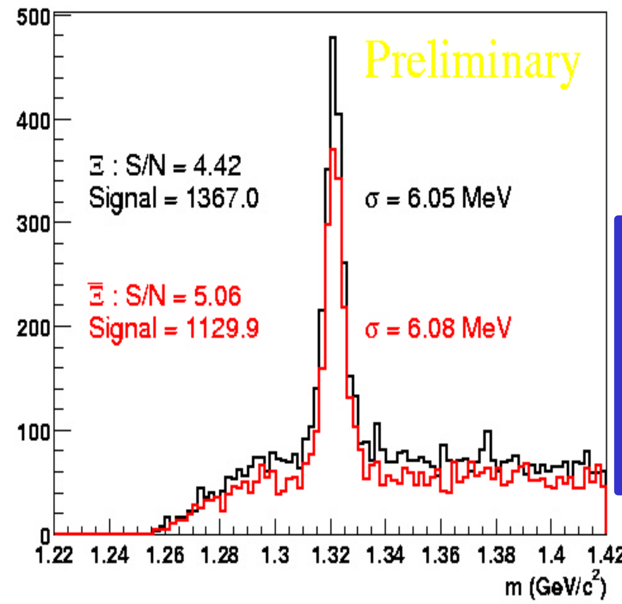
$K^0_s$**/ evt ~ 1.6**

**$K^+$: dn/dy|$_{cm}$ ~ 46**

**$K^0_s$: dn/dy|$_{cm}$ ~ 40**

**$K^-$: dn/dy|$_{cm}$ ~ 43**




**$X^-$/ evt ~0.006**

**$\overline{X}^+$/ evt ~0.005**

**$X^-$: dn/dy|$_{cm}$ ~ 3.07 +/- 0.13**

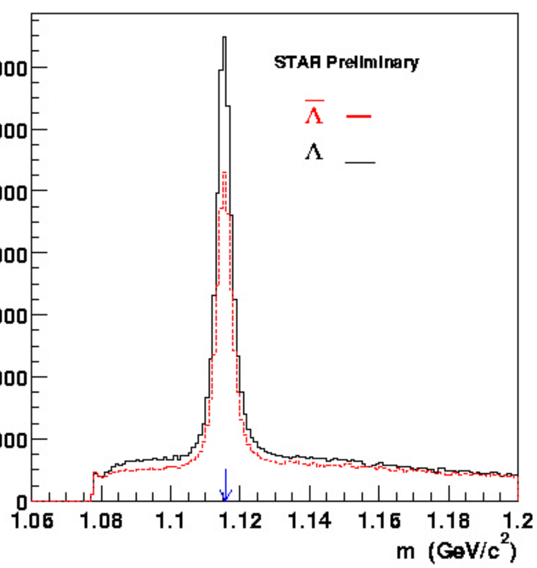
**$\overline{X}^+$: dn/dy|$_{cm}$ ~ 2.63 +/- 0.12**

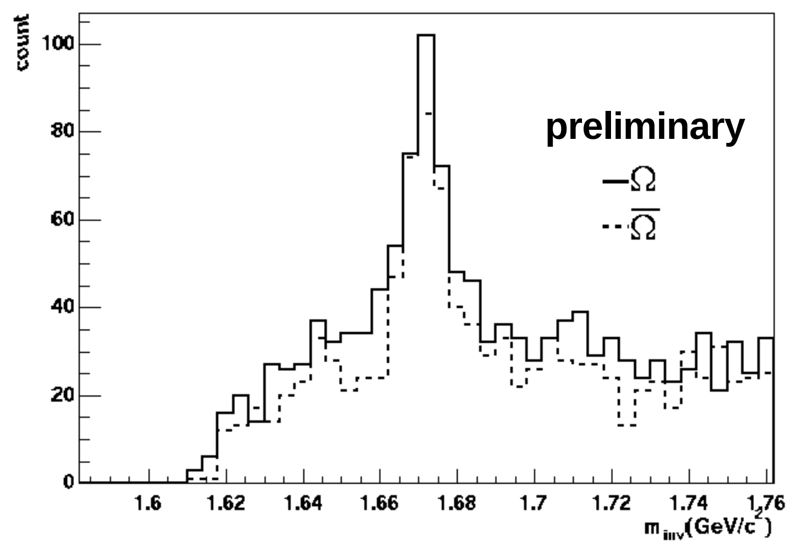
**L/ evt ~ 0.84,**

**$\overline{L}$/ evt ~ 0.61**

**L: dn/dy|$_{cm}$ ~ 16.0 +/- 0.4**

**$\overline{L}$: dn/dy|$_{cm}$ ~ 12.6 +/- 0.4**




**$W^-$/ evt ~ 6 x 10$^{-4}$, $W^+$/ ev ~ 6 x 10$^{-4}$**

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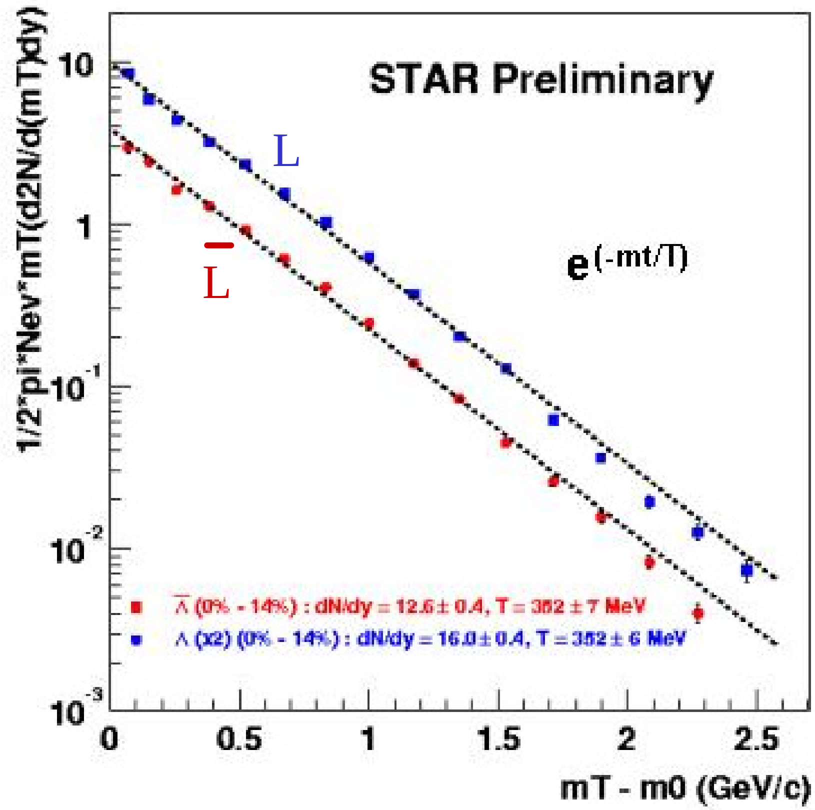
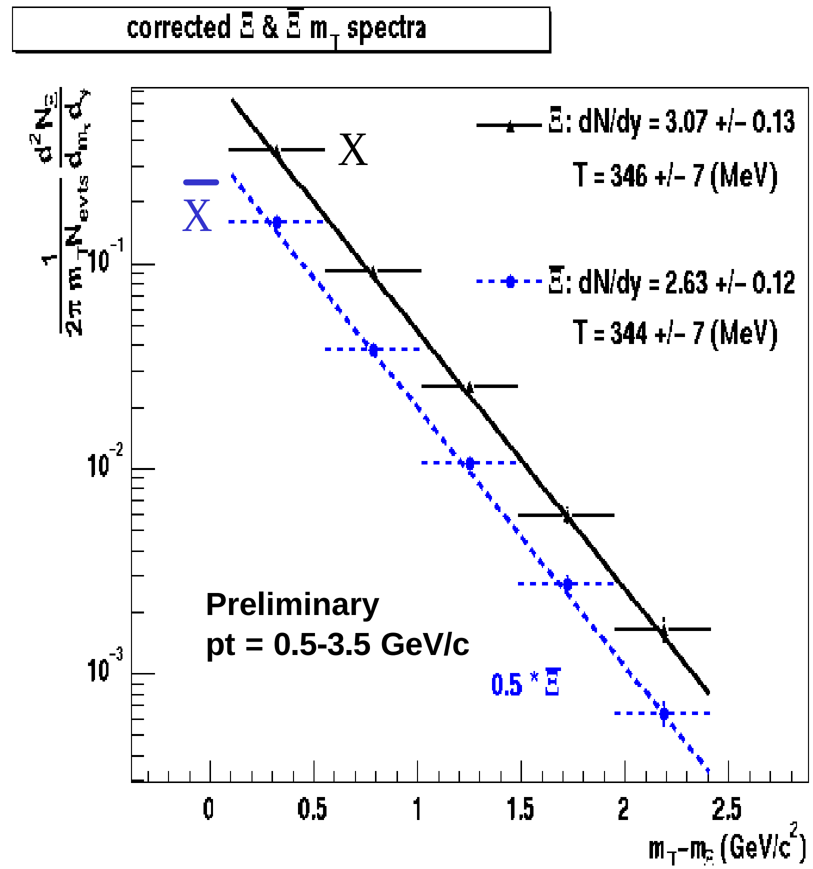
# Central $m_T$ Spectra and Slopes for L  and X



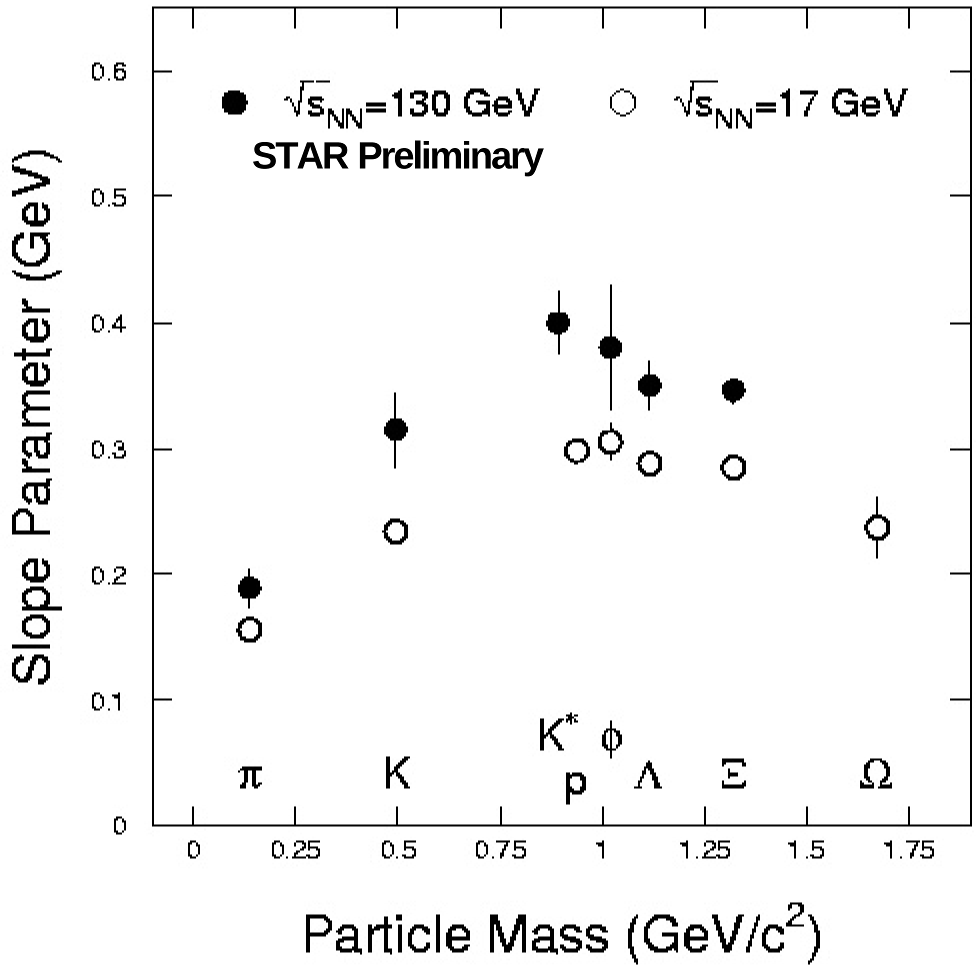




**Spectra are ~ exponential (deviate at high $p_t$)**

**L and X spectra and shapes ~ similar**

# STAR Mass Dependence of $m_T$ Slopes - Central Collisions

Slope T from fit to $m_T$ spectra: $$\frac{1}{m_T}\frac{dN}{dm_T} \propto A \exp\left(-\frac{m_T}{T}\right)$$




**Indicates stronger radial flow at RHIC relative to SPS**

**Proton slope varies strongly with pt (not shown).**

**PHENIX p slope ~ 350 MeV in $m_T$ region of STAR Λs.**

**Multi-strange baryons appear to decouple earlier!**

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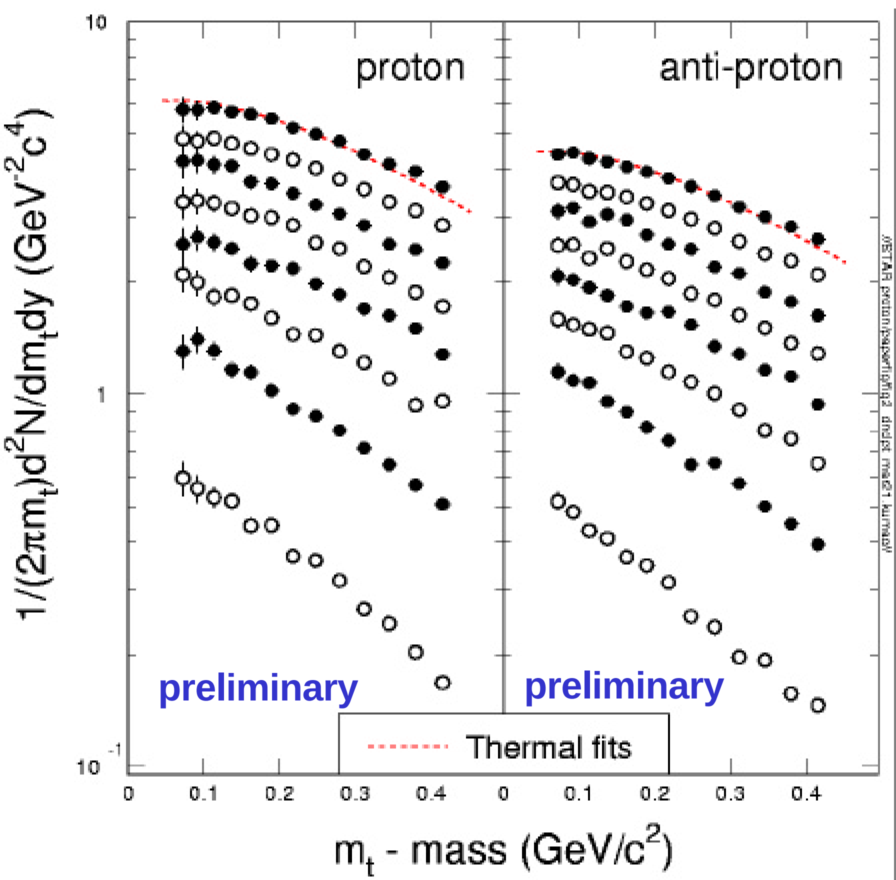
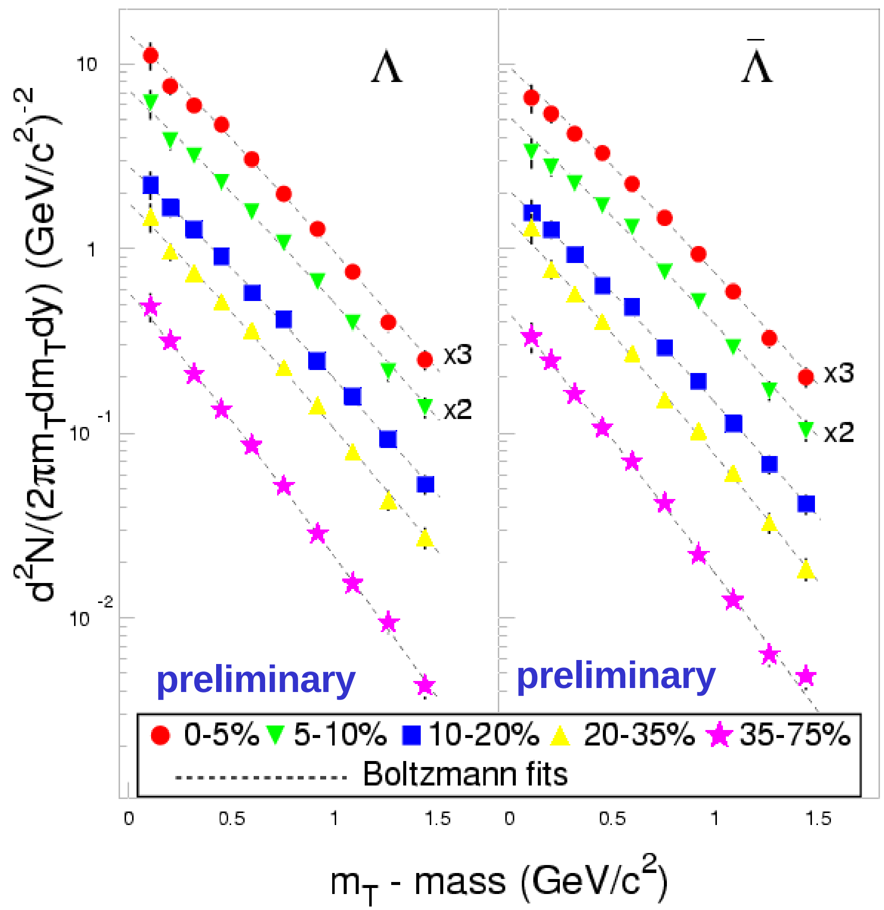
# Centrality Dependence of $m_T$ Spectra for p, $\bar{p}$, L & $\bar{L}$




Boltzmann fits better than exponential

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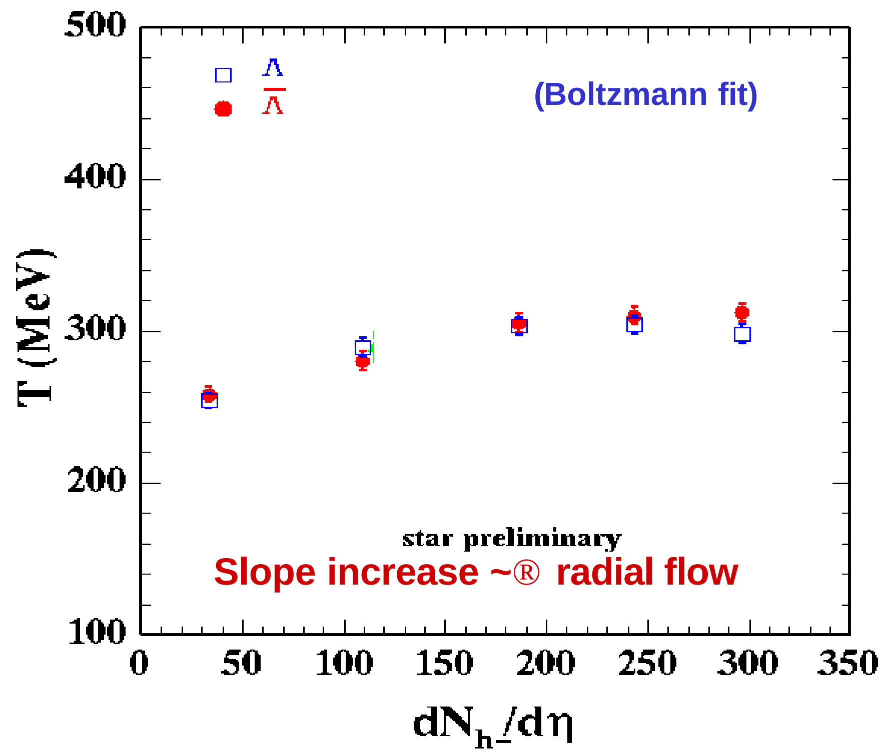
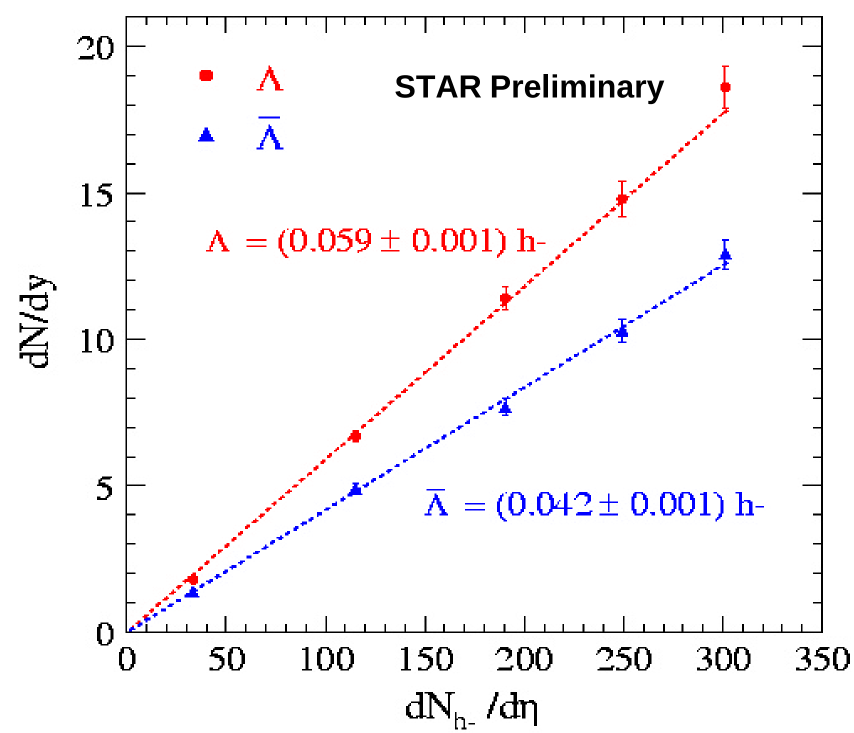
# Centrality Dependence: $m_T$ Spectra & Yields for L & $\bar{\mathrm{L}}$




L and $\bar{\mathrm{L}}$ slopes and spectra ~ identical

production mechanisms the same

rescattering effects the same?

$\bar{\mathrm{L}}$ / L ratio constant vs centrality (out to pt ~ 2.5 GeV/c)

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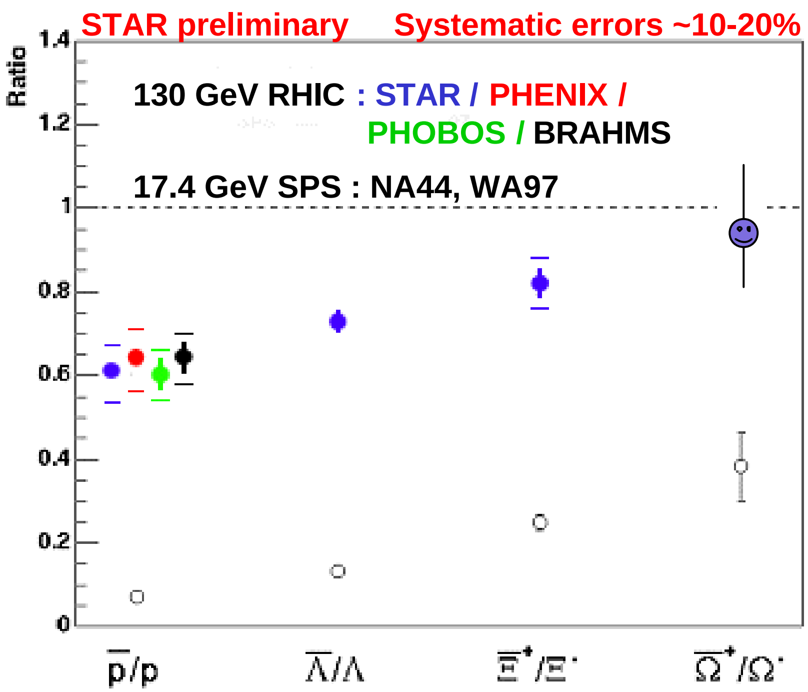
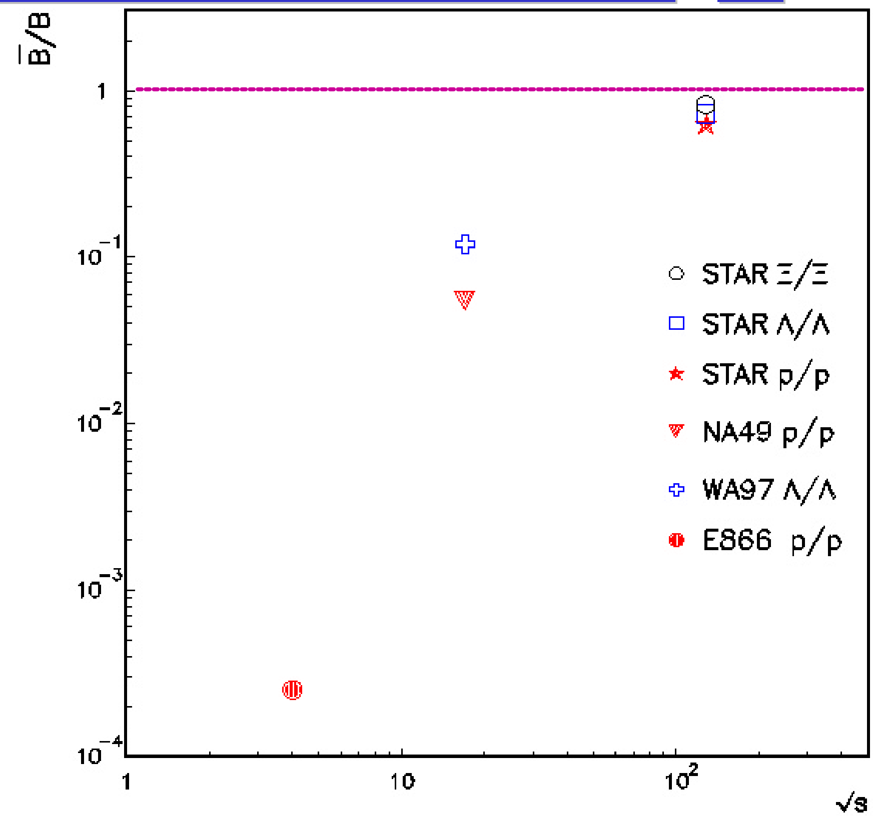
# Anti-baryon/Baryon Ratios (and vs Ös)




- **Ratios fit into Quark Coalescence Model or Statistical Model!**

  **Data for |y| < 0.5 only:**

  **i.e. not global ® local equilibrium?**

- **fit all ratios in statistical model (c²/dof = 3):**

  **$m_B$ / T = 0.28 +/- 0.03**

  **$m_s$ / T = 0.03 +/- 0.01**

- **Baryon-pair production increases with Ös**
- **Mid-rapidity region near `B/B = 1 at RHIC**

  **® low net baryon density**

- **at RHIC - Not baryon-free!** $\frac{Y_{pbar}}{Y_p} = \frac{Y_{pair}}{Y_{pair}+Y_{Tr}} \approx 0.65$

**Pair production > baryon transport:** $\frac{Y_{pair}}{Y_{Tr}} \approx 2$

**2/3 of protons from pair production**

**1/3 from initial baryon number**

**(transported over 5 units of rapidity!)**

**Baryon transport dynamics?**

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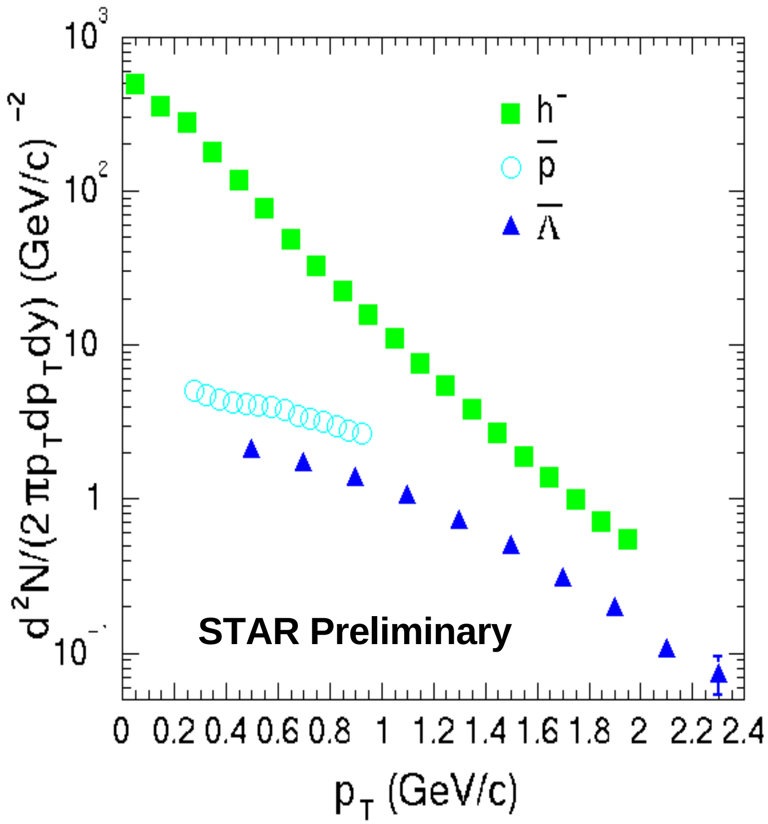
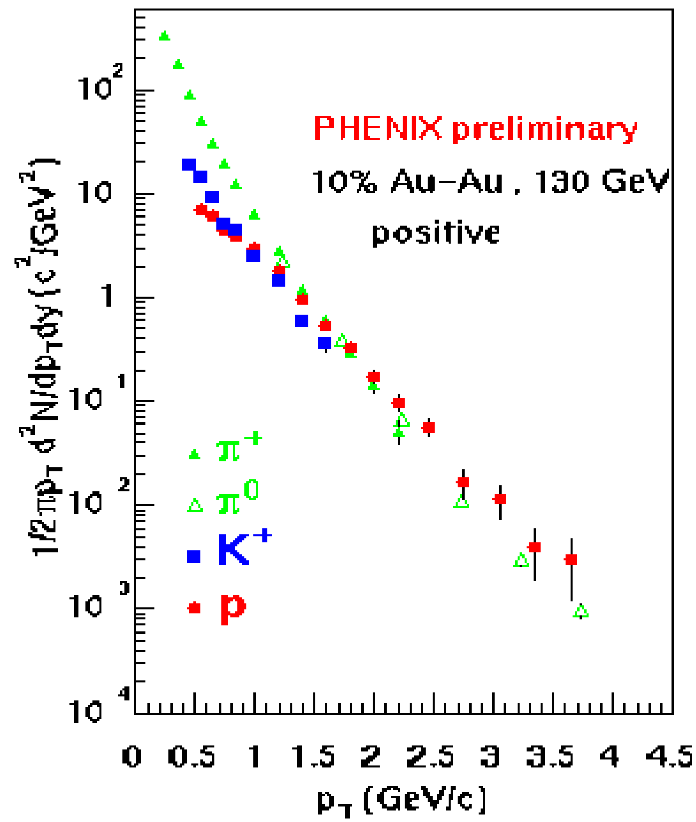
# Baryons vs. Mesons as $p_T$ Increases




**Suggests that the ratio baryons/mesons > 1 at higher $p_T$**

**Consequence of radial flow or novel baryon dynamics?**

**(e.g. Vitev and Gyulassy nucl-th/0104066)**

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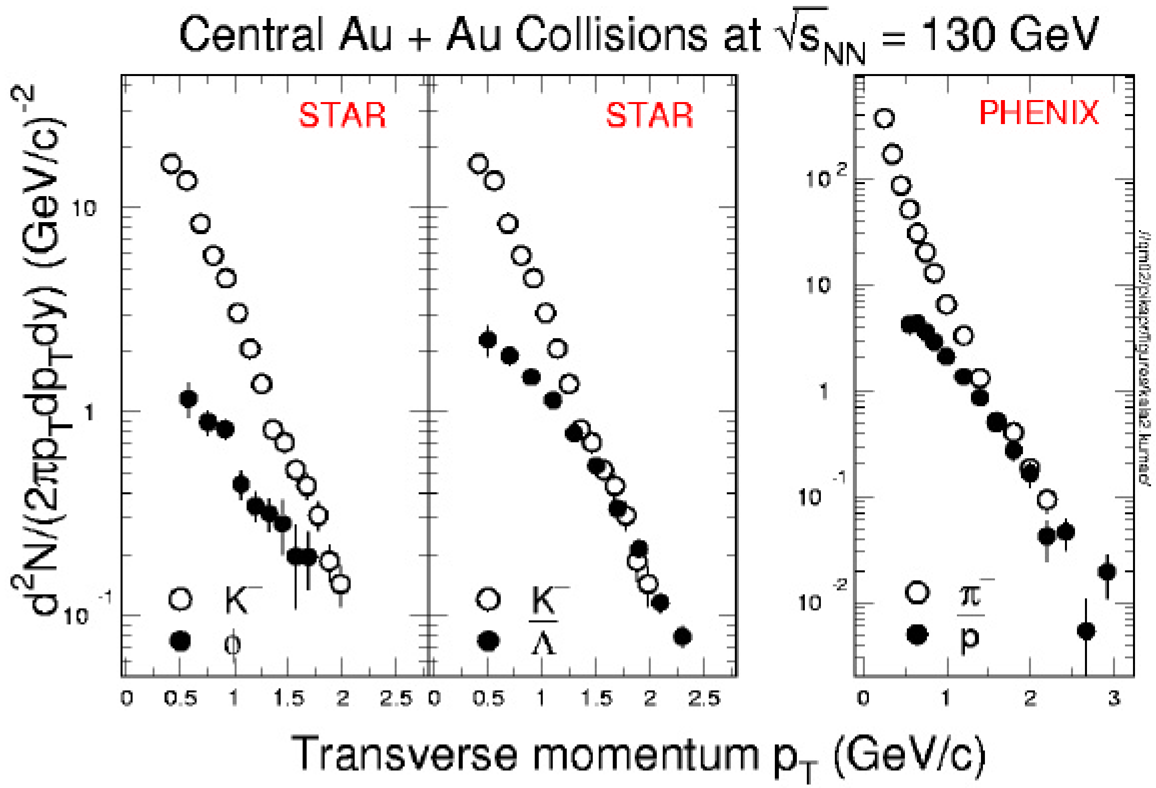
# Strange Baryons and Strange Mesons as $p_T$ Increases



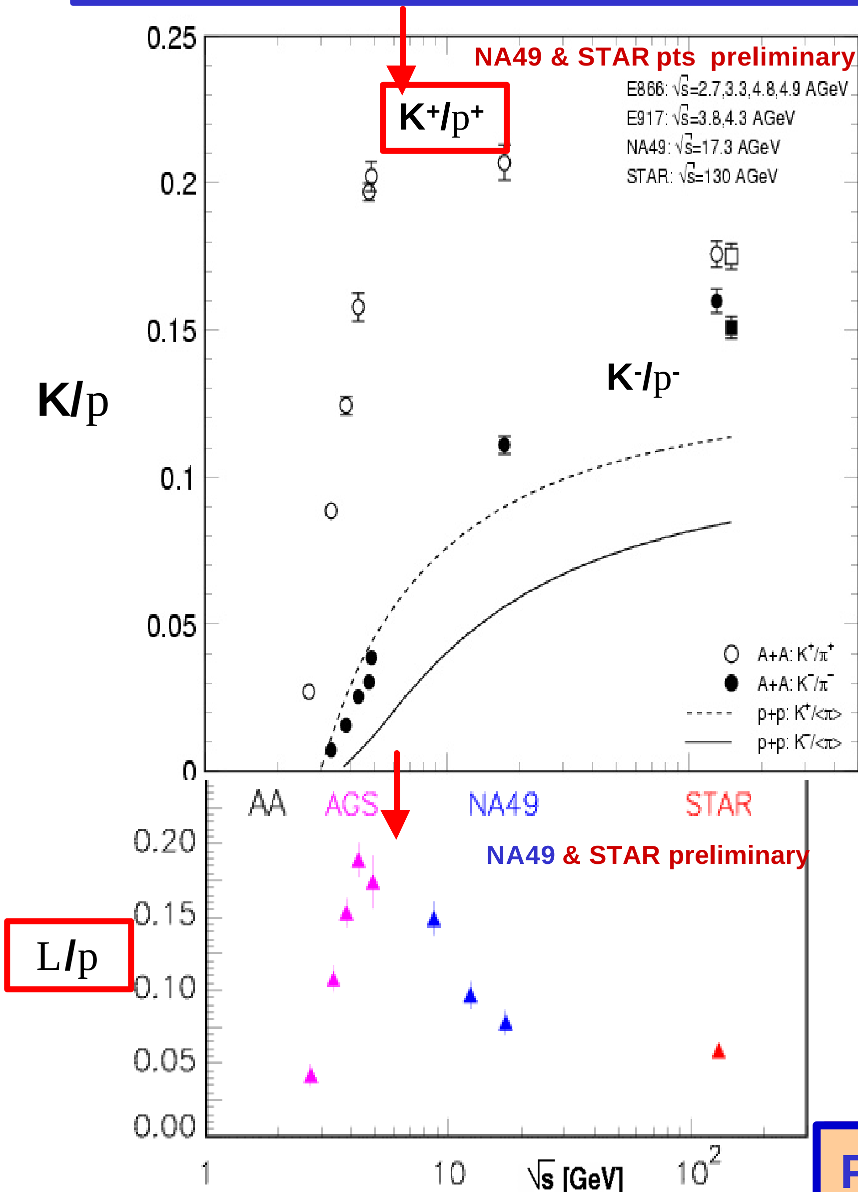

**strong mass dependence of $p_T$ spectra.**

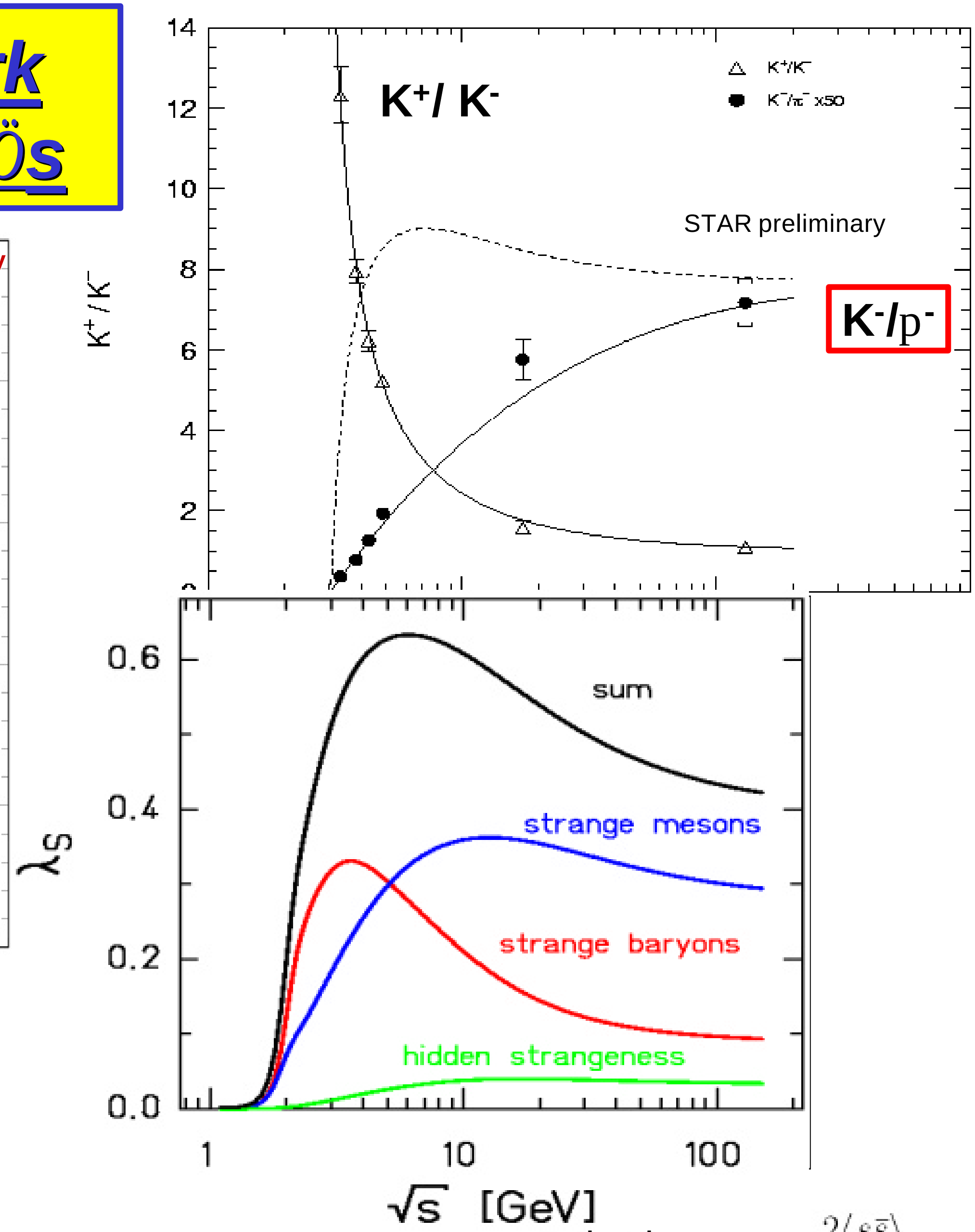
L/K$^-$ , f**/K- ratios increase as $p_t$ increases!**

**Ratio ® 1 at high pt**

**Indicates flow (+rescattering) rather than novel baryon dynamics at high pt**

# Strange / light Quark Ratios - K/p, L/p vs Ös

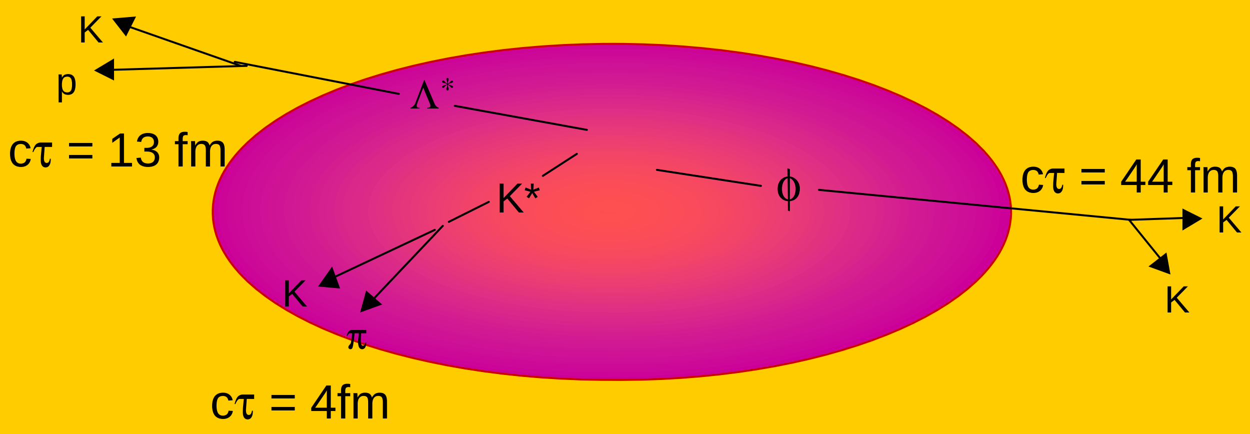



$$\lambda_s \equiv \frac{2\langle s\bar{s}\rangle}{\langle u\bar{u}\rangle + \langle d\bar{d}\rangle}$$

**Pair production increases with Ös**

# Short-lived Resonance Production




- Resonances formed at Chemical Freeze-out
- Extract yield, spectra, mass, width of various resonances
- Survival time between Chemical and Kinetic Freeze-outs
- Resonances sensitive to Time Scale & Dynamics of System

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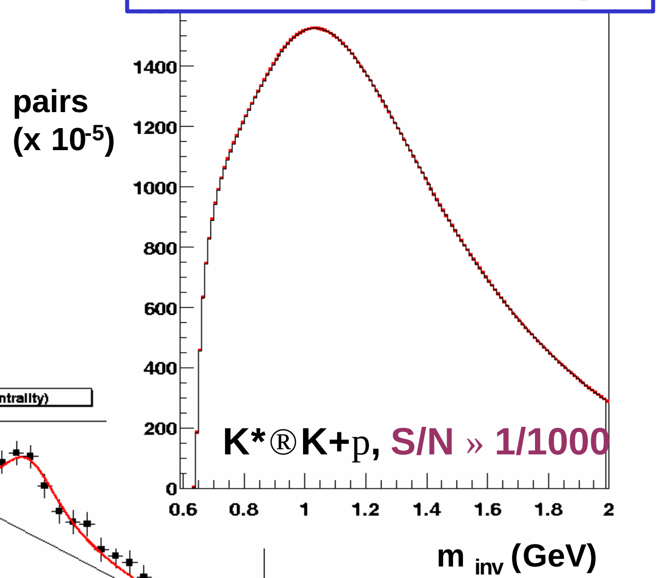
# Short-lived Resonances

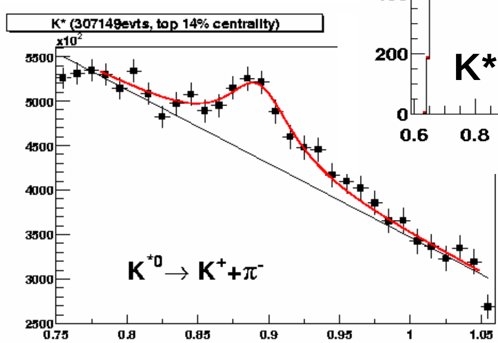
| | K*(892) | f (1020) | S(1385) | L(1520) |
|---|---|---|---|---|
| **Width** G **:** | 50.7 MeV | 4.4 MeV | 36-39 MeV | 15.6 MeV |
| **Lifetime** t : | 3.9 fm/c | 44 fm/c | 5.2 fm/c | 12.8 fm/c |
| **Decay mode:** | Kπ (~100%) | $K^+K^-$(49%) | Λπ (88%) | pK (~22%) |

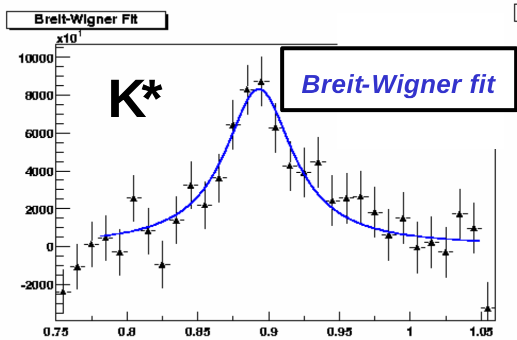
- **Useful when resonance lifetimes span the range of fireball lifetimes.**
- S**(1385) and K*(892) 2 - 3 times shorter lifetimes than** L**(1520).**

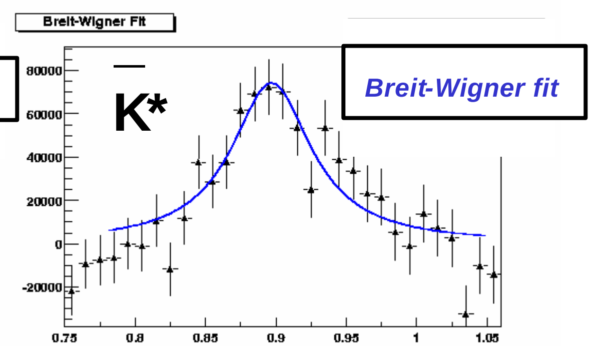
# STAR Resonances via Mixed Event Method

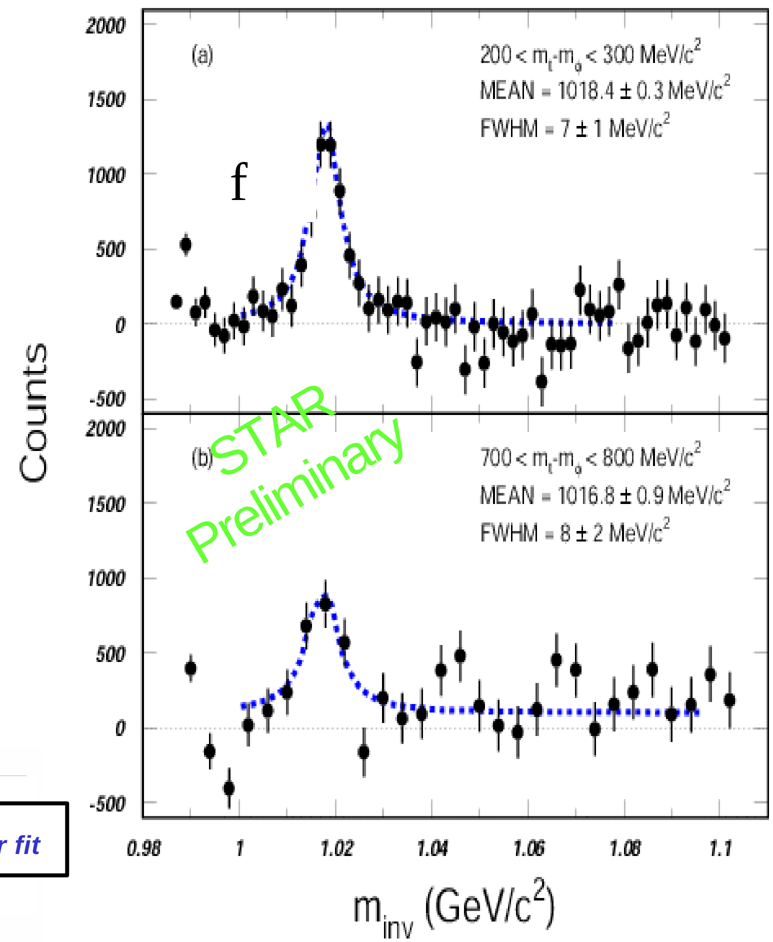
*K* combine all $K^+$ and $\pi^-$*



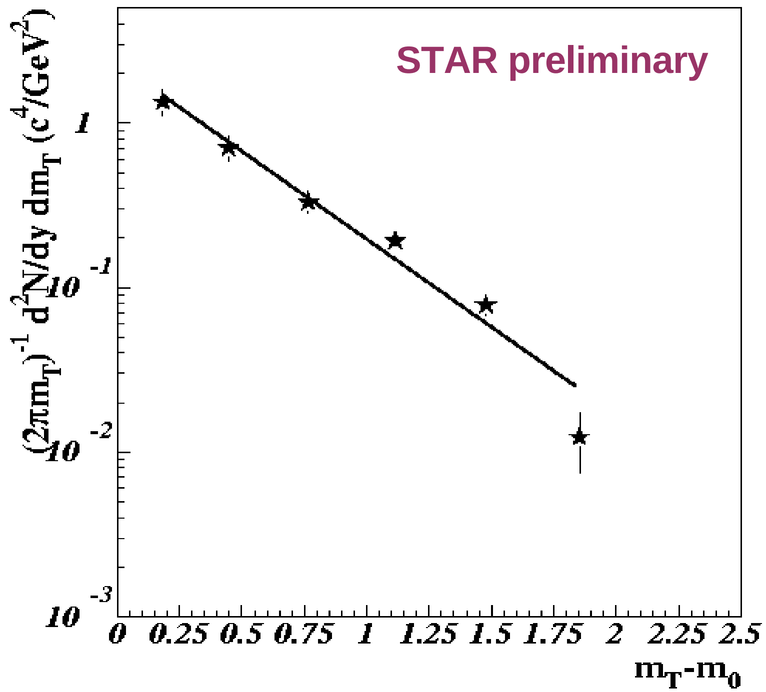



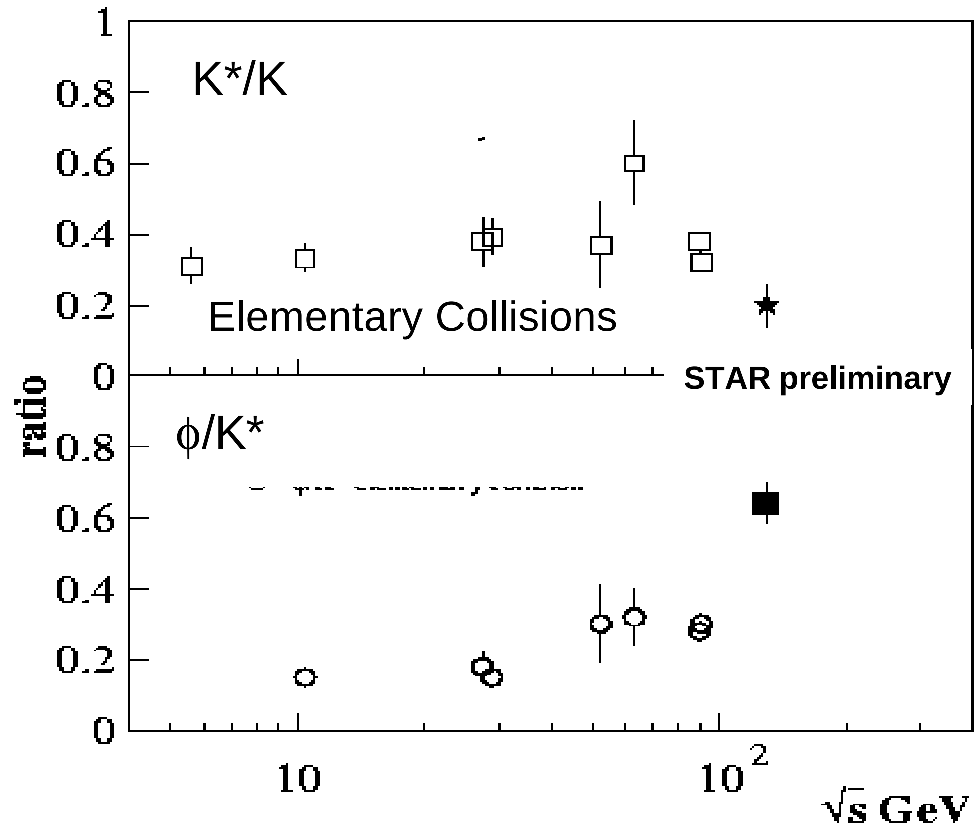




**Masses and widths are consistent with PDG book (convoluted with TPC resolution)**

# K* Spectrum and Measured Ratios




Inverse Slope (T = 400 ± 20 ± 40 MeV)

T(K*) ~ T(f) ~ T(L)

K*/K ® in AA less than in e+e- and pp

f/K* ® strangeness enhancement or loss of K*?

Another prospect : K+p®K* regeneration after chemical freezeout.

**T and K*/K ~ consistent with sudden freeze-out scenario?**

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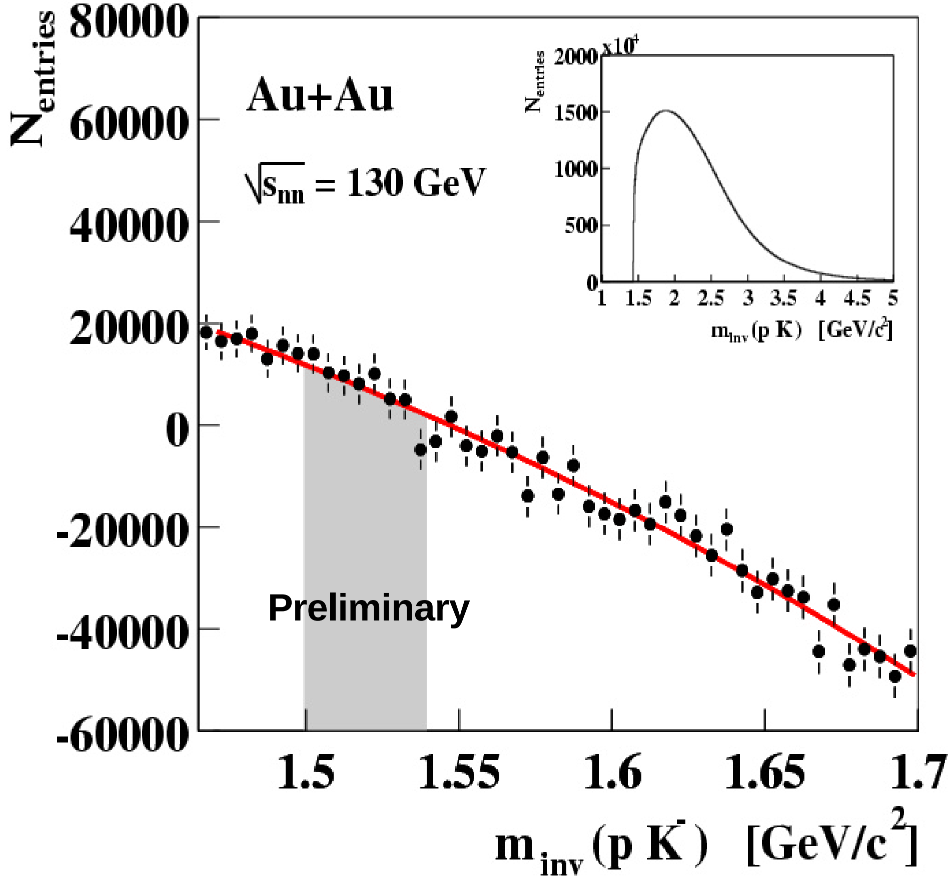
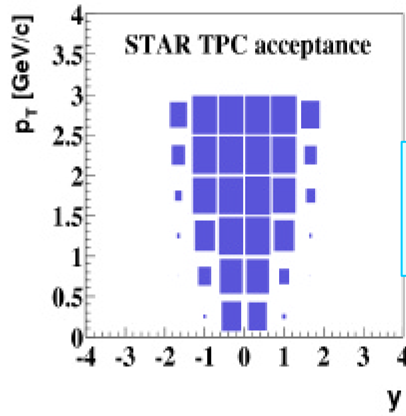
# L(1520) in STAR

**No L(1520) observed!**

**14% most central events** 370K events




T = 350 MeV taken from Λ

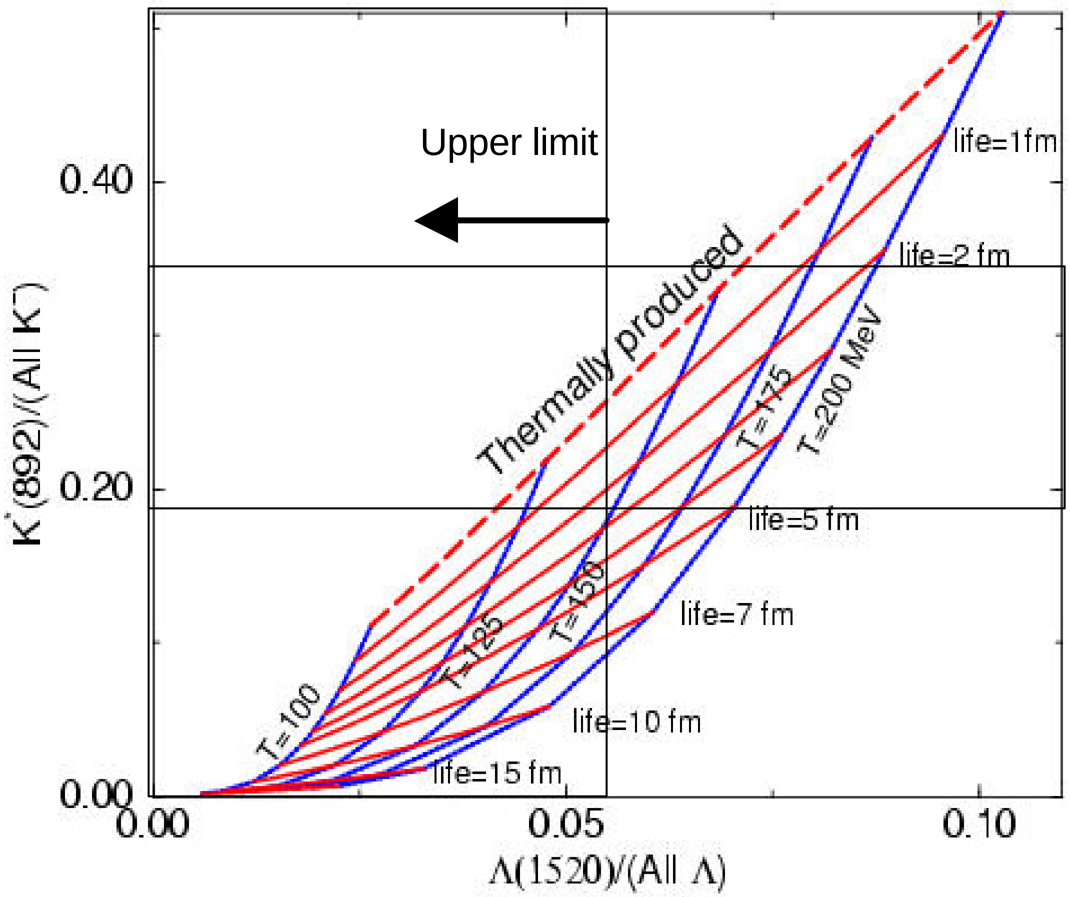
|y| <1 **acceptance ~87±5%**

**Upper limit estimate: dN/dy preliminary**

$\langle\Lambda(1520)\rangle_{|y|<1}$ < 1.2 at 95% C. L.

# Start at Temperature and Lifetime from L(1520)/L and K*/K Ratios

G. Torrieri and J. Rafelski, Phys. Lett. **B509** (2001) 239




**Example of future prospects - this Thermal Model:**

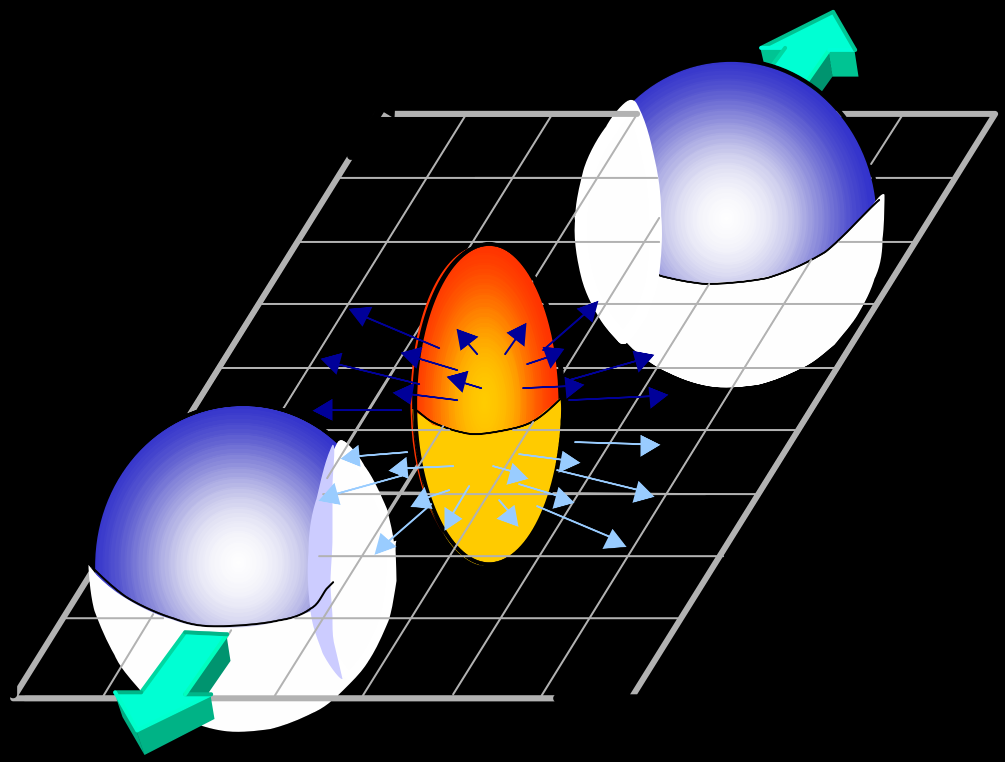
• Compares these two particle ratios & gets:

➔ **low chemical freeze-out temperature T<150 MeV.**

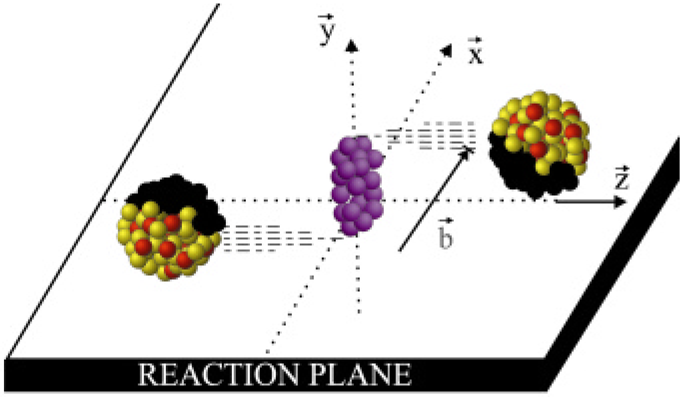
➔ **very short fireball lifetime t ~0 between chemical and thermal freeze out.**

**STAR: L(1520)/allL < 0.055 at 95% C.L**

# Elliptic Flow



# *Elliptic Flow - A Sensitive Probe of Early Dynamics*

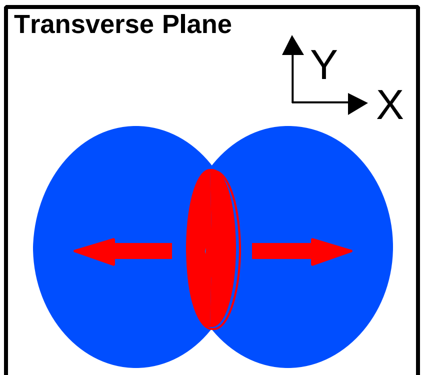



**Elliptic flow measures:**

® **response of the system to early pressure**

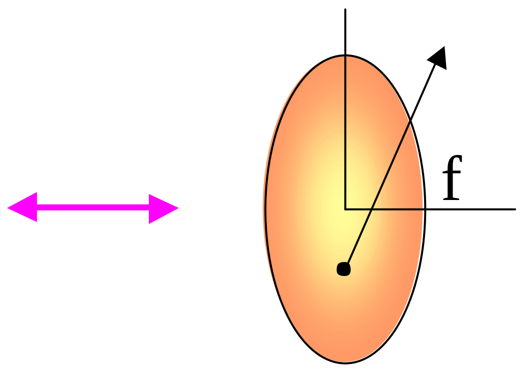
® **the system's ability to convert original spatial anisotropy into momentum anisotropy**

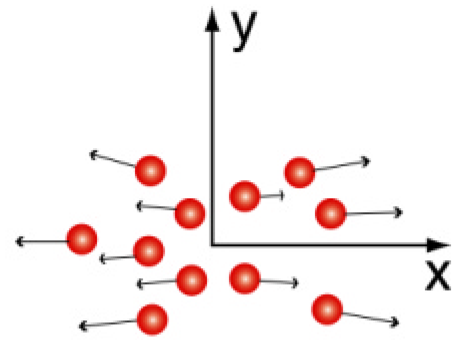
- **Elliptic flow** predictions from hydrodynamic models sensitive to **early dynamics of initial system**




$$e = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

**XZ-plane - the reaction plane**



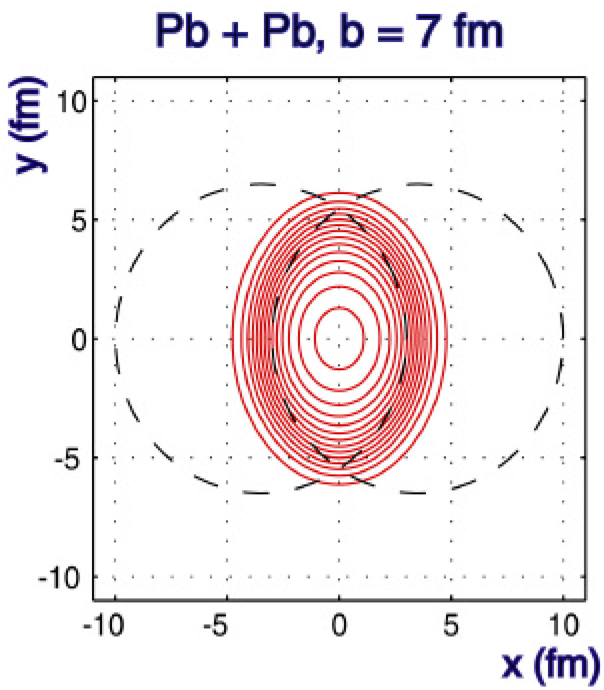

$$f = \mathrm{atan}\frac{p_y}{p_x}$$

$$v_2 = \langle \cos 2f \rangle$$

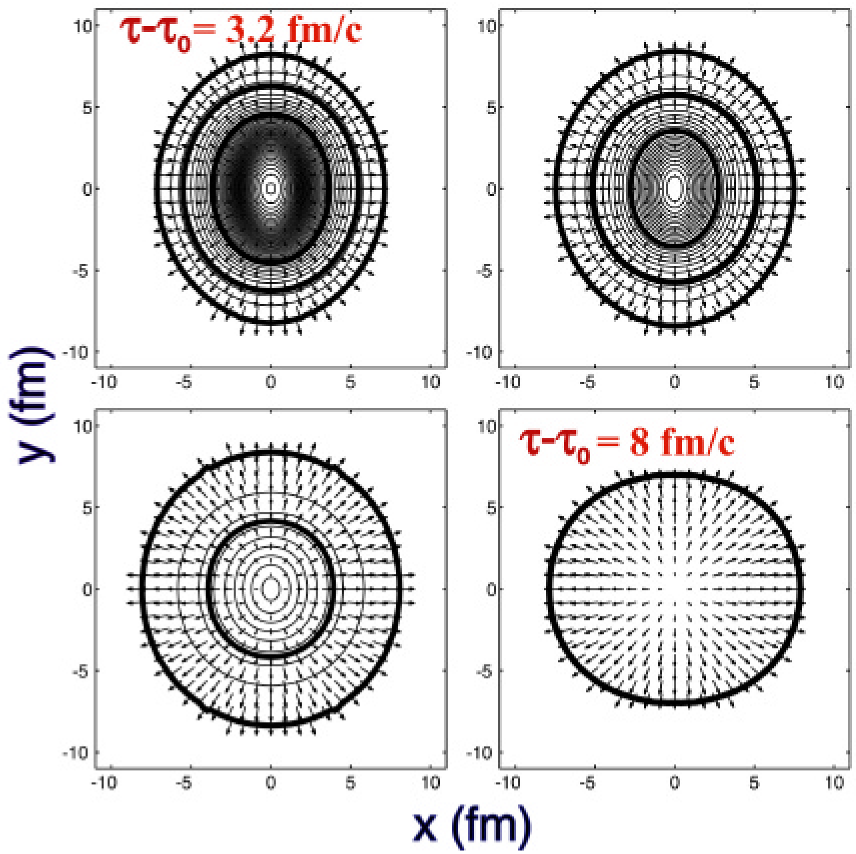
**$v_2$: 2nd Fourier harmonic coefficient of azimuthal distribution of particles with respect to the reaction plane ® measures elliptic flow**

# STAR Hydrodynamic Calculation of Elliptic Flow

P. Kolb, J. Sollfrank, and U. Heinz

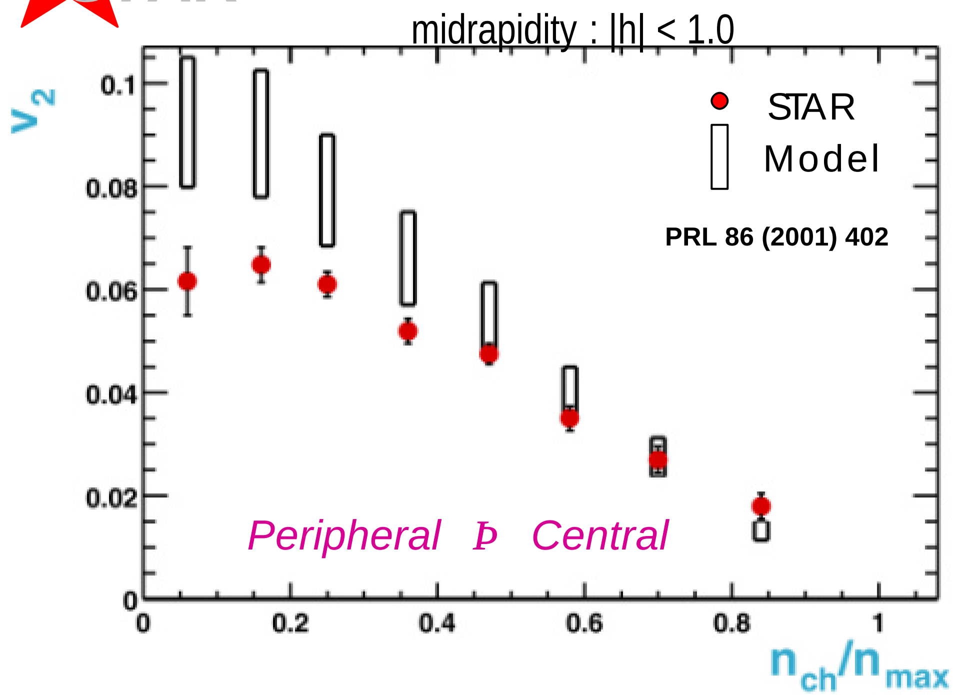


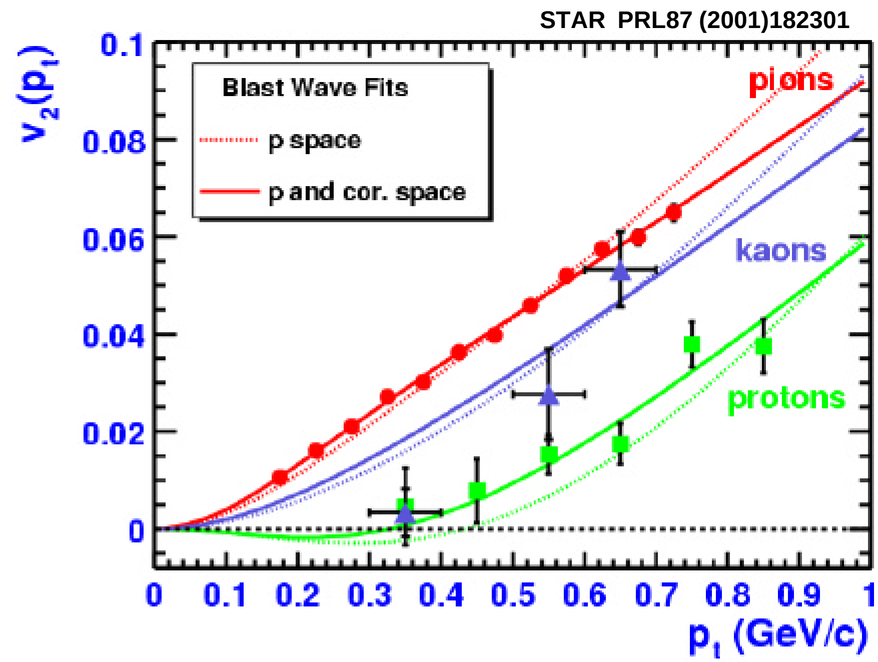

Equal energy density lines



# Charged Particle Elliptic Flow ($v_2$) vs. Centrality

STAR




**Initial data ® hydro model limit**

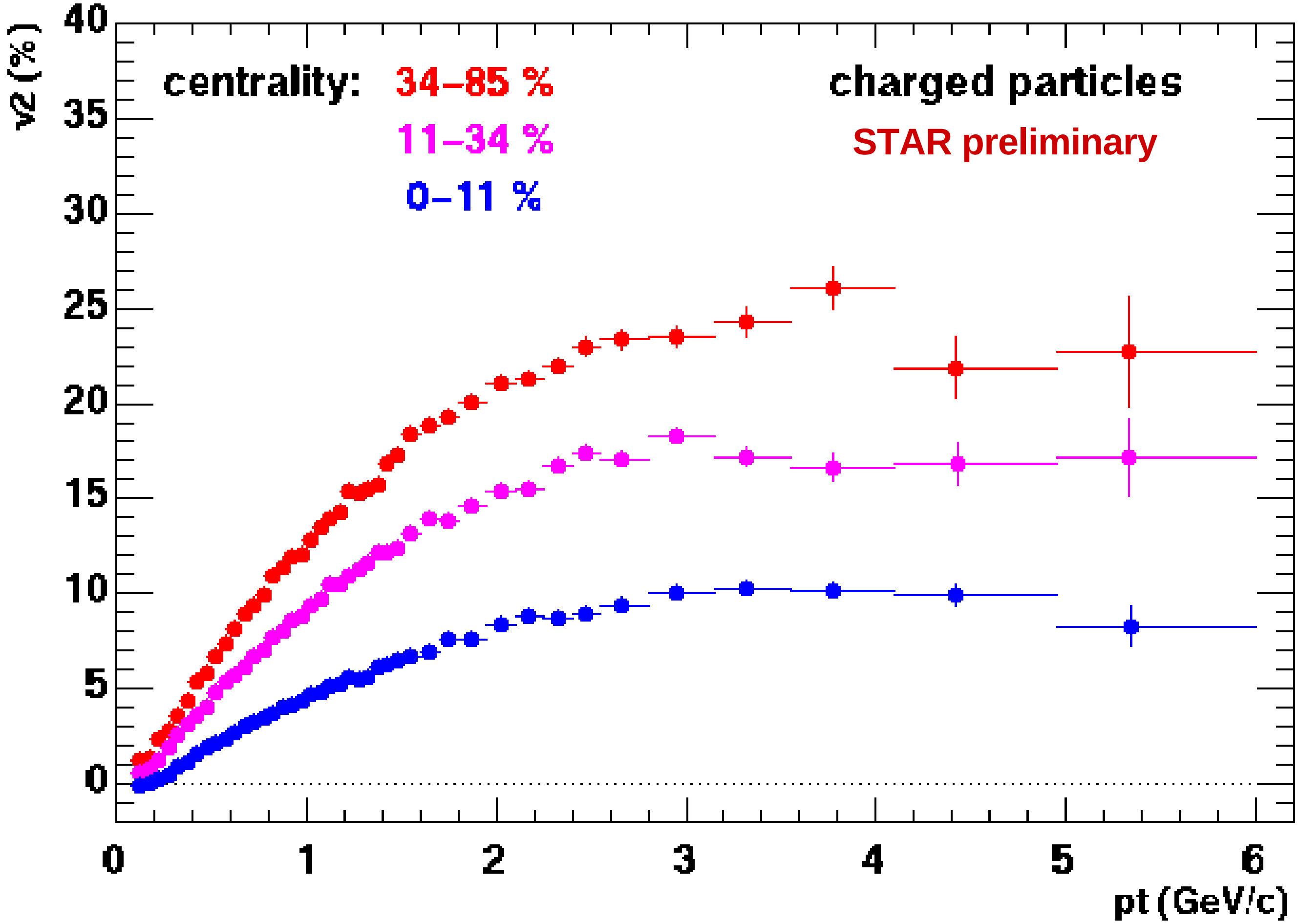
**® larger $v_2$ than at SPS**

**Particle mass dependence**

**® typical hydro behavior**

**Evidence that initial spatial asymmetry is efficiently translated into momentum space anisotropy (as in hydro)**

# Centrality Dependence of $v_2(p_t)$

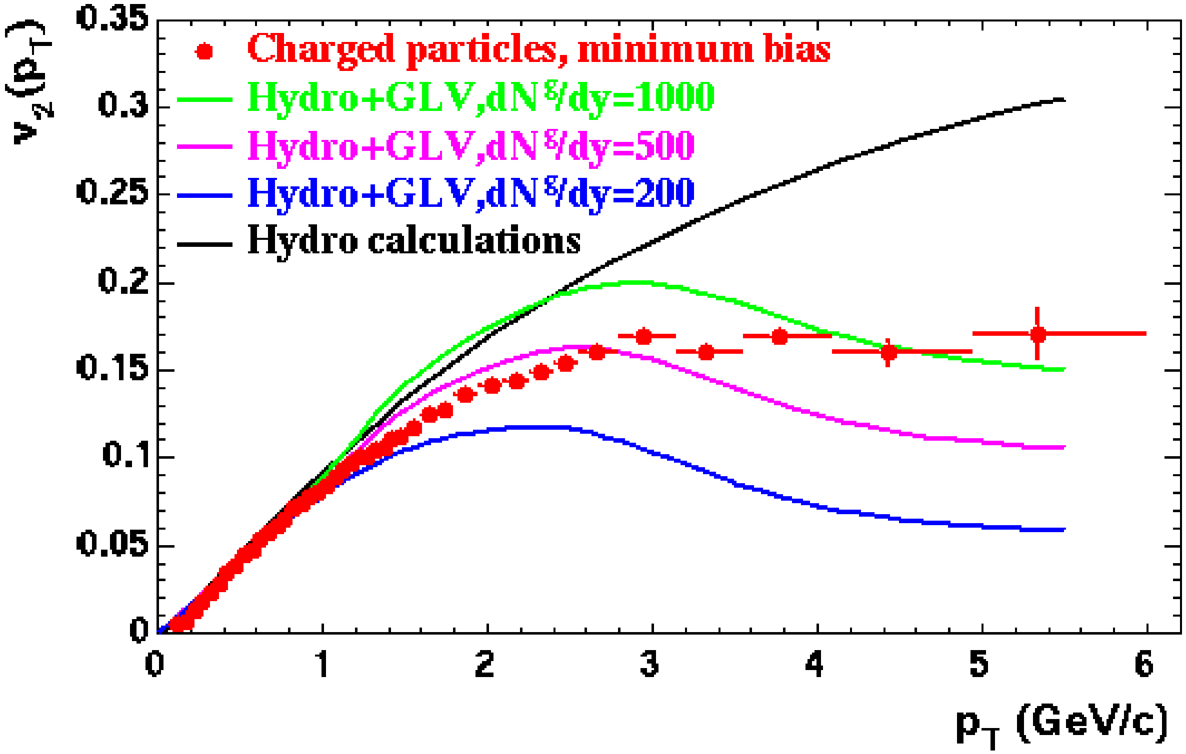



- Measured $v_2$ increases with increasing $p_t$ and flattens above ~ 3 GeV/c.
  - also observed in STAR for L and $K^o_s$ out to 3 GeV/c
- Relatively large values of $v_2$ out to $p_t$ ~ 6 GeV/c.
- Larger values of $v_2$ for more peripheral collisions.
- Turn over at high $p_t$ ?

# STAR Charged Particle Anisotropy at High Pt in STAR

**Calculation: Hydrodynamics + hard scattering**

**(M. Gyulassy, I. Vitev & X.N. Wang, nucl-th/00012092, PRL)**




**Hydro + hard scattering model and data:**

- hydrodynamic behavior up to ~1.5 GeV/c
- $v_2$ flattens / decreases (?) at high $p_t$
  - reflects gluon density at high $p_t$
- data ® compatible with scenario of parton energy loss in deconfined medium

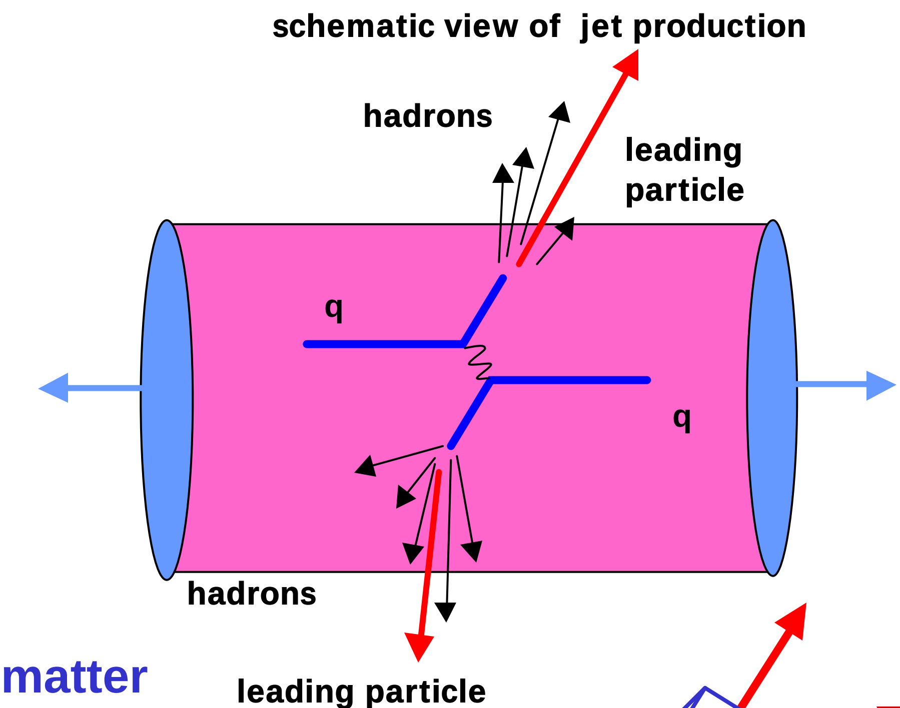
# ***High Transverse Momentum Physics at RHIC:***

# ***Parton Energy Loss / Jet Quenching?***

# New with Heavy Ions at RHIC

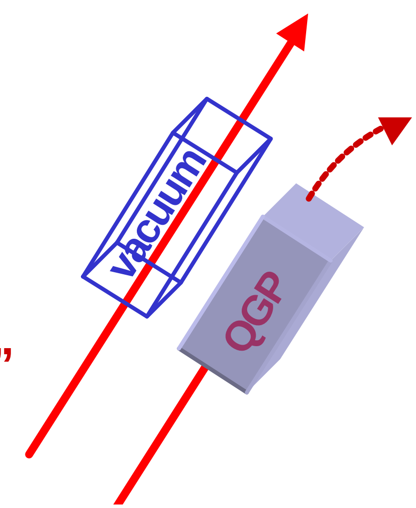
- New opportunity for heavy ion physics ® ***Hard Parton Scattering***
  - Ö$s_{NN}$ = 130 GeV at RHIC vs Ö$s_{NN}$ = 17 GeV at CERN SPS

- Jets and mini-jets
  (from hard-scattering of partons)
  ® 30 - 50 % of particle production
  ® high $p_t$ leading particles
  ® azimuthal correlations



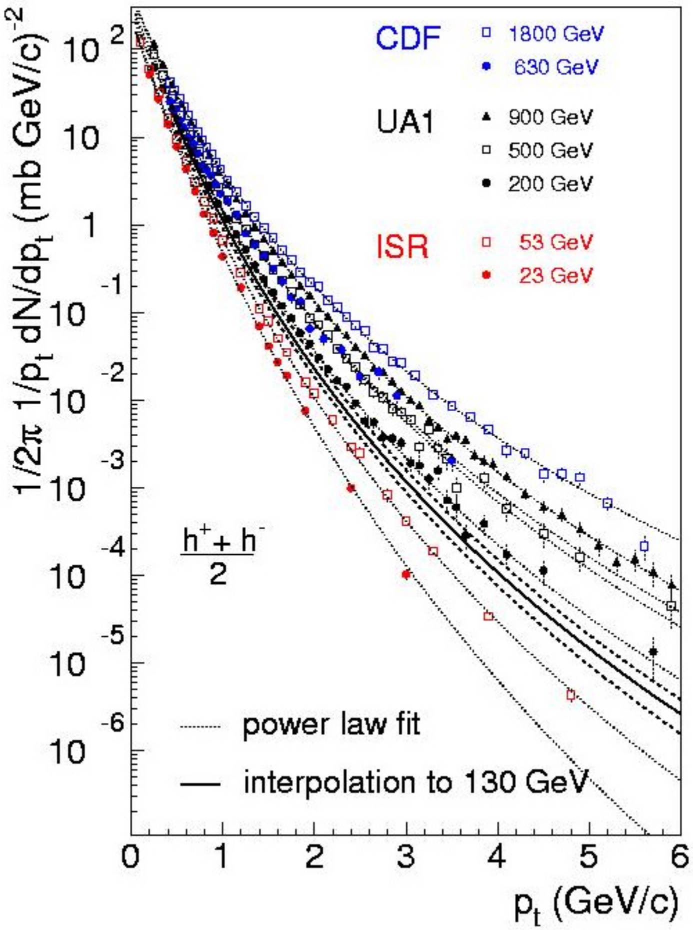

- Extend into perturbative regime
  - Calculations reliable

- Scattered partons propagate through matter
  radiate energy (~ GeV/fm) in colored medium
  - interaction of parton with partonic matter
  - suppression of high $p_t$ particles
    called "parton energy loss" or "jet quenching"
  - suppression of angular correlation

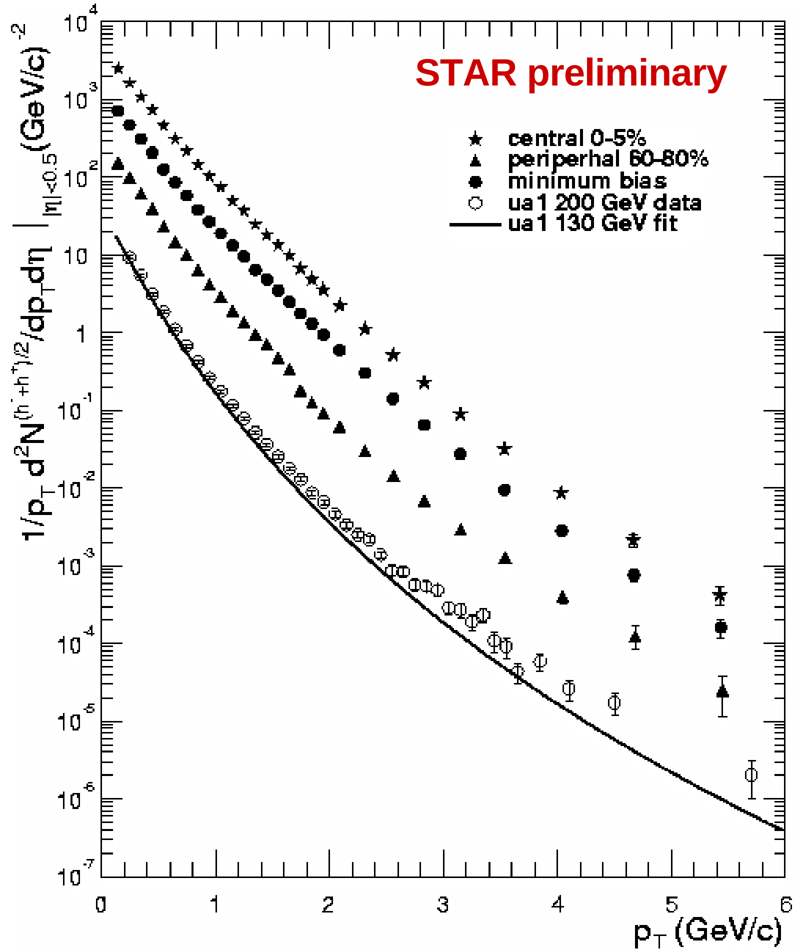


# *Inclusive Negative Hadron $p_t$-distributions*

**elementary collisions**




**Ös = 130 GeV Au + Au**

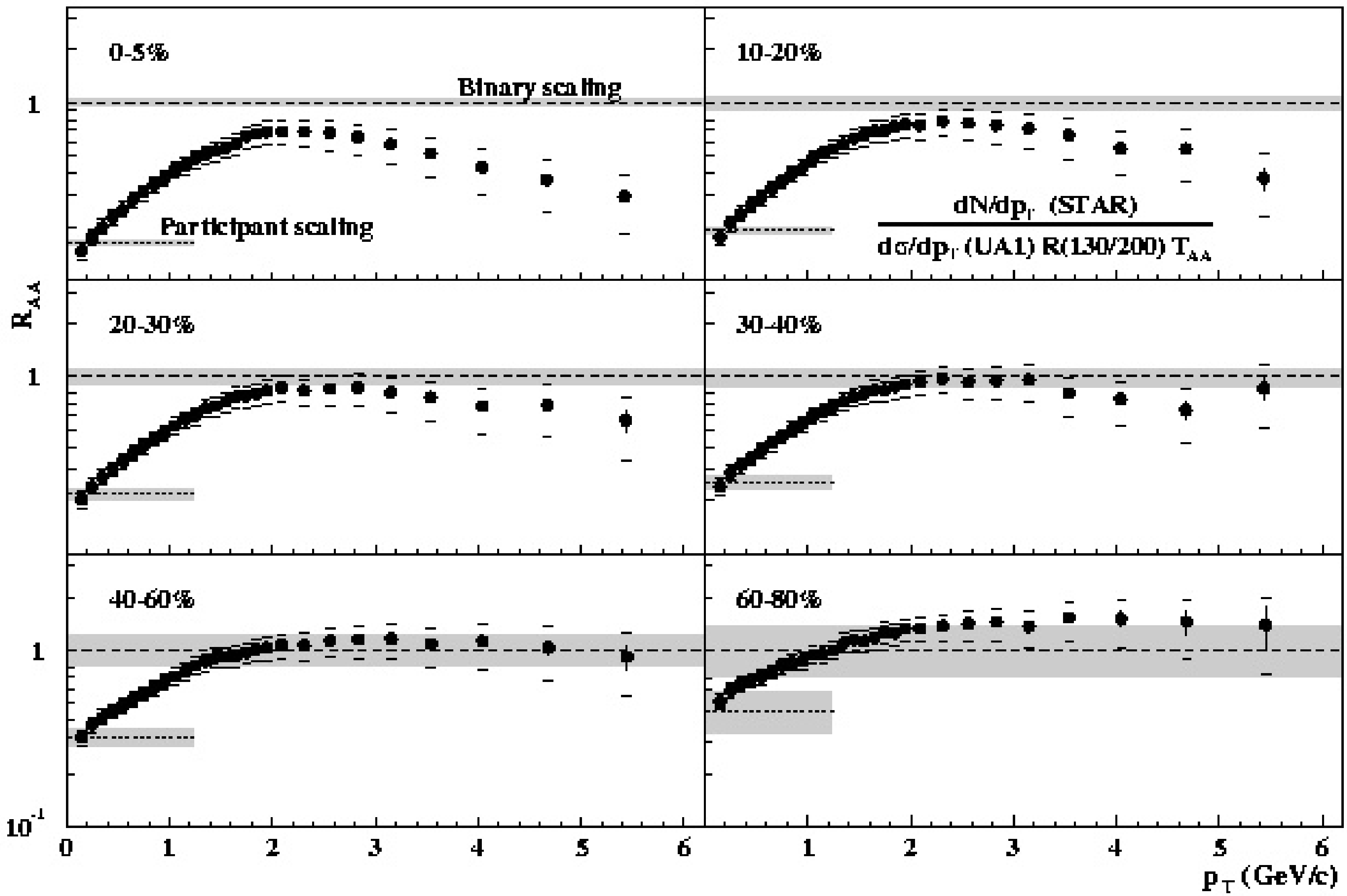



**Good power law fits:**

**$s_{pp} = d^2N/dp_t^2 = A\ (p_0+p_t)^{-n}$**

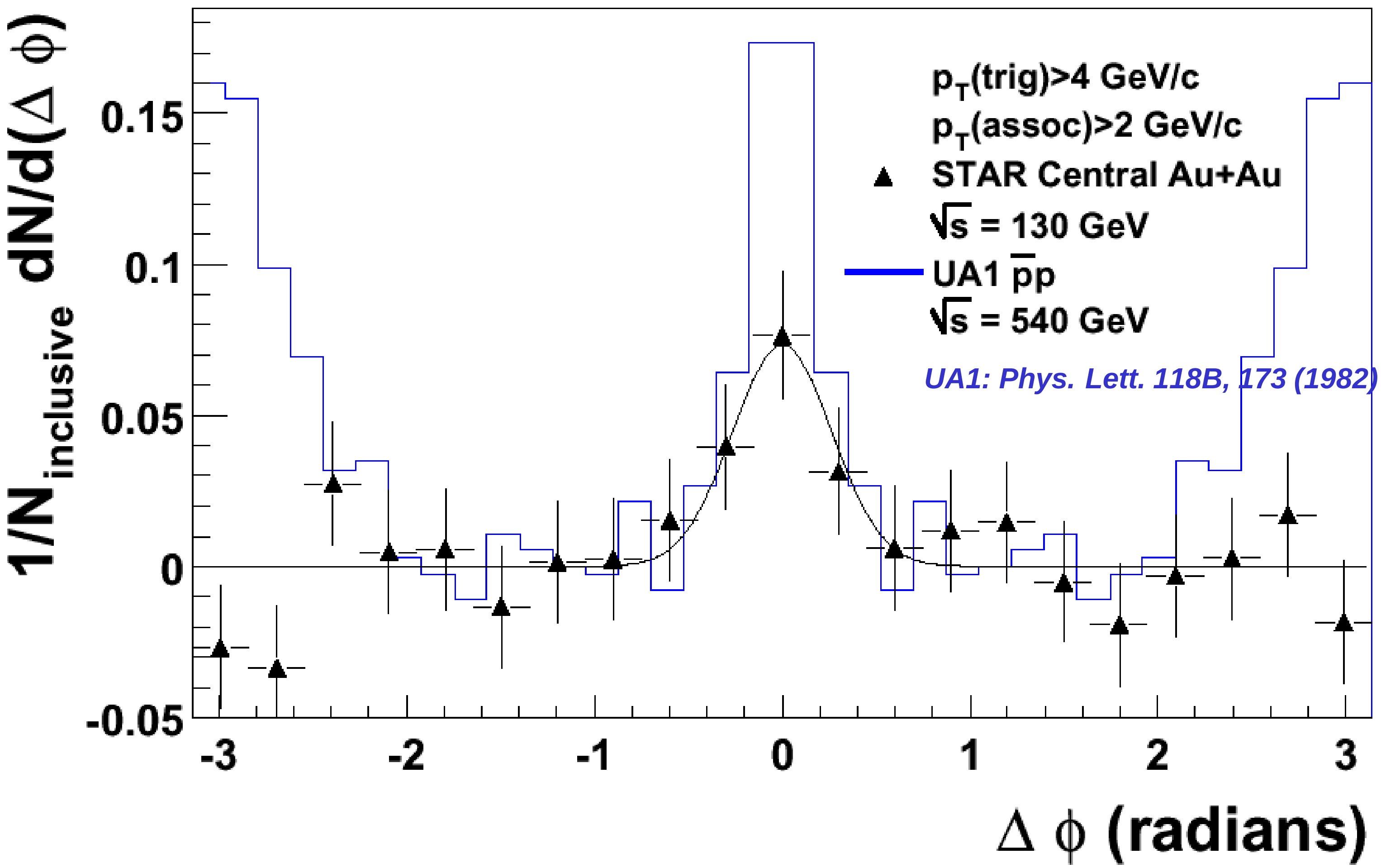
**interpolate A, $p_0$, n to 130 GeV**

# Centrality Dependence Relative to UA1



STAR

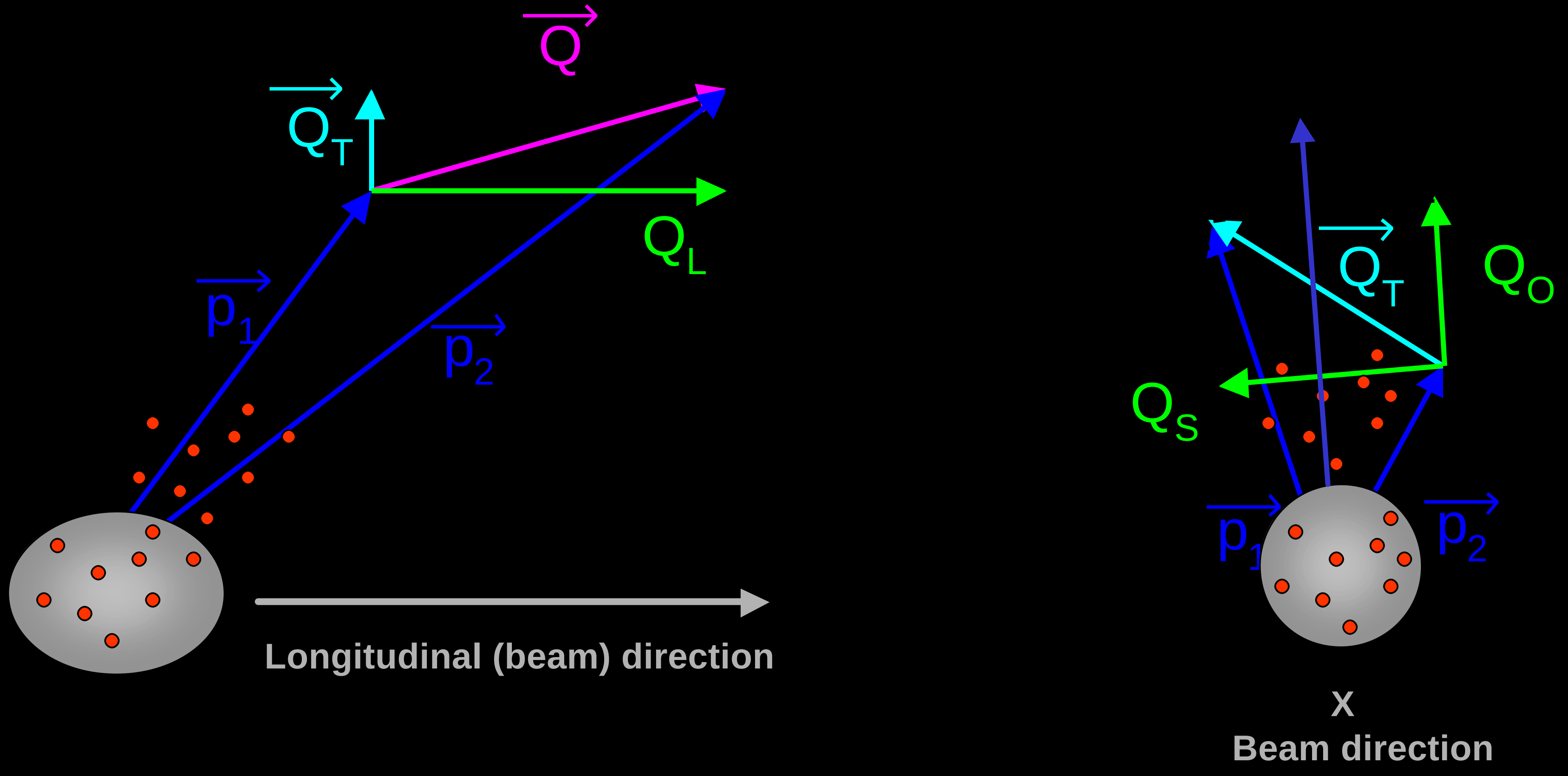
# High $p_T$ Azimuthal Correlation ® Hard Scattering




**See P. Jacobs talk tomorrow**

# Two-Particle Correlations - HBT

For non-interacting identical bosons:



# Two-Particle Interferometry (HBT)

**Use Pratt-Bertsch parameterization:**

**Decomposition of the pair relative momentum (measured in the LCMS frame; $(p_1 + p_2)_z = 0$)**

$$C(q_{Out}, q_{Side}, q_{Long}) = 1 + l e^{-(q_{Out}^2 R_{Out}^2 + q_{Side}^2 R_{Side}^2 + q_{Long}^2 R_{Long}^2)}$$

**Information (for simple sources!):**

**geometrical source size: $R_{side}$**

$$R_{side}^2 = R_{0ut}^2 - (b_{pair} t)^2$$

**lifetime**

**Complications:**

**Source in RHI collisions are not simple!**

**Space-momentum correlations (flow, opacity,…)**

**See/measure partial source ($p_t$, volumes of homogeneity)**

**Interpretations model dependent**

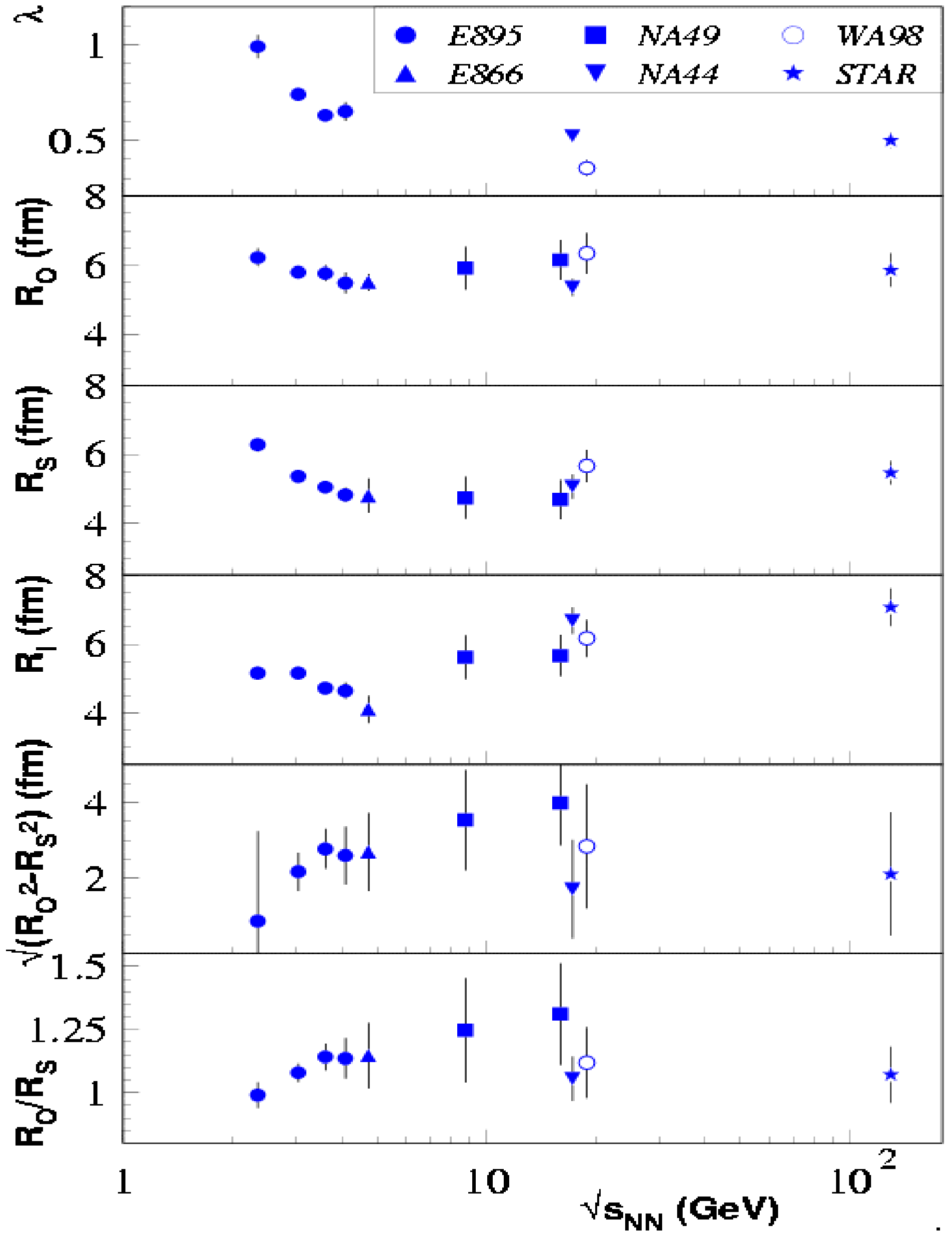
**Some predictions on size and lifetime**

**(Gyulassy and Rischke NPA608 (1996) 479)**

**$R_{out}/R_{side} \sim 2 - 4$ at $k_t = 350$ MeV)**

STAR

# Pion HBT Excitation Function




Compilation of world 3D pp-HBT parameters for

~ 10% central AuAu or PbPb

y ~ 0

$k_t$ ~ 170 MeV.

- **Surprising: no increase in spacial-temporal source sizes which are roughly same as at AGS/SPS ( < 10fm)**

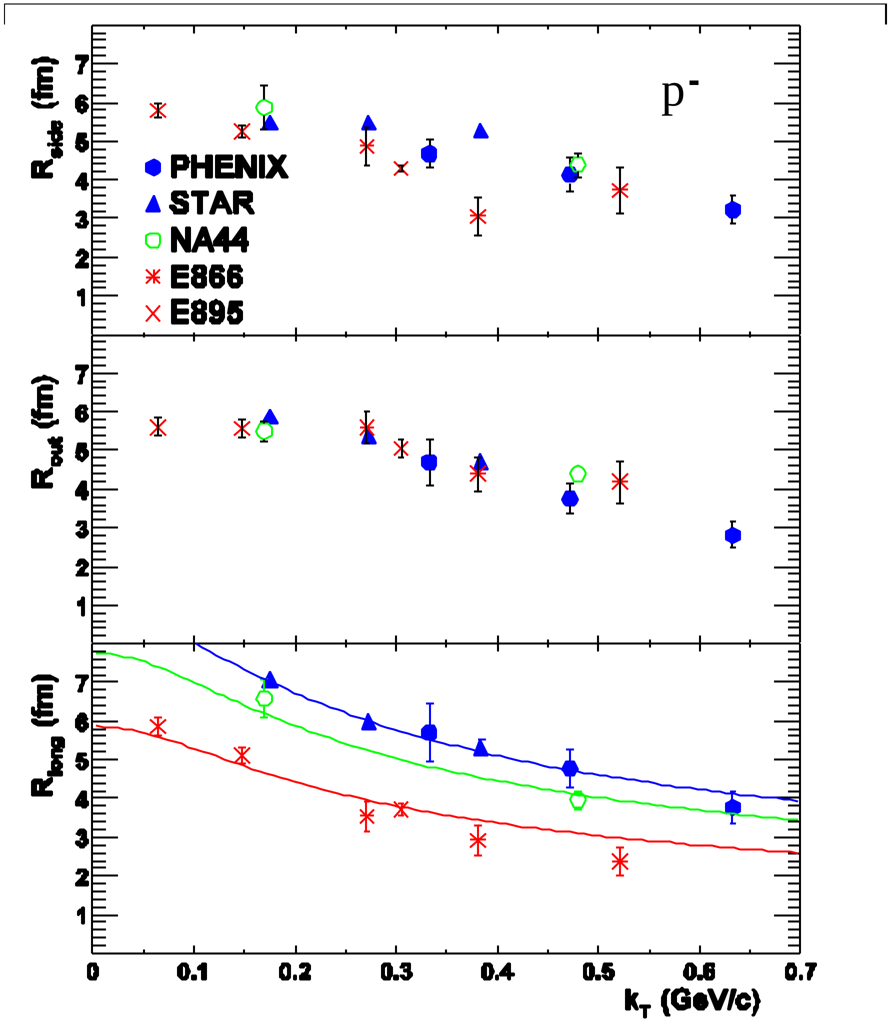
- **radii increase with centrality (expected for $R_{Out}$,$R_{Side}$)**

- **Radii decrease with increasing $k_T$**
  - **flow**

- **$R_{Out}/R_{Side}$ ~ 1**
  - **explosive source**
  - **short freeze-out**

STAR - Phys. Rev. Lett. **87** , 082301 (2001).

# Kt - Dependence of Source Parameters




Compilation from:
M. Lisa *et al.*, PRL **84**, 2798 (2000)
R. Soltz *et al.*, to be sub PRC
C. Adler *et al.*, PRL **87**, 082301
I.G. Bearden *et al.*, EJP **C18**, 317 (2000)

**$R_s$ and $R_o$**

- **decrease with $k_T$ ® flow**
- **similar in size and shape**

**No new behavior at RHIC relative to SPS?**

**But no models predict measured $R_s$, $R_o$ , $R_l$!**

**To force $R_s$, $R_o$ , $R_l$ *fits* models have:**

**systems which *live too long***

**with *very short emission time***

**New information coming from KK and Kp correlations**

***Conclusions and Expectations***

# Some Controversial Conclusions for Discussion

## General conclusions that are least understood theoretically!:

$\bar{B}/B$ ratios

- ® quark coalescence or statistical hadronic production?
- ® baryon number transport dynamics?

Baryon to meson ratio >1 at high pt also in strange baryons

- ® flow rather than novel baryon mechanisms at high pt?

HBT

- ® no long-lived mixed phase (freezeout at critical point or sudden hadronization?)
- ® models predict systems that are too long-lived with short freezeout time
- ® dynamics of chemical and thermal freezeout times not understood!

Short freeze-out time also from

- ® $m_t$ slopes for multi-strange baryons
- ® resonances
- ® HBT

Suppression of high Pt hadrons ® quenching/energy loss?

Azimuthal asymmetry (elliptic flow) at high Pt ® reflect gluon density / energy loss?

# STAR Data Accumulated ® Expectations

***Data Summer 2000*** Ö$s_{nn}$ = 130 GeV Au + Au

- ® 2.0 M total trigger events taken
  - ® 844 K central (top 15%)
  - ® 331 K (top 5%) central trigger events
  - ® 458 K good minimum bias trigger events

***Data Fall 2001*** Ö$s_{nn}$ = 200 GeV Au + Au

- ® ~ 14 M total trigger events taken
  - ® 3.5 M (top 10%) central trigger events
  - ® 4.7 M minimum bias trigger events

***Data Fall 2001 (1-day)*** Ö$s_{nn}$ = 20 GeV Au + Au

- ® ~ 14 M total trigger events taken
  - ® 30 K central trigger events
  - ® 200 K minimum bias events

***Winter 2001-2 Data*** Ö$s$ = 200 GeV $\vec{p} + \vec{p}$

- ® ~ 25 M total trigger events taken
- ® 20 M minimum bias trigger events for RHI reference data
- ® subset with forward pi-zero trigger (single spin asymmetry)