Hadron Production at $\sqrt{s_{NN}} = 19.6\ GeV\ Au + Au$ Collisions at STAR

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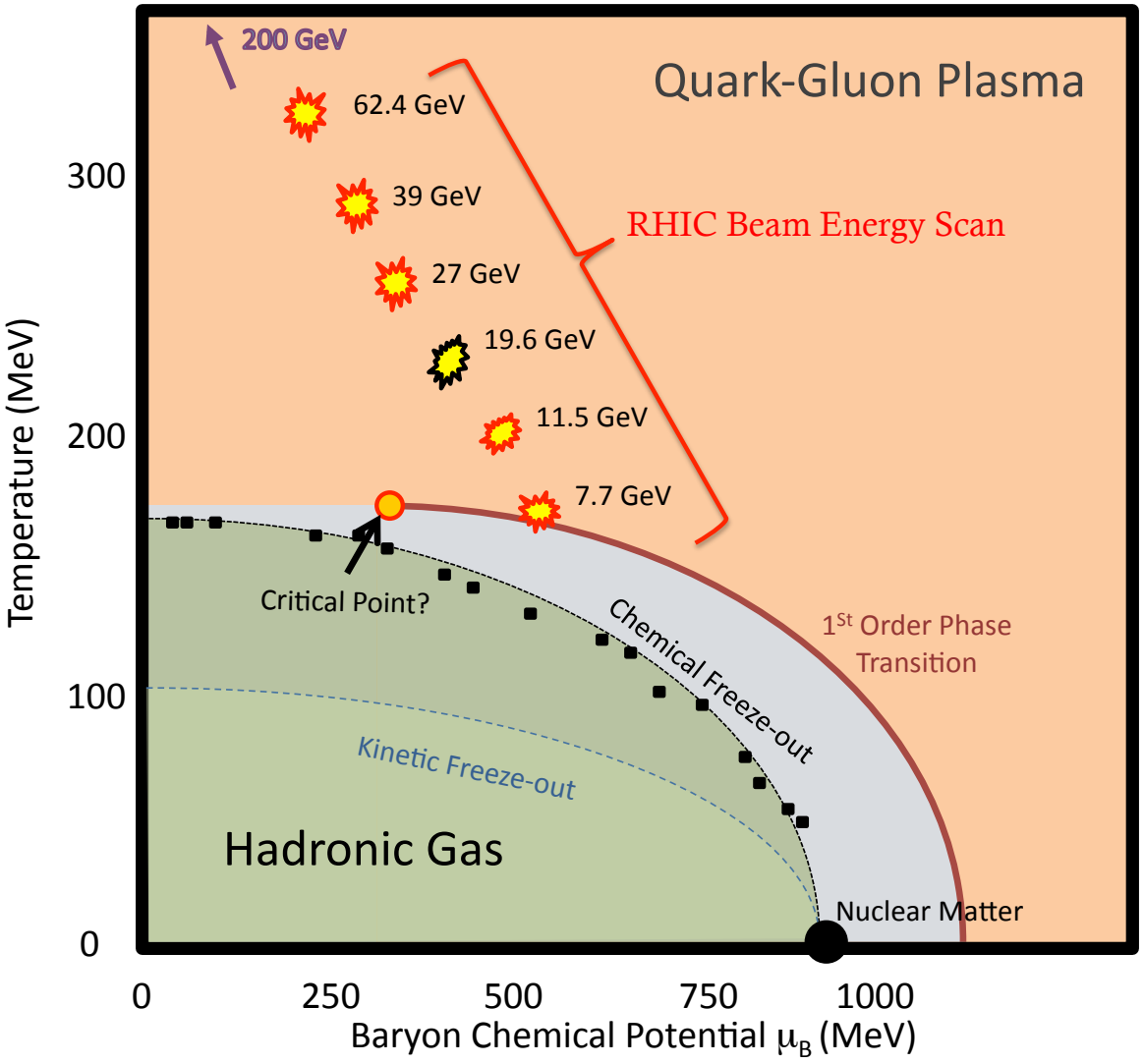
For the STAR Collaboration

Outline

- Phase Diagram
- Chemical Equilibrium
- 19.6 GeV Au+Au in 2001
  - Comparison to SPS
  - Results from STAR in 2001
- NEW 19.6 GeV Au+Au in 2011
  - Statistics, Time of Flight, Particle Identification
  - Particle Ratios: π^+/π^- and K^+/K^-
    - Extracted Coulomb potential and overall π^+/π^- ratio
- Outlook
- Preliminary Results

Nuclear Matter: Phase Diagram



- Form QGP in ultra-relativistic heavy ion collisions
- Mapping the phase diagram with Beam Energy Scan at RHIC
  - Characterize phase transition, T_{kin}, T_{ch}, and μ_B

Nuclear Matter: Chemical Equilibrium

- Utilize identified particle distributions to determine kinetic freeze-out temperatures
- Use several particle ratios to determine μ_B and T_{ch}, chemical freeze-out parameters
  - Goal is to compare many particle species' ratios
  - More accurate ratios lead to more accurate μ_B

$$\mu_i = (\mu_B B_i) - (\mu_S S_i) - (\mu_{I_3} I_3)$$

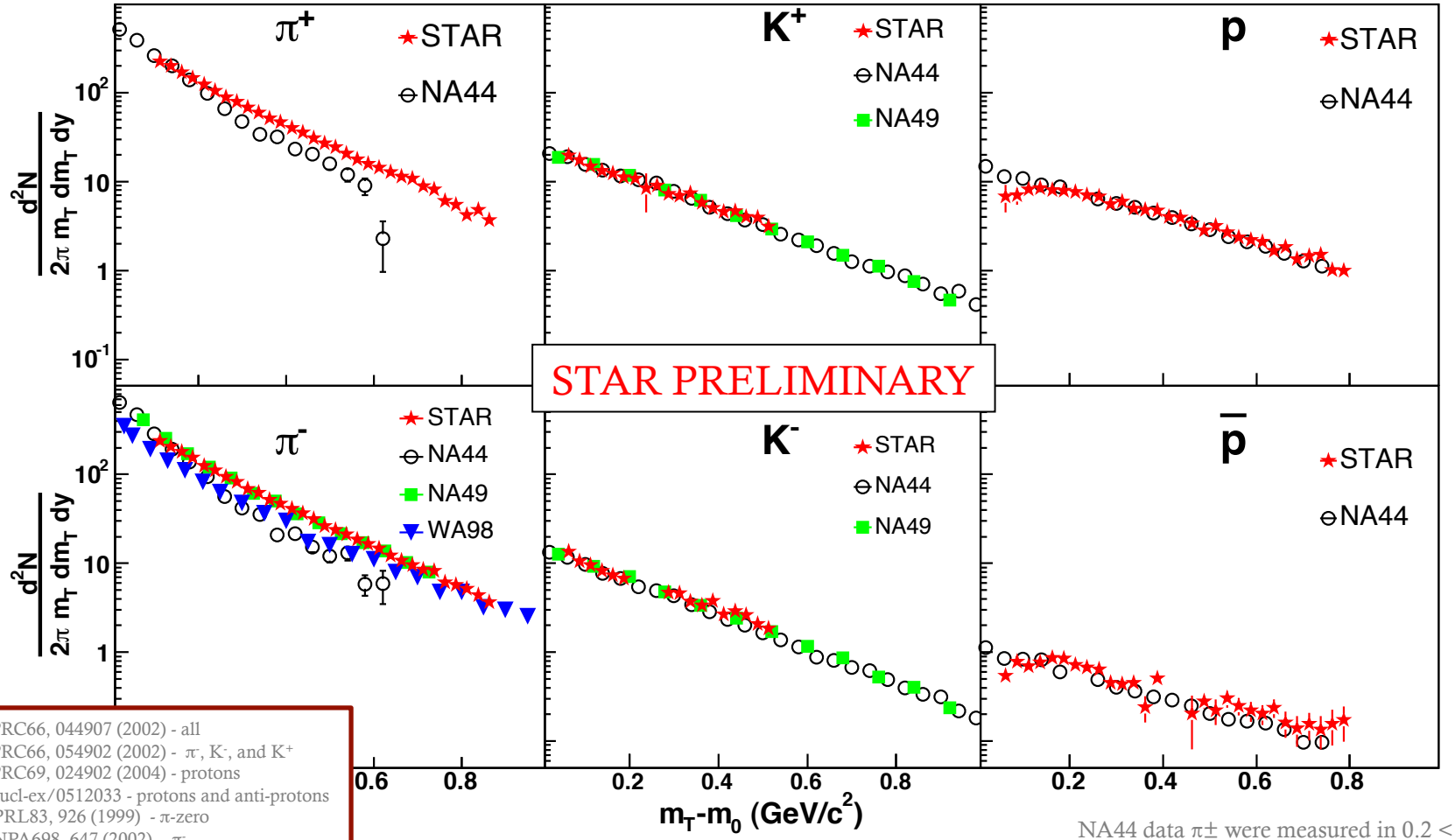
$$n_i(T, \mu_i) \sim \exp \frac{\mu_i - m_i}{T}$$

$$\frac{N_i}{N_j} \sim \exp\left(\frac{\mu_{i,ch} - \mu_{j,ch}}{T_{ch}} - \frac{m_i - m_j}{T_{ch}}\right)$$

Braun-Munzinger, Heppe, Stachel Phys.Lett.B465.15-20. 1999
Kaneta, Xu, QM04 nucl-th/0405068

STAR, 2001: 19.6 GeV Au+Au

The central mid-rapidity spectra are displayed against the most comparable SPS spectra

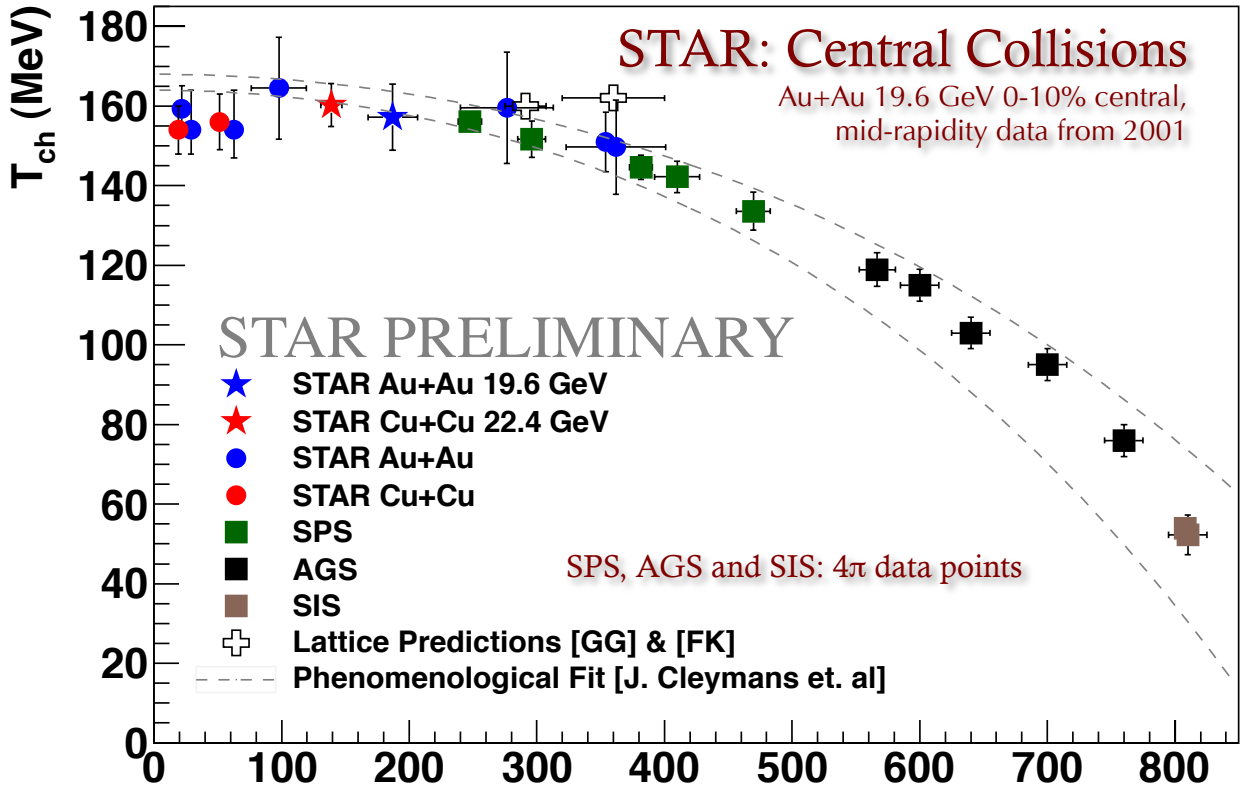


$$m_T = \sqrt{p_T^2 + m^2}$$

NA44 PRC66, 044907 (2002) - all
NA49 PRC66, 054902 (2002) - π^-, K^-, and K^+
NA49 PRC69, 024902 (2004) - protons
NA49 nucl-ex/0512033 - protons and anti-protons
WA98 PRL83, 926 (1999) - π-zero
WA98 NPA698, 647 (2002) - π^-
WA98 PRC67, 014906 (2003) - π^- and K^-
STAR 2001: arXiv:0903.4702

NA44 data $\pi\pm$ were measured in $0.2 < y < 1.2$
$K\pm$ are from $-0.5 < y < 0.6$
p and anti-p are from $-0.6 < y < 0.0$

T and μ_B at STAR and SPS



$$\mu_B(\sqrt{s_{NN}}) = \frac{1.308\text{GeV}}{1+0.273\text{GeV}^{-1}\sqrt{s_{NN}}}$$

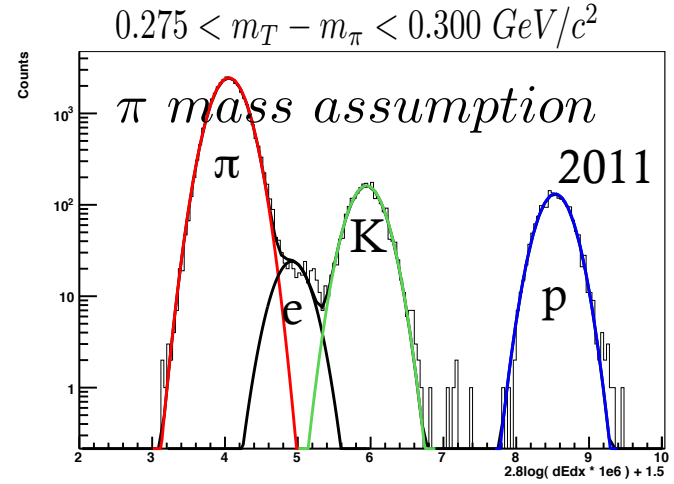
p+p 200, Au+Au 200, 130, 62.4 GeV
[STAR: PhysRevC.79.034909]
Cu+Cu 62.4, 200 GeV
[STAR: PhysRevC.83.034910]
Au+Au 9.2 GeV
[STAR: PhysRevC.81.024911]
7.7, 11, 39 GeV: Kumar QM2011
19.6 Au+Au & 22.4 GeV Cu+Cu:
Mall SQM2011
E866/917 PLB476.1.2000
E895 PRC68.054905.2003
E802 PRC58.3523.1998
NA44 PRC66.044907.2002
NA49 PRC66.054902.2002
Braun-Munzinger, Heppe, Stachel
Phys.Lett.B465.15-20. 1999
Kaneta, Xu, QM04 nucl-th/0405068

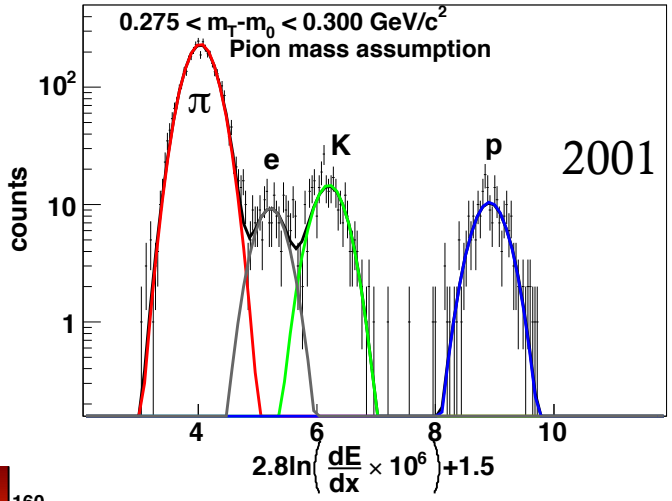
Without efficiency and acceptance corrections, freeze-out parameters cannot be extracted from 2011 19.6 GeV Au+Au data.

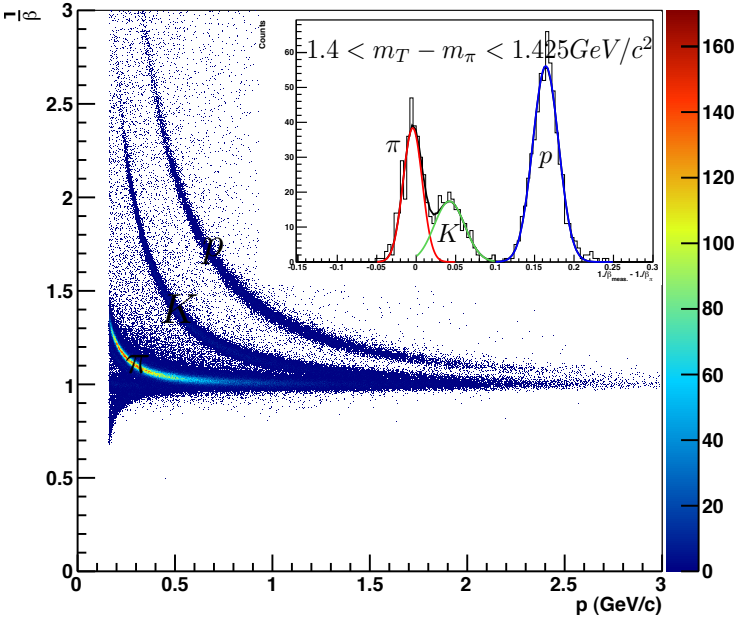
2006 *Phys.Rev.C* ***73 034905***

New STAR, 2011: 19.6 GeV Au+Au

- Compare 0-5% from 2011 to 0-10% from 2001 central events
- Minimum bias data collection
  - 10% of total 2011 dataset analyzed
- Statistics improve particle fits
- Time of Flight extends PID to higher momentum than dE/dx







	2001	2011
# Events taken	~285k	~145 M
# Good Events	~43k	~14.6 M
# Events Used	~5k	~74k
B-Field	0.25 T	0.5 T
TOF	No	Yes
TPC	Yes	Yes
SVT (e- bkgd)	Supports + Ladder	Supports only

Source Coulomb Potential

$$\frac{\pi^+}{\pi^-}(m_T - m_\pi) = R\,\frac{\exp\left[\left(E + V_{\text{eff}}\right)/T_\pi\right] - 1}{\exp\left[\left(E - V_{\text{eff}}\right)/T_\pi\right] - 1} \cdot J$$

Ratio as a function of transverse kinetic energy with transformed B-E distribution

- Net positive charge in the collision zone
  - Expanding spherical source → effective potential
- Coulomb potential (V_c) of the source modifies momentum distribution
  - Greater effect for low-momentum π
- R – initial ratio from initial yields, unmodified by the coulomb source
- Extracted parameters include initial ratio R and the full coulomb potential V_c

Source Coulomb Potential

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Ratio as a function of transverse kinetic energy with transformed B-E distribution

$$J = \frac{E - V_{\text{eff}}}{E + V_{\text{eff}}} \frac{\sqrt{\left(E - V_{\text{eff}}\right)^2 - m_\pi^2}}{\sqrt{\left(E + V_{\text{eff}}\right)^2 - m_\pi^2}}$$

← Jacobian of the transformation

- Net positive charge in the collision zone
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Ratio as a function of transverse kinetic energy with transformed B-E distribution

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Jacobian of the transformation

$$V_{\text{eff}}\left(\gamma_\pi \beta_\pi\right) = V_C\left(1 - e^{-E_{\max}(\gamma_\pi \beta_\pi)/T_p}\right)$$

Effective Coulomb potential accounting for the reduced charge seen by low momentum π

- Net positive charge in the collision zone
  - Expanding spherical source → effective potential
- Coulomb potential (V_c) of the source modifies momentum distribution
  - Greater effect for low-momentum π
- R – initial ratio from initial yields, unmodified by the coulomb source
- Extracted parameters include initial ratio R and the full coulomb potential V_c

Source Coulomb Potential

$$\frac{\pi^+}{\pi^-}(m_T - m_\pi) = R\,\frac{\exp\left[\left(E + V_{\text{eff}}\right)/T_\pi\right] - 1}{\exp\left[\left(E - V_{\text{eff}}\right)/T_\pi\right] - 1} \cdot J$$

Ratio as a function of transverse kinetic energy with transformed B-E distribution

$$J = \frac{E - V_{\text{eff}}}{E + V_{\text{eff}}} \frac{\sqrt{\left(E - V_{\text{eff}}\right)^2 - m_\pi^2}}{\sqrt{\left(E + V_{\text{eff}}\right)^2 - m_\pi^2}}$$

Jacobian of the transformation

$$V_{\text{eff}}(\gamma_\pi \beta_\pi) = V_C\left(1 - e^{-E_{\max}(\gamma_\pi \beta_\pi)/T_p}\right)$$

Effective Coulomb potential accounting for the reduced charge seen by low momentum π

$$E_{\max}(\gamma_\pi \beta_\pi) = \sqrt{\left(m_p \gamma_\pi \beta_\pi\right)^2 + m_p^2} - m_p$$

Maximum kinetic energy of the corresponding π velocity

- Net positive charge in the collision zone
  - Expanding spherical source → effective potential
- Coulomb potential (V_c) of the source modifies momentum distribution
  - Greater effect for low-momentum π
- R – primordial ratio from initial yields, unmodified by the coulomb source
- Extracted parameters include initial ratio R and the full coulomb potential V_c

STAR, 2011: New 19.6 GeV Au+Au

Source Coulomb Potential, V_c (Mvolts)

Y11: 8.07 +/- 0.61

WA98: 9.83 +/- 0.63

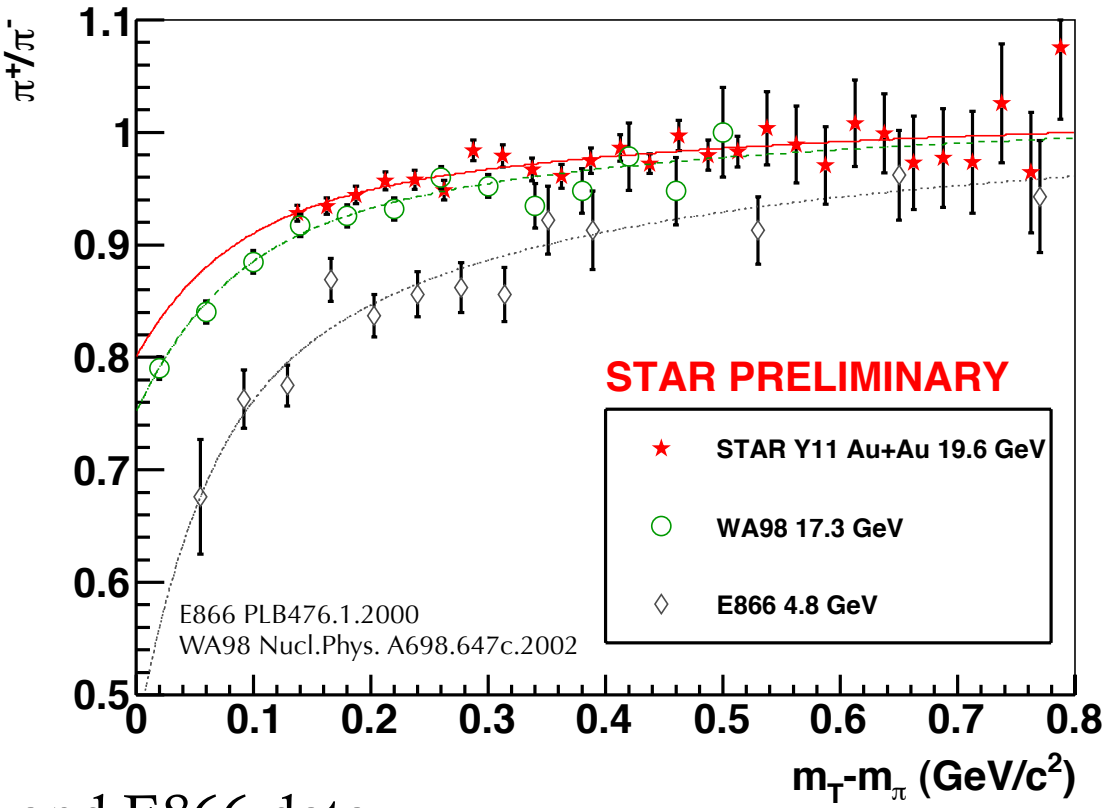
E866: 16.32 +/- 1.92

Overall Pion Ratio, R

Y11: 0.953 +/- 0.002

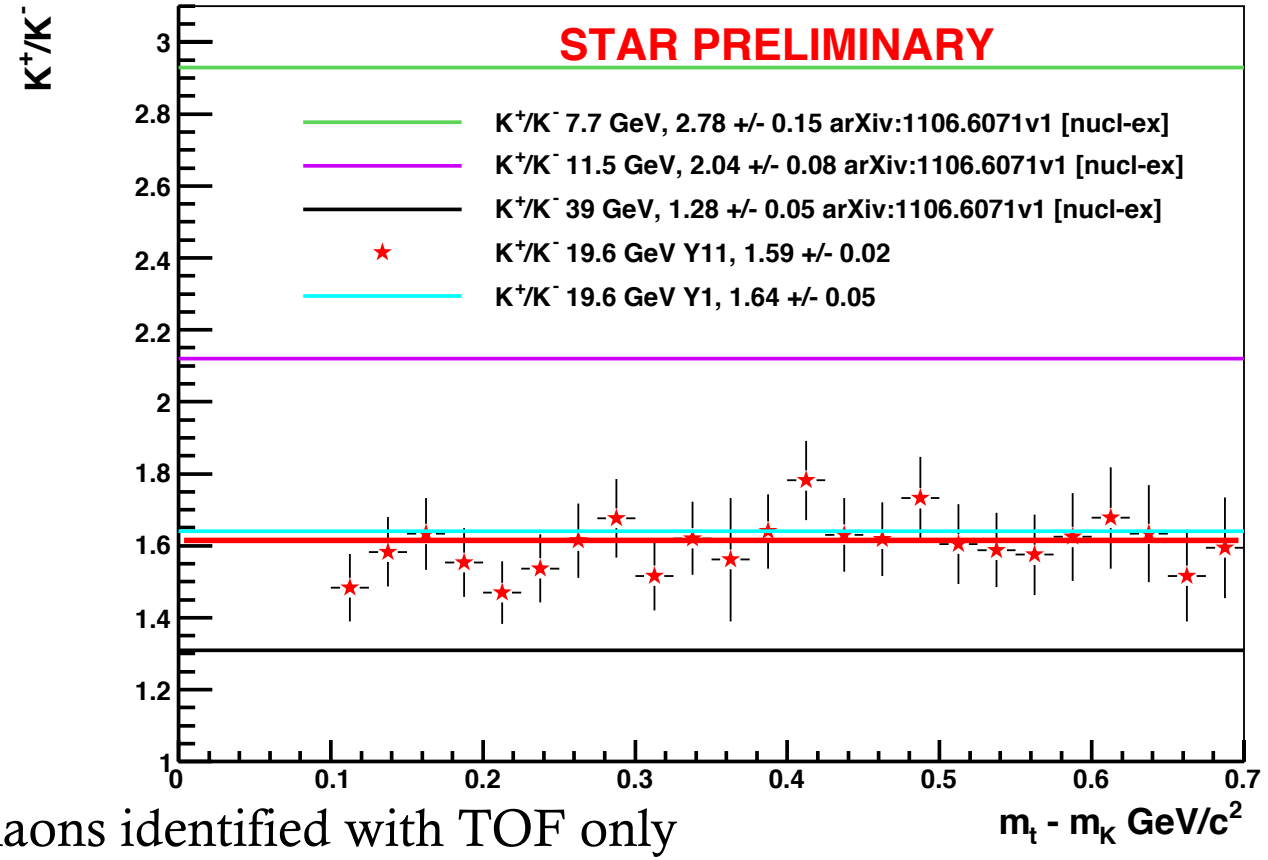
WA98: 0.935 +/- 0.004

E866: 0.771 +/- 0.011



- Fits to published WA98 and E866 data
- Use TOF data above 0.5 GeV/c^2, TPC data below that for Y11 STAR data
- Extracted ratio including V_c is different from ratio via integrated yields, 0.965 +/- 0.01 in 2001

STAR, 2011: 19.6 GeV Au+Au



- Kaons identified with TOF only
- K^+/K^- ratio fits to 1.59 +/- 0.02
  - Y1 ratio is 1.64 +/- 0.05, results are consistent
  - Ratio >1 indicates 19.6 GeV in the region where associated production contributes to K^+ yield

Preliminary Results & Outlook

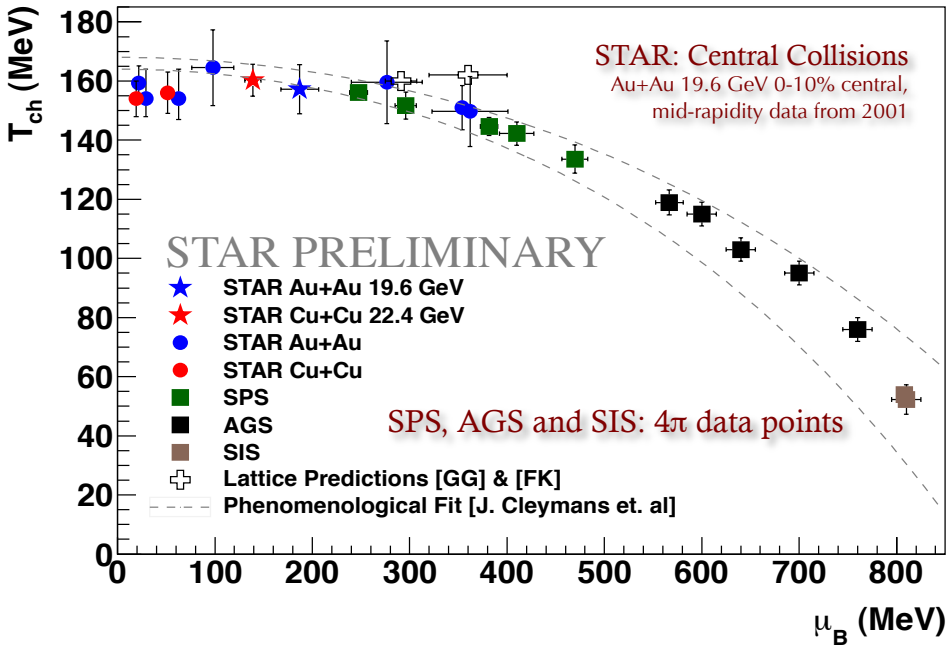
- New 2011 dataset is better than test run in 2001
  - Time of Flight detector extends range in p_T for PID
  - More statistics to reduce errors
- Given only part of the dataset has been analyzed
  - Pion ratio comparable to similar SPS energies
    - Coulomb potential of the source is V_c = 8.07 +/- 0.61 MVolts
  - Kaon ratio falls between 11.5 and 39 GeV ratio
    - Ratio > 1 indicates associated production contributes to K^+ yield
  - Systematic studies are underway
- Will produce corrected spectra, freeze-out parameters and dN/dy soon for 2011 19.6 GeV Au+Au dataset

- Thank you!

Back-up

T and mB for STAR and SPS

- Tabulated values
- Rapidity windows + correction factors in next slide
  - To compare datasets with similar acceptances and rapidity selections



Energy (Expt)	T_{ch}	μ_B	μ_B(J.C.)
6.27 (SPS)	134(5)	470(13)	482
7.62 (SPS)	142(4)	410(18)	425
7.7 (STAR)	150(12)	362(39)	422
8.76 (SPS)	145(3)	382(9)	386
11.5 (STAR)	160(14)	277(36)	316
12.32 (SPS)	152(5)	296(10)	300
17.27 (SPS)	156(3)	247(9)	229
19.6 (STAR '01)	157(8)	187(19)	206
39 (STAR)	165(13)	98(22)	112

2006 *Phys.Rev.C* ***73 034905***

$$\mu_B(\sqrt{s_{NN}}) = \frac{1.308\text{GeV}}{1+0.273\text{GeV}^{-1}\sqrt{s_{NN}}}$$

Correcting the Comparisons

Centrality (Np) Effect

Collaboration	System	$\sigma_{trig}/\sigma_{inel}$	$\langle N_{part} \rangle$	Ratio
STAR	Au+Au	0-10%	337	1.000
NA49	Pb+Pb	0-5%	357	1.059
NA44	Pb+Pb	0-3.7%	340	1.009
WA98	Pb+Pb	0-10%	330	0.979

Studied the rapidity densities, then determine the effect of the rapidity slice for each particle

Particle	dN/dy (y=0)	σ
π−	180+/-5	1.40+/-0.03
π+	164+/-4	1.44+/-0.04
K-	17.4+/-1.6	1.14+/-0.10
K+	31.2+/-2.1	1.25+/-0.13
p-bar	3.5+/-0.6	1.10+/-0.26
p	33.9+/-1.7	2.50+/-0.35

NA49 rapidity density data
N(A661, 45c (1999)

Particle	Experiment	<y>	Ratio
π−	NA49	-0.1	0.997
π−	NA44	0.4	0.96
π−	WA98	-0.55	0.926
π+	NA44	0.4	0.926
π0	WA98	-0.3	0.978
K-	NA49	0	1
K-	NA44	0.15	0.991
K-	WA98	-0.8	0.782
K+	NA49	0	1
K+	NA44	0.15	0.993
p-bar	NA49	-0.3	0.963
p-bar	NA44	-0.45	0.92
p	NA49	-0.3	0.993
p	NA44	-0.45	0.984

STAR, 2011: 19.6 GeV Au+Au

Source Coulomb Potential, V_c (MVolts)

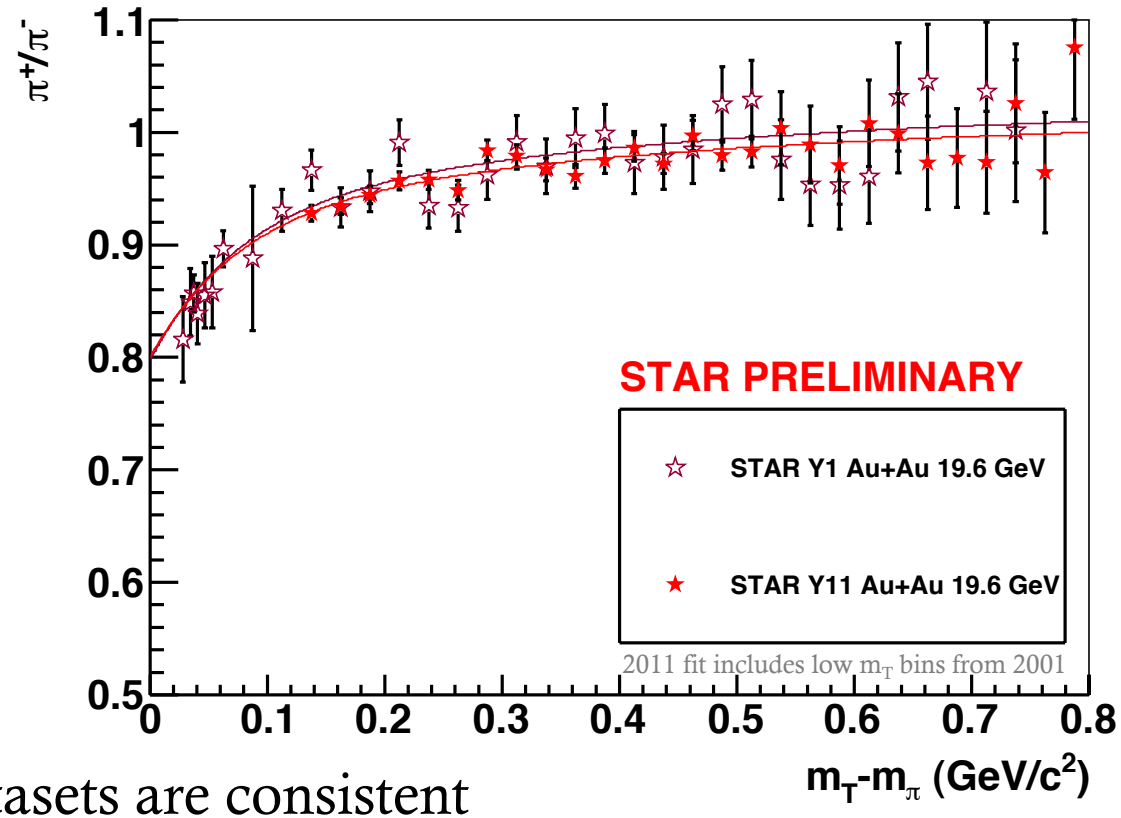
Y1: 8.54 +/- 0.78

Y11: 8.07 +/- 0.61

Overall Pion Ratio, R

Y1: 0.960 +/- 0.005

Y11: 0.953 +/- 0.002



- 2001 and new 2011 datasets are consistent
  - No feed-down corrections
- Extracted ratio including V_c is different from ratio via integrated yields, 0.965 +/- 0.01 in 2001
  - Will modify particle ratio fits to extract μ_B

Coulomb Potential

Source Coulomb Potential, V_c (MVolts)

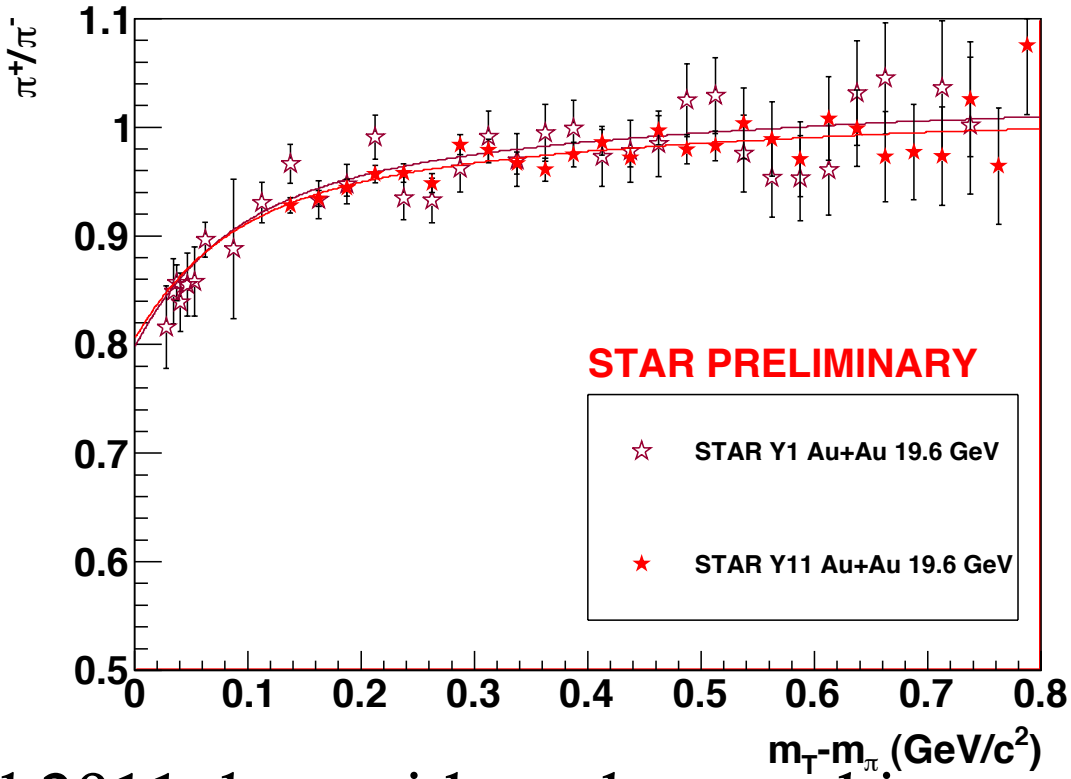
Y11: 7.83 +/- 0.99

Y1: 8.54 +/- 0.78

Overall Pion Ratio, R

Y11: 0.953 +/- 0.002

Y1: 0.976 +/- 0.003



- Fits to 2001 data and 2011 data without low m_T bins
- 2011 Extracted ratio is consistent with low m_T bins
  - Will modify particle ratio fits to extract μ_B

Fit Parameters and Chi^2

NO.	NAME	VALUE	ERROR	SIZE	DERIVATIVE
1	p0	9.53414e-01	2.22968e-03	5.34319e-06	-1.63735e-04
2	p1	8.07025e+00	6.14906e-01	1.47355e-03	-3.00940e-06
3	p2	1.99000e-01	fixed		
4	p3	0.00000e+00	fixed		
5	p4	3.09000e-01	fixed		

Chi^2 0.595597

2011 Au+Au 0.028 < mt-m0 < 0.9875 GeV

Pion freeze-out temperature

NO.	NAME	VALUE	ERROR	SIZE	DERIVATIVE
1	p0	9.60183e-01	4.75827e-03	1.17667e-05	-1.10450e-04
2	p1	8.53669e+00	7.83732e-01	1.93810e-03	-2.94375e-05
3	p2	1.99000e-01	fixed		
4	p3	0.00000e+00	fixed		
5	p4	3.09000e-01	fixed		

Chi^2 0.85664

2001 Au+Au 0.028 < mt-m0 < 0.9875 GeV

Average rapidity window

NO.	NAME	VALUE	ERROR	SIZE	DERIVATIVE
1	p0	7.71114e-01	1.14871e-02	1.22945e-05	-5.15275e-04
2	p1	1.63202e+01	1.92414e+00	2.05922e-03	-1.39505e-05
3	p2	1.12800e-01	fixed		
4	p3	0.00000e+00	fixed		
5	p4	2.28900e-01	fixed		

Chi^2 1.20046

E866 Au+Au 0.055 < mt-m0 < 1.2 GeV

Proton freeze-out temperature

NO.	NAME	VALUE	ERROR	SIZE	DERIVATIVE
1	p0	9.34634e-01	3.84297e-03	4.75806e-06	2.06208e-03
2	p1	9.83486e+00	6.25222e-01	7.74103e-04	6.09141e-07
3	p2	1.90000e-01	fixed		
4	p3	0.00000e+00	fixed		
5	p4	3.03000e-01	fixed		

Chi^2 0.62265

WA98 Pb+Pb 0.02 < mt-m0 < 0.5 GeV

NO.	NAME	VALUE	ERROR	SIZE	DERIVATIVE
1	p0	9.75948e-01	2.74199e-03	6.23062e-06	3.38629e-05
2	p1	4.86380e+00	8.69440e-01	1.97564e-03	6.92330e-07
3	p2	1.94000e-01	fixed		
4	p3	0.00000e+00	fixed		
5	p4	2.56000e-01	fixed		

Chi^2 0.896979

2005 Cu+Cu 0.1375 < mt-m0 < 0.9875 GeV