Selected highlights from STAR experiment at RHIC

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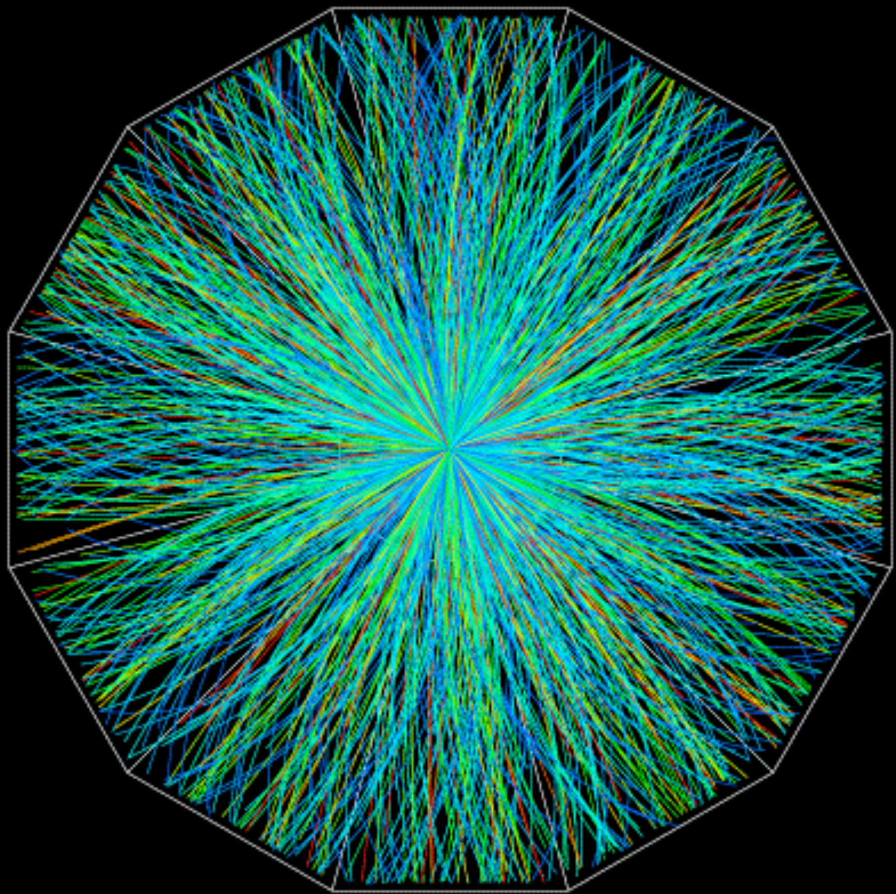
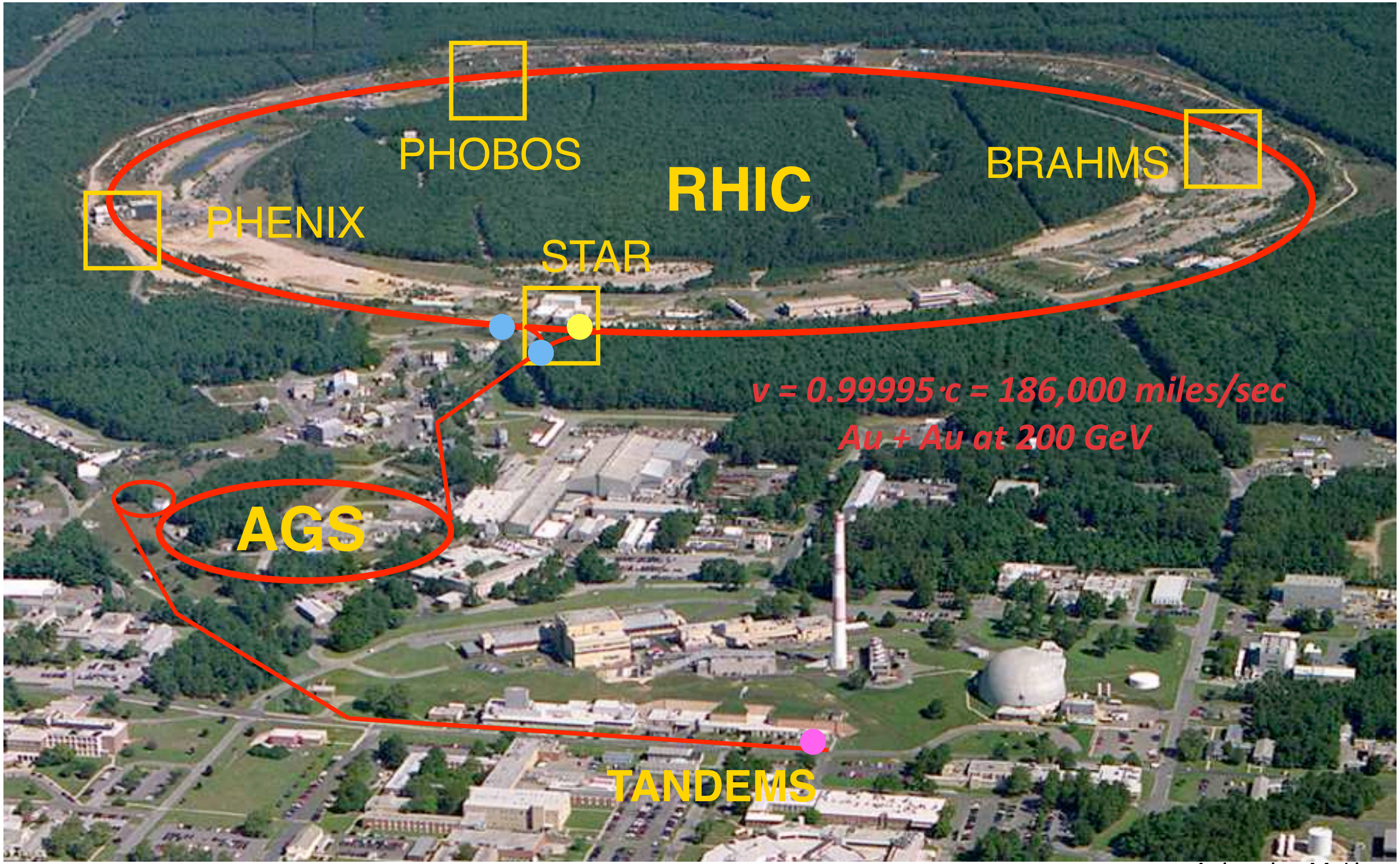
(for the STAR Collaboration)




STAR
- 550 scientists
- 55 institutes
- 13 countries

Relativistic Heavy Ion Collider (RHIC)

Brookhaven National Laboratory (BNL), Upton, NY



Animation M. Lisa

World's (second) largest operational heavy-ion collider

World's largest polarized proton collider

Year	System	$\sqrt{s_{NN}}$ [GeV]
2000	Au+Au	130
2001	Au+Au	200
2002	p+p	200
2003	d+Au	200
2004	Au+Au p+p	62.4 200
2005	Cu+Cu	200, 62.4, 22
2006	p+p	62.4, 200, 500
2007	Au+Au	200
2008	d+Au p+p Au+Au	200 200 9.2
2009	p+p	200, 500
2010	Au+Au	200, 62.4, 39, 11.5, 7.7

Remarkable discoveries at RHIC

The first six years

- A+A collisions
  - Perfect liquid
  - Jet quenching
  - Number of constituent quark scaling
  - Heavy-quark suppression

- Polarized p+p collisions
  - Large transverse spin asymmetries in the pQCD regime

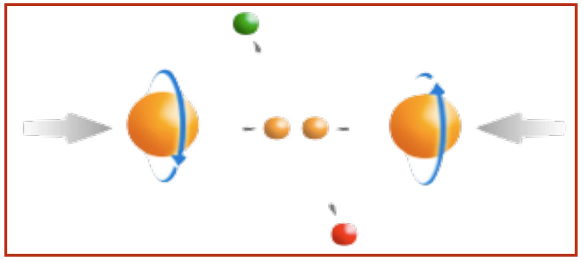
- d+A collisions
  - Possible indications of gluon saturation at small *x*

Key unanswered questions

- What are the properties of the strongly coupled system produced at RHIC, and how does it thermalize?
- What is the phase structure of QCD matter?
- What is the mechanism for partonic energy loss?
- What exotic particles are created at RHIC?
- Does QCD matter demonstrate novel symmetry properties?
- What is the partonic spin structure of the proton?
- What are the dynamical origins of spin-dependent interactions in hadronic collisions?
- What is the nature of the initial state in nuclear collisions?

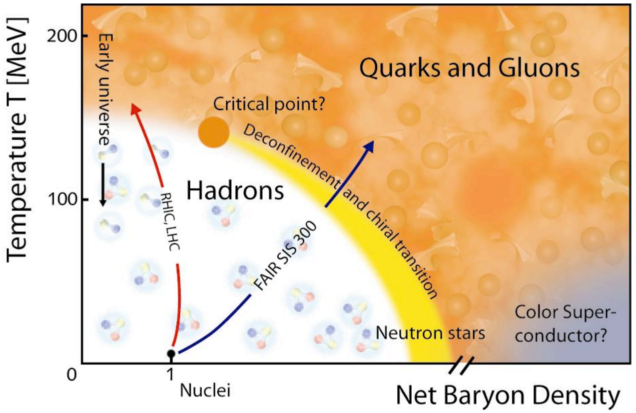
Due to length limitations, will only cover three of these in my talk

STAR results in this talk



Polarized *p+p* program

- Study ***proton intrinsic properties***

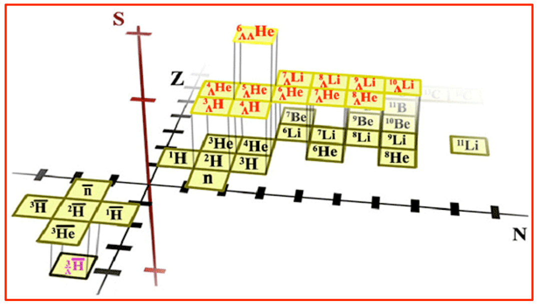


1) At 200 GeV top energy

- Study ***medium properties, EoS***
- pQCD in hot and dense medium

2) RHIC beam energy scan

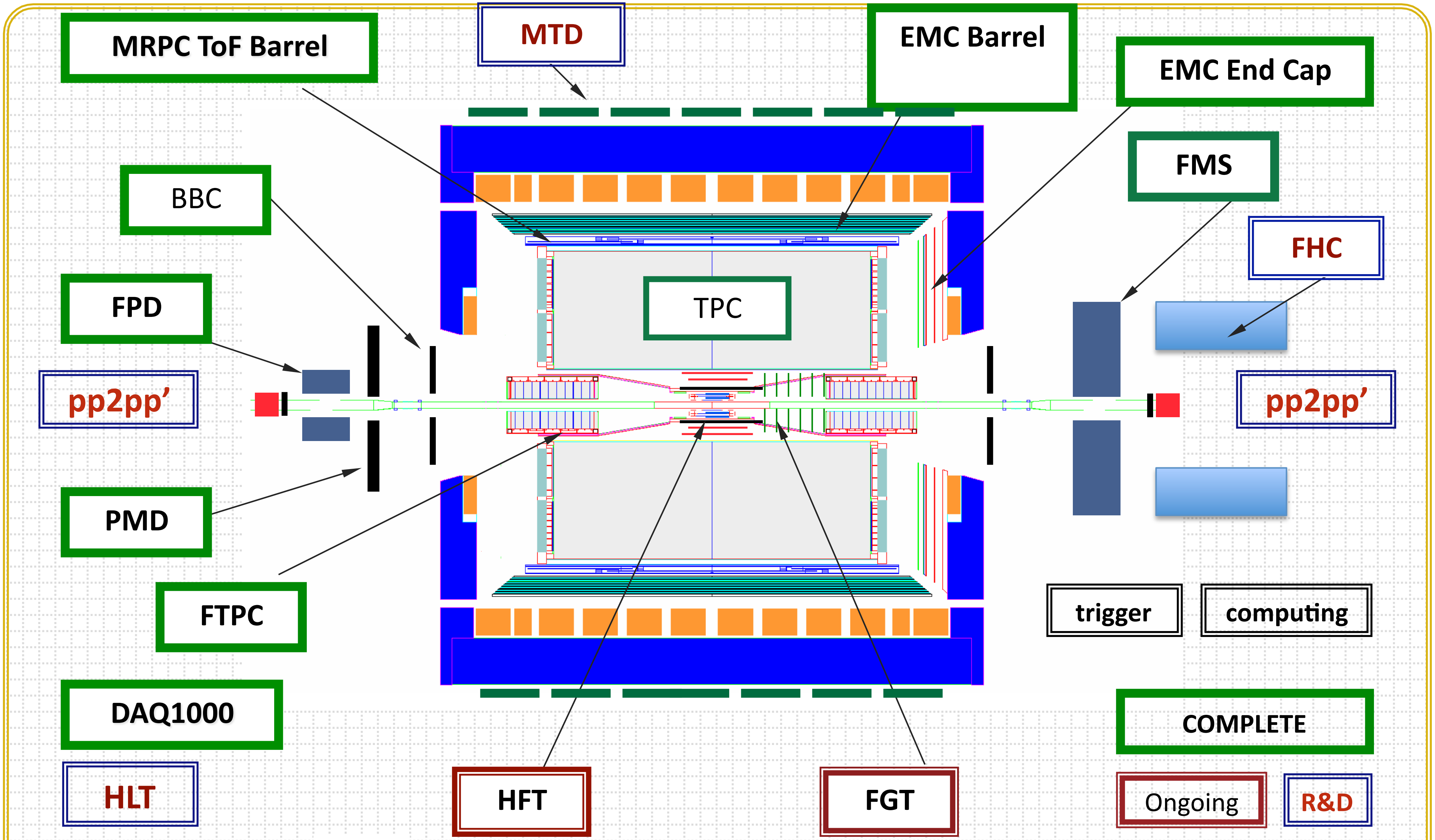
- Search for the ***QCD critical point***
- Chiral symmetry restoration



Exotic systems created in nuclear collisions

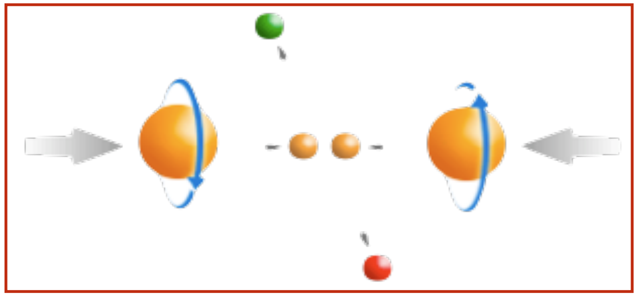
- ***antihypernuclei*** *etc.*

STAR Detector



Full 2π in azimuth at ~ 2 units in midrapidity

G. Bunce *et al.*, *Prospects for spin physics at RHIC*, Ann.Rev.Nucl.Part.Sci. 50(2000)525



Polarized *p+p* program

- Study ***proton intrinsic properties***

Longitudinal double-spin asymmetry and cross section for inclusive neutral pion production at midrapidity in polarized proton collisions at √s = 200 GeV. Phys. Rev. D 80 (2009) 111108

Forward Neutral Pion Transverse Single Spin Asymmetries in p+p Collisions at √s = 200 GeV. Phys. Rev. Lett. 101 (2008) 222001

Longitudinal double-spin asymmetry for inclusive jet production in p + p collisions at √s= 200 GeV. Phys. Rev. Lett. 100 (2008) 232003

Measurement of Transverse Single-Spin Asymmetries for Di-Jet Production in Proton-Proton Collisions √s = 200 GeV. Phys. Rev. Lett. 99 (2007) 142003

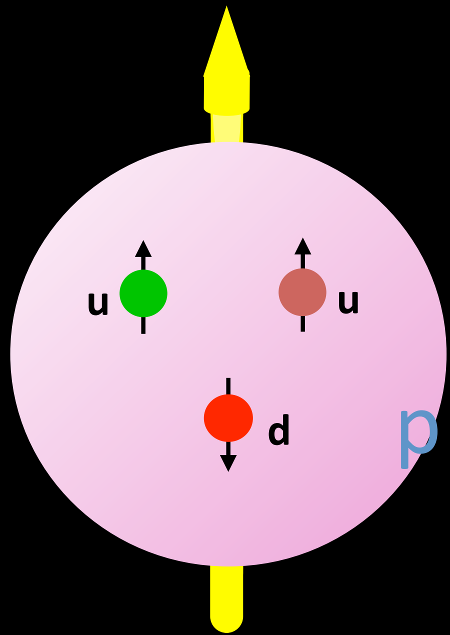
Longitudinal Double-Spin Asymmetry and Cross Section for Inclusive Jet Production in Polarized Proton Collisions at at √s = 200 GeV. Phys. Rev. Lett. 97 (2006) 252001

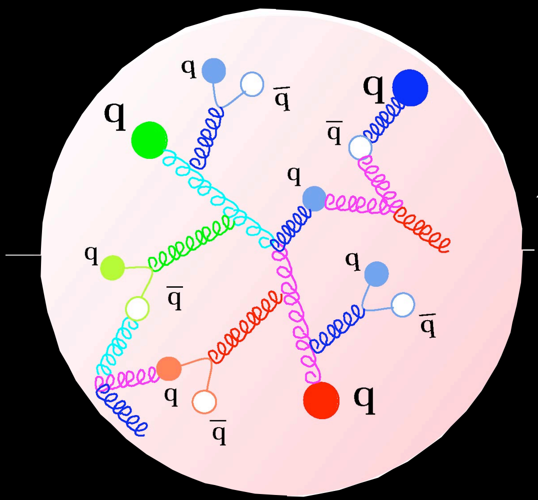
Where does the proton's spin come from?

p is made of 2u and 1d quark

$S = \frac{1}{2} = \Sigma S_q$

✓ Explains magnetic moment of baryon octet





BUT partons have an x distribution and there are also sea quarks and gluons

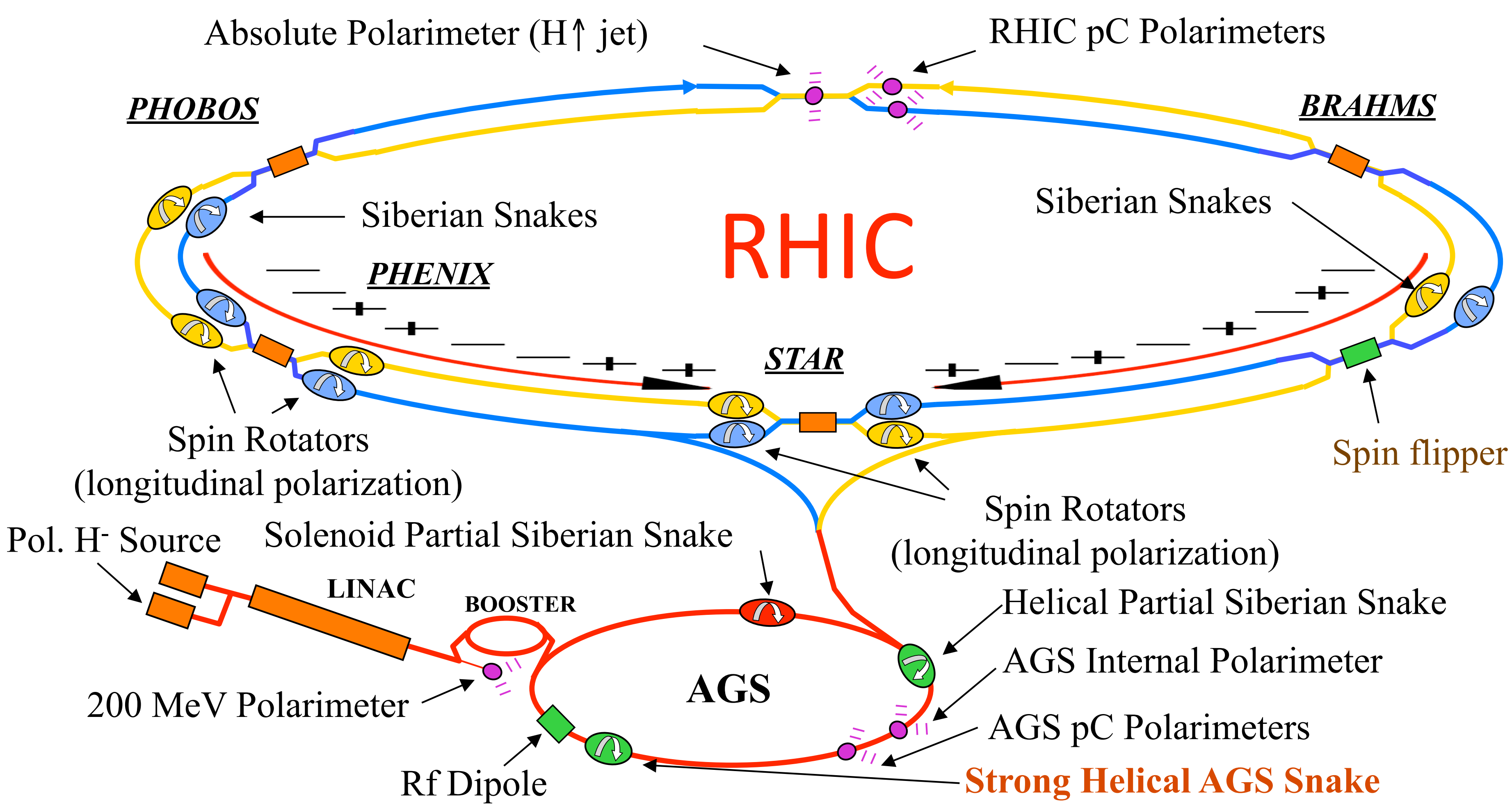
Check via electron scattering and find quarks carry only ~1/4-1/3 of the proton's spin! => SPIN CRISIS

$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$

Jets,pions,A_{LL}

Di-jets, Sivers A_N

First Collider of Polarized Hadrons



- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- Billions of spin reversals during a fill with little if any depolarization

Asymmetry in the sea quarks: W program

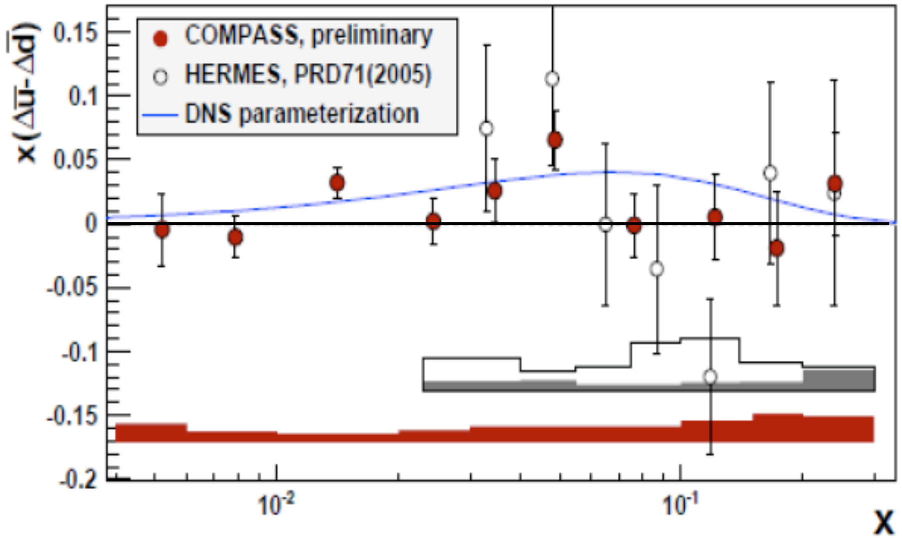
$$S_z = \tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + L_z^g + L_z^q$$

$\Delta\Sigma$: u, d, s, $\bar{u}$, $\bar{d}$, $\bar{s}$

$\Delta G + L_z^g$: J_g

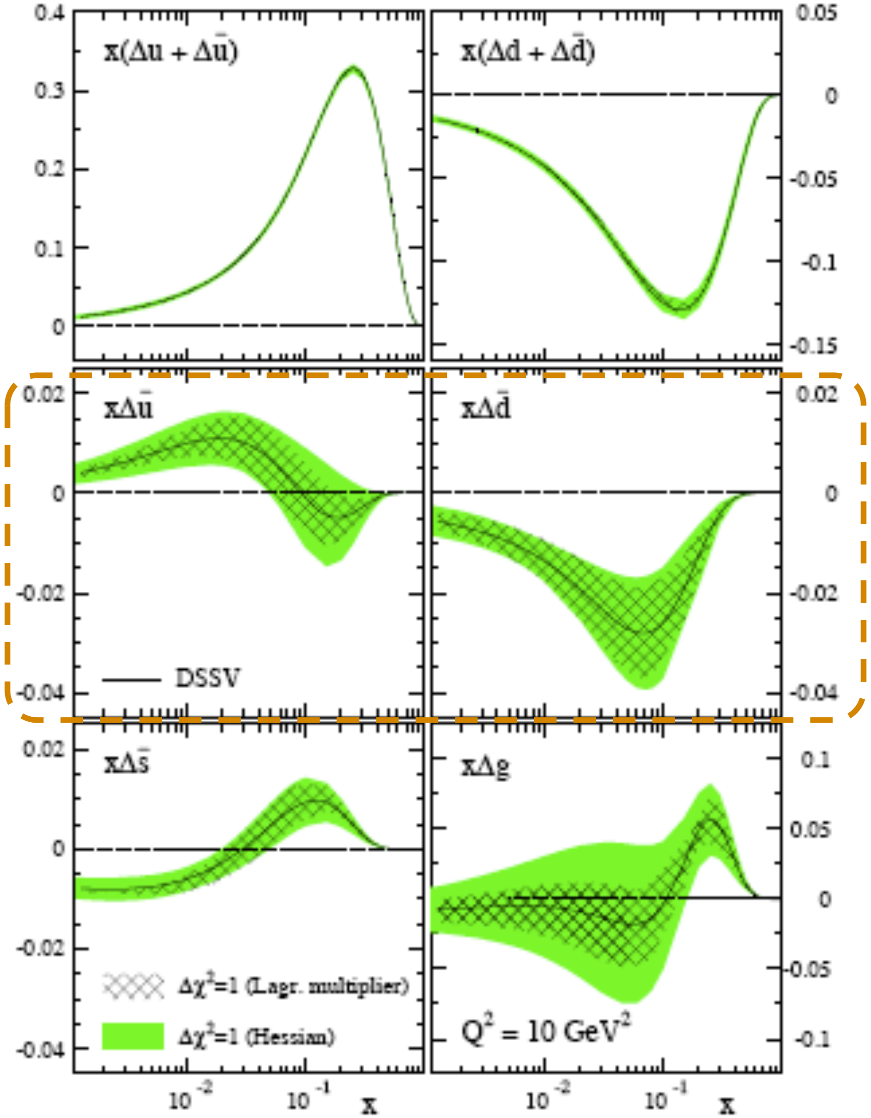
$L_z^g + L_z^q$: L

Global analysis predicts positive net helicity difference

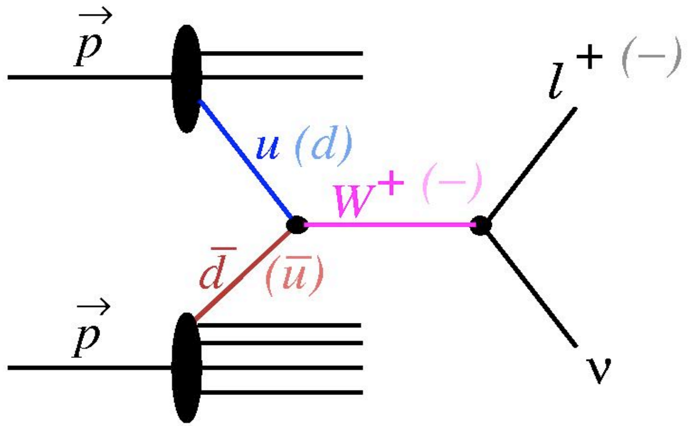


de Florian *et al.*, Phys.Rev. D80 (2009) 034030

Recent global fit of polarized u,d anti-quarks distributions to DIS and SI-DIS measurement



$W^{\pm}$ detection via $e^{\pm}$ decay



$$u + \bar{d} \quad \rightarrow \quad W^{+} \rightarrow e^{+} + \nu$$
$$\bar{u} + d \quad \rightarrow \quad W^{-} \rightarrow e + \bar{\nu}$$

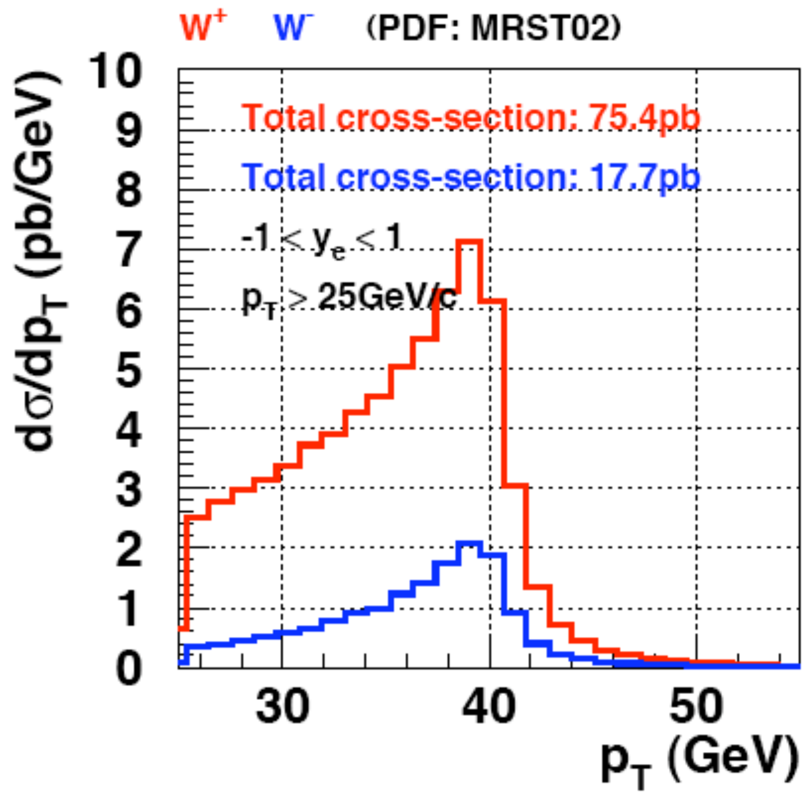
deFlorian/Vogelsang

•Measure the parity-violating, single-spin helicity asymmetry

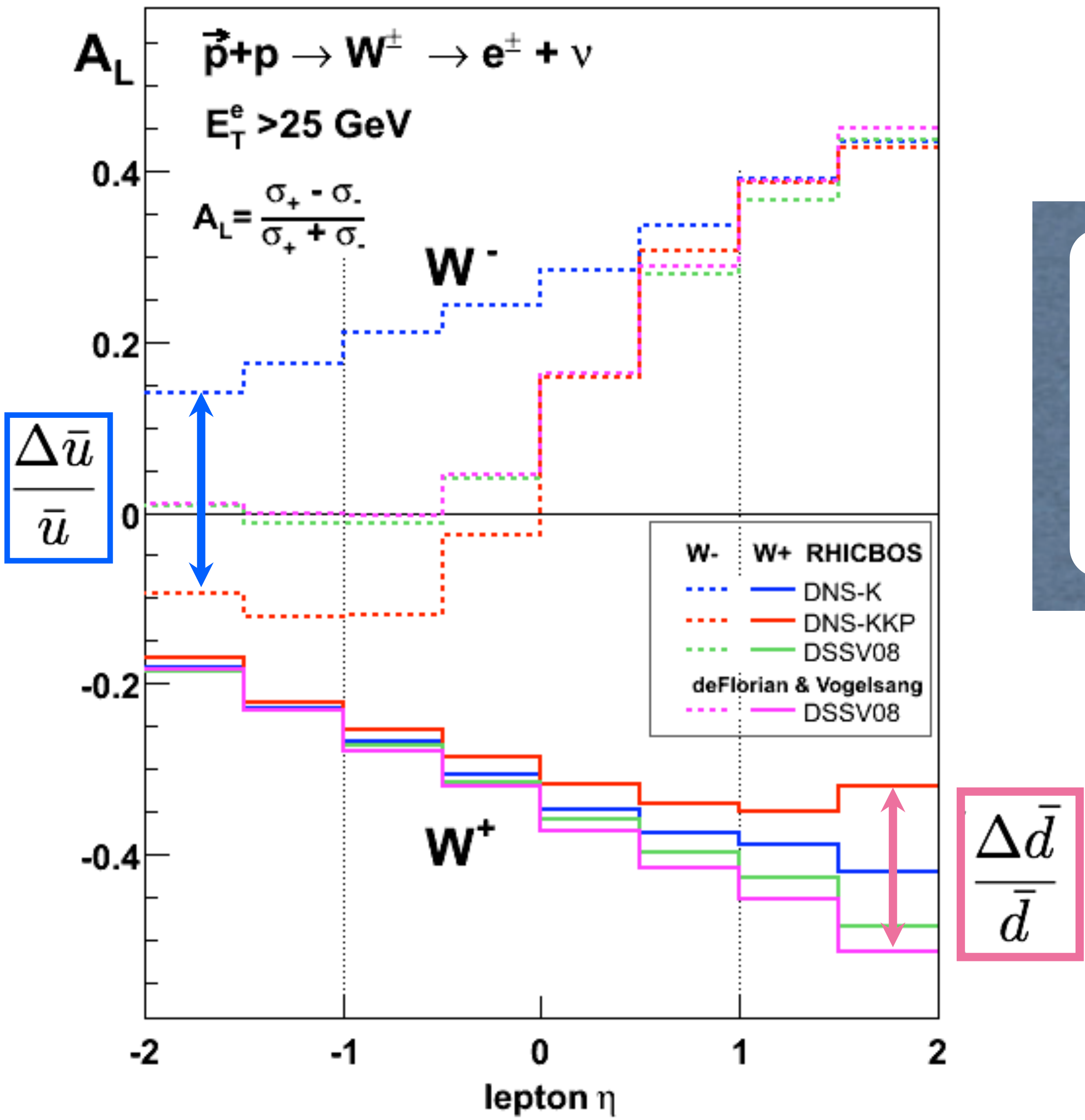
$$A_L = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\overrightarrow{\sigma} + \overleftarrow{\sigma}}$$

•where at LO:

$$A_L^{W^+} \propto -\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)$$
$$A_L^{W-} \propto -\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)$$

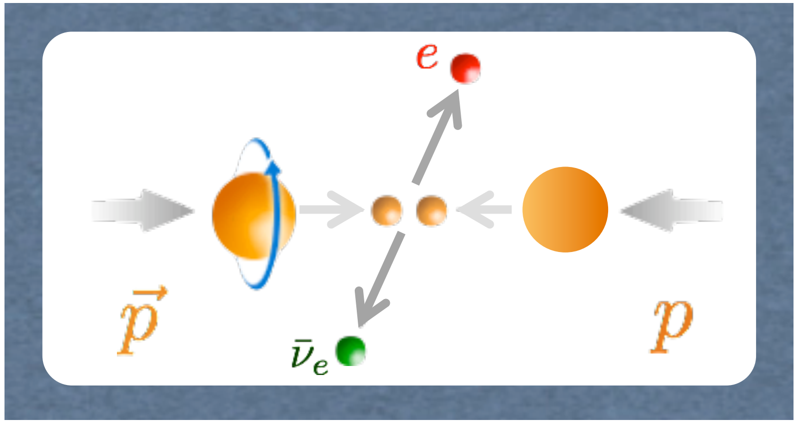


Predictions for A_L for p+p →W



STAR Barrel EMC

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$



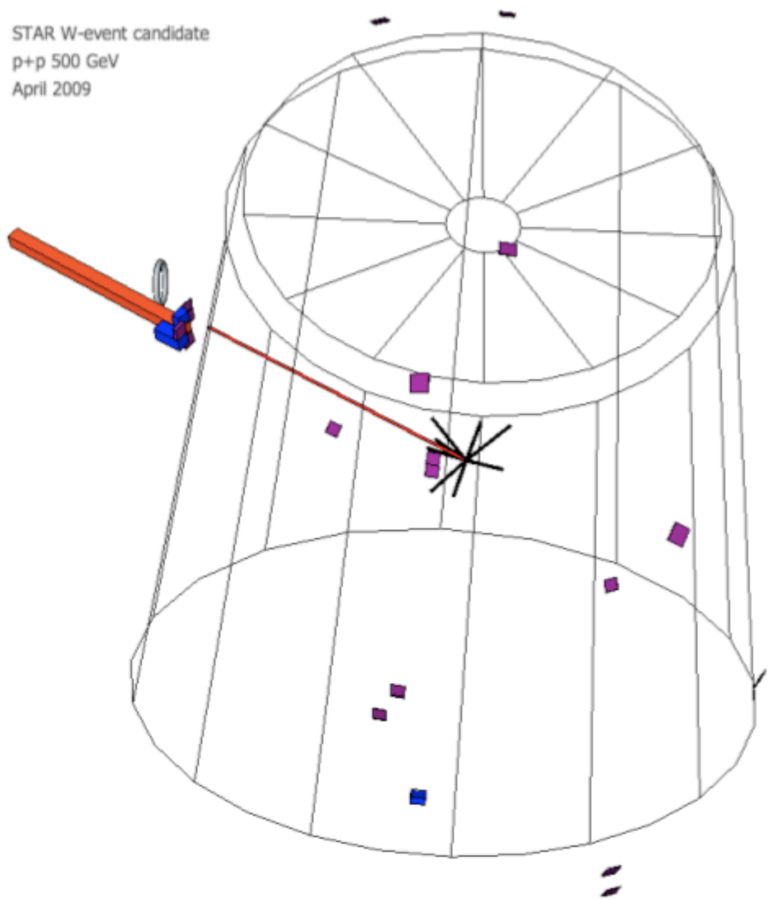
$$A_L^{W^-} = \frac{1}{2}\left(\frac{\Delta\bar{u}}{\bar{u}} - \frac{\Delta d}{d}\right)$$

$$A_L^{W^+} = \frac{1}{2}\left(\frac{\Delta\bar{d}}{\bar{d}} - \frac{\Delta u}{u}\right)$$

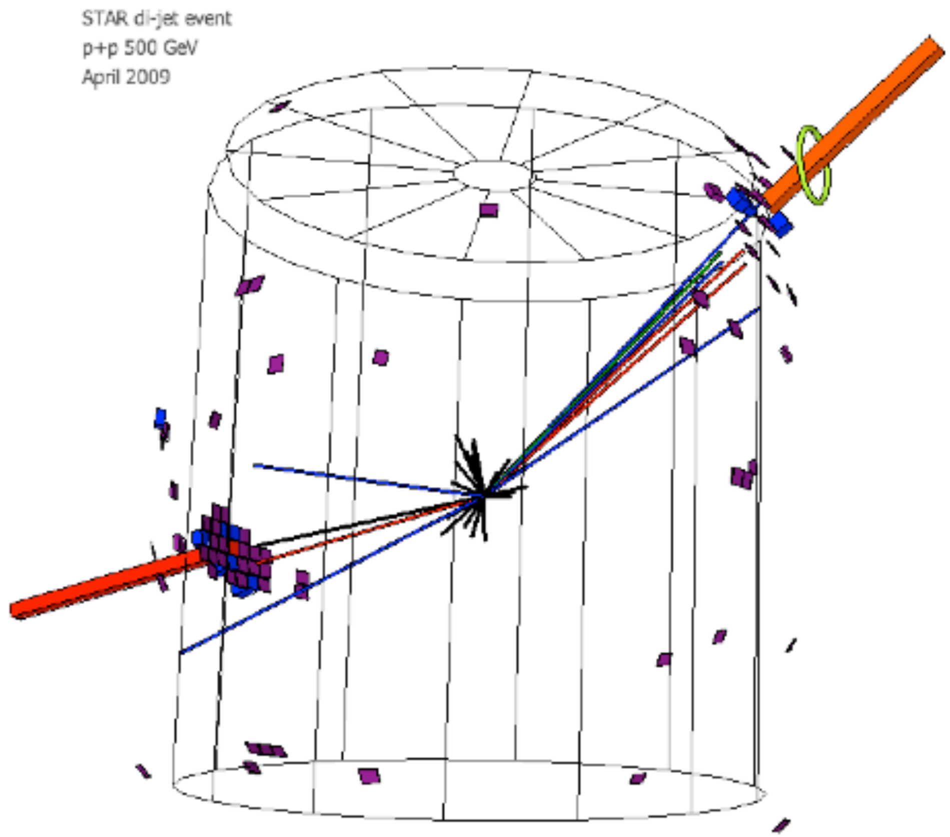
LO interpretation for $x_1=x_2$

W selection: monojets

What we want to accept

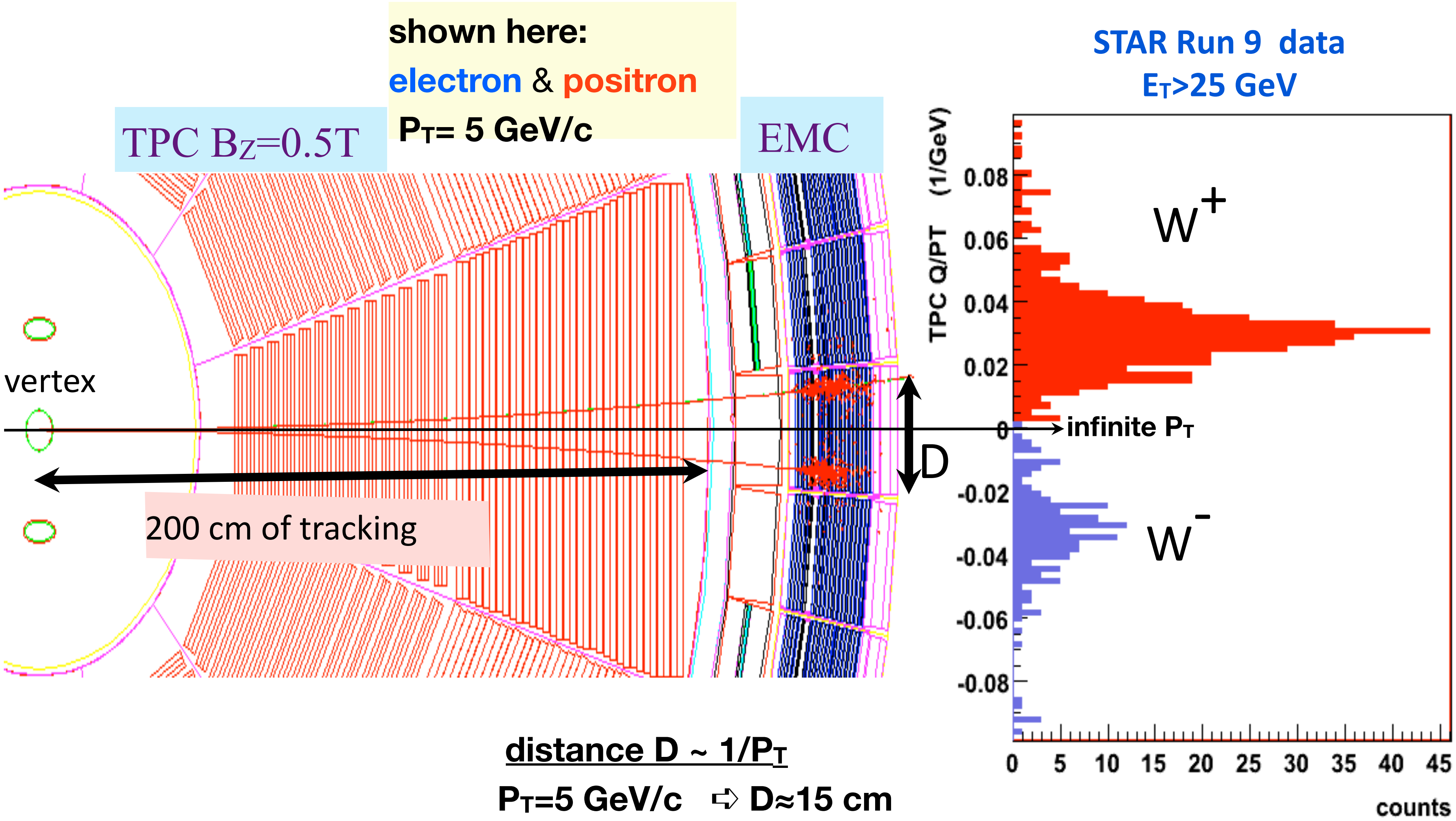


What we want to reject



Look for the electron-type events with no energy/momentum on the away side

W^+/W^- charge separation in TPC



distance $D \sim 1/P_T$

P_T=5 GeV/c ➪ D≈15 cm

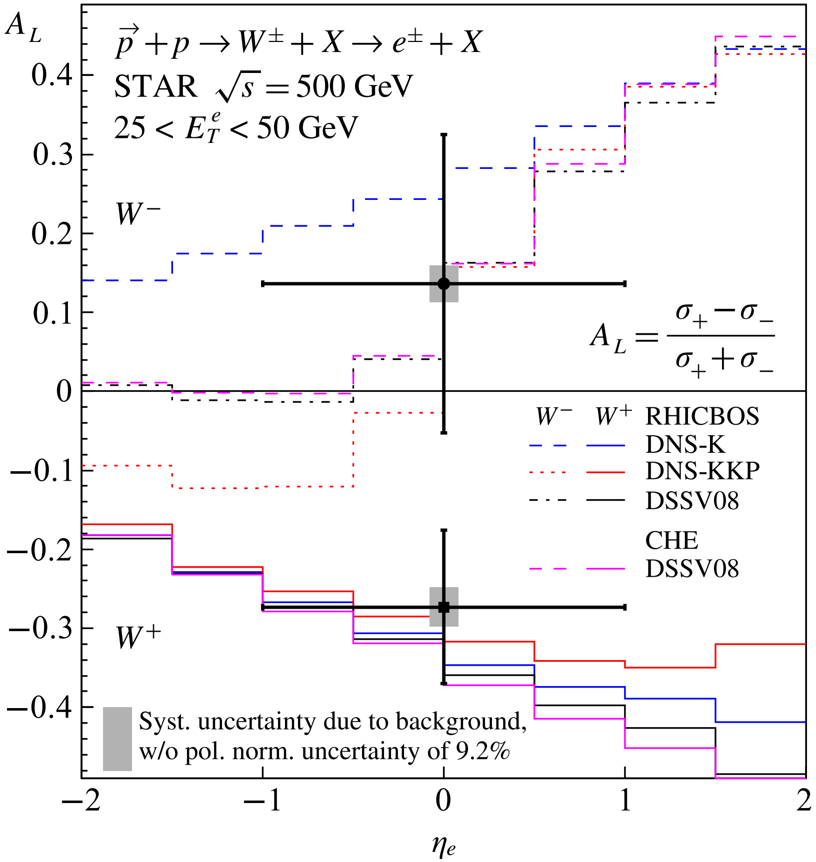
P_T=40 GeV/c ➪D≈2 cm

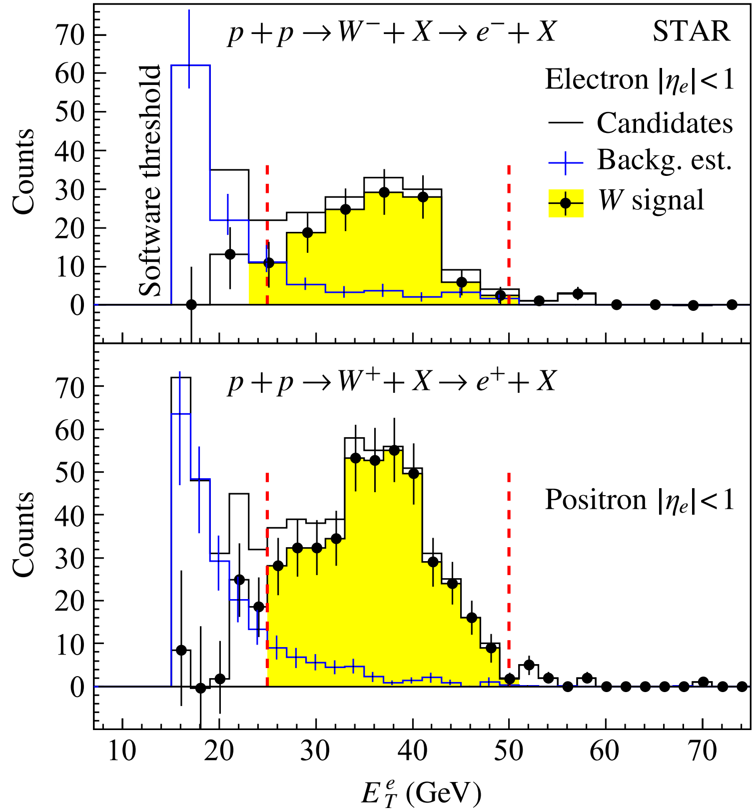
A_L for Ws measured in Run 9

STAR, arXiv:1009.0326v2 [hep-ex]

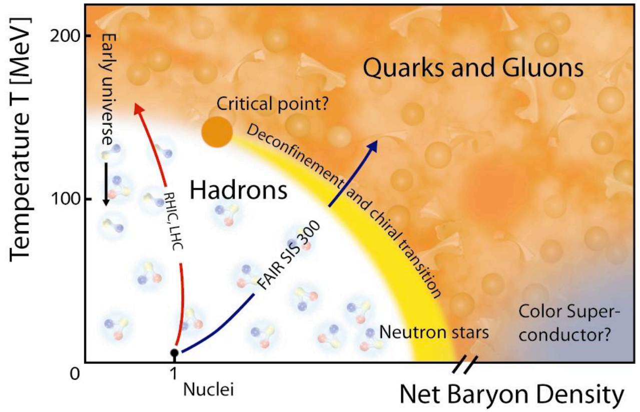
$A_L(W^+)$ = -0.27 ± 0.10 (stat.) ± 0.02 (syst.)± 0.03 (norm.)

$A_L(W^-)$ = +0.14 ± 0.19 (stat.) ± 0.02 (syst.)± 0.01 (norm.)





- ✓ $A_L(W^+)$ < 0 , as predicted, ~**3σ**
- ✓ $A_L(W^-)$ central value > 0, as expected
- ✓ systematic errors of A_L under control
- ✓ TPC charge separation works up to E_T~50 GeV



1) At 200 GeV top energy

- Study ***medium properties, EoS***
- pQCD in hot and dense medium

Jet-medium interactions

- Probing the medium
- How to spot?
  - Correlations and hadron distributions

    High p_T spectra and R_{AA}

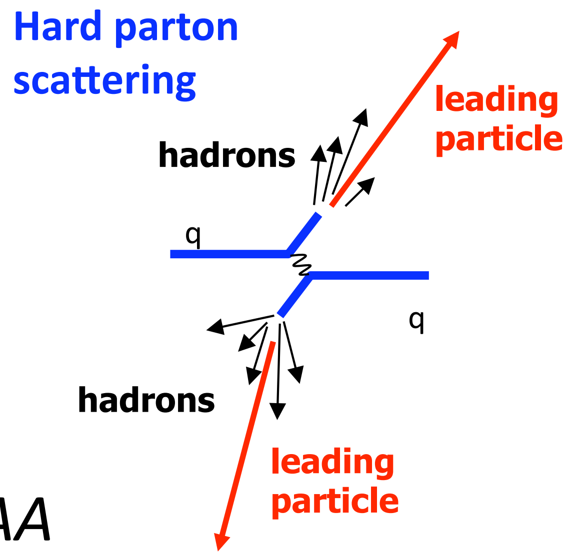
    Triggered and inclusive correlations: *pp* vs. *AA*

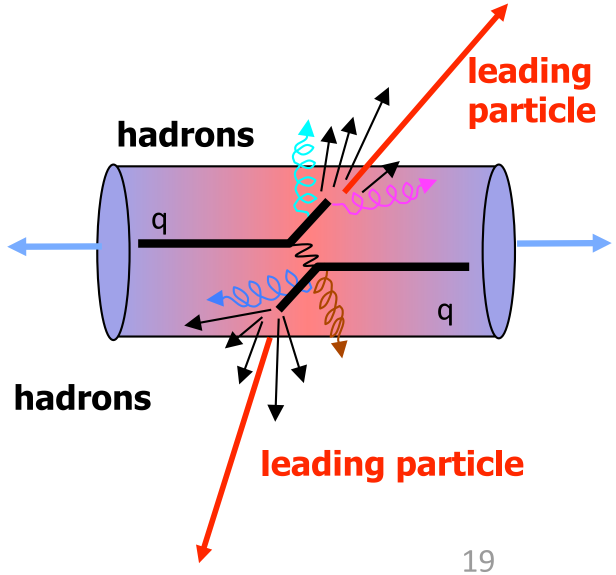
  - Reconstructed jets

    Cross-sections and R_{AA}^{Jet}

    Shape modifications (broadening)

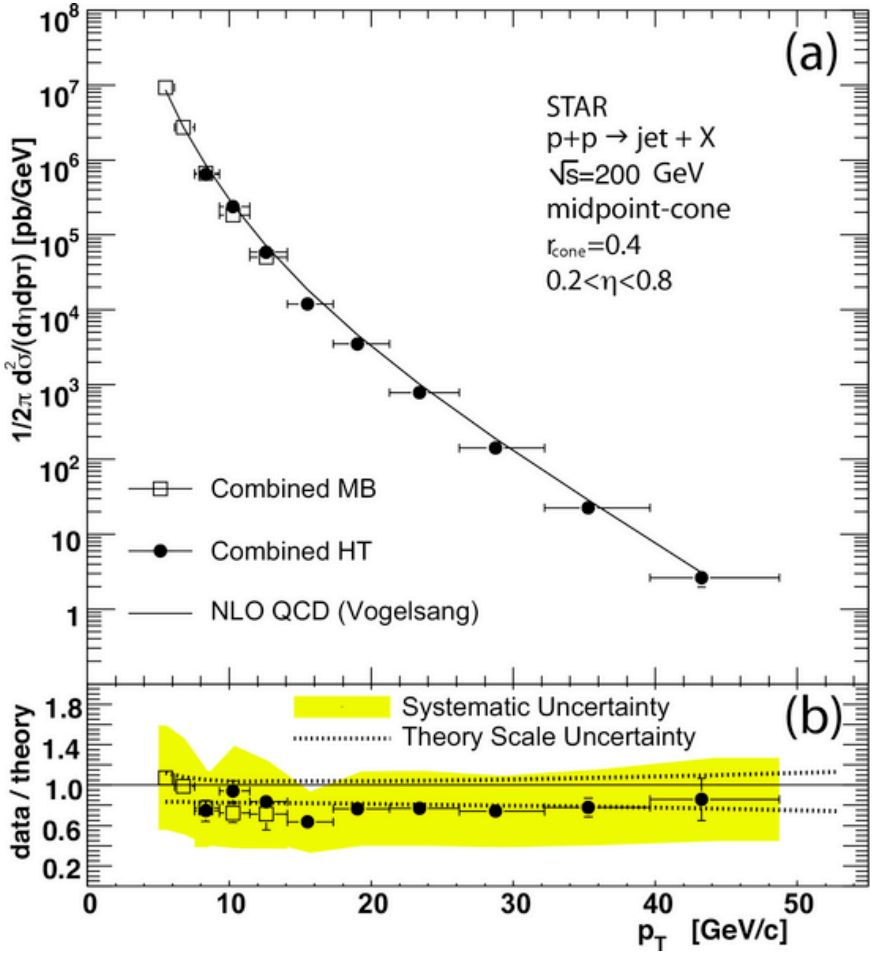
    Jet-jet, hadron-jet correlations





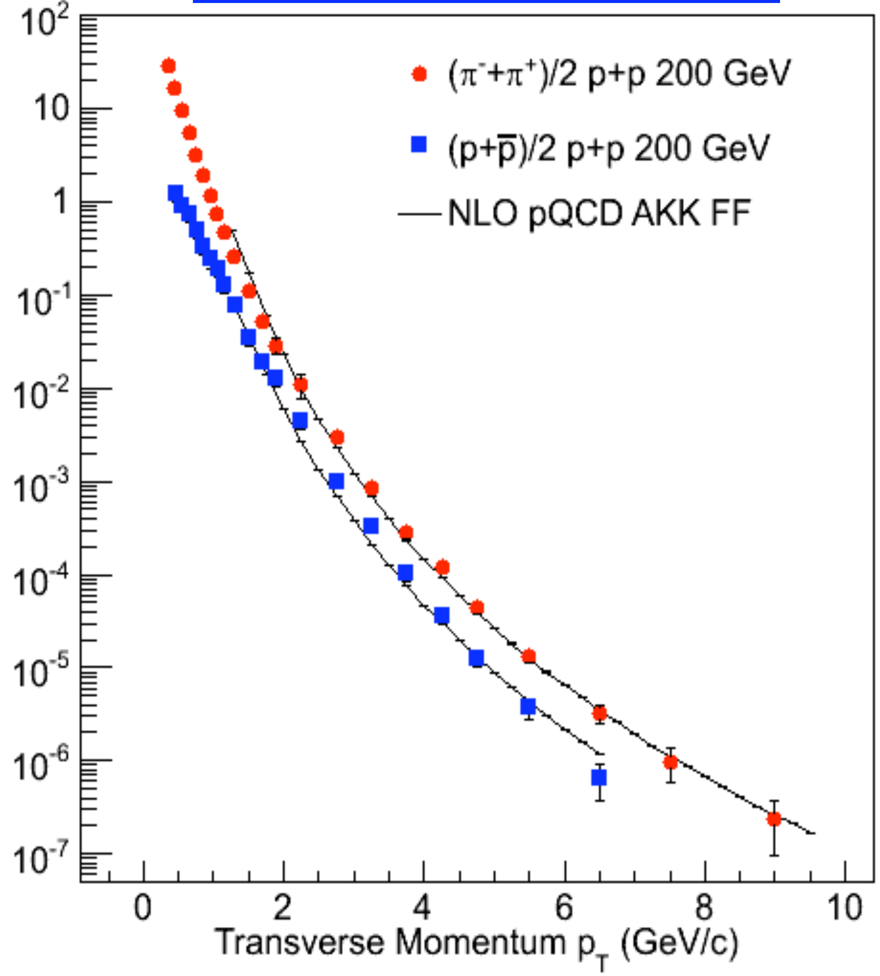
p+p collisions and pQCD at RHIC

STAR : PRL 97 (2006) 252001



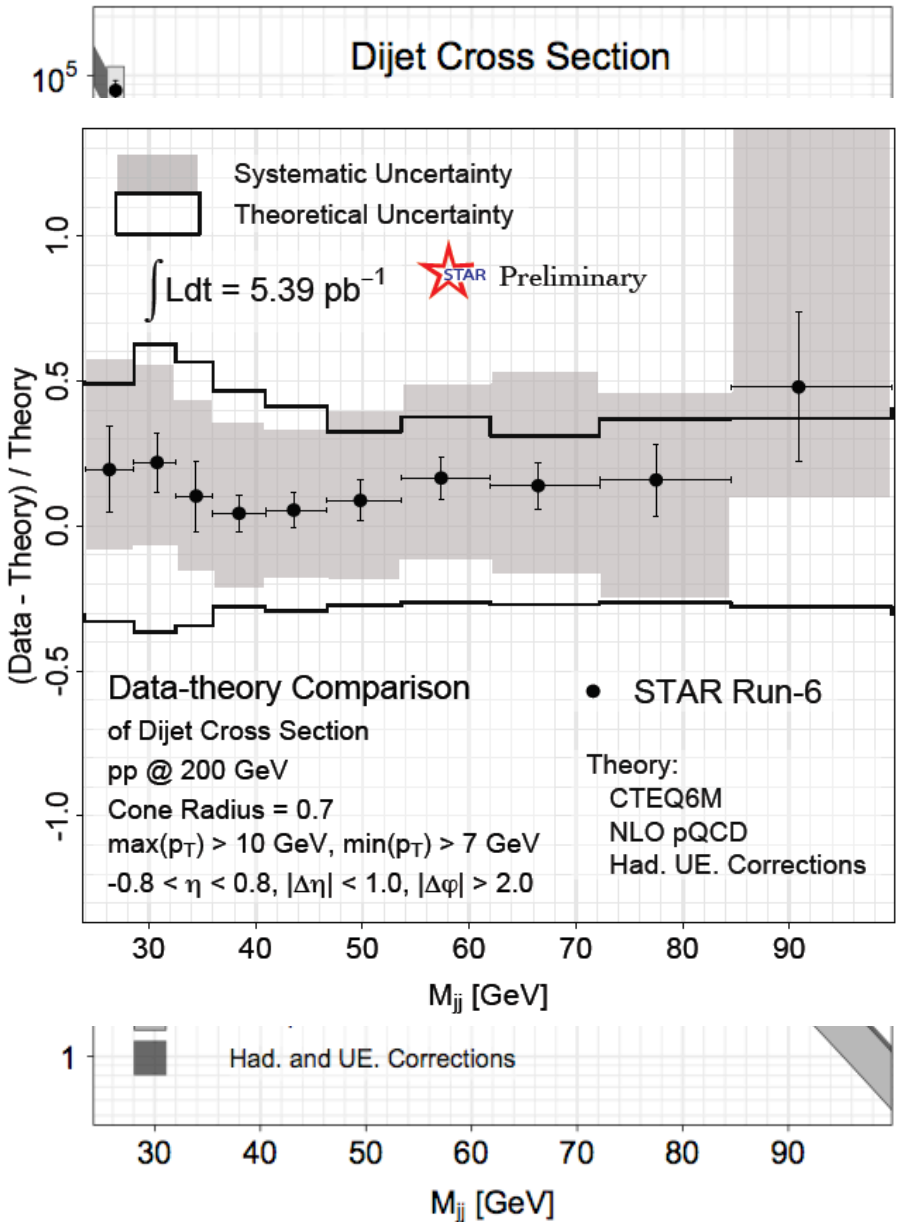
Jet production well explained by NLO pQCD calculations

STAR : PLB 637 (2006) 161



High p_T particle production well explained by NLO pQCD calculations

p+p collisions and pQCD at RHIC



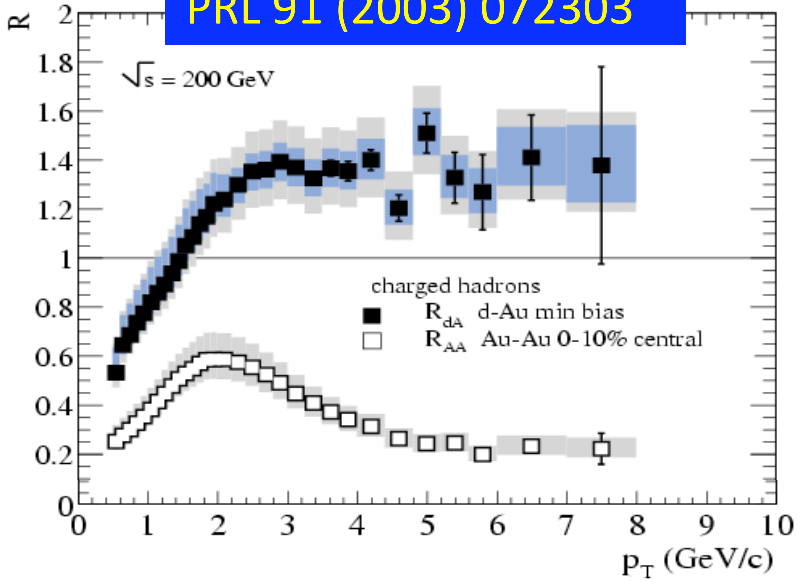
SPIN-2010: Matt Walker
for the collaboration

- Unpolarized differential cross section 24< M_{JJ} <100 (GeV/c^2)
- NLO theory predictions using CTEQ6M with and without corrections for hadronization and underlying event from PYTHIA
- Statistical uncertainties as lines, systematics as rectangles

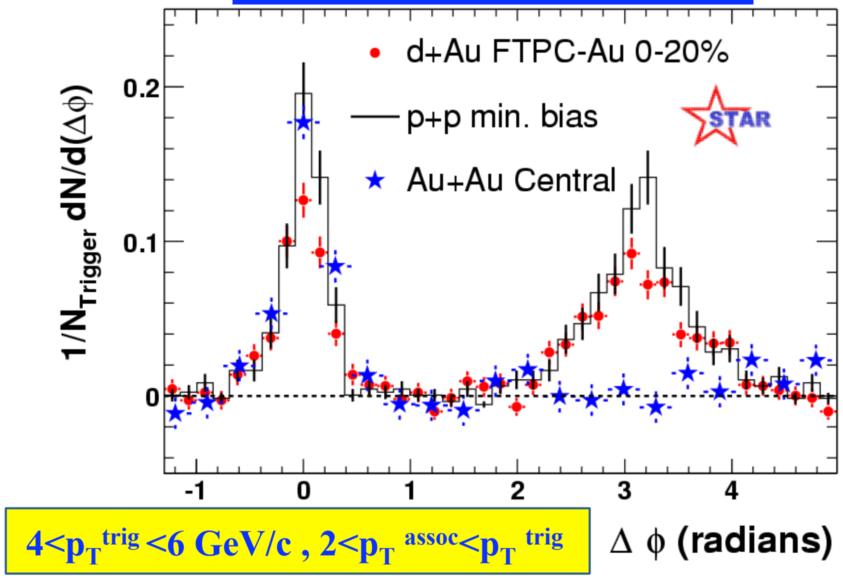
✓ **Dijet production well explained by NLO pQCD calculations**

Jet quenching: the discovery

PRL 91 (2003) 072303



PRL 91 (2003) 072304



★ **High p_T hadron suppression**:

- Final state effect in Au+Au collisions
- Observation extends to all accessible p_T range

★ **Two-particle correlation result**:

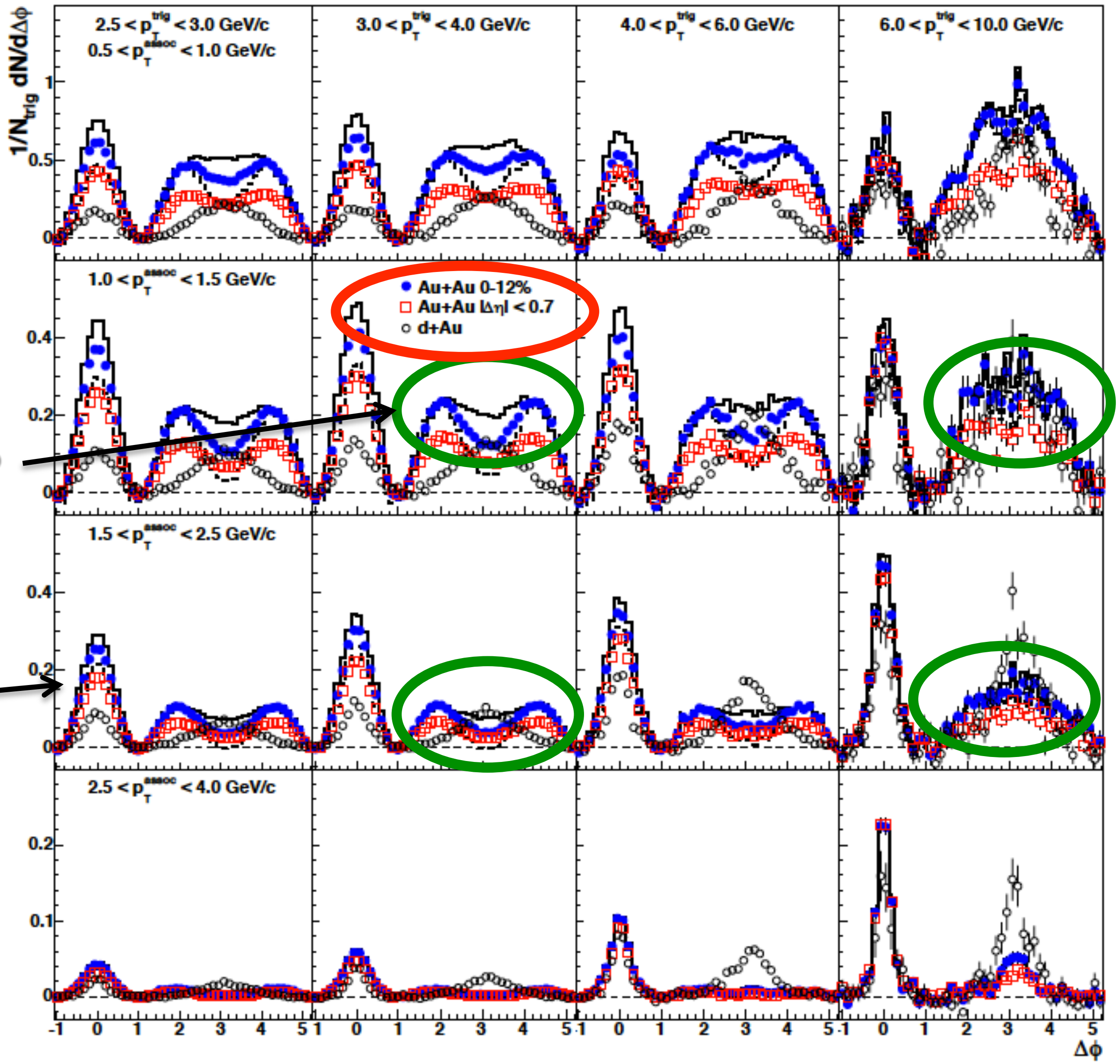
- "Disappearance" of the away-side high-p_T particle in central Au+Au collisions (for hadrons $p_T^{assoc}>2$ *GeV/c*)
- Effect not present in peripheral/d+Au collisions

Di-hadron correlations: p_T dependence

Phys.Rev. C82 (2010) 024912

Higher trigger p_T

Higher associate p_T



Conical emission?

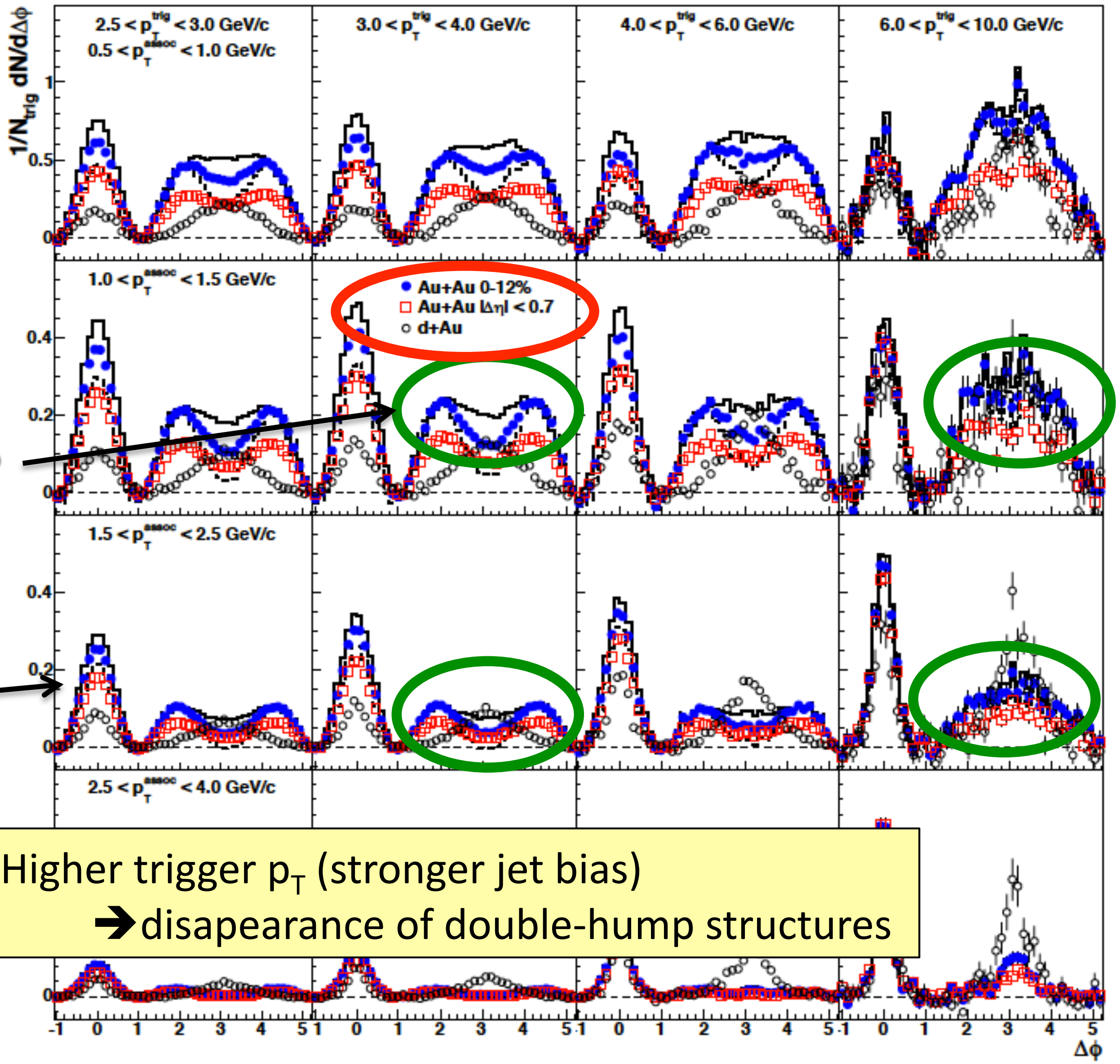
What causes the increase at near-side?

Di-hadron correlations: p_T dependence

Phys.Rev. C82 (2010) 024912

Higher trigger p_T

Higher associate p_T



Conical emission?

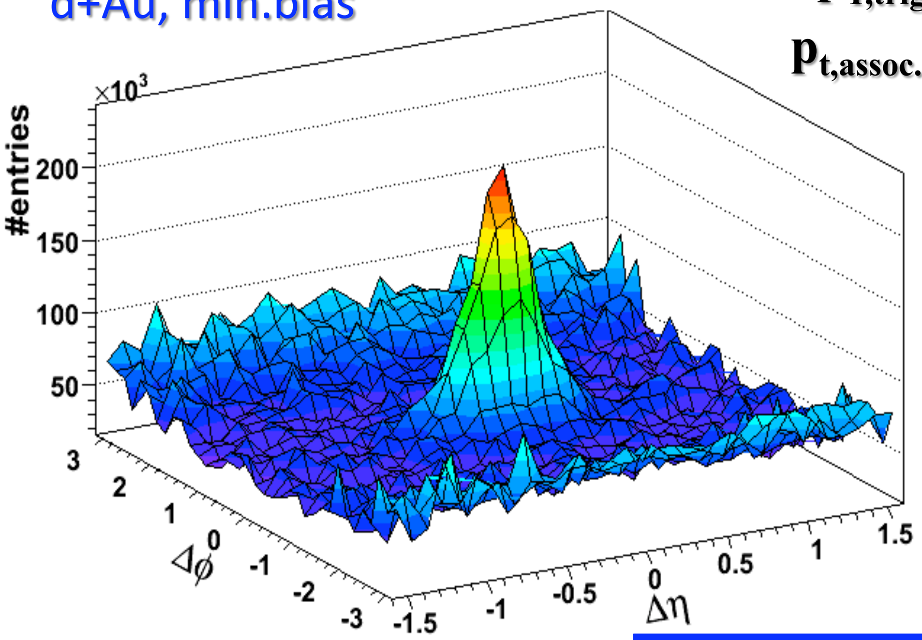
What causes the increase at near-side?

Higher trigger p_T (stronger jet bias)

➔disapearance of double-hump structures

A closer look at near-side

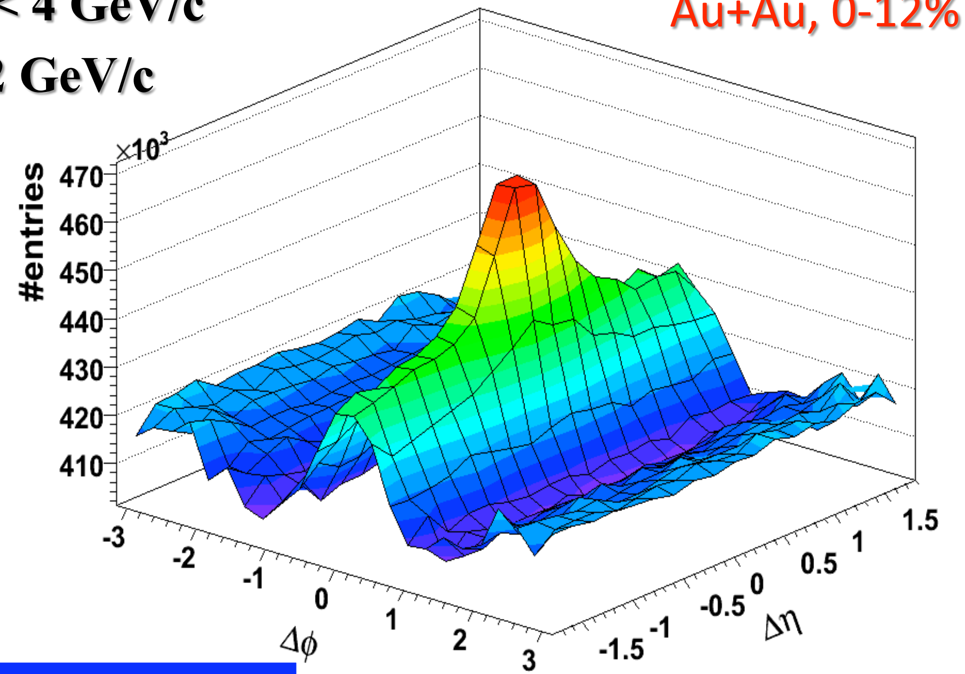
d+Au, min.bias



$3 < p_{T,trigger} < 4$ GeV/c

$p_{t,assoc.} > 2$ GeV/c

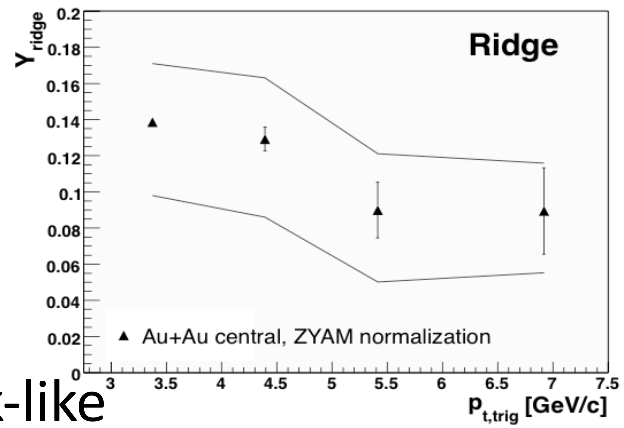
Au+Au, 0-12%



Phys. Rev. C 80 (2009) 064912

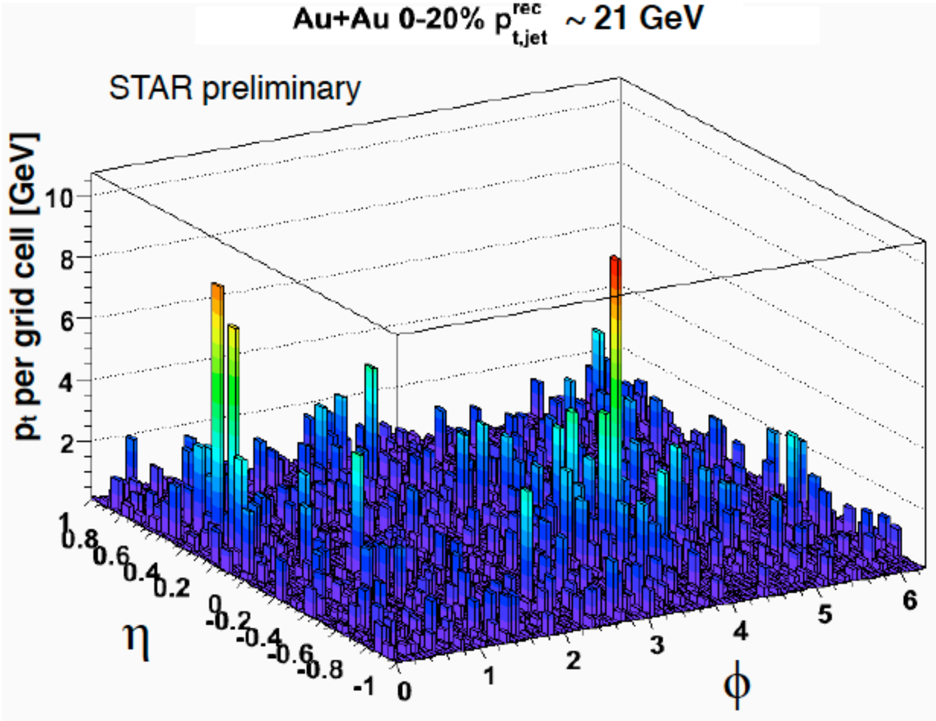
★ Near-side correlation structure:

- Central Au+Au: jet-like + ridge-like
- Ridge correlated with jet direction
- Approximately independent of Δη
- Ridge spectra and particle composition bulk-like

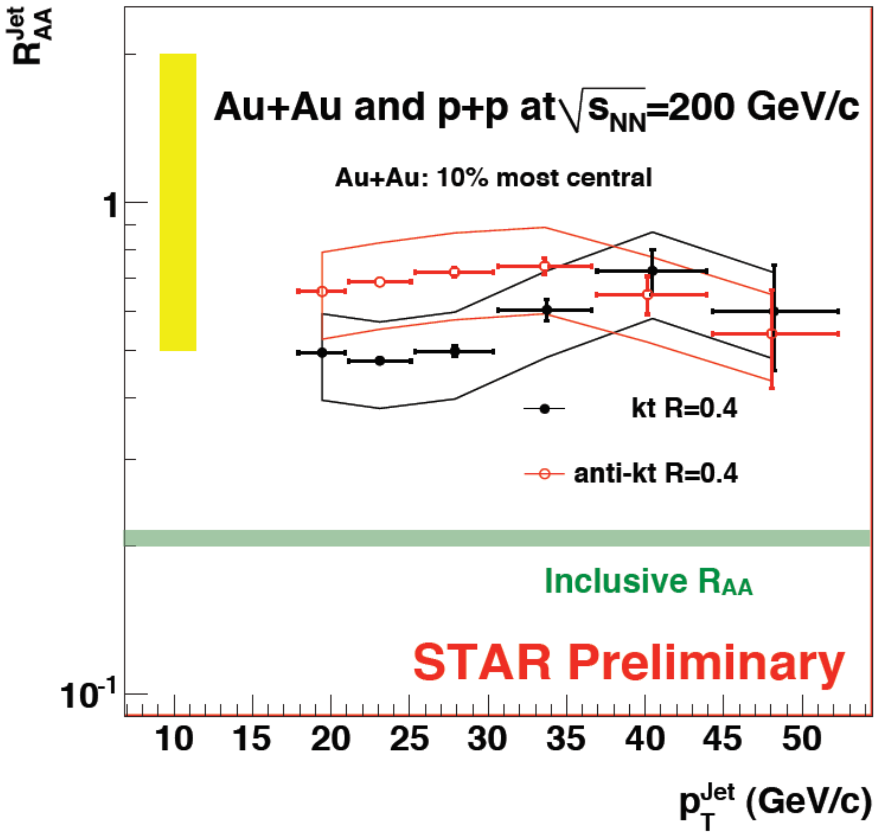


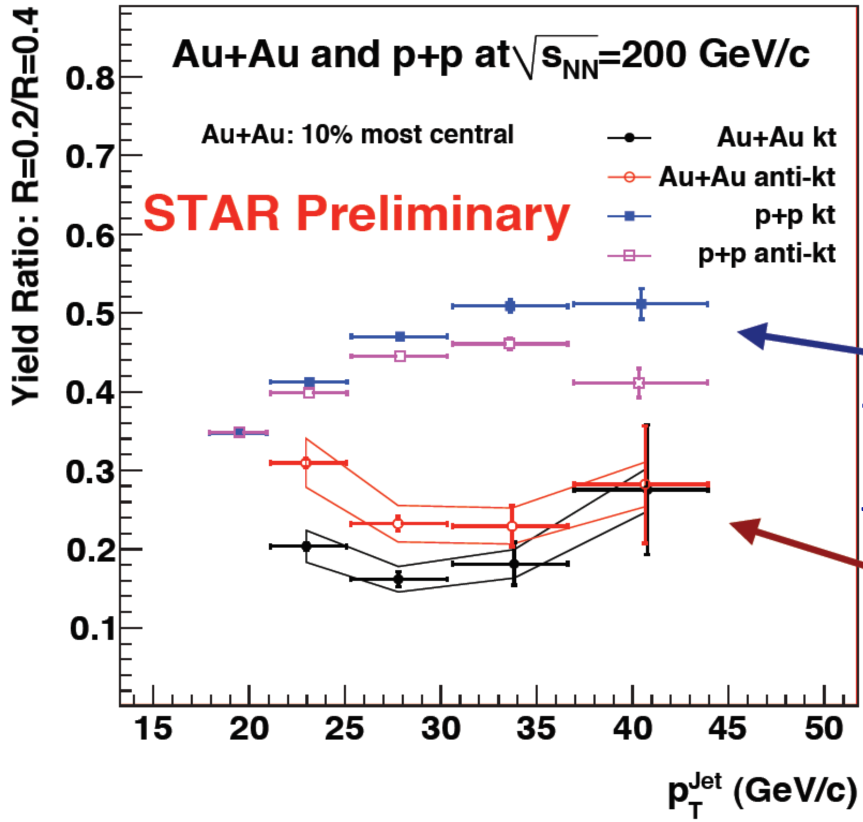
Full jet reconstruction

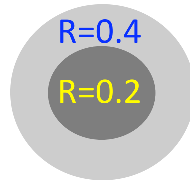
- High p_T hadrons bias towards non-interacting jets
- Full jet reconstruction reduces the bias
- Hadronization
- Very complex due to underlying event
- Algorithmic biases
- Data driven correction schemes



Nuclear modification factor and jet energy profile





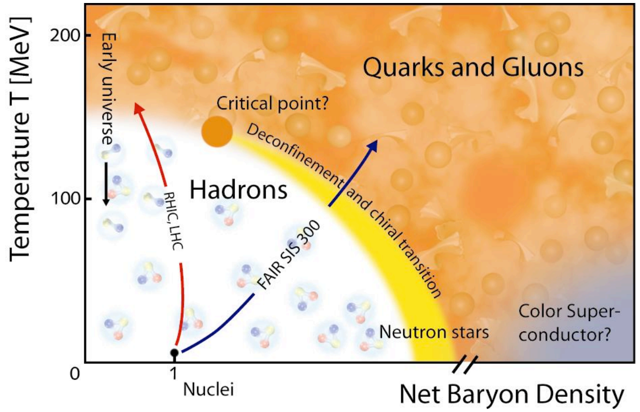


Jet "narrowing" With increasing jet energy

"Deficit" of jet energy for jets reconstructed with R=0.2

Substantial fraction of jets recovered in Au+Au collisions - in contrast to 5x suppression for light hadron R_{AA}

Strong evidence of broadening in the jet energy profile



2) RHIC beam energy scan

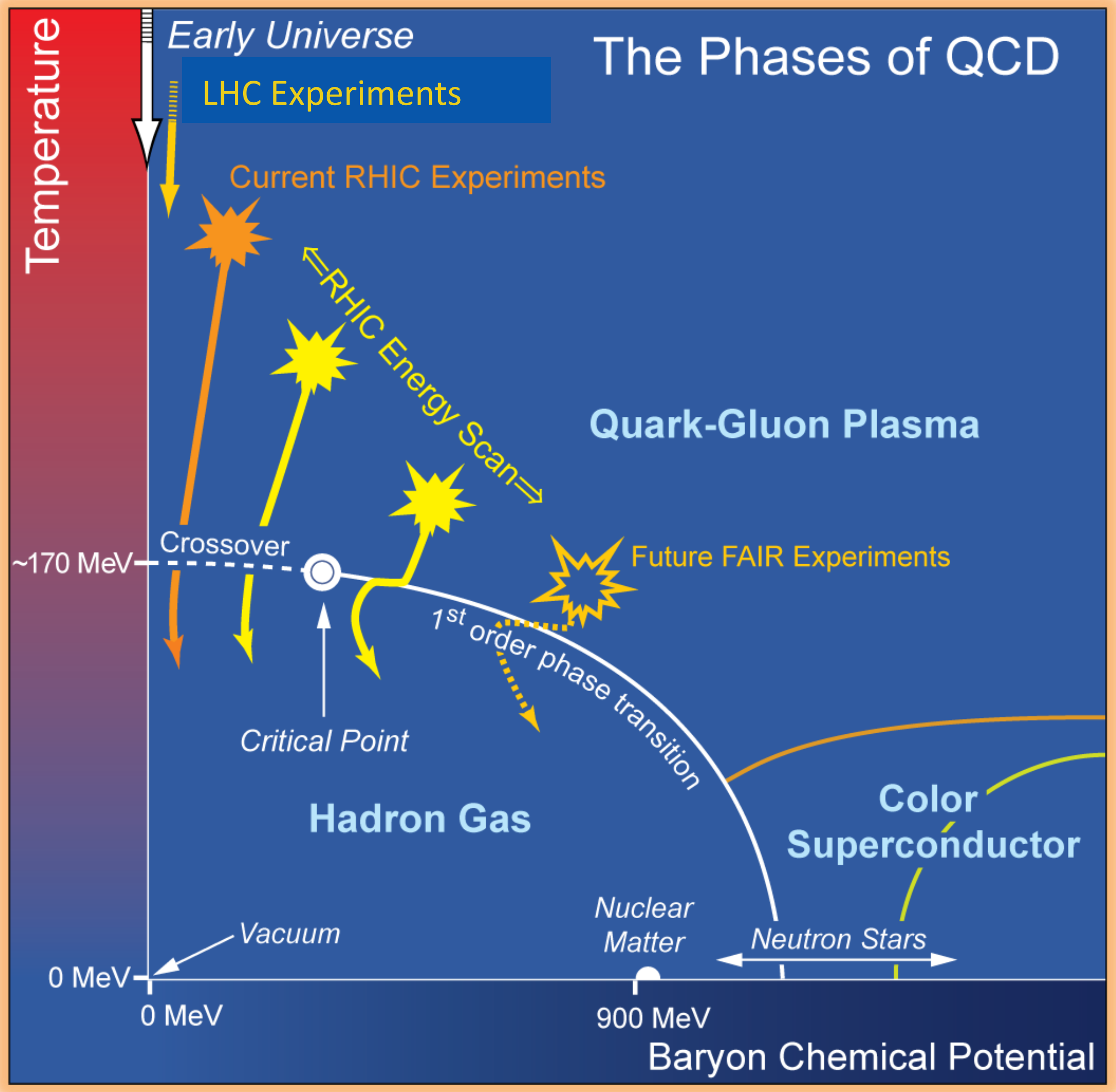
- Search for the ***QCD critical point***
- Chiral symmetry restoration

STAR Collaboration:

An Experimental Exploration of the QCD Phase Diagram: The Search for the Critical Point and the Onset of De-confinement

arXiv:1007.2613v1 [nucl-ex]

The QCD Critical Point



- Lattice Gauge Theory (LGT) prediction on the transition temperature T_C is robust.

- LGT calculation, universality, and models hinted the existence of the critical point on the QCD phase diagram* at finite baryon chemical potential.

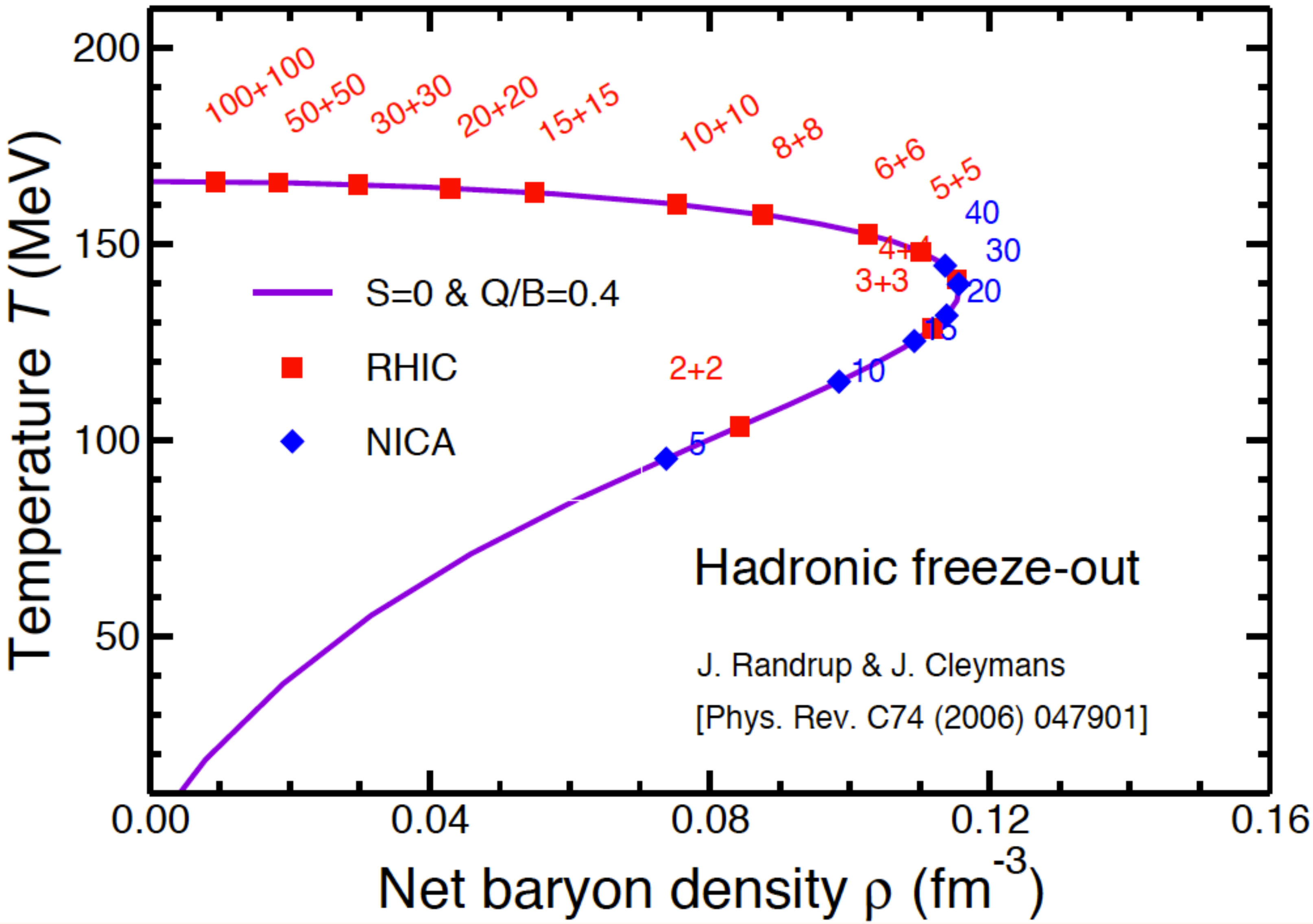
- Experimental evidence for either the critical point or 1st order transition is important for our knowledge of the QCD phase diagram*.

** Thermalization has been assumed*

*M. Stephanov, K. Rajagopal, and E. Shuryak, PRL **81**, 4816(98);*
*K. Rajagopal, PR **D61**, 105017 (00)*

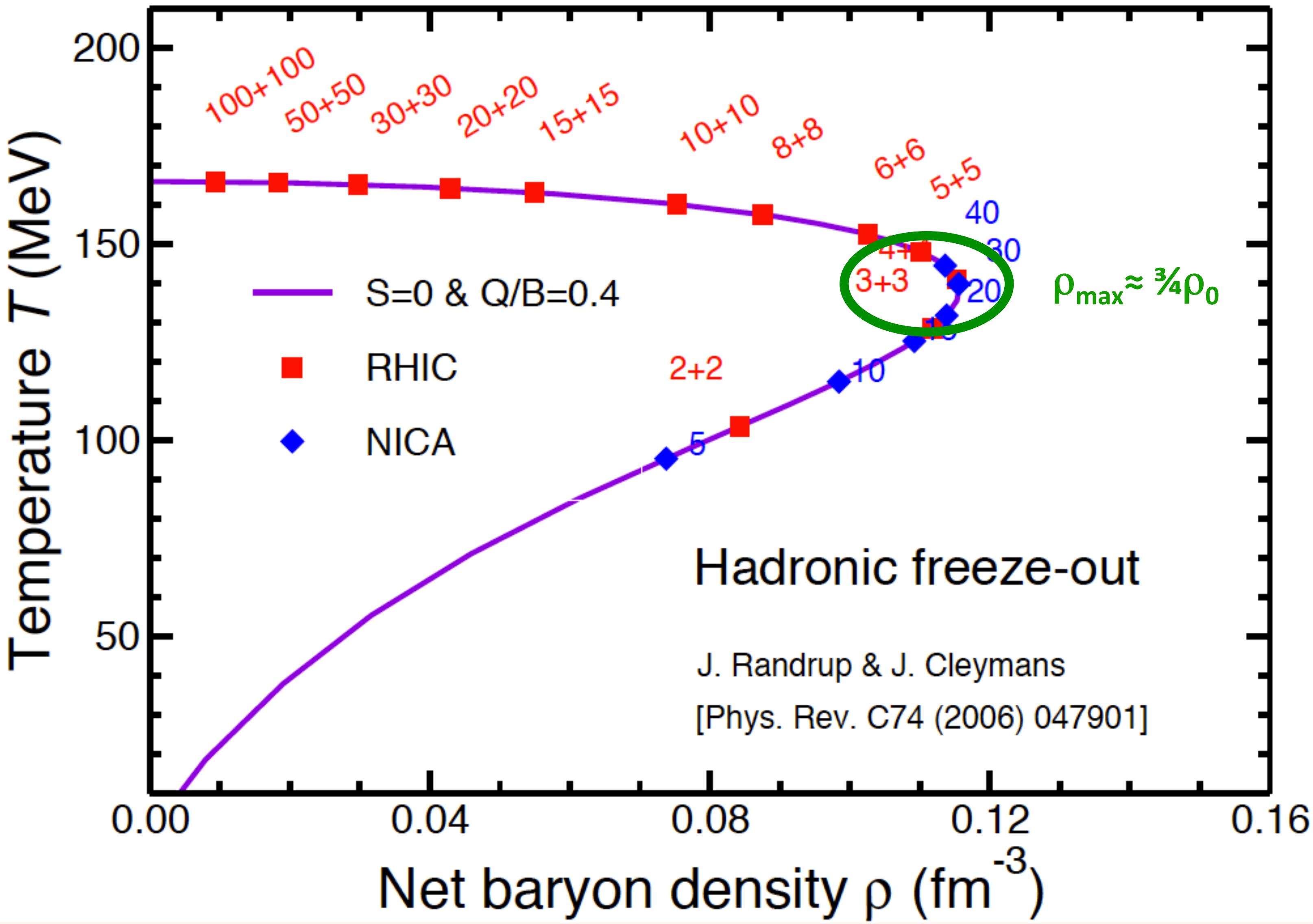
http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf

Maximum Baryon Density



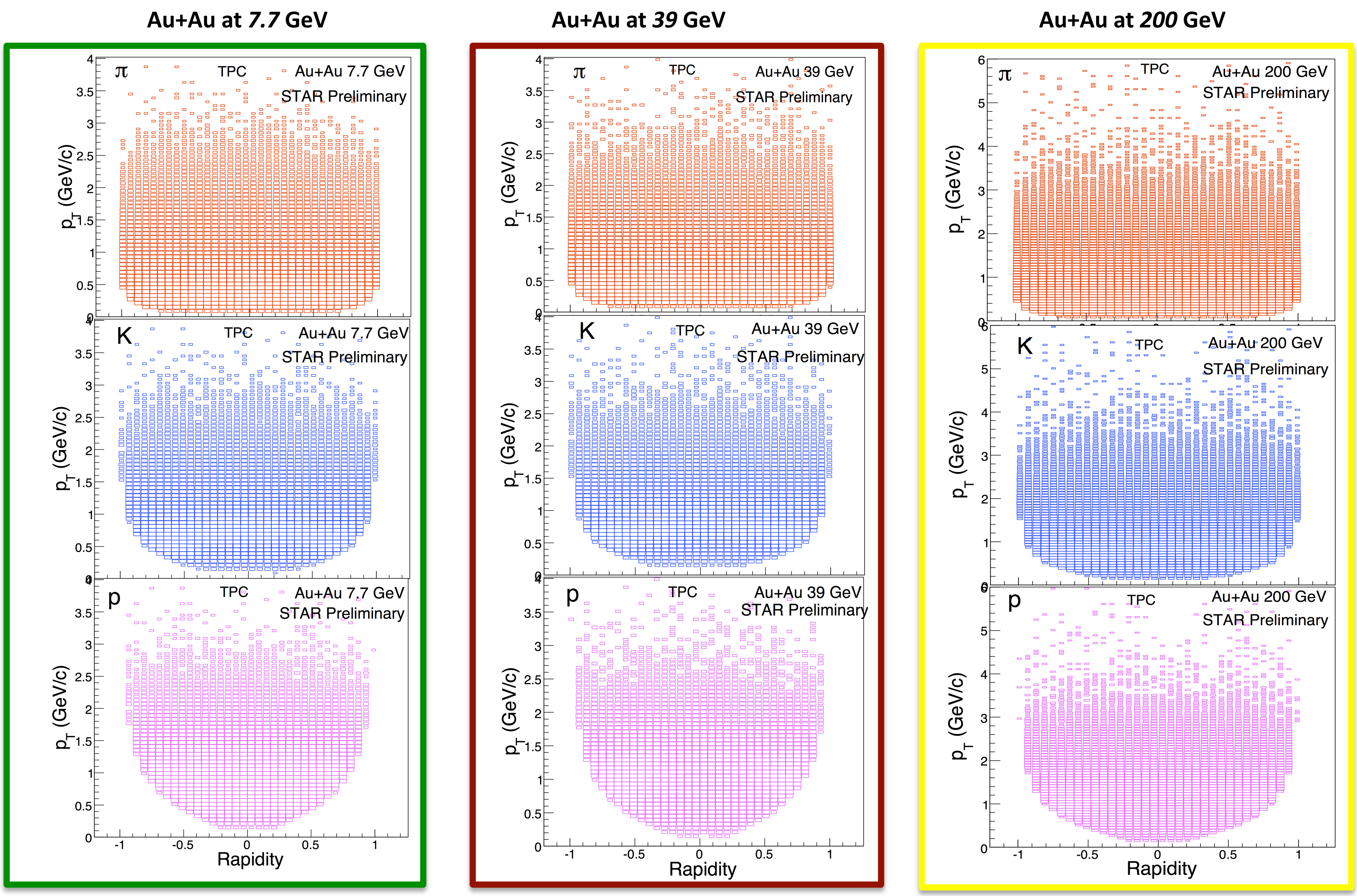
The maximum baryon density at freeze-out expected for **$\sqrt{s_{NN}}$≈6-8 GeV**

Maximum Baryon Density



The maximum baryon density at freeze-out expected for **$\sqrt{s_{NN}}\approx$6-8 GeV**

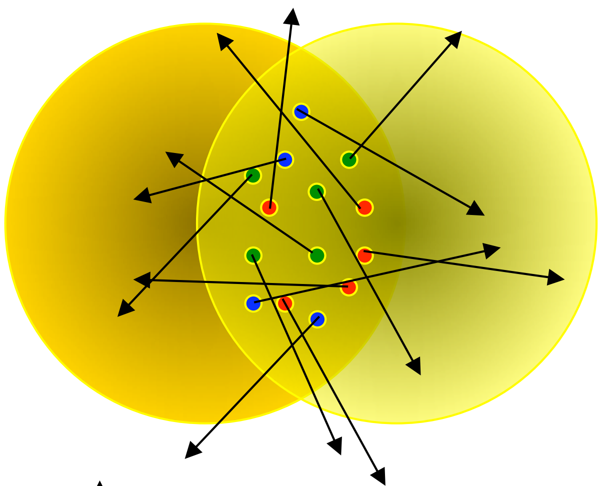
Uniform Acceptance over all RHIC Energies

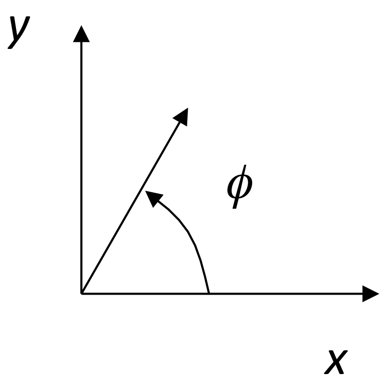


- Crucial for all analyses

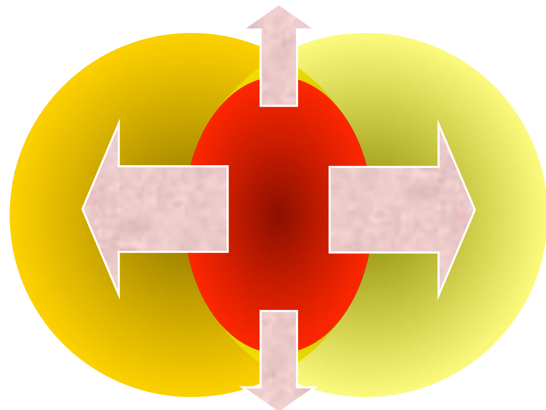
Collectivity

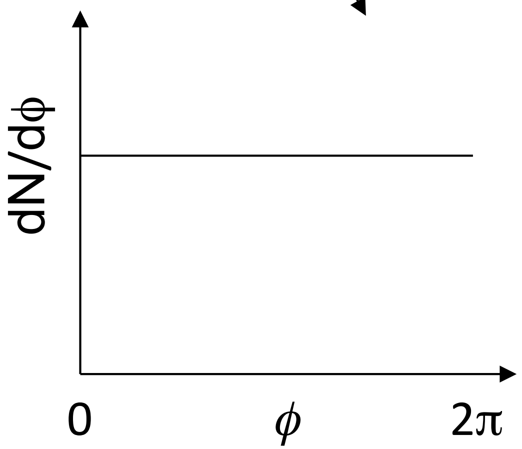
Initial spatial anisotropy





Pressure gradient





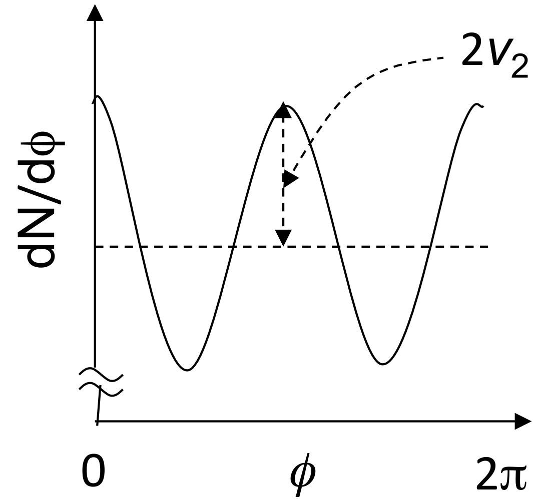
INPUT

Spatial Anisotropy

Interaction among produced particles

OUTPUT

Momentum Anisotropy



$$\varepsilon_x = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$$

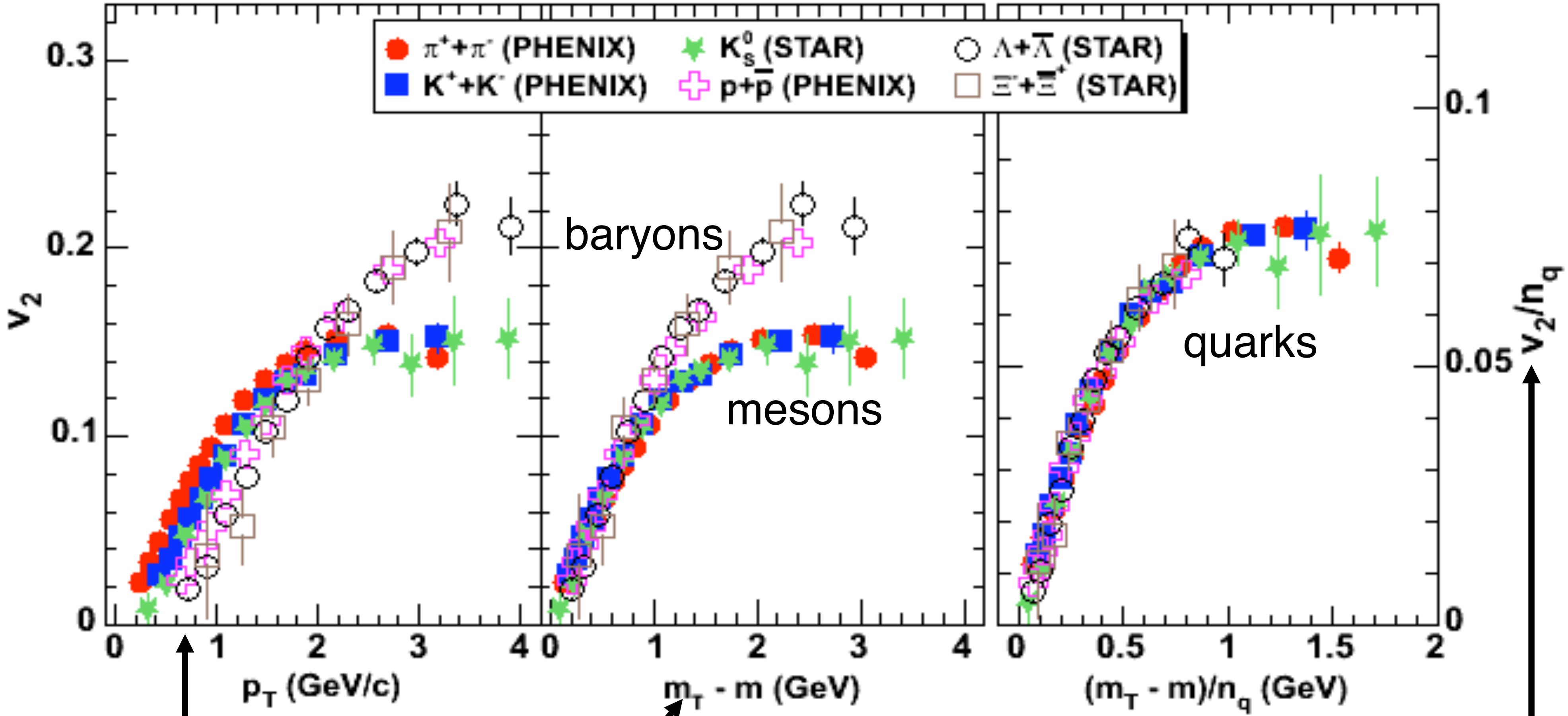
$\lambda = (\sigma\rho)^{-1}$

Adapted from B. Mohanty

$$v_2 = \langle \cos 2\varphi \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

Free streaming
v_2=0

Collectivity at Partonic Stage



particle mass dependence

plotted vs. trans. kinetic energy

both axes scaled by number of constituent quarks

n_q = 2 for mesons

n_q = 3 for baryons

recombination of constituent quarks
quarks have v_2 before hadronization

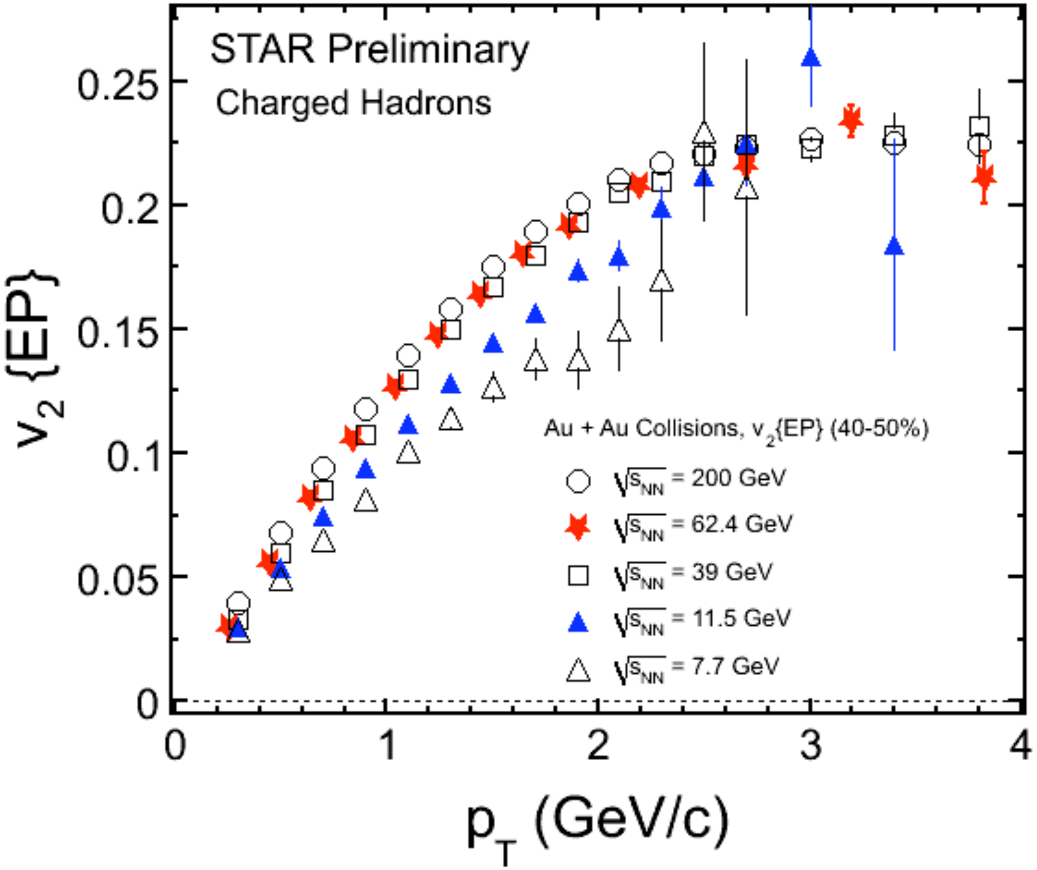
STAR: PRL **95**, 122301 (2005)

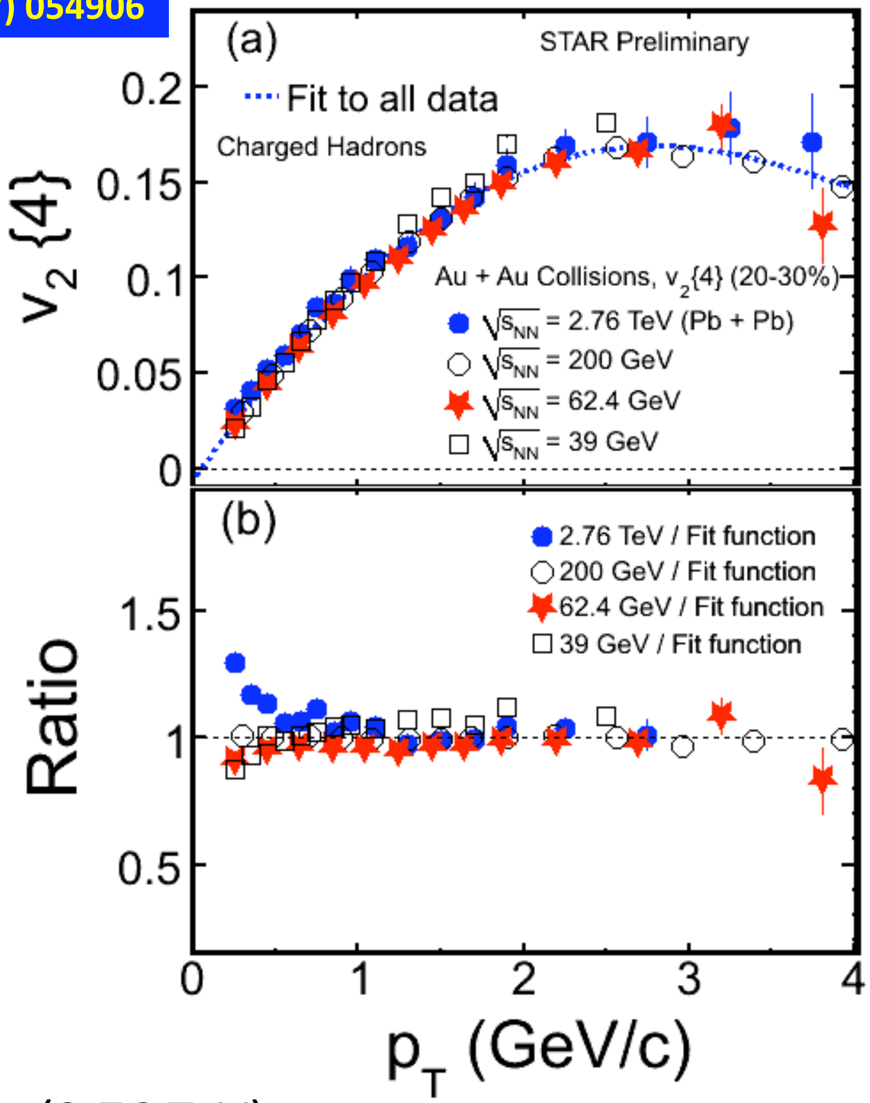
PHENIX: PRL **98**, 162301 (2007)

Azimuthal Anisotropy: v_2

ALICE:arXiv 1011.3914 (PRL…)
STAR: PRC 77 (2008) 054901; PRC 75 (2007) 054906

Compilation by S. Shi





✓ v_2 (7.7 GeV) < v_2 (11.5 GeV) < v_2 (39 GeV)

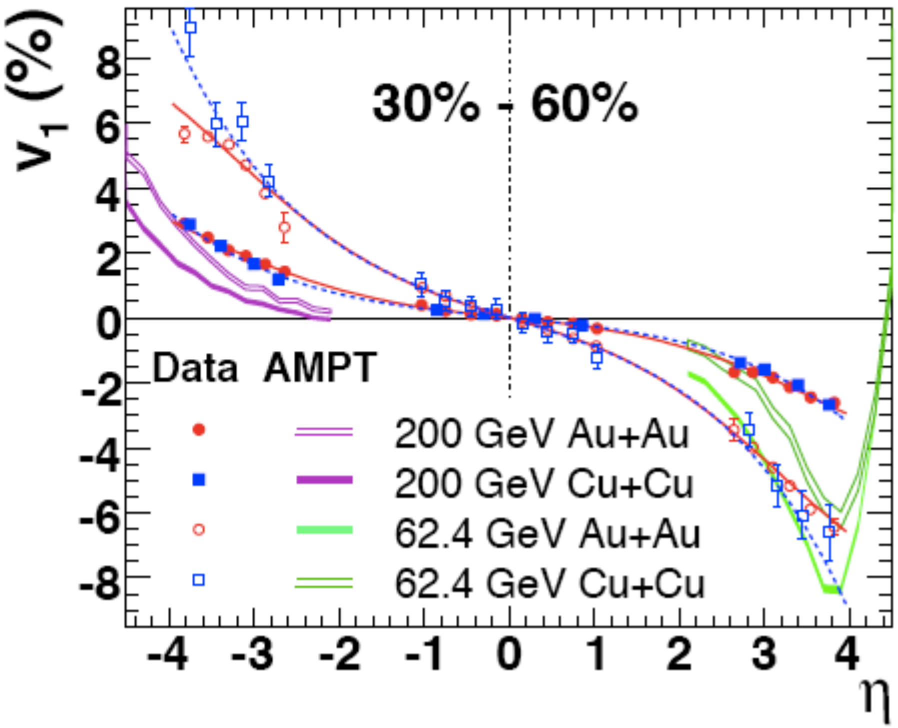
★ v_2 (39 GeV) ≈ v_2 (62.4 GeV) ≈ v_2 (200 GeV) ≈ v_2 (2.76 TeV)

Azimuthal Anisotropy: v_1

$$v_1 = \langle \cos(\phi - \Psi_r) \rangle, \quad \phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

$v_1(y)$ is sensitive to baryon transport, space - momentum correlations and QGP formation

STAR: PRL **101,** 252301 (2008)



- Forward rapidity v_1: energy dependence, **no N_{part} dependence**
- Model calculations show **both** beam energy and system size dependence!

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STAR

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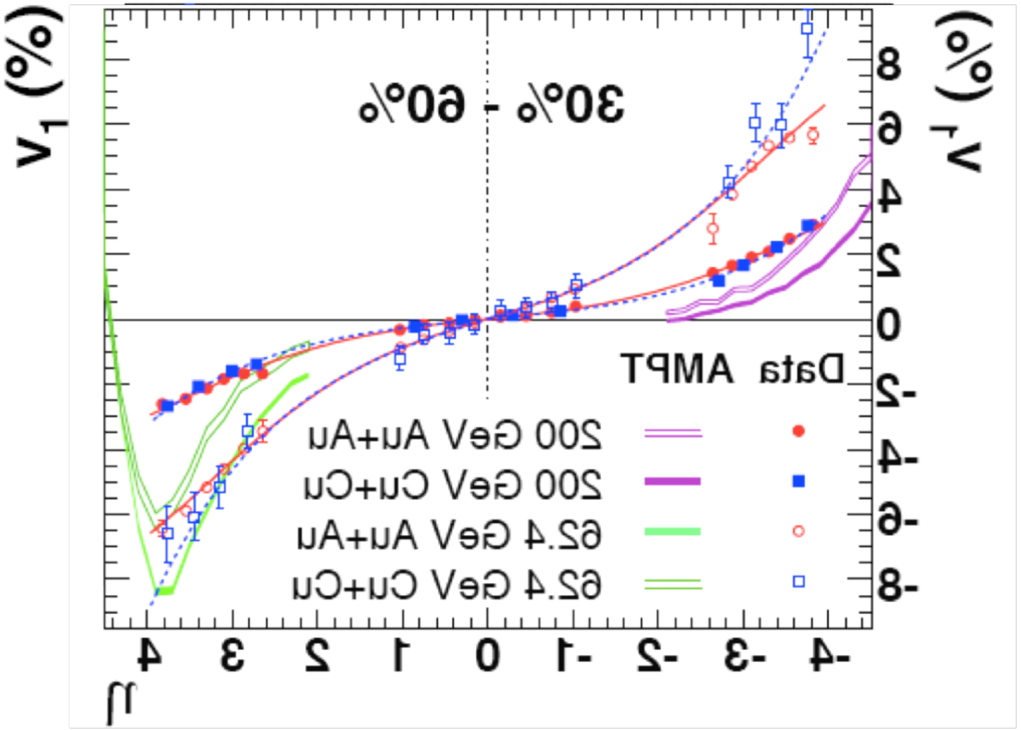
STAR: PRL **101,** 252301 (2008)



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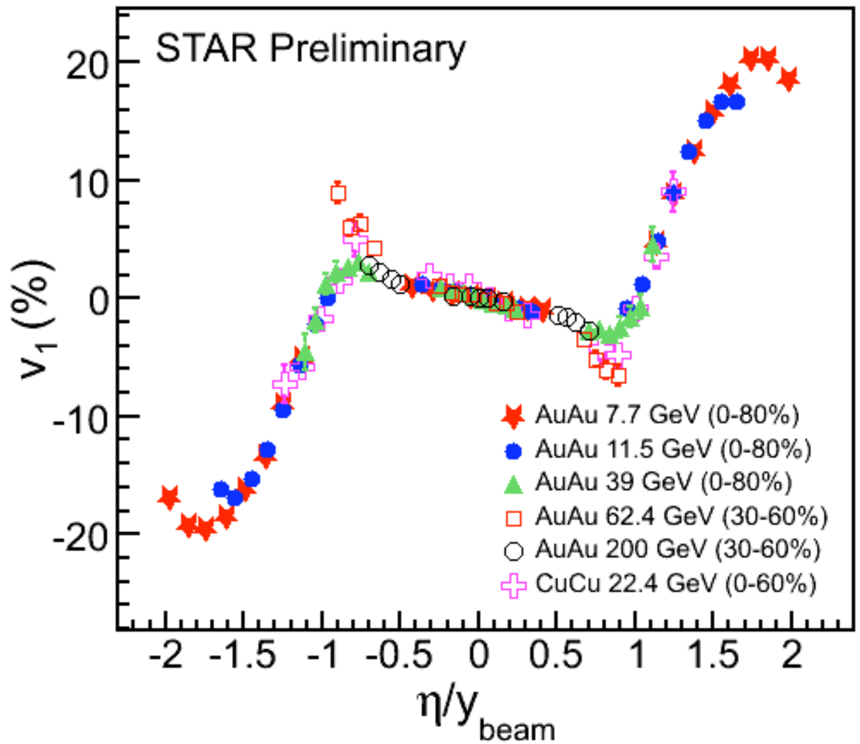
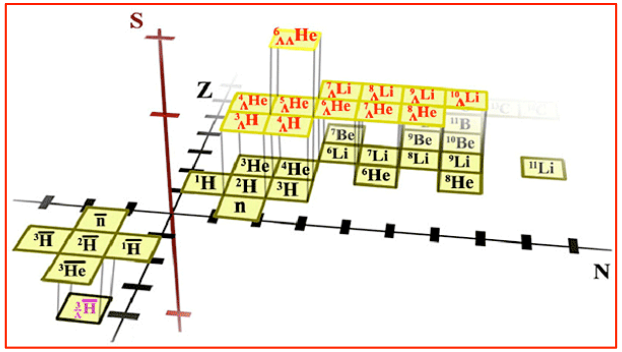
- Model calculations show **both** beam energy and system size dependence!

ICPAQGP 2010: Lokesh Kumar
for the collaboration



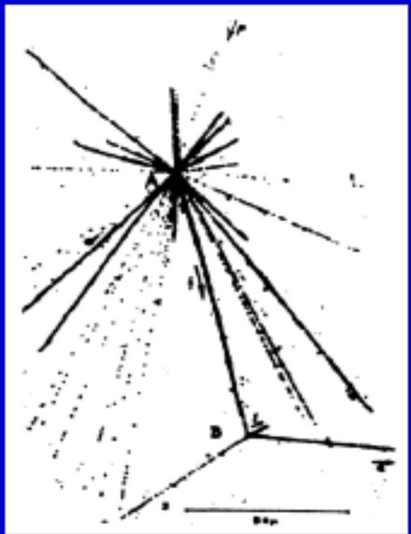
With v_1 divided by the respective y_{beam} values, data seem to follow a common trend for the measured $|\eta|/y_{beam} < 1$ range.



Exotic systems created in nuclear collisions

- ***antihypernuclei*** *etc.*

Hypernucleus = Nucleus containing at least one hyperon



The first hypernucleus was discovered by Danysz and Pniewski in 1952. It was formed in a cosmic ray interaction in a balloon-flown emulsion plate.

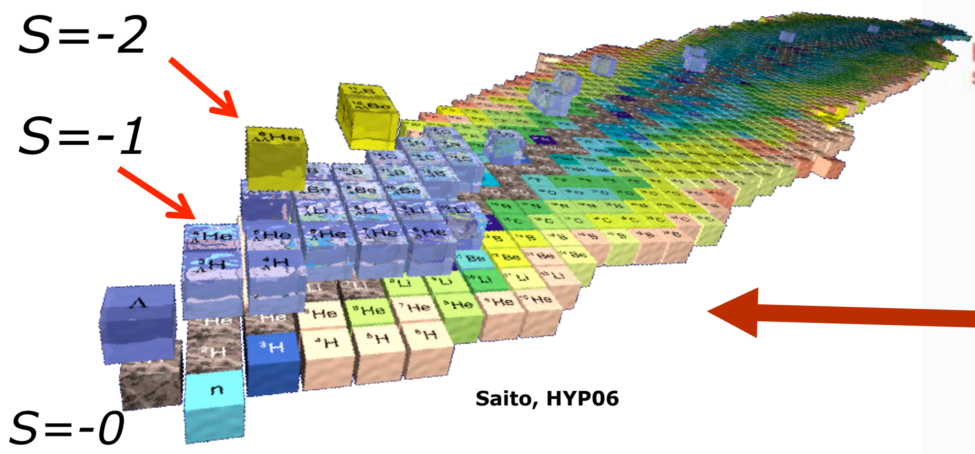
M. Danysz and J. Pniewski, Phil. Mag. 44 (1953) 348

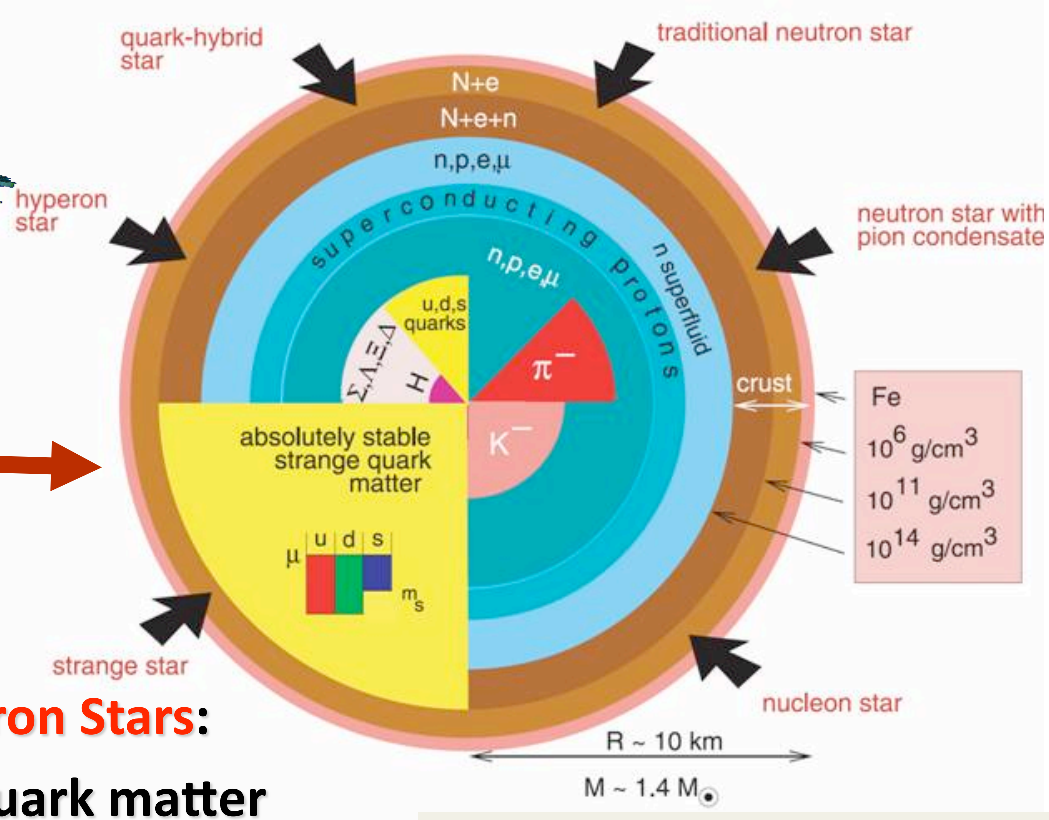
Until recently anti-hypernucleus was never observed experimentally

- Y-N interaction: a good window to understand the baryon potential
- Binding energy and lifetime are very sensitive to **Y-N interactions**
- Hypertriton: **ΔB=130±50 keV; r~10fm**
- Production rate via **coalescence** at RHIC depends on overlapping wave functions of **n+p+Λ** in the final state
- Important first step for searching for other **exotic** hypernuclei (double-Λ).

From Hypernuclei to Neutron Stars

Hypernuclei ⟵ Λ-B Interaction ⟶ Neutron Stars





- **Several possible configurations of Neutron Stars:**
  - **Kaon condensate, hyperons, strange quark matter**
- ***Single* and *double* hypernuclei in the laboratory:**
  - **study the strange sector of the B-B interaction**
  - **provide info on EOS of neutron stars**
- **Extension of the nuclear chart into anti-matter with S[1]**

[1] W. Greiner, Int. J. Mod. Phys. E 5 (1995) 1

J.M. Lattimer and M. Prakash, *The Physics of Neutron Stars*, Science 304, 536 (2004)
J. Schaffner and I. Mishustin, *Hyperon-rich matter in neutron stars*, Phys. Rev. C 53 (1996)

Data-set and track selection

$^{3}_{\Lambda}H$ mesonic decay, m=2.991 GeV/c^2, B.R. 0.25

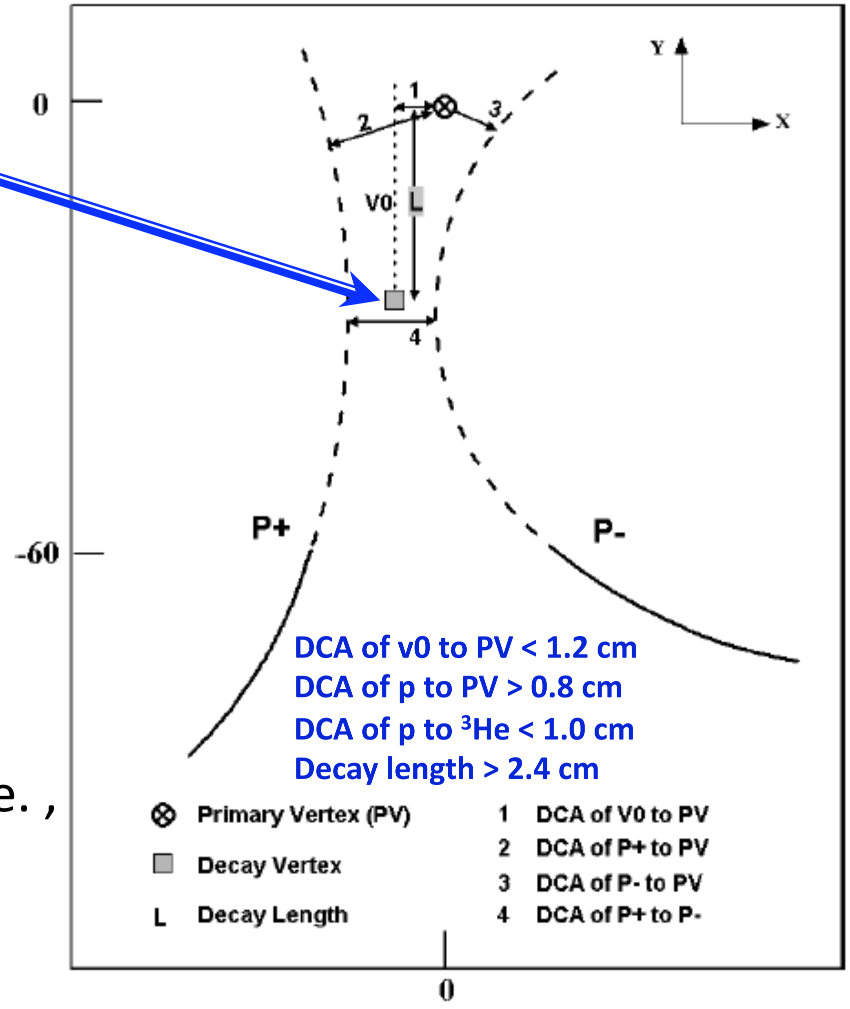
$$ {}^{3}_{\overline{\Lambda}}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+} $$

$$ {}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-} $$

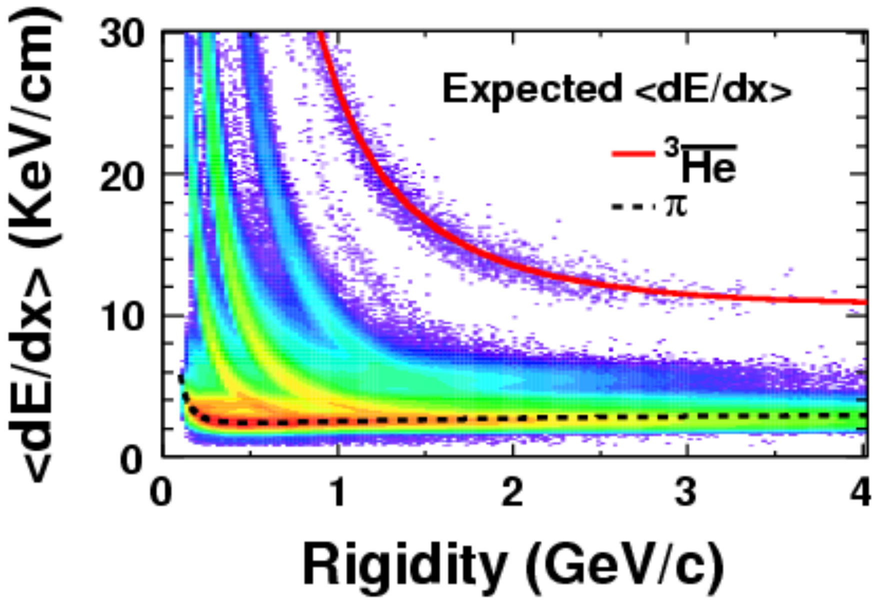
- Data-set used, Au+Au 200 GeV
  - ✓~67M year 2007 minimum-bias
  - ✓~22M year 2004 minimum-bias
  - ✓~23M year 2004 central,
  - ✓ $|V_Z|$<30cm
- Tracks level: standard STAR quality cuts, i.e. , *not near edges of acceptance, good momentum & dE/dx resolution.*

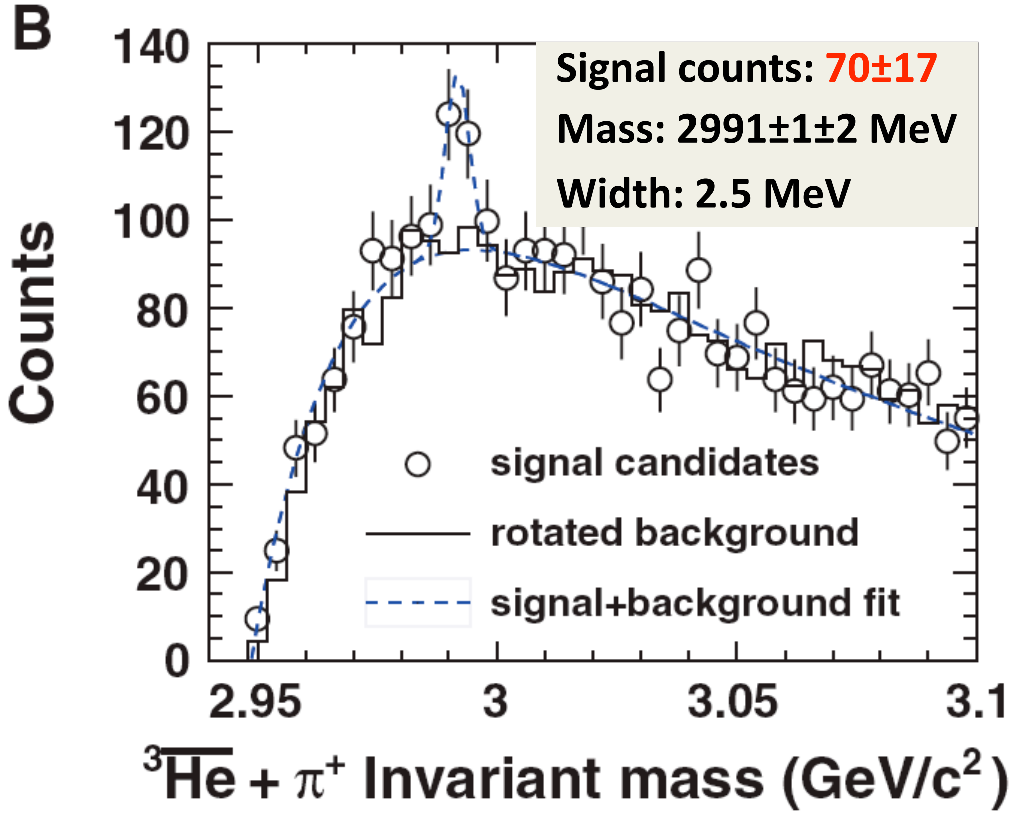
J.H. Chen (STAR), Nucl.Phys. A830 (2009) 761c

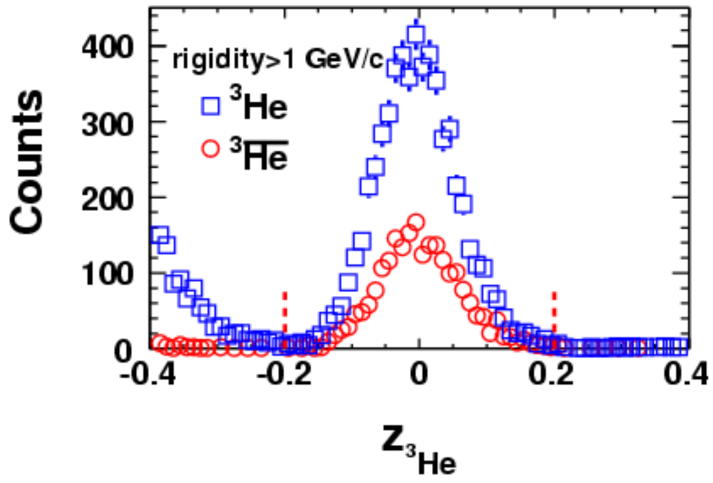
Secondary vertex finding technique



Discovery of Anti-Strange Matter



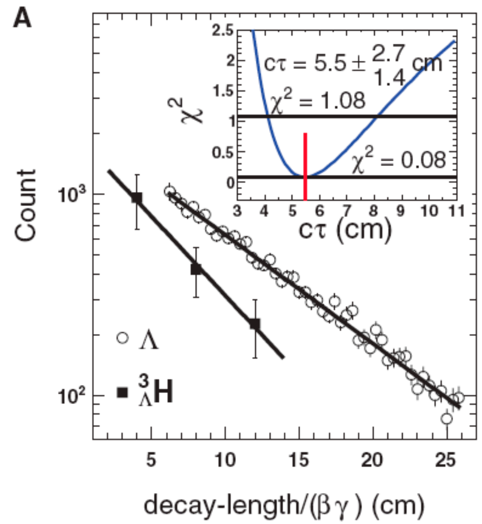




τ_Λ = 267±5 ps

PDG = 263±2 ps

$$\tau({}^{3}_{\Lambda}H) = 182^{+89}_{-45} \pm 27$$



STAR, Science 328 (2010) 58
arXiv:1003.2030v1 [nucl-ex]

Summary

- ★ STAR experiment at RHIC provides wealth of new and exciting results on QCD condense matter, hadronic and particle physics.
- ★ STAR spin program has reached its maturity.
- ★ STAR measurements provide a strong evidence for non-trivial jet-medium interaction.
- ★ First STAR results from Beam Energy Scan program are exciting. Search for the critical point is ongoing.
- ★ Discovery of anti-hypernucleus puts STAR into the forefront of hypernuclear physics.