STAR results of relevance for cosmic rays

Joanna Kiryluk (LBNL)
for the STAR collaboration

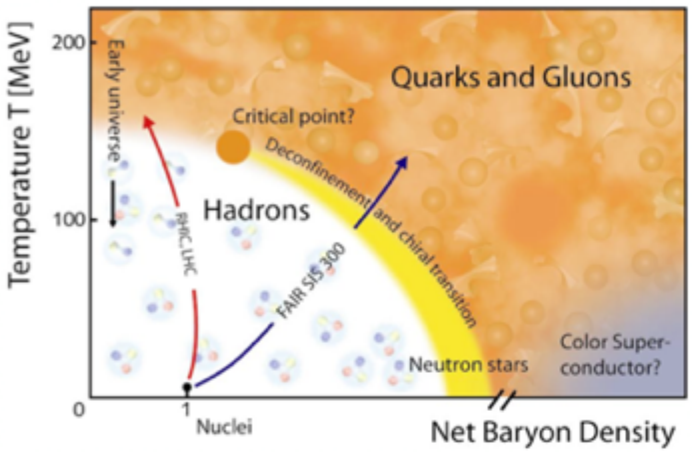
ECT Workshop on “Hadron-Hadron and Cosmic-RaysCollisions at multi-TeV Energies“
Trento, Italy

The Relativistic Heavy Ion Collider
a QCD lab

Brookhaven National Laboratory

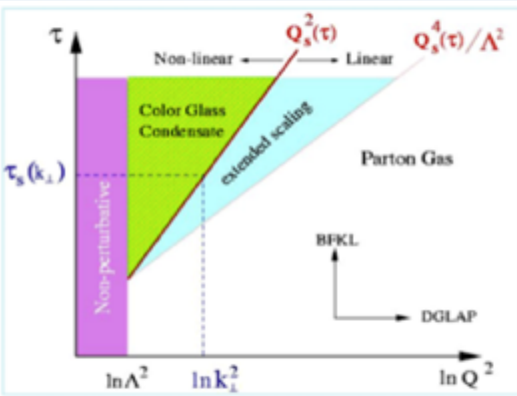
- 3.8 km circumference
- counter-rotating beams of ions from p to Au

STAR Physics Focus

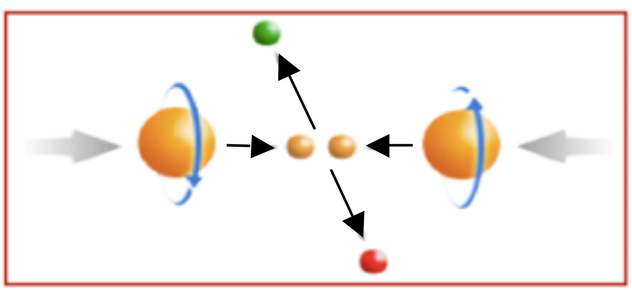


1) At 200 GeV top energy
- Study ***medium properties, EoS***
- pQCD in hot and dense medium

2) RHIC beam energy scan (BES)
- Search for the ***QCD critical point***
- Chiral symmetry restoration



Forward program
- Study low-x properties, initial condition, search for ***CGC***
- Study elastic and inelastic processes in pp2pp



Polarized *p+p* program
- Study ***proton intrinsic properties***
  role of spin in QCD
- Tests of QCD calculations

STAR - Solenoid Tracker at RHIC

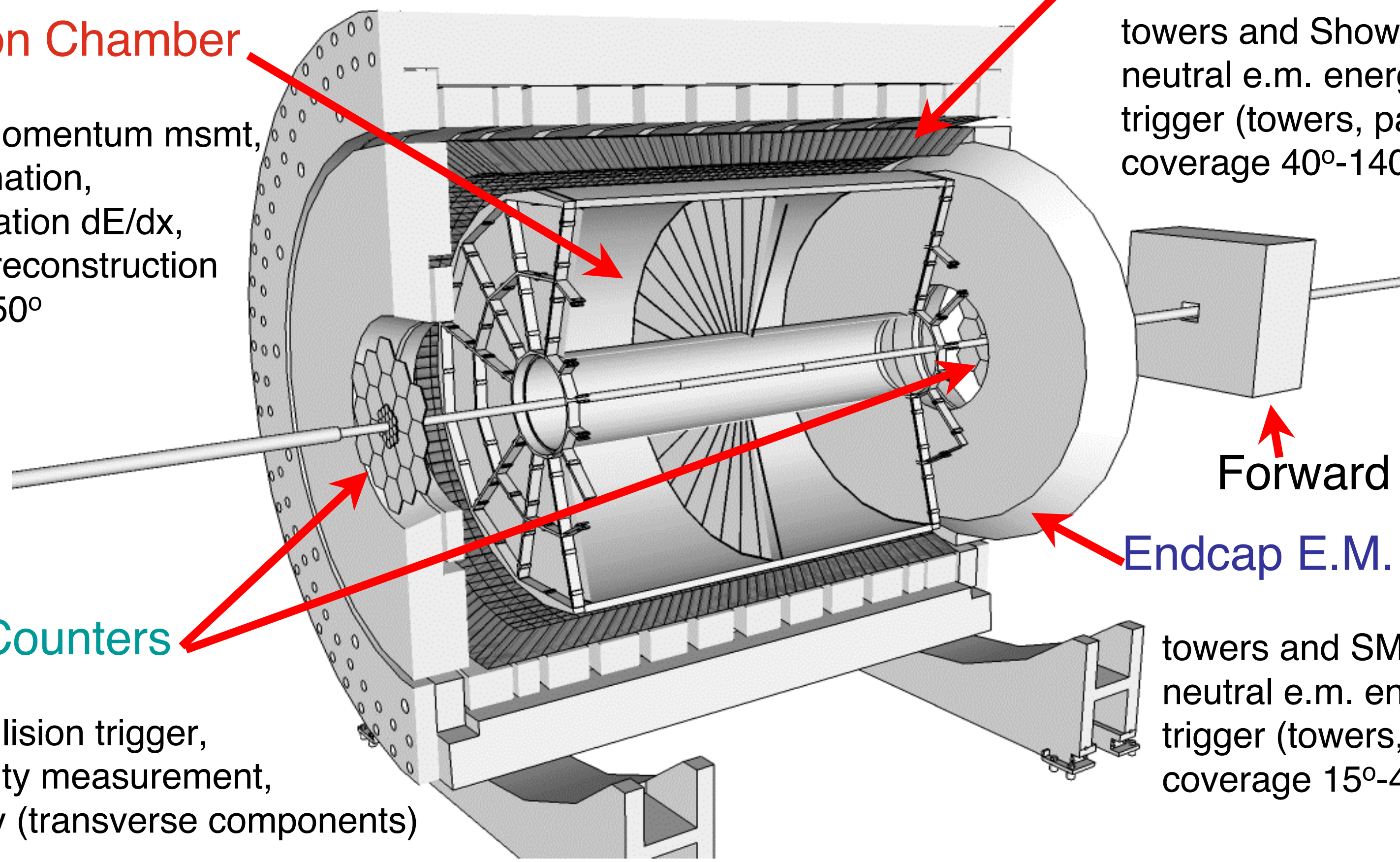
Nucl. Instrum. Meth. A499, 624, 2003

Time Projection Chamber

charged track momentum msmt,
charge determination,
particle identification dE/dx,
collision vertex reconstruction
coverage 30°-150°

Barrel E.M. Calorimeter

towers and Shower Maximum Det.
neutral e.m. energy measurement,
trigger (towers, patches of towers)
coverage 40°-140°



Forward Meson Spectr.

Endcap E.M. Calorimeter

towers and SMD.
neutral e.m. energy measurement,
trigger (towers, patches of towers)
coverage 15°-40°

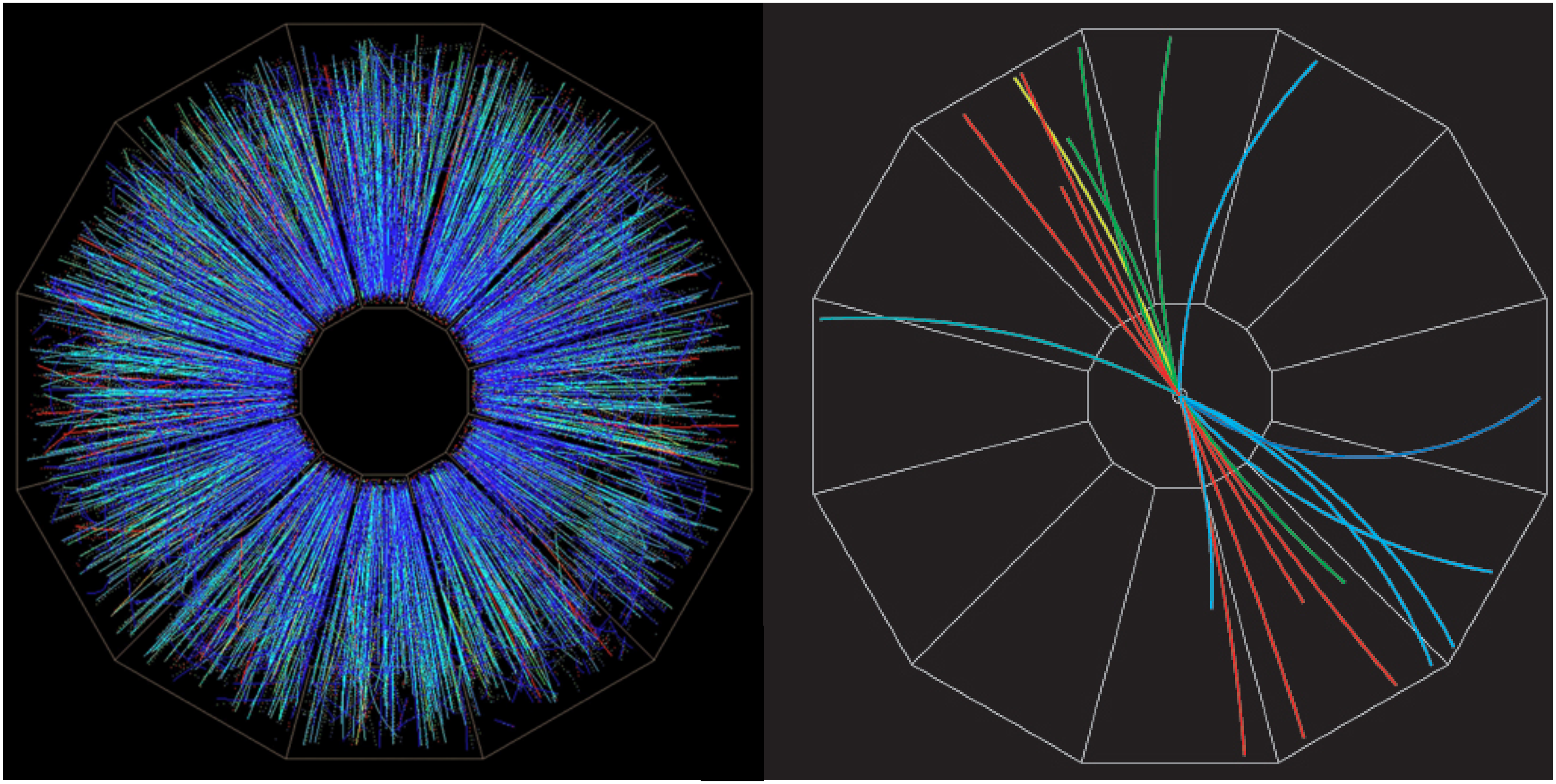
Beam-Beam Counters

proton beam collision trigger,
relative luminosity measurement,
local polarimetry (transverse components)

0.5 T Solenoidal Magnetic Field

Several detectors not discussed above, e.g. Time-of-Flight (complete for run-10), ZDC, RP, ...
A very versatile instrument, an active upgrade program

STAR - Solenoid Tracker at RHIC

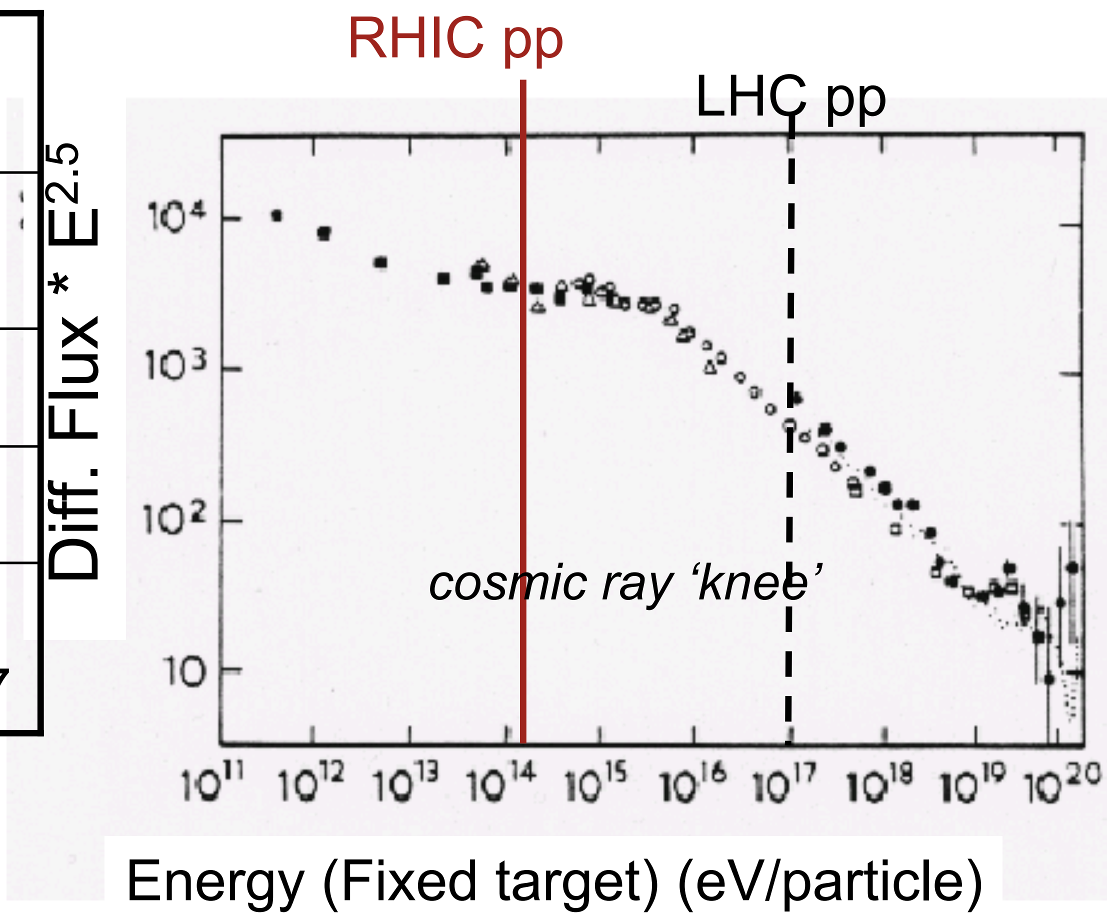


A versatile instrument to study QCD: Au+Au, d+Au, p+p, $\sqrt{s}$ = 7.7 - 500 GeV, polarization.

RHIC datasets from p+p to Au+Au
10 years of data taking

System size	CMS energy per nucleon [GeV]
p+p (polarized)	200, 500
d+Au	200
Cu+Cu	200
Au+Au	200, 130, 62.4, BES: 39, 11.5, 7.7

RHIC/LHC vs. cosmic-rays



RHIC Luminosity (Au+Au)

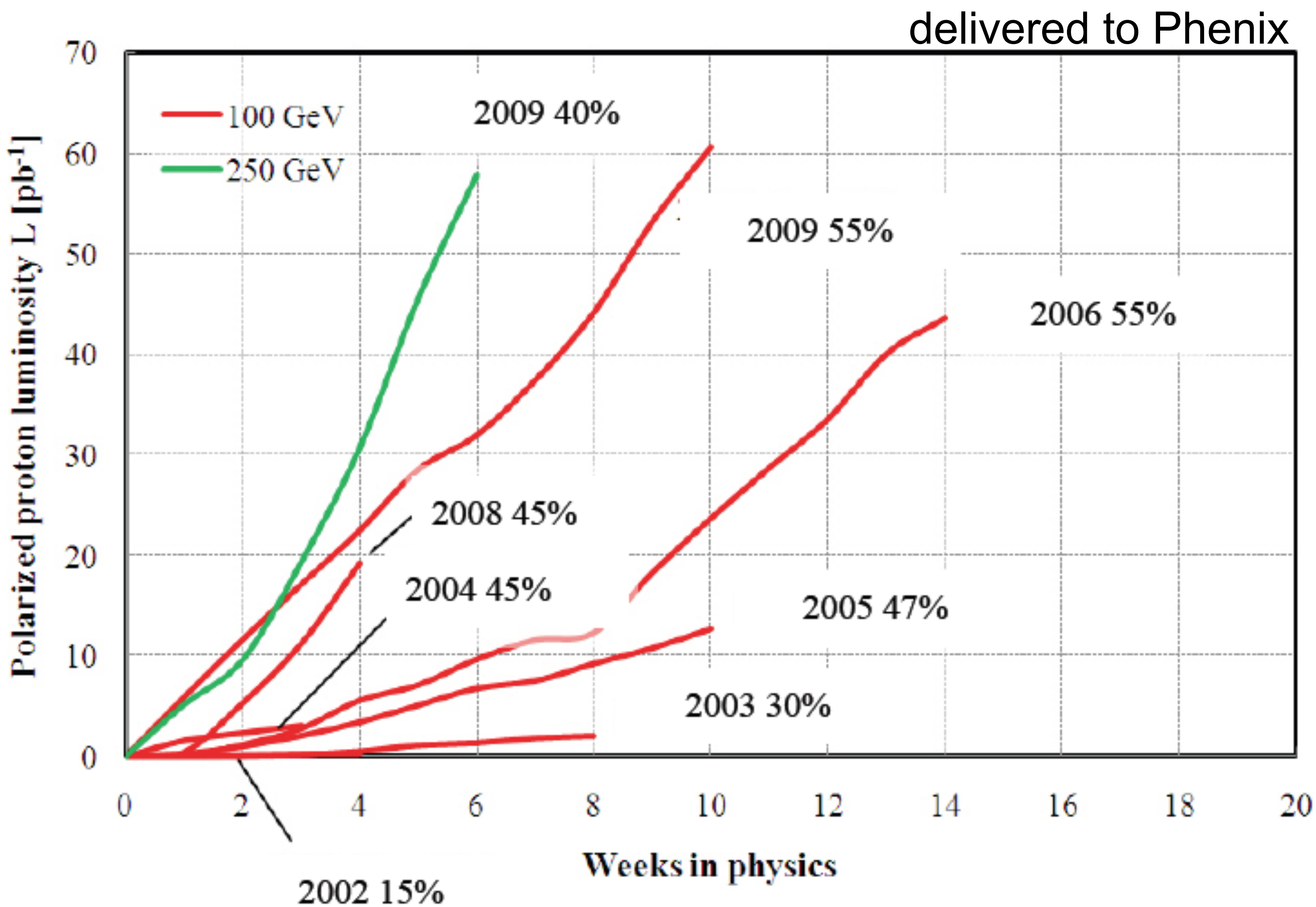
Table 1: Evolution of RHIC performance parameters $\sqrt{s}_{NN} = 200$ GeV/nucleon RHIC Au+Au runs including the preliminary 2010 results.The enhanced design goals were defined in 2006. In Run-7 the set β^* was 0.85m (the table gives the measured values). The β^* value of 0.75 m in Run-10 has not yet been confirmed. Transverse beam emittances for Runs 2, 4, and 7 ranged from 17 to 35 $\pi\mu$m during a store. In Run 10 they ranged from 17 to 20 $\pi\mu$m. The reason for the improvement was the use of bunched beam transverse stochastic cooling.

Run	Year	β^* [m]	no. of bunches	ions/bunch [$\times 10^9$]	L_{peak} [10^{26} cm^{-2}sec^{-1}]	$L_{ave.}$ [10^{26} cm^{-2}sec^{-1}]	L_{week} [μ b^{-1}]	Physics Weeks	$L_{Delivered}$ [n b^{-1}]
design		2	55	1.0	9	2	50		
enhanced design		1	111	1.0	30	8	300		
Run-2	2001	1	55	0.6	4	1.5	24	15.9	0.26
Run-4	2004	1	45	1.1	15	5	160	12	3.53
Run-7	2007	0.83 (PHENIX) 0.77 (STAR)	103	1.1	30	12	380	12.8	7.25
Run-10	2010	0.75	111	1.1	40	20	650	10.9	10.0

RHIC Run-10 was a highly successful run. We commissioned a new LLRF system, new stochastic cooling systems, proving that we can effectively cool high energy bunched beams in all three dimensions simultaneously, and we succeeded in reaching new luminosity records, operating RHIC almost twice as high as the previous run and an order of magnitude beyond the original design goals for average luminosity.

http://www.agsrhichome.bnl.gov/RHIC/Runs/RhicRun10ASummary.pdf

RHIC Luminosity (p+p)

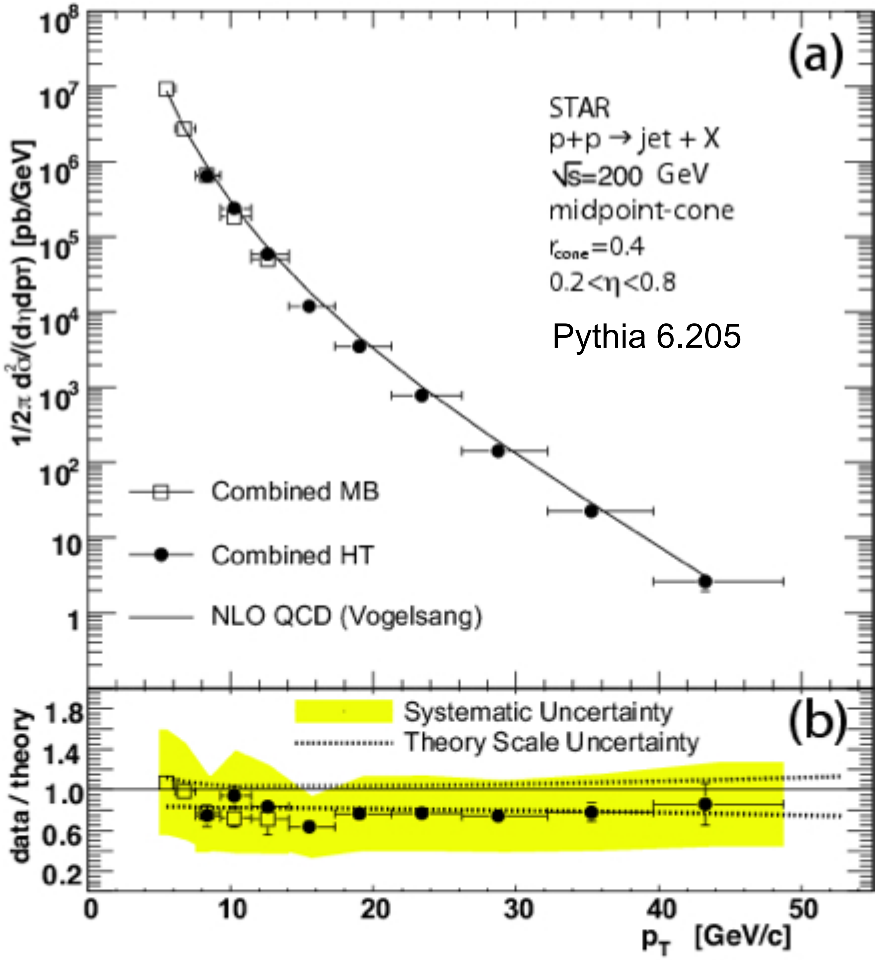


- 200 GeV: Run5,6,8,9
- 500 GeV: Run9 (first collisions of polarized pp)

Tests of QCD in p+p collisions: High p_T particles production at mid and forward rapidity at sqrt(s)= 200 GeV

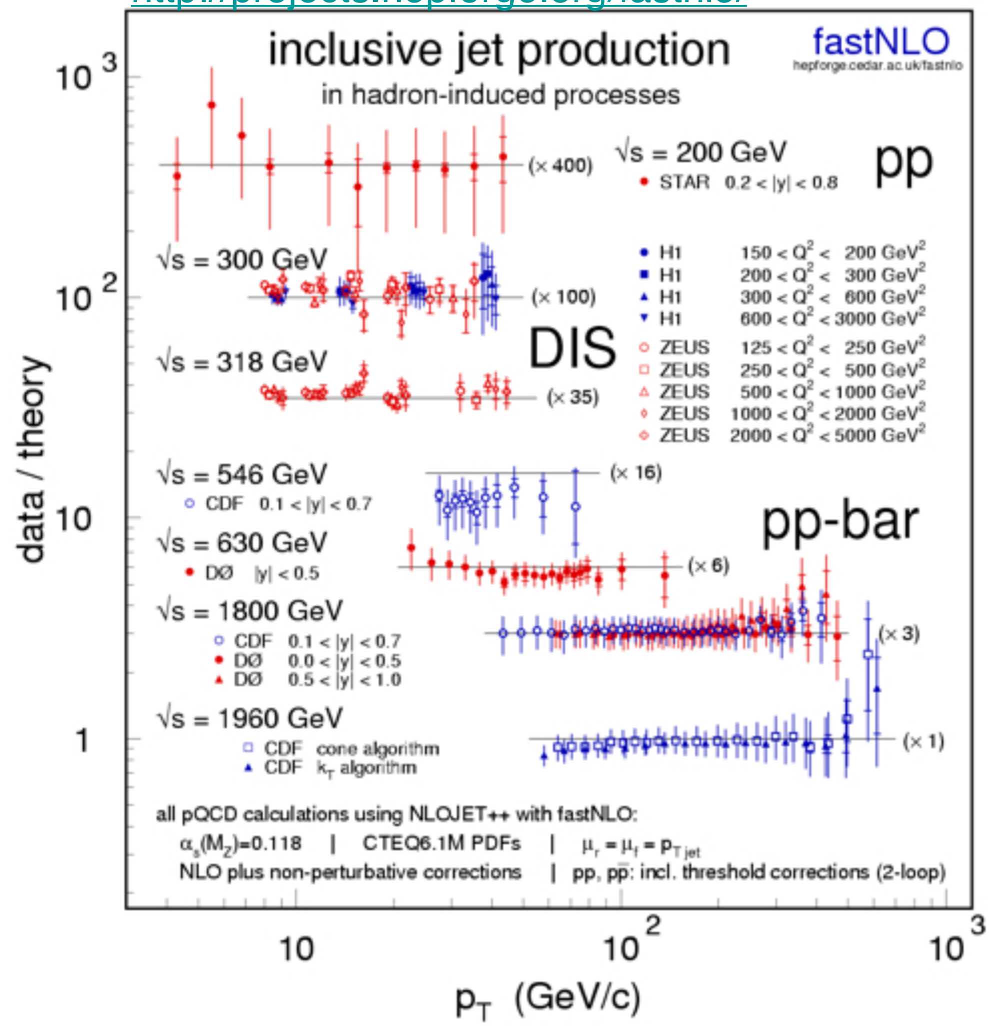
STAR midrapidity inclusive jet cross section in 200 GeV p+p

Phys. Rev. Lett. 97, 252001 (2006)



Data well described by NLO pQCD (cone R=0.4) within uncertainties

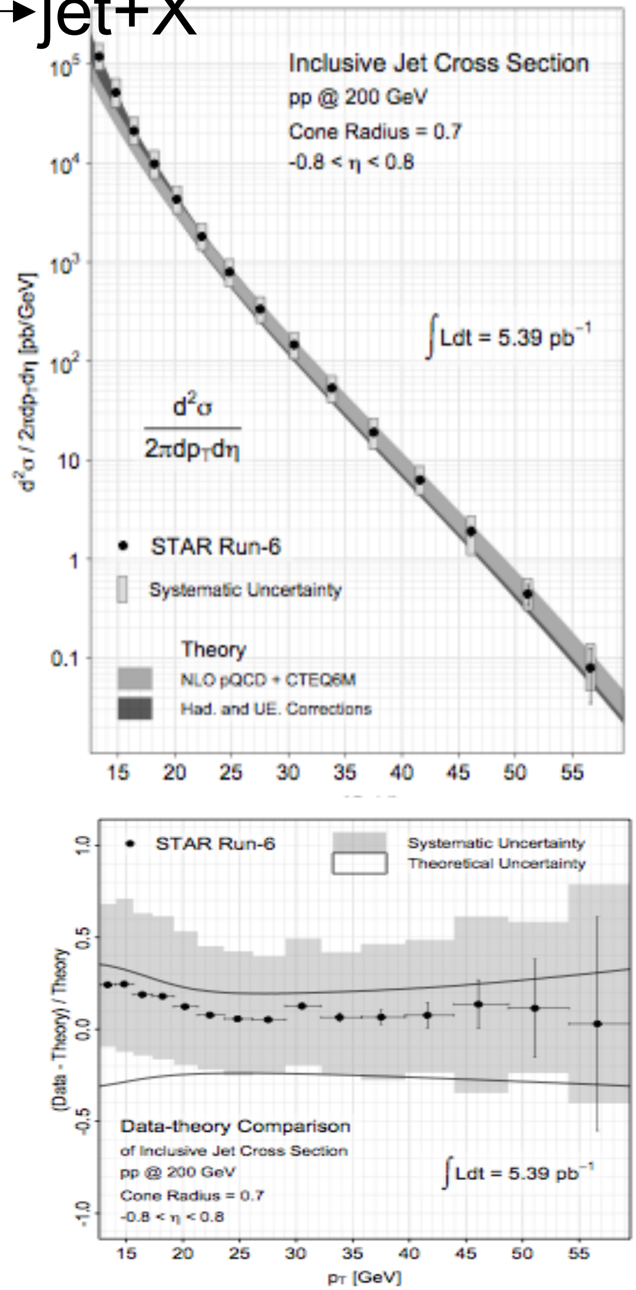
T. Kluge, K. Rabbertz, M. Wobisch,
http://projects.hepforge.org/fastnlo/



- Good agreement with data at other colliders
- STAR is extending jet finding to d+Au and Au+Au (!) collisions.

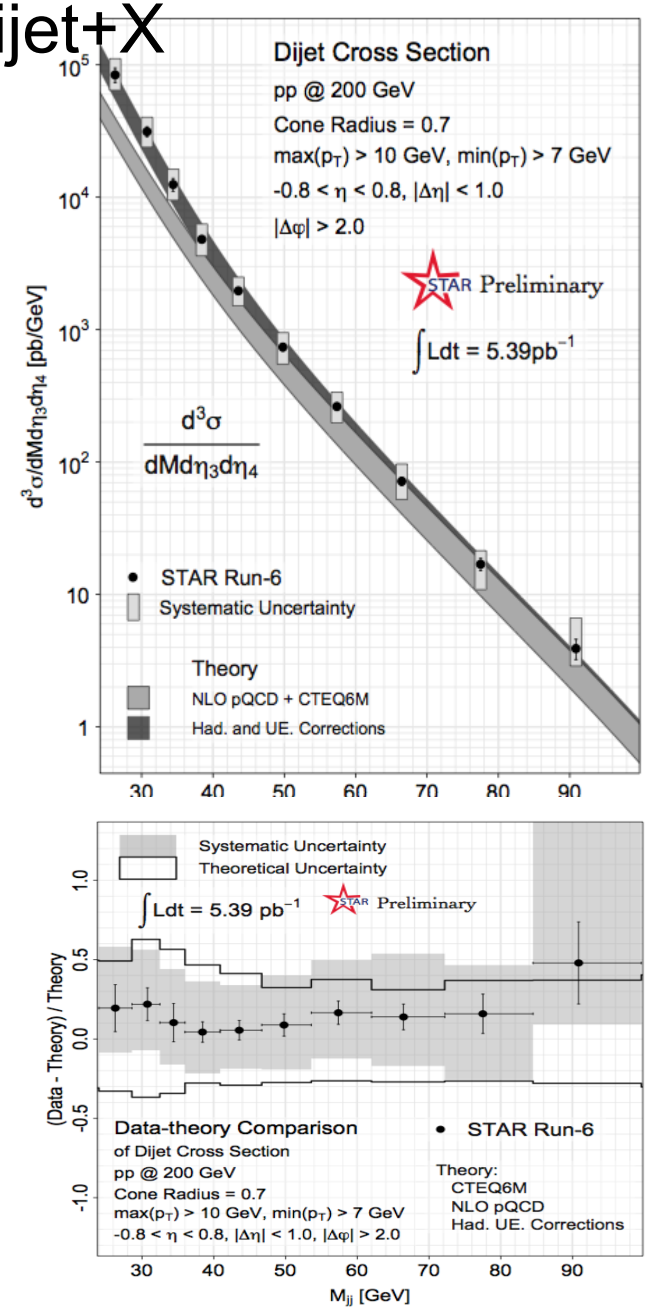
STAR midrapidity jet(s) cross sections in 200 GeV p+p

- p+p→jet+X



APS-2010: Tai Sakuma *for the collaboration*

- p+p→dijet+X

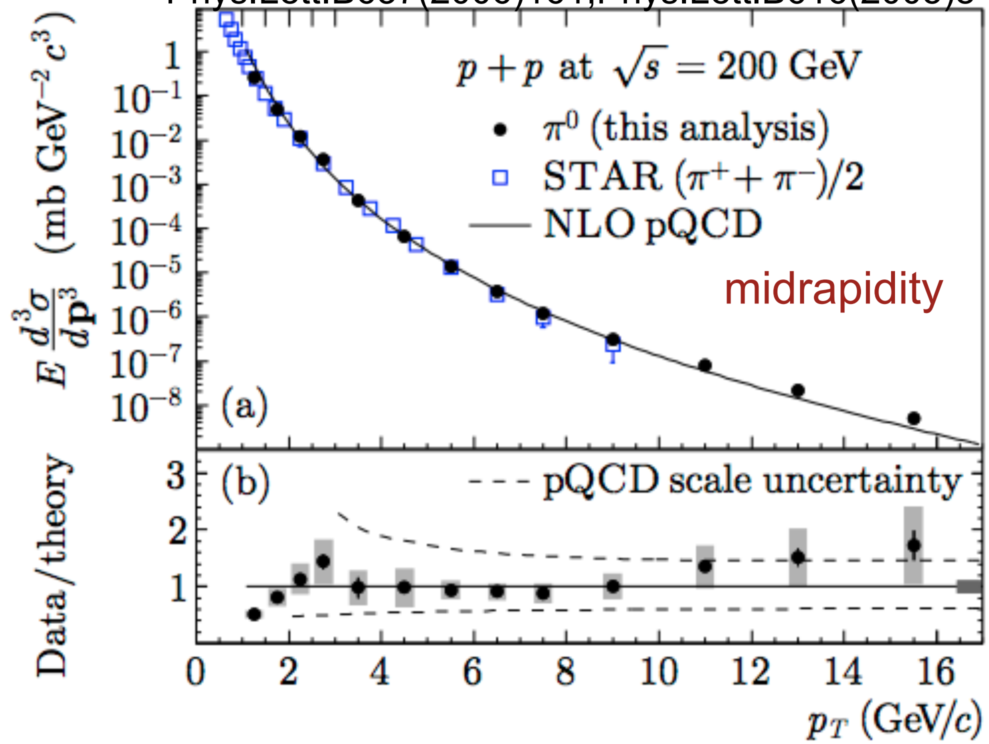


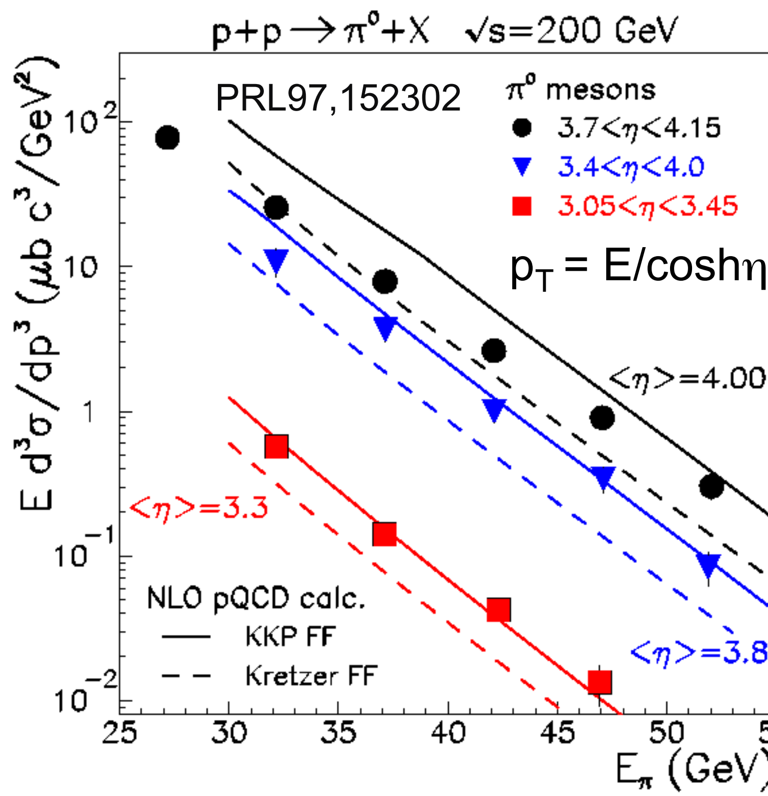
SPIN-2010: Matt Walker/Tai Sakuma, *for the collaboration*

Data well described by NLO pQCD+Hadronization+Underlying Event (cone R=0.7) within uncertainties

STAR mid and forward rapidity inclusive pion cross section in 200 GeV p+p

Phys.Rev.D 80 (2009)111108
Phys.Lett.B637(2006)161;Phys.Lett.B616(2005)8

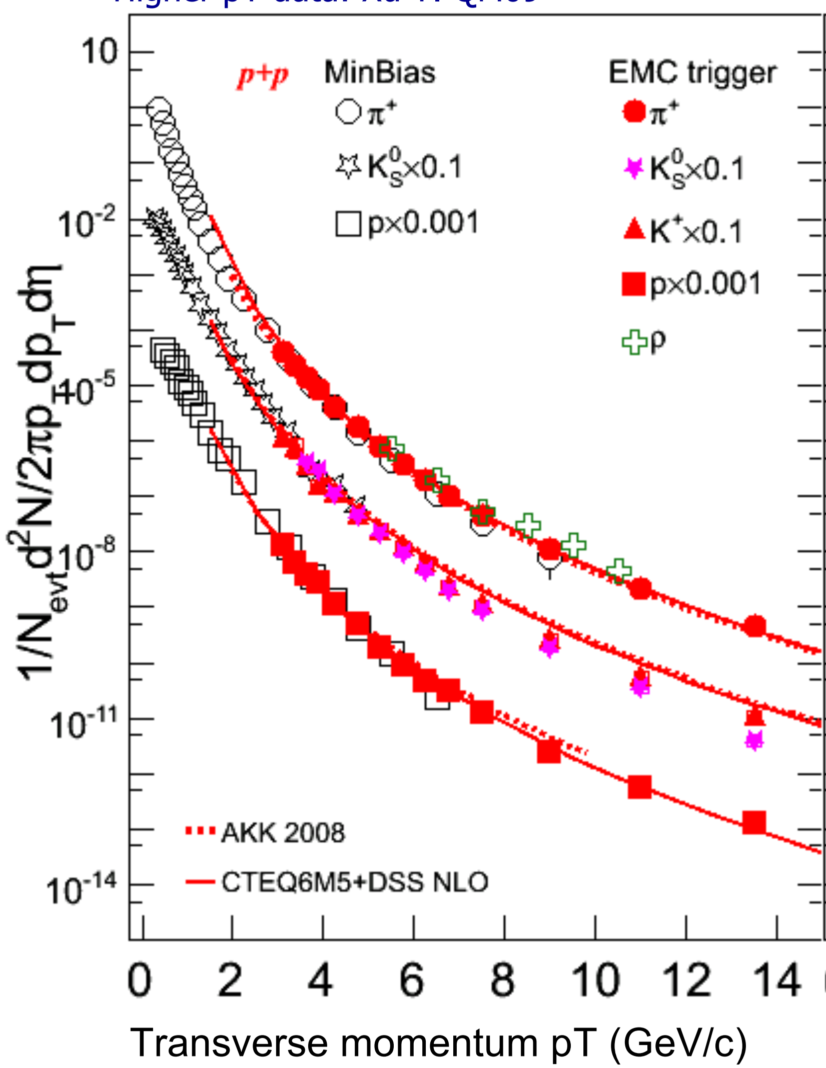




pQCD+FF describe midrapidity and forward rapidity pion yields

Midrapidity inclusive particle cross section in p+p at 200 GeV

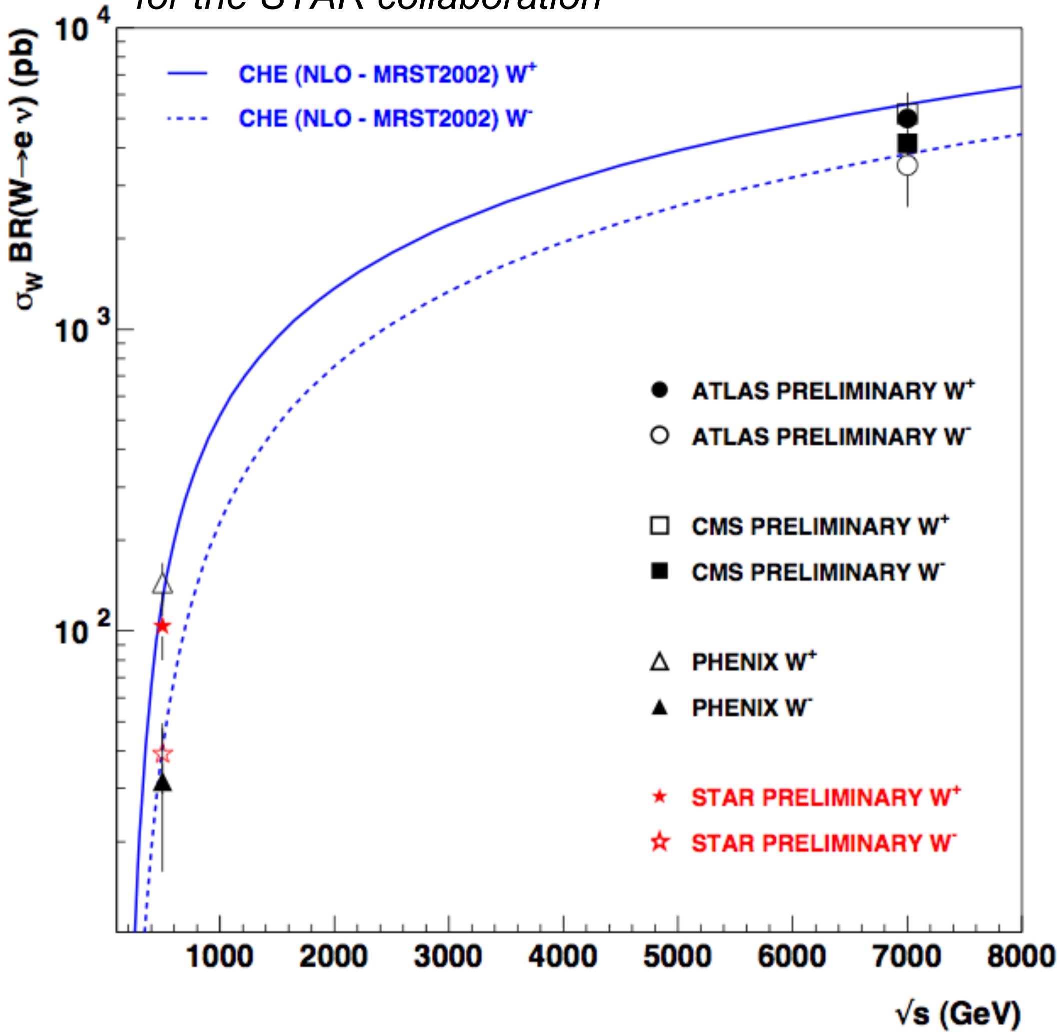
MinBias p+p data: Phys. Lett. B. 637 (2006) 161
Higher pT data: Xu Y. QM09



pQCD does a very good job describing hadron yields

STAR midrapidity W boson cross section in 500 GeV p+p

J.Stevens(APS2010) and J.Seele (SPIN2010)
for the STAR collaboration



Data and NLO pQCD predictions agree within uncertainties over a wide range of sqrt(s)

Measurements of the flux of *prompt* leptons at Earth

- is important for:

  ✓ Cosmic Rays (CR) physics

  Flux of CR muons provides a way of testing the inputs of nuclear cascade models (parameters of the primary CR flux: energy spectrum chemical compositions) and particle interactions at high energies

  ✓ Neutrino physics

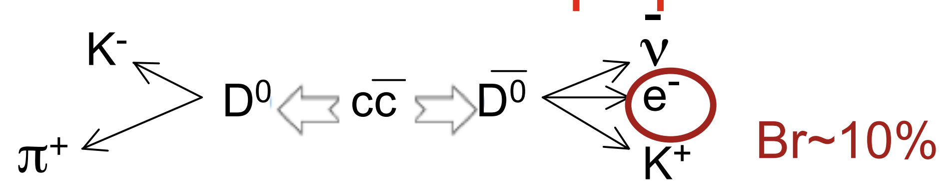
  Flux of atmospheric ν and μ at very HE provides the main background of searches of high energy extragalactic ν in neutrino experiments.

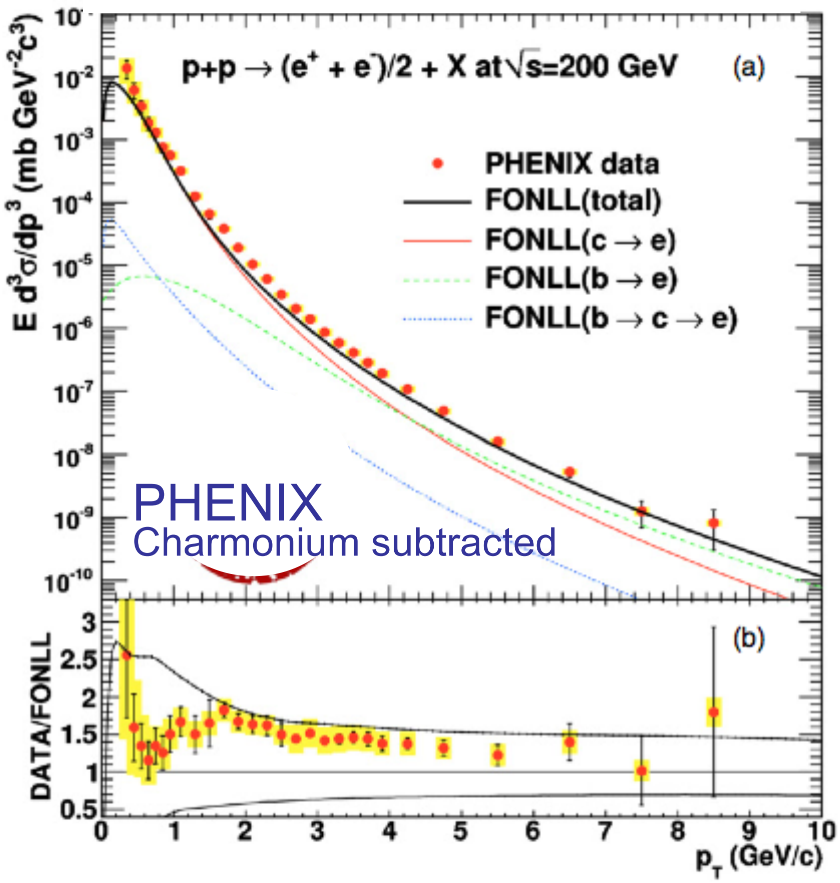
- is connected to the charmed particle production and its decays:

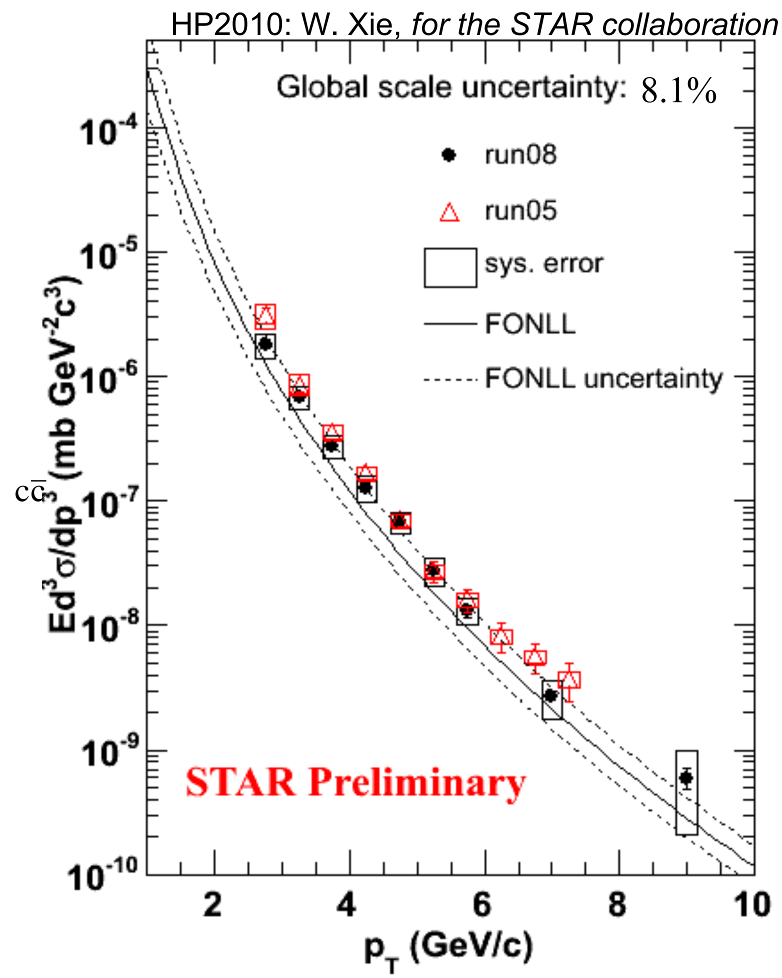
  Flux of prompt leptons is strongly dependent on the model used to calculate the charm cross section and energy spectra (pQCD framework and extrapolation of charm production data obtained at collider energies to CR energies)

Connection to the cosmic ray physics?

Non-photonic electron cross section in 200 GeV p+p collisions



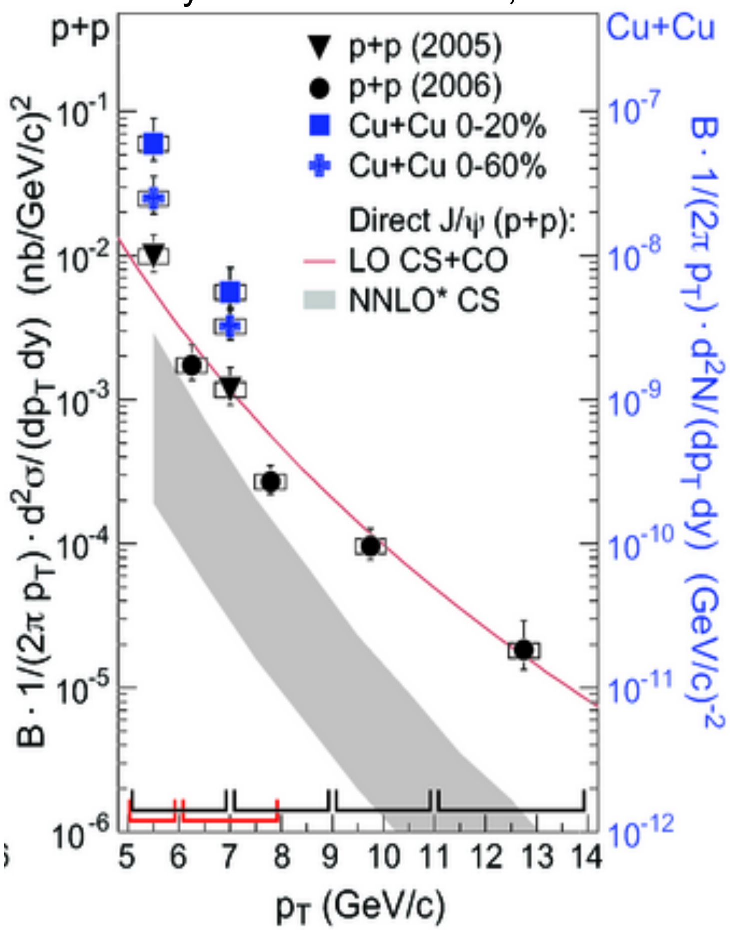




- STAR high p_T (p_T>2.5 GeV/c)measurement done using TPC+EMC run08 and run05 data, with dramatically different background. Run8 and Run5 results agree.
- STAR and PHENIX measurements consistent in the overlap region and in agreement with FONLL

STAR quarkonia cross section in 200 GeV p+p

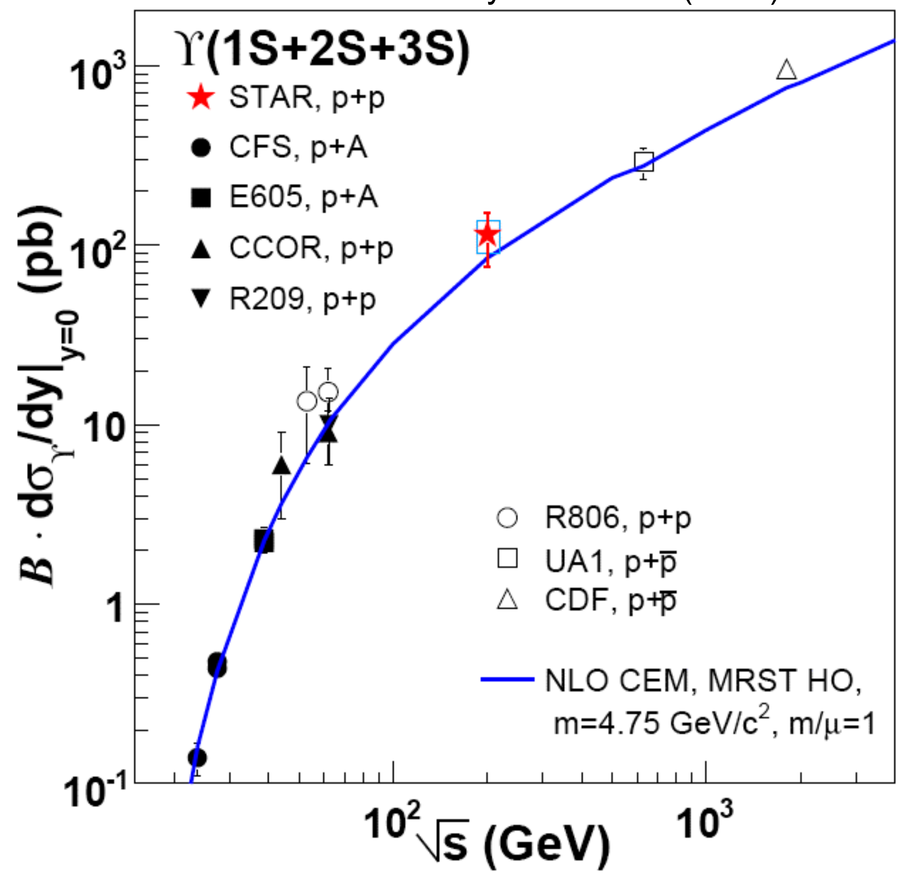
Phys.Rev.C80:041902,2009



NRQCD (LO CO+CS) – describes data well, little room for feed down from ψ' , χ_c, B

G. C. Nayak, e.al., Phys. Rev. D68, 034003 (2003)

Phys.Rev.D 82 (2010) 12004



$$\sum_{n=1} \mathcal{B}(nS) \times \sigma(nS) = 114 \pm 38 \,^{+23}_{-24}\ \text{pb}$$

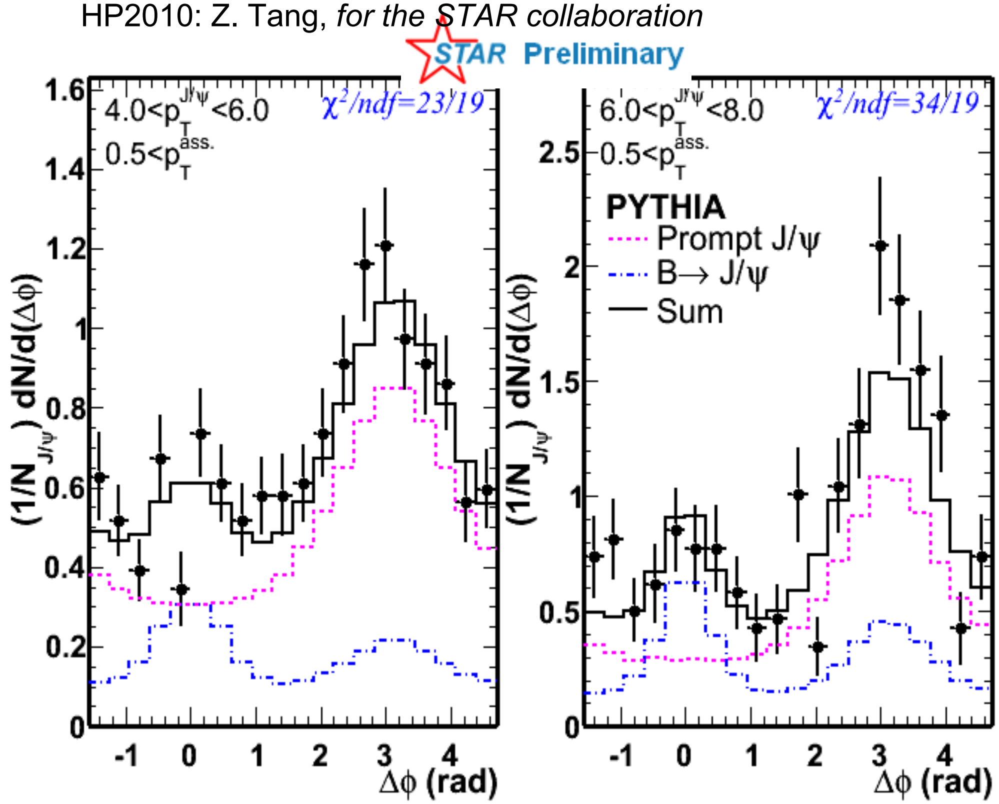
Consistent with world data trend and CEM

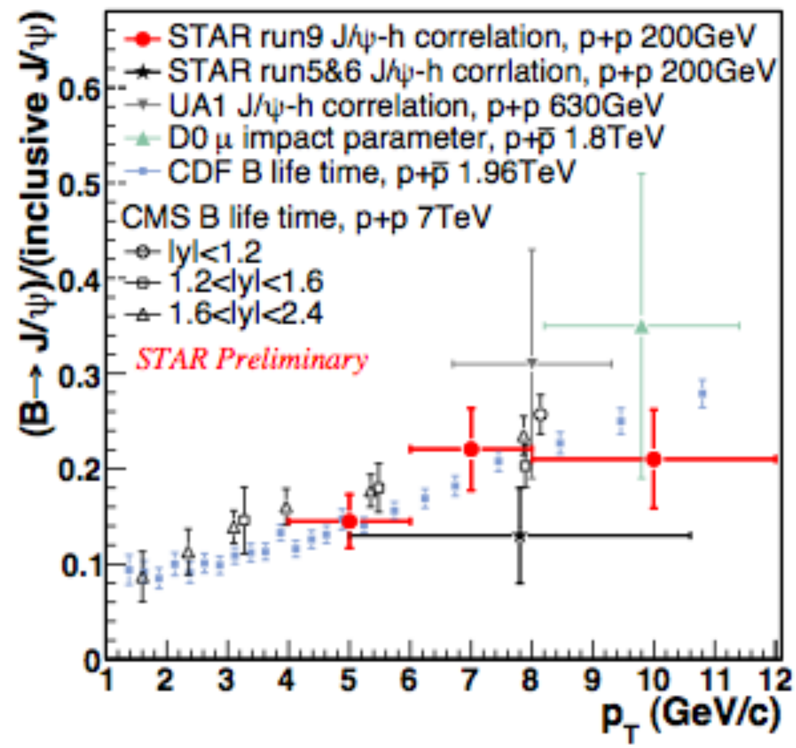
Color Singlet Model (CSM) PRL 100, 032006(2008),

Color Evaporation Model (CEM) Phys. Rept. 462, 125 (2008)

J/ψ-hadron Azimuthal Correlation in 200GeV p+p Collisions

HP2010: Z. Tang, *for the STAR collaboration*

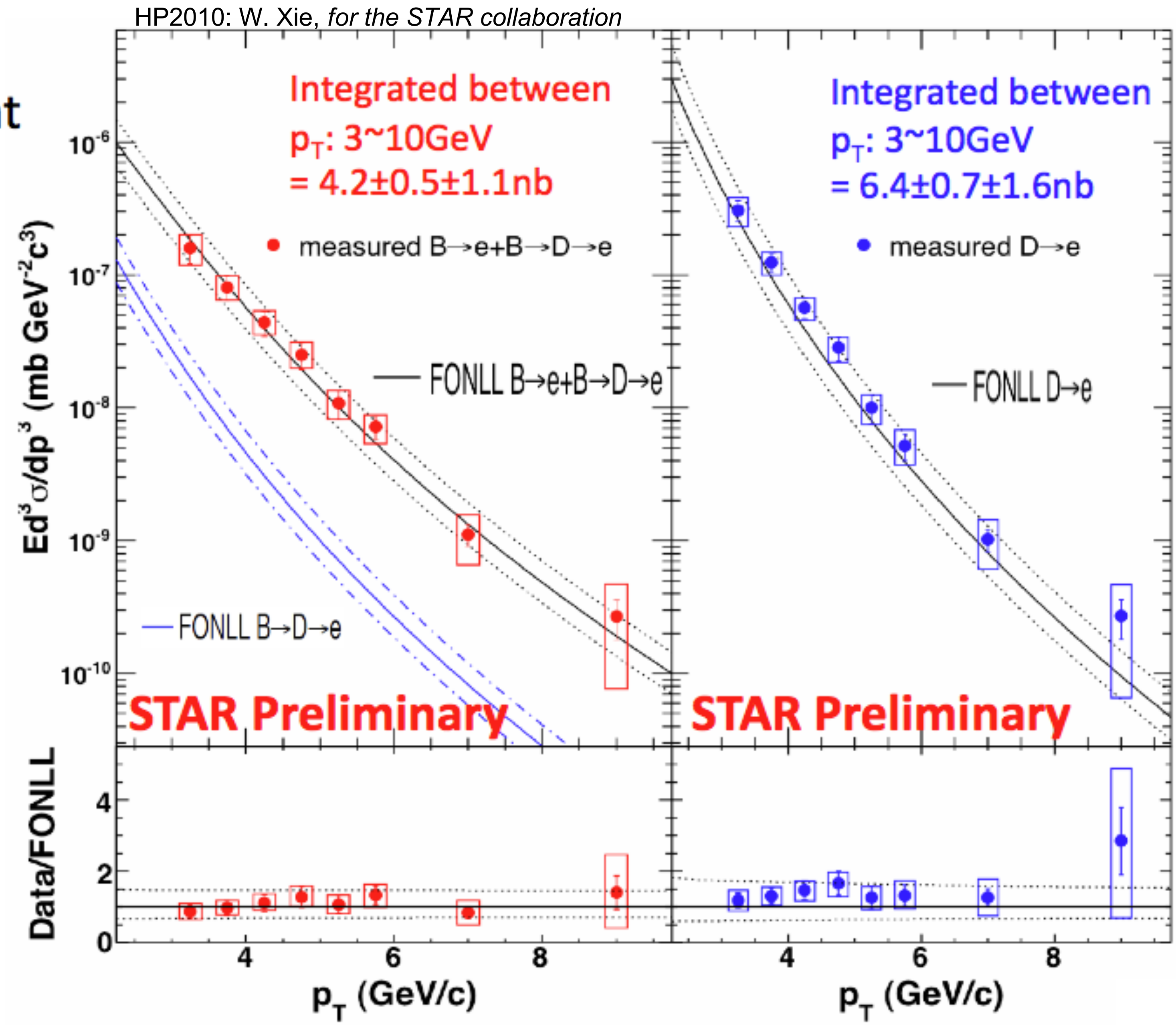




- B→J/ψ: **10-20%** of total J/ψ (pT > 4GeV/c) at RHIC
- The ratio has no significant dependence on collisions energy.

Invariant cross section of electrons from bottom and charm decays

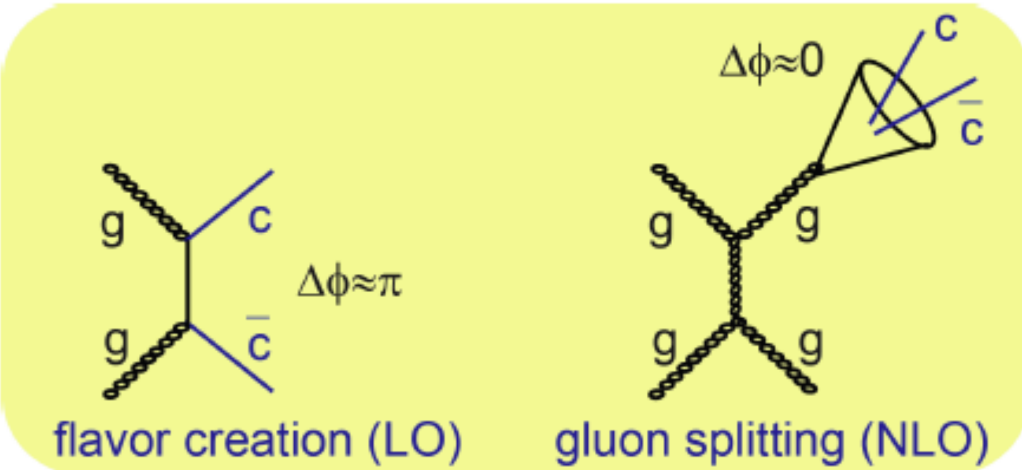
pp collisions at $\sqrt{s} = 200\text{GeV}$



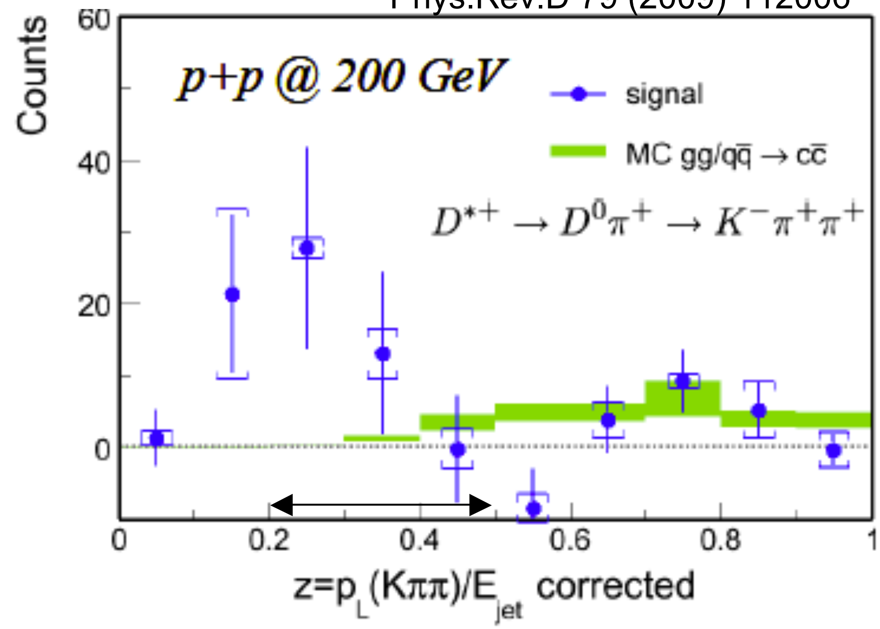
FONLL is from [1]

[1]:M. Cacciari, P. Nason and R. Vogt, Phys. Rev. Lett. **95, 20 122001 (2005);**
M. Cacciari, R. Vogt, private communications

STAR Charm production in jets



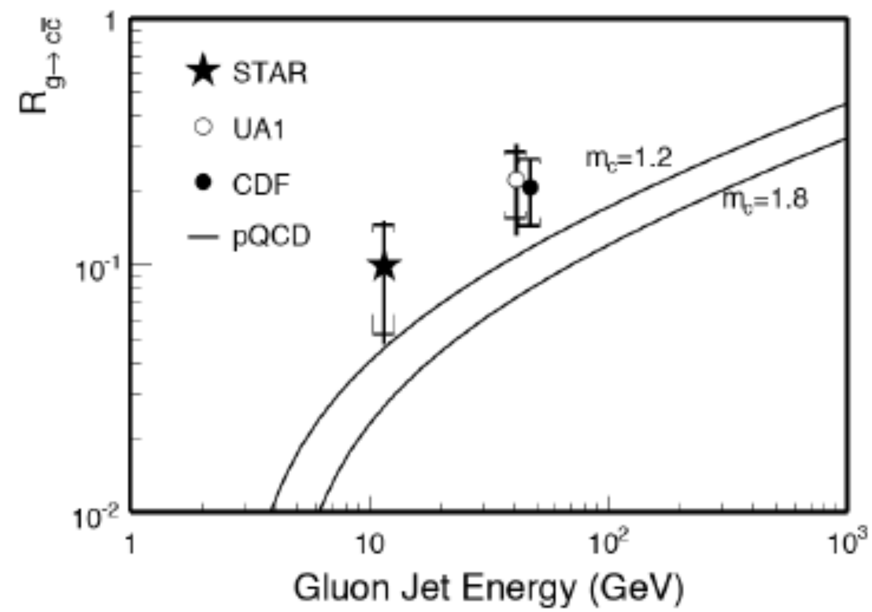
Phys.Rev.D 79 (2009) 112006



To study charm production via gluon splitting process

$$p + p \rightarrow \text{jet (charm)} + X$$

- The gluon splitting production rate is consistent with pQCD calculation.
- Charm content in jets at RHIC has a small contribution from gluon splitting and is dominated by jets initiated by charm quarks.



Measurements of the flux of *prompt* leptons at the Earth

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  Flux of CR muons provides a way of testing the inputs of nuclear cascade models (parameters of the primary CR flux: energy spectrum chemical compositions) and particle interactions at high energies

  ✓ Neutrino physics

  Flux of atmospheric ν and μ at very HE provides the main background of searches of high energy extragalactic ν in neutrino experiments.

- is strongly dependent on the behavior of the gluon distribution at small-x and it is determined by the QCD dynamics

  ✓ Any new dynamical effect will modify the estimates of the lepton fluxes. For example, the presence of the parton saturation effects will modify the linear DGLAP dynamics.
  Current open question is related to the possibility of the breakdown of the collinear factorization at higher energies due to saturation effects which are expected in this regime.

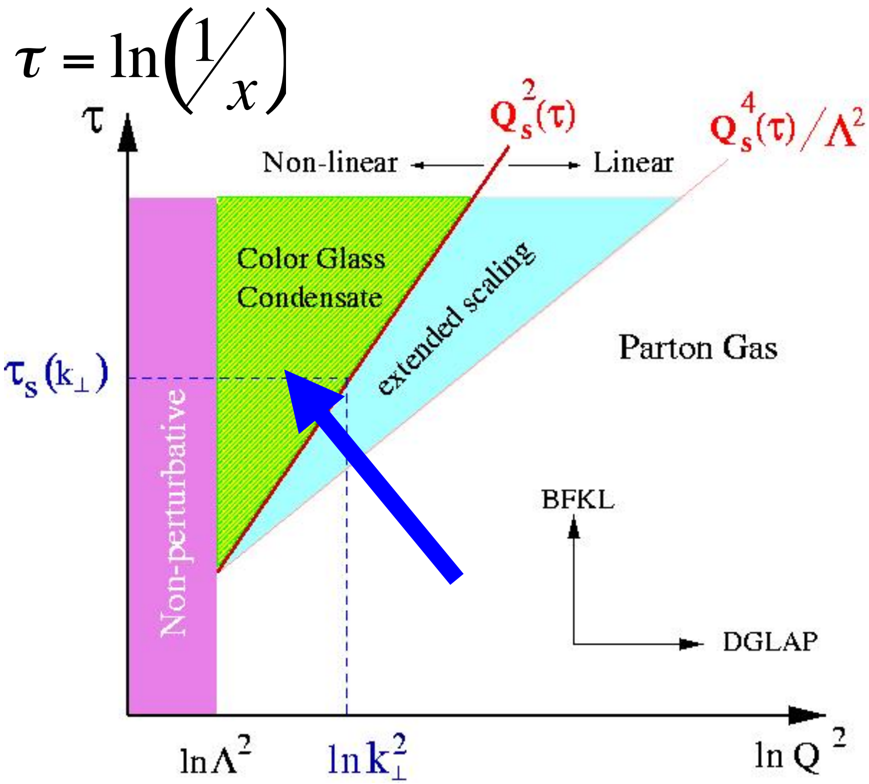
Nucleon Structure in Nuclei from d+Au collisions

Goal: Probe gluon distributions at low x and high parton densities (in nuclei)

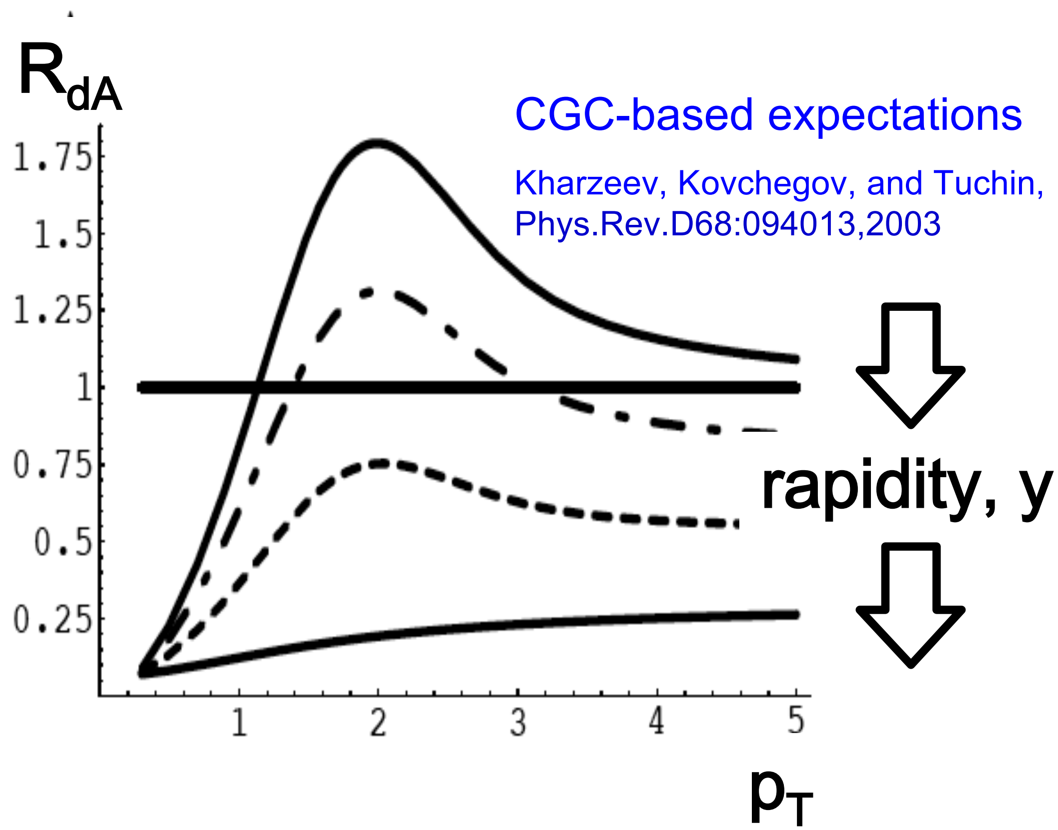
Signatures of saturation include suppressions of cross sections in d+Au collisions compared to p+p at forward rapidities.

Expectations from Color Glass Condensate

Nuclear Modification Factor: $R_{dAu} \equiv \frac{1}{\langle N_{coll} \rangle} \frac{d^2N^{d+Au}/dp_T d\eta}{d^2N^{p+p}_{inel}/dp_T d\eta}$



Iancu and Venugopalan, hep-ph/0303204

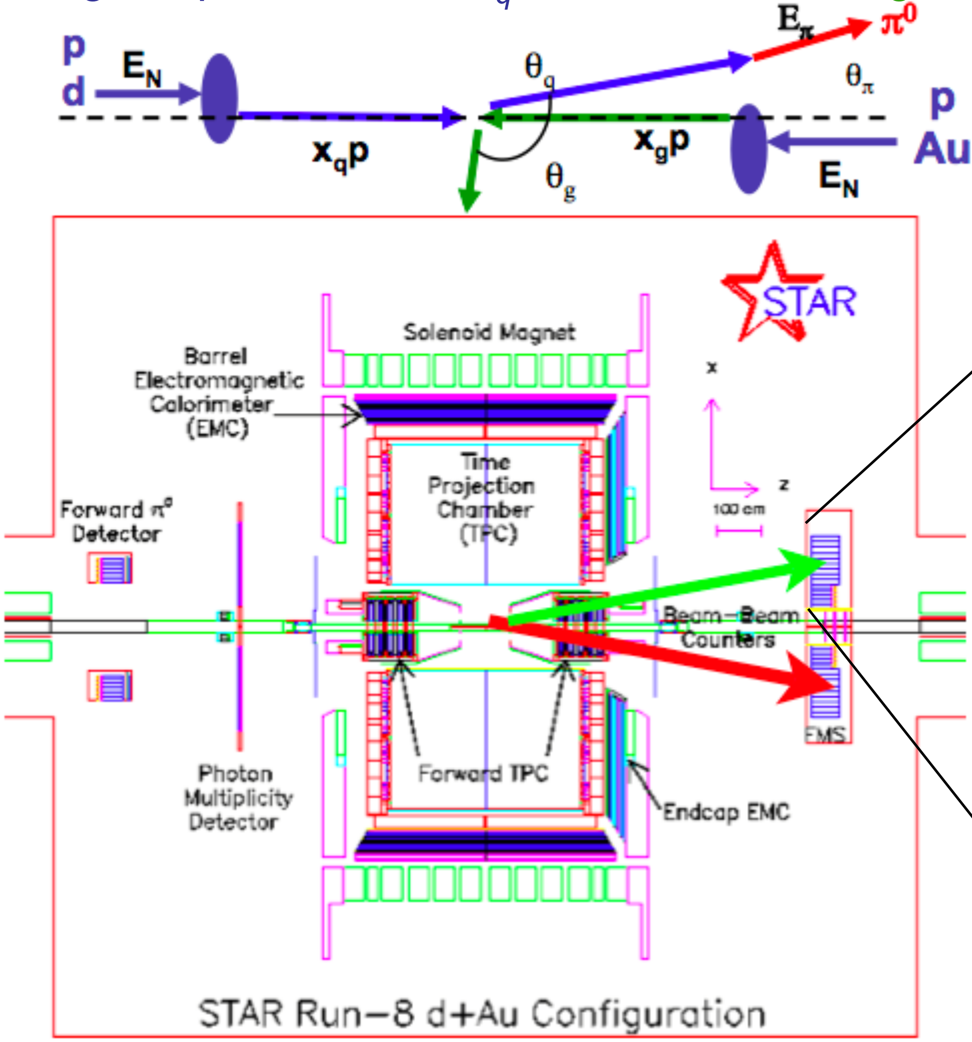


CGC expects suppression of forward hadron production

STAR - Forward Rapidity

- Forward scattering probes asymmetric partonic collisions
  x_1 (d) >> x_2 (Au) for forward particle, $x_g = x_2 \rightarrow 0$

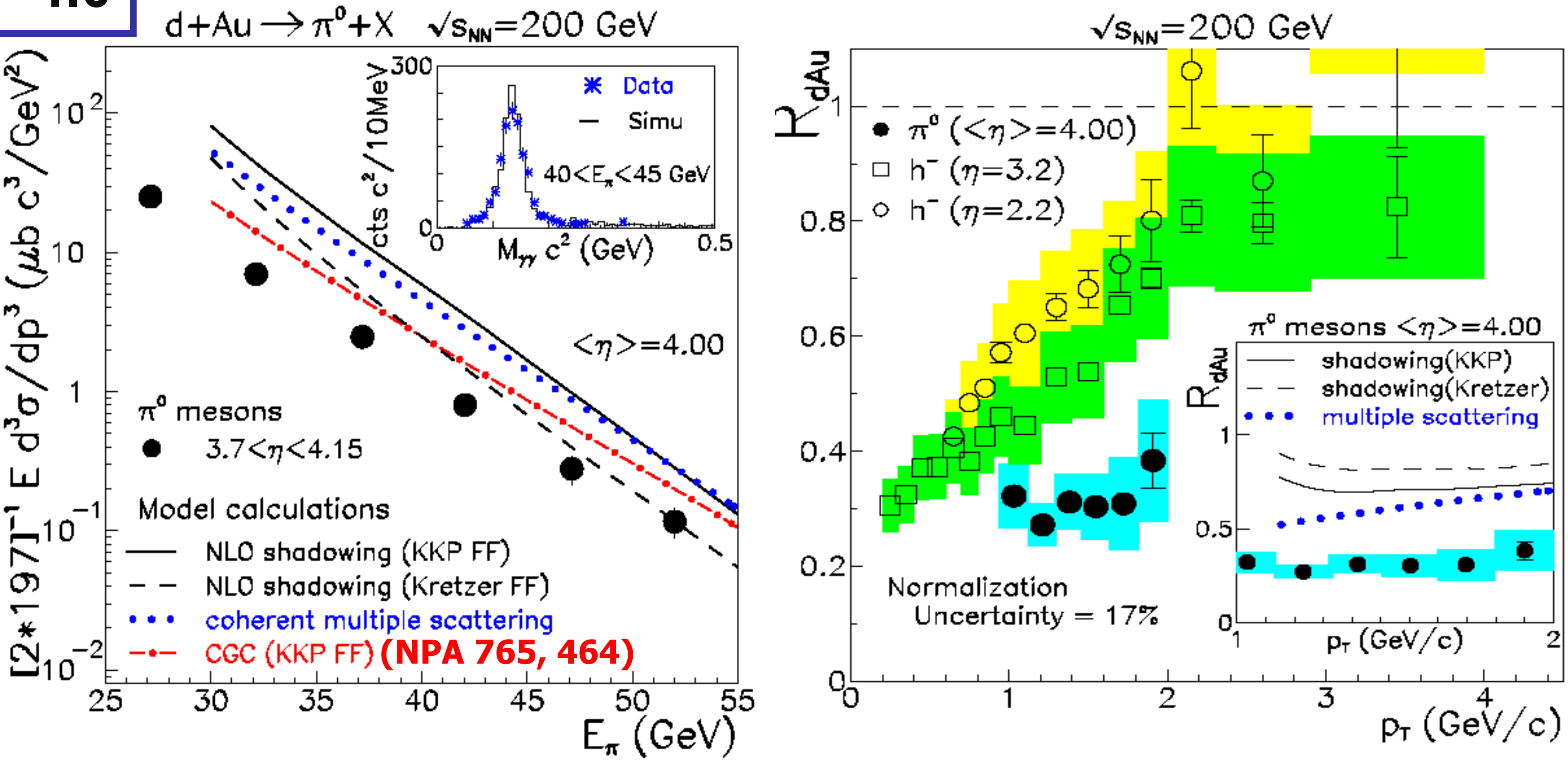
high-x quarks $0.25 < x_q < 0.7$ and low-x gluons $0.001 < x_g < 0.1$



STAR d+Au forward π^0

η = 4.0

PRL 97, 152302



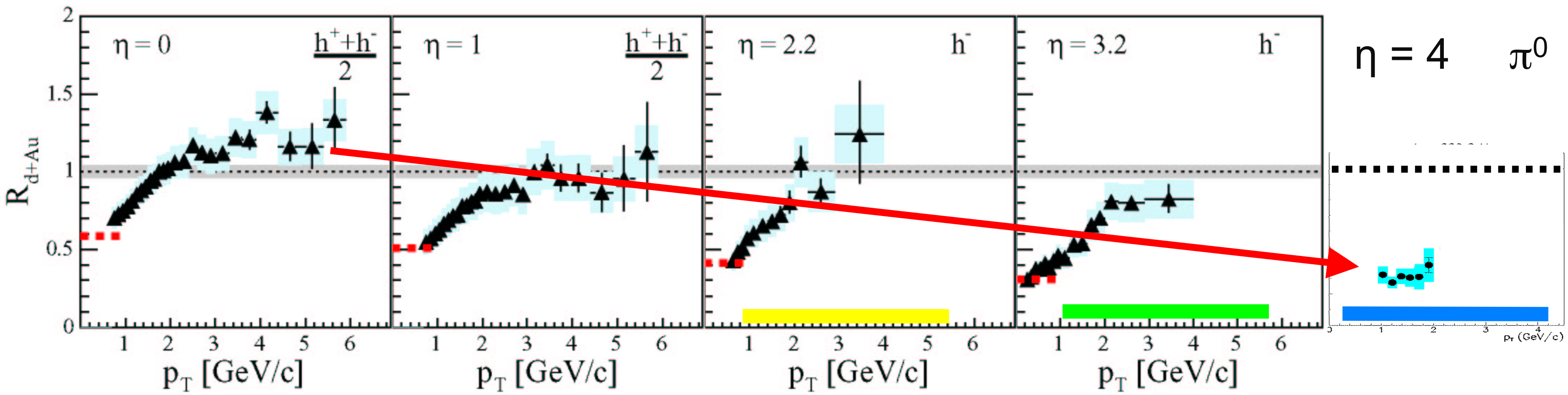
- Sizable suppression
- pQCD+Shadowing expects suppression, but not enough
- CGC gives best description on p_T dependence

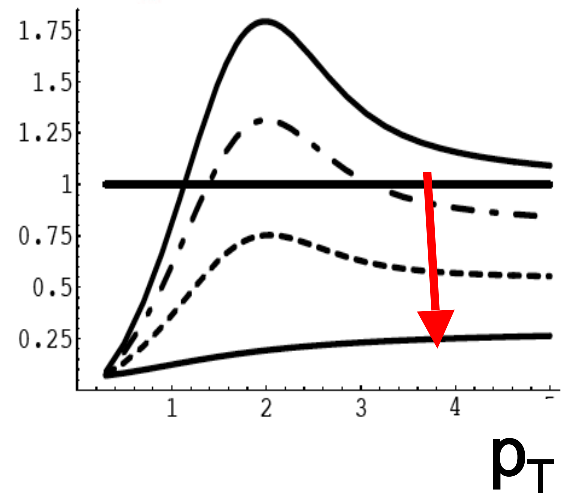
R_{dAu} rapidity dependence

$\eta = 0 \rightarrow 4$

BRAHMS PRL 93, 242303

STAR PRL 97, 152302

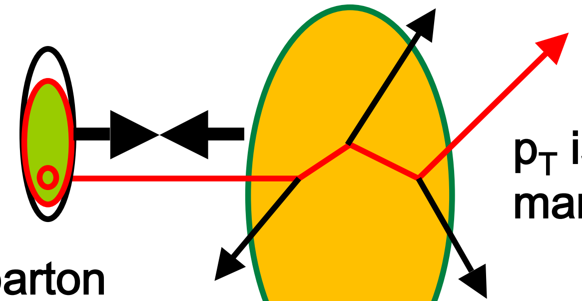




Hadron production is suppressed at large rapidity, consistent with saturation effects at low x in the Au gluon densities (CGC)

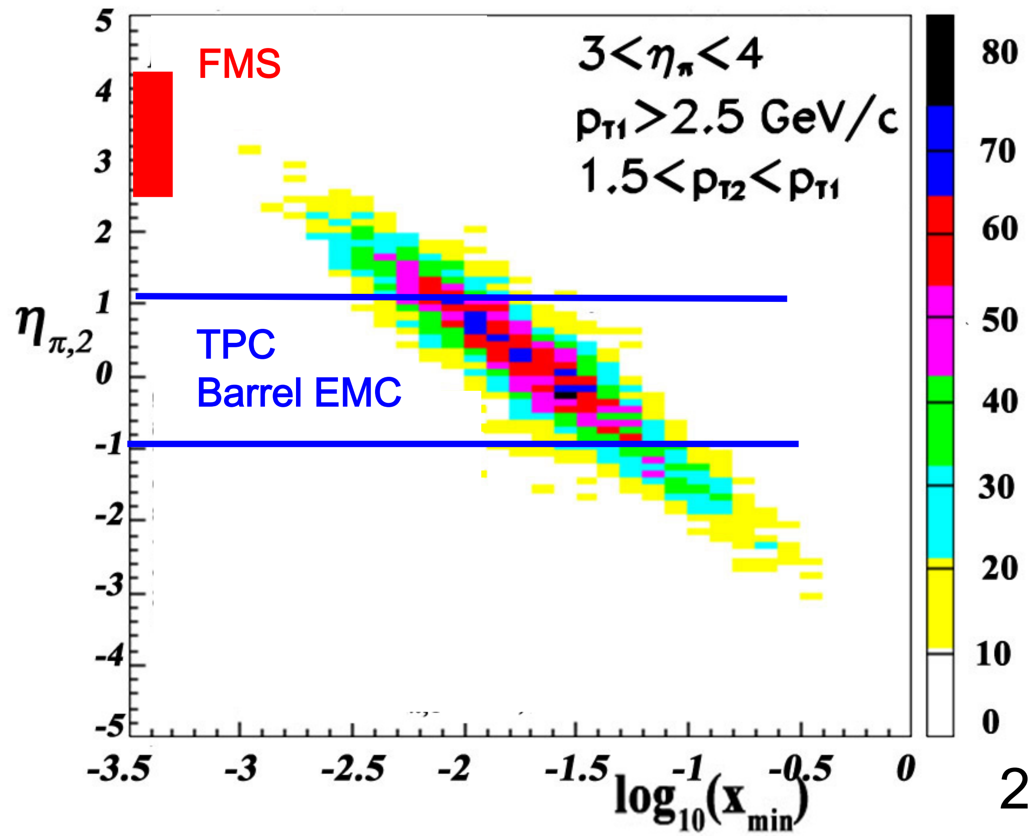
… but these results alone do not uniquely demonstrate gluon saturation. Additional data and different observables will be needed.

Probing for Saturation Effects with di-hadron Correlations in d+Au



Idea:
Presence of dense gluon field in the Au nucleus leads to multiple scattering and parton can distribute its energy to many scattering centers: "Mono-jet signature".
D.Kharzeev,E.Levin,L.McLerran, Nucl.Phys.A748:627-640,2005

PYTHIA p+p study, STAR

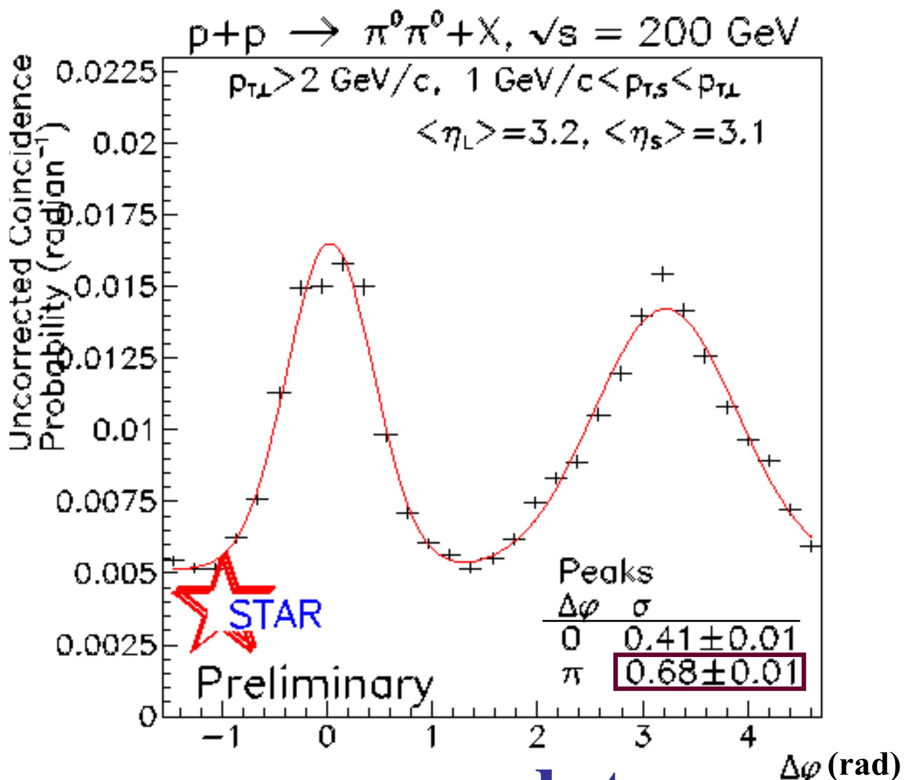


Experimental signature:

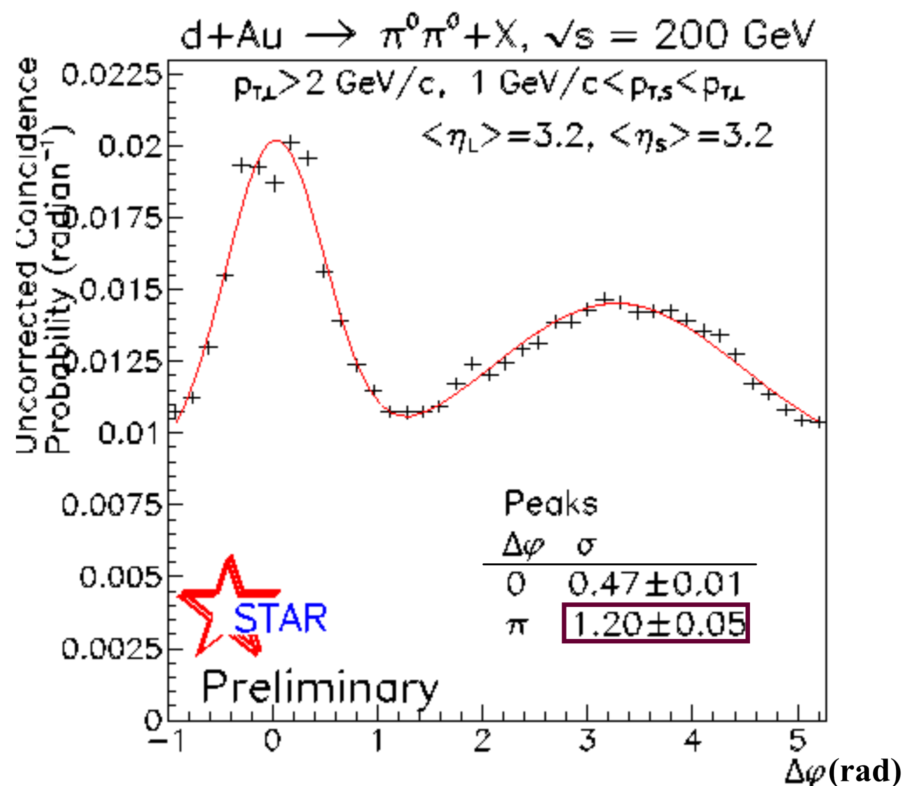
- widening of correlation width of d-Au compared to pp?
- reduction in associated yield of hadrons on the away site
- di-hadron correlations at the lowest possible x for forward-forward correlations: reach down to $\langle x_g \rangle \sim 10^{-3}$

With nuclear enhancement $x_g \sim 10^{-4}$

STAR Forward π^0 - Forward π^0 Correlations



pp data



dAu data

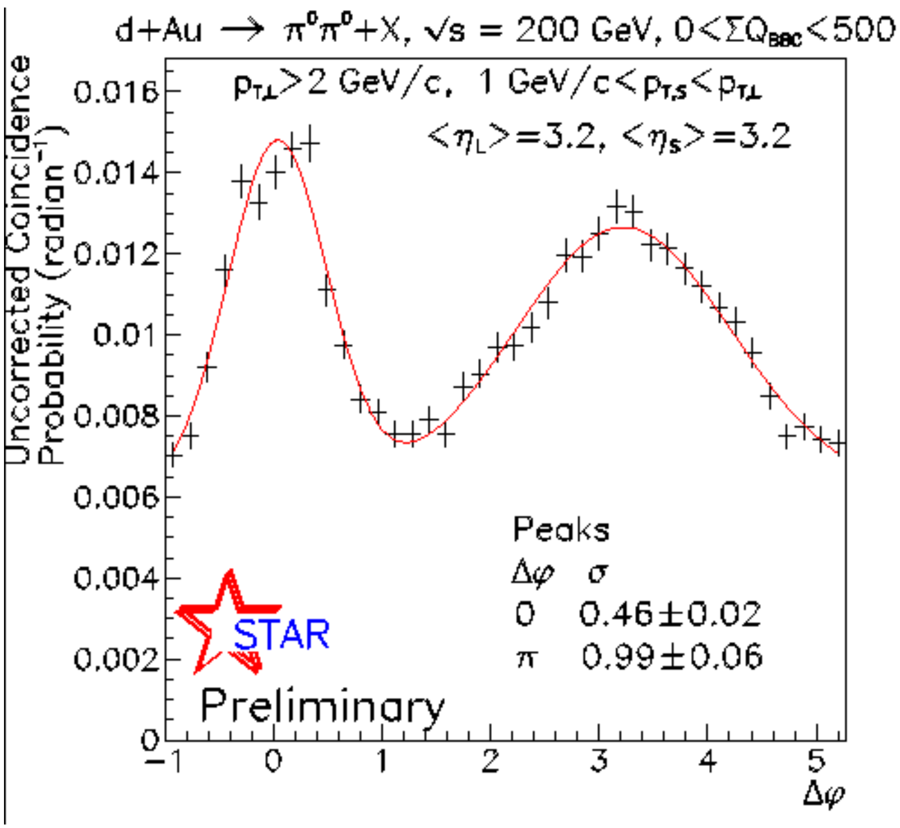
Strong azimuthal broadening from pp to dAu for away side, while near side remains unchanged.

σ(dAu)-σ (pp)=0.52±0.05

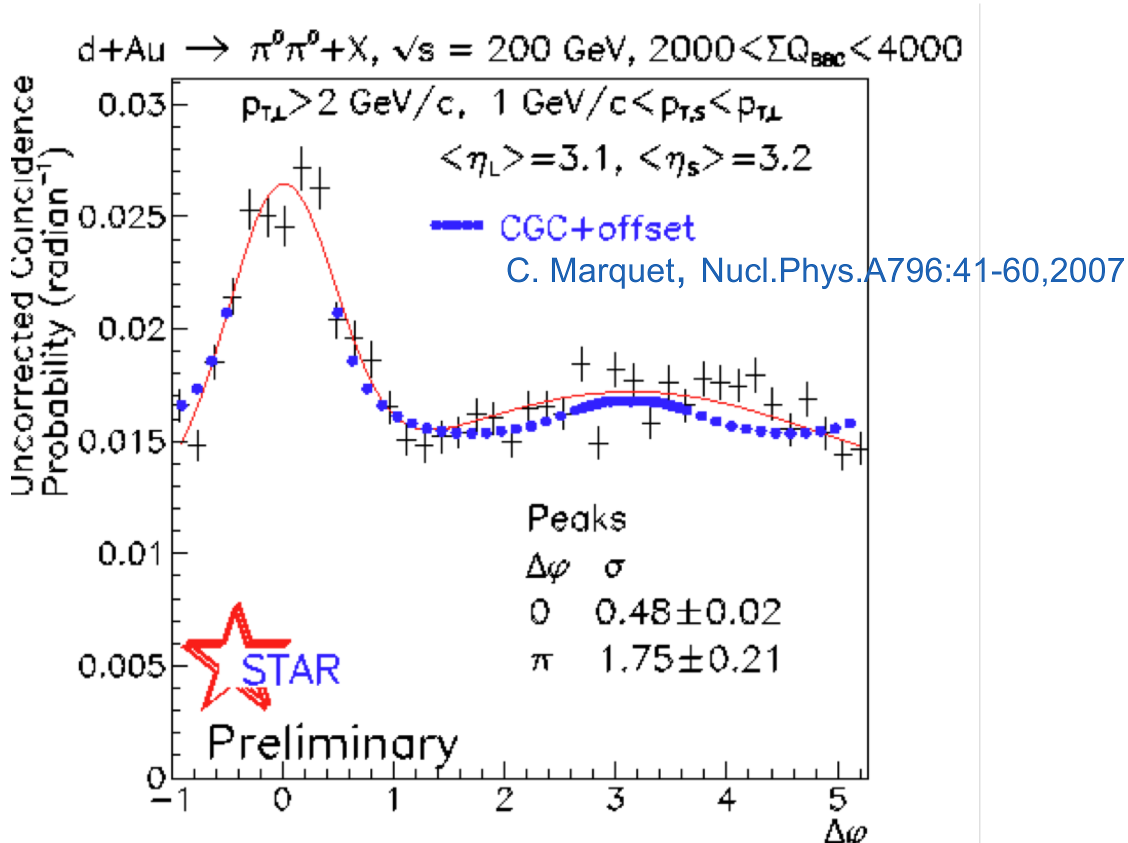
STAR Forward π^0 - Forward π^0 correlations

- Azimuthal decorrelations show significant dependence on centrality.

dAu peripheral



dAu central



- Strong suppression of away side peak in central dAu is consistent with CGC
- Offset in calculations adjusted to fit bg in data

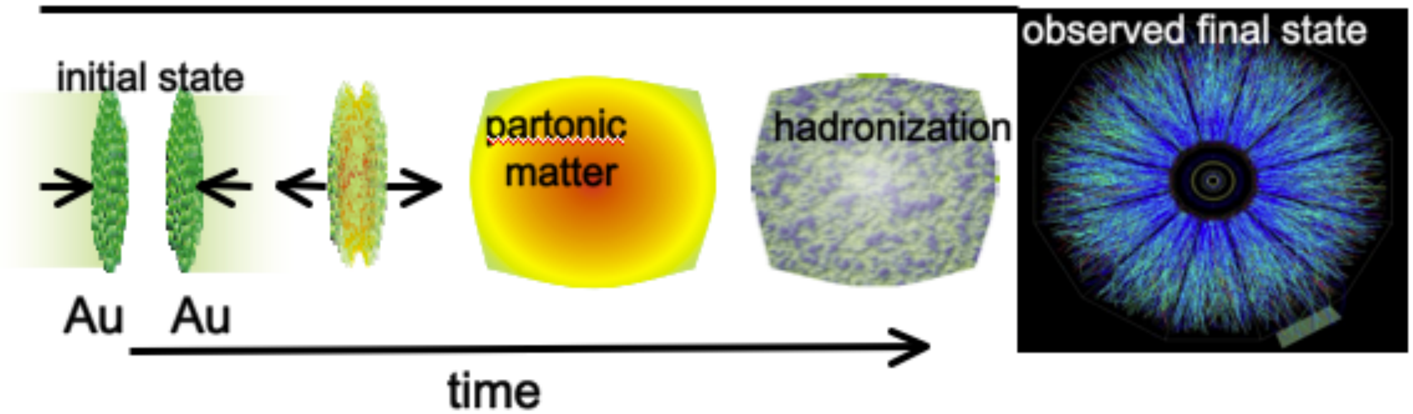
… Multiple parton interactions effects?

See M. Strikman and W. Vogelsang arXiv:1009.6123 [hep-ph]

What is the nature of QCD matter at the extremes?

Au+Au collisions at RHIC

Au+Au Collisions at RHIC and the Initial State



Major discoveries at RHIC:

- Strong elliptic flow

  Collective flow of created matter (close to hydro limit)

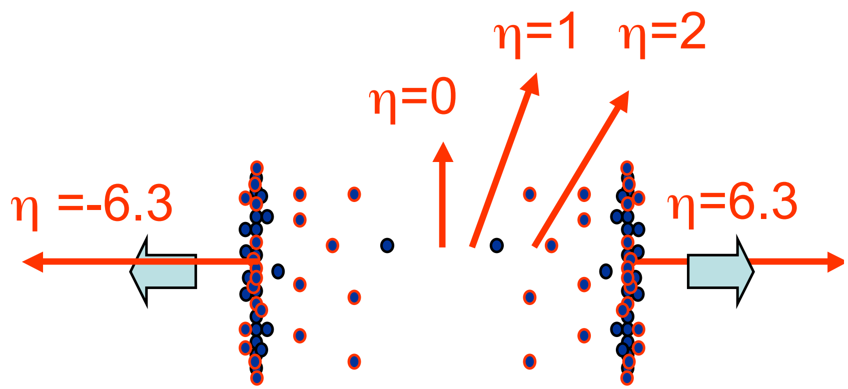
- Jet quenching

  Energy loss of high pT partons traversing the dense matter

Data + model calculations led to the perfect fluid hypothesis

sQGP= hot and dense matter with partonic dof

Early Results: Charged Particle Distributions

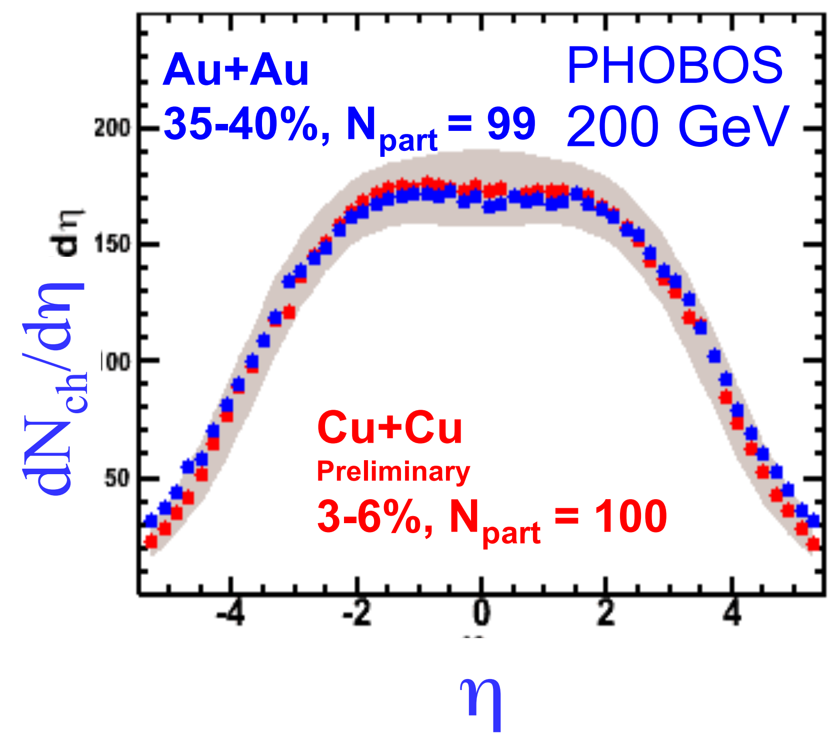


- Pseudorapidity η related to longitudinal velocity (m~0)

- Rapidity plateau dN/dη ~ constant for |η| <2

- dN/dη scales with N_{part}
  Independent of incident nuclei!

Can be used for Cosmic Rays?



Early results: R_{AA}

- Compare AA, dA, pp using

$$R_{AA} = \frac{d^2N(Au+Au)/d\eta dp_T}{\langle N_{binary}\rangle d^2N(p+p)/d\eta dp_T}$$

QCD: R_{AA}=1

- R_{AA} ~>1 for dAu

  Initial state scattering gives partons p_T

- R_{AA} ~ 1 for direct γ in Au+Au

  Photons do not lose energy

- R_{AA} ~ 0.2 for π^0 in Au+Au

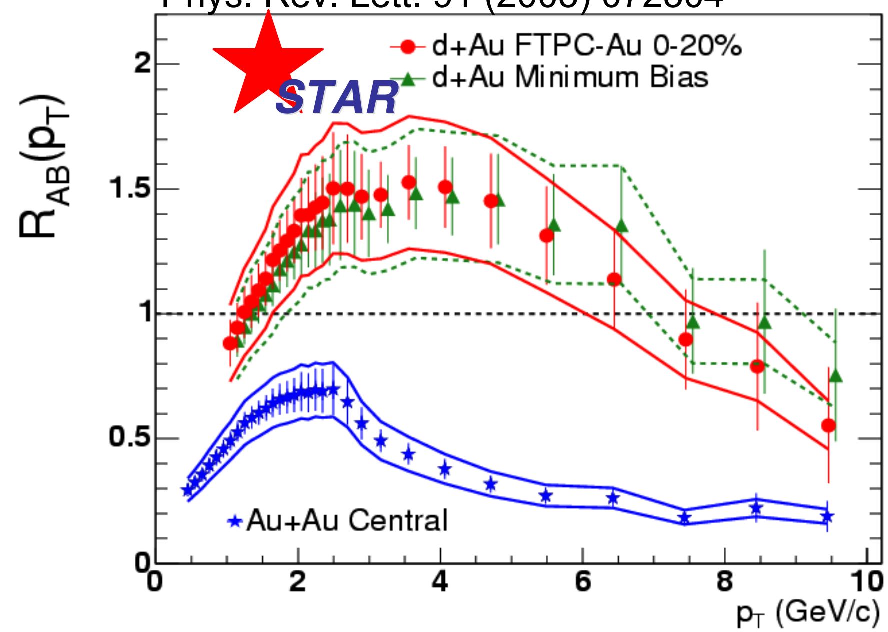
  and 4 < p_T < 20 GeV/c

- Energy loss seems very large;

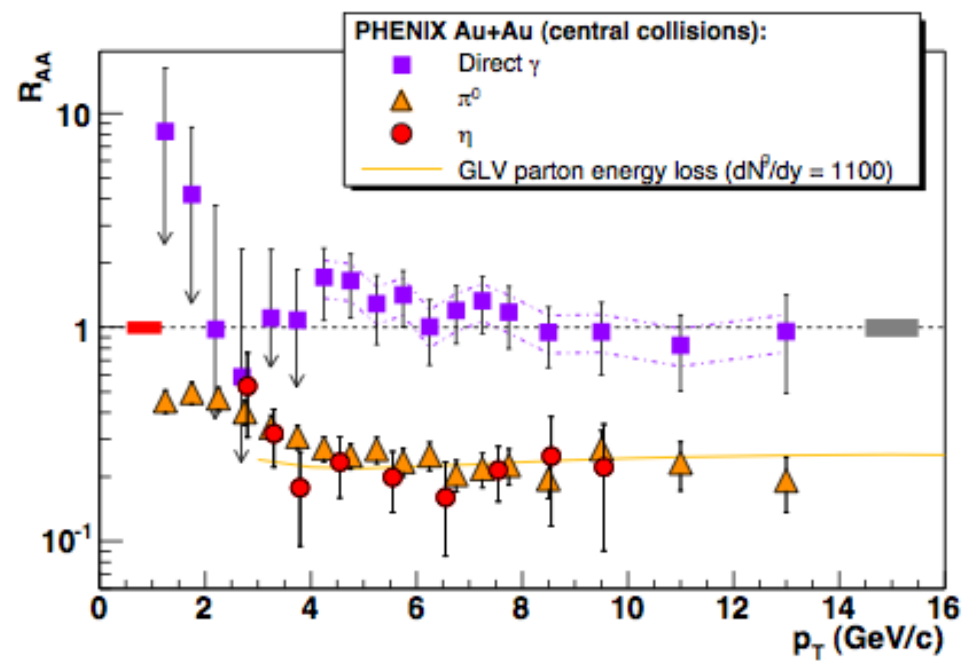
high p_T particle production suppression

Not predicted by QCD

Phys. Rev. Lett. 91 (2003) 072304

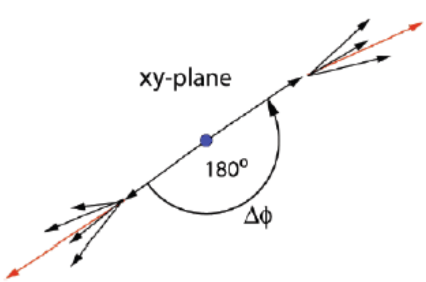


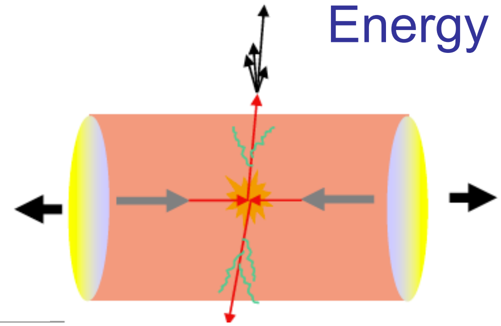
Phys.Rev.C75(2007)024909

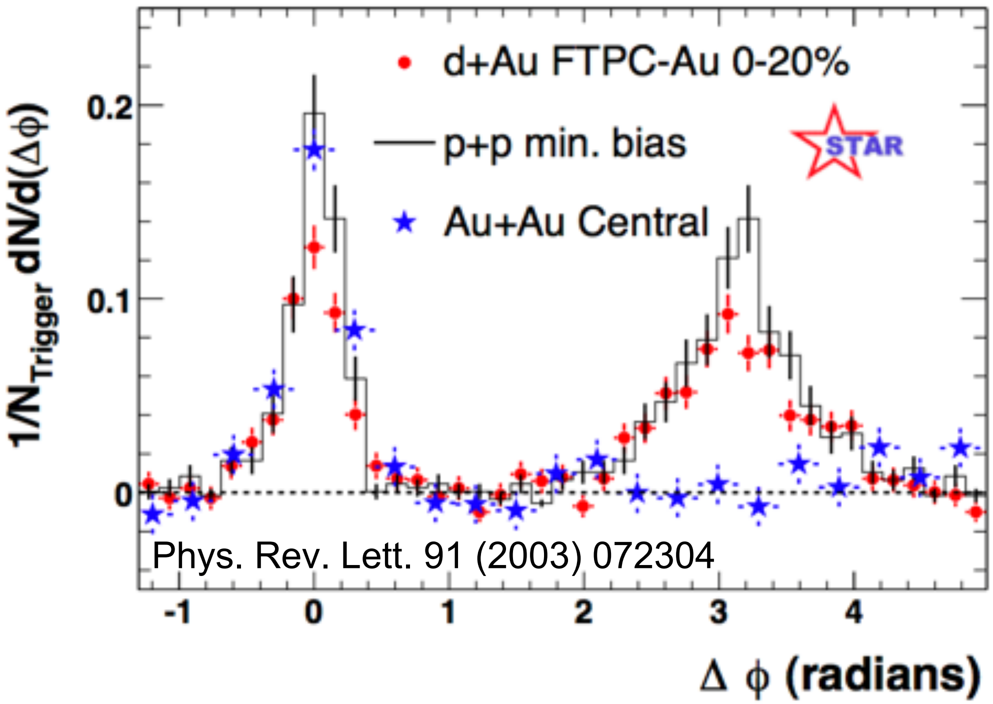


Early results: Jet quenching

Energy loss of high pT partons in dense medium





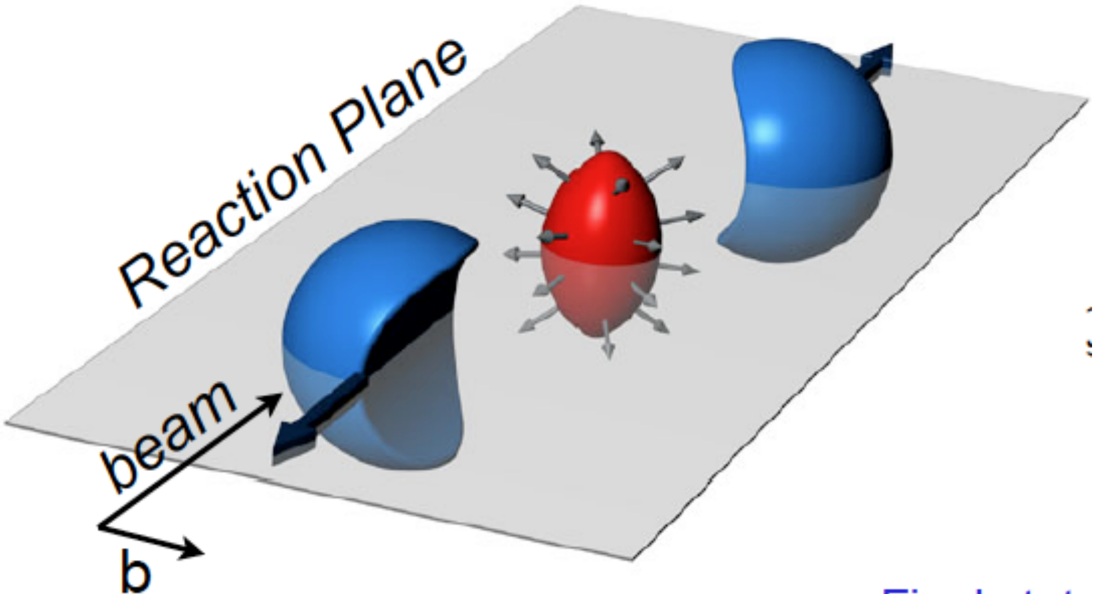


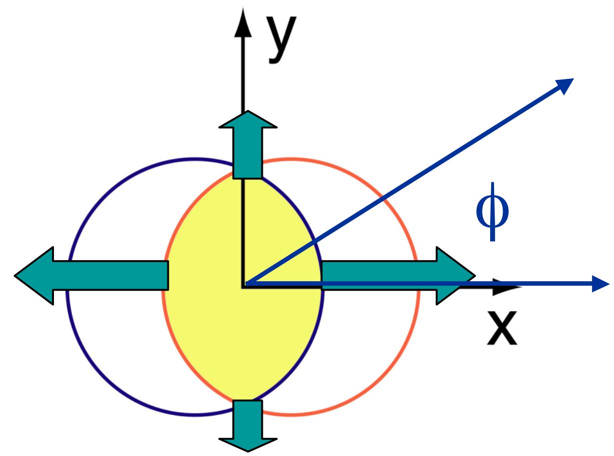
Hadrons suppressed in central collisions; absense of away side jet (absorbed in dense medium)

Evidence for formation of partonic matter at RHIC

Early results: Elliptic flow

<u>Origin:</u> spacial anisotropy of the system when created
and rescattering of evolving system



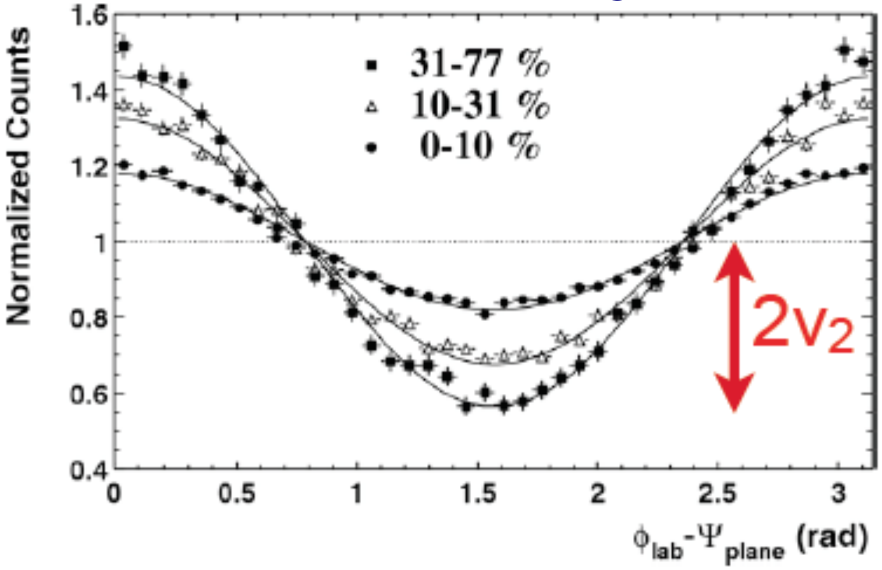


Initial spatial anisotropy → Interactions → Final state anisotropy in momentum space

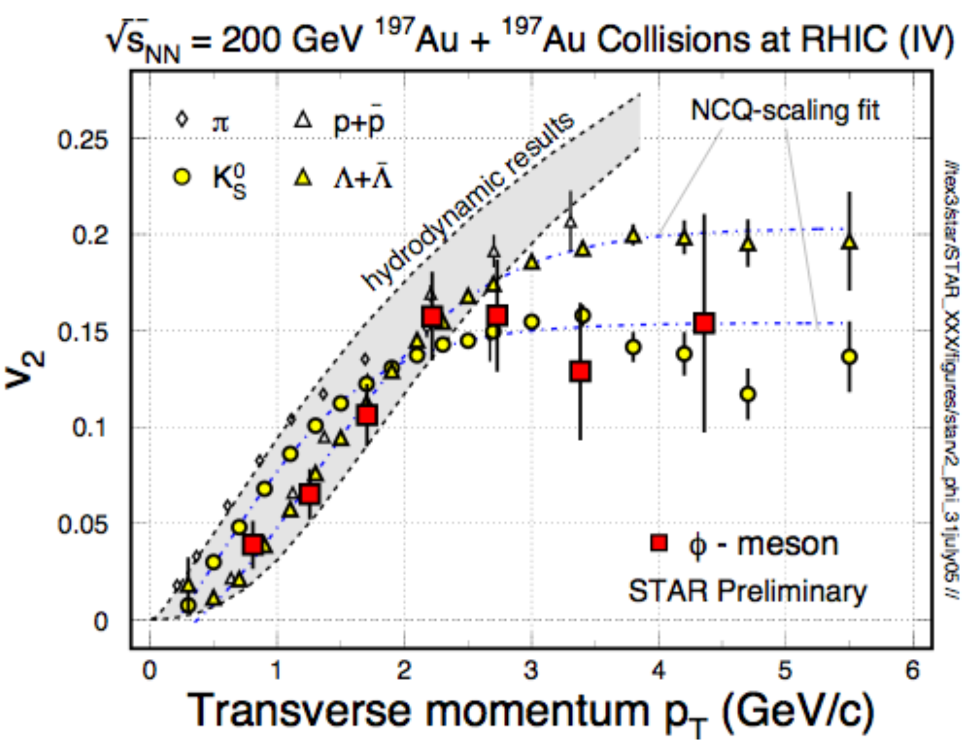
Final state particle density:
$dN/d\phi \sim 1+2v_2 \cos(2\phi) + \ldots$

- v_2 sensitive to early interactions and pressure gradients
- large elliptic flow: a signal of strong space-momentum correlations

Early results: Elliptic flow



- Huge asymmetry found at RHIC
  - -massive effect in azimuthal distribution w.r.t. reaction plane
- "fine structure" $v_2(p_T)$ for different mass particles

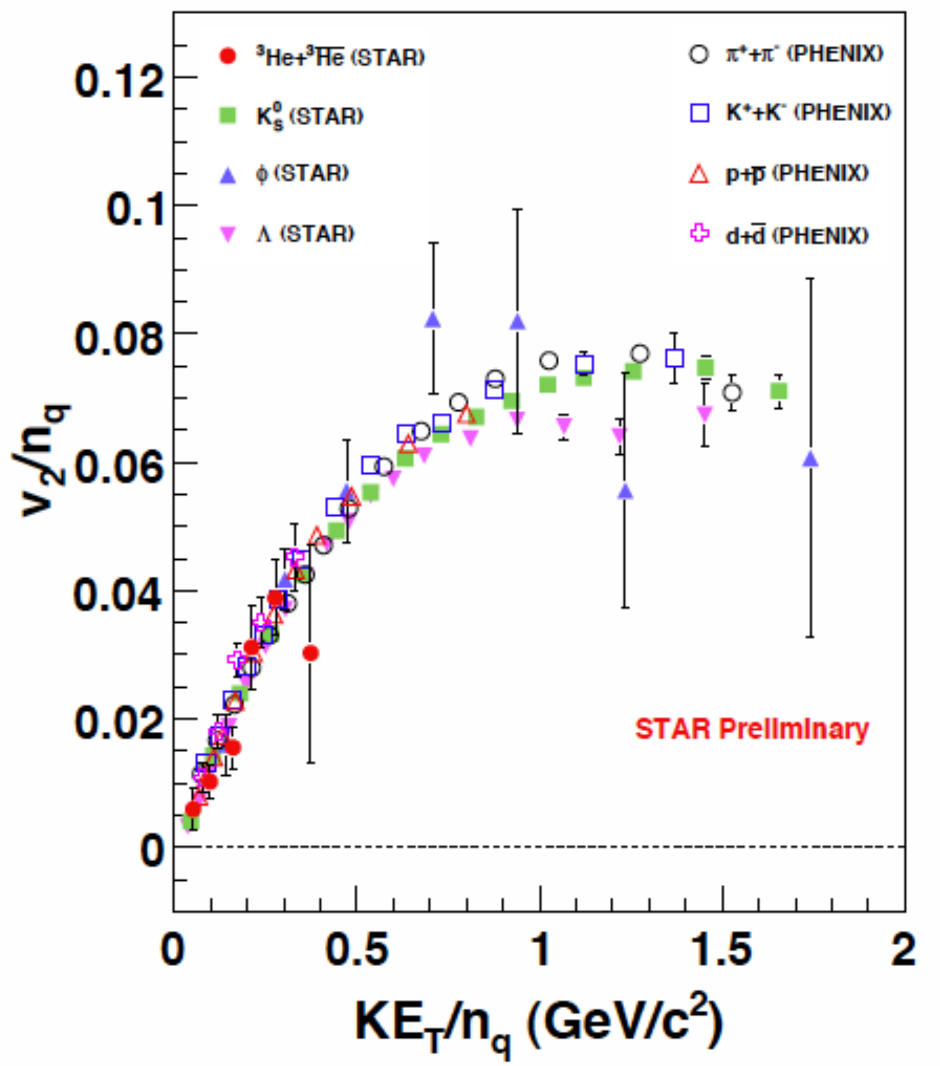


- $v_2 \sim p_T$ for $p_T < 2.5$ GeV
  - –v_2 is at hydrodynamic limits
  - –Hot nuclear matter acts like a nearly perfect fluid
- $v_2 \sim$constant for $4 < p_T < 8$ GeV
- separation between baryon and meson band
  - - ϕ also flows (flow developed in pre-hadronic stage)

Early results: Elliptic flow

Evidence for Formation of Partonic Matter at RHIC

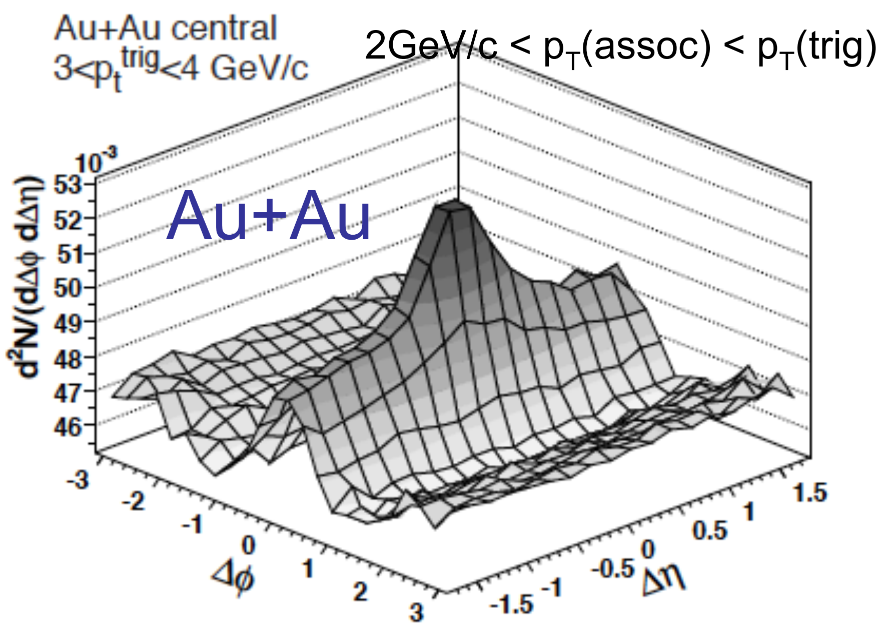
J. Adams et al.. Nucl.Phys.A757:102.2005.

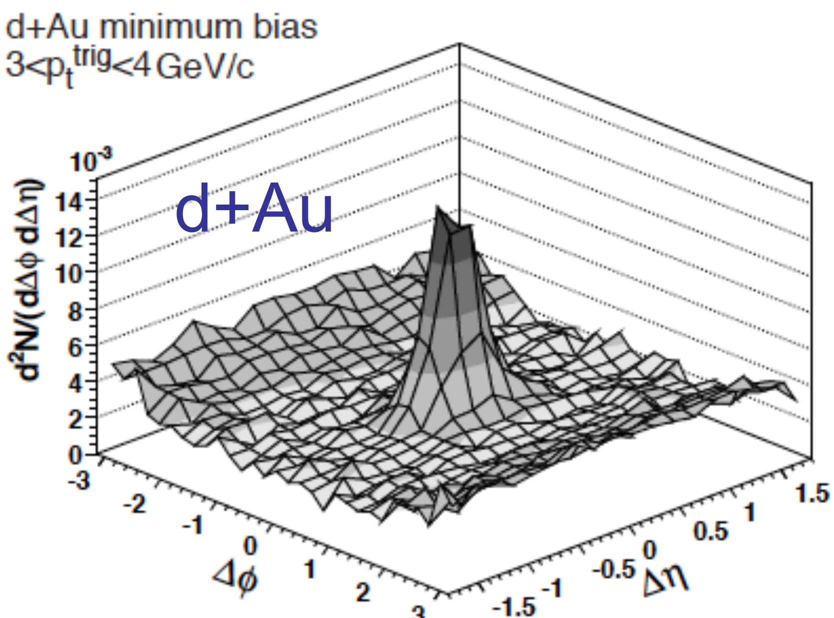


Scaling v_2 by quark content n_q (baryons=3, mesons=2) resolves meson-baryon separation of final state hadrons

Liquid of partons!

STAR: The Ridge in Au+Au





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…. not explained in QCD medium response?

- Long range $\Delta\eta$ correlations on the near side: the “Ridge”.
- 2 components:
  - η independent ridge
  - jet (seen in reference data)

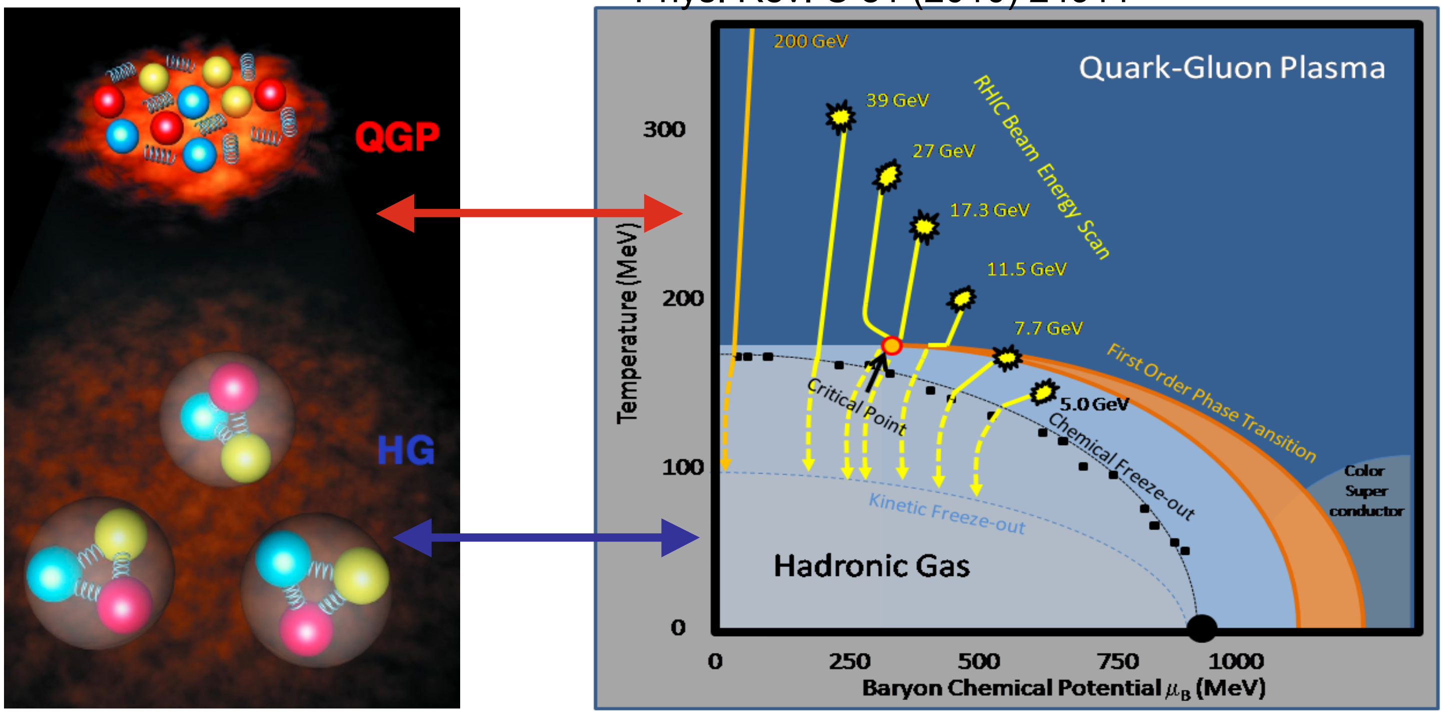
Example expanation:

- CGC: ridge due to flux tubes formed from CGC in the early Glasma phase

Dumitru, Gelis, McLerran, Venugopalan; Gavin, Moschelli '09

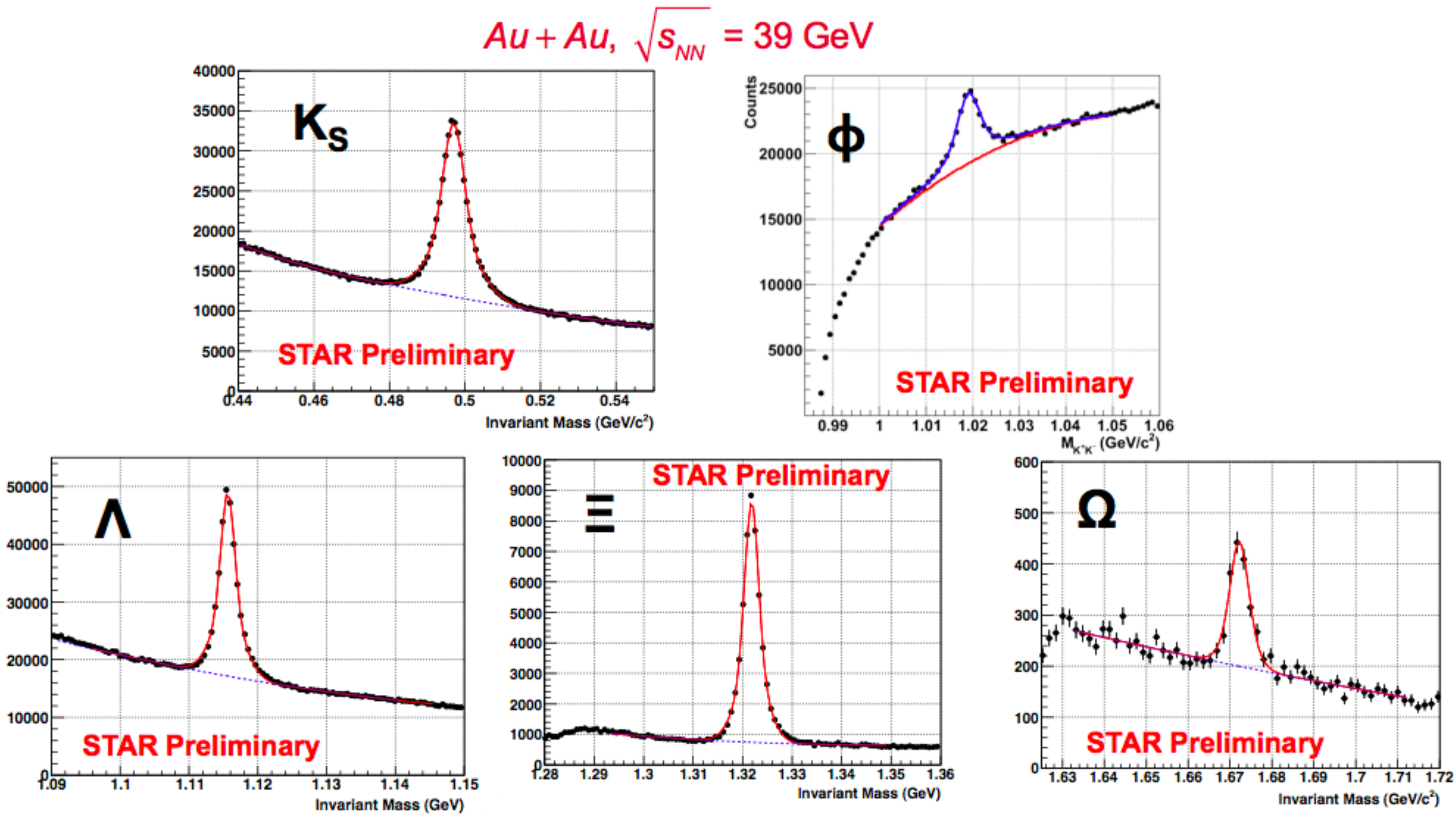
QCD Phase diagram of strongly interacting matter is under study

Phys. Rev. C 81 (2010) 24911



- STAR Beam Energy Scan, sqrt(s)=5-50GeV (μ_B ~ 600-150 MeV)
- Search for:
  - turn-off of major sQGP signatures established at RHIC top energies
  - phase transition signatures of the type that appear and disappear as beam energy is scanned and the evidence of CP

STAR - Run 10

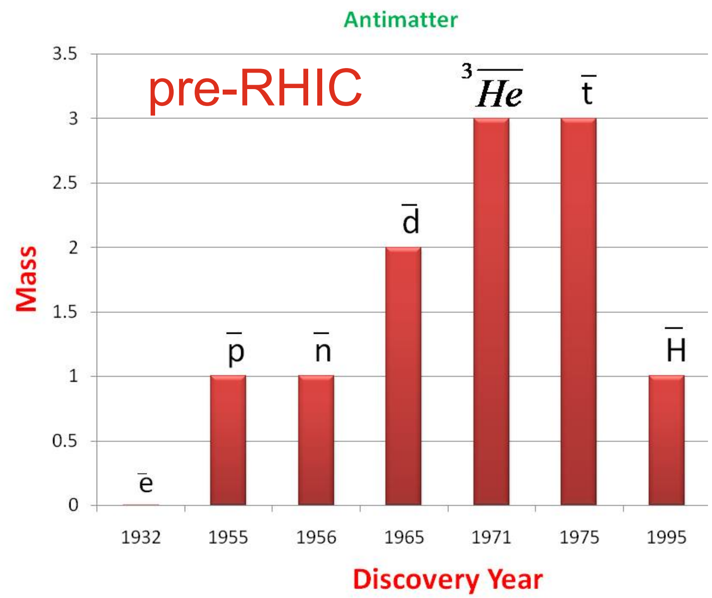


Analyses aim to establish disappearance of signals of partonic degrees of freedom seen at 200 GeV, and find the existence of a Critical Point and phase transition.

RHIC: an antimatter machine

Rare antimatter creation:

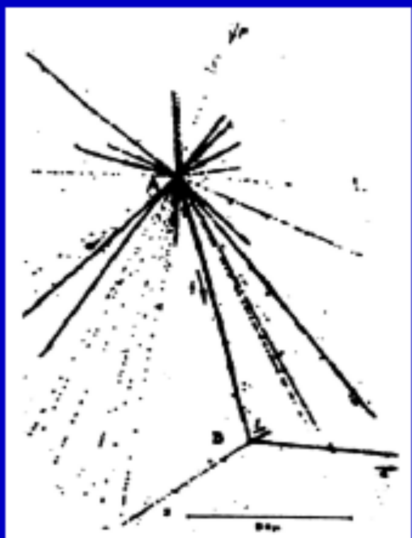
- Complex nuclei like anti-helium or anti-carbon are almost never created in collisions.

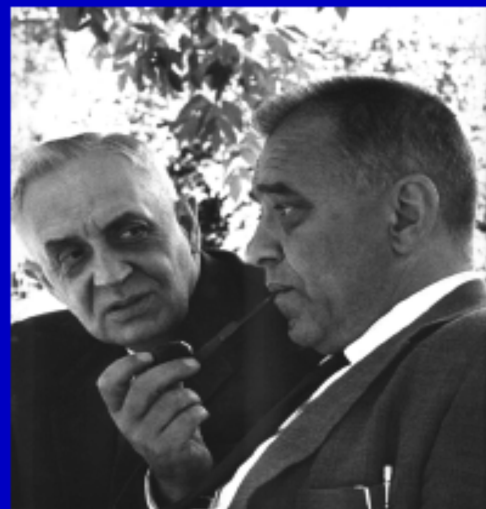


- Such nuclei would be made abundantly by nuclear fusion in an anti-star if the Big Bang made antimatter somewhere … (Alpha Magnetic Spectrometer mission)

What are (anti-)hypernuclei?

Nucleus which contains at least one (anti-)hyperon in addition to nucleons.





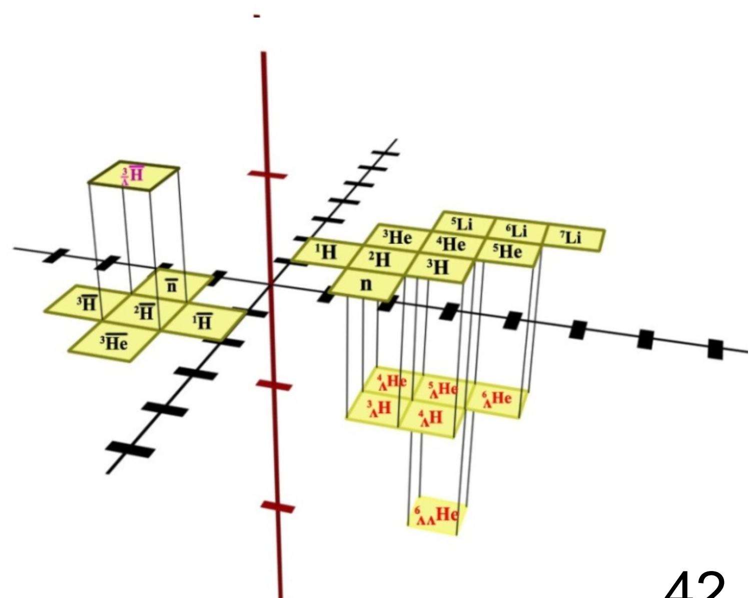
Hypernuclei of lowest A

$$ {}^{3}_{\Lambda}H(n+p+\Lambda) $$

$$ {}^{3}_{\overline{\Lambda}}\overline{H}(\overline{n}+\overline{p}+\overline{\Lambda}) $$

No one has ever observed **any** antihypernucleus

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*

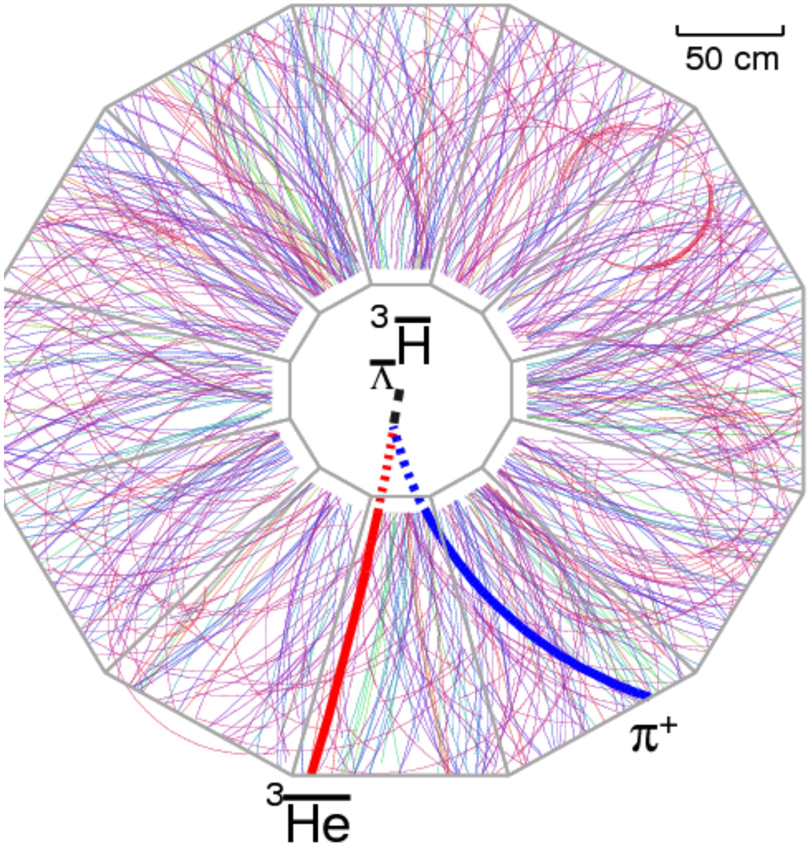


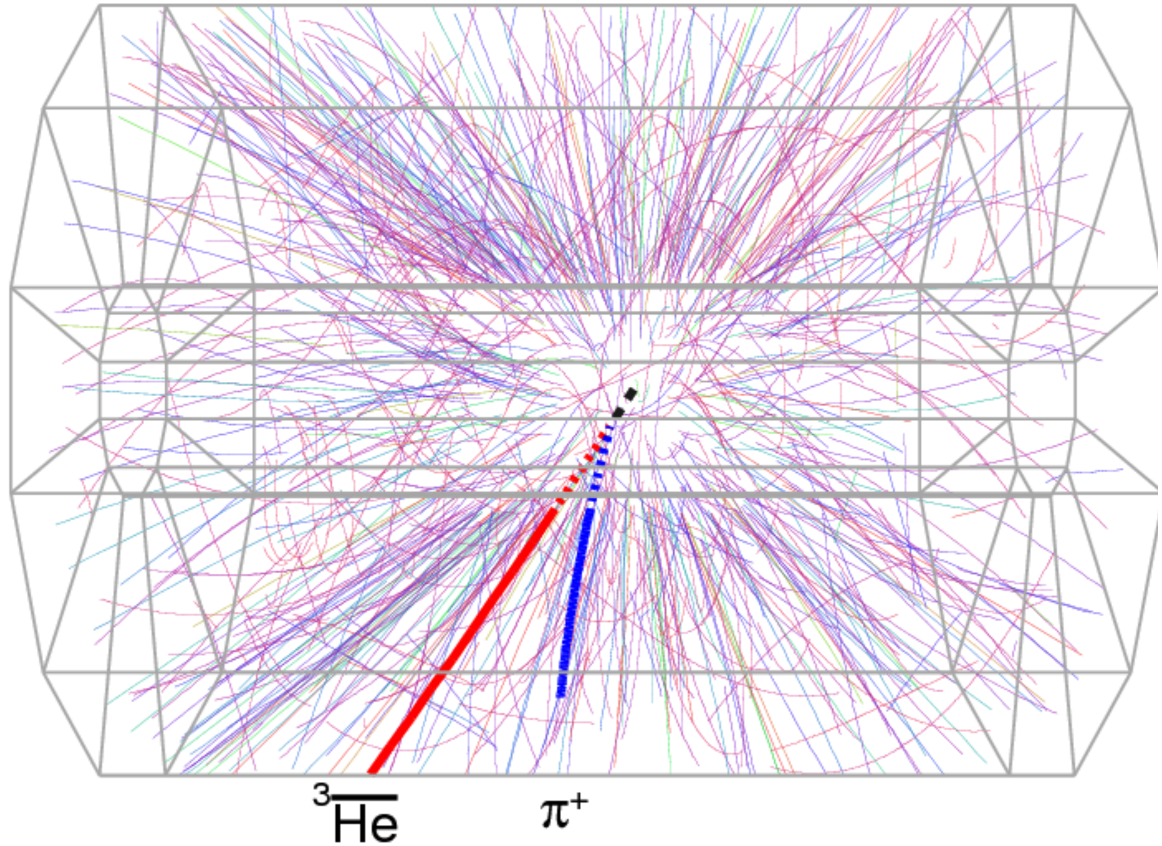
The extension of the periodic system into the sectors of hypermatter (strangeness) and antimatter is of general and astrophysical importance. … The ideas proposed here, the verification of which will need the **commitment for 2-4 decades of research, could be such a vision with considerable** attraction for the best young physicists… I can already see the enthusiasm in the eyes of young scientists, when I unfold these ideas to them— similarly as it was 30 years ago…
---- Walter Greiner (2001)

A candidate event at STAR

Run4 (2004)
200 GeV Au+Au collision

Science 328 (2010) 58





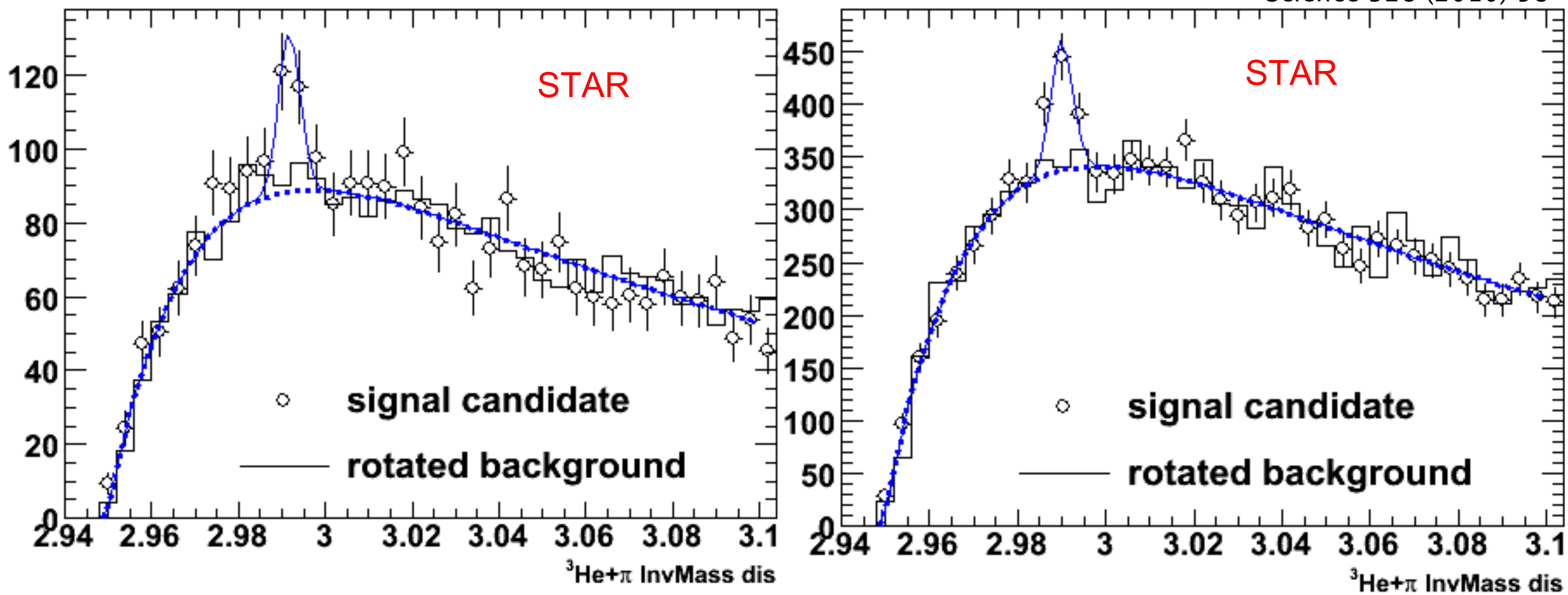
STAR talks:
J.H. Chen, QM09
J.H. Chen, HYP09
Z.B. Xu, RHIC/AGS 09

$$^{3}_{\bar{\Lambda}}\overline{H}(\overline{\Lambda}\overline{p}\overline{n}) \rightarrow {}^{3}\,\overline{He}\,(\overline{p}\overline{p}\overline{n}) + \pi^{+} \quad (BR \sim 25\%)$$

$^{3}_{\bar{\Lambda}}\overline{H}$

STAR: Discovery of Heaviest Known Antimatter Nucleus and First Antinucleus Containing an Anti-Strange Quark

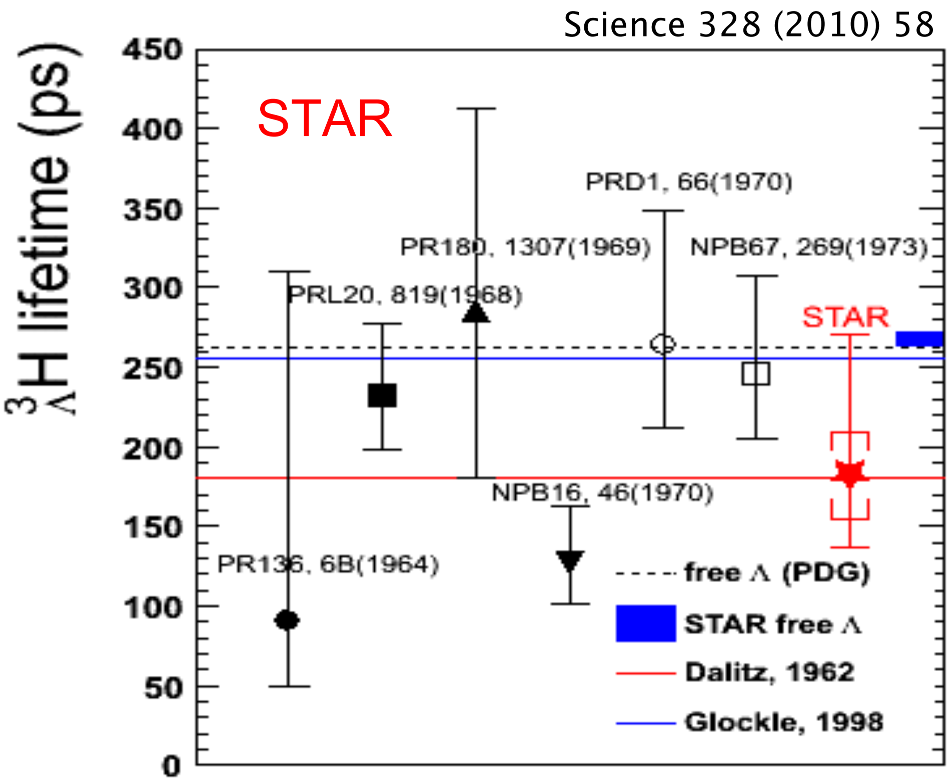
Science 328 (2010) 58

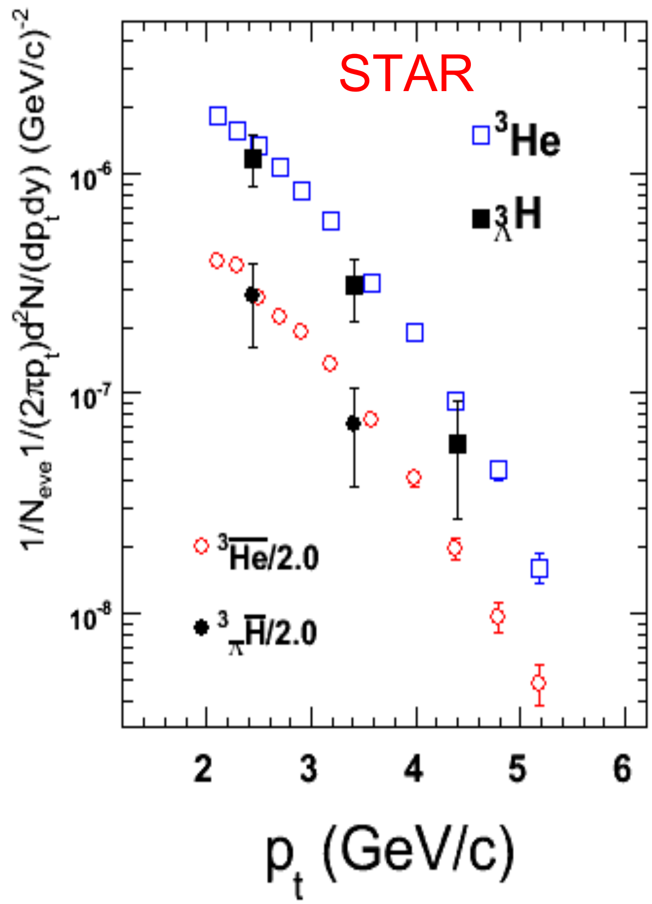


- Signal observed from the data (bin-by-bin counting) **70±17**
- Mass = 2.991±0.001 GeV, Width (fixed) = 0.0025 GeV.
- Combine hypertriton and antihypertriton signal: 225±35

This provides a >6σ signal for discovery

${}^{3}_{\Lambda}\overline{\mathrm{H}}$ STAR Results





Strangeness phase space population is similar to that of light quarks

- Lifetime related to binding energy

$$\tau = 182 \pm^{89}_{45} \pm 27\, ps$$

- the Λ is lightly bound in the ${}^{3}_{\Lambda}\overline{\mathrm{H}}$

[1] R.H. Dalitz, *Nuclear Interactions of the Hyperons* (1965).
[2] R.H. Dalitz and G. Rajasekharan, Phys. Letts. 1, 58 (1962).
[3] H. Kamada, W. Glockle at al., Phys. Rev. C 57, 1595(1998).

- The ${}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}/{}^{3}_{\Lambda}\mathrm{H}$ ratio is measured: 0.49±0.18 and $^{3}\overline{\mathrm{He}}$ / ^{3}He is 0.45±0.02

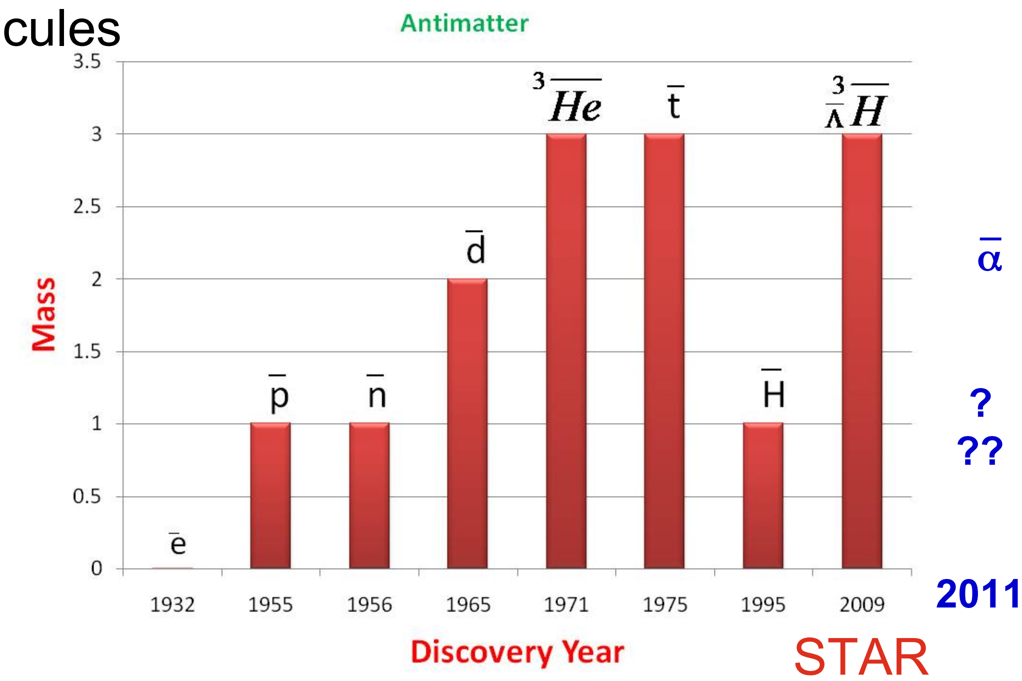
$$ {}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}/{}^{3}_{\Lambda}\mathrm{H} \sim \overline{\Lambda}/\Lambda \times \overline{p}/p \times \overline{n}/n$$

favoring the *coalescence* picture.

Search for exotic hypernuclei and antinuclei with STAR continues …

- The antihypernucleus observation demonstrates that RHIC is an ideal facility for producing exotic hypernuclei and antinuclei.

- STAR is well suited for detecting them:
  - ➔ ${}_{\Lambda}^{3}H \rightarrow d+p+\pi$ channel measurement: *d* and dbar via ToF.
  - ➔ Search for other hypernucleus: ${}^{4}_{\Lambda}H$, double Λ-hypernucleus.
  - ➔ Search for anti-α, antinucleus atomcules



Summary

- STAR is a versatile instrument to study QCD using Au+Au, d+Au, p+p over a wide rage of energies sqrt(s) = 7.7 - 500 GeV, in p+p with polarization.
- Key strengths include jet reconstruction, correlation and particle identification
- Measurements in p+p collisions well described by the pQCD
- In d+Au collisions, forward particle production is suppressed and back-to-back correlations are reduced, consistent with saturation models.
- In heavy-ion collisions, the measurements are consistent with expectations from models assuming thermalization. The new state of matter, a perfect liquid, is created.
- Discovery of Heaviest Known Antimatter Nucleus and First Antinucleus containing an Anti-Strange Quark (anti-hypernuclei)!