Hot matter at RHIC: hot physics at Kent, STAR, PHENIX

Given at the Physics Department, Kent State University, Ohio.

Mikhail Kopytine

Kent State University

http://www.star.bnl.gov/~kopytin/

April 10, 2007

1 Outline

What:

- Motivation
- Data and future directions
- Conclusions

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- Motivation
- Data and future directions
- Conclusions

How:

- Focus on recent developments (2005 $\longrightarrow$)
- Place them in historical and conceptual context

2 The RHIC

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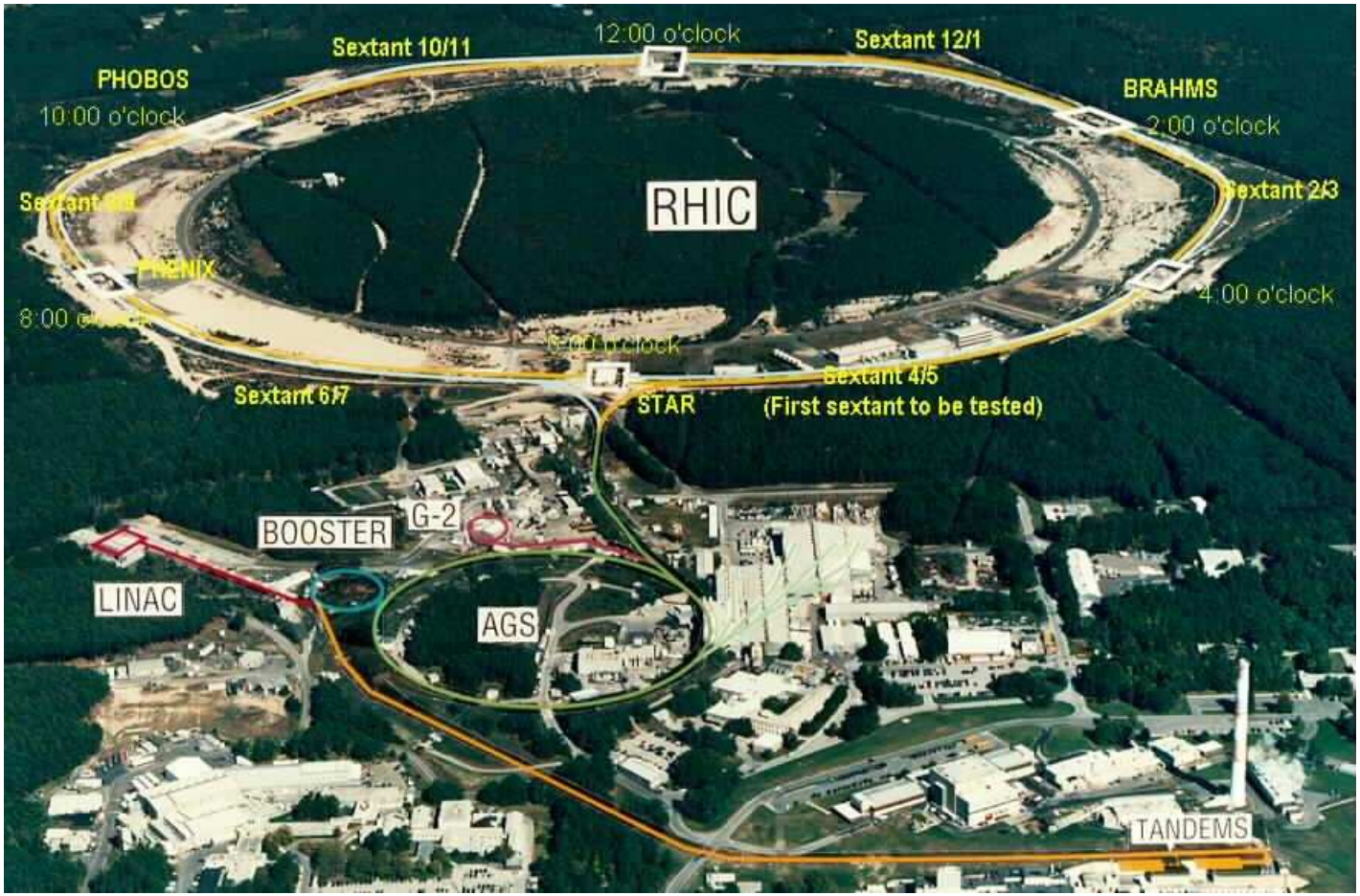
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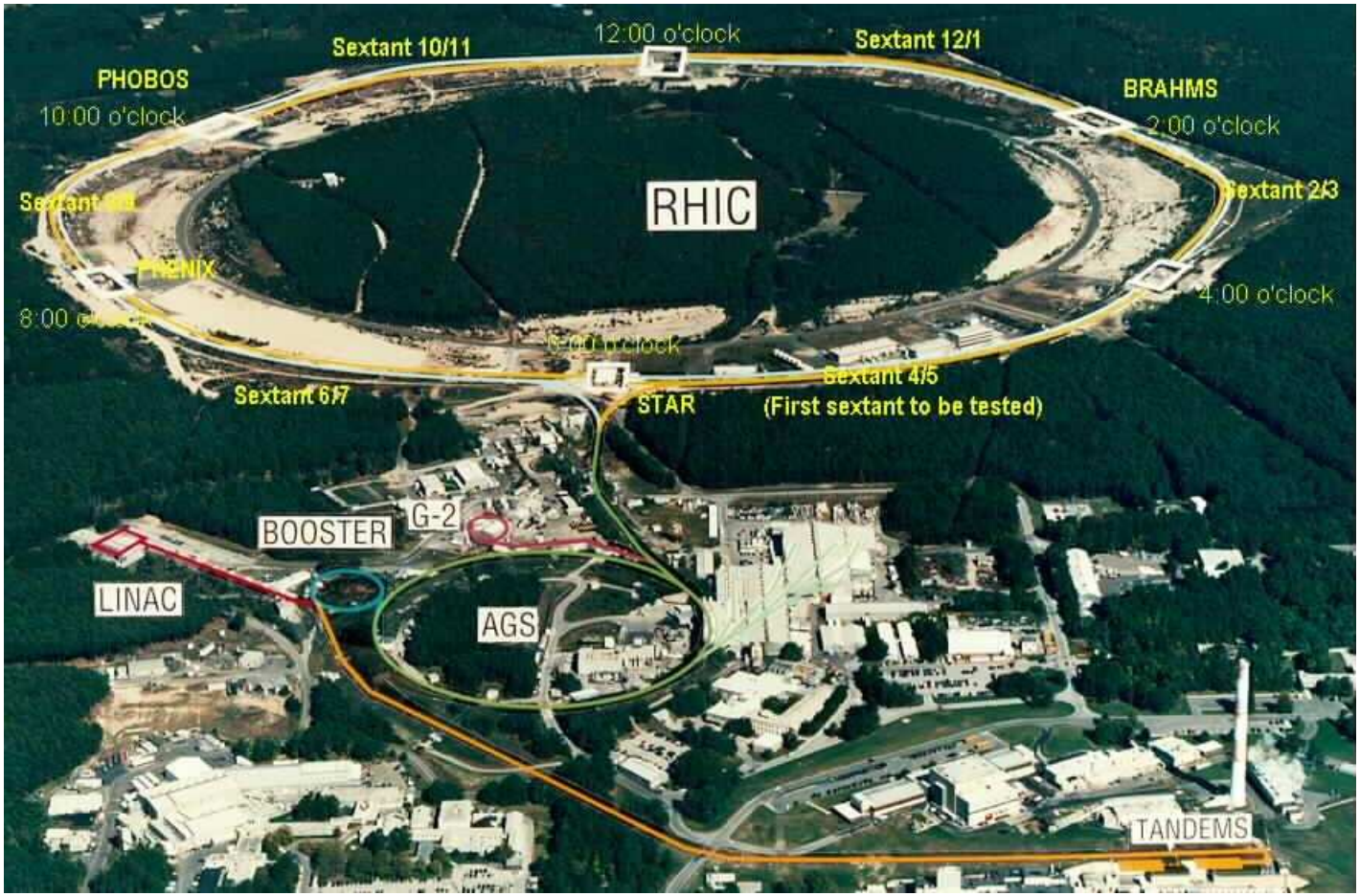
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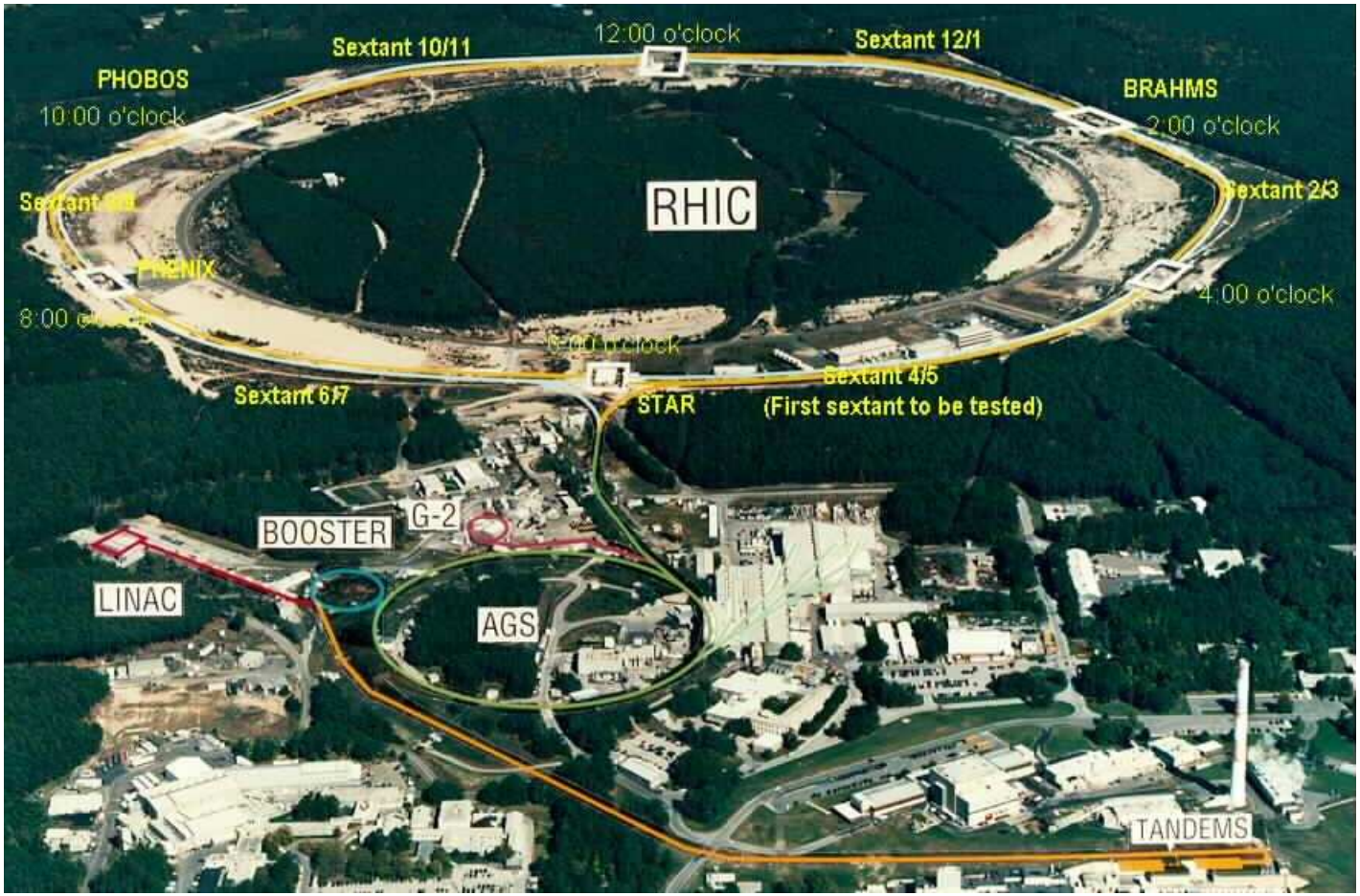
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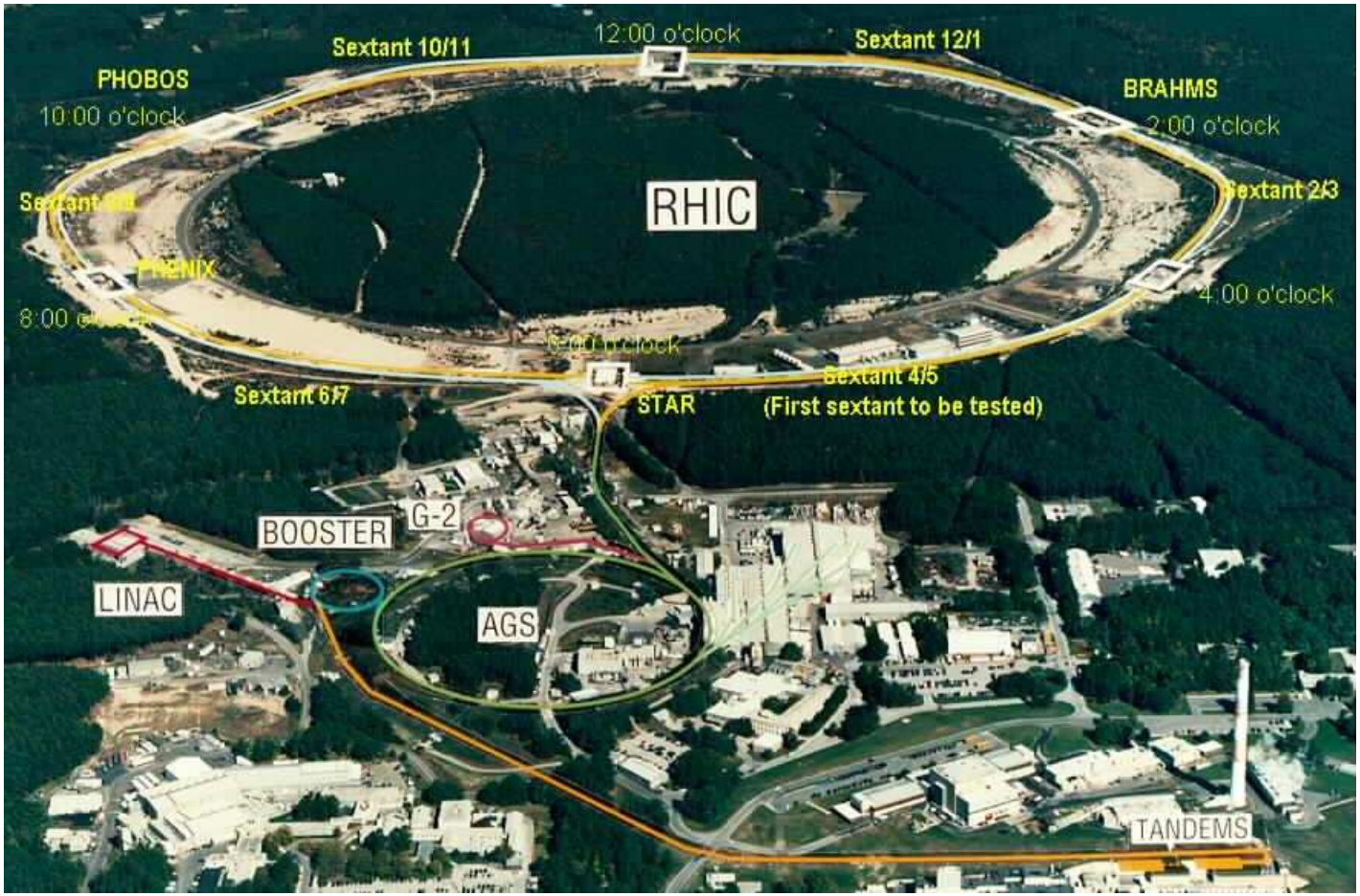
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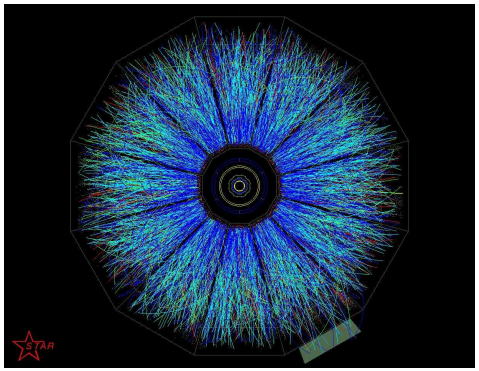

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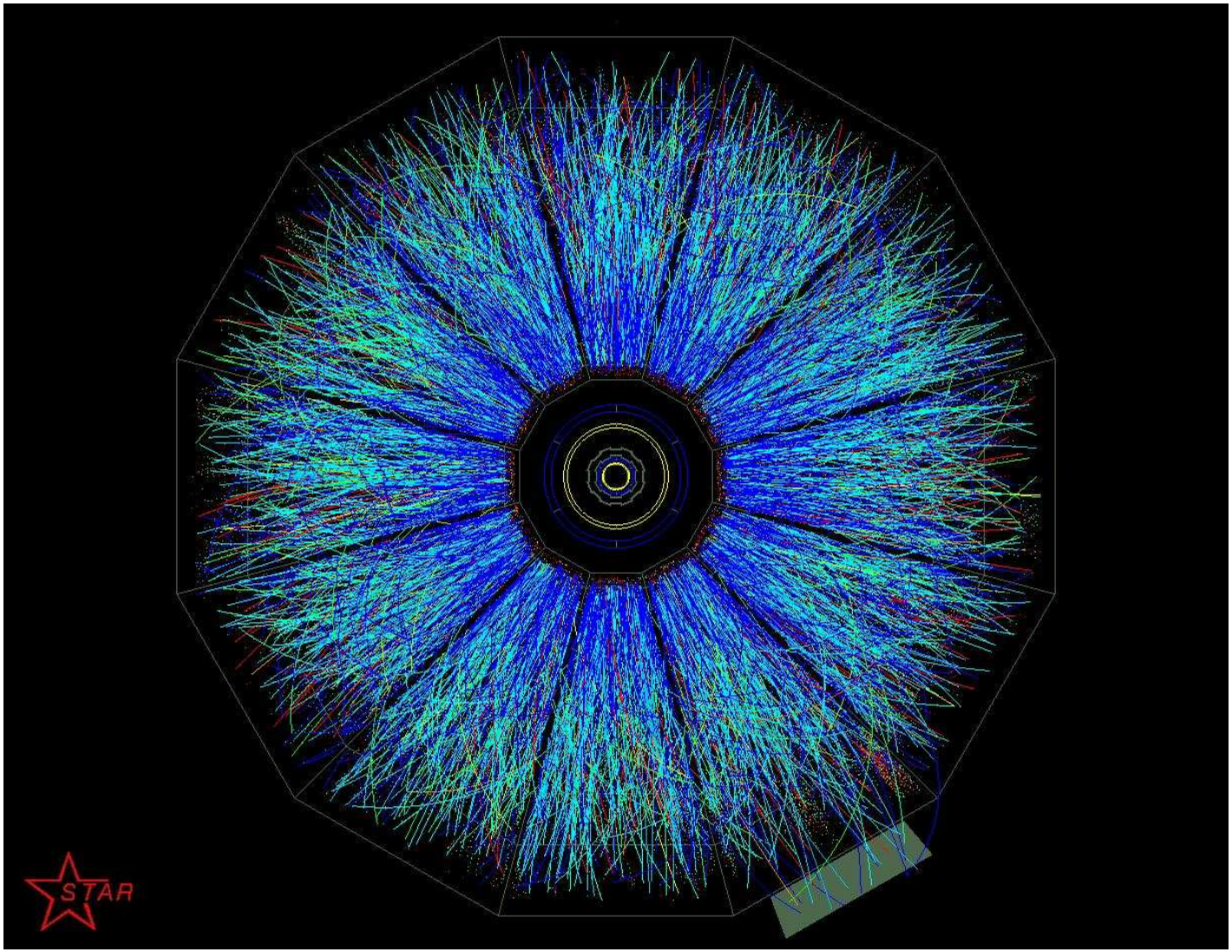

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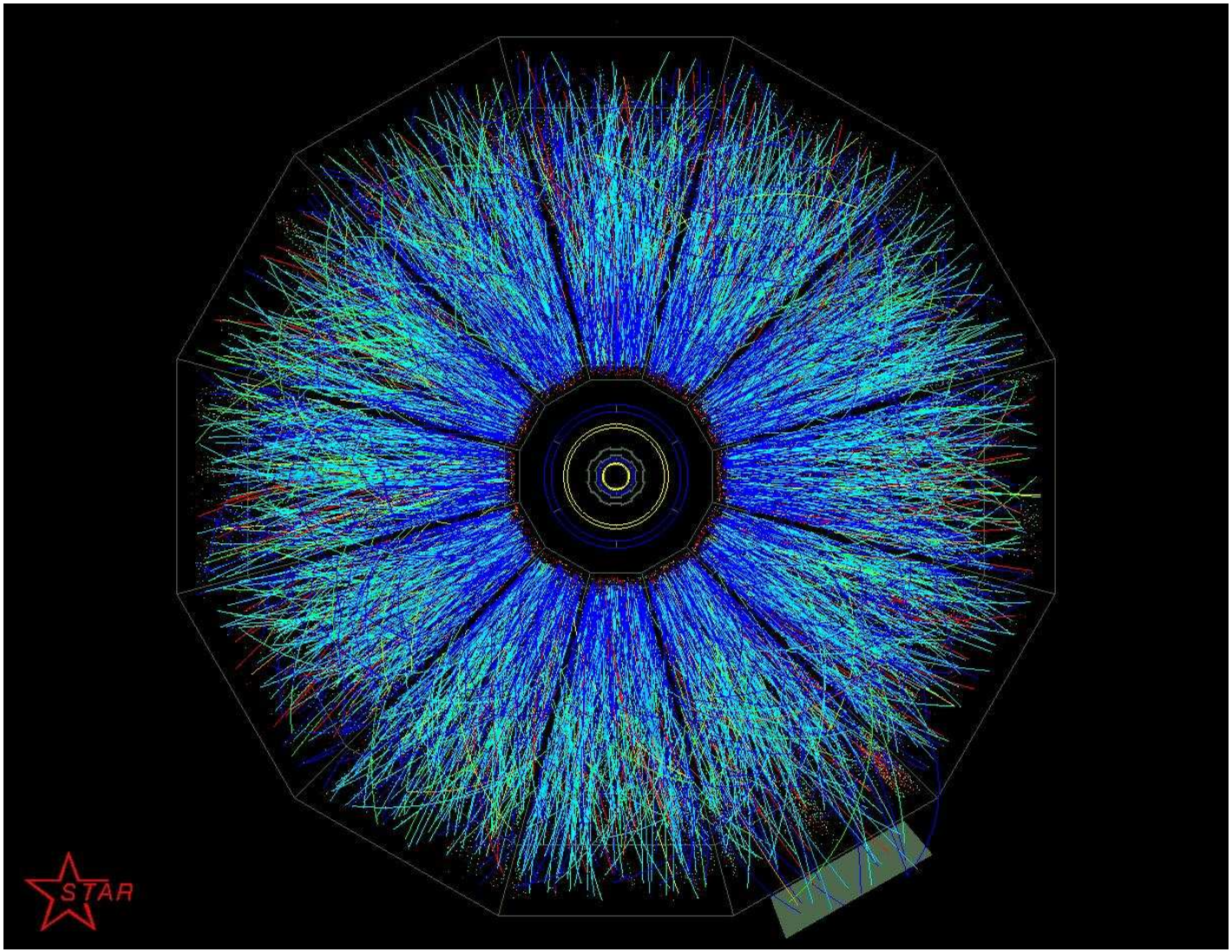

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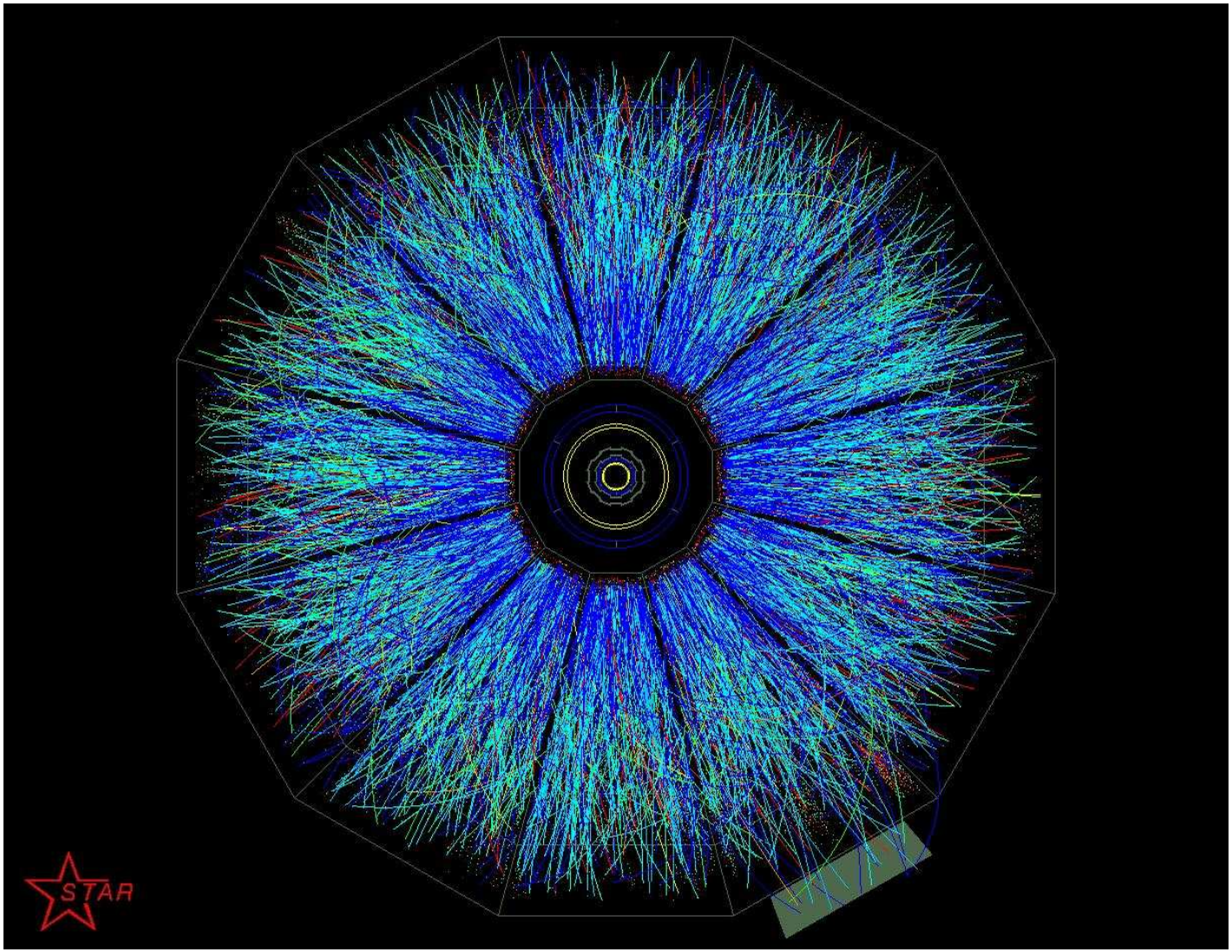

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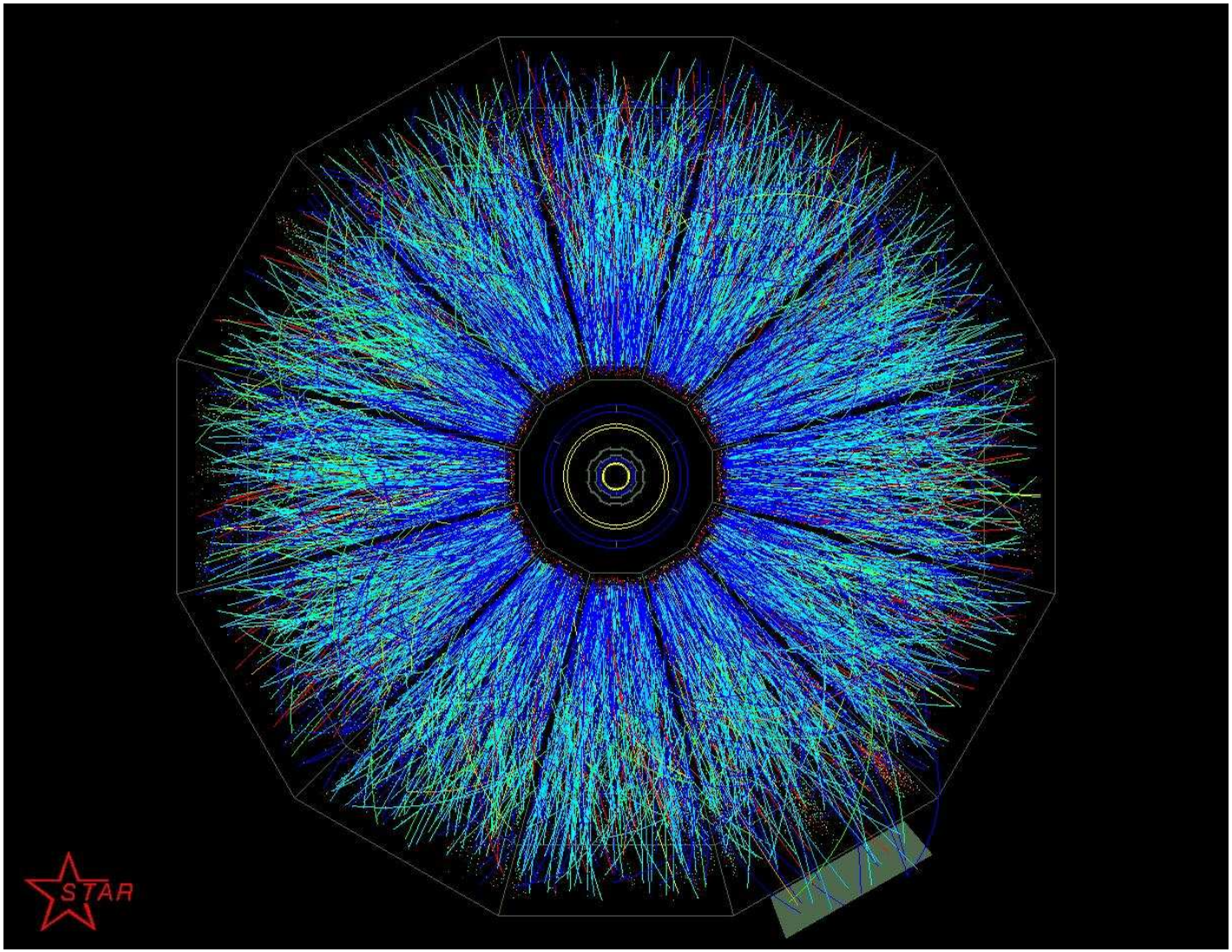

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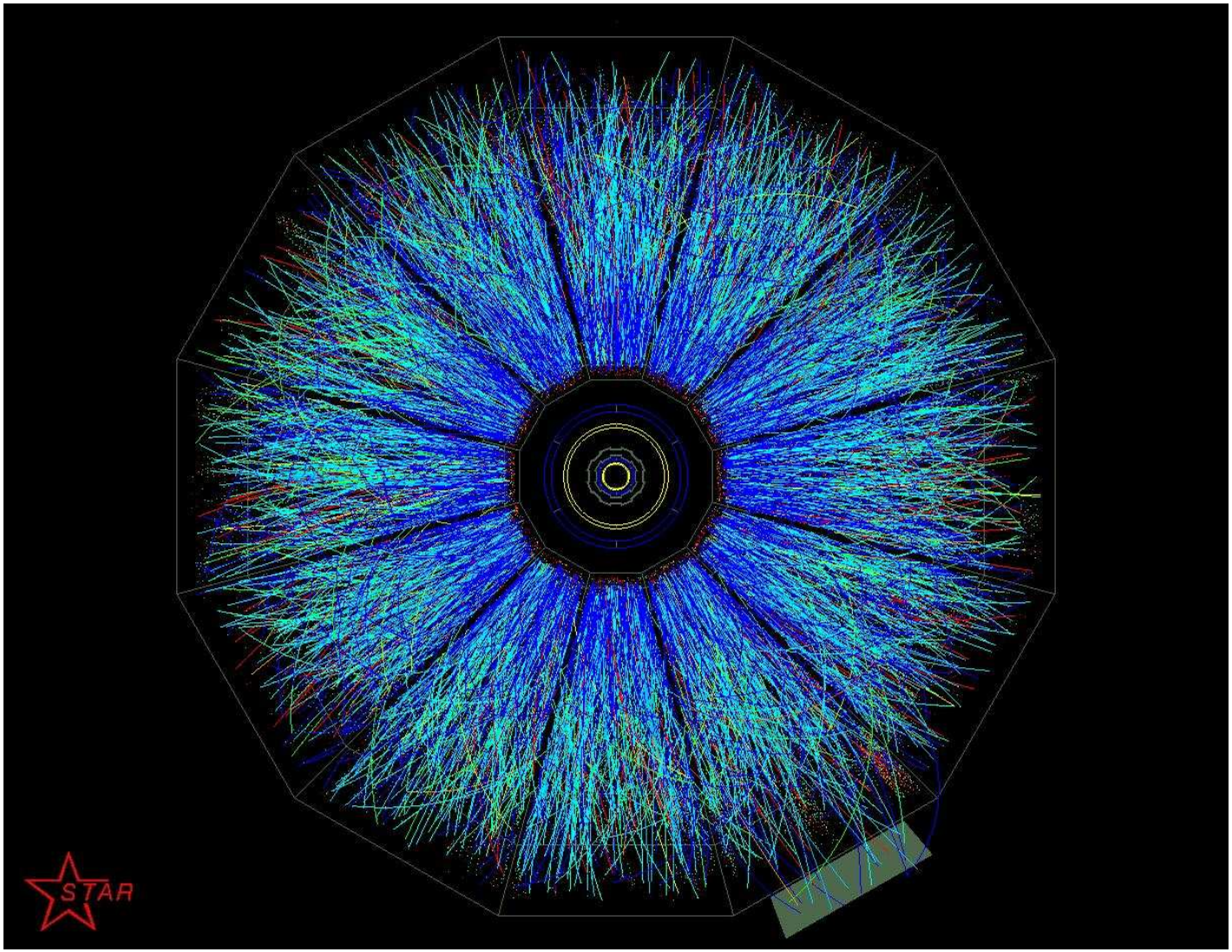

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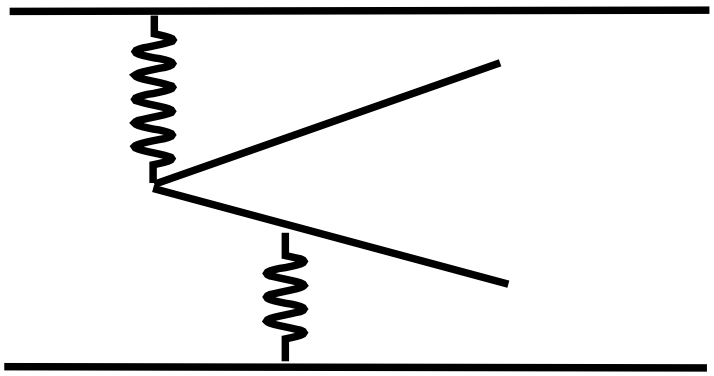

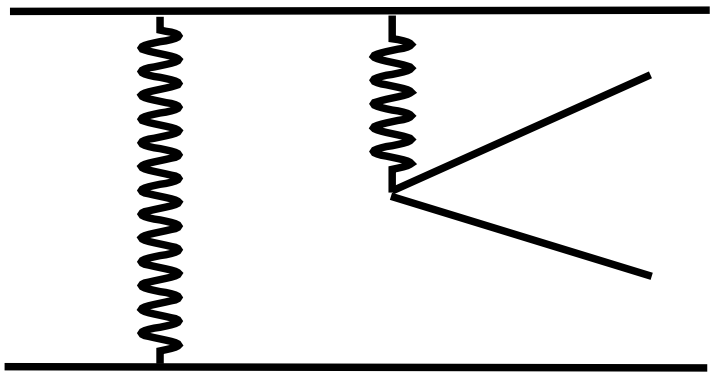

Expansion in powers of $\alpha \approx 1/137$, higher orders matter less...

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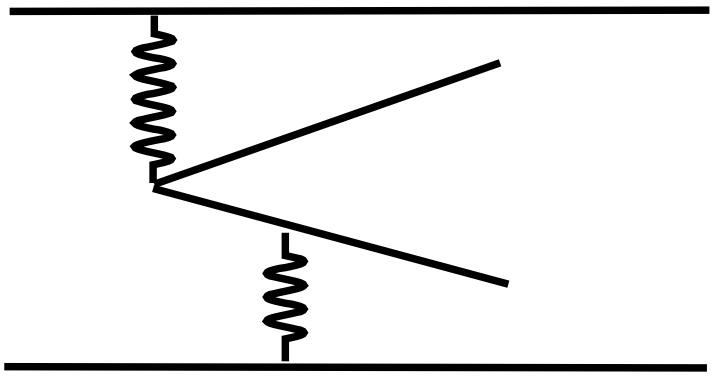

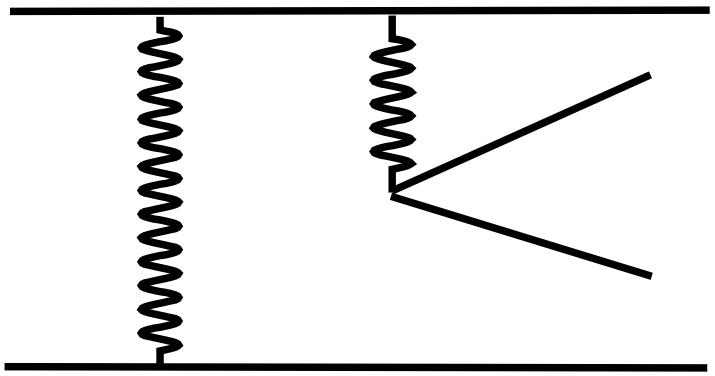

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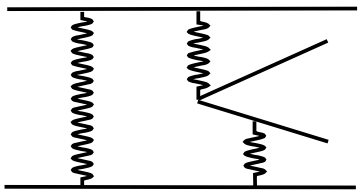

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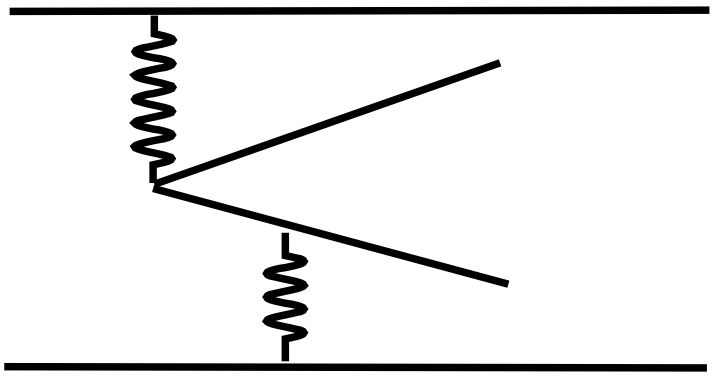

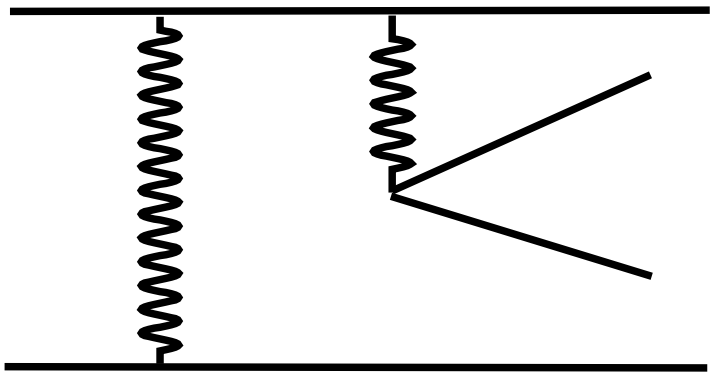

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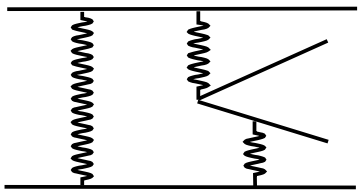

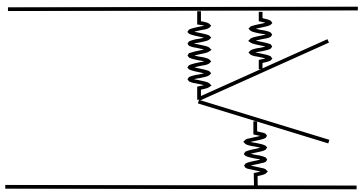

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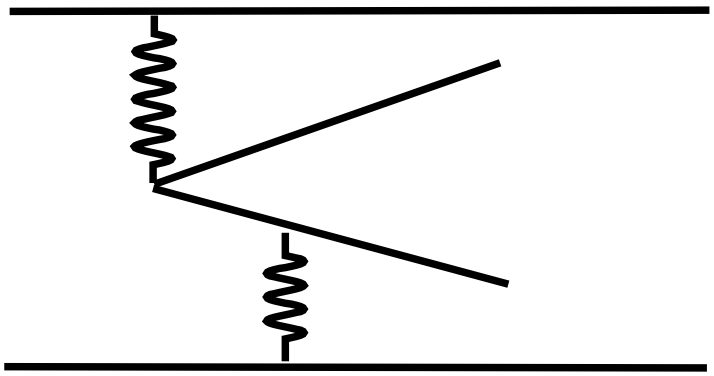

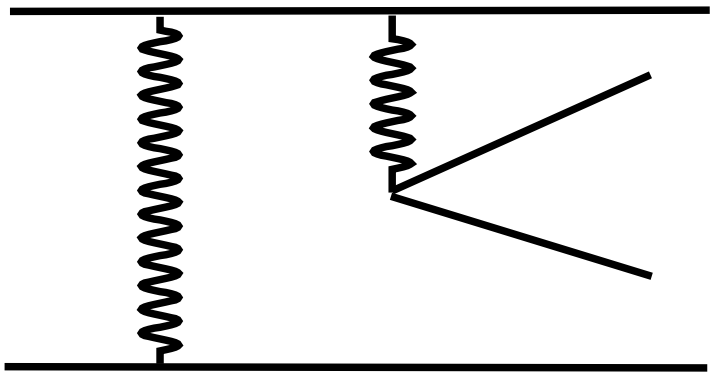

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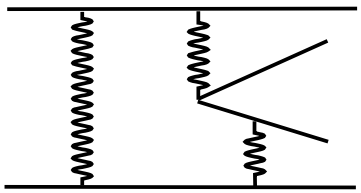

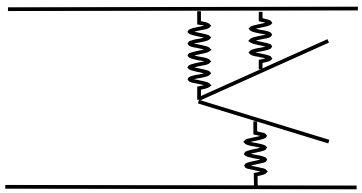

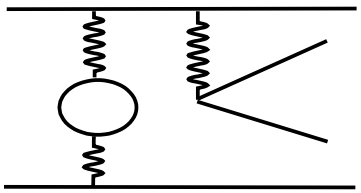

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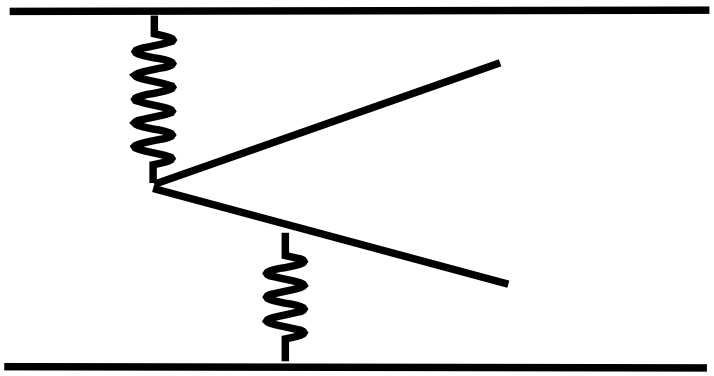

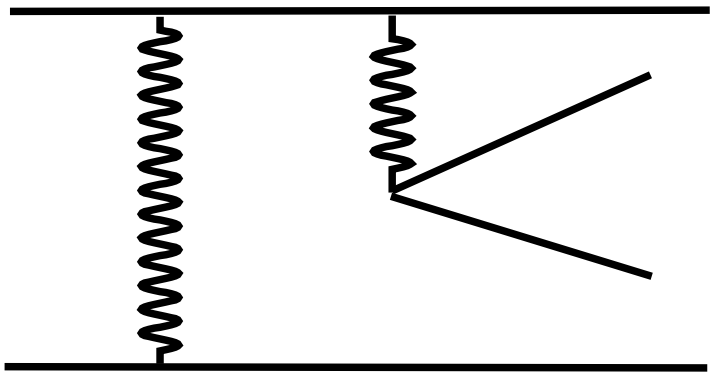

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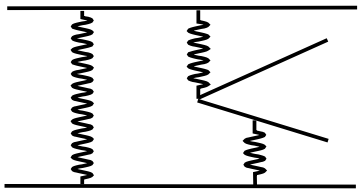

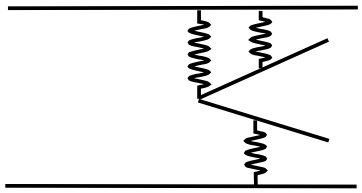

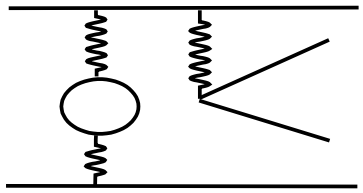

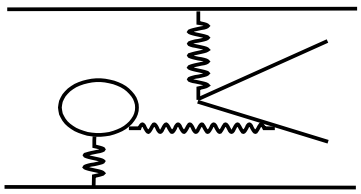

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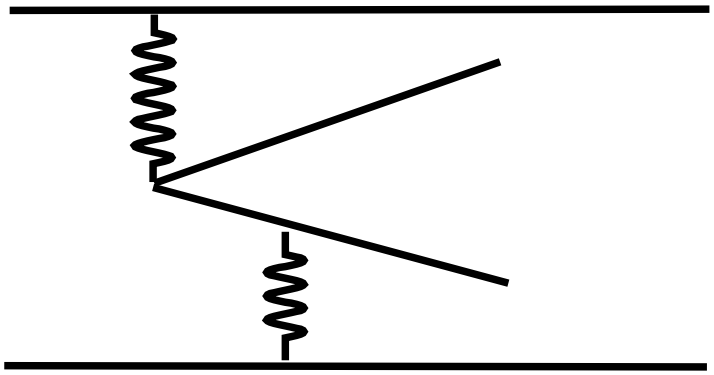

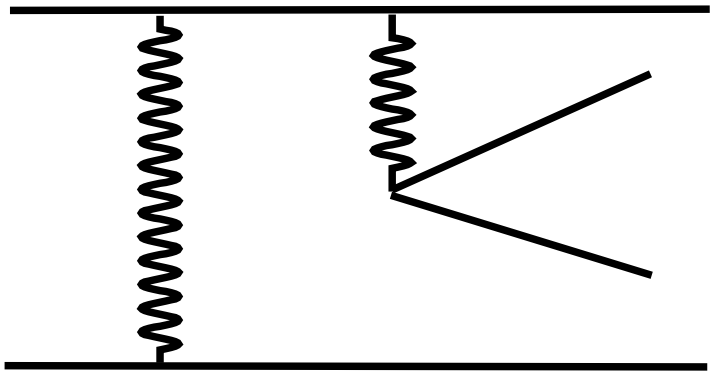

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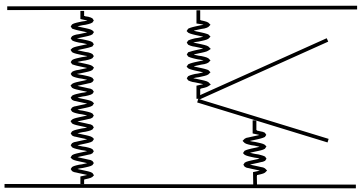

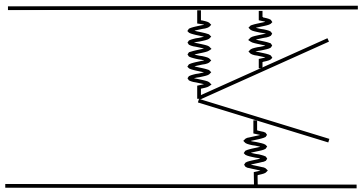

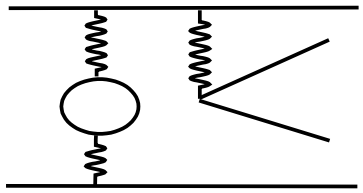

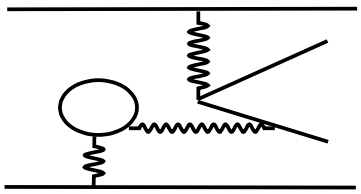

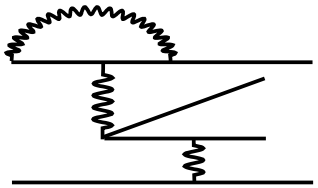

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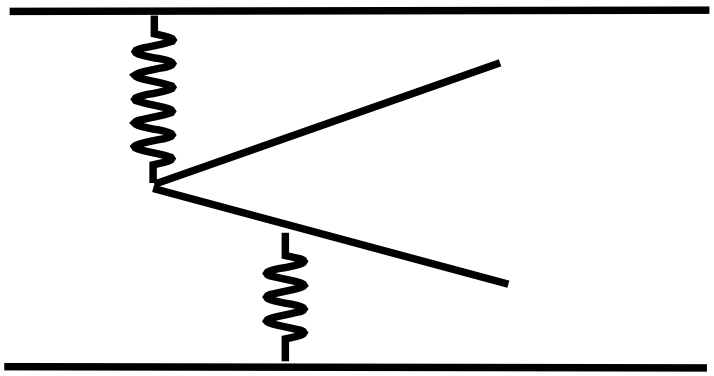

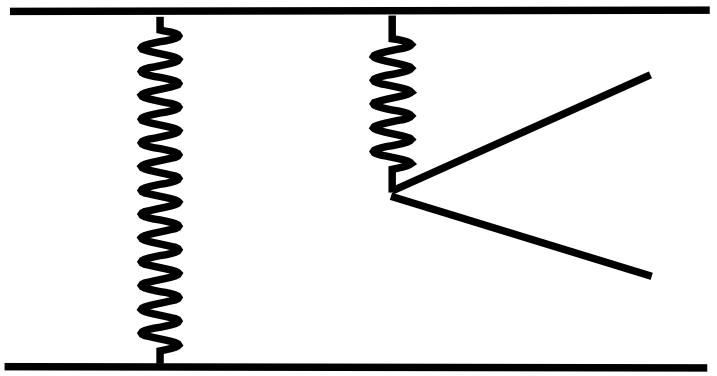

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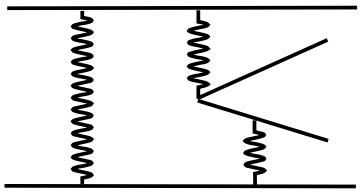

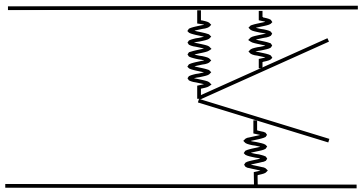

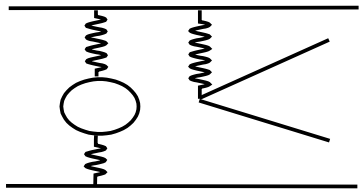

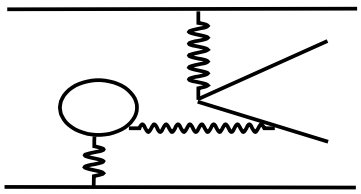

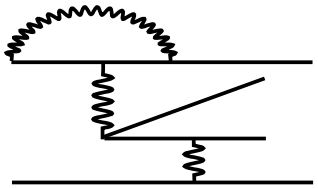

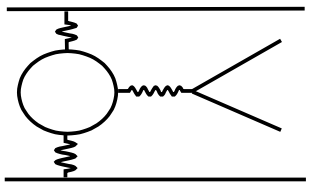

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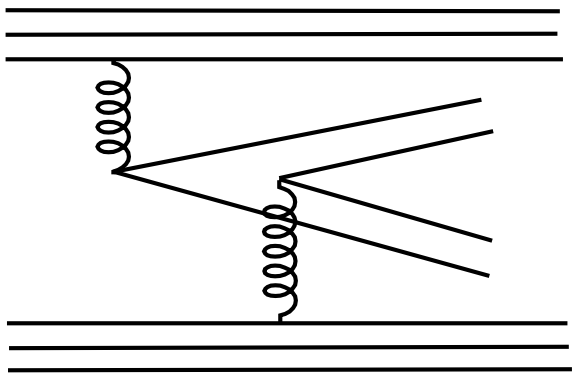

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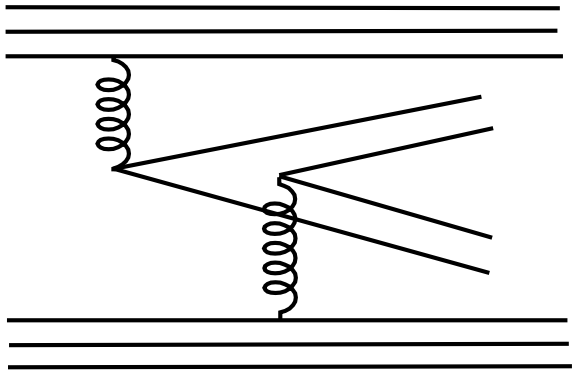

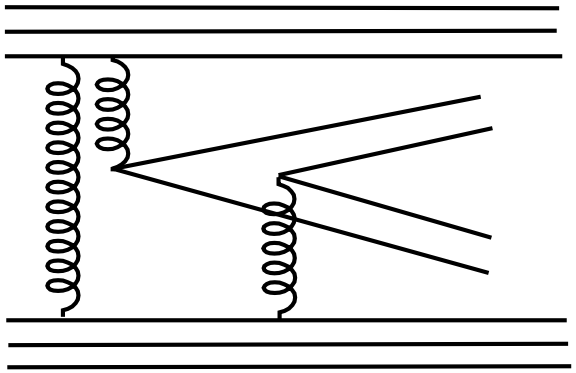

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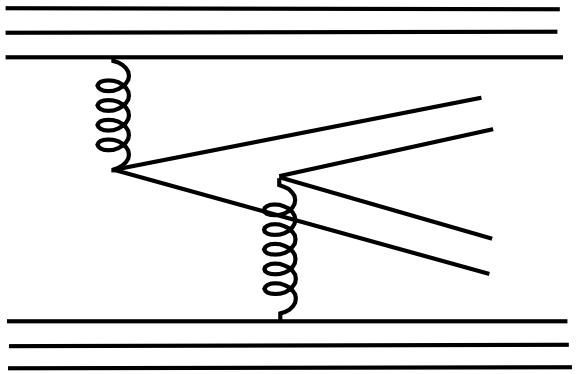

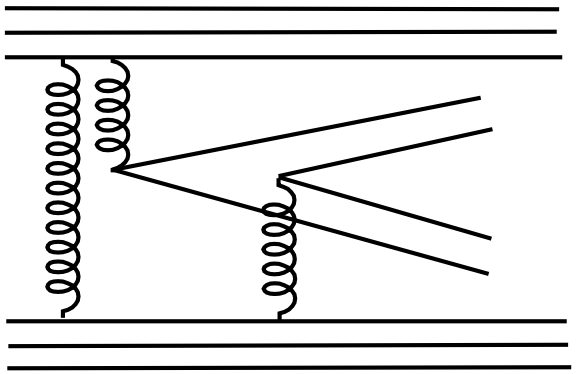

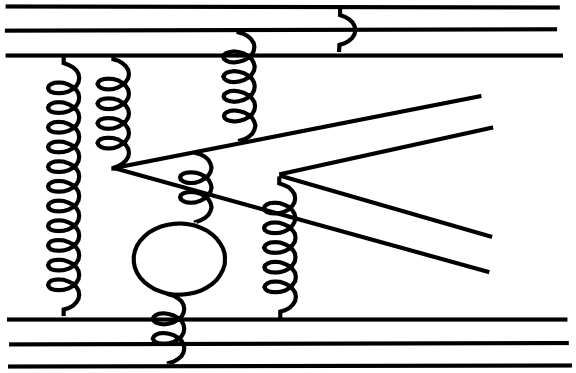

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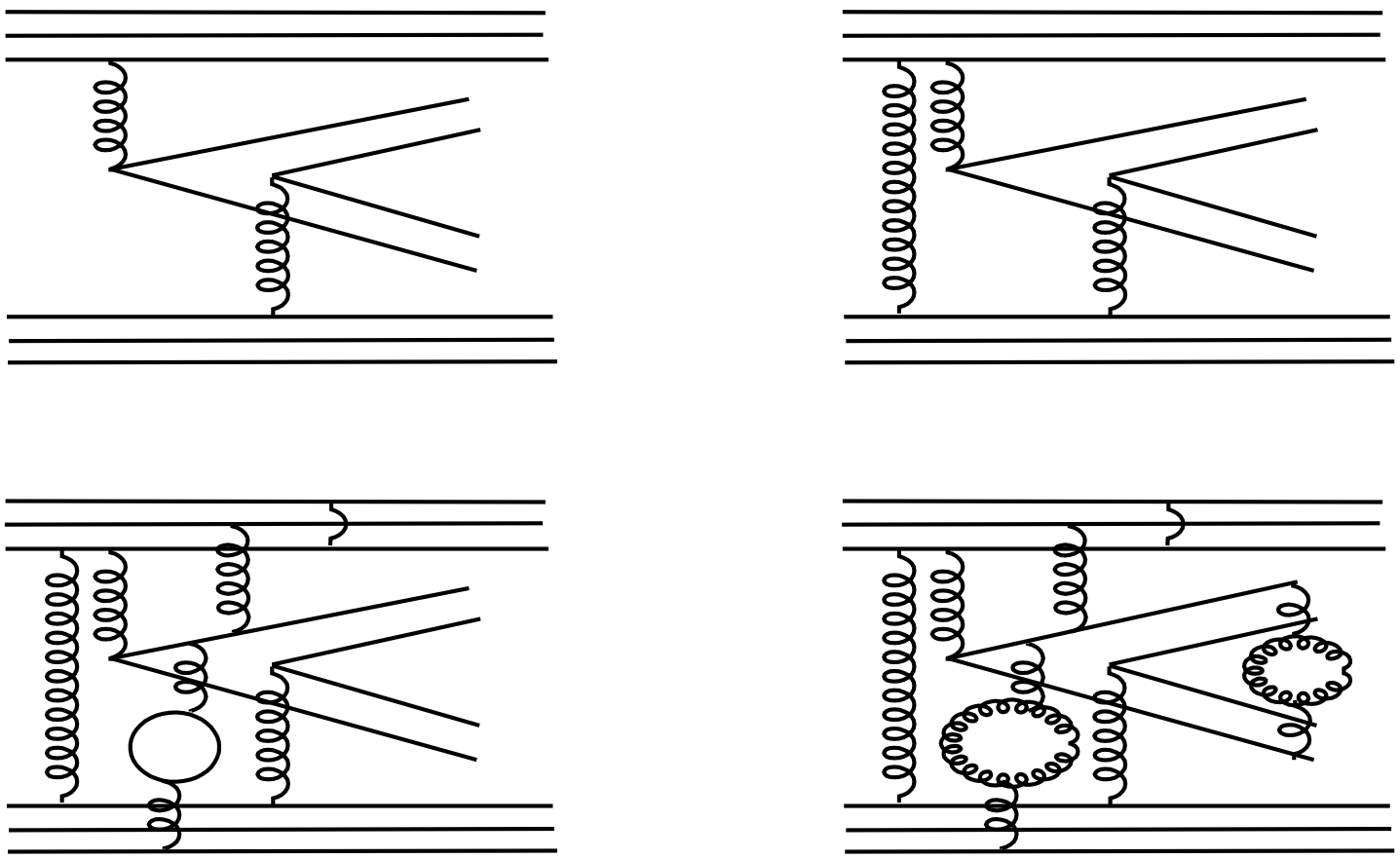


Hard to get matrix elements:

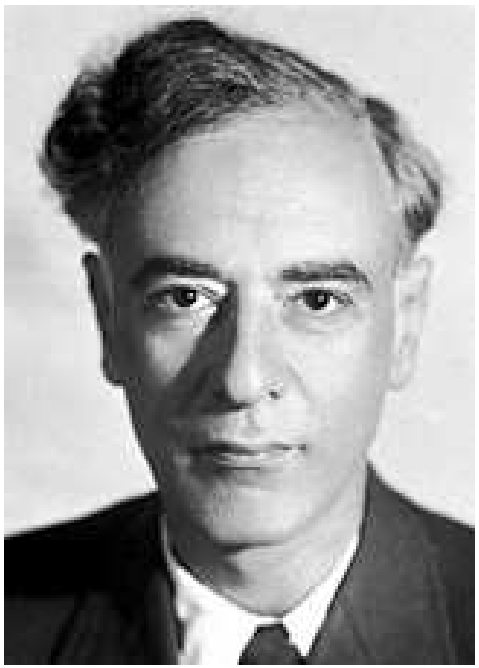
- with $\alpha_S \sim 1$, comparable contributions in all orders, series converge slowly (if at all)

6 E.Fermi – an extreme view: forget about matrix elements!

E.Fermi, "High Energy Nuclear Events", Progr. Theor. Phys. 5, No.4, 1950 (Yukawa theory, no QCD!)

"When two nucleons collide with very great energy in their center of mass system this energy will be suddenly released in a small volume surrounding the two nucleons. ⟨...⟩ Since the interactions of the pion field are strong we may expect that rapidly this energy will be distributed among the various degrees of freedom ⟨...⟩ according to statistical laws. ⟨...⟩ It is realized that this description of the phenomenon is probably as extreme, although in the opposite direction, as is the perturbation theory approach."

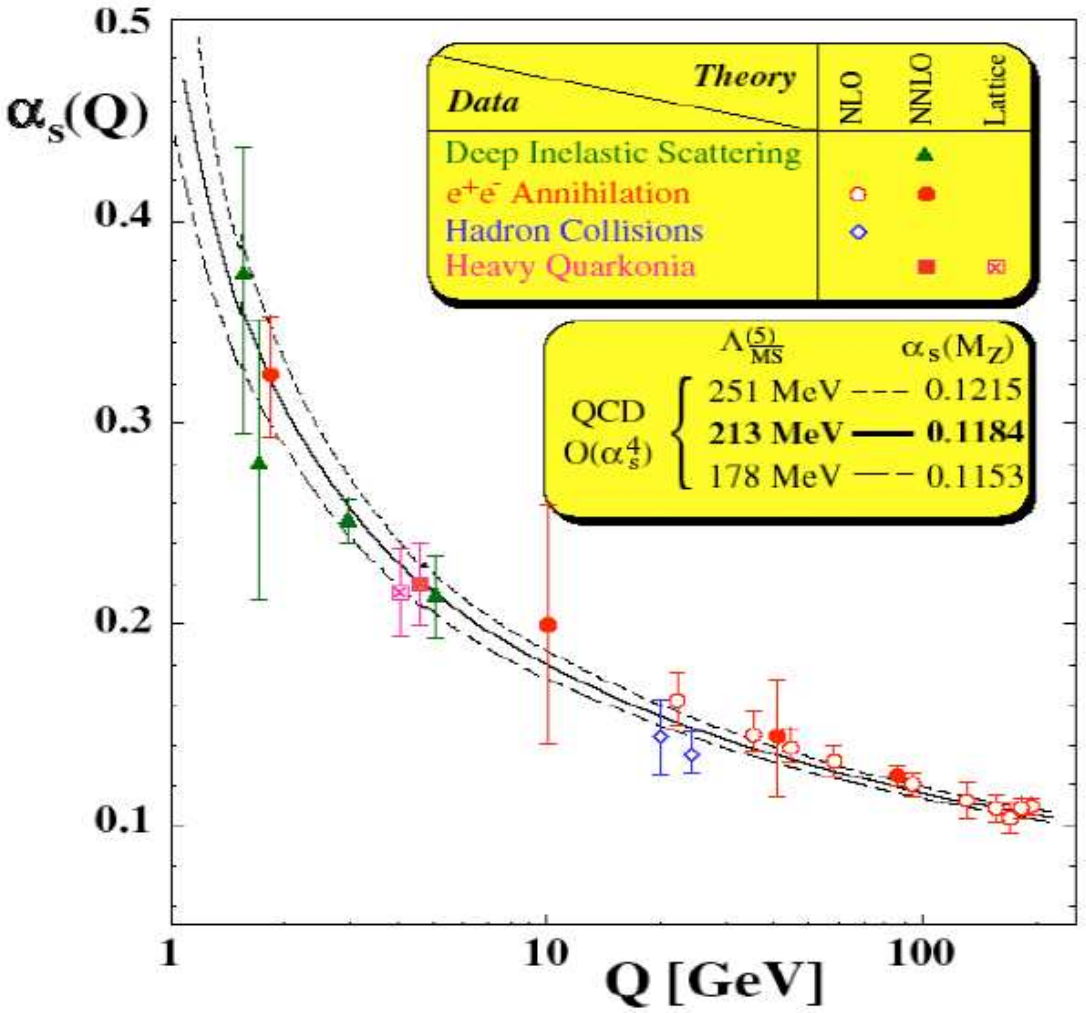
7 I.Ya.Pomeranchuk (1951), L.D.Landau (1953) – forget about "individual" particles!



Time evolution of non-viscous hydro with freeze-out.

- "Hot and dense" phase – no "particles", mean free path $\lambda \ll L \Rightarrow$ relativistic hydrodynamics of an ideal (non-viscous and non-heat-conducting) liquid is applicable.
- Free separation at temperature $T \sim m_\pi$ and $\lambda \sim L$, particles reappear.

8 QCD running coupling: ifrared slavery and asymptotic freedom

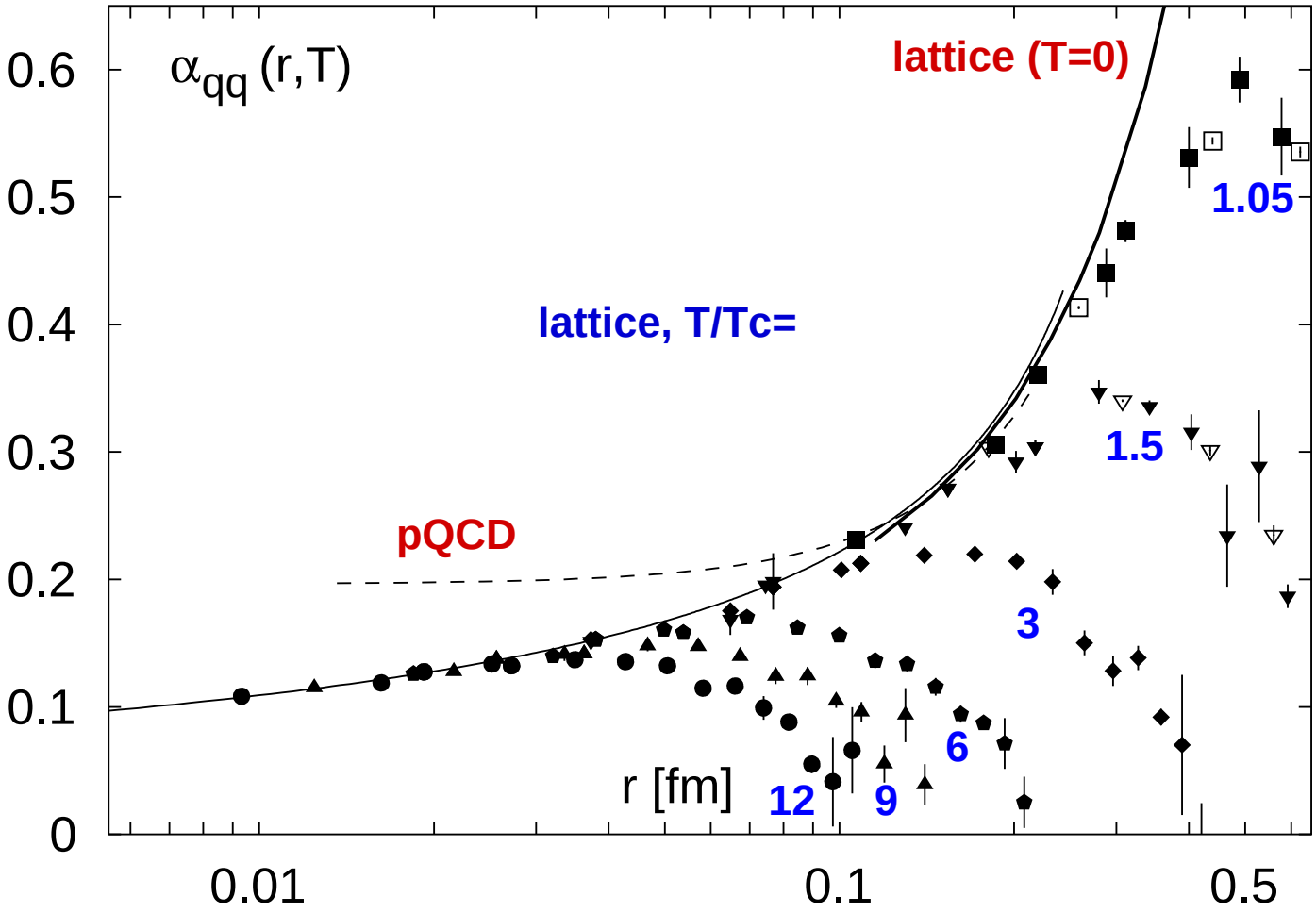


Gross, Politzer, Wilczek

Remember $\Delta p_x \Delta x \approx \hbar$! Asymptotic freedom as seen in particle physics experiments (F.Wilczek's Nobel Lecture 2004)

9 Deconfinement

Kaczmarek, Karsch, Zantow, Petreczky PRD70(074505) 2004



QCD running coupling at $T > T_c$, showing screening of strong force, albeit at relatively large distances.

10 A more intuitive picture...

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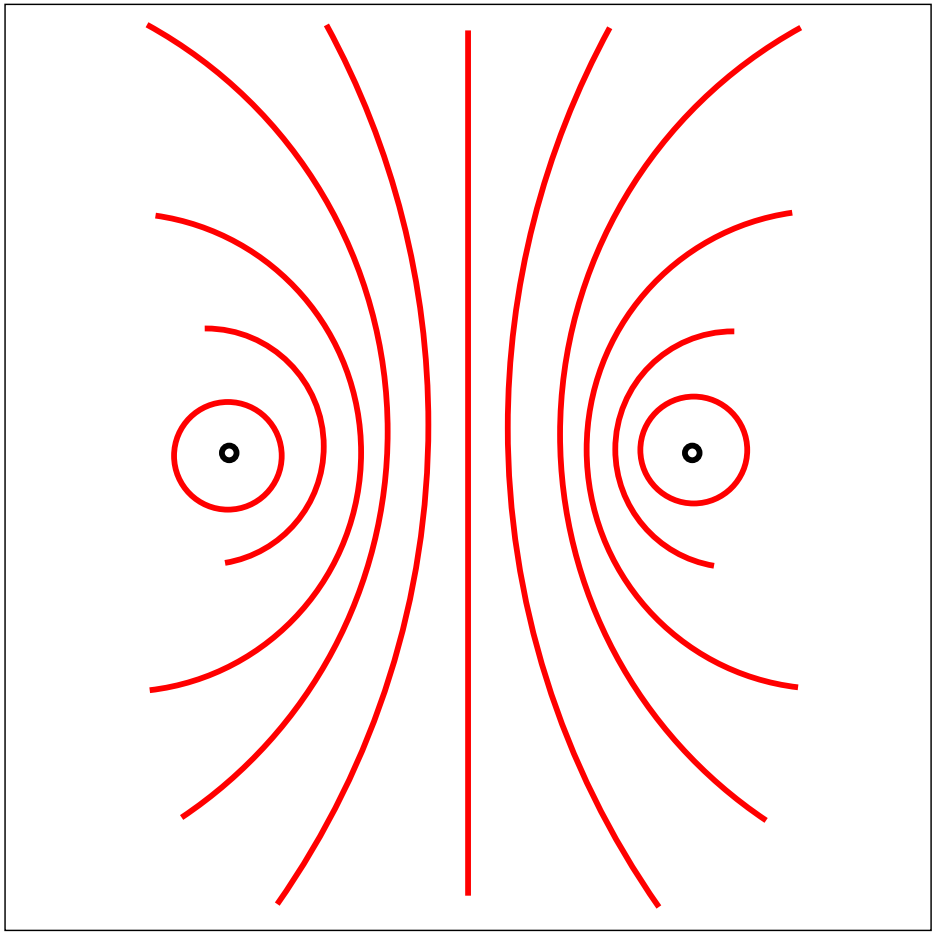
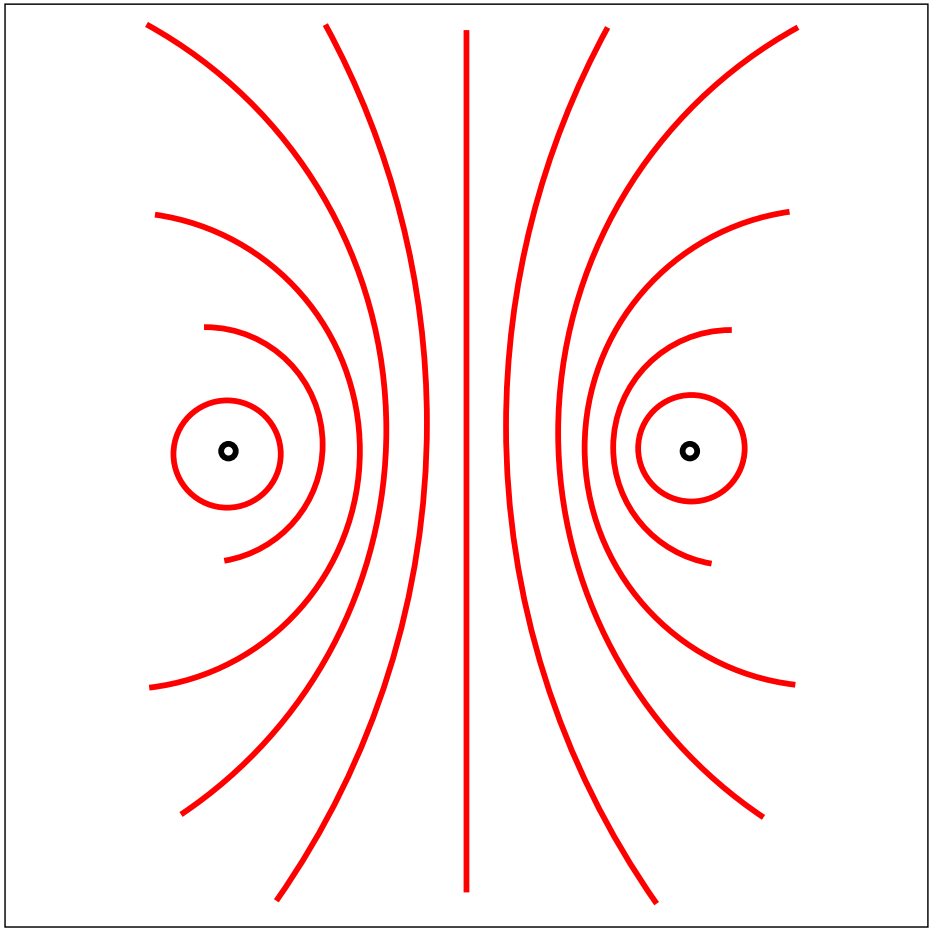
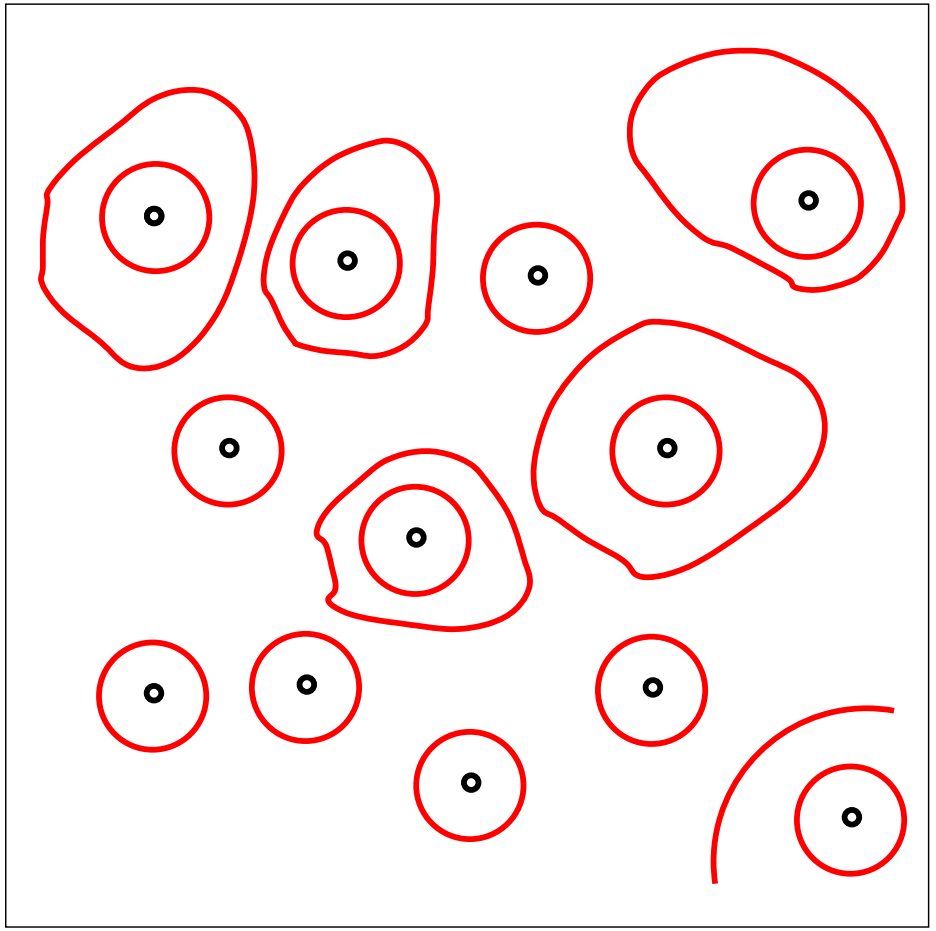


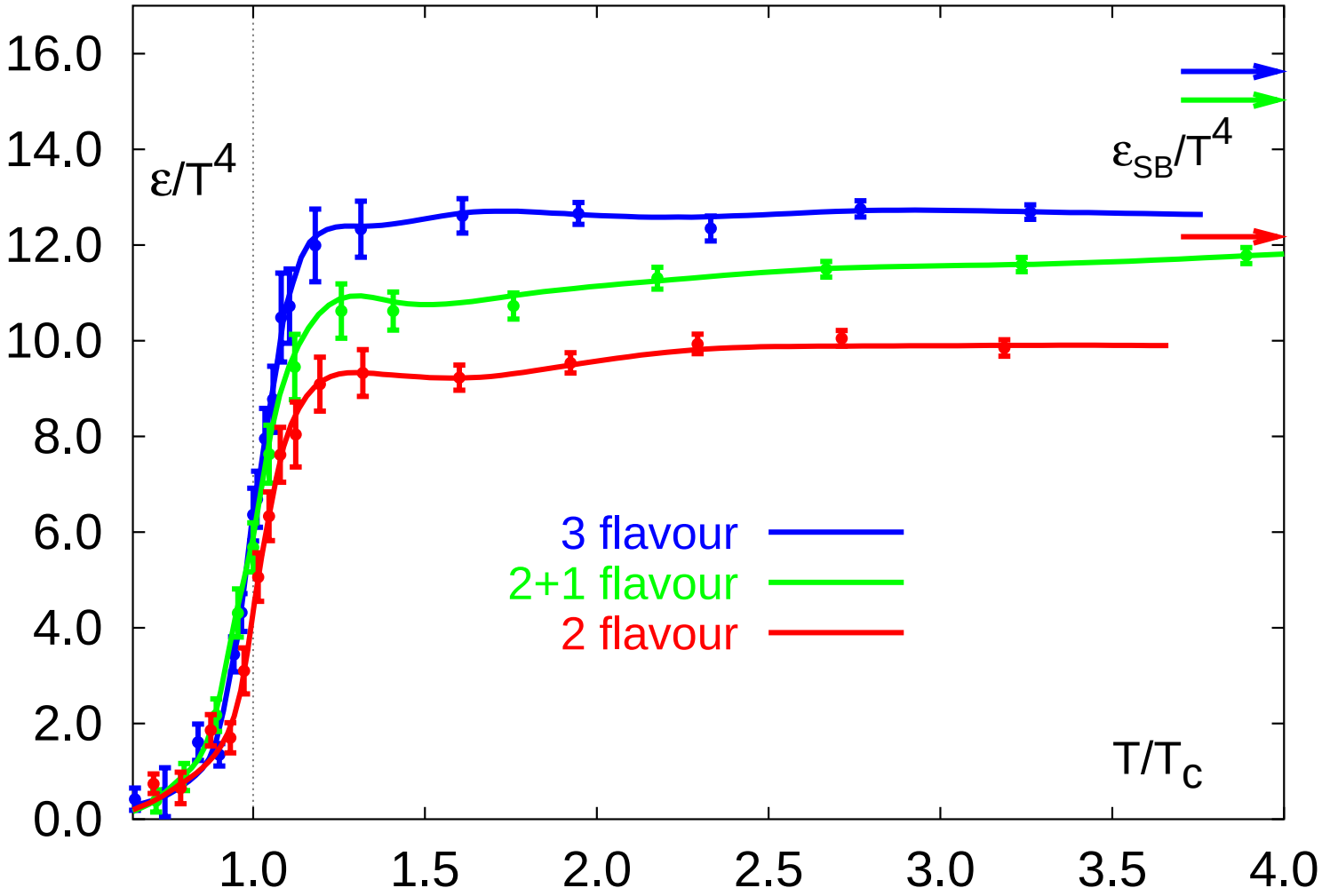
10 A more intuitive picture...





Screening leads to deconfinement at high density or temperature. Analogous to Debye screening in ordinary plasma, there is r_D.

11 Phase transition $\Rightarrow$ increase in the number of degrees of freedom, EOS change



F. Karsch Lect. Notes Phys. 583 (2002) 209 Pressure becomes excessive after phase transition back to ordinary matter $\Rightarrow$ fireball may "explode".

12 Approaches in theory

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- "Freedom": test the nature of the medium by falsifying perturbative predictions. High p_t, "jet tomography", photons, leptons. Work with a subset of specific particles or even expect QGP itself to be "asymptotically free" $\Rightarrow$ perturbative.

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- Lattice QCD is not considered a "paradigm", it's heavy artillery, ultima ratio regum

13 Coming next...

- Experimental strategies

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- Perturbative diagnostics
  - high p_t spectra (hadrons, γ)
  - charm

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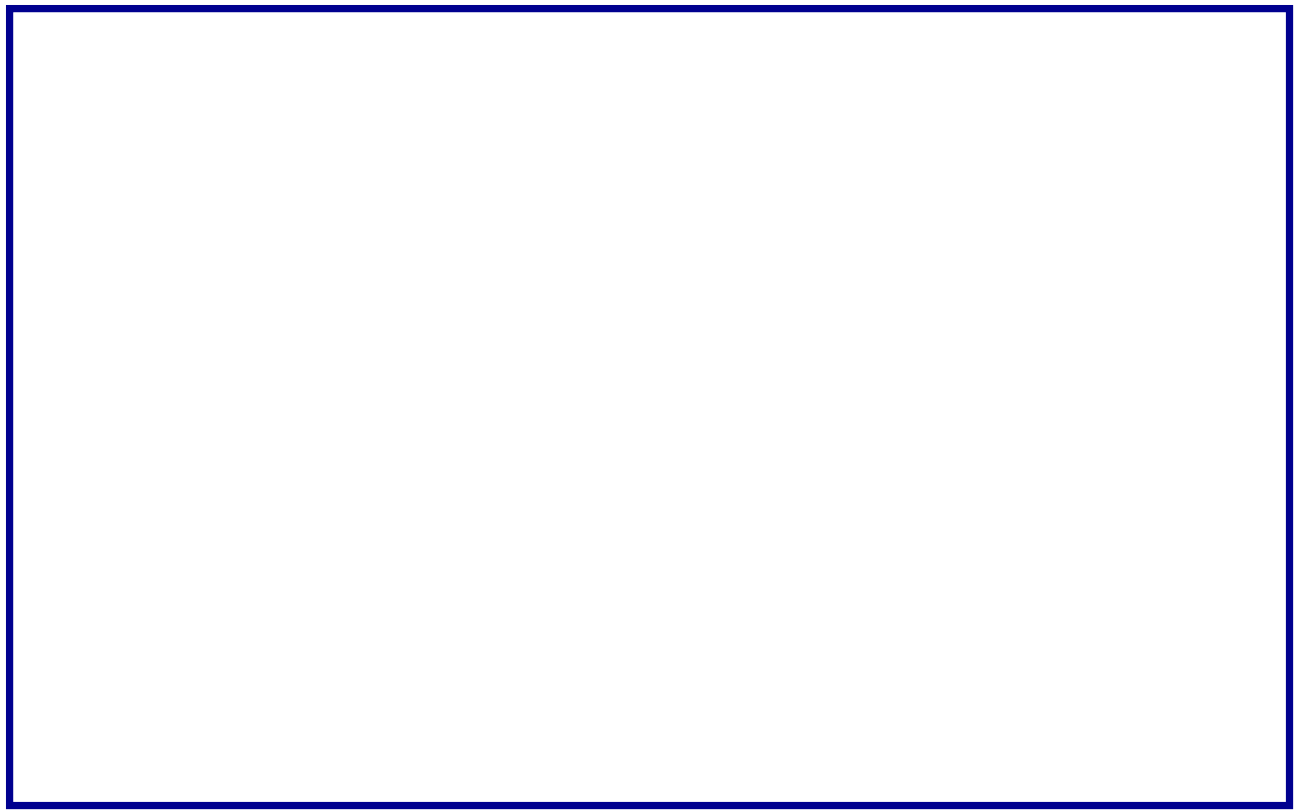
- Experimental strategies
- Perturbative diagnostics
  - high p_t spectra (hadrons, γ)
  - charm
- Quasi-classical diagnostics
  - flow (hydro)
  - mini-jets in the medium (dissipation ?!)
  - hadro-chemistry

14 Strategy dilemmas in experiment

identify many particle IDs including leptons and gamma



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can sacrifice acceptance to improve quality of particle ID and tracking

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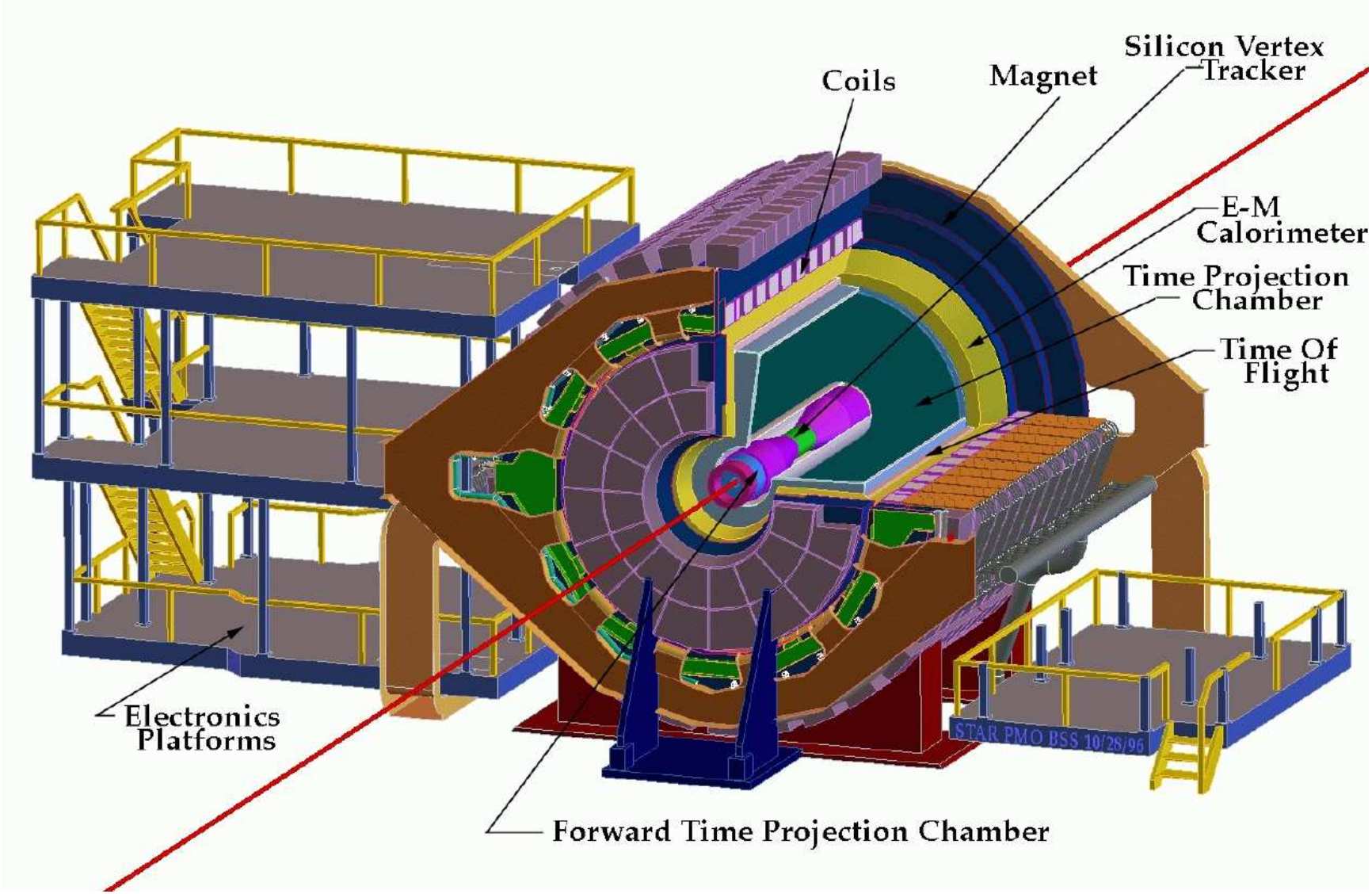
PHOBOS **BRAHMS**

physics is in hadrons, rare = irrelevant

15 STAR — subsystems



recent Kent contributions: EEMC, ZDC SMD, computing infrastructure

16 STAR — strategy

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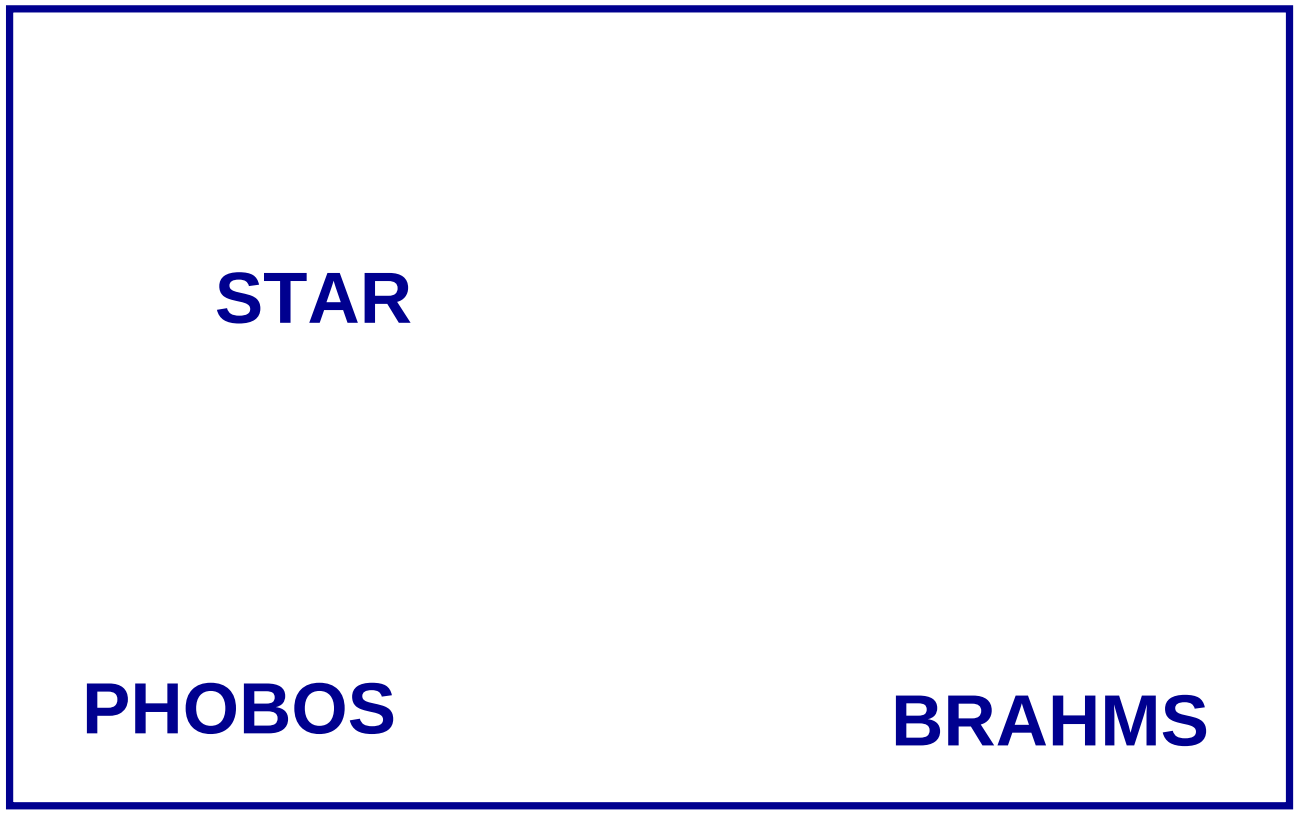

can sacrifice acceptance to improve quality of particle ID and tracking

physics is in hadrons, rare = irrelevant

TPC is the key; relatively infrequent large events

17 STAR — growth

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LBL-29488

Concept for an Experiment on Particle and Jet Production at Midrapidity

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This work was supported in part by the Director, Office of Energy Research, division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under contract DE-AC03-76SF00098.

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Scaling Properties of Hyperon Production in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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(Dated: April 4, 2007)

We present the scaling properties of Λ, Ξ, Ω and their anti-particles produced at mid-rapidity in Au+Au collisions at RHIC at $\sqrt{s_{NN}} = 200$ GeV. The yield of multi-strange baryons per participant nucleon increases from peripheral to central collisions more rapidly than the Λ yield, which appears to correspond to an increasing strange quark density of matter produced. The value of the strange phase space occupancy factor γ_s, obtained from a thermal model fit to the data, approaches unity for the most central collisions. We also show that the nuclear modification factors, R_{cp}, of Λ and Ξ are consistent with each other and with that of protons in the transverse momentum range $2.0 < p_T < 5.0$ GeV/c. This scaling behaviour is consistent with a scenario of hadron formation from constituent quark degrees of freedom through quark recombination or coalescence.

18 STAR — computing challenges

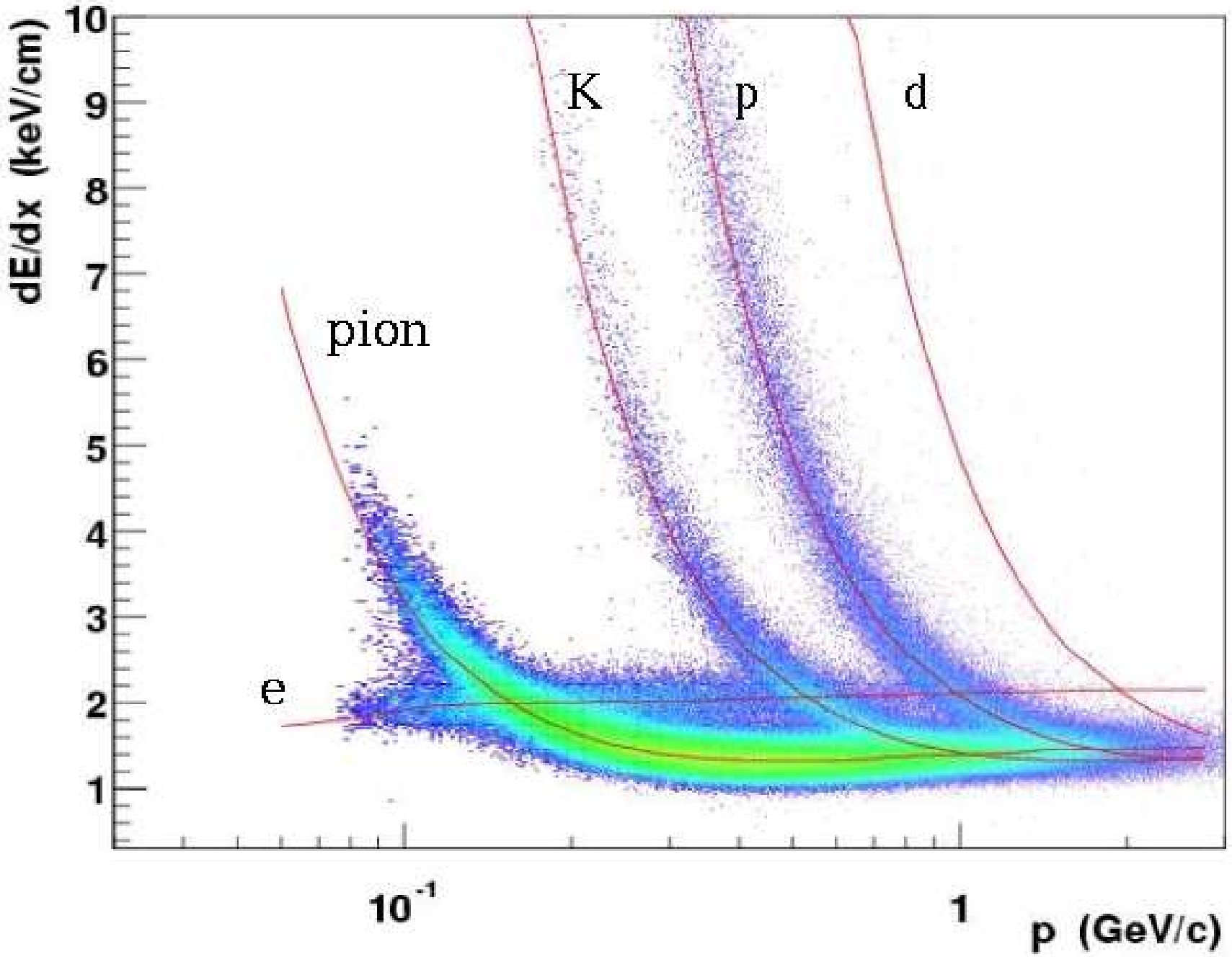
- high volume of data $\rightarrow 10^9$ events next year
- distributed resources and users

Solution: distributed computing (grid).

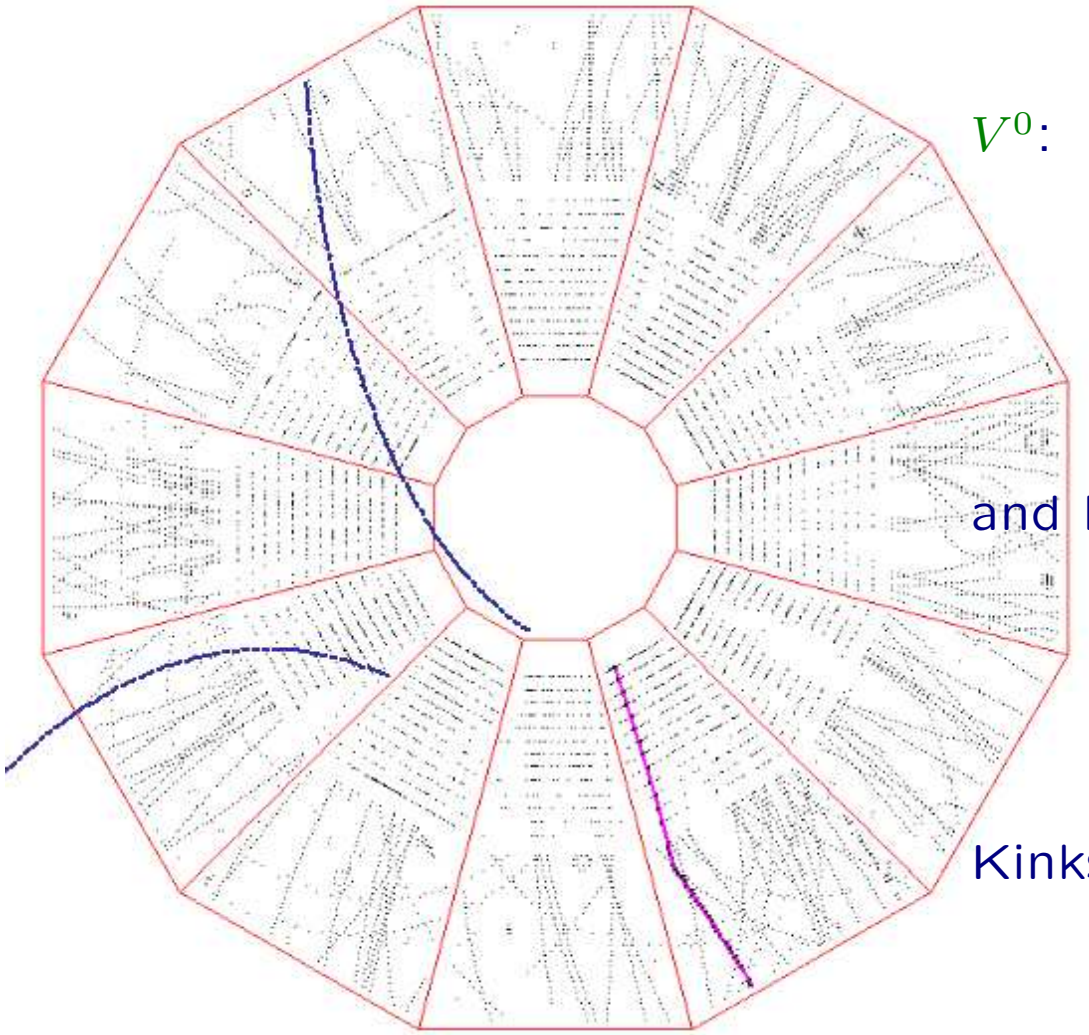
Projects with Kent contribution:

- grid collector (event catalog) – Wei-Ming Zhang
- database API, load-balancer – Mikhail Kopytine

19 STAR — Particle identification — by dE/dx



20 STAR — Particle identification — by topology



V^0:

$$K^0 \rightarrow \pi^+\pi^- \quad (1)$$

$$\Lambda \rightarrow p\pi^- \quad (2)$$

$$\bar{\Lambda} \rightarrow \bar{p}\pi^+ \quad (3)$$

and by extension:

$$\Sigma^- \rightarrow \Lambda\pi^- \quad (4)$$

$$\Omega^- \rightarrow \Lambda K^- \quad (5)$$

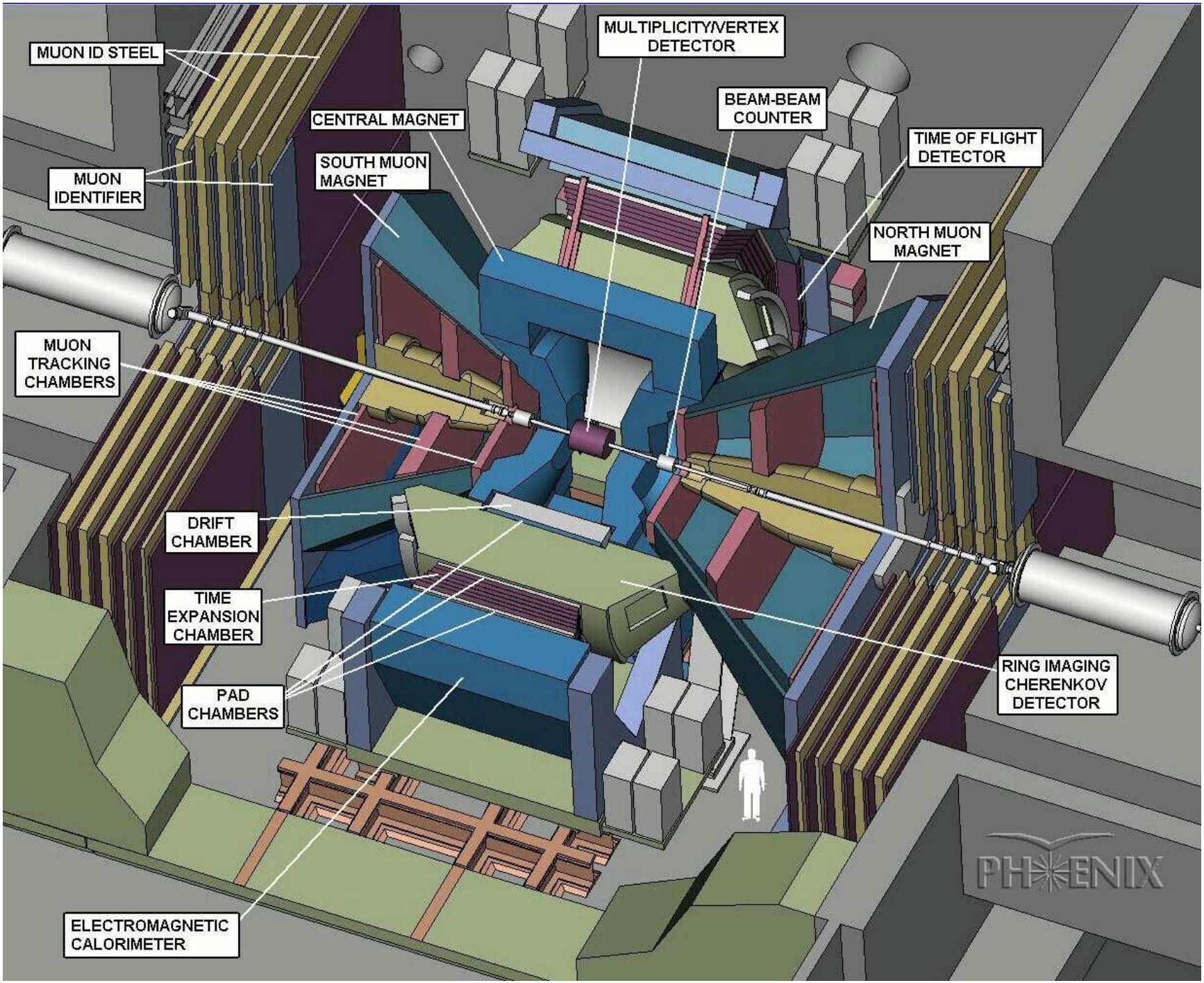
Kinks:

$$K^\pm \rightarrow \mu^\pm\nu \quad (6)$$

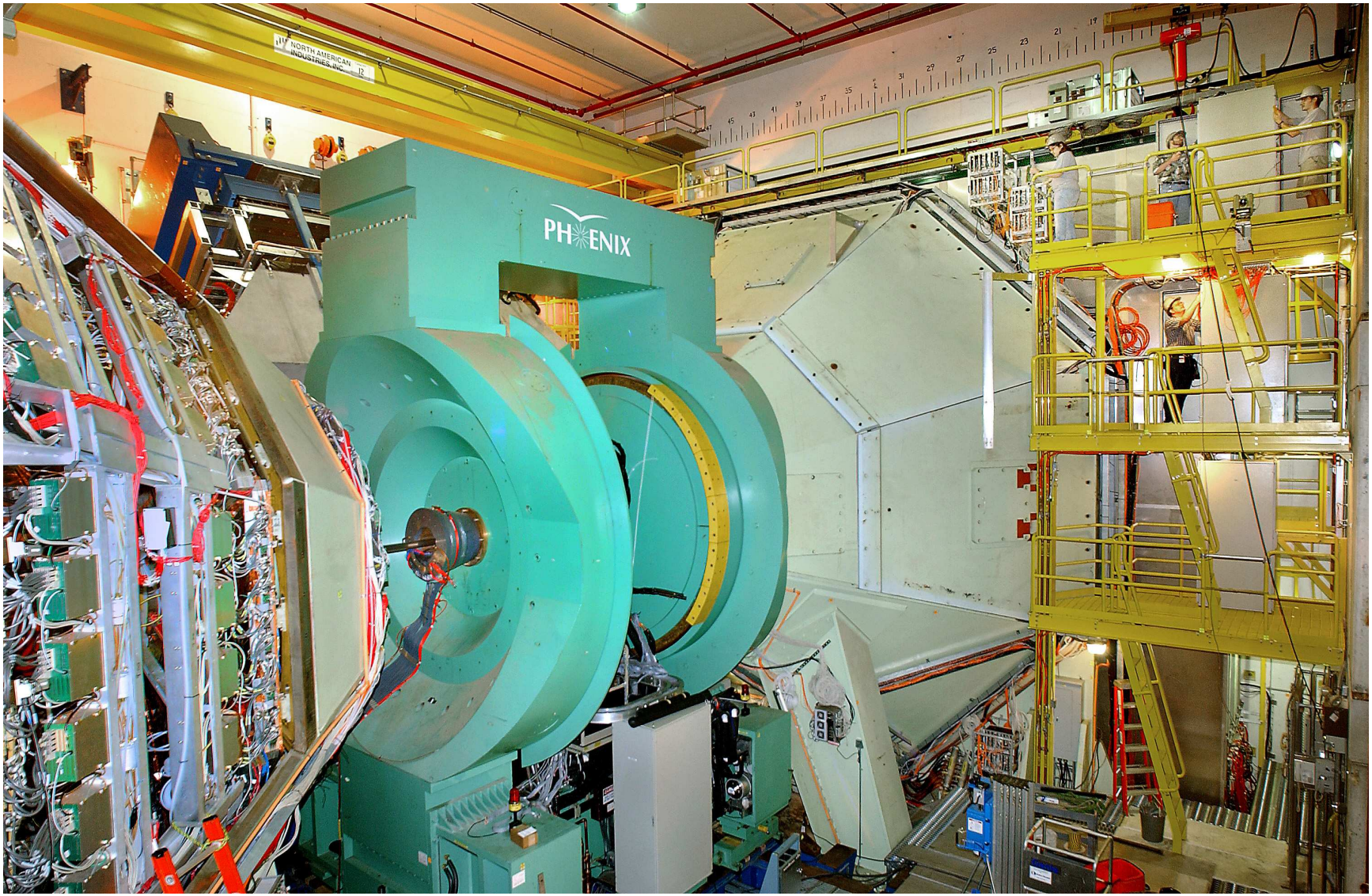
$$K^\pm \rightarrow \pi^\pm\pi^0 \quad (7)$$

About 10% of a central event.

21 PHENIX — subsystems



22 PHENIX — photograph



Accepts $\theta = (90 \pm 20)^\circ$, highly inhomogeneous $\vec{B}$-field up to 0.8T.

23 PHENIX — strategy

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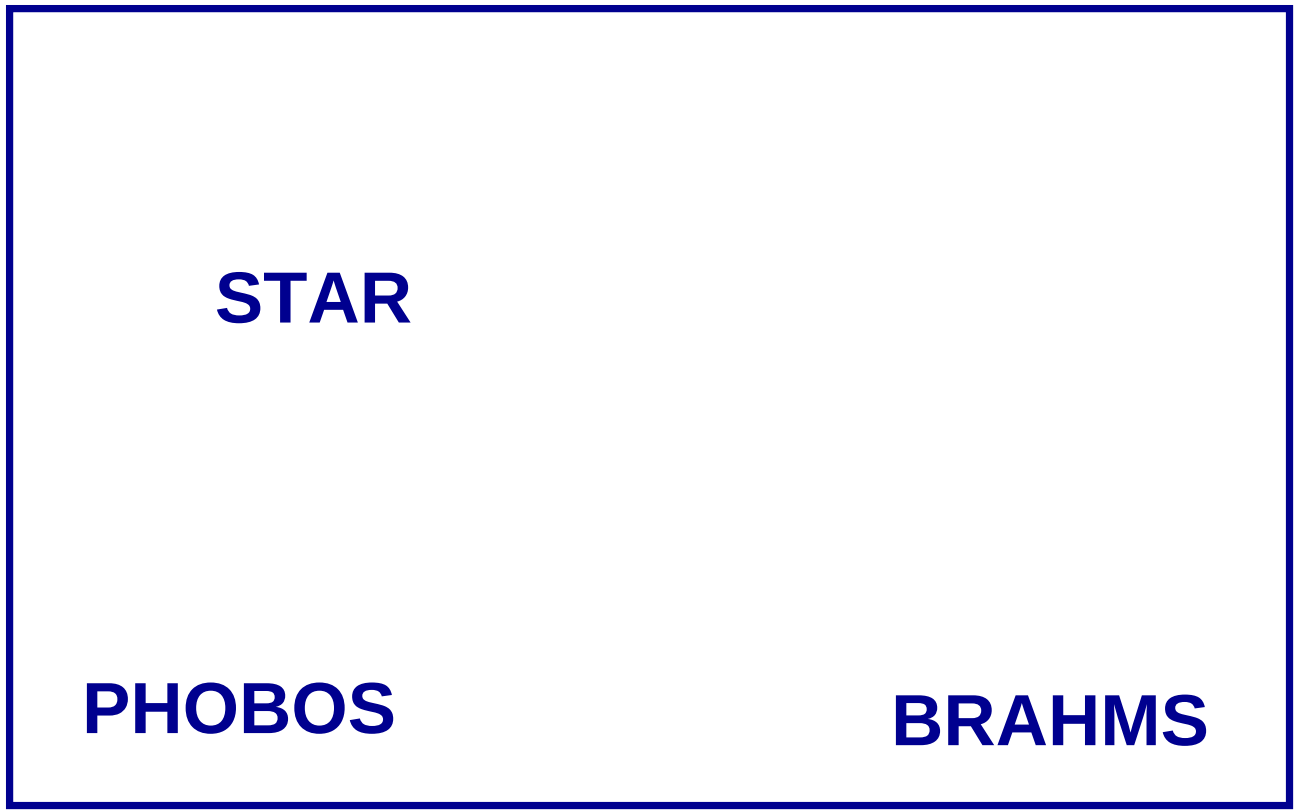
identify many particle IDs including leptons and gamma

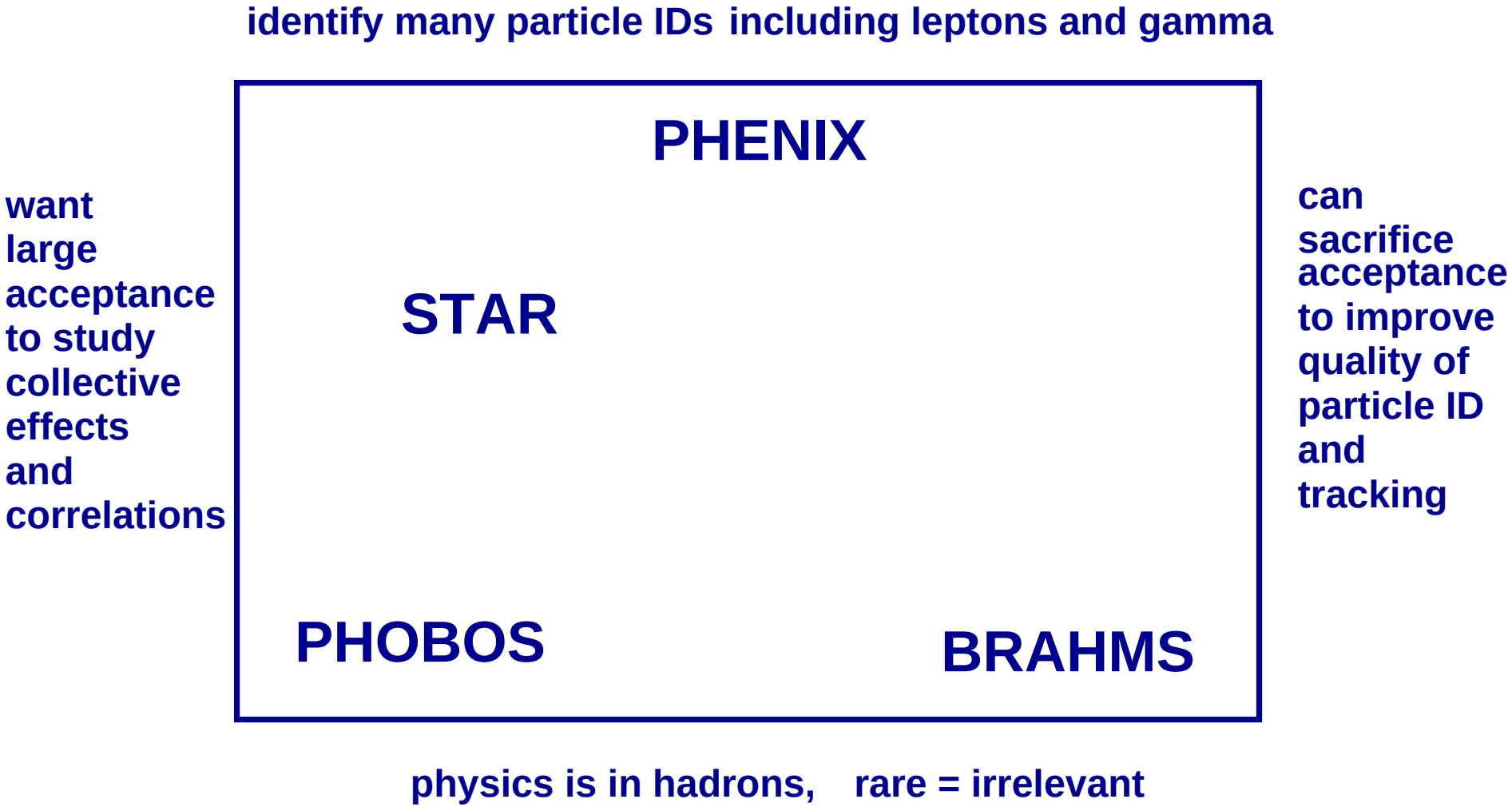
want large acceptance to study collective effects and correlations



can sacrifice acceptance to improve quality of particle ID and tracking

physics is in hadrons, rare = irrelevant

23 PHENIX — strategy



Technologically heterogeneous, high rate, limited acceptance, + leptons and γ

24 Stopping — Longitudinal expansion — Energy density

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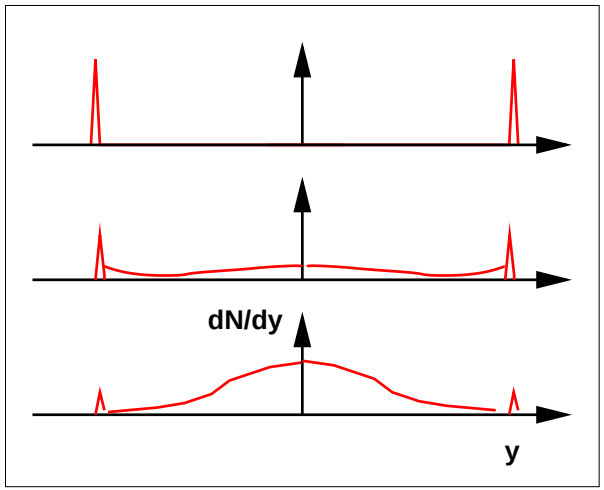

$$y = \frac{1}{2} \ln \left(\frac{1+v}{1-v} \right) = v + \mathcal{O}(v^3) \tag{8}$$

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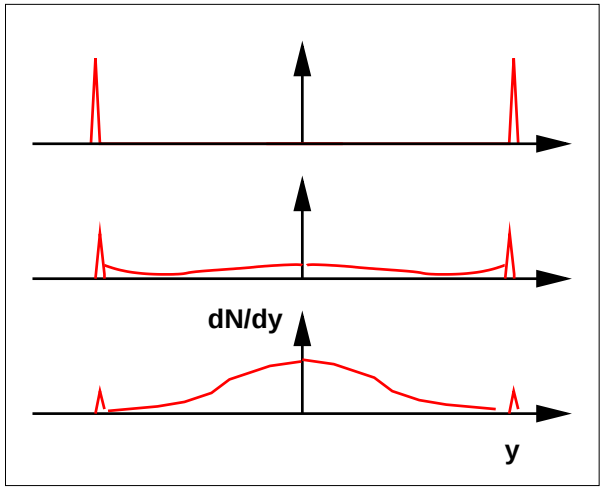

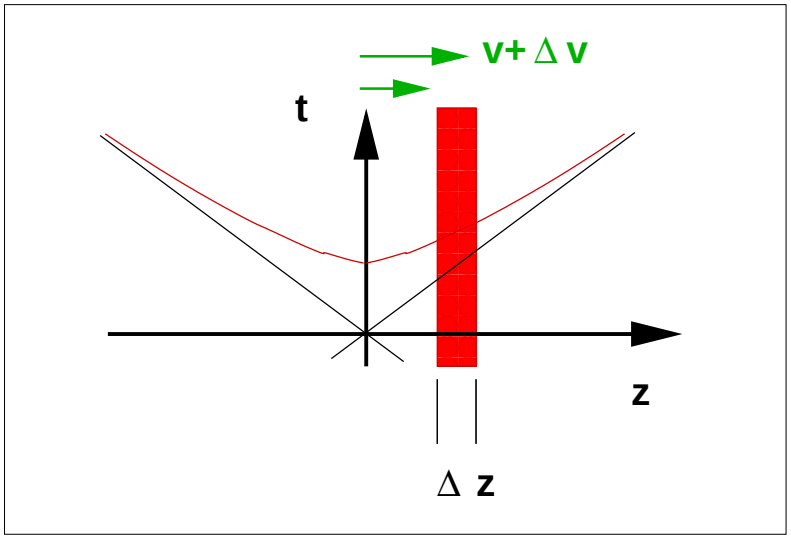

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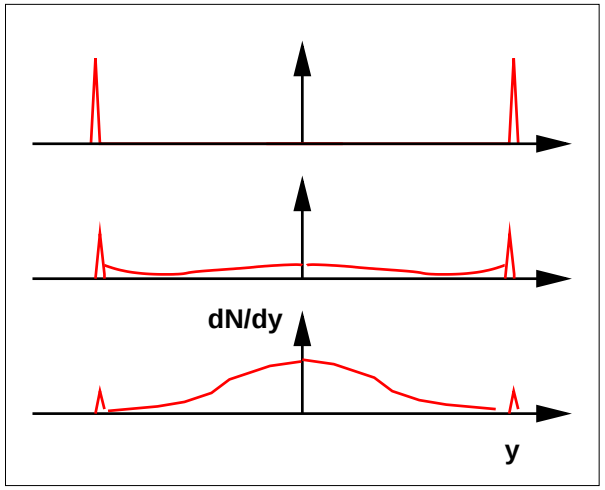

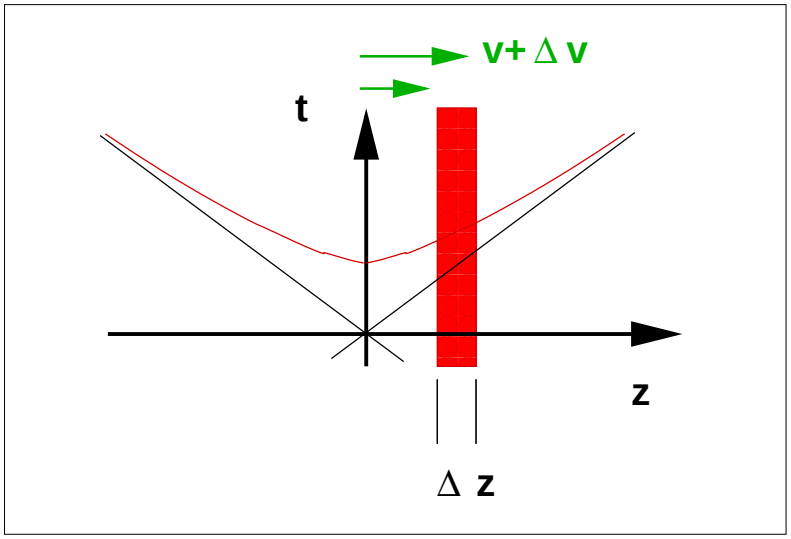

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Bjorken:

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$$E = N\frac{d\langle E\rangle}{dy}\Delta y = N\frac{d\langle E\rangle}{dy}\frac{\Delta z}{t} \tag{10}$$

$$\epsilon(t = t_{\rm form}) = \frac{E}{S\Delta z} = \frac{N}{St_{\rm form}}\frac{d\langle E\rangle}{dy} \approx \frac{dN}{dy}\frac{\langle m_t\rangle}{St_{\rm form}} \tag{11}$$

25 Energy density

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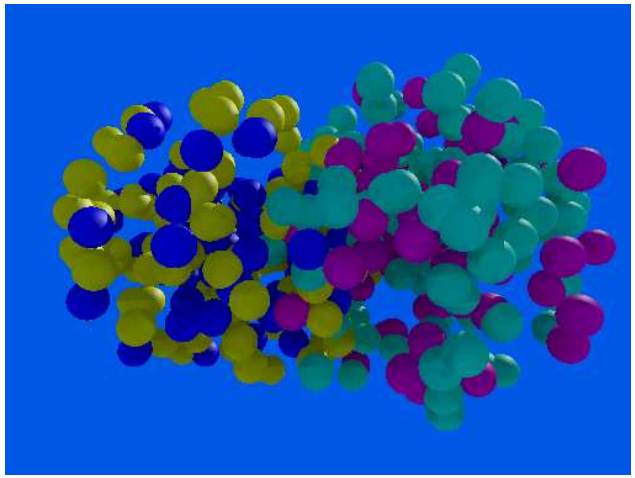
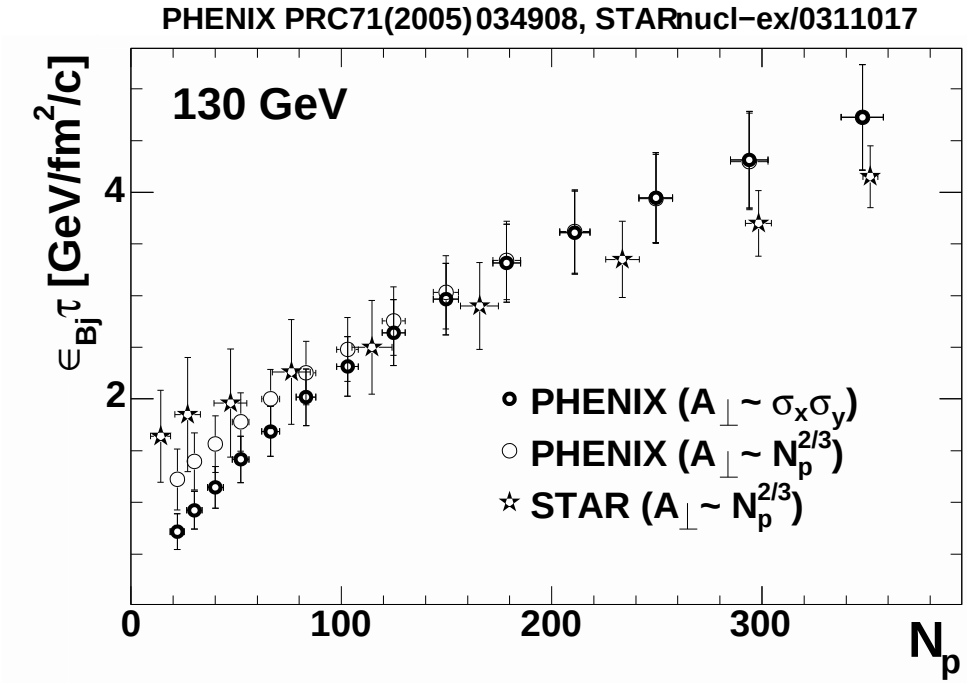
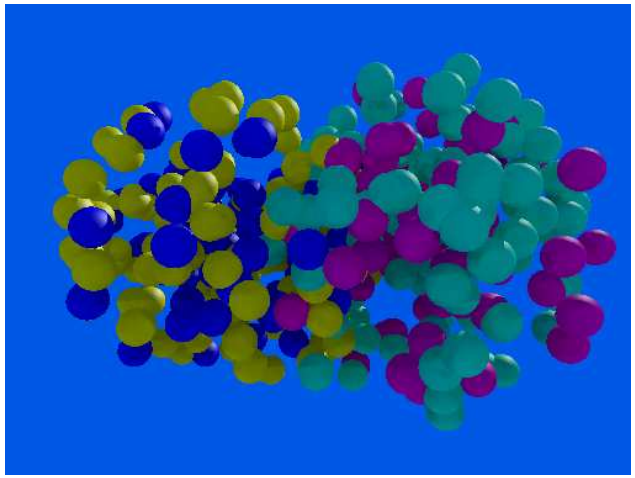


N_p is number of participants. Energy density $> 1GeV/fm^3$ is believed to be adequate for the phase transition.

25 Energy density





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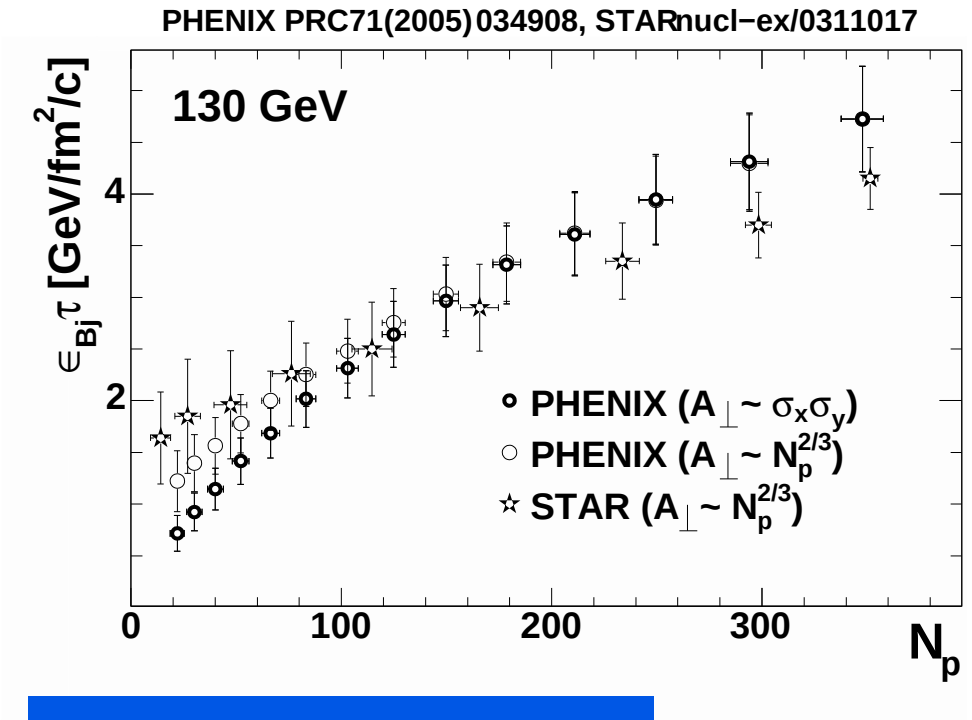

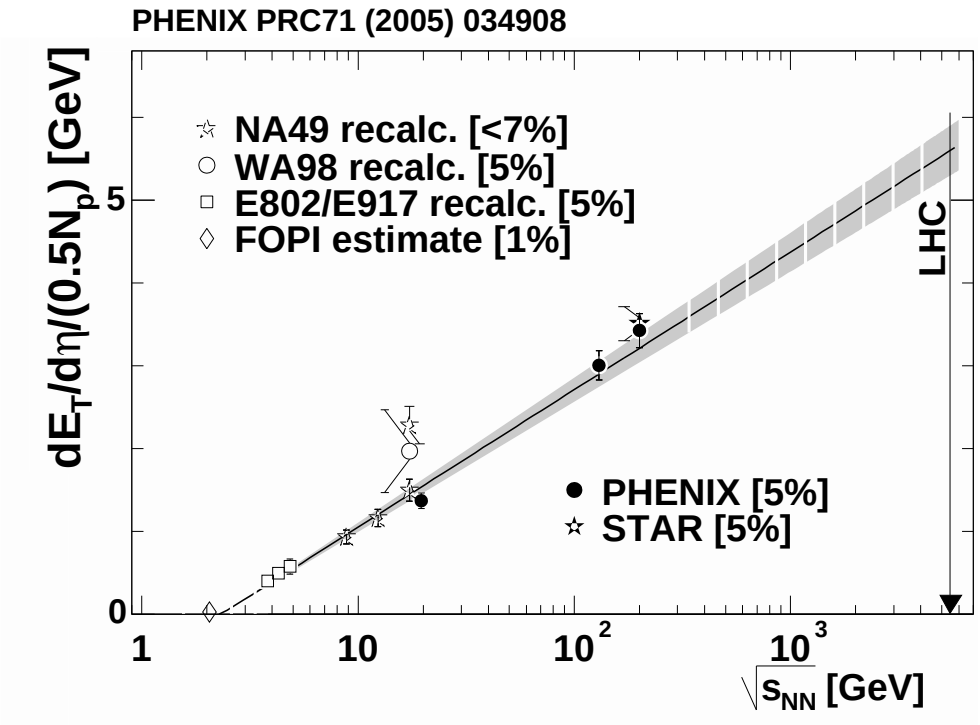

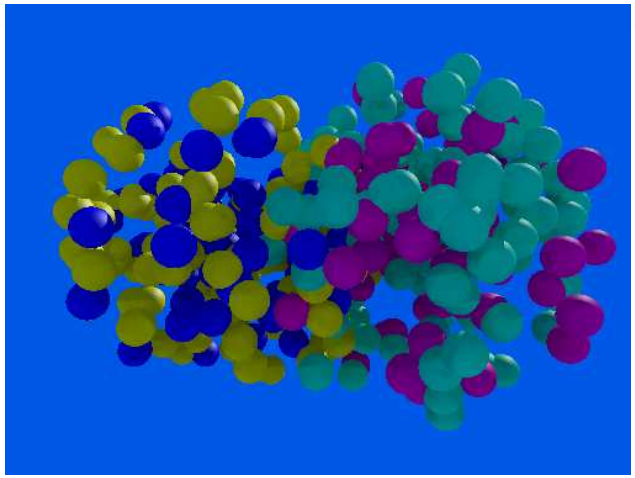

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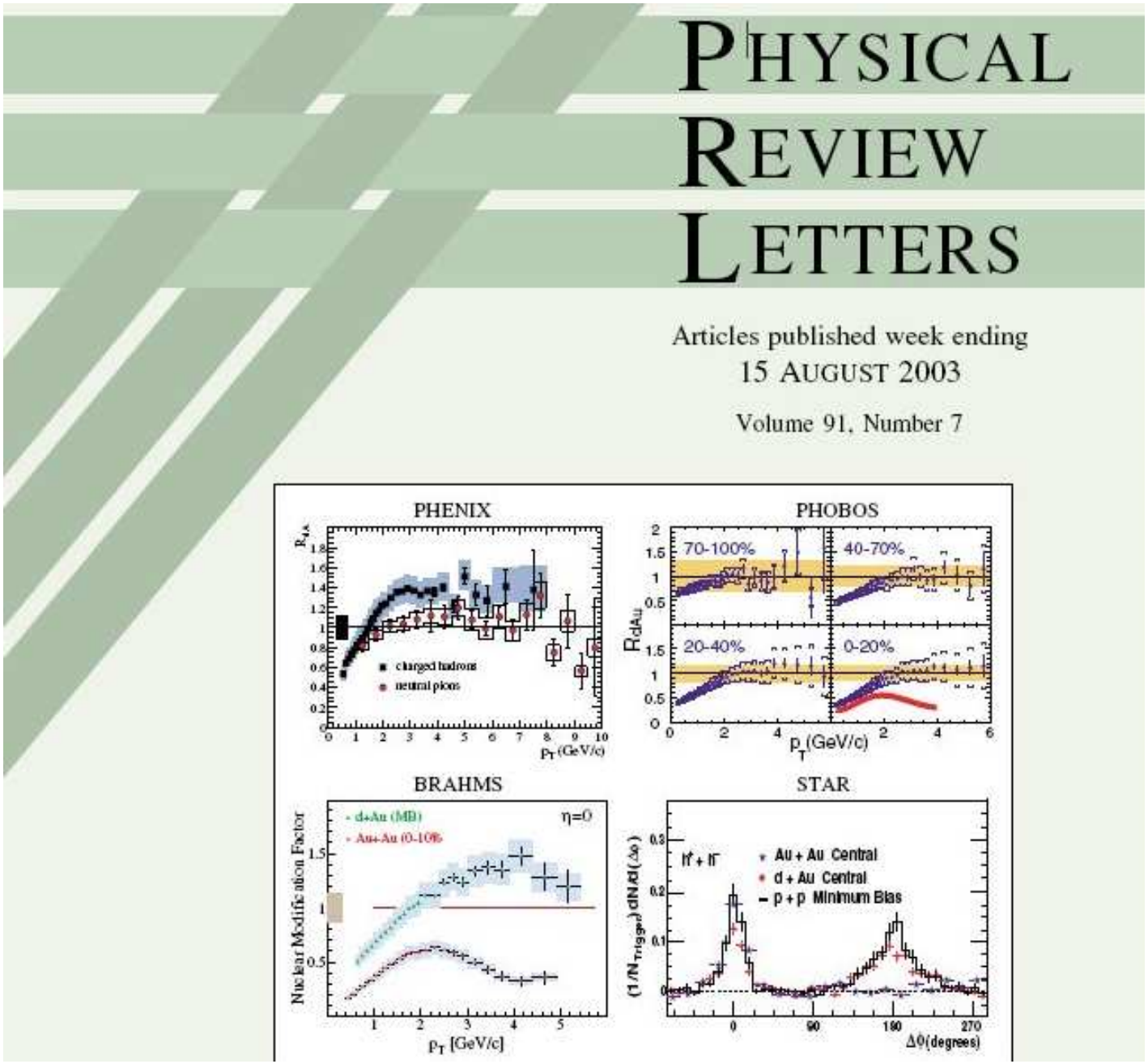
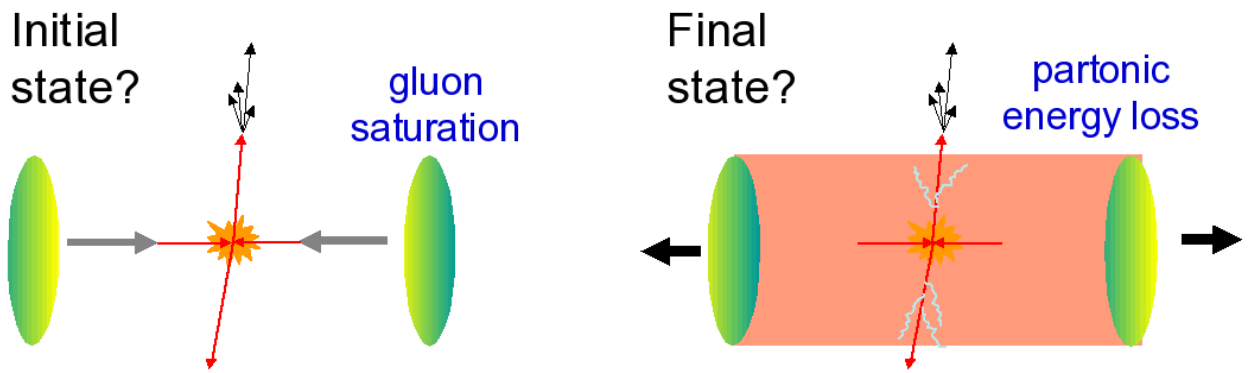
26 High p_t suppression — hadrons

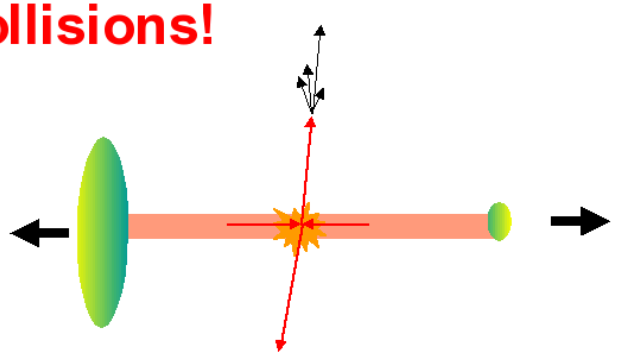


27 High p_t suppression — alternatives



How to discriminate? Turn off final state $\Rightarrow$

d+Au collisions!



$$R_{AA}(p_t) = \frac{\frac{1}{n_{\rm evt}} \frac{d^2 N_{AA}}{dp_t\, dy}}{\frac{\langle N_{\rm coll}\rangle}{\sigma_{pp}^{\rm inel}} \frac{d^2\sigma_{pp}}{dp_t\, dy}} \qquad (12)$$

28 High p_t suppression — hadrons — STAR and PHENIX

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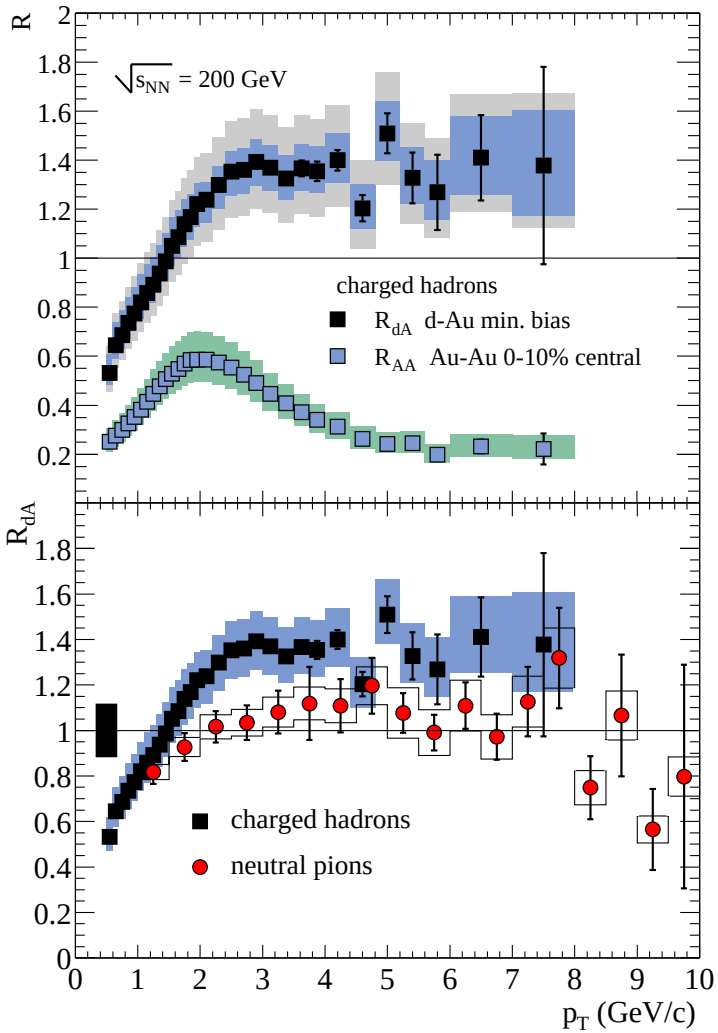
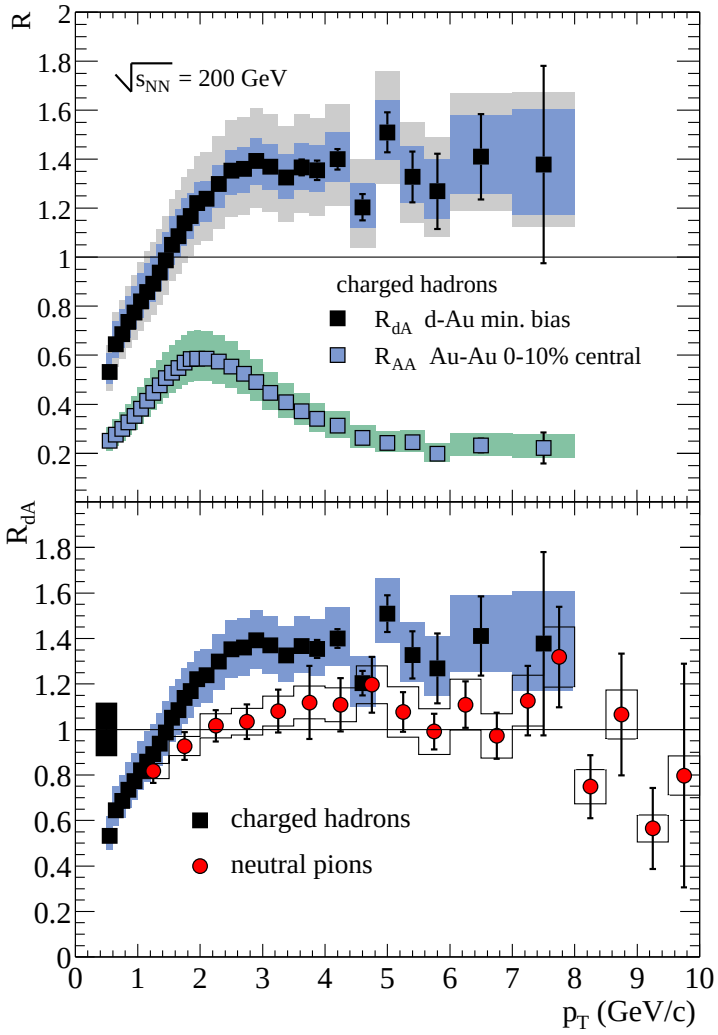
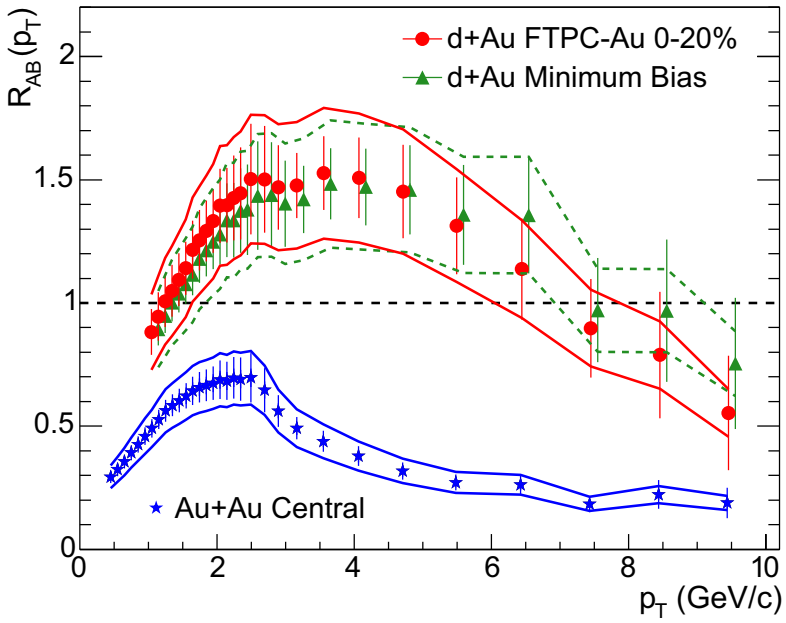


PHENIX

28 High p_t suppression — hadrons — STAR and PHENIX

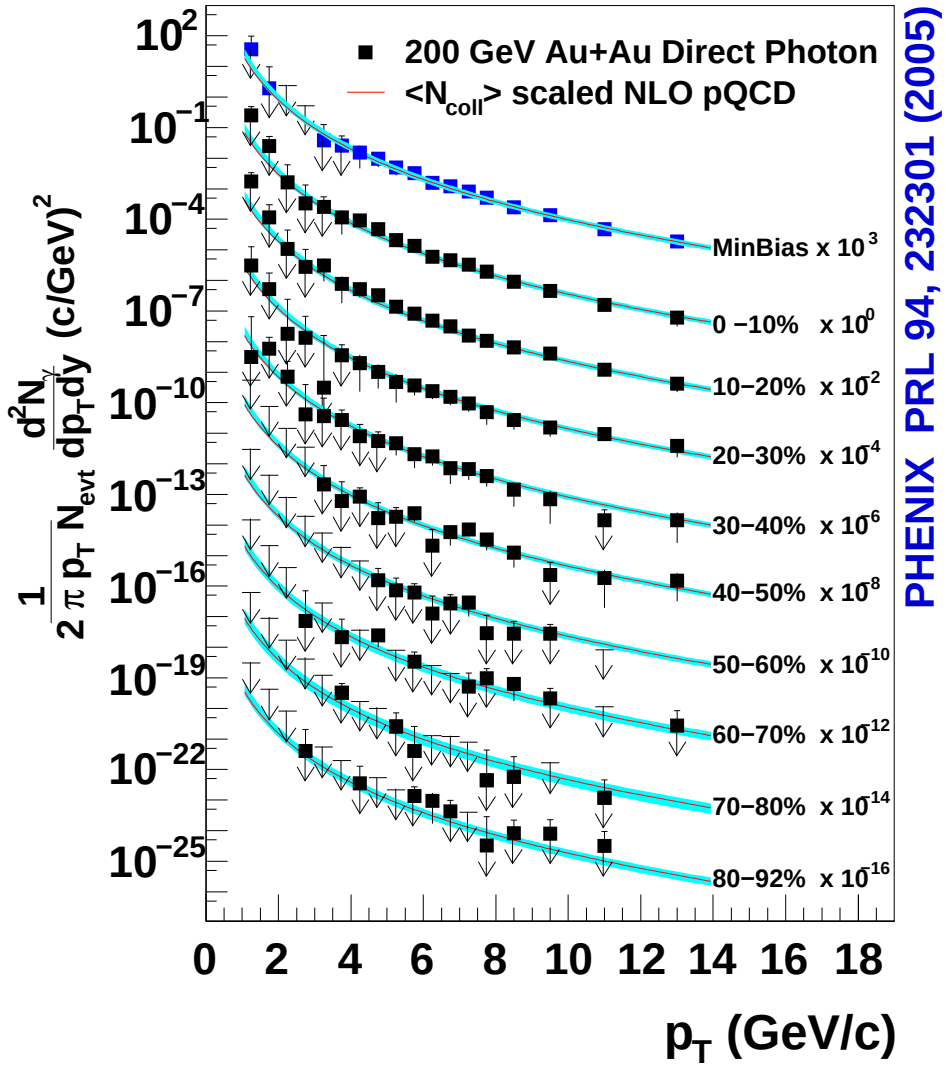


PHENIX

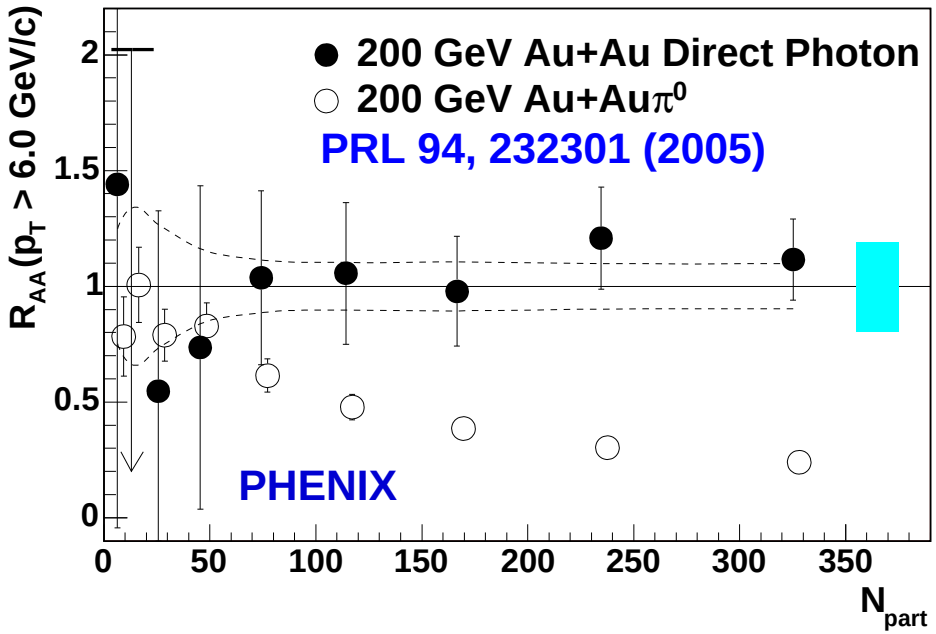


STAR

29 High p_t suppression — photons — spectra



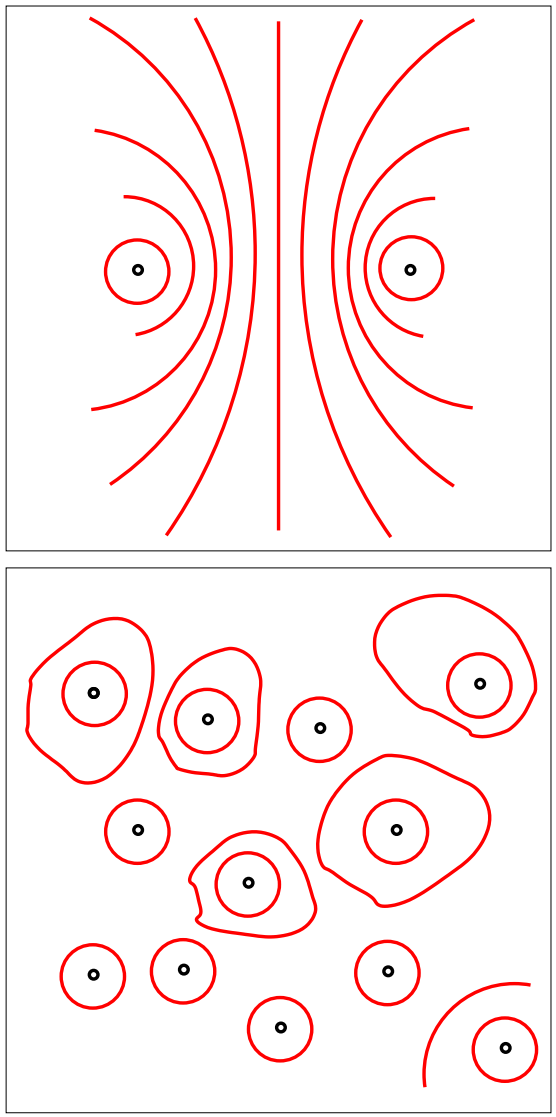
Binary-collision scaled pQCD gets it right



Photons are produced in participant NN collisions with no initial state modification. The high p_t suppression in hadronic sector is not an initial state effect.

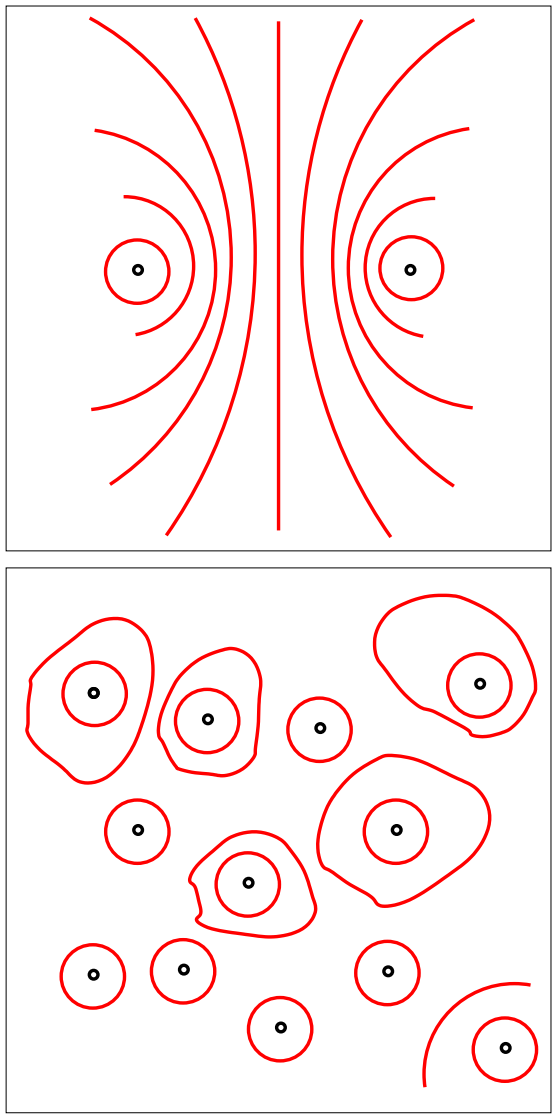
30 Charm

30 Charm



Matsui, Satz mechanism of J/Ψ suppression. PLB 178:416, 1986.

30 Charm



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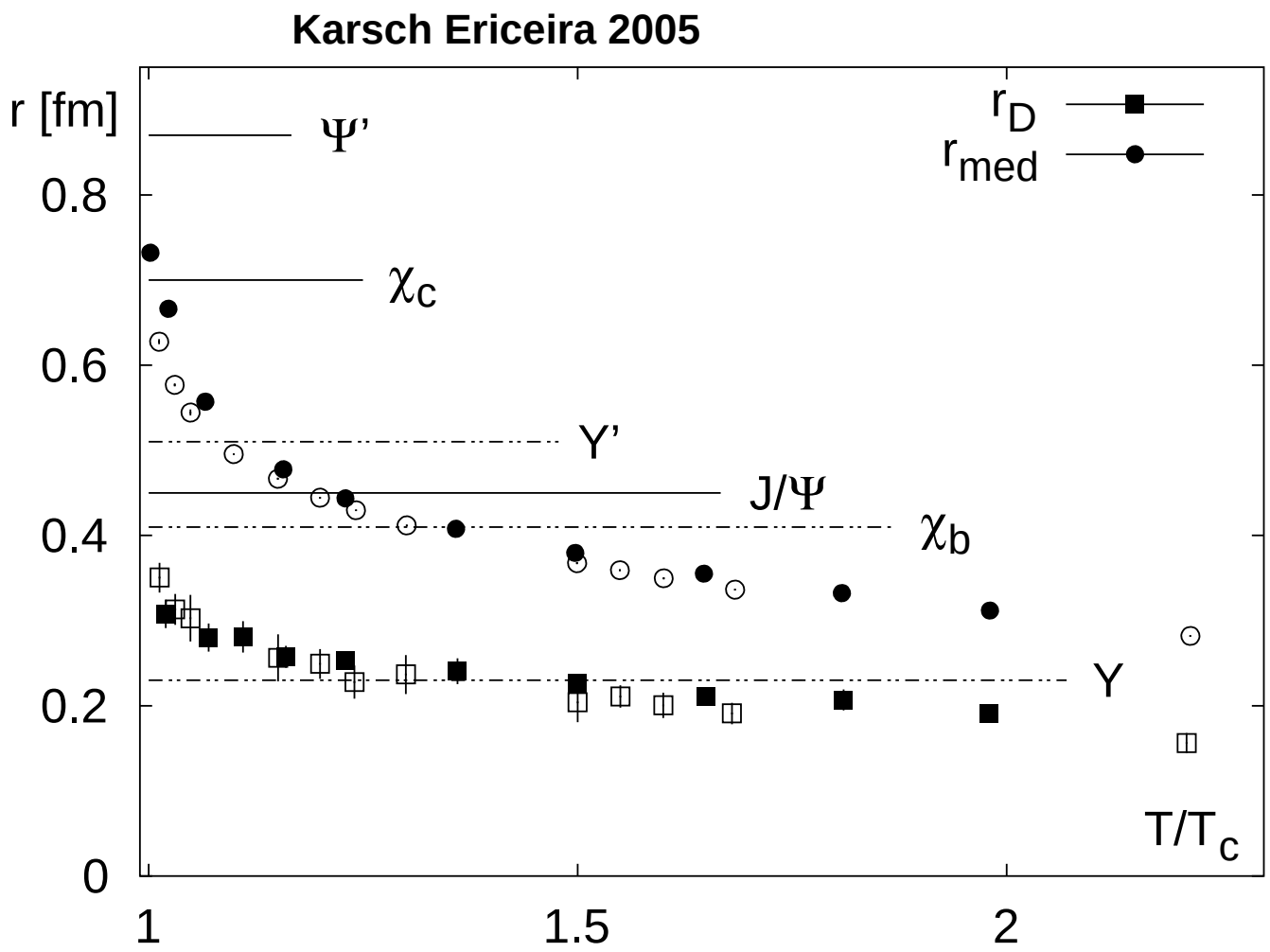

Open/closed SU(3)/SU(2); for $r > r_{\rm med}$ the $q\bar{q}$ force is strongly modified by the colored medium; r_D is the Debye screening radius. Horizontal lines are $\sqrt{\overline{r^2_{q\bar{q}}}}$ for charmonium states.

31 PHENIX — sources of electrons

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photonic (calibrated out using γ converter of known thickness):

$$\pi^0 \to \gamma e^+ e^- \to \gamma - \text{conversion} \tag{13}$$

$$\eta, \eta', \rho, \omega, \phi \to \pi^0 \to \gamma e^+ e^- \to \gamma - \text{conversion} \tag{14}$$

31 PHENIX — sources of electrons

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non-photonic (wanted):

$$D^+ \to e^+ X \tag{15}$$

$$D^0 \to e^+ X \tag{16}$$

$$B \to \tag{17}$$

non-photonic (unwanted):

$$K \to \pi e \nu \tag{18}$$

(GEANT)

$$\rho, \omega, \phi \to e^+ e^- \tag{19}$$

m_t scaling of measured π^0 spectra

32 PHENIX — non-photonic single electrons

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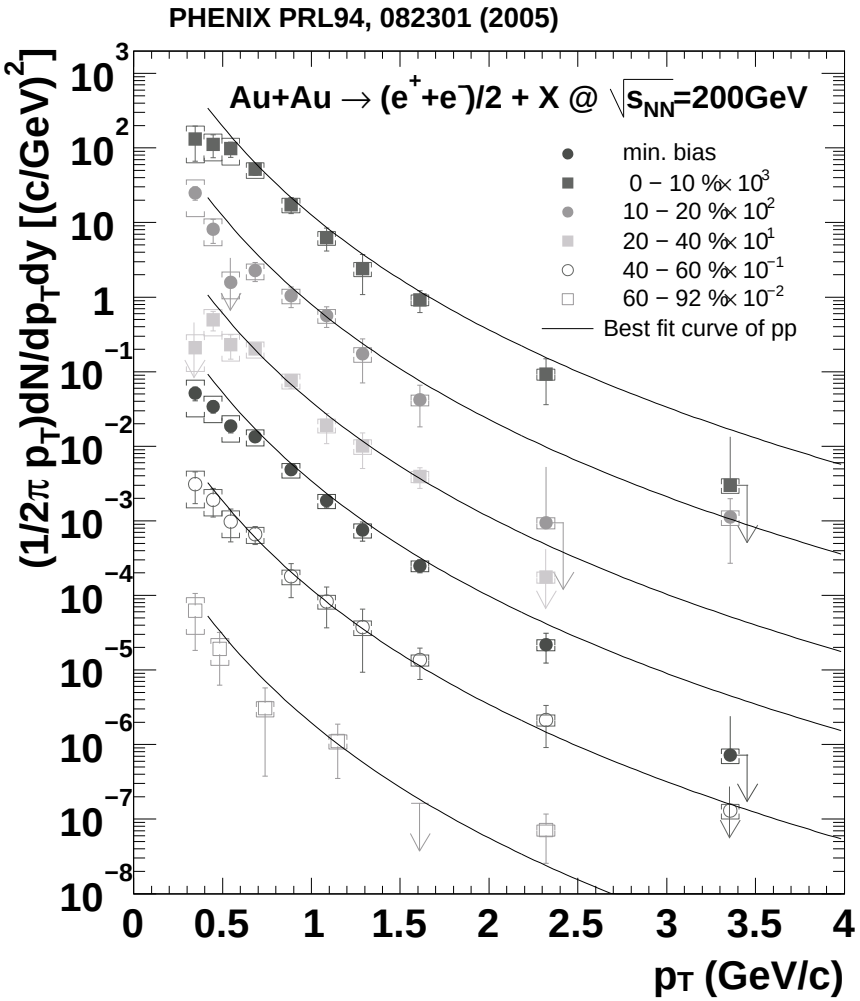

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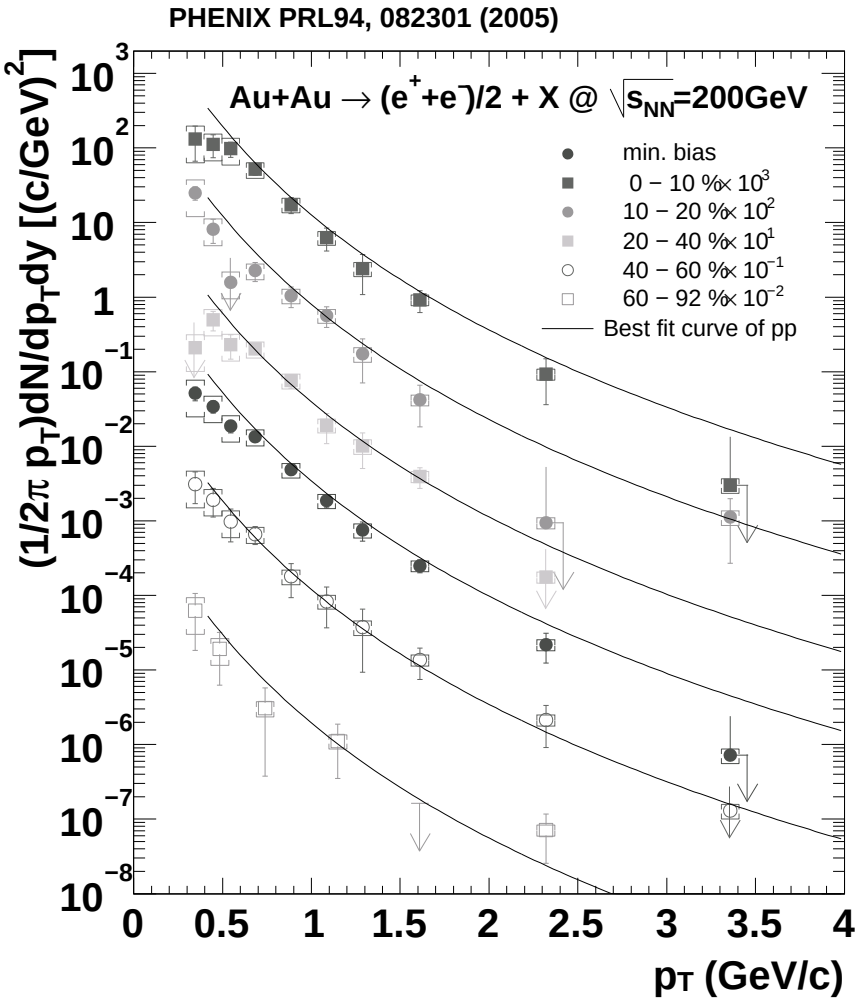
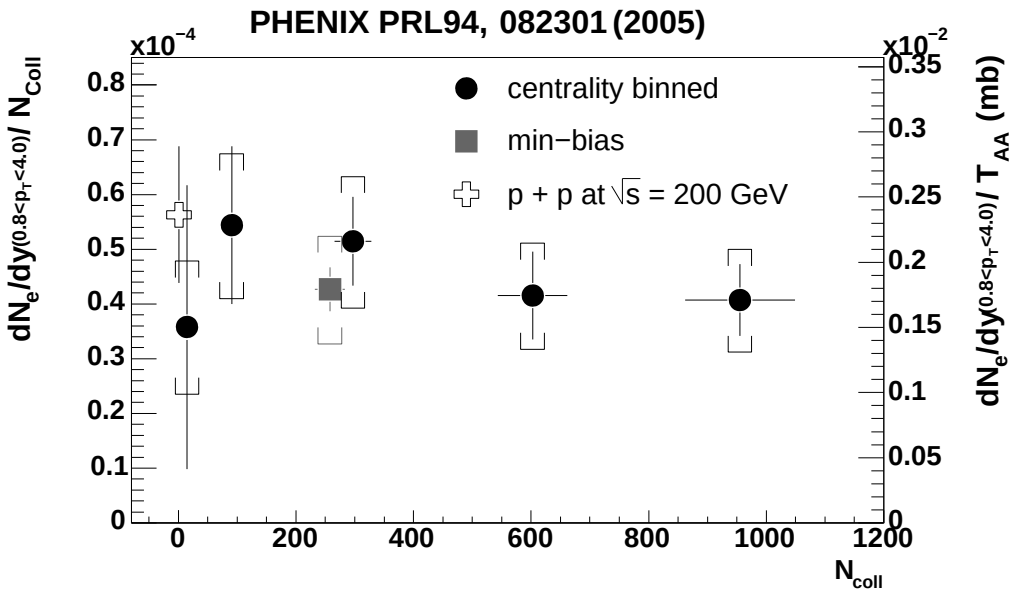
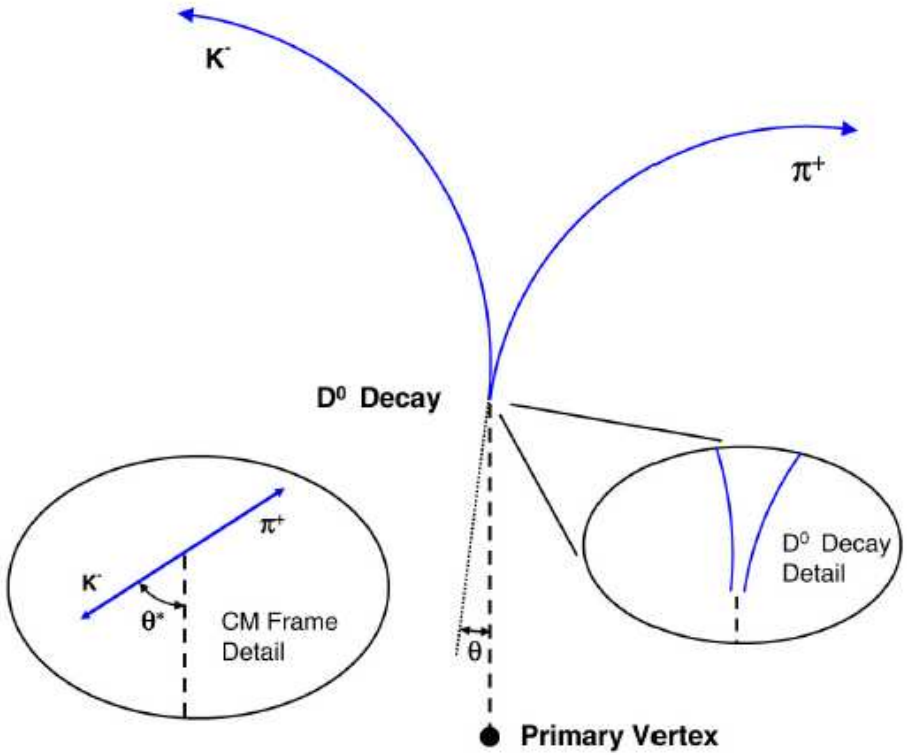


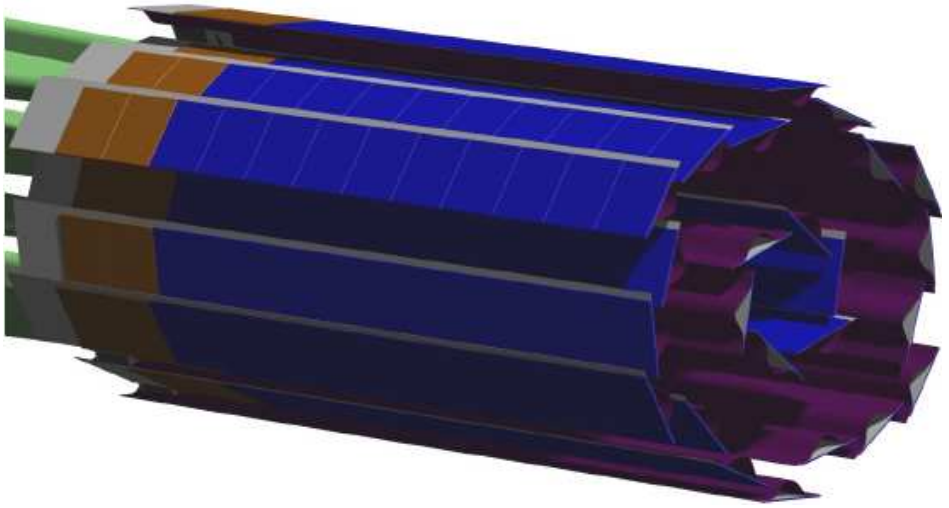


Believed to come from open heavy flavor decays, non-photonic electrons do not show high p_t suppression: the spectra scale with binary collisions.

33 Future of charm: STAR Heavy Flavor Tracker

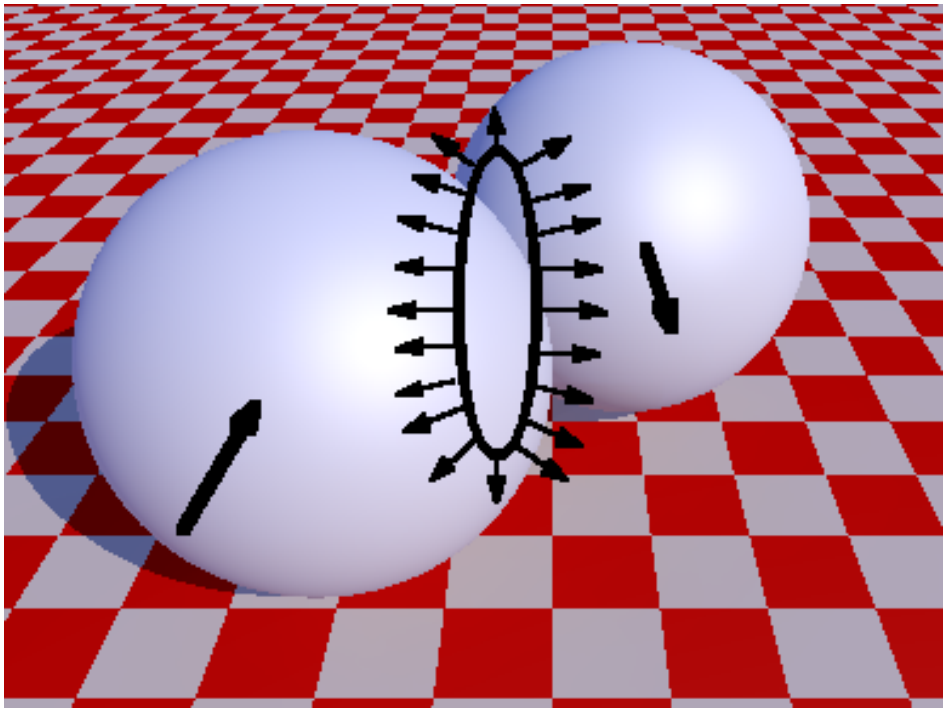
- charm production for J/Ψ signature
- clarify charm R_{AA} story
- elliptic flow of D mesons – is flow partonic ? is c part of it ?





$c\tau \propto 100 - 300 \mu m$. Reduce combinatorics by vertex-finding. 10 μm resolution.

34 Azimuthal asymmetry — flow



(x, y) anisotropy $\rightarrow$ rescattering $\rightarrow$ (p_x, p_y) anisotropy

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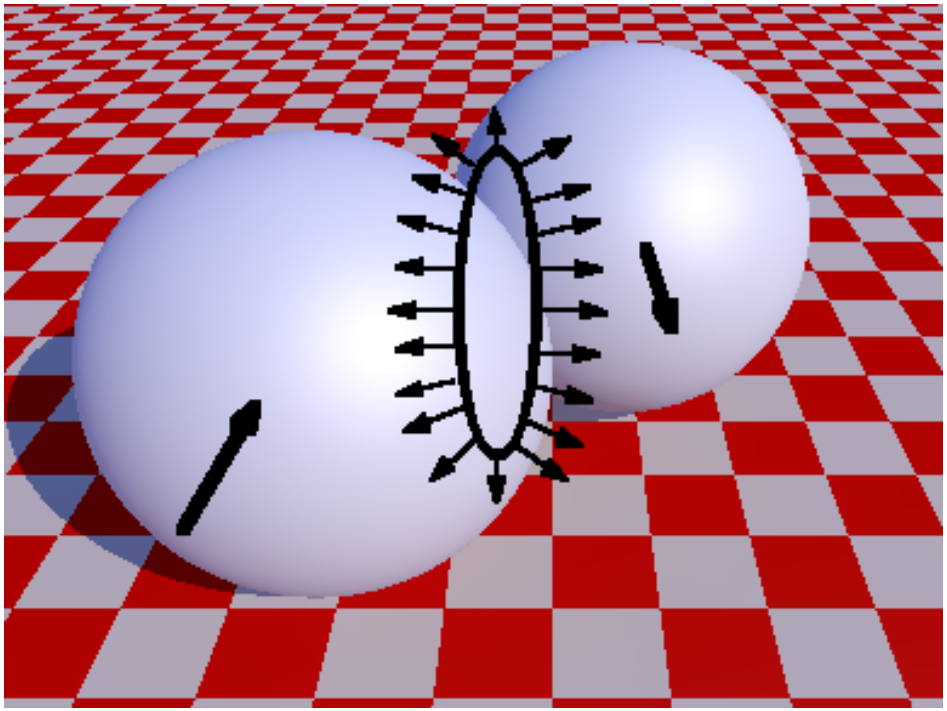

(x, y) anisotropy $\rightarrow$ rescattering $\rightarrow$ (p_x, p_y) anisotropy

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t\,dp_t\,dy}\{1 + \sum_{m=1}^{\infty} 2v_m \cos[m(\phi - \Psi_r)]\} \qquad (20)$$

- flow starts early – perhaps before hydro is applicable (stopping stage)
- testifies to equilibration
- sensitive to pressure and density gradients
- flow is a multiparticle effect; there is "non-flow"

35 Directed flow — Importance of impact vector

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for v_1, need to know $0 \le \Psi_r < 2\pi$:

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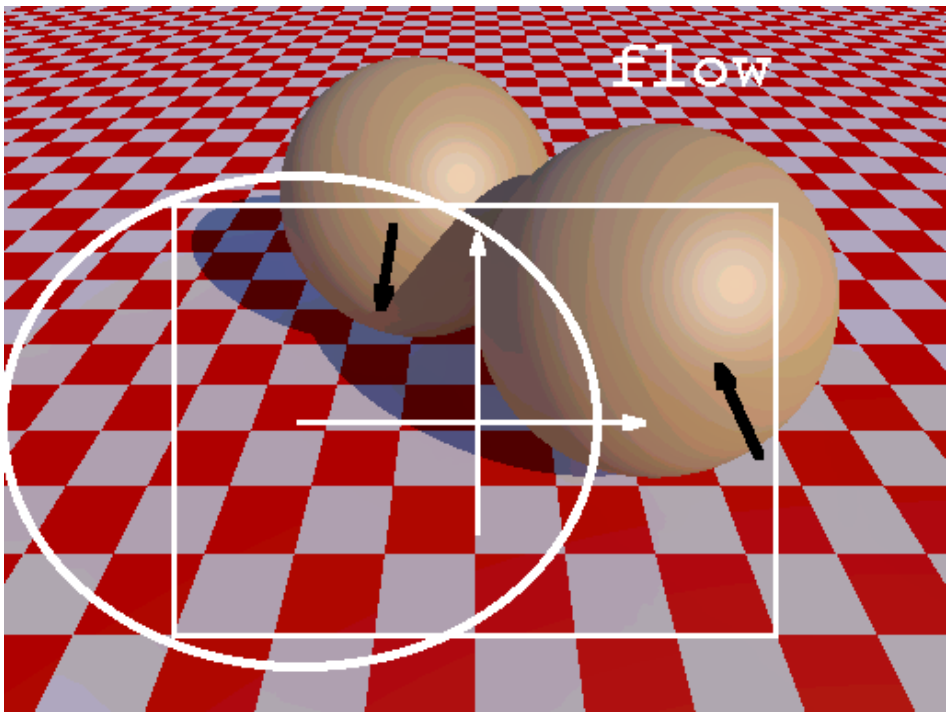

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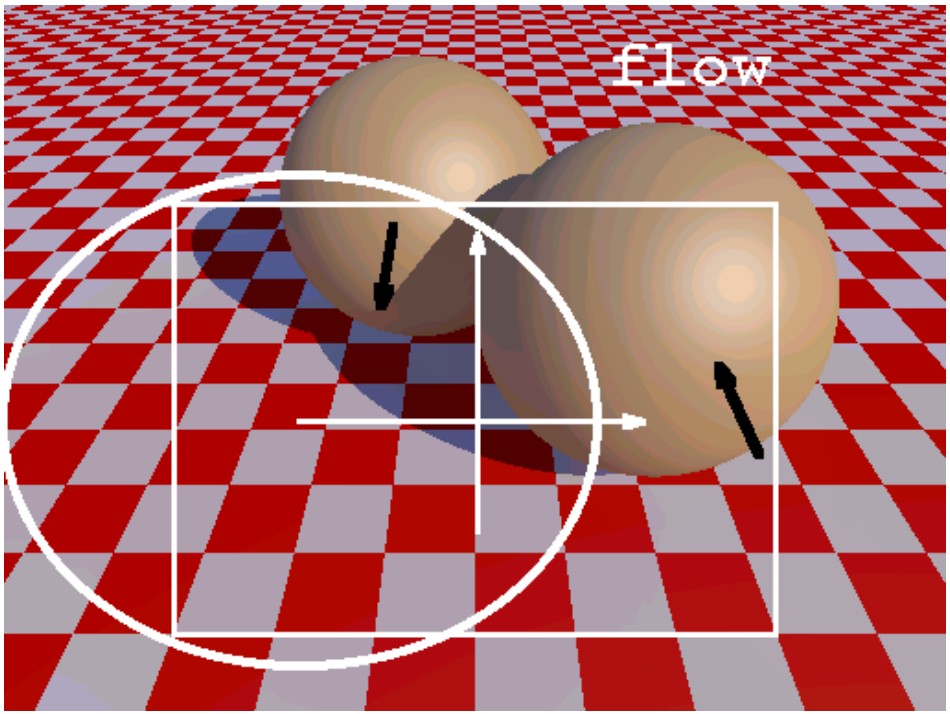

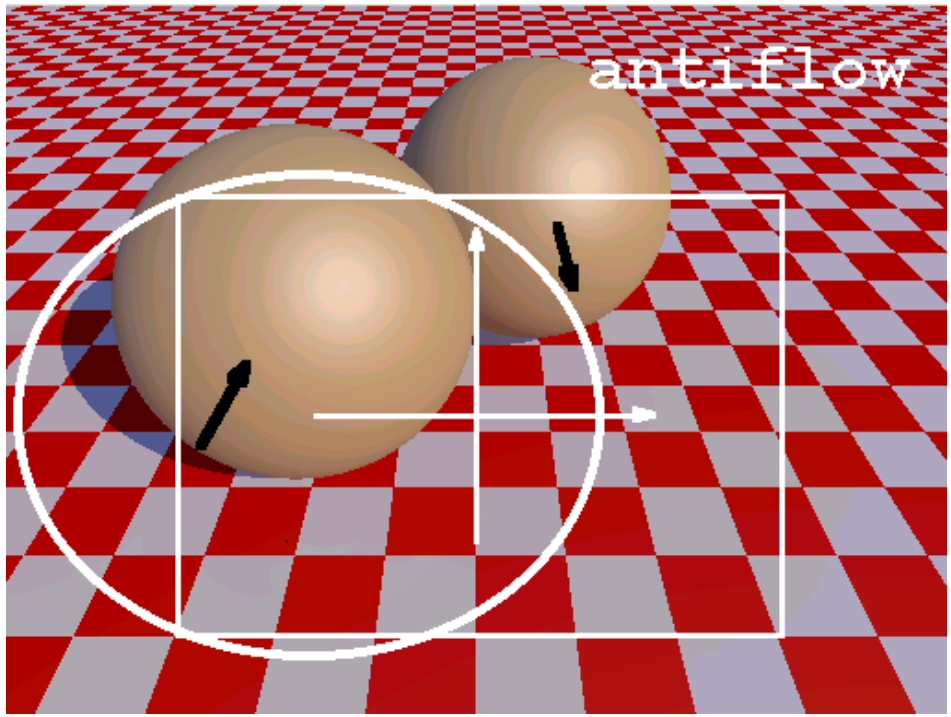

need to be able to distinguish the two !

36 Directed flow — STAR ZDC SMD

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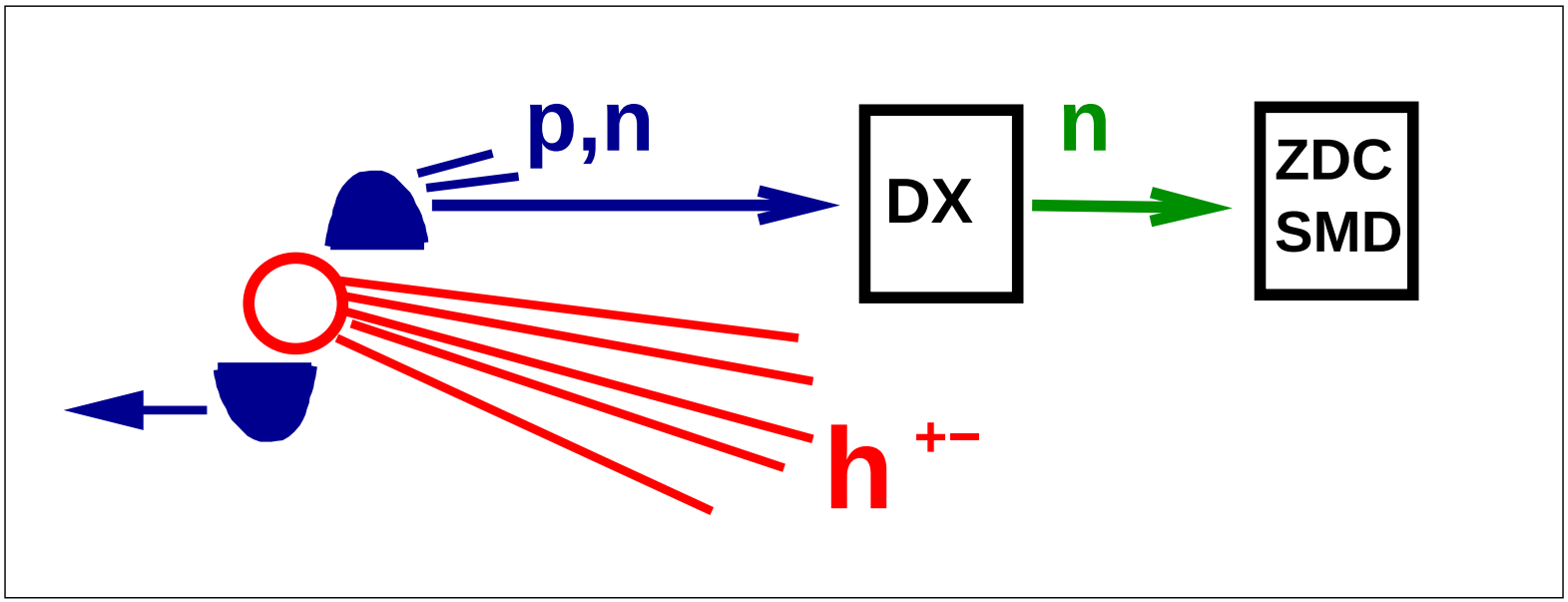
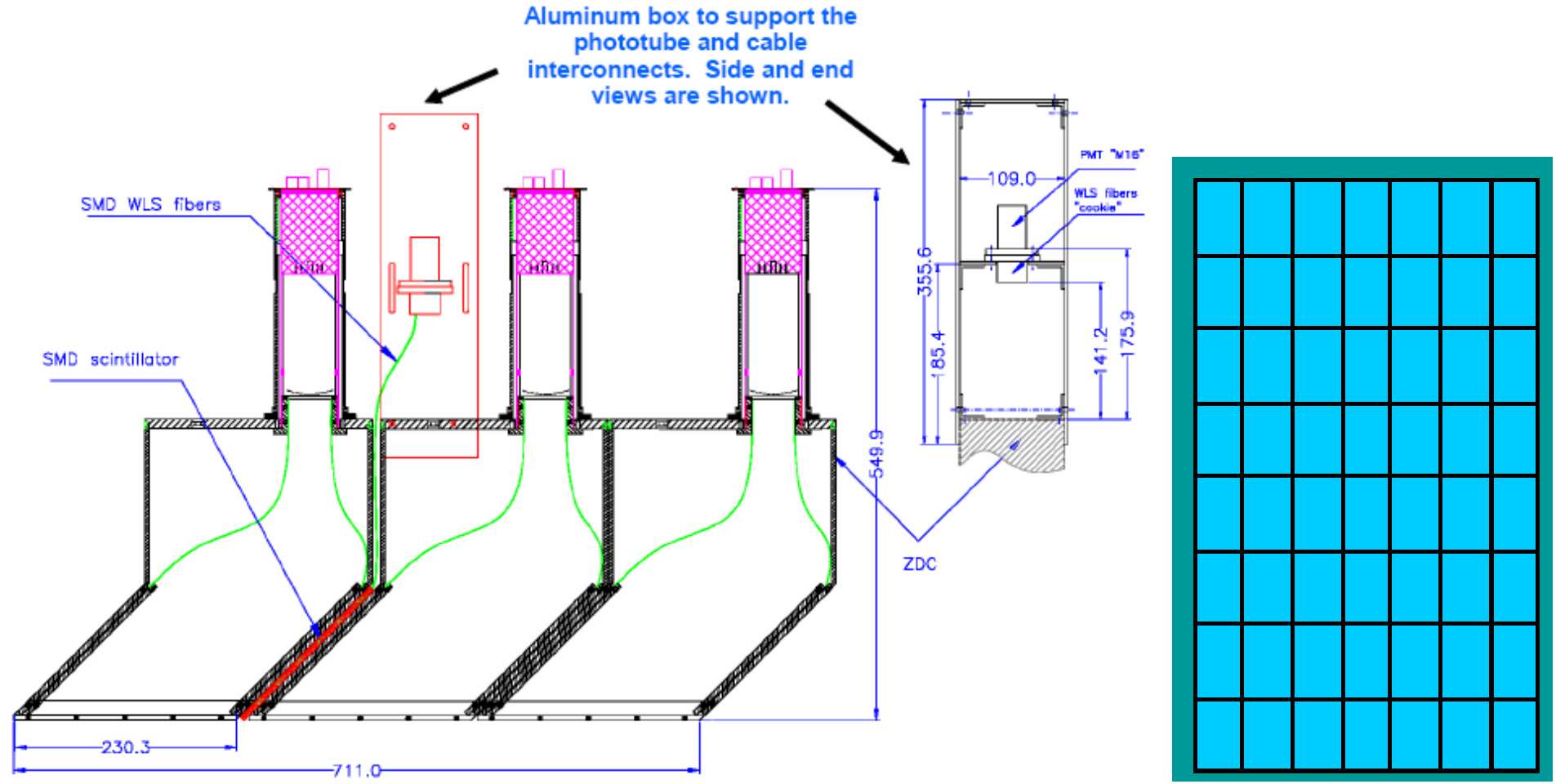
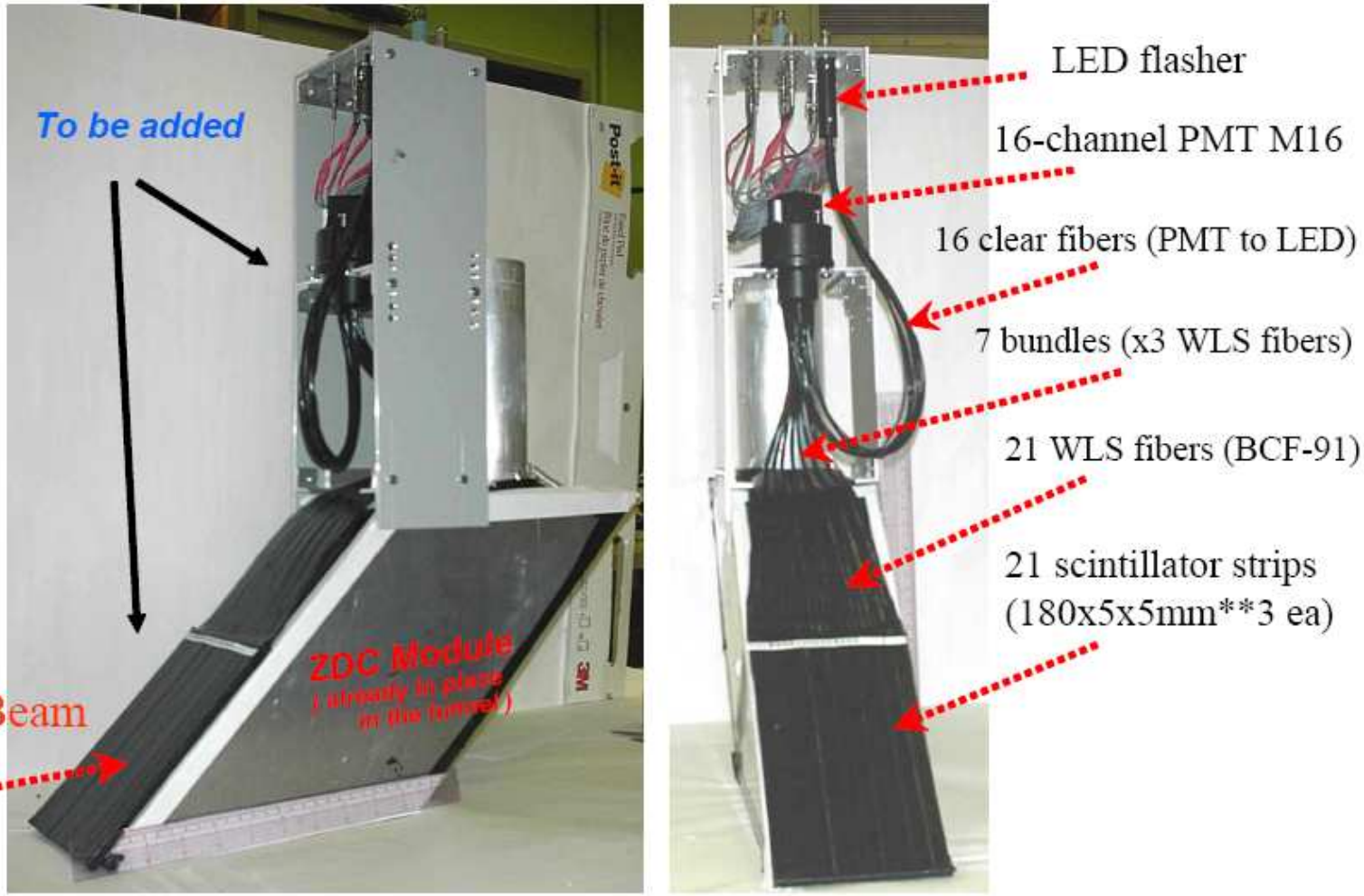


36 Directed flow — STAR ZDC SMD



7 vertical and 8 horizontal SMD slats at 1/3 of ZDC depth measure transverse asymmetry of spectator neutrons

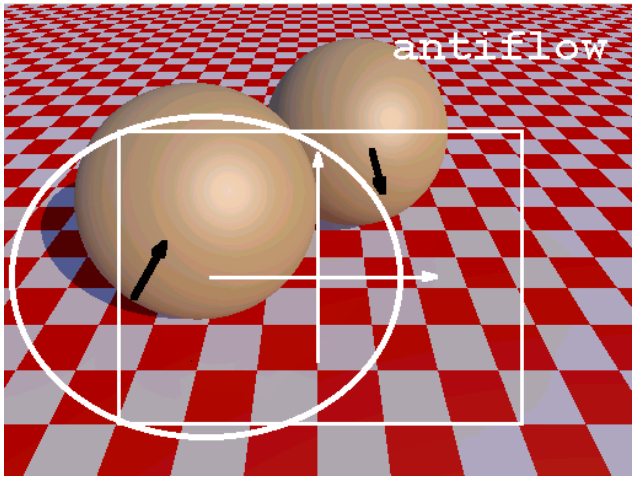
36 Directed flow — STAR ZDC SMD

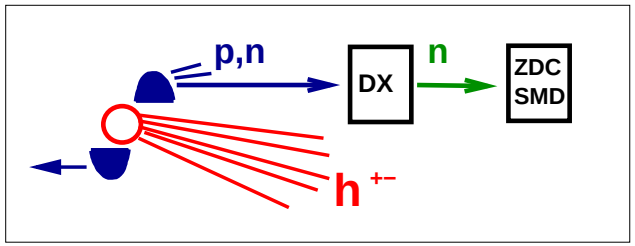


- effort spearheaded by Kent people
- besides flow, contributes to strangelet search, UPC and spin physics

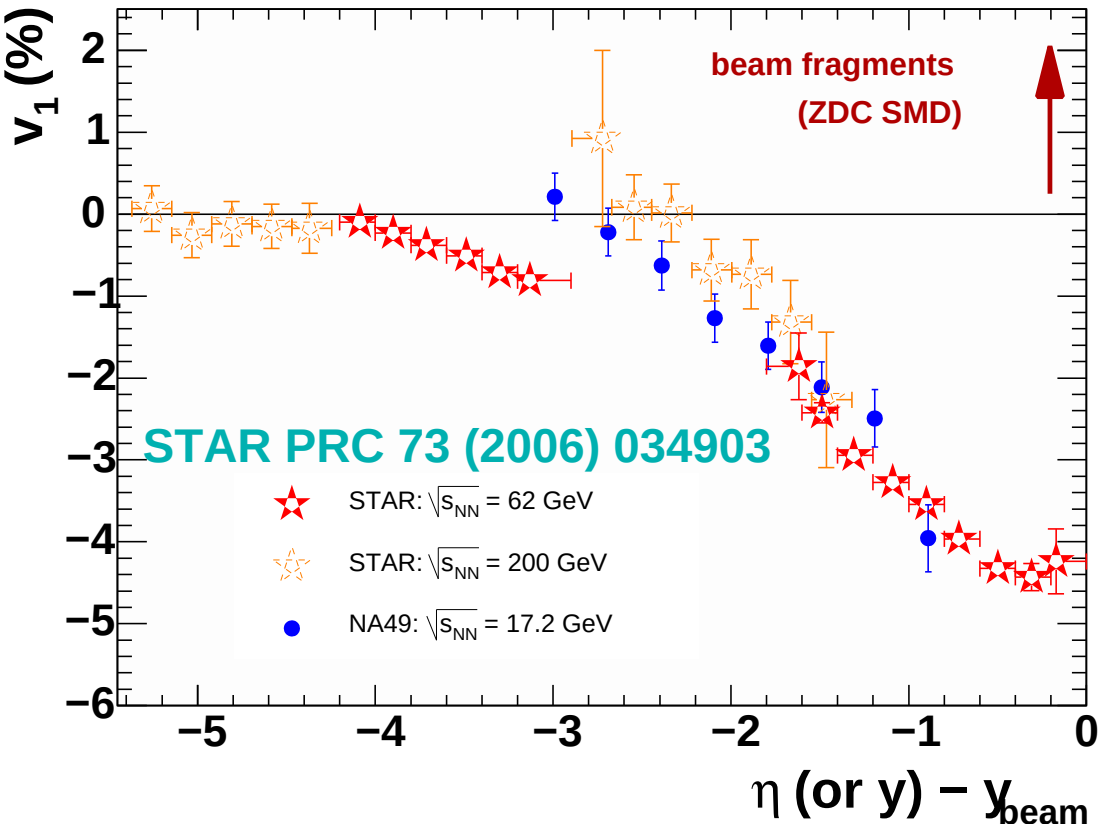
37 Directed flow

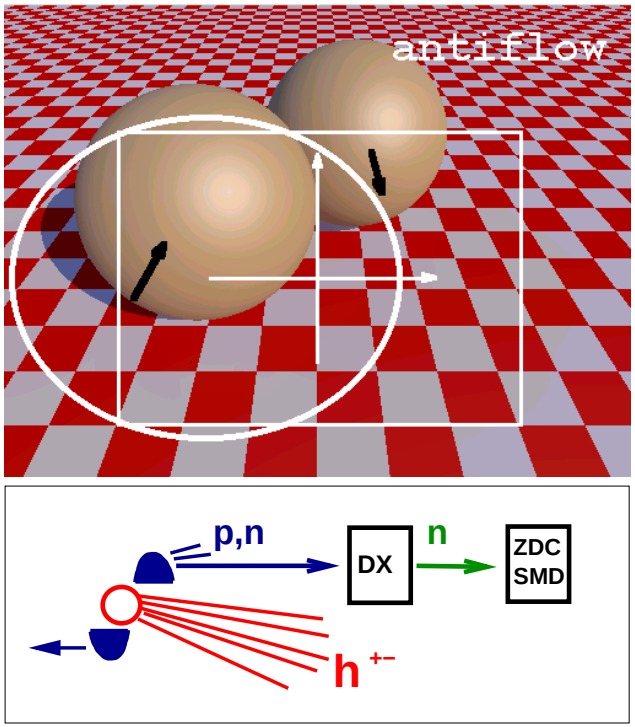
37 Directed flow





37 Directed flow





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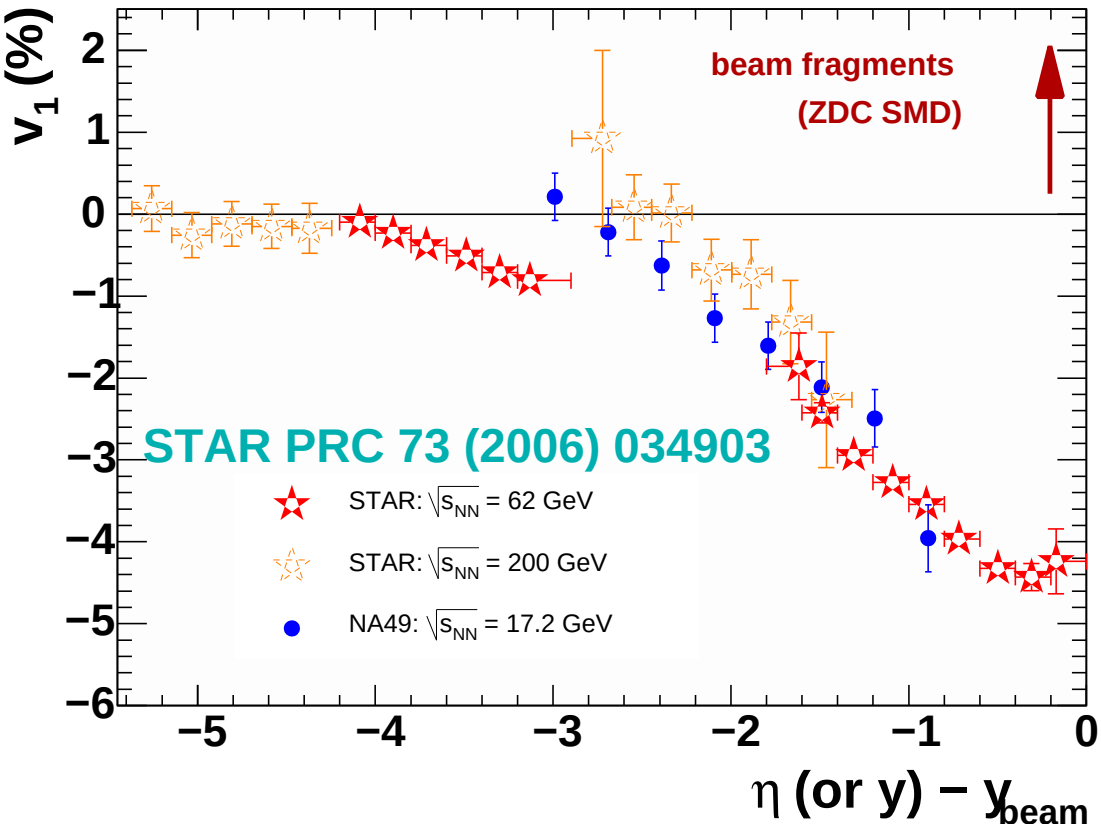

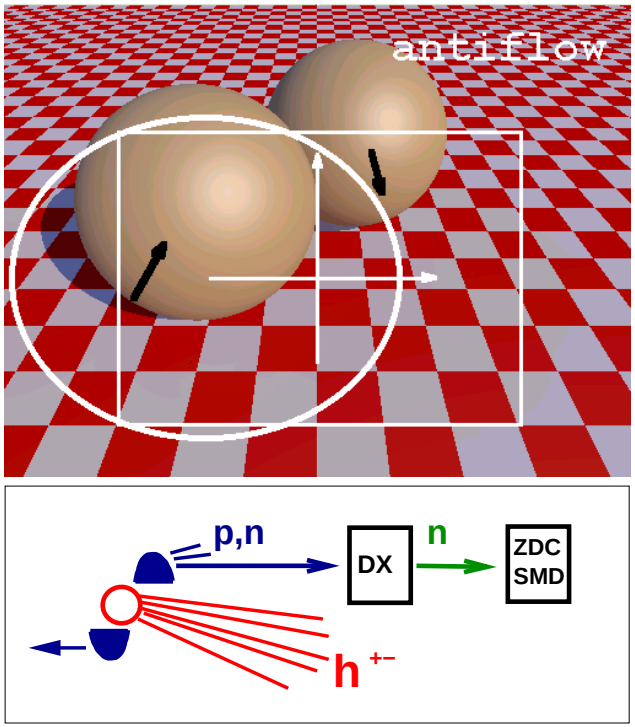

Charged-particles v_1 from 3-particle cumulants in the projectile frame.

- monotonic around midrapidity
- Supports limiting fragmentation
- Antiflow !

38 Elliptic flow and hydro fluidity

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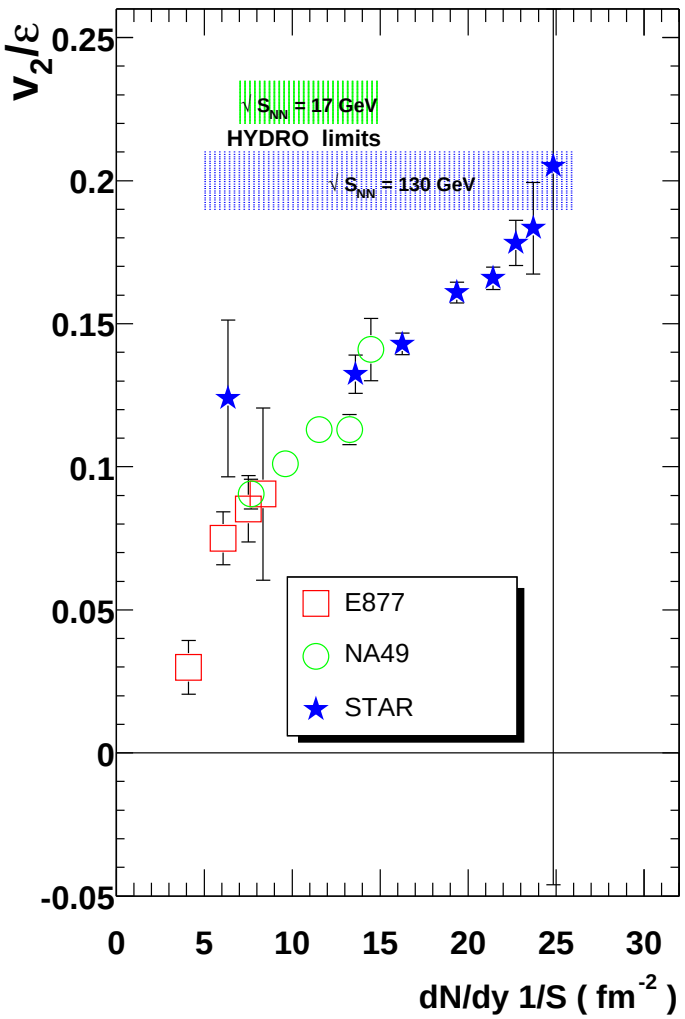

STAR PRC66 (2002) 034904 (cumulant v_2). Hydro limits by Kolb, Sollfrank, Heinz, PRC62 (2000) 054909.

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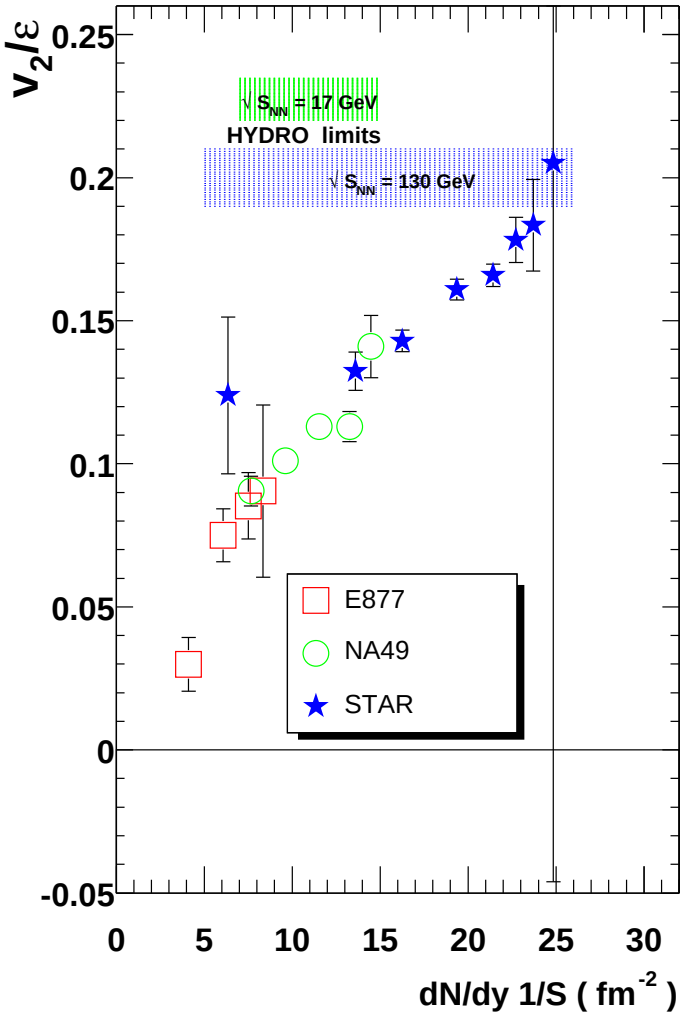
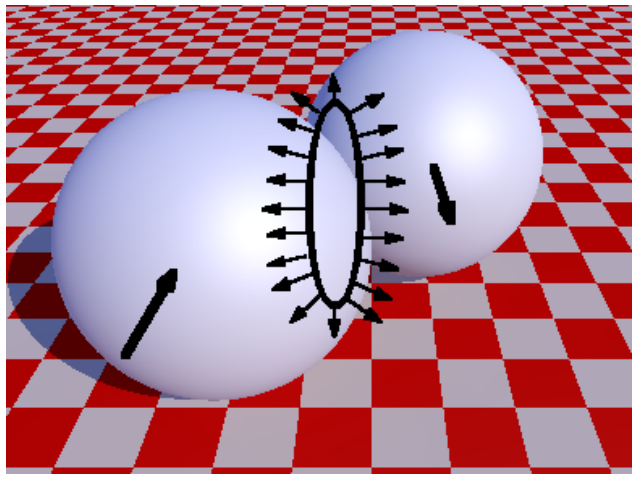


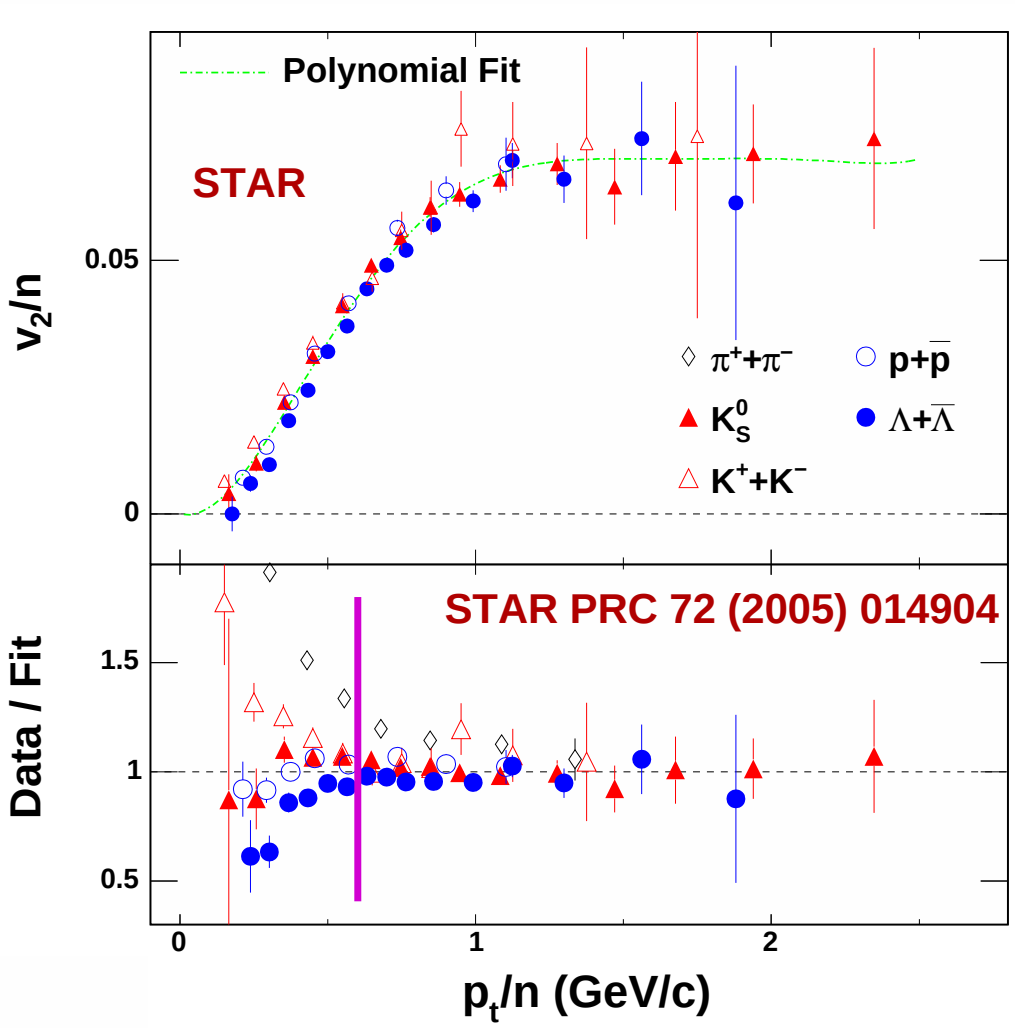
STAR PRC66 (2002) 034904 (cumulant v_2). Hydro limits by Kolb, Sollfrank, Heinz, PRC62 (2000) 054909.

- v_2 is a response to excentricity $\varepsilon = \overline{(y^2 - x^2)/(y^2 + x^2)}$



- low viscosity $\Leftrightarrow$ high cross-sections ! **"sQGP".**

39 Elliptic flow and quark coalescence



$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos(2\phi) \qquad (22)$$

$$\frac{dN_{\mathrm{clscnc},n}}{d\phi}(p_t) \propto \left(\frac{dN(\frac{p_t}{n})}{d\phi} \right)^n \qquad (23)$$

$$(1 + 2v_2 \cos(2\phi))^n = \qquad (24)$$

$$1 + 2v_2 n \cos(2\phi) + \mathcal{O}(v_2^2)$$

STAR AuAu 200 GeV minbas; n is number of constituent quarks. Expect universality if quark coalescence dominates hadronization after the universal flow sets in. Valid at $p_t/n > 0.6$ GeV/c for K^0_S,$K^{\pm}$,p,$\bar{p}$,Λ,$\bar{\Lambda}$.

40 Local hadron density fluctuations and Discrete Wavelet Transform (DWT)

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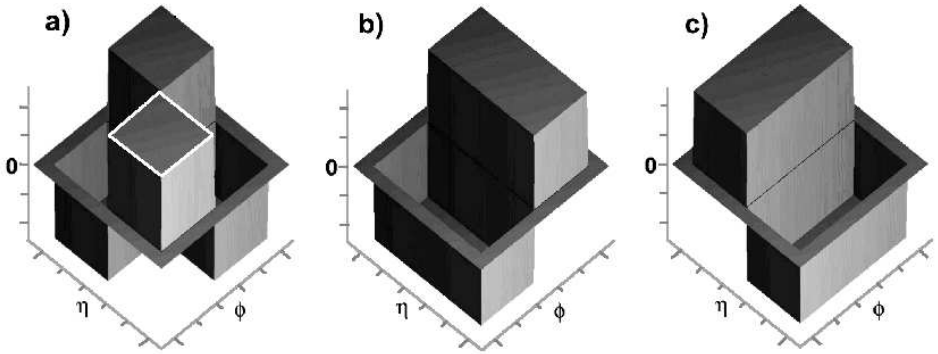

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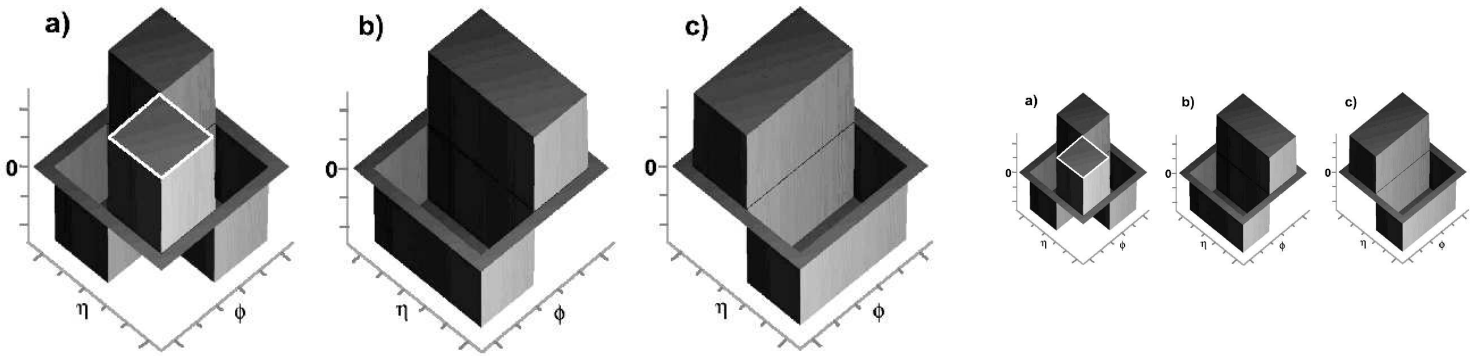

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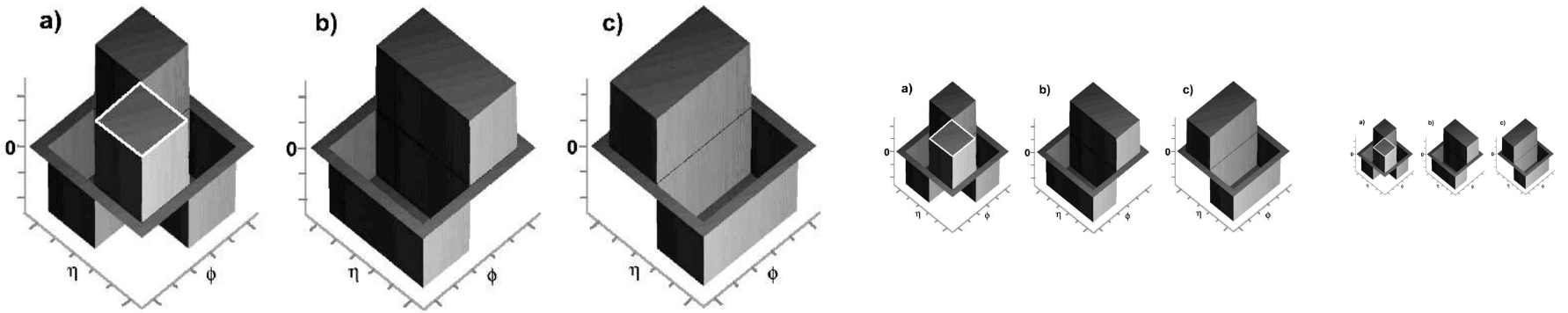

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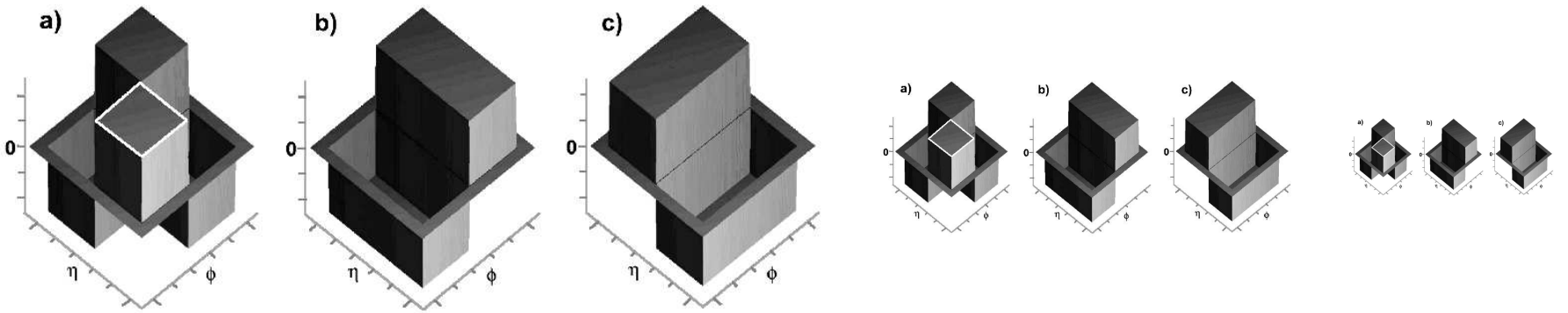

$F^{\lambda}_{m,l,k}(\phi,\eta)$–Haar wavelet **orthonormal basis** in (ϕ,η). scale fineness (m), directional modes of sensitivity (λ), track density $\rho(\eta,\phi,p_t)$, locations in 2D (l,k). **DWT is an expansion in this basis.**

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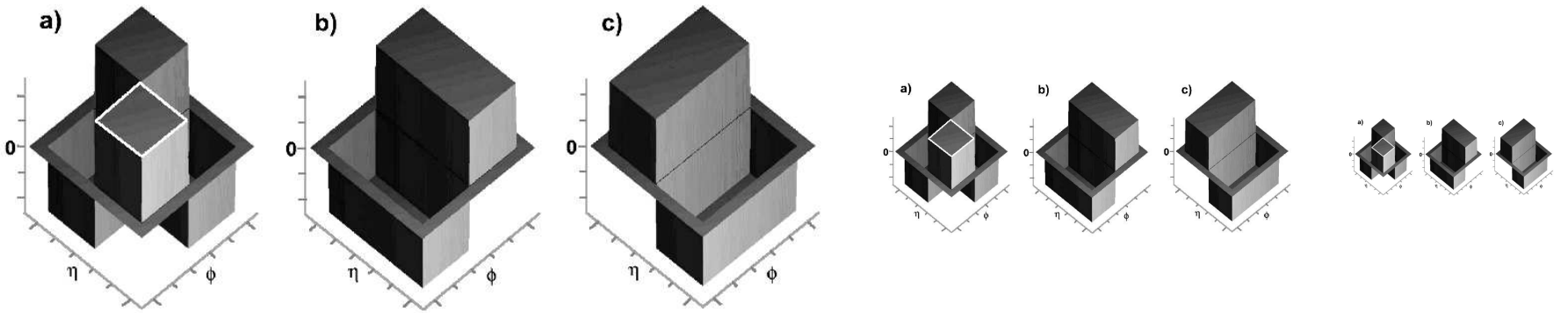

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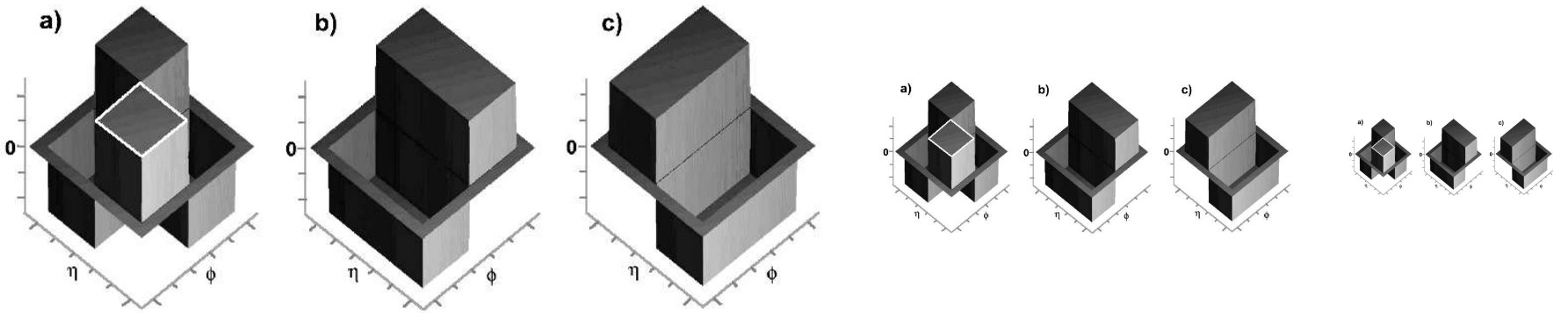

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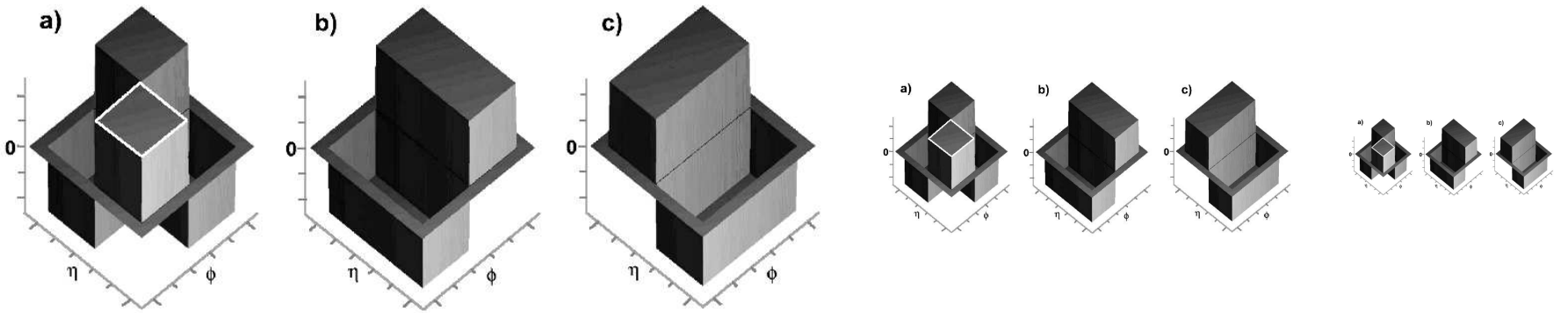

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Normalized:

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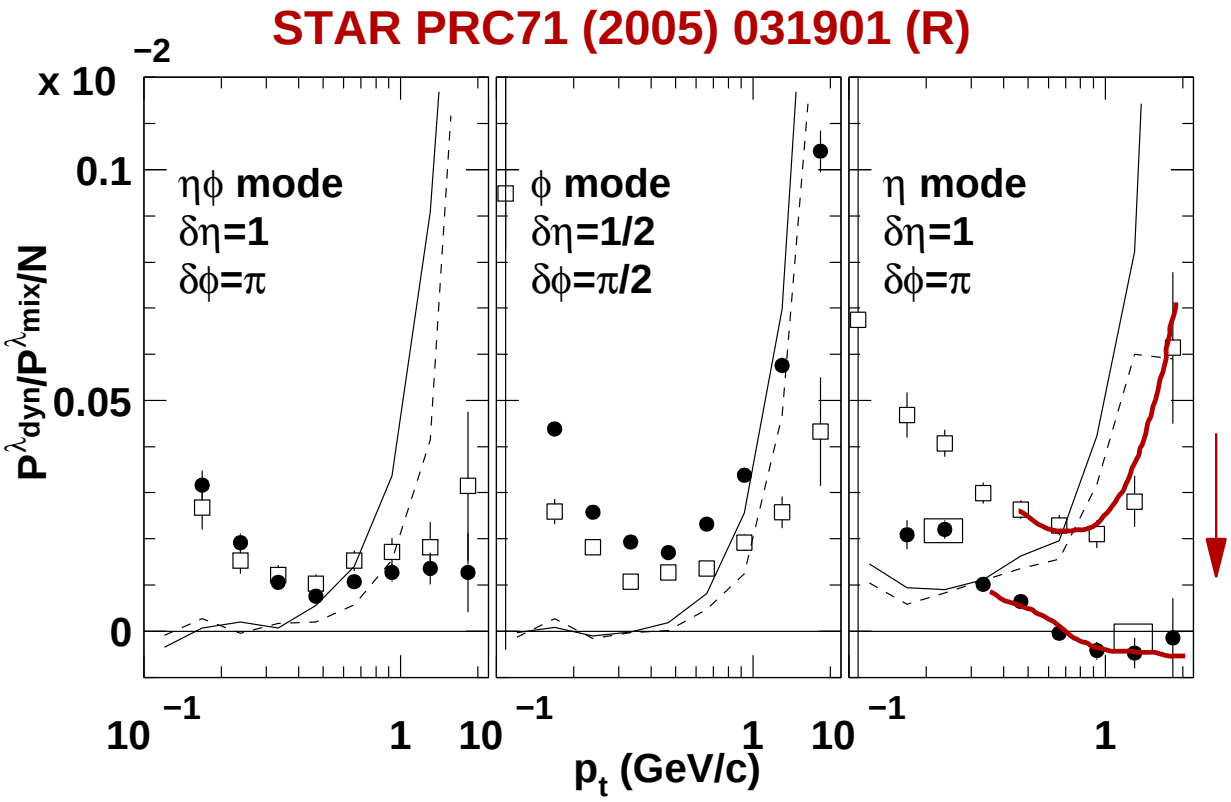
41 Longitudinal minijet broadening – wavelet-based technique



Central events: normalized dynamic texture for fineness scales $m = 0, 1, 0$ from left to right panels, respectively, as a function of p_t. ● STAR data; solid line – Hijing without jet quenching; dashed line – Hijing with quenching; □ peripheral STAR data renormalized to compare.

42 Longitudinal minijet broadening – traditional technique

$$r(\vec{p}_1, \vec{p}_2) \equiv \rho_{sib}(\vec{p}_1, \vec{p}_2)/\rho_{mix}(\vec{p}_1, \vec{p}_2). \tag{28}$$

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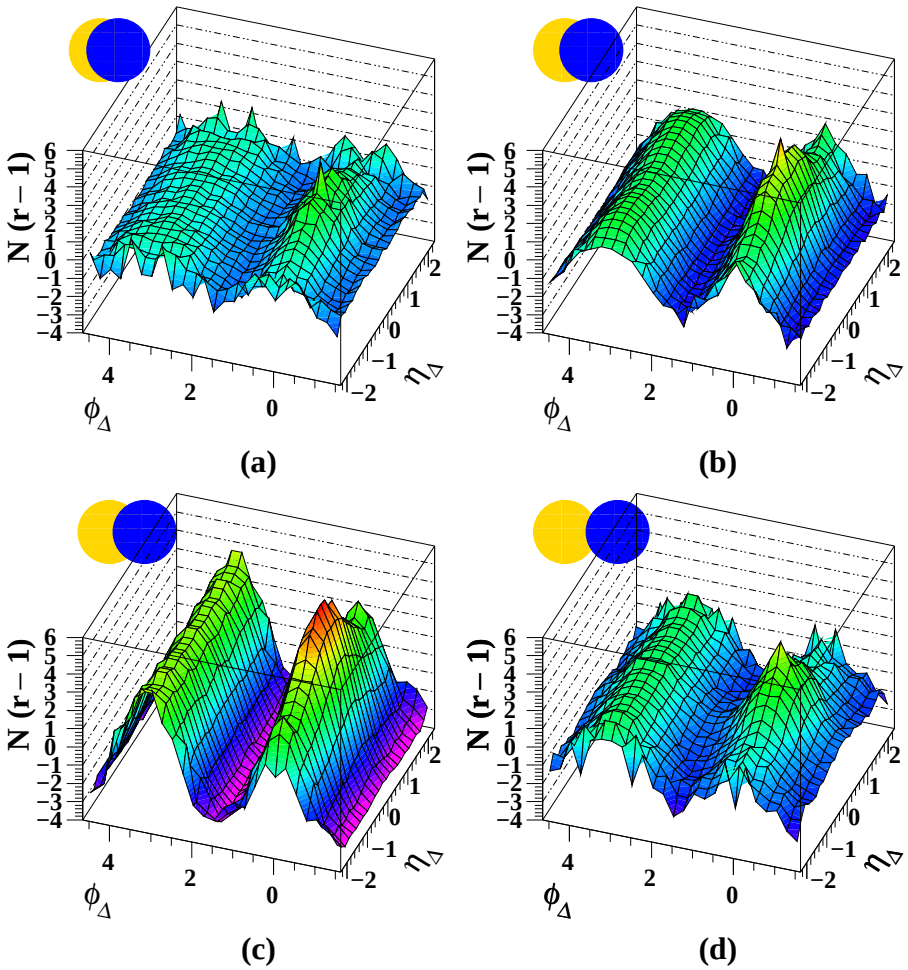
STAR PRC73 (2006) 064907



Two-particle charge-idependent joint correlations $\bar{N}(\hat{r}-1)$ on $(\eta_\Delta \equiv \eta_1 - \eta_2$, $\phi_\Delta \equiv \phi_1 - \phi_2)$ for central (a) to peripheral (d) collisions.

43 Connecting DWT and two-point correlation measures

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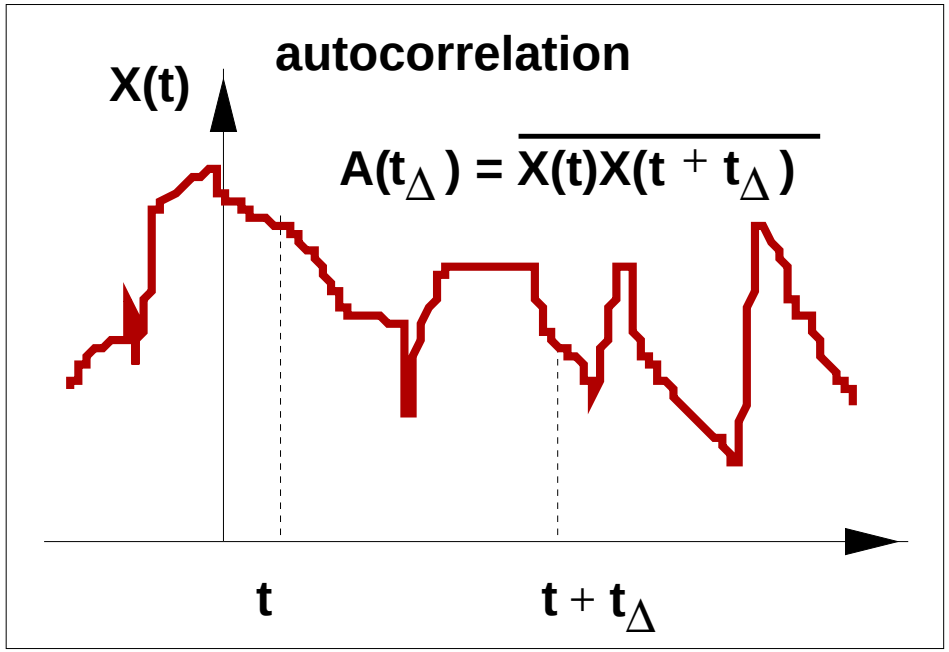

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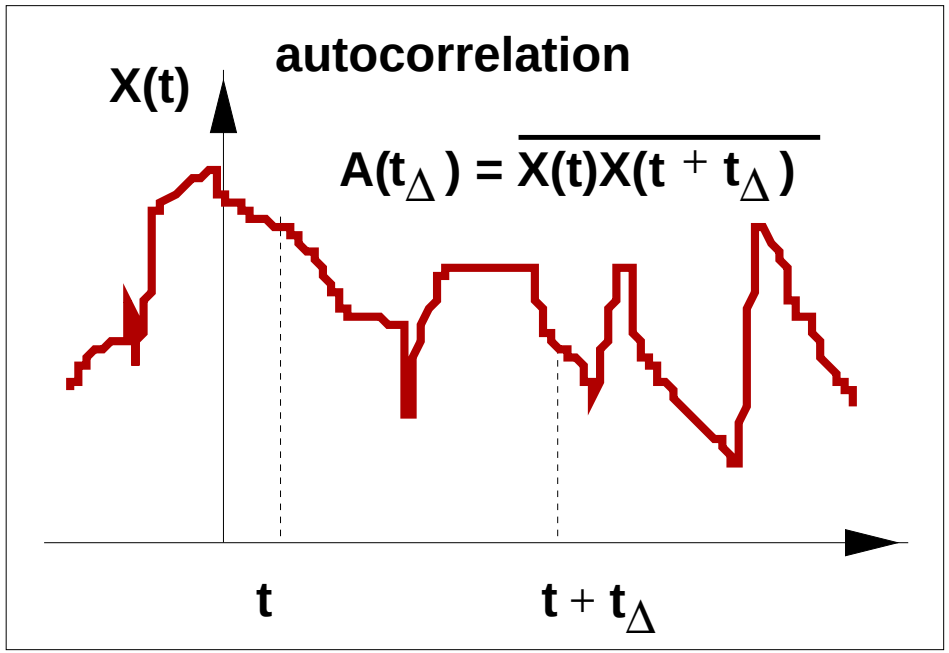

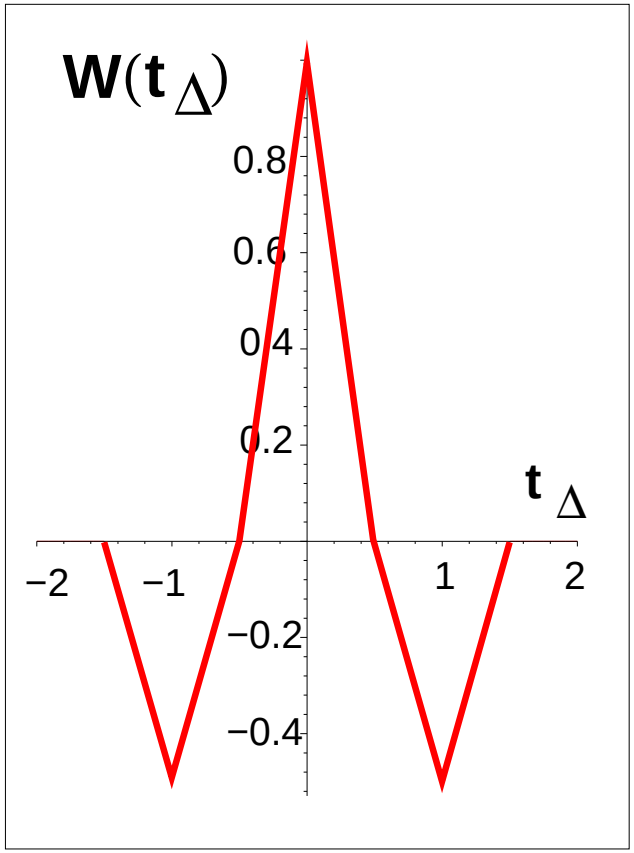

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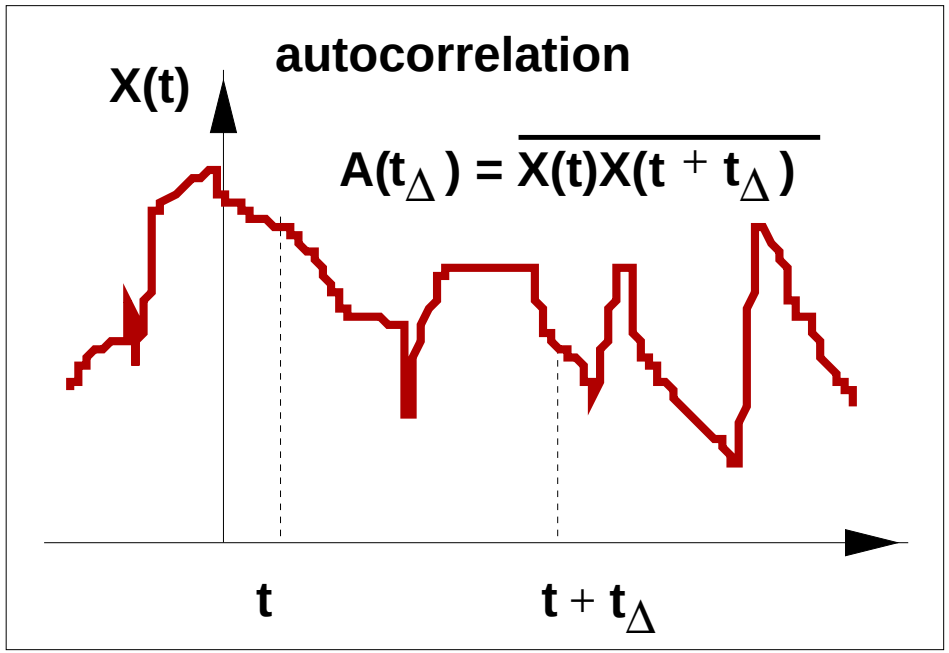

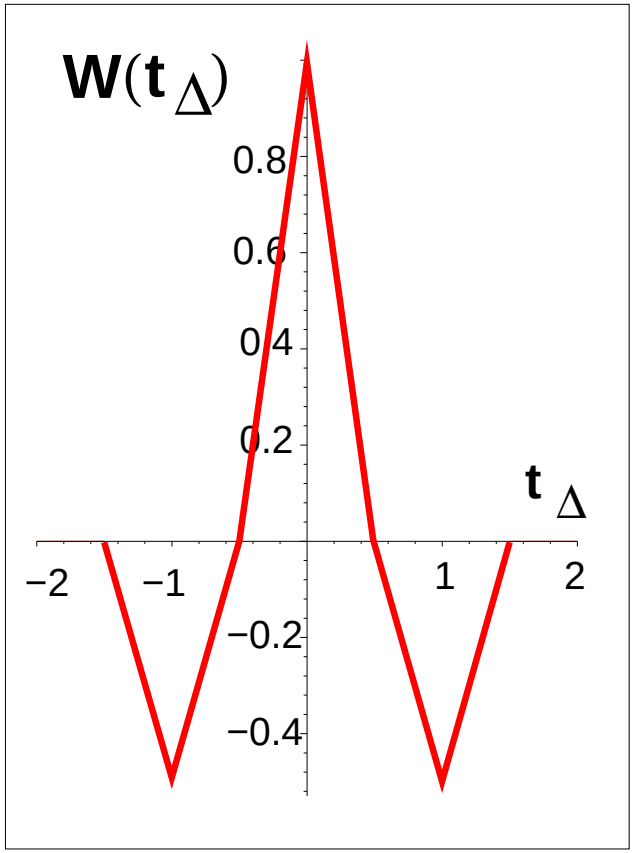

$$P(m) = \overline{\int_{-\infty}^{\infty} X(t_\Delta/2)X(-t_\Delta/2)W(t_\Delta, m)\, dt_\Delta}, \qquad (29)$$

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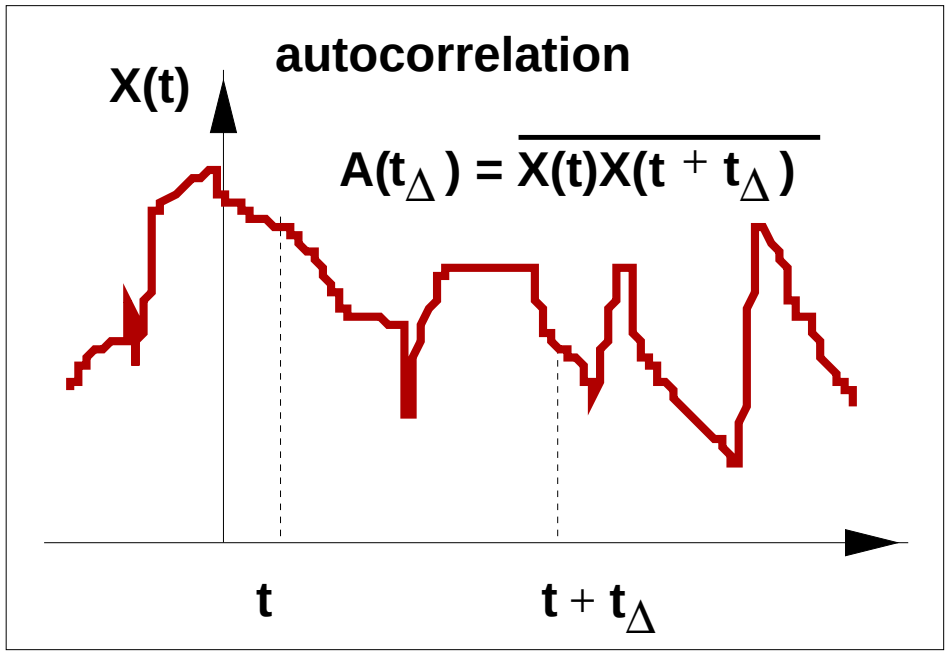

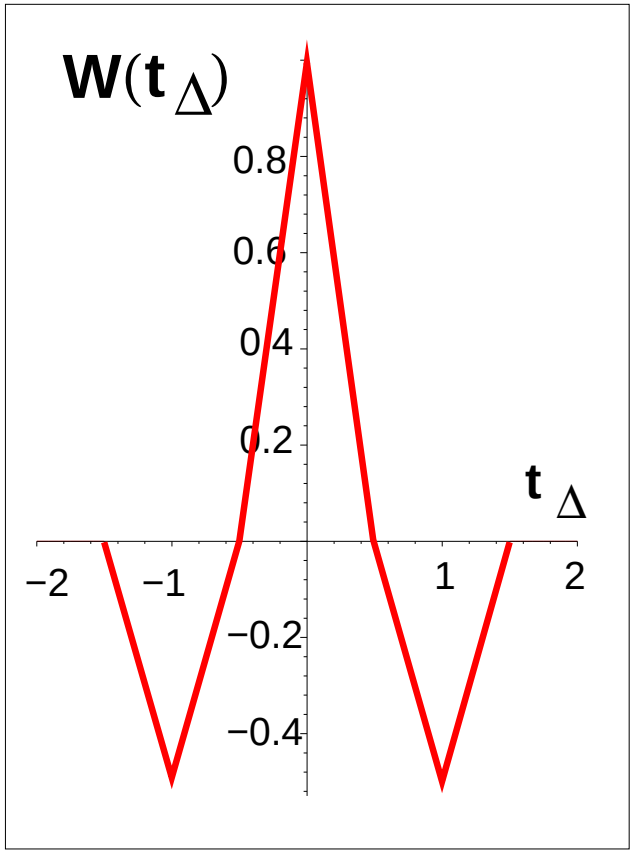

$P(m)$ differentiates correlation on scale m. Minijet elongation $\Rightarrow$ correlation broadening $\Leftrightarrow$ reduced correlation gradient $\Leftrightarrow$ reduced "texture"

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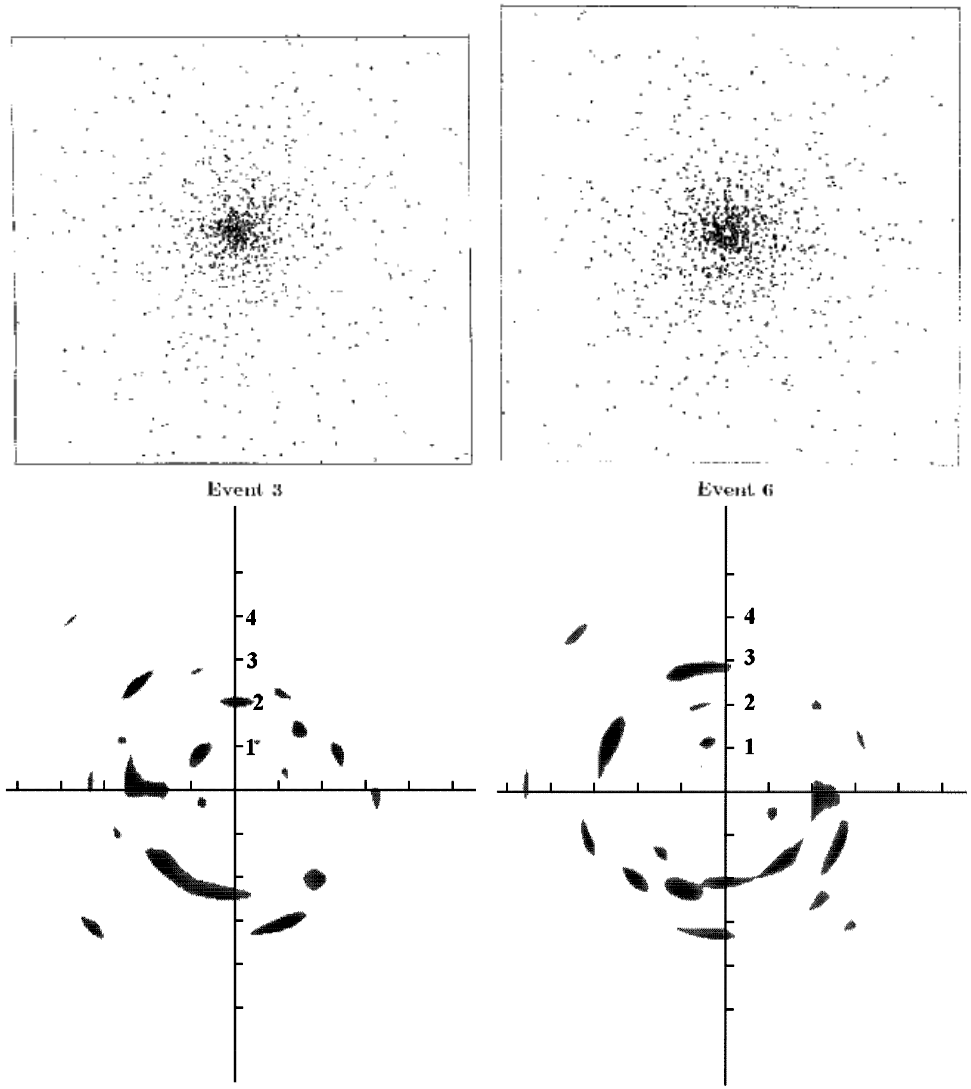
44 Future of wavelet correlations: Kent — P.N.Lebedev — MEPhI project

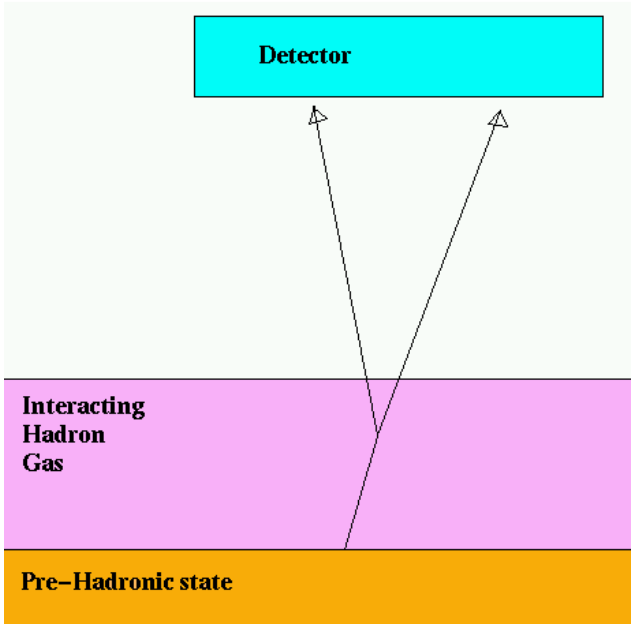


Dremin et al.,
Phys.Lett.B499:97-103,2001.
Emulsion plates exposed at SPS.
Top image → DWT → suppress certain scales → inverse DWT → bottom image.
Rings of Cherenkov gluons ?
Could determine "dielectric permeability" of QCD matter at RHIC.

45 Resonances in hadronic matter

Markert, Torrieri, Rafelski, Campos do Jordao 2002

45 Resonances in hadronic matter



$$\bar{K}^{*0}(892) \rightarrow \pi^+ + K^- \quad (30)$$

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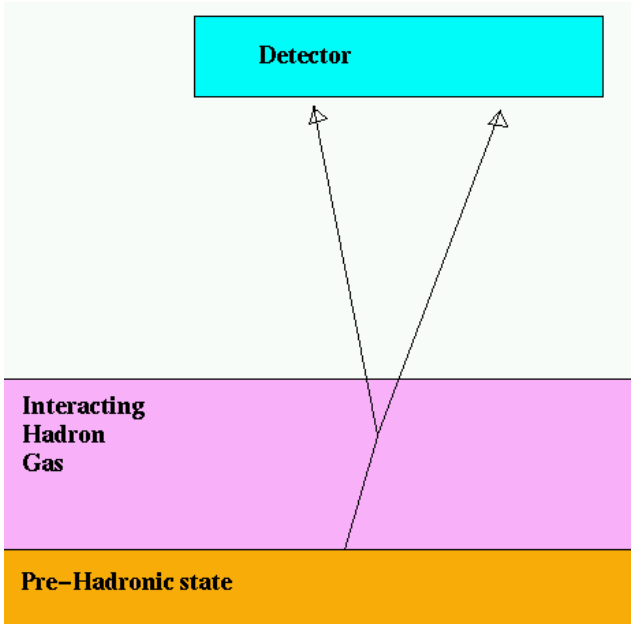

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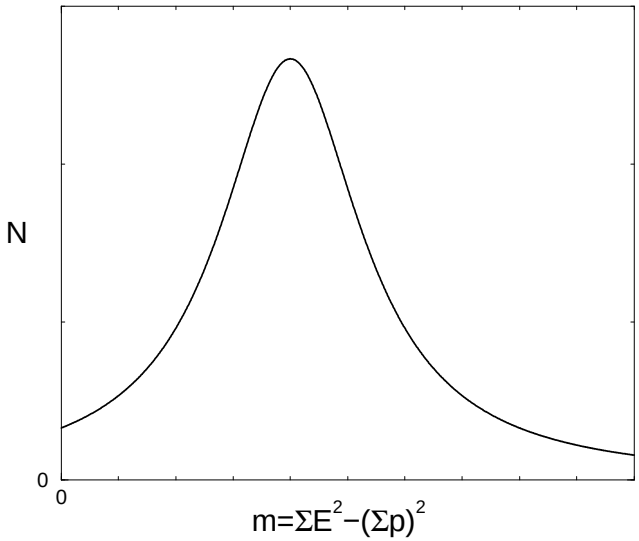

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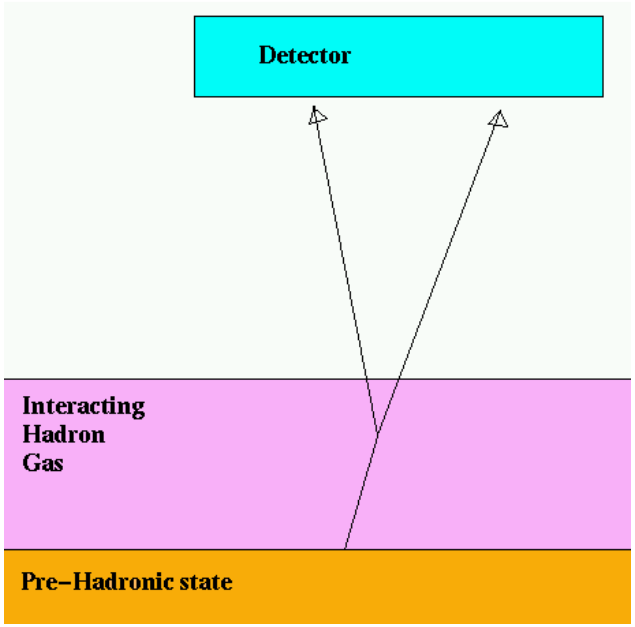

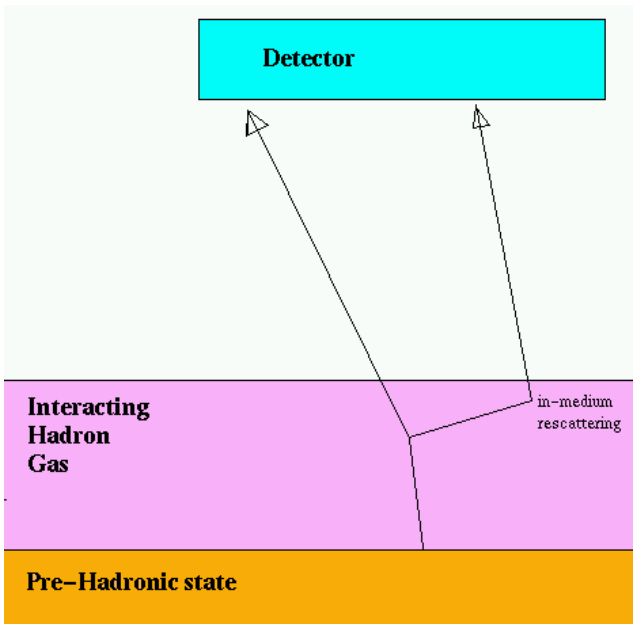

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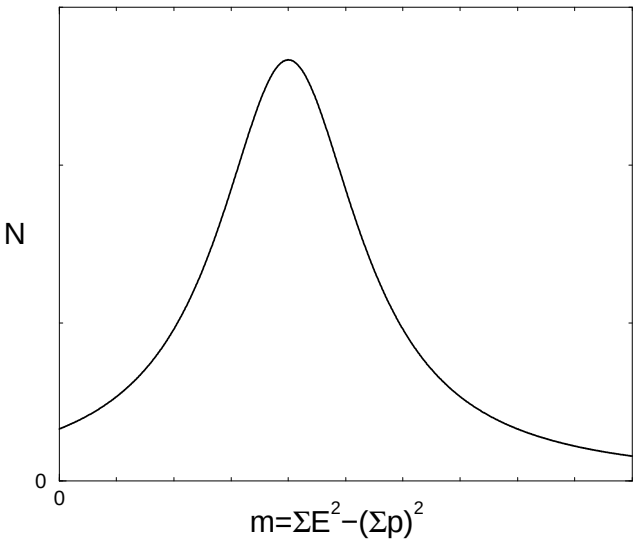

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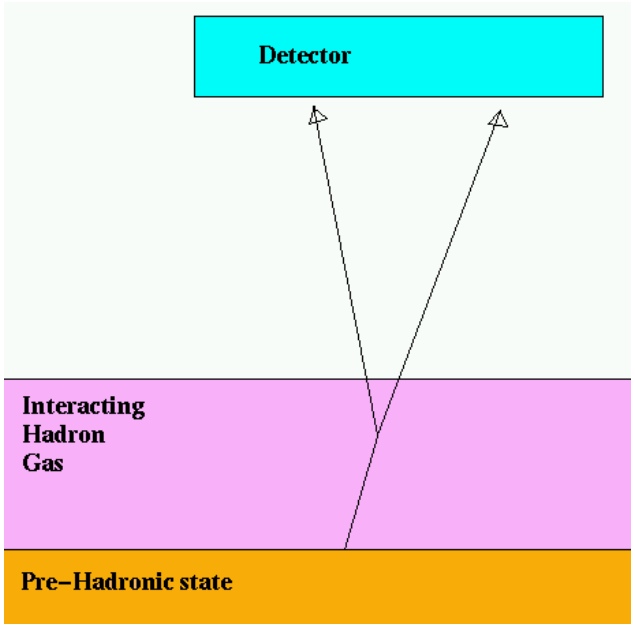

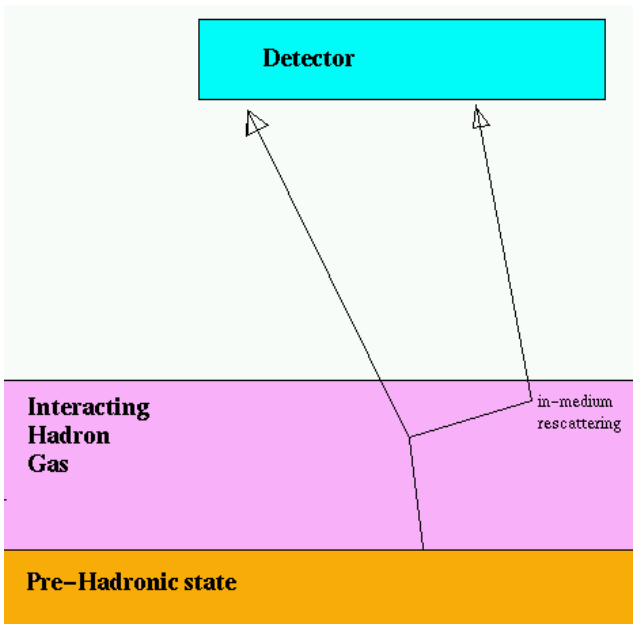

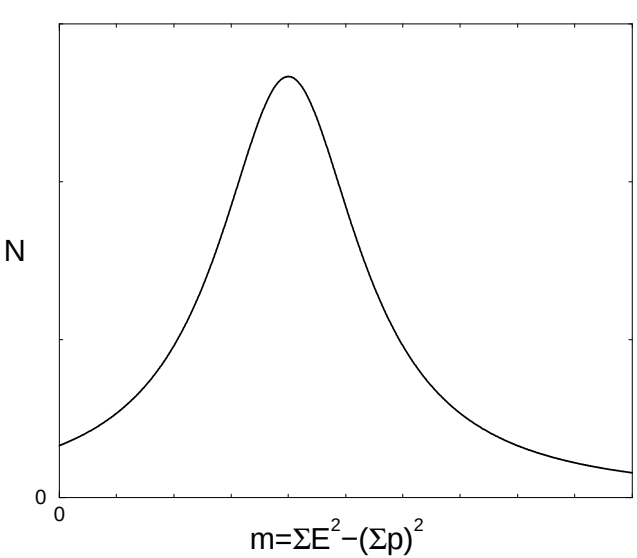

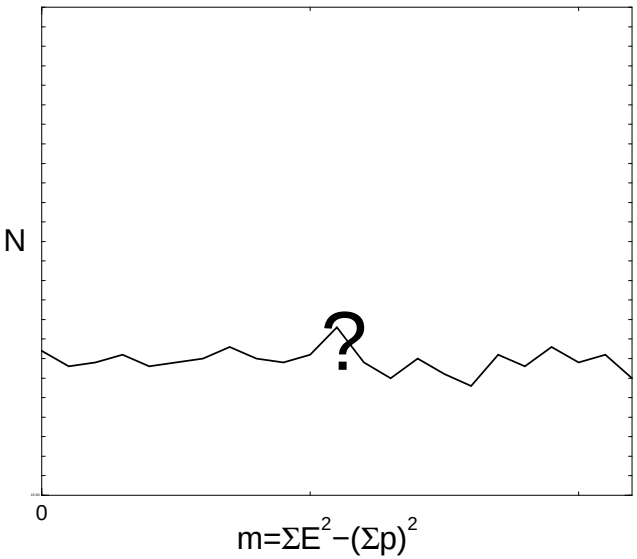

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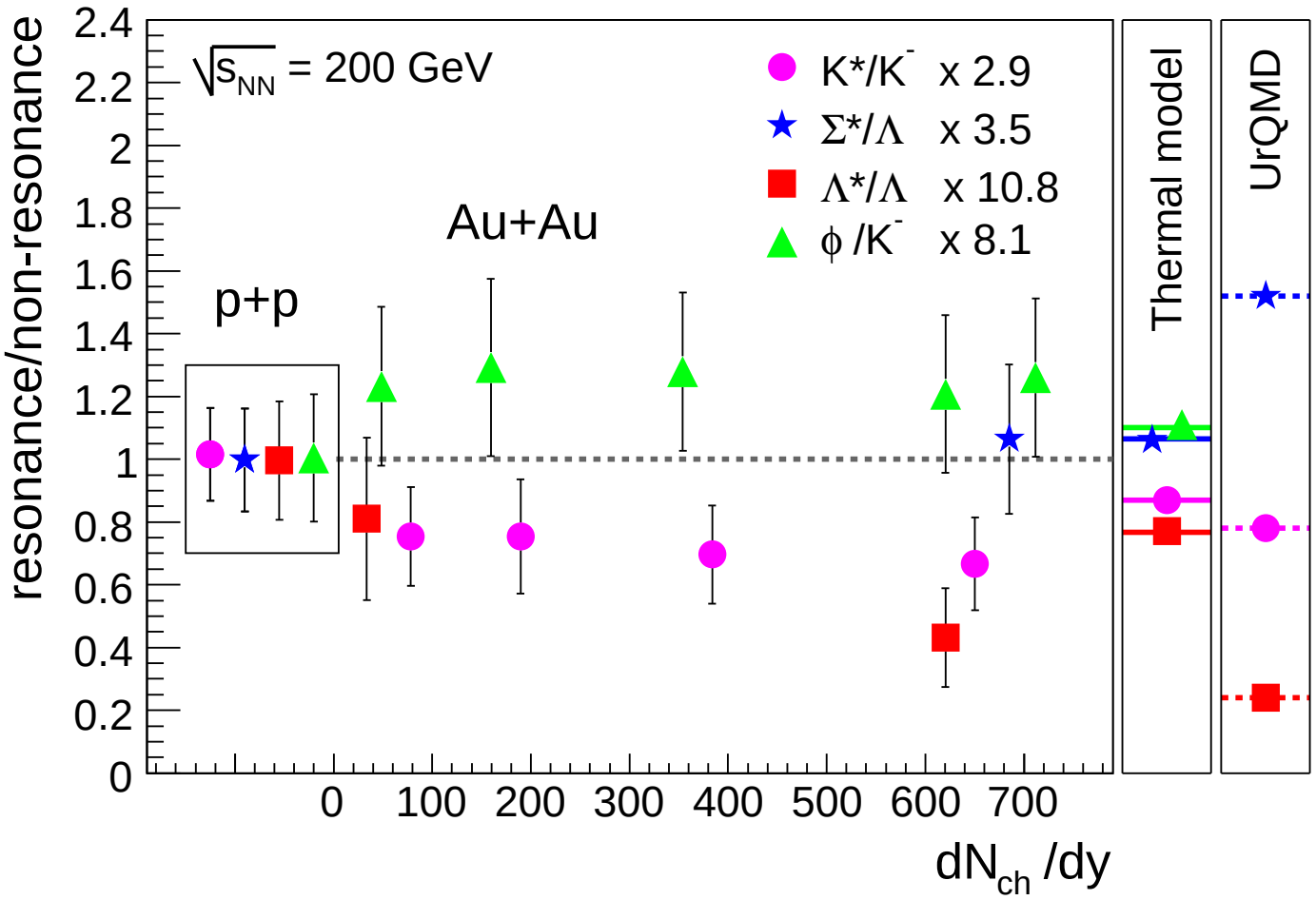

STAR PRL 97, 132301 (2006): a thermal model with rescattering. Can use models to put limits on the system evolution time.

47 QGP: physical reality or a justifiable ansatz?

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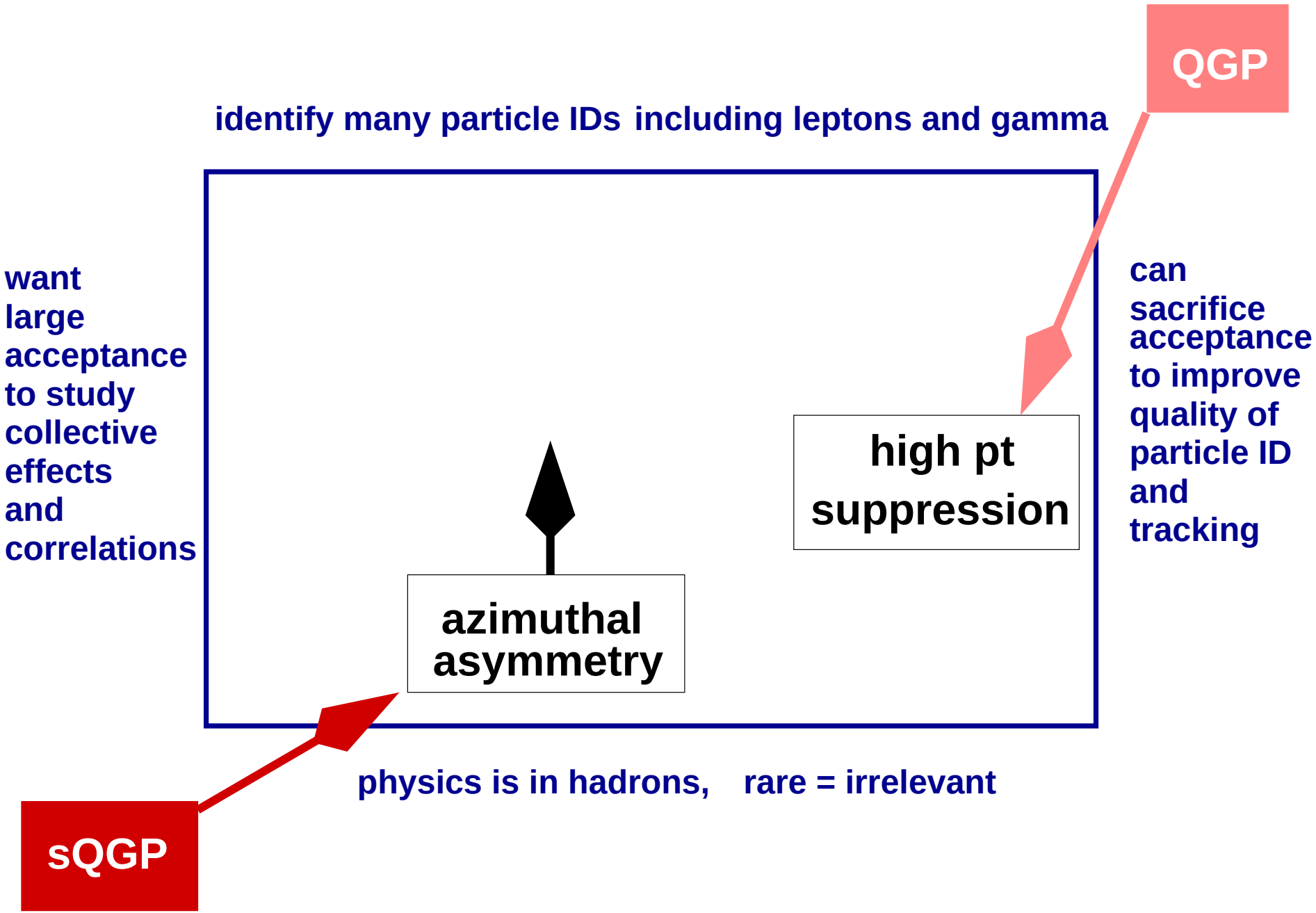

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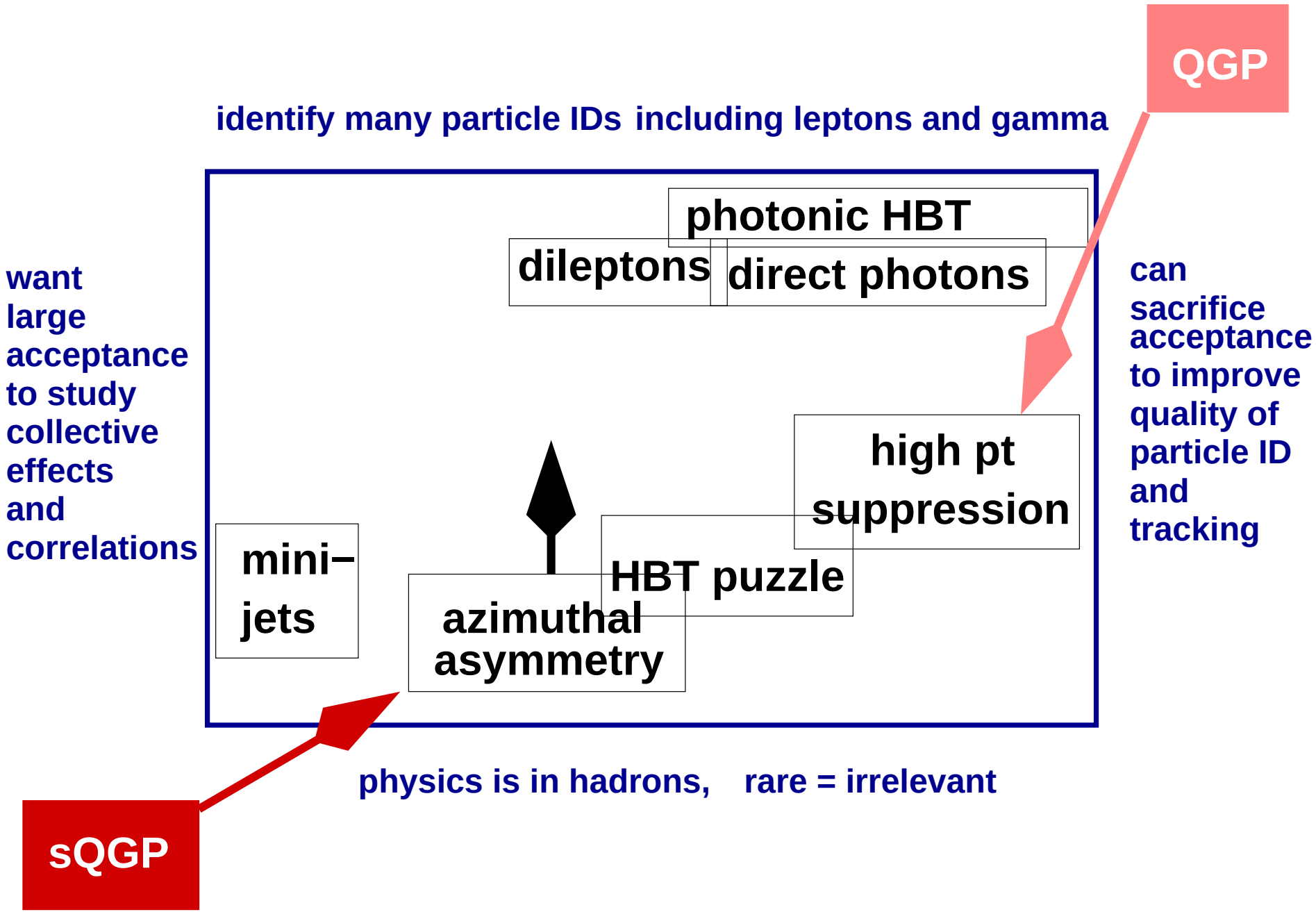
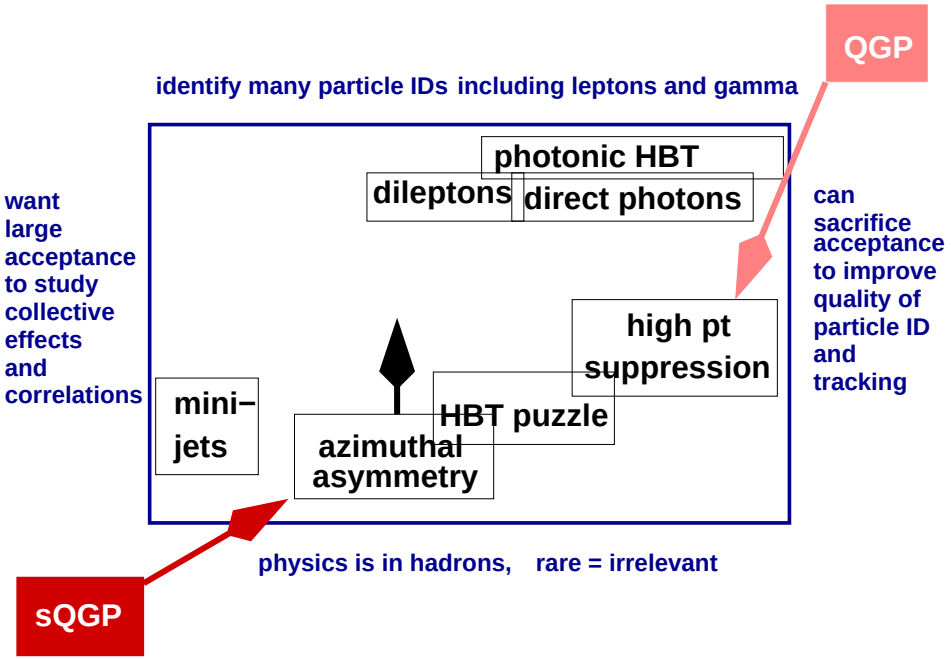


48 So what happened at RHIC ? Conclusions so far:



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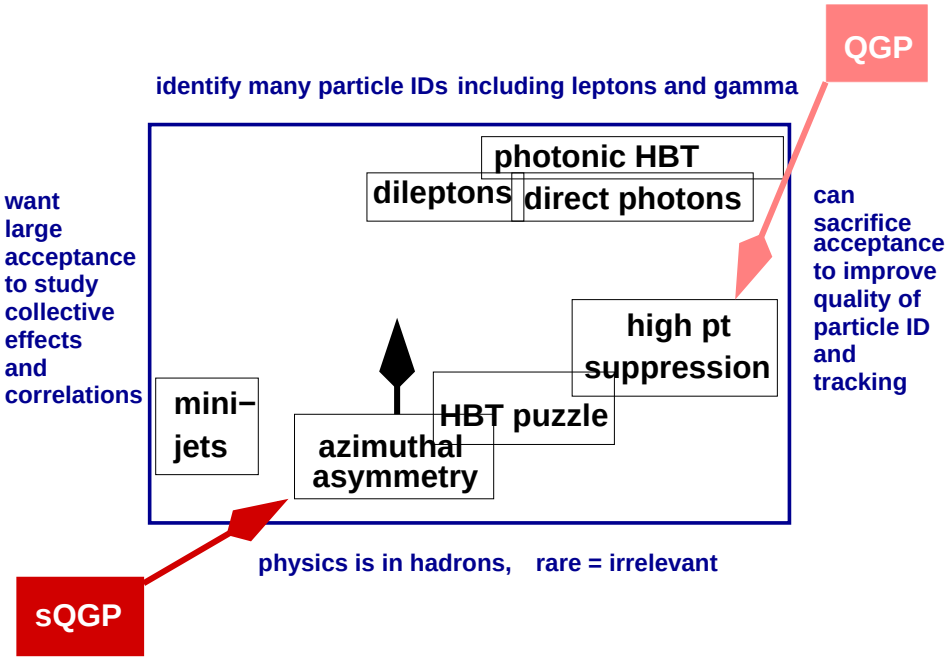

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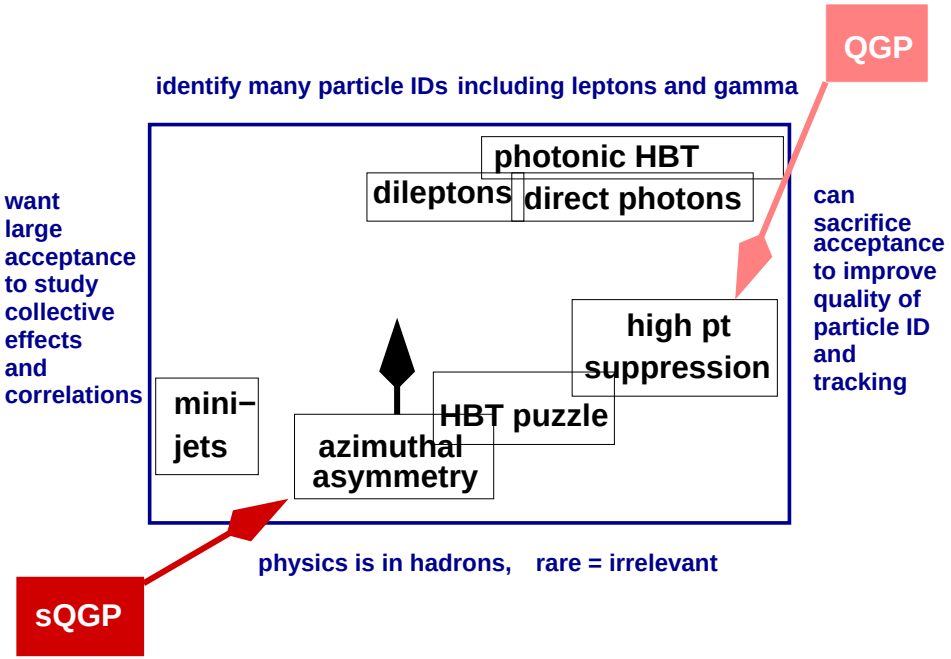

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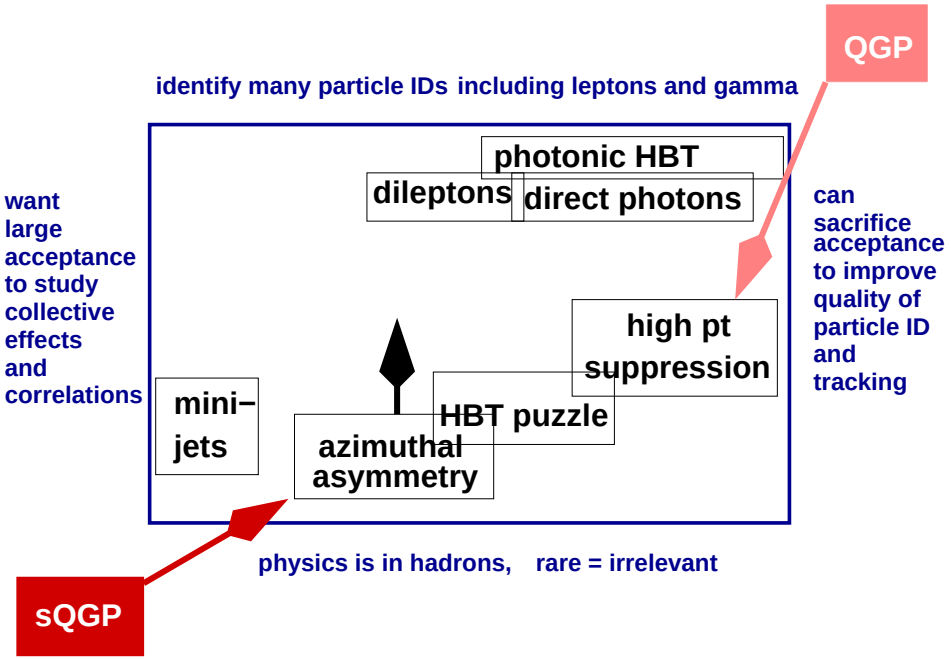

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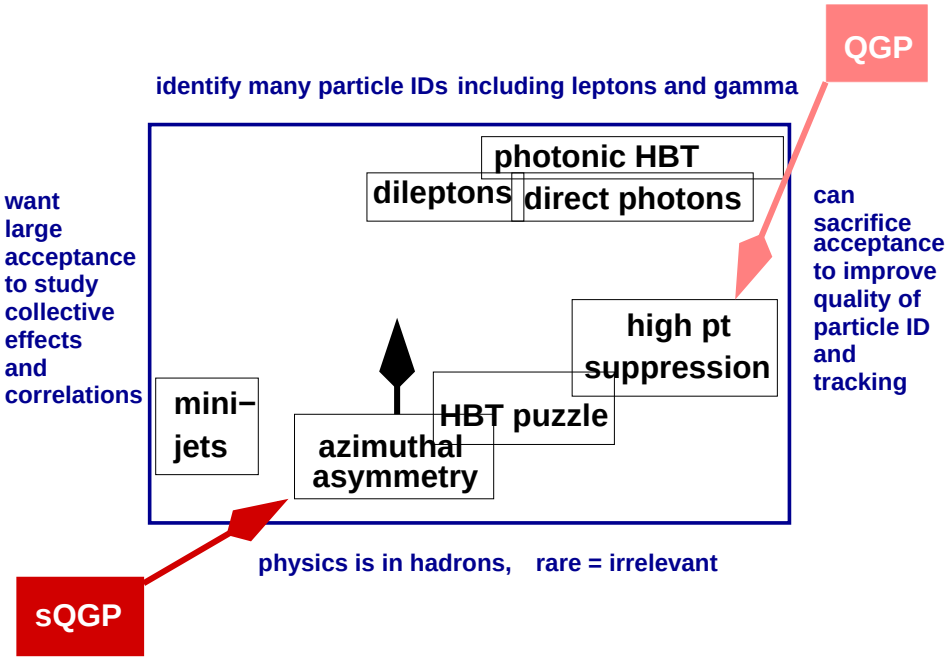
48 So what happened at RHIC ? Conclusions so far:



- first phase of the campaign: unexpectedly, a lot of action is taking place on the South-Western front! (of minimum-bias hadronic correlations)
- QGP as a theory ansatz may have been justified by the data
- to elevate QGP to the status of a discovered physical reality, need to demonstrate uniqueness of the interpretations, embrace full gamut of the phenomena, avoid "confirmation bias".