Is q-hat a physical quantity or just a parameter ? and other unanswered questions in high p_T physics

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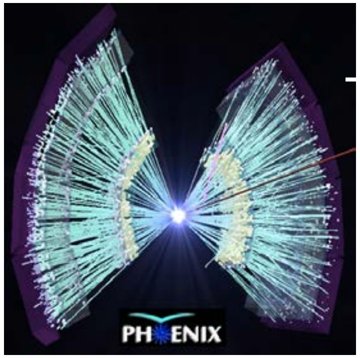


10th International Workshop on High-p_T Physics at LHC
September 9-12, 2014
Subatech, Nantes, France

First QCD-based model BDMPSZ c. 1997

I don't want to discuss models in detail, since they are nothing like QED or QCD, theories that you can set your watch by (at least QED). I just mention this one example which stimulated the use of hard-probes at RHIC. See Baier, Schiff, Zakharov, Ann. Rev. Nucl. Part. Sci. **50**, 37 (2000).

It is interesting to note that the original STAR Letter of Intent (LBL-29651) in 1990 following Wang and Gyulassy (LBL-29390) did cite as one objective: "the use of hard scattering of partons as a probe of high density nuclear matter... Passage through hadronic or nuclear matter is predicted to result in an attenuation of the jet energy and broadening of jets. Relative to this damped case, a QGP is transparent and an enhanced yield is expected."

Of course this is precisely the opposite of what was actually discovered at RHIC. Furthermore, what had been observed in A+A and p+A collisions was an enhancement of the hard scattering, a.k.a. the Cronin Effect [Phys. Rev. D**11** (1975) 3105] , rather than an attenuation. Thus, until the QCD based models, starting with Baier, Dokshitzer, Mueller, Peigné, Schiff [Nucl. Phys. B**483** (1997) 291], which I found out about only in 1998 at the IV Workshop on QCD when Rolf Baier asked me whether we could measure jets in A+A collisions at RHIC, I described the original WangGyulassy Jet Quenching as "the vanishing of something that doesn't exist in the first place".

Jets vs single high p_T particles--RHIC

- In 1998 at the QCD workshop in Paris, Rolf Baier asked me whether jets could be measured in Au+Au collisions because he had a prediction of a QCD medium-effect on colored partons in a hot-dense-medium with lots of unscreened color charge.

- As the expected energy in a typical jet cone $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is $\pi R^2 \times 1/2\pi \times dE_T/d\eta = R^2/2 \times dE_T/d\eta \sim$ 350 GeV for R=1 at $\sqrt{s_{NN}}$=200 GeV where the maximum Jet energy is 100 GeV, I said that Jets can not be reconstructed in Au+Au central collisions at RHIC—still correct after 16 years.

- Hard scattering was discovered in p-p at the CERN-ISR 1972 with single particle and few particle correlations, while jets had a long learning curve from 1977-1982, with false claims! So use single and few particles---which we did and it WORKED!

- The solution (LHC 2010 and) RHIC c.2014 is to take smaller cones: 60 GeV in R=0.4, 34 GeV in R=0.3, 15 GeV in R=0.2.

q-hat ($\hat{q}$)

The many different theoretical studies of energy loss of a quark or gluon with their color charges fully exposed passing through a medium with a large density of similarly exposed color charges (i.e. a QGP), have one thing in common: the transport coefficient of a gluon in the medium, denoted $\hat{q}$, which is defined from the mean 4-momentum transfer^2/collision but is expressed as the mean 4-momentum transfer^2 per mean free path of a gluon in the medium. Thus the mean 4-momentum transfer^2 for a gluon traversing length L in the medium is, $\langle q^2(L)\rangle = \hat{q}\,L = \mu^2\,L/\lambda_{\rm mfp}$, where $\lambda_{\rm mfp}$ is the mean free path for a gluon interaction in the medium, and μ, the mean momentum transfer per collision, is the Debye screening mass acquired by gluons in the medium. In this, the original BDMPSZ formalism, the energy loss of an outgoing parton due to coherent gluon bremsstrahlung per unit length (x) of the medium, $-dE/dx$, takes the form:

$$\frac{-dE}{dx} \simeq \alpha_s \left\langle q^2(L)\right\rangle = \alpha_s\,\hat{q}\,L = \alpha_s\,\mu^2\,L/\lambda_{\rm mfp} \qquad ,$$

so that the total energy loss in the medium goes like L^2. Also the accumulated transverse momentum^2, $\langle k_\perp^2\rangle$, for a gluon traversing a length L in the medium is well approximated by $\langle k_\perp^2\rangle \approx \langle q^2(L)\rangle = \hat{q}\,L$.

Is q-hat visible in di-jet broadening?

Also, Rolf Baier thinks that it is possible for a parton to emerge from the center of the medium without a large energy loss (i.e. no LPM) , only BH , which Salgado and Wiedemann seem to have ignored and which is the result of multiple scattering with total $Q^2=\mu^2 L/\lambda=\hat{q}L$, where L is the length of the medium traversed. However, this accentuates something that is puzzling to me. Why has nobody ever seen evidence for this?

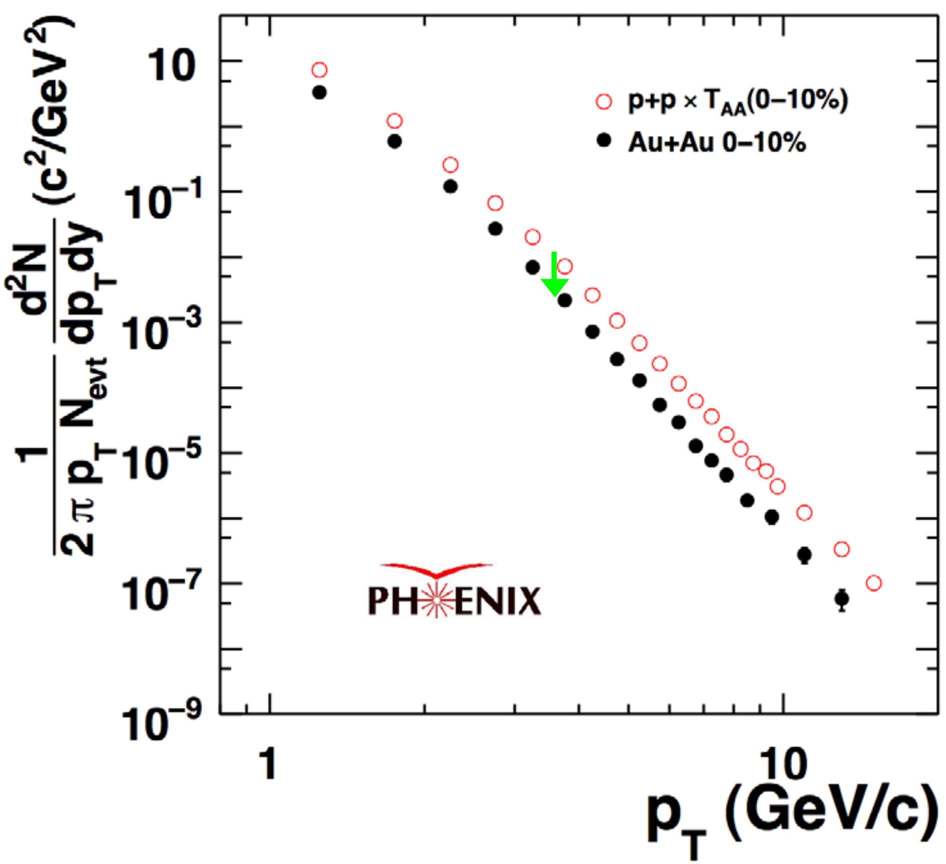
A simple estimate shows that the $\langle k_\perp^2 \rangle \approx \hat{q}\,L$ should be observable at RHIC via the broadening of di-hadron azimuthal correlations. For a trigger particle with p_{T_t}, assume that the away-parton traverses slightly more than half the diameter of the QGP for central collisions of Au+Au, say 8 fm. This corresponds to $\langle k_\perp^2 \rangle = \hat{q}\,L = 8$ GeV^2, for $\hat{q} = 1$ GeV^2/fm, compared to the measured $\langle k_T^2 \rangle = 8.0 \pm 0.2$ (GeV/c)^2 for di-hadrons in $p-p$ collisions at $\sqrt{s_{NN}}$ =200 GeV, which should be visible as an azimuthal width $\sim \sqrt{2}$ larger in Au+Au than in $p-p$ collisions . So far the systematic uncertainties due to the flow background, v_2, $v_3 \ldots v_n$, for di-hadron measurements, or the very large $p_T \simeq 100$ GeV where di-jets are measured have obscured this signal.

A long story!

The BDMPSZ prediction led to the most important innovation at RHIC: the use of hard-scattering as an in-situ probe of the medium in RHI collisions

RHIC π^0 pp vs AuAu

π^0 are suppressed in Au+Au eg 200 GeV



Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{d^2N^{\pi}_{AA}/dp_T dy N^{inel}_{AA}}{\langle T_{AA}\rangle d^2\sigma^{\pi}_{pp}/dp_T dy}$$

RHIC π^0 pp vs AuAu

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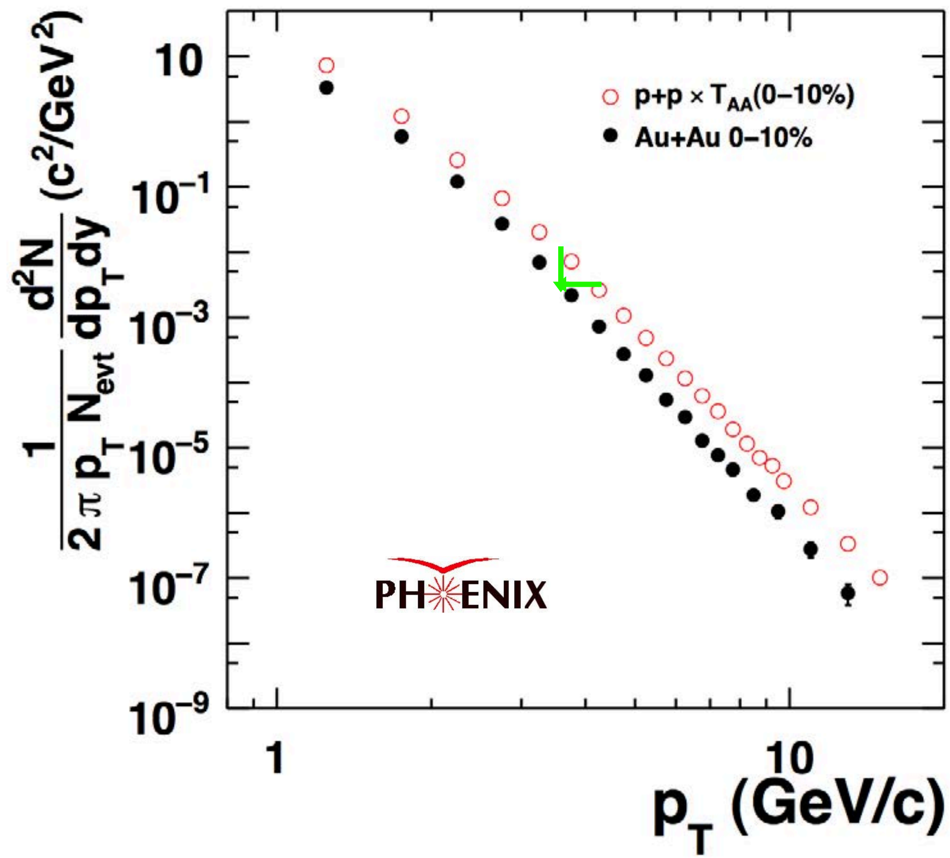

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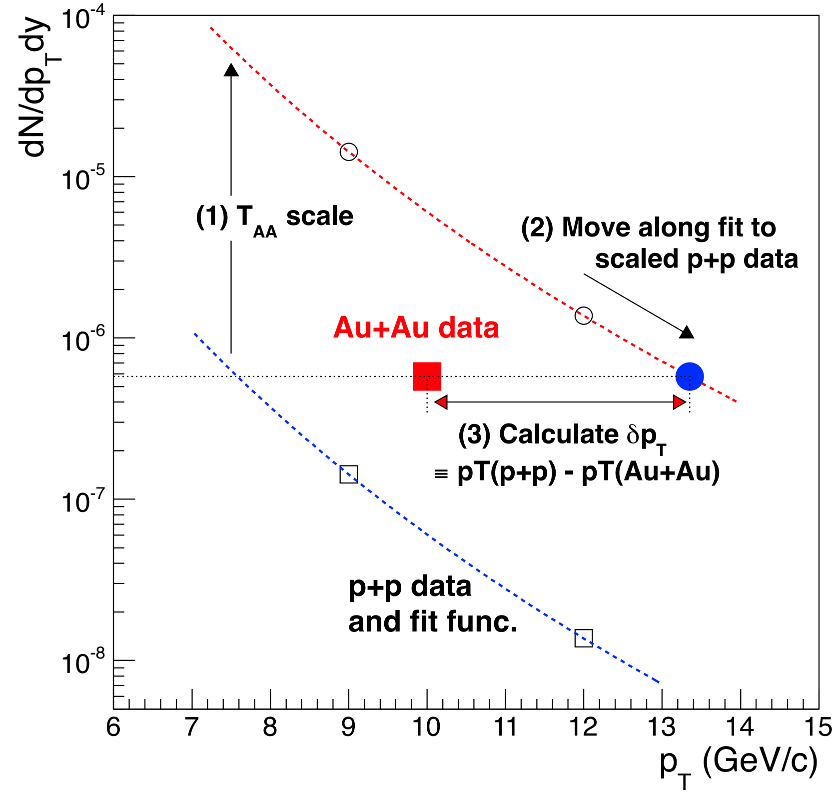
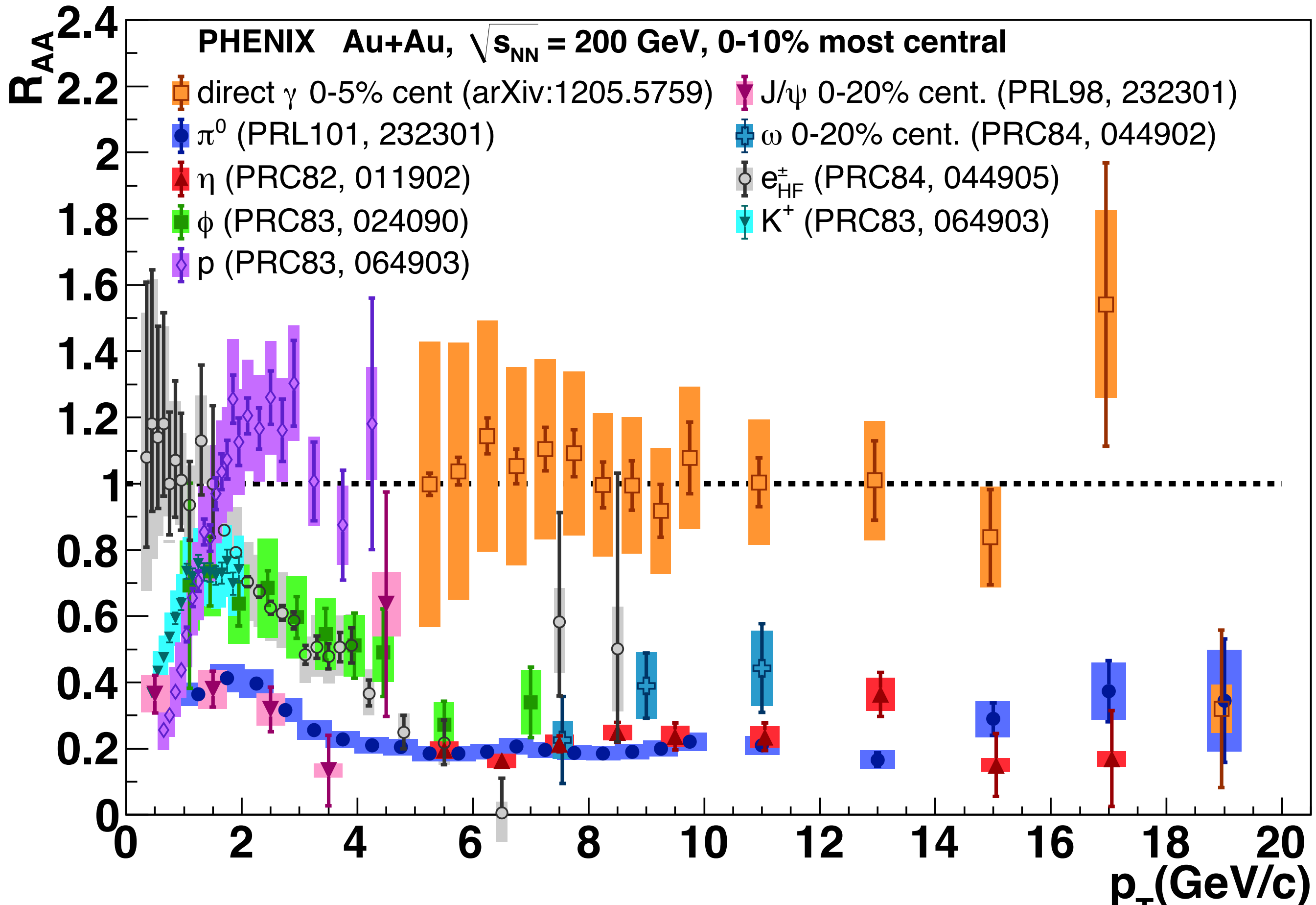
$$R_{AA}(p_T) = \frac{d^2N^{\pi}_{AA} / dp_T dy N^{inel}_{AA}}{\langle T_{AA} \rangle d^2\sigma^{\pi}_{pp} / dp_T dy}$$



After a decade of the ratio R_{AA} we are now paying more attention to δp_T the shift in the p_T spectrum as an indicator of energy loss in the QGP

Status of R_{AA} in AuAu at $\sqrt{s_{NN}}$=200 GeV 2013

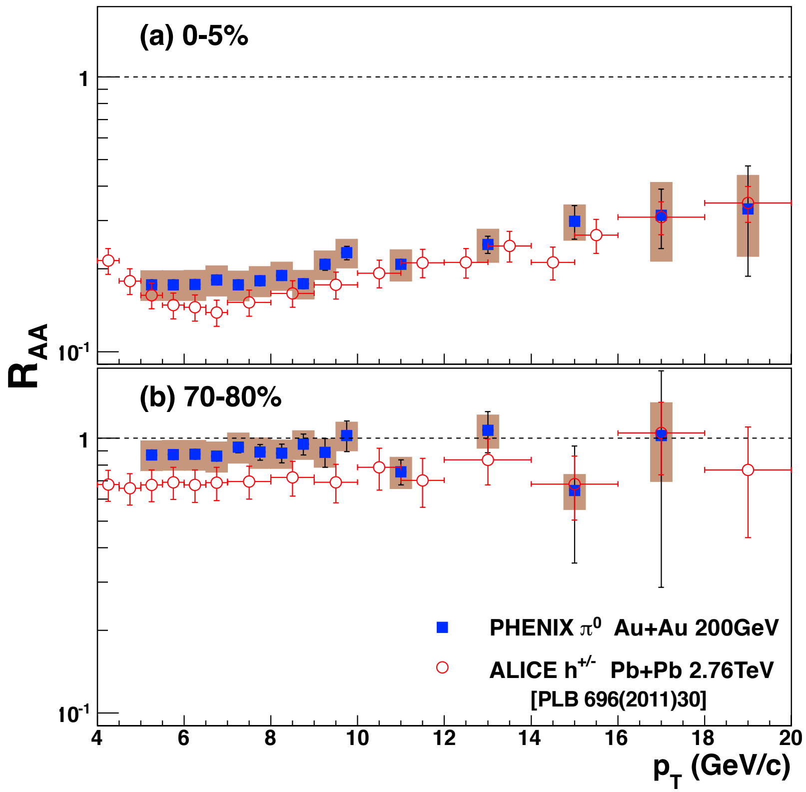


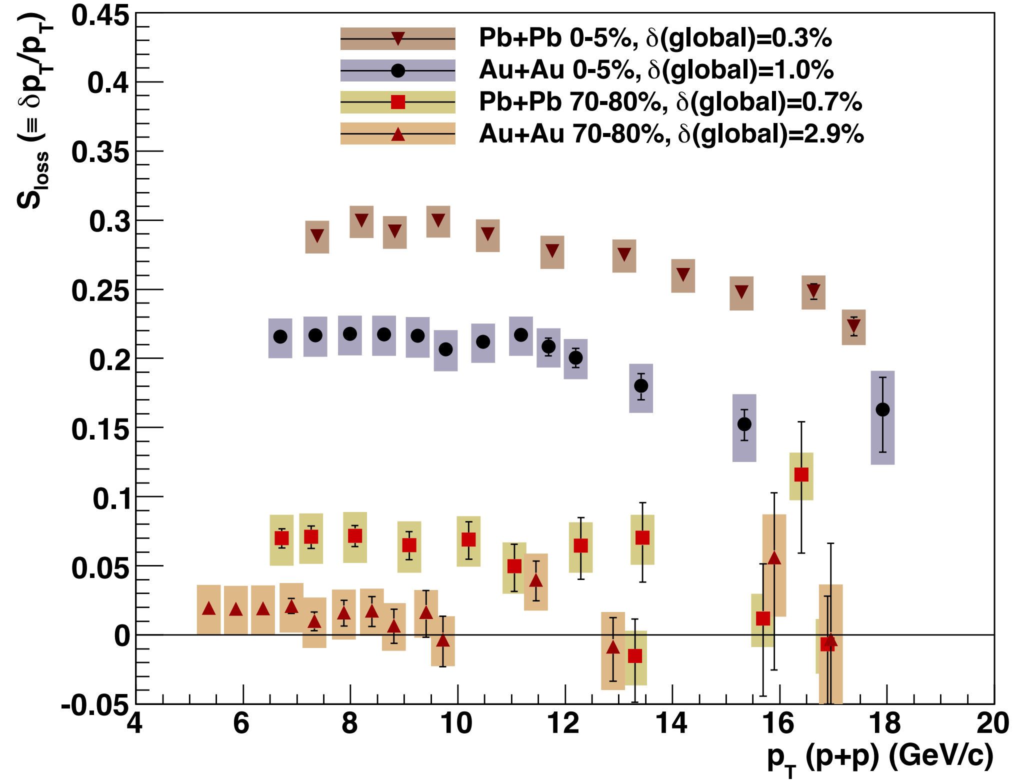
particle ID is crucial: different particles behave differently

Notable are that ALL particles are suppressed for p_T>2 GeV/c (except for direct-γ), even electrons from c and b quark decay; with one notable exception: the protons are enhanced-(baryon anomaly)

RHIC $\sqrt{s_{NN}}$=200 GeV cf. LHC $\sqrt{s_{NN}}$=2.76 TeV

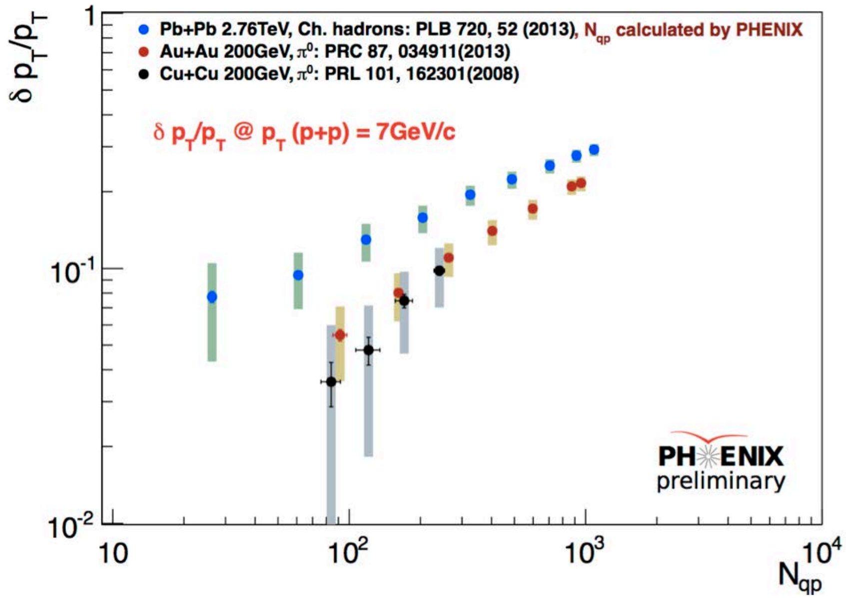
PHENIX PRC **87** (2013) 034911

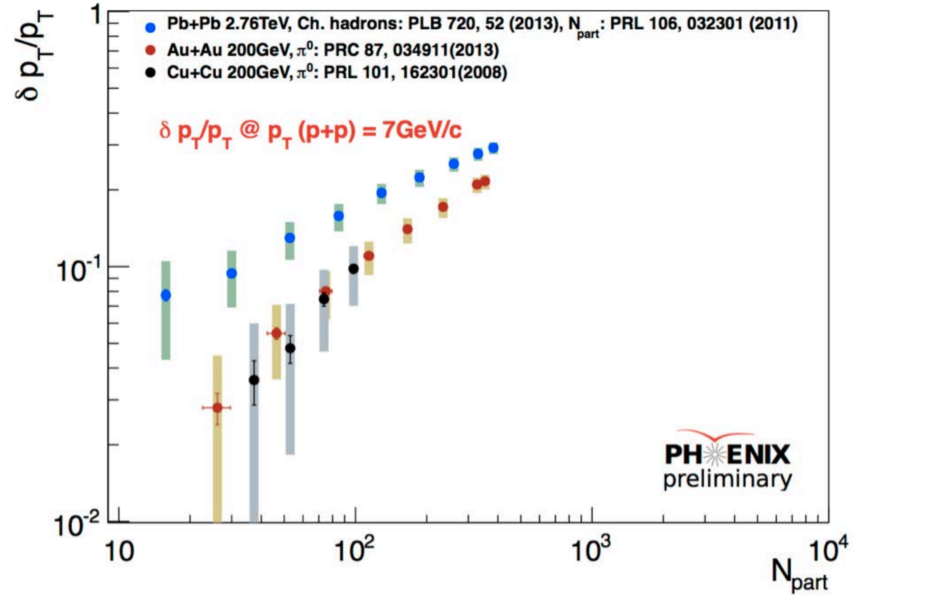


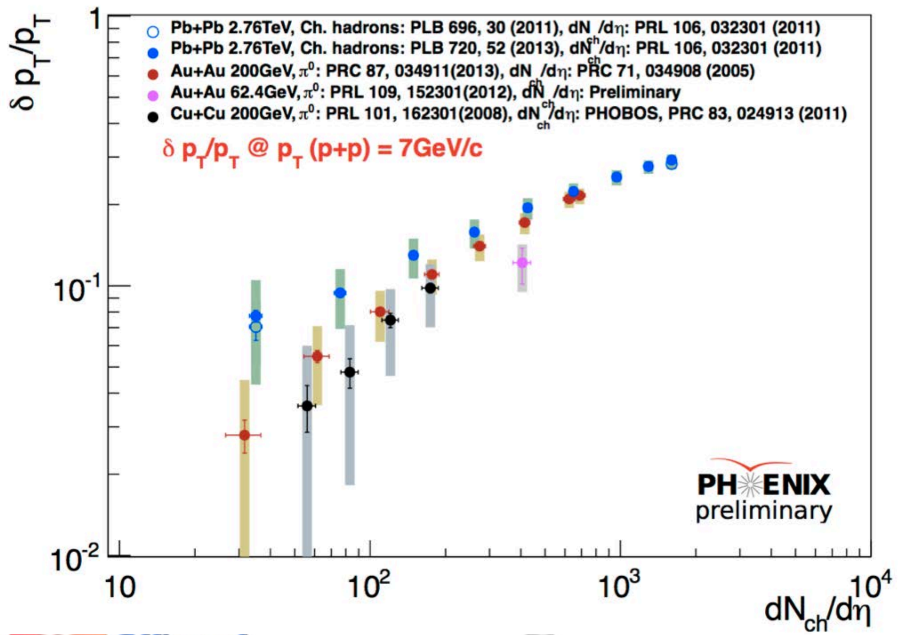


Agreement of ALICE $h^{\pm}$ R_{AA} with PHENIX π^0 in the overlap region $5<p_T<20$ GeV/c is incredible; BUT because invariant p_T spectrum at LHC is flatter than at RHIC, spectrum shift $\delta p_T/p_T$ is ~40% larger at LHC than at RHIC presumably due to the hotter and possibly denser medium.

NEW-What determines energy loss $\delta p_T/p_T$?

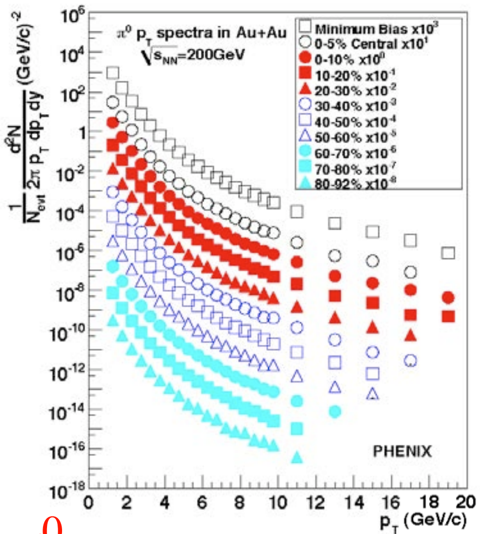






As suggested by Shuryak at this meeting last year $\delta p_T/p_T$ scales best with $dN_{ch}/d\eta$ but is not quite universal $\delta p_T/p_T \approx (dN_{ch}/d\eta)^{\alpha}$,
$\alpha \approx 0.35$ @ 2.76 TeV,
$\alpha \approx 0.55$ @200 GeV
but curves merge at large $dN_{ch}/d\eta$

RHI physics is based on Precision Msmts + QCD

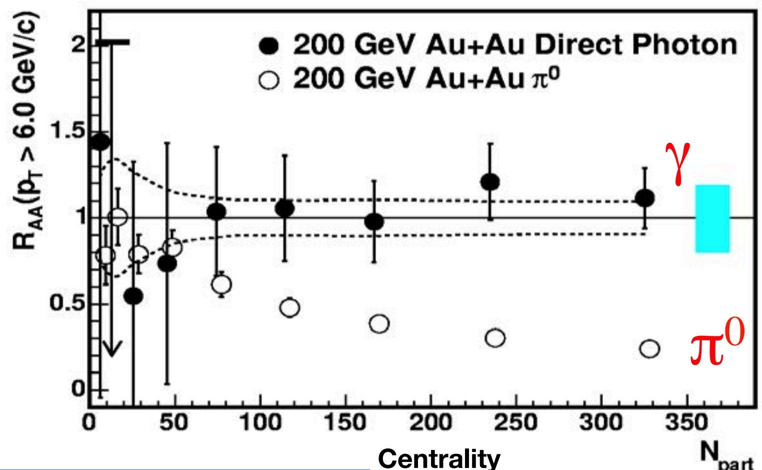


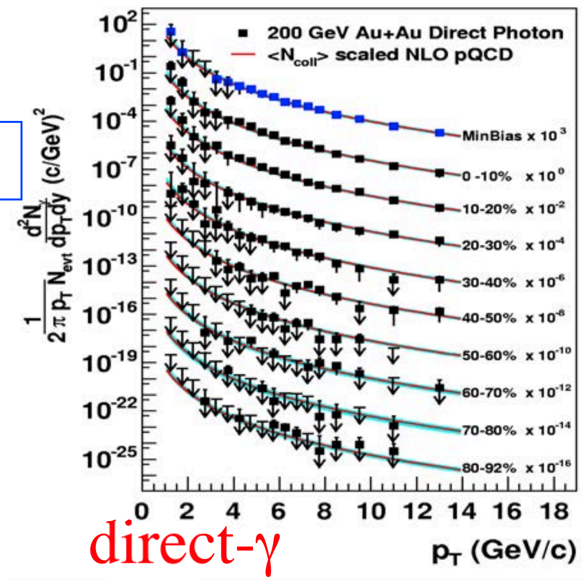
π^0

- This one figure encodes rigorous control of systematics

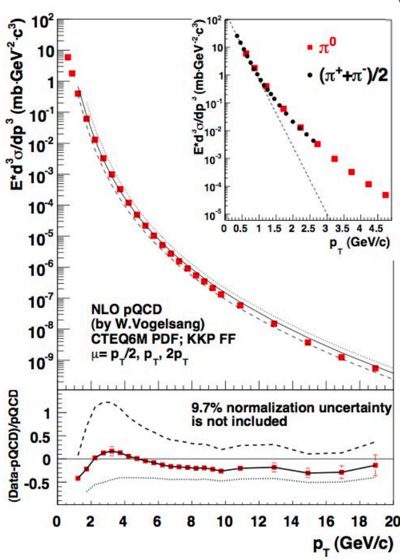
PRL**94** (2005) 232301

PRL**101** (2008) 232301



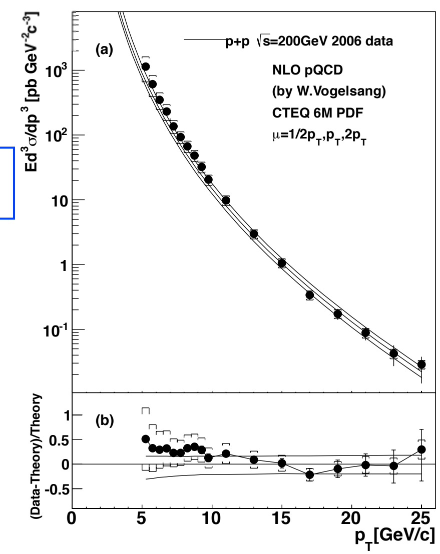


direct-γ



PRD**76** (2007) 051106(R)

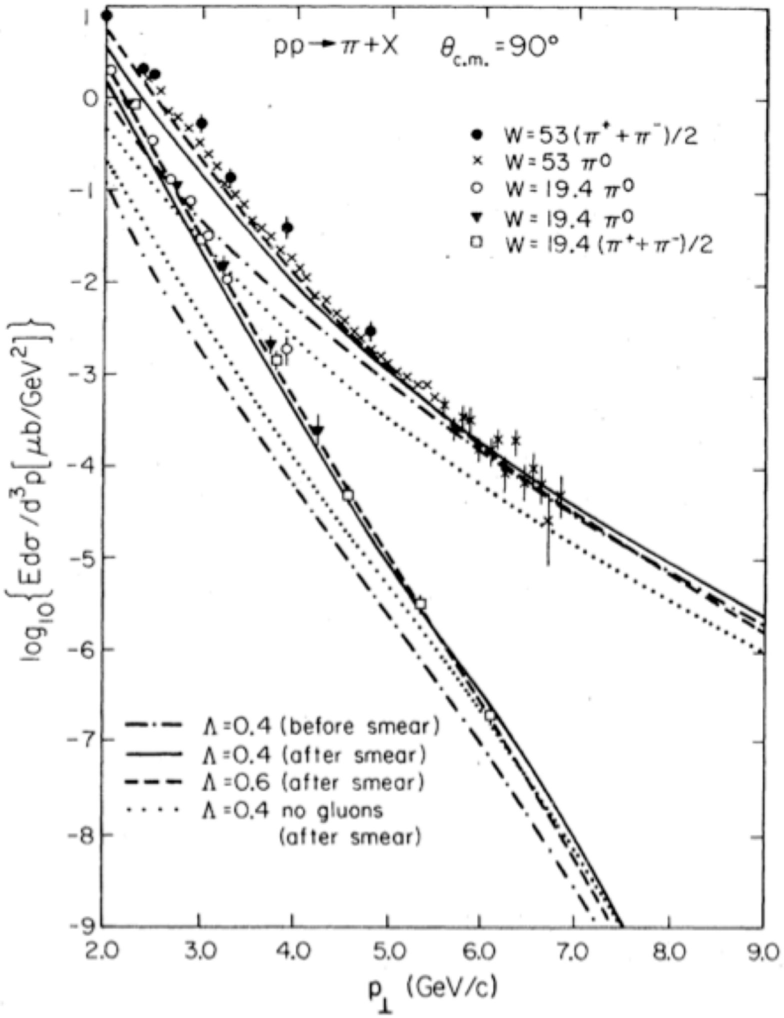
PRD **86** (2012) 072008



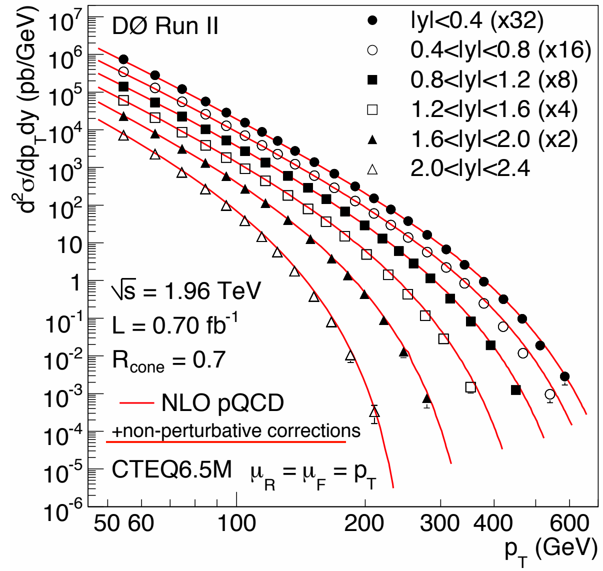
- in four different measurements over many orders of magnitude

Direct photons unaffected by QGP medium in Au+Au →
π^0 suppression is medium effect

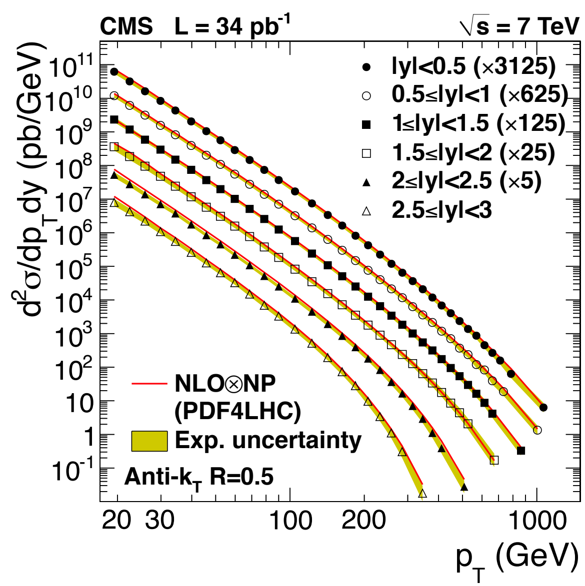
pQCD works for single particle and jets



Feynman, Field, Fox PRD 18 (1978) 3320 with $<k_T>$=0.85 GeV/c and $\Lambda_{QCD}\approx$0.5 GeV



D0 1.96 TeV PRL **101** (2008) 062001 Note power laws steepen at larger y and drop sharply at largest p_T due energy conservation



CMS 7 TeV PRL **107** (2011) 132001 Note power laws have weaker drop and smaller change with rapidity. We knew that QCD worked. This shows that partons are pointlike to $Q^2=2p_T^2$=2million $(GeV/c)^2$ =1.4 10^{-19}m

LO-QCD in 1 slide

Cross Section in p-p collisions c.m. energy $\sqrt{s}$

The overall p-p reaction cross section
is the sum over constituent reactions

$$a + b \rightarrow c + d$$

$f_a^A(x_1)$, $f_b^B(x_2)$, are structure functions, the differential probabilities for constituents a and b to carry momentum fractions x_1 and x_2 of their respective protons, e.g. $u(x_1)$,

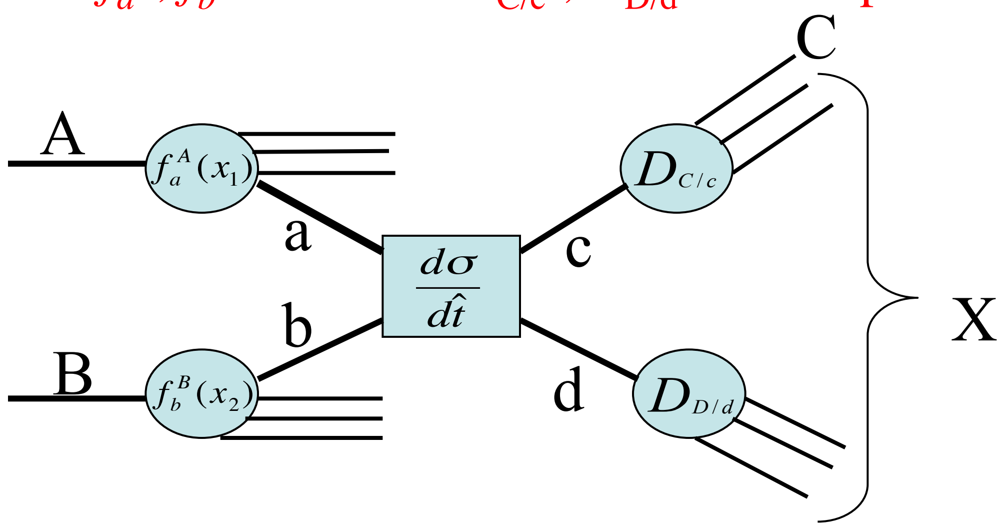
$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{1}{s}\sum_{ab} f_a^A(x_1) f_b^B(x_2) \frac{\pi\alpha_s^2(Q^2)}{2x_1x_2}\Sigma^{ab}(\cos\theta^*)$$

$\Sigma^{ab}(\cos\theta^*)$, the characteristic subprocess angular distributions and $\alpha_s(Q^2) = \frac{12\pi}{25\ln(Q^2/\Lambda^2)}$ are predicted by QCD

LO-QCD in 1 slide

Cros... $\sqrt{s}$

PDF's f_a^A, f_b^B and FF's $D_{C/c}$, $D_{D/d}$ are not predicted



$f_a^A(x_1)$, f_b^B ... robabilities
for const... $_1$ and x_2

$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{1}{s}\sum_{ab} f_a^A(x_1) f_b^B(x_2) \frac{\pi\alpha_s^2(Q^2)}{2x_1x_2}\Sigma^{ab}(\cos\theta^*)$$

$\Sigma^{ab}(\cos\theta^*)$, the characteristic subprocess angular distributions and $\alpha_s(Q^2) = \frac{12\pi}{25\ln(Q^2/\Lambda^2)}$ are predicted by QCD

Σ^{ab} (cosθ*) in LO-QCD

a) $qq' \to qq'$, $\bar{q}q' \to \bar{q}q'$ $\quad \dfrac{4}{9}\dfrac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$

b) $qq \to qq$ $\quad \dfrac{4}{9}\left(\dfrac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\dfrac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\dfrac{8}{27}\dfrac{\hat{s}^2}{\hat{u}\hat{t}}$

c) $\bar{q}q \to \bar{q}'q'$ $\quad \dfrac{4}{9}\dfrac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$

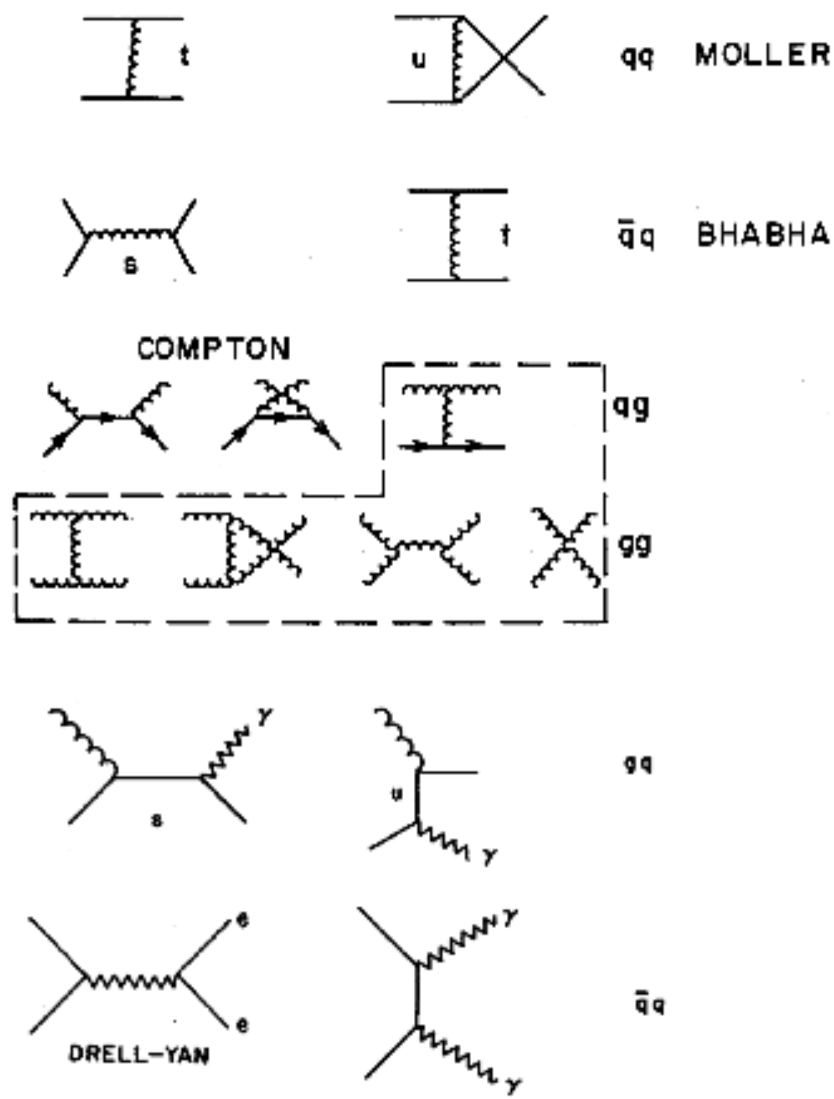
d) $\bar{q}q \to \bar{q}q$ $\quad \dfrac{4}{9}\left(\dfrac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\dfrac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\dfrac{8}{27}\dfrac{\hat{u}^2}{\hat{s}\hat{t}}$

e) $\bar{q}q \to gg$ $\quad \dfrac{32}{27}\dfrac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\dfrac{8}{3}\dfrac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}$

f) $gg \to \bar{q}q$ $\quad \dfrac{1}{6}\dfrac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\dfrac{3}{8}\dfrac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}$

g) $qg \to qg$ $\quad -\dfrac{4}{9}\dfrac{\hat{u}^2+\hat{s}^2}{\hat{u}\hat{s}}+\dfrac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}$

h) $gg \to gg$ $\quad \dfrac{9}{2}\left(3-\dfrac{\hat{u}\hat{t}}{\hat{s}^2}-\dfrac{\hat{u}\hat{s}}{\hat{t}^2}-\dfrac{\hat{s}\hat{t}}{\hat{u}^2}\right)$



$\Sigma^{ab}(\cos\theta^*)$ and the spin asymmetry are Fundamental predictions of QCD

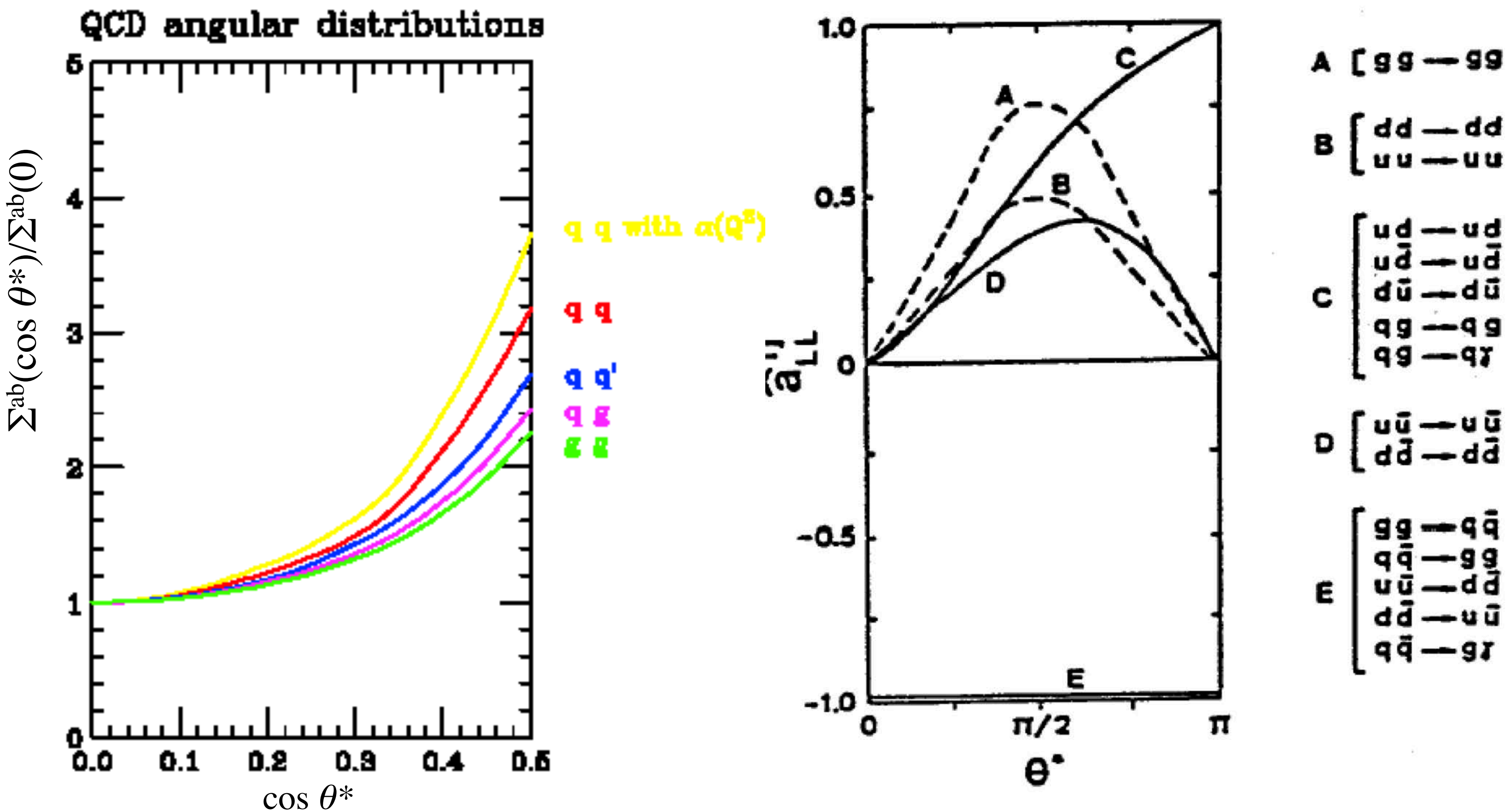
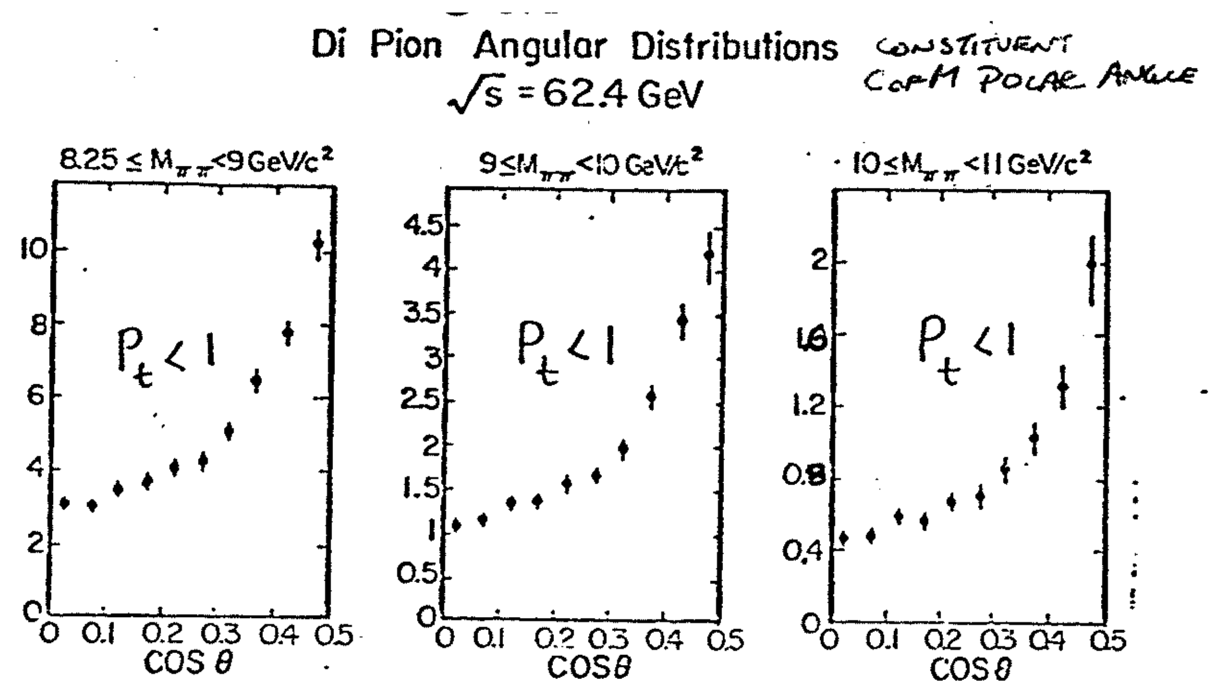


Fig. 2. Characteristic QCD Subprocess angular distributions: (a) scattering; (b) spin asymmetry

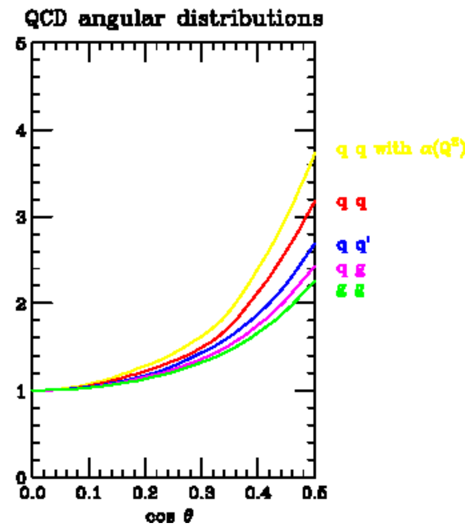
QCD is the correct theory of the strong interactions which generally works in p-p collisions at RHIC and LHC; BUT one of the major problems is that the structure and fragmentation functions must be put in by hand. So I think that pure data-driven analyses are a better test of the basic theory.

ICHEP Paris1982-first measurement of QCD subprocess angular distribution $S^{ab}(\cos q^*)$ using π^0-π^0 correlations

DATA: CCOR NPB 209, 284 (1982)



QCD



$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{1}{s}\sum_{ab} f_a^A(x_1) f_b^B(x_2) \frac{\pi\alpha_s^2(Q^2)}{2x_1x_2}\Sigma^{ab}(\cos\theta^*)$$

$\Sigma^{ab}(\cos\theta^*)$, the characteristic subprocess angular distributions and $\alpha_s(Q^2) = \frac{12\pi}{25\ln(Q^2/\Lambda^2)}$ are predicted by QCD

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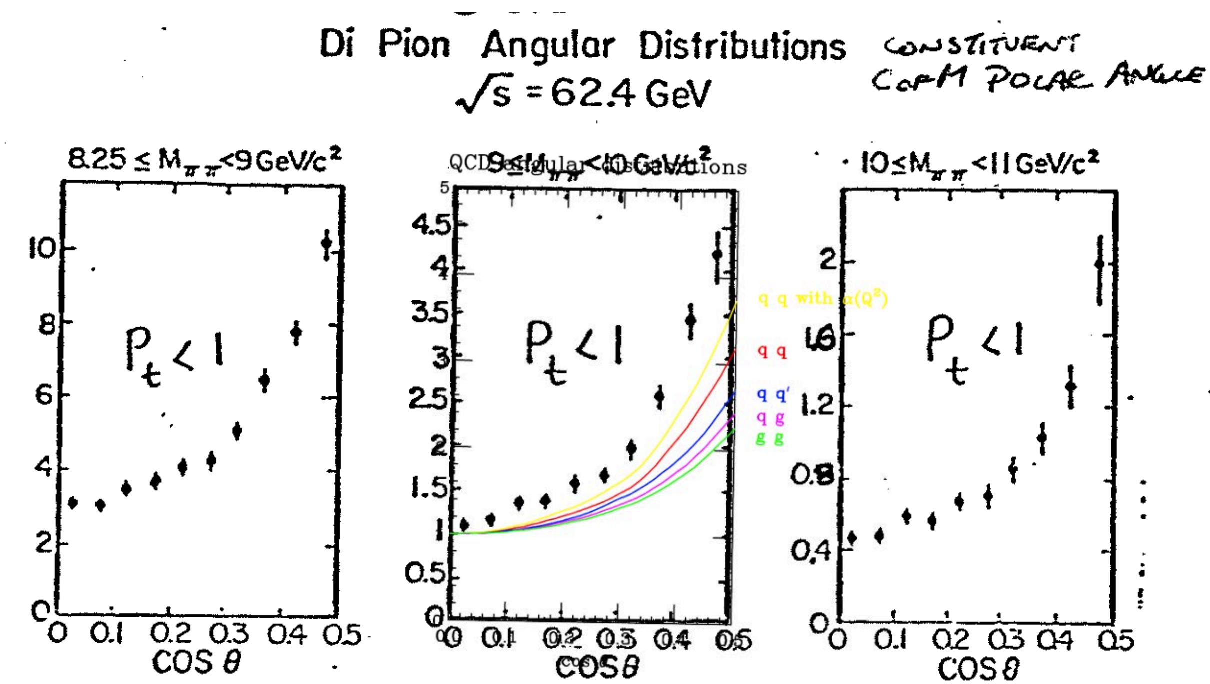
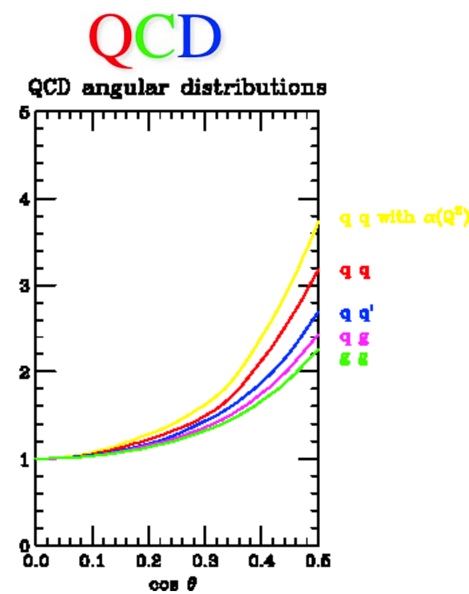




$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{1}{s}\sum_{ab} f_a^A(x_1) f_b^B(x_2) \frac{\pi\alpha_s^2(Q^2)}{2x_1x_2} \Sigma^{ab}(\cos\theta^*)$$

$\Sigma^{ab}(\cos\theta^*)$, the characteristic subprocess angular distributions and $\alpha_s(Q^2) = \frac{12\pi}{25\ln(Q^2/\Lambda^2)}$ are predicted by QCD

x_T scaling

The invariant cross section for the single-particle inclusive reaction $p + p \to C + X$ where particle C has transverse momentum p_T near mid-rapidity, was given by the general scaling form [54]:

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^n} F\left(\frac{2p_T}{\sqrt{s}}\right) \quad \text{where} \quad x_T = 2p_T/\sqrt{s}$$

There are 2 factors: a function F which depends only on the ratio of momenta, and a dimensioned factor, p_T^{-n}, where n depends on the quantum exchanged in the hard-scattering. For QED or Vector Gluon exchange [53], $n = 4$. For the case of quark-meson scattering by the exchange of a quark [54], n=8.

Inclusion of QCD [58] into the scaling form led to the x_T-scaling law

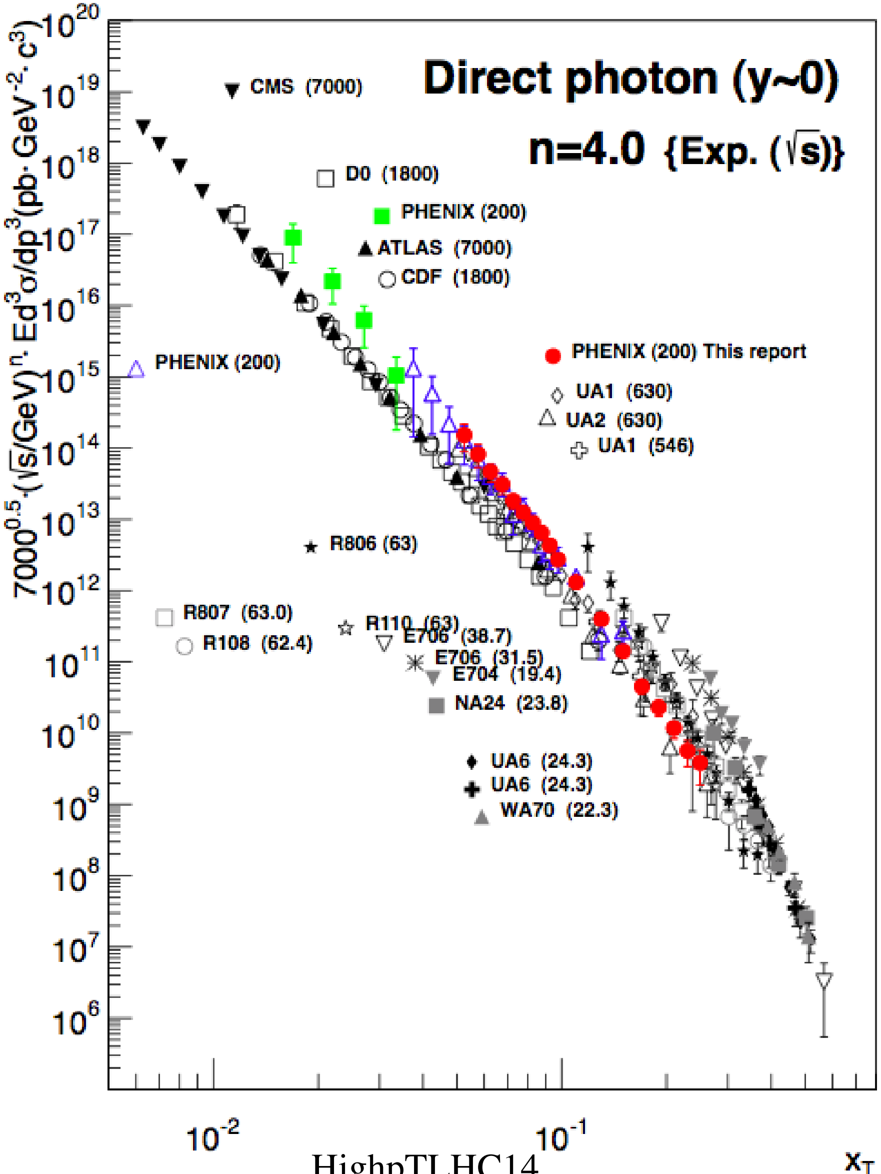
$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^{\,n(x_T,\sqrt{s})}} G(x_T)$$

where the "x_T-scaling power" $n(x_T, \sqrt{s})$ should equal 4 in lowest order (LO) calculations, analogous to the $1/q^4$ form of Rutherford Scattering in QED. The structure and fragmentation functions, which scale as the ratios of momenta are all in the $G(x_T)$ term. Due to higher order effects such as the running of the coupling constant, $\alpha_s(Q^2)$, the evolution of the structure and fragmentation functions, and the initial state k_T, measured values of $n(x_T, \sqrt{s})$ in $p + p$ collisions are in the range from 5 to 8.

QCD in Action 2012 in Direct γ production g+q→γ+q

See the classic paper of Fritzsch and Minkowski, PLB **69** (1977) 316-320

Plot by PHENIX Phys. Rev. D86(2012) 072008



x_T scaling with n_{eff}=4 (parton model) QCD non-scaling is visible

Collection of World's direct-γ measurements in (p+p / p+pbar) including PHENIX low p_T msmt. PRL104(2010)132301and PRC87(2013)054907

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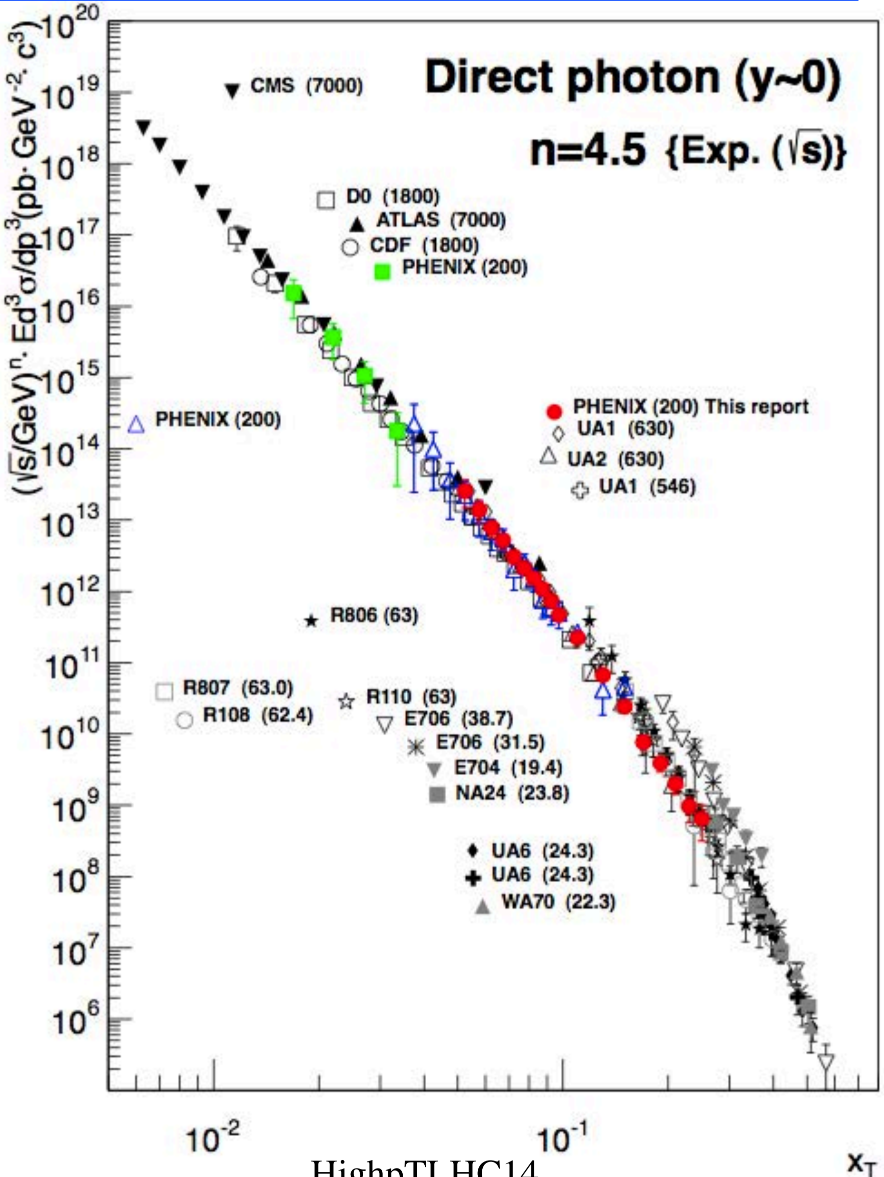


x_T scaling with n_{eff}=4.5 works for direct-γ due to QCD non-scaling

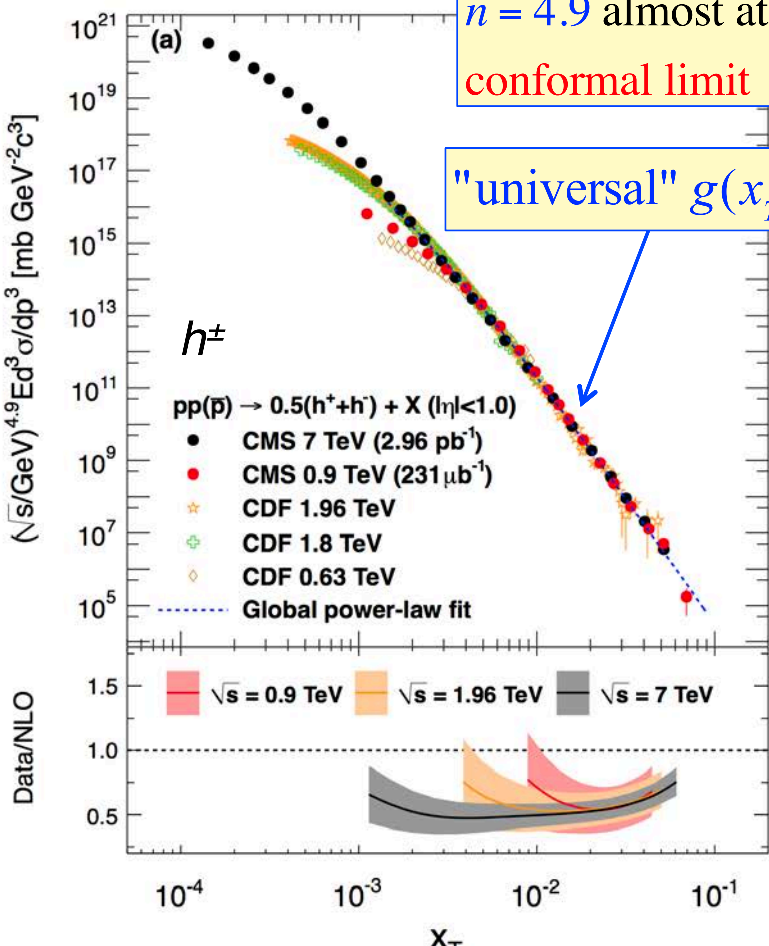
Collection of World's direct-γ measurements in (p+p / p+pbar) including PHENIX low p_T msmt. PRL104(2010)132301and PRC87(2013)054907

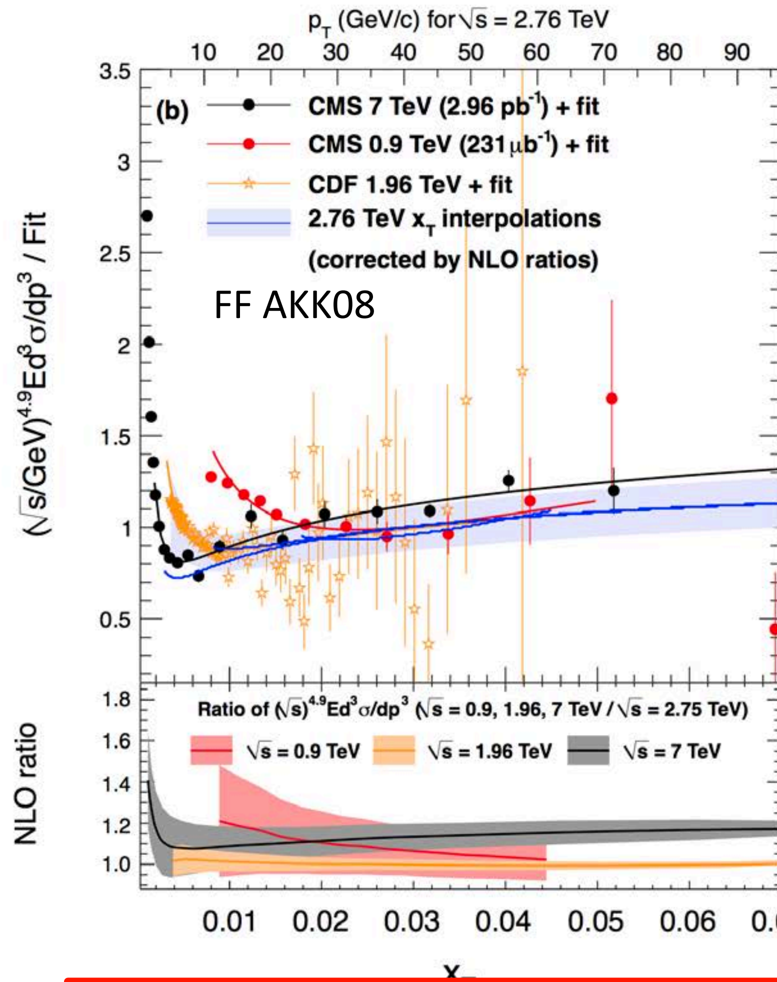
$$E\frac{d^3\sigma}{d^3p} \propto \frac{1}{\sqrt{s}^{4.9}}\, g(x_T), \quad x_T \equiv \frac{2p_T}{\sqrt{s}}$$

Good old x_T scaling holds at LHC

$n = 4.9$ almost at conformal limit

"universal" $g(x_T)$





$g(x_T,\vartheta)$ scaled empirically $(\sqrt{s})^{4.9}$

Scaling holds in $\sqrt{s}$=0.6-7 TeV !

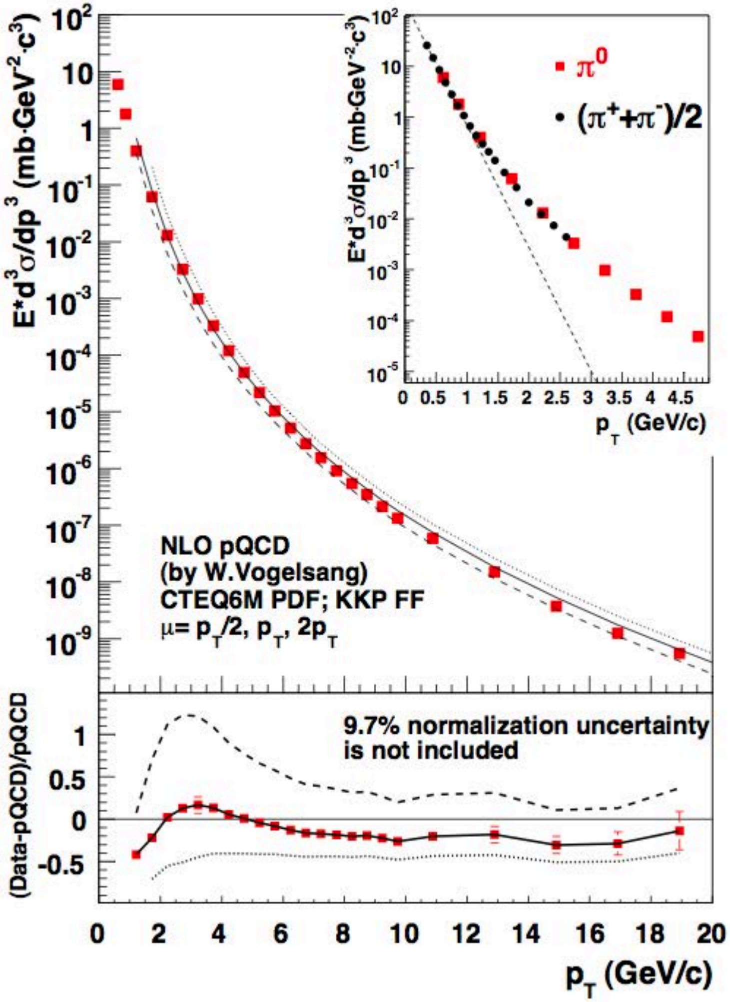
Factor of 2 deviation from NLO

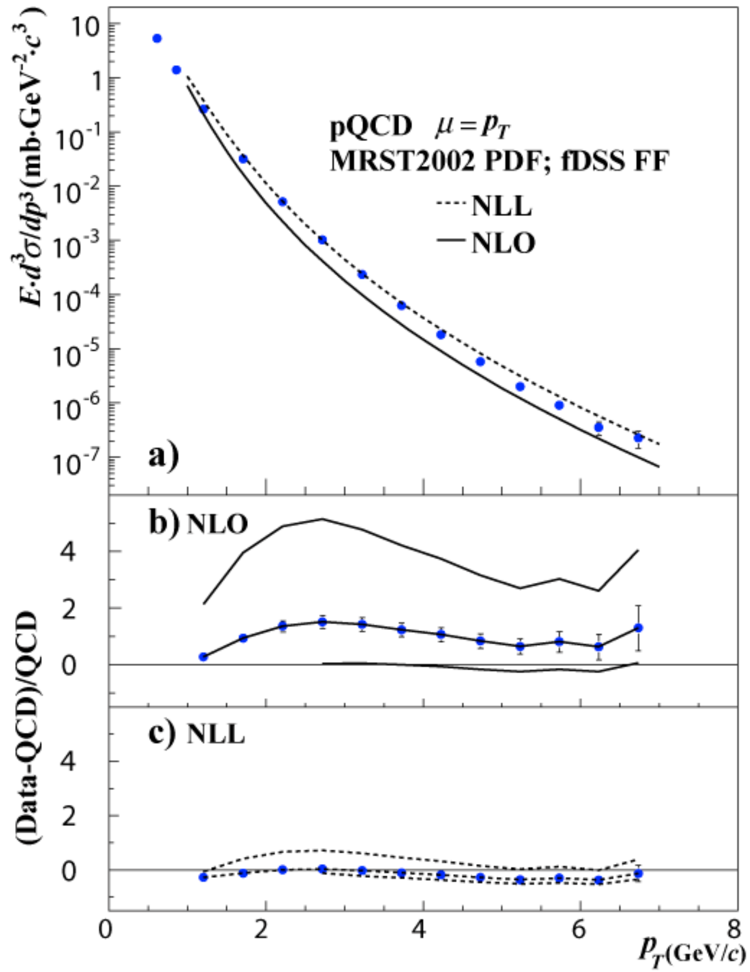
JHEP08 **2011** 086

Note that x_T scaling works but the data disagree with NLO-QCD. Not every calculation labeled QCD is correct, according to me. In Prague, Kari Eskola asked me whether I believed in QCD. I said, "of course but I am skeptical of many calculations that claim to be QCD."

Even the good calculations have issues

p-p √s=200 GeV PHENIX **PRD76** (2007) 051106(R)





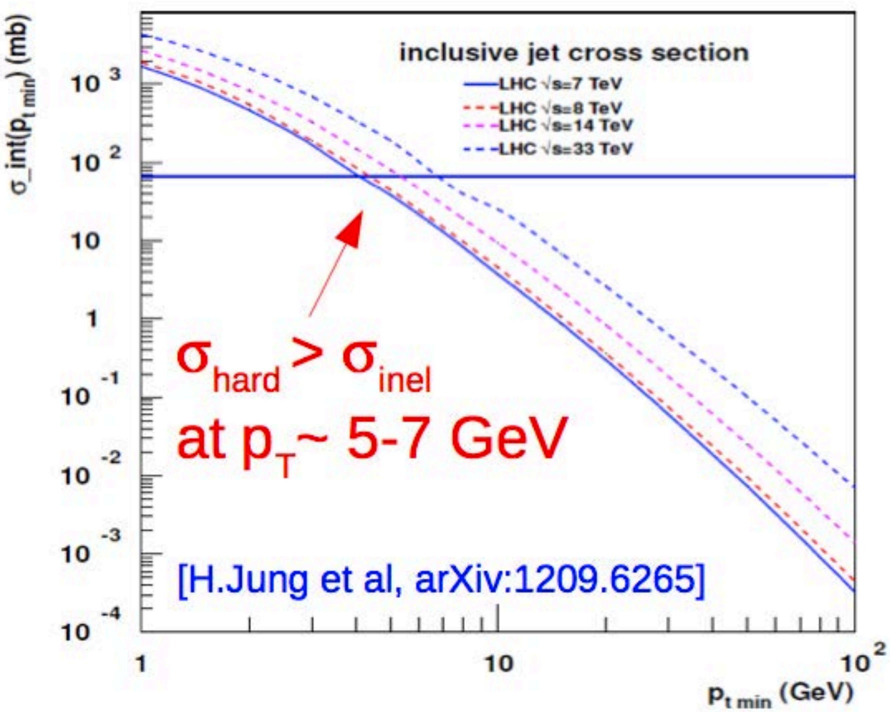
p-p √s=62.4 GeV PHENIX **PRD79** (2008) 241803

Uncertainties are factorization scales for PDF and FF and renormalization scale for $\alpha_s(Q^2)$, all represented by a parameter μ, which lead to uncertainties of factor of ~2 as well as disagreements, e.g. by factor of 2 at 62.4 GeV, in NLO QCD calculations

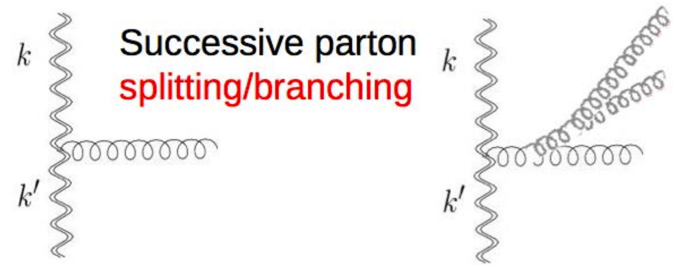
Then there are the others (from Jan Rak-Crete)

pQCD (mini)jet production x-section is larger than total inelastic *p-p* x-section for p_{Tmin}~ 5-7 GeV at the LHC !

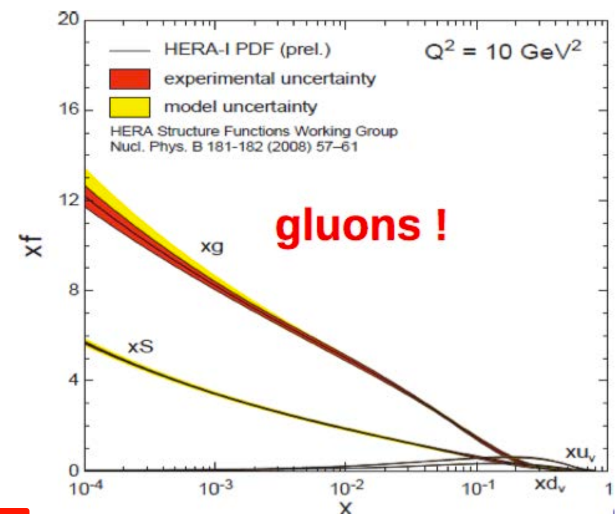
Phys.Rev., 2012, D86, 117501



DGLAP PDF evolution



Too many gluons at low *x*



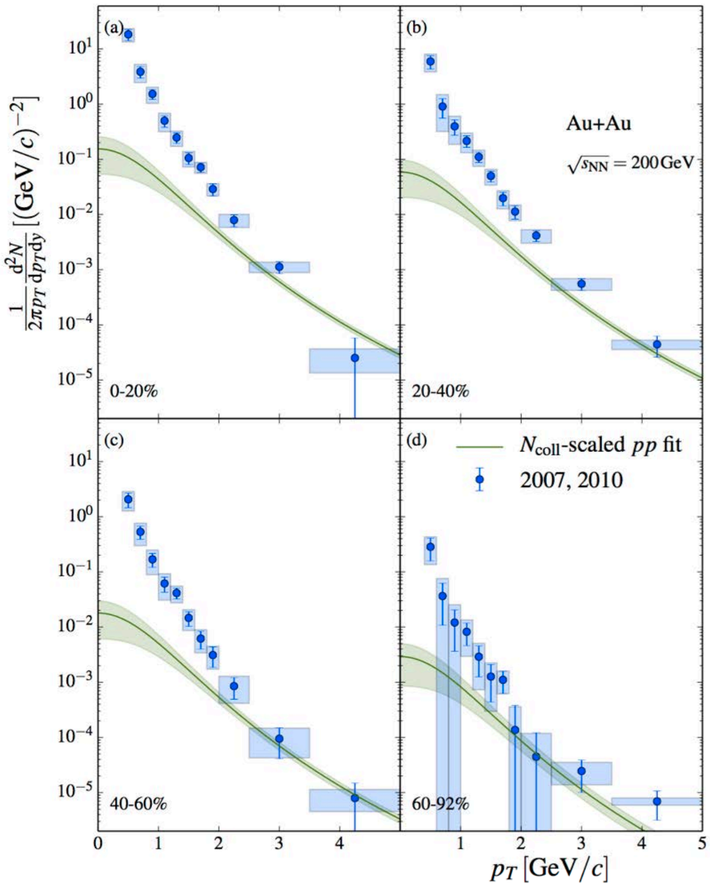
Possible solutions:

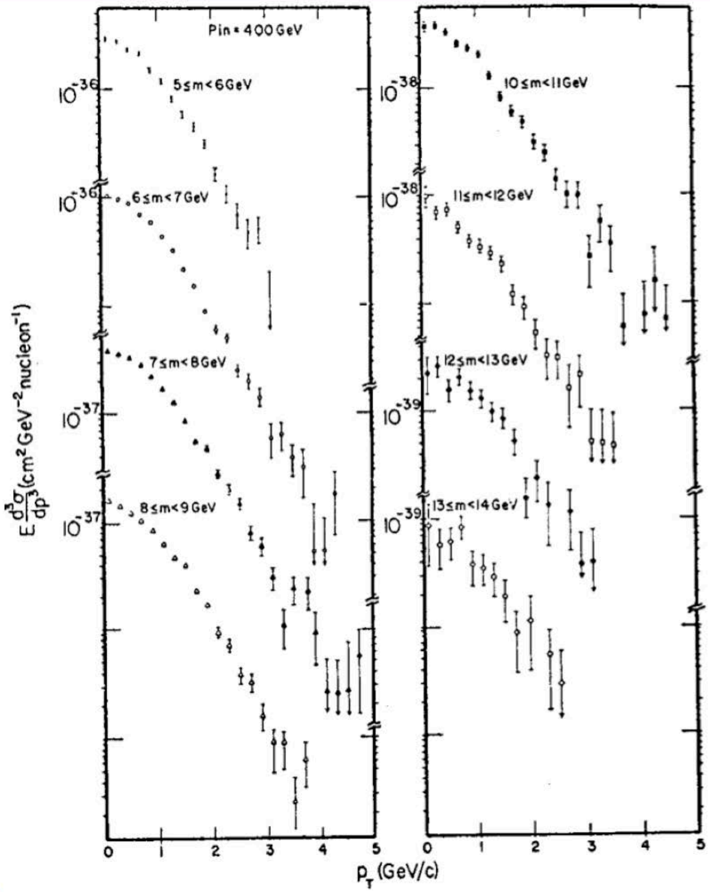
– Do a real QCD calculation with all order log corrections

MJT comment

What really happens to hard scattering at low p_T

PHENIX arXiv:1405.3940





p-p $\sqrt{s}$=27.4 GeV CFS PRD**23** (1981) 604

AuAu direct γ spectra vs centrality is exponential p_T<3 GeV/c compared to scaled p-p power-law spectrum which flattens for p_T<3 GeV/c

p_T distribution of Drell-Yan pairs also turns over at low p_T and does not diverge. In LO-QCD, p_T=0. In NLO, cross section is infinite because color-charged partons are all massless in QCD unlike electrically-charged particles in QED, m_e=0.51 MeV/c^2

A similar misuse of pQCD at low p_T led to the proposal that there were significant hard-scattering contributions to E_T and N_{ch} distributions well known from HEP to be absent (see book). This led to the ansatz:

$$\boxed{dE_T{}^{AA}/d\eta = [(1-x)\,\langle N_{\rm part}\rangle\, dE_T{}^{pp}/d\eta/2 + x\,\langle N_{\rm coll}\rangle\, dE_T{}^{pp}/d\eta]}$$

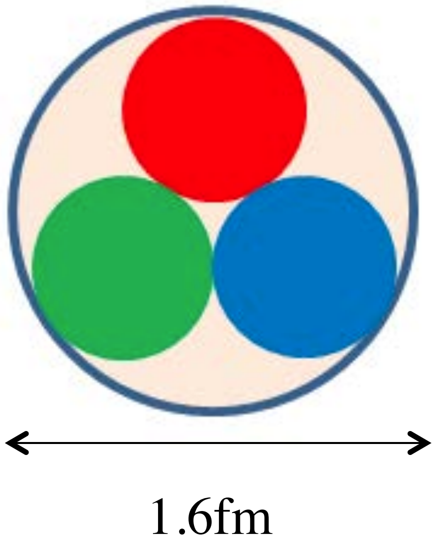
We showed, this year, that the Constituent Quark Participant Model (N_{qp}) works at mid-rapidity for A+B collisions in the range (~30 GeV) 62.4 GeV< $\sqrt{s_{NN}}$< 2.76 TeV. The two component ansatz $[(1\text{-}x)N_{part}/2+x\, N_{coll}]$ also works but does not imply a hard-scattering component in N_{ch} and E_T distributions. It is instead a proxy for N_{qp} as a function of centrality. The ratio $N_{qp}/[(1\text{-}x)N_{part}/2+x\, N_{coll}]$, with x=0.08, equals 3.38 on the average at $\sqrt{s_{NN}}$=200 and varies by less than 1% over the entire centrality range.

PHENIX PRC **80** (2014) 044905, also MJT QM2014 proc, QM1984 proc!

Constituent Quarks cf. Partons

Constituent quarks are Gell-Mann's quarks from Phys. Lett. 8 (1964)214, proton=uud [Zweig's Aces].These are relevant for static properties and soft physics, low $Q^2<2$ GeV^2 ; resolution> 0.14fm

For hard-scattering, $p_T>2$ GeV/c, $Q^2=2p_T^2>8$ GeV^2, the partons (~massless current quarks, gluons and sea quarks) become visible



Resolution ~0.5fm

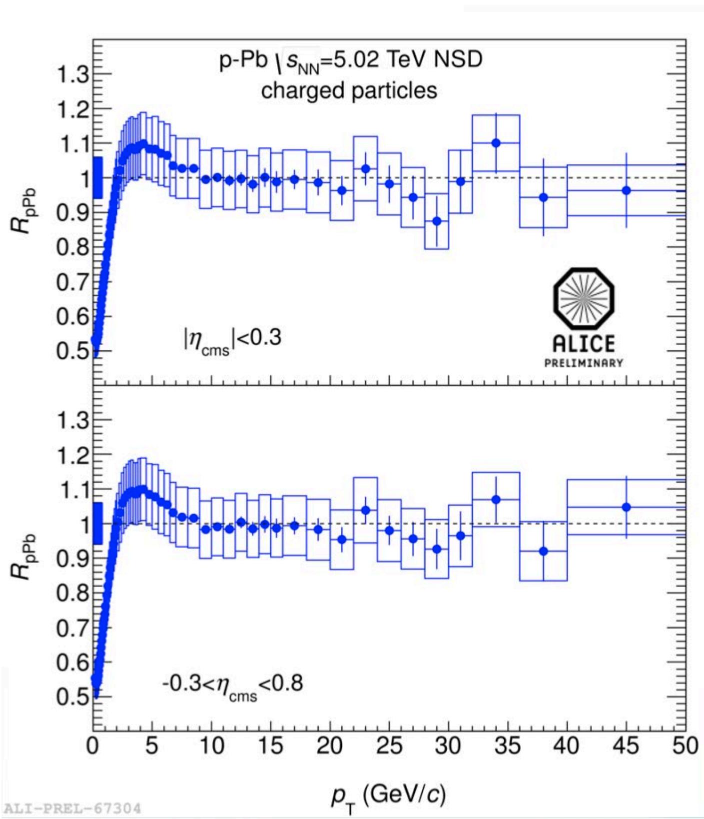
Resolution ~0.1fm

Resolution <0.07fm

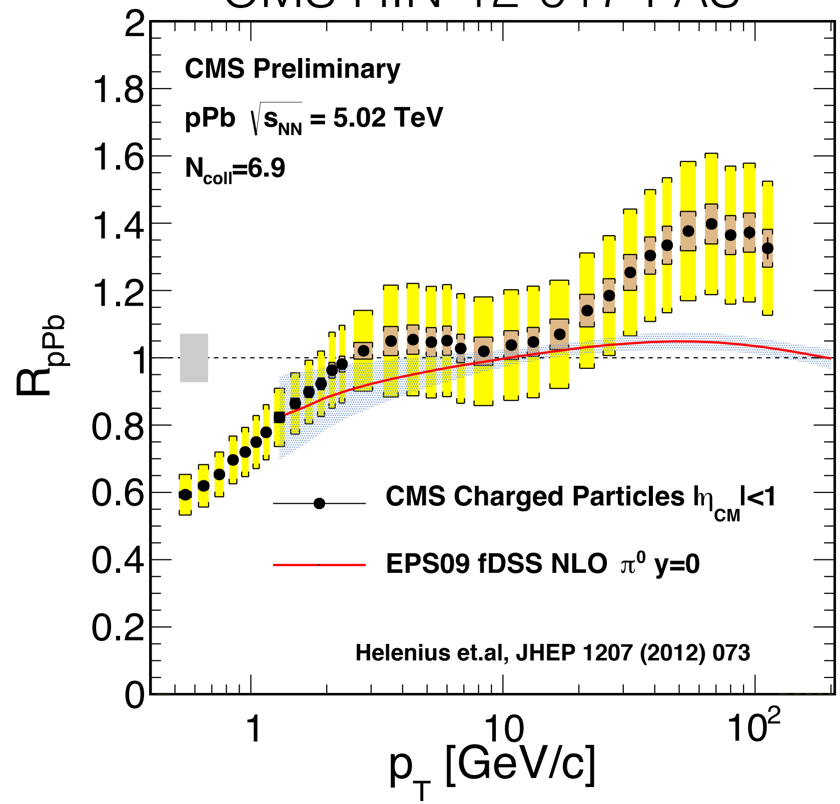
The importance of p-p comparison data at the same √s measured in the same detector

Slide by Dennis.V. Perepelitsa, BNL

Single particles: confusion at very high-p_T



CMS HIN-12-017-PAS

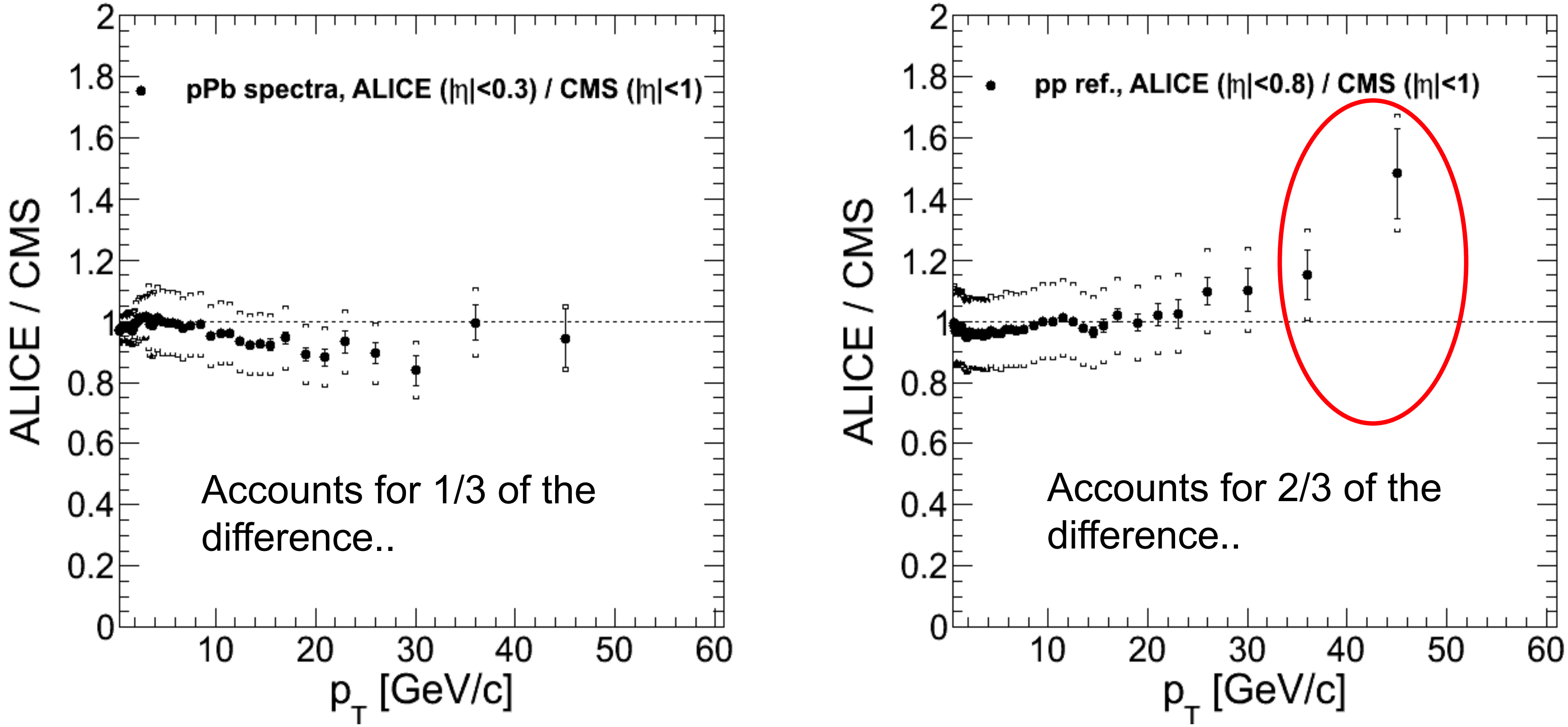


- ALICE reports no effect out to 50 GeV…
- CMS shows a 40% enhancement above 20 GeV!
  - challenging to accommodate within nPDF frameworks

The explanation?

pPb charged particle spectra ratio (ALICE/CMS)

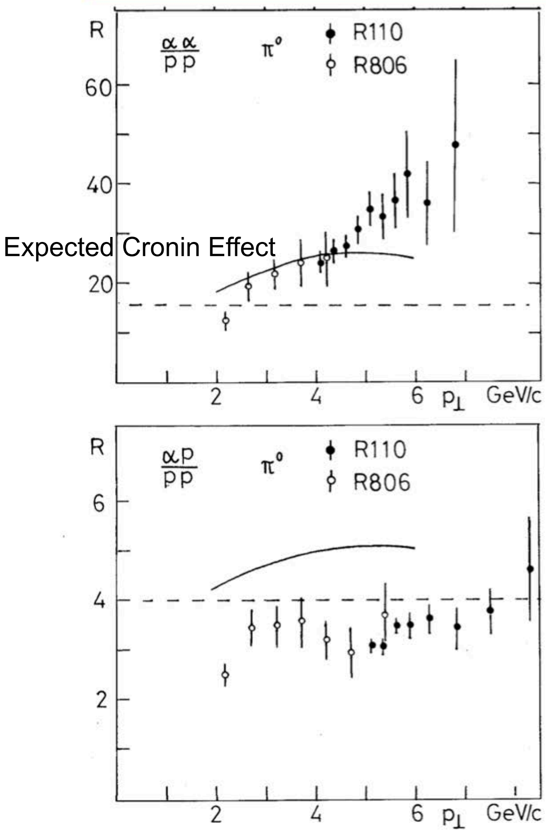
pp reference spectra ratio (ALICE/CMS)



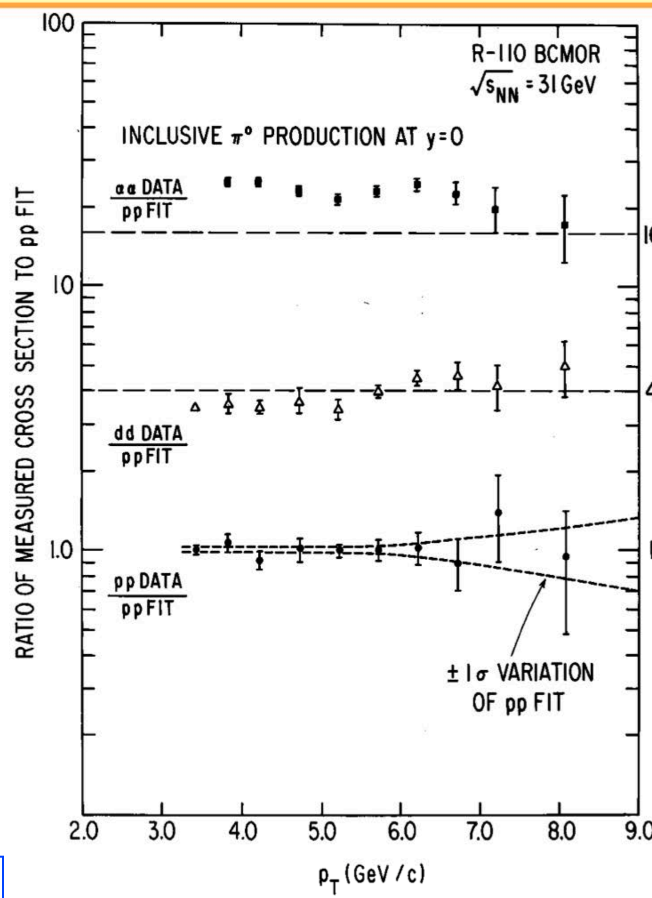
Discrepancy mainly comes from pp reference
Urgently need 5.02 TeV pp reference data!

A similar issue caused excitement at CERN and helped the approval of SpS Heavy Ions

In 1984 a program of Heavy ions in the CERN-SPS was approved by the DG, Herwig Schopper, partly due to some "exciting results" from α-α collisions at the CERN-ISR



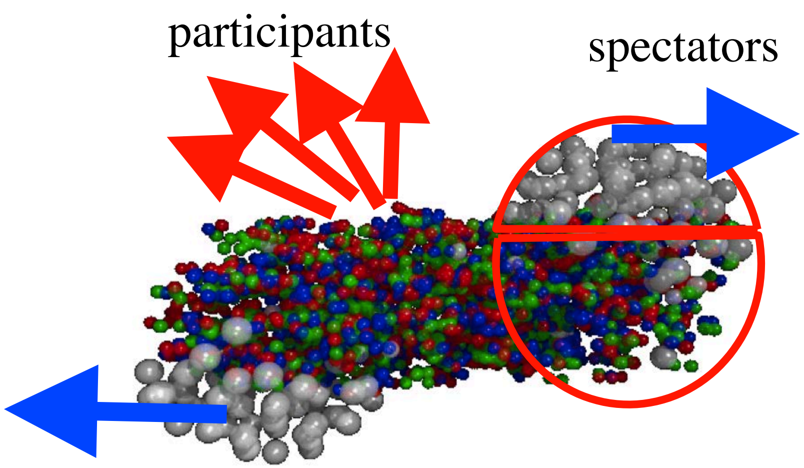
COR PLB **116** (1982) 379
replotted by Martin Faessler

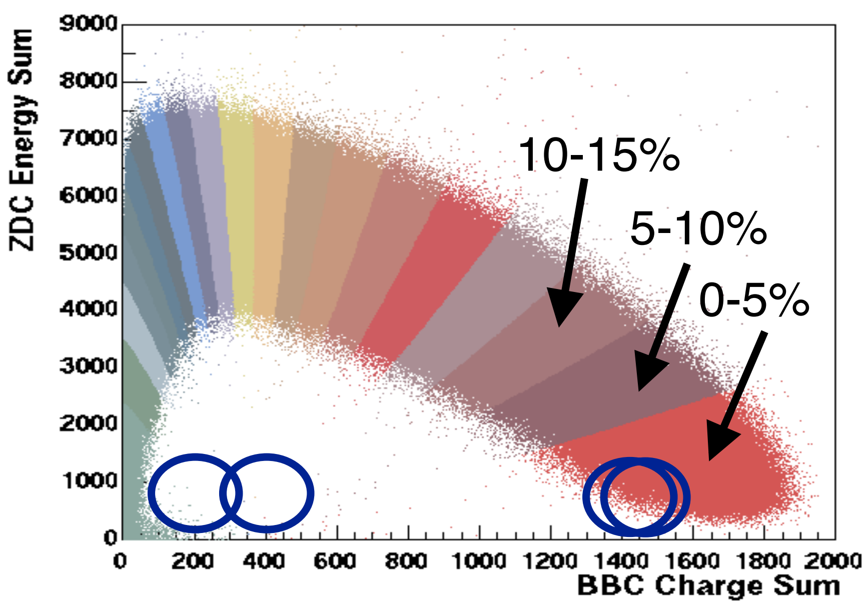


BCMOR PLB 185 (1987) 213

The large value of the αα/pp cross sections in PLB116 was WRONG because of an incorrect extrapolation of p-p measurements from √s=62.4 to 31 (αα) and 44 (αp) GeV. I complained about this but I was busy making magnets at ISABELLE at the time—a lucky break in retrospect. This shows that sometimes WRONG RESULTS have a bigger impact than correct results because they are EXCITING; but this does not excuse making mistakes.

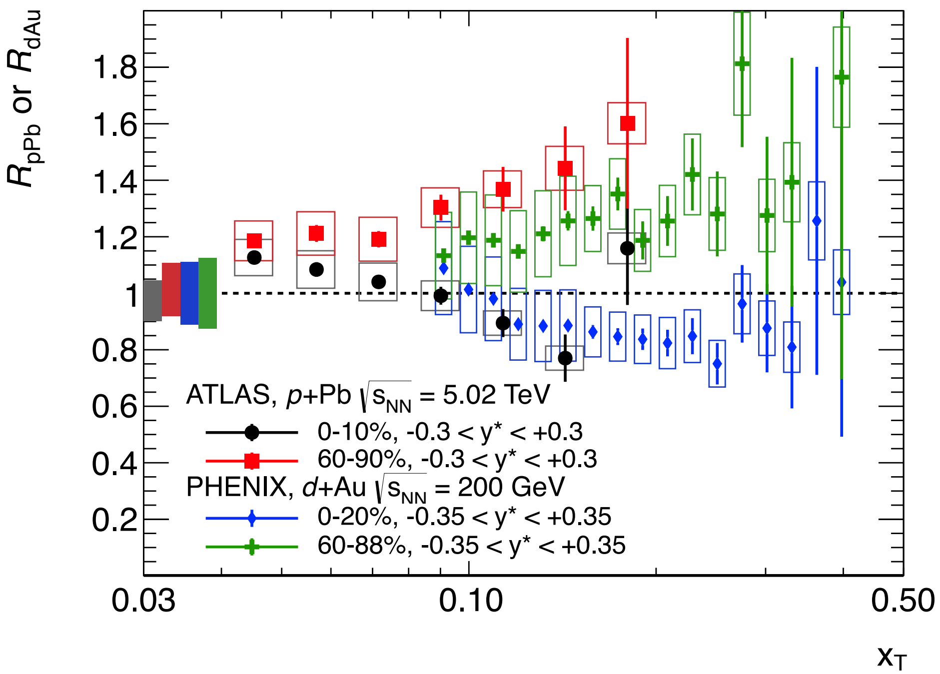
Collision Centrality defined by the number of participating nucleons N_{part} can be measured from spectators in Zero Degree Calorimeter for fixed target but not at a collider

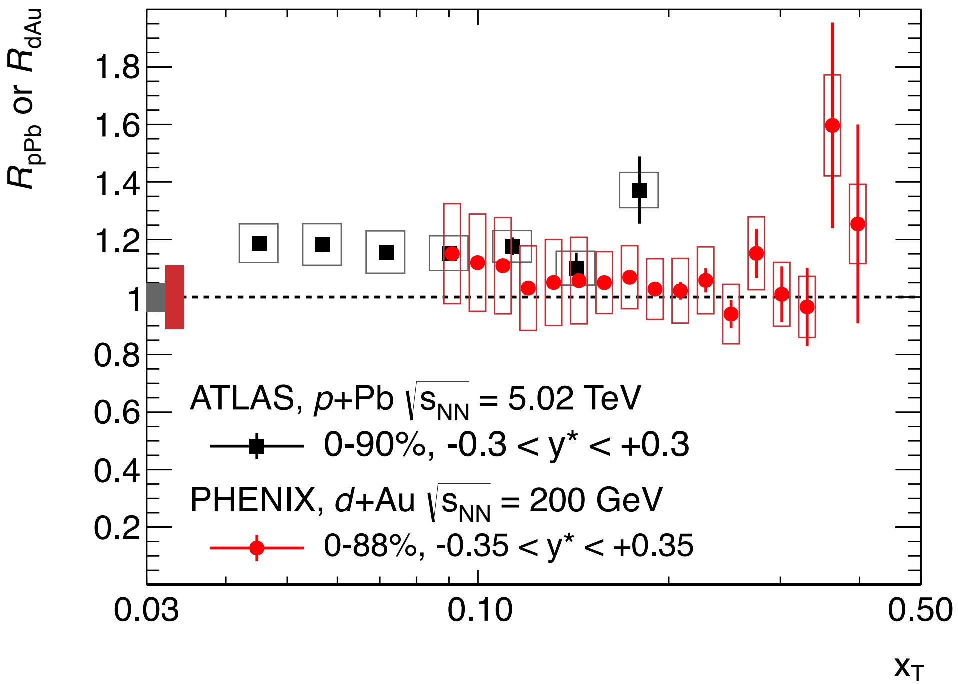




- Number of Spectators (i.e. non-participants) N_s can be measured directly in Zero Degree Calorimeters in fixed target experiments.
- Enables unambiguous measurement of (projectile) participants = A_p -N_s
- For symmetric A+A collision N_{part}=2 $N_{projpart}$
- At a collider can not measure the spectators which may be free neutrons, protons or clusters. If Z/A of cluster is same as the beam, it stays in the beam; but the neutrons can be detected at zero degrees. The distribution of Energy in Beam Beam Counters can be measured and the centrality defined by upper percentile of the distributions, but N_{part} is model dependent and may have biases

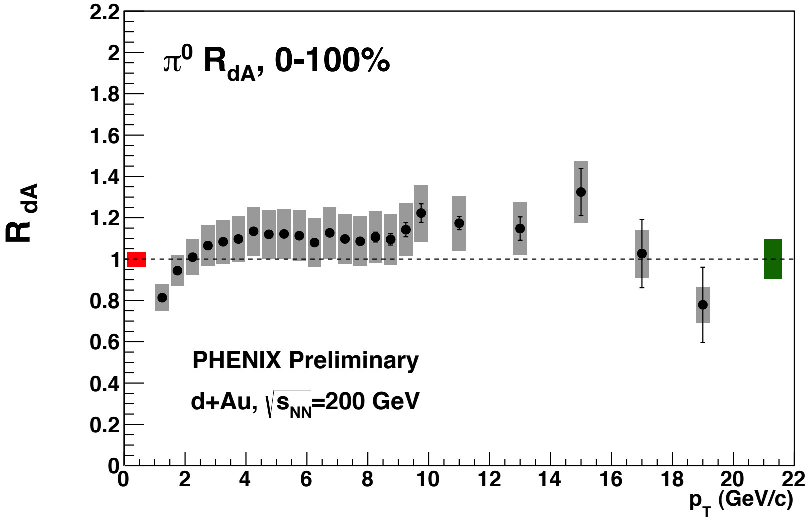
At LHC as at RHIC, cuts on centrality are weird in dAu, pPb: Minimum Bias tells all

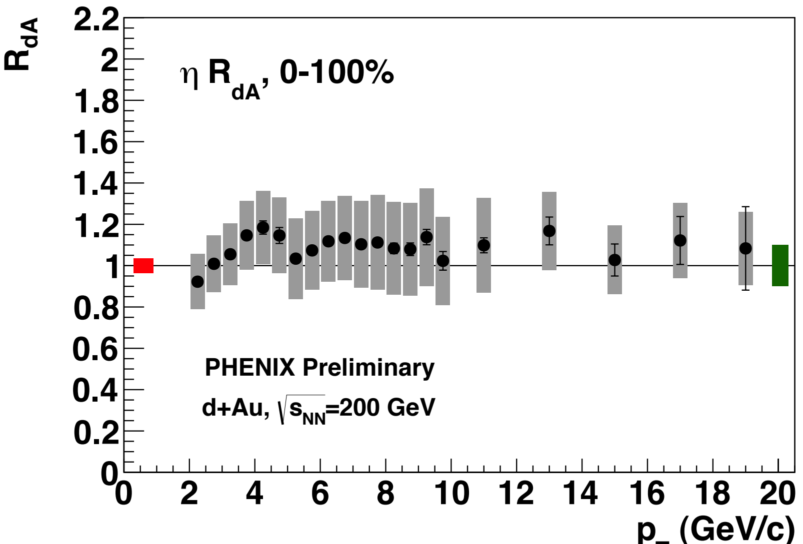


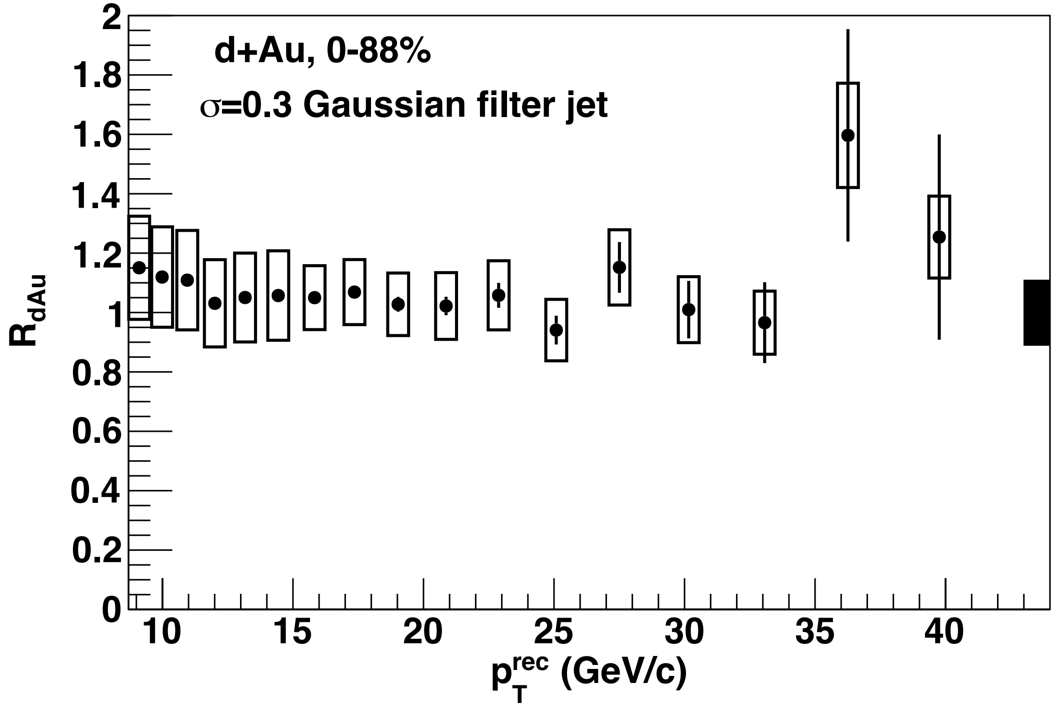


From PhD Thesis, Dennis V. Perepelitsa, Physics Dept. Columbia University, 2014.

Minimum bias tells the true story—The principal argument for a p+A run at RHIC

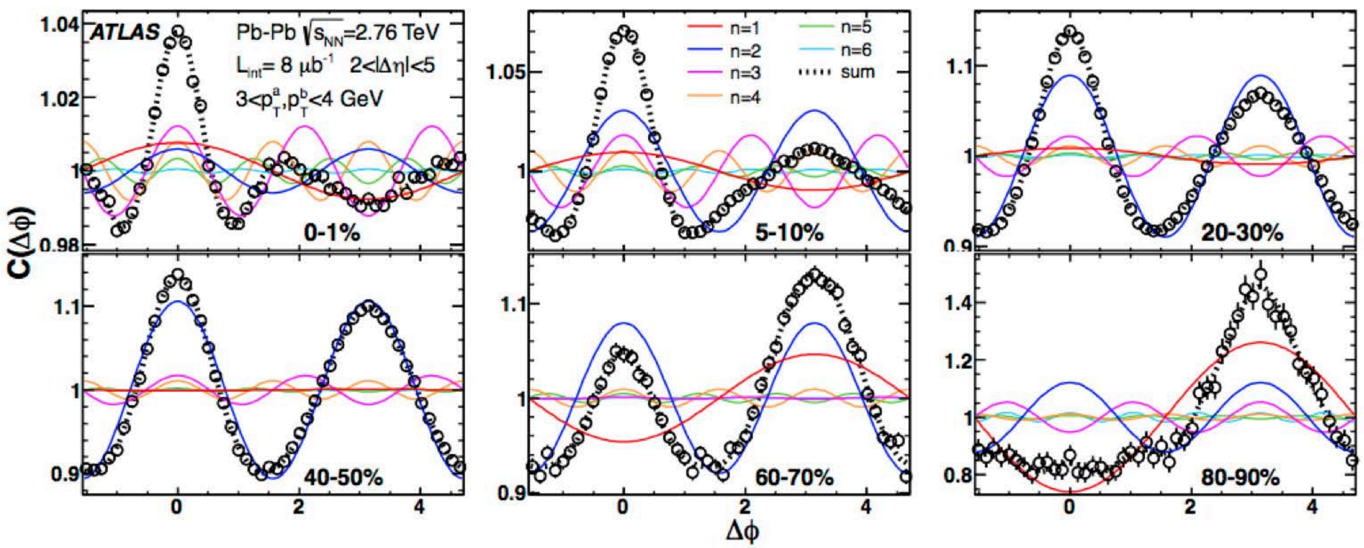






Di-Hadron, Di-Jet or recently Jet-Hadron Correlations in AA interactions suffer from a HUGE problem due to v_2,v_3,v_4 flow modulations of the background which obscure the hard-scattering away-side peak and had led to such RHIC "discoveries" as "Mach Cones", The Ridge, "Head & Shoulders". Uncertainties in determining the v_n modulated soft background (the bulk) still lead to large systematic uncertainties for the hard-scattering peaks.

At LHC, more interest in Fourier series than in di-hadron correlations from di-jets



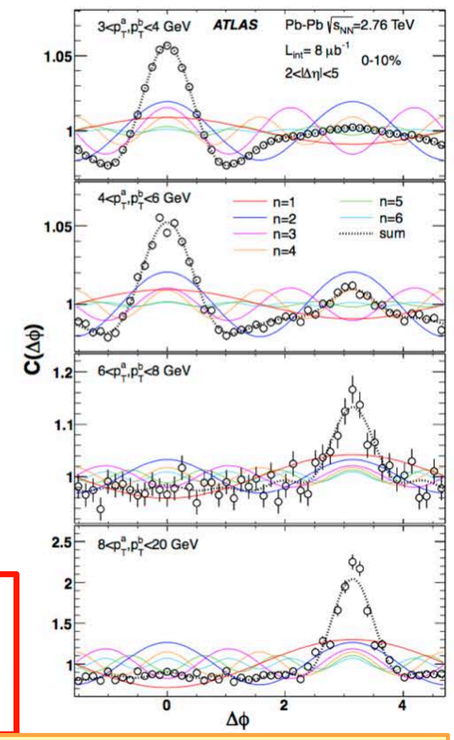


FIG. 9. (Color online) Centrality dependence of $\Delta\phi$ correlations for $3 < p_T^a, p_T^b < 4$ GeV. A rapidity gap of $2 < |\Delta\eta| < 5$ i required to isolate the long-range structures of the correlation functions, i.e. the near-side peaks reflect the "ridge" instead of th autocorrelations from jet fragments. The error bars on the data points indicate the statistical uncertainty. The superimpose solid lines (thick-dashed lines) indicate contributions from individual $v_{n,n}$ components (sum of the first six components).

ATLAS PRC **86** (2012) 014907

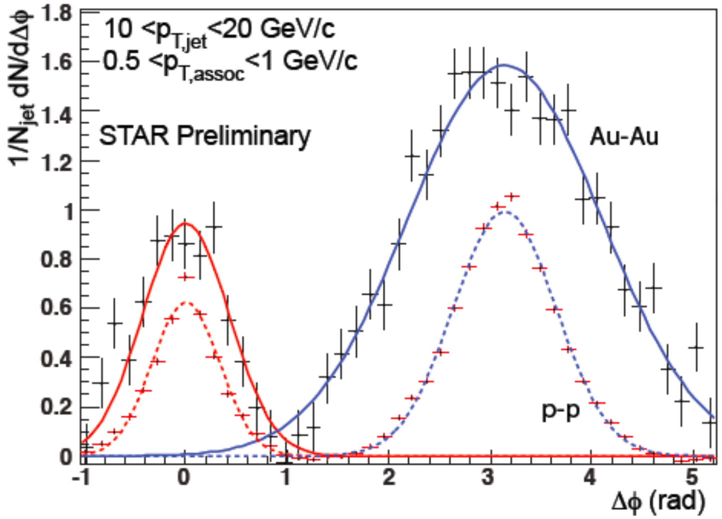
$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T d\eta}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)\right)$$

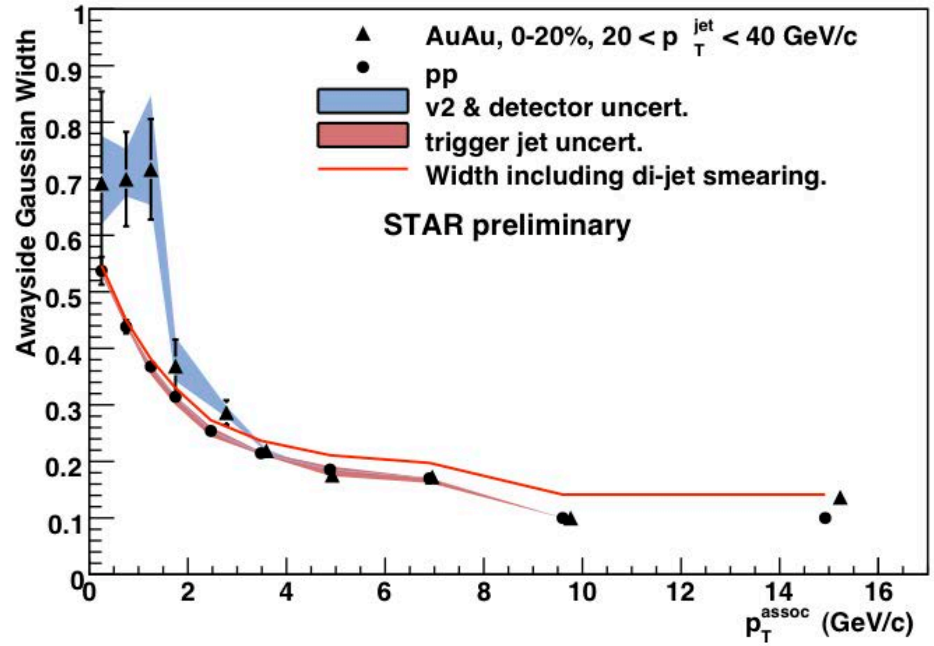
If you like wiggles instead of peaks remember that for a Dirac δ function

$$\delta(\phi - \Phi) = \frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} \cos n(\phi - \Phi)\right)$$

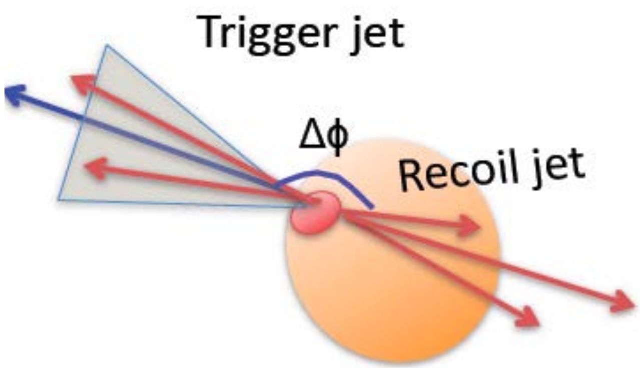
STAR Jet-hadron correlations-preliminary 2012

A.Ohlson, Hard Probes 2012





H. Caines , QM 2011

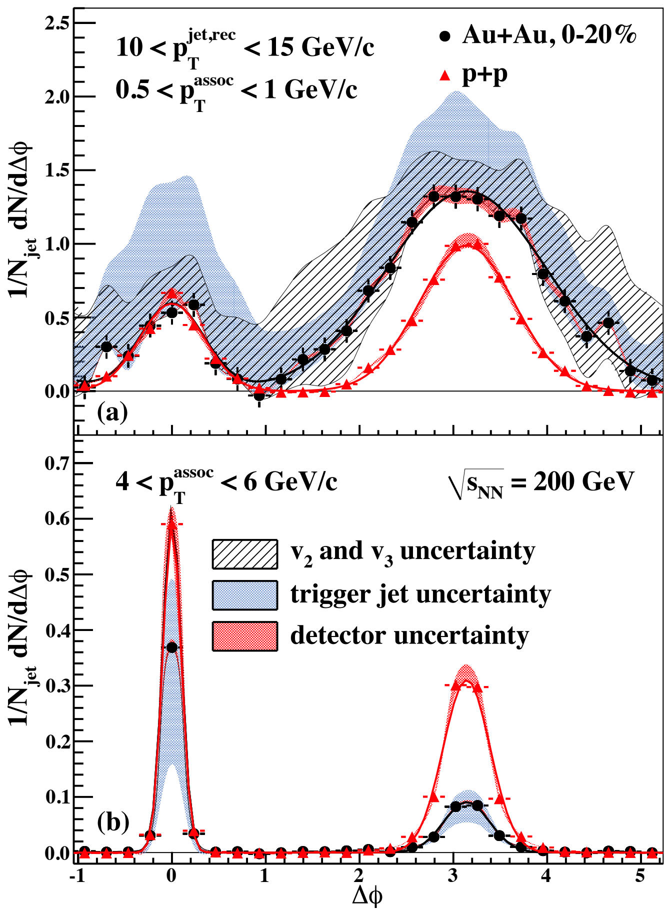


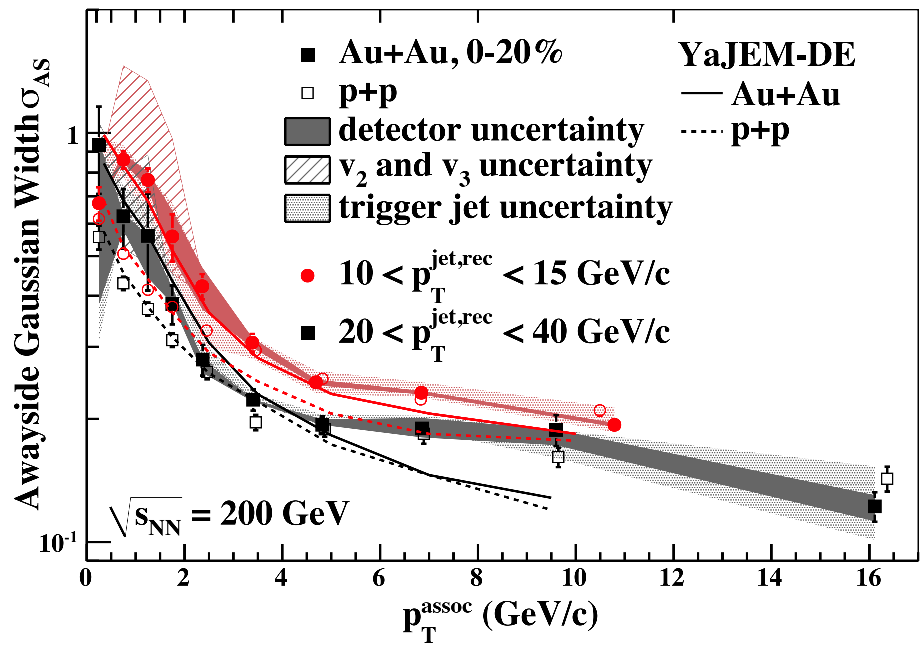
$$\Delta\Phi = \Phi_{jet} - \Phi_{assoc.\text{-}hadron}$$

Use Jet-hadron correlations to look for medium-induced-broadening of the away parton (Jet) w.respect to trigger Jet

Preliminary seems to look promising, but final data show no evidence:

STAR Jet-Hadron 2013 final—suggestive? (!)





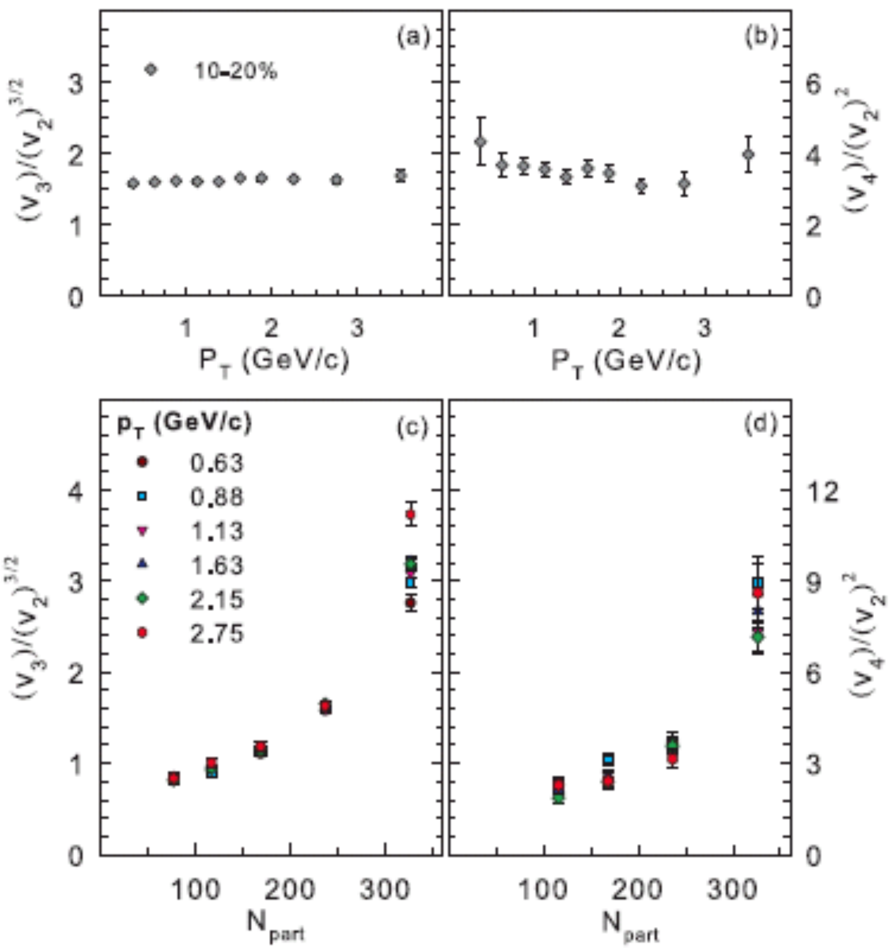
STAR PRL **112** (2014)122301, with systematic errors, is inconclusive due to v_2, v_3, ... uncertainties.

"While the widths of the awayside jet peaks are suggestive of medium-induced broadening, they are highly-dependent on the shape of the subtracted background,..."

My idea is to use acoustic scaling to constrain v_3,v_4... from v_2

Lacey: Acoustic Scaling from PHENIX v_2, v_3, v_4

In arXiv: 1105.3782v2 they claim that from hydrodynamics and kinetic theory, for a fixed initial collision geometry (centrality) one should get:



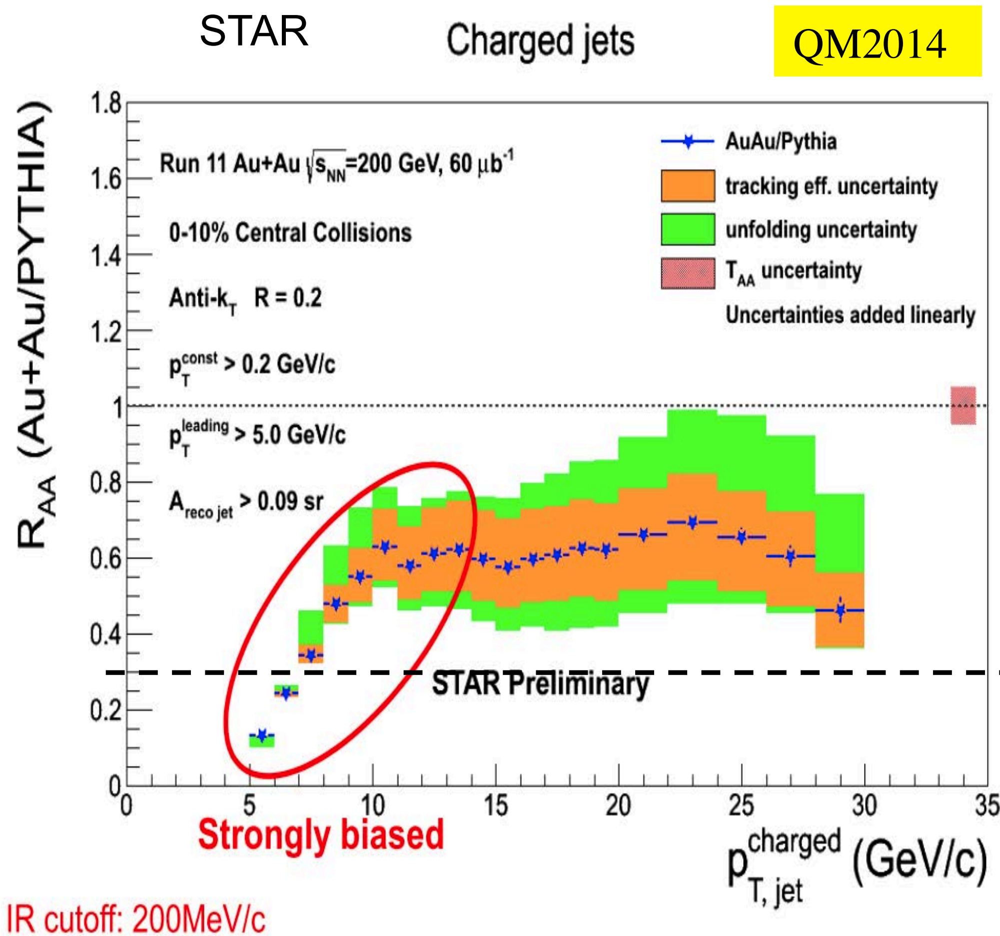
$$v_n / v_2^{n/2} = \text{constant, independent of } p_T$$

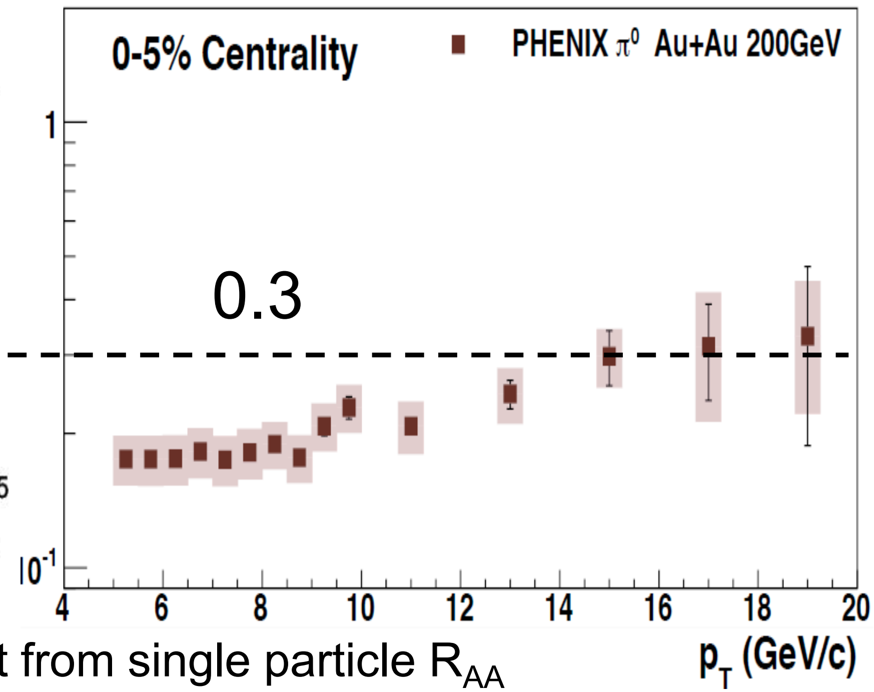
It works for PHENIX, v_2, v_3, v_4 data from PRL 107(2011) 252301. I checked it myself using Excel. Will allow us to measure hard-scattering correlations with good constraint on flow: know v_2 know everything.

I didn't do it yet because I was too busy working on Constituent-Quark Participants

New STAR Jet results this year show very different behavior than Jets measured at LHC

STAR Charged jets R_{AA}>>single particle



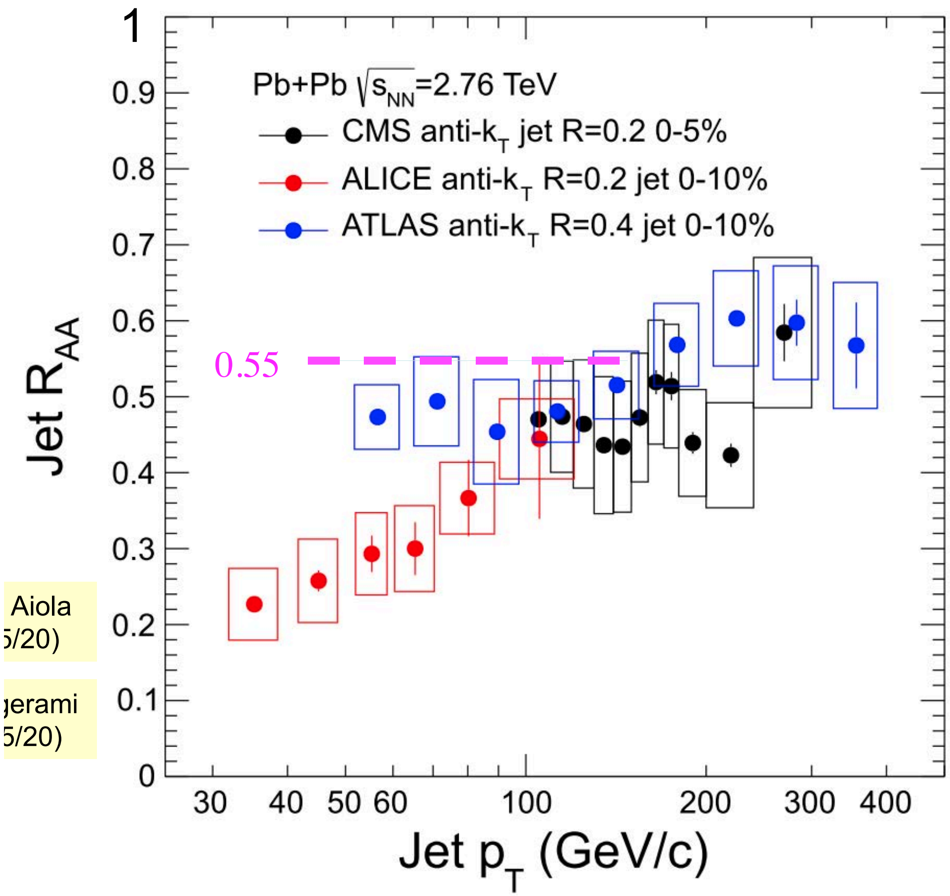


Charged jet R_{AA} results: different from single particle R_{AA}

Gets worse with increasing cone size

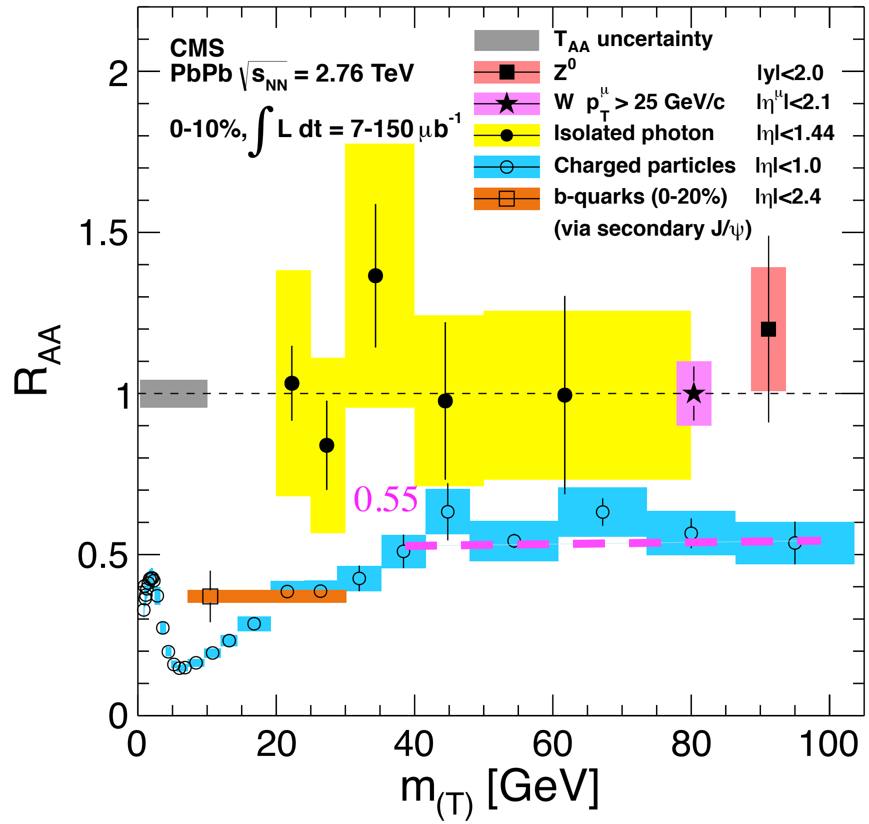
At LHC Jet and single particle R_{AA} ~ equal for p_T>40 GeV/c

LHC Jets have comparable or lower R_{AA} than single particles

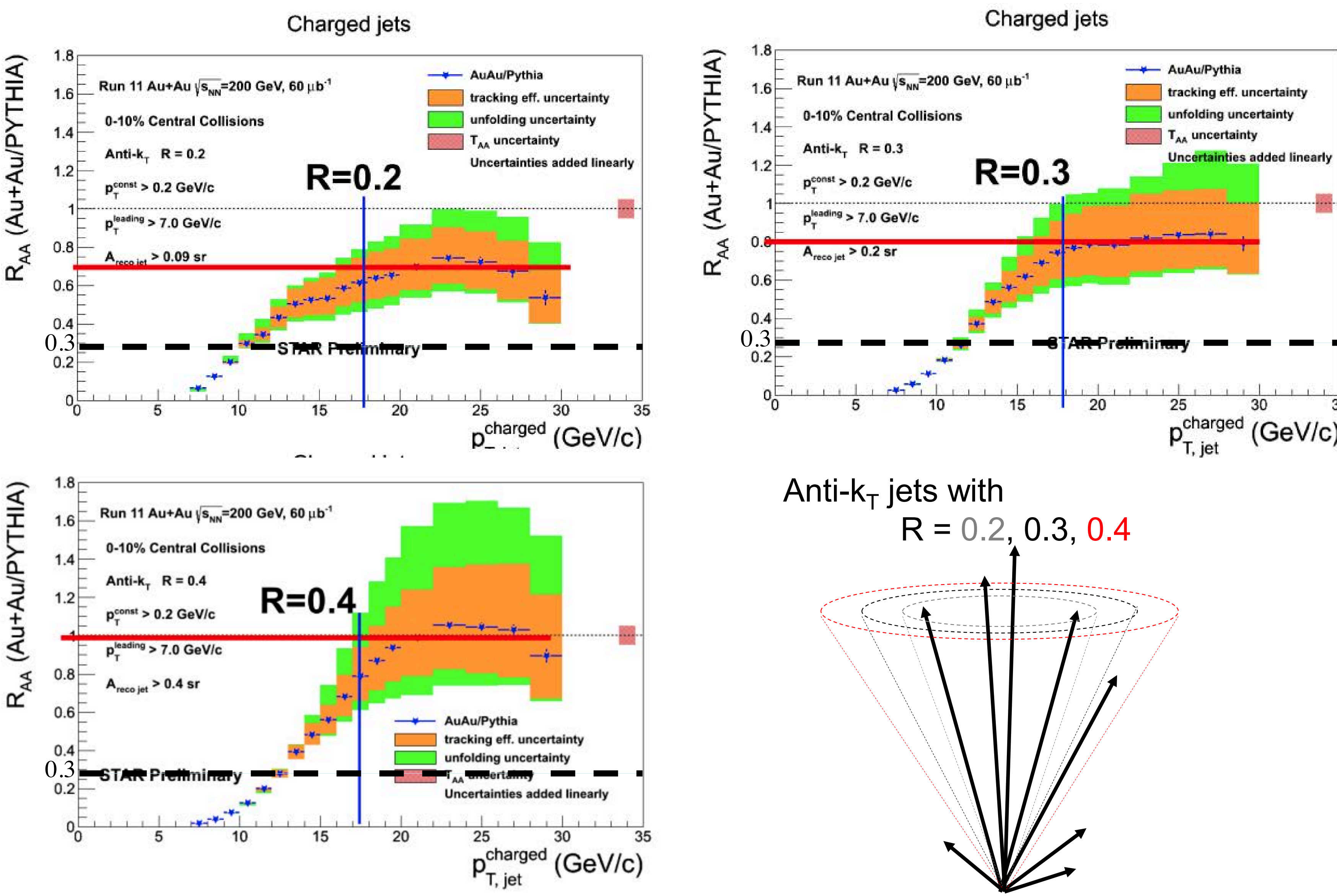


Aiola
5/20)

gerami
5/20)



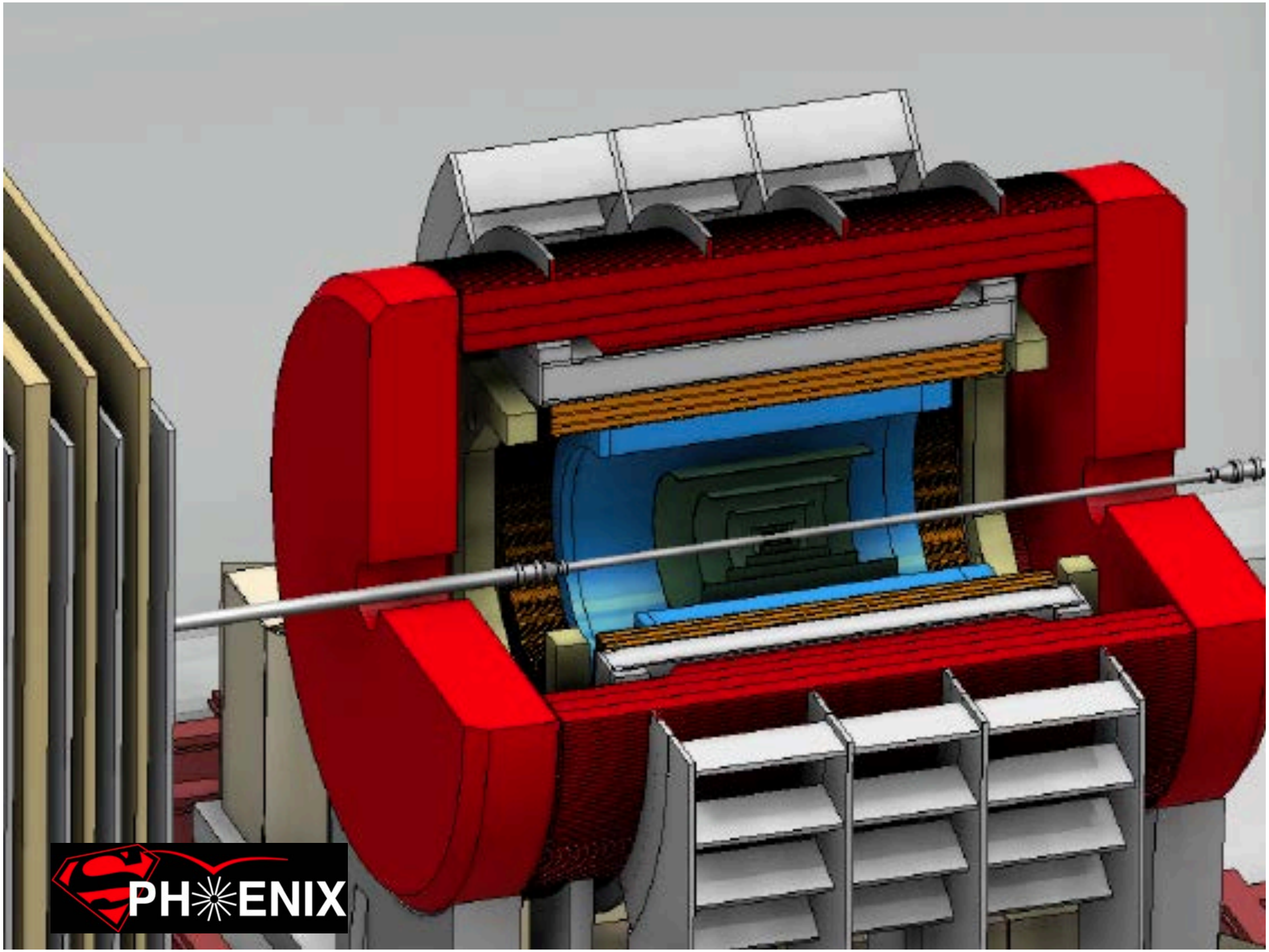
The disagreement gets worse with larger R



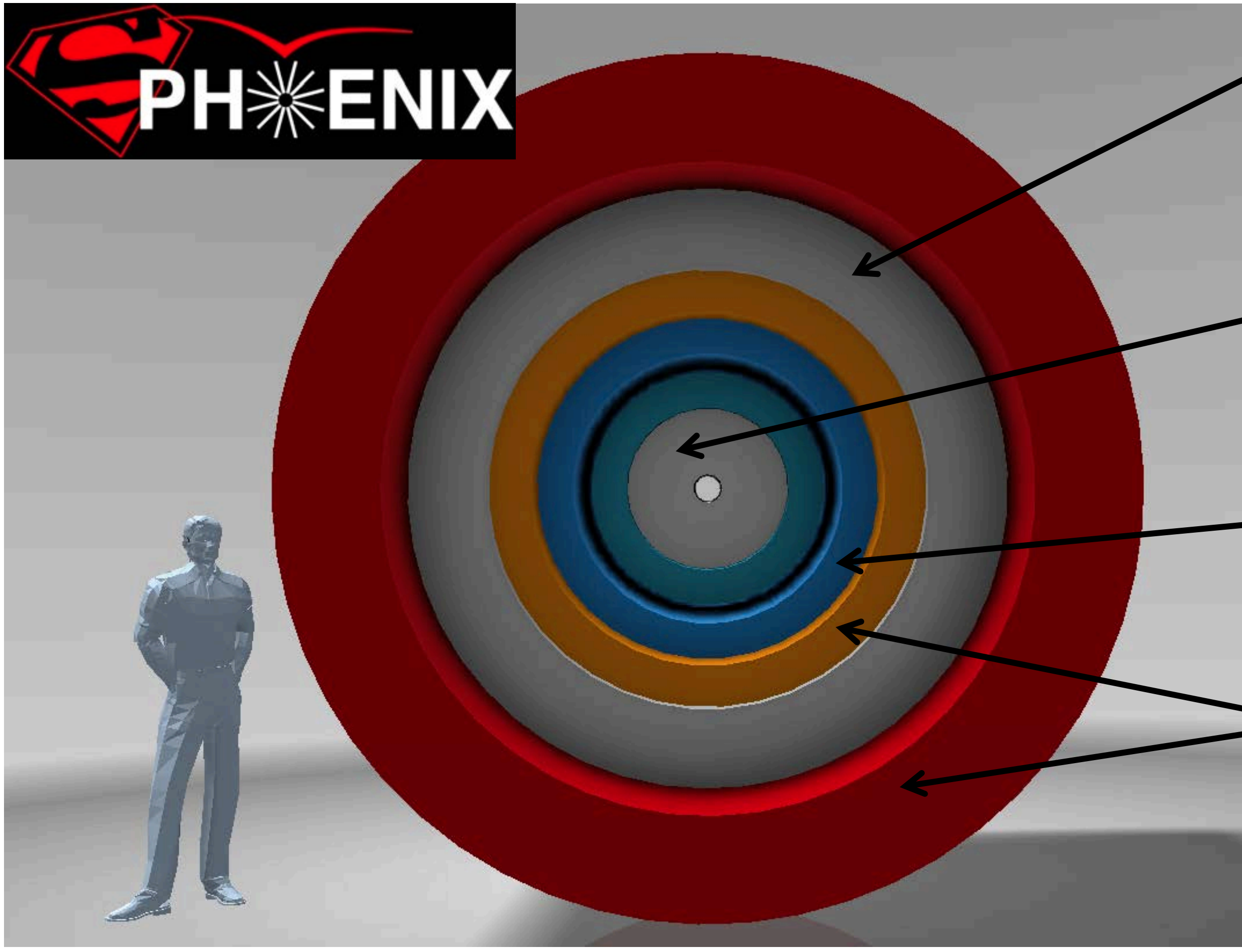
So, even after 14 runs at RHIC, the jet learning curve still has a way to go. One solution is to make a new detector to find jets by the more traditional method using Hadron Calorimetry with continuous coverage, large acceptance, $\Delta\phi=2\pi$, $|\eta|<1.1$, and high rate capability to get to ~60 GeV jets to overlap with the LHC measurements.

This is the sPHENIX proposal

sPHENIX at DoE review July 1, 2014



Jamie Nagle: “sPHENIX in a Nutshell”



BaBar Magnet 1.5 T

Coverage $|\eta| < 1.1$

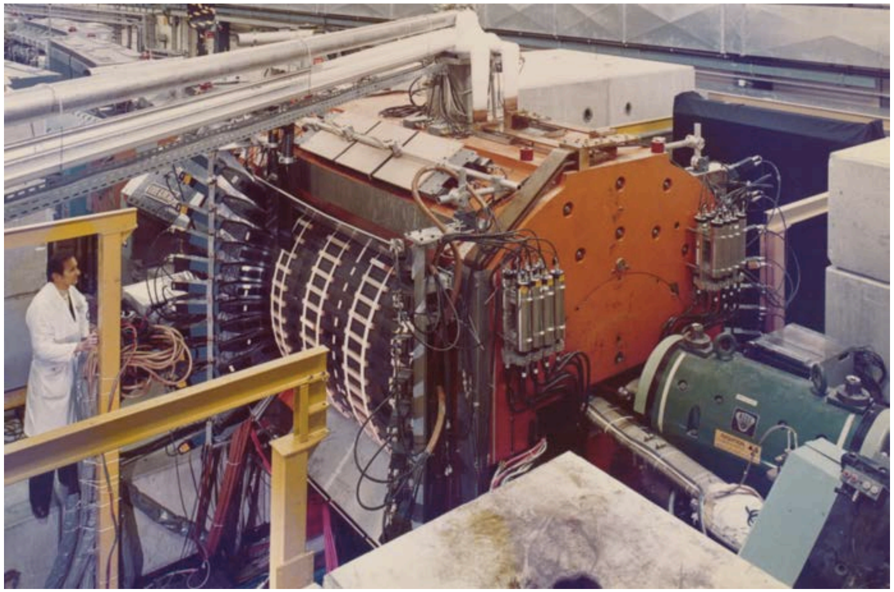
All silicon tracking
Heavy flavor tagging

Electromagnetic
Calorimeter

Two longitudinal
Segment Hadronic
Calorimeter

Common Silicon Photomultiplier readout for Calorimeters
Full clock speed digitizers, digital information for triggering
High data acquisition rate capability ~ 10 kHz

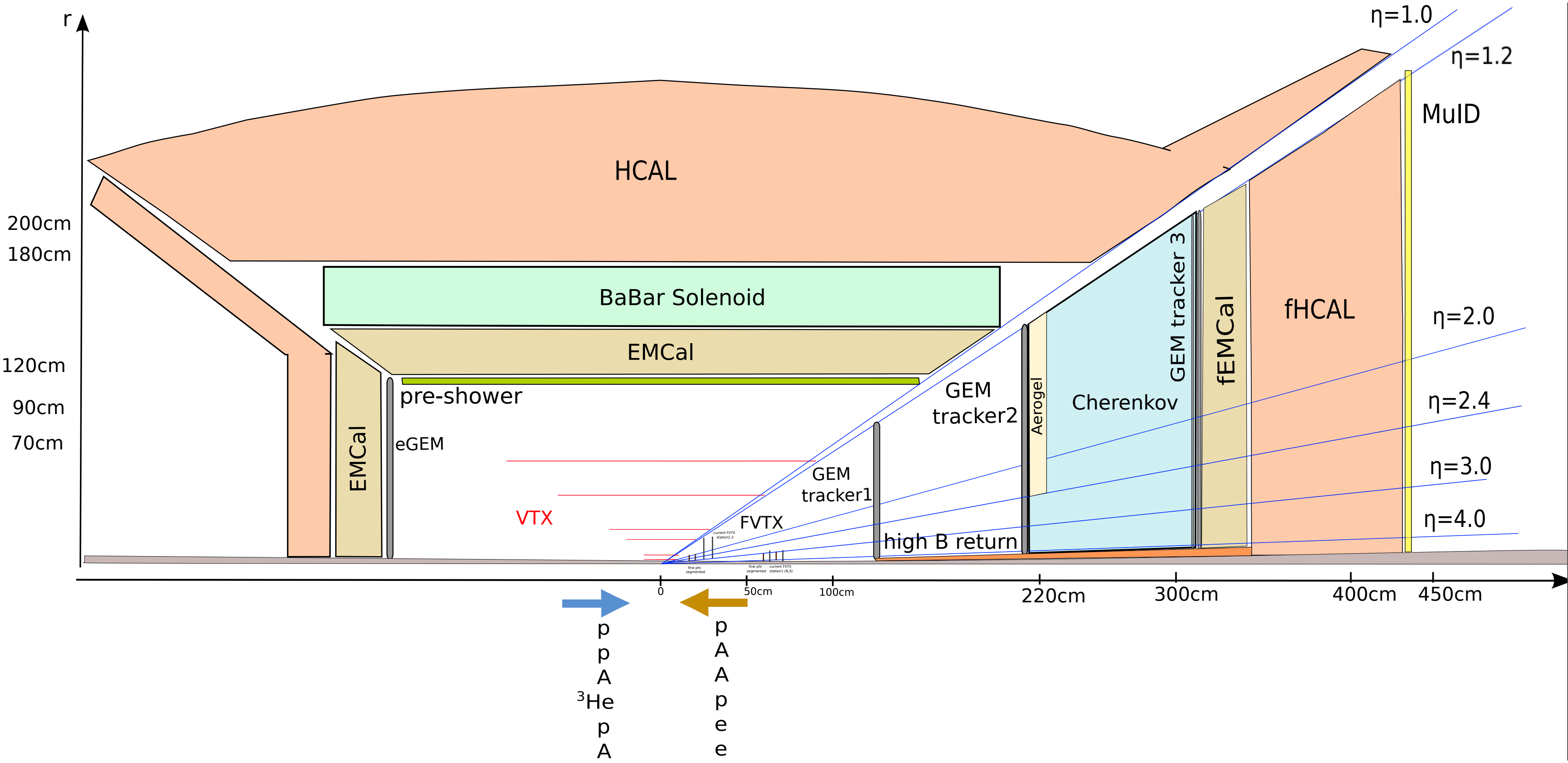
sPHENIX new detector with BABAR solenoid



CCOR 1977 First thin coil superconducting solenoid detector at a collider r=70cm

BABAR thin coil superconducting solenoid r=1.5m being shipped from Ansaldo, Italy to SLAC 1997. Will be shipped to BNL soon.

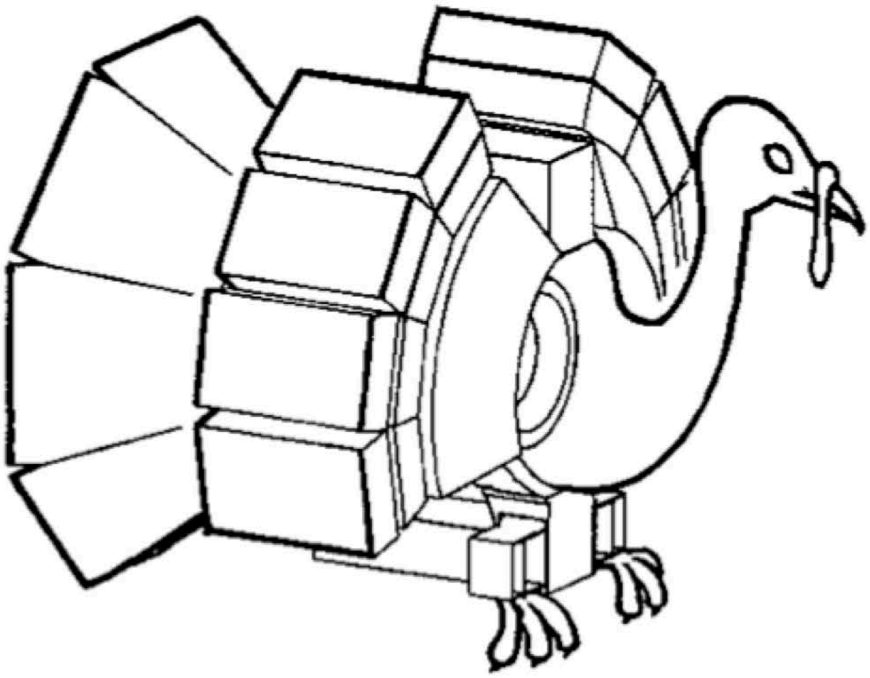
e/sPHENIX design with high B return piston

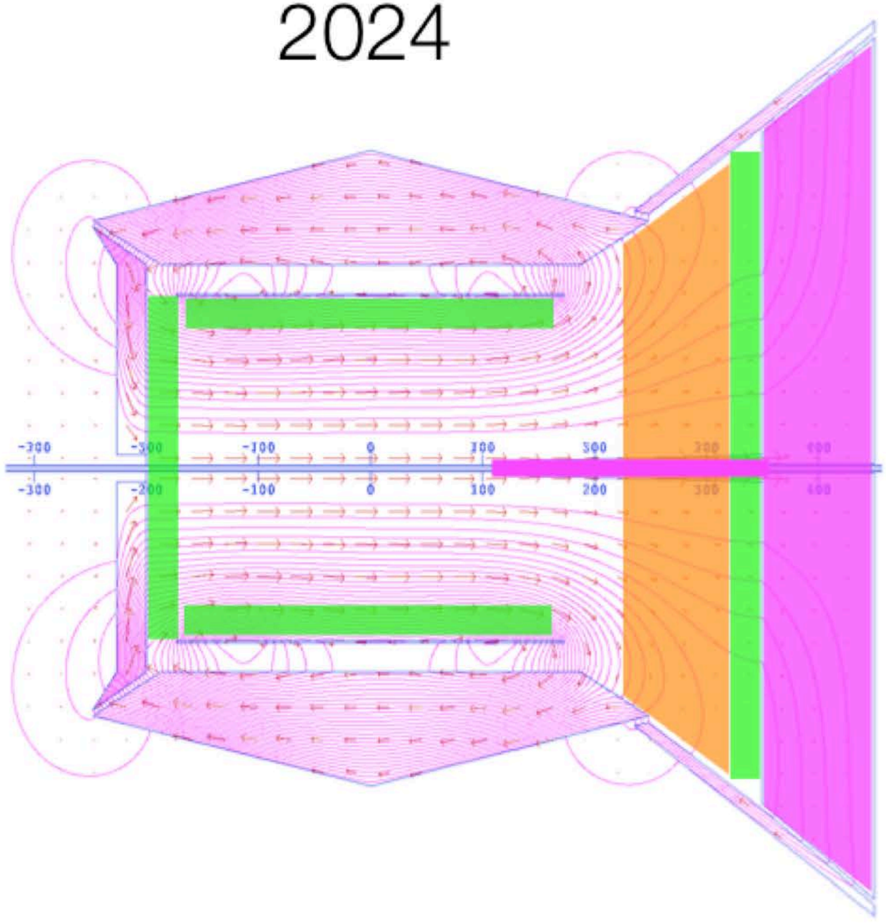


It's not a Turkey, it's a PHENIX

convergent evolution?

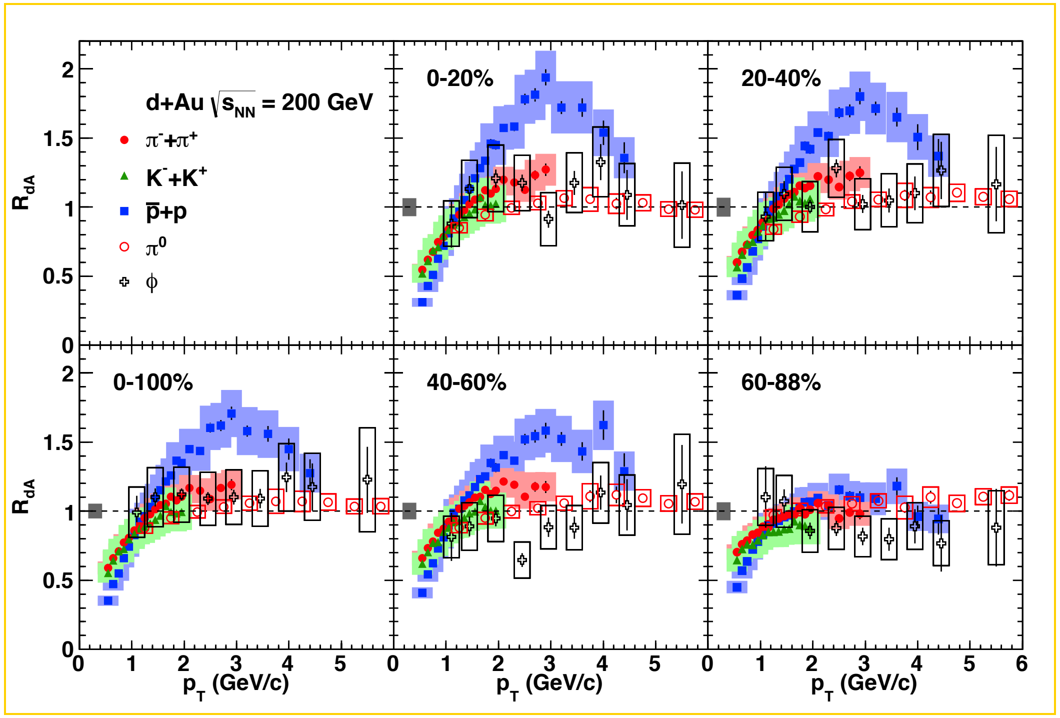
1994	2024



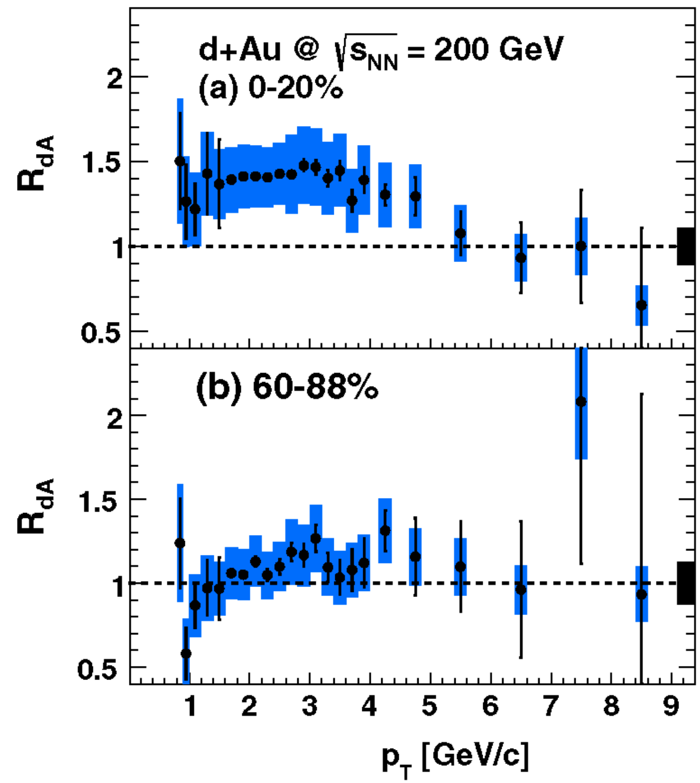


JOIN US

New dAu data this year give another clue



PHENIX PRL109 (2012) 242301



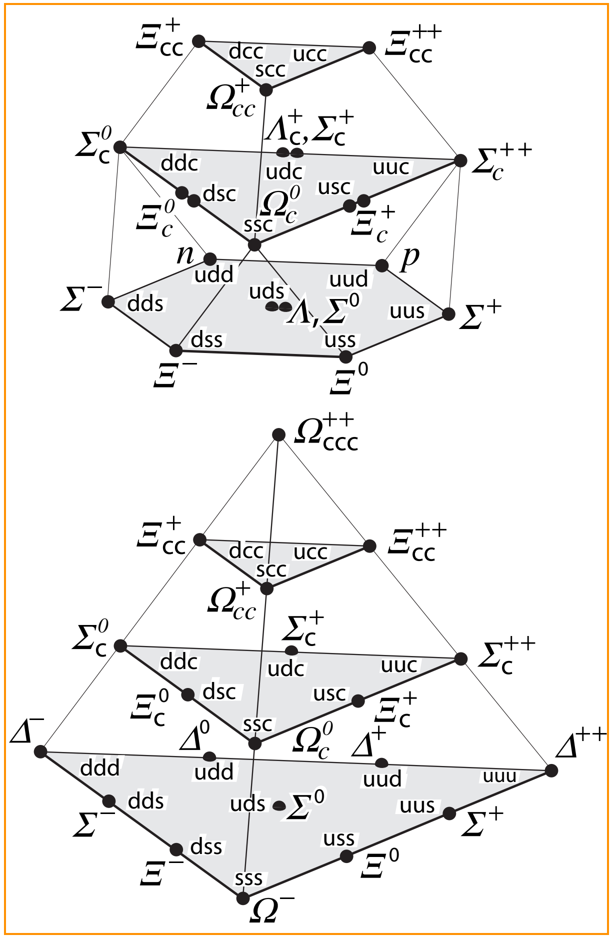
No effect in dAu (R_{dA}=1) with the exception of protons which have a huge enhancement (Cronin Effect). A common explanation of the dAu and AuAu baryon enhancements for p_T<6 GeV/c is needed.

Note the absence of any centrality effect for light mesons in dAu in this p_T range.

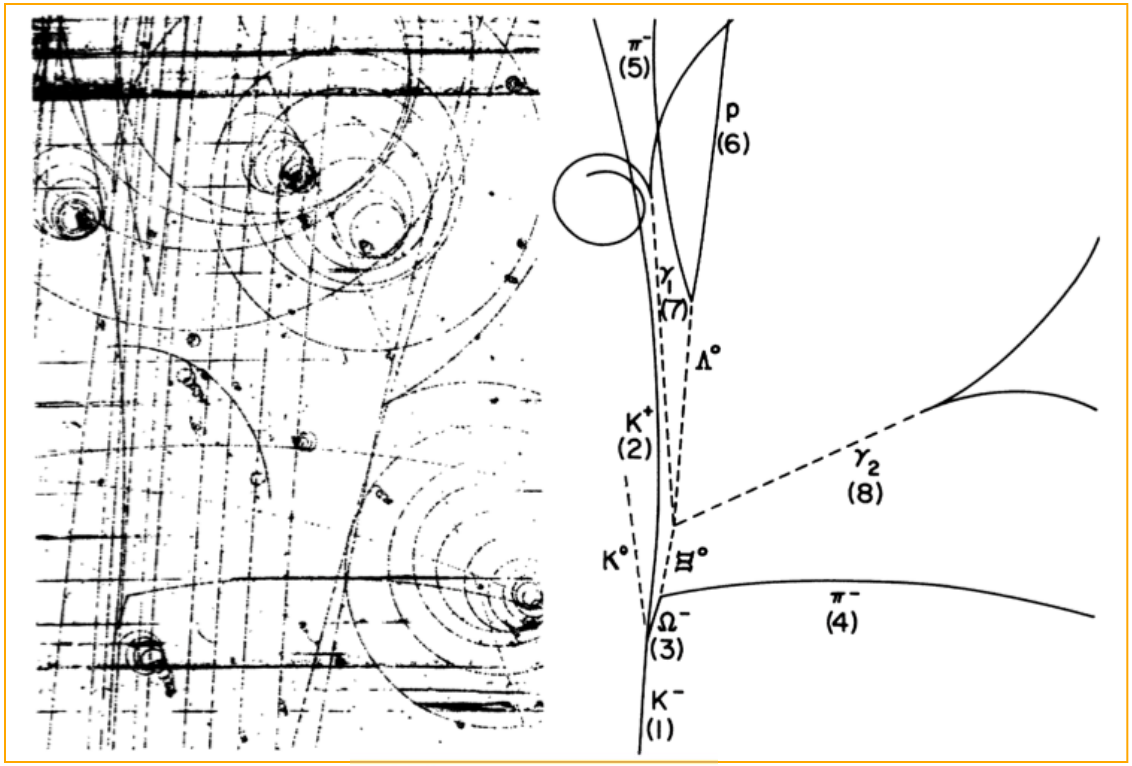
But direct $e^\pm$ from heavy charm mesons have a Cronin Effect. Peripheral 60-88 looks reasonable.

PHENIX arXiv:1304.3410

Constituent quarks are Gell-Mann's quarks from Phys. Lett. **8** (1964)214, Zweig's Aces



Constituent quark model of Baryons

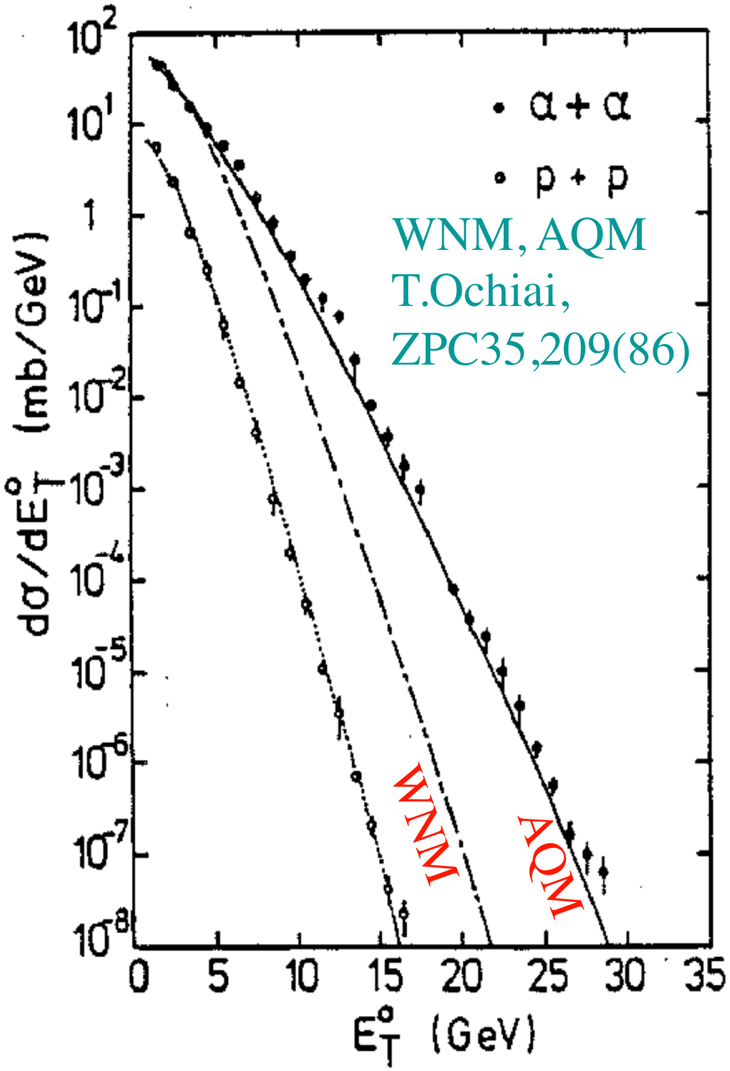


Ω^- (sss)

BNL-Barnes, Samios *et al*., PRL**12**, 204 (1964)

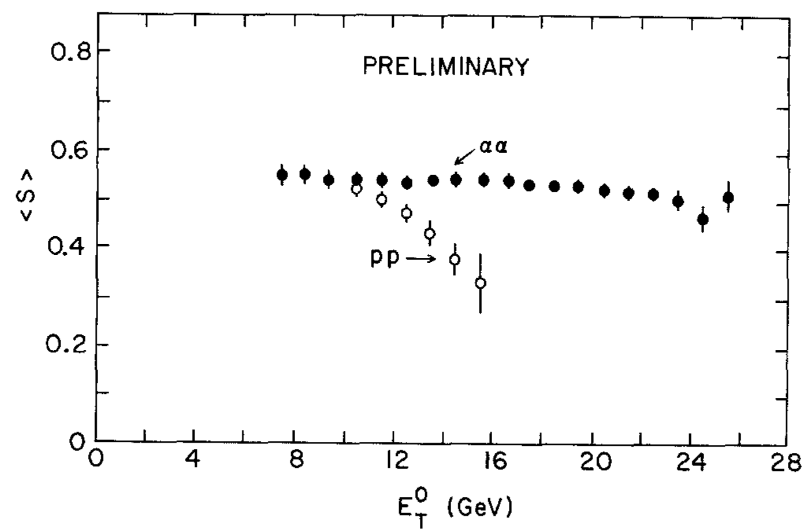
For more on Constituent quarks in QCD see E. V. Shuryak, Nucl. Phys. B 203, 116 (1982).

From My First Quark Matter Talk 1984
ISR-BCMOR-αα $\sqrt{s_{NN}}$=31GeV: WNM FAILS! AQM works



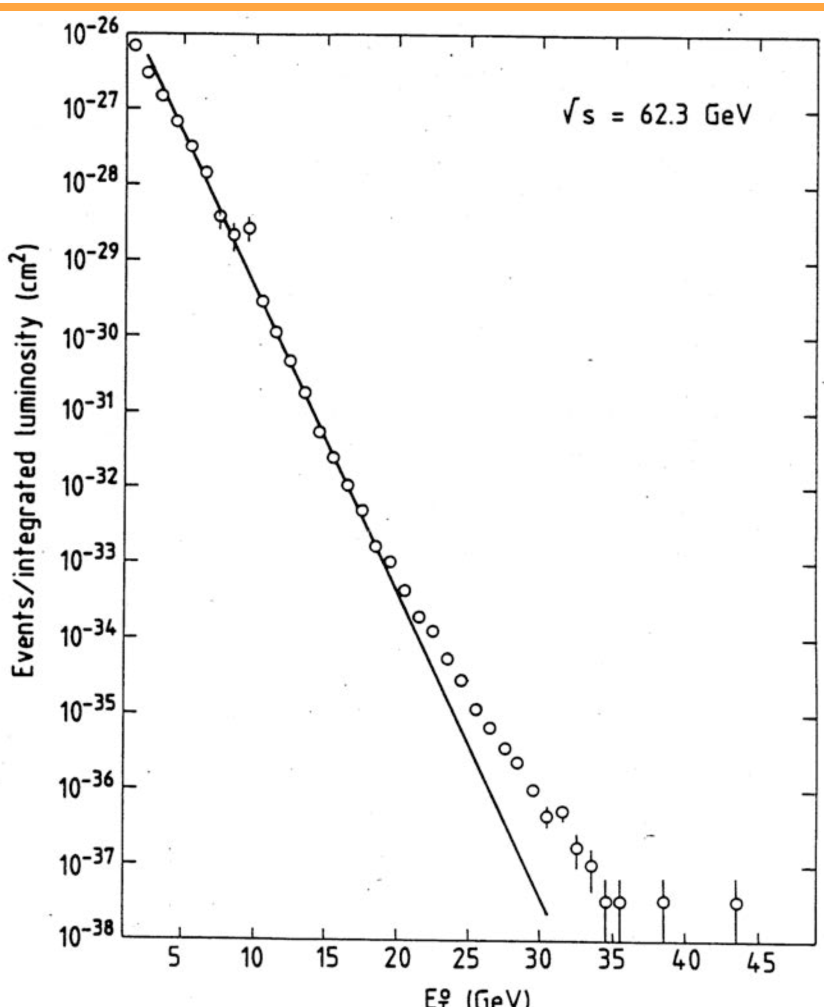
BCMOR PLB**168**(1986)158

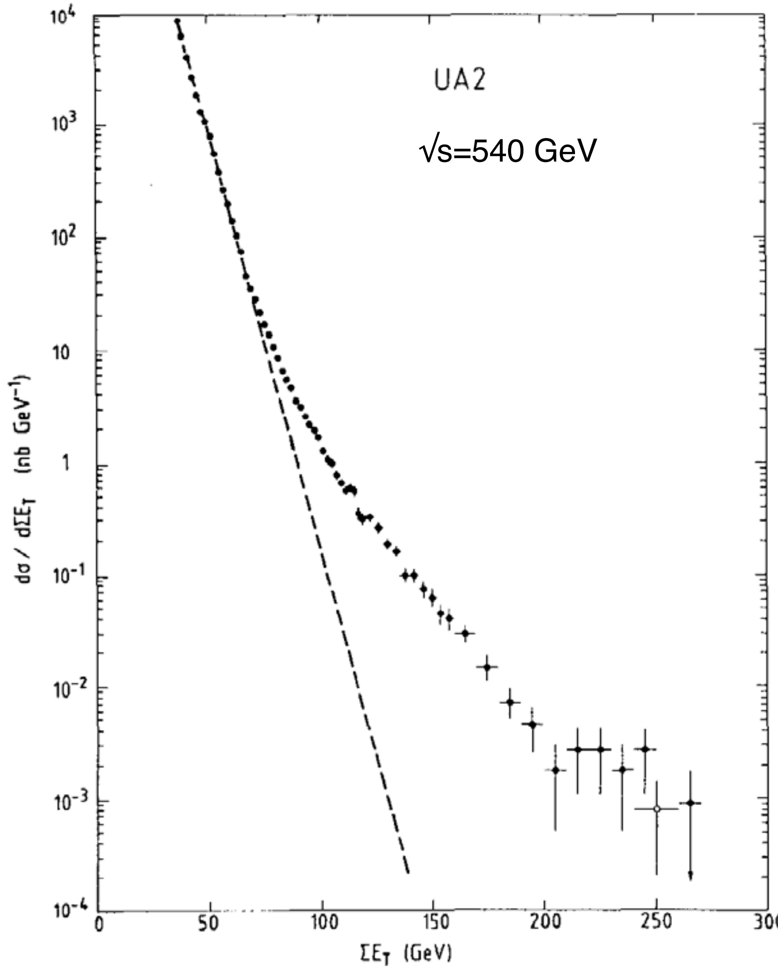
The Wounded Nucleon (Npart) Model agrees with αα data for 1 order of magnitude but disagrees for the other 10 orders of magnitude. The Additive Quark Model (AQM) [wounded projectile quarks] is in excellent agreement over the entire distribution.



A youngster, Bill Zajc, and other Penn collaborators claimed that failure of WNM was due to jets. BUT, from measured sphericity, E^o_T is not jetty in pp for E^o_T <10 GeV, four orders of magnitude down in cross section. No jet effect in whole measured region in α-α.

Jets are a <<10^{-3} effect in p-p E_T distributions





COR PLB**126**(1983)132 E_T in $\Delta\Phi=2\pi$, $|\eta|<0.8$ EMCal. Break above 20 GeV is due to jets. Also see NuclPhys B**244**(1984)1

UA2 PLB**138**(1984)430 (from DiLella) Break from jets ~5-6 orders of magnitude down for E_T in $\Delta\Phi=2\pi$, $|\eta|<1.0$

Edward Shuryak is Happy, (CGC types less so)

Collective interaction of QCD strings and early stages of high multiplicity pA collisions

arXiv:1404.1888

Tigran Kalaydzhyan and Edward Shuryak
Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA
(Dated: April 8, 2014)

We study early stages of "central" pA and peripheral AA collisions. Several observables indicate that at the sufficiently large number of participant nucleons the system undergoes transition into a new "explosive" regime. By defining a string-string interaction and performing molecular dynamics simulation, we argue that one should expect a strong collective implosion of the multi-string "spaghetti" state, creating significant compression of the system in the transverse plane. Another consequence is collectivization of the "sigma clouds" of all strings into collective chorally symmetric fireball. We find that those effects happen provided the number of strings $N_s > 30$ or so, as only such number compensates small sigma-string coupling. Those finding should help to understand subsequent explosive behavior, observed for particle multiplicities roughly corresponding to this number of strings.

I. INTRODUCTION

A. The evolving views on the high energy collisions

Before we got into discussion of high multiplicity pA collisions, let us start by briefly reviewing the current views on the two extremes: the AA and the minimum bias pp collisions.

The "not-too-peripheral" AA we will define as those which have the number of participant nucleons $N_p > 40$, and the corresponding multiplicity of the order of few hundreds. (*Peripheral* AA, complementary to this definition, we will discuss in this paper, below in section IV B.) Central AA collisions produce many thousands of secondaries: the corresponding fireball has the

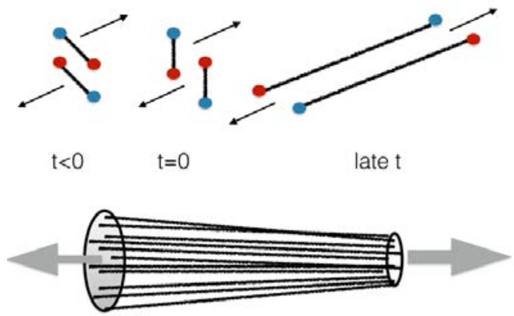


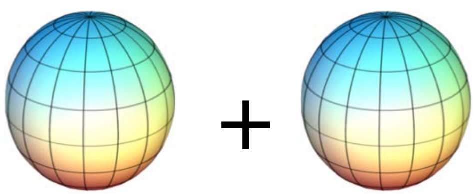
FIG. 1: The upper plot reminds the basic mechanism of two string production, resulting from color reconnection. The lower plot is a sketch of the simplest multi-string state, produced in pA collisions or very peripheral AA collisions, known as "spaghetti".

U+U Collisions-STAR Motivation

Allows us to manipulate the initial geometry and study:

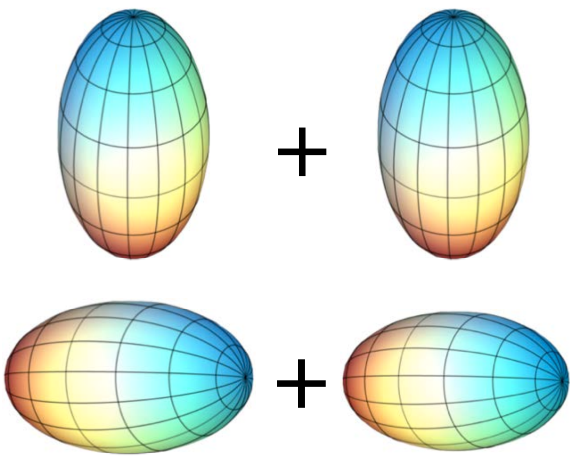
- How multiplicity depends on N_{part} and N_{coll} They won't be happy
- Path-length dependence of jet quenching
- Particle production in heavy-ion collisions
- Other effects most importantly v_2 in central collisions

Au+Au Collisions



Oblate

U+U Collisions

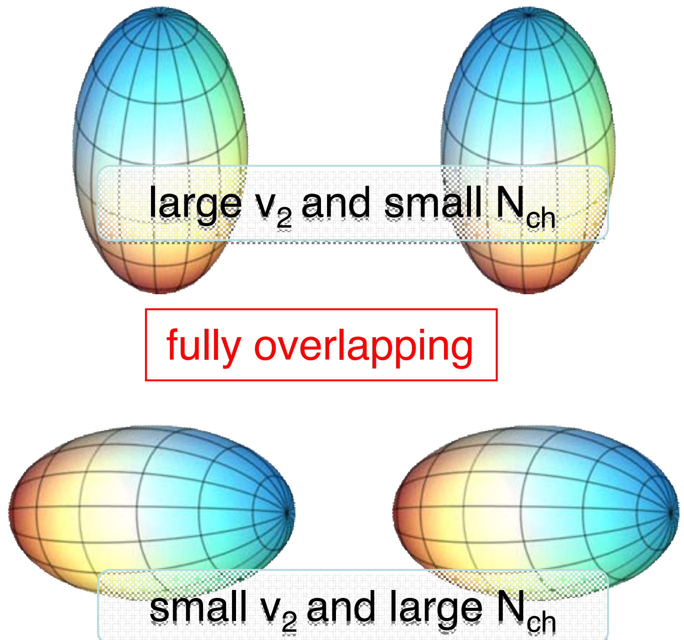


Prolate

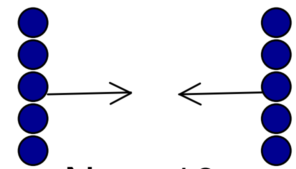
Can we see a difference between Au+Au and U+U and preferentially select body-body or tip-tip U+U collisions?

Selecting Body-body or Tip-tip

In two-component model, multiplicity depends on the N_{part} and N_{coll} and since v_2 is propotional to initial eccentricity

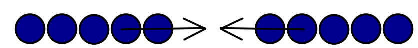


$$n_{AA} \propto n_{pp}[(1-x_{hard})\frac{N_{part}}{2} + x_{hard}N_{coll}]$$



N_{part}=10
N_{coll}= **5**

**idealizations*



N_{part}= 10
N_{coll}= **25**

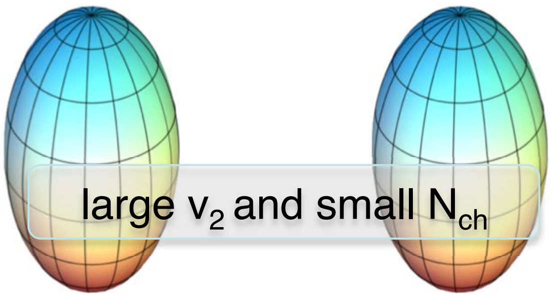
If dN/dη depends on N_{coll}, large dN/dη should correlate with small v_2.
_*Central U+U collisions are ideal for testing particle production*

Strategy: select events with few spectators (fully over-lapping), then measure v_2 vs. multiplicity: **how strong is the correlation?**

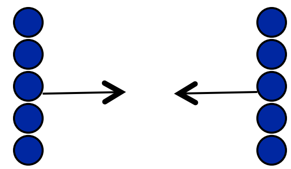
Selecting Body-body or Tip-tip

In two-component model, multiplicity depends on the N_{part} and N_{coll} and since v_2 is propotional to initial eccentricity

$$n_{AA} \propto n_{pp}[(1-x_{hard})\frac{N_{part}}{2} + x_{hard}N_{coll}]$$



fully overlapping



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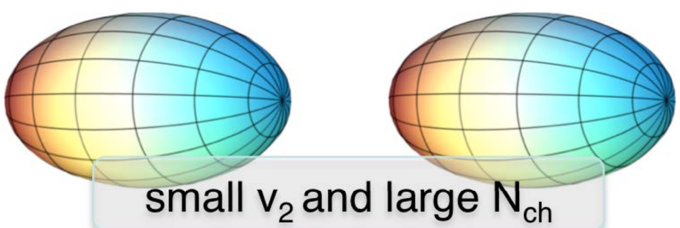
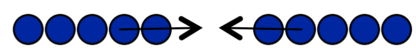




N_{part}= 10
N_{coll}= **25**

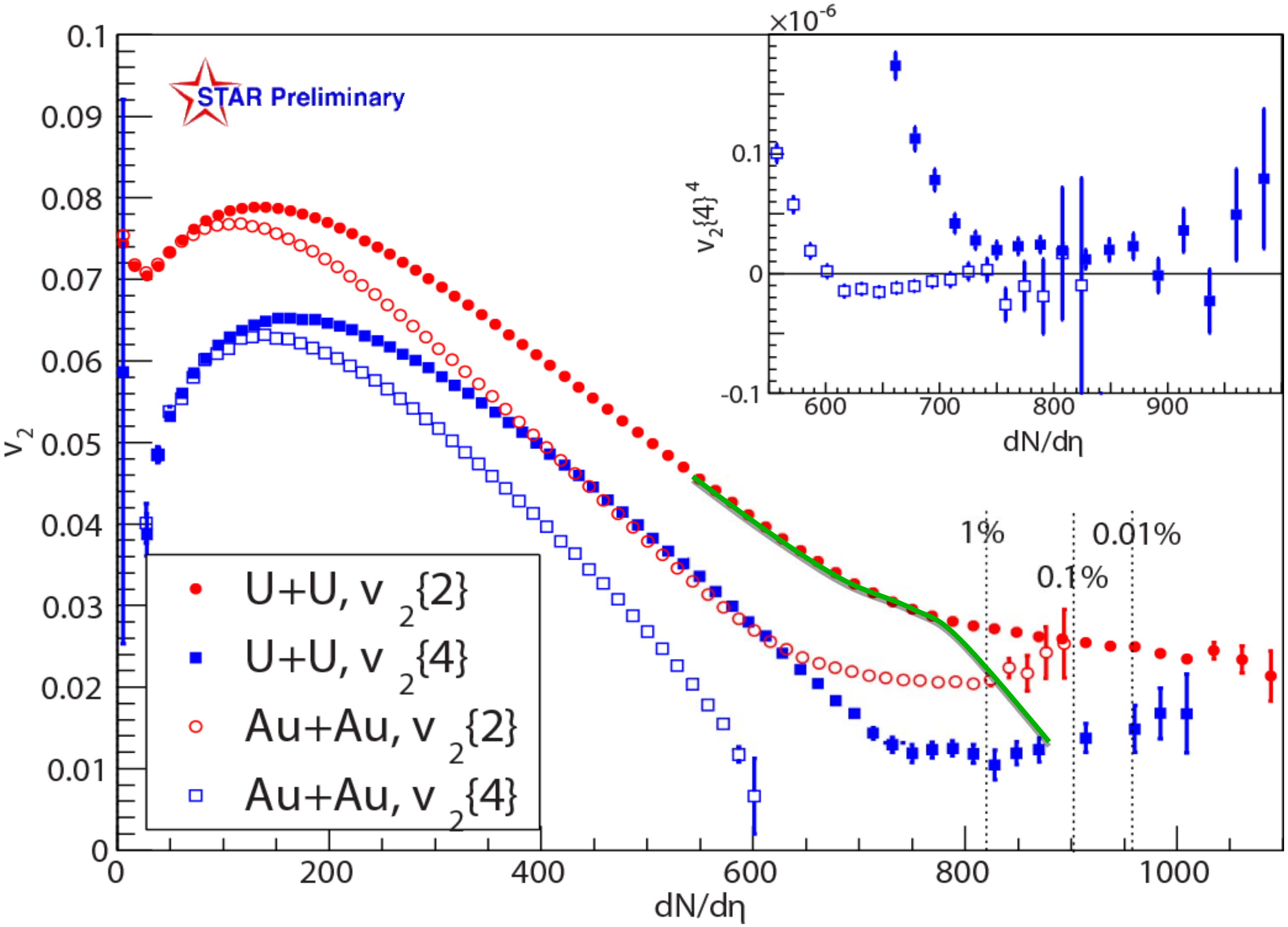
This is wrong they will be disappointed

If dN/dη depends on N_{coll}, large dN/dη should correlate with small v_2.

➪ *Central U+U collisions are ideal for testing particle production*

Strategy: select events with few spectators (fully over-lapping), then measure v_2 vs. multiplicity: **how strong is the correlation?**

Minimum-bias U+U and Au+Au



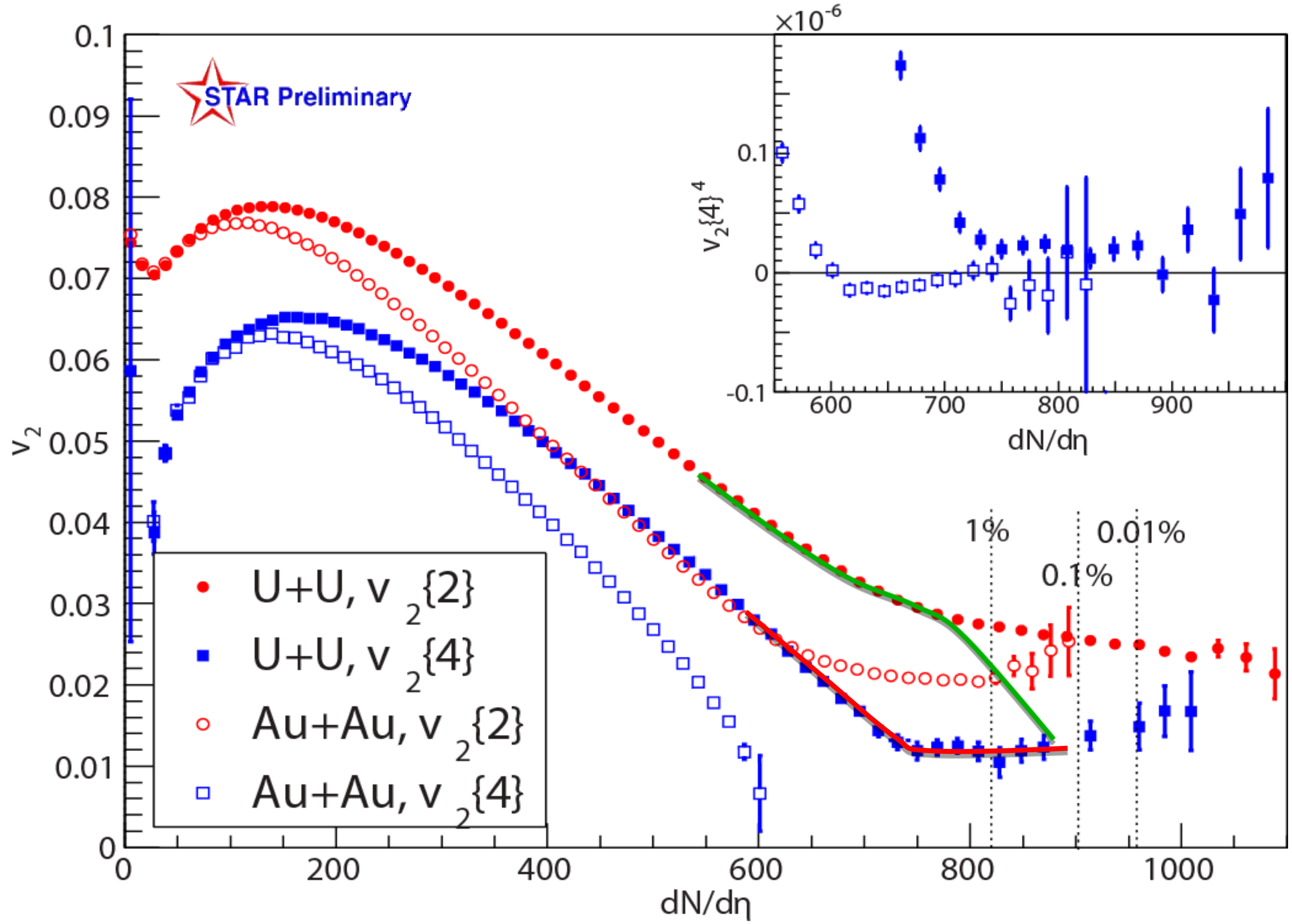
No evidence of knee structure for central U+U

- ✓Glauber plus 2-component model suggests knee structure at ~2% centrality
- ✓Knee washed out by additional multiplicity fluctuations?1
- ✓Other interpretations?

[1]Maciej Rybczy_ski, et. al. Phys.Rev. C87 (2013) 044908

Dashed lines represent top centrality percentages for U+U collisions based on multiplicity, curves are used to guide the eye

Minimum-bias U+U and Au+Au



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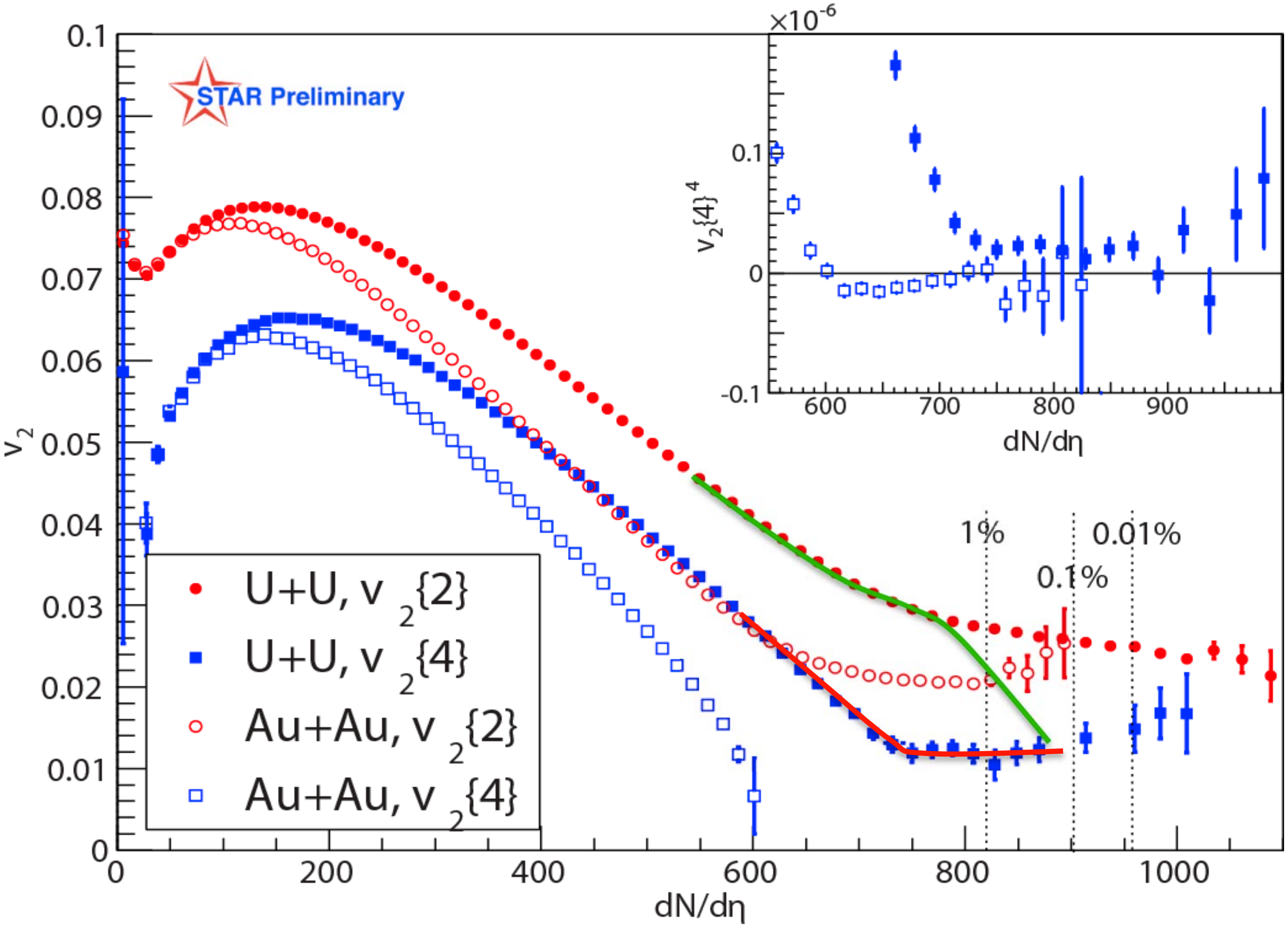
The U+U $v_2\{4\}$ results are non-zero in central

✓Result of intrinsic prolate shape of the Uranium nucleus
✓Au $v_2\{4\}$4 becomes consistent with zero

Dashed lines represent top centrality percentages for U+U collisions based on multiplicity, curves are used to guide the eye

Minimum-bias U+U and Au+Au



No evidence of knee structure for central U+U

- ✓Glauber plus 2-component model suggests knee structure at ~2% centrality
- ✓Knee washed out by additional multiplicity fluctuations?1
- ✓Other interpretations? Yes,Nqp!!!

[1]Maciej Rybczyński, et. al. Phys.Rev. C87 (2013) 044908

The U+U $v_2\{4\}$ results are non-zero in central

✓Result of intrinsic prolate shape of the Uranium nucleus
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Dashed lines represent top centrality percentages for U+U collisions based on multiplicity, curves are used to guide the eye

$v_2\{4\}$ data: we see the prolate shape of the Uranium nucleus ✓

The lack of a knee indicates a weakness in Ncoll multiplicity models

I rushed through the previous slides because:

- 1) It was an introduction: the material has been covered in previous Highp_TLHC lectures and proceedings by me;
- New this year: I wrote a book with Jan Rak with all this kind of information, “High p_T physics in the Heavy Ion Era”

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High-pT Physics in the Heavy Ion Era

Jan Rak, University of Jyväskylä, Finland
Michael J. Tannenbaum, Brookhaven National Laboratory, New York

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Aimed at graduate students and researchers in the field of high-energy nuclear physics, this book provides an overview of the basic concepts of large transverse momentum particle physics, with a focus on pQCD phenomena. It examines high-pT probes of relativistic heavy-ion collisions and will serve as a handbook for those working on RHIC and LHC data analyses. Starting with an introduction and review of the field, the authors look at basic observables and experimental techniques, concentrating on relativistic particle kinematics, before moving onto a discussion about the origins of high-pT physics. The main features of high-pT physics are placed within a historical context and the authors adopt an experimental outlook, highlighting the most important discoveries leading up to the foundation of modern QCD theory. Advanced methods are described in detail, making this book especially useful for newcomers to the field.

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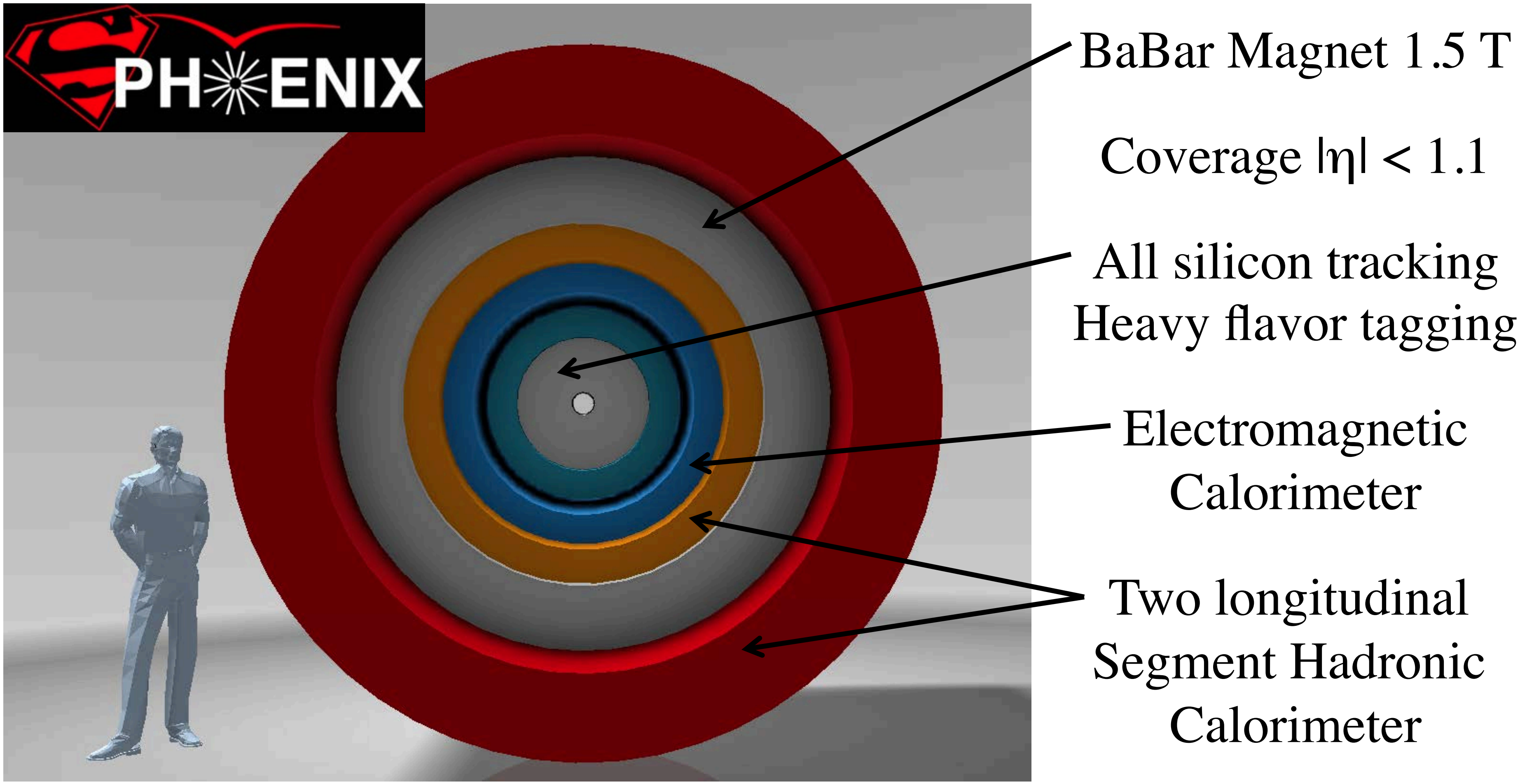
Jamie Nagle: "sPHENIX in a Nutshell"



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