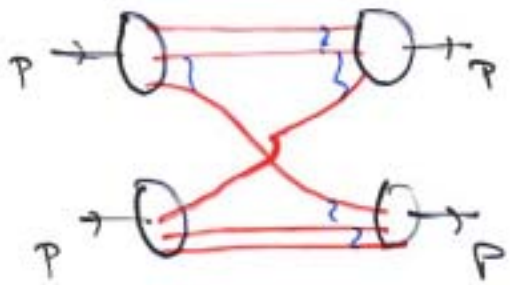
High p_T Exclusive Reactions

Consider $pp \to pp$ at large p_T:



$$\frac{d\sigma}{dt} \sim \alpha_s^{10} f_p^8 \frac{1}{s^2} \frac{1}{u^4} \frac{1}{t^4}$$

$$\sim \frac{1}{s^{10}} f(\theta_{cm})$$

QCM dominant at large N_c
in t'Hooft fixed $\alpha_s N_c$ limit.

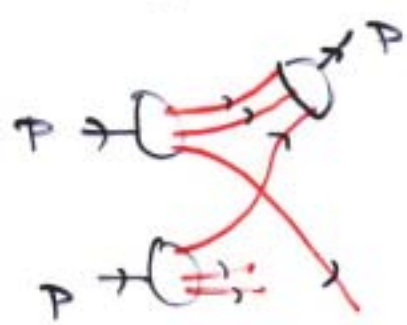
Good fit to data, ANN. (except at heavy quark thresholds)

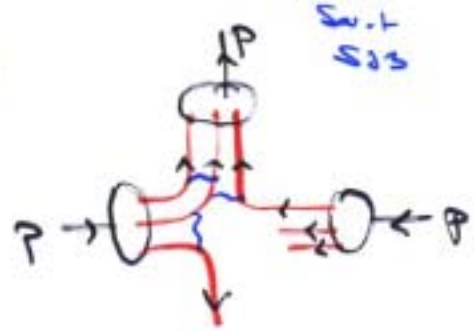
$\alpha_s \sim$ const $\Rightarrow$ near conformal QCD

AdS/CFT counting rules

Blankenbecler
Gunion
Swift
SJB

Duality:





$$\frac{d\sigma}{d^2p/E}(pp \to p\,X) \sim \frac{(1-x_T)^3}{p_T^{12}} \quad *$$

$n_{active} = 8$
$n_{spect} = 2$

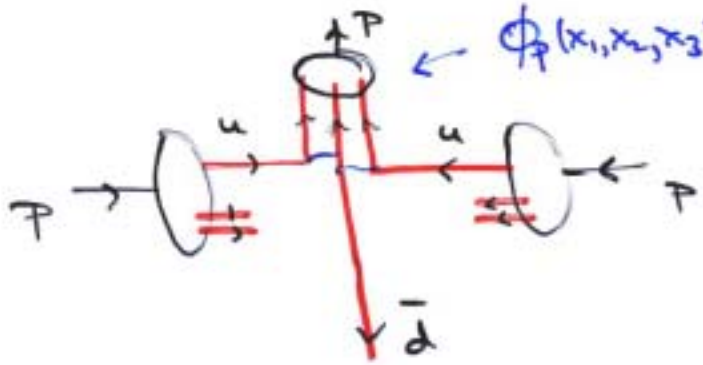
vs.

$$\frac{(1-x_T)^{11}}{p_T^4}$$

$n_{active} = 4$
$n_{spect} = 6$

Example of Higher Twist Process

$$pp \to pX$$



$\phi_p(x_1, x_2, x_3) \propto f_p \sim [m]^2$

$n_{spec} = 2+2$

$n_{active} = 6$

Bjorken

$$\frac{d\sigma}{dt}(qq \to p\bar{q}) \sim \frac{1}{(p_T^2)^4} \alpha_s^4 f_p^2$$

proton produced directly or resonance decay

$$\frac{d\sigma}{d^2p/E}(pp \to pX) \sim \frac{(1-x_T)^7}{p_T^8}$$

counting rules:

$$\frac{(1-x_T)^{2n_s-1}}{(p_T^2)^{n_{active}-2}}$$

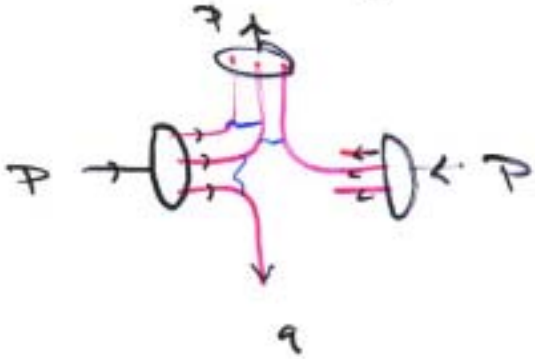
Data: FNAL / ISR:

$$\frac{(1-x_T)^7}{p_T^{12}}$$

Exclusive - Inclusive Duality ⇒ "Direct" Production

$$pp \to p X \cong pp \to p p^*$$

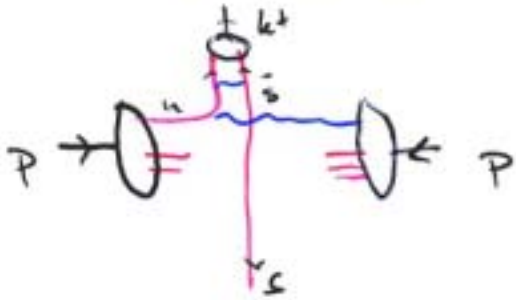
at fixed s, t, M_X^2



$qp \to qp$

- No same-side jet
- no beam fragments
- analog of QIM for $pp \to pp$
- dominant at large N_c

Related subprocesses



$ug \to k^+ s$

- Direct meson production
- no same-side jet

$$\frac{d\sigma}{d^2p_\perp dy}(pp \to k^+ X) \sim \frac{p_\perp^2}{p_T^6}(1-x_T)^8$$

⇒ Implications of "Direct Hadron Production" for RHIC

$pA \to h X$:
- Color transparency : No FSI , Energy loss
- No final state hadronization
- No comovers

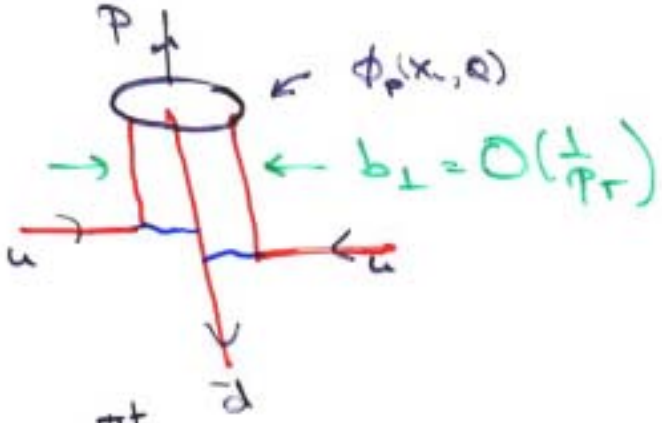
Mueller
SJB
Kopeliovich

Direct subprocesses

⇒ Color transparency

= reduced nuclear absorption !

Direct higher twist

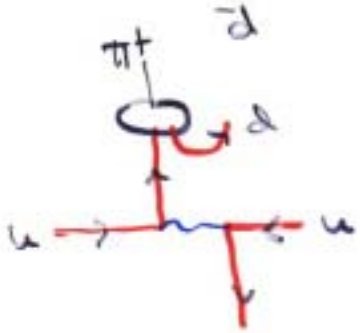


Small color dipole

diminished FSI

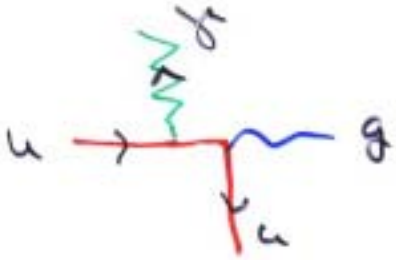
vs.

Fragmentation leading twist



large FSI: energy loss of quark (limited by LPM)

Direct γ



no FSI.

$$\frac{\frac{d\sigma}{d^3p/E}(pp \to \gamma X)}{\frac{d\sigma}{d^3p/E}(pp \to HX)} = F(x_T, \theta_{cm})$$ if leading twist

Lesson from $pp \to H X$: sum of QCD hard processes

Higher twist subprocesses

→ "direct" reactions $\qquad x_T = \frac{2p_T}{\sqrt{s}}$

important at large x_T, x_R

enhanced by trigger bias effect

dominate over leading twist

unless x_T small

RHIC $\sqrt{s_{NN}} = 200$ GeV

P, A production dom. by higher twist processes

color transparency eliminates some side suppression

Pion: PQCD prob. okay

Crucial to interpretation of A-A effects

Need Data at fixed p_T, vary $\sqrt{s}$

Elliptic Flow

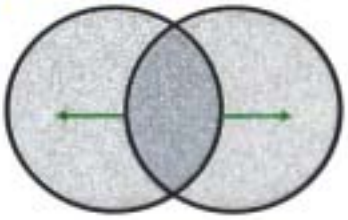
$$\frac{\dfrac{d^2N}{dp_T^2\, d\phi}}{\dfrac{dN}{dp_T^2}} = \frac{1}{2\pi}\left(1 + 2v_2 \cos(2\phi_p)\right)$$

Modeled from hydrodynamics

Elliptic Flow

- anisotropic or "elliptic" flow is sensitive to initial geometry

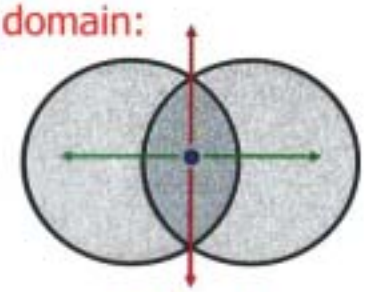
low p_t domain:



$$Force = -\nabla P$$

more flow in collision plane than perpendicular to it

high p_t domain:



$$\Delta E \quad L$$

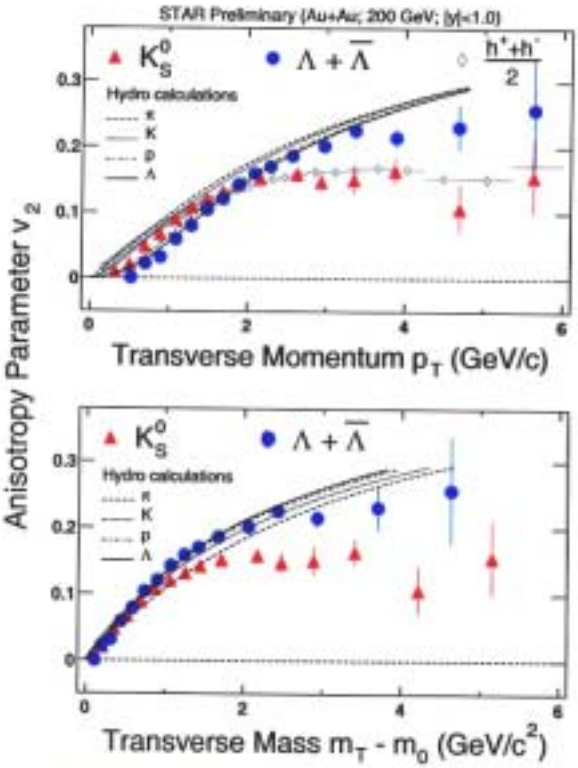
less absorption in collision plane than perpendicular to it

- total elliptic flow is the sum of both contributions:

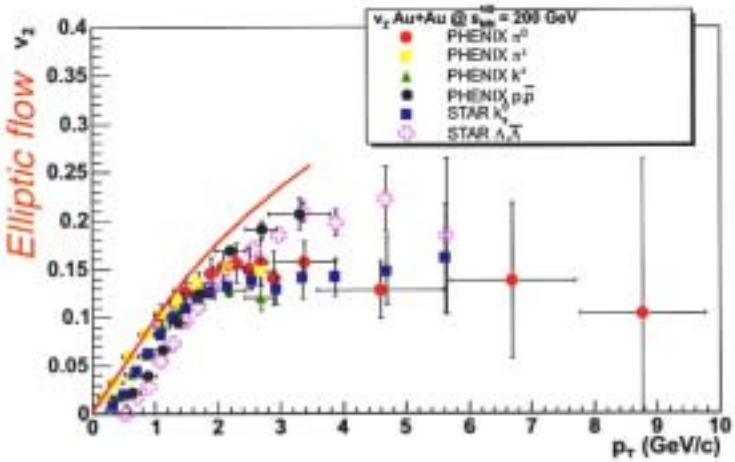
$$v_2(p_t) = r(p_t)\, v_2^{\text{recomb}}(p_t) + \left(1 - r(p_t)\right) v_2^{\text{frag}}(p_t)$$

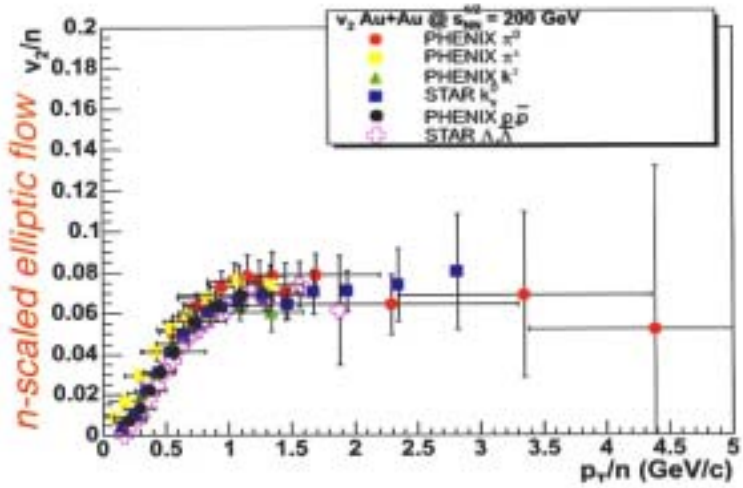
$r(p_t)$: relative weight of the recombination contribution in spectra

Elliptic flow of K^0 and Λ



- hyperon v_2 saturates later and higher than kaon v_2.
- same effect observed for protons and pions.
- what drives the different p_T scales for K_S and Λ v_2?
  - novel mechanism of baryon formation?





$V_2(p_T)$: strength
↑ correlation ↑
particle with event plane

Data Compilation from:

PHENIX Collab.
to appear in PRL
nucl-ex/0305013

STAR Collab.
to appear in PRL
nucl-ex/0306007

A - A collisions:

Fraction of $\sqrt{s_{AA}}$ converted to high density q, g medium

materialize as hadrons $\sim 10^4$

hot, dense hadronic system

$\frac{dN}{dy}$ uniform : as limited by energy avail.

more hadrons produced transverse to principal axis

$\Rightarrow$ production axis

Correlation between event and production axes

$$V_2(p_T) = \langle \cos(\phi_{p_T} - \phi_0) \rangle$$

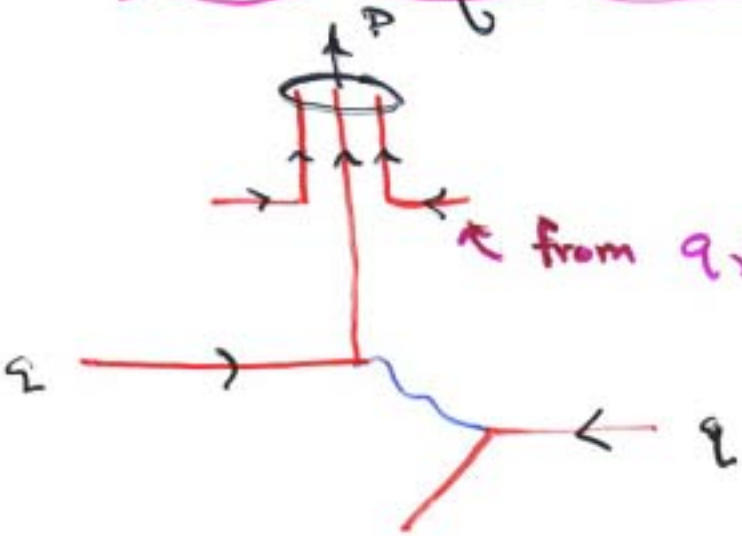
High p_T particles aligned with event axis!

away side jet strongly suppressed

"Recombination"

Another model for large p_T baryon production in central A-A collisions

Coalescence of Comovers



from q,g plasma

R. Fries
B. Müller

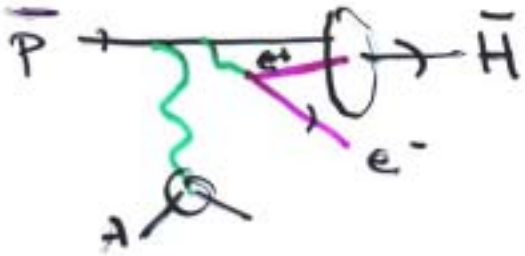
$\boxed{V_2/n \text{ vs } p_T/n \text{ scaling}}$

n = 2 baryons
n = 1 mesons

picks up motion of plasma

Recombination analogous to antihydrogen production

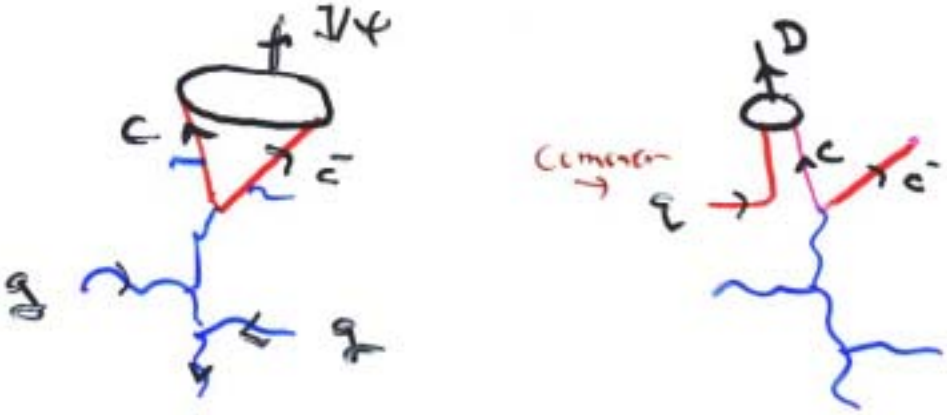
CERN, FNAL



quantum mechanical analysis (off-shell)

Schmidt
Munger, SJB

Comovers can explain J/ψ Suppression



Coalescence with comover enhances D
Suppresses J/ψ.

R. Vogt
P. Hoyer
SVR

Explains leading particle effects

$pp \to \Sigma X$

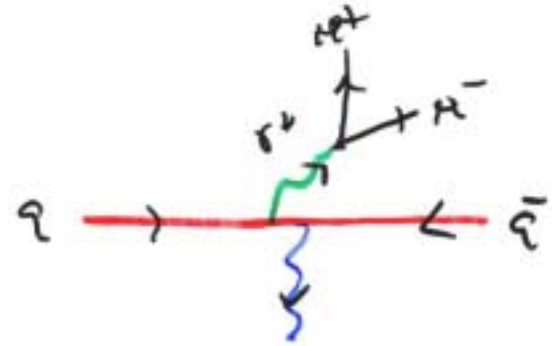
$pp \to \Lambda_c X$, $D X$

assuming Intrinsic charm distributions

$pp \to J/\psi X$

$pp \to J/\psi\, J/\psi\, X$

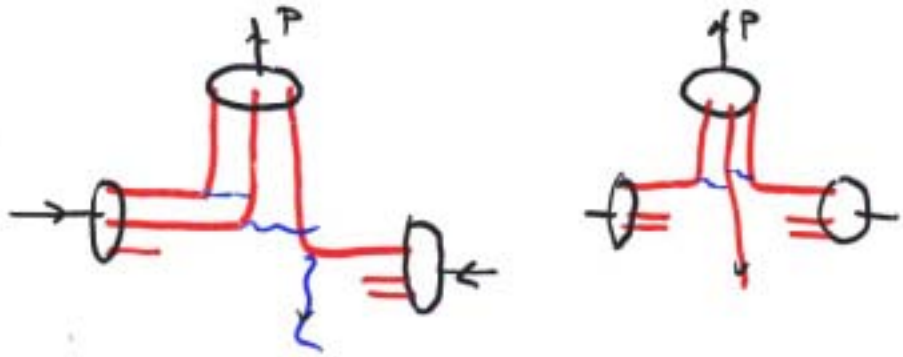
Crucial Test for RHIC A-A



Drell-Yan pairs at high $Q_\perp$

$\phi_{\mu^+\mu^-}$ uncorrelated with event plane!

higher twist model



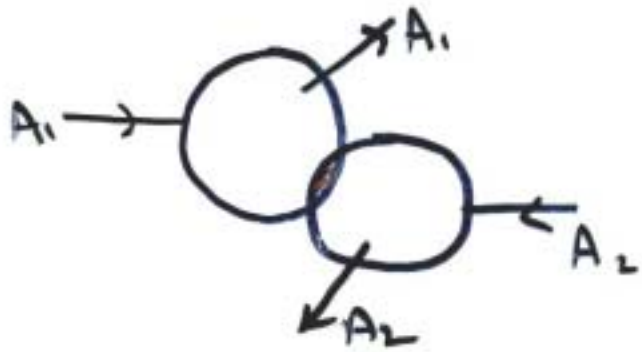
minimal $v_2(p_T)$ at large p_T when color transp is effective

Comover model

$v_2(p_T)$ from coalescence with partons in plasma

"Bump Effect"

Generate v_2 correlations from elastic collisions?



First collisions

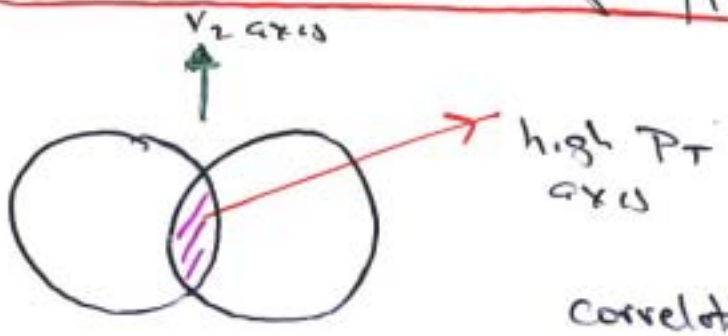
$NN \to NN$

sets nuclei in motion

$\Delta p_T \sim \frac{1}{R_A} \sqrt{n}$

Assoc to Cronin Effect

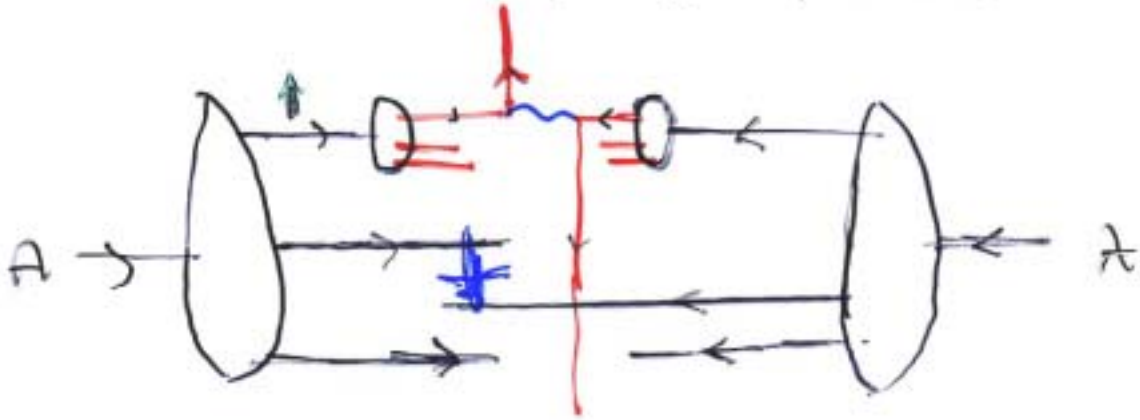
Azimuthal Correlations in High p_T A-A Collisions



Correlation between axes?

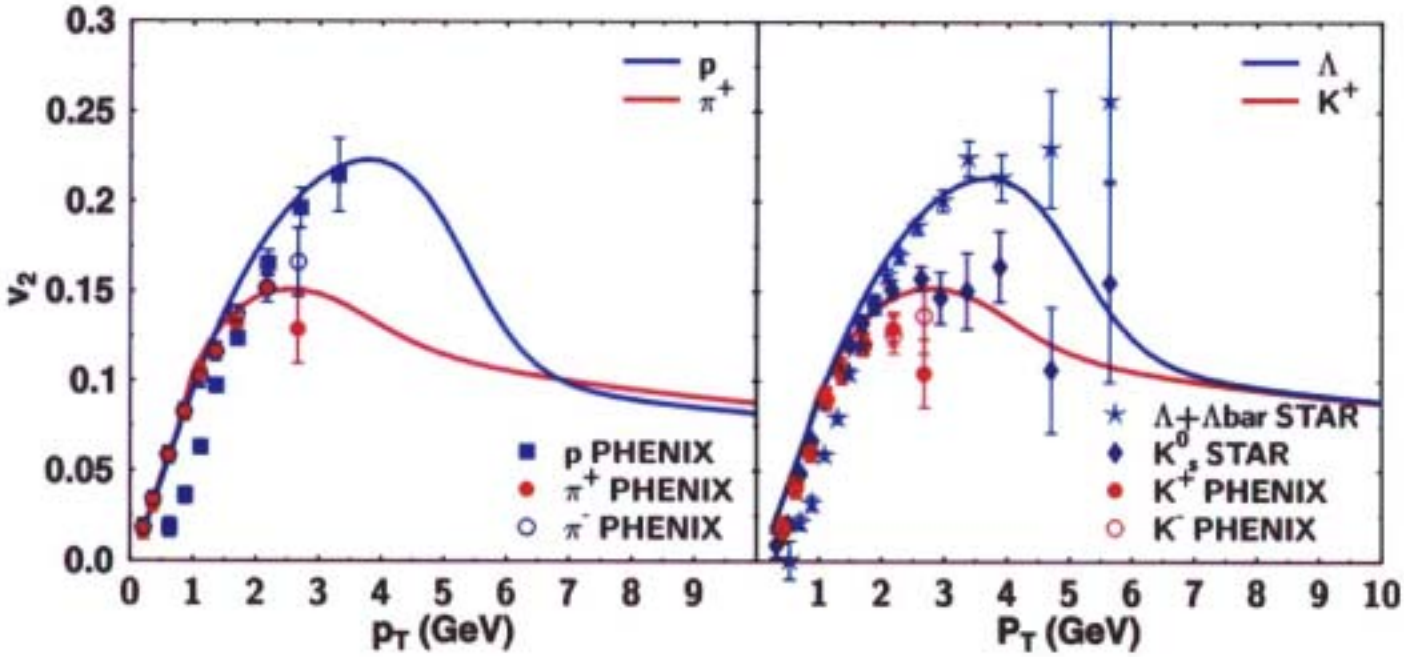
In principle no correlation

In practice, multiple collisions affect high p_T production



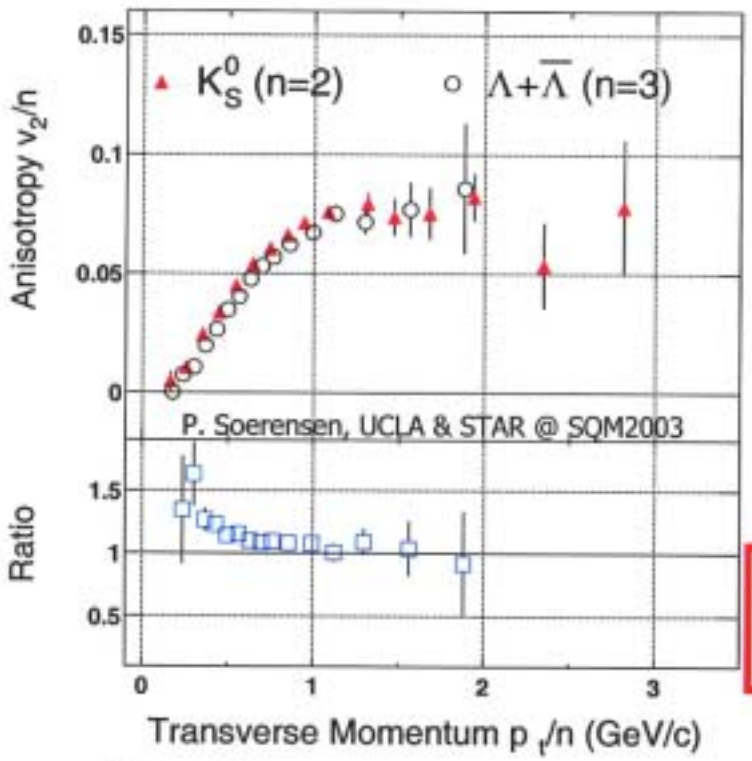
Nuclear correlations increase $k_\perp$ fluctuations increase fast-falling cross section.

Flavor Dependence of Recombination



- Recombination describes measured flavor-dependence!

Parton Number Scaling of v_2



- in leading order of v_2, recombination predicts:

$$v_2^M(p_t) = 2v_2^p\left(\frac{p_t}{2}\right)$$

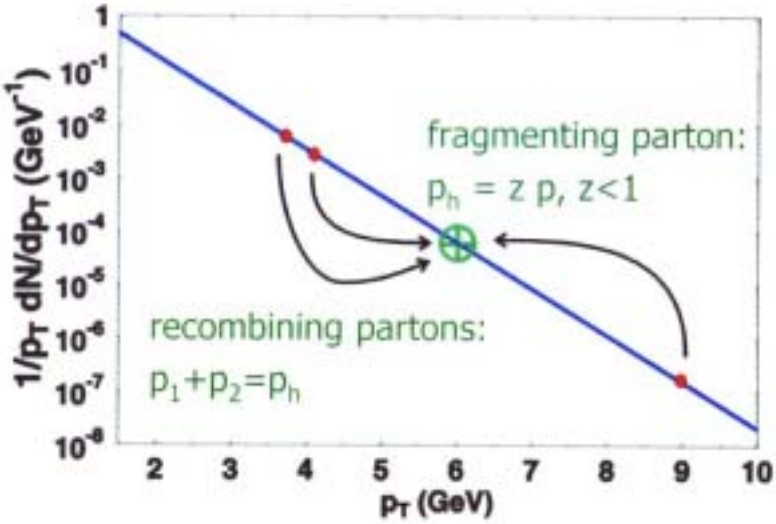
$$v_2^B(p_t) = 3v_2^p\left(\frac{p_t}{3}\right)$$

- smoking gun for recombination
- measurement of partonic v_2 !

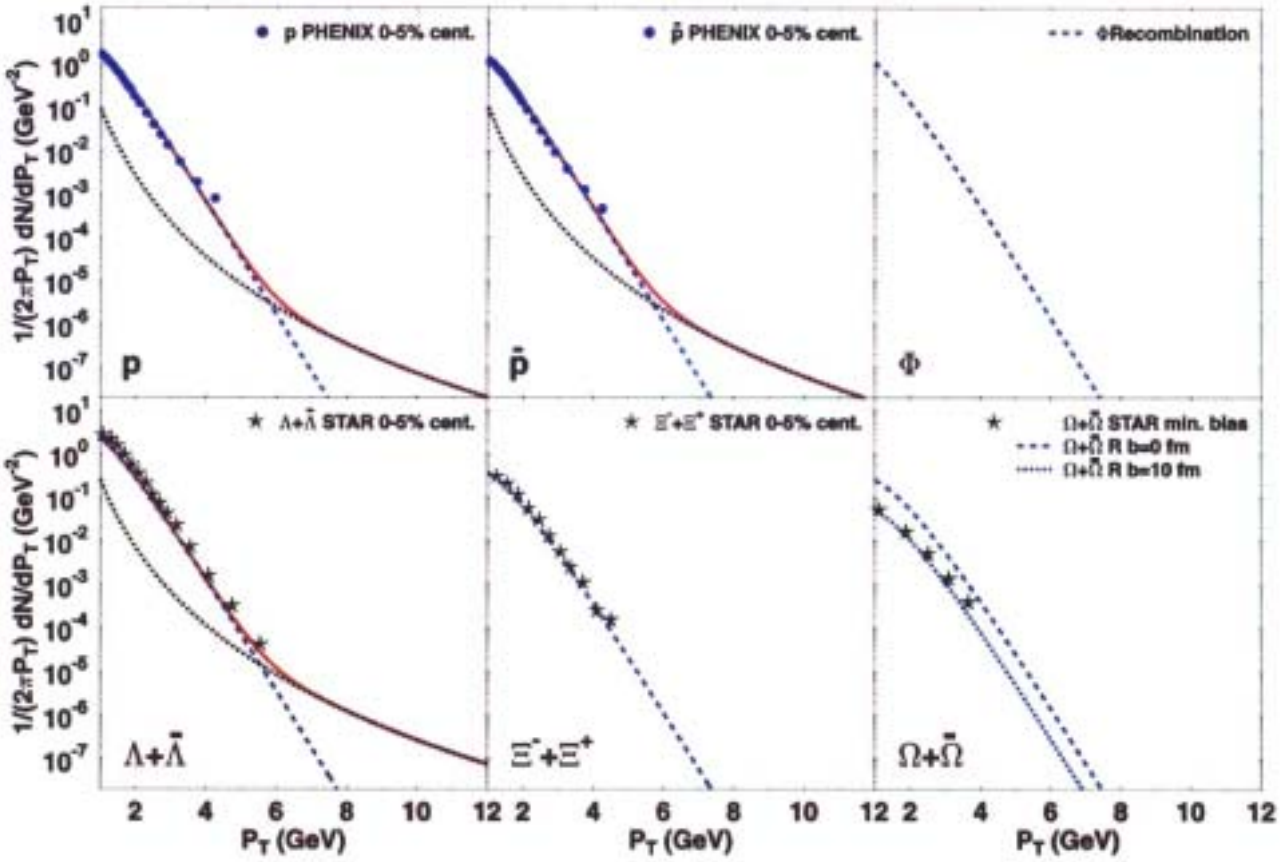
Recombination vs Fragmentation

- for exponential parton spectrum, recombination is more effective than fragmentation
- baryons are shifted to higher p_t than mesons, for same quark distribution

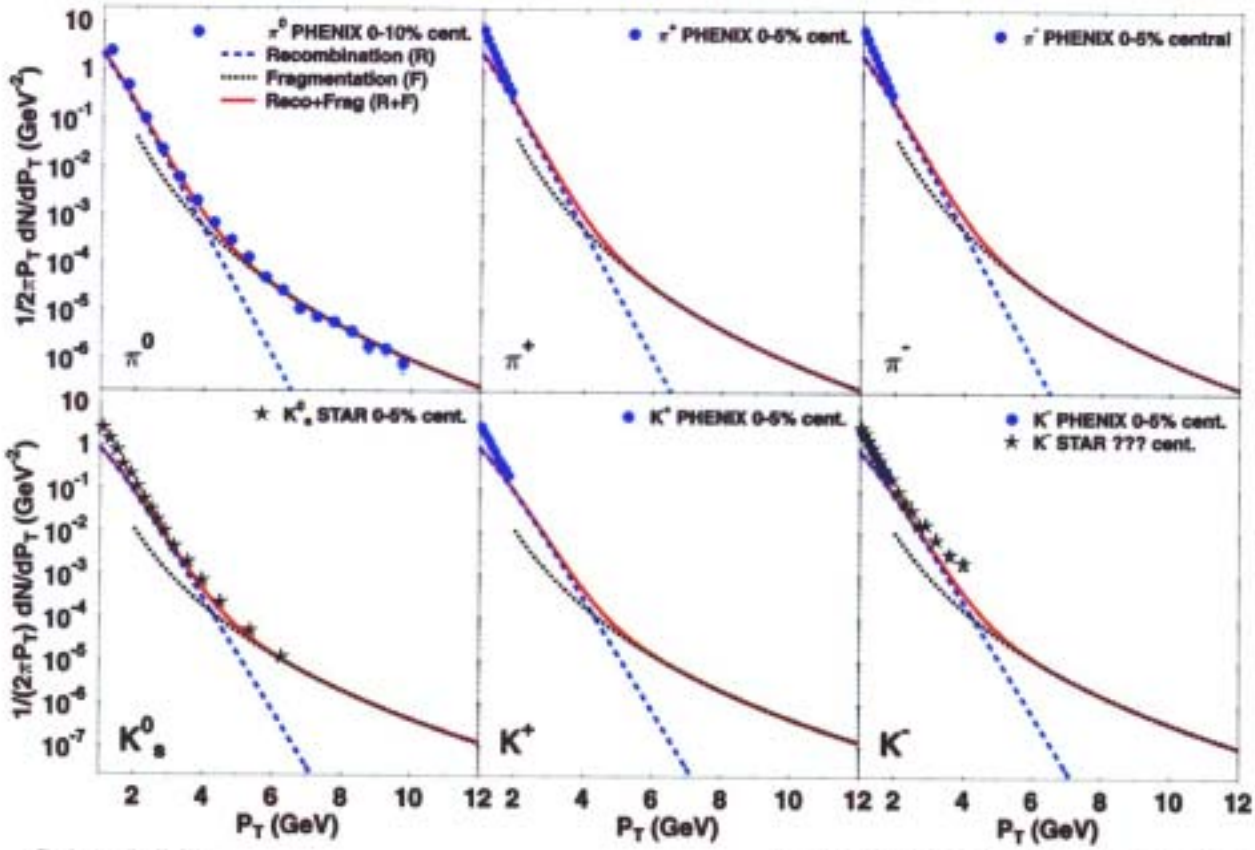
➢ understand behavior of protons!



Hadron Spectra II

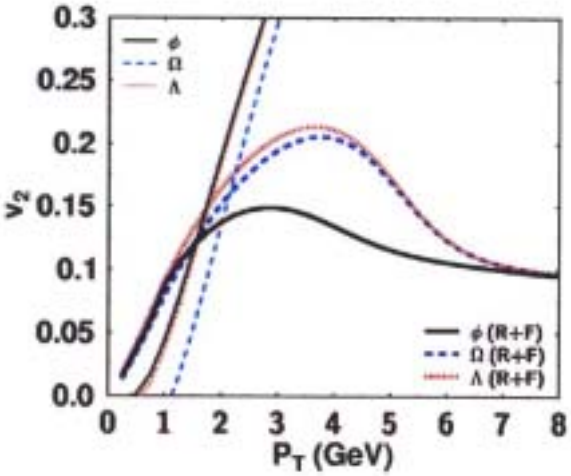


Hadron Spectra I



New developments I

- Another test: the ϕ meson. Do we see a mass effect or the valence quark structure of hadrons?
- Reco different from Nara & Hirano's hydro+pQCD calculation.
- The deuteron and the pentaquark should have tremendous v_2.
- STAR: deuteron v_2 follows the scaling law!



Belle (hep-ex/0205104)

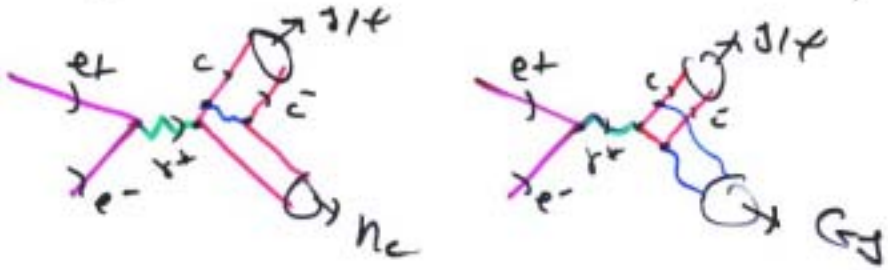
$\sqrt{s} \cong 10.6$ GeV

$$\frac{\sigma(e^+e^- \to J/\psi\, c\bar{c})}{\sigma(e^+e^- \to J/\psi\, X)} = 0.59\ (+0.15\ -0.13\ \pm 0.12)$$

large associated open charm rates $J/\psi\, D^{*+} X$

associated charmonia $J/\psi\, \eta_c$

– Possible explanation : two dominant subprocesses



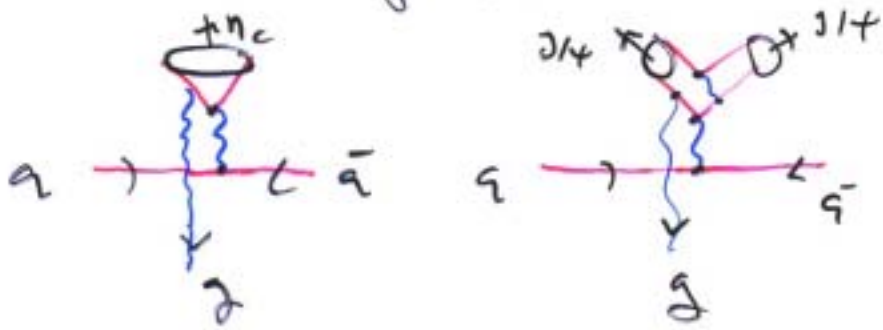
Kharzeev
Zoffe

0^{++}, 2^{++} glueballs

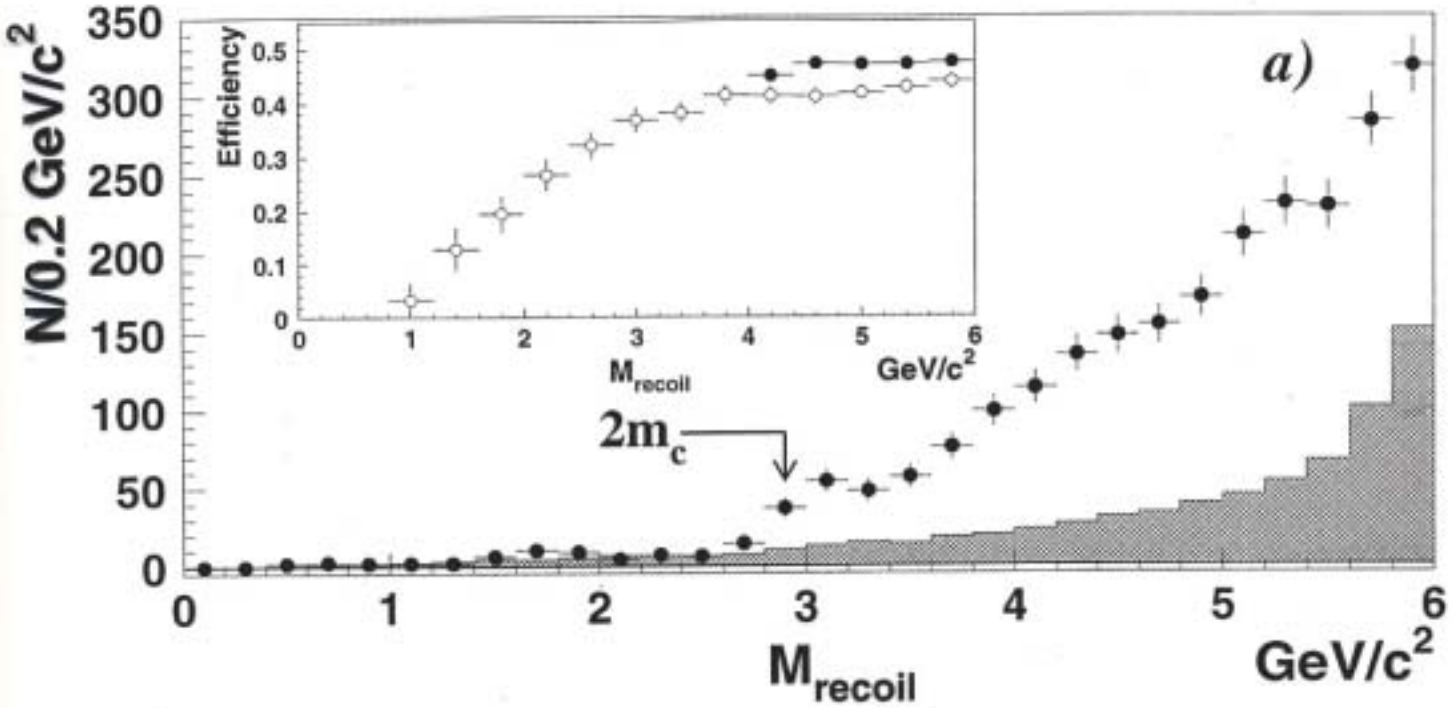
⇒ Opportunity to observe associated gluonia

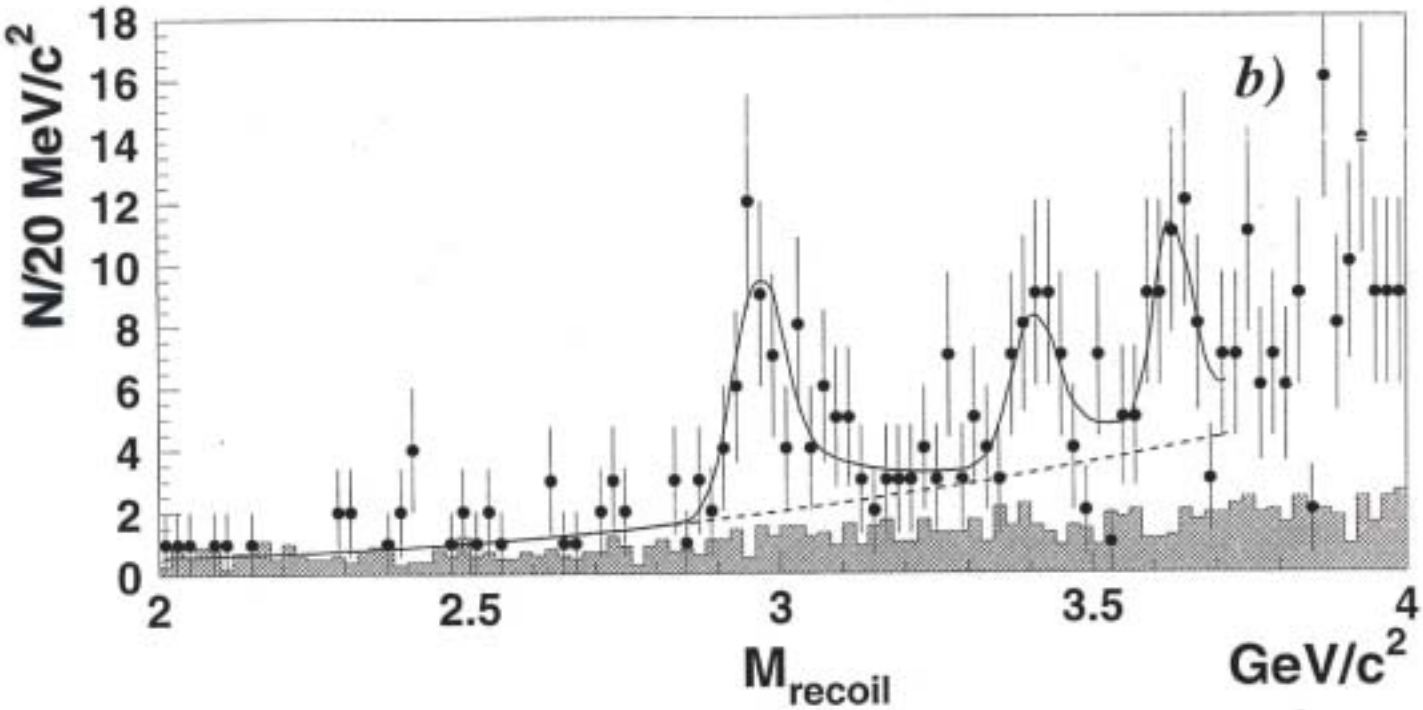
Goldhaber
Lee
SJB

* Implications for pp collisions



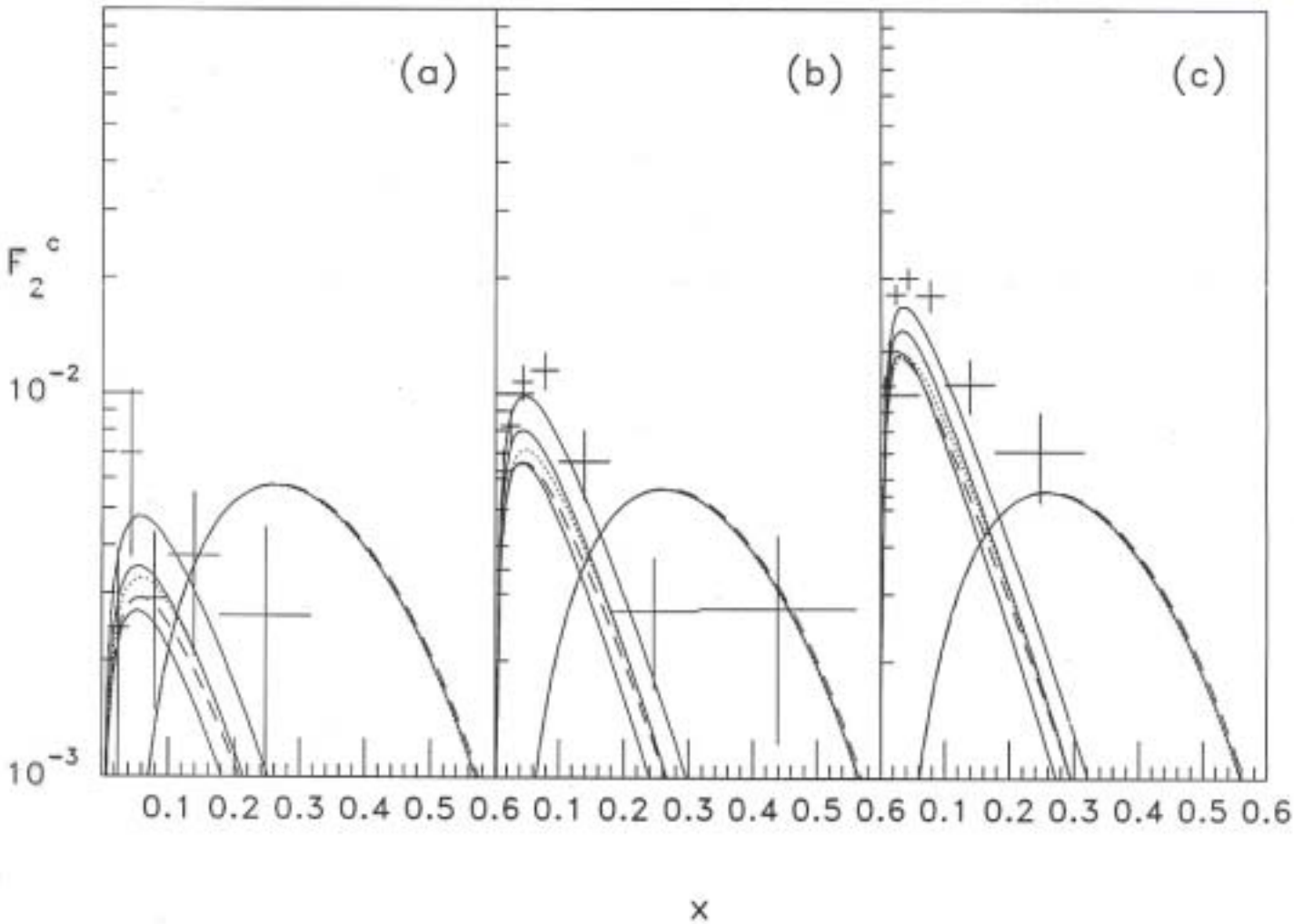
double J/ψ production!


a)
N/0.2 GeV/c^2
Efficiency
M_{recoil}
GeV/c^2
$2m_c$
M_{recoil}
GeV/c^2


b)
N/20 MeV/c^2
M_{recoil}
GeV/c^2

EMC
Data

Harris, Smith, Vogt



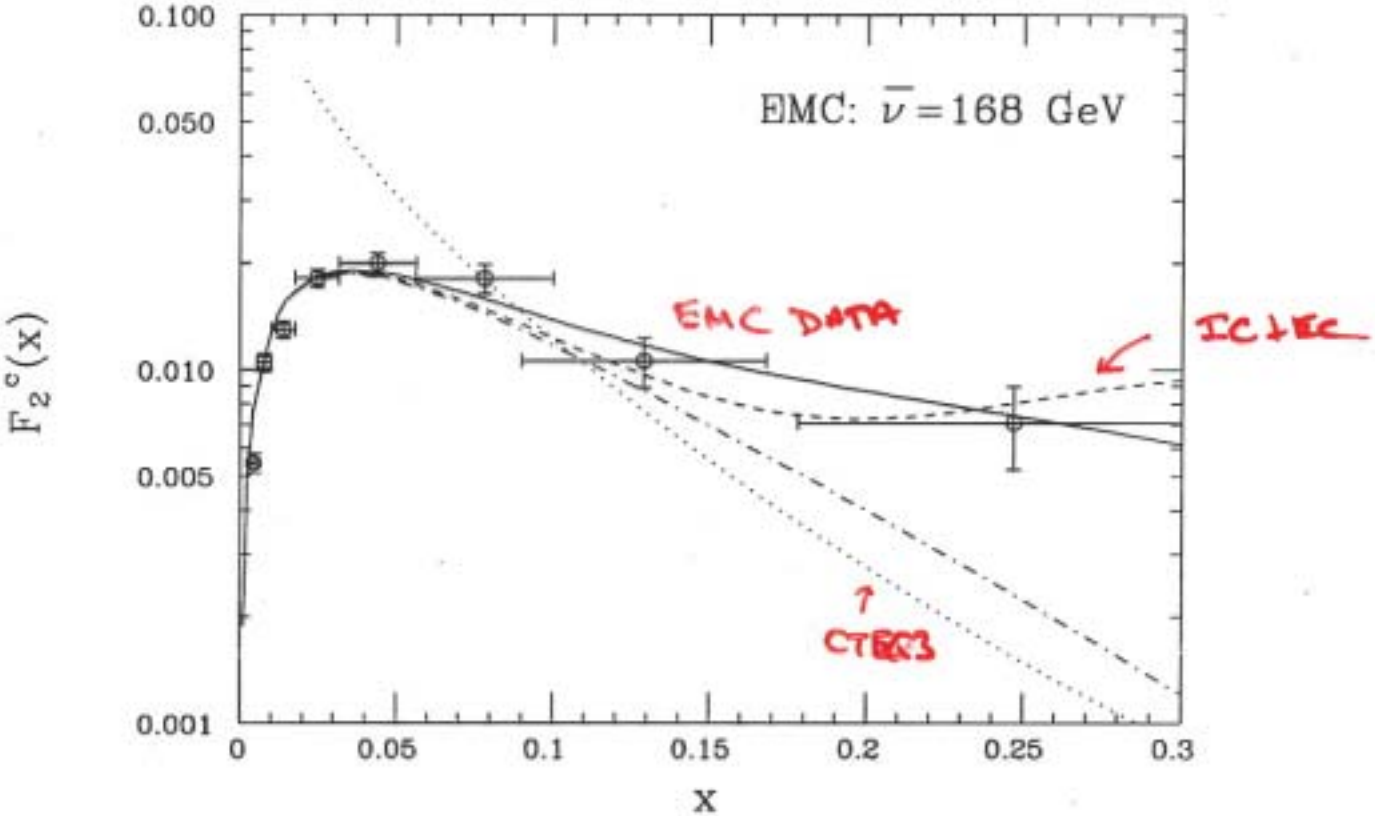
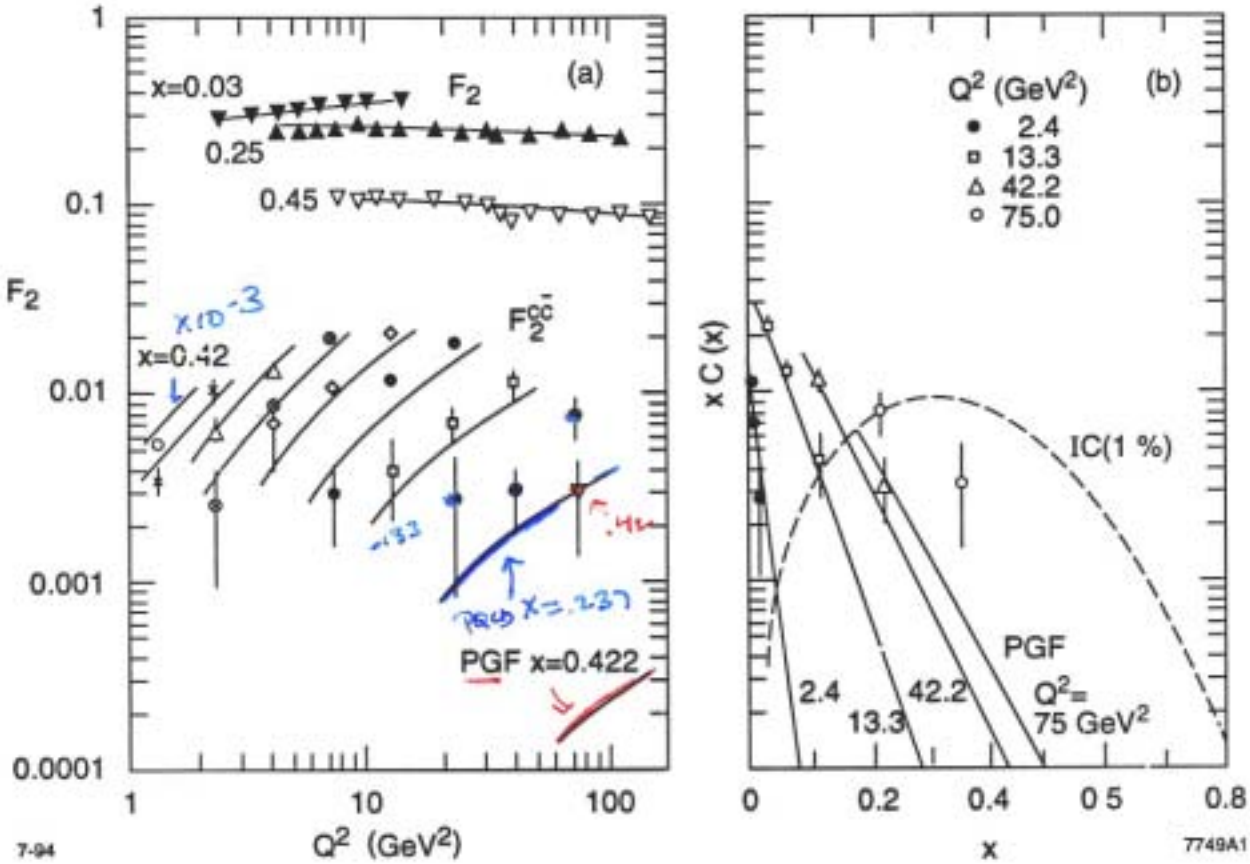


Figure 2: EMC data for $F_2^c(x)$ at $\overline{\nu} = 168$ GeV compared to: (i) dotdash — the extrinsic charm prediction of Ref. [5]; (ii) dots — the CTEQ3 perturbative prediction; (iii) solid — EC+IC prediction for $n = 2$; (iv) dashes — EC+IC prediction for $n = 8$.

R. vogt



x = .42 Q^2 = 75 GeV^2

~30 times PGF prediction

$C(x,Q^2)$ still may increase further with increasing Q^2

Confirmation From Other Results

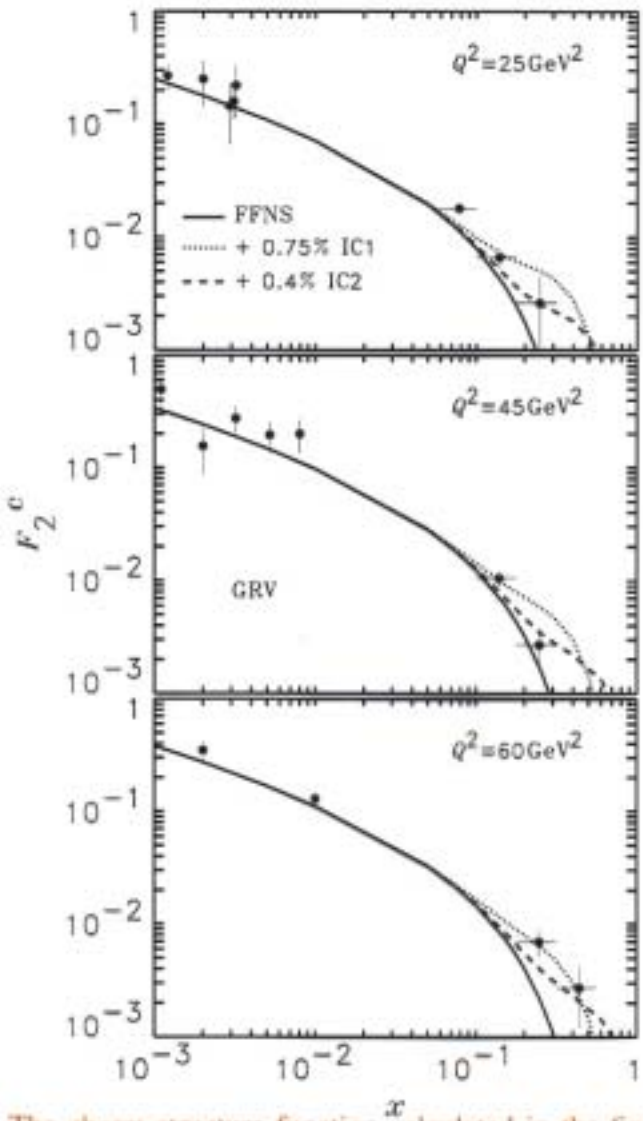


Figure 25: The charm structure function calculated in the fixed flavor number scheme (FFNS) with GRV98 parton densities for three Q^2 bins using standard LO massless IC (IC1) and IC in a meson cloud model (IC2). (From Steffens *et al.*.)