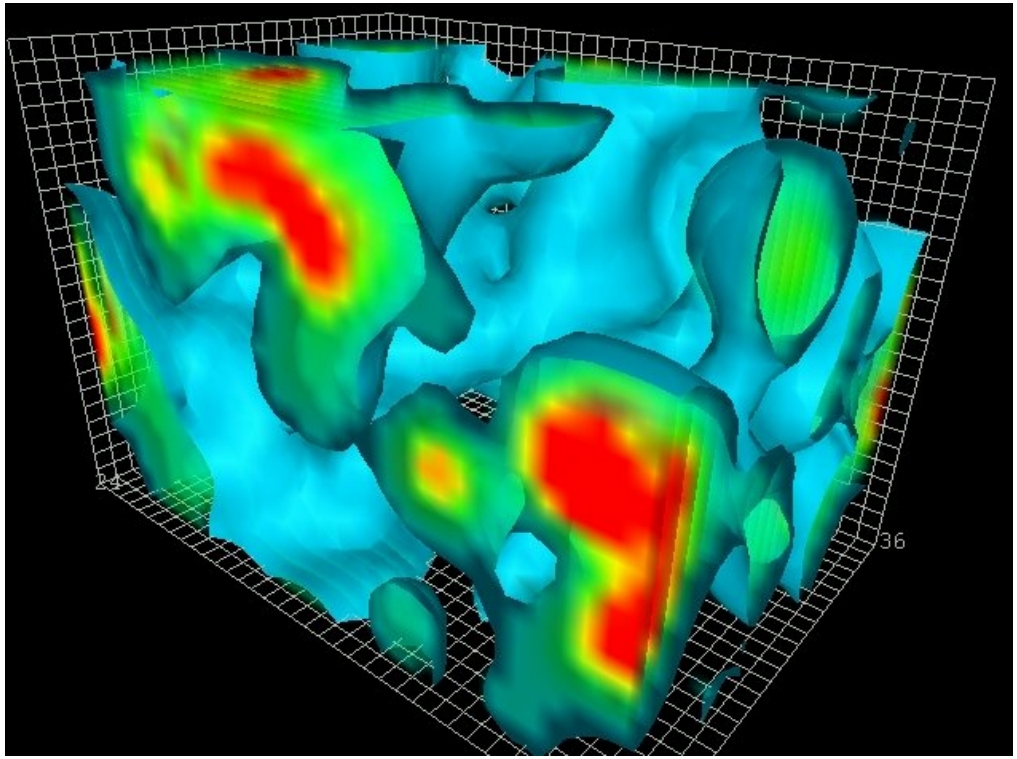
High p_T measurements in PHENIX



The Partonic Structure of Hadrons
ECT* Trento

Kenneth N. Barish

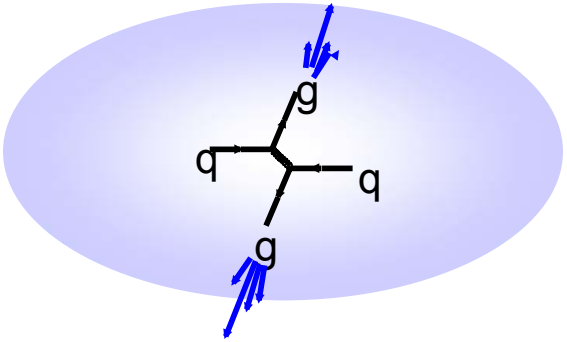
May 9-14, 2005

University of California Riverside

Outline

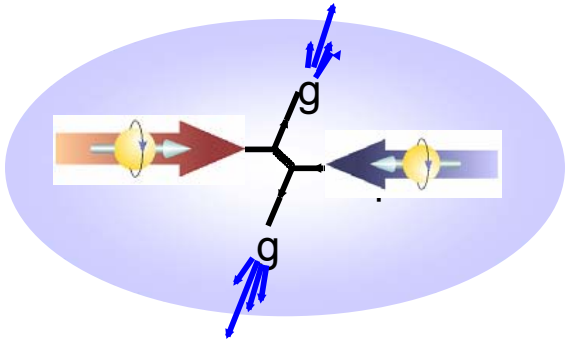
Cross sections in p+p

- » Charged hadrons, π^0, prompt γ
- » Comparisons with pQCD expectations



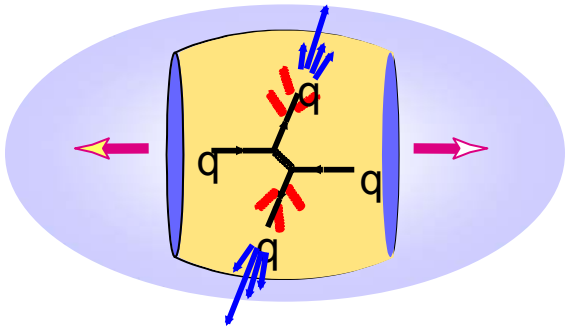
Spin asymmetry measurements with neutral pions

- » Measurement of A_{LL}



Measurements with heavy-ions

- » Au+Au comparisons with p+p
- » d+Au



Present PHENIX Detector Capabilities

Designed to measure low σ:

- ✓ High rate capability & granularity
- ✓ Good mass resolution and particle ID
- ➢ Sacrifice acceptance

2 central arms:

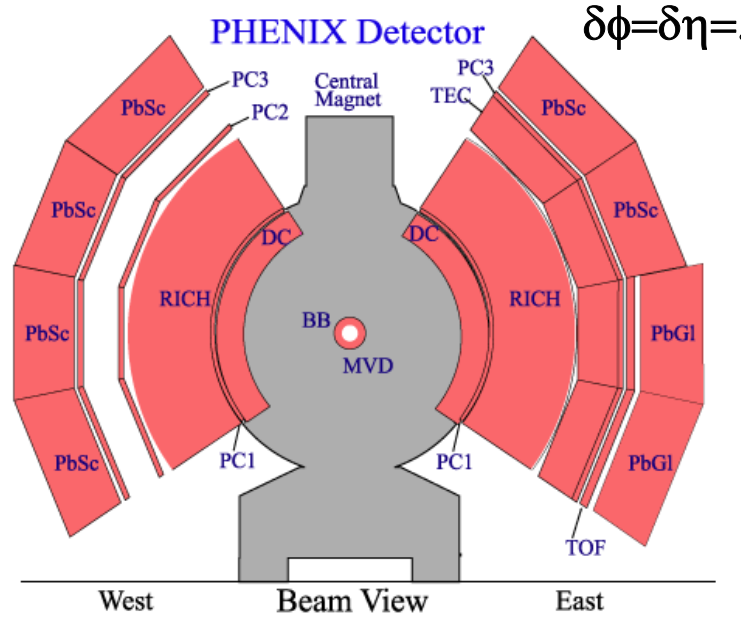
electrons, photons, hadrons

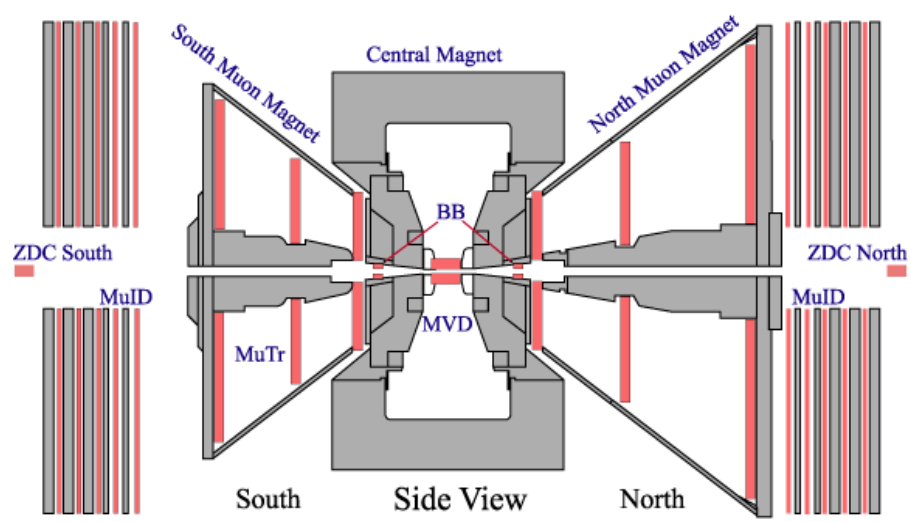
- » charmonium J/ψ, $\psi' \rightarrow e+e-$
- » vector meson $\rho, \omega, \phi \rightarrow e+e-$
- » **high p_T** π^0, π^+, π^-
- » **prompt photons**
- » open charm
- » **hadron physics**

2 muon arms: **muons**

- » "onium" J/ψ, ψ', $\Upsilon \rightarrow \mu+\mu-$
- » vector meson $\phi \rightarrow \mu+\mu-$
- » open charm

$\delta\phi=\delta\eta=.01$





PHENIX Heavy Ion Run History

Run	Year	Species	$s^{1/2}$ [GeV]	$\int Ldt$	N_{tot}	p-p Equivalent	Data Size
01	2000	Au+Au	130	1 μb^{-1}	10M	0.04 pb^{-1}	3 TB
02	2001/2002	Au+Au	200	24 μb^{-1}	170M	1.0 pb^{-1}	10 TB
		p+p	200	0.15 pb^{-1}	3.7G	0.15 pb^{-1}	20 TB
03	2002/2003	d+Au	200	2.74 nb^{-1}	5.5G	1.1 pb^{-1}	46 TB
		p+p	200	0.35 pb^{-1}	6.6G	0.35 pb^{-1}	35 TB
04	2003/2004	Au+Au	200	241 μb^{-1}	1.5G	10.0 pb^{-1}	270 TB
		Au+Au	62	9 μb^{-1}	58M	0.36 pb^{-1}	10 TB

p+p running at RHIC-PHENIX

Run2: 2001-2002

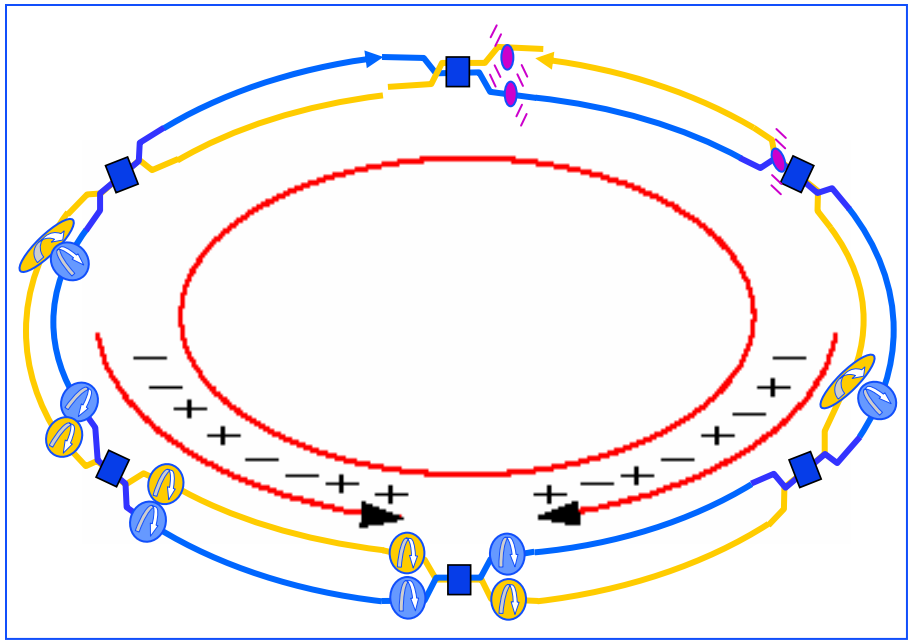
- *Transversely* polarized p+p collisions
- Average polarization of ~15%
- Integrated luminosity 0.15 pb^{-1}

Run3: 2003

- *Longitudinally* polarized p+p collisions achieved
- Average polarization of ~27%
- Integrated luminosity 0.35 pb^{-1}

Run4: 2004

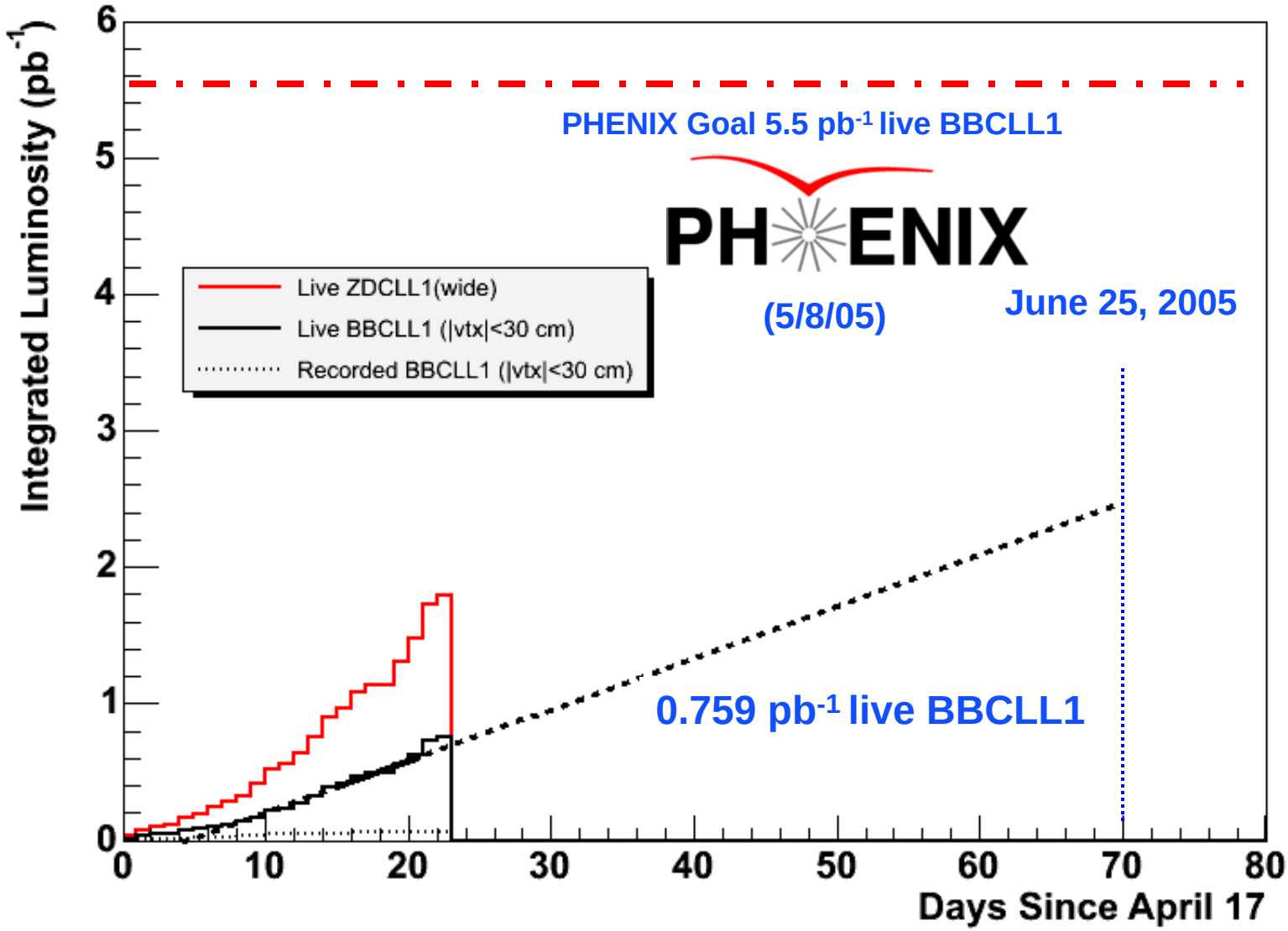
- *Longitudinally* polarized p+p collisions
- Polarization of ~40-45%
- Integrated luminosity 0.15 pb^{-1}



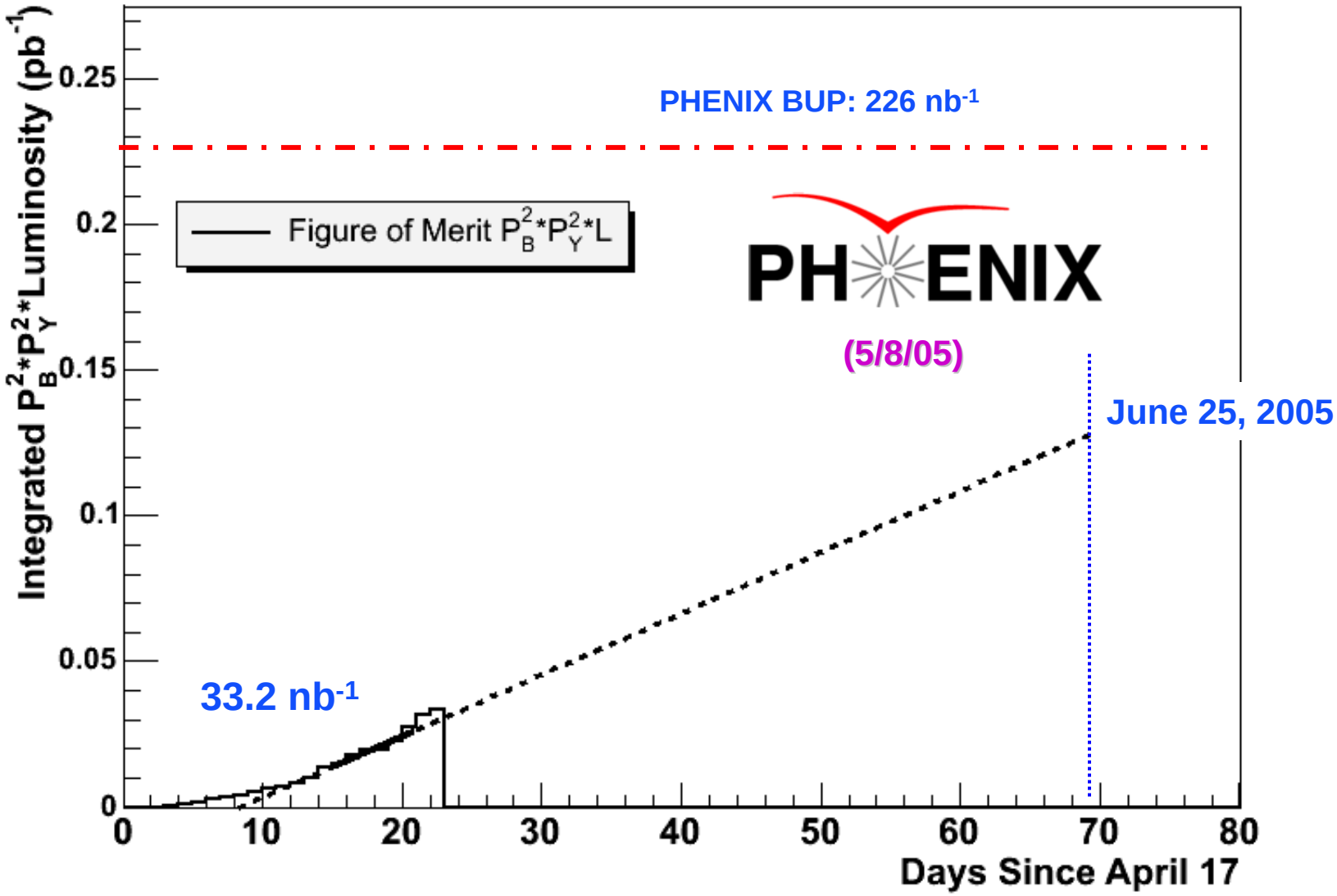
Run5: started last month

- *Longitudinally* polarized p+p collisions
- PHENIX Beam Use Proposal
  - P ~ 45%
  - Expected L ~ 5.5 pb^{-1}

200 GeV p+p Luminosity



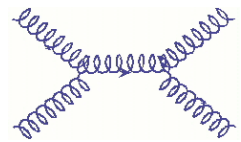
200 GeV p+p "Figure of Merit" for A_{LL}



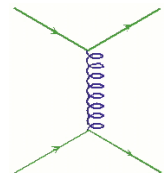
Results from 200GeV p+p Collisions

- Charged hadrons
- Neutral pions
- Prompt photons

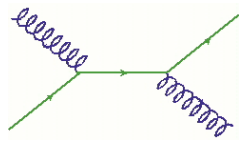
$gg \rightarrow gg$

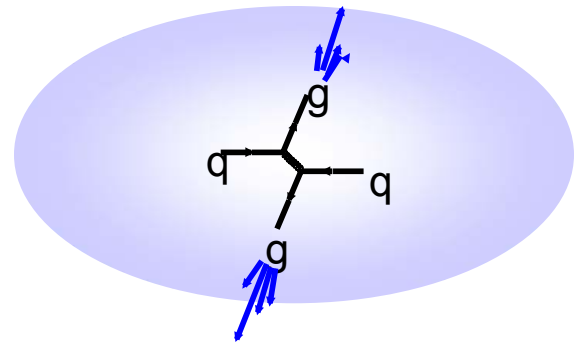


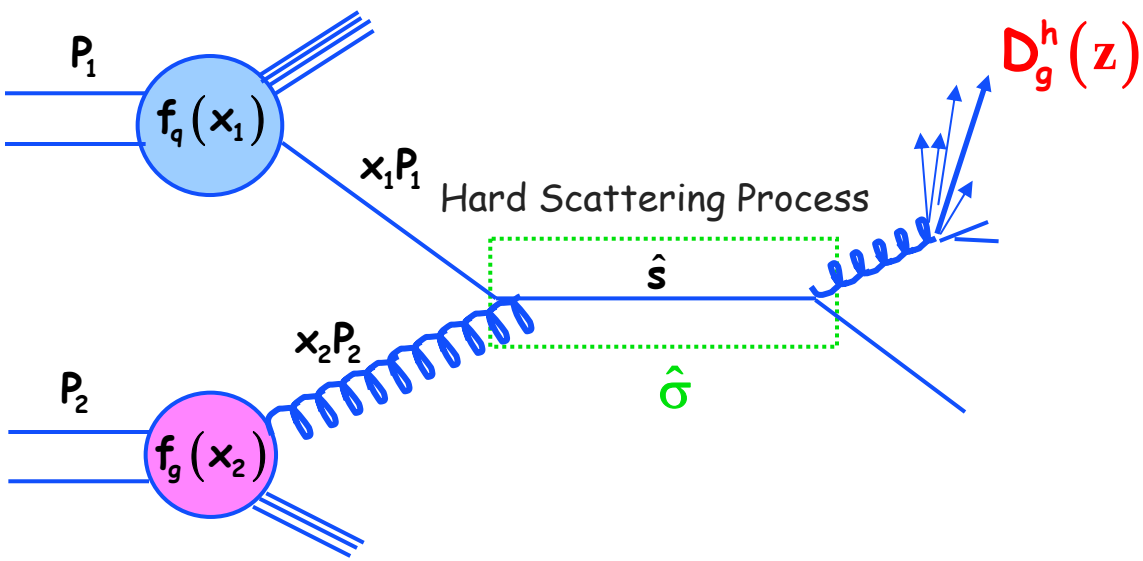
$qq \rightarrow qq$



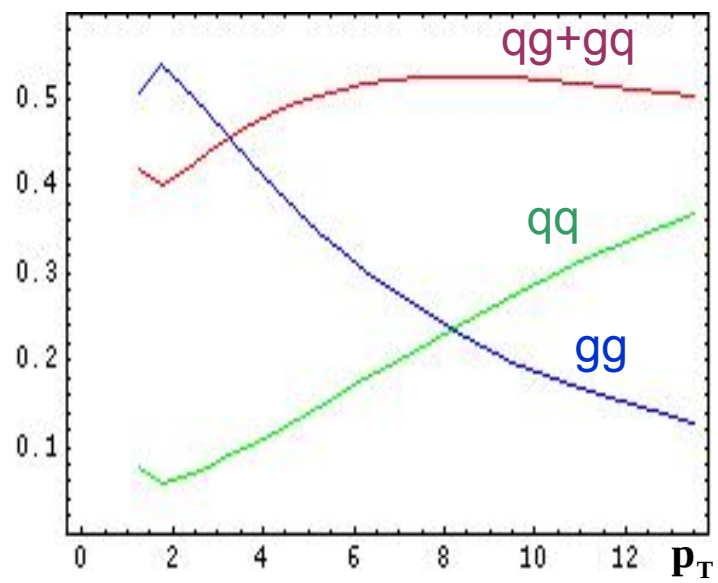
$gq \rightarrow gq$







Fraction π^0's produced



Charged hadrons (I)

Charged particle Tracking

$|\eta|<0.35$, $\Delta\varphi=\pi$

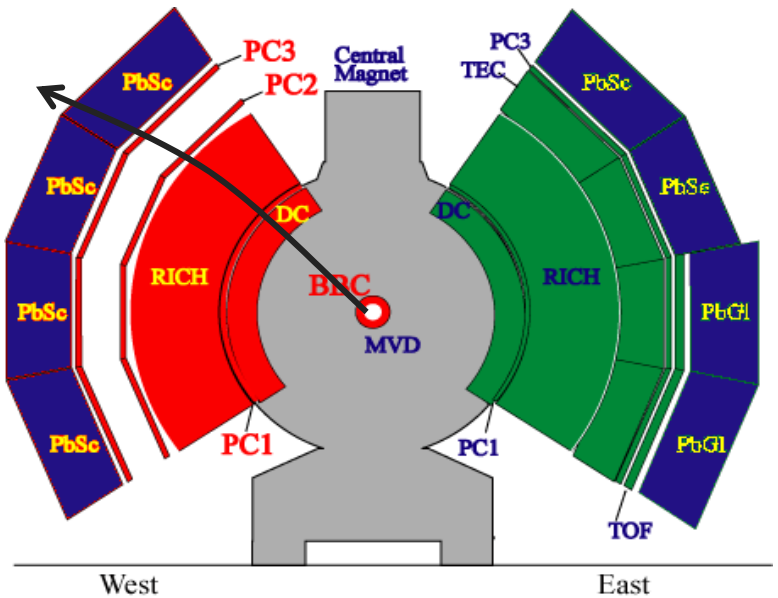
Drift Chamber :DC

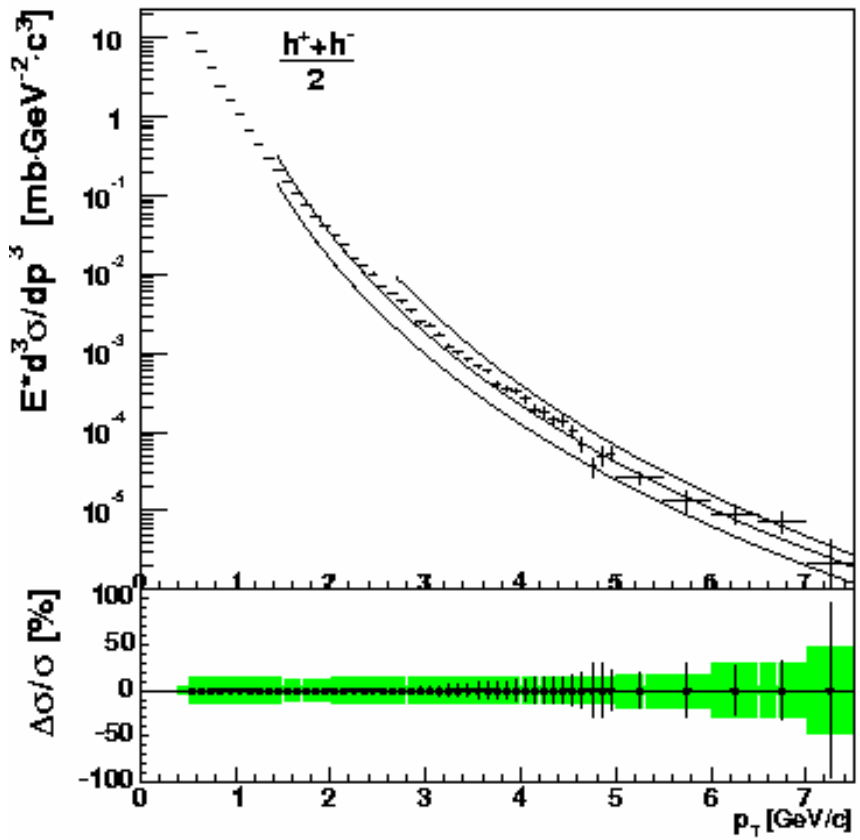
R_{DC} = 2-2.4 m

Pad Chamber 1:PC1

R_{PC1} = 2.4 m

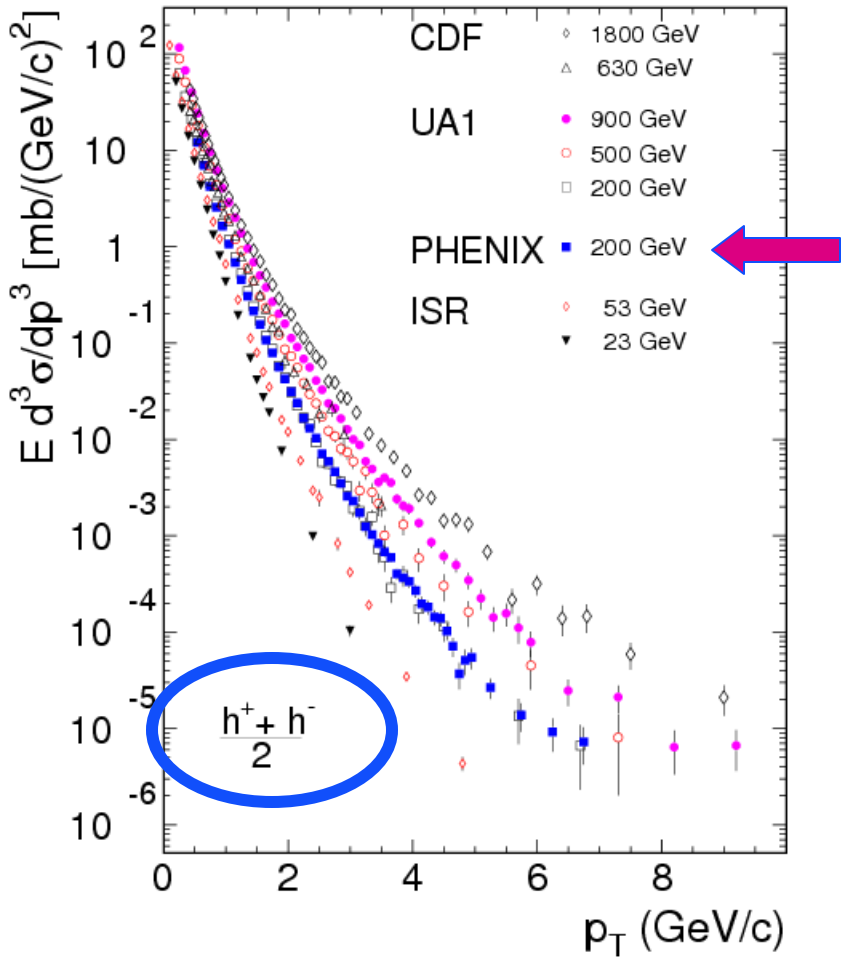
PC2, PC3 and RICH used for background rejection

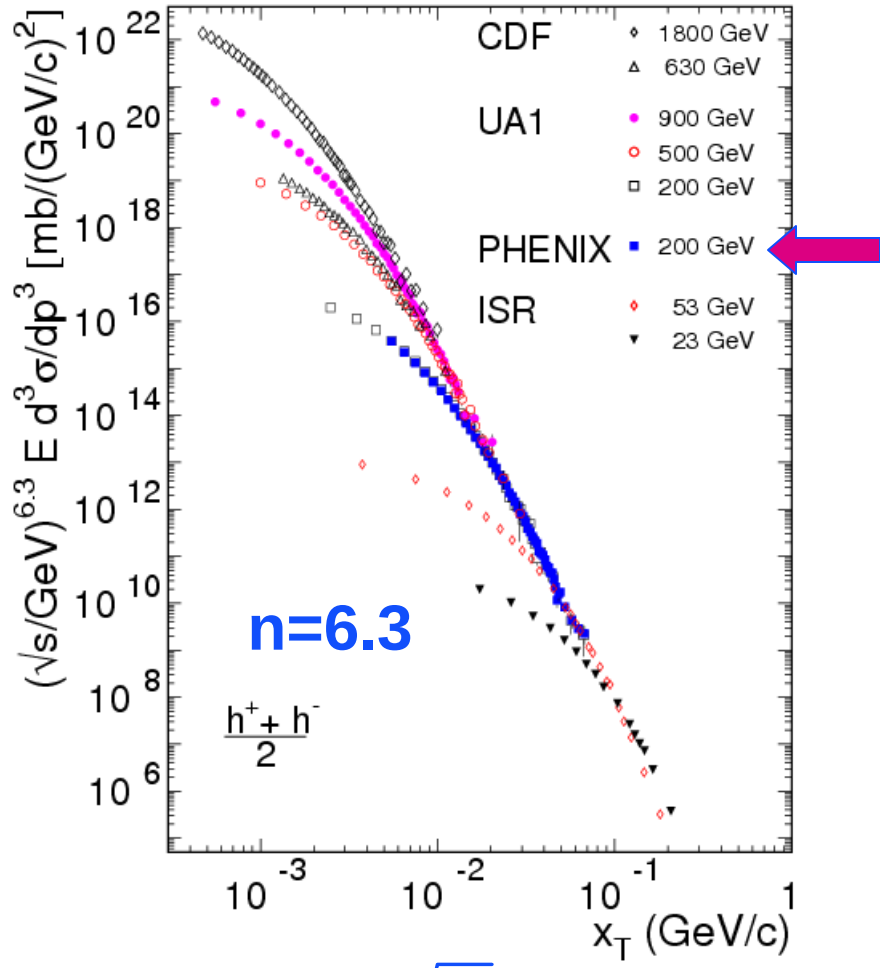




✓ pQCD calculations consistent with NLO pQCD calculations.

Charged hadrons (II)





$$E\frac{d^3\sigma}{d^3p} = \frac{1}{p_T^n}F(x_T) = \frac{1}{\sqrt{s}^n}G(x_T)$$

$$x_T = 2\,p_T / \sqrt{s}$$

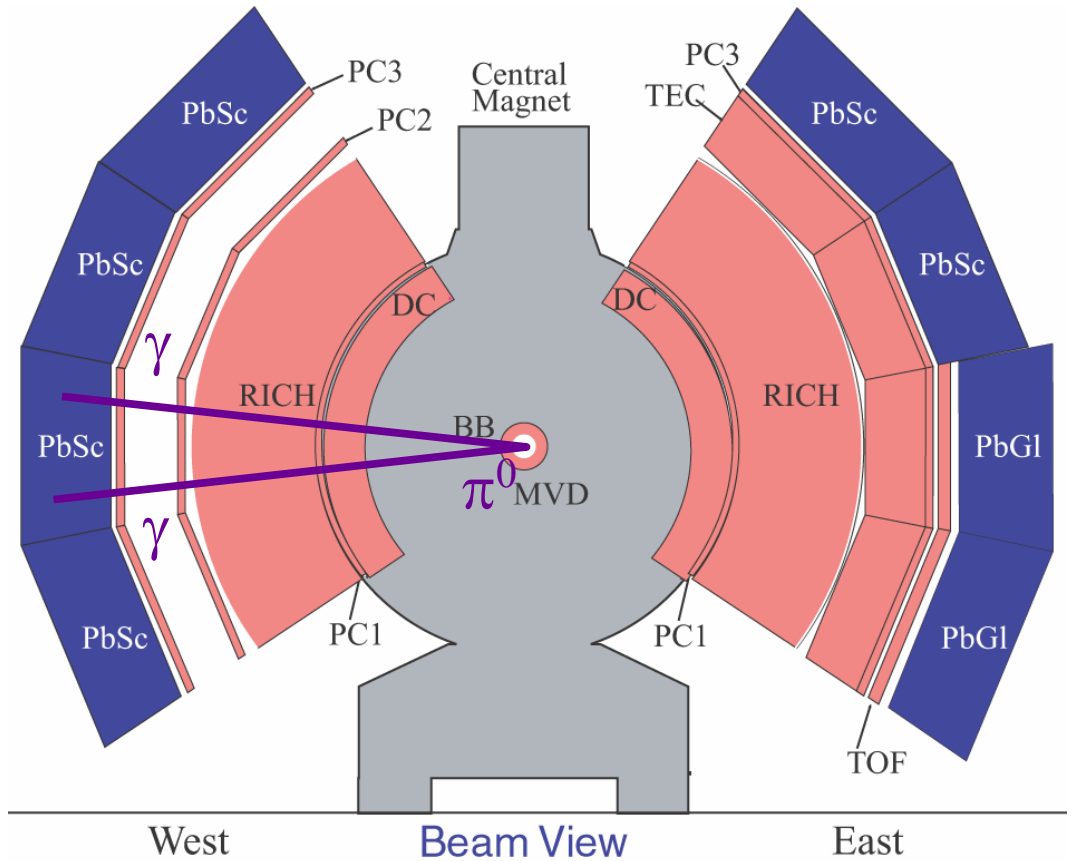
Scales with x_T (n~6.3) at high p_T

Neutral Pions

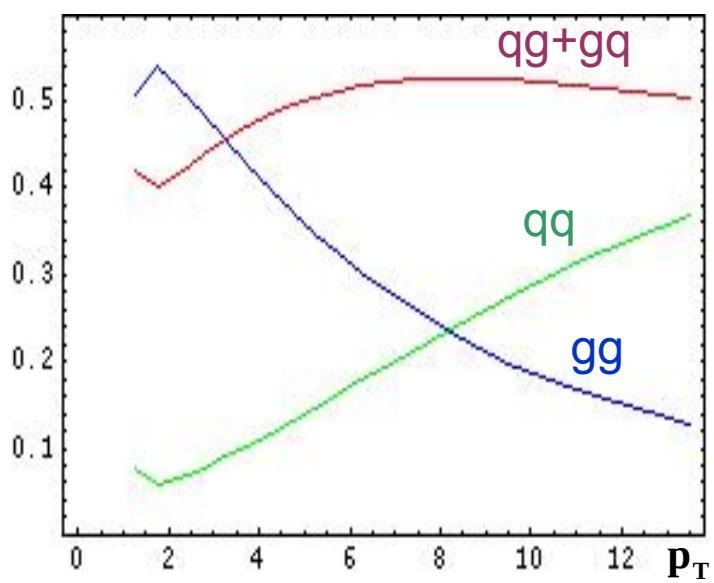
Central spectrometer arms $|\eta| < 0.35$

$\delta\phi=\delta\eta=.01$

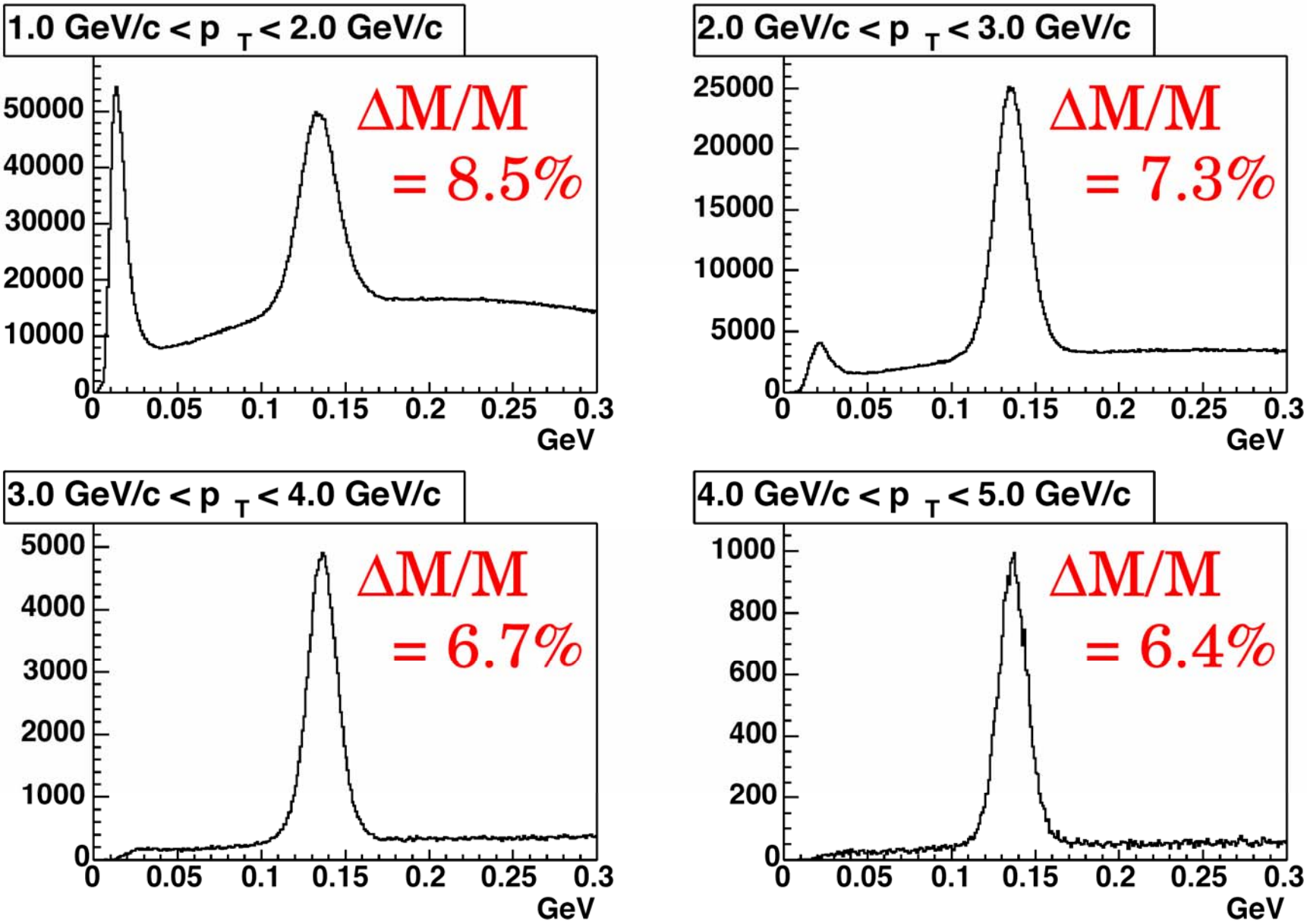
- » γ, π^0 via $\pi^0 \rightarrow \gamma\gamma$
- » Electromagnetic calorimeter (EMCal)
  - – Lead scintillator calorimeter (PbSc)
  - – Lead glass calorimeter (PbGl)



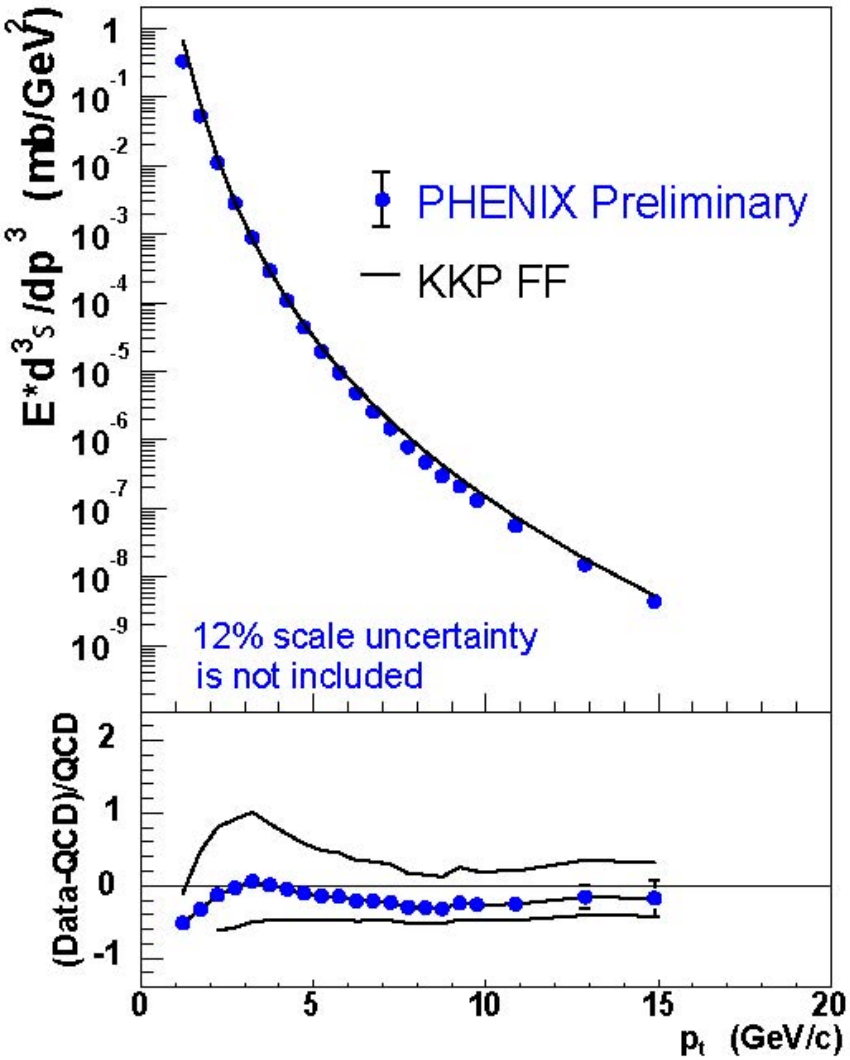
Fraction π^0's produced



π^0 Reconstruction



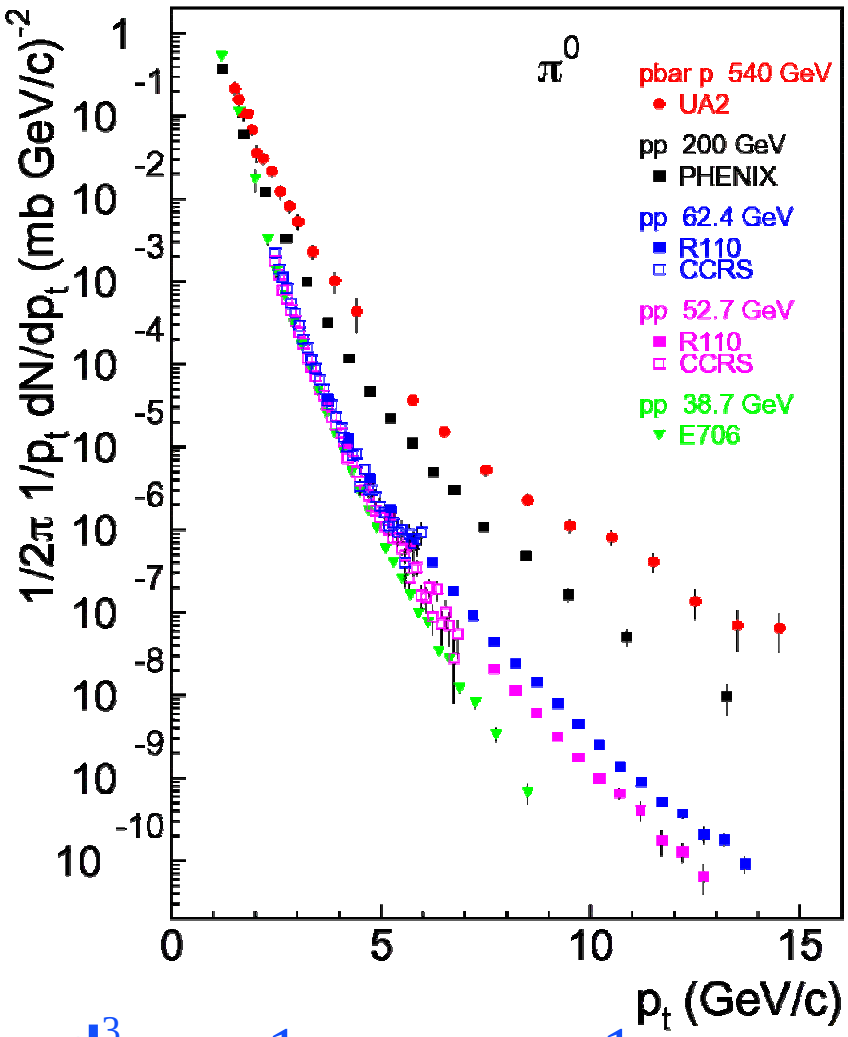
π^0 Cross Section in p+p (I)

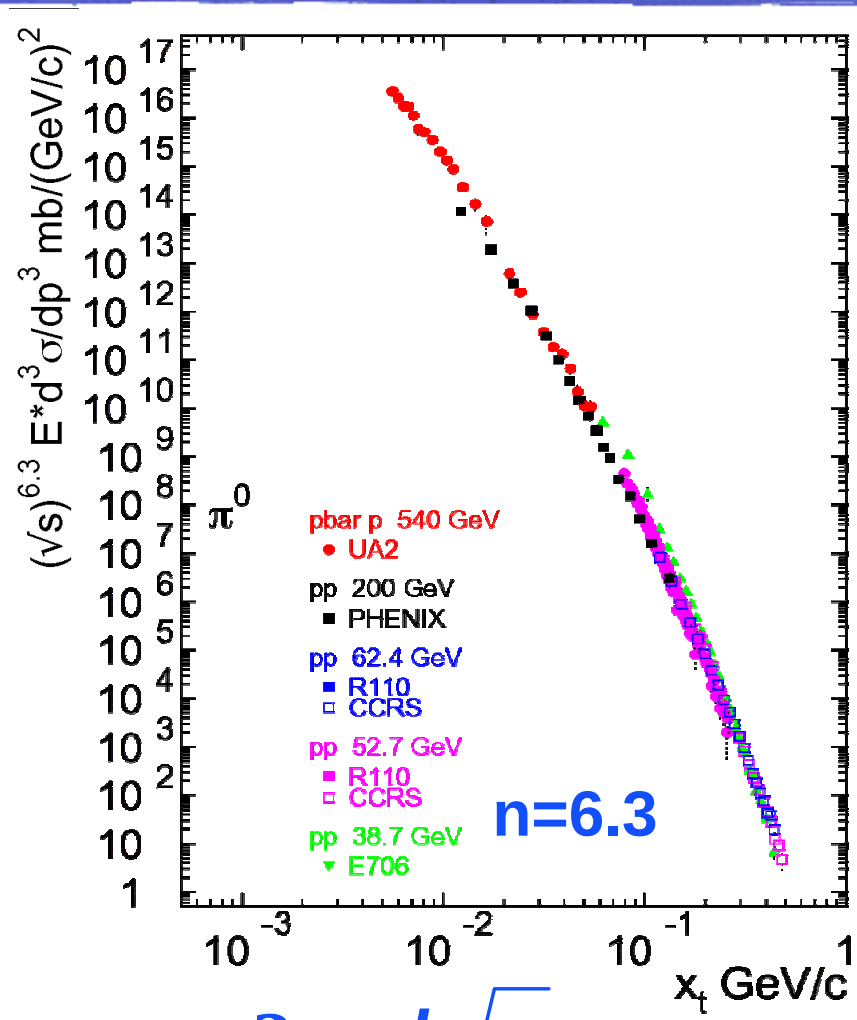


- NLO pQCD consistent with data within theoretical uncertainties
  - PDF: CTEQ5M
  - Fragmentation functions:
    - Kniehl-Kramer-Potter (KKP)
    - Kretzer
  - Spectrum constrains D(gluon→π) fragmentation function

- Gives us confidence that pQCD can be used to extract spin dependent pdf's.
  - Same comparison fails at lower energies

π^0 Cross Section in p+p (II)





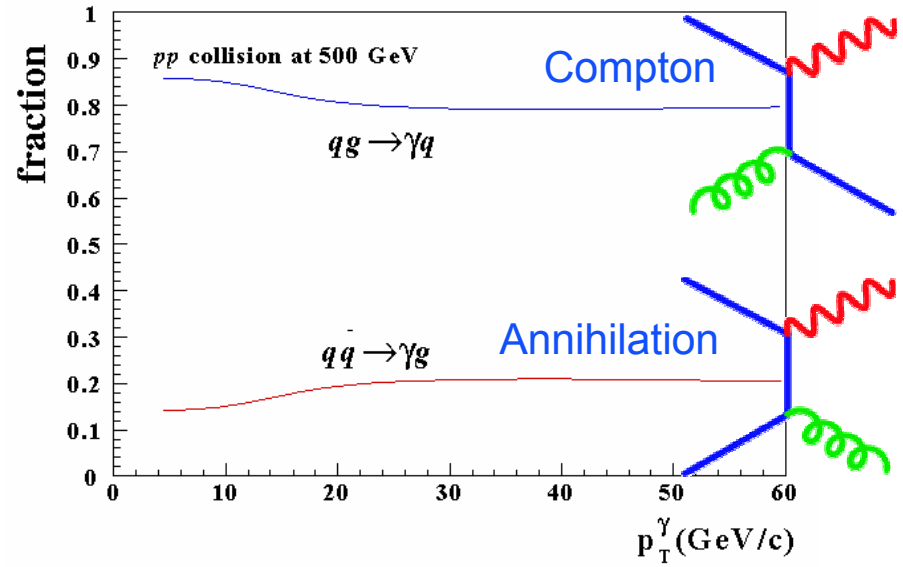
$$E\frac{d^3\sigma}{d^3p} = \frac{1}{p_T^n}F(x_T) = \frac{1}{\sqrt{s}^n}G(x_T)$$

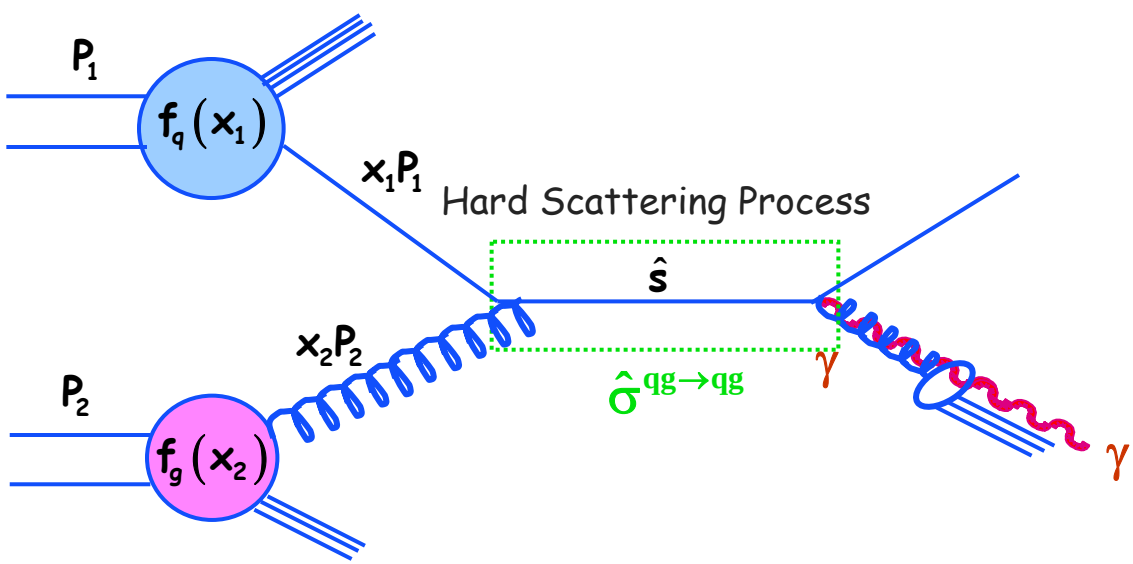
$$x_T = 2\,p_T / \sqrt{s}$$

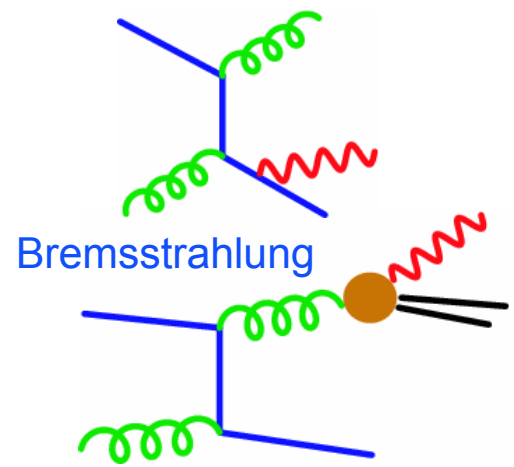
Scales with x_T (n~6.3) at high p_T

Prompt photon production

- ✓ **Gluon Compton Dominates**
  - » Small contamination from annihilation
- ✓ **At LO no fragmentation function**
- ✓ **NLO Calculations are available**



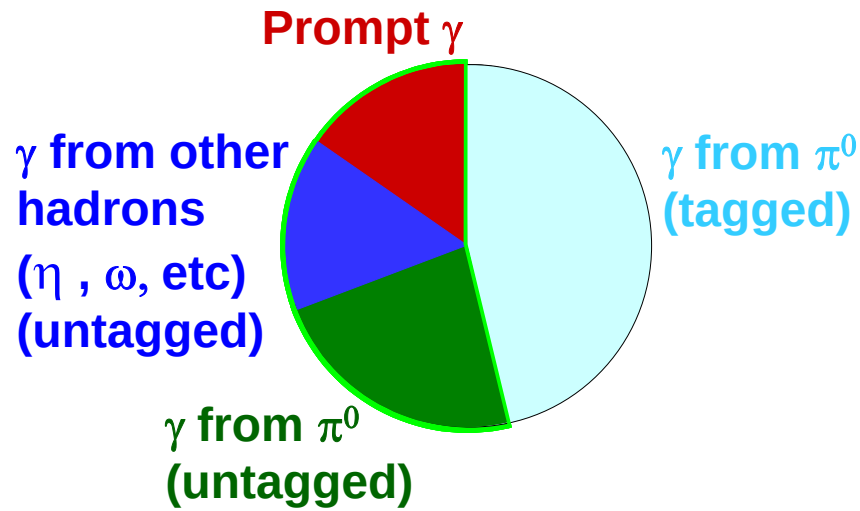


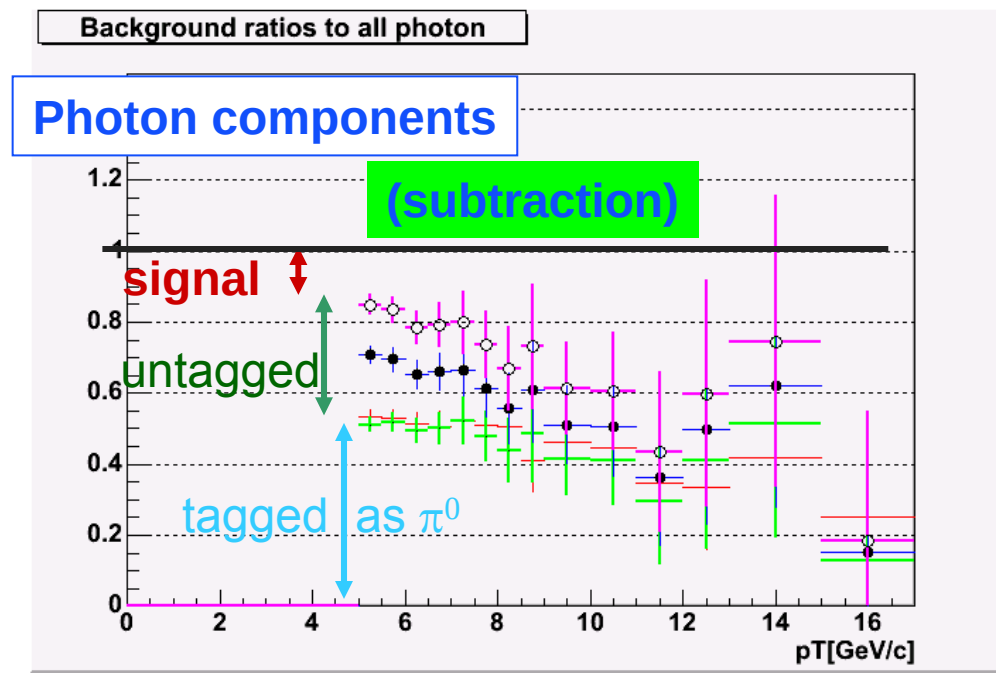


Measurement of Prompt Photons

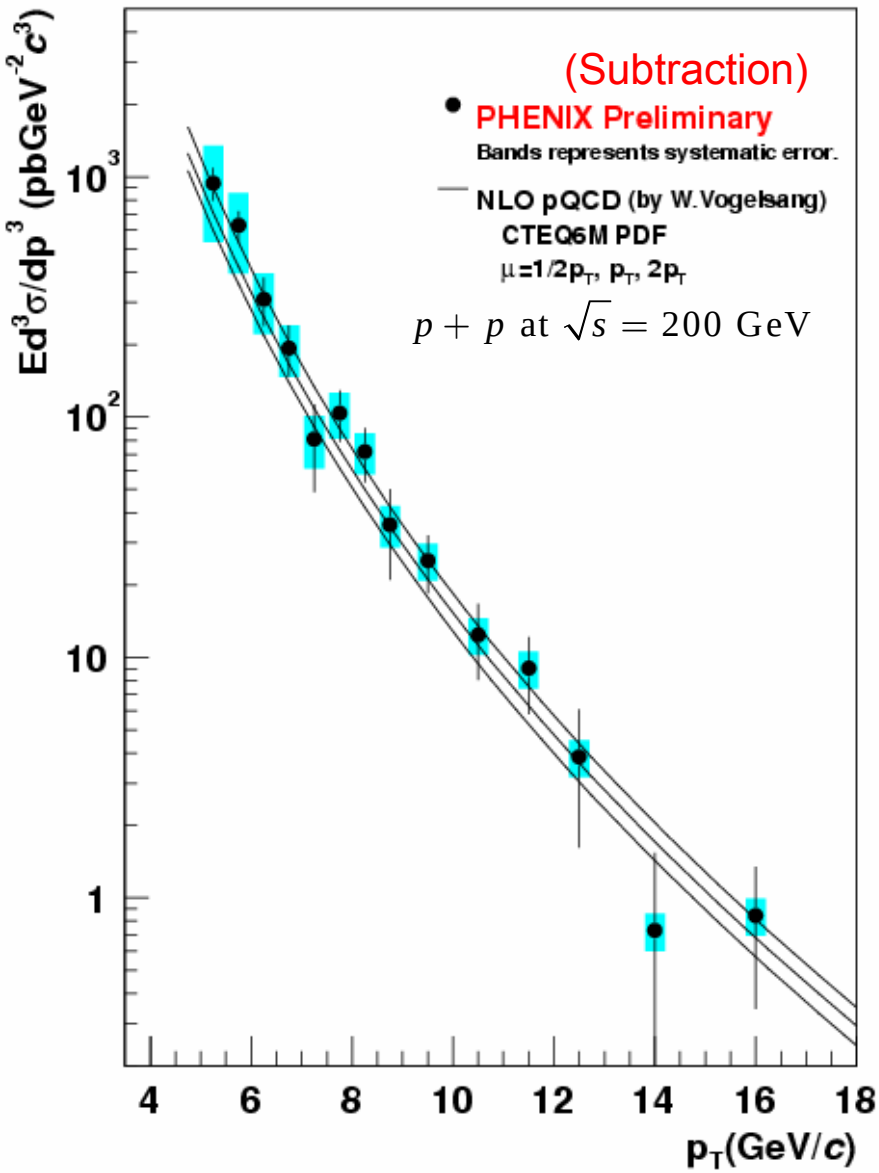
- **Obtain inclusive-photon sample**
  - Veto charged particles
  - Impose EM shower shape
- **Remove photon contributions from hadron decays (e.g. π^0, η, ω, etc)**
  - Tag π^0's with both photons seen in detector
  - Estimate π^0's with only one photon seen in detector.
  - Estimate contributions from η, ω, decay with Monte Carlo and measured η spectra used as input.

$$"\gamma_{prompt} = \gamma_{inclusive} - \gamma_{decay}"$$





Prompt photon cross-section



Bands represent systematic errors.

Errors on the backgrounds result in enlarged errors on the signal, especially at low-pT region.

NLO-pQCD calculation

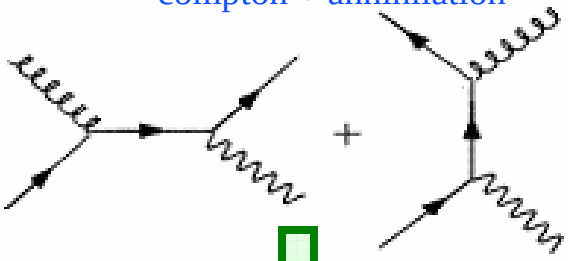
- » CTEQ6M PDF.
- » Gluon Compton scattering + fragmentation photon
- » Set Renormalization scale and factorization scale $p_T/2, p_T, 2p_T$

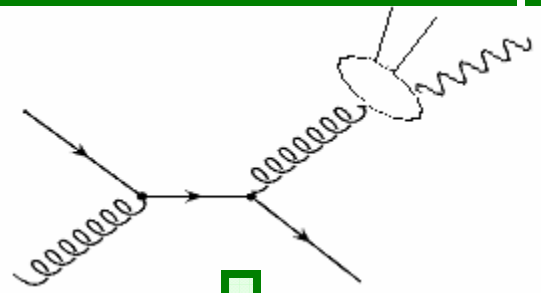
The NLO pQCD calculation is Consistent with our preliminary measurement.

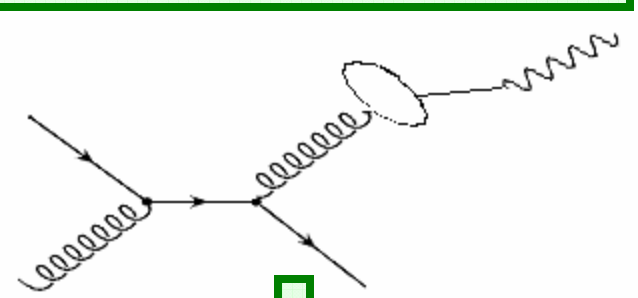
Development of an Isolation Method

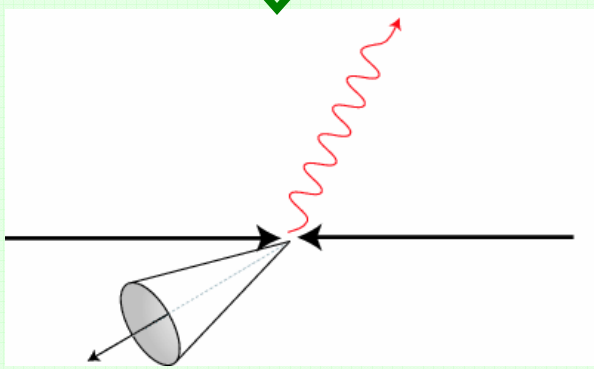
(1)Signal(direct)	(2)Signal(fragmentation)	(3)Background(hadron decay)

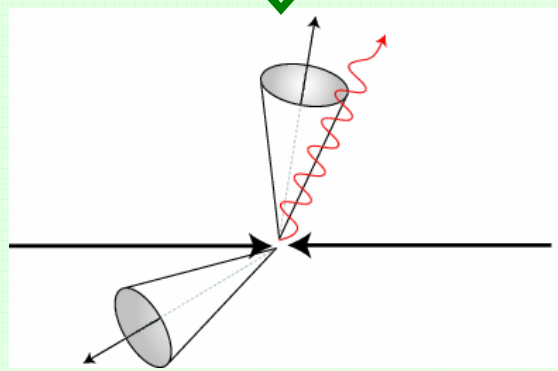
compton + annihilation

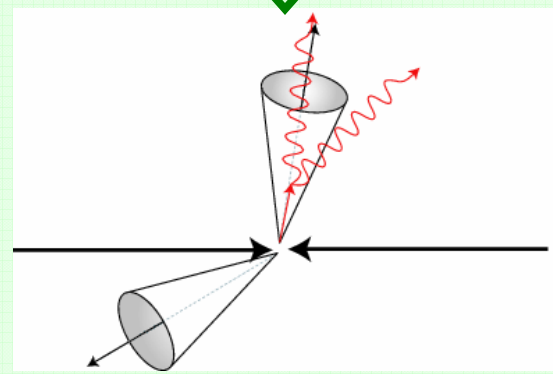








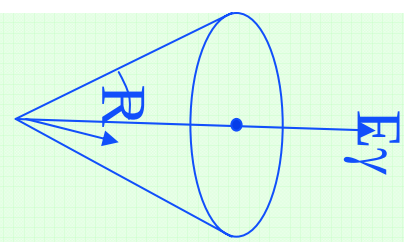




Isolation cut to reduce background

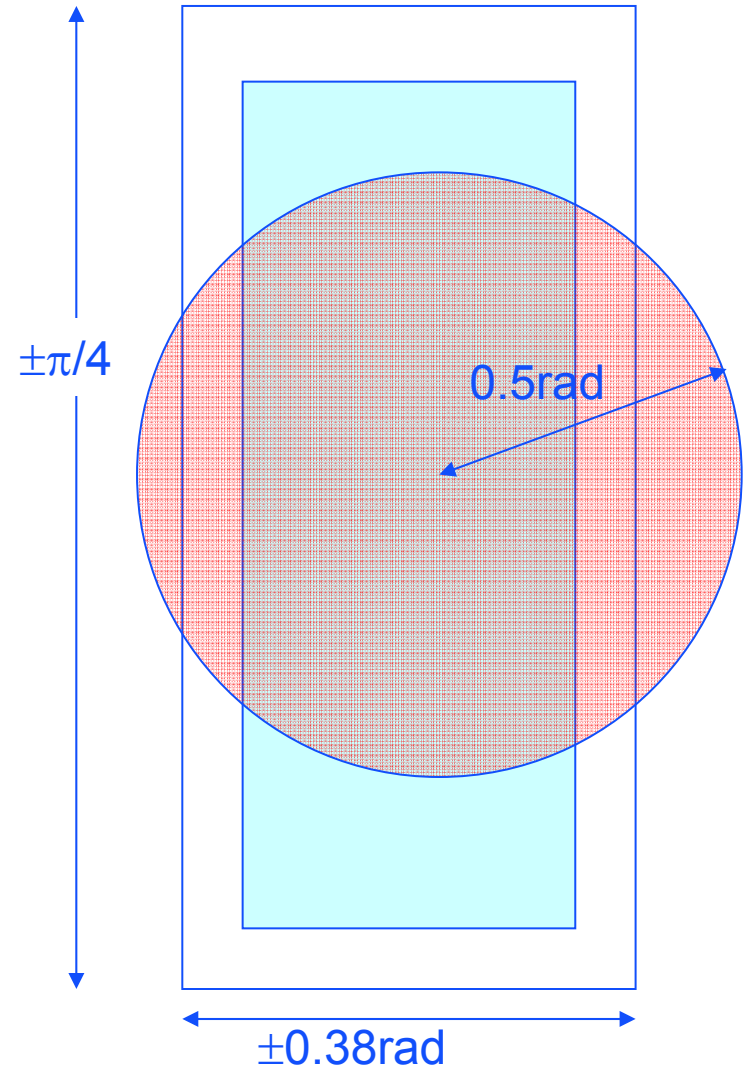
$$R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.5$$

$$E_{sum}(R < 0.5) < E_\gamma \times 0.1$$



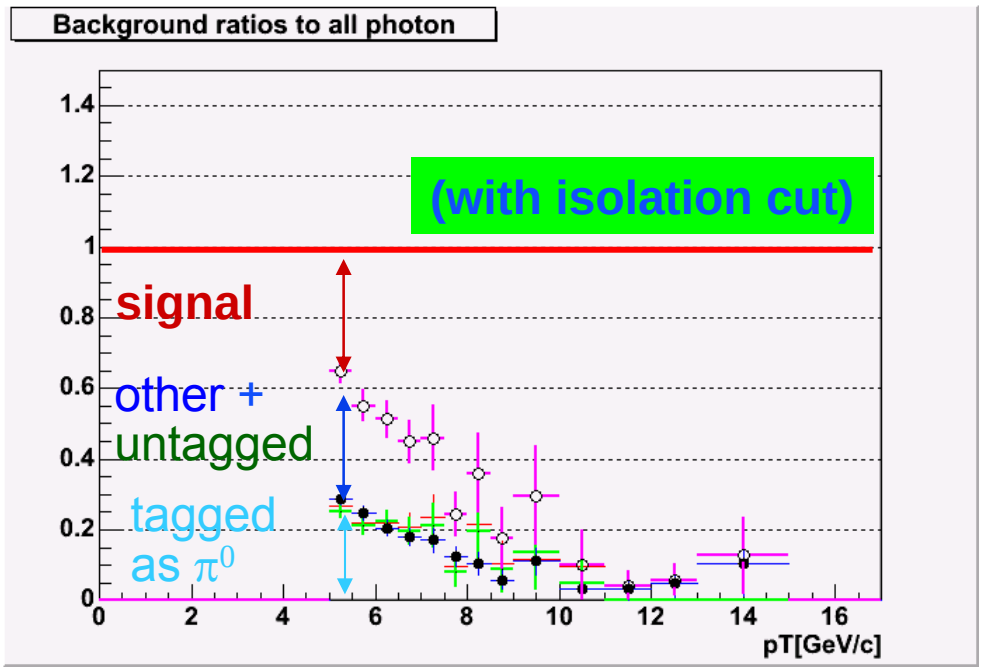
Efficiency of the Isolation Cut

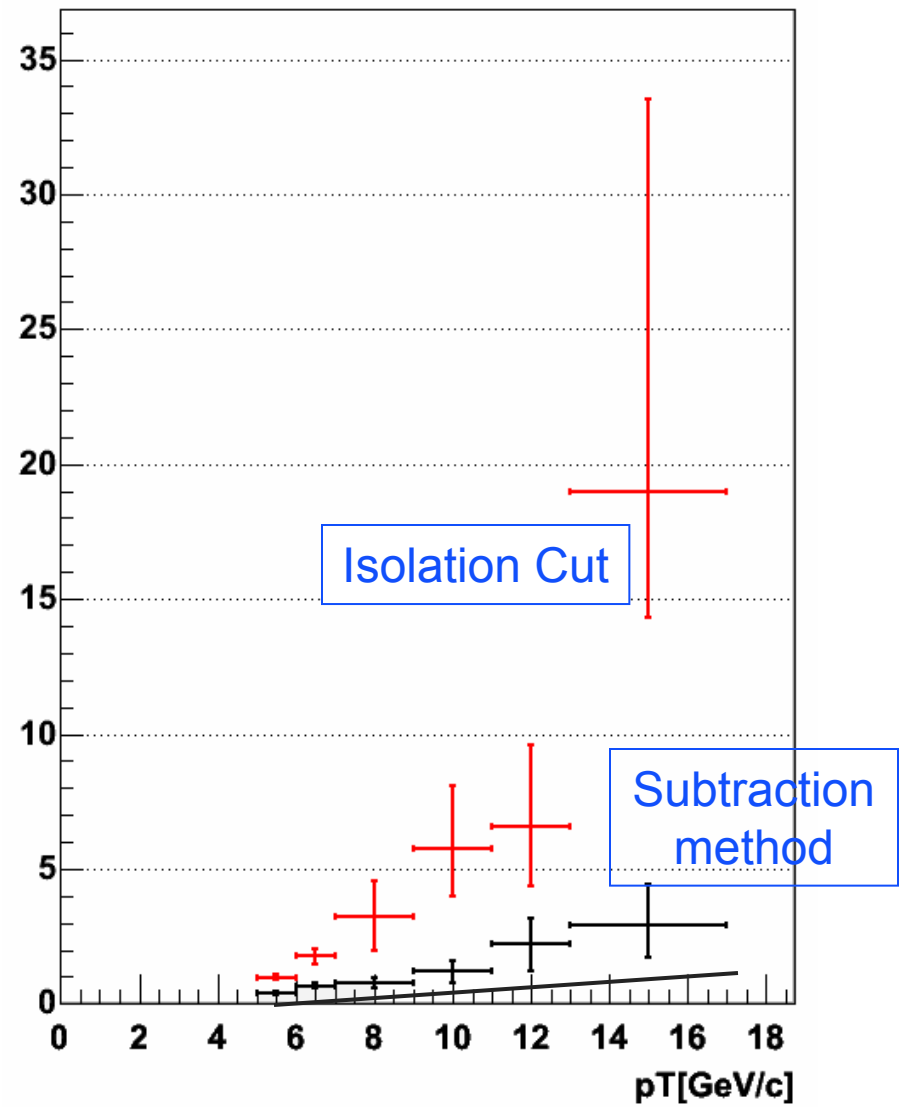
- What cause the efficiency/inefficiency?
  - » Event structure
    - – Especially, the signal of fragmentation type will be reduced by this cut.
  - » PHENIX has limited acceptance and does not cover the entire cone.
  - » Underlying event due to the multi-parton scattering.
- The efficiency of the isolation cut needs to be estimated by Monte Carlo Simulation.
- For now we compare the previous result and the result from the isolation method without correction for the efficiency.



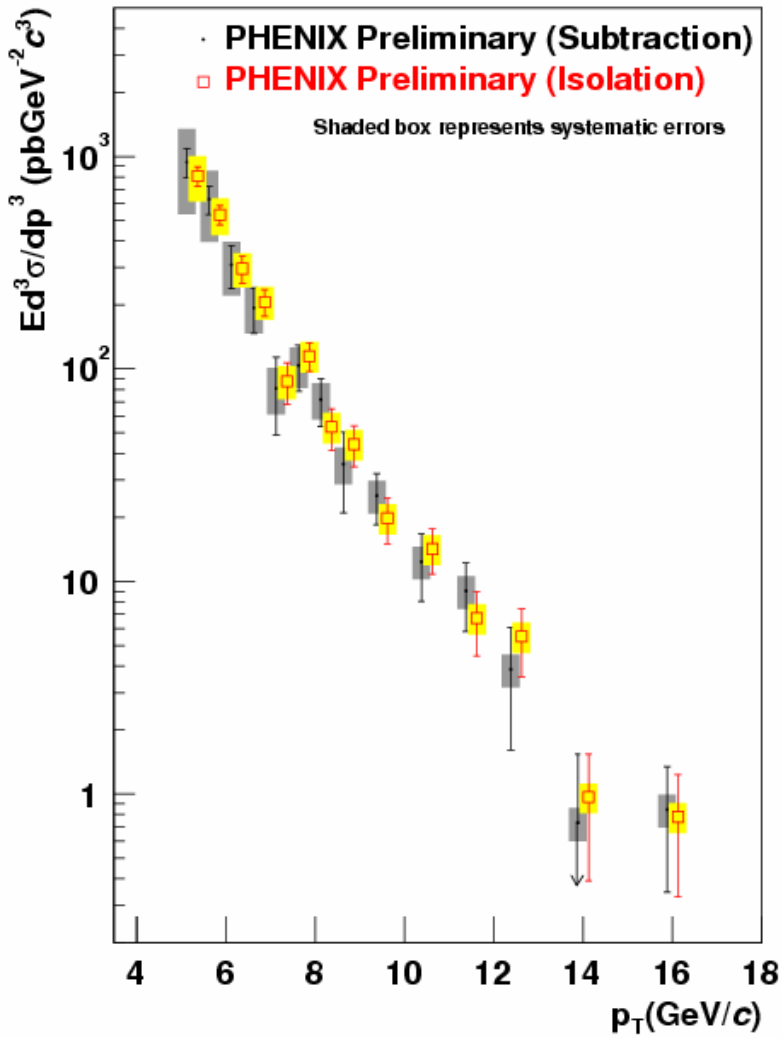
S/N Ratio with Isolation Cut

- The S/N ratio improves by a factor of about 5
- Good S/N ratio is important for future measurements.





Influence of Isolation Cut

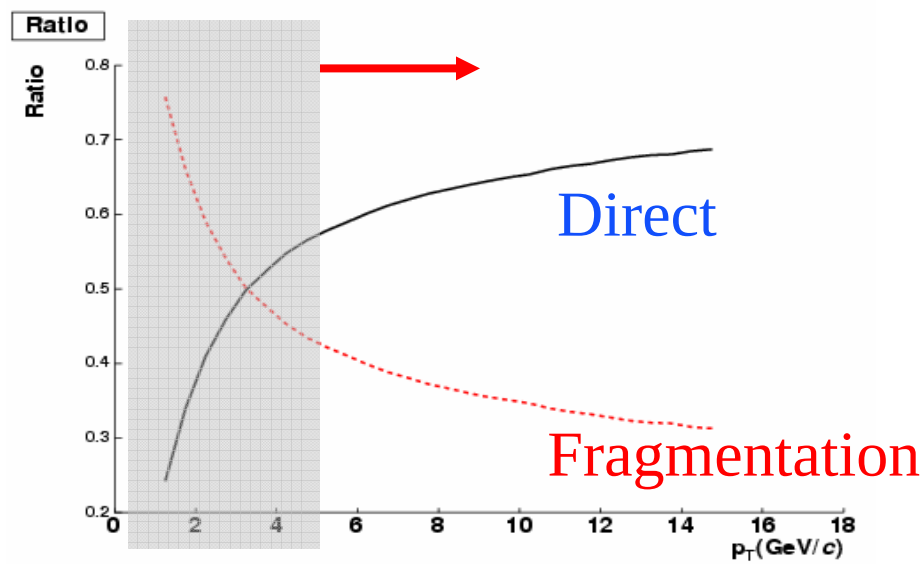


- No correction for direct photon loss due to isolation cut
- Note: this isolation cut is not infrared safe
- Nevertheless, cross sections with and without isolation cut are consistent.
- Suggests small contribution of fragmentation photons, which would be found within jets?

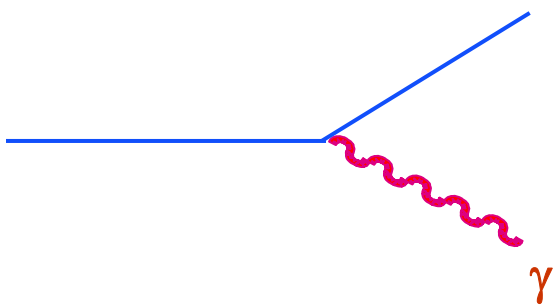
Direct vs. fragmentation

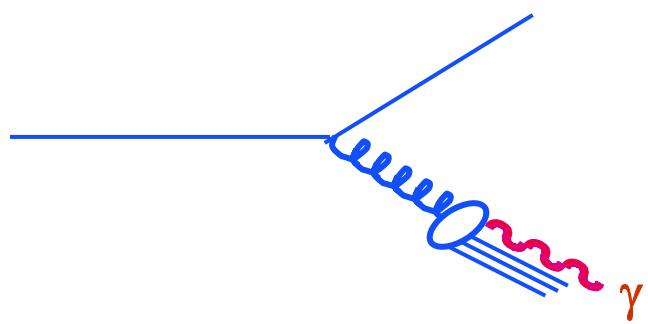
- **Two processes**
  - » Direct
  - » Fragmentation

- **Direct photon measurement become dominant at high pT.**
  - » The difference between two methods is small.



Private communication with W.Vogelsang

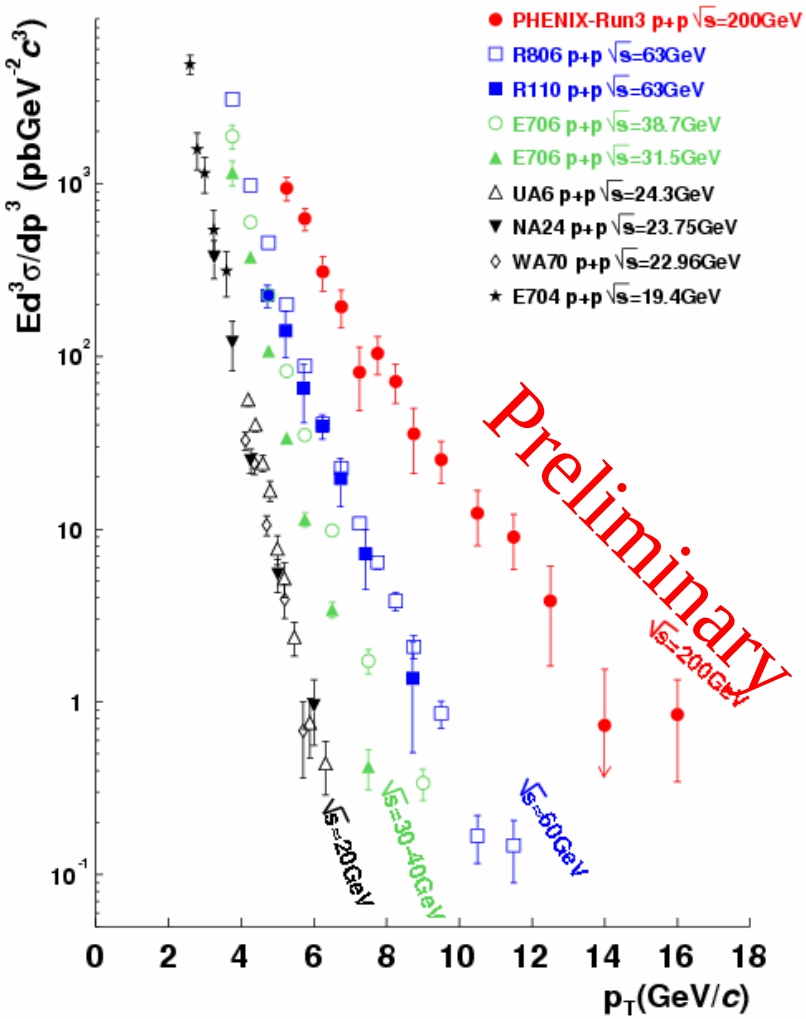


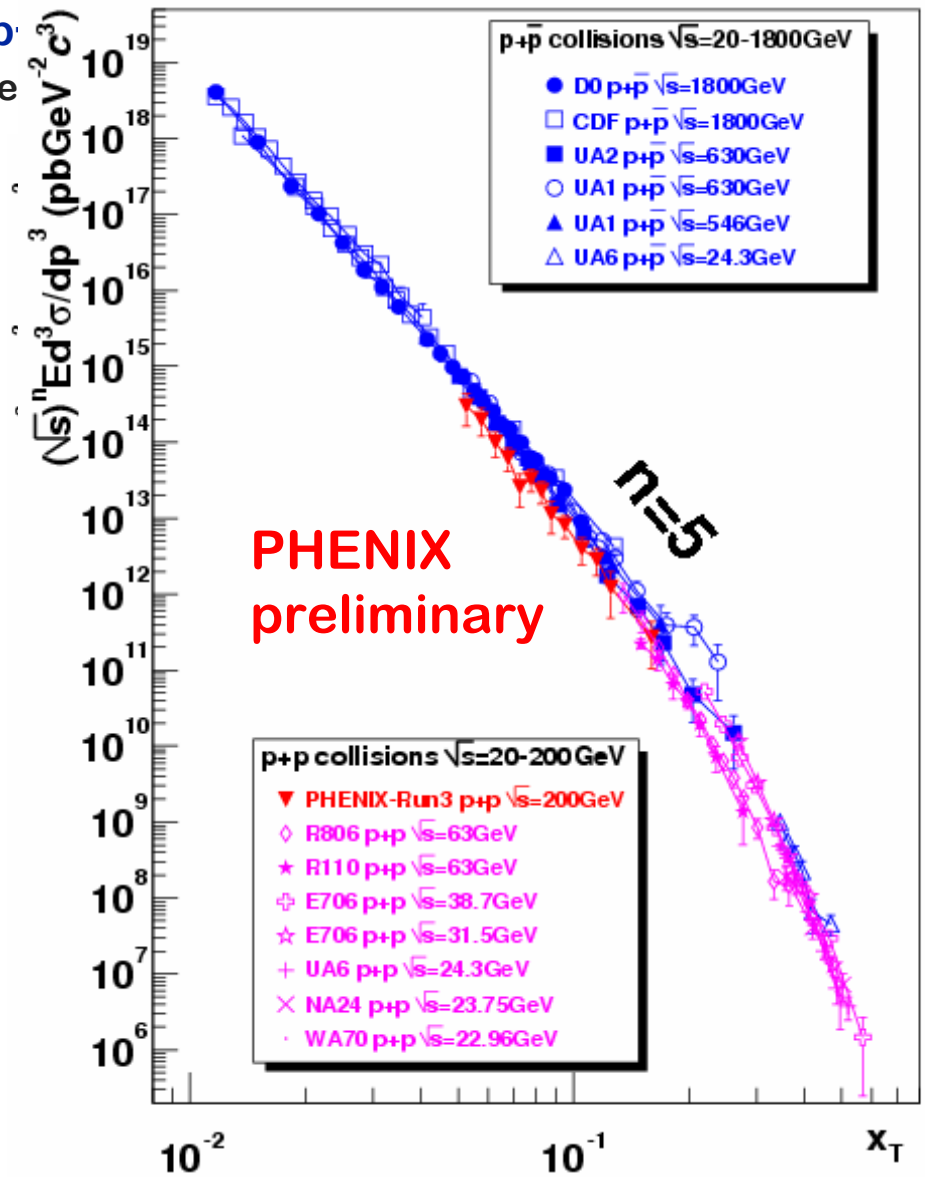


Photon cross section comparison

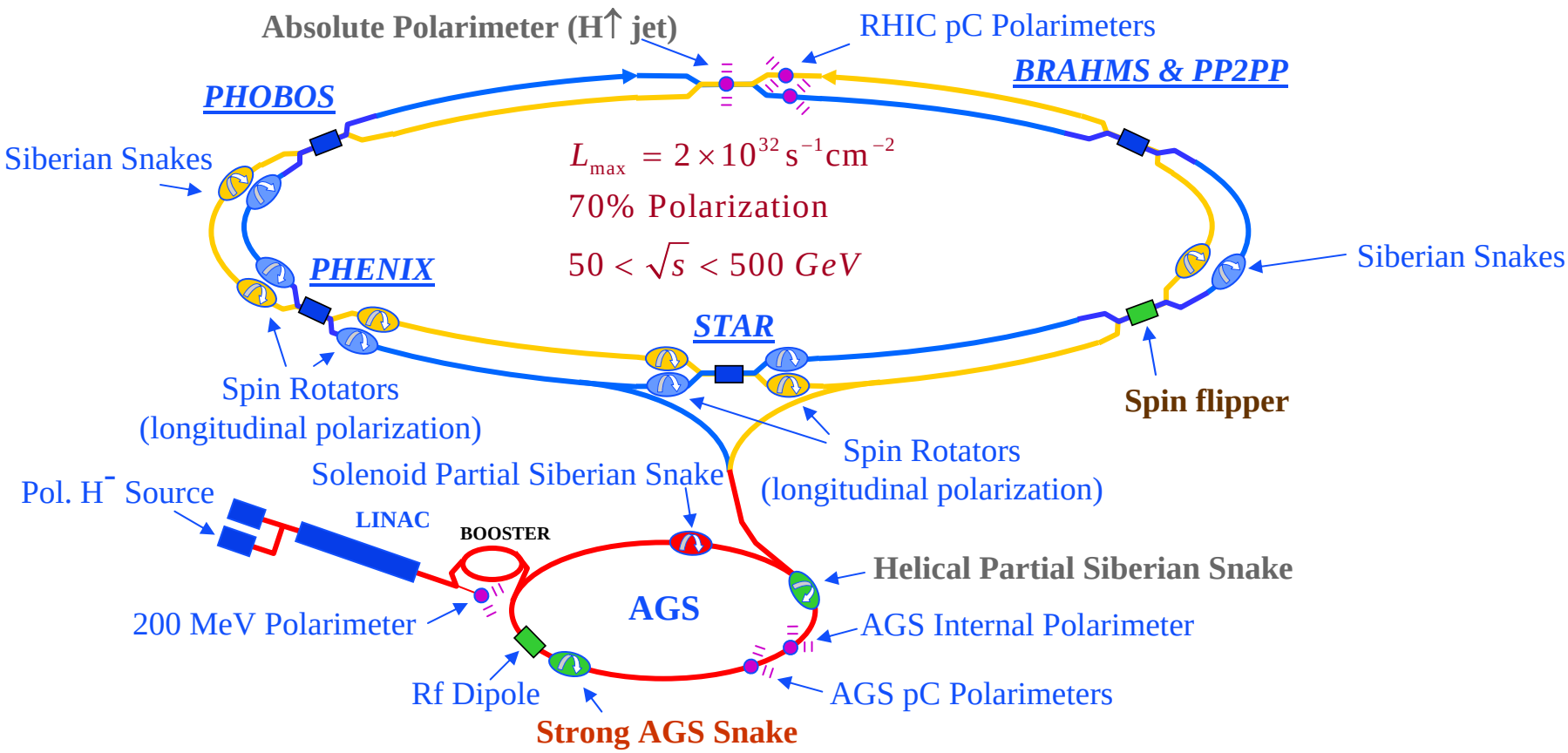
Comparison with existing data from p

» The cross section increases syste





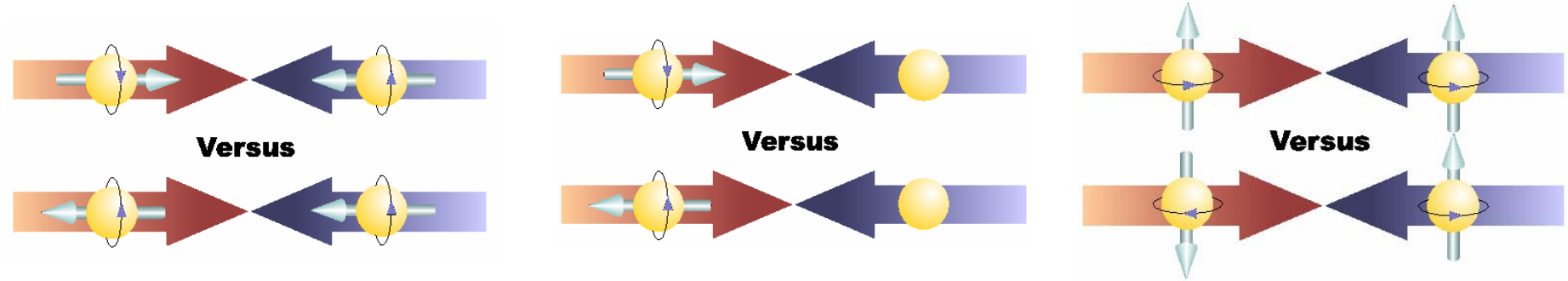
RHIC Polarized Collider



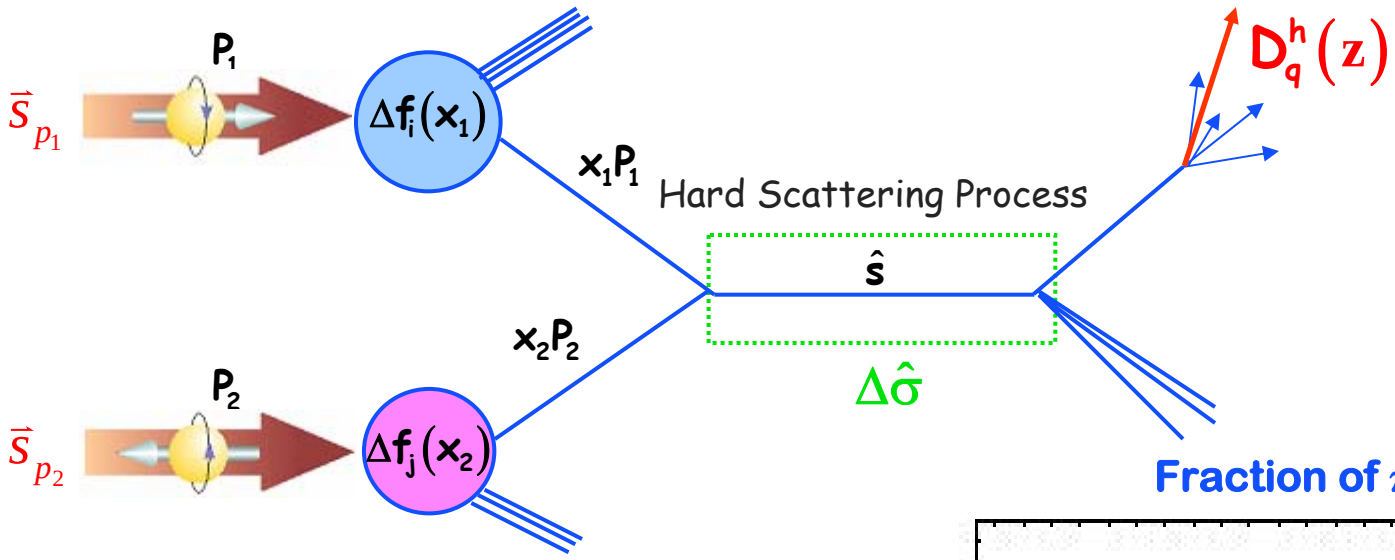
- Installed and commissioned during FY04 run
- Plan to be commissioned during FY05 run
- Installed and in process of being commissioned during FY05 run

Proton Spin Structure at PHENIX

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
π Production $A_{LL}(gg, gq \to \pi + X)$	W Production	Transversity δq:
Prompt Photon $A_{LL}(gq \to \gamma + X)$	$A_L(u + \bar{d} \to W^+ \to \ell^+ + \nu_l)$	π^+, π^- Interference fragmentation: $A_T\left(p_\perp p \to (\pi^+, \pi^-) + X\right)$
Heavy Flavors $A_{LL}(gg \to c\bar{c}, b\bar{b} + X)$	$A_L(\bar{u} + d \to W^- \to \ell^- + \bar{\nu}_l)$	Drell Yan A_{TT}
		Single Asymmetries A_N

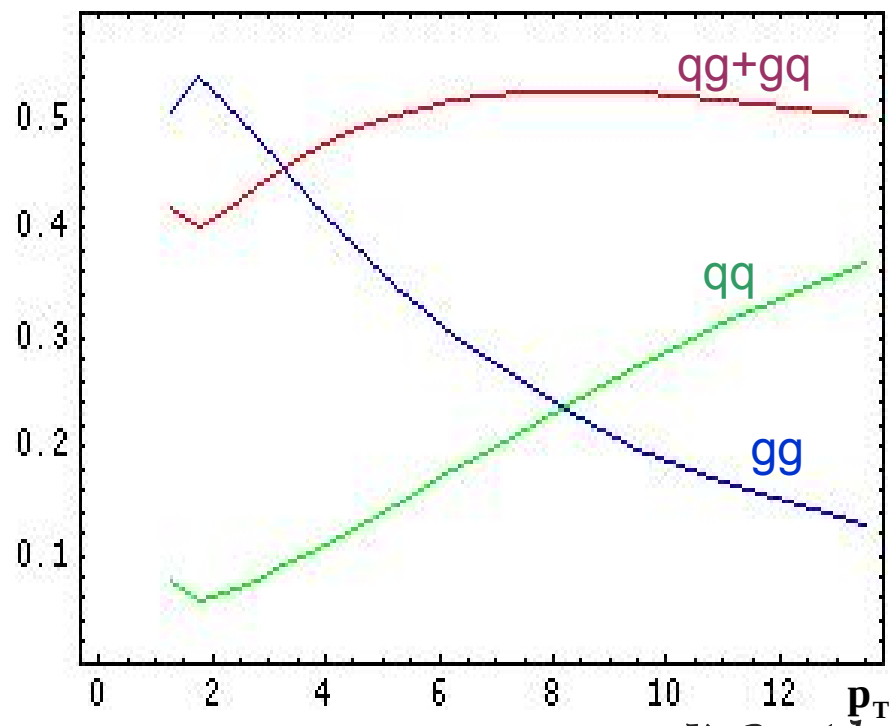


Leading hadrons as jet tags

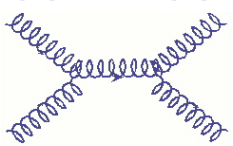


$h = \pi^0$

Fraction of π^0 produced

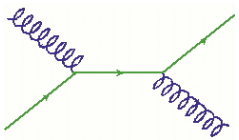


$gg \to gg$



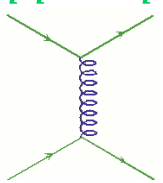
$\propto \frac{\Delta G}{G}\frac{\Delta G}{G}$

$gq \to gq$



$\propto \frac{\Delta q}{q}\frac{\Delta G}{G}$

$qq \to qq$



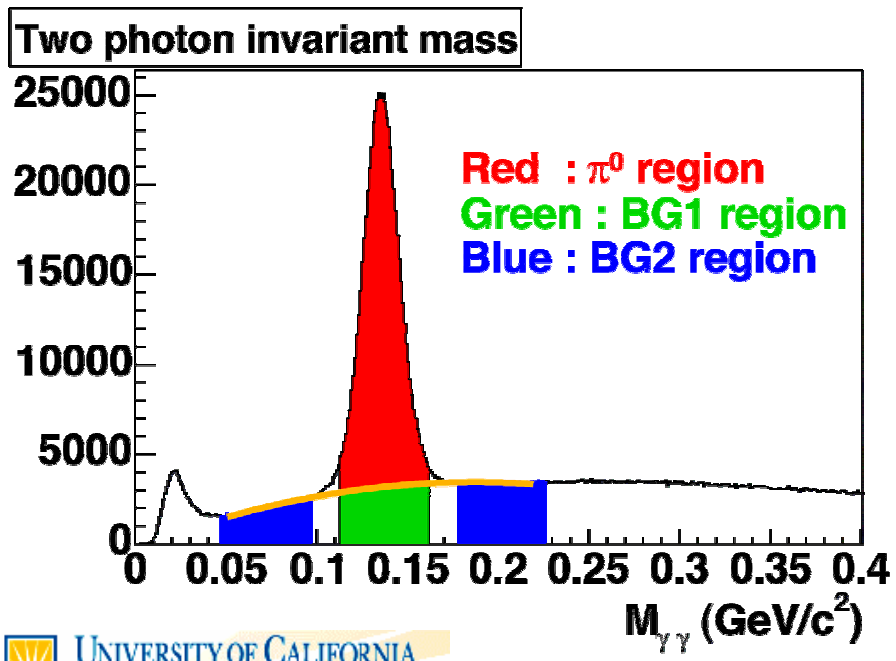
$\propto \frac{\Delta q}{q}\frac{\Delta q}{q}$

A_{LL} & Background Subtraction

Calculate A_{LL} (π^0 + BG1) and A_{LL}(BG2) independently

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P \cdot P} \cdot \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}} \text{where} R = \frac{L_{++}}{L_{+-}}$$

Subtract A_{LL}(BG2) from A_{LL}(π^0 + BG1) to get A_{LL}(π^0)



p_T (GeV/c)	π^0 stat. (w_{BG})
1-2	1151k (31%)
2-3	510k (13%)
3-4	91k (7%)
4-5	17k (5%)

Gluon Spin Program has begun!

Data taken in 4 weeks in Run 3 & 4 days of 2004

Longitudinal spin asymmetry measurement at PHENIX

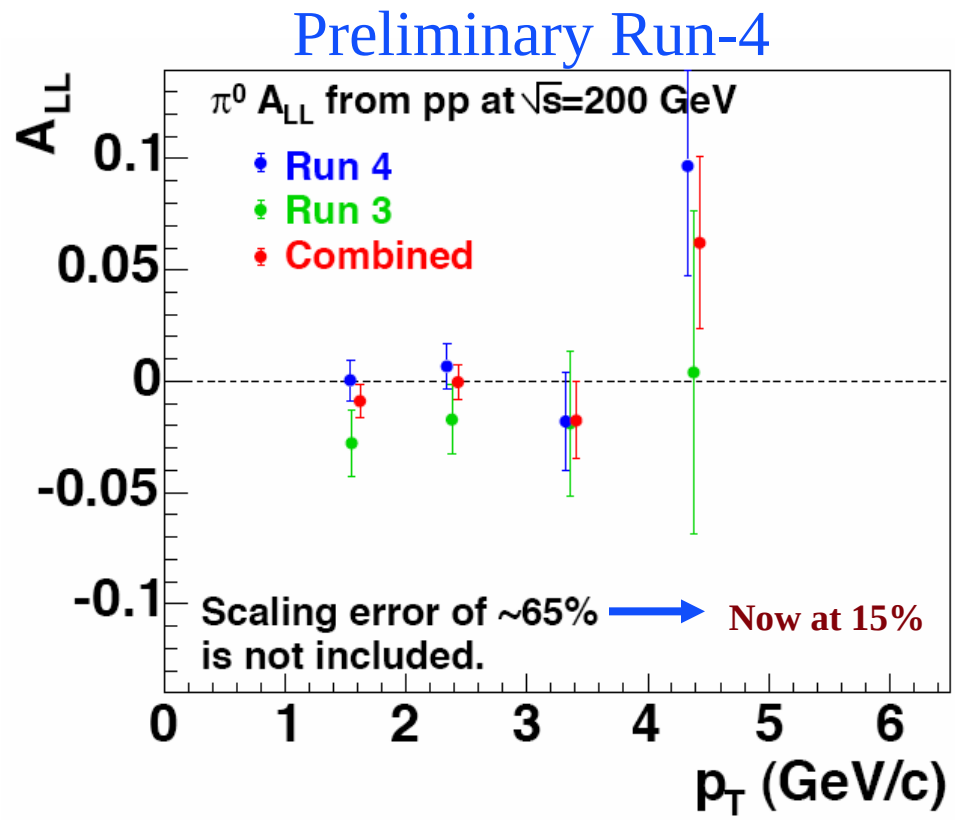
- » *Beam polarization measurement using p-Carbon CNI polarimetry and Jet-Polarimetry*
- » *Forward neutron production based local polarimetry*
- » *Relative luminosity variations less than 2.5×10^{-4}*

Uncertainties improve As $P^2\sqrt{L}$

	Run Time	Int. Lum.	Pol.	P^4L
Run 3 (2003)	4 weeks	220 nb^{-1}	27%	1.17 nb^{-1}
Run 4 (2004)	4 days	75 nb^{-1}	40%	1.92 nb^{-1}

Double helicity asymmetry in inclusive mid-rapidity neutral pion production for polarized -pp collisions at Sqrt(s)=200 GeV hep-ex/0404027, Published: PRL 93, 202002 (2004)

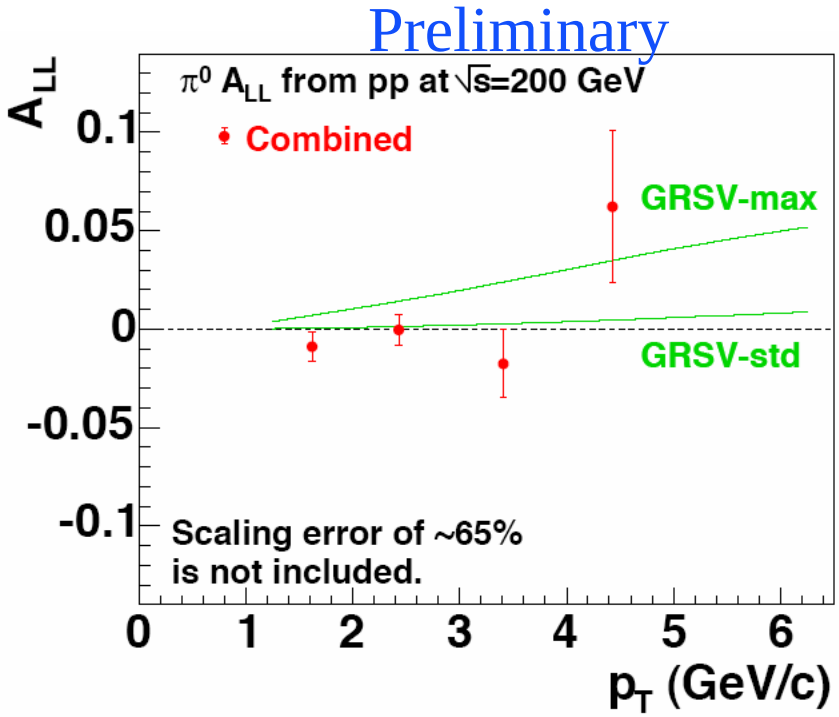
$A_{LL}(\pi^0)$: Run-3 & Preliminary Run-4



- **Data from Run-3 and Run-4 consistent:**
  - » Ch²/DF = 5.7/4
- **Figure of merit of Run3 and Run4 are: 1.17 and 1.92, respectively**
  - » Uncertainties in Run-4 smaller in spite of significantly fewer events

p_T (GeV/c)	$A_{LL}^{\pi^0}$ (Run 4) (%)	$A_{LL}^{\pi^0}$ (Run 3) (%)	$A_{LL}^{\pi^0}$ comb. (%)
1-2	0.0± 0.9	-2.7± 1.3	-0.9±0.7
2-3	0.7± 1.0	-1.3± 1.3	0.0±0.8
3-4	-1.8± 2.2	-1.7± 2.8	-1.8±1.7
4-5	9.7± 4.9	0.7± 6.2	6.2±3.8

Connection to ΔG



GRSV-std: best fit to DIS data

$$\int_0^1 \Delta G(x)dx \sim 0.7 \text{ at } Q^2\ 1\ \text{GeV}^2$$

GRSV-max

$$\Delta G(x) = G(x) \text{ at } Q^2_{\text{input}} = 0.40\ \text{GeV}^2$$

Data prefers the GRSV-std curve (and hence the gluon distribution and its first

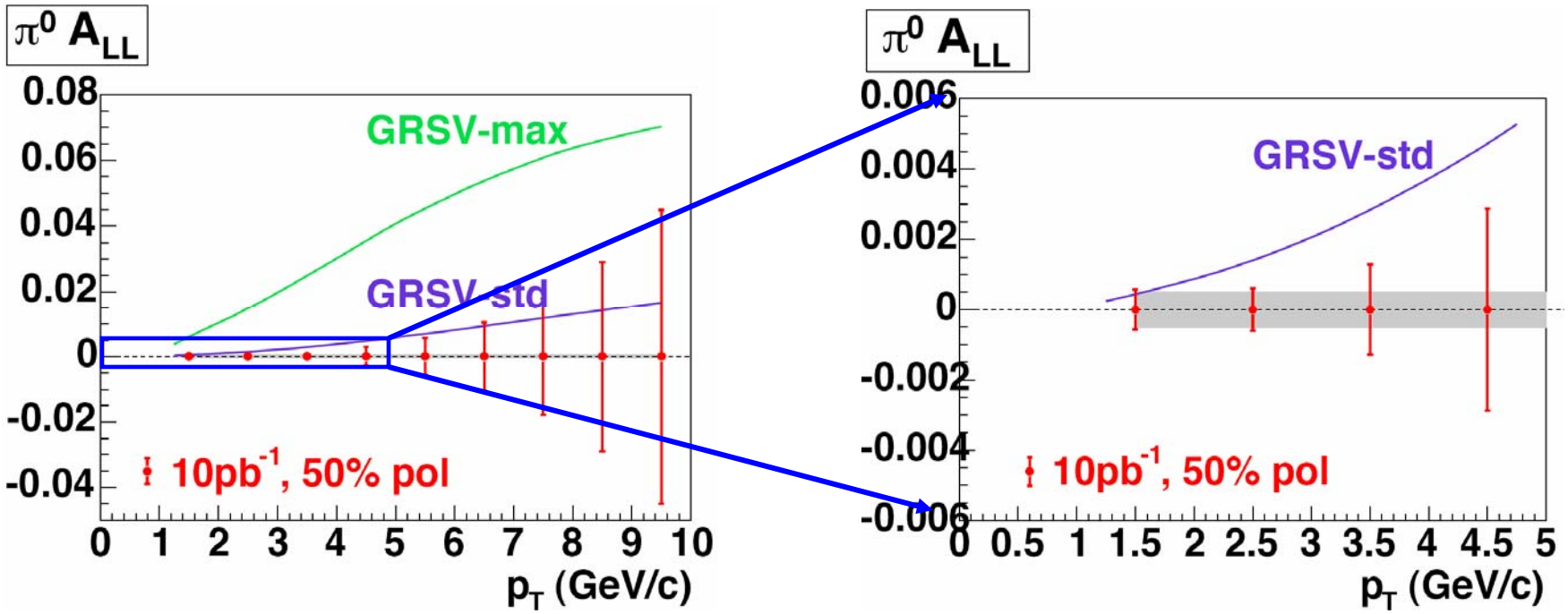
Confidence Levels

» **B. Jaeger et al. Phys. Rev. D67, 054005 (2003)**

	GRSV-std	GRSV-max
4 points (1-5 GeV/c)	21-24%	0.00-6%
3 points (2-5 GeV/c)	27-29%	0.01-13%

Major run on-going

- Run started April 19th
- Run ends June 25th
- 8-9 Physics Weeks
  - » Expect ~5-10 pb-1 with ~45% average beam polarization
  - » **Status Last Week**: beam polarization > 45% last week, luminosity within a factor of 2 of expected.

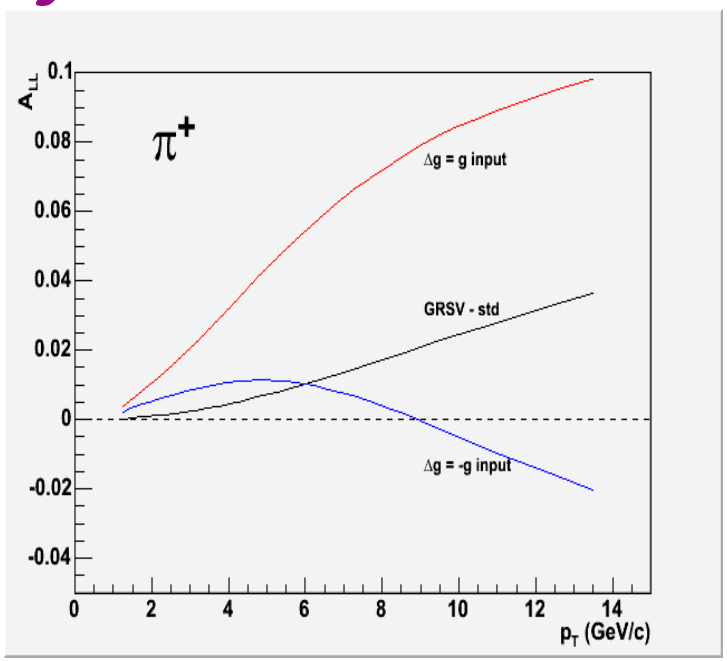


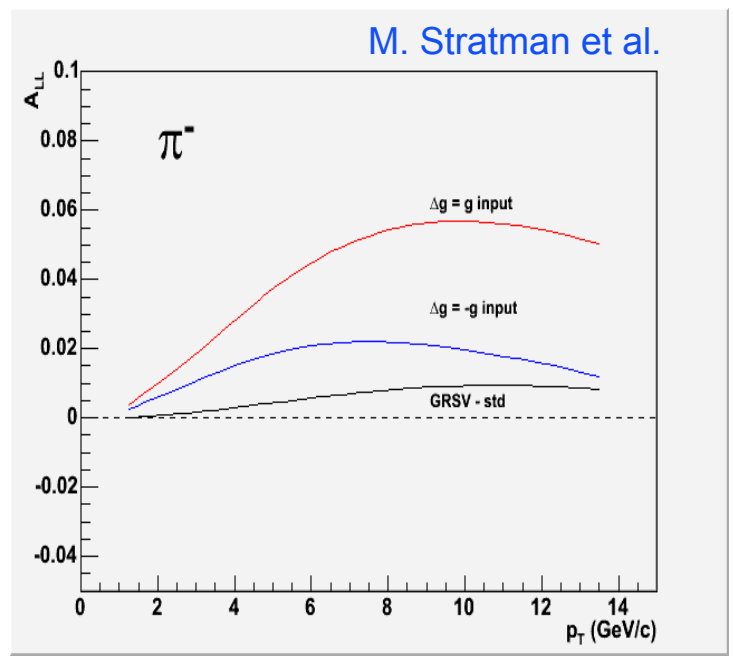
Near Term Outlook

Run-6 a strong siberian snake to go in AGS:

- » Beam Polarization 50% ==> 65-70%
- » Luminosity expected to increase as well ~35 pb-1

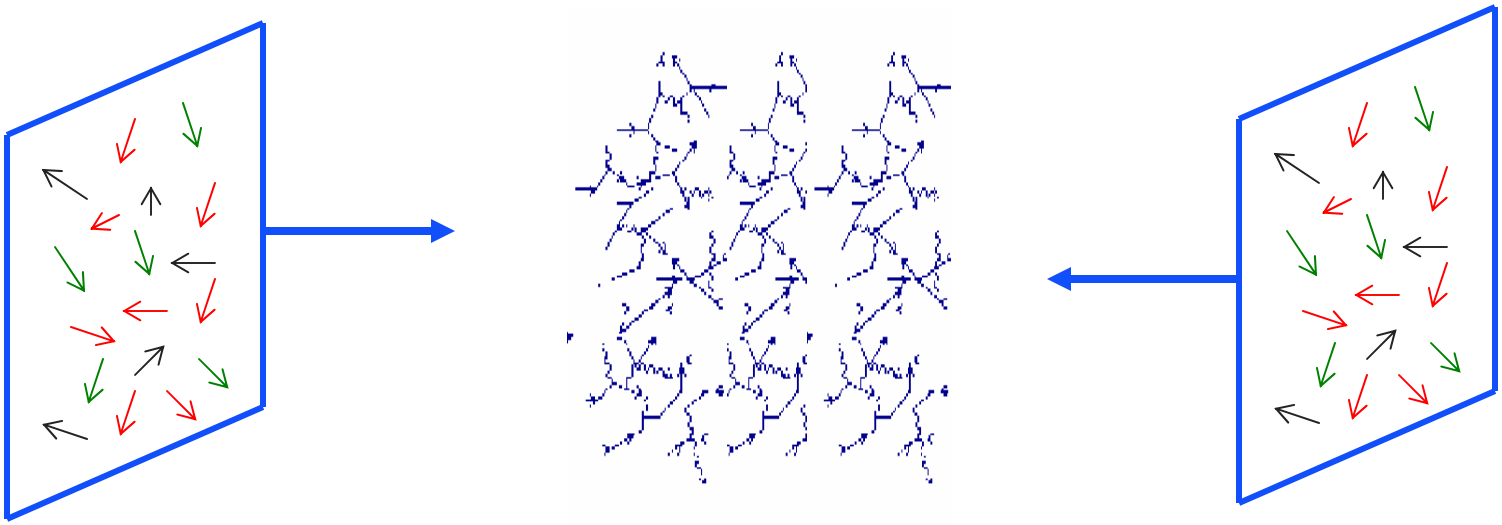
Helicity asymmetry for π^0 at Higher p_T (> 6 GeV/c) and also *relative sizes of charged pion double spin asymmetries*





$$\Delta G > 0 \Rightarrow A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$$

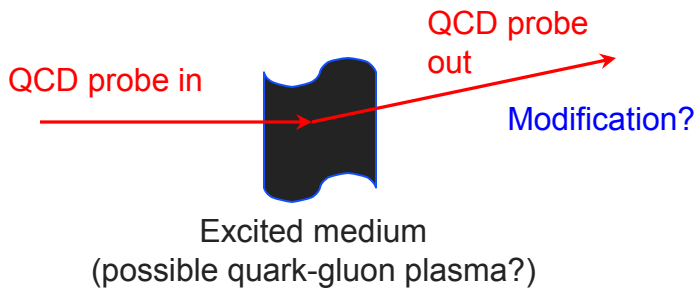
Heavy Ion Collisions

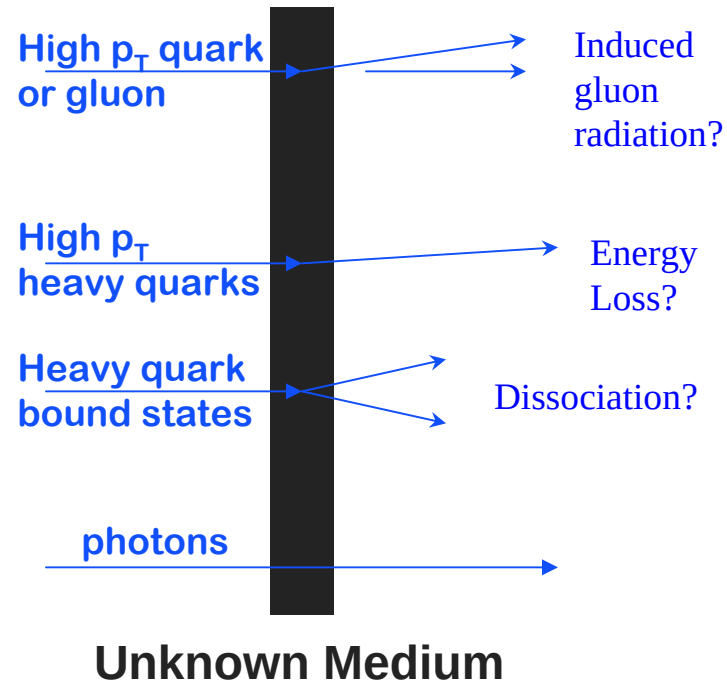


10,000 gluons, quarks, and antiquarks
from the nuclear wavefunctions
are made physical in the laboratory

Probing the excited vacuum or another
type of partonic matter

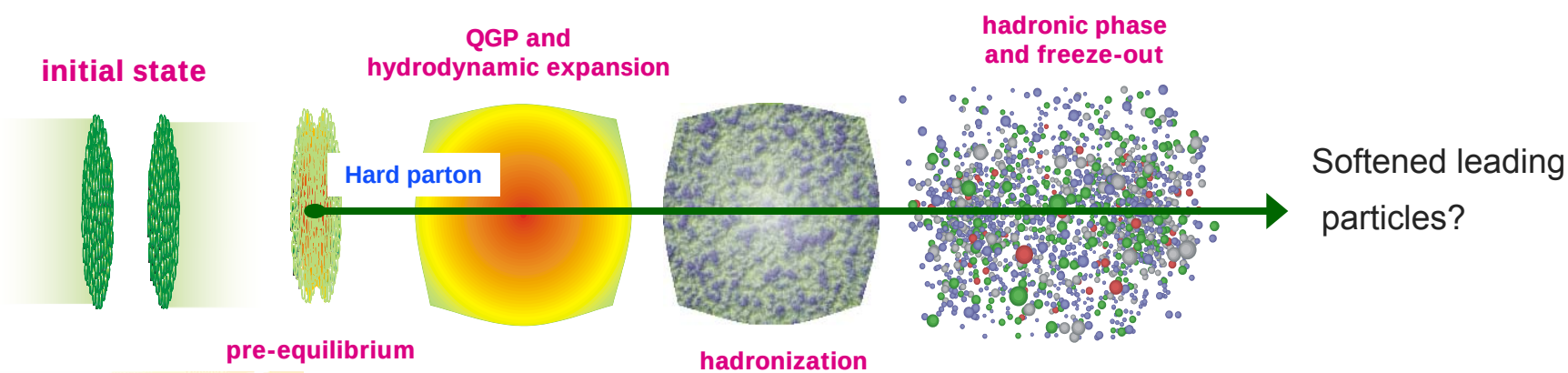
How can we study the produced matter?





Study the QCD medium by shooting a QCD-sensitive probe through it, then look for any modifications due to the medium.

All probes must be auto-generated

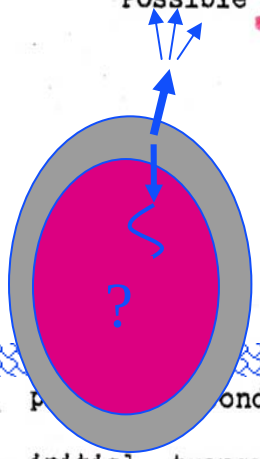


Can we look directly at jets?

20 YEARS AGO

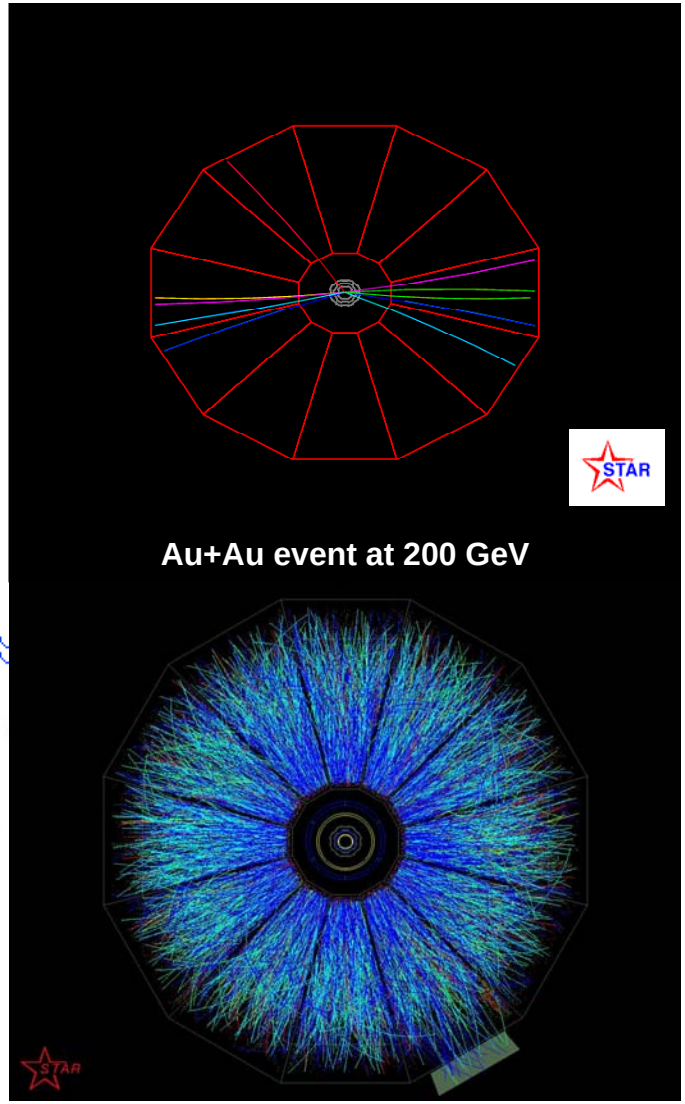
FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.



J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

p ondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.



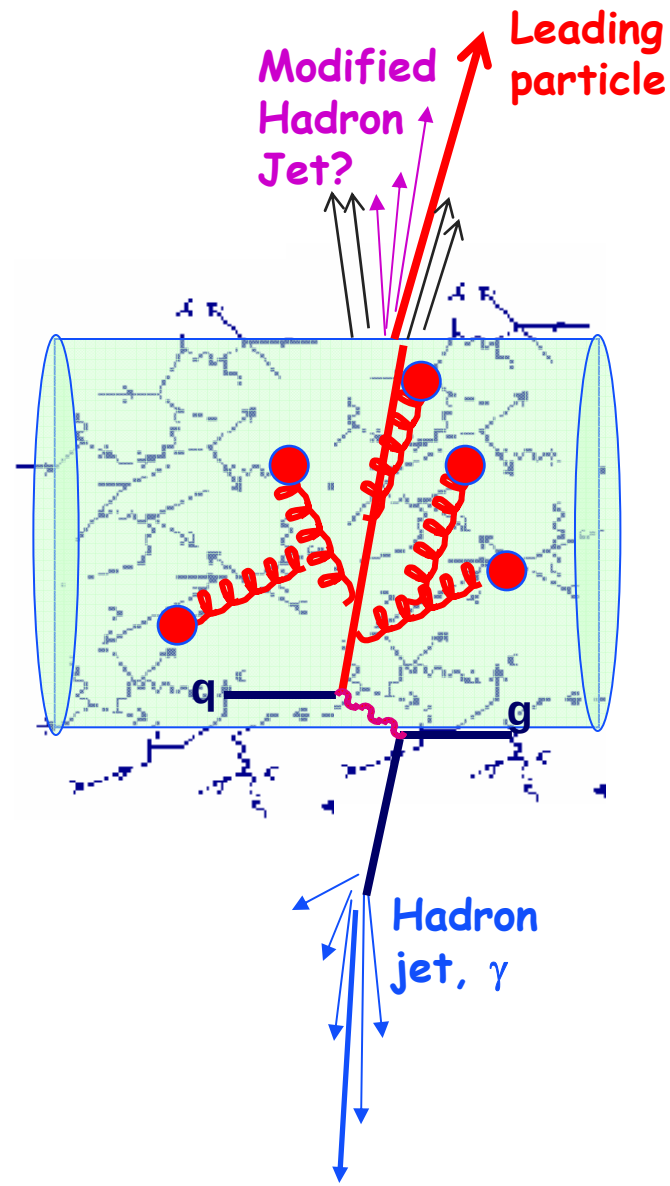
Leading particles as a probe

Advantage

- ✓ Can avoid soft background in a jet cone by letting $R \rightarrow 0$
- ✓ Best to measure using a fine grained calorimeter
  - Can identify neutral pions in PHENIX calorimeter $\delta\phi = \delta\eta = .01$
  - Fractional energy resolution improves with increasing energy
  - Relatively easy to trigger on

Disadvantage

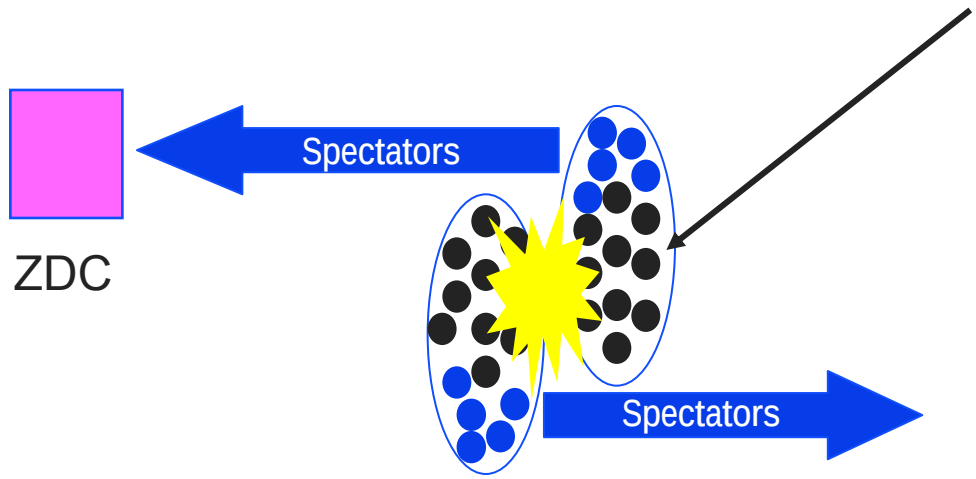
- ➢ Parent parton energy uncertain
  - Will dilute determination of the properties of the created state of matter



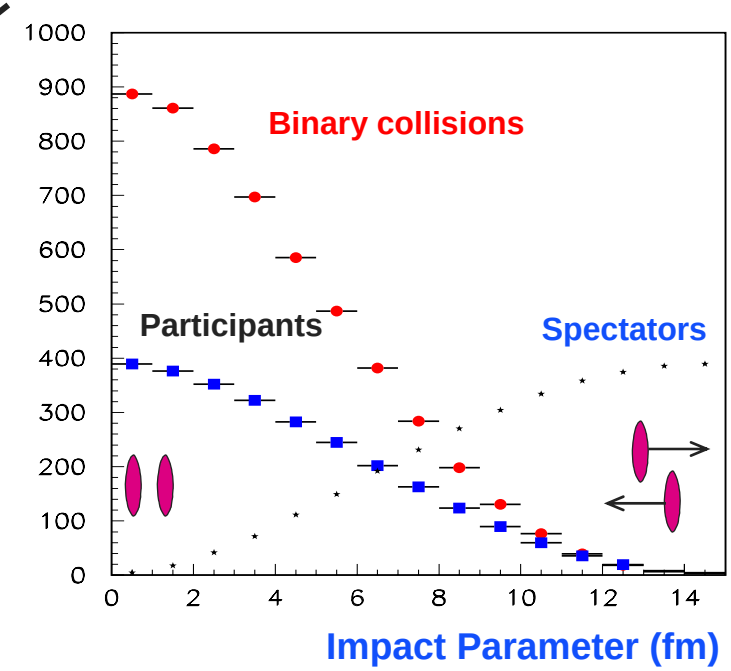
Collision Characterization

We can vary the collision size by selecting different impact parameter events

Different number of participating nucleons

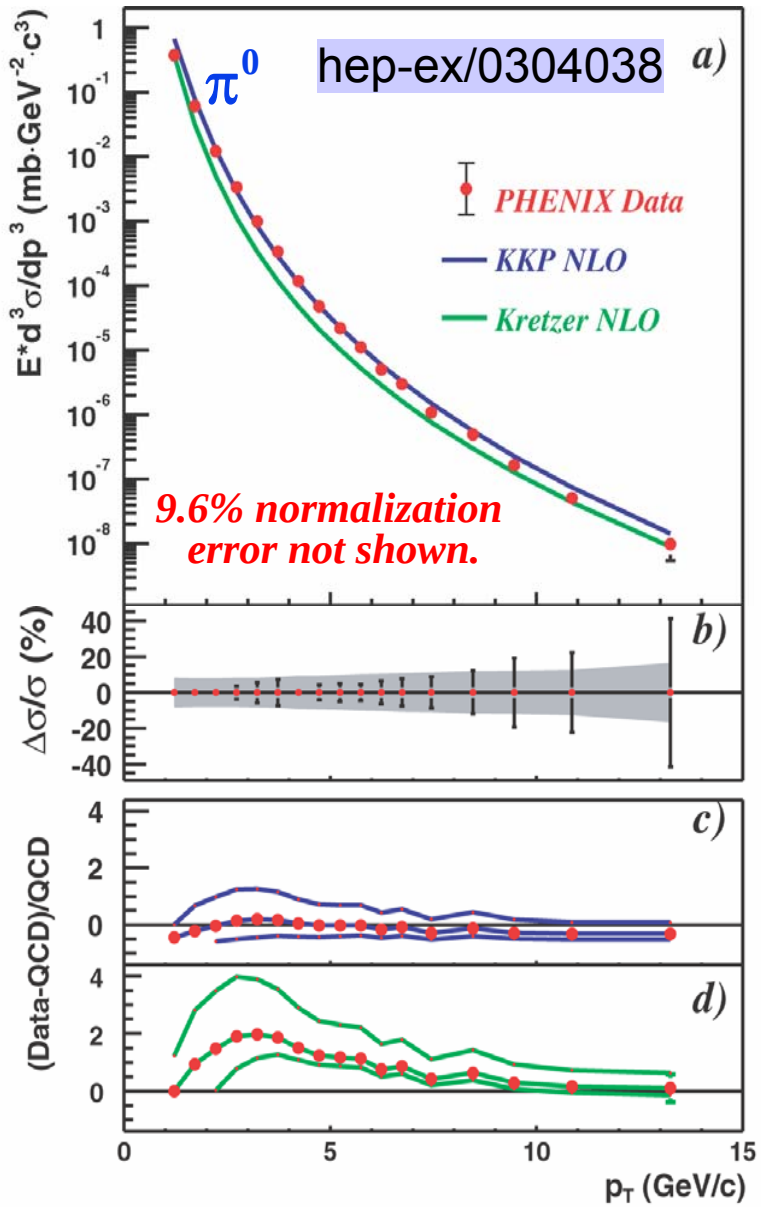


Participants = 2 x 197 - Spectators



PHENIX π^0 spectrum in p+p collisions

- ✓ What should we compare these results with?
  - Start with baseline that Au+Au is incoherent superposition of N+N collisions
  - Scale p+p collisions with number of binary collisions
- ✓ PHENIX has measured the neutral pion spectrum in p+p at 200 GeV.
- ✓ Results consistent with pQCD NLO calculation



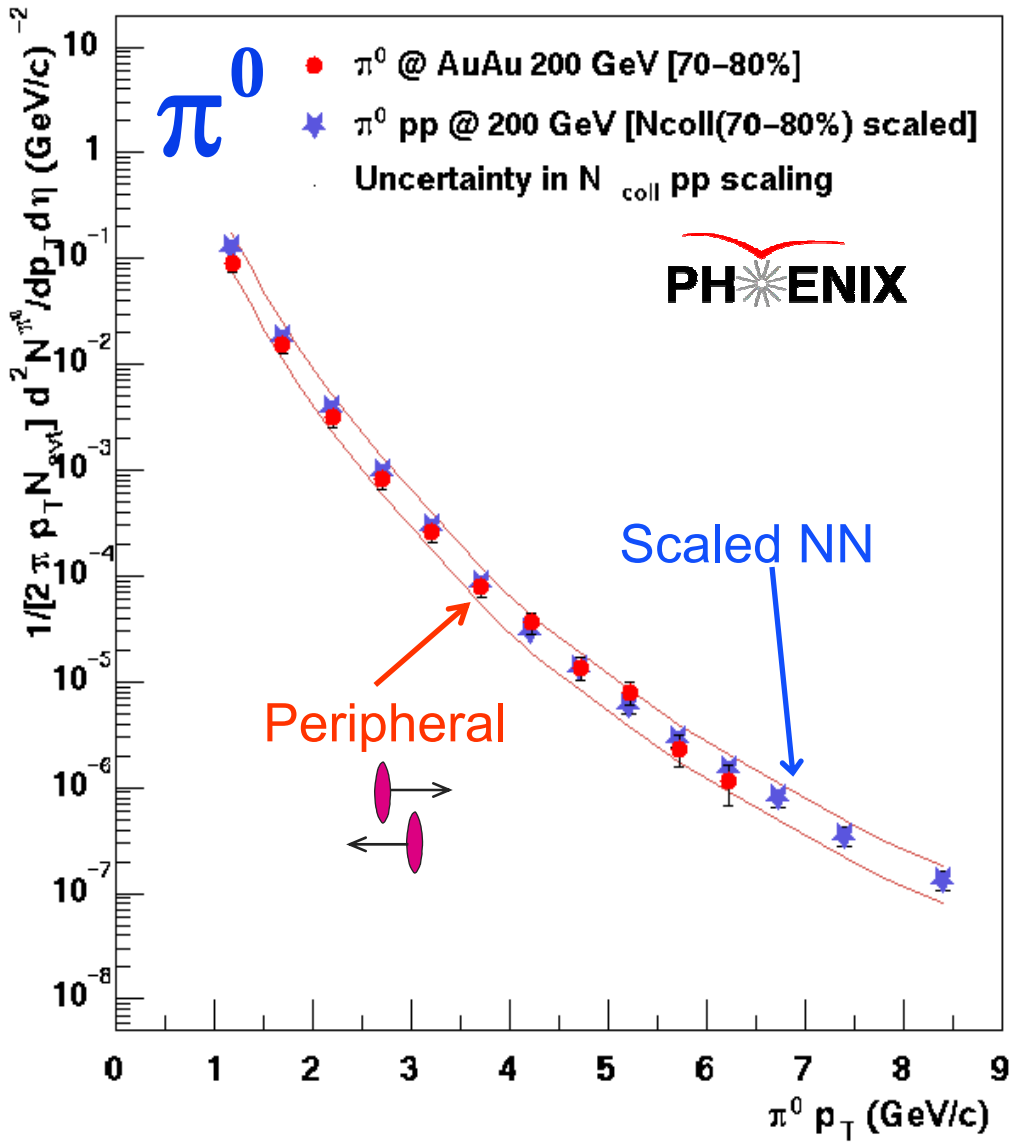
π^0 spectra in Au+Au at 200GeV

Peripheral Collisions

- ✓ PHENIX (Run-2) data on π^0 production in peripheral (70-80%) collisions
- ✓ Consistent with N+N, as measured by PHENIX, scaled by number of binary collisions

Scale p-p data by the number of binary collision in central peripheral collisions.

$$N_{collisions}^{70-80\%} = 12.3 \pm 4.0$$



Phys. Rev. Lett. 91, 072301 (2003)

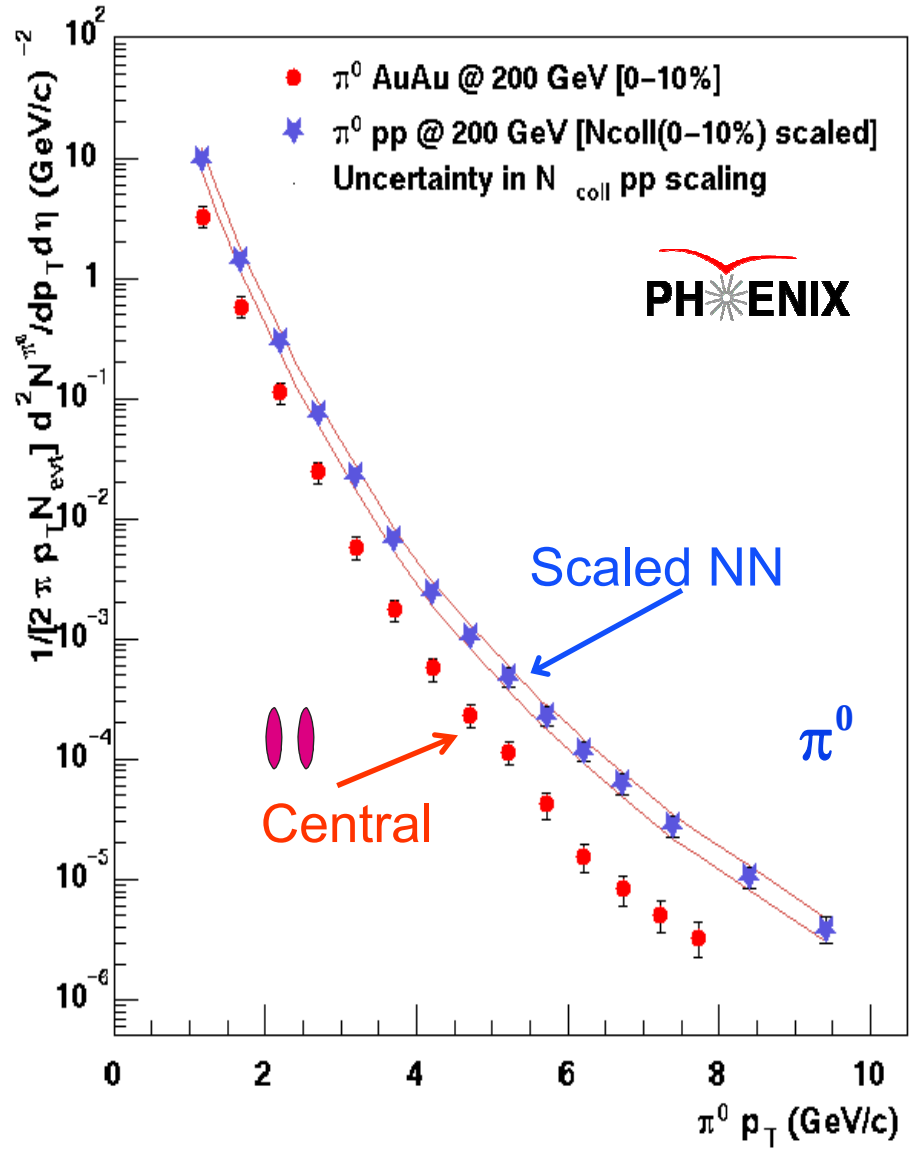
π^0 spectra in Au+Au at 200GeV

Central Collisions

- ✓ PHENIX (Run-2) data on π^0 production in central (0-10%) collisions
- ✓ Clearly lower than the scaled N+N collisions
  - Factor 6 at p_T=6-8GeV/c.
- ✓ **At least qualitatively this is what we expect from energy loss in a dense medium.**

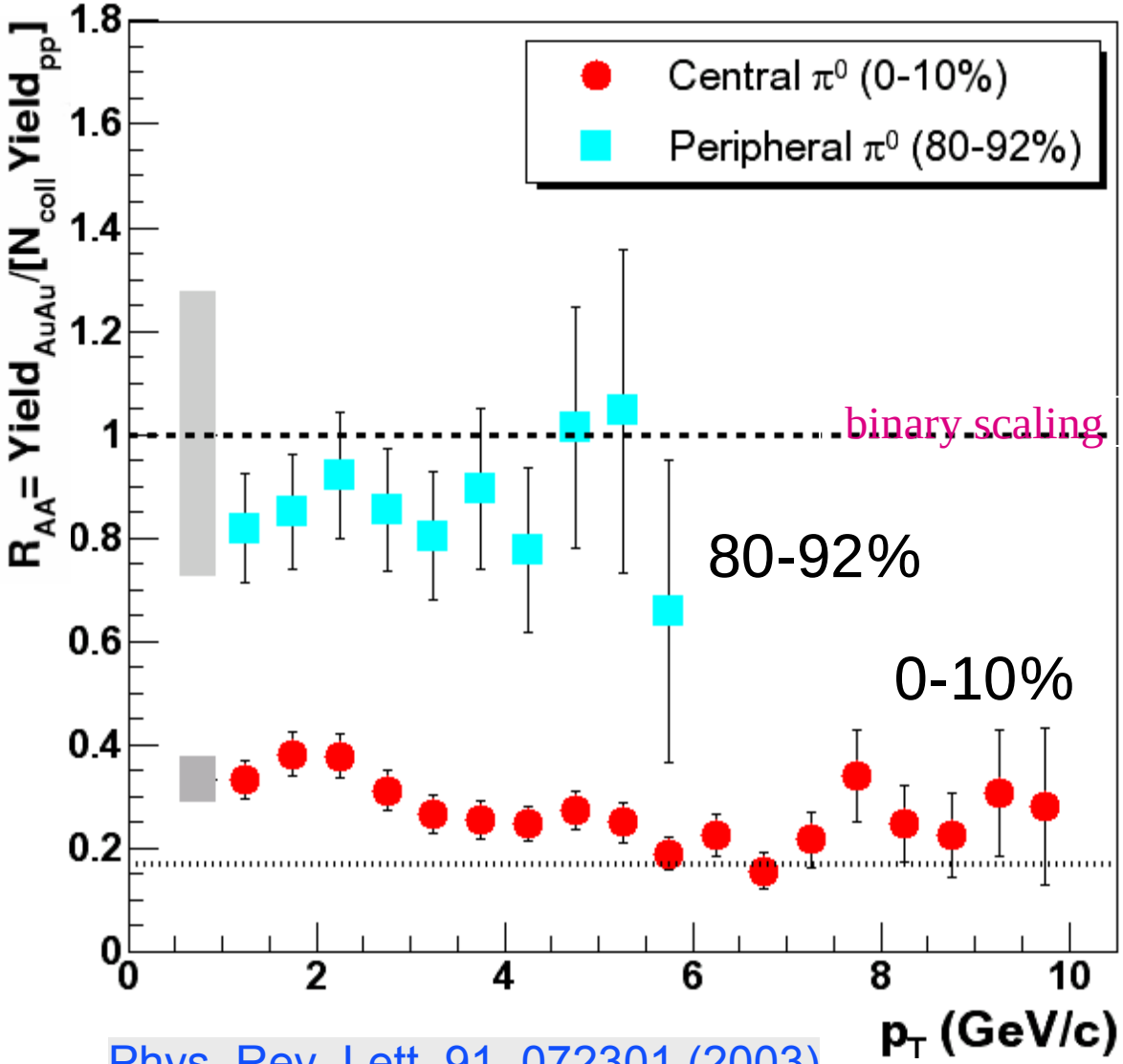
Scale p-p data by the number of binary collision in central and peripheral collisions.

$$N_{collisions}^{0-10\%} = 975 \pm 94$$

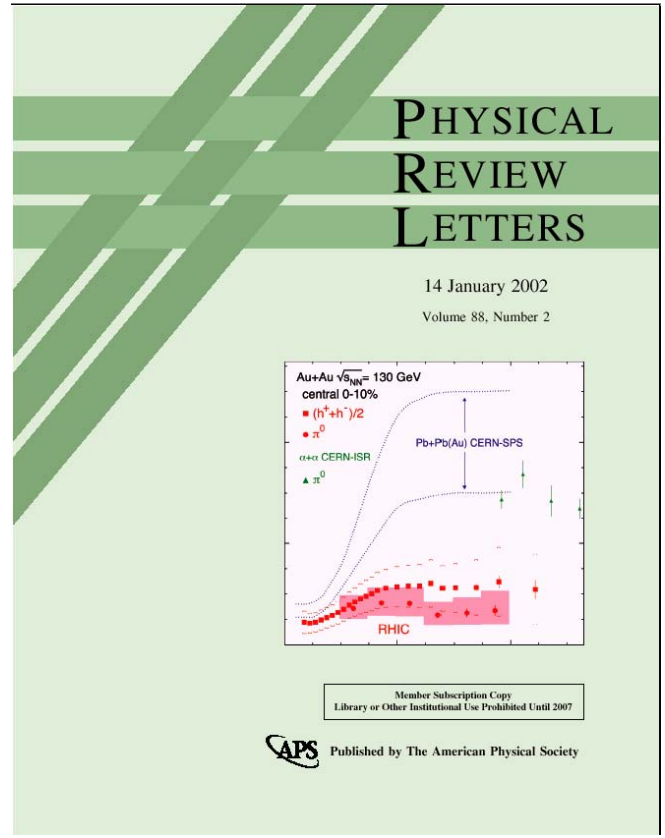


Phys. Rev. Lett. 91, 072301 (2003)

π^0 yield in Au+Au vs. p+p collisions

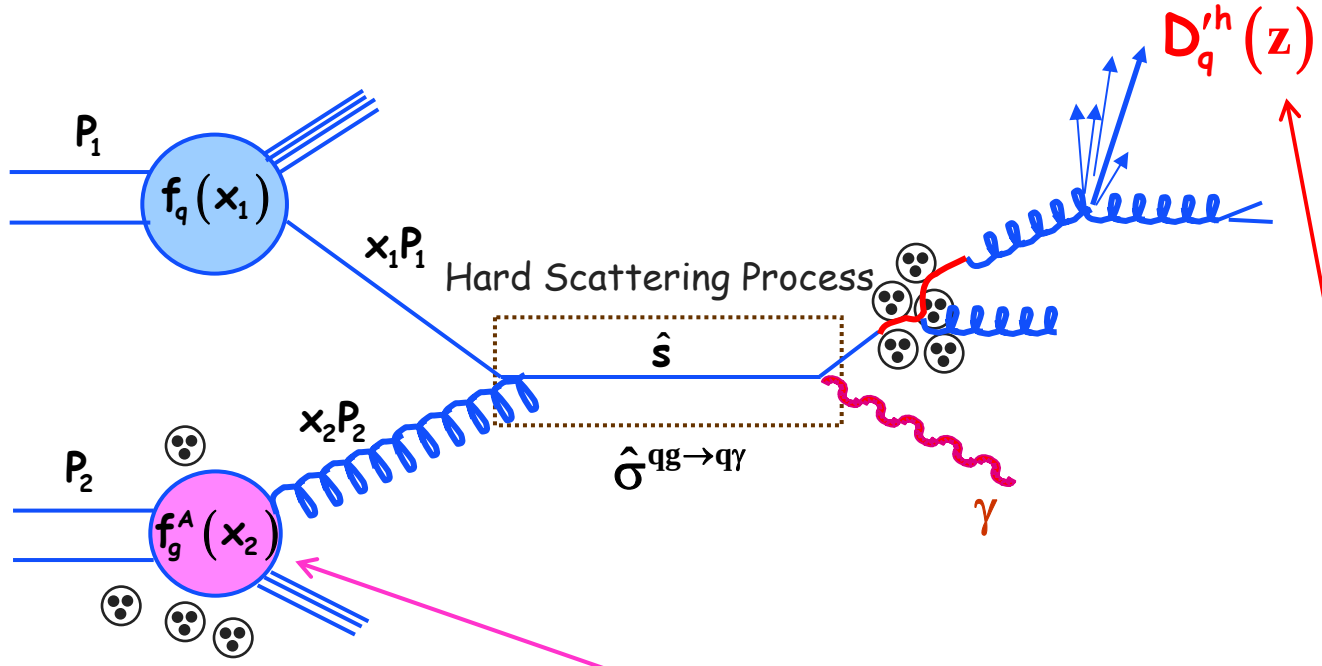


Phys. Rev. Lett. 91, 072301 (2003)



Discovery of high p_T suppression

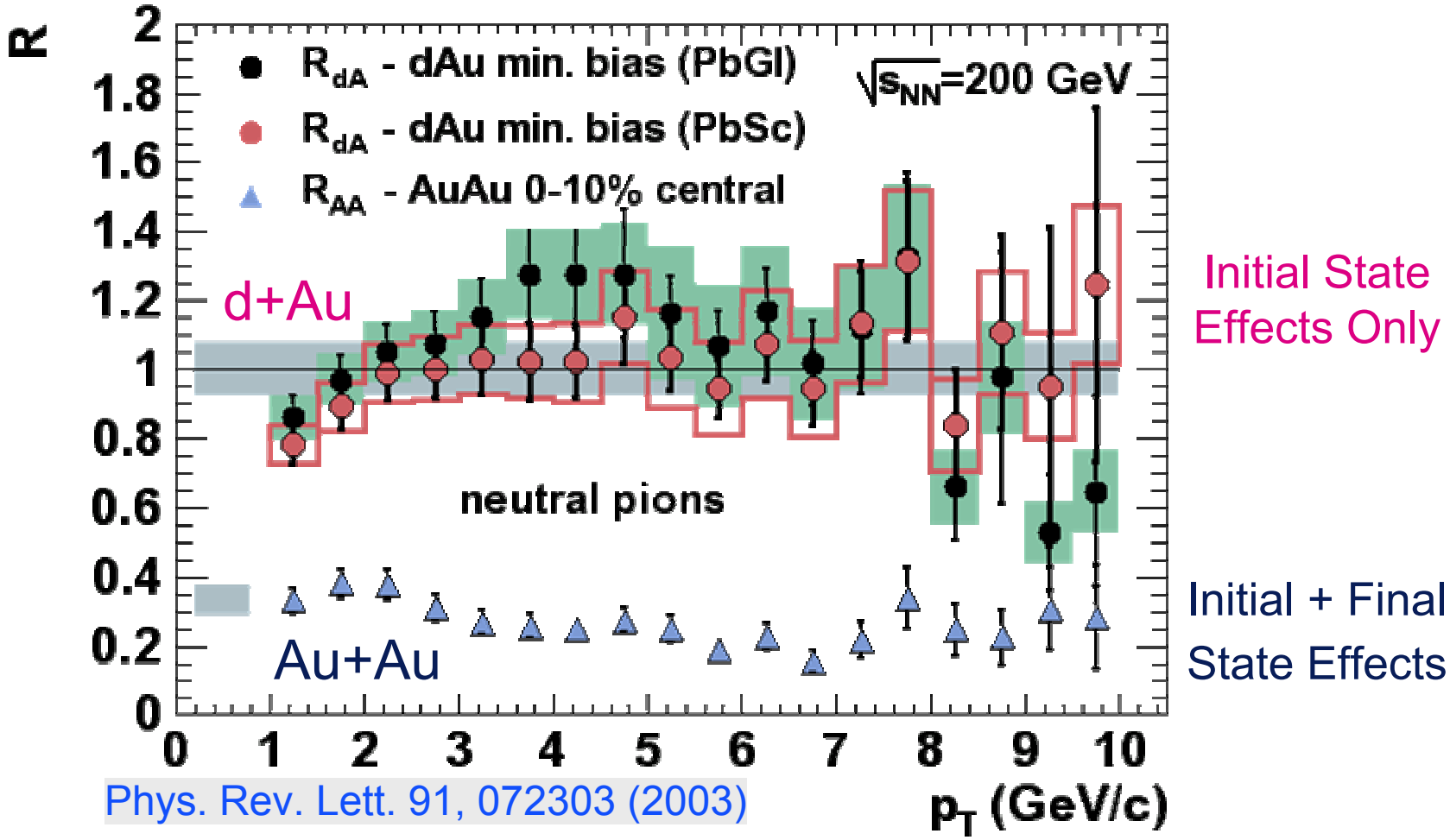
Hard scattering processes in p+A



$$\sigma(pA \to hX) \sim f_q(x_1) \otimes f_g^A(x_2) \otimes \hat{\sigma}^{qg\to q\gamma}(\hat{s}) \otimes D_q'^h(z)$$

The structure functions and fragmentation function can effectively be modified due to nuclear effects such as: "Cronin", "shadowing", saturation, and re-scattering.

R_{AA} vs. R_{dA} for Identified π^0



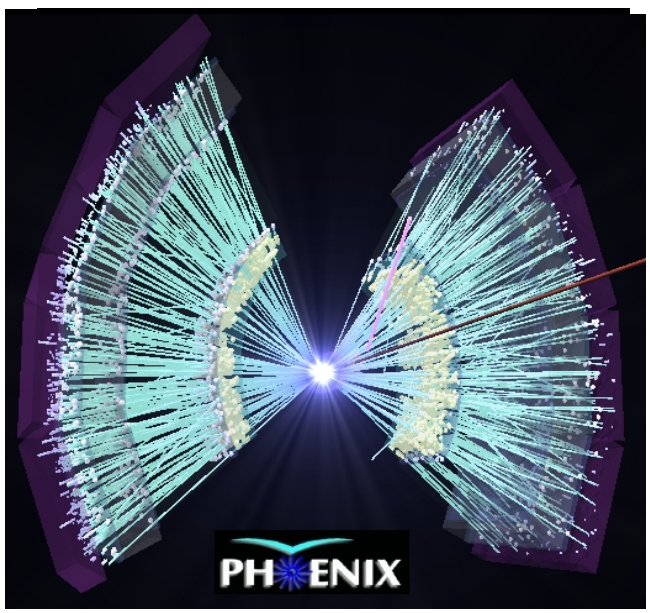
Phys. Rev. Lett. 91, 072303 (2003)

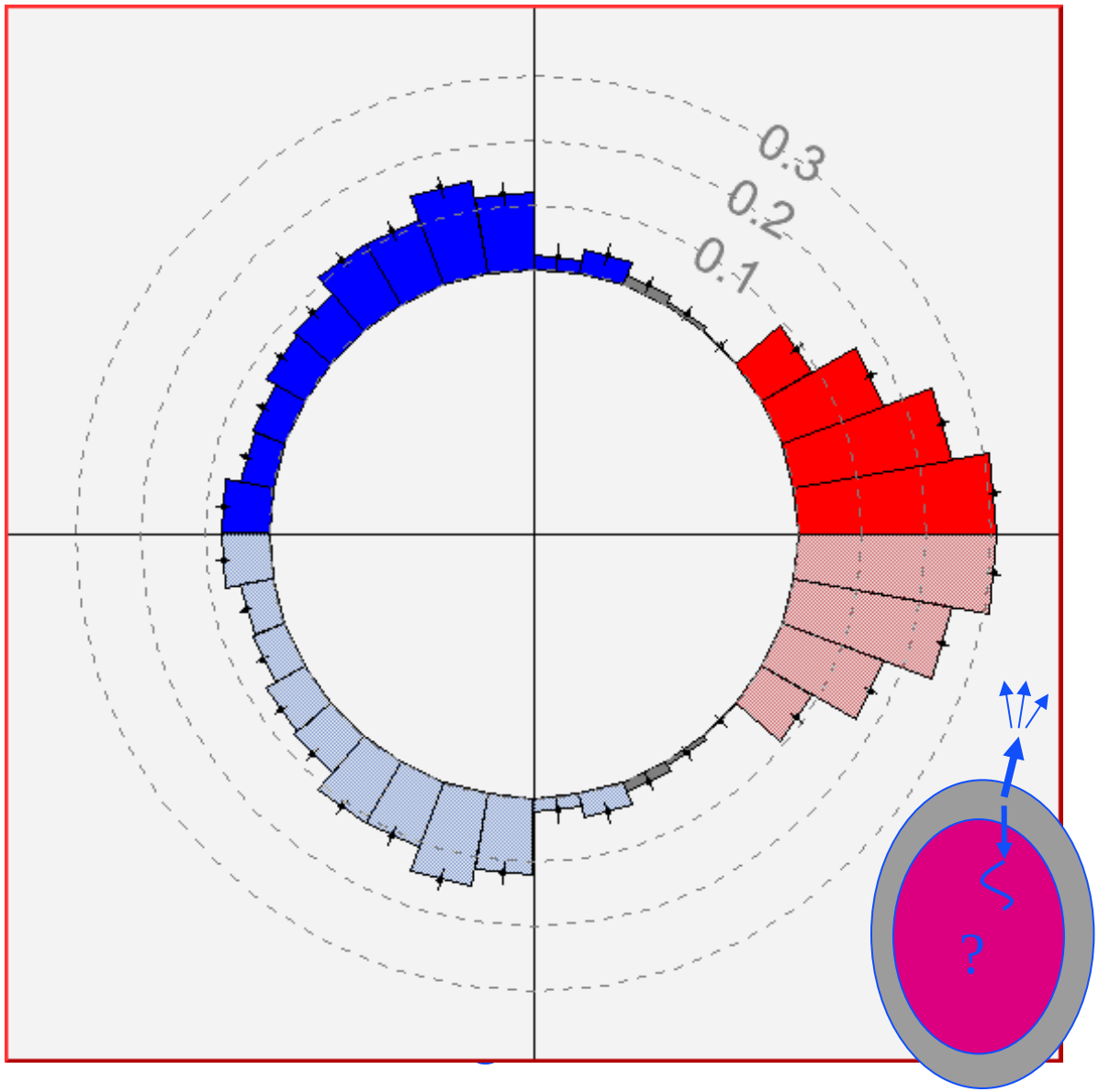
d-Au results rule out CGC as the explanation for Jet Suppression at Central Rapidity and high p_T

Jets through angular correlations

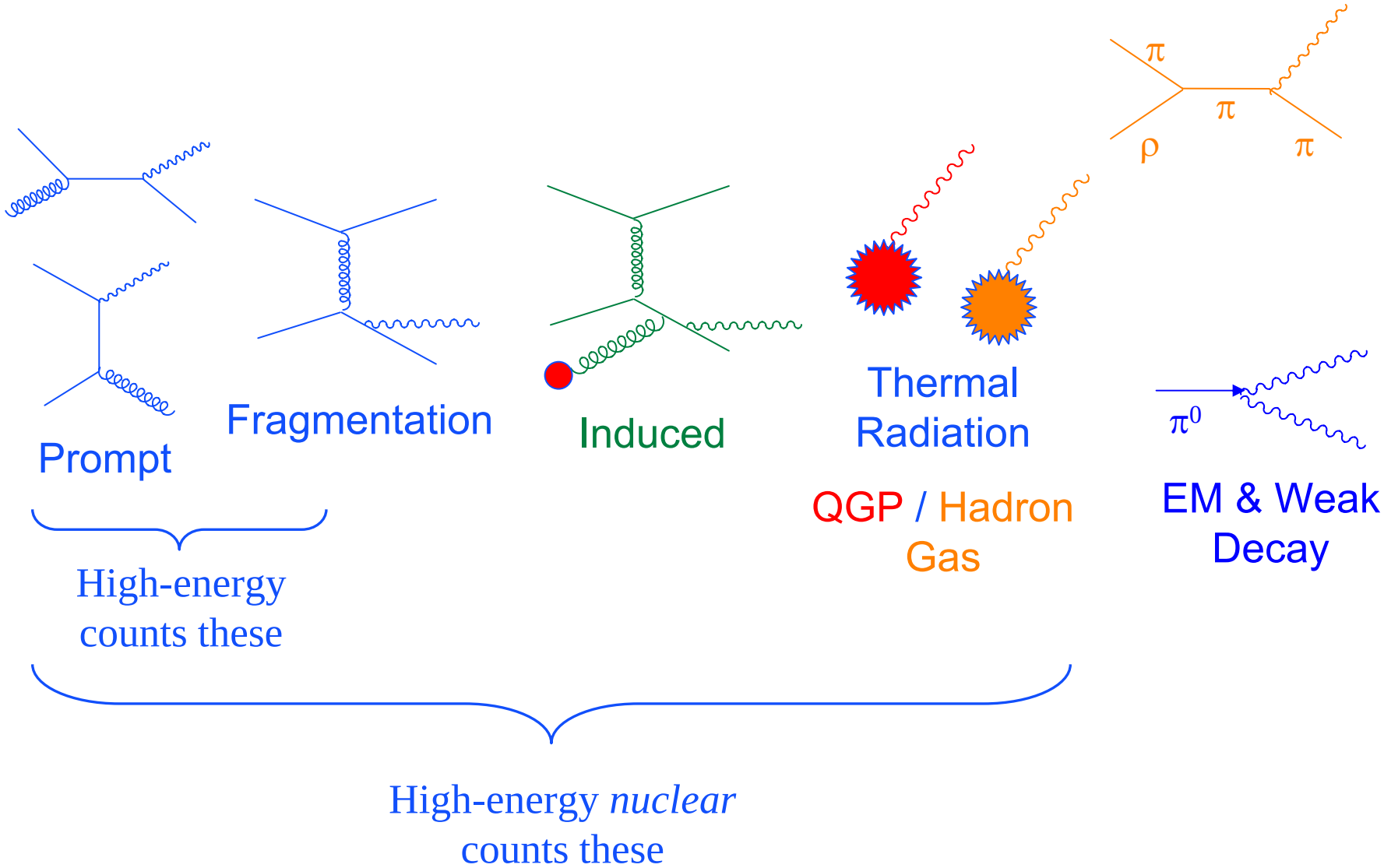
Jet correlations in central Gold-Gold.

Away side jet reappears for particles p_T>200 MeV

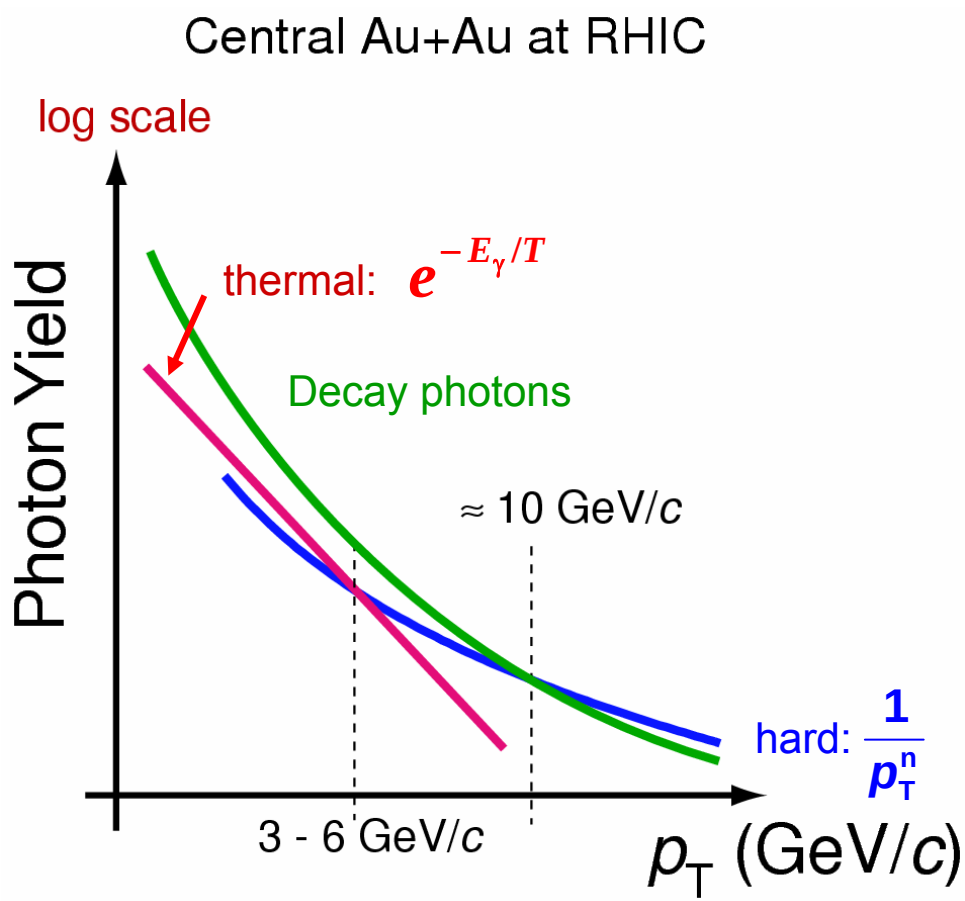




“Direct” photons in heavy-ions



Schematic Photon Spectrum in A+A



Advantage in central A+A at RHIC:

Decay photon background strongly reduced due to π^0 suppression

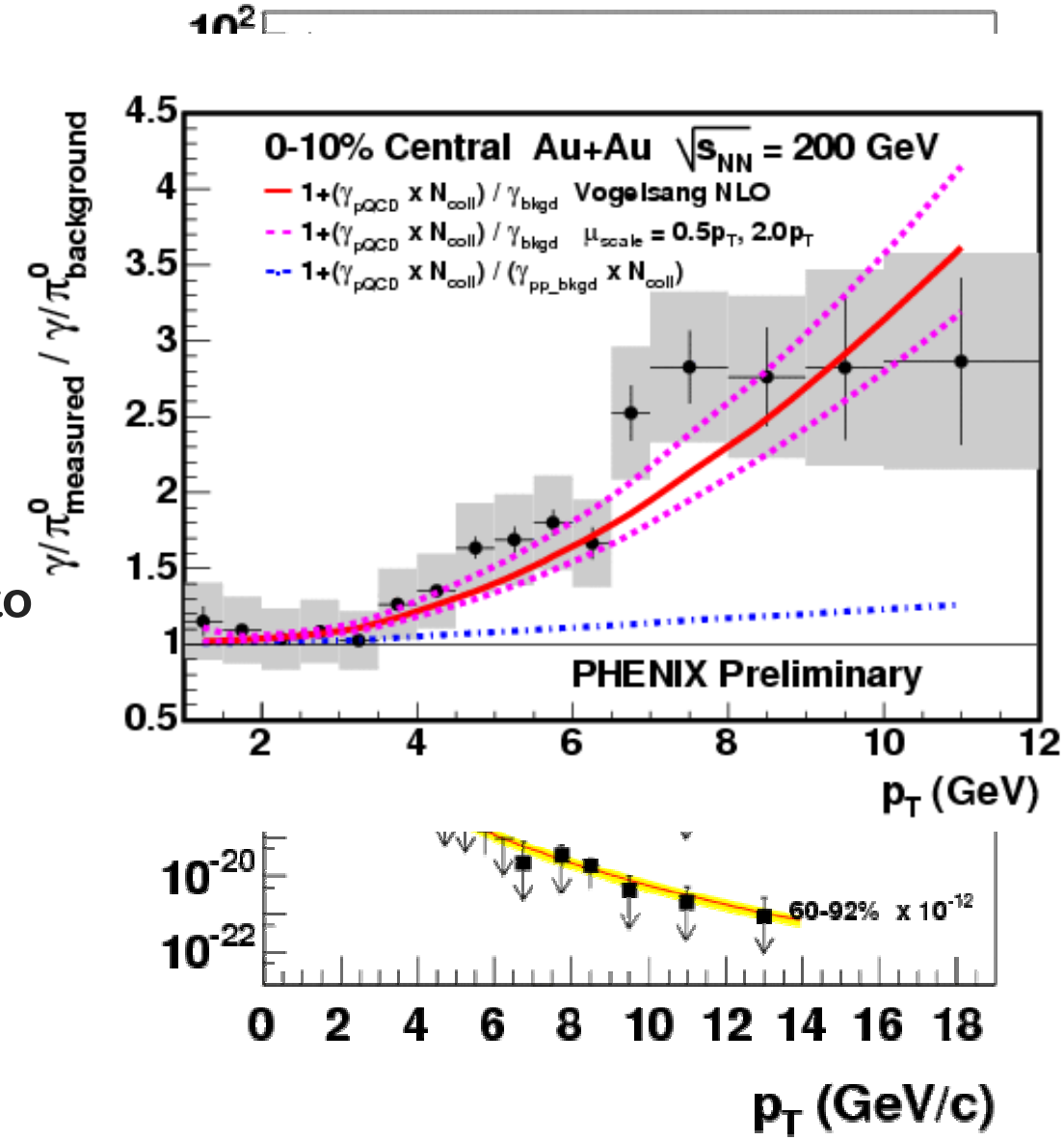
Binary scaling - direct photons

Important test of QCD and initial state

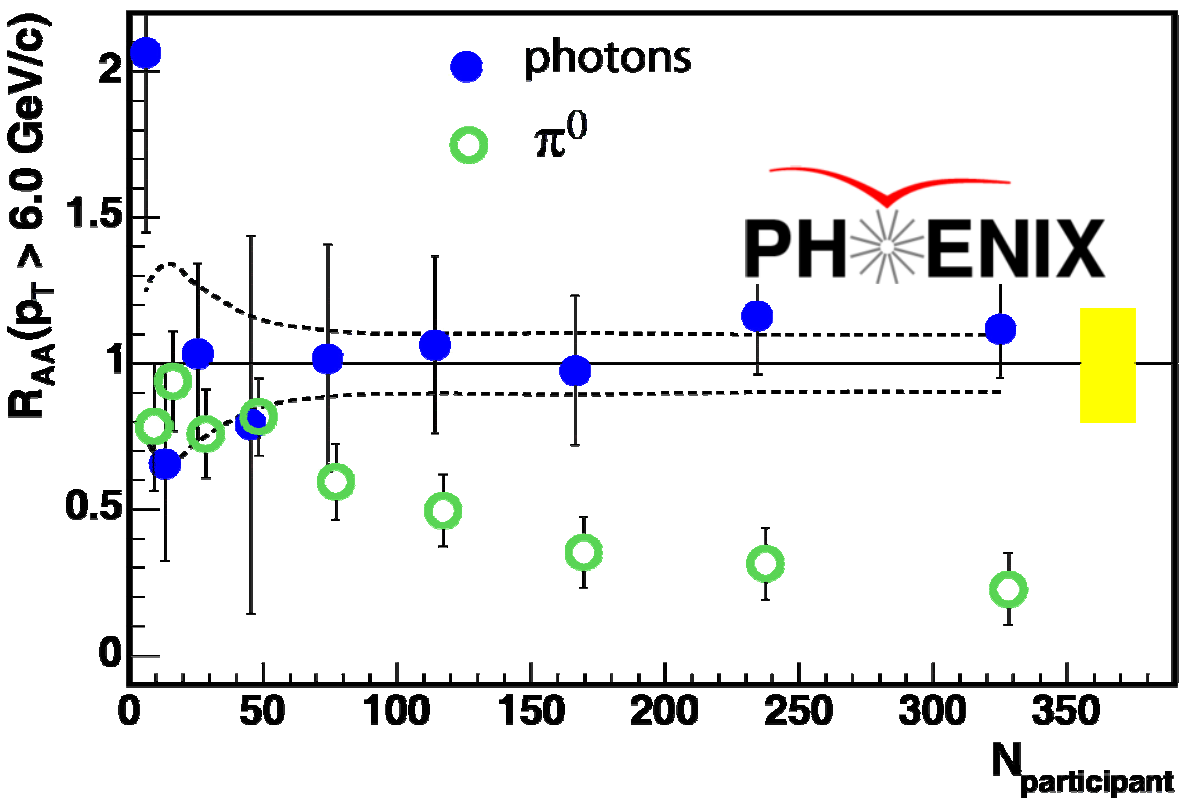
- » Only interact electromagnetically
- » No interaction with medium

Observation:

- » N_{Coll} scaling relative to pQCD calculation is consistent with data within errors.



Comparing to π^0's

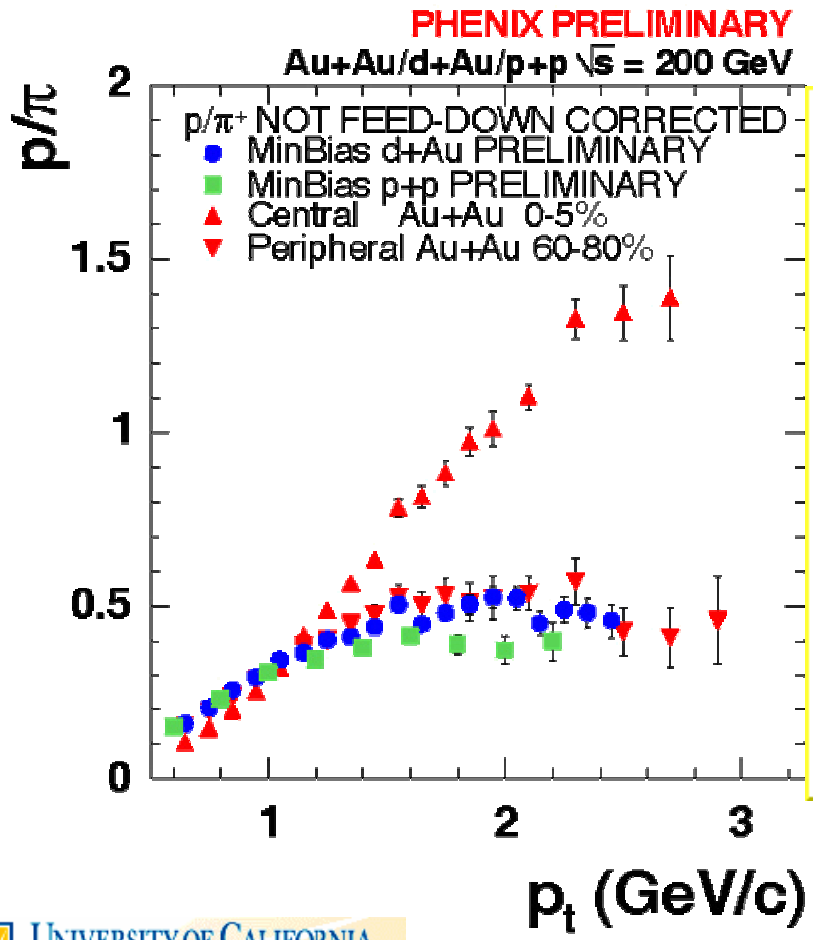


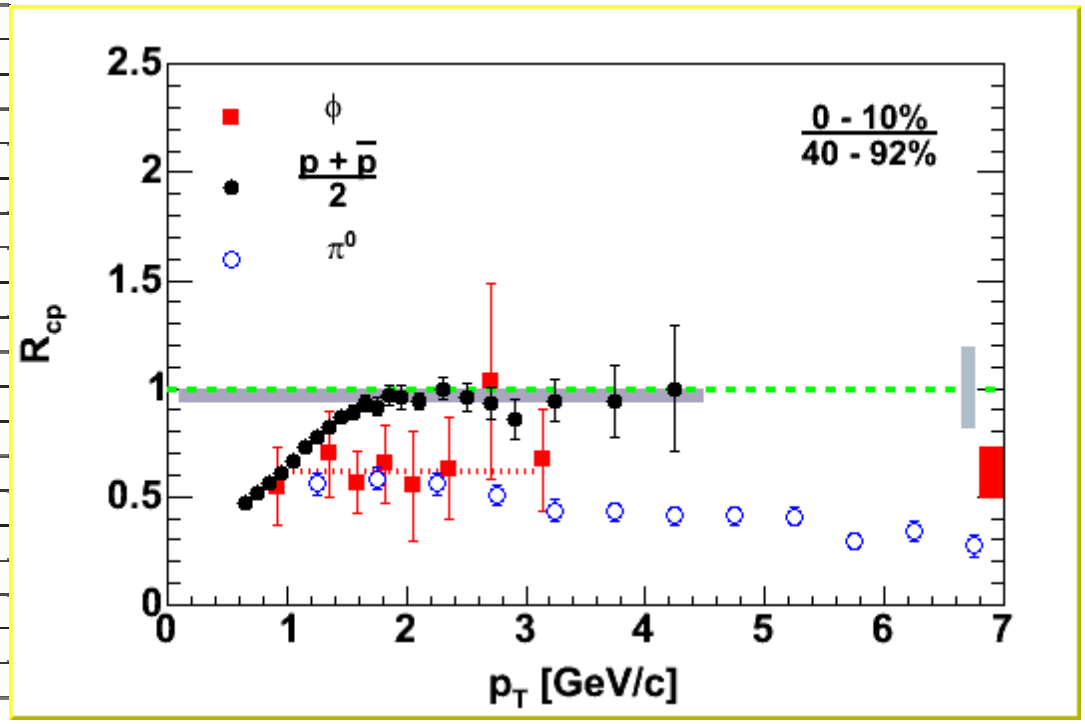
- π^0's suppressed going to central collisions
- Direct photons consistent with N_{coll} scaling
- π^0 suppression caused by medium created in A+A collisions

Baryons Are Different

p/π ratio in central Au+Au substantially in excess of expectations from jet fragmentation (~.25 at high p_T).

Baryons are not suppressed, mesons are.





Recombination

The (normal) *in vacuo* fragmentation of a high momentum quark to produce hadrons *competes* with the (new) *in medium* recombination of lower momentum quarks to produce hadrons

Example:

» Fragmentation: $D_{q\to h}(z)$
  – produces a 6 GeV/c π from a 10 GeV/c quark

» Recombination:
  – produces a 6 GeV/c π from *two* 3 GeV/c quarks
  – produces a 6 GeV/c proton from *three* 2 GeV/c quarks

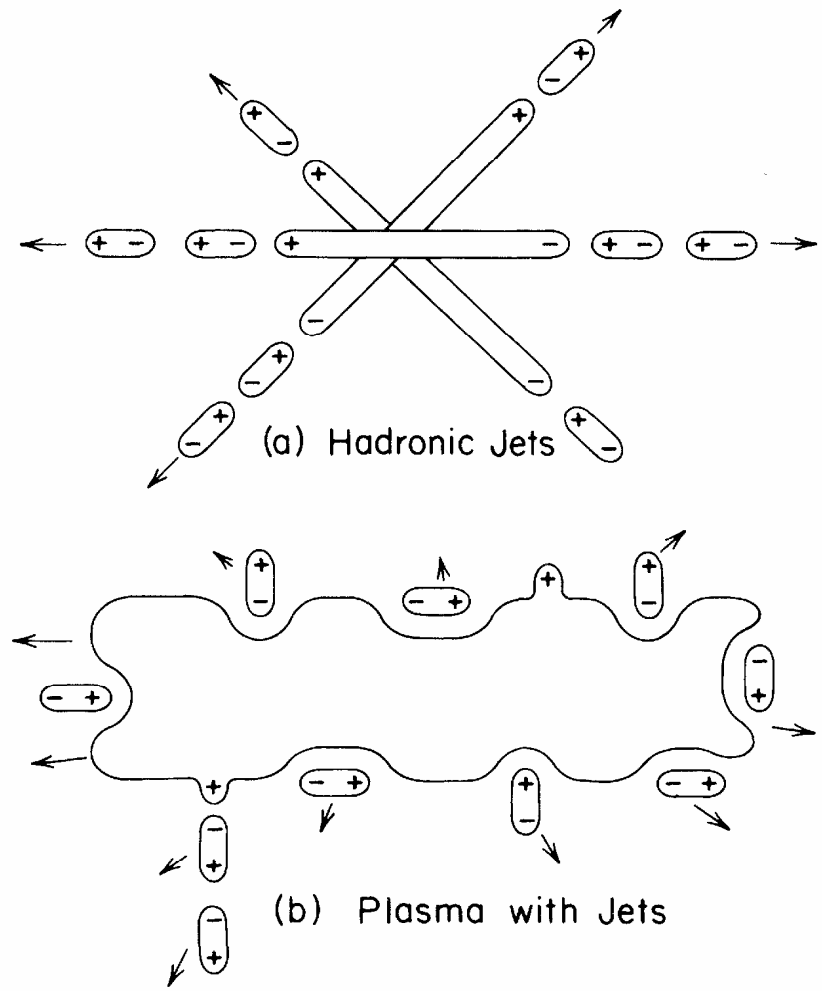
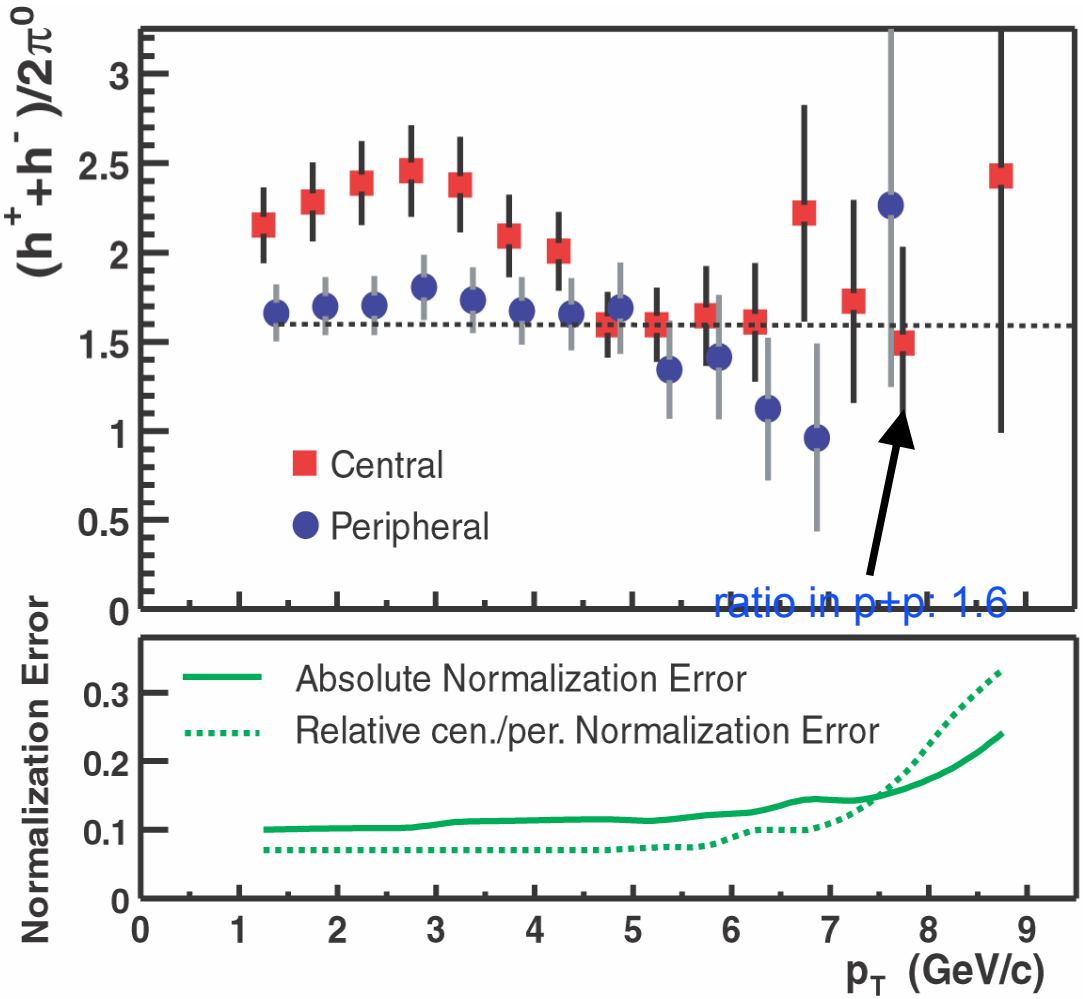


FIG. 1. Schematic conception of contrasting hadronization mechanisms for (a) a superposition of hadronic jets and (b) a plasma with a jet caused by a fast quark escaping.

Lepez, Parikh, Siemens, PRL 53 (1984) 1216

Charged Hadron / π^0



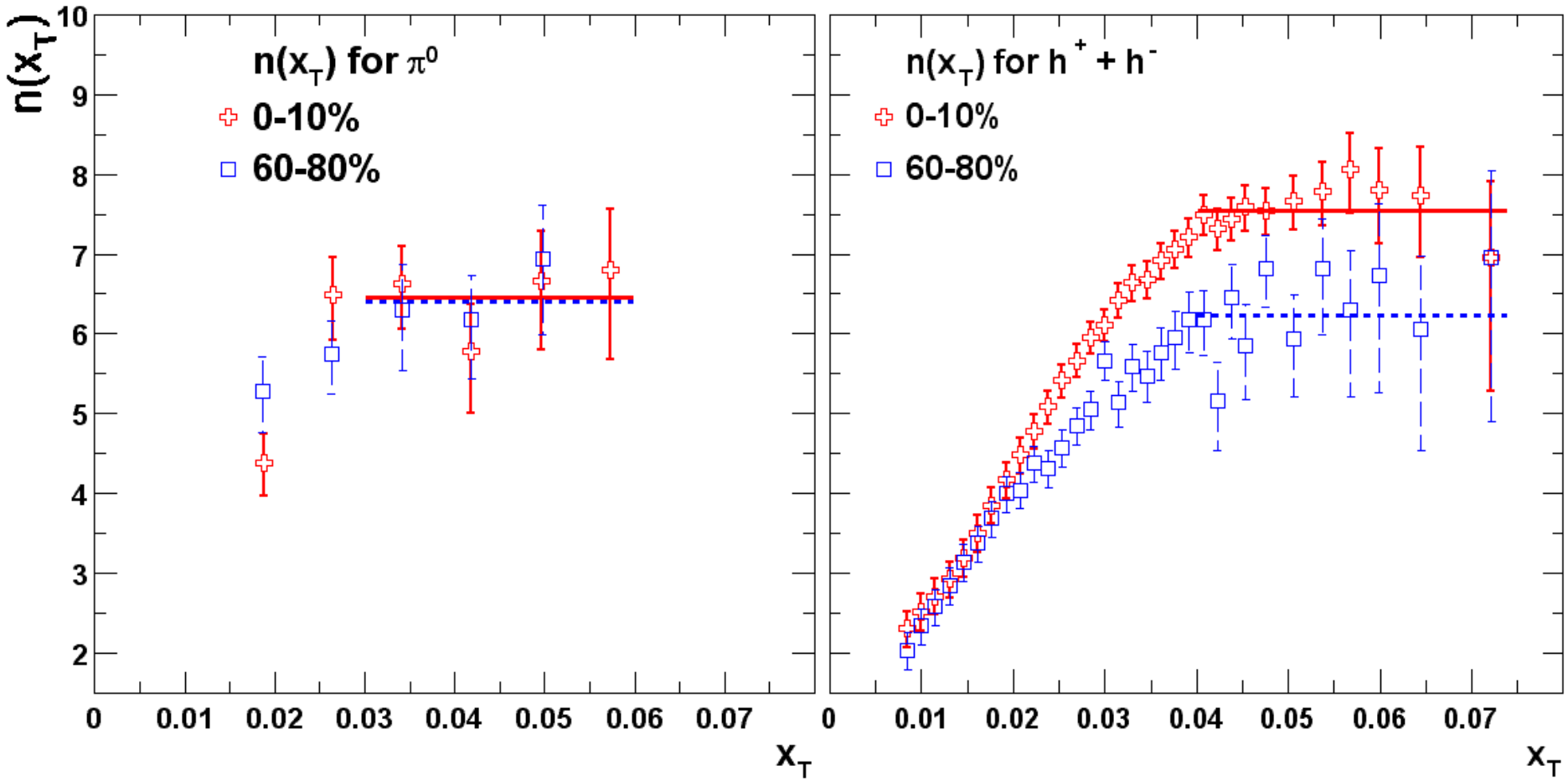
Unidentified charged hadrons can be measured up to p_T = 9 GeV/*c*

Ratio above 5 GeV/c similar for

- » *central Au+Au*
- » *peripheral Au+Au*
- » *p+p*

This implies that p/π ratio goes back to "normal" value at high p_T

x_T scaling in Au+Au

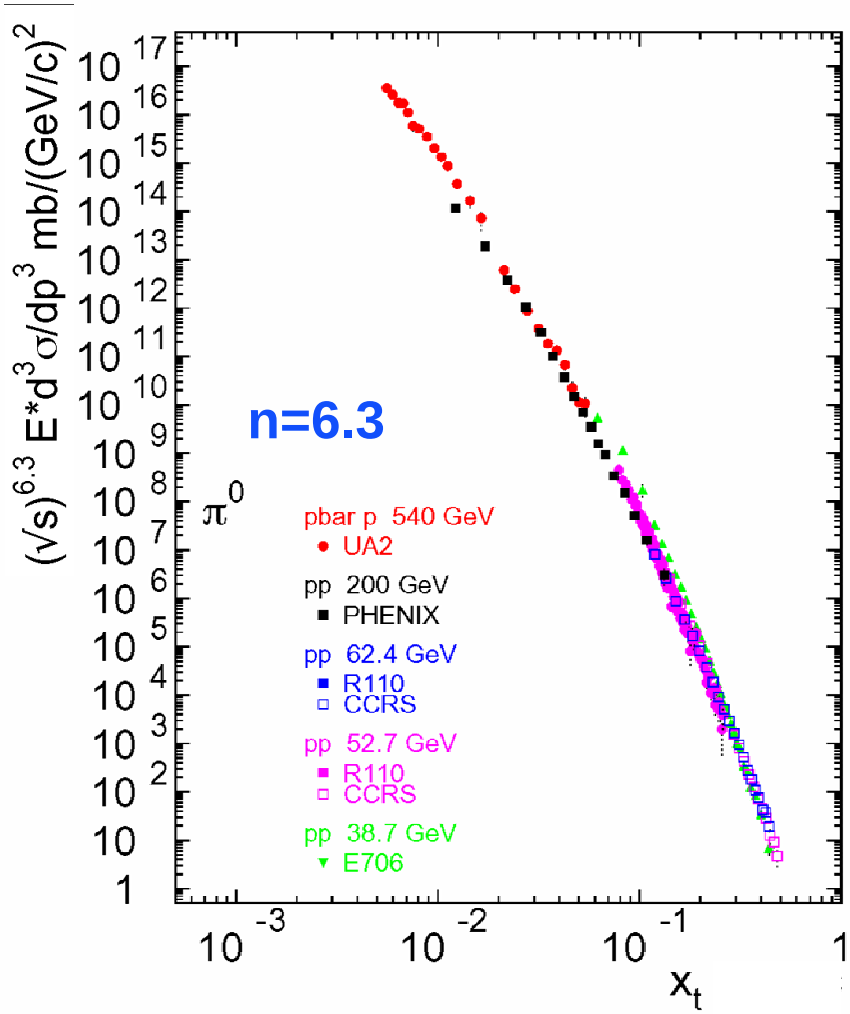


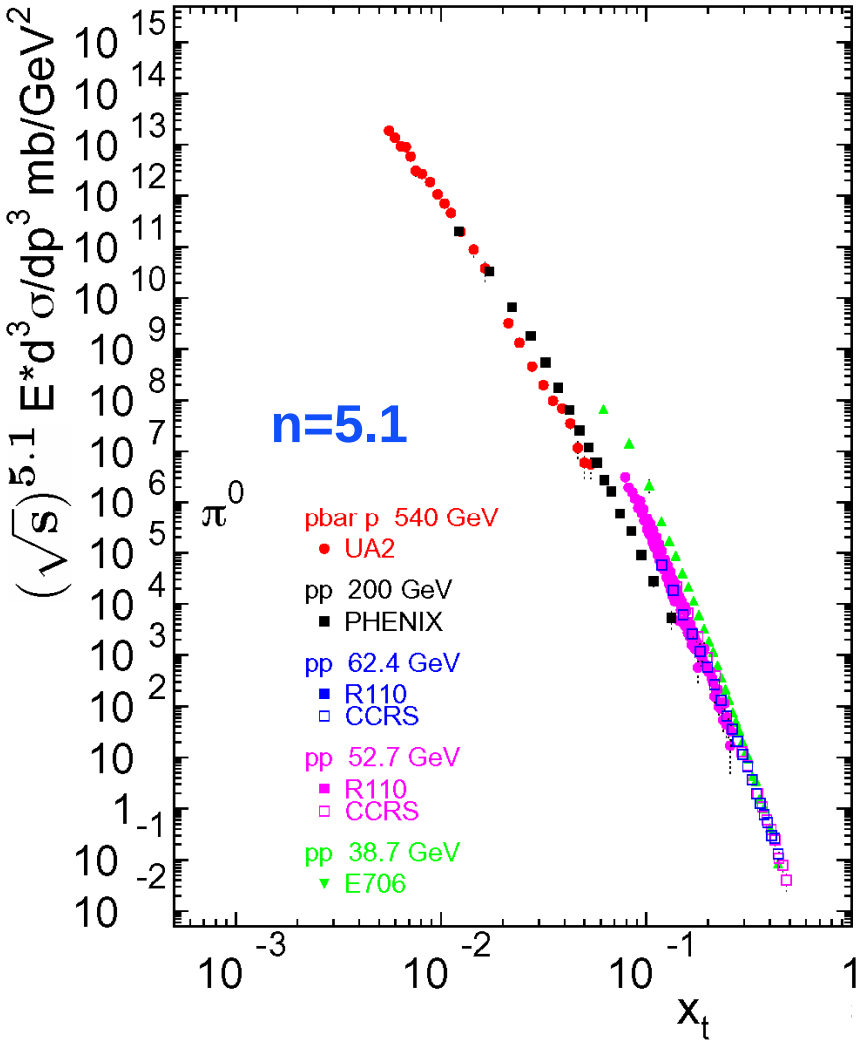
- π^0 x_T scales in peripheral and central Au+Au with same value of n=6.3 as in p-p
- $(h^+ + h^-)/2$ x_T scales in peripheral same as p-p but difference between central and peripheral is significant

Summary and Outlook

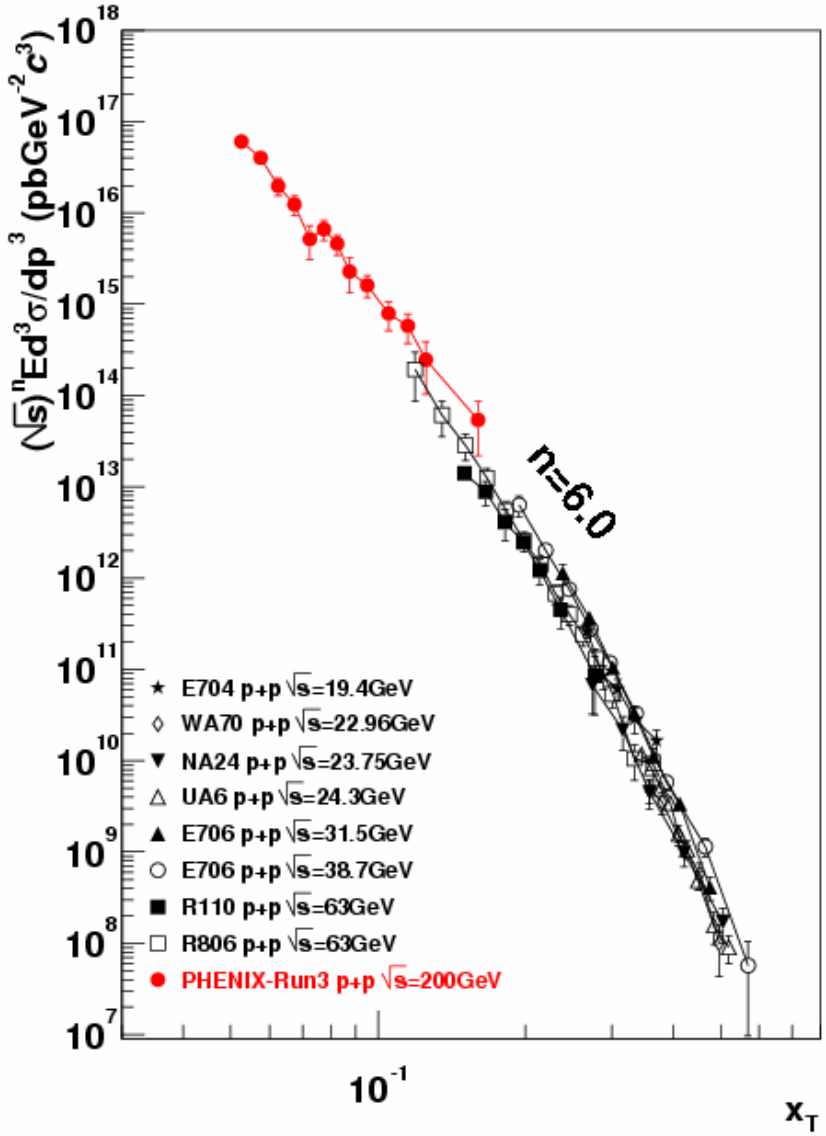
- pQCD calculations are consistent with our measured cross sections.
  - Provides foundations for spin and heavy-ion program
- The longitudinal spin program is well under way
- High p_T particles are sensitive probes of the produced media in Au+Au collisions.
- Starting with this years p+p run we will have far more statistics.
- Running at additional energies is foreseen.
- PHENIX plans upgrades that will enhance this physics: a nose-cone calorimeter will allow measurements η~3, muon trigger will facilitate our W measurements, and a silicon tracker will enhance our heavy-flavor program.

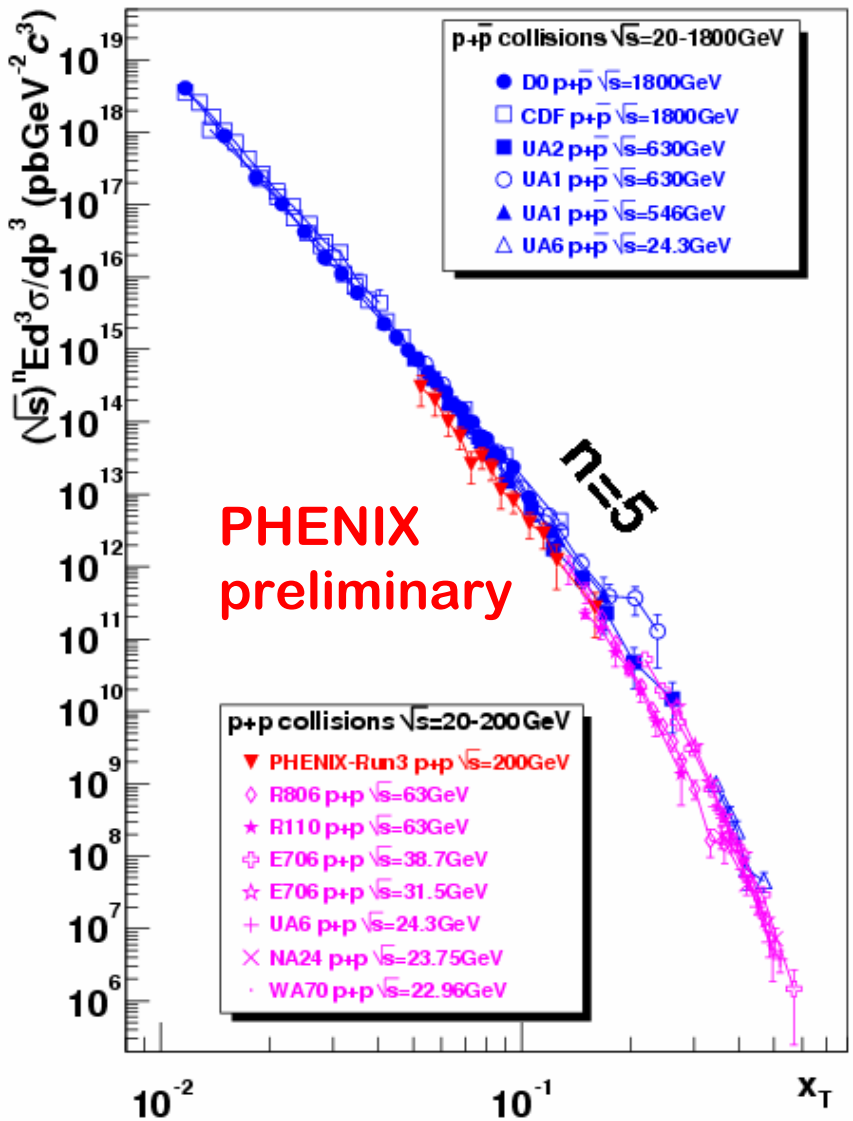
n=5.1 works better for $x_T > 0.2$



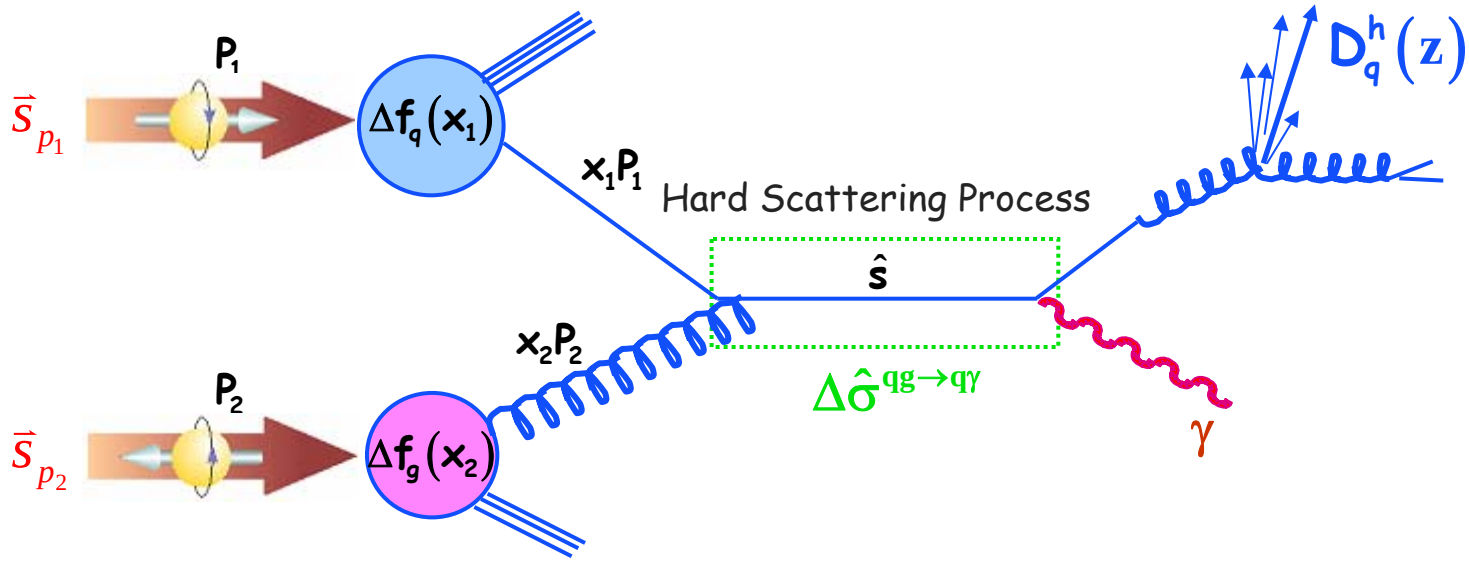


x_T scaling of direct γ in p+p





Scattering processes in polarized p+p

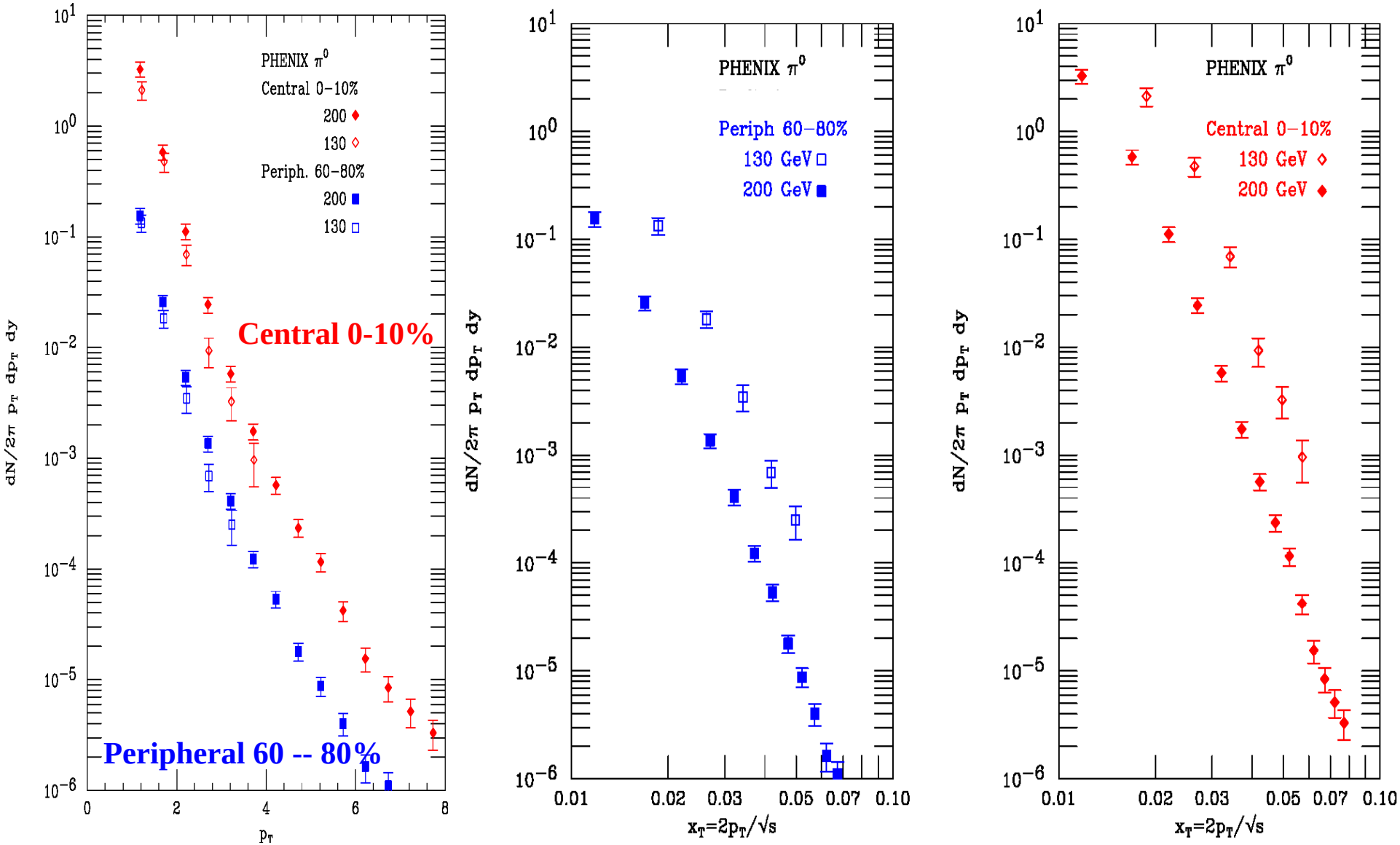


$$\Delta\sigma(pp \to \gamma X) \sim \Delta f_q(x_1) \otimes \Delta f_g(x_2) \otimes \Delta\hat{\sigma}^{qg\to q\gamma}(\hat{s})$$

$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \equiv \frac{\Delta\sigma}{\sigma} = \hat{a}_{LL}(qg \to q\gamma) \otimes \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta q(x_2)}{q(x_2)}$$

$\Delta\hat{\sigma}/\hat{\sigma}$

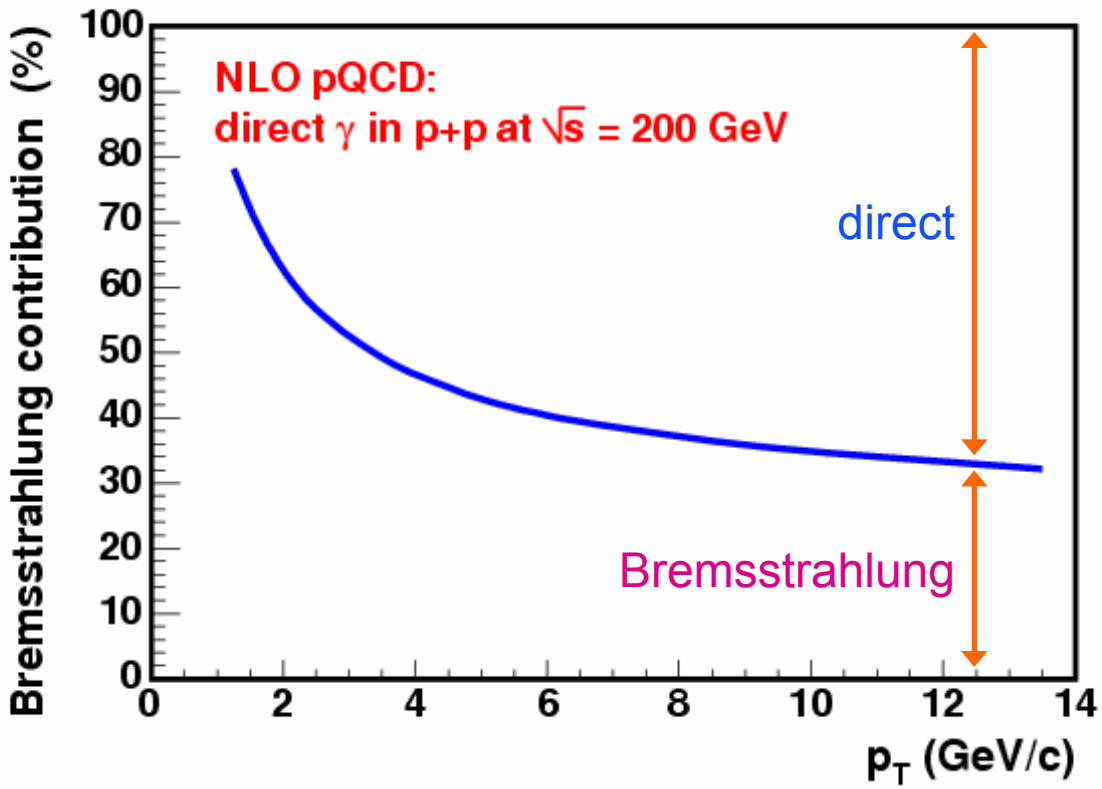
Semi-Inclusive π_0 Au+Au



S.S.Adler, et al, PRC **69**, 034910 (2004)

What about Photon Bremsstrahlung in A+A ?

calculation by W. Vogelsang

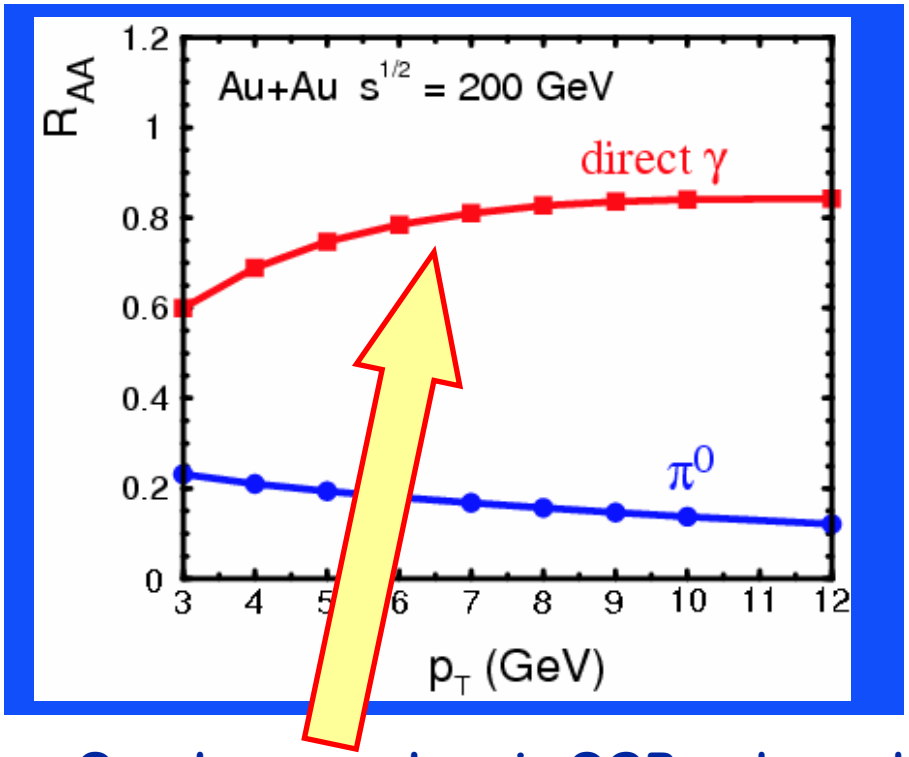


Bremsstrahlung contribution large

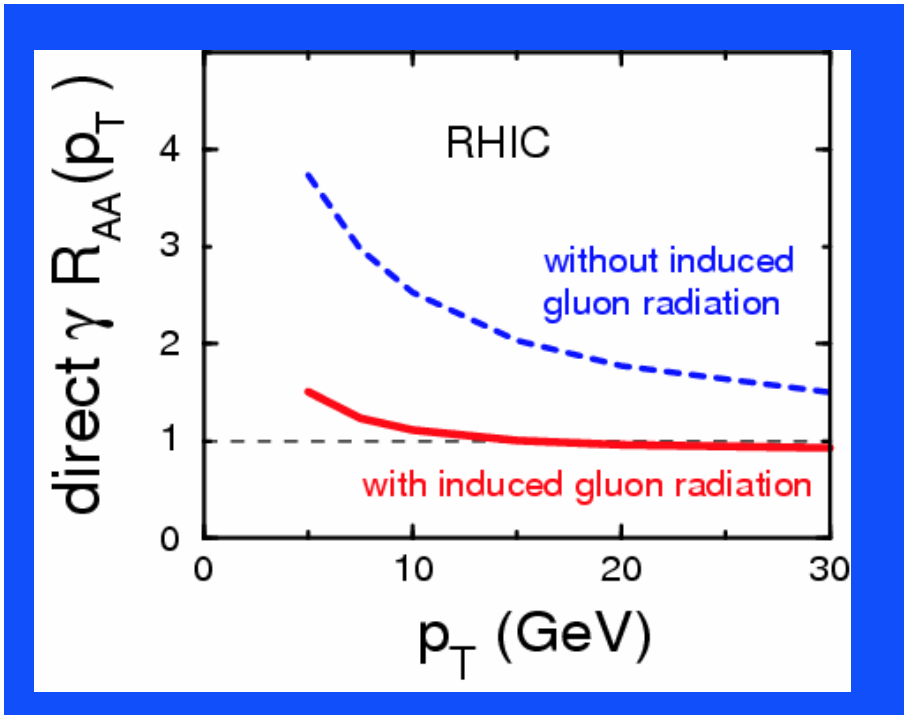
Modification of Bremsstrahlung contribution expected in A+A

Bremsstrahlung Contribution in A+A

Jeon, Jalilian-Marian, Sarcevic,
Nucl. Phys. A 715, 795 (2003)



Zakharov, hep-ph/0405101



Quark energy loss in QGP reduces bremsstrahlung contribution in A+A

However, this is compensated by induced photon bremsstrahlung in QGP (according to Zakharov)

Net result: direct photon $R_{AA} \geq 1$ at high p_T