A_{LL} of π^0 and Direct Photon Cross Section Measurements at PHENIX

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5th Circum-Pan-Pacific Symposium on High Energy Spin Physics

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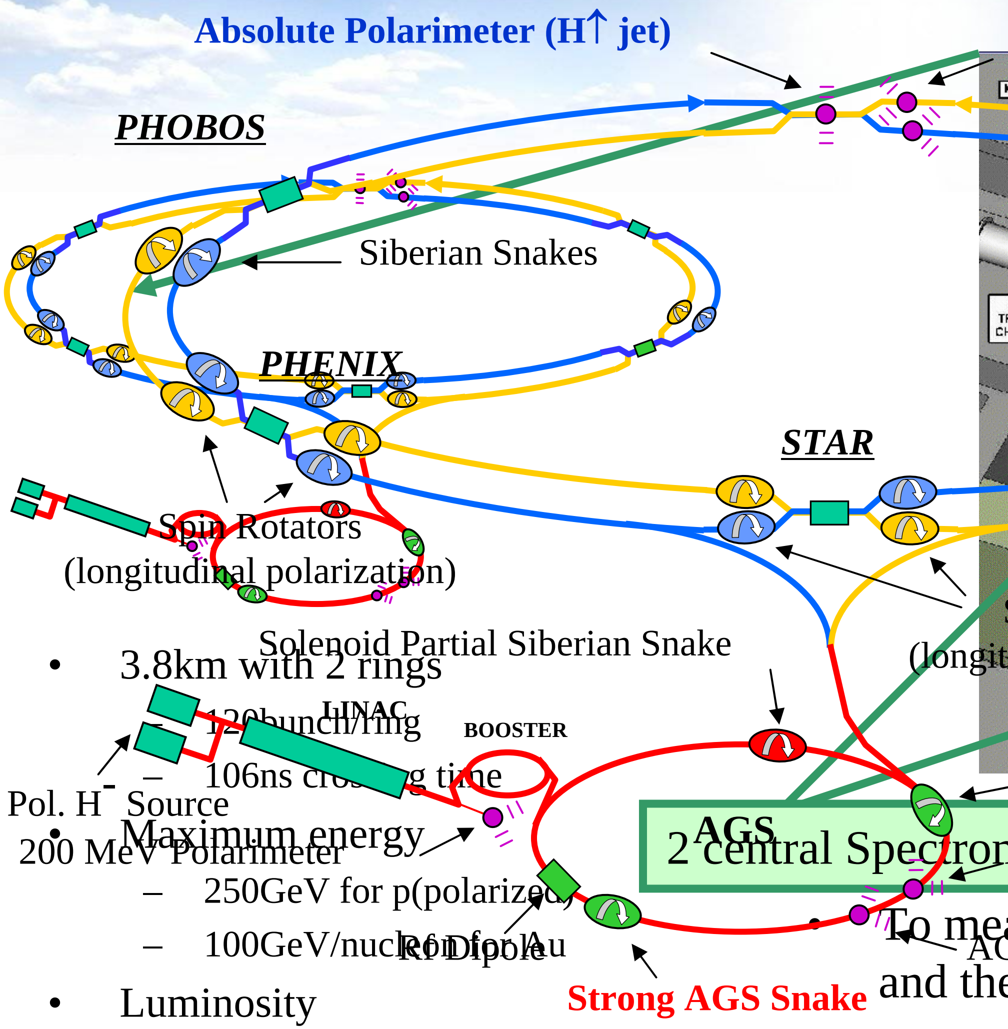
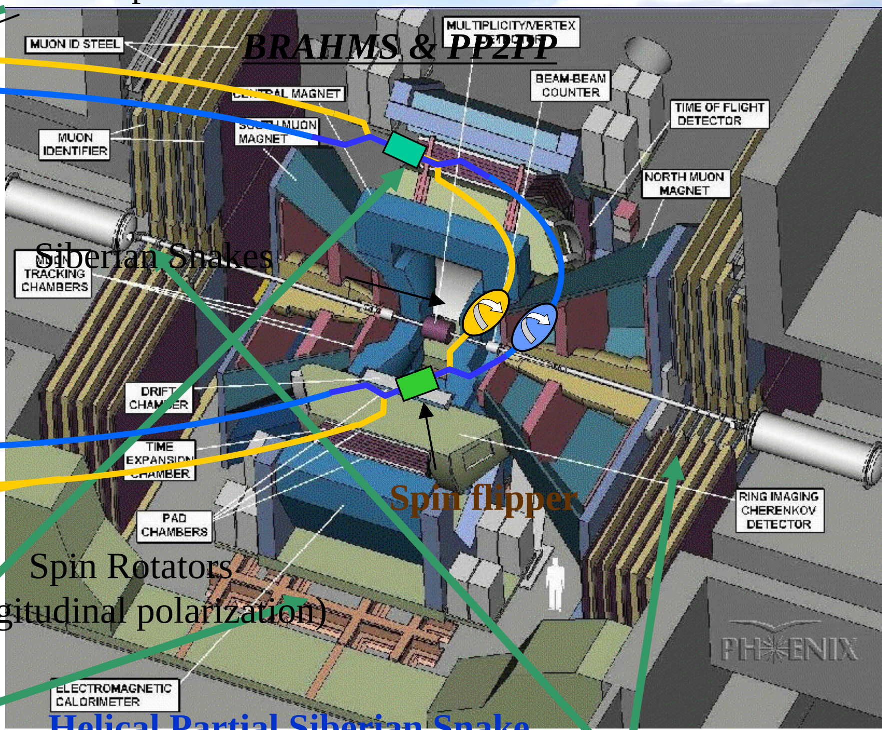
Outlines

- Experiment
  - PHENIX
  - Electro Magnetic Calorimeter
- Analysis and Results
  - A_{LL} of π^0
  - Direct photon cross section
- Conclusion

RHIC spin @ BNL

PHENIX





- 3.8km with 2 rings
  - 120bunch/ring
  - 106ns crossing time
- Maximum energy
  - 250GeV for p(polarized)
  - 100GeV/nucleon for Au
- Luminosity
  - Au-Au : 2 x 10^{26}cm^{-2}s^{-2}
  - p-p : 2 x 10^{32}cm^{-2}s^{-2}
- 6 Crossing points

2 central Spectrometers

2 forward Spectrometers

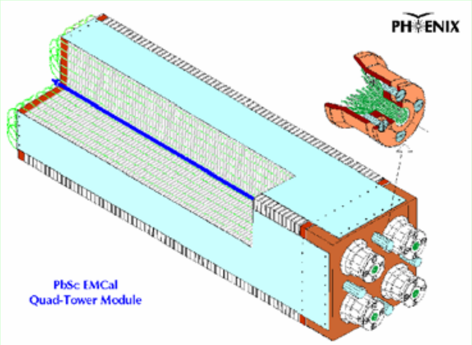
To measure the collision point, the luminosity, and the multiplicity, and transeverse polarization.

- Beam Beam Counter(BBC)
- Zero Degree Calorimeter(ZDC)
- Multiplicity and Vertex Detector(MVD)

Electro-Magnetic Calorimeter

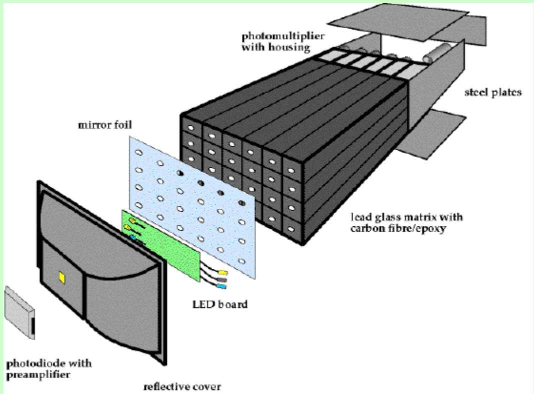
Lead Scintillator (PbSc)

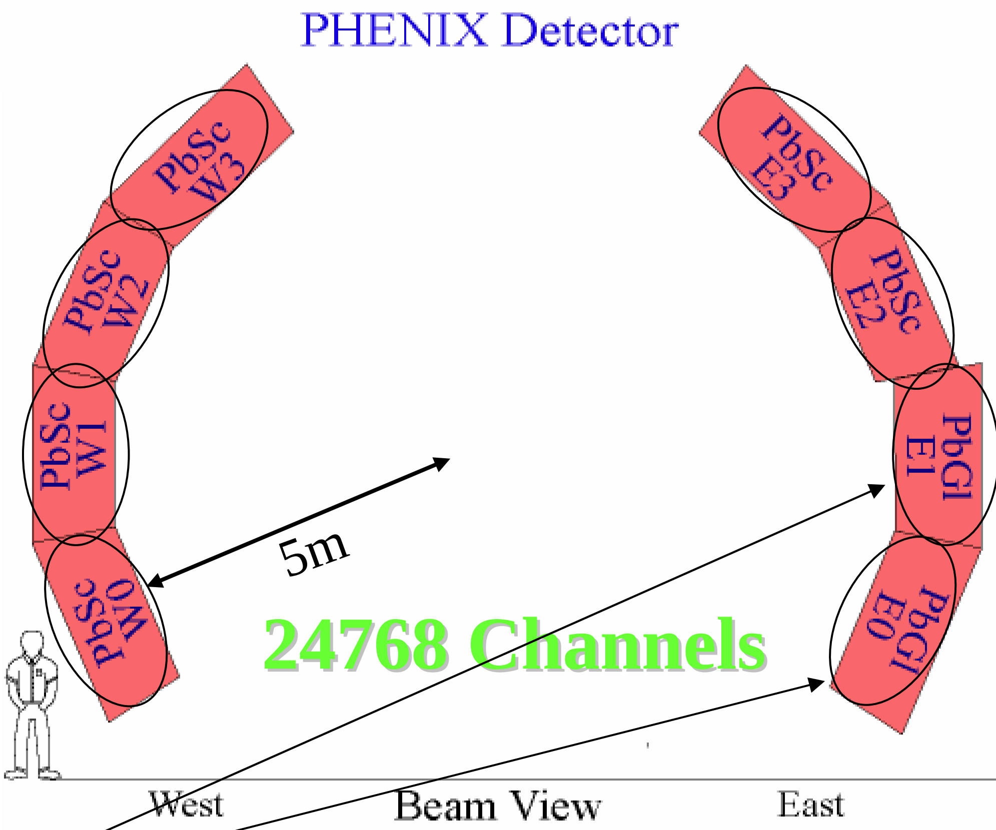
- Sandwich type calorimeter
  - Lead and scintillation plate
  - Shish-kebab type readout



Lead Glass (PbGl)

- Total reflection calorimeter





Coverage $|\eta|<0.38$ $\phi = 180°$

Fine segmented calorimeter.

distinguish two photons from $\pi 0$ photonspT~25GeV/c

History

Run	Year	Species	$s^{1/2}$ [GeV]	$\int L dt$	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
						Transverse Pol.	
		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
						Longitudinal Pol.	
		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
						Longitudinal Pol.	
		p+p	200	0.075 pb^{-1}	G	0.075 pb^{-1}	10 TB
05	2004/2005	Cu+Cu	200	? pb^{-1}	G	pb^{-1}	TB
						Longitudinal & Transverse Pol.	
		p+p	200	3.8 pb^{-1}	G	3.8 pb^{-1}	260 TB

A_{LL} of π^0

Introduction : A_{LL} of π^0

A_{LL} in π0 production

mid-rapidity |η| < 0.35, √s = 200 GeV

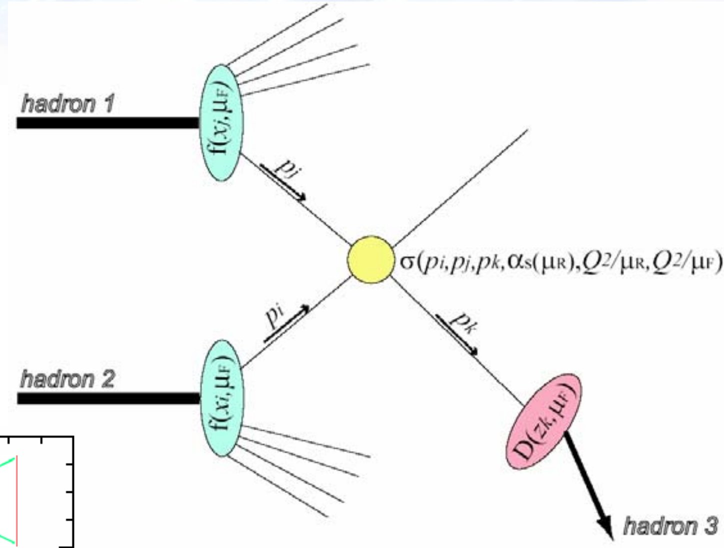
$$\sigma^{3}_{1+2} = \sum_{i,j,k} \int dx_i dx_j dx_k \times \boxed{f_1^{k}(x_k,\mu)\cdot f_2^{j}(x_j,\mu)}$$

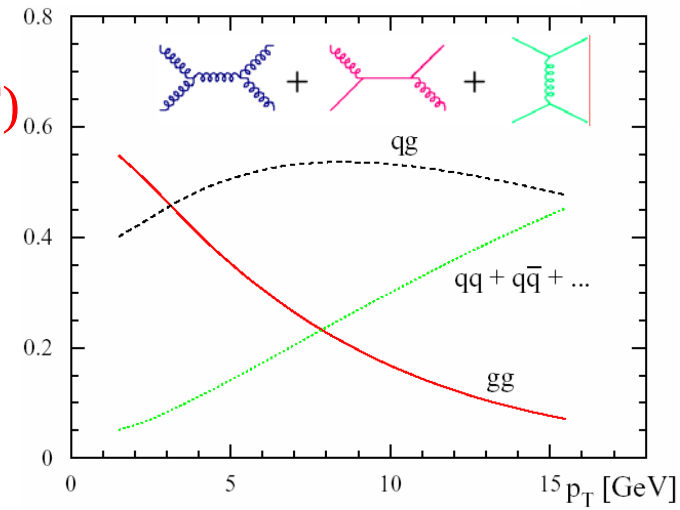
parton distribution function(PDF)

$$\times \boxed{\sigma^{k}_{i,j}\left(p_i, p_j, p_k, \alpha_s(\mu_R), Q^2/\mu_F, Q^2/\mu_F\right)}$$

$$\times \boxed{D^{3}_{k}(z_k,\mu_F)}$$

fragmentation function(FF)





gg+qg dominant at low pT

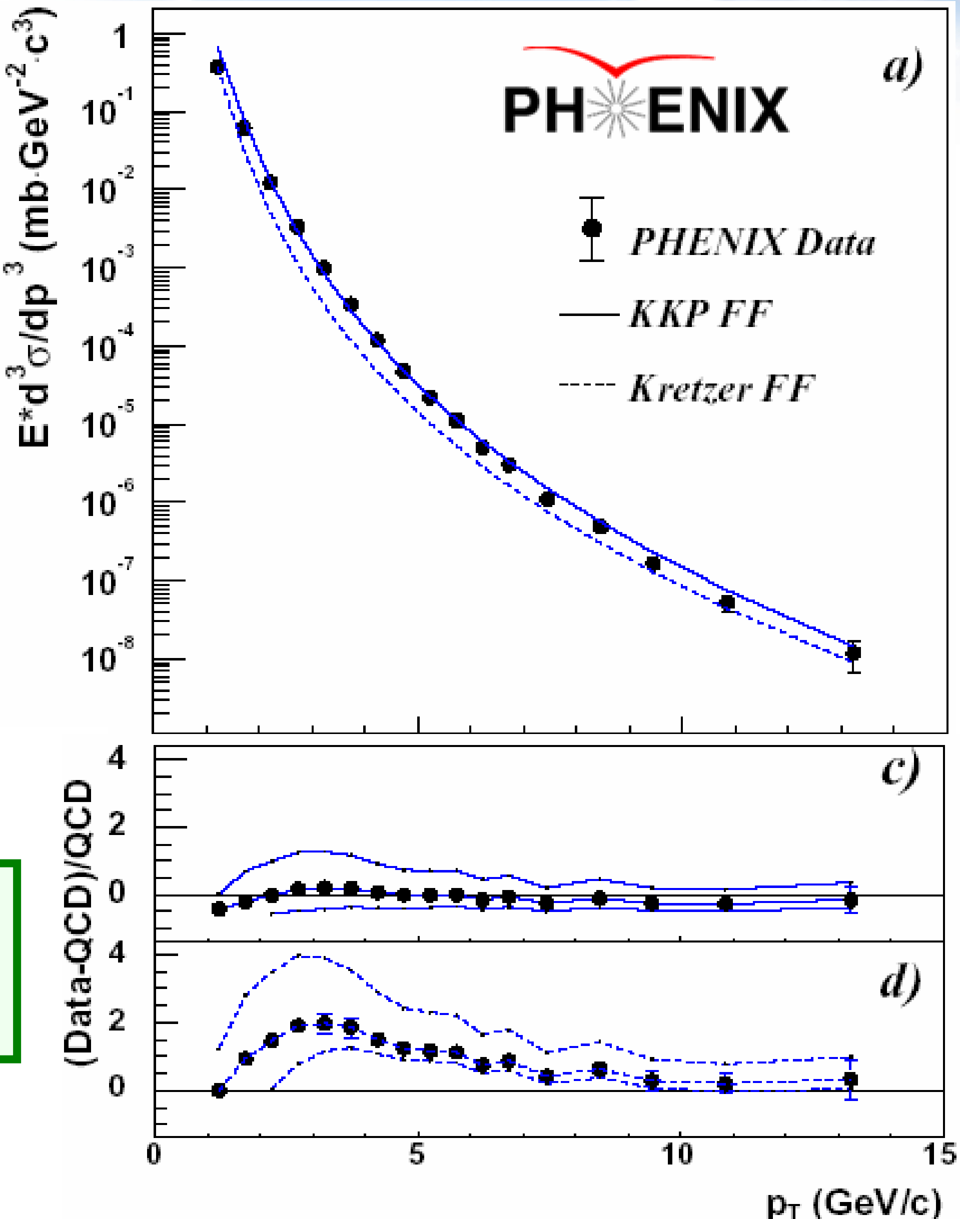
Sensitive to the gluon reaction

Cross section

- Result from run2 result
  - PRL91 (2003) 241803
- Comparison of π^0 cross section
  - Next-to-leading order(NLO) pQCD
    - CTEQ6M + KKP
    - Matrix calculation by Aversa, et. al
    - Renormalization and factorization scales are set to be equal and set to

      $1/2p_T$, p_T, $2p_T$

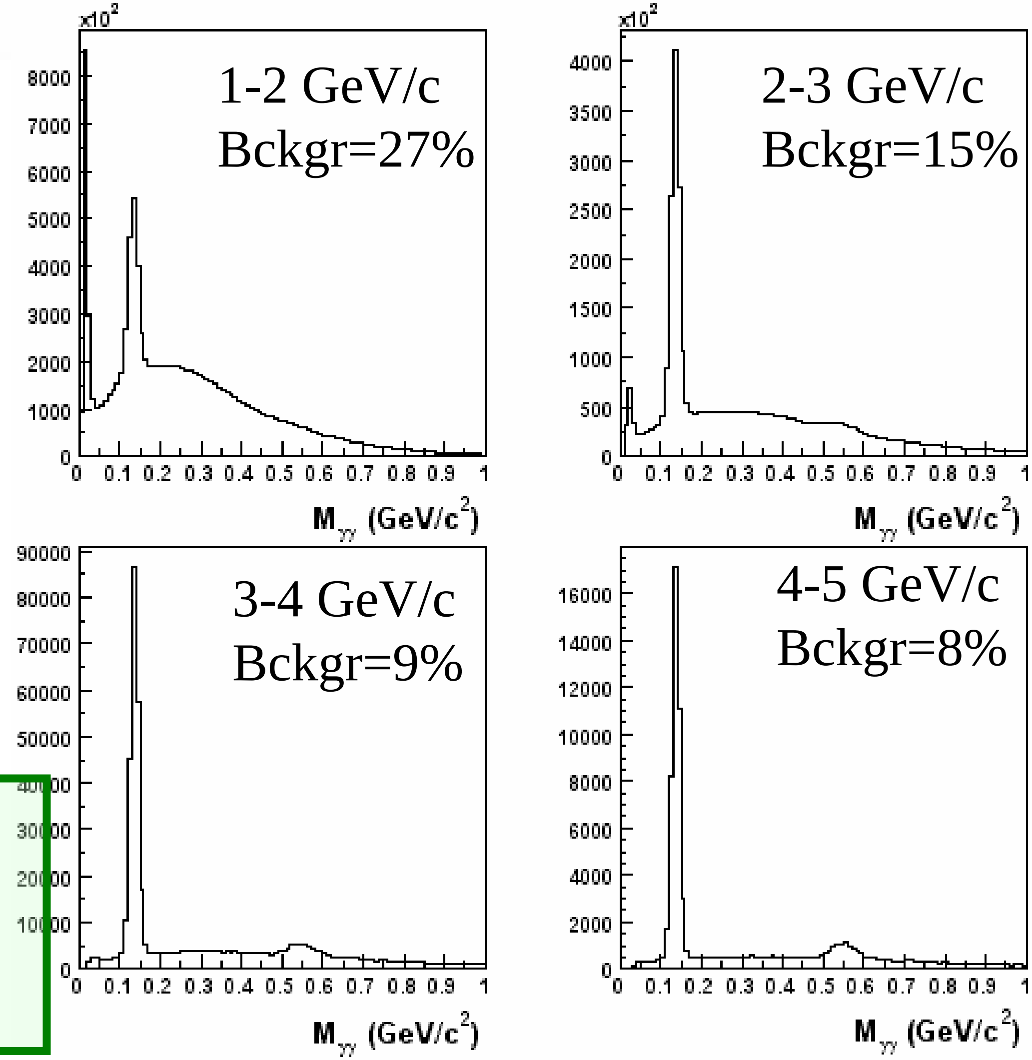
    - Calculated by W.Vogelsang



NLO-pQCD described very well down even to $p_T \sim 1$ GeV/c

π^0 reconstruction for A_{LL}

- Results obtained for four pT bins from 1 to 5 GeV/c
  - π^0 peak width is 9.5-12 MeV/c^2
  - Background contribution under π^0 peak varies from 27% to 8%
  - π^0 reconstruction efficiency varies from 84% to 93%



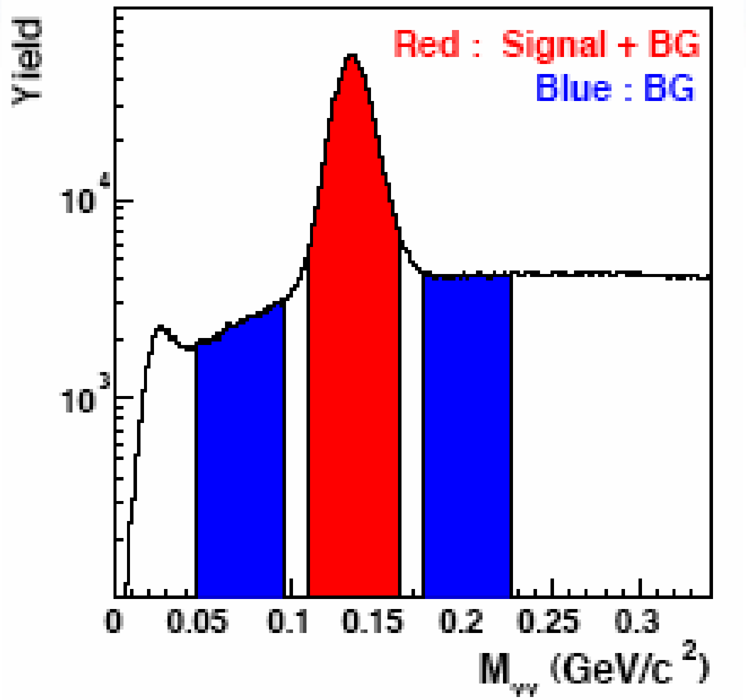
Background contribution at higher p_T is small.

➔ Still need estimate the effect

π^0 counting & background

$N_{\pi 0}$: ±25 MeV/c^2 around π^0 signal

N_{bck1}: Two 50 MeV/c^2 wide areas adjacent to π^0 peak



$N_{\pi 0}$ and N_{bck} accumulated statistics

pt GeV/c	$N_{\pi 0}$ 25 MeV/c^2	N_{bck1}
1-2	1777k	1470k
2-3	1059k	335k
3-4	201k	27k
4-5	38k	3.9k

$$A_{LL}^{\pi^0} = \frac{A_{LL}^{FG+BG} - rA_{LL}^{BG}}{1-r}$$

$$\sigma_{A_{LL}^{\pi^0}} = \frac{\sqrt{\sigma^2_{A_{LL}^{raw}} + r^2\sigma^2_{A_{LL}^{BG}}}}{1-r}$$

r = normalized counts of background [(red)/(blue)]

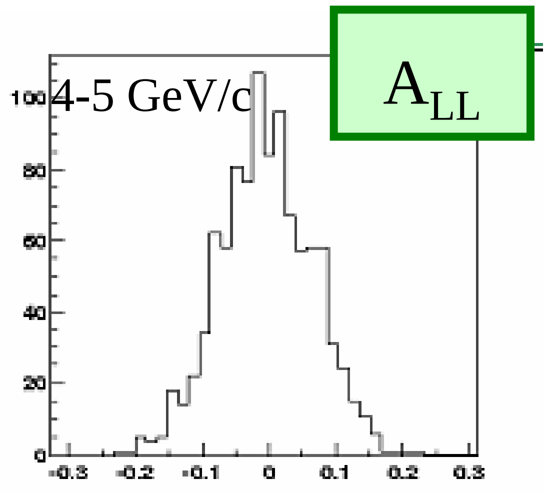
A_{LL} & Systematic Studies

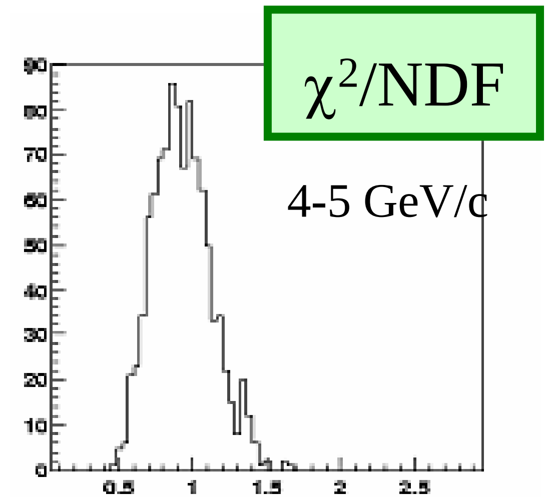
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{|P_B P_Y|} \frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$

++ same helicity
+– opposite helicity

$$\delta_{A_{LL}} = \frac{1}{|P_B P_Y|} \frac{1}{\sqrt{N_{++} + N_{+-}}}$$

Bunch shuffling = Randomly assigns helicity for each crossing





Widths are consistent with obtained errors $\delta(A_{LL})$

All $\langle\chi^2/NDF\rangle$ from beam bunchs are ~1

Comparison with theory

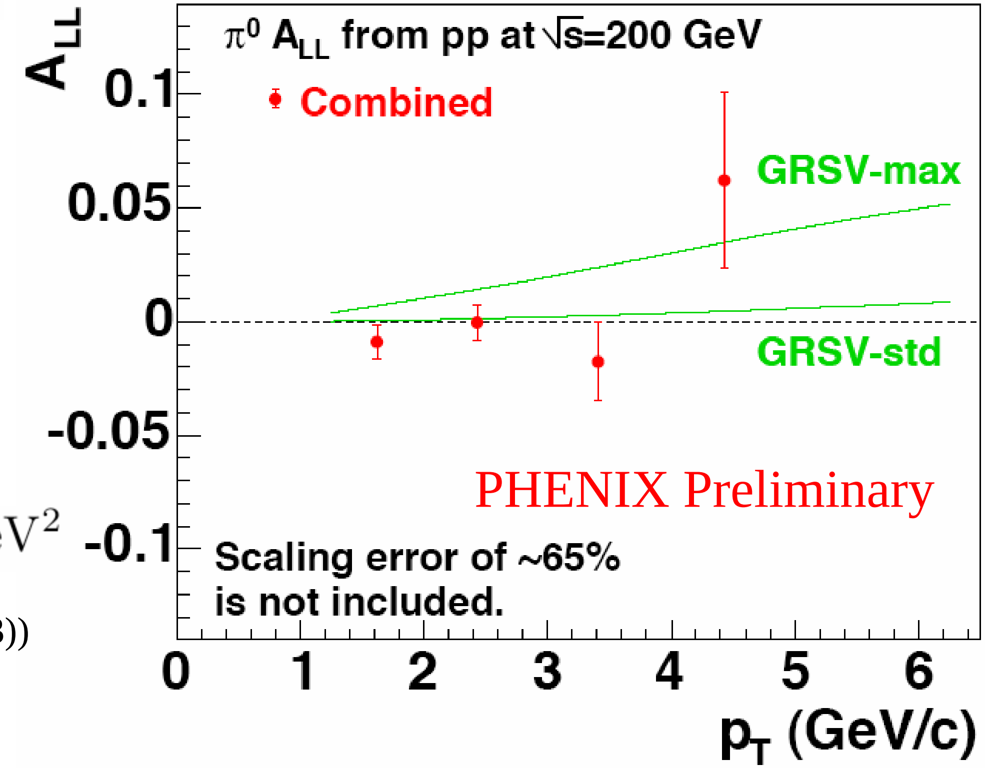
- GRSV-std:
  - best fit to DIS data

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

- GRSV-max

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

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

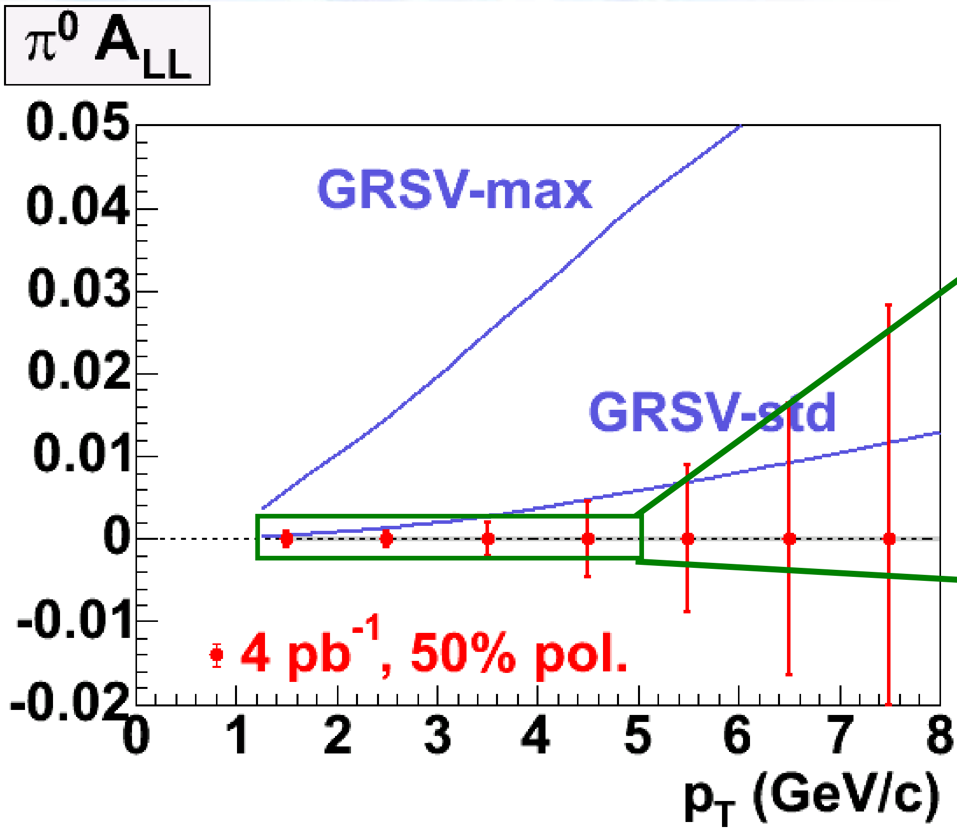


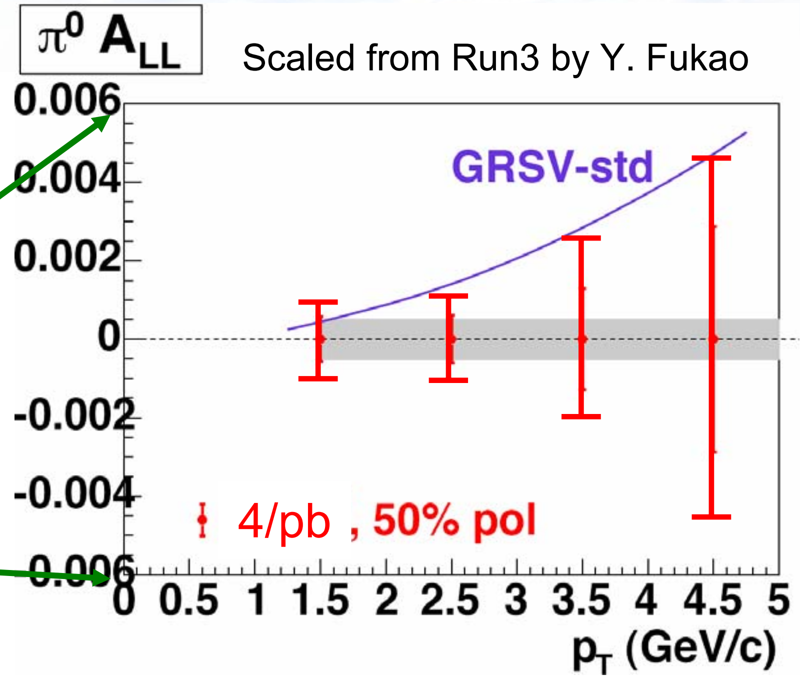
	GRSV-std	GRSV-max
4 points (1-5 GeV/c)	21-24%	0.00-6%
3 points (2-5 GeV/c)	27-29%	0.01-13%

Confidence Levels

Data prefers the GRSV-std curve

π^0 A_{LL} Expectations from Run05





Run05 will distinguish between
GRSV-std and $\Delta G = 0$ (or GRSV-min).

Direct Photon Production

Prompt Photon Production

Prompt photon production consists of two processes

$$\sigma = \sigma_{dir} + \sigma_{frag} = \sum_{i,j,k} \int dx_i dx_j \times \boxed{f_1^i(x_i,\mu) \cdot f_2^j(x_j,\mu)}$$

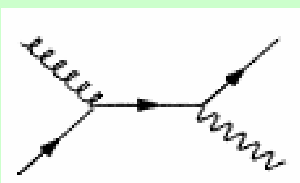
parton distribution function(PDF)

fragmentation function(FF)

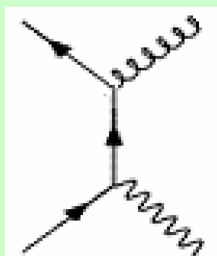
$$\times \left\{ \boxed{\sigma(i + j \to \gamma)} + \int dz \boxed{\sigma(i + j \to k)} \times \boxed{D_k^3(z_k, \mu_F)} \right\}$$

Direct Process

Bremsstrahlung Process



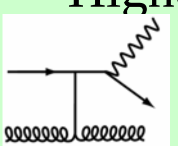
compton

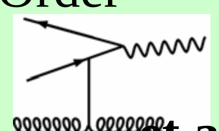


annihillation

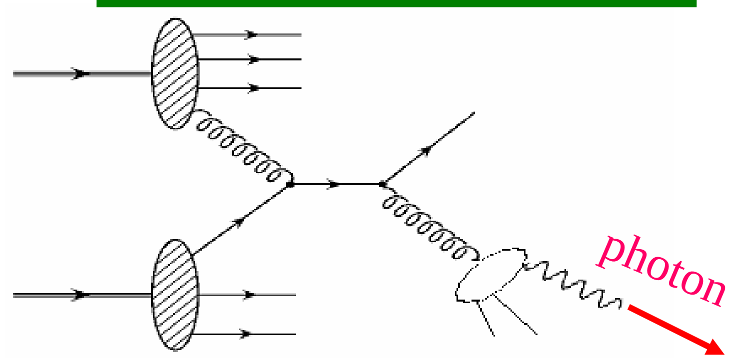
+

Higher Order





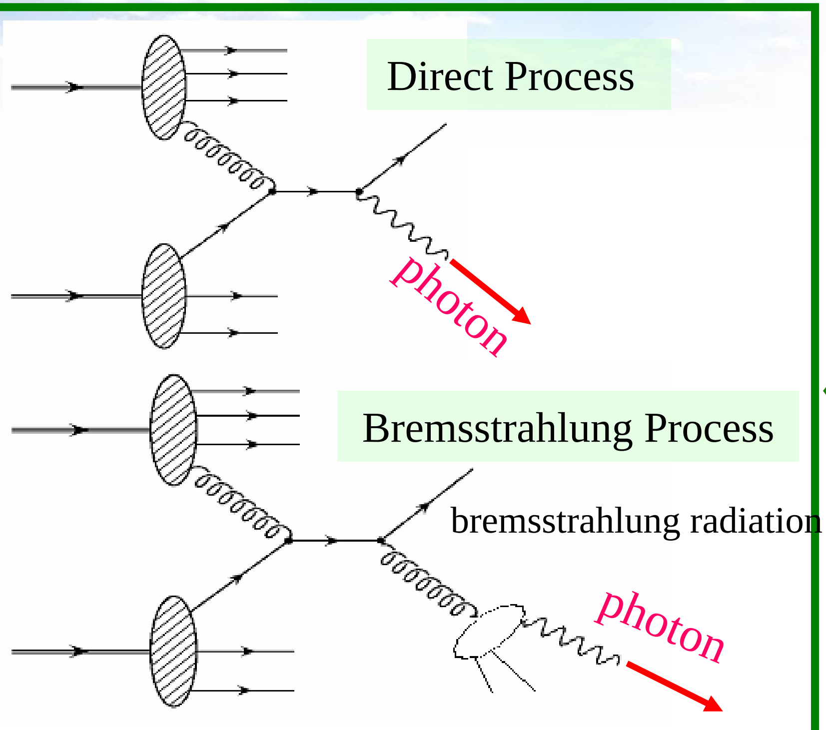
et.al.



gluon compton process dominant ~75%

➔ Sensitive to the gluon polarization.

How to Measure?



No one know which photon from what.

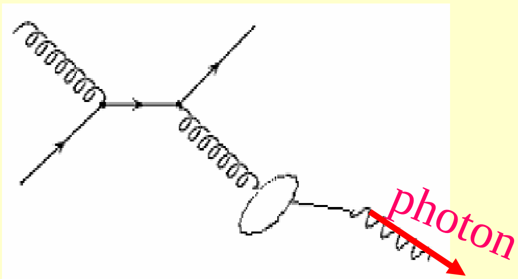
Background

Non-vertex Photon

Neutral hadron contribution

Noise in the detector

Hadron(π^0,η,ω..) decay

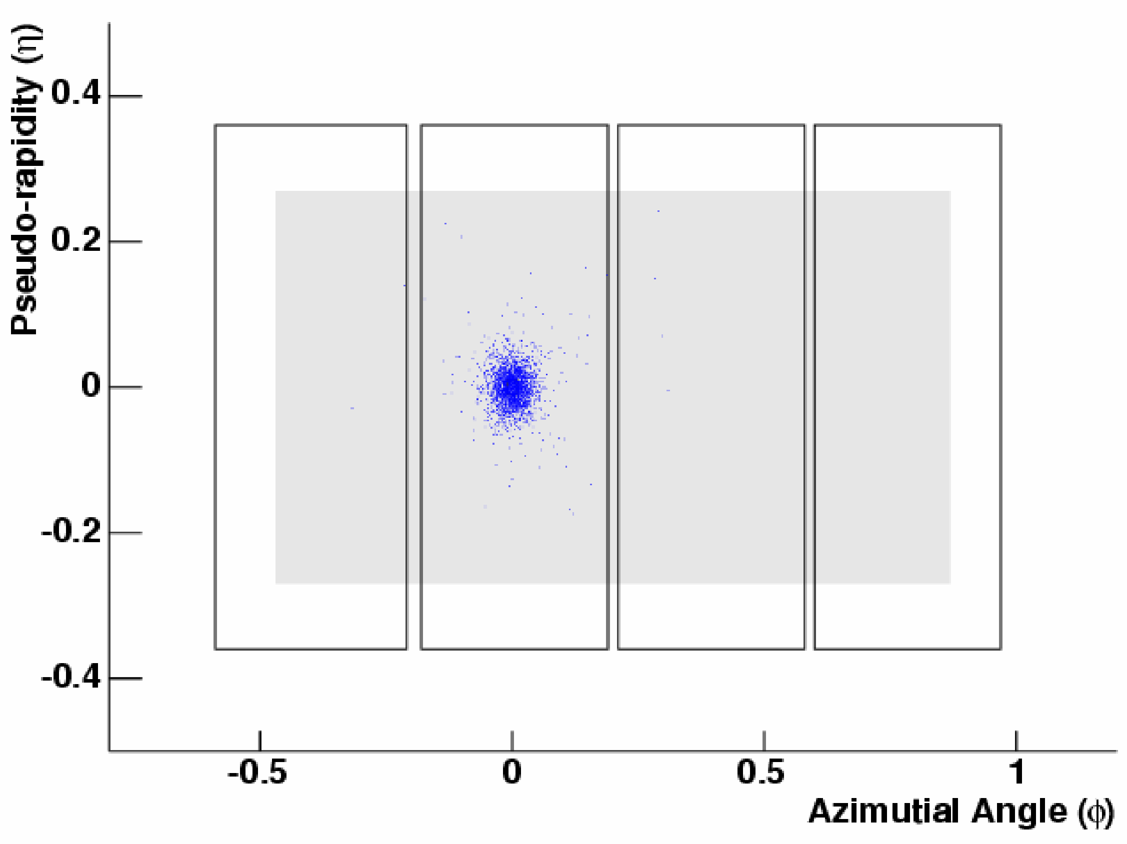


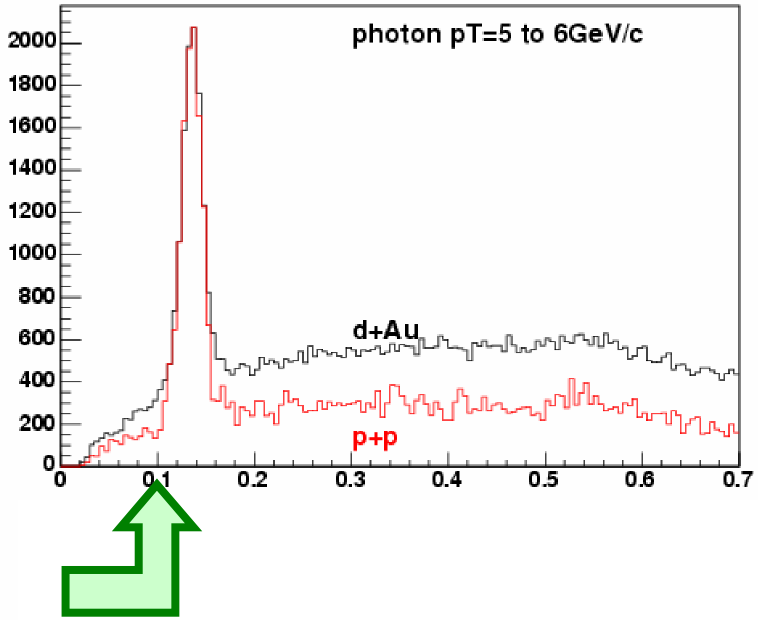
Estimate all backgrounds

After subtracting all backgrounds,

the remained photons are the signals.

Background from π^0

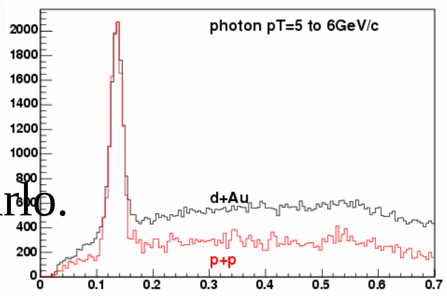




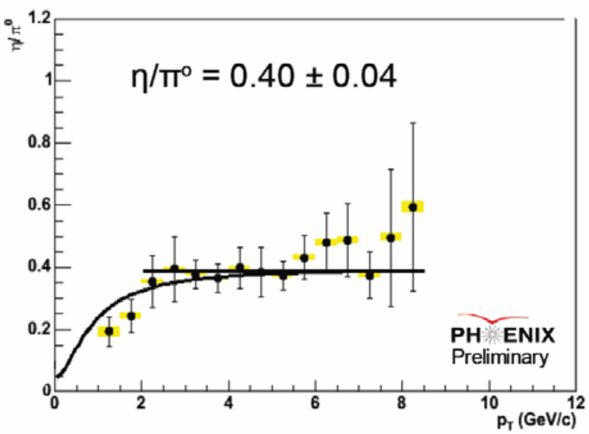
By taking all combination between the target photon and the surrounding photons, we can know the photon from pi0 decay.

➔ 70% of pi0 decay can be identified from the mass distribution

Background Subtraction

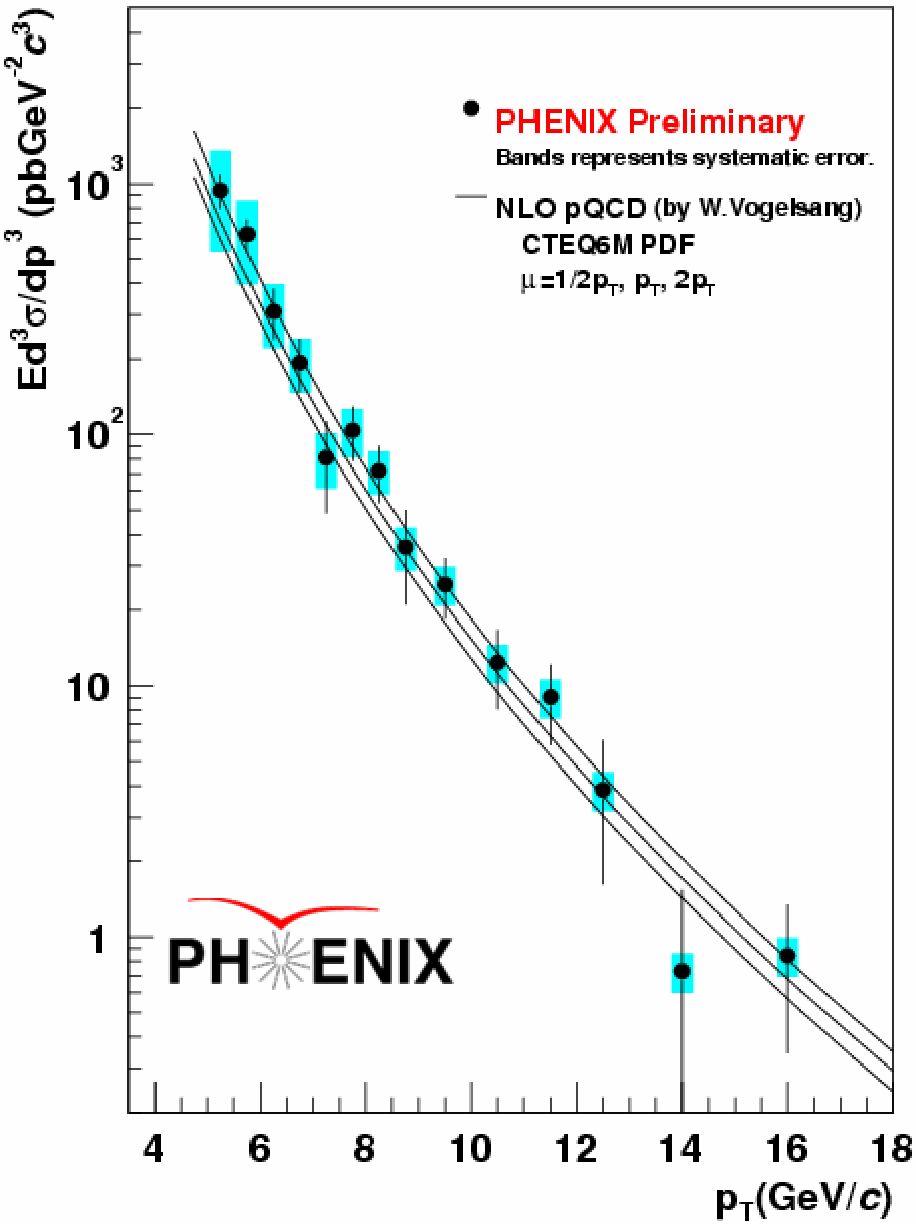


- Background photon from Identified π^0
  - π^0 mass distribution
    - The mass position and width is well discribed by the Monte Carlo.
  - All channels (as defined as healthy) are working properly。
    - No π^0 is miss-identified.
  - Systematic error in estimate of combinatorial background is small(3%)
- Background photon from π^0 going to out of our fiducial area.
  - Estimated by Monte Carlo simulation
    - Systematic error due to lack of knowledge in Monte Carlo is taken an account of. The largest contribution is due to the edge of sector.
- Photon from other hadrons
  - Measurement of η/π^0 ratio at PHENIX is used.
  - Assumption of mT scaling for other hadron
- Neutral hadron and photons from non-vertex.
  - Estimated from GEANT simulation



Result

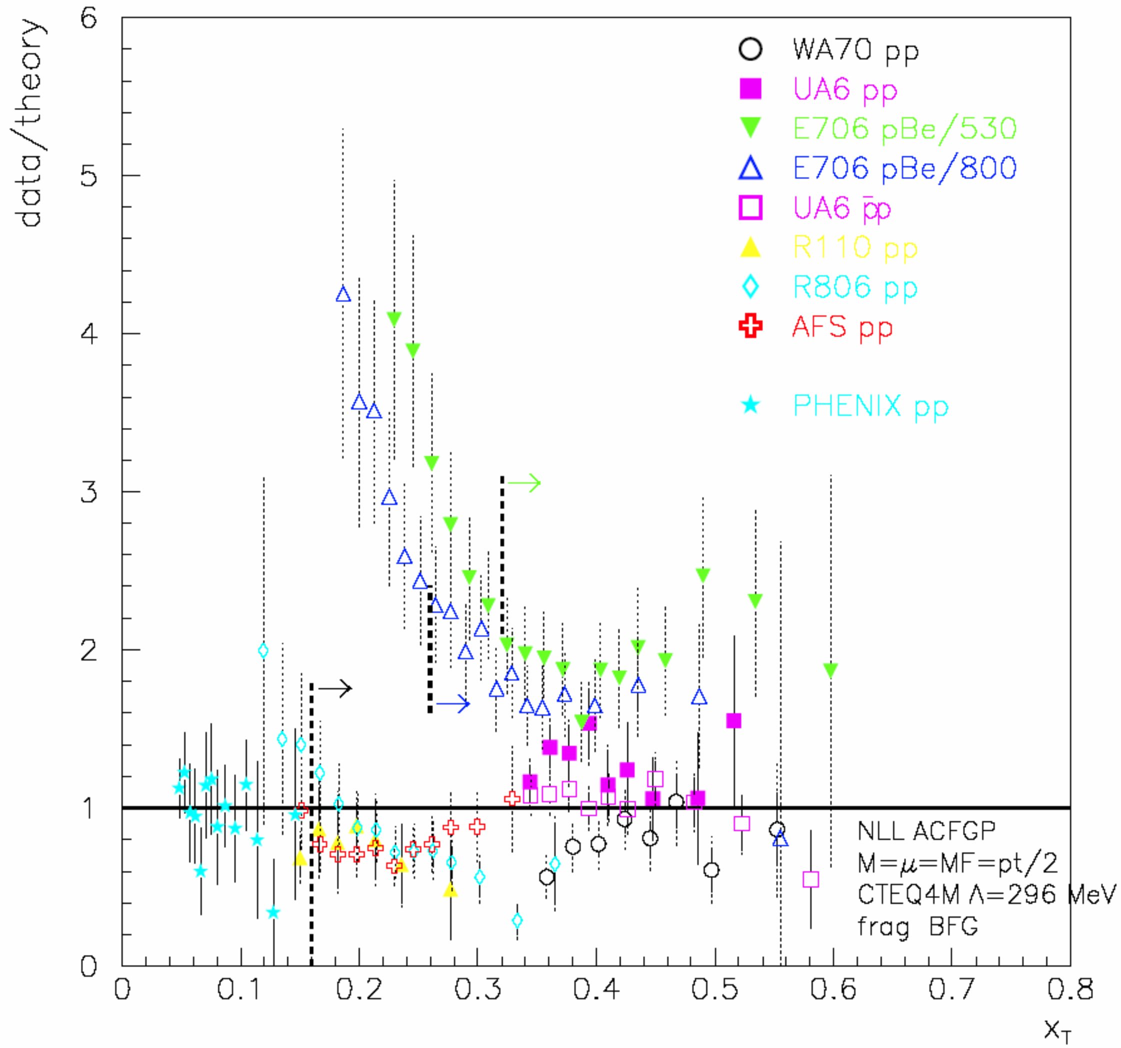
- PHENIX preliminary result.
- NLO-pQCD calculation
  - Private communication with W.Vogelsang
  - CTEQ6M PDF.
  - Sum of direct photon bremsstrhlung photon
  - 3 scales (1/2pT,1pT,2 pT)
    - For renormalization scale factorization scale



pQCD calculation can describe our result very well.

Comparison with Other Exp.

Aurenche et al Eur. Phys. JC9,10(1999)



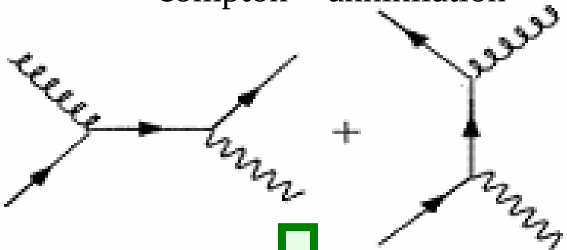
Talk by Monique Werlen at RHIC&AGS users meeting

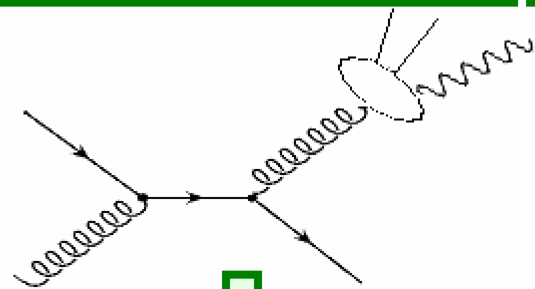
Phenix data clarifies the data/theory puzzle

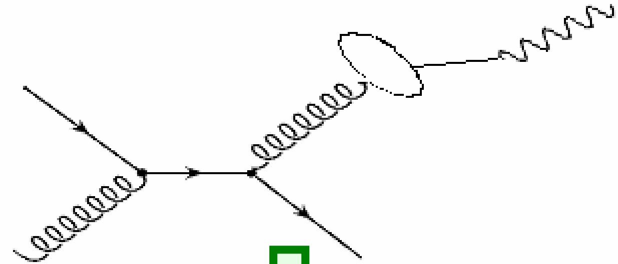
Strategy of Isolation Method

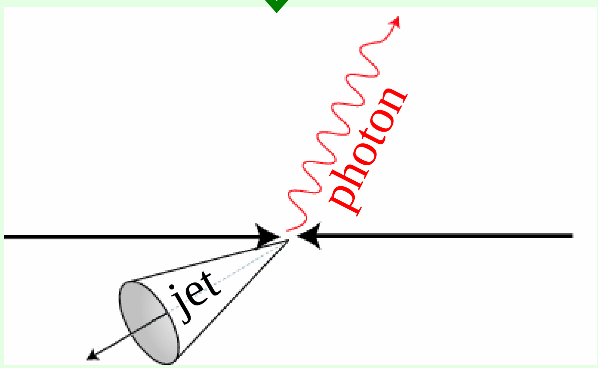
(1)Signal(direct)	(2)Signal(fragmentation)	(3)Background(hadron decay)

compton + annihilation

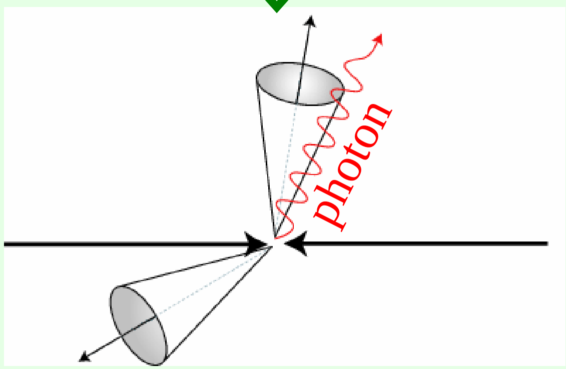




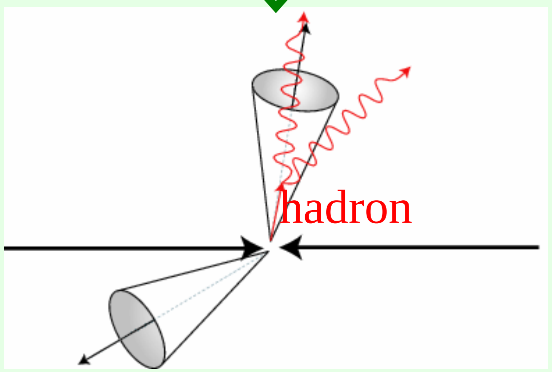




約30%@10GeV



約10%@10GeV

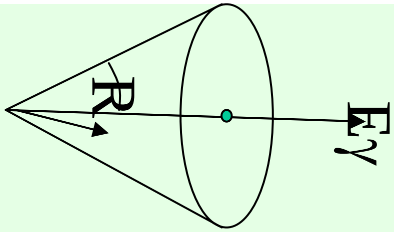


約60%@10GeV

Isolation cut to reduce background

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

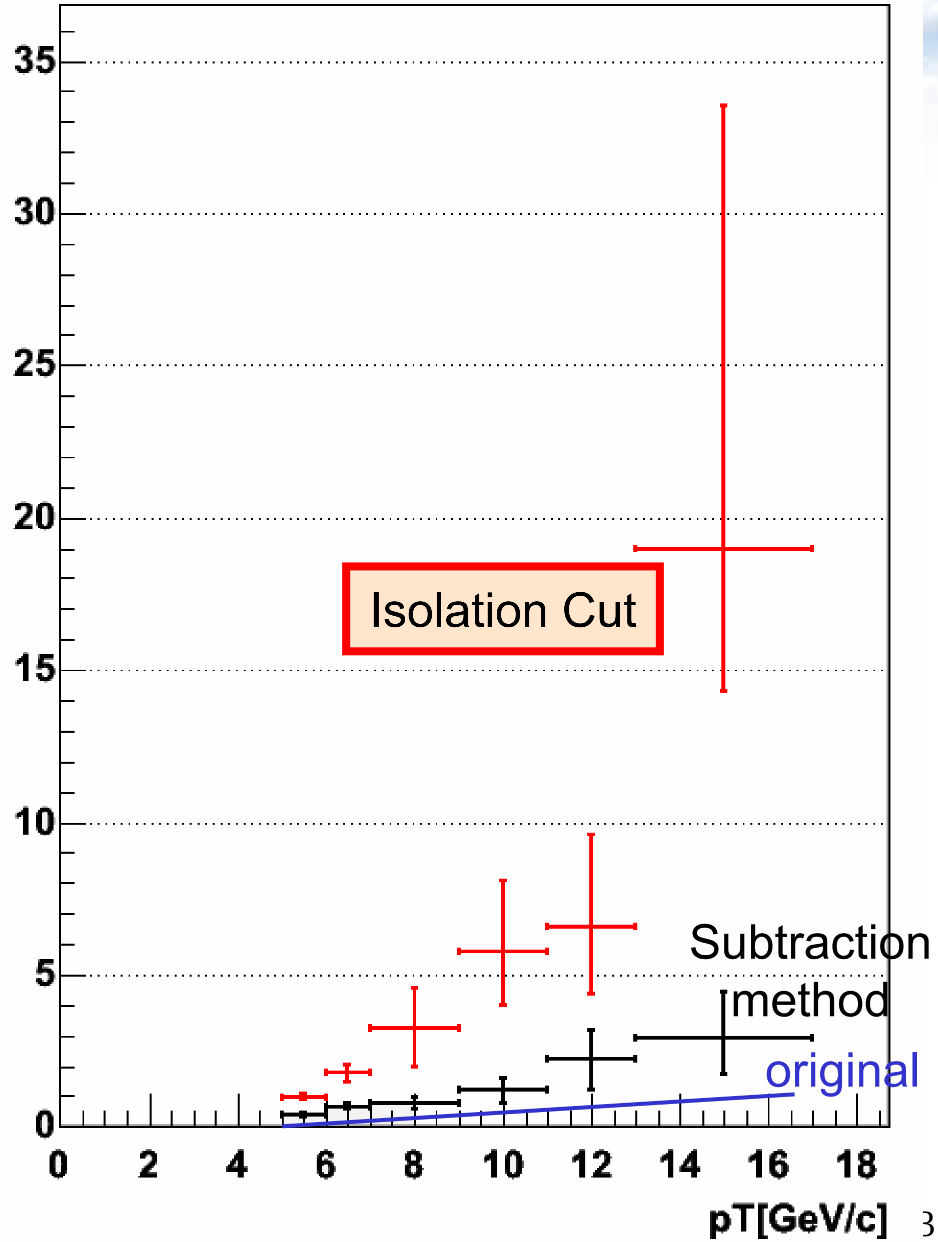
$$E_{sum}(R < 0.5) < E_\gamma \times 0.1$$



What is the efficiency by this cut for signal 1)&2)➔Next slide

S/N Ratio with Isolation Cut

- S/N ratio
  - S = Direct photon
  - N = Remained Bg. Photon
- Isolation cut help to reduce S/N ratio
  - 5 times better than the subtraction method
  - p_T = 5-17GeV/c



Isolation cut is useful for the future measurement of

ALL in direct photon

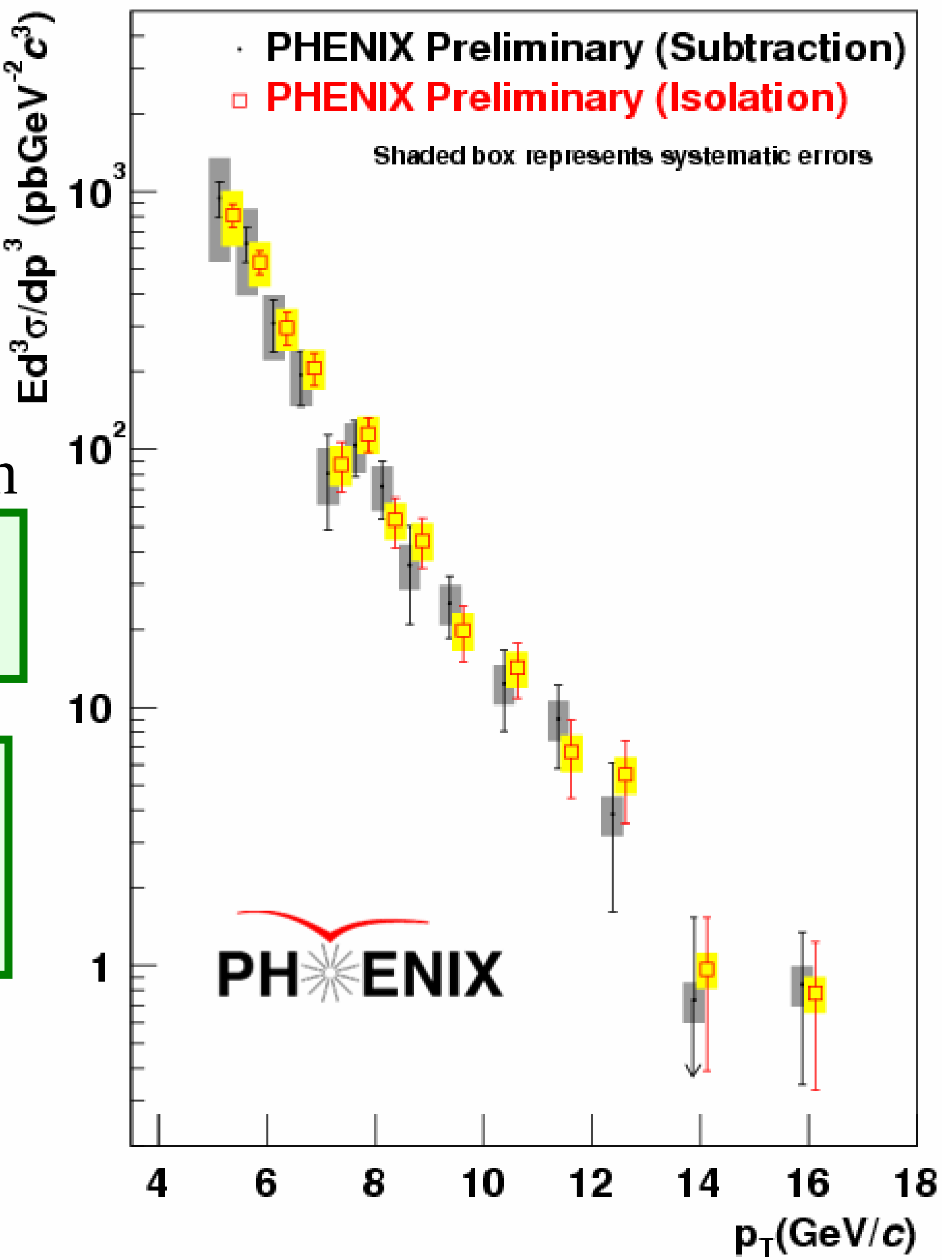
Result

- Two methods
  - Subtraction method
  - isolation method
    - To be smaller by 20-40%
- They are not different as we expected from pQCD calculation

Rejection for fragmentation photon
Is not perfect

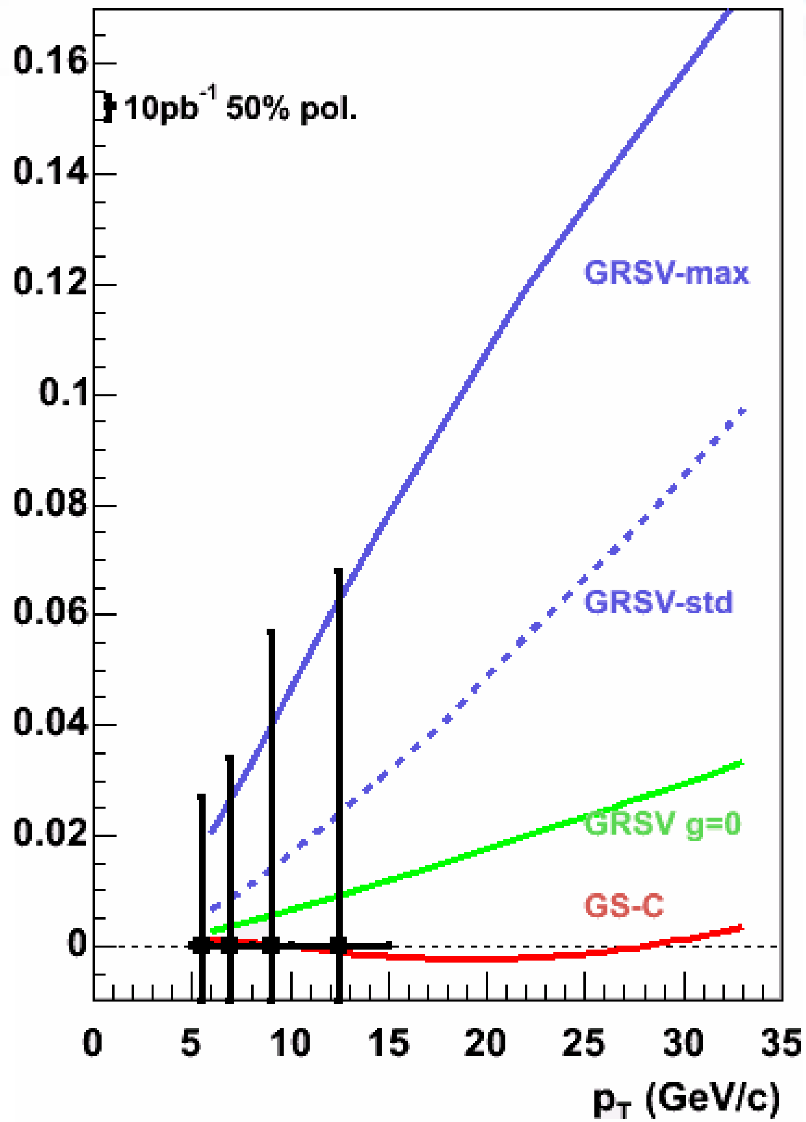
or

Most of measured photon are
From direct process
(compton, annihilation, or NLO)

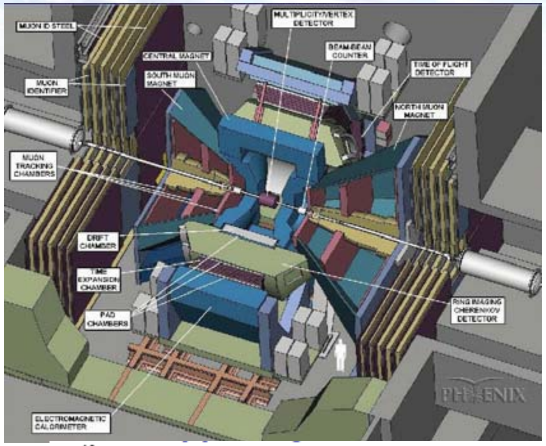


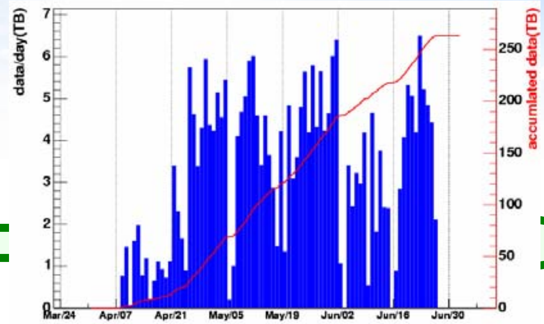
Prospect of Photon A_{LL} from Run5

- Direct photon
  - Based on 10pb^{-1} 50% pol.
  - The error will be larger by factor ~2.
- Need more statistics.



PHENIX run5 Status



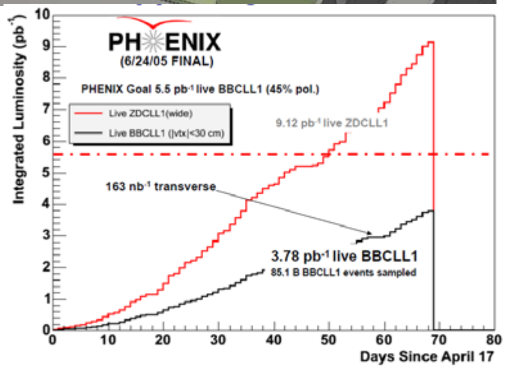


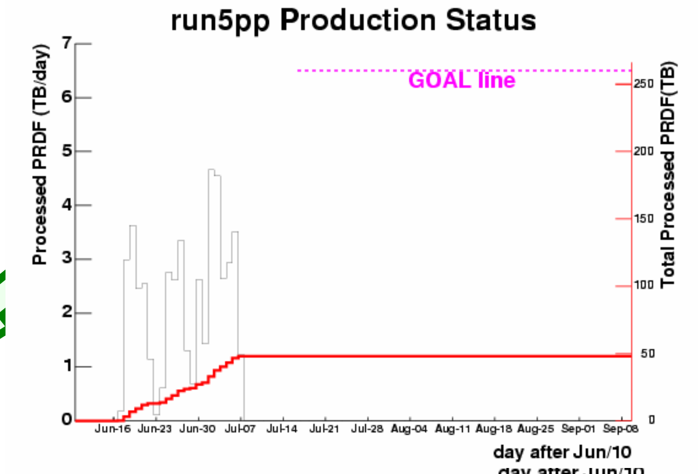
➔260TB transferred to RIKEN

(50MB/sec on average)

Large Computing Power at RIKEN (RSCC

ranked No. 7 in the Top500 most powerful supercomputers in the world at 2004/06





April/17 – May/25

➔5+kHz DAQ rate

➔3.78pb-1

DST production will finish in the end of August

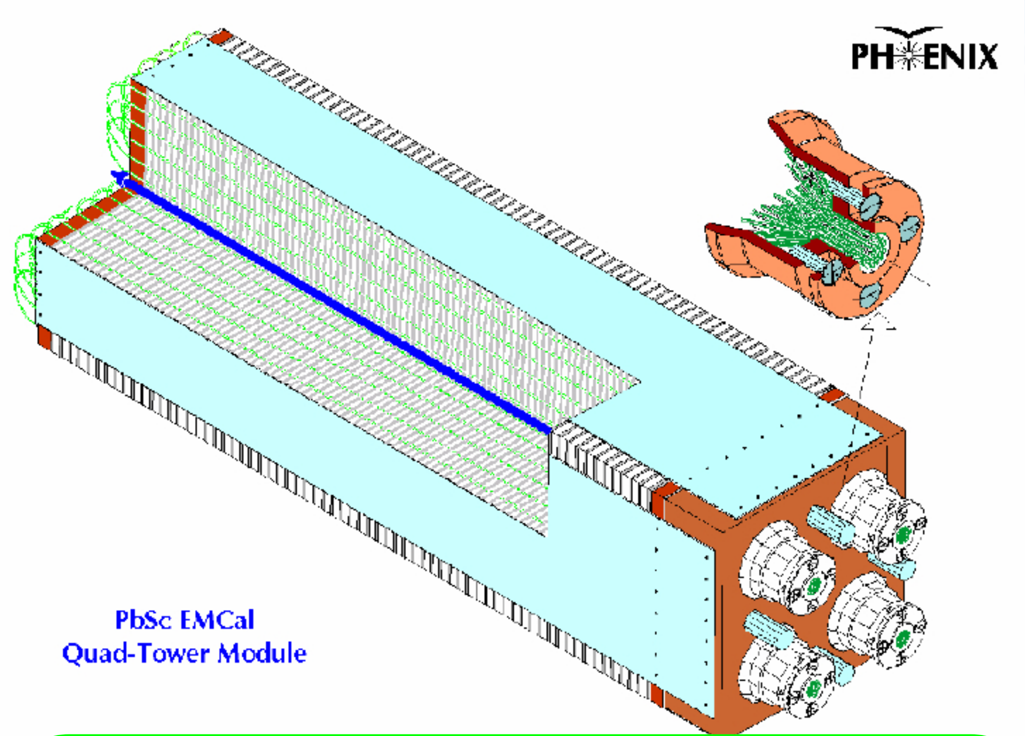
New result will be available this fall!!!

Summary

$\pi 0$	Direct Photon
Inclusive Cross Section	
Consistent with NLO-pQCD	Consistent with NLO-pQCD
A_{LL} in RUN3&4	
Favor GRSV-std than GRSV-max	Need more statistics
A_{LL} in RUN5	
Will distinguish GRSV-std and $\Delta G = 0$	more,more

Backup slide

PbSc EM Calorimeter



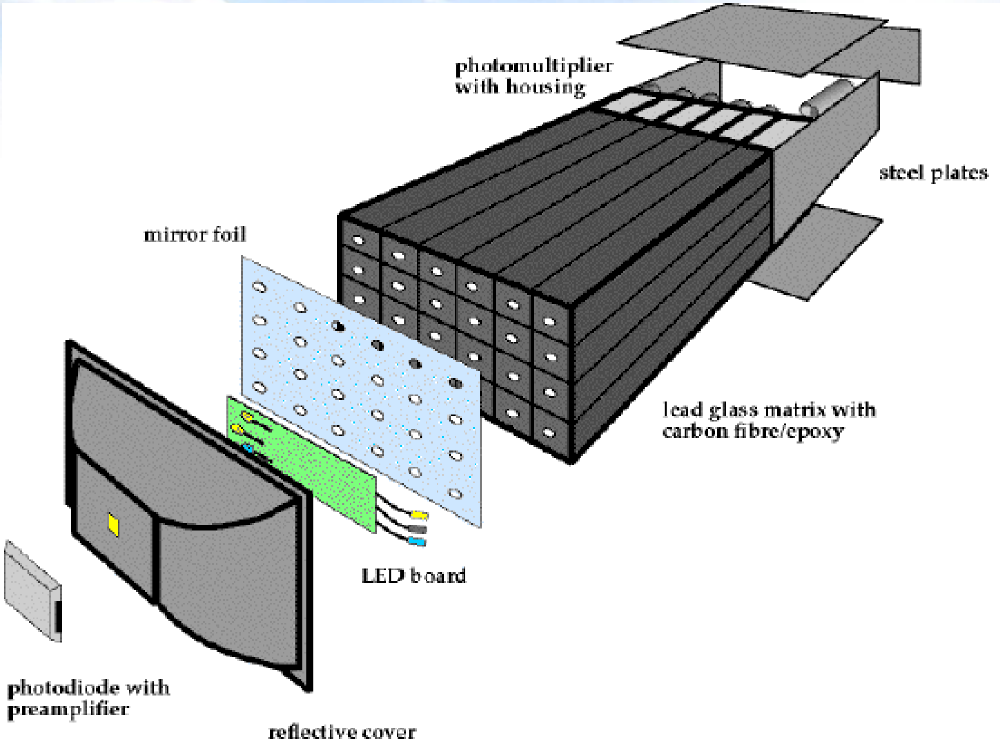
	PbSc
Size(cm x cm)	5.52 x 5.52
Depth(cm)	37.5
Number of towers	15552
Sampling fraction	~ 20%
η cov.	0.7
ϕ cov.	90+45deg
η/mod	0.011
ϕ/mod	0.011
X_0	18
Molière Radius	~ 3cm

Sandwich type calorimeter
- Lead plates 55.2x55.2x1.5mm
- Scintillator plates 110.4x110.4x4mm

Shish-kebab geometry wave shifter fiber readout
- 6x6 fibers → 1 PMT = 1 tower
- 2 x 2 towers = 1 module
- 6 x 6 module = 1 super module
- 6 x 3 super module = 1 sector

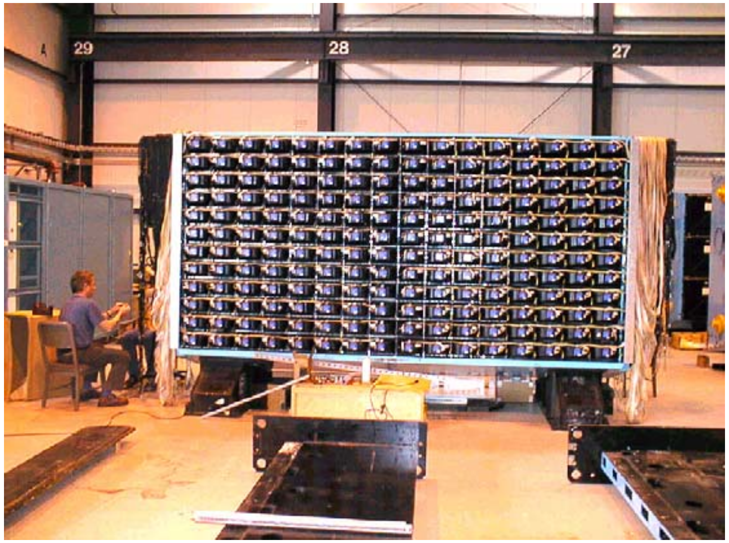
PbSc sector 2.0m x 4.0m

PbGl EM Calorimeter



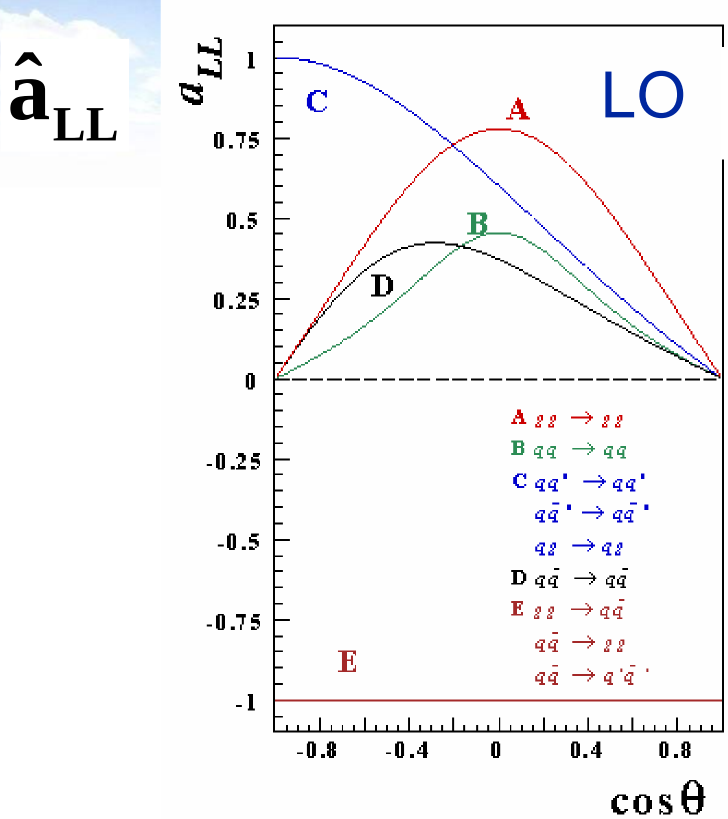
	PbGl
Size(cm x cm)	4.0 x 4.0
Depth(cm)	40
Number of towers	9216
Sampling fraction	100%
η cov.	0.7
ϕ cov.	45deg
η/mod	0.008
ϕ/mod	0.008
X_0	14.4
Molière Radius	3.68cm

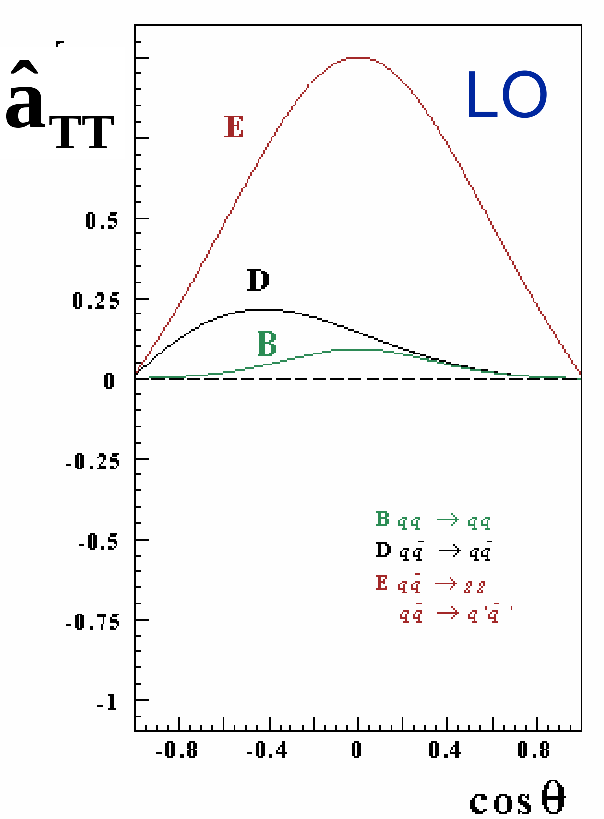
Lead Glass calorimeter
Lead Glass 40x40x400mm
used at WA98 exp.
4x6 towers = 1 super module
15*12 super module = 1 sector



PbGl sector 2.1m x 3.9m

Analyzing powers

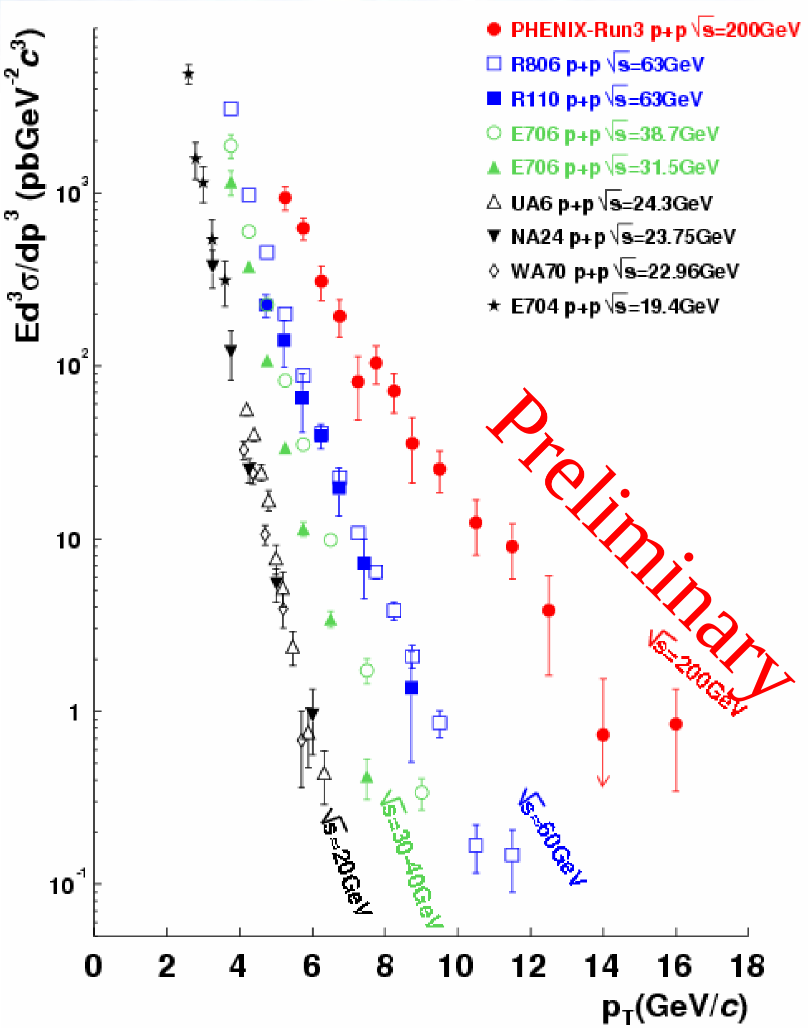




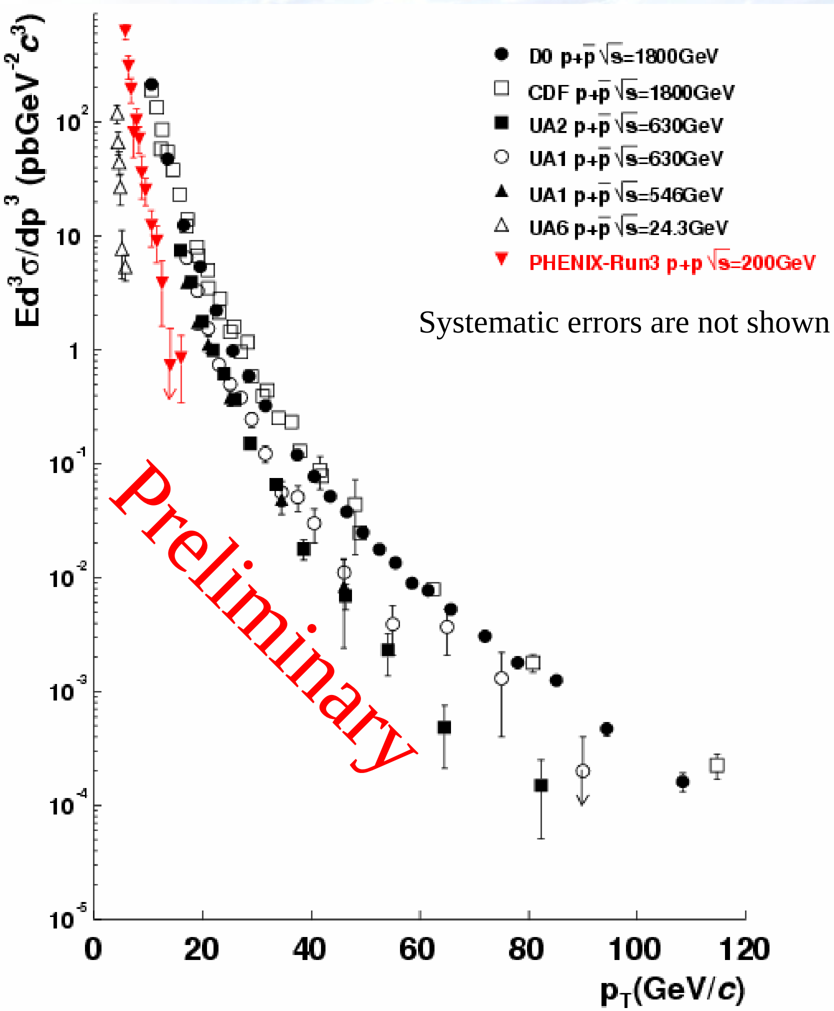
- NLO corrections are now known for all relevant

$$A_{LL} \propto \frac{\Delta q}{q} \frac{\Delta G}{G} a_{ll}(qg \to qg)$$

Comparison with Other Experiment



proton-proton collisions



proton-antiproton collisions

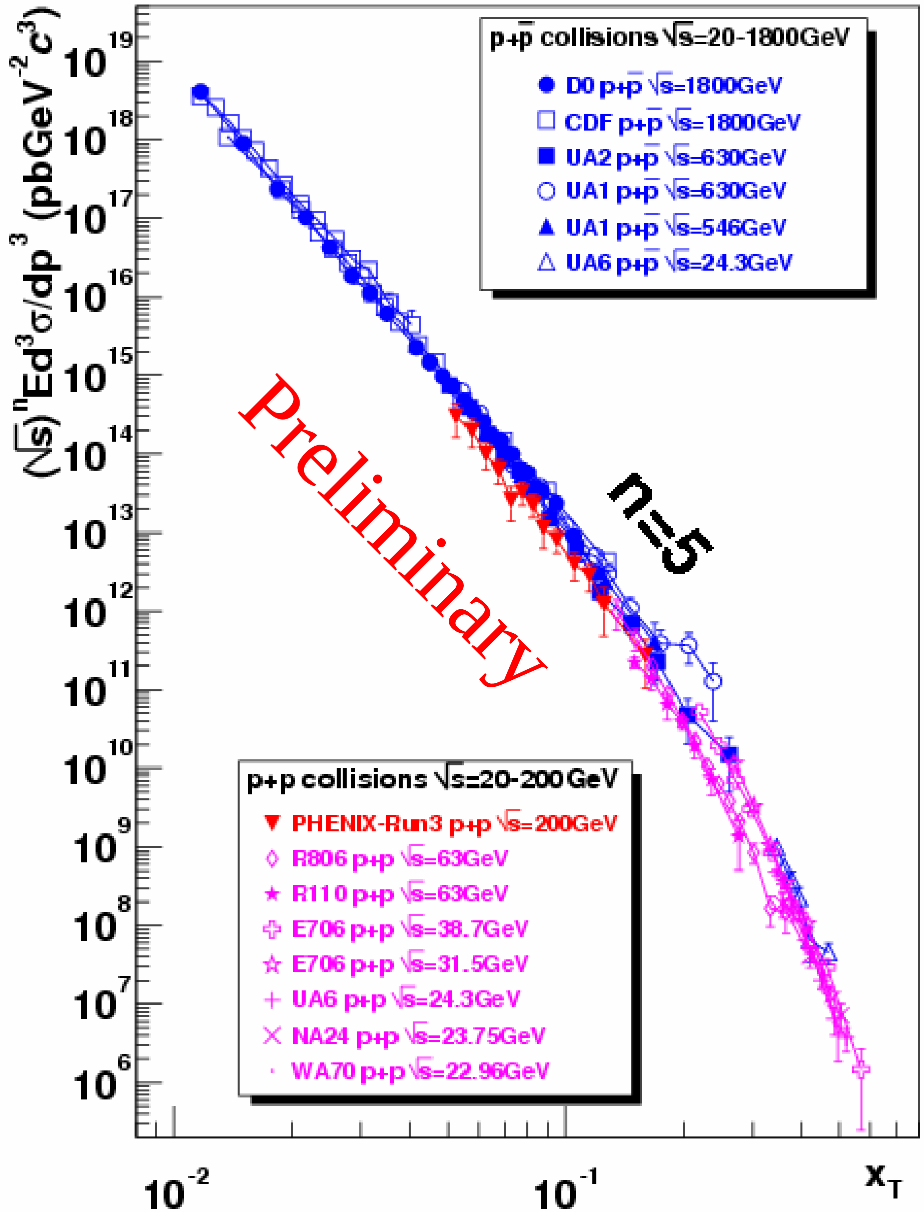
x_T Scaling

- From QCD, if
  - Q^2-Scaling of PDF,FF
  - No running coupling constant(α_s)

$$\boxed{\sigma = \left(\sqrt{s}\right)^{-n} \times F\left(x_T\right)}$$

n=constant。$x_T=2p_T/\sqrt{s}$

  - Can be express as two terms
    - Interaction
    - Structure
  - If leading order n=4
    - Next-to-leading order: n=4+α

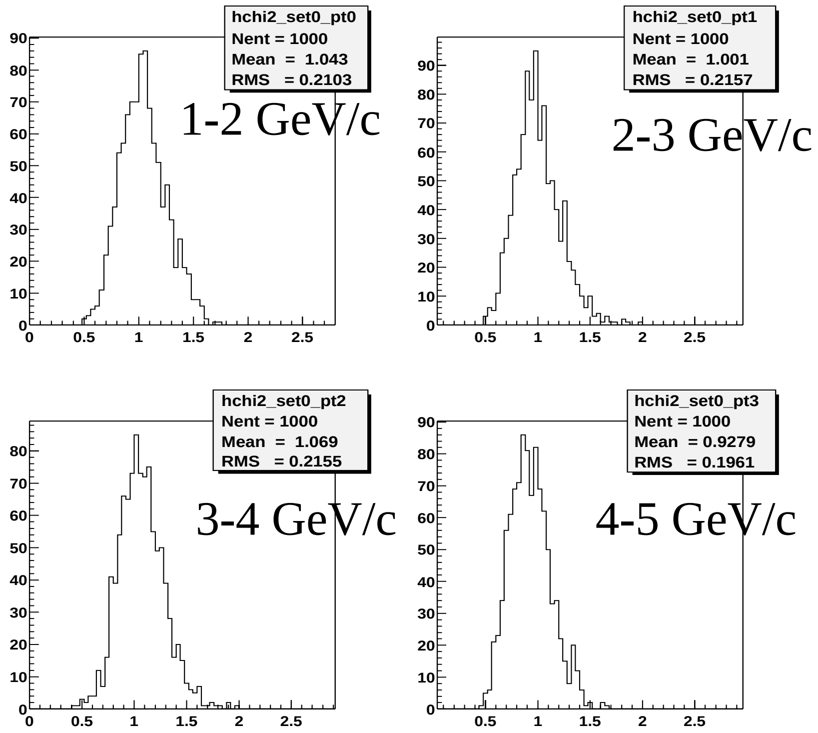


x_T-Scaling n=~5

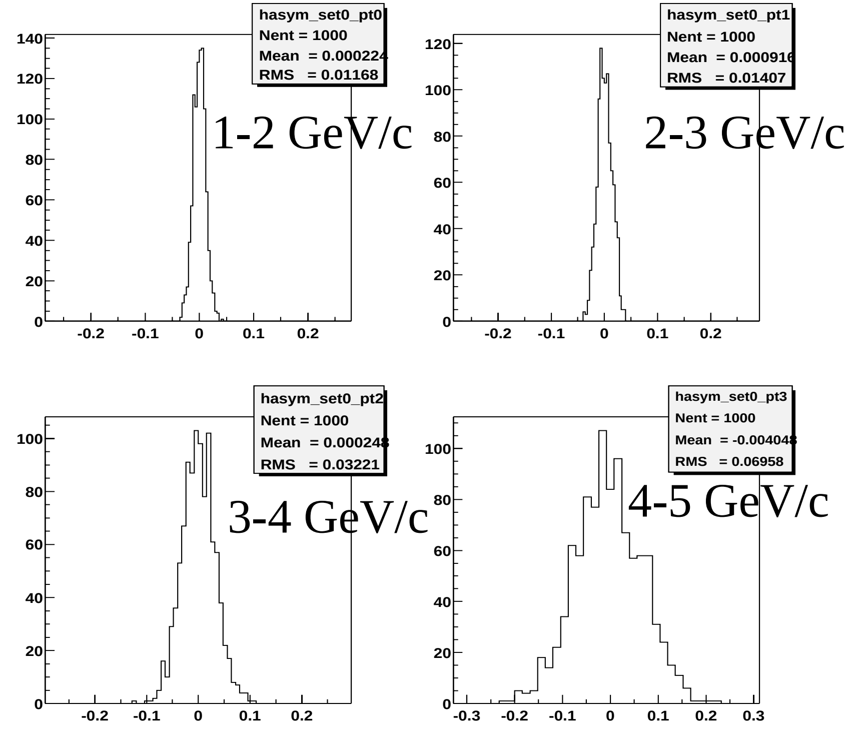
Systematic check: bunch shuffling

Bunch shuffling = Randomly assigns helicity for each crossing

χ^2/NDF



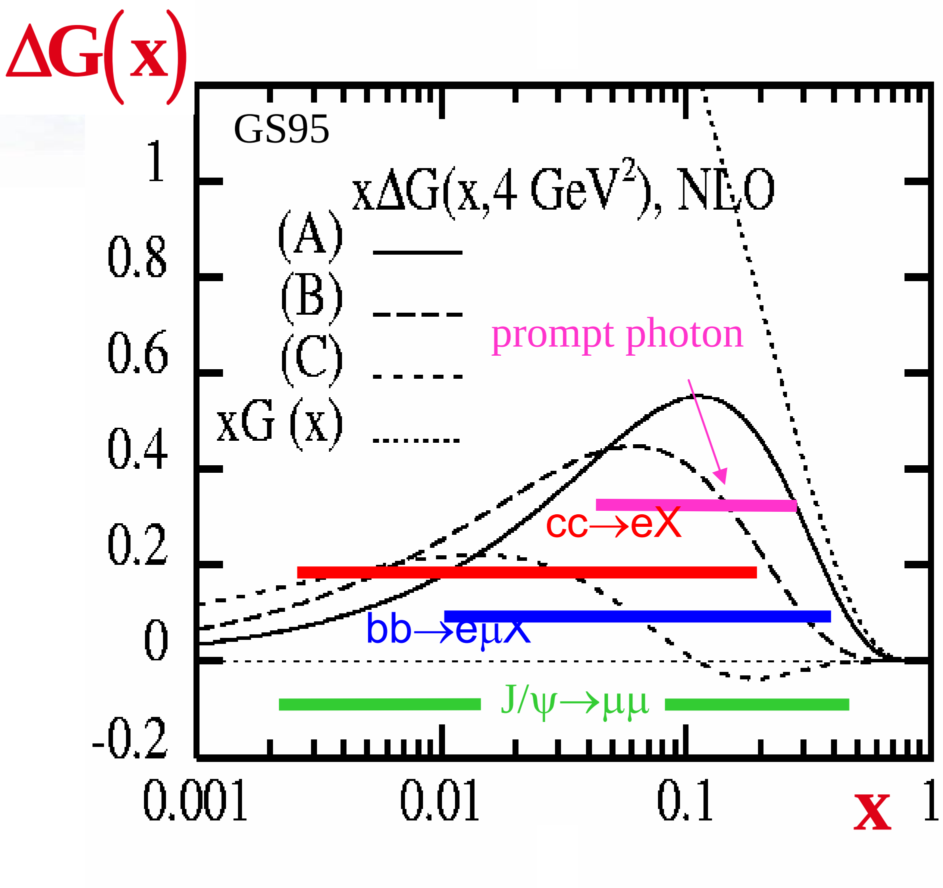
A_{LL}

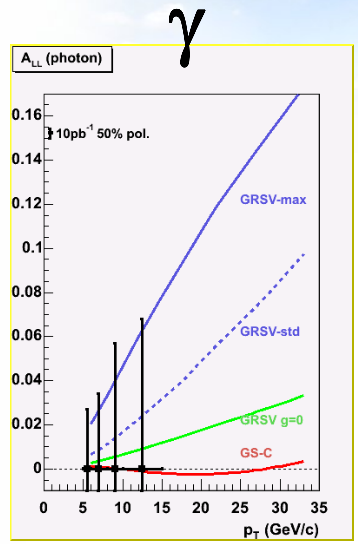


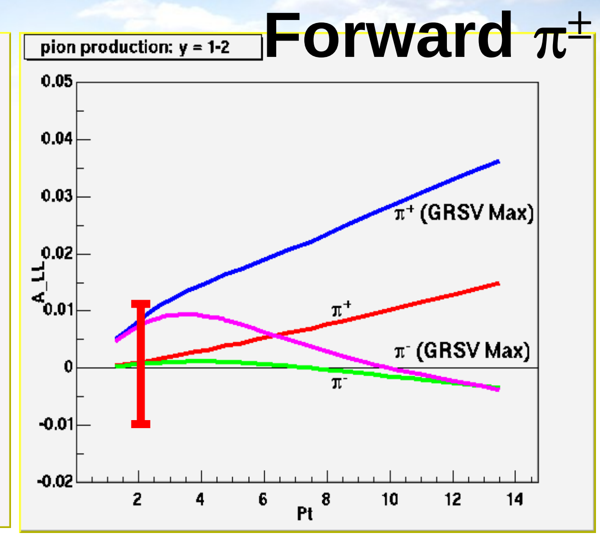
All $\langle\chi^2/NDF\rangle$ are ~1

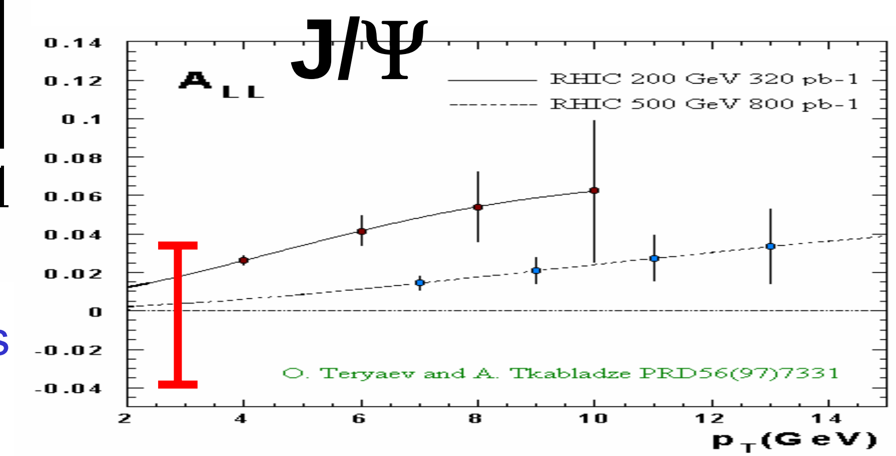
Widths are consistent with obtained errors $\delta(A_{LL})$

PHENIX run5





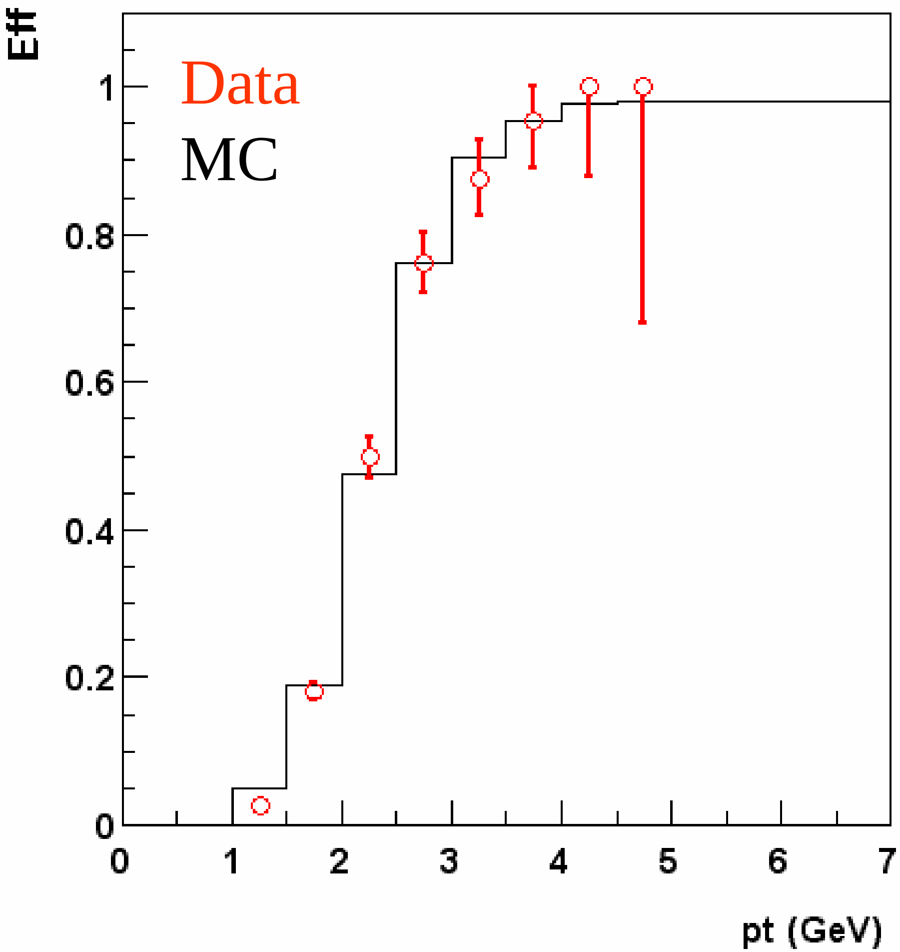




- Important to measure a variety of processes
  - reduce exp. and th. systematics
  - extend x coverage
- At least another order of magnitude needed…

γ trigger efficiency for π^0

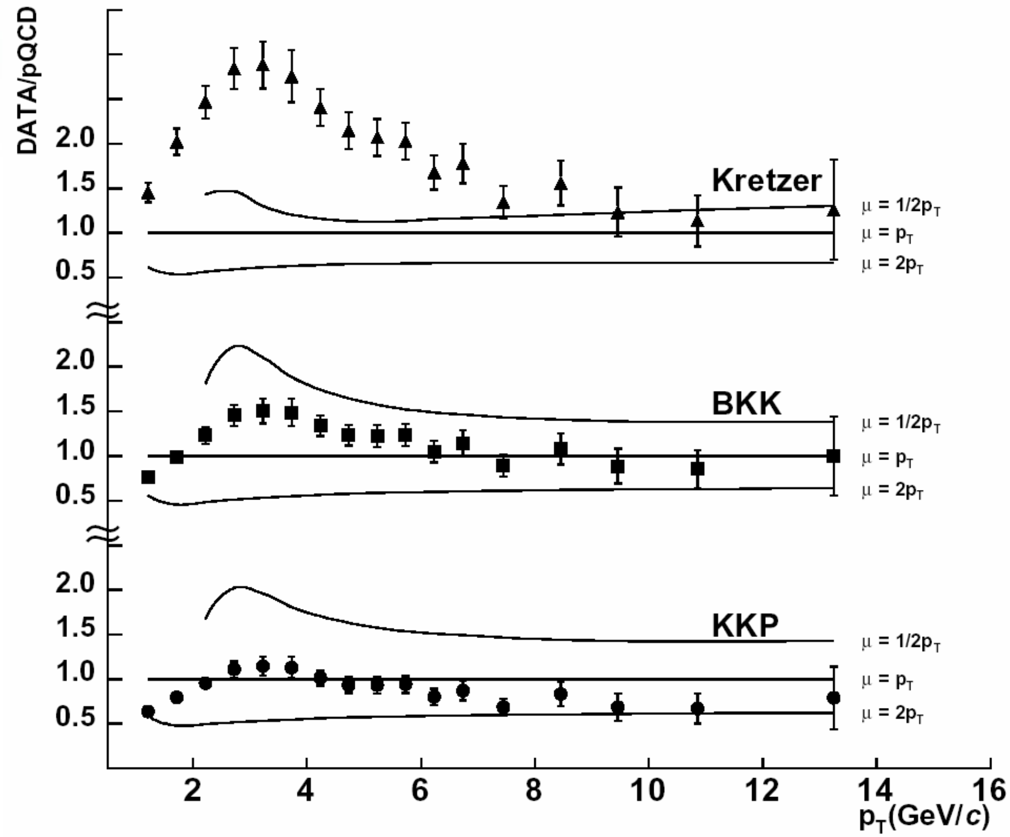
- p0 efficiency plateaus for pT>4 GeV/c
- Limited efficiency at pT<4 GeV/c:
  - 1-2 GeV/c: 6%
  - 2-3 GeV/c: 60%
  - 3-4 GeV/c: 90%
  - 4-5 GeV/c: 95%
- Monte Carlo reproduces Data well

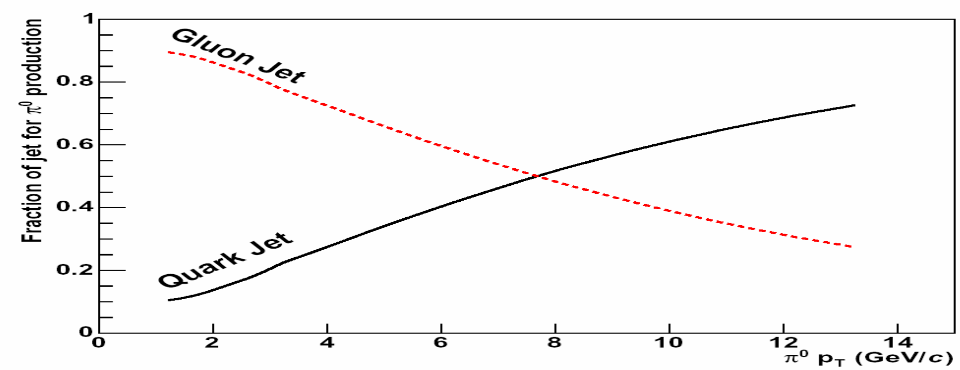


π^0 p_T (GeV/c)

破砕関数の比較

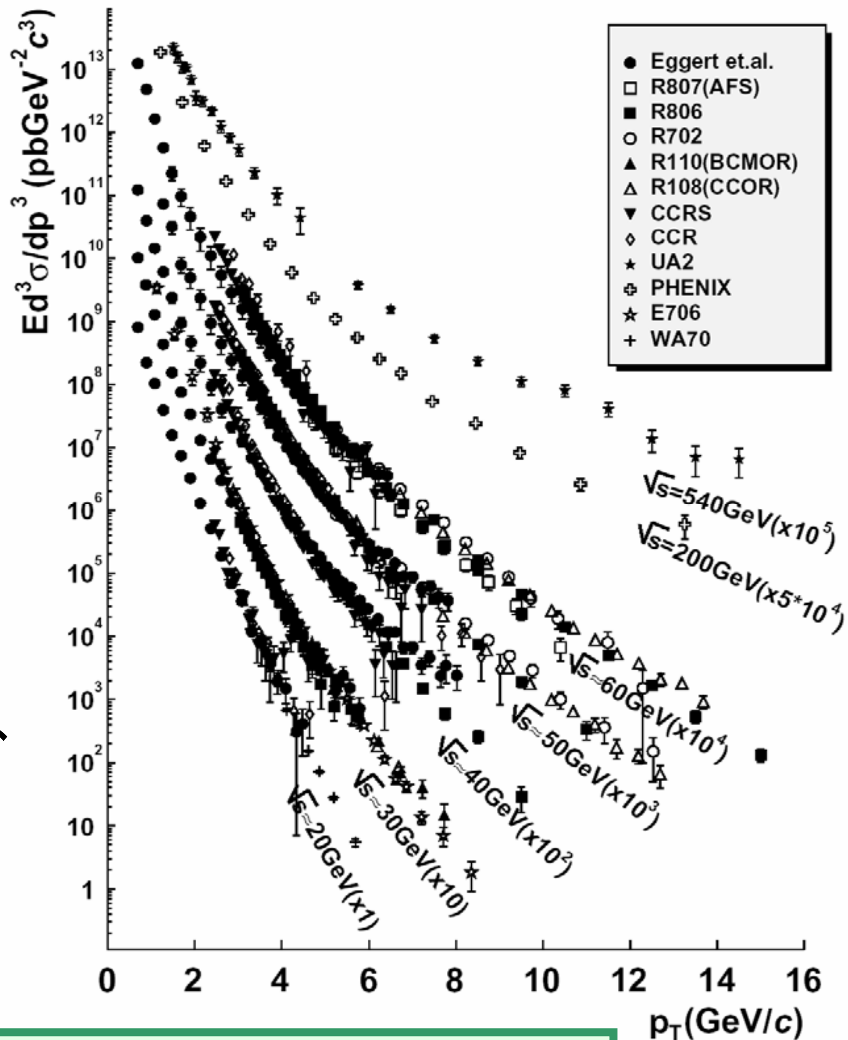
- データと他のFFを用いたNLO-pQCD計算との比較。
  - FFとして、Kretzer, BKK, KKPを使用
  - BKKとKKPを用いた計算はデータと一致
  - Kretzerを用いた計算はpT<8GeV/cにおいてデータより低く見積もっている。
    - この大きな違いは、gluonからの破砕関数にある。
    - Gluon と quarkジェットの寄与は、pi0 pT=8GeV/c辺りでクロスする。





過去のデータとの比較

- 陽子陽子衝突では最高エネルギー
  - CERN
    - ISR (1971~) p+p $\sqrt{s}$=10-60GeV
    - SPS(1977~) p-beam p≤450GeV
    - $Sp\bar{p}S$(1981~) p+ $\bar{p}$ $\sqrt{s}$≤640GeV
  - FermiLab
    - Syncrotron(1972~) p-beam p≤400GeV
    - Tevatron(1981~) p-beam p≤0.9TeV
- p_T分布
  - High p_T では、$\sqrt{s}$が大きくなるにつれて、p_T分布の形の傾きは緩やか。
  - Low p_Tでは、傾きは$\sqrt{s}$によらずほぼ一定に収束している。



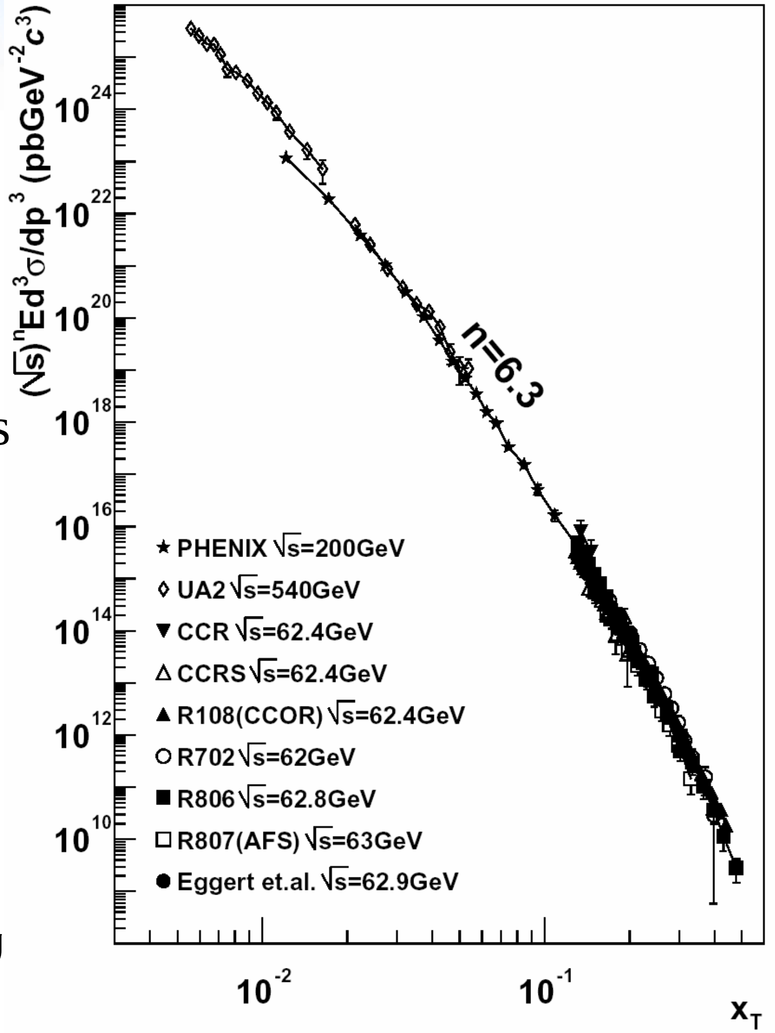
今回得られたp_T分布が、パートン(QCD)描像で説明できることを、過去のデータとの比較において考察を行う。

x_Tスケーリング

- QCD理論によると、以下の仮定
  - PDFとFFのQ^2スケーリング
  - Coupling constant(α_s)がQ^2に非依存。

$$\boxed{\sigma = \left(\sqrt{s}\right)^{-n} \times F(x_T)}$$

n=定数。$x_T=2p_T/\sqrt{s}$



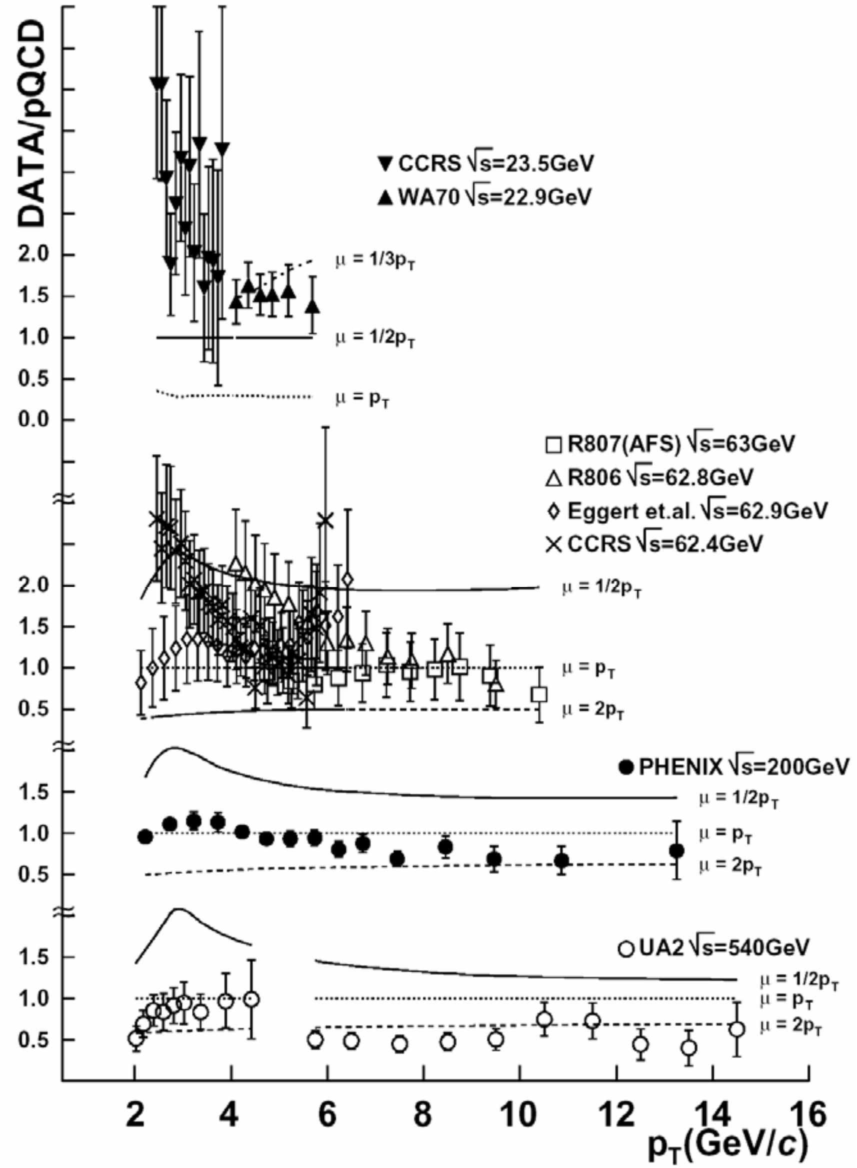
  - 定数nに対する予想
    - Leading order n=4
    - Next-to-leading order: n=4+α
    - 過去の実験から n=6.3 (by R108 collaboration)
  - x_T分布は$\sqrt{s}$に依存しない

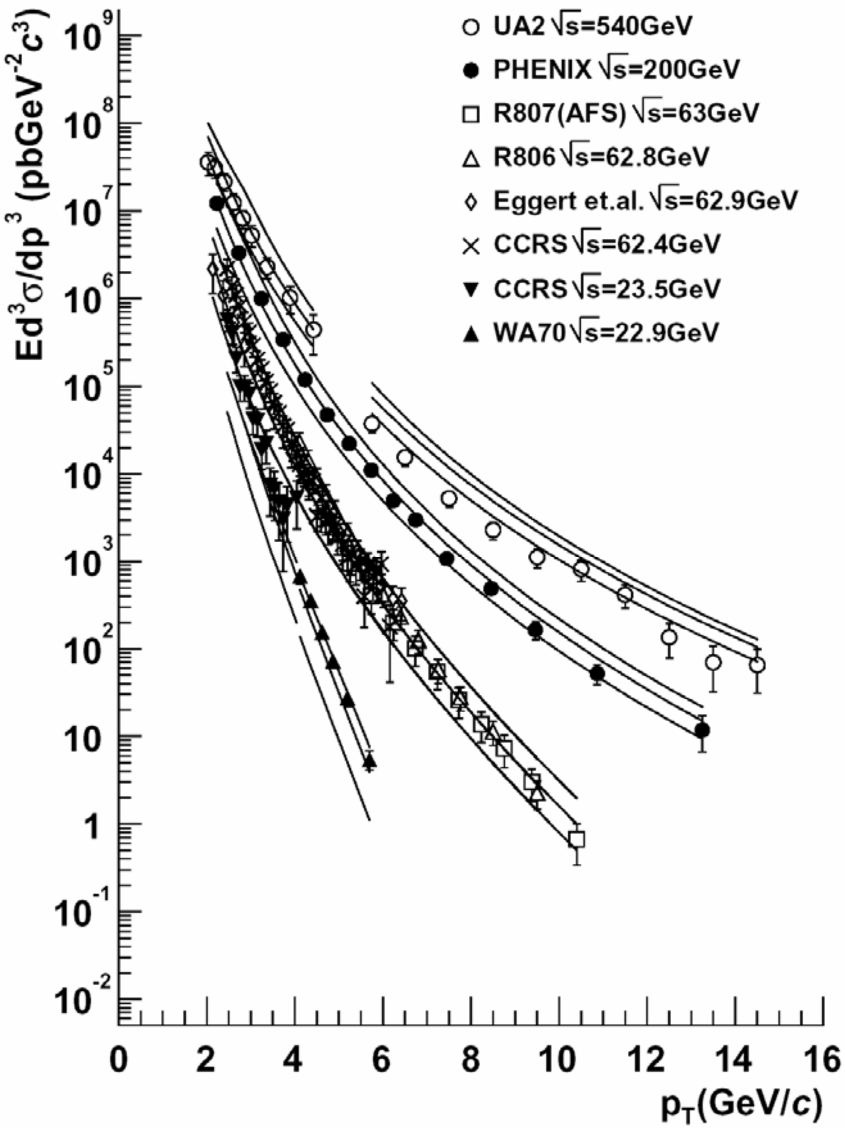
➔x_Tスケーリング

- ここでは、今回得られたデータと過去のデータ$\sqrt{s}$>60GeVと比較して、x_Tスケーリングがn=6.3で成り立つかどうか見る。

x_Tスケーリングがn=6.3で成り立つ➔パートン描像

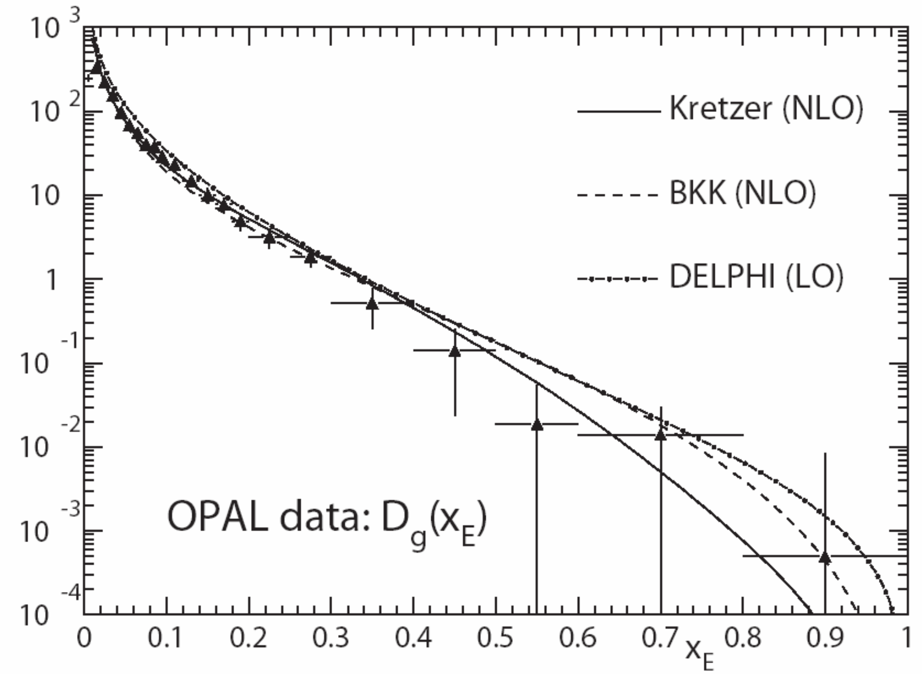
√s Dependence with NLO-pQCD





グルーオンからの破砕関数

- gluon FFは、$e^{+}+e^{-} \rightarrow qqg$(3-jet) 反応を使って測定されてきた。
  - 最大10倍の違い
  - BKK = KKP > Kretzer
- 今回のデータとの比較により、z>0.5の領域では、Krezerの予想よりハードな破砕関数であることがわかった。



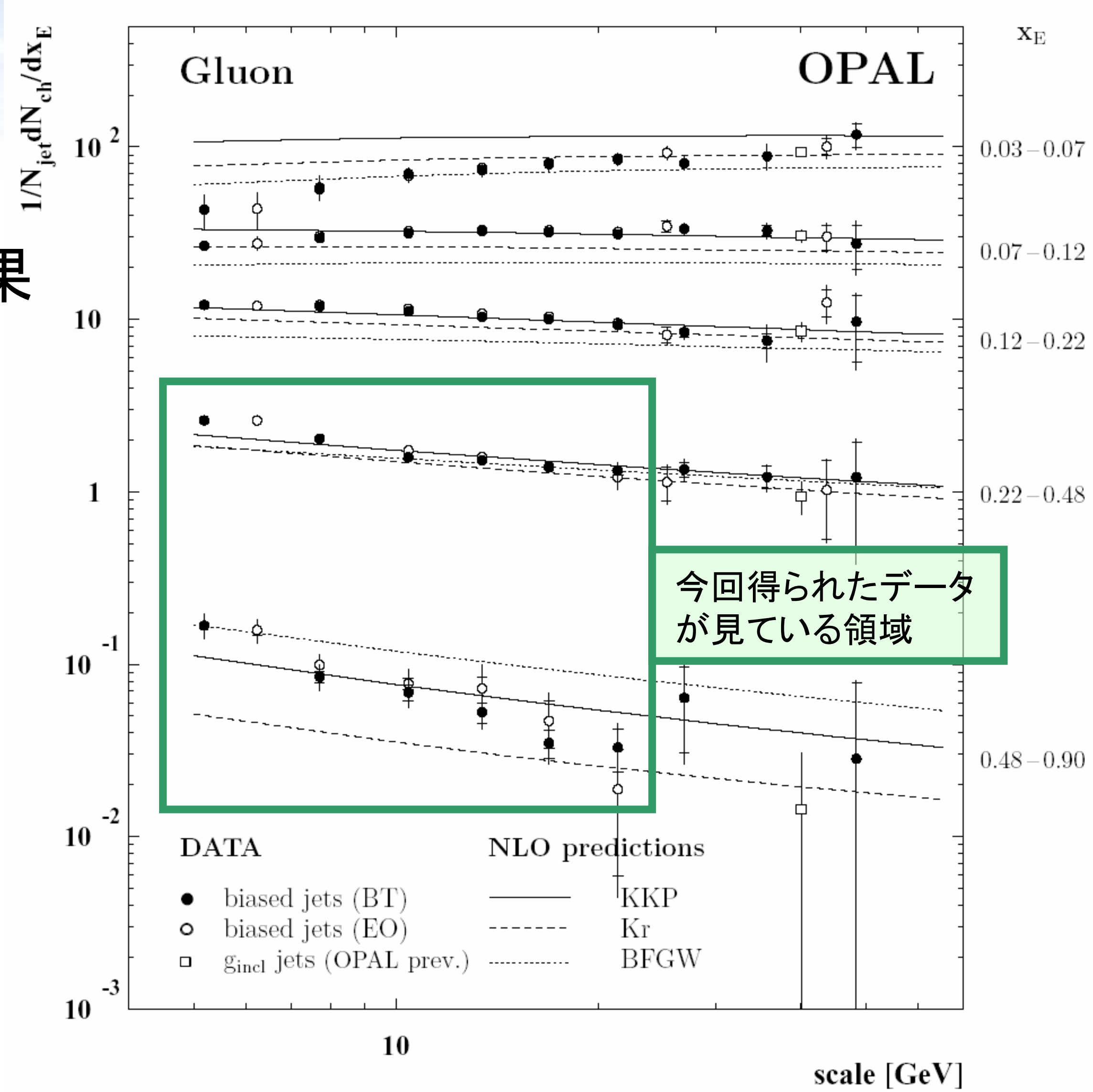
本研究によりgluonからの破砕関数、特にz>0.5 の領域に対し情報を与えることが出来た。

- 将来の課題
  - NNLO
  - Initial k_T
  - Multi-jetイベントにおけるJet-jet final interaction
    - Space and time evolution of the color field

LEP2の結果から

- 最近のLEP2-OPALの結果
  - Z>0.5の領域では、Kretzerはunderestimationである。

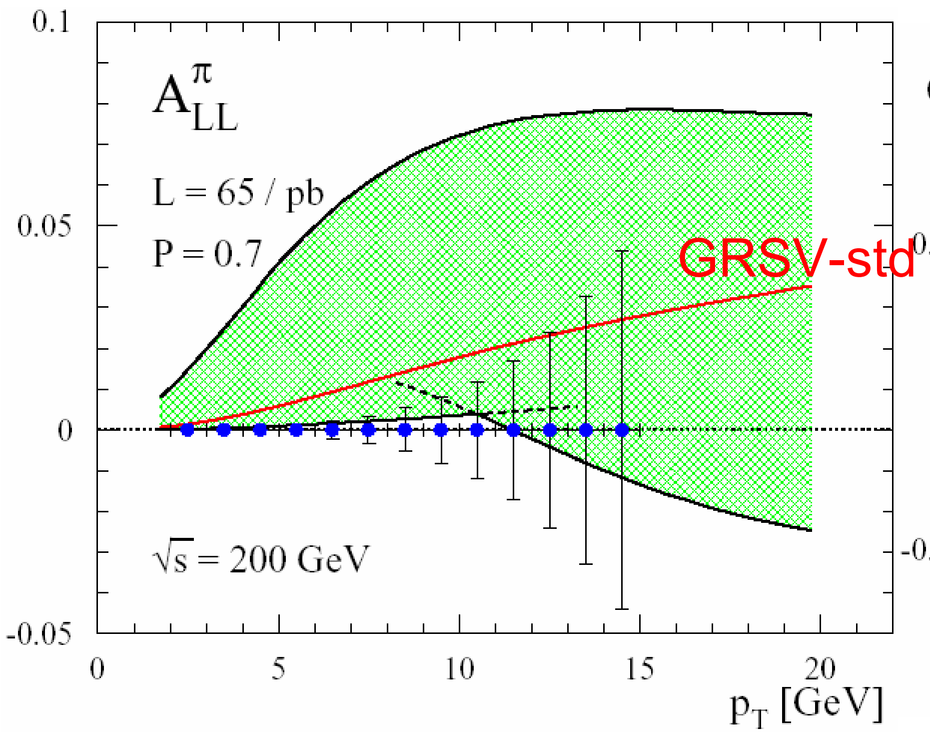
今回得た結論と一致

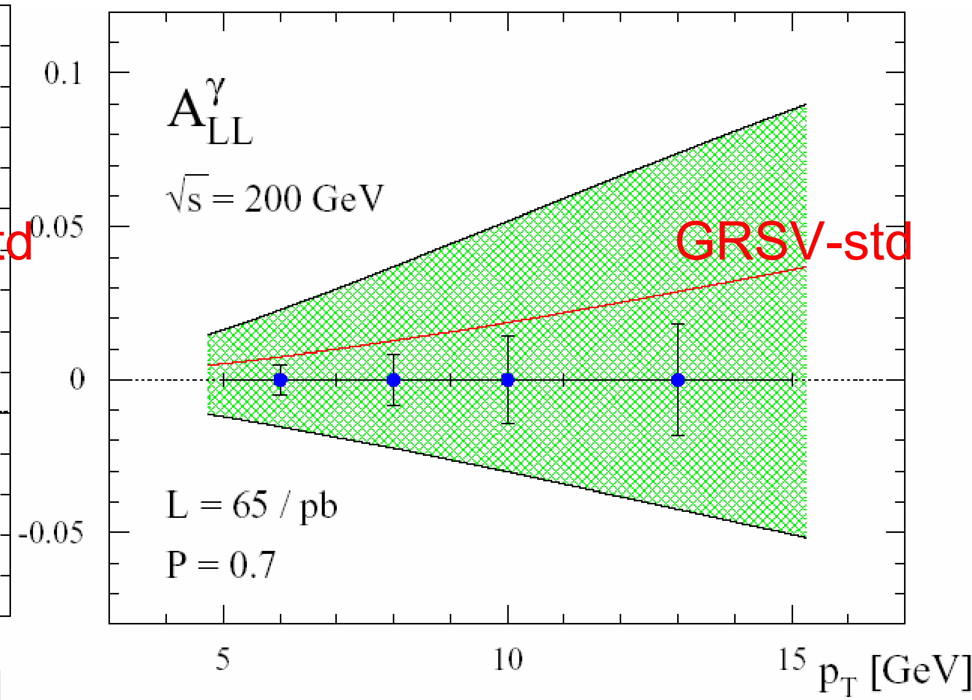


hep-ex/0404026

Gluon polarization

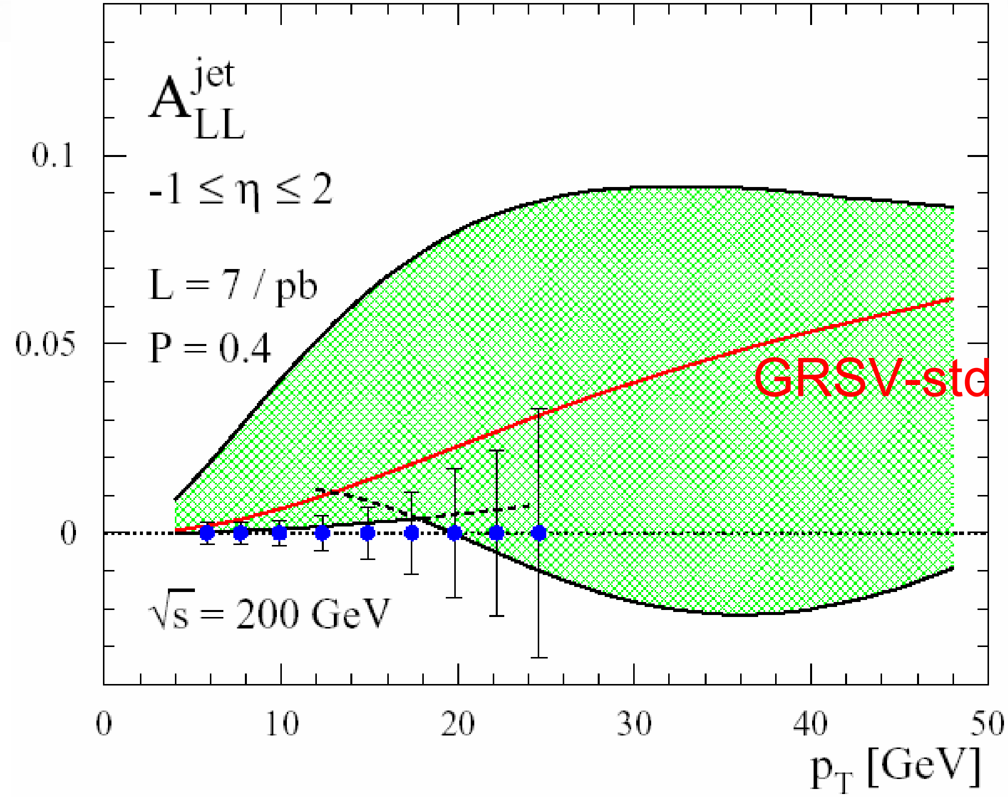
- A_{LL} projection
  - π^0 and direct photon at PHENIX
    - mid-rapidity $|\eta| < 0.35$, $\sqrt{s}$ = 200 GeV
    - 2005 – 2009 runs





Gluon polarization

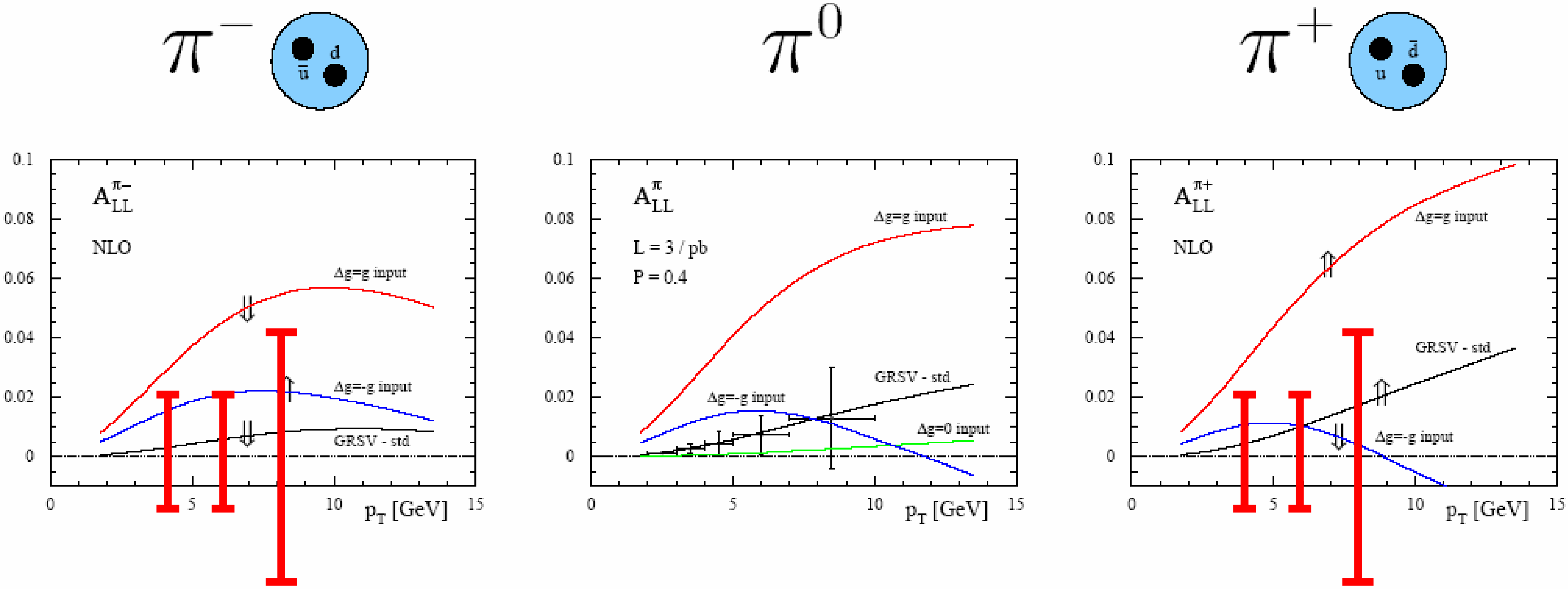
- A_{LL} projection
  - jet at STAR
    - $-1 < \eta < 2$
    - $\sqrt{s}$ = 200 GeV
    - 2005 run



  - coincidence channels
    - dijet, π^0-π^0, γ-jet, γ-π^0
    - reconstruction of partonic kinematics

$\pi^{\pm}$ A_{LL}

Stratmann Lecture, BNL 1st Spin School



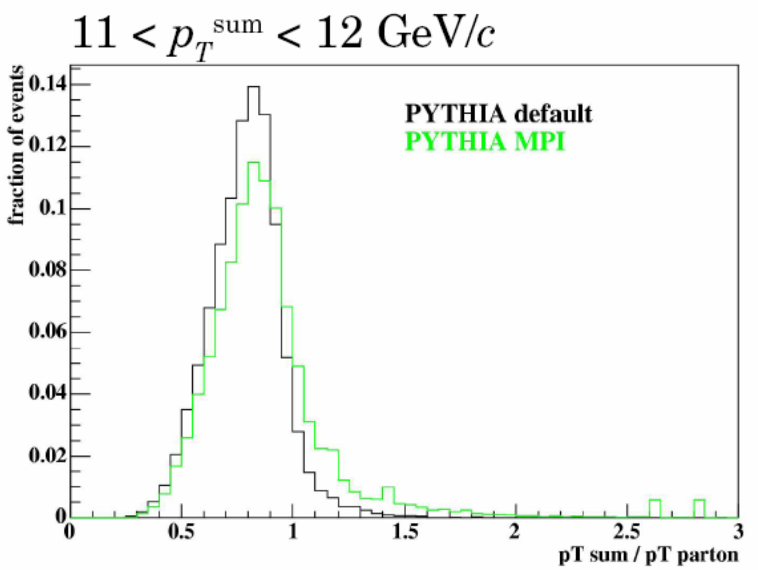
idea: qg starts to dominate for $p_T \gtrsim 5\,\mathrm{GeV}$ and $D_u^{\pi^+} > D_u^{\pi^0} > D_u^{\pi^-}$, $D_g^{\pi^+} = D_g^{\pi^-}$

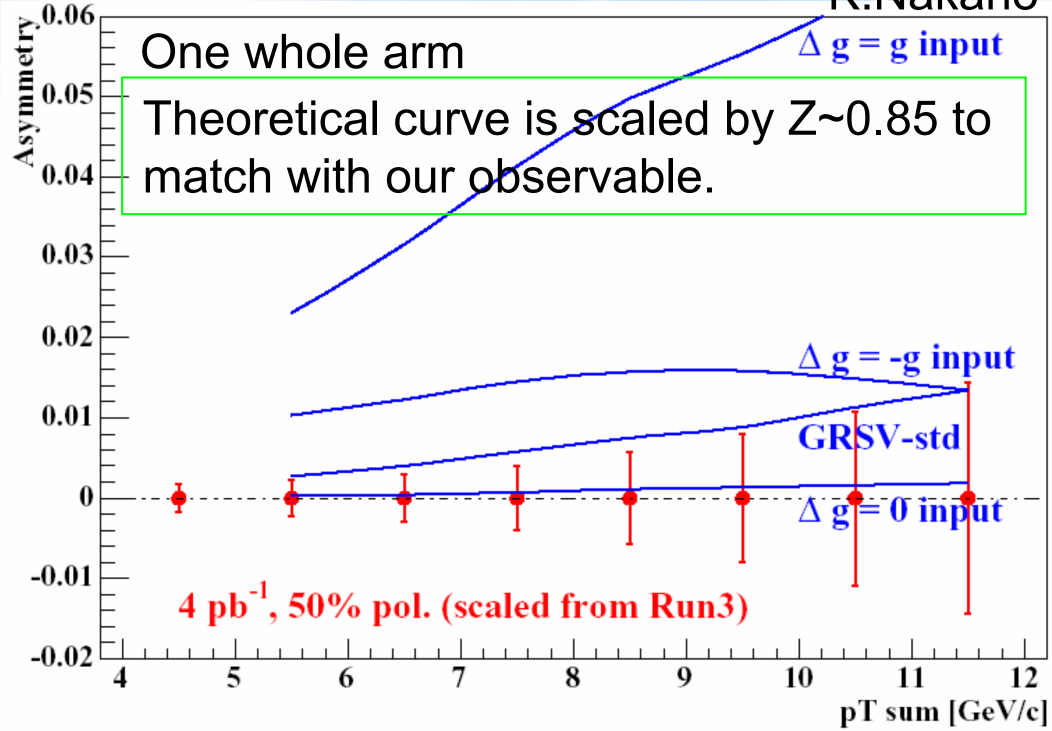
expect: sensitivity to sign of Δg, e.g., positive Δg: $A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$

- 5-15 GeV π± identified by RICH and EMC hadronic shower
- Not yet possible to determine sign of Δg

A_{LL} of Jet?

K.Nakano





Even with a limited acceptance in PHENIX central arm, we can capture most of a Jet.

→ Tag one photon, sum all energy in one arm.

Question :

1. Are those really jets? (agreement much worse at low p_T)
2. How much fraction (Z) do we catch? How much is its ambiguity (ΔZ)?

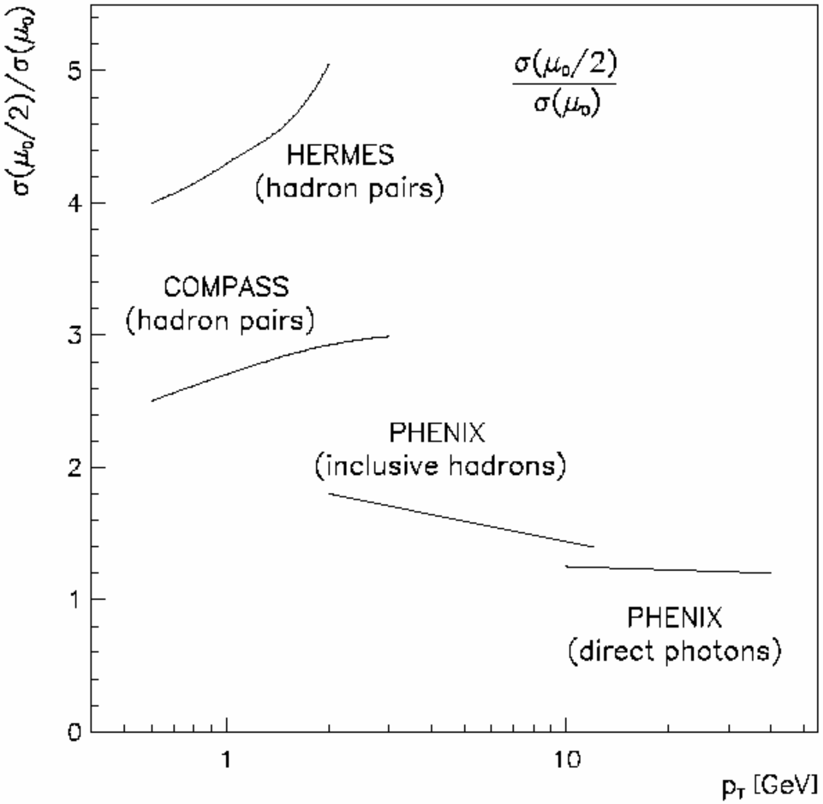
Compared to pi0:

— More statistics, but Systematic uncertainty in interpretation

Cross section

- perturbative QCD applicable ?
  - dependence of the calculated cross section on μ represents an uncertainty in the theoretical prediction

$$\frac{\sigma(\mu_0/2)}{\sigma(\mu_0)}$$

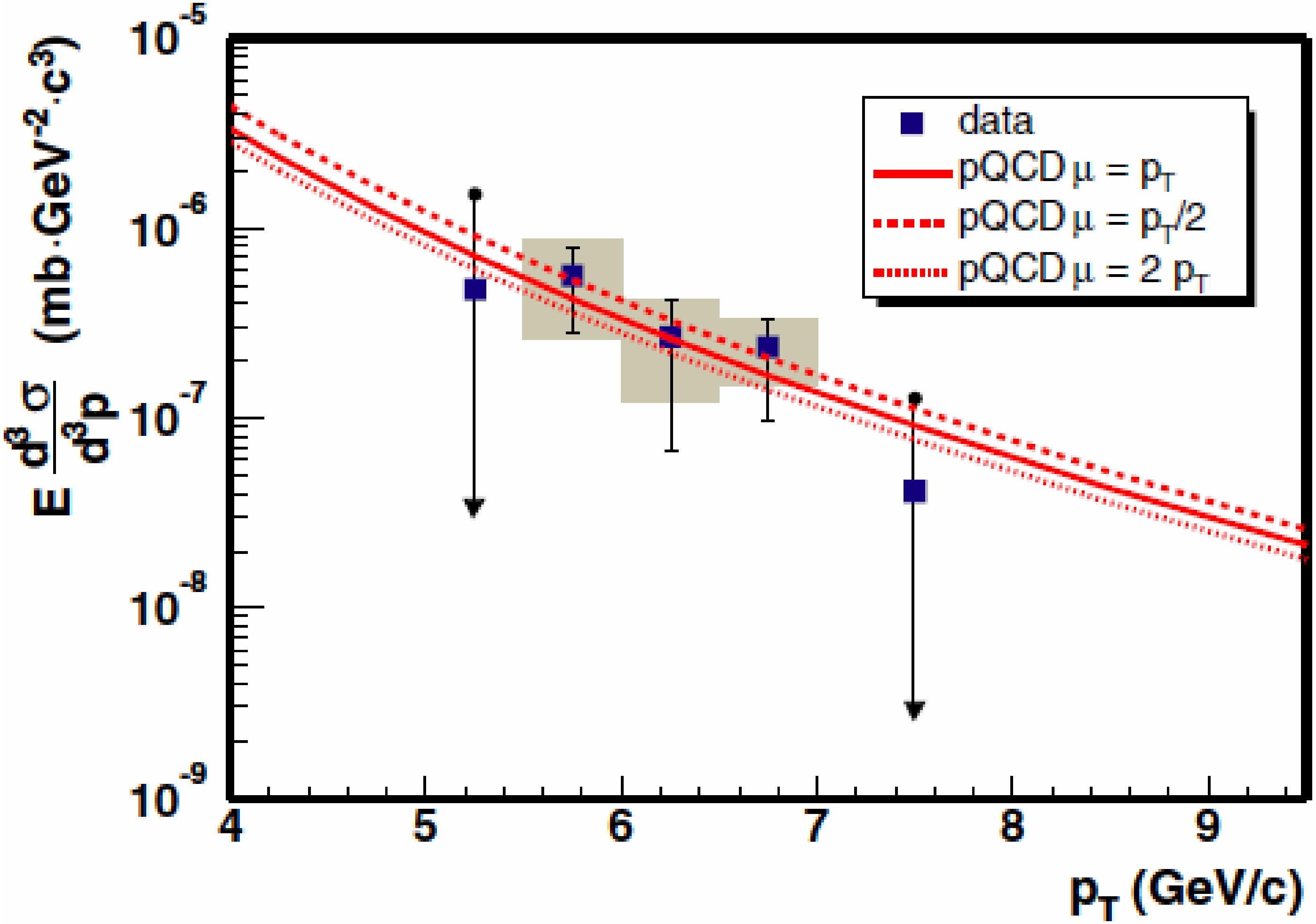


M. Stratmann and W. Vogelsang

p_T (GeV/c)

Photon from run2 p+p

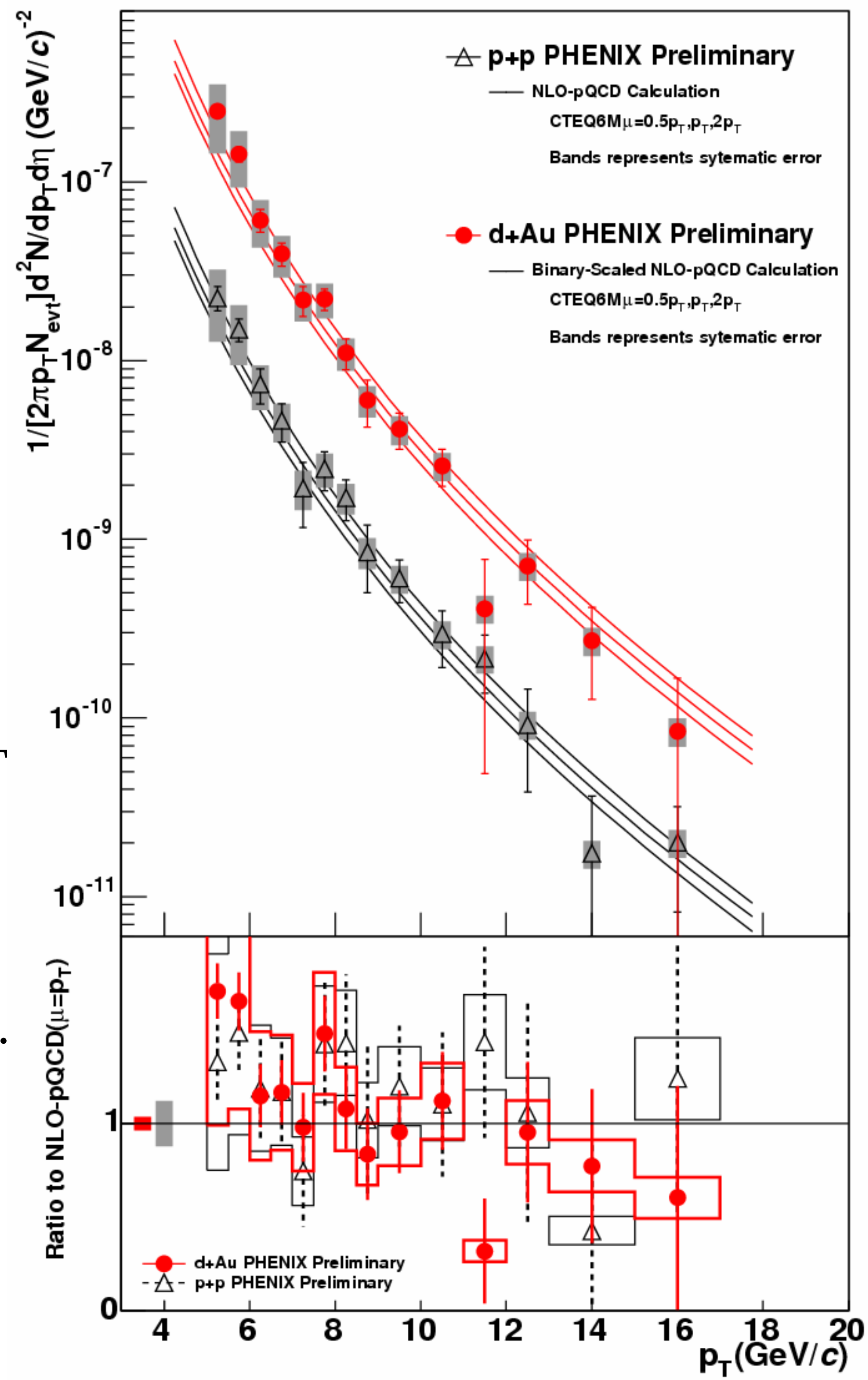
PHYSICAL REVIEW D **71**, 071102 (2005)



Result

- The analysis method is similar to p+p
- NLO pQCD Calculation
  - p+p collisions
  - Calculated by W.Vogelsang
  - CTEQ6M
  - Scale(renormalization and factorization scale) 0.5,1.0,2.0pT
- In comparison with d+Au
  - Averaged number of collisions (8.42) from the Glauber model was multiplied to the calculation.

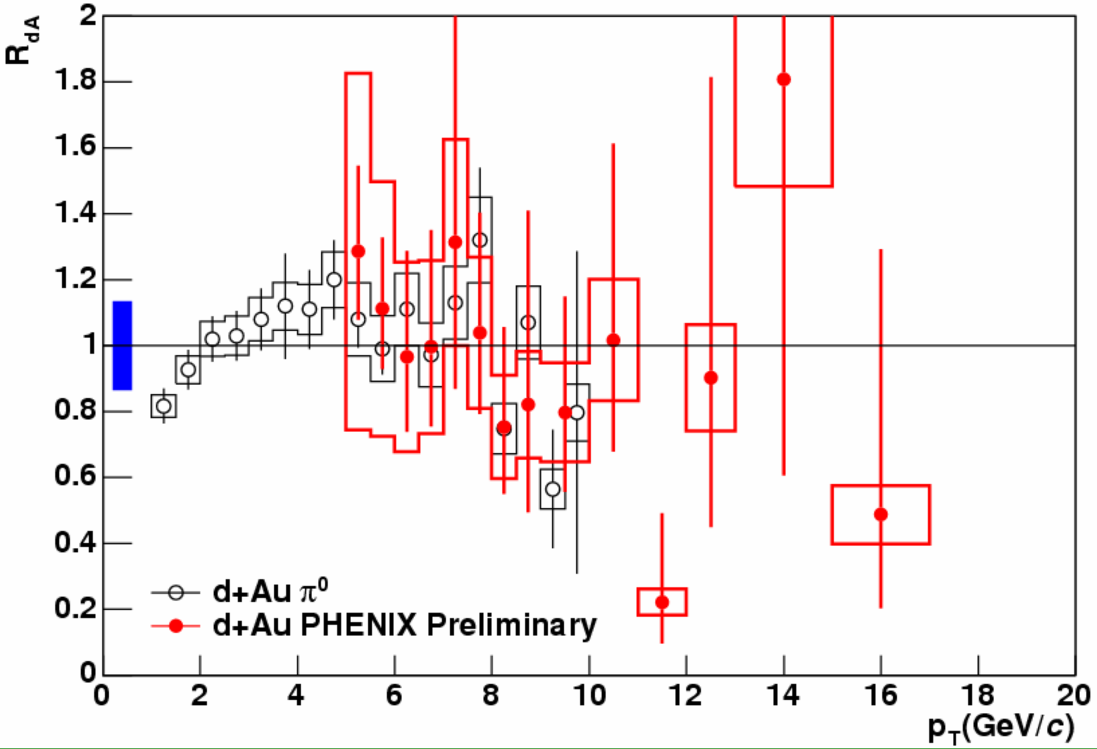
Result is consistent with the binary – scaled NLO-pQCD calculation



Result

Nuclear Modification Factor

$$R_{dA} = \frac{\left[d^2N_{dA}/dp_T\, d\eta\, dN_{evt}\right]}{\langle N_{coll}\rangle / \sigma_{pp}^{inel} \times \left[d^2\sigma_{pp}/dp_T\, d\eta\right]}$$



Consistent with 1 ➔ No modification within the error

This is consistent with what we measured in π^0