Prompt photon measurements with PHENIX's MPC-EX detector

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2/8/2013

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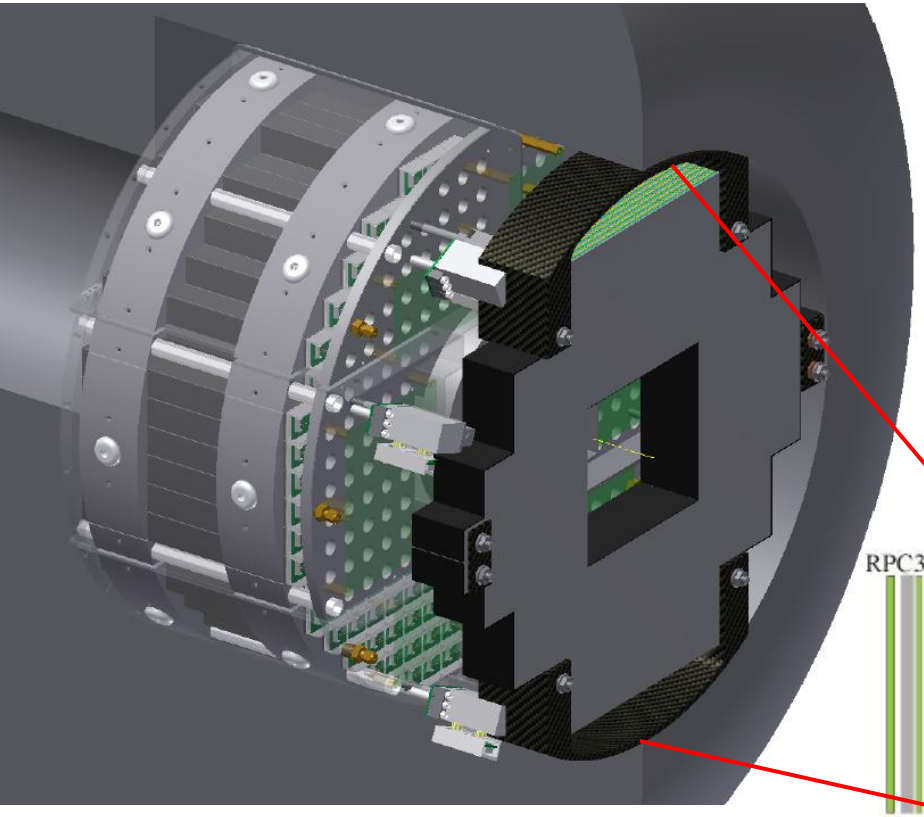
Outline

- MPC-EX detector
- Prompt photon in p+Au
- Prompt photon A_N in p+p
- Polarized p+Au

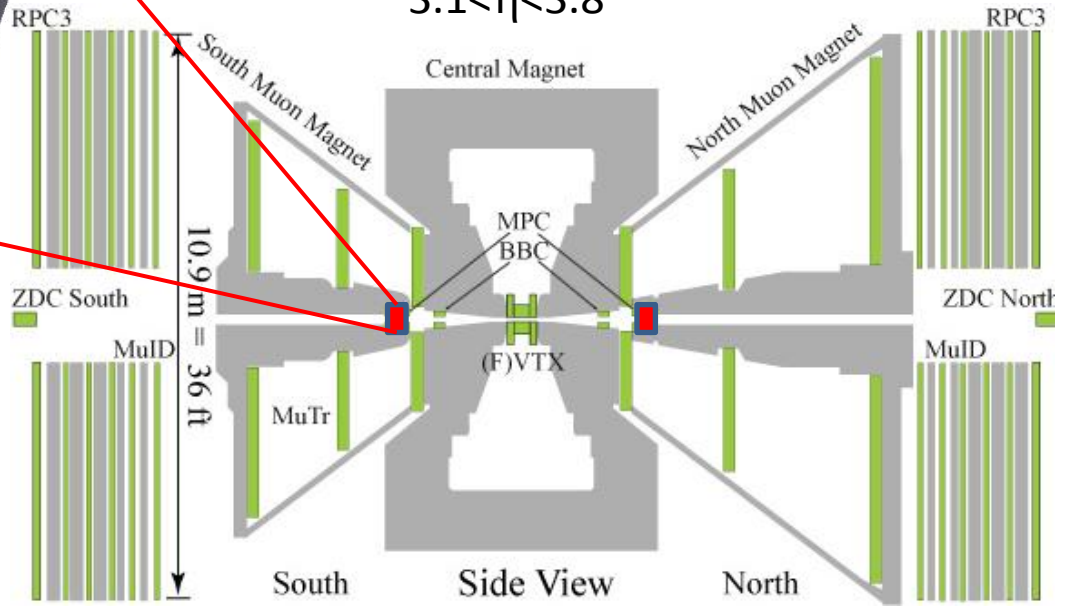
The MPC-EX Detector



A combined charged particle tracker and EM preshower detector – dual gain readout allows sensitivity to MIPs and full energy EM showers.

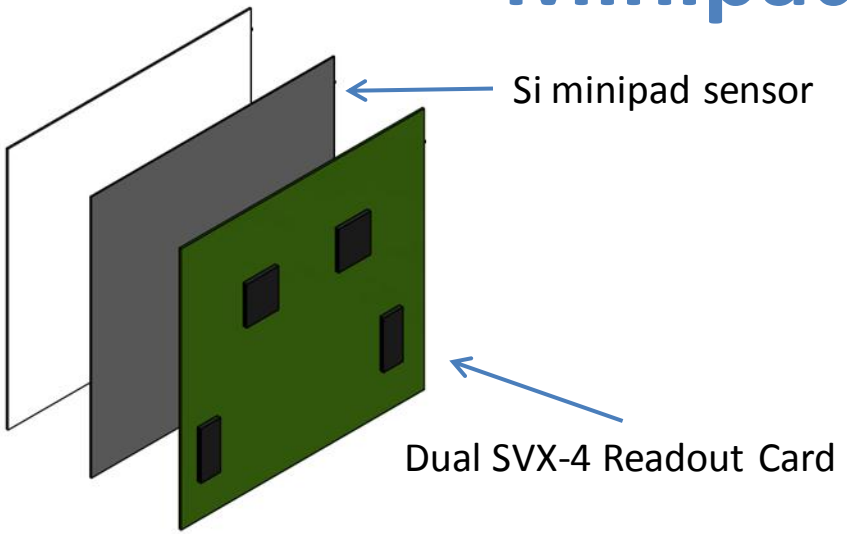
- π^0 rejection (prompt photons)
- π^0 reconstruction out to >80GeV
- Charged track identification

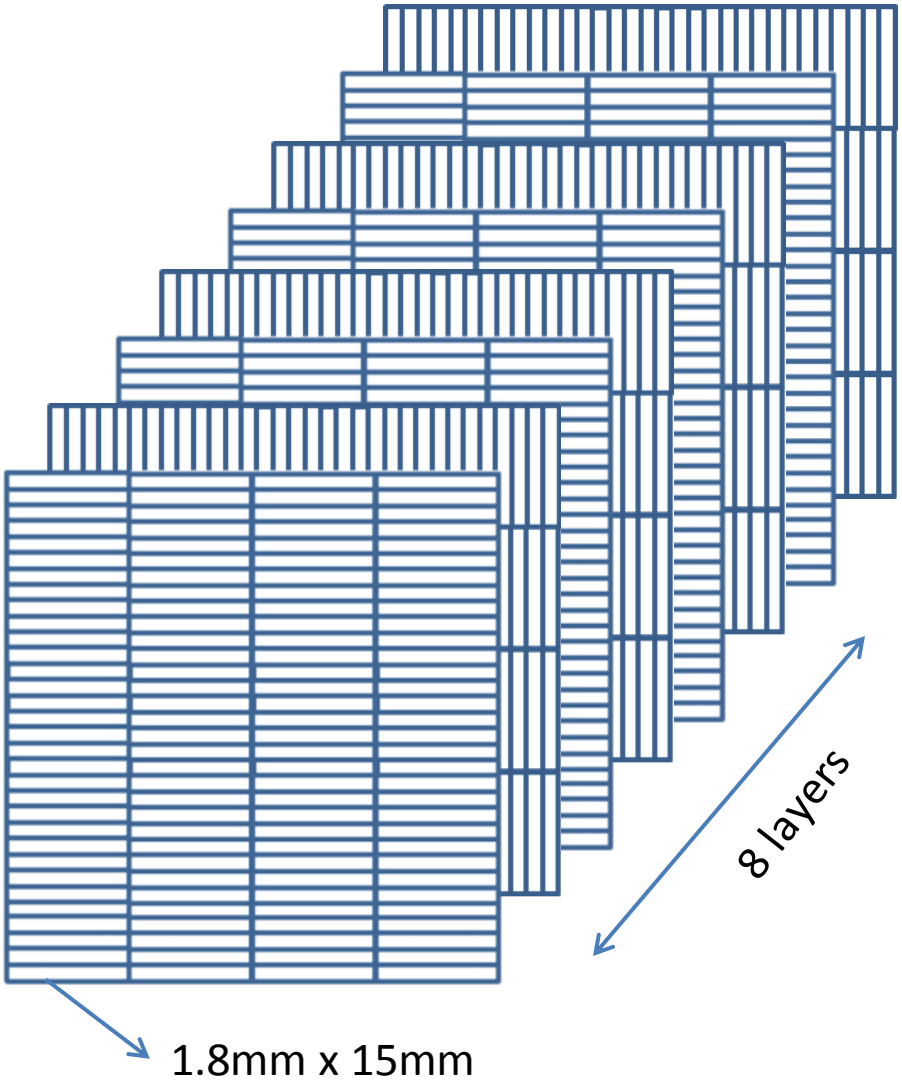
$3.1<\eta<3.8$



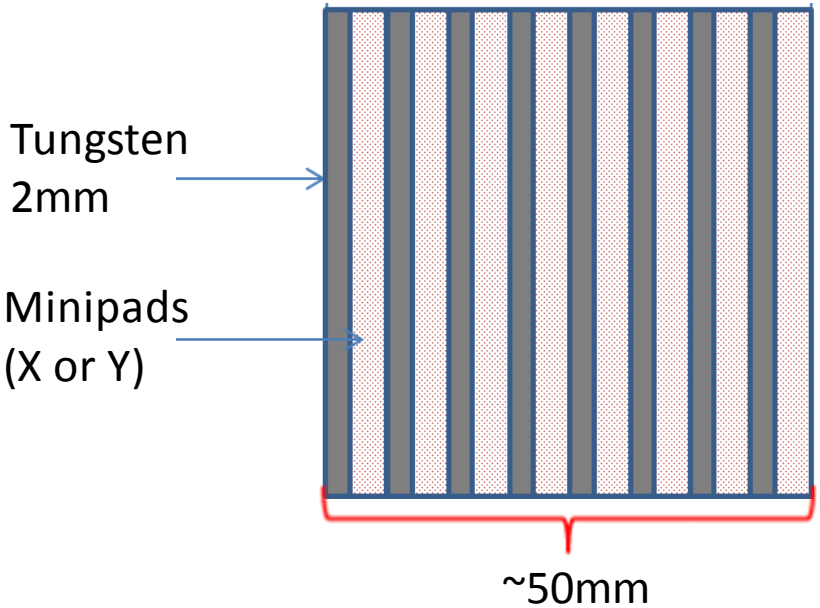
Approved by BNL and DOE
→ will be ready for Run-15
(earliest p+Au run)

Minipad Sensors



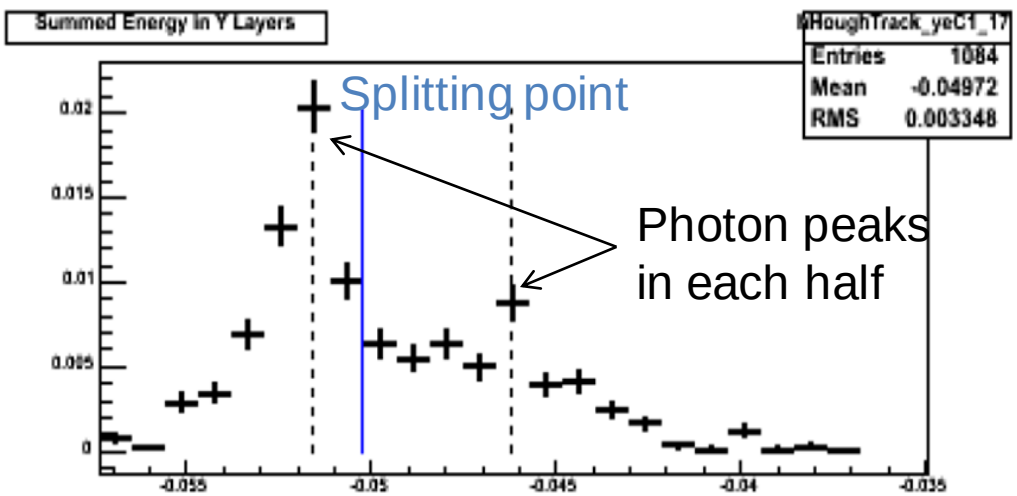


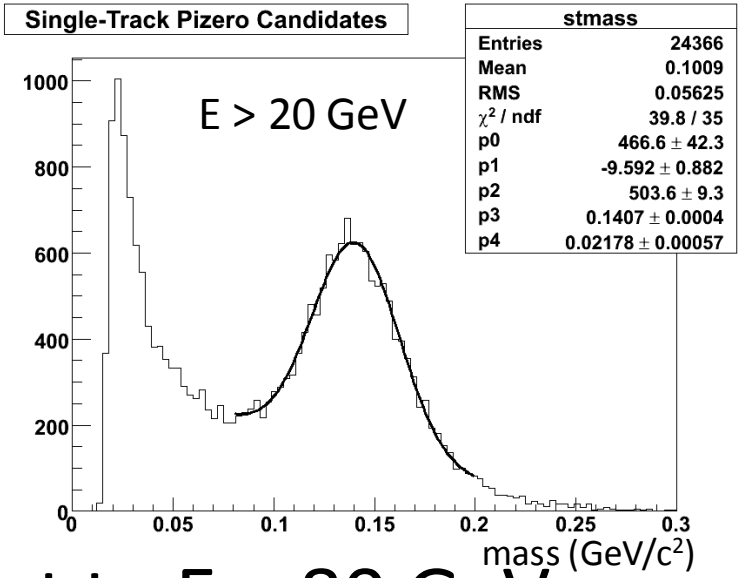
Cross-Section View:



π^0 rejection

- At E > 20 GeV, π^0s in one track in MPC-EX
- Split energy distributions into two parts
  - Iterate until find stable splitting point
  - Find energy of the halves
- Calculate mass from two halves



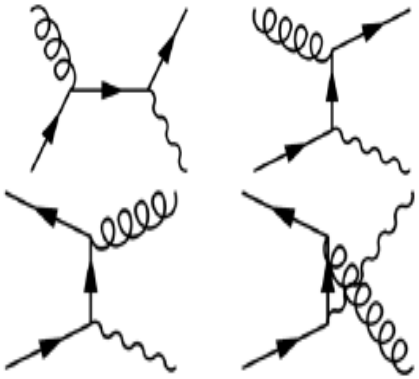


- Able to separate π^0 and γ out to E > 80 GeV

Prompt Photons at Forward Rapidity

Direct Photons

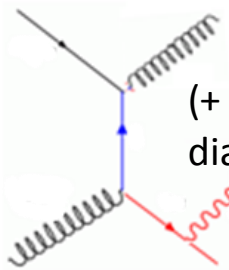
Dominated by gluon Compton at forward rapidites



Same level of production in Pythia and NLO calculations (within ~2x)

Fragmentation Photons

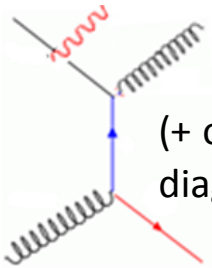
Comparable between pythia and NLO calculations



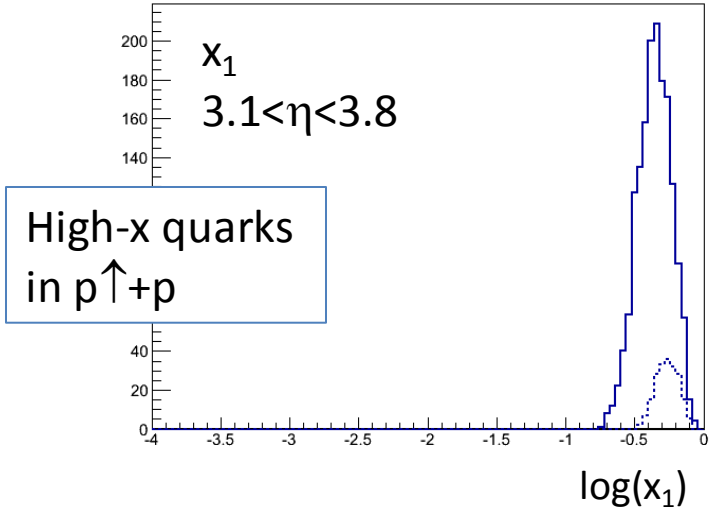
(+ other diagrams)

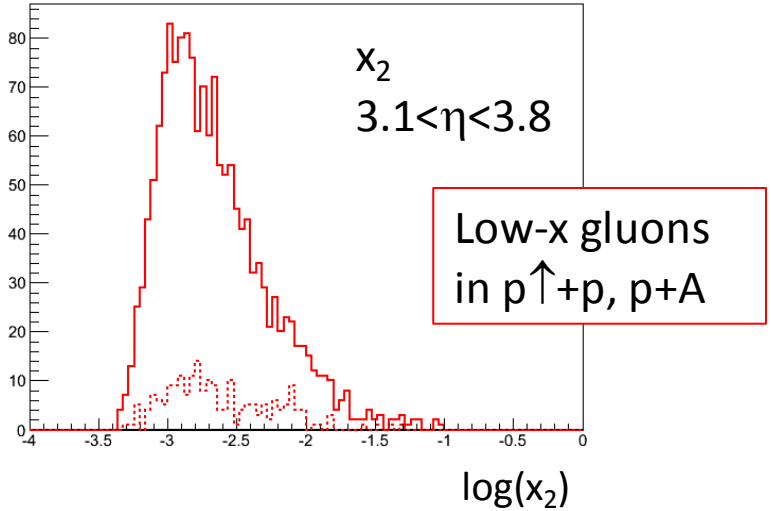
QED Radiation (initial state)

Production over-estimated in Pythia (Included in direct in NLO)



(+ other diagrams)



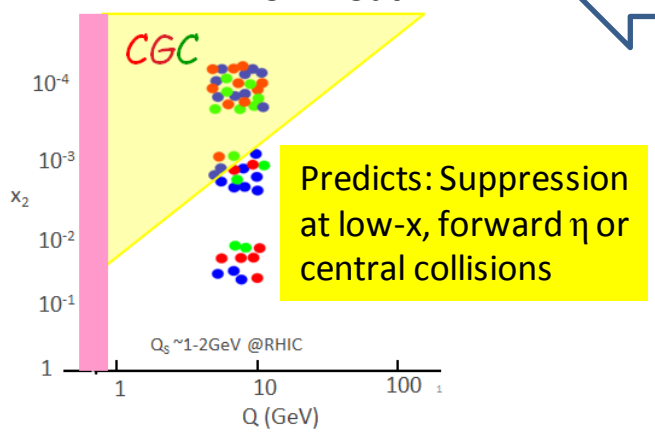


Prompt photons in p+Au

Two pictures of p+Au

Color Glass Condensate

- High gluon density
  - Treat classically
- Saturation scale: Q_{sat}
- Assumes $\alpha_S(Q_{Sat})$ small



Equivalence

F Dominguez, C. Marquet, B-W. Xiao, F. Yuan
PRD 83 (2011) 105005

???

Non-perturbative extensions to pQCD

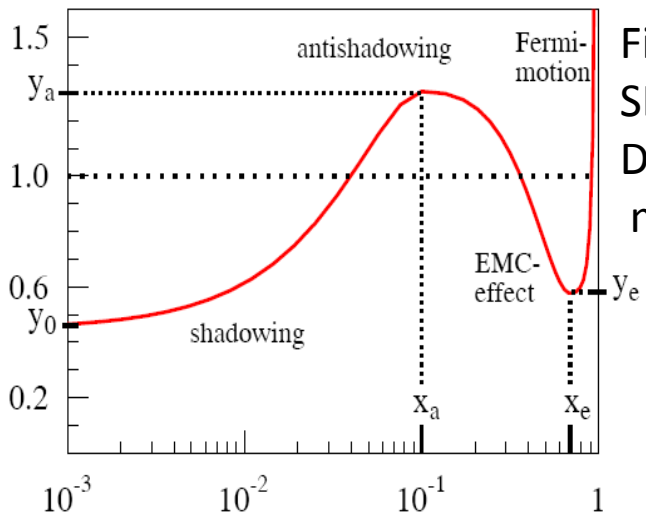
- Transverse momentum (k_T) dependent PDFs at low-x
  - G^1, G^2
- Higher twist shadowing effects
- Initial state energy loss
- Absorption
- Modified structure functions
- Coherent effects

Important:

- Fundamental understanding of partonic processes in nuclei
- Initial conditions at RHIC and the LHC

Gluons in Nuclei

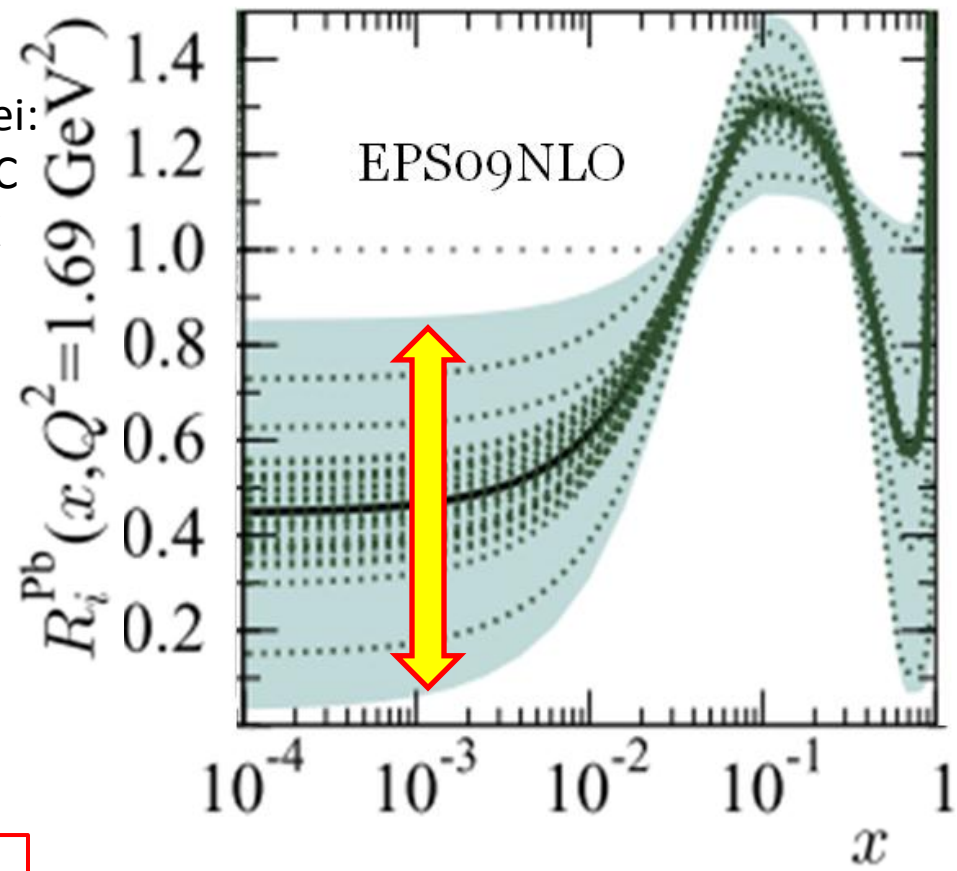
Shadowing/Saturation in nuclei



$$R_G{}^A(x,Q^2) = \frac{xG_A(x,Q^2)}{AxG_p(x,Q^2)}$$

Fit data on nuclei:
SLAC, NMC, EMC
DIS+DY+PHENIX
midrapidty π^0

Eskola , Paukkunen, Salgado, JHP04 (2009)065



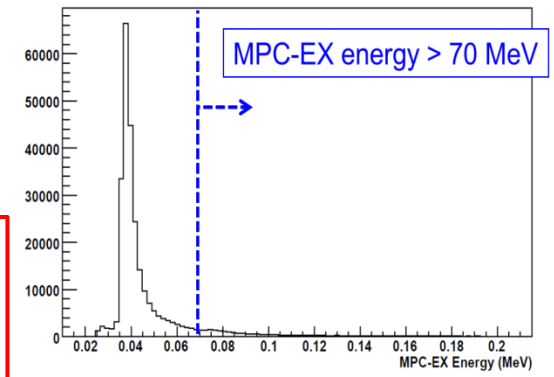
Large uncertainties in gluon nPDF at low-x

→ Lack of data at low-x

EPS09 is used as a baseline for comparison. The MPC-EX measurement will address any model of low-x gluons.

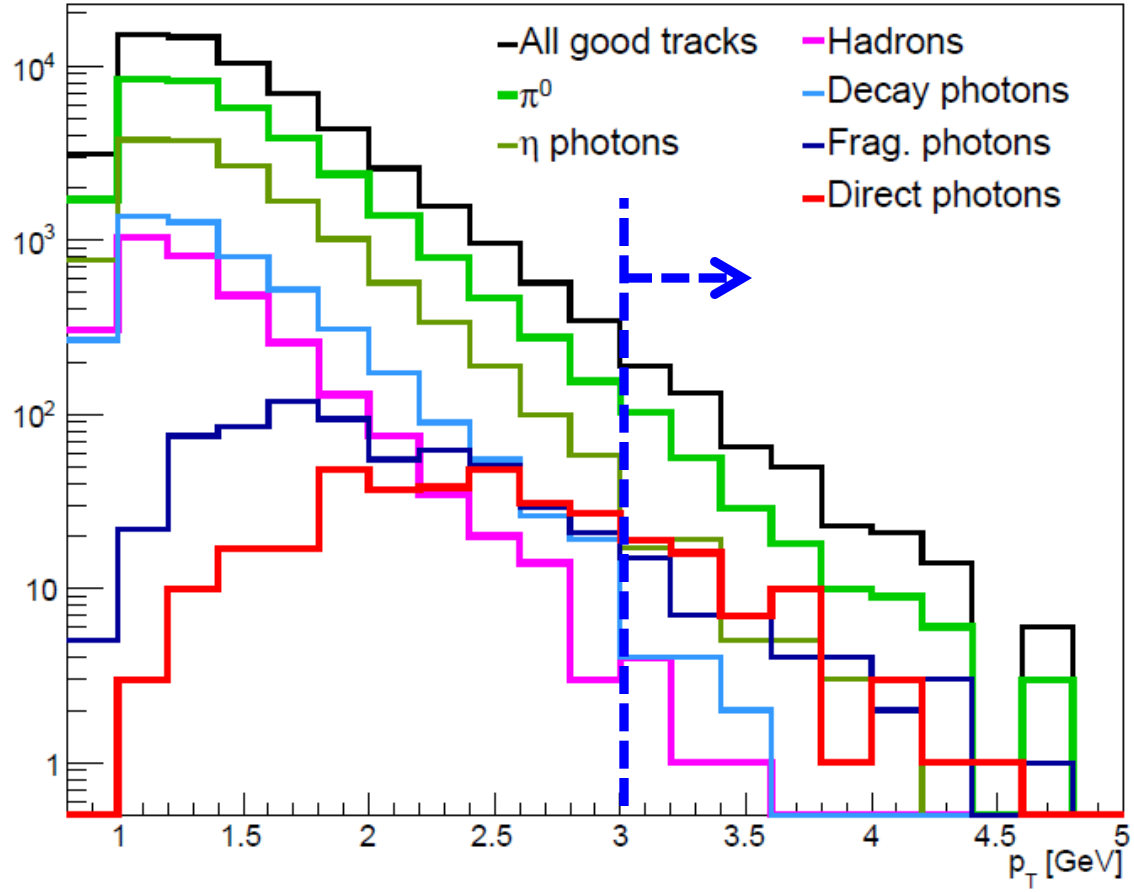
Finding prompt photons

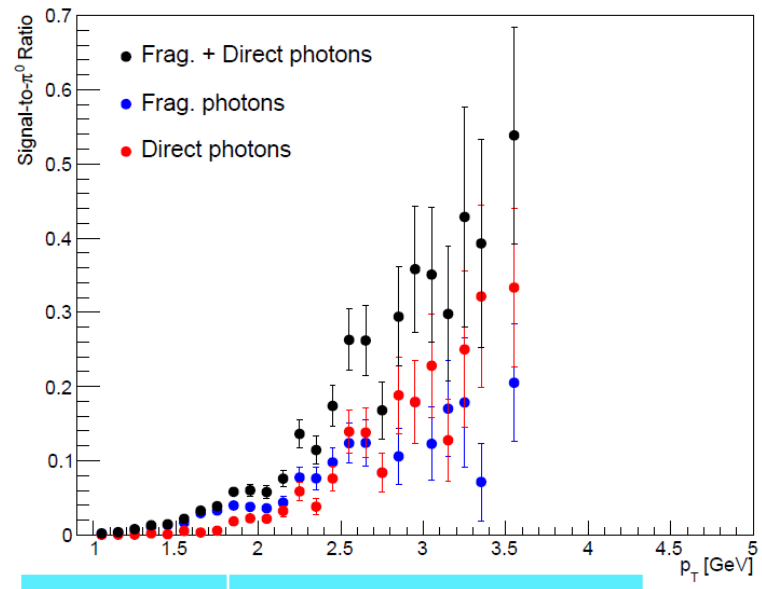
- 868 million MB p+p Pythia events
  - 16.5 GeV MPC trigger, +/- 50 cm vertex cut
- Remove hadrons
  - MPC-EX energy deposition
  - Shower shape in MPC, MPC-EX
  - p_T > 3 GeV
- Remove π^0s
  - MPC-EX energy distribution i.e. mass
  - Shower shape in MPC, MPC-EX
  - p_T > 3 GeV
- Reduce frag. photons
  - Track isolation cuts



Cuts optimized using multivariate analysis

Prompt photon yields

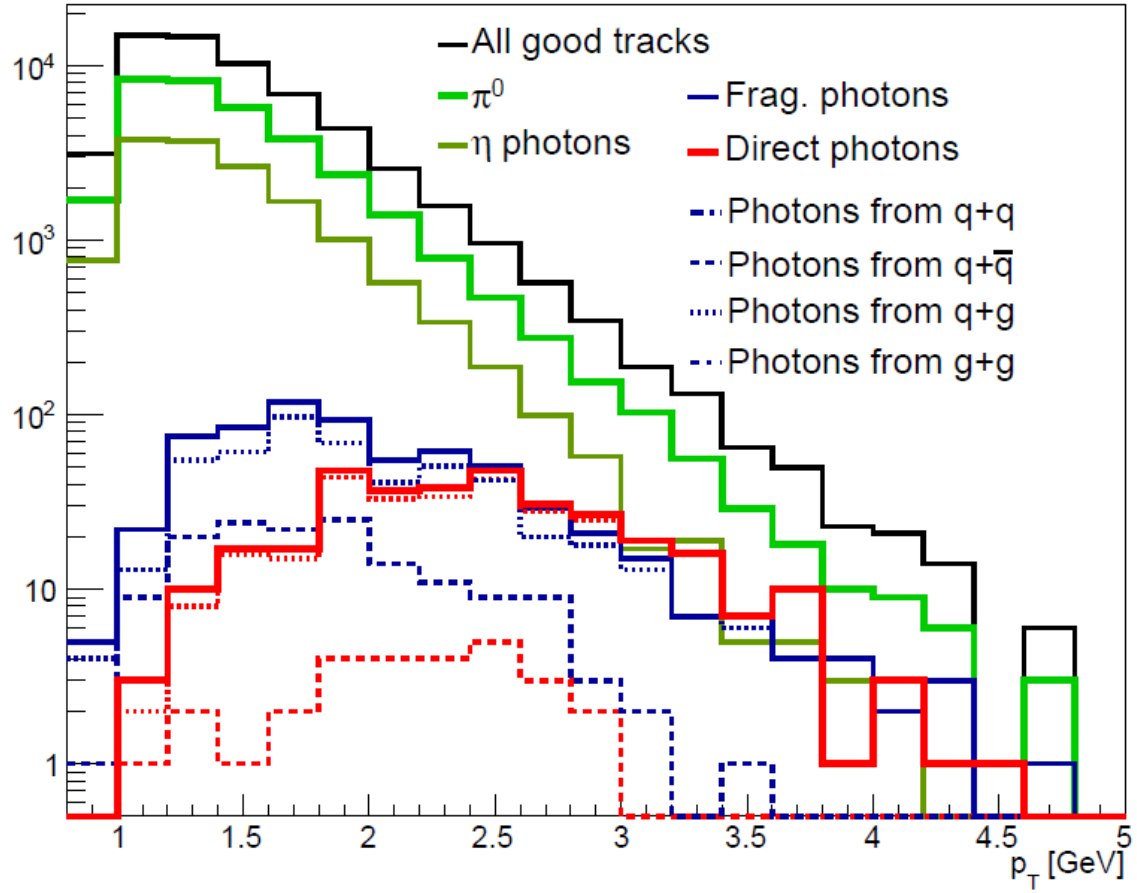




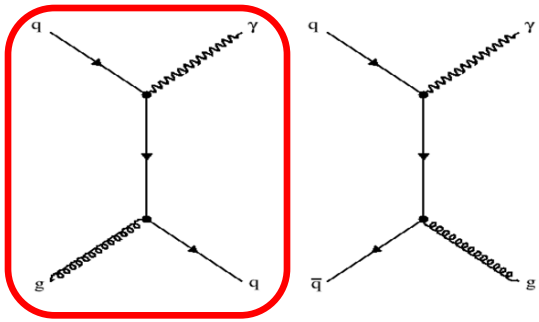
- 49 pb^{-1} p+p, 350 nb^{-1} p+Au
- 43% signal-to-π^0 ratio
- 57.4% direct-to-signal ratio

Particle	Yield p_T > 3 GeV	
	p+p	p+Au
Hadrons	14,294	847
π^0	557,448	33,049
η	121,495	7,203
Decay γ	26,205	1,554
γ_{Signal}	240,608	14,265
$\gamma_{Frag.}$	102,437	6,073
γ_{Direct}	138,171	8,191

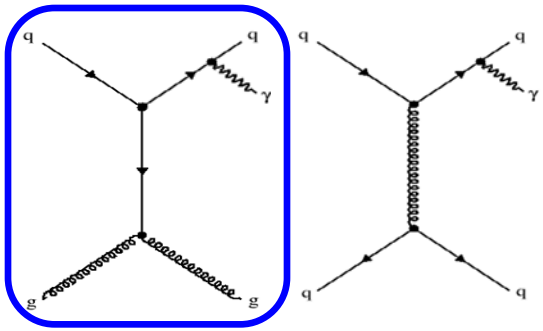
Processes breakdown



Direct photons



Frag. photons

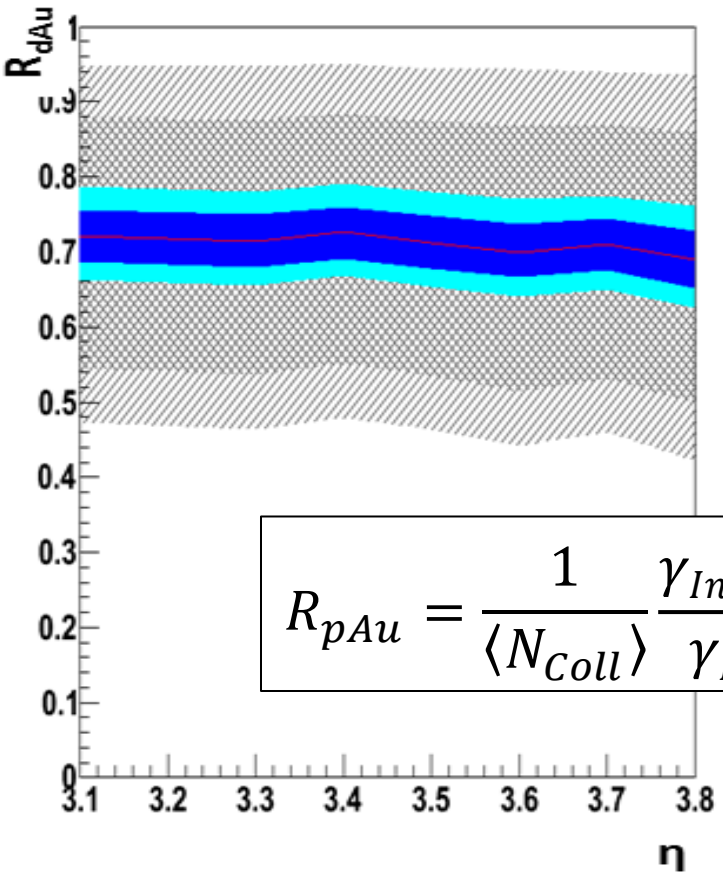


- Direct photons 100% $q + g$ at $p_T > 3$ GeV
- Frag. Photons 93% $q + g$ at $p_T > 3$ GeV
  - 7% $q + \bar{q}$ at $p_T > 3$ GeV

Double ratio method

$$\gamma_{\text{Signal}} = \gamma_{Incl} * (1 - 1/R_\gamma)$$

$$R_\gamma = \frac{\left(\frac{\gamma_{Incl}}{\pi^0}\right)_{Meas}}{\left(\frac{\gamma_{Incl}}{\pi^0}\right)_{Sim}} = 1.34$$



- γ_{Incl} is the inclusive photon yield after hadron subtraction
- $(\gamma_{Incl} / \pi^0)_{Sim}$ is the simulated photon-to-pion ratio

$$R_{pAu} = \frac{1}{\langle N_{Coll} \rangle} \frac{\gamma_{Incl}{}^{pAu} * (1 - 1/R_\gamma{}^{pAu})}{\gamma_{Incl}{}^{pp} * (1 - 1/R_\gamma{}^{pp})}$$

- R_{pA} using EPS09 baseline

Systematic errors

$$\Delta R_\gamma = \frac{\delta R_\gamma}{\delta \gamma_{Incl}} \Delta \gamma_{Incl} \oplus \frac{\delta R_\gamma}{\delta \pi^0} \Delta \pi^0 \oplus \frac{\delta R_\gamma}{\delta MC_{sim}} \Delta MC_{sim}$$

- 6% error in π^0 cross section
- 4% error in MC simulation
- 20% error in hadron subtraction

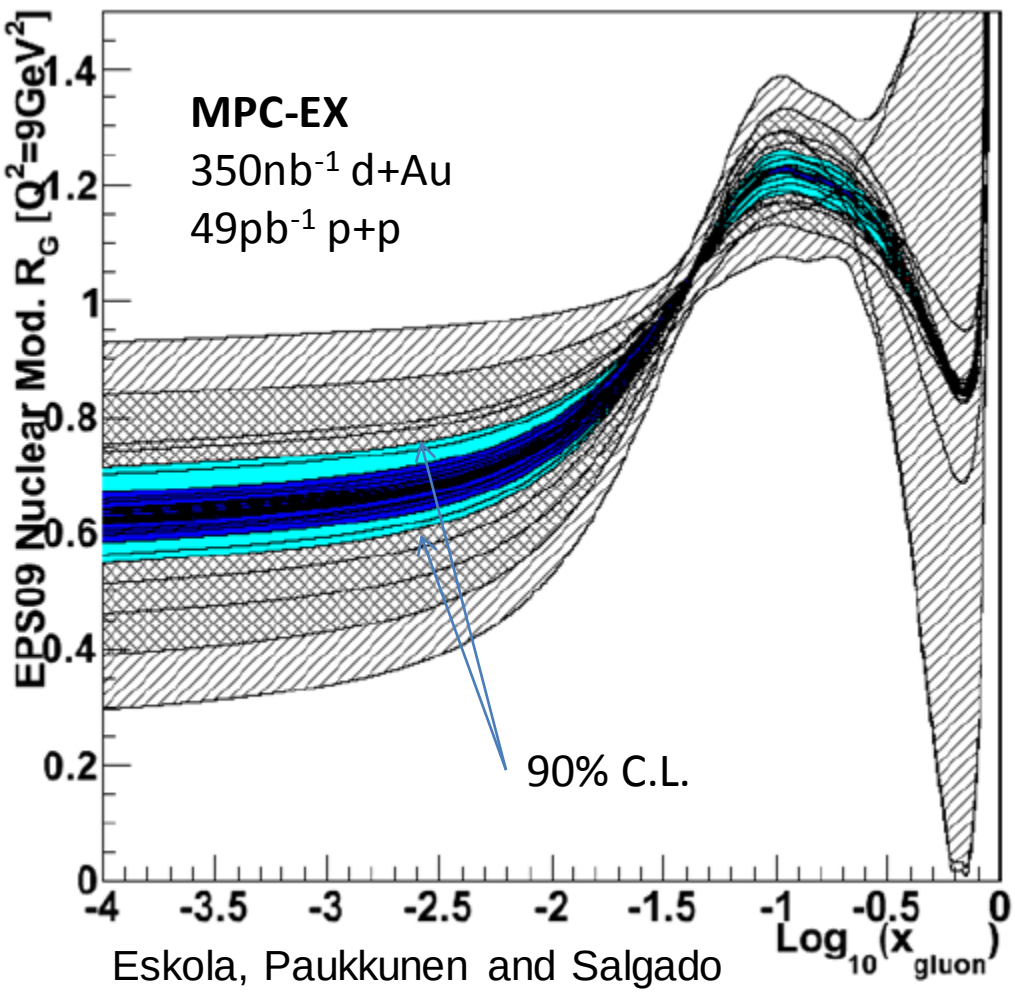
direct-to-signal ratio	57.4%
$\Delta\gamma_{Incl}/\gamma_{Incl}$	0.65%
R_γ	1.34
$\Delta R_\gamma / R_\gamma$	7.22%

- Correlated and uncorrelated components of sys. error between p+Au and p+p

Quantity	Sys. Error
Sys. error $\Delta R_\gamma/R_\gamma$ correlated	7.2%
Sys. error $\Delta R_\gamma/R_\gamma$ uncorrelated	1%
Sys. error $\Delta\gamma_{Incl}/\gamma_{Incl}$ uncorrelated	2%
Relative sys. error on $\langle N_{Coll} \rangle$	3%

EPS09 Limits from Prompt Photons

- Weight events in x, Q^2 according to EPS09 to generate R_{pAu} for each curve
- Assume the R_{pAu} value we measure corresponds to the EPS09 baseline
- Vary R^{pp}_{γ}, R^{pAu}_{γ}, γ^{pAu}_{incl} and γ^{pp}_{incl} within 3-sigma systematic errors
- Evaluate EPS09 curves to see which are consistent within 90% C.L.

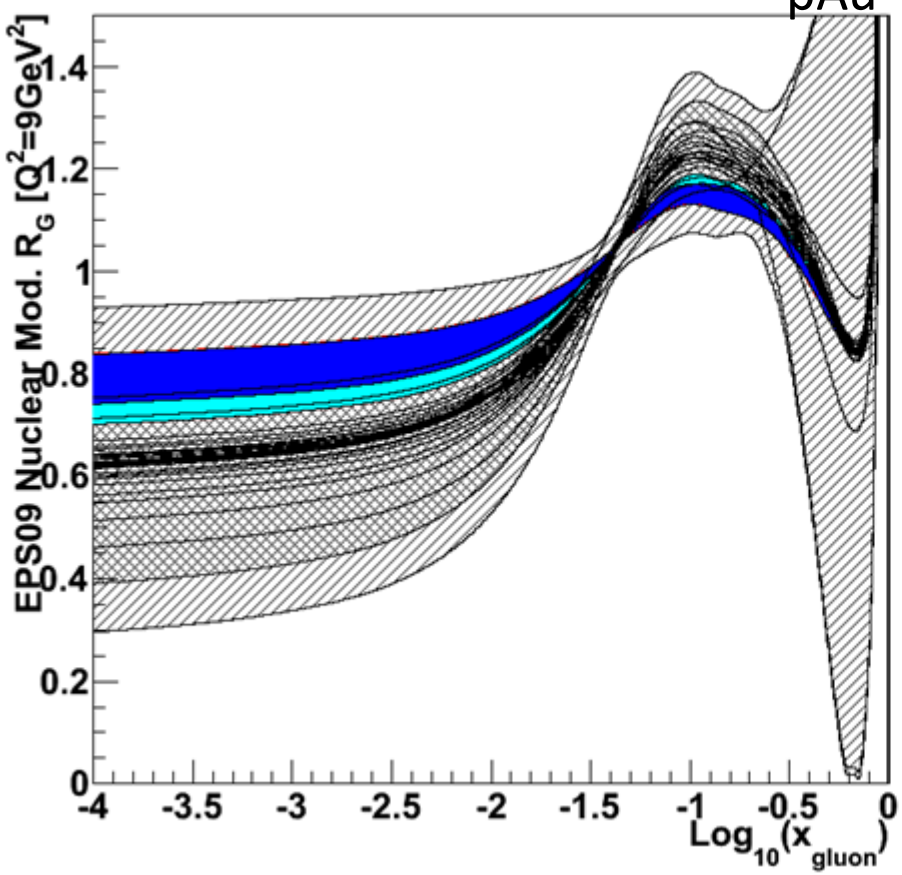


Eskola, Paukkunen and Salgado 2009 *JHEP* 0904:0652

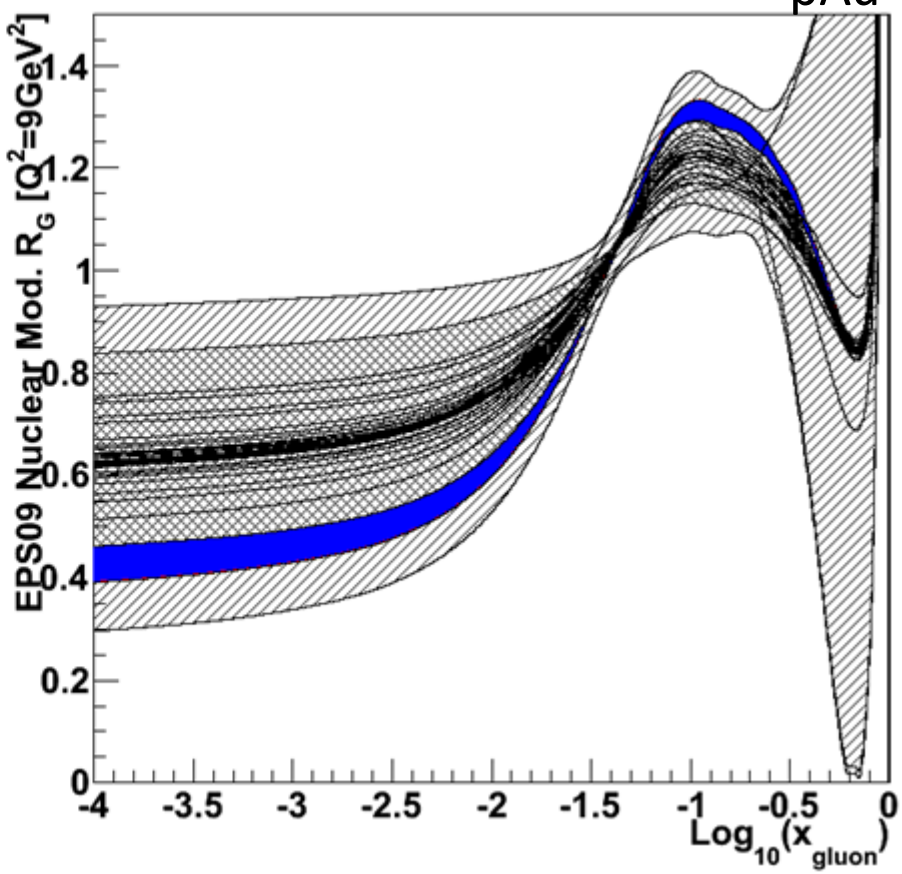
Prompt photons in MPC-EX -> Precise Measurement of the Nuclear Gluon PDF

Additional EPS09 limits

- Assume maximum EPS09 value for R_{pAu}



- Assume minimum EPS09 value for R_{pAu}



Prompt photon in p↑+p

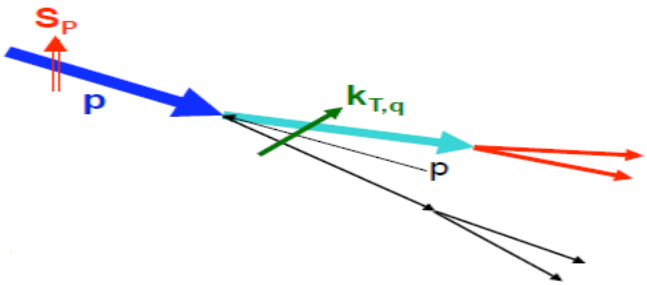
Sources of Transverse SSA's

- **"Sivers effect"**

TMD: Correlation between nucleon spin and parton k_T.

Phys. Rev. D **41**, 83 (1990)
Phys. Rev. D **43**, 261, (1991)

$$d\sigma^{\uparrow} \propto \underbrace{\bar{f}_{1T}^{\perp q}(x,k_{\perp}^{2})}_{\text{Sivers distribution}} \cdot D_{q}^{h}(z)$$



Twist-3: Quark-gluon correlations in polarized hadron

Phys. Rev. D **59**, 014004 (1998)

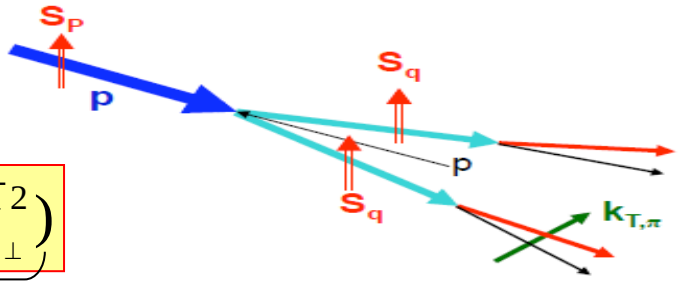
$$gT_{q,F}(x,x) = -\int d^{2}k_{\perp} \frac{|k_{\perp}|^{2}}{M} f_{1T}^{\perp q}(x,k_{\perp}^{2})$$

- **"Collins effect"**

TMD: Transversity distributions + Spin dependent fragmentation functions

Nucl. Phys. B 396, 161 (1993)

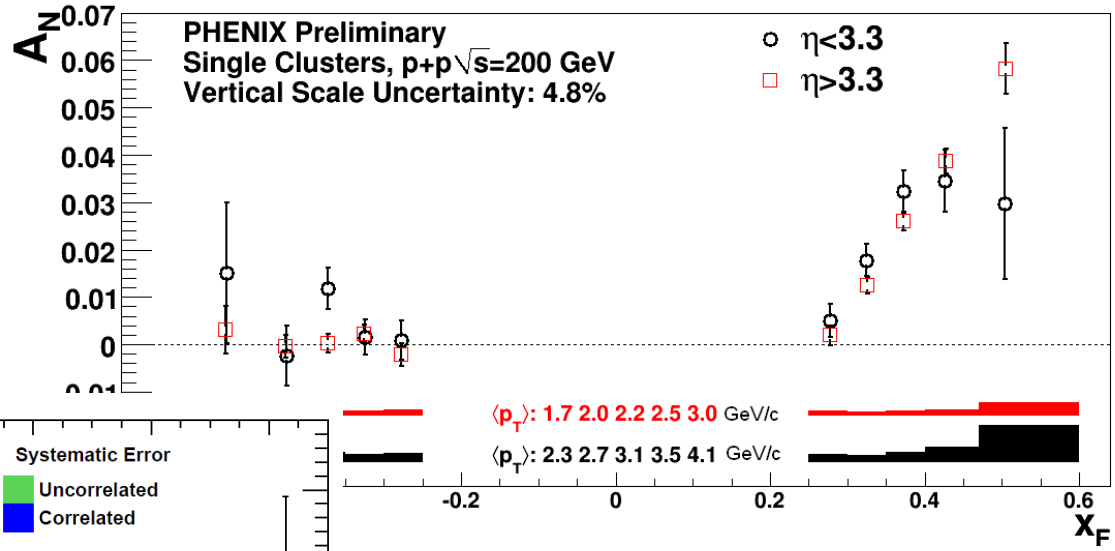
$$d\sigma^{\uparrow} \propto \underbrace{\delta q(x)}_{\text{Transversity}} \cdot \underbrace{H_{1}^{\perp}(z_{2},\bar{k}_{\perp}^{2})}_{\text{Collins FF}}$$

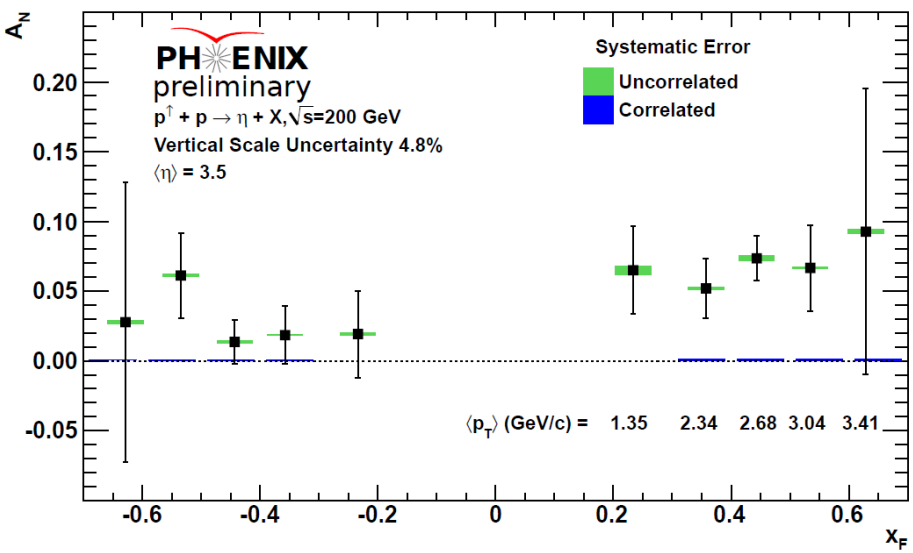


Twist-3: Transversity combined with twist-3 quark-gluon fragmentation function

Single Spin Asymmetries in PHENIX MPC

Neutral Clusters





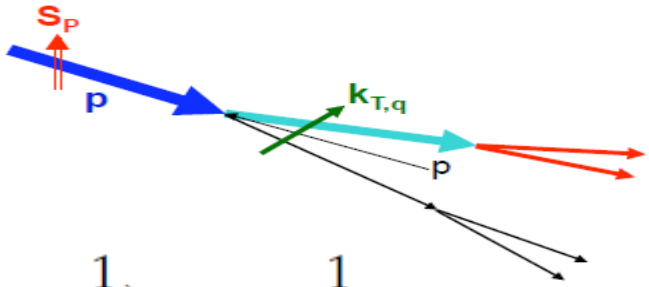
Identified η mesons

Current measurements cannot determine the <u>source</u> of these asymmetries

- Need more targeted measurements

Prompt Photon A_N (x_F>0)

- High-x quark in proton

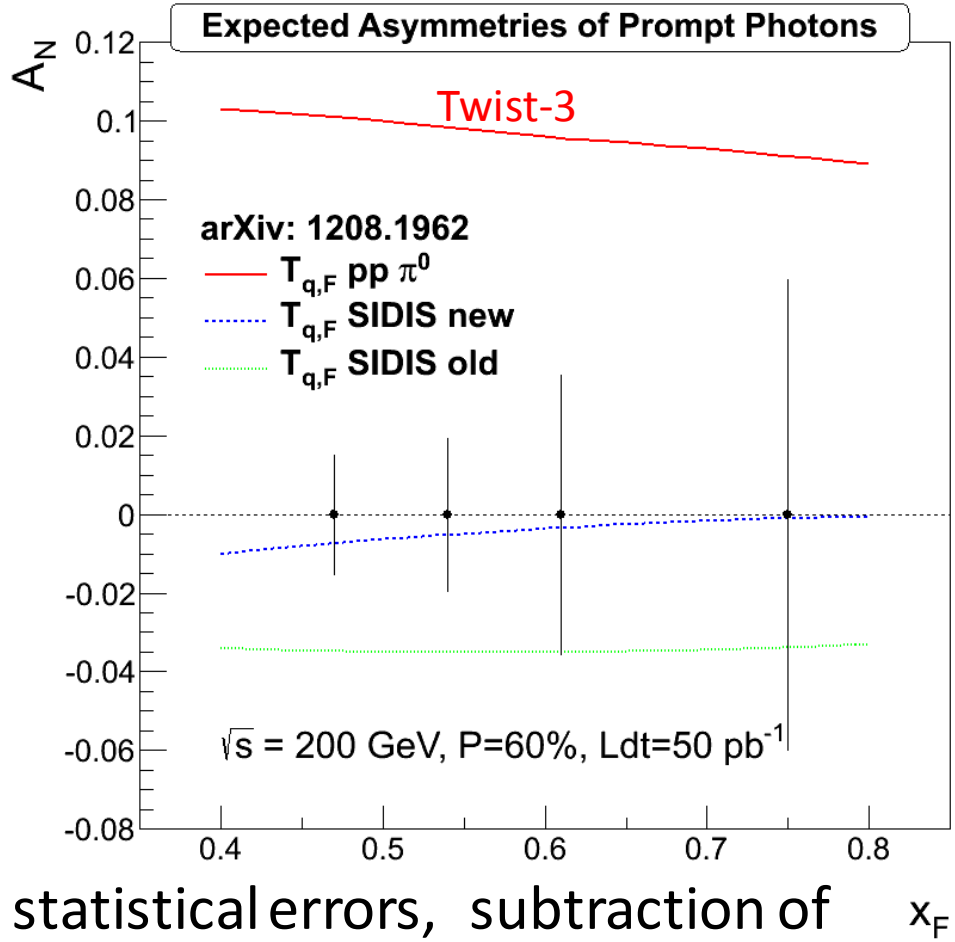


$$A_S = (1+\frac{1}{r})A_{meas} - \frac{1}{r}A_B.$$

r= S/B = 0.34

$$(\delta A_S)^2 = (1+\frac{1}{r})^2(\delta A_{meas})^2 + (\frac{1}{r})^2(\delta A_B)^2.$$

Kang, Qiu, Vogelsang and Yua, Phys Rev. D 83 094001 (2011)
Gamberg and Kang, arXiv 1208.1962v1 (2012)

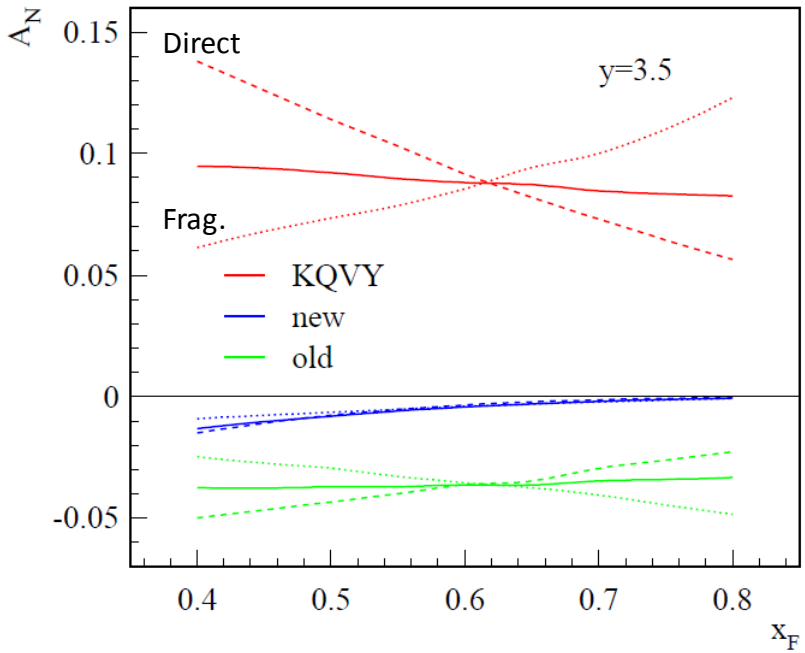


- <u>Prompt Photon A_N</u>
  - Measure quark Sivers effect
  - Test theoretical frameworks
  - Projected error bars assume statistical errors, subtraction of π^0 and η photon asymmetry, and 60% polarization

Prompt photon A_N (x_F > 0) with MPC-EX will determine the sign of the Sivers Effect.

Separating Direct and Frag. Photons

Gamberg and Kang, arXiv 1208.1962v1 (2012)



Can control the direct/frag ratio with tightened isolation cuts in the MPC/MPC-EX

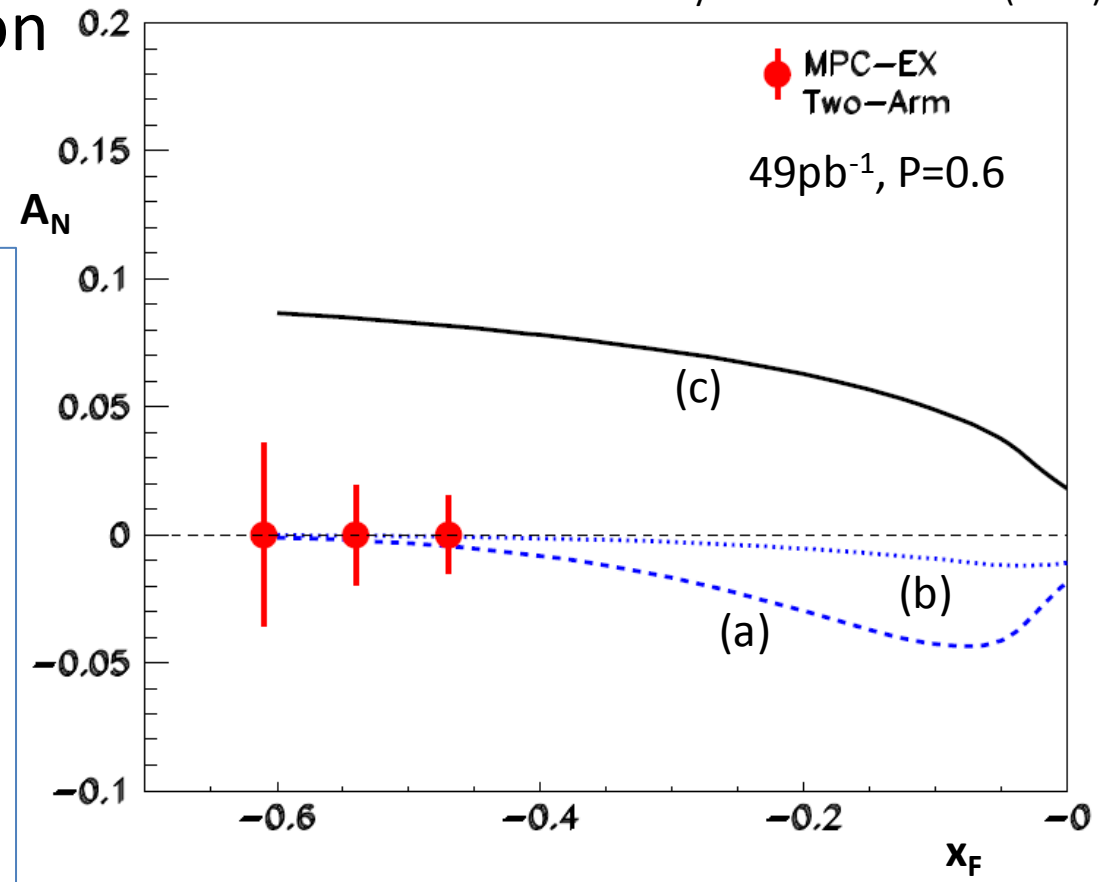
Tightening cuts →

	Basic Cuts	Cuts 1	Cuts 2
Direct-to-signal ratio	57.4%	68.3%	78.6%
R_γ	1.34	1.31	1.31
Signal-to-π^0 ratio	43 ± 5 %	37 ± 7 %	40 ±13 %
Direct photon ϵ	31.2%	15.1%	5.9%
Frag. photon ϵ	24.3%	7.3%	1.7%

Prompt Photon A_N (x_F<0)

- Low-x gluon distribution in proton

Koike and Yoshida Phys Rev. D 85 034030 (2012)



Two tri-gluon correlation functions: *O(x)* and *N(x)*

Models:

$(a)\ O(x) = K_G x G(x) \qquad N(x) = O(x)$

$(b)\ O(x) = K_G' \sqrt{x} G(x) \qquad N(x) = O(x)$

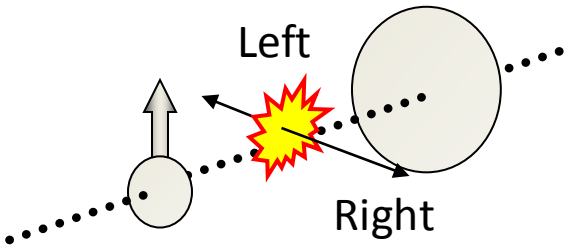
$(c)\ O(x) = K_G x G(x) \qquad N(x) = -O(x)$

Parameters constrained by open heavy flavor production at RHIC.

Prompt photon A_N (x_F<0) carries information about the tri-gluon correlation function.

p↑+A

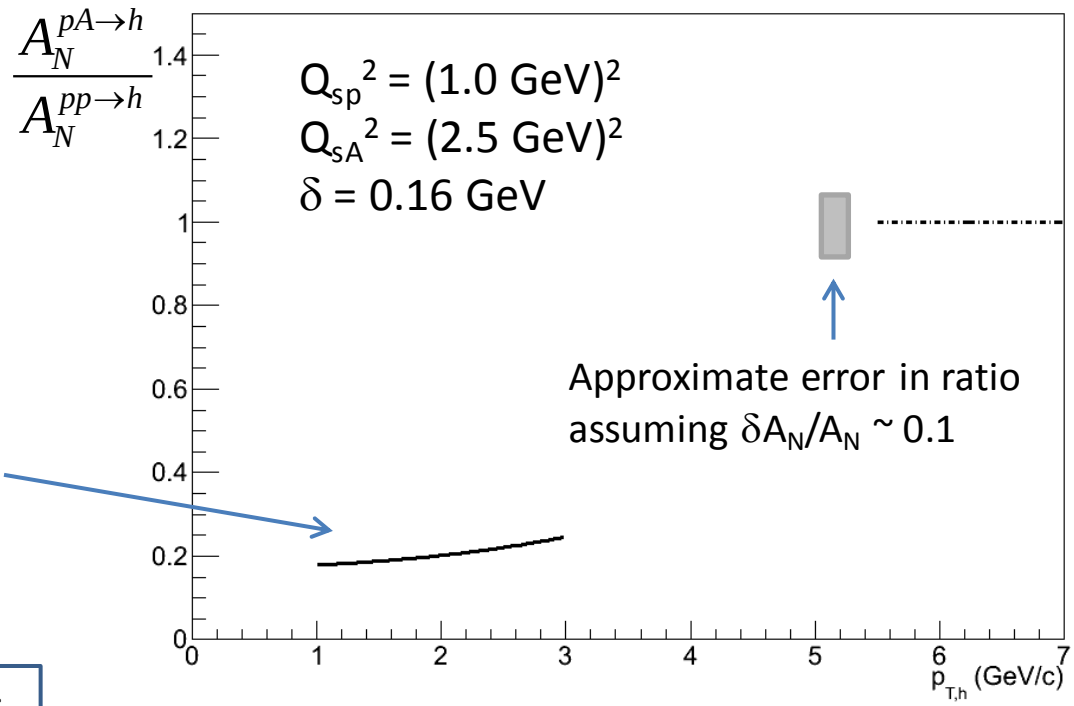
Polarized p+A Collisions



$$A_N = \frac{1}{P}\frac{\sigma_L^\pi - \sigma_R^\pi}{\sigma_L^\pi + \sigma_R^\pi}$$

$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 << Q_{sA}^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{P_{h\perp}^2 \delta^2 / Q_{sp}^2}$$

Kang and Yaun, PRD 84 034019 (2011)
(asymmetries modeled as Collins)



Single spin asymmetries can act as a probe of the saturation scale.

- Dependence of Q_{sA} on A
- With other measurements, estimate Q_{sp}

A unique capability of RHIC!

SSA's in p↑+A Collisions

$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 << Q_{sA}^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{P_{h\perp}^2 \delta^2 / Q_{sp}^4}$$

$$\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\Big|_{P_{h\perp} \gg Q_s^2} \approx 1$$

δ = 0.16 GeV

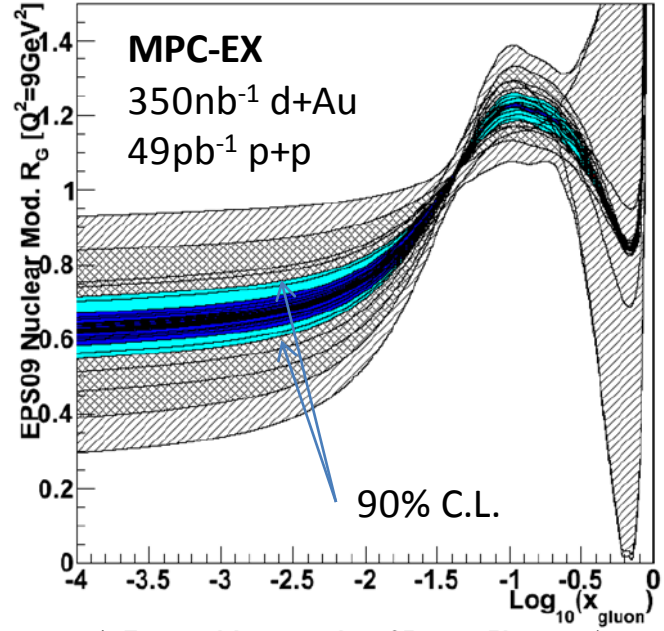
Kang and Yuan PRD 84 034019 (2011)

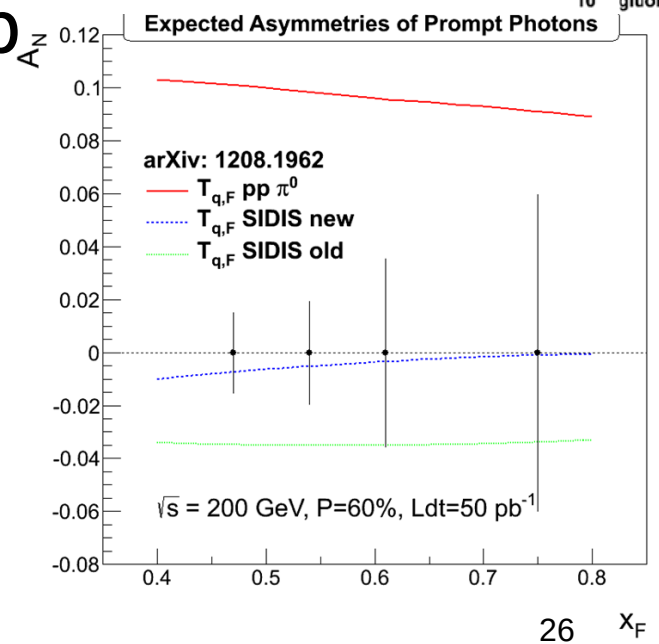
- π^0 A_N in p+p, p+Au, and p+Cu → $Q_{sA}^2 \propto A^{1/3} Q_{sp}^2$
- Intermediate p_T dependence being developed by Zhongbo Kang → Fit p_T dependence to get Q_{sp}^2 and Q_{sA}^2
- Prompt photon A_N → Change proportion of Sivers to Collins

Systematic study of SSA's in p↑+A collisions will allow us to study Q_{Sat}

Conclusions

- Measure the low-x gluon nPDF in cold nuclear matter
  - Further understanding saturation, shadowing, …
  - Set initial conditions for heavy ion collisions at RHIC and LHC
- Separate sources of SSA's in p↑+p
  - Deepen understanding of hadron structure
  - Continued progress in applying fundamental QCD to p+p
- Exciting future in p↑+A





Backup

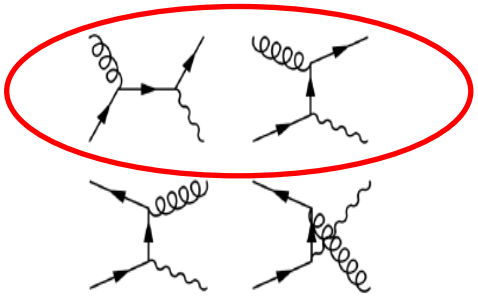
pA: Where to look?

- To study the precursor state of sQGP → pT ~ 1 GeV
  - E.g. multiplicity distributions
  - Pion correlations at low p_T
  - Problem: dependent on FF and/or gluon multiplication factor (CGC)
- Can we use "hard probes", something that comes directly from the vertex?

➡ Direct photons

- "low" Q^2 p_T> 3 GeV
- Forward region to probe "low-x" gluons

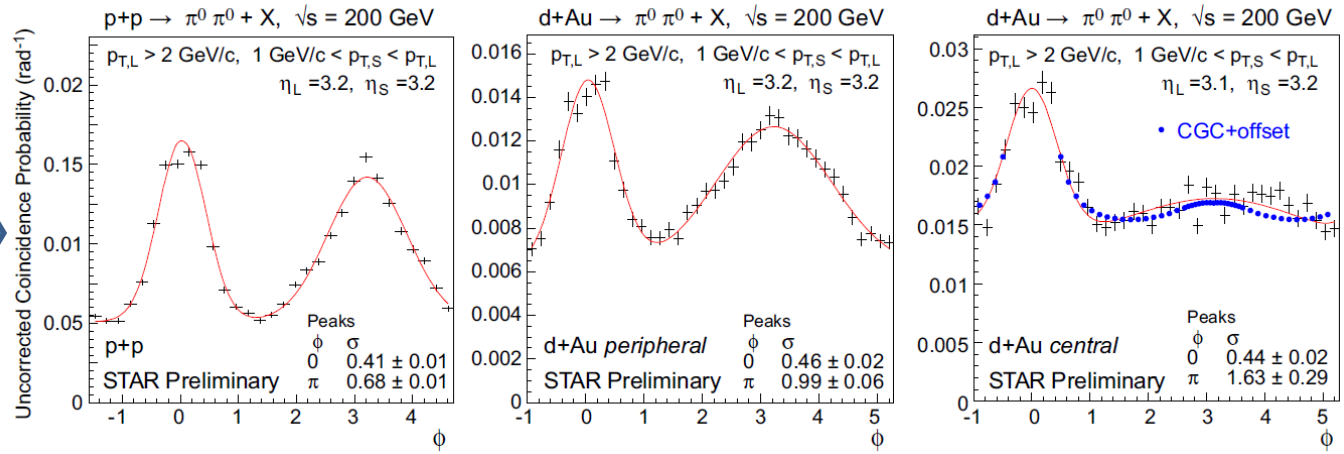
LO Direct Photon Diagrams:

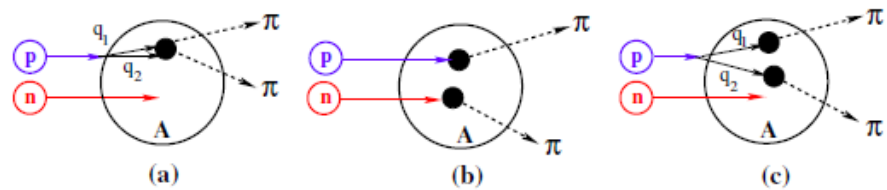


➡ Add direct photon capability to the MPC

Why p+A instead of d+A?

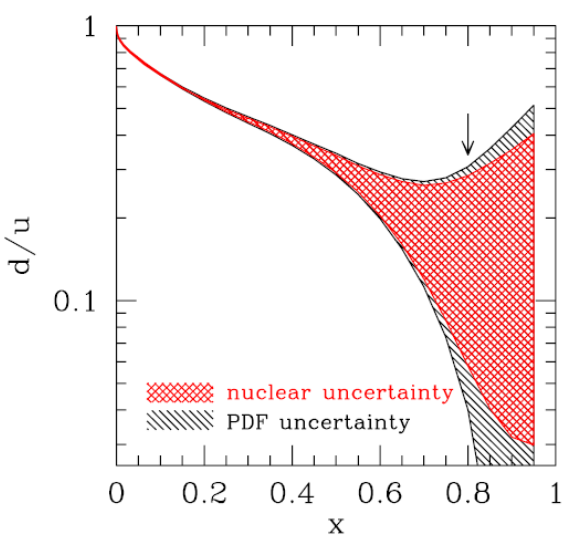
Multi-parton interactions not in p+A can contribute to the suppression of the away-side correlation strength.





M. Strikman, 1112.3834

Phys. Rev. D 84 014008 (2011)

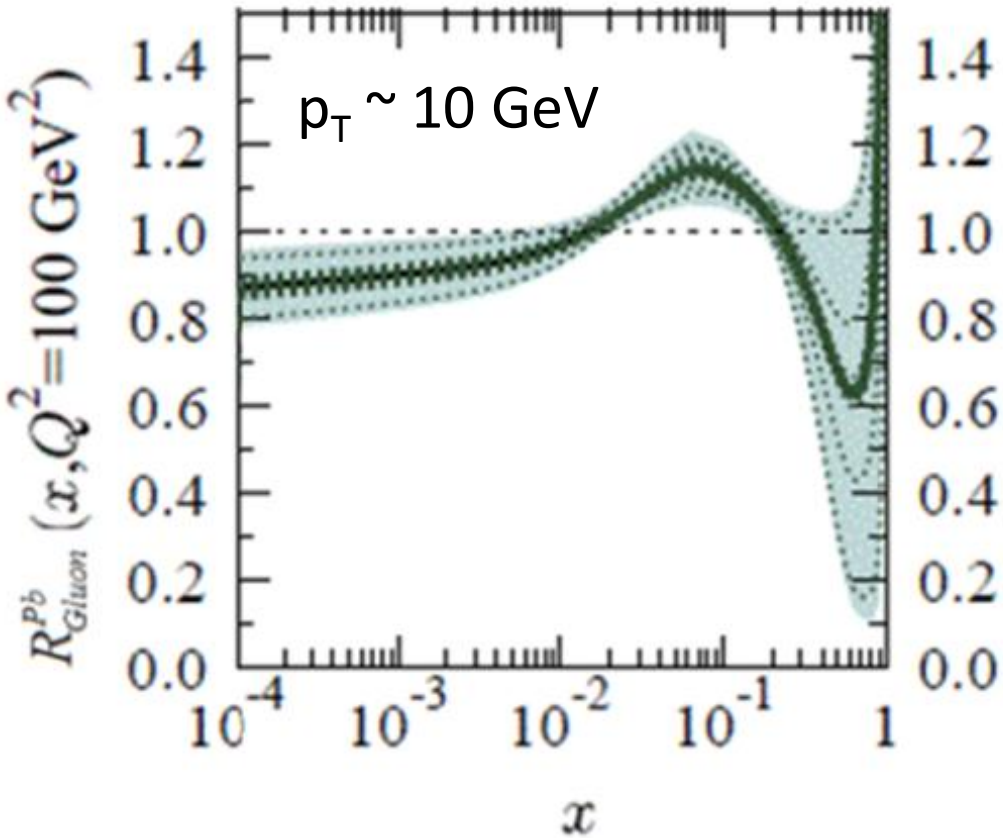


Forward rapidity corresponds to *high-x* in the projectile nucleon (d or p). Nuclear corrections at high-x are large for the deuteron, which may necessitate d+p running for proper comparison.

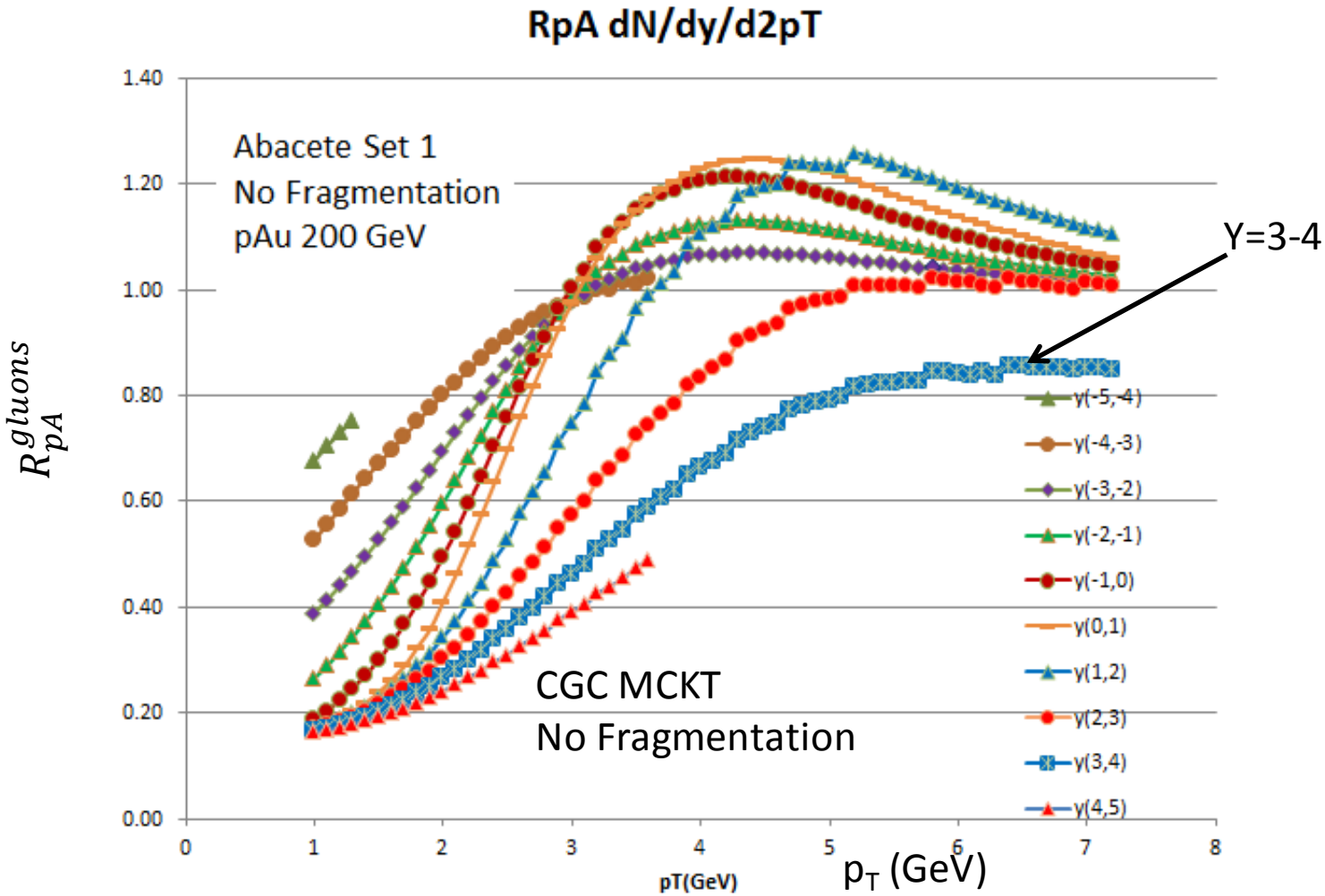
…and you can't polarize the deuteron at RHIC…

LHC – p+Pb

- ATLAS and CMS have forward calorimeters
  - ALICE has upgrade plans
- $\gamma/\pi^0 > 100$ at $p_T \sim 10$ GeV



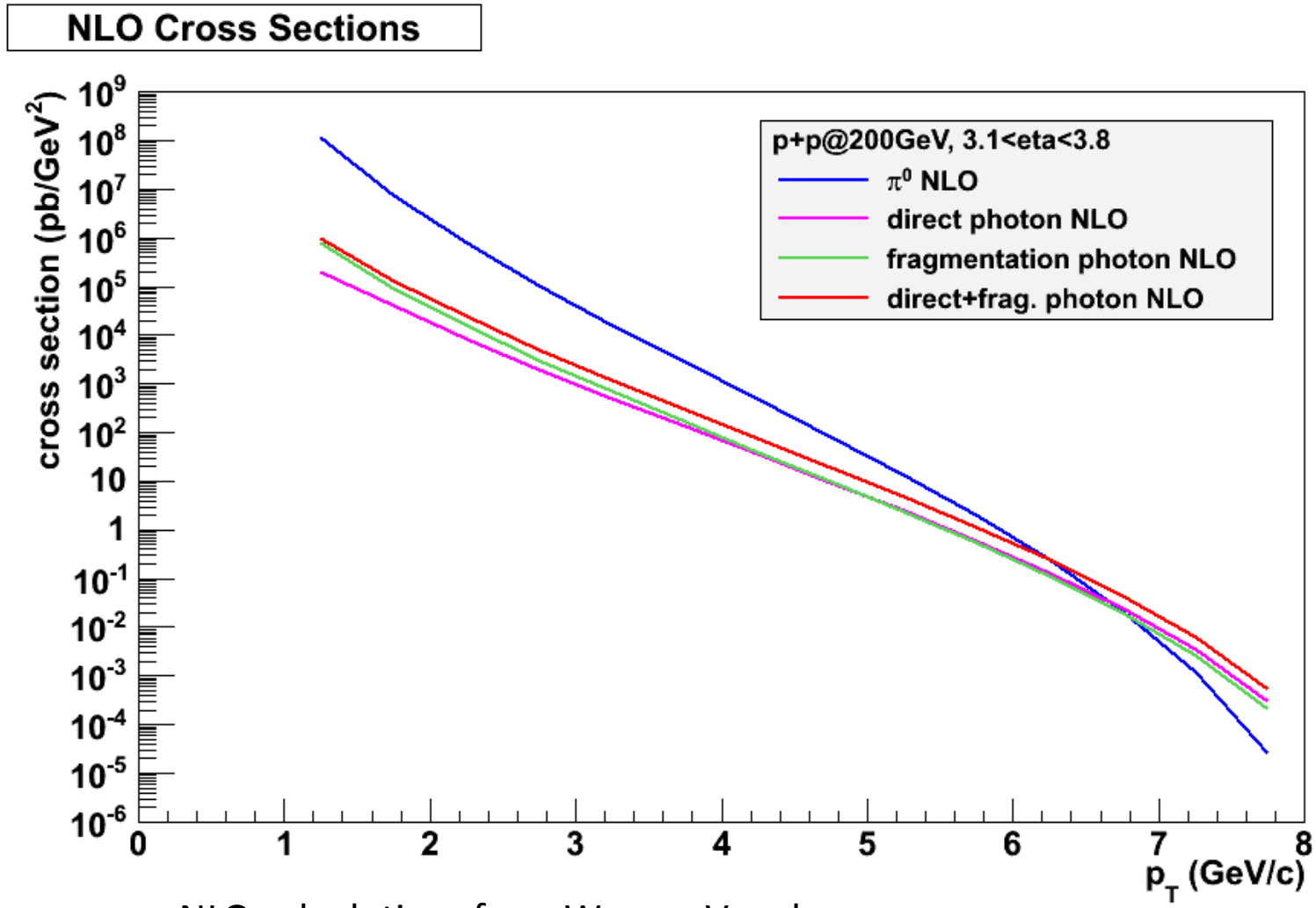
Where to look – from the CGC



(Note: this is a user generated plot stolen from Rich Seto)

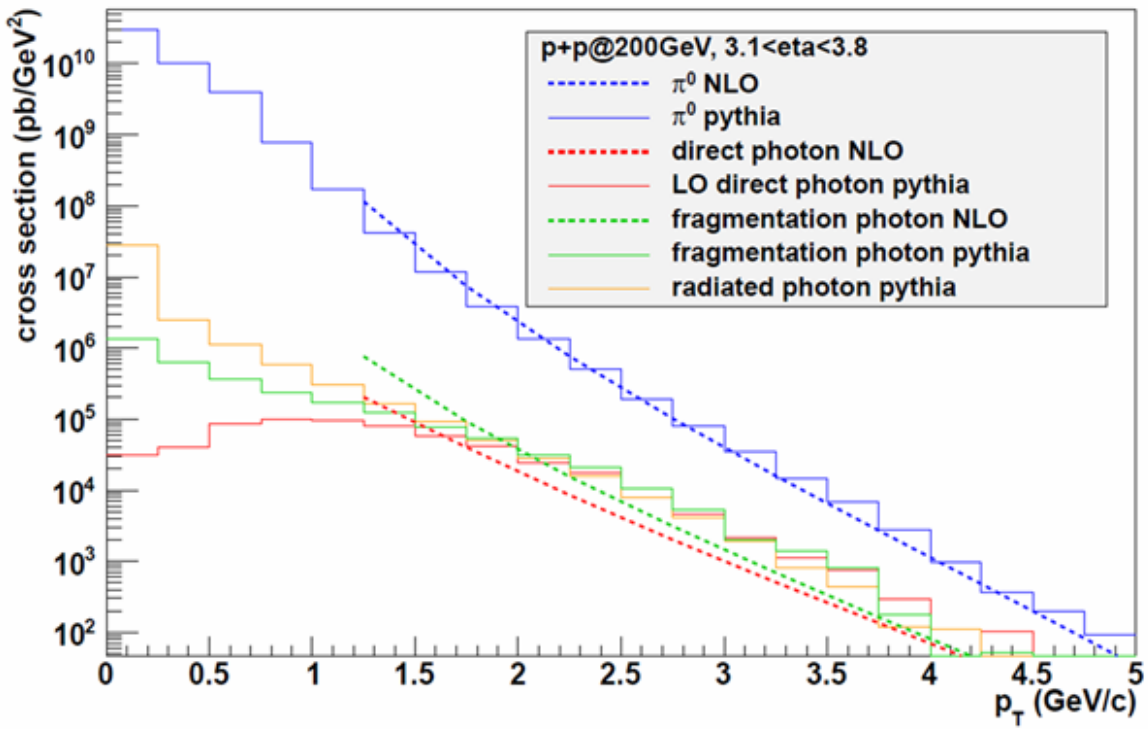
MPC-EX
MPC
π^0 →

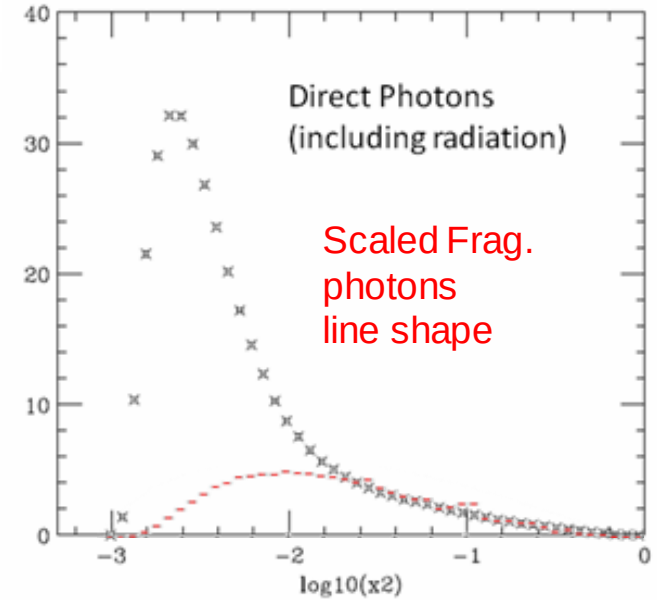
Direct Photon NLO Cross Sections

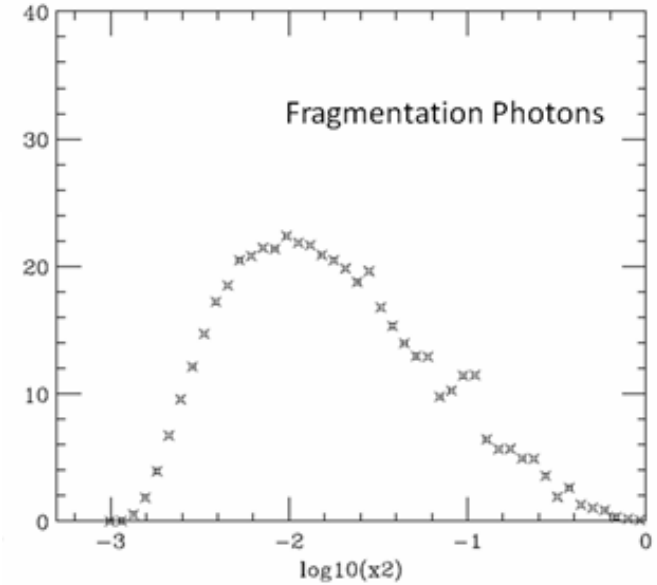


NLO calculations from Werner Vogelsang

Pythia and NLO Cross Sections







- Pythia: Radiated γ ~ Direct γ at high p_T
- Werner: Radiated γ < Direct γ

MPC-EX Event Reconstruction

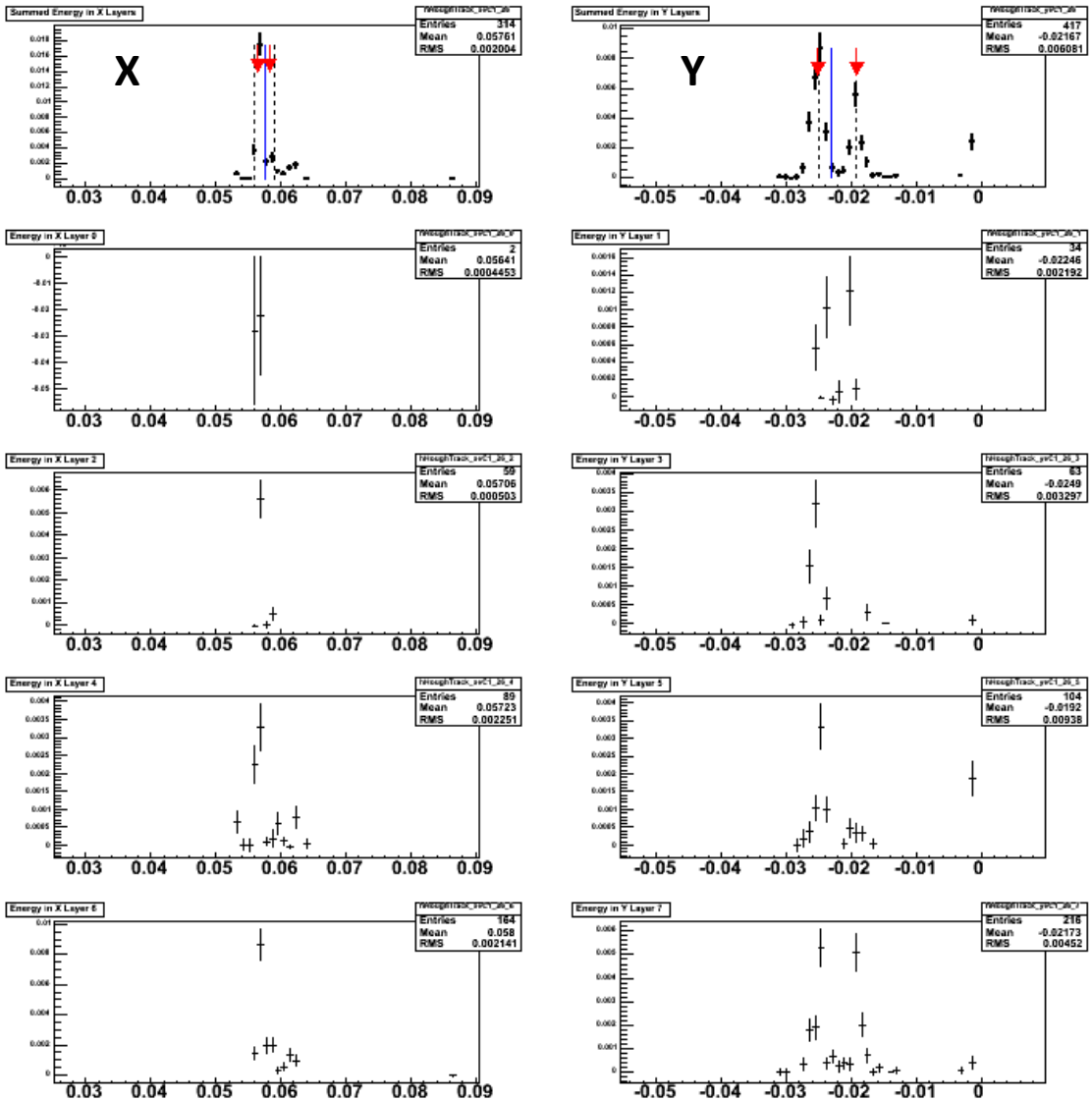
Layer Sum

Layer 1

Layer 2

Layer 3

Layer 4



Event 26

Arm = 1
Energy = 45.60 GeV
Mass = 0.147 GeV
Vertex = 0.40 cm

Hough Slope 1x = 0.05601
Hough Slope 1y = -0.02504
Hough Slope 2x = 0.05892
Hough Slope 2y = -0.01924

E1 = 23.94 GeV
E2 = 21.65 GeV
Asymmetry = 0.050

True Energy = 43.66 GeV
True Asymmetry = 0.197

True Hough Slope 1x = 0.05832
True Hough Slope 1y = -0.01916
True Hough Slope 2x = 0.05644
True Hough Slope 2y = -0.02519

First X Layer = 0
First Y Layer = 1

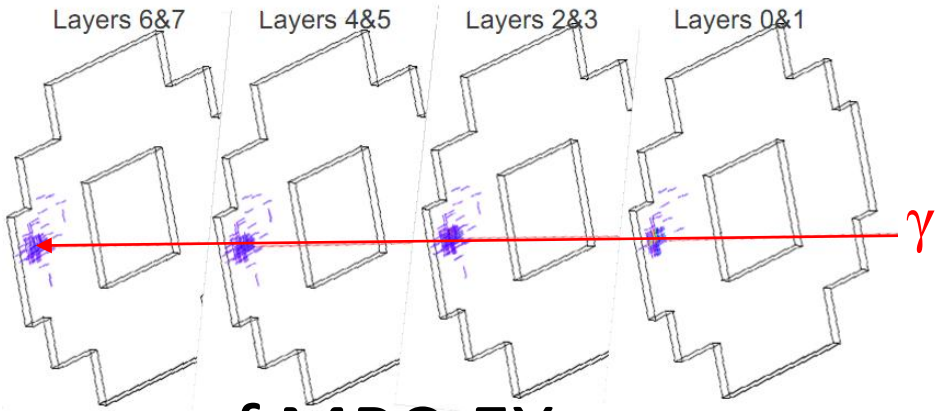
MIPs in Last Layer = 244.3

radius of hit = 13.42 cm

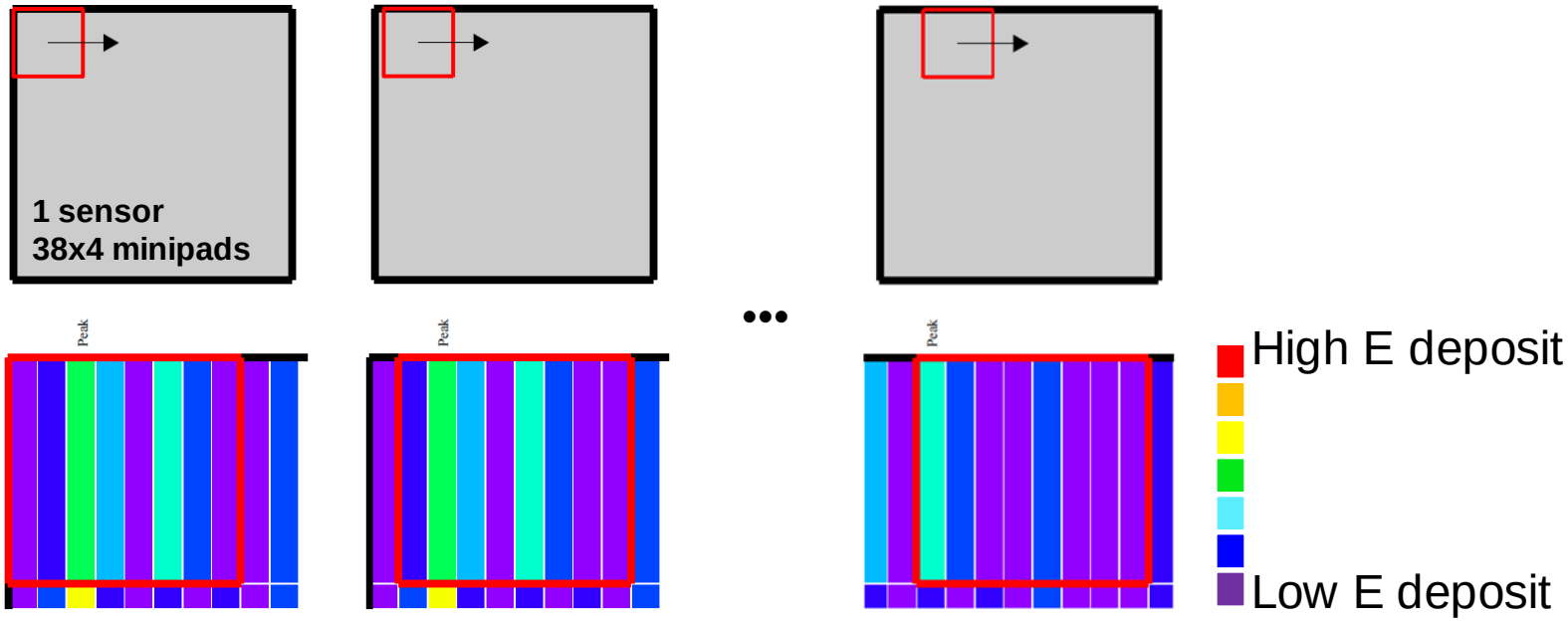
Exit

Cluster reconstruction

- Separately sum energy in x and y towers



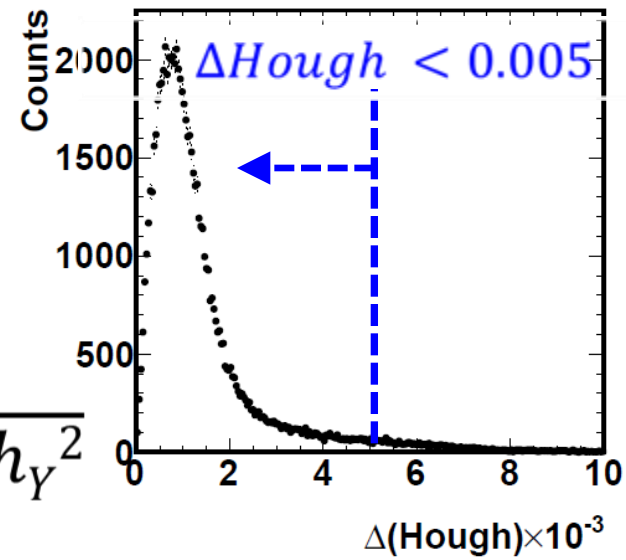
- Identifiy local maxima in scan of MPC-EX



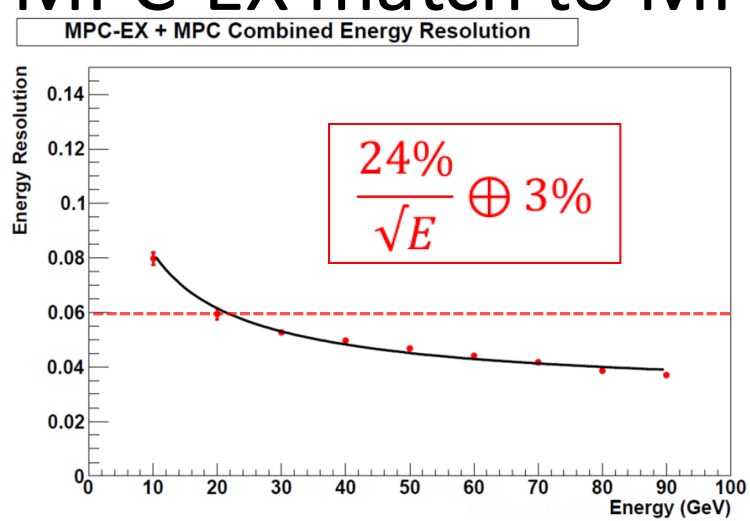
– Energy and position of local maxima are found

Match to MPC

- Match MPC-EX to MPC in Hough space
  - Constant parameters to define the linear trajectory to each point
    - $Hough_X = p_X/p_Z$
    - $Hough_Y = p_Y/p_Z$
  - $\Delta Hough = \sqrt{\Delta Hough_X{}^2 + \Delta Hough_Y{}^2}$

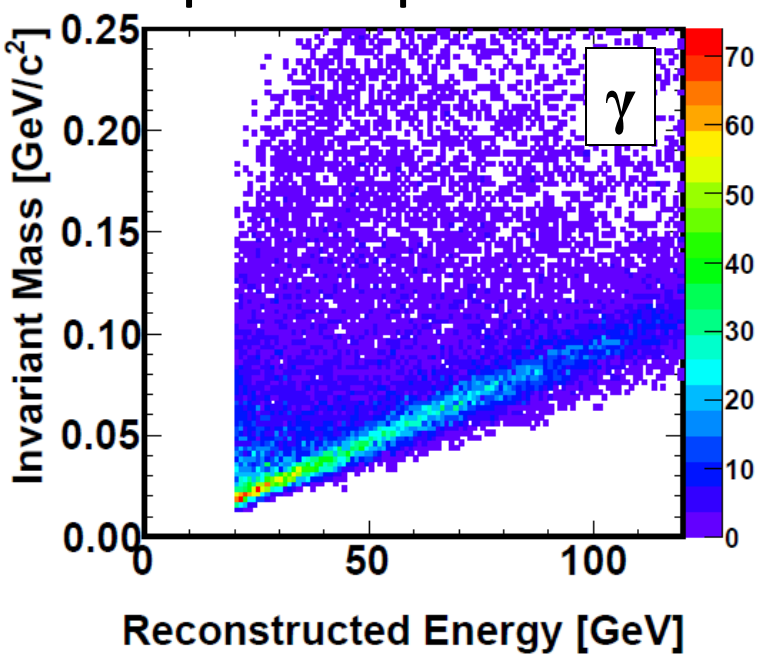


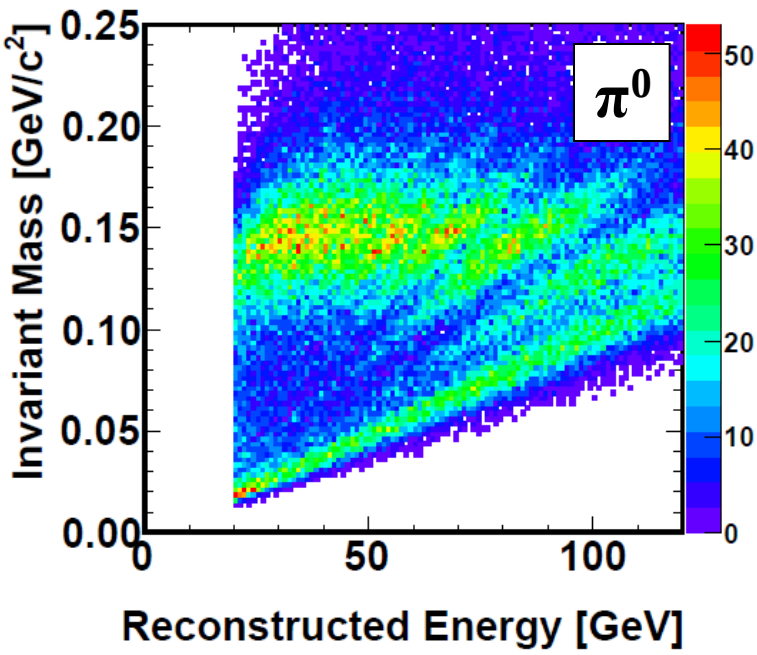
- Keep closest MPC-EX match to MPC hit



Neutral Pion Identification

- E < 20 GeV two-track π^0s -- Reconstruct pairs
- E > 20 GeV one-track π^0s
  - Reconstruct inv. mass to determine if pi0
    - Find stable splitting of energy distribution in two parts
  - Separate pi0s out to E > 80 GeV





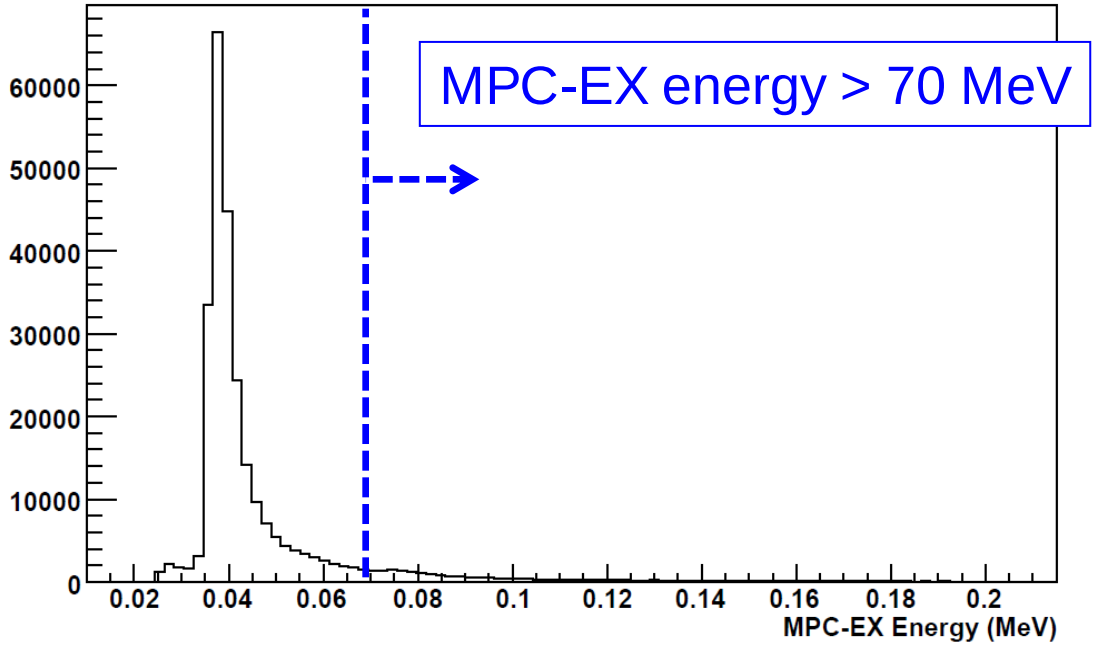
Finding prompt photons

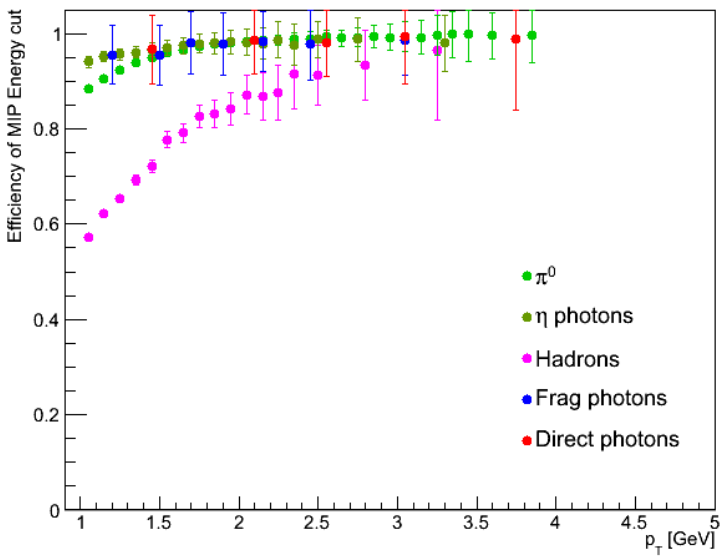
- Keep only the highest energy track in the event

Particle	Efficiency p_T > 1 GeV
Hadrons	97.9%
π^0	97.3%
$\gamma_{Frag.}$	99.2%
γ_{Direct}	99.5%

- Remove hadrons and π^0s
  - Energy deposition, shower shape, and p_T > 3 GeV
- Reduce frag. photons
  - Track isolation

Remove obvious hadron tracks

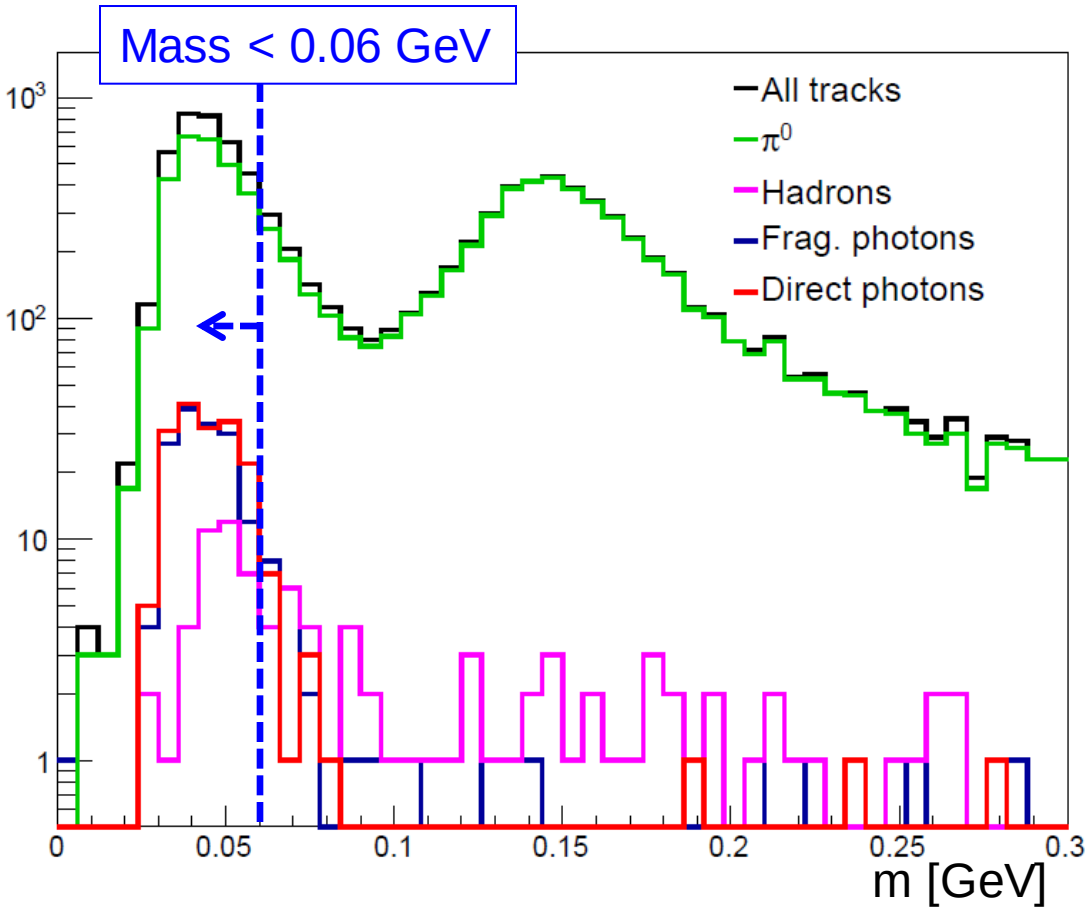


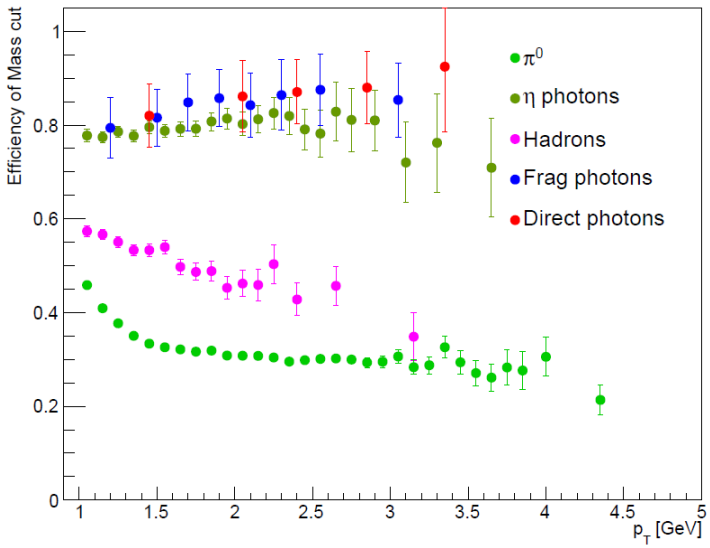


- Charged hadrons hit all layers with MIP energy deposited in MPC-EX
  - MIP peak ~ 36 MeV

Particle	Efficiency	
	$p_T > 1$ GeV	$p_T > 3$ GeV
Hadrons	67.4%	95.5%
$\pi 0$	94.9%	99.5%
$\gamma_{Frag.}$	97.3%	98.9%
γ_{Direct}	98.1%	98.9%

Mass cut



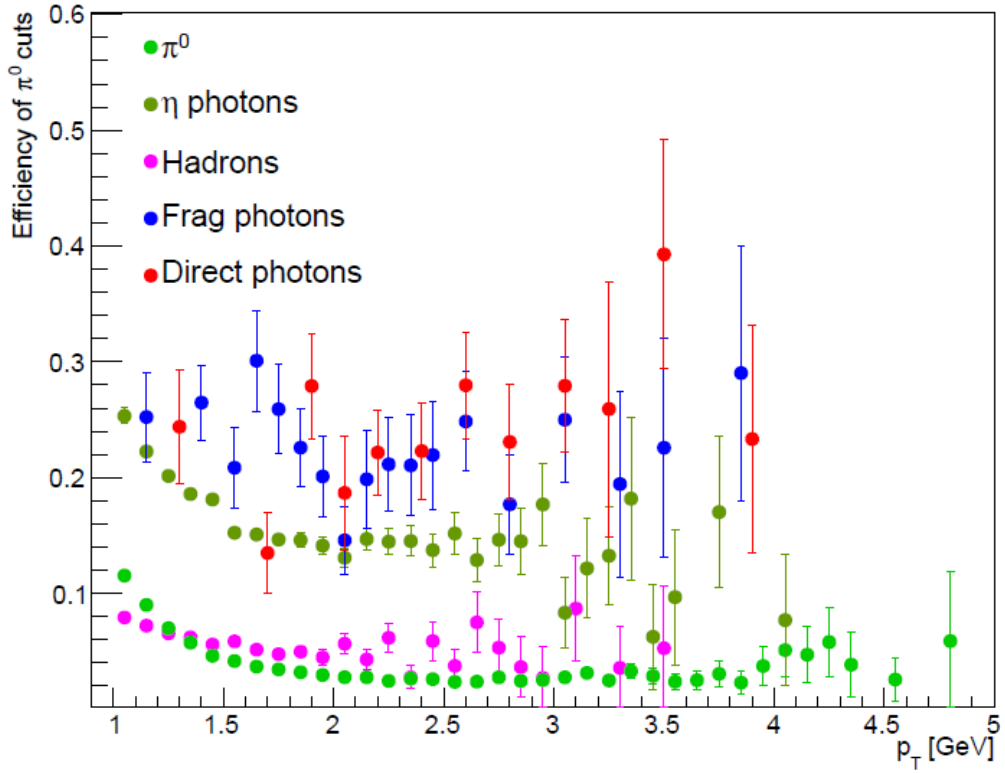


Particle	Efficiency $p_T > 3$ GeV
Hadrons	37.5%
π^0	29.1%
$\gamma_{Frag.}$	84.2%
γ_{Direct}	90.3%

- Fluctuations in energy distributions give low mass peak

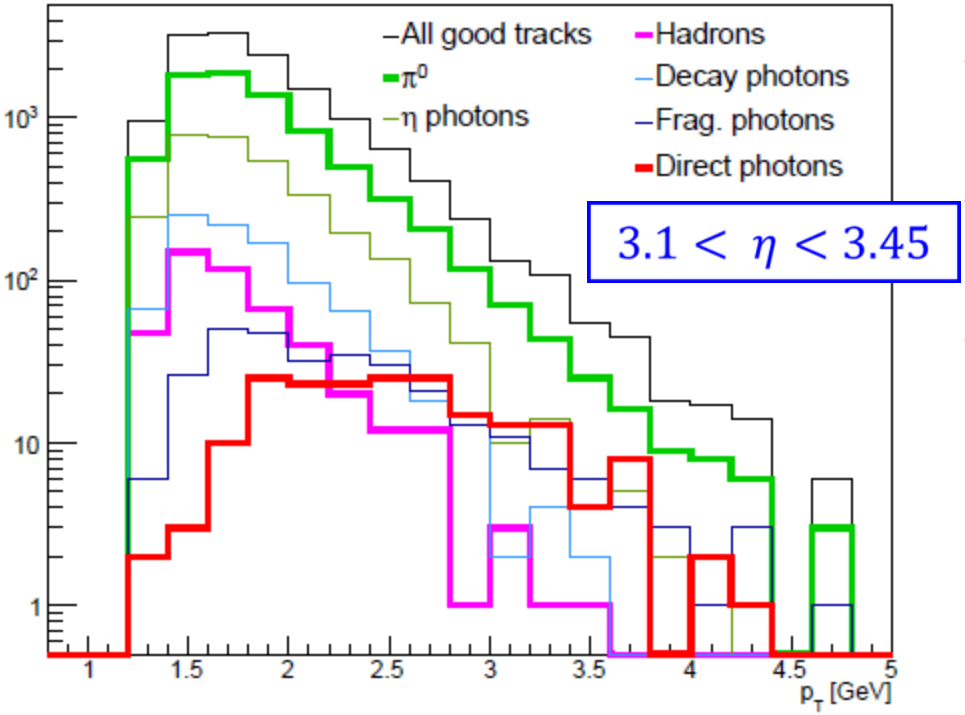
Efficiency of cuts

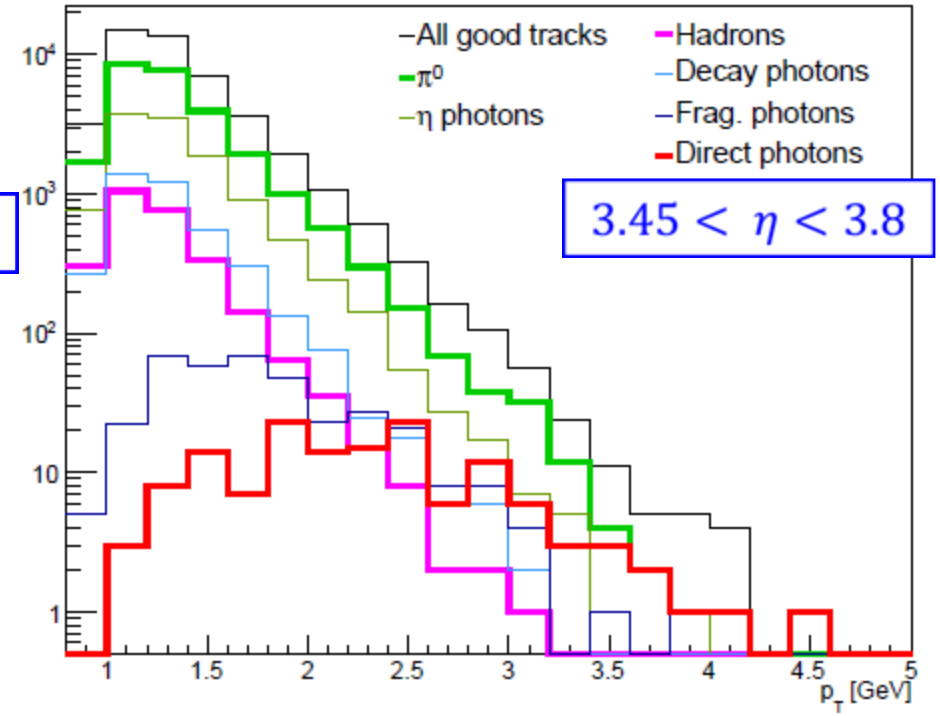
Particle type	Efficiency $p_T > 3$ GeV
Hadrons	6.1%
π^0	2.9%
$\gamma_{Frag.}$	24.3%
γ_{Direct}	31.2%



- Hadron and π^0 efficiencies are a factor of 5 to 10 lower than direct photon efficiencies

In η ranges





	$3.1 < \eta < 3.8$	$3.1 < \eta < 3.45$	$3.45 < \eta < 3.8$
Direct-to-signal ratio	57.4%	58.3%	56.6%
R_γ	1.34	1.34	1.35
Signal-to-π^0 ratio	43 ± 5 %	42 ± 6 %	46 ±11 %
Signal yield p_T > 3 GeV	101	77	24

Removing frag. photons

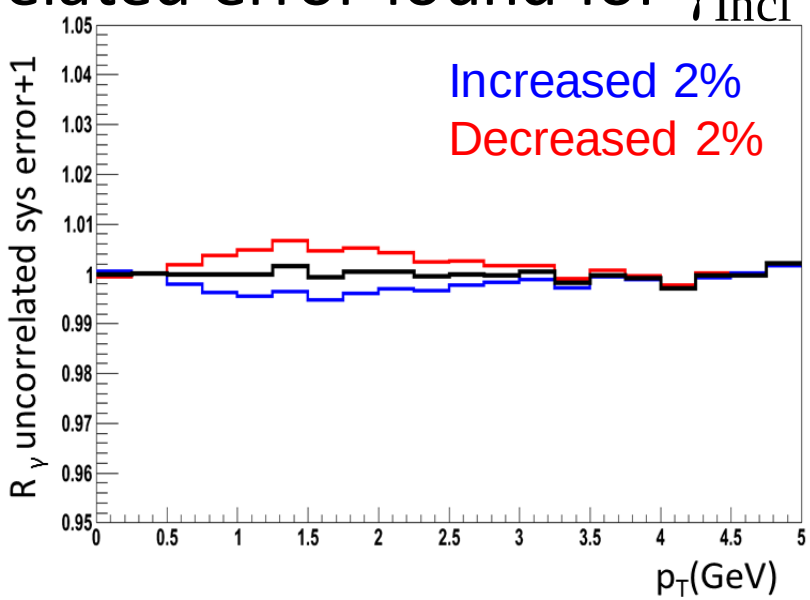
- By tightening the shower shape and isolation cuts we can remove frag. photons

Tightening cuts →

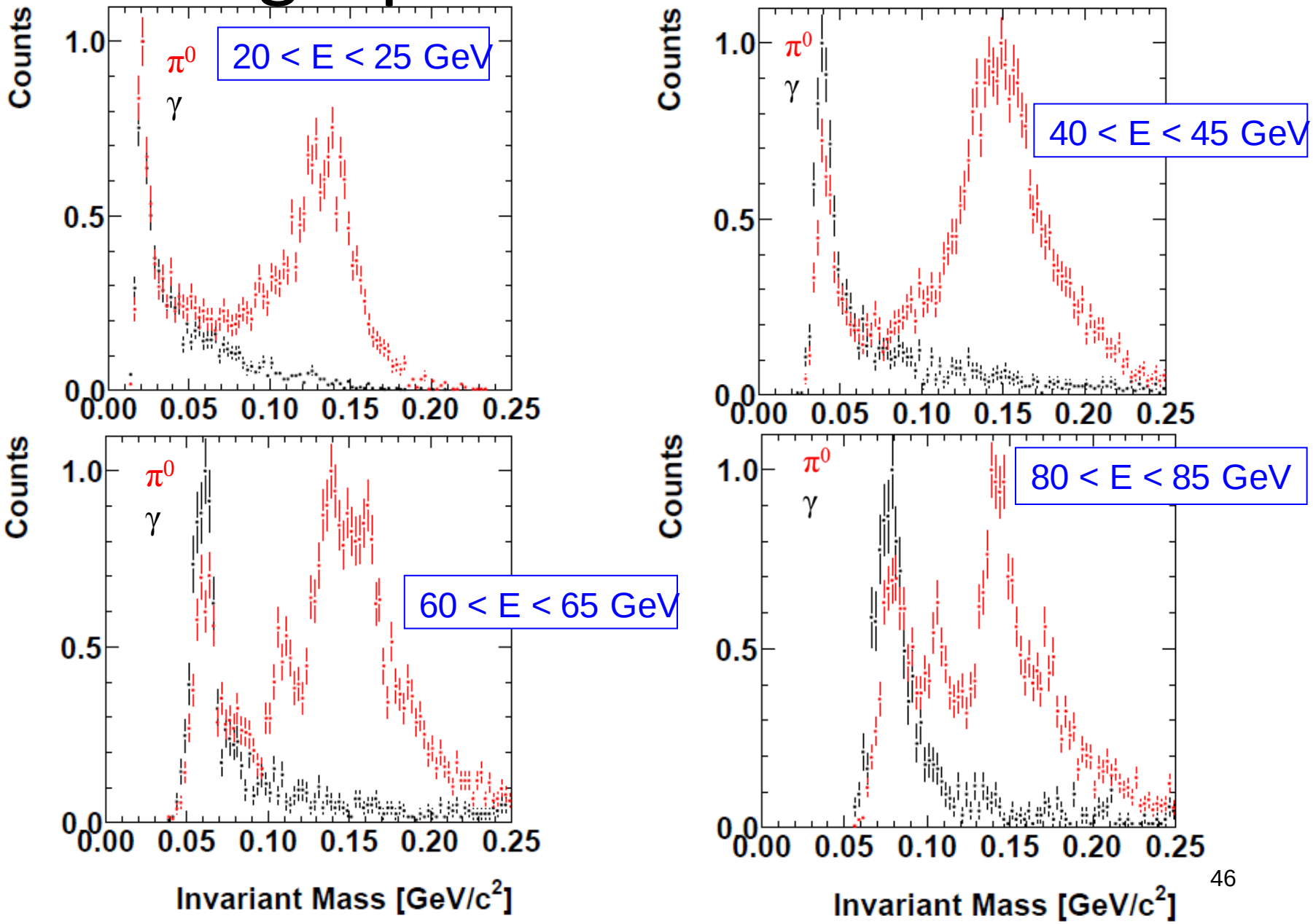
	π^0 Cuts	Cuts 1	Cuts 2
Direct-to-signal ratio	57.4%	68.3%	78.6%
R_γ	1.34	1.31	1.31
Signal-to-π^0 ratio	43 ± 5 %	37 ± 7 %	40 ±13 %
Direct photon ϵ	31.2%	15.1%	5.9%
Frag. photon ϵ	24.3%	7.3%	1.7%

Uncorrelated errors

- 2% energy scale error is propagated into $\Delta R_\gamma/R_\gamma$ and $\Delta\gamma_{Incl}/\gamma_{Incl}$
- Toy model determined the effect of a 2% energy shift between p+p and d+Au
  - 1% uncorrelated error bound for R_γ
  - 1% uncorrelated error found for γ_{Incl}

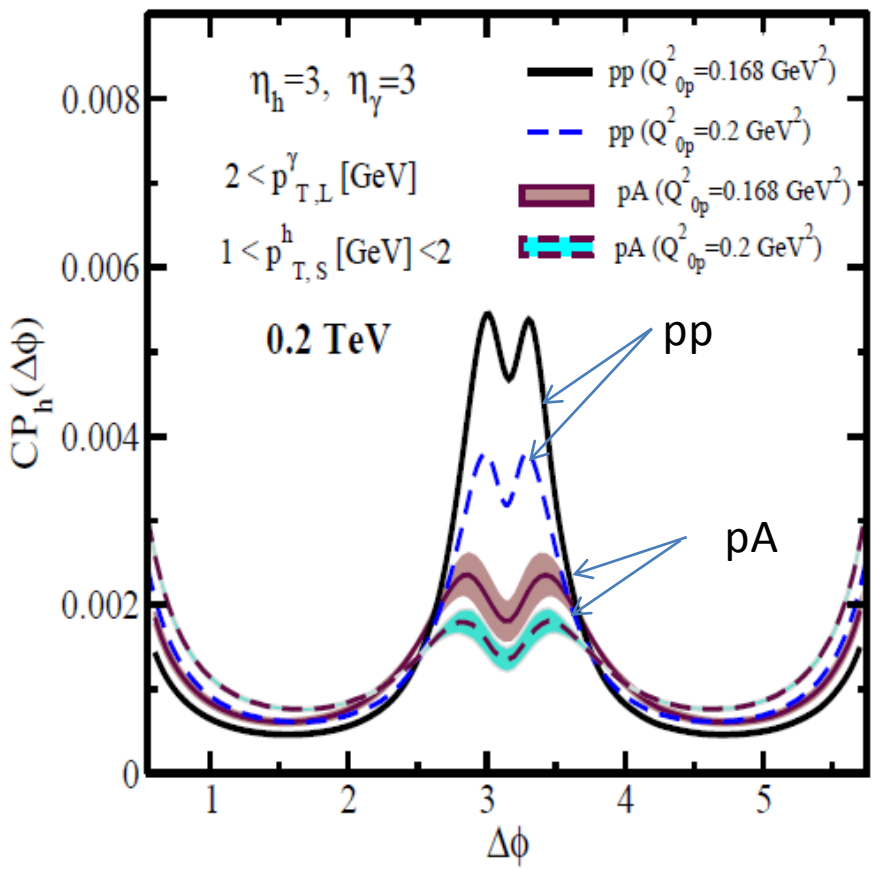


Single particle simulations



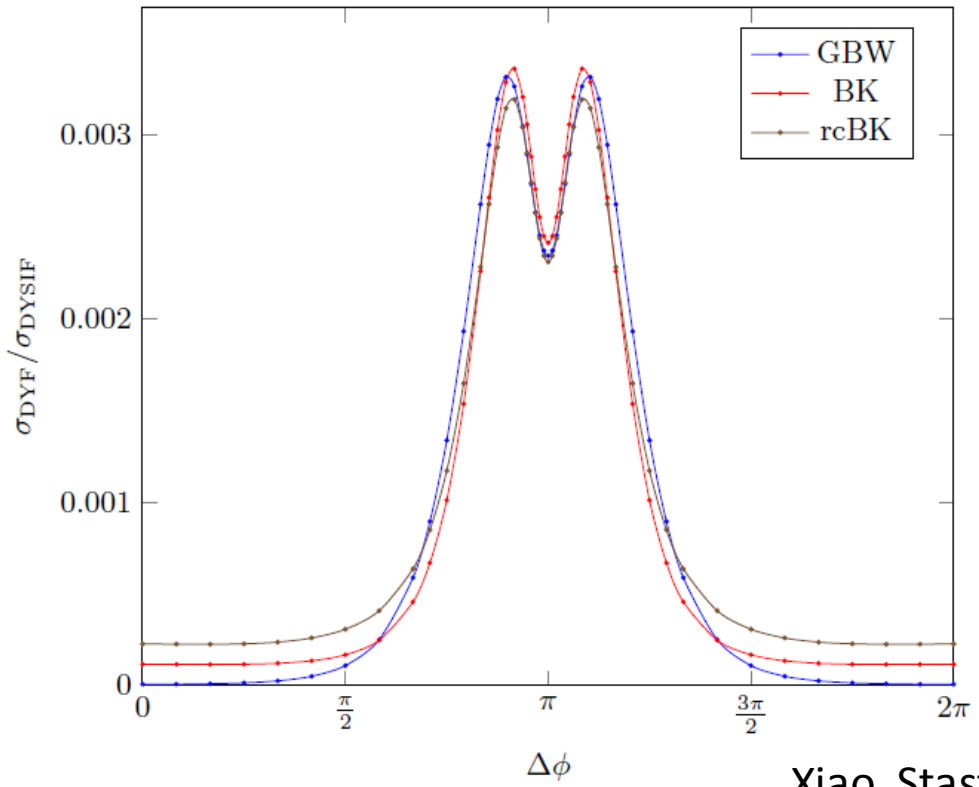
Additional Measurements
γ+hadrons

- Pick p_T of photon, measure hadron correlation in bins of $\Delta\theta$, and p_T of hadron
- Sensitive to Q_{Sat}



Resaein (1209.0478)

The future? DY hadron correlations



Xiao, Stasto et al

Double hump structure (preponderance of signatures)

Rate??? Possible at RHIC in pCu?

To Conclude: Some theoretical help

- A better understanding of the equivalence if there is one between different pictures so we don't chase "smoking guns" only to be told that the smoking gun is not discriminatory – maybe it's because the picture are in some way equivalent (which of course may be good, but make it difficult when setting up experimental strategy)
- Easy access to CGC MC generator as there are for pp and heavy ions (control of parameters and final states
  - ala, EPS09, pythia, AMPT, HIJING….
  - MCKT is a nice start

Why is the LHC R_{pA} at midrpaidity~1 in pA ($x<10^{-3}$)
Is this consistent with the forward RpA data at RHIC?

To Conclude

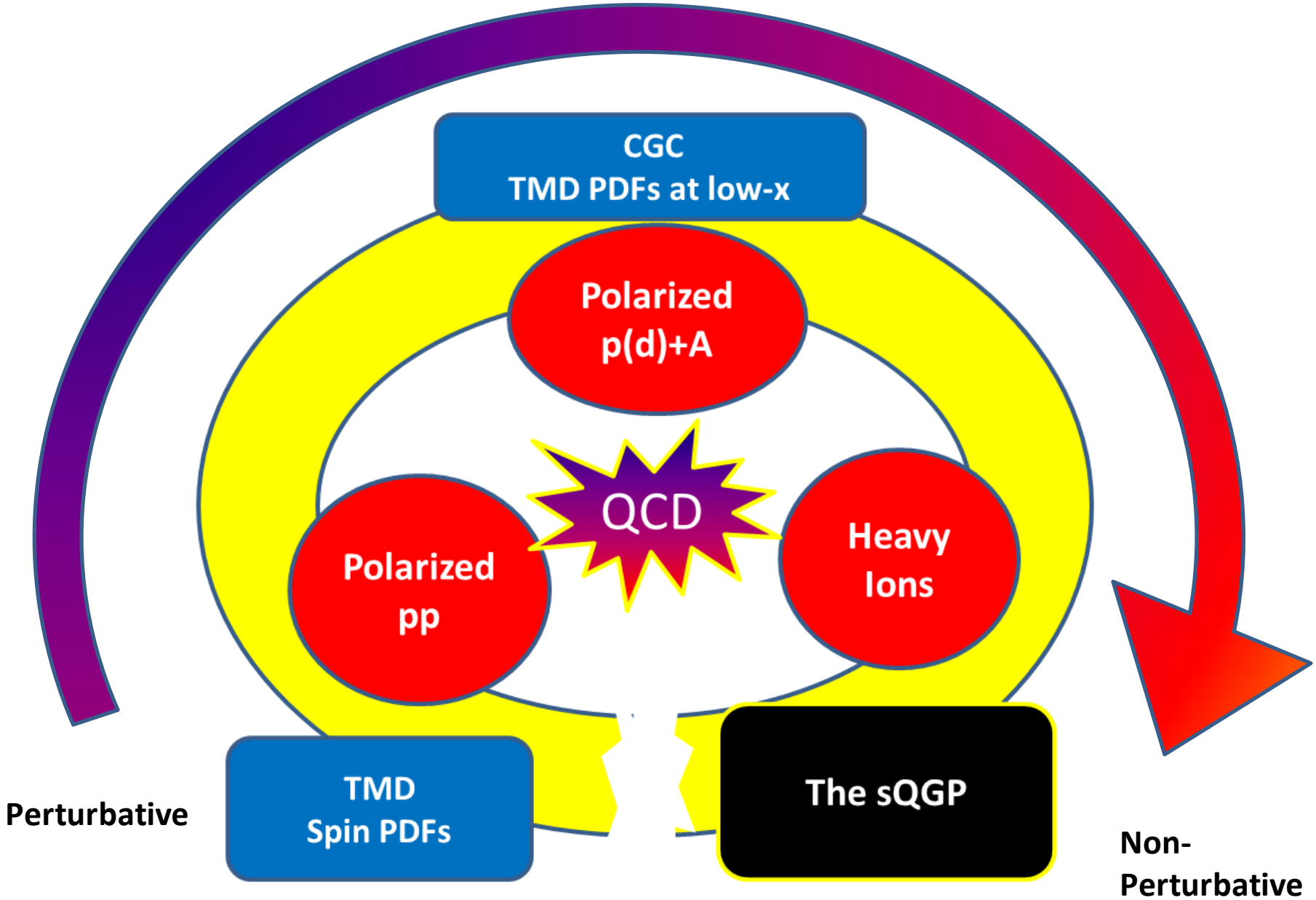
- MPC-EX, a plan into the future (fsPHENIX), and a plan for pA
  - Direct photons
  - Pion-pion correlation (as begun in the MPC) to higher p_T, look at multiplicity dependence
  - Direct photons-pion correlations
  - Polarized pA A_N (direct photon to look at Sivers ala Yuri K?)
  - Centrality Selection
    - PHENIX will need to use a larger coverage detector for centrality selection
    - Probably will still need to run several nuclear species however
- Is it worth thinking about a lower energy?
- Can pA help get a handle of the "Glasma". Signatures? (more than ridge?)
- It is crucial to understand the initial state and themalization phase of a heavy ion collisions to understand the sQGP
  - Only unified picture that I know

    CGC→Glasma→sQGP (hydro)

The hope is to use the various signatures to "box" in the phenomena to yield the correct theoretical description of

1) initial state of sQGP 2) CNM 3) themalization stage of sQGP

Parameters extracted from different measurements should be "universal"



Non-equilibrium?