Stony Brook University PHENIX UCLA

Measurement of Direct Photon Cross Section and Double Helicity Asymmetry at $\sqrt{s} = 510$ GeV in $\vec{p} + \vec{p}$ Collisions at PHENIX

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This work was done while as a graduate student at Stony Brook University

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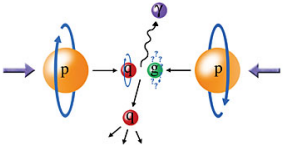
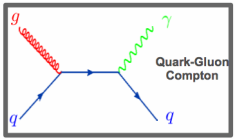
Outline

1. Motivations
2. Experimental setup
3. Direct photon cross section
4. Direct photon double helicity asymmetry
5. Summary

Direct photon as the "golden" channel



$$A_{LL}^{pp\to\gamma X} \sim \frac{\Delta q(x_q)}{q(x_q)} \cdot \frac{\Delta g(x_g)}{g(x_g)} \cdot a_{LL}^{qg\to\gamma q}$$



- $A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$
- Little fragmentation contributions.

- "Golden" channel.
- Linear in Δg: probe the sign of gluon spin.

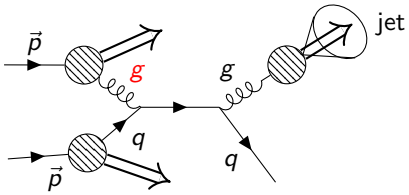
Challenges in the direct photon measurement:

- Low statistics.
- π^0 decay photon merging at high p_T in the EMCal detector.

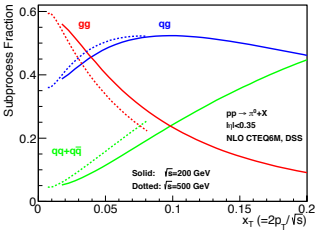
Advantages at PHENIX with RHIC running period of year 2013:

- The largest integrated luminosity (155 pb^{-1}) in $\vec{p} + \vec{p}$
- EMCal with fine granularity to separate π^0 decay photons up to p_T of 12 GeV/c, and a shower profile analysis extends the γ/π^0 discrimination to 30 GeV/c.

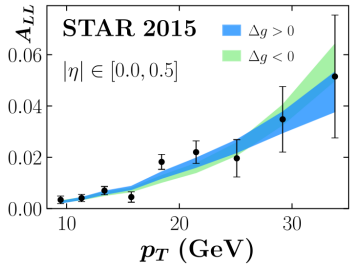
Jet and charged pion productions



Jet production

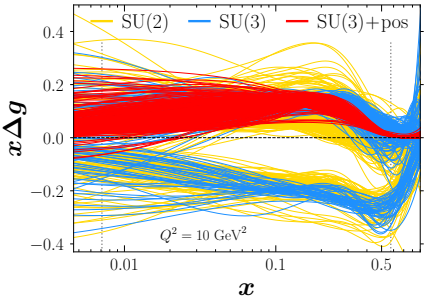


- Fragmentation introducing syst. err.
- Both quark-gluon and gluon-gluon scattering.
- Unable to decide the sign of Δg.
- Right fig.: Jet A_{LL} [PRD 105, 074022 (2022)]



From A_{LL} to Δg

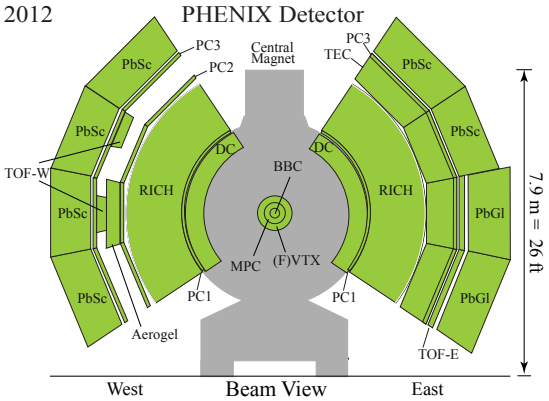
- Existing RHIC data mainly probe $0.05 < x_g < 0.2$.
- PHENIX π^0 A_{LL} at 510 GeV confirms a nonzero Δg and extend x_g to 0.01.
- STAR jet data clearly imply a polarization of gluons in this range.
- Existing inclusive DIS and p+p Jet A_{LL} data cannot decide the sign of Δg.
- Direct photon is good at separating $\Delta g > 0$ and $\Delta g < 0$.
- First published direct photon A_{LL} result [PRL 130, 251901 (2023)].



PRD 105, 074022 (2022)
No SIDIS or RHIC pion data

PHENIX detector

- Pseudorapidity $|\eta| < 0.35$
- Azimuthal angle ϕ: π radians coverage.
- Electromagnetic Calorimeter (EMCal):
  - primary detector for photons.
- EMCal trigger:
  - Select high energy photons.
- Drift Chamber (DC):
  - Measure charged particle momenta.
  - Charge veto criteria.



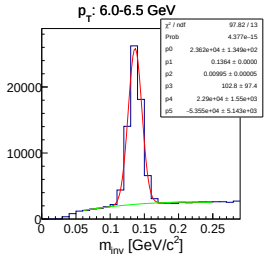
Direct photon signal extraction

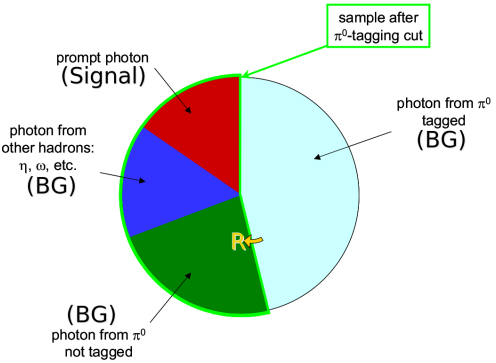
Source of direct photon:

- Compton scattering: $g + q \rightarrow \gamma + q$
- Annihilation: $q + \bar{q} \rightarrow \gamma + g$
- Parton fragmentation to photon.
- Quark bremsstrahlung.

Source of direct photon background:

- Decay photons from mesons (π^0, η, ω, η').

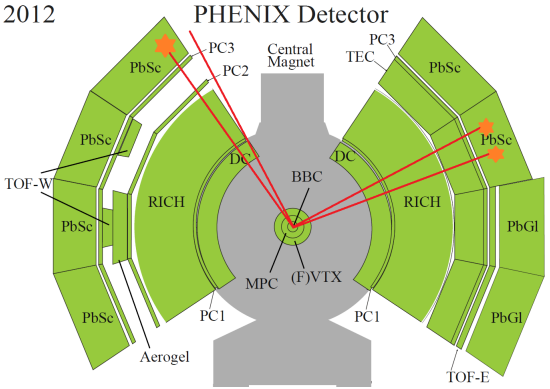




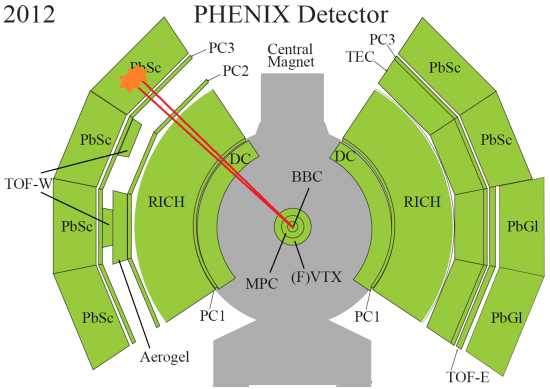
Yield of direct photon:

- $N_{dir} = N_{total} - (1 + A)(1 + R)N_{\pi^0}$
  - R: π^0 one photon missing ratio.
  - A: Other hadrons' to π^0's photon ratio.

Contamination of direct photon sample

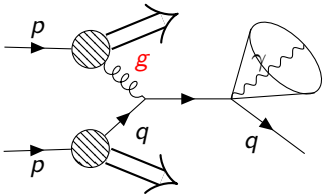


Missing partner of the decay photon
Acceptance limitations



Merging of the decay photons
Resolution limitations

Identifying direct photon through isolation

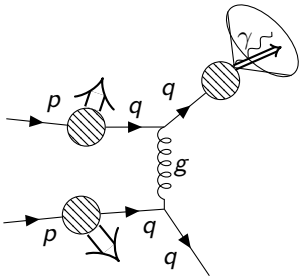


$$r_{\text{cone}} = \sqrt{(\delta\eta)^2 + (\delta\phi)^2} = 0.5$$

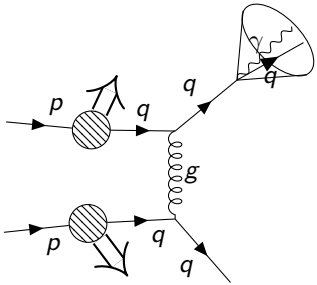
Isolation cut requirement:

$$\sum E_{\text{in cone}} < 0.1 E_\gamma$$

Quark-gluon Compton scattering: Easy to pass isolation cut



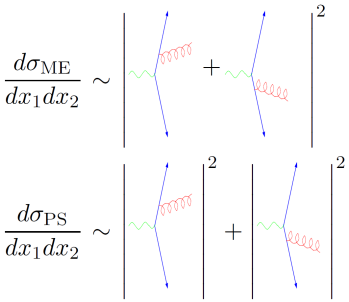
Fragmentation: Hard to pass isolation cut

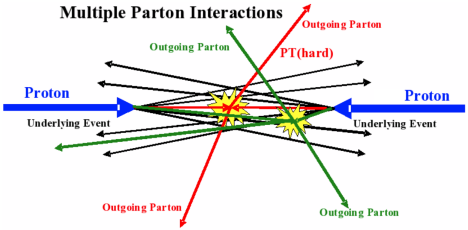


Bremsstrahlung: Hard to pass isolation cut

POWHEG + PYTHIA8 for xsec

- Parton shower (PS) in PYTHIA8: leading log; no interference.
- Matrix element (ME) at NLO in POWHEG: with interference.
- NLO output (ME) of POWHEG as input (PS) of PYTHIA8.
- Overlapping between ME and PS is vetoed in PYTHIA8.





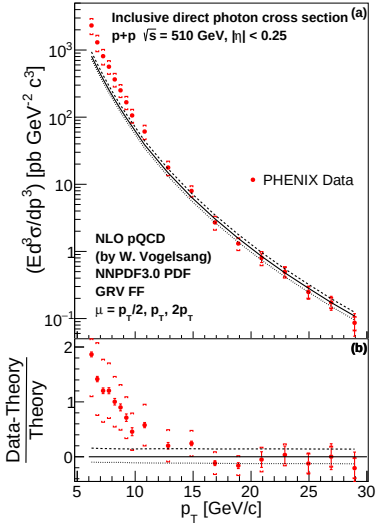
- Multiparton interactions (MPI) in PYTHIA8:

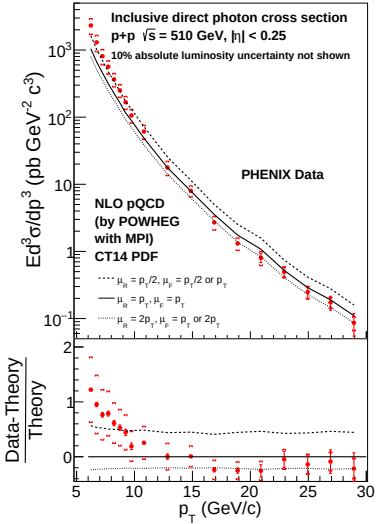
$$\frac{d\mathcal{P}_{\mathrm{MPI}}}{dp_\perp} = \frac{1}{\sigma_{\mathrm{ND}}} \frac{d\sigma_{2\to 2}}{dp_\perp} \exp\left(- \int_{p_\perp}^{p_{\perp i-1}} \frac{1}{\sigma_{\mathrm{ND}}} \frac{d\sigma_{2\to 2}}{dp'_\perp} dp'_\perp \right)$$

- $\sigma_{\mathrm{ND}} \simeq \sigma_{\mathrm{BBC}}$ is the nondiffractive xsec.

Inclusive xsec at 510 GeV

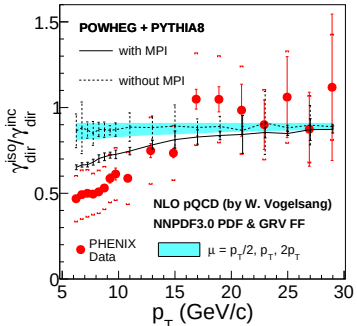
- PRL 130, 251901 (2023)
- NLO pQCD underestimates the data by a factor of $\sim$3 at low p_T.
- POWHEG + PYTHIY8 with MPI and parton shower gives better description of data.

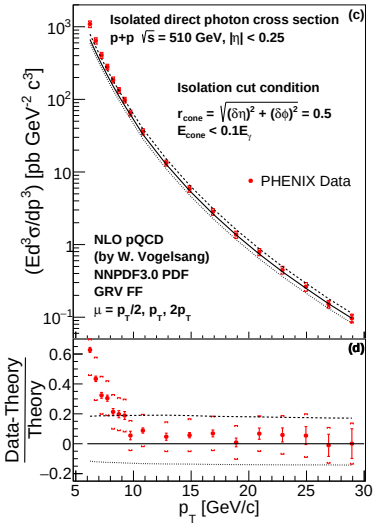




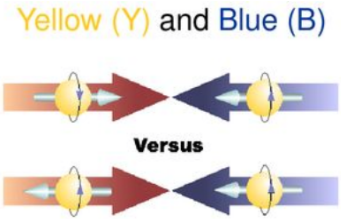
Isolated xsec at 510 GeV

- PRL 130, 251901 (2023)
- Cross section consistent with NLO pQCD.
- MPI is important to explain the data/theory discrepancy at low p_T.
- Constrain unpolarized gluon density function.





Double helicity asymmetry A_{LL}



$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma_{++} + \sigma_{--} - \sigma_{+-} - \sigma_{-+}}{\sigma_{++} + \sigma_{--} + \sigma_{+-} + \sigma_{-+}}$$
$$= \frac{1}{P_B P_Y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}, \quad R = \frac{L_{++}}{L_{+-}}$$

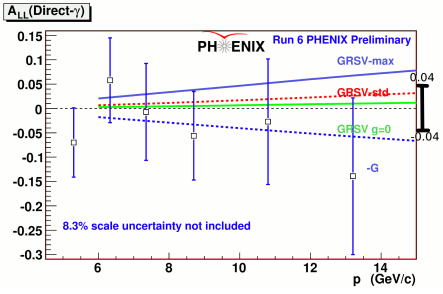
$$A_{LL}^{\text{dir}} = \frac{A_{LL}^{\text{total}} - r_{\pi^0} A_{LL}^{\pi^0} - r_h A_{LL}^{h}}{1 - r_{\pi^0} - r_h}$$

Measured in a run-by-run basis
Separated for 4 spin patterns
Separated for even and odd crossings
4 spin patterns $\times$ 2 crossings $=$ 8 groups

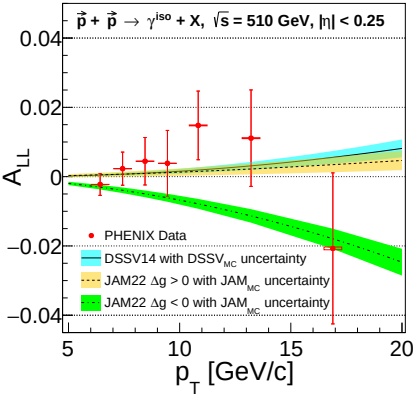
Crossing:	0	1	2	3	4	5	6	7
Blue:	+	+	−	−	+	+	−	−
Yellow:	+	+	+	+	−	−	−	−

Direct photon A_{LL} [PRL 130, 251901]

- Consistent with DSSV14.
- $\chi^2_{reduced}(\Delta g > 0) = 4.7/7$.
- $\chi^2_{reduced}(\Delta g < 0) = 12.6/7$.
- Neg. sol. disfavored at $\sim 2.8\sigma$.
- Much smaller uncertainty.



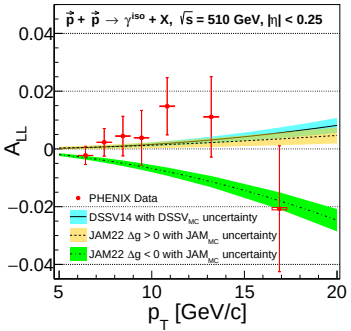
Not published [Bennett, PhD thesis (2009)]

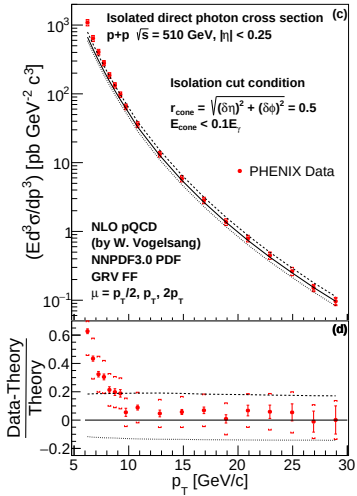


Code for JAM curves from W. Vogelsang
JAM PDF from [PRD 106, L031502 (2022)]

Summary [PRL 130, 251901 (2023)]

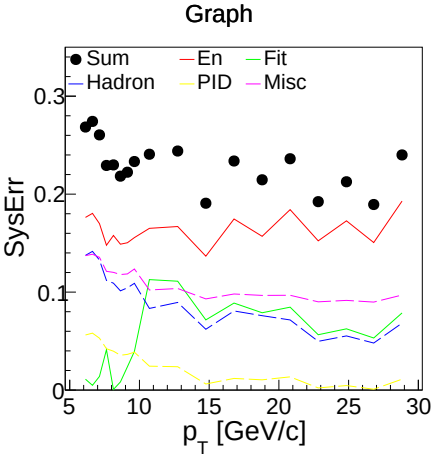
- Gluon spin is important for proton spin decomposition.
- Direct photons have little fragmentation contributions.
- Clearly favor the positive gluon spin contribution.
- First direct photon xsec and A_{LL} at 510 GeV.



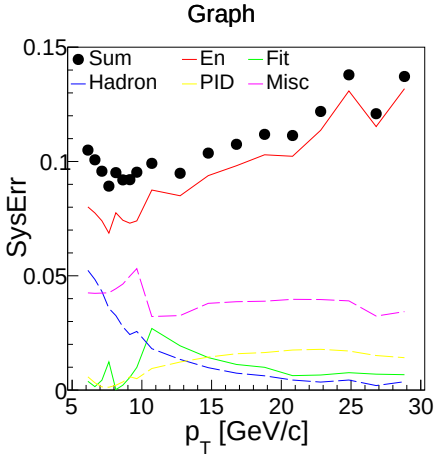


Backup

Systematic uncertainties of cross sections

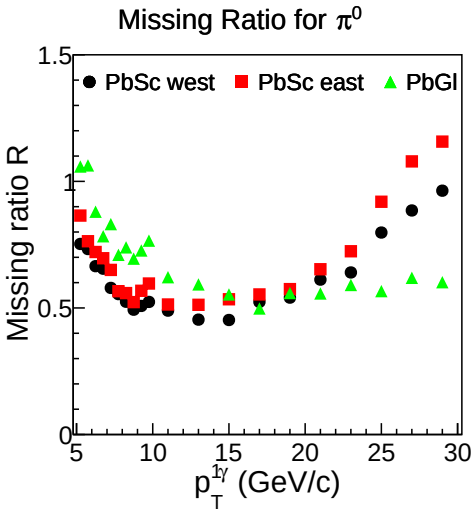


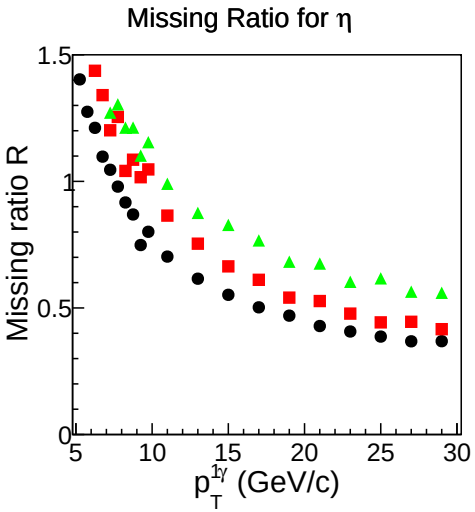
Inclusive cross section



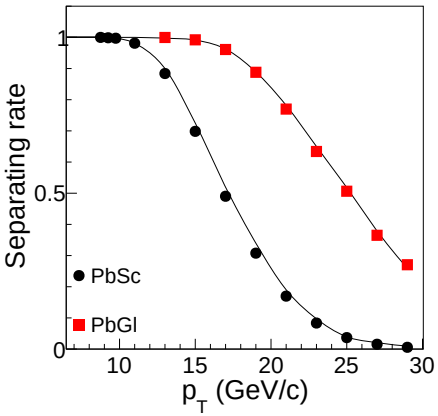
Isolated cross section

π^0 and η missing ratios

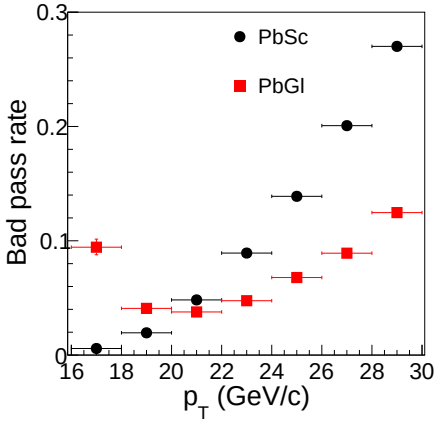




π^0 decay photon separating rate

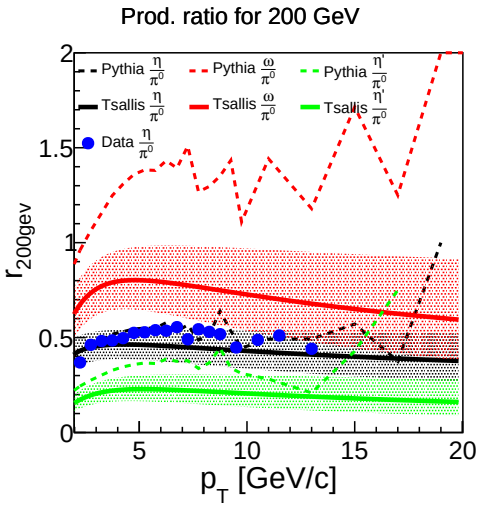


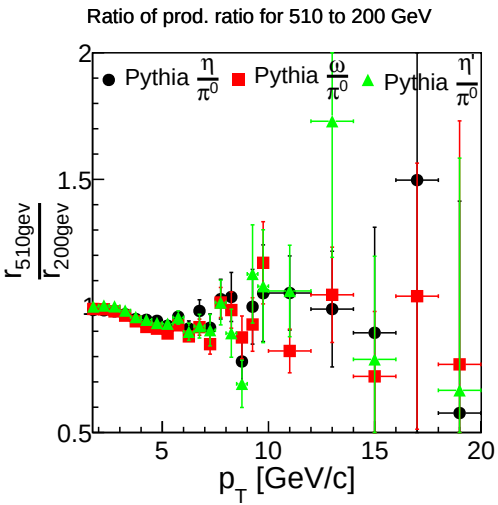
Two-photon separating rate



Merged-photon passing criteria rate

Other meson production rate



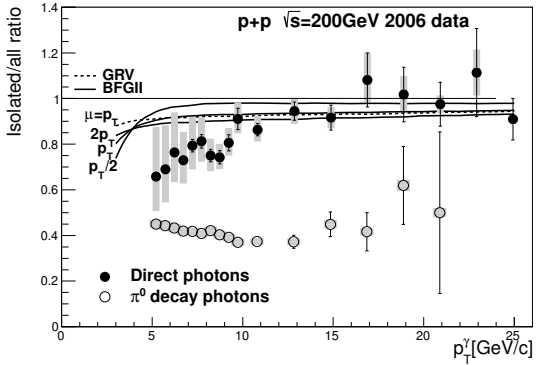


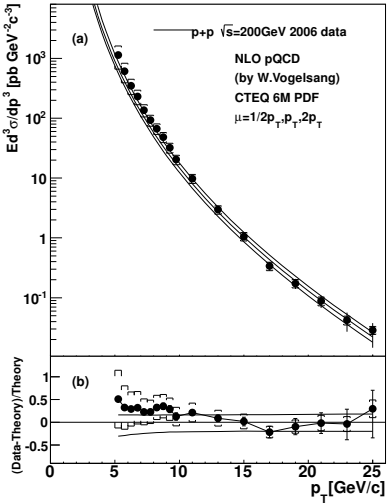
Other meson decay photon ratios

Particle	Production ratio	Branching ratio	γ ratio
$\frac{\eta}{\pi^0}$	0.5 ± 0.1	$\frac{\mathrm{Br}(\eta \to 2\gamma \vert \pi^+\pi^-\gamma)}{\mathrm{Br}(\pi^0 \to 2\gamma)} = \frac{39.4+4.2/2}{98.8}$	0.21 ± 0.04
$\frac{\omega}{\pi^0}$	0.8 ± 0.3	$\frac{\mathrm{Br}(\omega \to \pi^0\gamma)}{\mathrm{Br}(\pi^0 \to 2\gamma)} = \frac{8.4/2}{98.8}$	0.034 ± 0.013
$\frac{\eta'}{\pi^0}$	0.2 ± 0.1	$\frac{\mathrm{Br}(\eta' \to \rho^0\gamma \vert \omega\gamma \vert 2\gamma)}{\mathrm{Br}(\pi^0 \to 2\gamma)} = \frac{28.9/2+2.6/2+2.2}{98.8}$	0.036 ± 0.018
Sum	-	-	0.28 ± 0.05

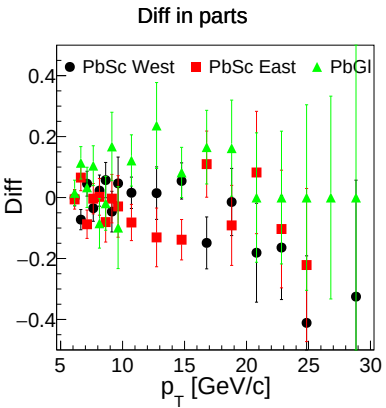
Previous inclusive xsec at 200 GeV

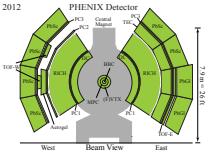
- Cross section consistent with NLO pQCD.
- NLO pQCD overestimates isolated/inclusive ratio.
- PHENIX, PRD 86, 072008 (2012).

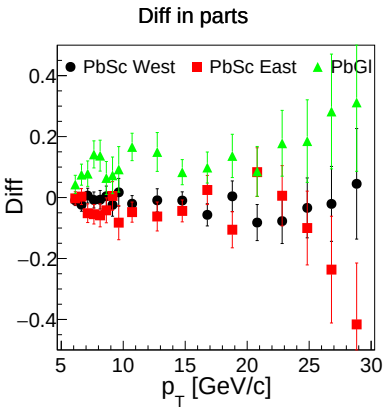




Cross check between three EMCal subsystems (PbScW, PbScE, PbGl)



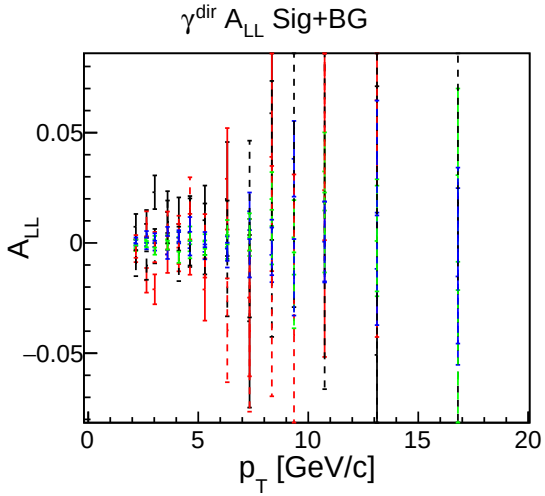




Inclusive cross section

Isolated cross sections

Cross check between the 8 groups

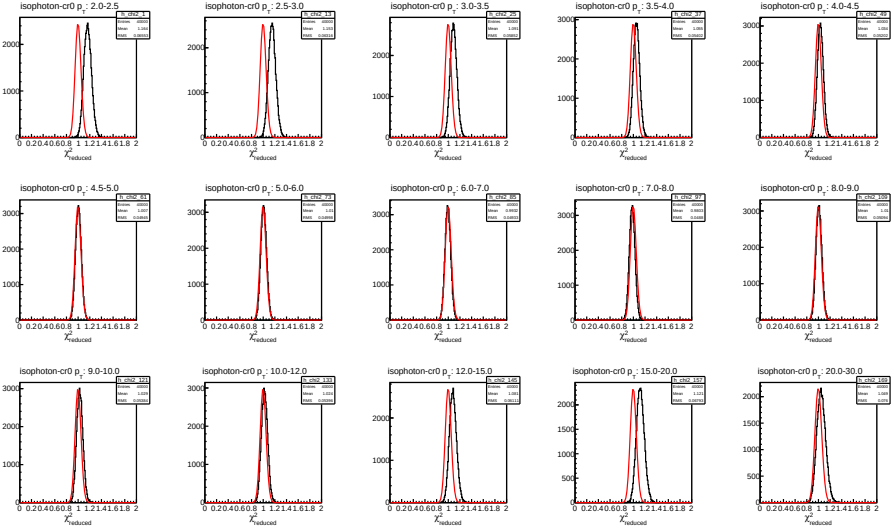


8 colors for the 8 groups

$$F = \frac{\text{between-group variabilty}}{\text{within-group variabilty}}$$

p_T [GeV]	F	p
2-2.5	1.125	0.3445
2.5-3	3.452	0.001132
3-3.5	4.174	0.0001452
3.5-4	2.546	0.01316
4-4.5	1.545	0.1477
4.5-5	1.501	0.1624
5-6	0.6462	0.7178
6-7	1.047	0.3962
7-8	0.9306	0.4815
8-9	0.6235	0.7369
9-10	1.434	0.1875
10-12	0.8384	0.5553
12-15	0.7312	0.6455
15-20	0.812	0.5773

Bunch shuffling results



A_L cross checks