Stony Brook University

PHENIX

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

Zhongling Ji for the PHENIX Collaboration

UCLA & Stony Brook University

24th International Spin Symposium

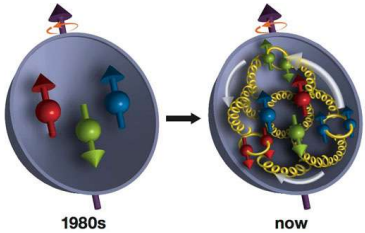
October 22, 2021

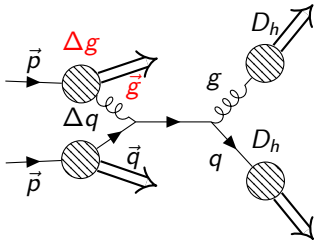
Probing the gluon spin inside the proton

- The proton spin can be decomposed as

$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \Delta g + L_q + L_g$$

- Gluon spin Δg is important for the proton spin puzzle.



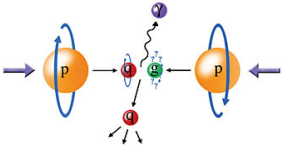


$$\Delta\sigma^{\vec{p}\vec{p}} \sim \Delta g \otimes \Delta q \otimes \Delta\hat{\sigma}^{\vec{g}\vec{q}} \otimes D_h$$

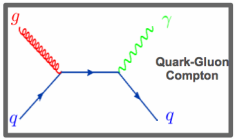
- $\Delta\hat{\sigma}^{\vec{g}\vec{q}}$: from pQCD.
- Δq and D_h: from other measurements.
- Purpose: extract Δg by measuring $\Delta\sigma^{\vec{p}\vec{p}}$
- Observable: jet and hadron (larger statistics); direct photon ("clean" without hadronization).

$$A_{LL} = \frac{\Delta\sigma^{\vec{p}\vec{p}}}{\sigma^{pp}}$$

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:

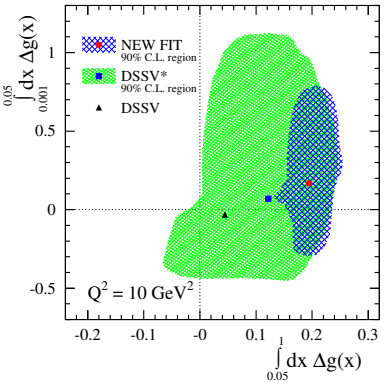
- Low statistics.
- π^0 decay photon merging at high p_T in the EMCal detector.

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 beyond 20 GeV/c.

From A_{LL} to Δg

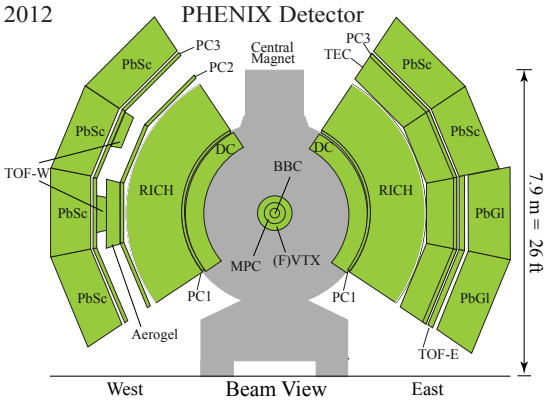
- Existing RHIC data mainly probe $0.05 < x_g < 0.2$
- PHENIX π^0 A_{LL} at 510 GeV confirms a nonzero Δg and extend x_g to 0.01
- STAR jet data clearly imply a polarization of gluons in this range.
- This will be the first direct photon A_{LL} result to be published.
- Our results will add independent constraints on the Δg



PRL 113, 012001 (2014)

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.



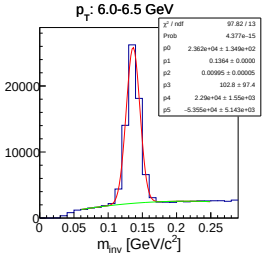
Direct photon signal extraction

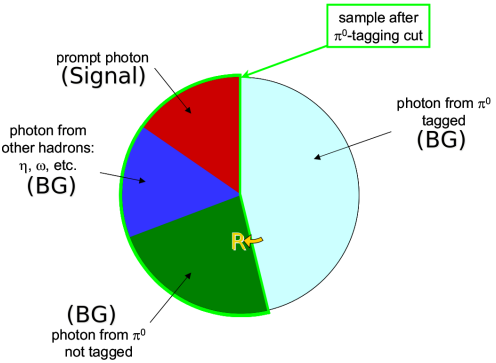
Source of direct photon:

- 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').

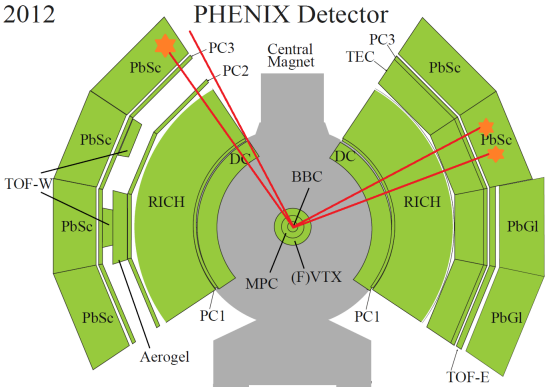




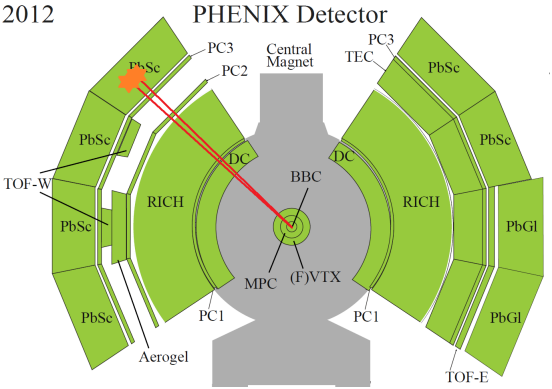
Yield of direct photon:

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

Contamination of direct photon sample

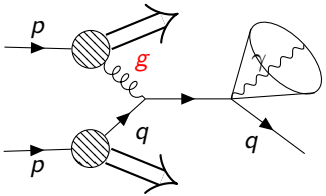


Missing partner of the decay photon
Acceptance limitations



Merging of the decay photons
Resolution limitations

Identifying direct photon through isolation

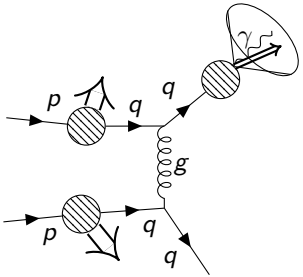


$$r_{\text{cone}} = \sqrt{(\delta\eta)^2 + (\delta\phi)^2} = 0.5$$

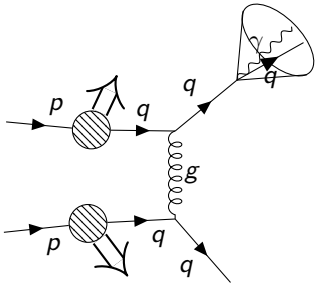
Isolation cut requirement:

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

Quark-gluon Compton scattering: Easy to pass isolation cut



Fragmentation: Hard to pass isolation cut

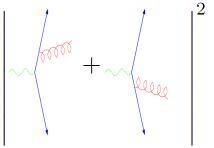


Bremsstrahlung: Hard to pass isolation cut

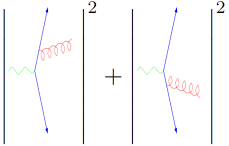
POWHEG + PYTHIA8 for xsec

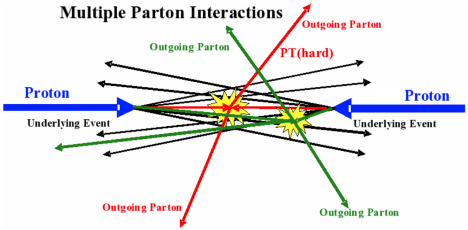
- Parton shower (PS) in PYTHIA8: leading log; no interference.
- Matrix element (ME) at NLO in POWHEG: with interference.
- NLO output (ME) of POWHEG as input (PS) of PYTHIA8.
- Overlapping between ME and PS is vetoed in PYTHIA8.

$$\frac{d\sigma_{\rm ME}}{dx_1 dx_2} \sim$$



$$\frac{d\sigma_{\rm PS}}{dx_1 dx_2} \sim$$





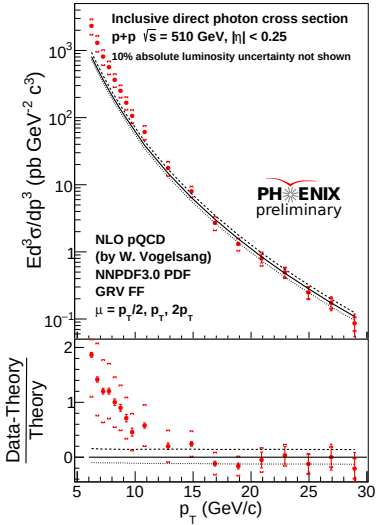
- Multiparton interactions (MPI) in PYTHIA8:

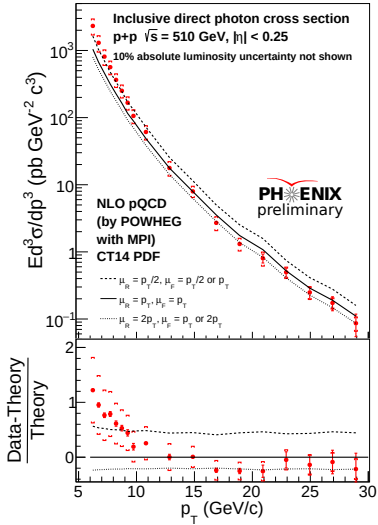
$$\frac{d\mathcal{P}_{\rm MPI}}{dp_\perp} = \frac{1}{\sigma_{\rm ND}} \frac{d\sigma_{2\to 2}}{dp_\perp} \exp\left(- \int_{p_\perp}^{p_{\perp i-1}} \frac{1}{\sigma_{\rm ND}} \frac{d\sigma_{2\to 2}}{dp'_\perp} dp'_\perp \right)$$

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

Inclusive xsec at 510 GeV

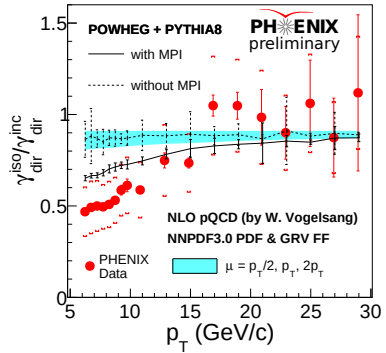
- NLO pQCD underestimates the data by a factor of $\sim$3 at low p_T.
- POWHEG + PYTHIY8 with MPI and parton shower gives better description of data.

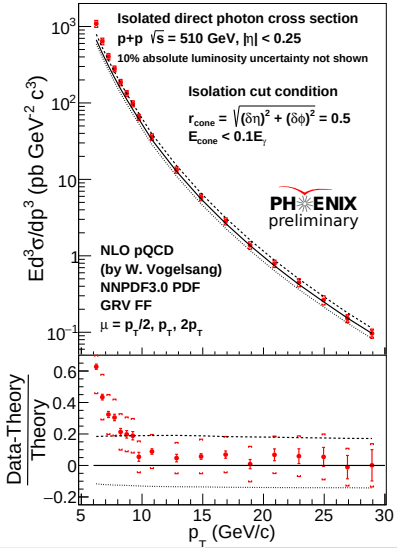




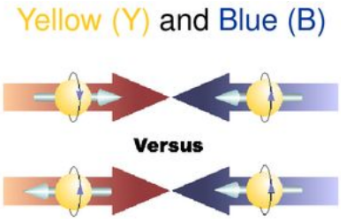
Isolated xsec at 510 GeV

- 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}



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

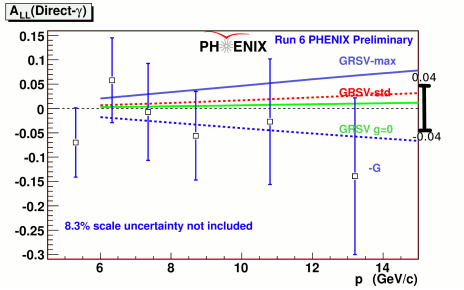
$$A_{LL}^{\text{dir}} = \frac{A_{LL}^{\text{total}} - r_{\pi^0} A_{LL}^{\pi^0} - r_h A_{LL}^{h}}{1 - r_{\pi^0} - r_h}$$

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

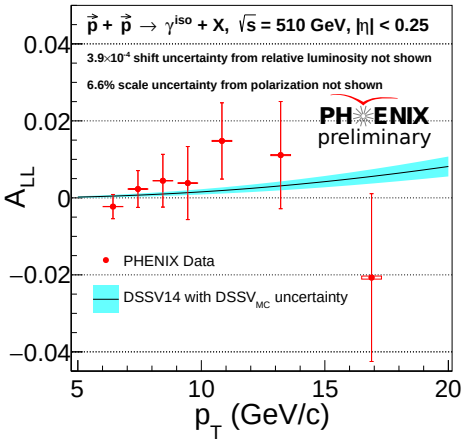
Crossing:	0	1	2	3	4	5	6	7
Blue:	+	+	−	−	+	+	−	−
Yellow:	+	+	+	+	−	−	−	−

Direct photon A_{LL}

- Consistent with NLO DSSV14.
- Will be the first published direct photon A_{LL}
- Constrain polarized gluon density function Δg
- Much smaller uncertainty compared with the previous preliminary at 200 GeV.

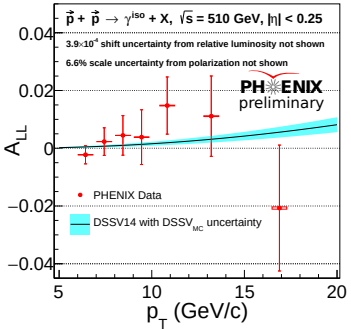


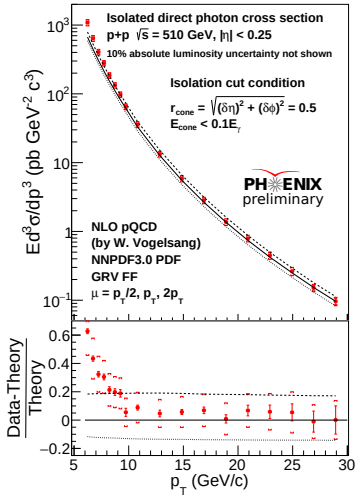
Not published [Bennett, PhD thesis (2009)]



Summary

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

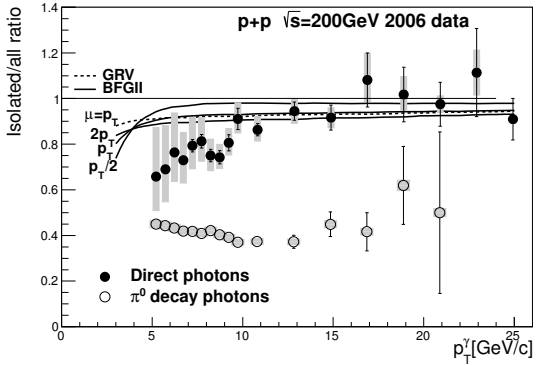


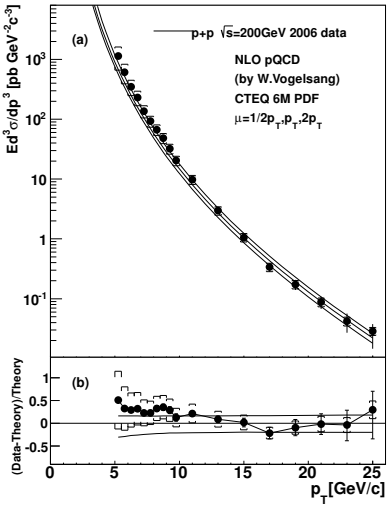


Backup

Previous inclusive xsec at 200 GeV

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



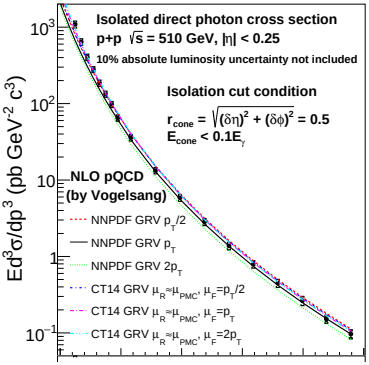


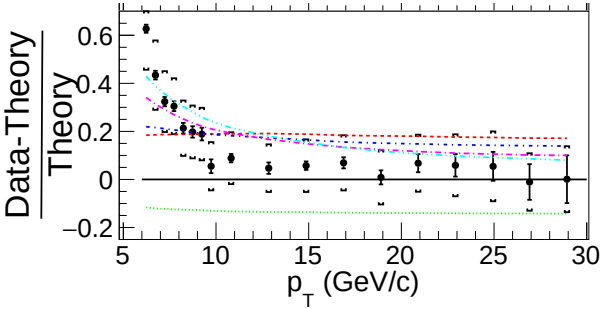
PMC scale for isolated xsec

- Running coupling from RGE:

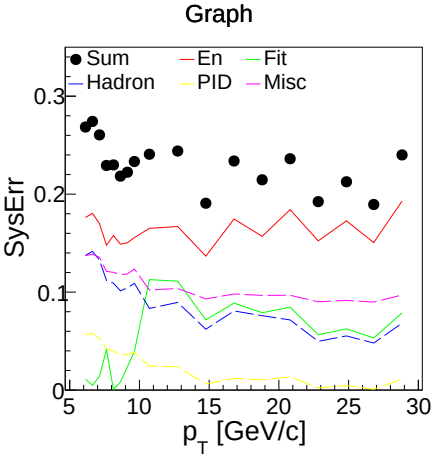
$$\frac{d\alpha_s(\mu^2)}{d\ln\mu^2} = \beta(\alpha_s) = -b_0\alpha_s^2(\mu^2)$$

- PMC resums the renormalization effect by RGE.
- PMC scale shows better agreement with data.
- PMC scale has smaller uncertainty.
- PRD 86, 085026 (2012).

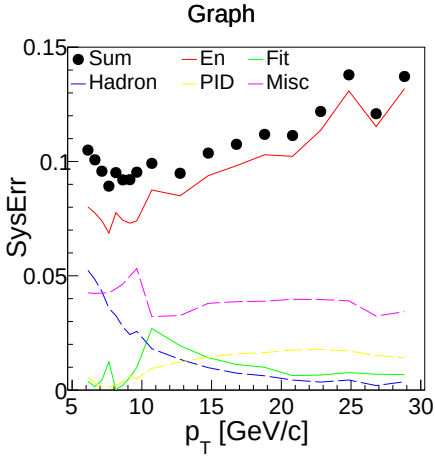




Systematic uncertainties of cross sections

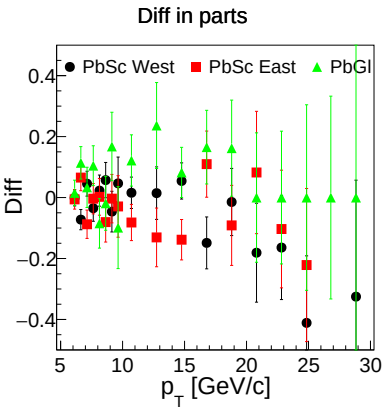


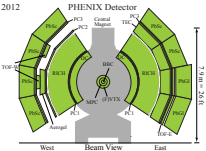
Inclusive cross section

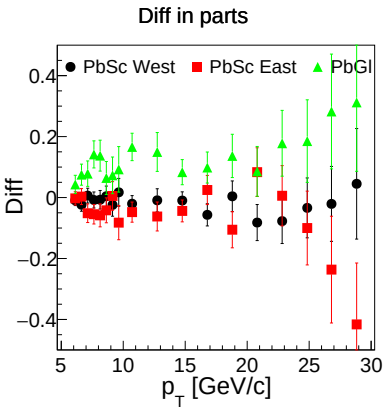


Isolated cross section

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



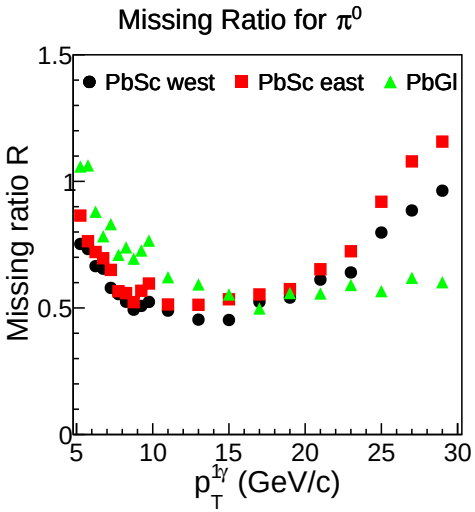


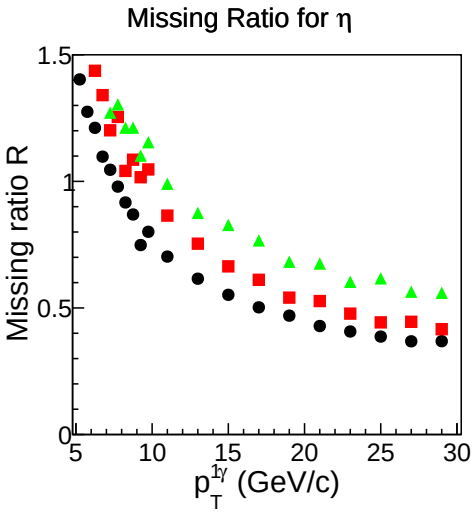


Inclusive cross section

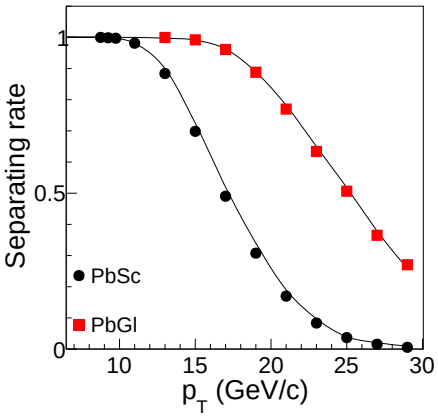
Isolated cross sections

π^0 and η missing ratios

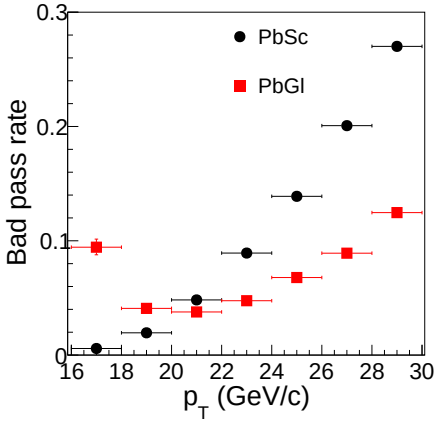




π^0 decay photon separating rate

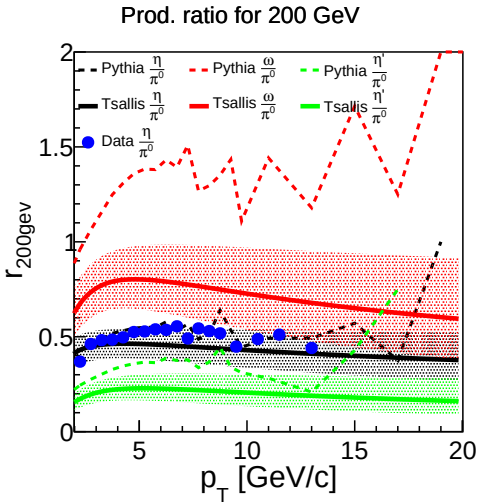


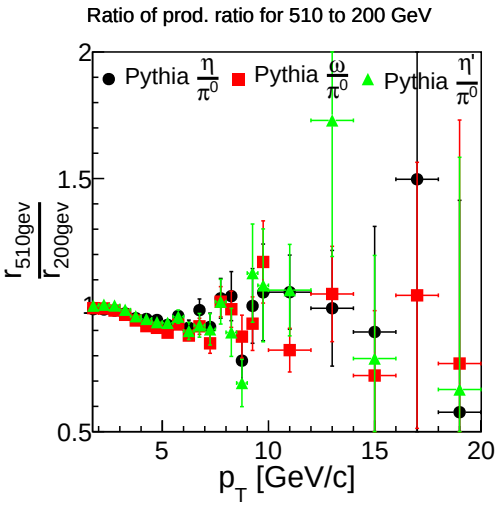
Two-photon separating rate



Merged-photon passing criteria rate

Other meson production rate at 200 and 510 GeV

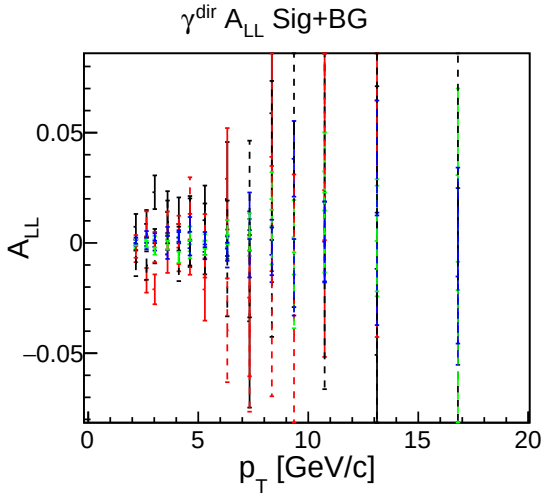




Other meson decay photon ratios

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

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

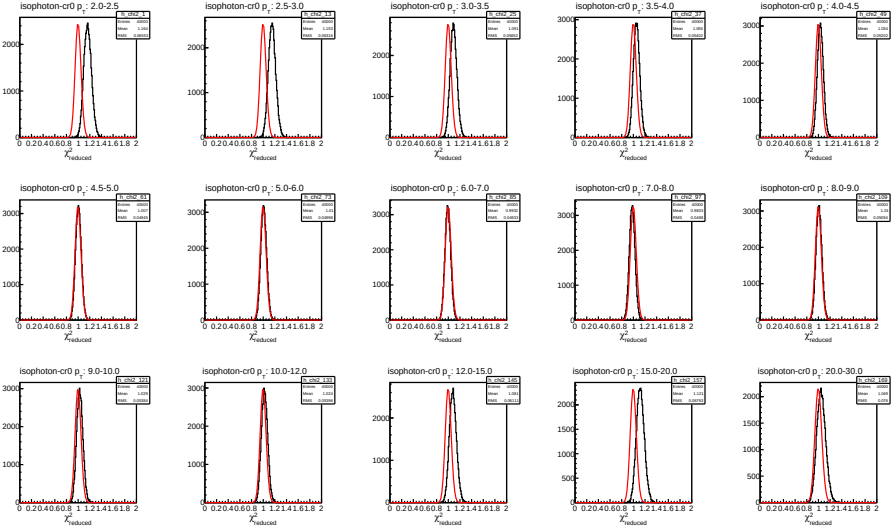
Bunch shuffling technique

- The uncertainty of A_{LL}^{run} for each run from the error propagation:

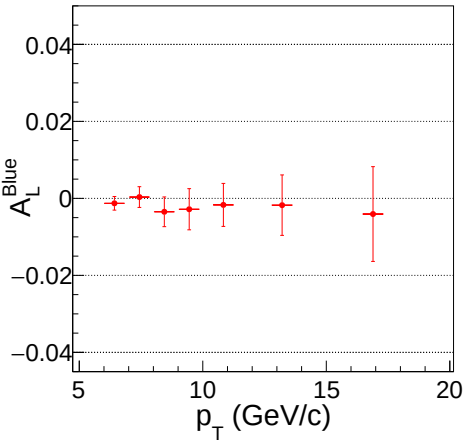
$$(\Delta A_{LL}^{\text{run}})^2 = \left(\frac{1}{P_B P_Y}\frac{2RN_{++}N_{+-}}{(N_{++}+RN_{+-})^2}\right)^2 \left(\left(\frac{\Delta N_{++}}{N_{++}}\right)^2 + \left(\frac{\Delta N_{+-}}{N_{+-}}\right)^2 + \left(\frac{\Delta R}{R}\right)^2\right) + \left(\left(\frac{\Delta P_B}{P_B}\right)^2 + \left(\frac{\Delta P_Y}{P_Y}\right)^2\right)(A_{LL}^{\text{run}})^2$$

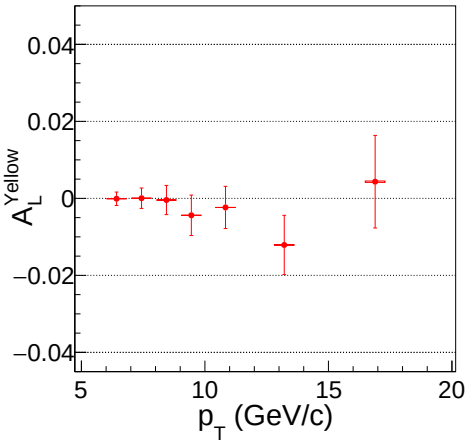
- Above assumptions: variables→independent; yields→Poisson distribution.
- Bunch shuffling: no assumptions about underlying statistical distributions.
- Procedures: randomize the spin pattern, calculate $\Delta A_{LL}^{\text{run}}$ by the error propagation, fit A_{LL}^{run} with a constant, get the fitting χ^2_{reduced}, repeat 40,000 times, plot the χ^2_{reduced} distribution, compare with the theoretical χ^2_{reduced} distribution.
- Purposes: check unknown systematic uncertainties or overestimation of the statistical uncertainties.

Bunch shuffling results

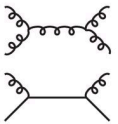
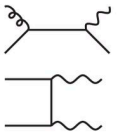


A_L cross checks

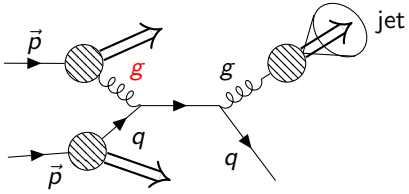




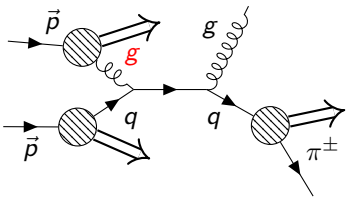
Processes probing parton helicity densities

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	

Jet and charged pion productions



Jet production



Charged pion production

- Larger statistics: not suppressed by small QED coupling.
- $\pi^{\pm}$: separate u and d quark.
- RHIC 200 GeV data probe $0.05 < x < 0.2$
- RHIC 510 GeV data probe $0.02 < x < 0.08$