Direct photon cross section and double helicity asymmetry at mid-rapidity in $\vec{p}+\vec{p}$ collisions at $\sqrt{s}$ = 510 GeV

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for the

PHENIX Collaboration

23rd International Spin Symposium

September 2018

PHENIX

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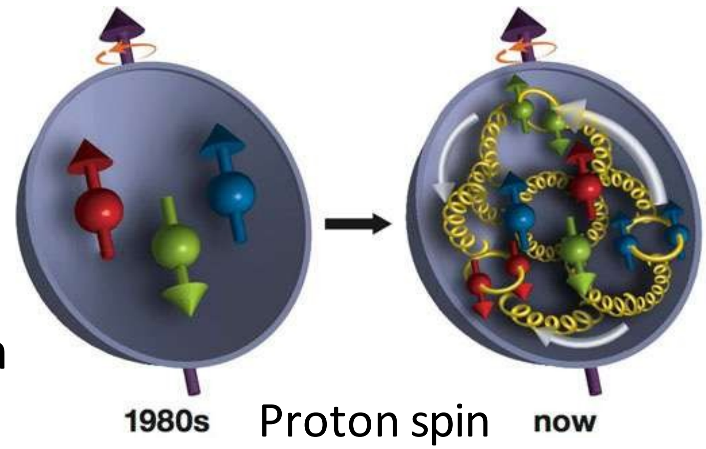
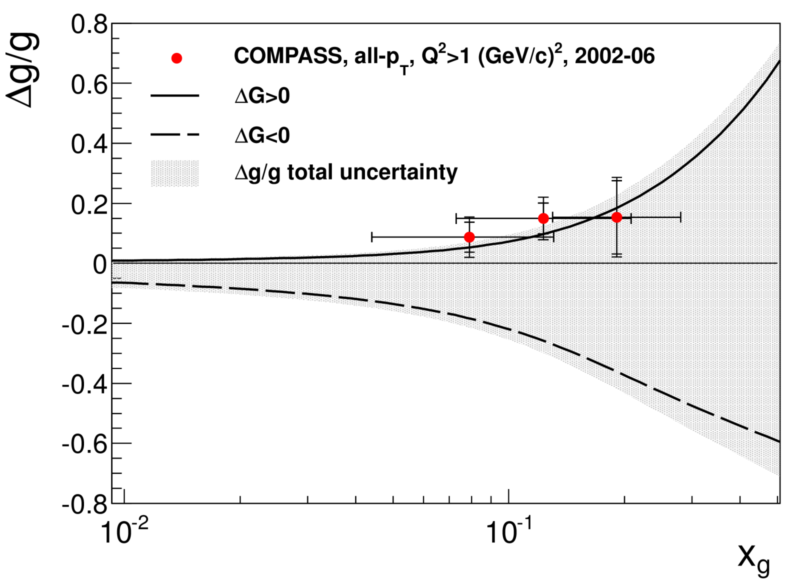
The proton spin decomposition

- The proton spin can be decomposed as

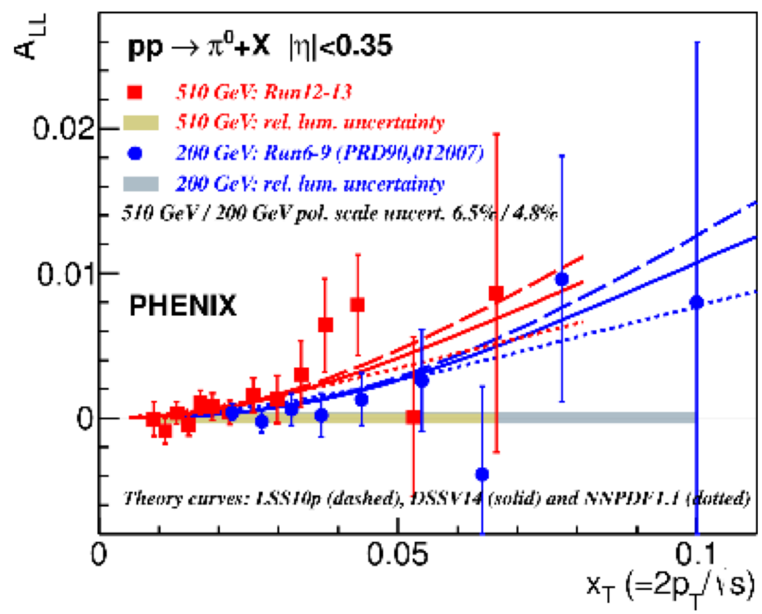
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

- We can measure polarized gluon distribution Δg(x), its first moment ΔG corresponds to the gluon spin in physical gauge and infinite-momentum frame (IMF).





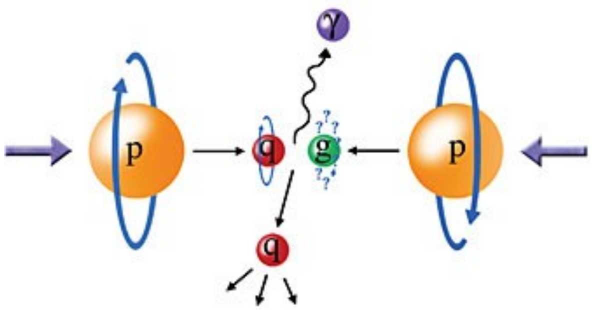
COMPASS in pSIDIS
[COMPASS Collaboration (2017)]

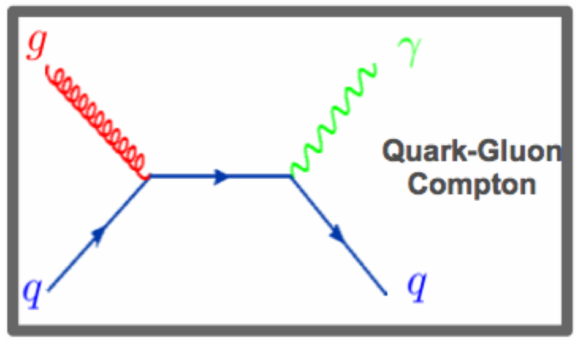


PHENIX in inclusive π^0 A_{LL}
[PHENIX Collaboration (2016)]

Direct photon: the golden channel

~85%



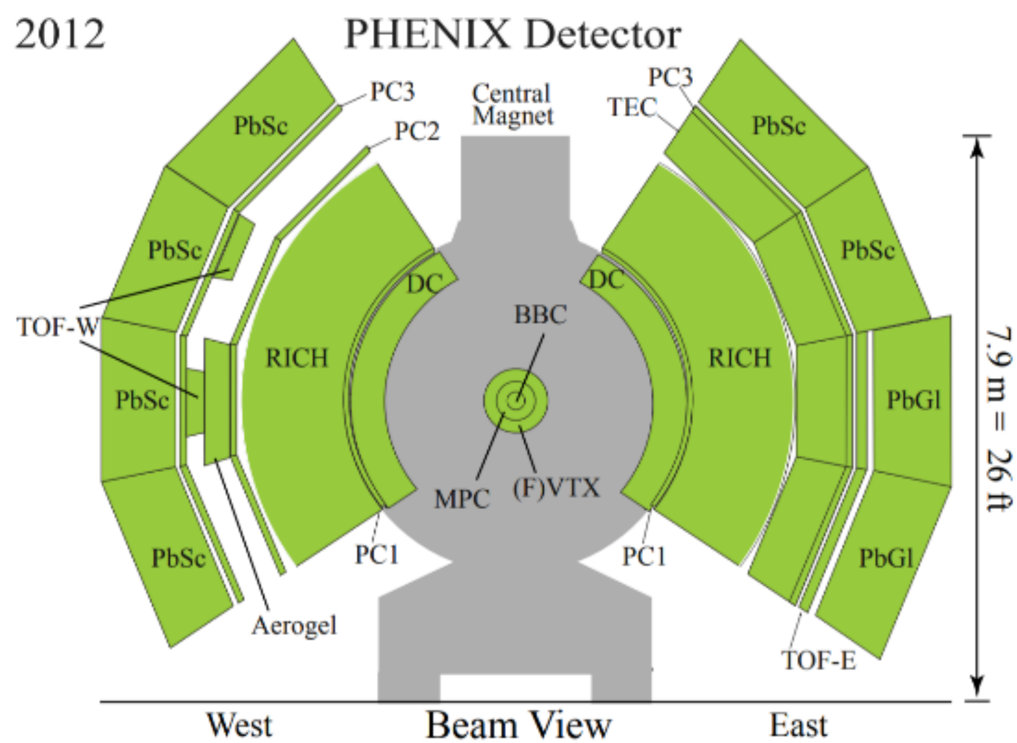


$$A_{LL}^{pp\to\gamma X} \approx \frac{\Delta G(x_g)}{G(x_g)} \cdot \frac{\Delta q(x_q)}{q(x_q)} \cdot a_{LL}^{qg\to\gamma q}$$

- Leading order for gluon polarization: jet, hadron and direct photon in $\vec{p} + \vec{p}$.
- Fragmentation in hadron and jet.
- No hadronizaion in direct photon: “cleanest” channel.
- Dominant process $q + g \to \gamma + q$: probe the sign of the gluon polarization.
- First measure direct photon cross section to confirm consistency with pQCD.
- Then use pQCD to extract gluon contribution.

PHENIX detector

- Electromagnetic Calorimeter (EMCal) is the primary detector for photons.
- EMCal trigger (ERT) is used to select high energy photons.
- Drift Chamber (DC) collect hadron energy.



Direct photon cross section

The direct photon cross section is calculated by

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{L}\cdot\frac{1}{2\pi p_T}\cdot\frac{1}{\Delta p_T \Delta y}\cdot\frac{N_{dir}\cdot r_{pileup}}{\varepsilon_{BBC}\varepsilon_{ERT}\varepsilon_{ToF}\varepsilon_{prob}\varepsilon_{acc}\varepsilon_{conv}}$$

- □ $L = \frac{N_{BBC}}{\sigma_{BBC}}$: absolute luminosity.
- □ ε_{BBC} (ε_{ERT}): *BBC (ERT) trigger efficiency.*
- □ ε_{acc}: acceptance, from single photon and detector geometry simulation.
- □ ε_{conv}: photon conversion rate, from radiation length in VTX detector.

Direct photon signal extraction

Source of direct photon:

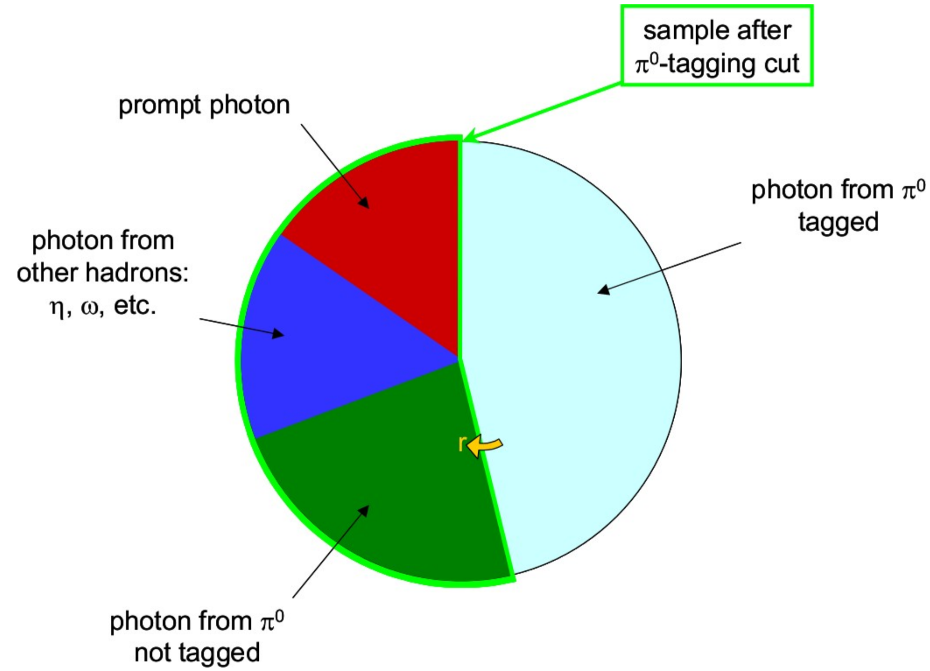
- □ Compton scattering: $q + g \rightarrow \gamma + q$
- □ Annihilation: $q + \overline{q} \rightarrow \gamma + g$
- □ Parton fragmentation to photon.
- □ Quark bremsstrahlung.

Source of direct photon background:

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

Yield of direct photon:

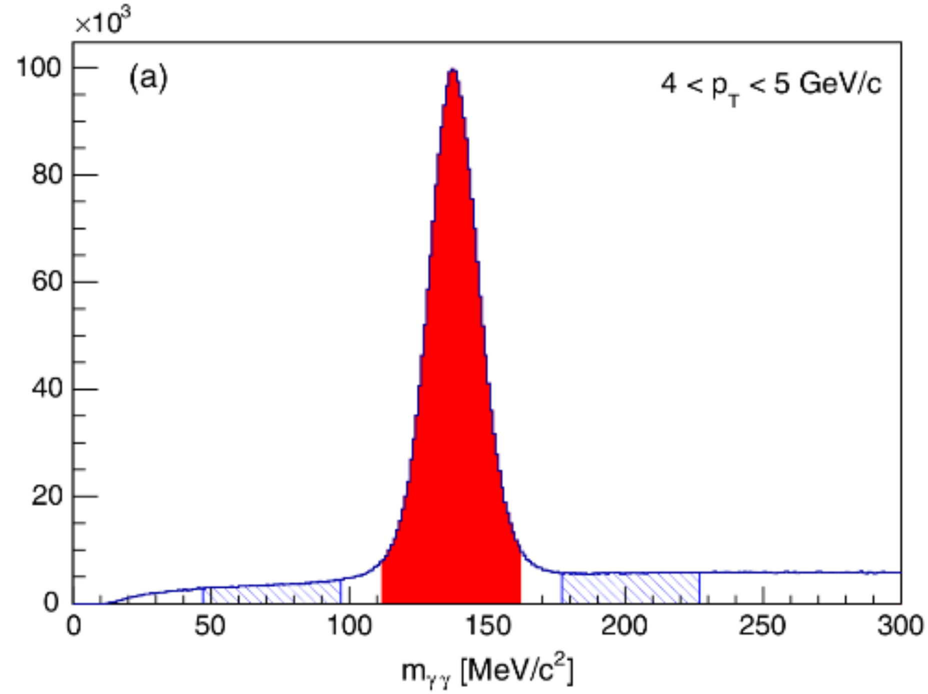
- □ $N_{dir} = N_{incl} - (1 + A)(1 + R)N_{\pi^0}$.
  - ➢ R: π^0 one photon missing ratio.
  - ➢ A: Other hadrons' to π^0's photon ratio.



π^0-tag method.

Direct photon background subtraction

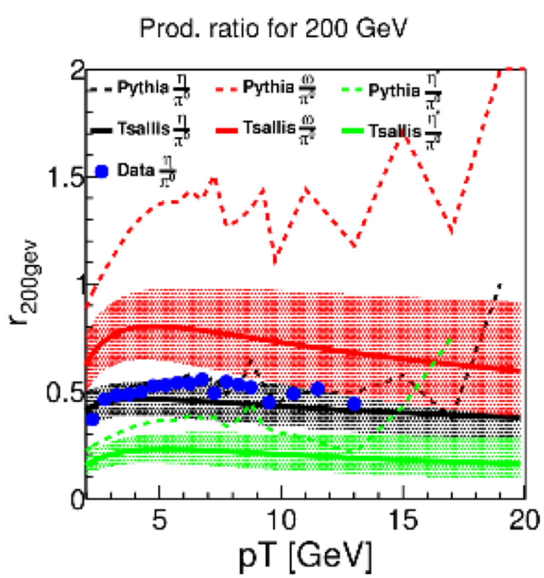
- π^0 can be reconstructed by its diphoton invariant mass:
  - Peak region subtract side region.
- Missing one photon ratio R:
  - minimum energy cut
  - masked detector areas
  - finite detector size
  - finite detector resolution
  - photon conversion

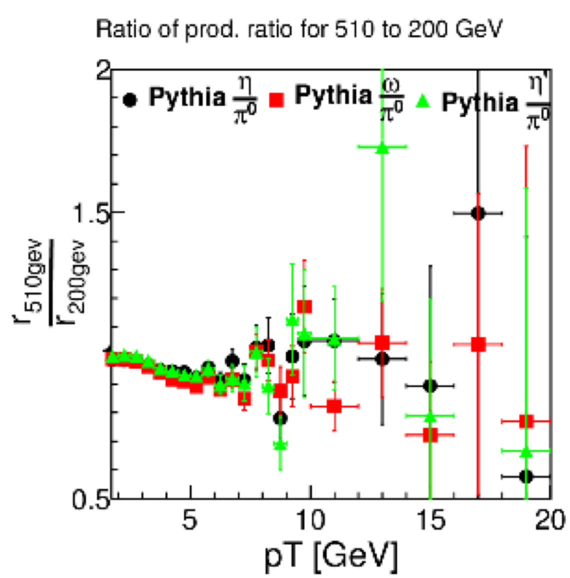


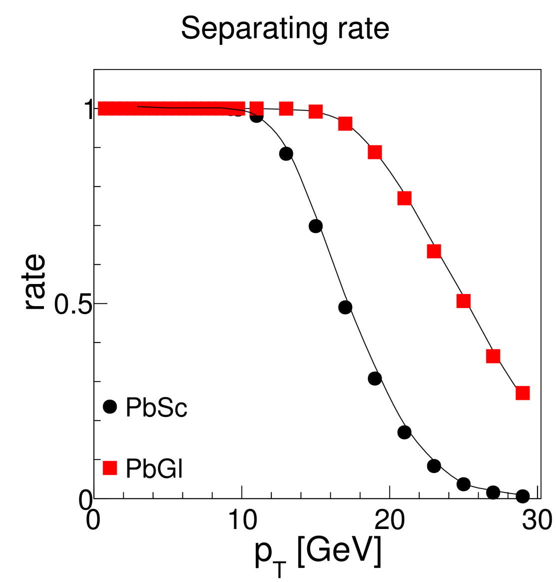
- Use single-π^0 and detector geometry simulation:
  - Missing ratio R.
  - Two photons merging at high p_T .
- Production ratio can be estimated by 200 GeV data:
  - η/π^0
  - ω/π^0
  - η'/π^0

Photon from other hadron decay

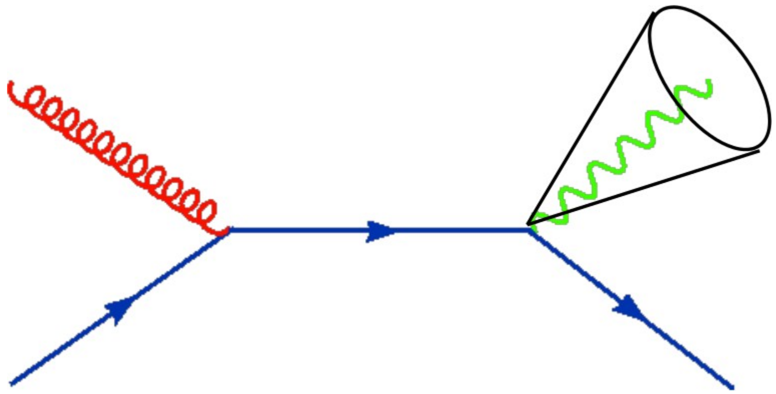
- Left plot: meson production from other hadrons with photon pT.
  - PYTHIA reproduces pseudoscalar mesons η and η' production ratio well.
  - Vector meson ω production ratio is incorrect in PYTHIA.
- Middle plot: production ratio between 200 GeV and 510 GeV with photon pT.
  - We use the production ratio from 200 GeV data.
- Right plot: two photons from π^0 start merging at high π^0 pT .
  - Simulated by photon shower shape and EMCal tower size.
  - It will increase the photon ratio from other hadrons, since only π^0 photons will merge at pT less than 30 GeV.







Isolation cut



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

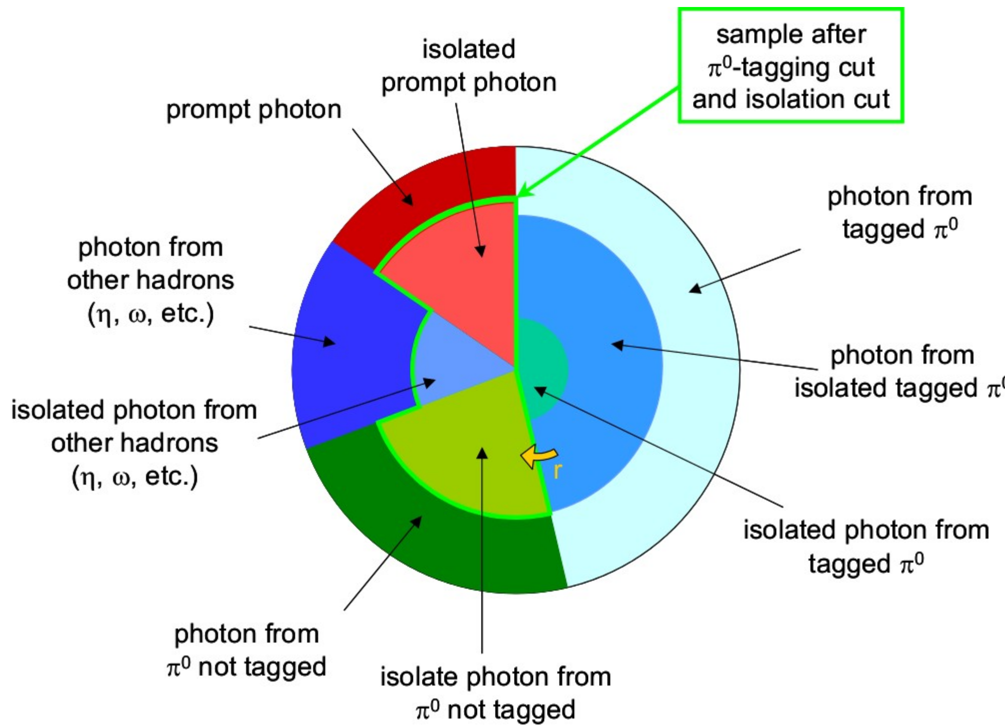
Isolation cut requirement:

$$\sum E_{neutral} + \sum E_{charged} < 0.1 E_\gamma$$

Remove fragmentation photons;
Increase S/B ratio.

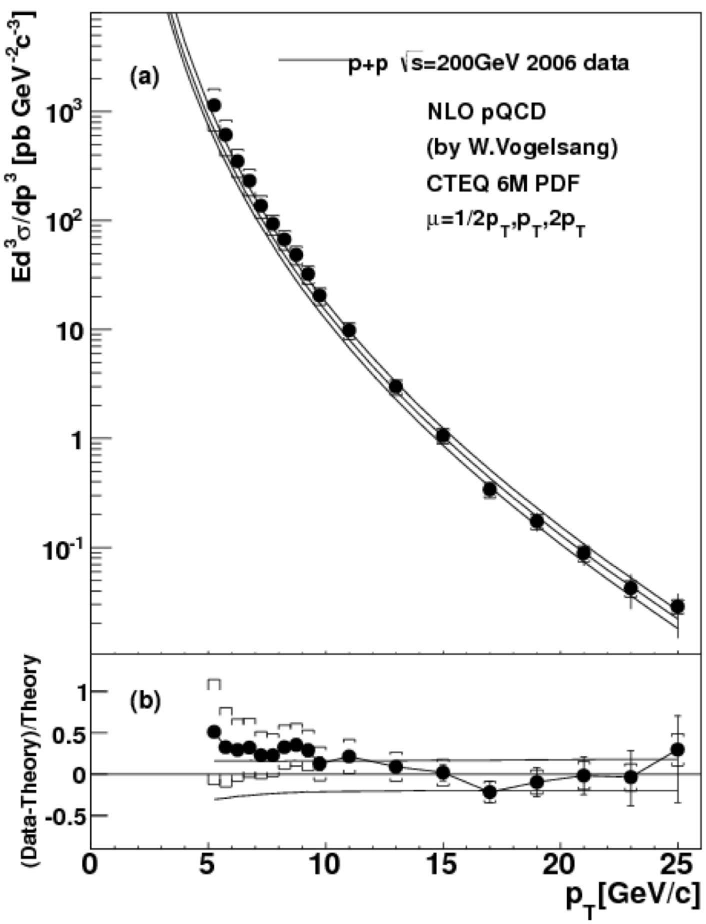
$$N_{\rm dir}^{iso} = N_{incl}^{iso} - (n_{\pi^0}^{iso} + R N_{\pi^0}^{iso}) - A^{iso}(1+R) N_{\pi^0}^{iso}.$$

- $n_{\pi^0}^{iso}$: π^0 decay photons pass isolation cut with partner photon.
- $N_{\pi^0}^{iso}$: π^0 decay photons pass isolation cut without partner photon.
- A^{iso}: Photon ratio from other hadrons' decay, including the effect of isolation cut.



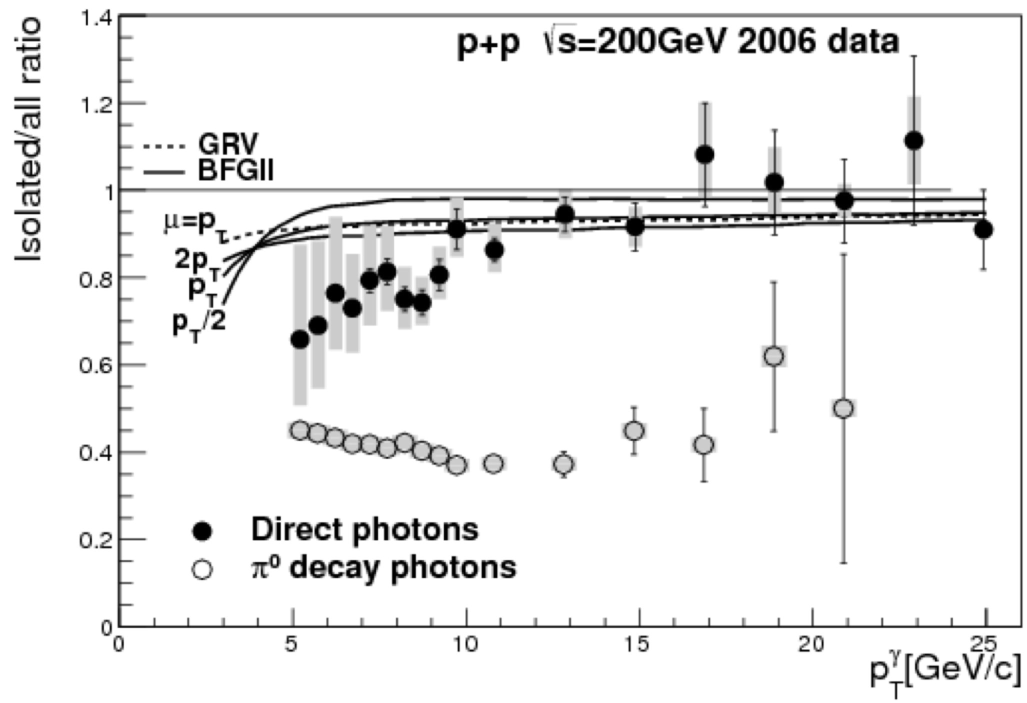
Run 6 direct photon cross section

Direct Photon Cross-Section



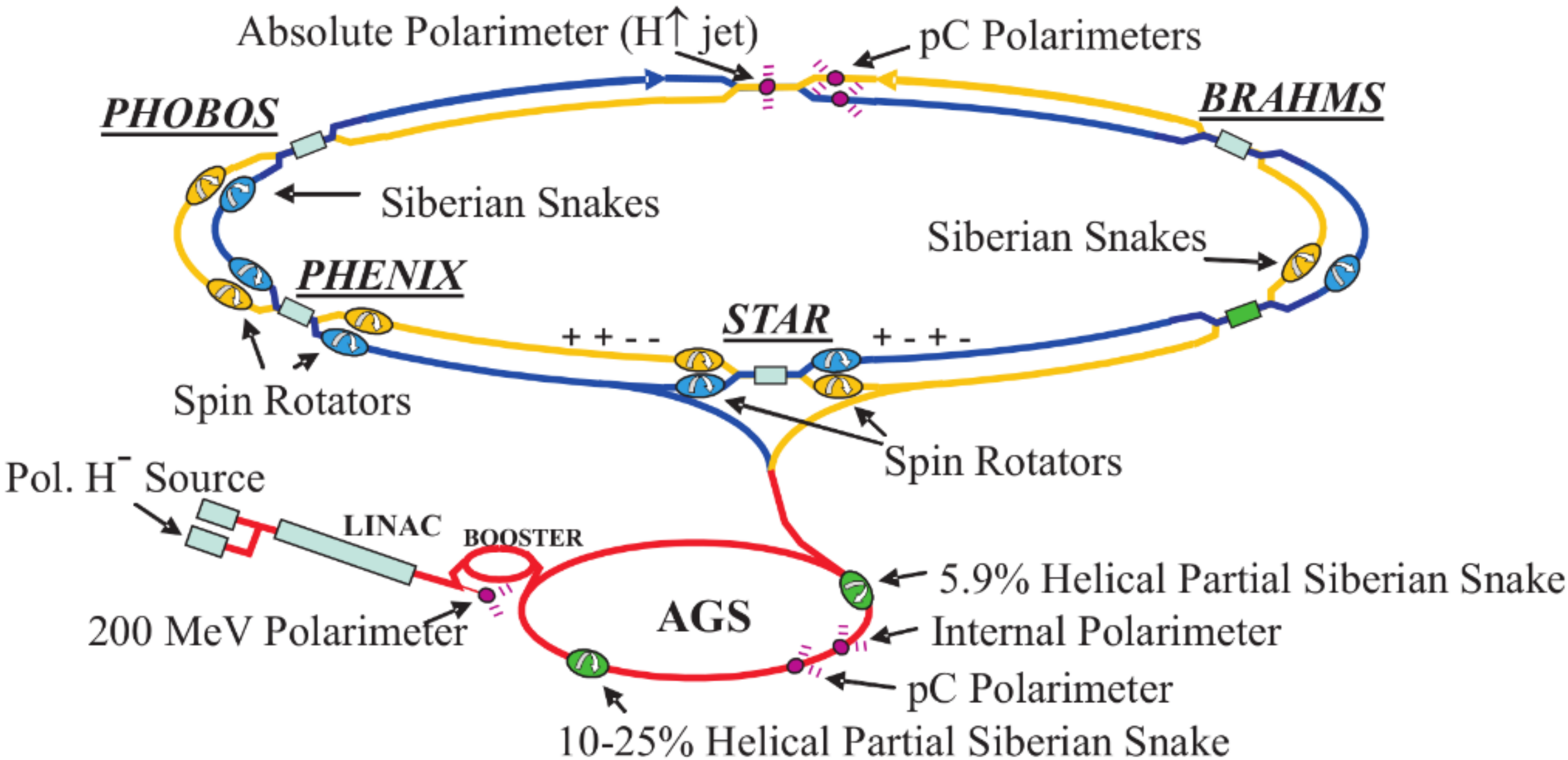
Phys.Rev.D 86, 072008 (2012)

Inclusive π^0 and photon ratio.



Phys.Rev.D 86, 072008 (2012)

Polarized proton collider at RHIC



- Siberian Snakes reduce the effect of depolarizing resonances.
- Polarimeter pC and H↑ jet monitor the beam polarization.
- Spin rotators rotate beam polarization from the stable vertical direction to the longitudinal direction before the IP and back to vertical afterward.

Longitudinal double-spin asymmetry A_{LL}

- Each beam has 120 bunches, of which 111 bunches are filled.
- The polarization patterns for bunches are called spin patterns.

+ − + − − + − +   − + − + + − + −
+ + − − + + − −   + + − − + + − −

Examples of spin patterns. Red and blue are even and odd crossings respectively.

- $A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_B P_Y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$
- $P_{B(Y)}$ is polarization of the blue (yellow) beam.
  - The polarization magnitude is measured by pC and HJet polarimeter.
  - The polarization direction is measured by ZDC.
- $R = \frac{L_{++}}{L_{+-}}$ is relative luminosity between different helicity states.
- Even and odd crossings have different trigger circuits with different effective trigger thresholds. A_{LL} is measured separately for even and odd crossings in each spin pattern.

Rate safe method for relative luminosity

- The systematic uncertainty from relative luminosity measured by BBC

  $R = \frac{N_{BBC}^{++}}{N_{BBC}^{+-}}$ can be determined by ZDC triggered events via

$$A_{LL}^{R} \equiv \frac{1}{P_B P_Y} \frac{r_{++} - r_{+-}}{r_{++} + r_{+-}}, r \equiv \frac{N_{ZDC}}{N_{BBC}}$$

- In high luminosity environment such as run 13, rate dependence must be taken into account when calculating relative luminosity.
- We will use the rate safe method given by Andrew Manion [Manion (2014)],

Cross check

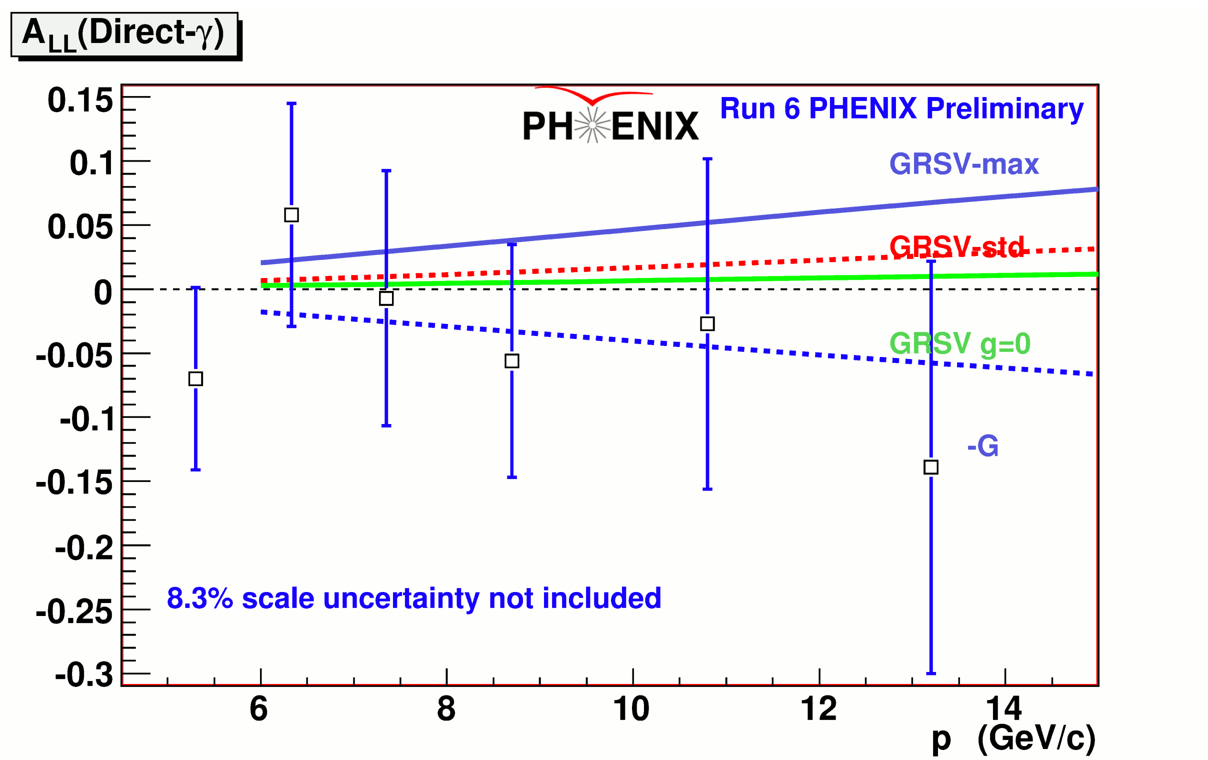
- Longitudinal single-spin asymmetry

$$A_L = -\frac{1}{P_{Beam}} \frac{N^+ - R_{Beam} N^-}{N^+ + R_{Beam} N^-}, R_{Beam} = \frac{L^+}{L^-}$$

should be zero due to parity.

- Bunch shuffling: Test for additional RHIC fill-to-fill uncorrelated systematic uncertainties that may have been overlooked.
    - Method: Assign each bunch a random polarization for ten-thousand iterations, calculate A_{LL}, δA_{LL} and χ^2 for each iteration. The resulting χ^2/DOF (here DOF = number of fills) can indicate whether the uncorrelated uncertainty is calculated correctly or not.

Run 6 A_{LL} preliminary

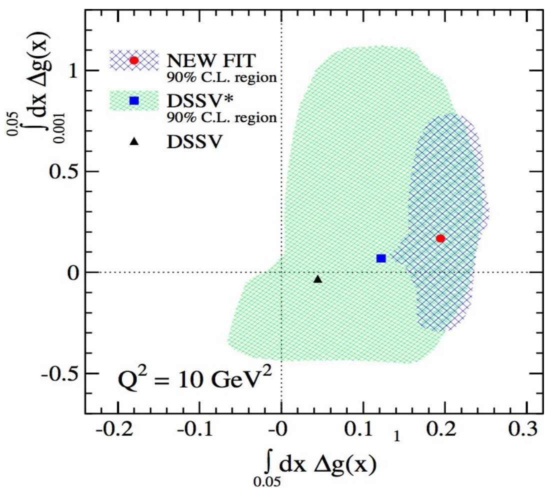


The run 6 A_{LL} preliminary [Bennett thesis (2009)].

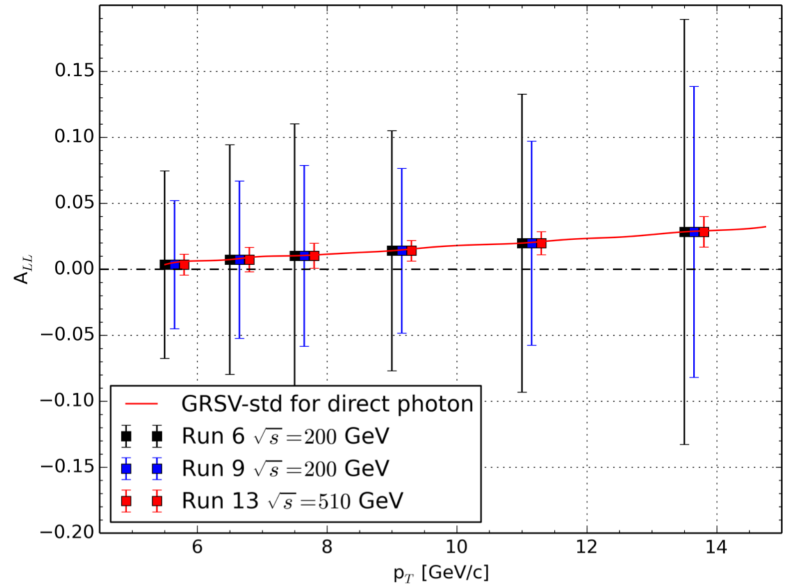
This result is not published.

Run 13 performance

- Existing RHIC data mainly probe the region $0.05 \leq x \leq 0.2$.
- PHENIX π^0 A_{LL} measurements in 510 GeV confirm a nonzero ΔG and extend the x range to 0.01.
- STAR jet data clearly imply a polarization of gluons in this range.
- The luminosity of Run 13 is twenty times larger than that of Run 6.
- The projected uncertainty is much smaller in Run 13.
- This will be the first direct photon analysis for gluon polarization.
- Our results will add additional independent constraints on the ΔG .



Global fit for ΔG from previous data.
[D. de Florian et al. (2014)]



Projected uncertainty for direct photon A_{LL} measurement.

Summary

- Making clear of the gluon spin is vital for explaining the proton spin puzzle, as well as understanding the proton spin composition.
- Direct photon production in p+p collisions probe the gluon spin at the leading order without fragmentation function. So this is the golden channel.
- Run 13 has much higher luminosity than that in previous direct photon A_{LL} analysis. So we expect it can give more constraint on gluon polarization distribution.

Current status

- □ Finished the cross check with π^0 cross section.
- □ Finalizing direct photon cross section.
- □ Prepared for direct photon A_{LL} measurement.

References

1. COMPASS Collaboration, EPJC 77,209 (2017).
2. PHENIX Collaboration, PRD 93, 011501(R) (2016).
3. D. de Florian et al., PRL 113, 012001 (2014).
4. Manion, Ph.D. thesis (2014).
5. Bennett, Ph.D. thesis (2009).