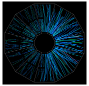
Transverse Single-Spin Asymmetry for Electromagnetic (EM) Jets at Forward Rapidities at STAR in $p^{\uparrow} + p$ Collisions at $\sqrt{s} = 200$ GeV

Latiful Kabir
University of California at Riverside
(For the STAR Collaboration)

April 15, 2021
9th GHP Workshop



Supported in part by
U.S. DEPARTMENT OF ENERGY | Office of Science

UNIVERSITY OF CALIFORNIA
UC RIVERSIDE

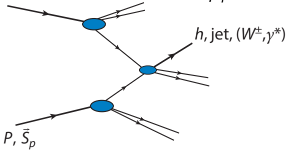
Outline

1. **Transverse Single-Spin Asymmetry (A_N)**
2. **RHIC and The STAR Experiment**
3. **FMS and EEMC Detectors**
4. **Jet Reconstruction**
5. **A_N Extraction Status**
6. **Outlook**

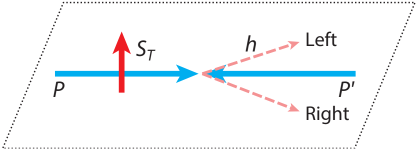
Transverse Single-Spin Asymmetry (A_N)

- Unexpected large transverse single-spin asymmetries (A_N) are observed in proton-proton collisions
- pQCD predicts $A_N \sim \frac{m_q}{p_T} \cdot \alpha_S \sim 0.001$

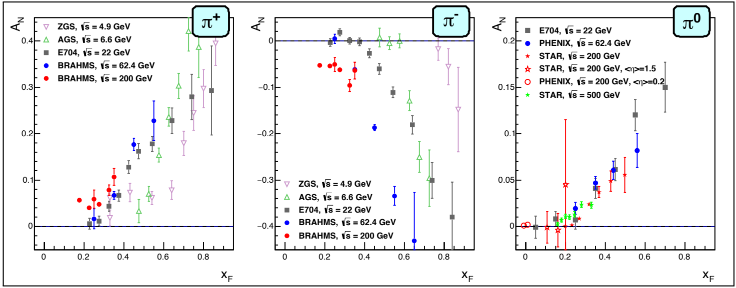
Kane, Pumplin and Repko
PRL 41 1689 (1978)



A_N in $p(S_T) + p \rightarrow h + X$



$$A_N = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$

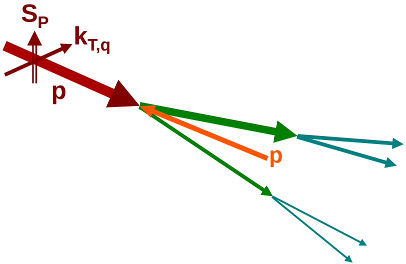


R. D. Klem *et al.*, PRL **36**, 929 (1976)
D.L. Adams *et al.*, PLB **264**, 462 - 466(1991)
I. Arsene *et al.*, PRL **101**, 042001 (2008)

D.L. Adams *et al.*, PLB **261**, 201(1991)
B. I. Abelev *et al.*, PRL **101**, 222001(2008)
A. Adare *et al.*, PRD **90**, 012006 (2014)
E.C. Aschenauer *et al.*, arXiv:1602.03922

Possible Mechanisms

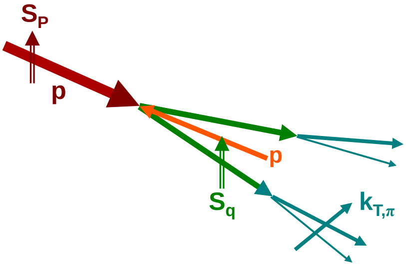
Sivers Mechanism:
Correlation between proton spin and parton k_T



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

Signatures: A_N for jets or direct photons, $W^{+/-}$, Z^0, Drell-Yan

Collins Mechanism:
Transversity (quark polarization) ⊗ jet fragmentation asymmetry



J. Collins, Nucl Phys B **396** (1993) 161

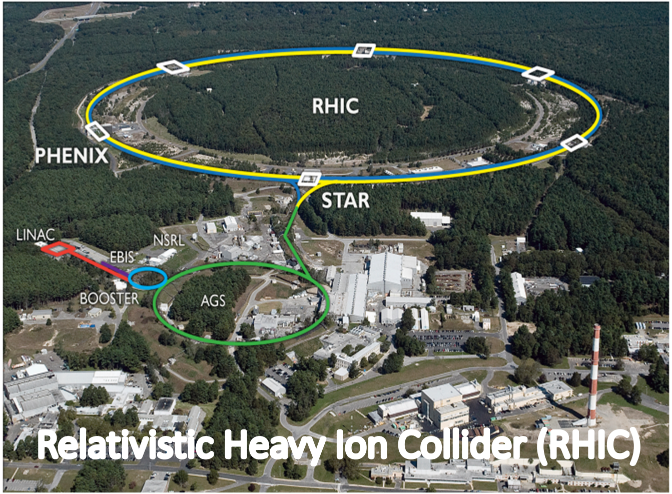
Signatures: Collins effect, Interference fragmentation function (IFF), pion A_N

Twist-3:
Quark-gluon / gluon-gluon correlations and fragmentation functions. A source for Sivers function.

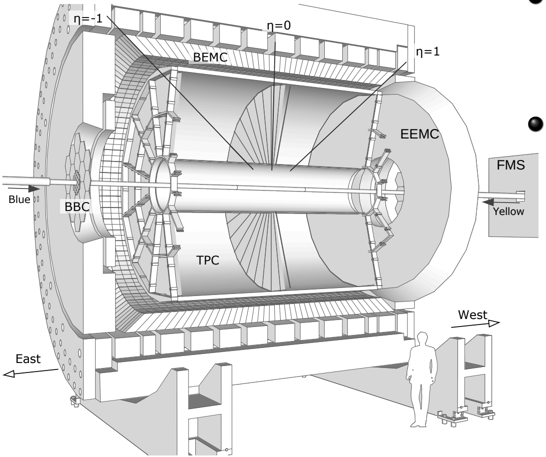
J.W. Qiu and G. Sterman, Phys Rev Lett **67** 2264 (1991)

Relativistic Heavy Ion Collider (RHIC)

- World's only polarized proton-proton collider
- Transverse and longitudinal polarization
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Fill-to-fill variations in spin pattern
- Polarized protons up to $\sqrt{s}$ = 510 GeV
- Allows to probe hard scattering processes with control of systematic effects



The STAR Experiment at RHIC

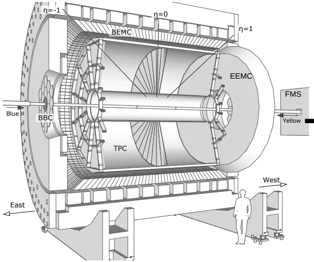


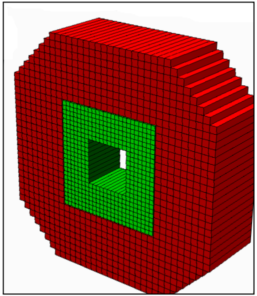
- **Calorimetry System:**
  - Barrel Electromagnetic Calorimeter (**BEMC**): $-1 < \eta < 1$
  - Endcap Electromagnetic Calorimeter (**EEMC**): $1.1 < \eta < 2$
  - Forward Meson Spectrometer (**FMS**): $2.6 < \eta < 4.1$
- Full azimuthal coverage

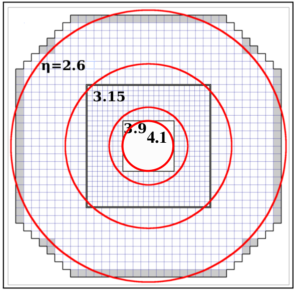
Year	$\sqrt{s}$ (GeV)	Recorded Luminosity (pb^{-1})	Polarization Orientation	B/Y $\langle P \rangle$
2009	200	25	Longitudinal	55
2009	500	10	Longitudinal	39
2011	500	12	Longitudinal	48
2011	500	25	Transverse	48
2012	200	22	Transverse	61/56
2012	510	82	Longitudinal	50/53
2013	510	300	Longitudinal	51/52
2015	200	52	Transverse	53/57
2015	200	52	Longitudinal	53/57
2017	510	320	Transverse	55

- Polarized pp dataset since 2009

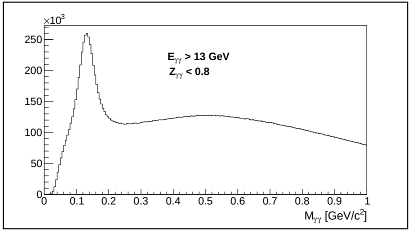
Forward Meson Spectrometer (FMS)



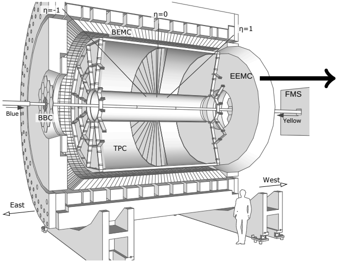


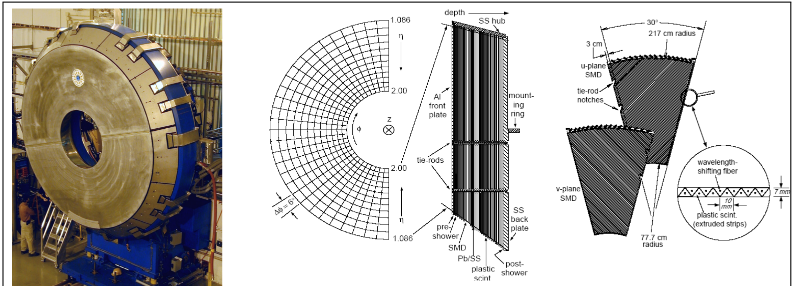


- FMS is a lead-glass electromagnetic calorimeter
- Array of ∼1200 Pb-glass cells coupled to PMTs
- Forward pseudorapidity coverage: $2.6 < \eta < 4.1$
- γ, e^-, e^+ $\rightarrow$ EM shower
- Observables: γ, π^0, EM-jet

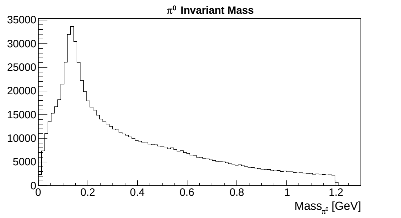


Endcap Electromagnetic Calorimeter (EEMC)





- Coverage: $1.1 < \eta < 2.0$, $0 < \phi < 2\pi$
- 12 sectors (matched to TPC sectors) $\times$ 5 subsectors x 12 η-bins = 720 towers.
- 1 tower = 24 layers, Layer 1 = pre-shower 1, Layer 2 = pre-shower 2, Layer 24 = post-shower
- SMD U and V planes at $5X_0$
- 288 SMD strips/plane/sector

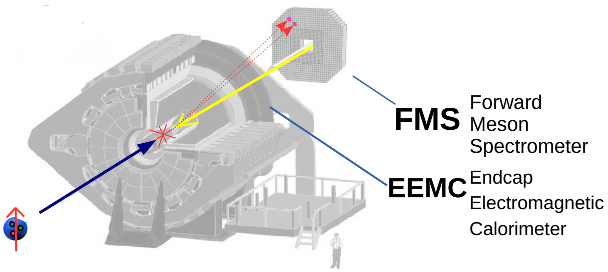


EM-Jet A_N with FMS and EEMC at STAR

- **Motivation:**
  - Explore potential sources of large A_N
  - Isolate subprocess contribution (EM-jet A_N) to the large A_N
  - Characterize EM-jet A_N as a function of EM-jet p_T, energy and photon multiplicity
- **Advantages of EM-jet:**
  - Allows to investigate EM component of a full jet
  - Enables us to classify EM-jet in terms of its constituent photon multiplicity
- **Dataset:**
  - RHIC Run 15 data
  - $p^{\uparrow}p$ collisions at $\sqrt{s} = 200$ GeV
  - Transversely polarized protons with <P> = 57%
  - $\mathcal{L} = 52\ \mathrm{pb}^{-1}$

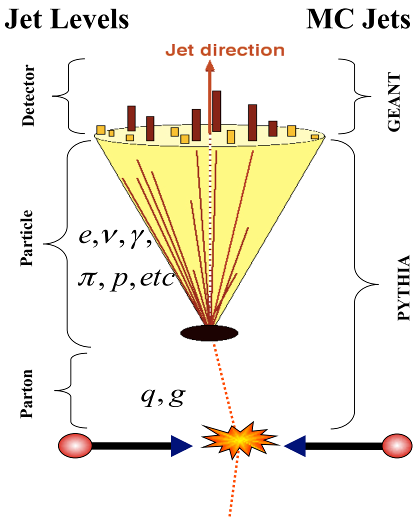
$$p^{\uparrow} + p \rightarrow \text{EM-jet} + X$$

EM-jet $\rightarrow$ Jet reconstructed out of photons only



Jet Reconstruction

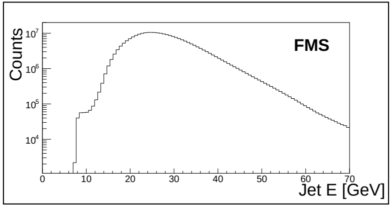
- Vertex z priority: TPC, VPD, BBC
- Reconstructed FMS photons / EEMC towers as input for FastJet
- Anti-k_T algorithm with R = 0.7
- $E_\gamma > 1.0$ GeV (For FMS EM-Jet)
- Jet p_T > 2.0 GeV/c
- -80 cm $< V_z <$ 80 cm

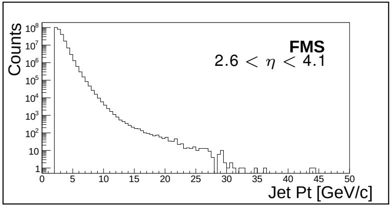


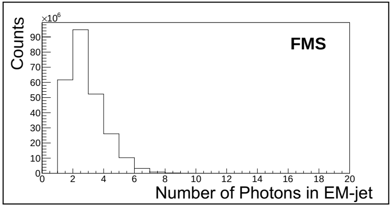
Monte Carlo

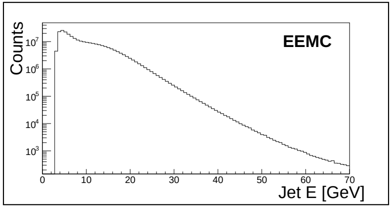
- PYTHIA 6.428 event generator
- Tune: Perugia 2012 with CTEQ6 PDFs
- GEANT based STAR detector simulation

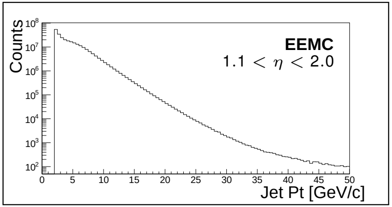
EM-Jets in FMS and EEMC

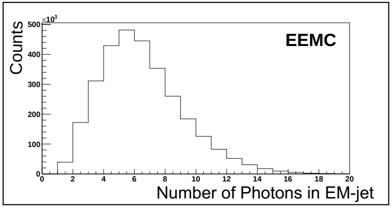












- EM-jets from forward (FMS) and intermediate (EEMC) rapidities provide different EM-jet E and p_T ranges to be explored
- Plots show EM-jet E, p_T and photon multiplicity from data

EM-Jet A_N Extraction

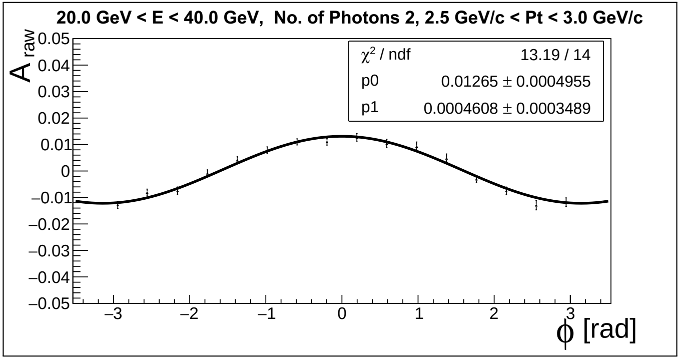
$$N^{\uparrow} = I_0^{\uparrow}\epsilon(1 + PA_N \cos\phi)$$
$$N^{\downarrow} = I_0^{\downarrow}\epsilon(1 - PA_N \cos\phi)$$

$$A(\phi) = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$A(\phi) \approx PA_N \cos\phi + \frac{I_0^{\uparrow} - I_0^{\downarrow}}{I_0^{\uparrow} + I_0^{\downarrow}}$$

$$A(\phi) = PA_N \cos(\phi) + p_1$$

$$A(\phi) + A(\phi + \pi) \approx 2\frac{I_0^{\uparrow} - I_0^{\downarrow}}{I_0^{\uparrow} + I_0^{\downarrow}}$$



- Allows extraction of both physics asymmetry and beam asymmetry

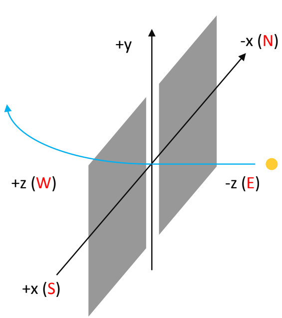
EM-Jet A_N Extraction

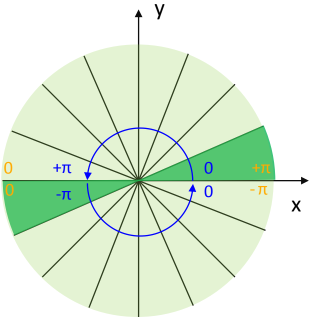
- Cross-ratio formula to calculate A_N

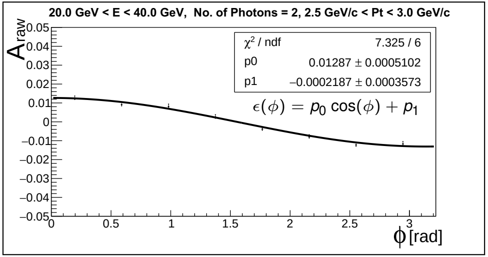
$$\epsilon = PA_N \cos(\phi)$$

$$\epsilon \approx \frac{\sqrt{N_\phi^\uparrow N_{\phi+\pi}^\downarrow} - \sqrt{N_{\phi+\pi}^\uparrow N_\phi^\downarrow}}{\sqrt{N_\phi^\uparrow N_{\phi+\pi}^\downarrow} + \sqrt{N_{\phi+\pi}^\uparrow N_\phi^\downarrow}}$$

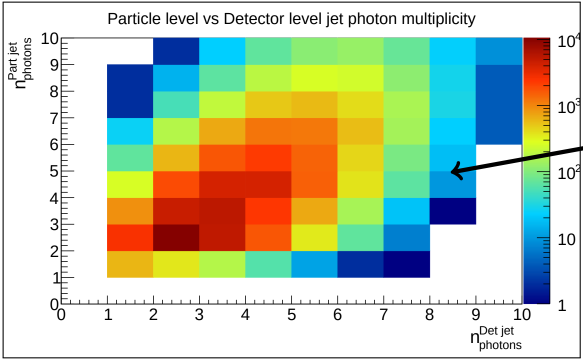
- **Advantages:** Cancels systematics, such as luminosity and detector effects



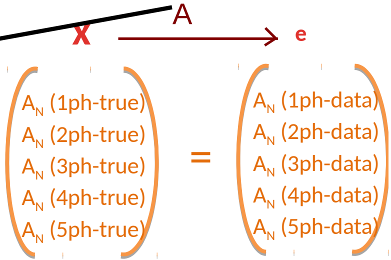




Corrections: Unfolding for Event Misidentification

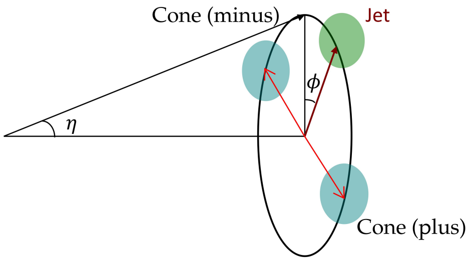


- The leading contributions come from A_N for EM-jets with photon multiplicity n < 6

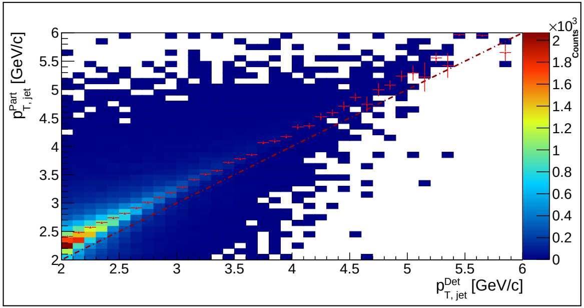


- Solve a set of five linear equations with five variables for each energy and p_T bin
- Decompose A_N as a linear composition of A_N^i corresponding to n_i photons
- Use SVD for the unfolding procedure (e.g. TSVDUnfolding class)

Corrections: Underlying Event and p_T Corrections



Phys Rev D **91** 112012 (2015), ALICE Collaboration

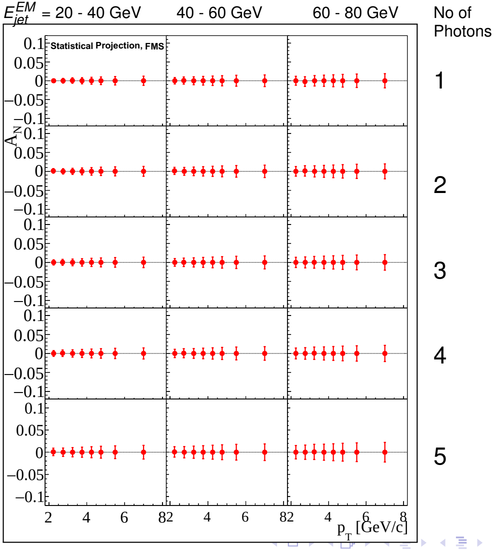


- EM-jet p_T values are corrected for contaminations from underlying events (UE) using off-axis cone method
- EM-jet observables are corrected to the particle level
- The asymmetry is corrected for the dilution from the background

EM-Jet A_N Projection

Leading Sources of Systematic Uncertainties

- A_N uncertainties:
  - Event misidentification
  - Background contamination
  - Beam polarization
- Energy or p_T uncertainties:
  - Calibration
  - Energy or p_T corrections
  - Effects of radiation damage



Current Status and Outlook

- We are studying A_N in the subprocess: $p^{\uparrow} + p \rightarrow$ EM-jet + X
- Understanding the dependences of A_N on photon multiplicity inside EM-jet, jet p_T and jet E can help further characterize large A_N in the forward rapidities
- Current efforts include: improving the EM-jet simulation and better understanding of the sources of systematic uncertainties
- Expect physics results soon!