Transverse Single-Spin Asymmetries for π^0 and Electromagnetic Jets at Forward Rapidities in $p^{\uparrow}$+p Collisions at $\sqrt{s}$ = 200 GeV and 500 GeV at STAR

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

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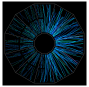

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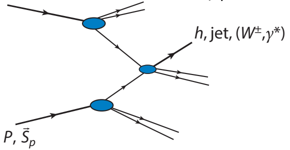
Outline

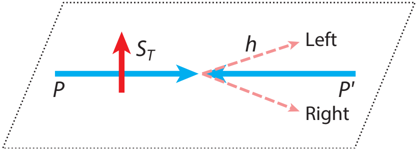
Transverse Single-Spin Asymmetry (A_N)

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

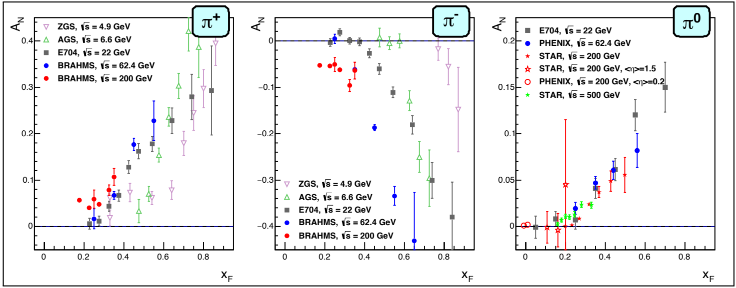
Kane, Pumplin and Repko
PRL 41 1689 (1978)



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



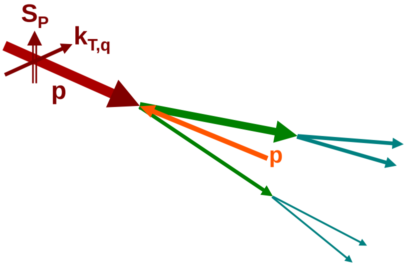
$$A_N = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$



R. D. Klem *et al.*, Phys. Rev. Lett. **36**, 929 (1976)
D.L. Adams *et al.*, Phys. Lett. B **264**, 462 - 466(1991)
I. Arsene *et al.*, Phys. Rev. Lett. **101**, 042001 (2008)
D.L. Adams *et al.*, Phys. Lett. B **261**, 201(1991)
B. I. Abelev *et al.*, Phys. Rev. Lett. **101**, 222001(2008)
A. Adare *et al.*, Phys. Rev. D **90**, 012006 (2014)
E.C. Aschenauer *et al.*, arXiv:1602.03922

Possible Mechanisms

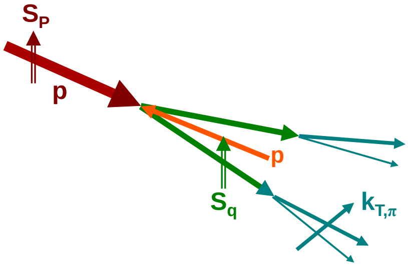
Sivers Mechanism:
Correlation between proton spin and parton k_T



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) $\otimes$ jet fragmentation asymmetry



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

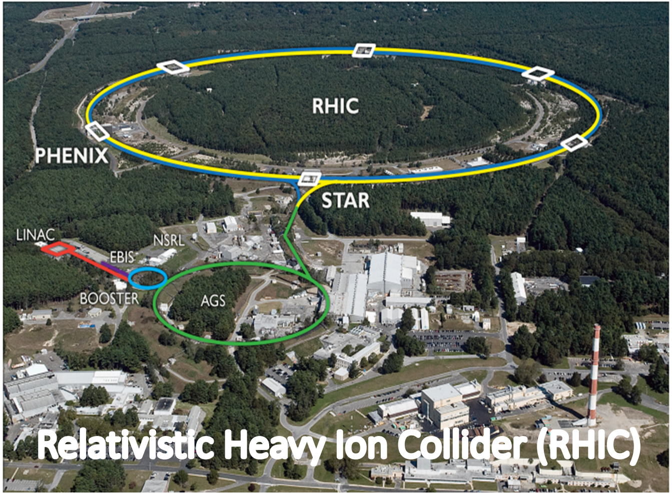
Signatures: Collins effect - Azimuthal asymmetry of hadrons in jets

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

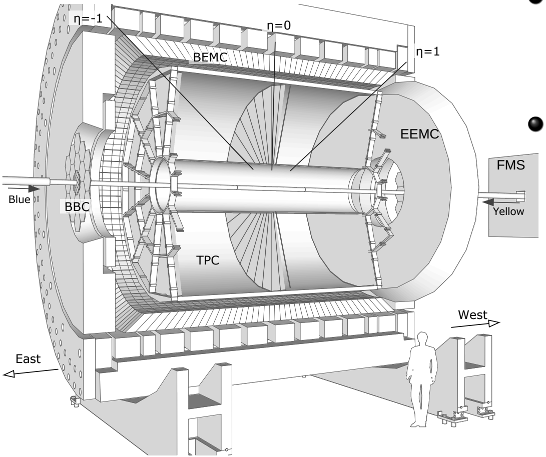
J.W. Qiu and G. Sterman, Phys. Rev. Lett. **67** 2264 (199

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 polarized 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	350	Transverse	58

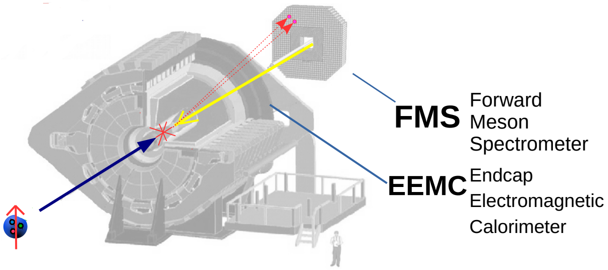
- Polarized pp dataset since 2009

π^0 and EM-Jet A_N with FMS and EEMC at STAR

- **Motivation:**
  - Explore potential sources of large A_N
  - Study π^0 A_N with different topologies
  - Isolate initial and final state effects by measuring EM-jet A_N and Collins asymmetry of π^0 inside EM-jet
  - 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 11 and 15 data
  - $p^\uparrow p$ collisions at $\sqrt{s}$ = 500 GeV and 200 GeV
  - Transversely polarized protons with <P> = 52% and 57%
  - $\mathcal{L}$ = 25 pb^{-1} and 52 pb^{-1}

$$p^\uparrow + p \rightarrow \pi^0 + X$$
$$p^\uparrow + p \rightarrow \text{EM-jet} + X$$

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

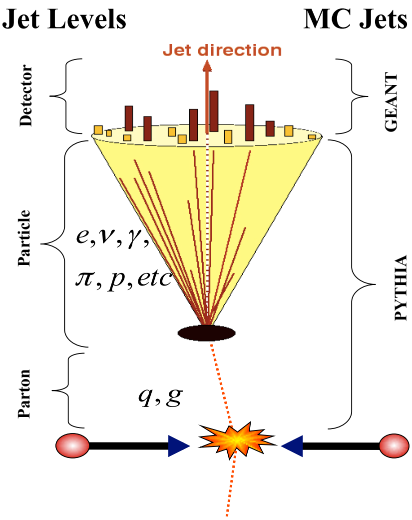


π^0 and Jet Reconstruction

π^0:
- p_T > 2.0 GeV/c
- $M_{\gamma\gamma}$ < 0.3 GeV/c^2
- $Z_{\gamma\gamma} = \frac{|E_1 - E_2|}{E_1 + E_2} < 0.7$

Jet:
- Reconstructed FMS photons / EEMC towers as inputs 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

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

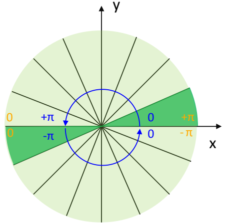


EM-Jet A_N Extraction

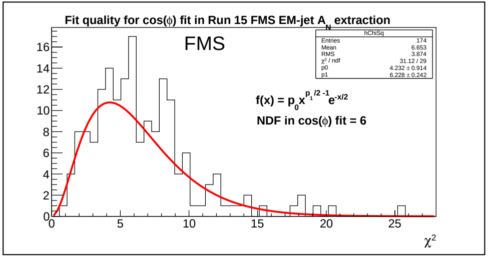
- Cross-ratio formula to calculate A_N

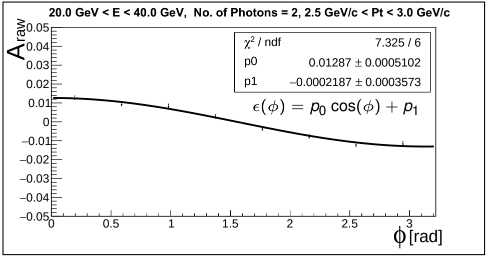
$$\epsilon = PA_N \cos(\phi)$$

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

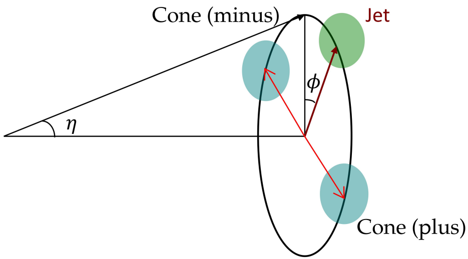


- **Advantages:** Cancels systematics, such as luminosity and detector effects

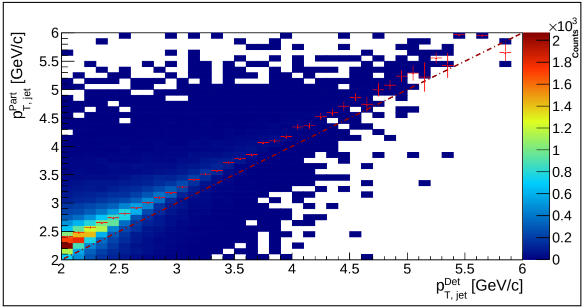




Corrections: Underlying Event and p_T Corrections

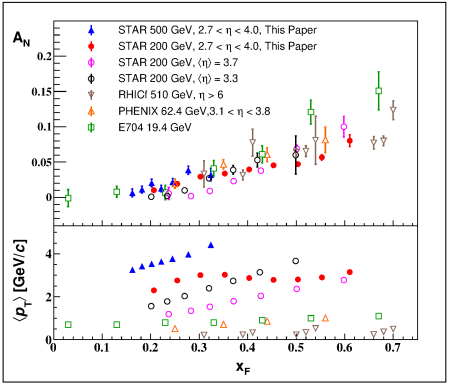


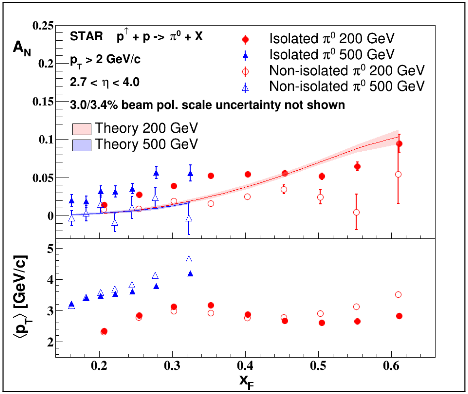
Phys. Rev. D **91** 112012 (2015), ALICE Collaboration



- 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

π^0 A_N at 200 GeV and 500 GeV

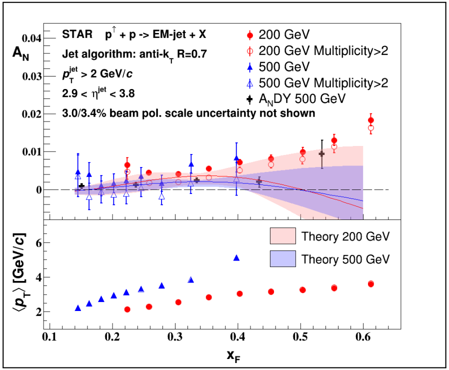




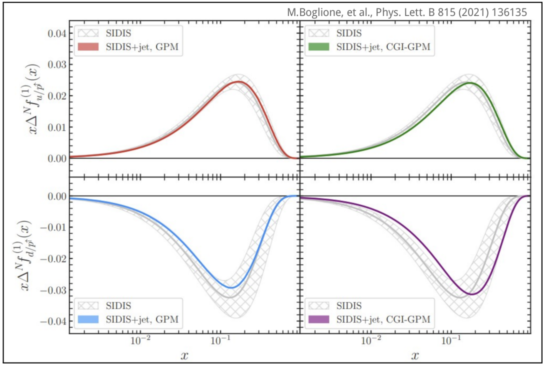
- π^0 A_N increases with x_F and is consistent with previous measurements
- π^0 A_N is almost independent of collision energy from 19.4 GeV to 500 GeV
- A_N for isolated π^0 is significantly larger than A_N of non-isolated π^0
  Isolated π^0: π^0 without any energy deposit around it

Phys. Rev. D **103** 092009

EM-jet A_N at 200 GeV and 500 GeV



Phys. Rev. D **103** 092009

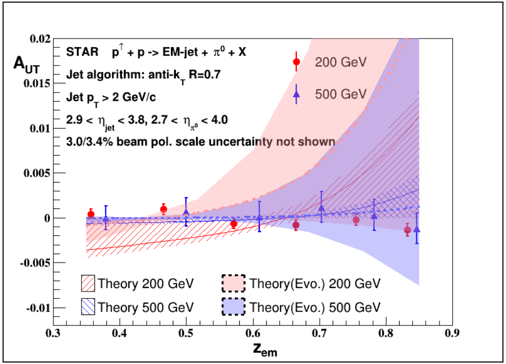


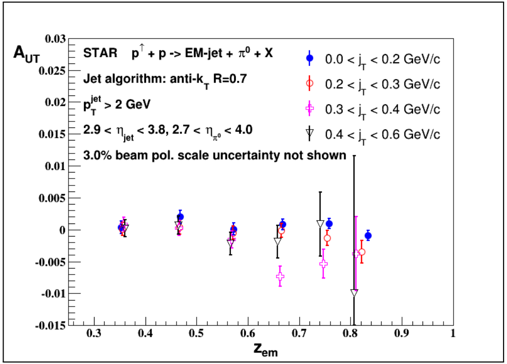
Impact of forward EM-jet A_N on u and d Sivers function

Theory curves: L. Gamberg, Z. Kang, A. Prokudin Phys. Rev. Lett. 110 **23** 232301 (2013)

- EM-jet A_N is small compare to π^0 A_N
- EM-jets with more than 2 photons have smaller asymmetries than EM-jets consisting of 1 or 2 photons

Collins Asymmetry for π^0 in a Jet at 200 GeV and 500 GeV





Phys. Rev. D **103** 092009

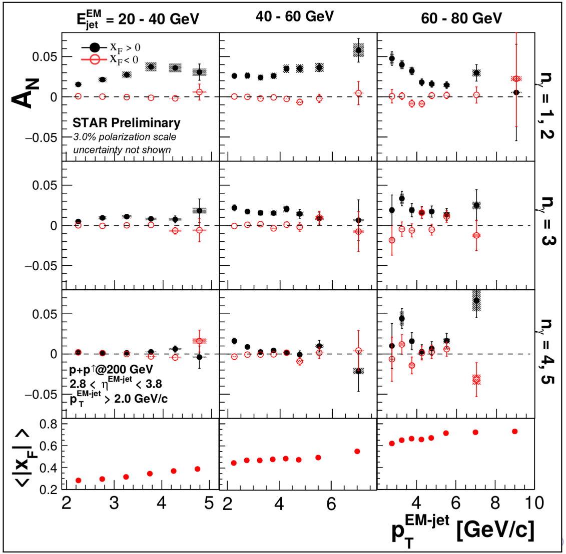
- The Collins asymmetries are very small at both energies
- Weak j_T dependence found

$$z_{em} = \frac{E_\pi}{E_{jet}}$$

j_T = E_π projection perpendicular to jet

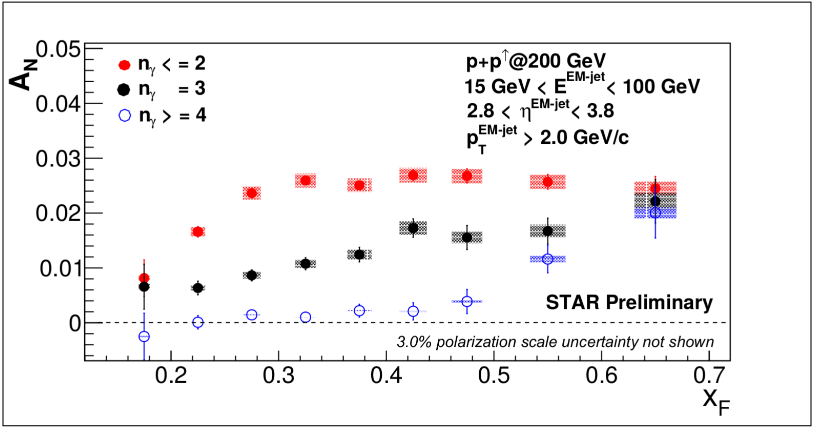
Detailed Investigations of EM-jet A_N at Forward Rapidity at 200 GeV

- EM-jet A_N decreases with increasing photon multiplicity (jettiness)
  - A_N is the strongest for EM-jets consisting of 1 or 2 photons
  - A_N is significantly smaller for EM-jets with 4 or 5 photons
- A_N at $x_F < 0$ is consistent with 0
- Systematic uncertainties (rectangular) come from possible misidentification of the event category



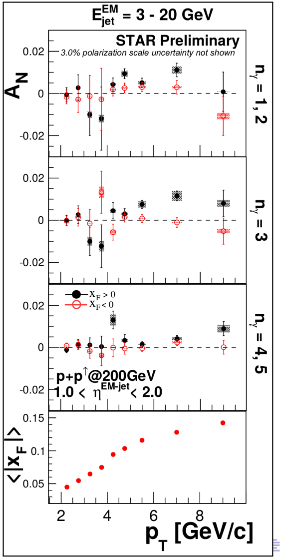
Photon-multiplicity Dependence of EM-jet A_N at Forward Rapidity at 200 GeV

- EM-jet A_N is the strongest for EM-jets consisting of 1 or 2 photons
- EM-jets with 3 photons has a non-zero A_N but lower than that of 1-photon or 2-photon EM-jets
- EM-jets with higher photon multiplicities have significantly smaller asymmetries
- A_N increases with increasing x_F



EM-jet A_N at Intermediate Rapidity Using EEMC at 200 GeV

- A_N is significantly smaller for EM-jets in the intermediate rapidity, probing much lower x_F range, compared to forward rapidity
- The trend of EM-jet A_N decreasing with increasing photon multiplicity (jettiness) seems to hold
- A_N is zero at low p_T and positive at higher p_T for $x_F > 0$
- A_N at $x_F < 0$ is consistent with 0

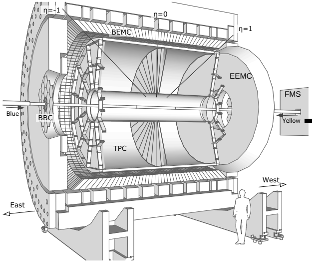


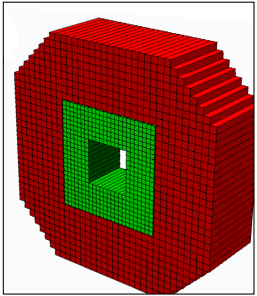
Summary

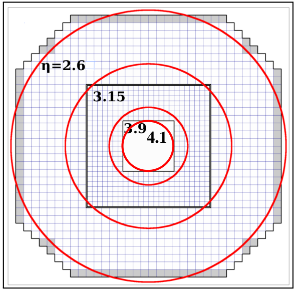
- We studied π^0 A_N with different topologies and A_N for EM-jets using FMS at STAR in pp$^\uparrow$ collisions at $\sqrt{s}$ = 200 and 500 GeV
  - A_N for isolated π^0 is significantly larger than A_N of non-isolated π^0
  - The Collins asymmetry was found to be small
- We also studied A_N for EM-jets of different substructures using FMS and EEMC at STAR at 200 GeV
  - EM-jet A_N decreases with increasing photon multiplicity (jettiness)
- These results provide rich information towards understanding the physics mechanism of large A_N in hadron collisions

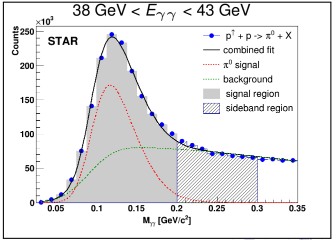
Backup Slides

Forward Meson Spectrometer (FMS)



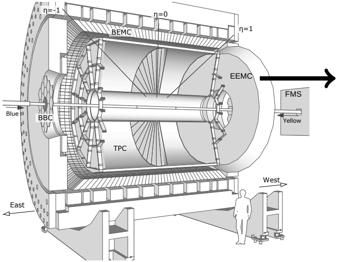


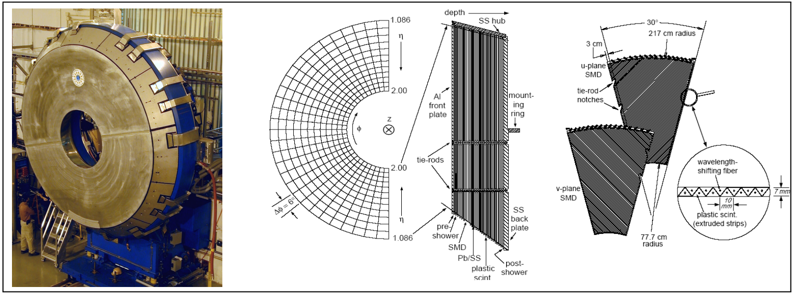




- FMS is a lead-glass electromagnetic calorimeter
- Array of ∼1200 Pb-glass cells coupled to PMTs
- Forward pseudorapidity coverage: $2.6 < \eta < 4.1$
- $\gamma, e^-, e^+ \rightarrow$ EM shower
- Observables: γ, π^0, EM-jet

Endcap Electromagnetic Calorimeter (EEMC)





- Coverage: 1.1 < η < 2.0, 0 < ϕ < 2π
- 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