STAR Forward Upgrade

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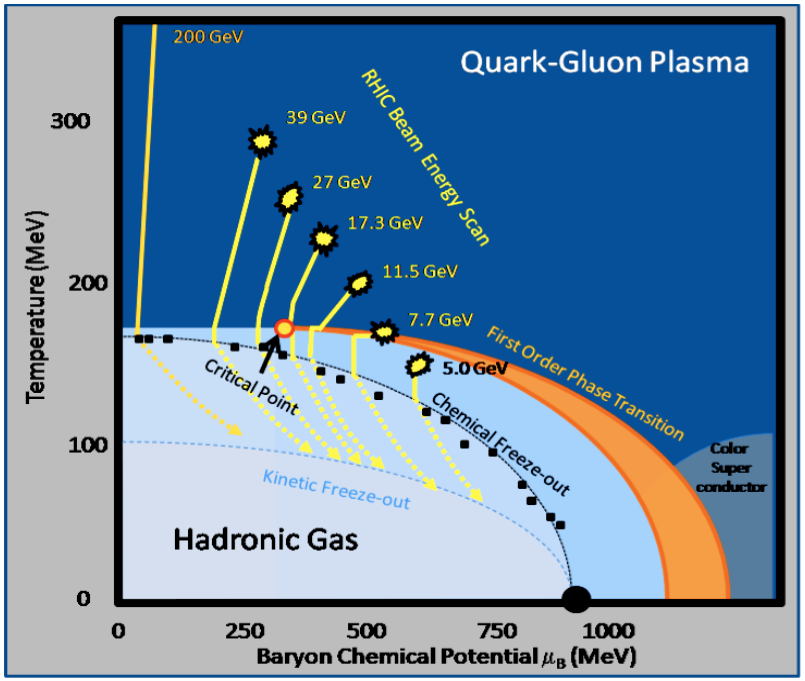
Outline

- Introduction
- Selected STAR measurements in a long-term RHIC operation
- Forward upgrade at STAR
- Summary

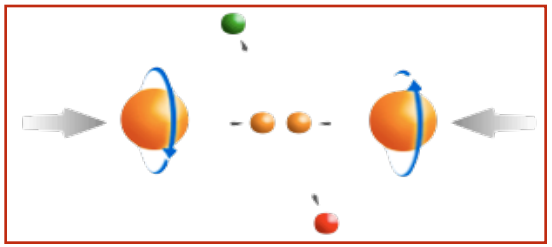
RHIC: eight key unanswered questions

Hot QCD Matter

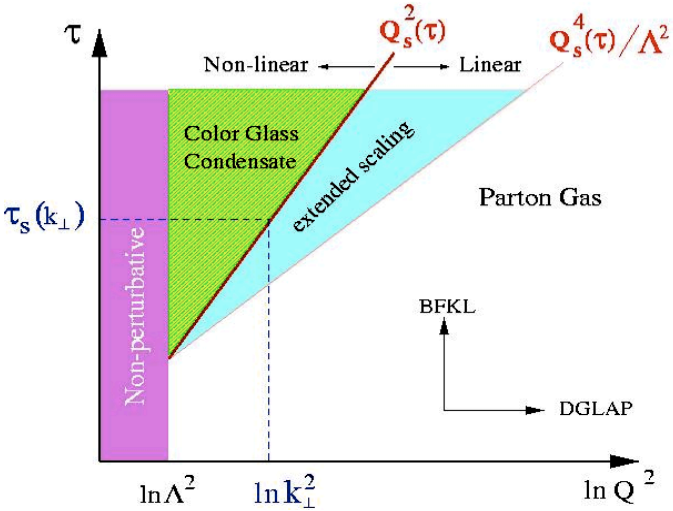


1: Properties of the sQGP
2: Mechanism of energy loss:
weak or strong coupling?
3: Is there a critical point, and if so, where?
4: Novel symmetry properties
5: Exotic particles

Partonic structure



6: Spin structure of the nucleon
7: How to go beyond leading twist and collinear factorization?



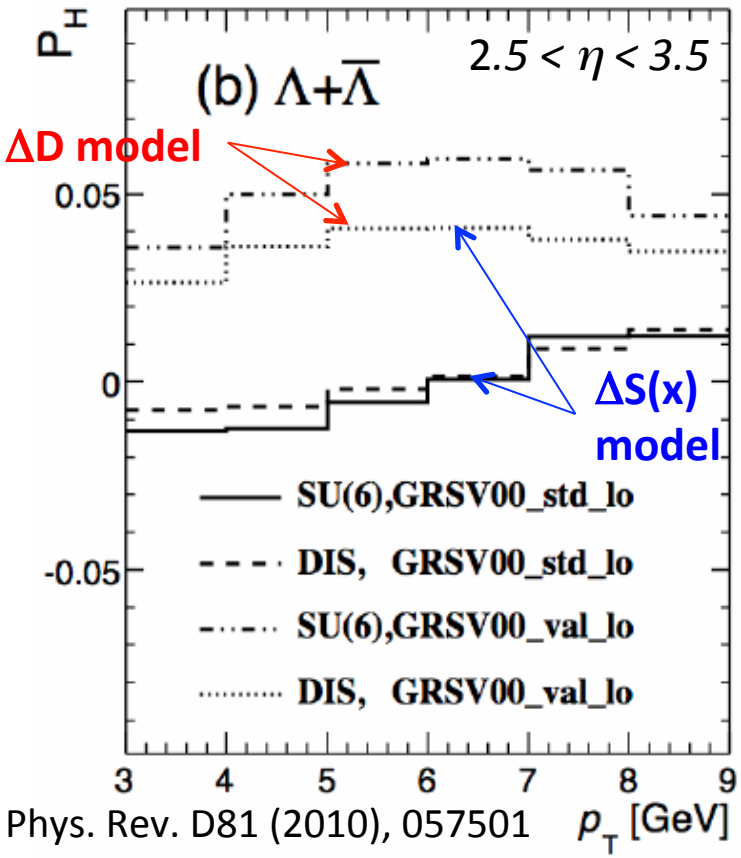
8: What are the properties of cold nuclear matter?

Summary of the STAR decadal plan

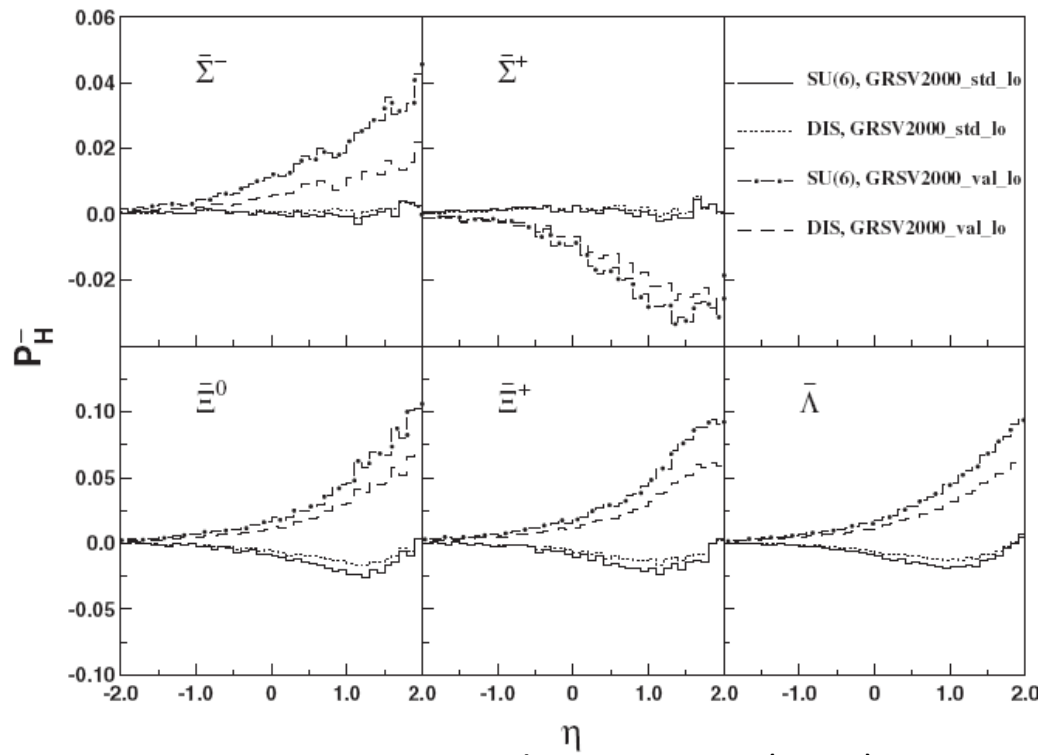
	Near term (Runs 11-13)	Mid-decade (Runs 14-16)	Long term (Runs 17–)
Colliding systems	*p*+*p*, A+A	*p*+*p*, A+A	*p*+*p*, *p*+A, A+A, *e*+*p*, *e*+A
Upgrades	FGT, FHC, RP, DAQ10K, Trigger	HFT, MTD, Trigger	Forward Instrum, eSTAR, Trigger
(1) Properties of sQGP	Υ, $J/\psi \rightarrow ee$, m_{ee}, v_2	Υ, $J/\psi \rightarrow \mu\mu$, Charm v_2, R_{CP}, corr, Λ_c/D ratio, μ-atoms	p+A comparison
(2) Mechanism of energy loss	Jets, γ-jet, NPE	Charm, Bottom	Jets in CNM, SIDIS, *c*/*b* in CNM
(3) QCD critical point	Fluctuations, correlations, particle ratios	Focused study of critical point region	
(4) Novel symmetries	Azimuthal corr, spectral function	*e*-μ corr, μ-μ corr	
(5) Exotic particles	Heavy anti-matter, glueballs		
(6) Proton spin structure	W A_L, jet and di-jet A_{LL}, intra-jet corr, (Λ+Λ) D_{LL}/D_{TT}		Λ_bar D_{LL}/D_{TT}, polarized DIS & SIDIS
(7) QCD beyond collinear fact.	Forward A_N		Drell-Yan, F-F corr, polarized SIDIS
(8) Properties of initial state	Detector Upgrade driven schedule Measurements listed when they first become possible Many will continue in future periods		Charm corr, Drell-Yan, J/ψ, F-F corr, Λ, DIS, SIDIS

Future D_{LL} measurement

Lambda Spin Transfer



Phys. Rev. D81 (2010), 057501



Phys. Rev. D78 (2008), 054007

Sensitive to the parton helicity distributions and to polarized fragmentation

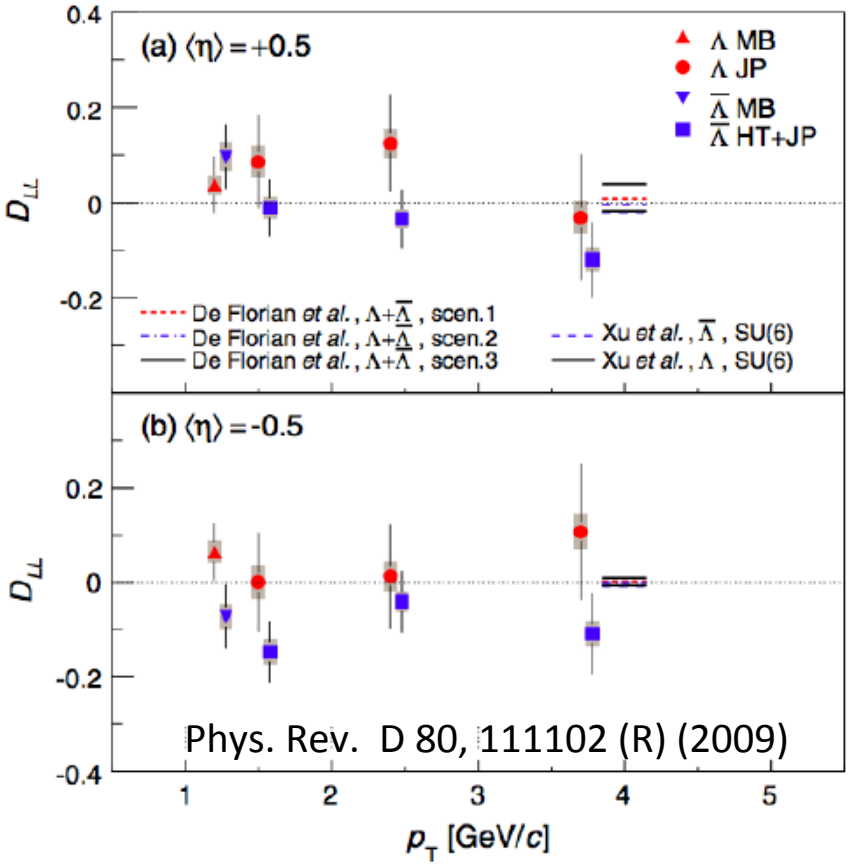
Better sensitivity at forward

Anti-Lambda more sensitive to parton helicity distributions

Transversity distribution can also be accessed by D_{TT}

D_{LL} at mid-rapidity

- **STAR has performed initial Λ D_{LL} measurements at mid-rapidity**
  – Provides access to strange quark helicity distribution
  – Most interesting with quite high p_T Λ (trigger and stat limited)
- Similar measurements at forward rapidity are **very promising**
  – Requires Forward Hadron Calorimeter upgrade



$$\Lambda \rightarrow n + \pi^0$$

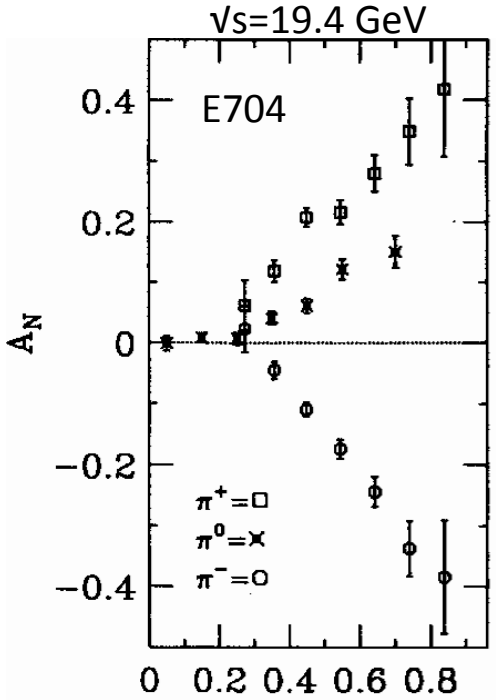
$$\bar{\Lambda} \rightarrow \bar{n} + \pi^0$$

Forward hadron calorimeter to measure (anti-)neutron

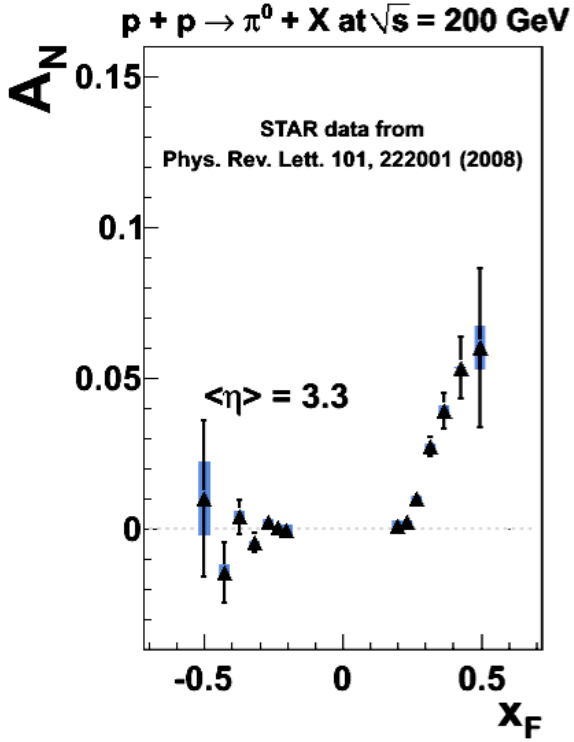
$$\bar{\Lambda} \rightarrow \bar{p} + \pi^+$$

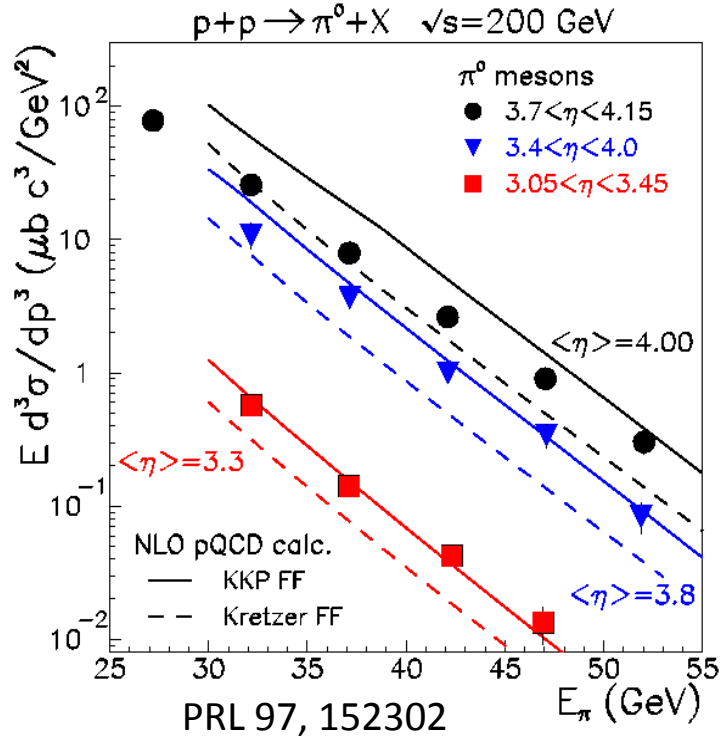
Experimental challenging, baryon/meson identification needed

Transverse Single Spin Asymmetries



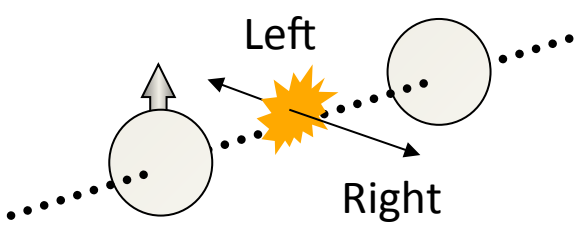
PLB 261, 201 (1991)





PRL 97, 152302

$$A_N = \frac{1}{P}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

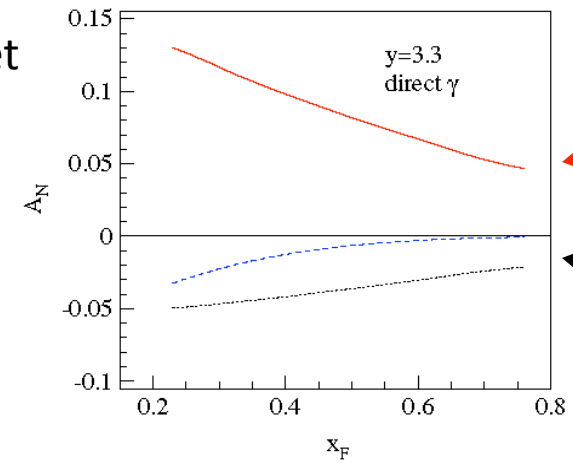


- Large transverse spin asymmetries consistent over an order of magnitude in √s up to 200 GeV
- Cross sections measured at forward rapidity at RHIC are reasonably described by pQCD
- Proposed pQCD mechanisms for large A_N:
  - Sivers Effect: parton orbital motion
  - Collins Effect: transversity + fragmentation

Future Transverse Measurements

- Forward rapidity direct γ A_N

Z-B. Kang et al, PRD 83, 094001

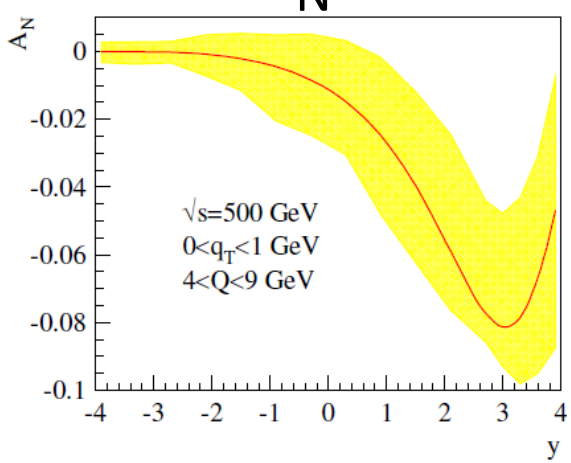


Extracted from $p+p^{\uparrow} \rightarrow \pi+X$ A_N

Extracted from SIDIS Sivers functions (**"new"** and **"old"**)

e/h, γ/π^0 discrimination crucial, forward upgrade needed!

- Drell-Yan A_N



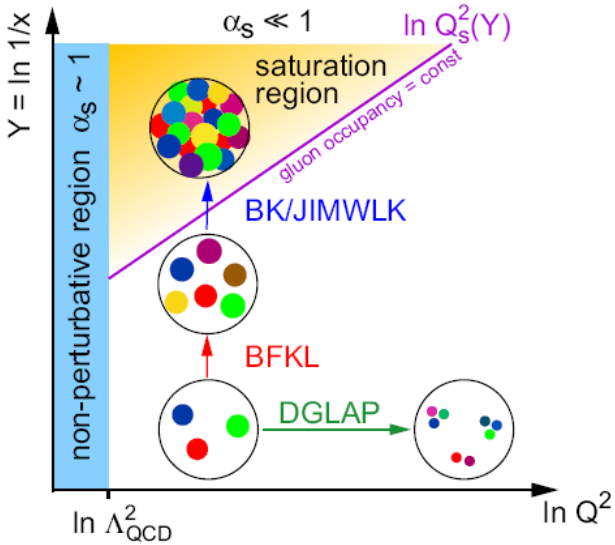
Sivers function measured in SIDIS vs DY expected to differ by a sign

$$\Delta^N f_{q/h^\uparrow}^{\mathrm{SIDIS}}(x, k_\perp) = -\Delta^N f_{q/h^\uparrow}^{\mathrm{DY}}(x, k_\perp)$$

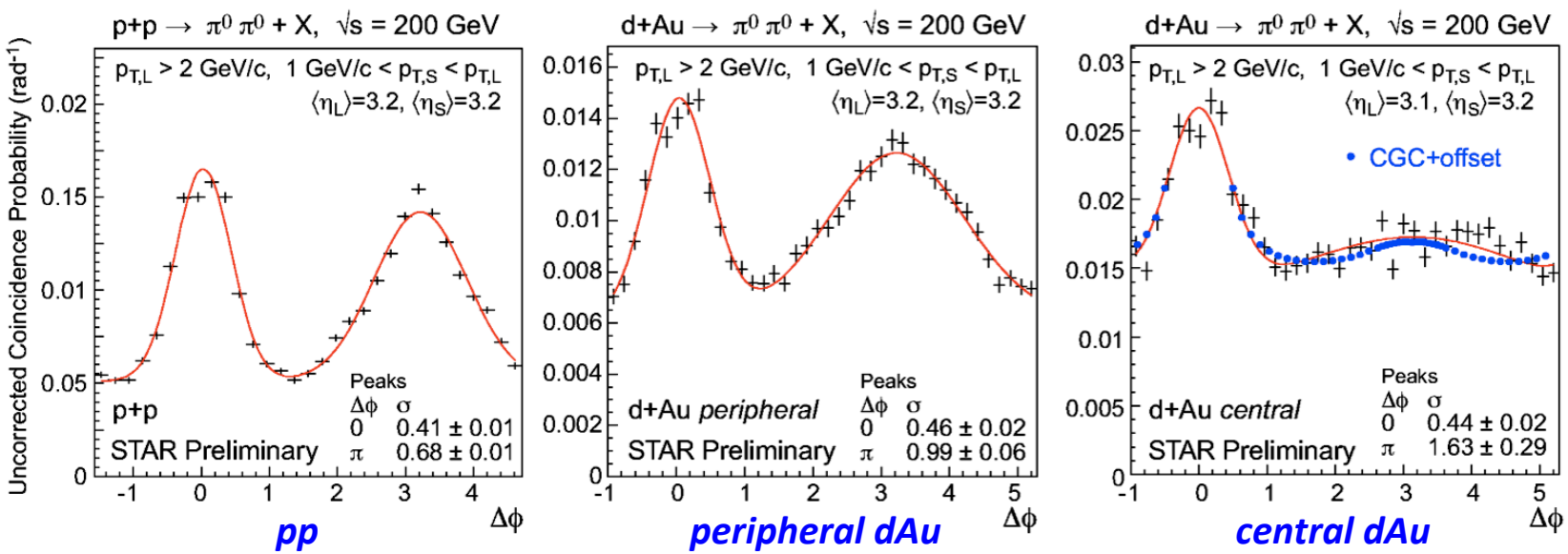
Need DY results to verify the sign change: critical test of TMD approach

- Forward jets and correlations **Full jet reconstruction**

Cold QCD matter – the initial state at RHIC



- RHIC may provide **unique access to the onset of saturation**
- Future questions for **p+A**
  - What is the gluon density in the (x,Q^2) range relevant at RHIC?
  - What role does saturation of gluon densities play at RHIC?
  - What is Q_s at RHIC, and how does it scale with A and x?
  - What is the impact parameter dependence of the gluon density?



Summary p+A measurements

- Nuclear modifications of the gluon PDF
  - Correlated charm production
- Gluon saturation
  - Forward-forward correlations (extension of existing π^0-π^0)
    - *h*-*h*
    - π^0-π^0

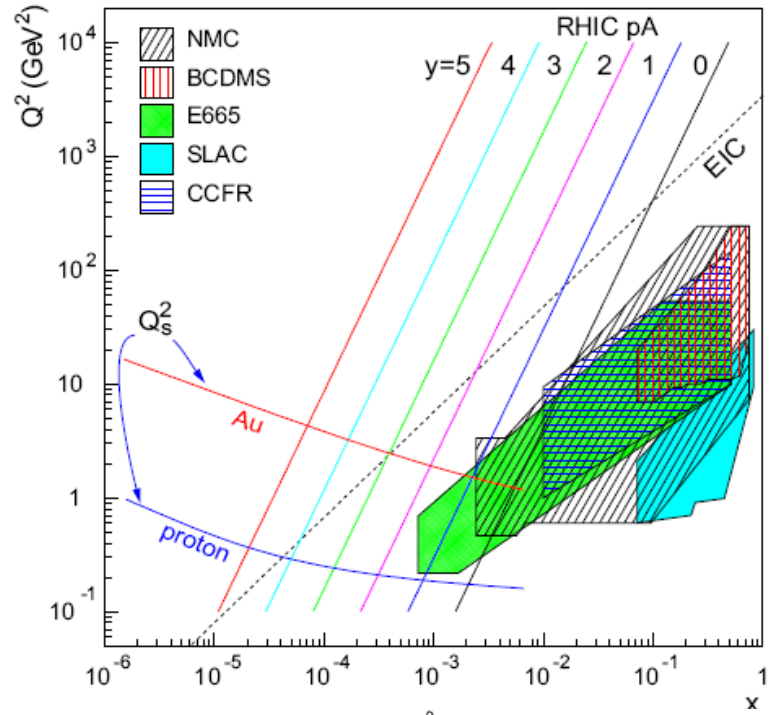
    } Easier to measure
    - γ-*h*
    - γ-π^0

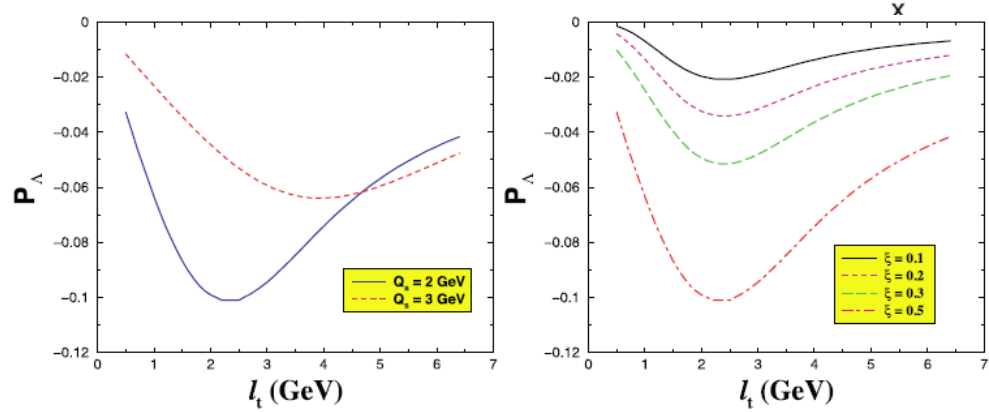
    } Easier to interpret
  - Drell-Yan
    - Able to reconstruct x_1, x_2, Q^2 event-by-event
    - Can be compared directly to nuclear DIS
    - True 2 → 1 provides model-independent access to $x_2 < 0.001$
  - Λ polarization
  - Baryon production at large x_F

- What more might we learn by scattering *polarized* protons off nuclei?

Future Gluon Saturation Measurements

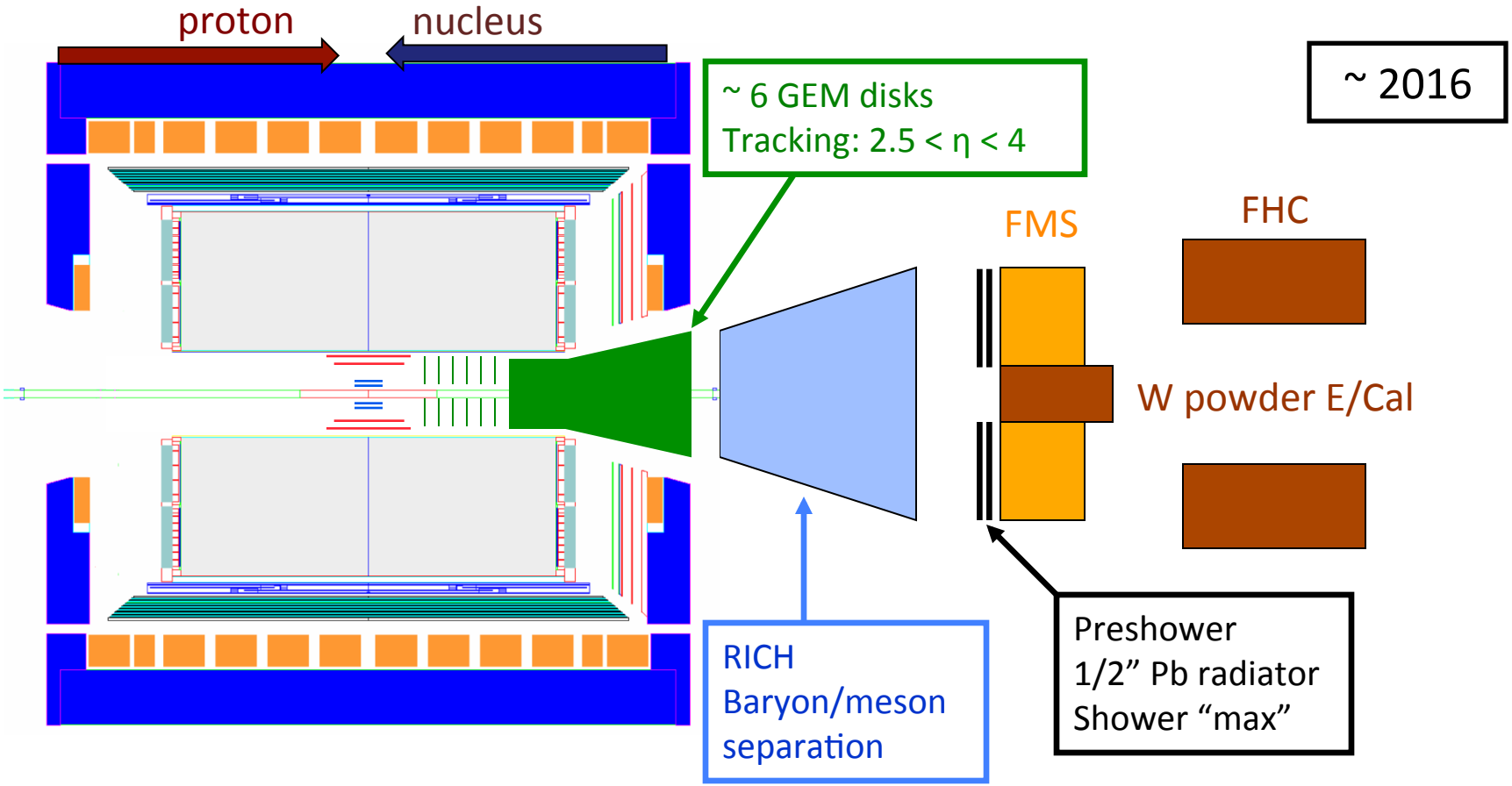
- Drell-Yan in the forward direction
  - access to sea quark distributions in the nucleus at x < 0.001.
  - an order of magnitude lower x than DIS data, and DY from EPS09.
  - significant constrain on nuclear gluon distribution
- Forward J/Psi
- Forward-forward correlation
  - h-h / π^0-π^0 / γ-h / γ-π^0
  - Scan on A mass
- Λ transverse polarization
  - unique in extracting x-dependence of saturation scale





Boer and Dumitru, Phys. Lett. B 556, 33 (2003)

STAR Detector Forward Upgrade

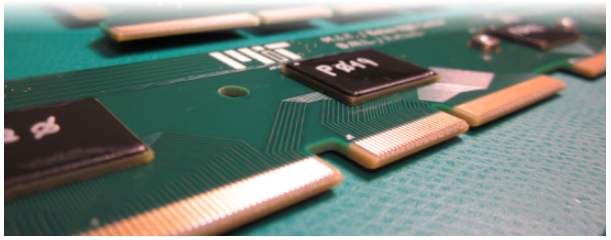


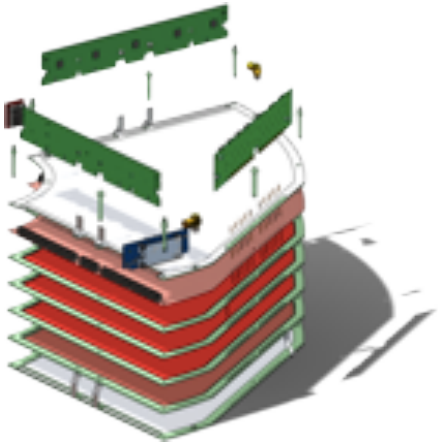
- Forward instrumentation optimized for **p+A** and **transverse spin** physics
  - Charged-particle tracking
  - *e*/*h* and γ/π^0 discrimination
  - Baryon/meson separation

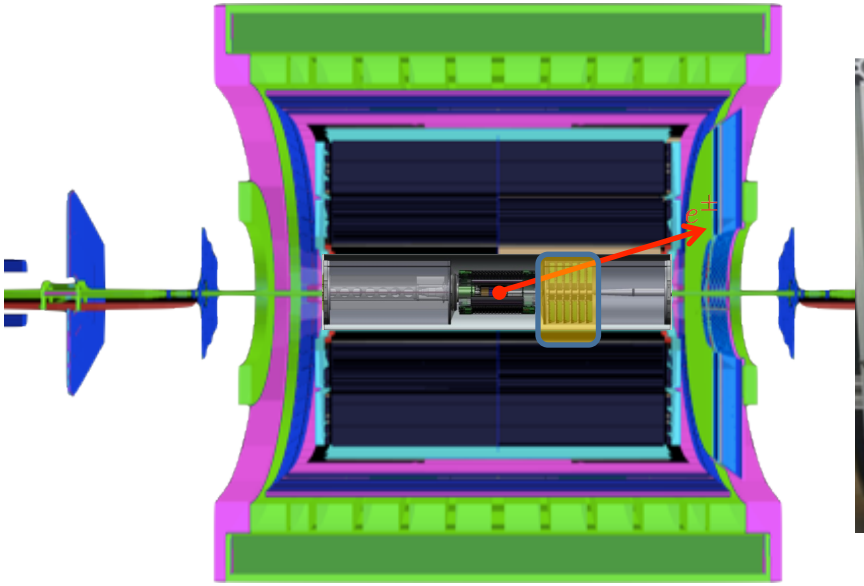
Several design exist, being evaluated

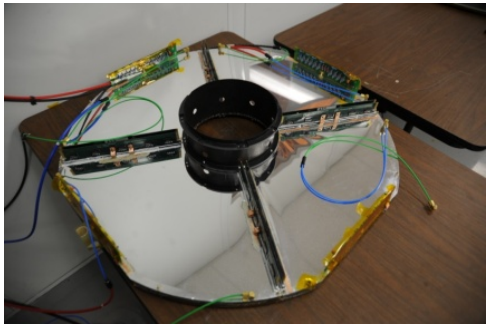
Very Forward GEM Tracker (VFGT)

- Add forward tracking to STAR
  - Drell-Yan
  - Transverse spin physics in valence quark region etc.
- Design based on FGT spatial resolution ~70 μm
  - Risks understood
  - Lower R&D costs
  - Fit in existing support structure
- Decadal Plan calls for such an upgrade

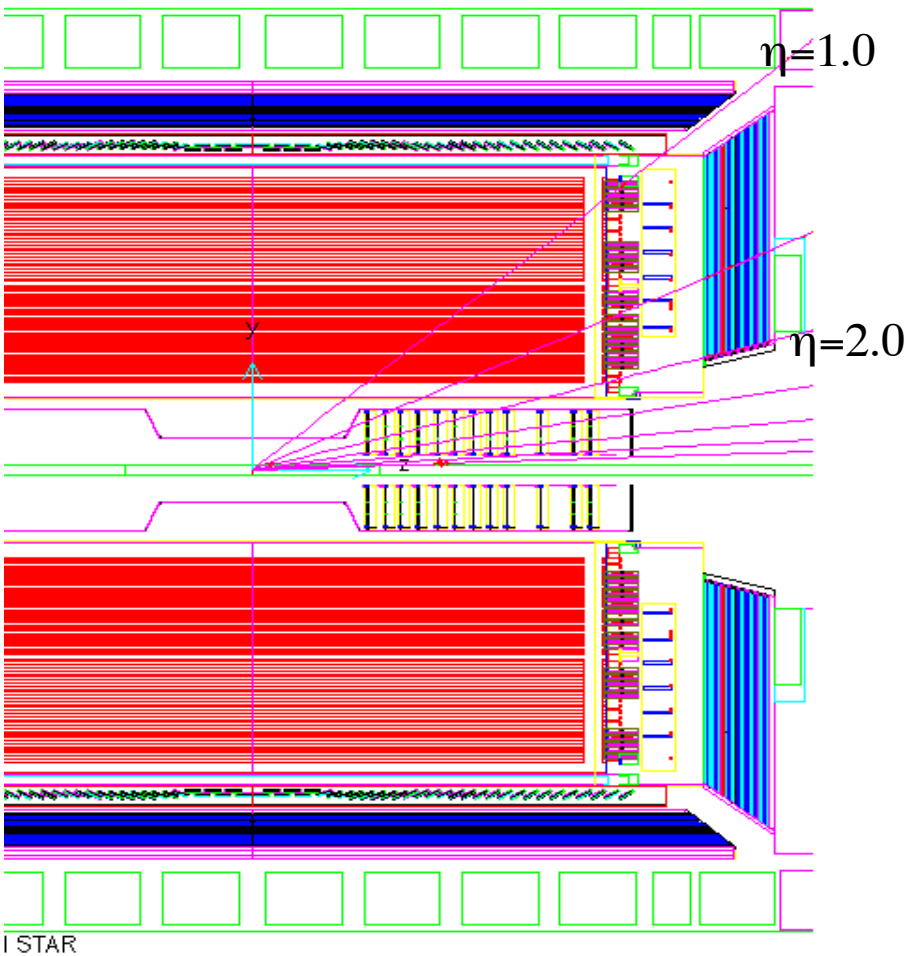




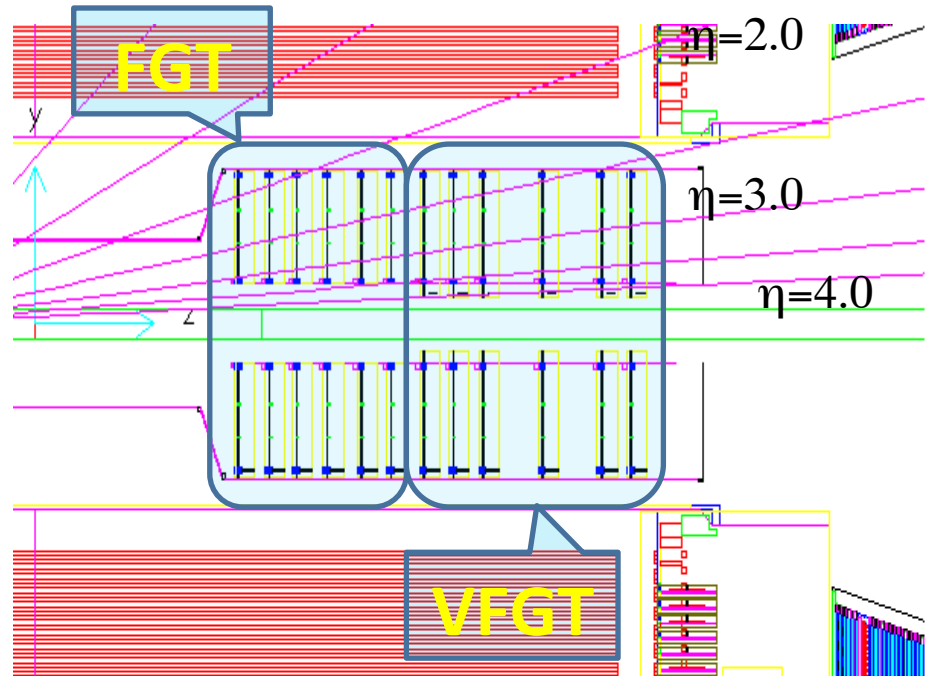




VFGT in the STAR simulation



inner radius of 7cm for last 6 discs

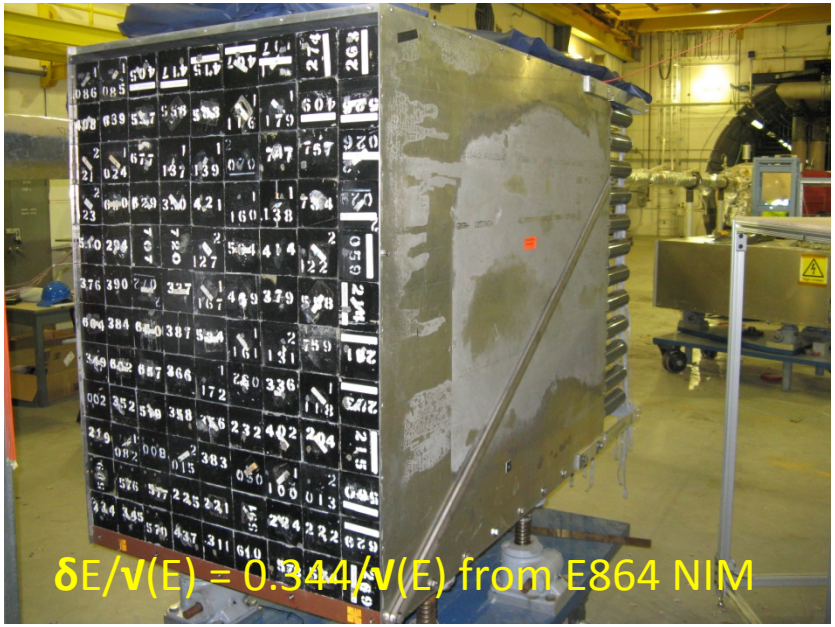


- IP at z=0 up to η~3.5
- IP at z=-50 up to η~4.0

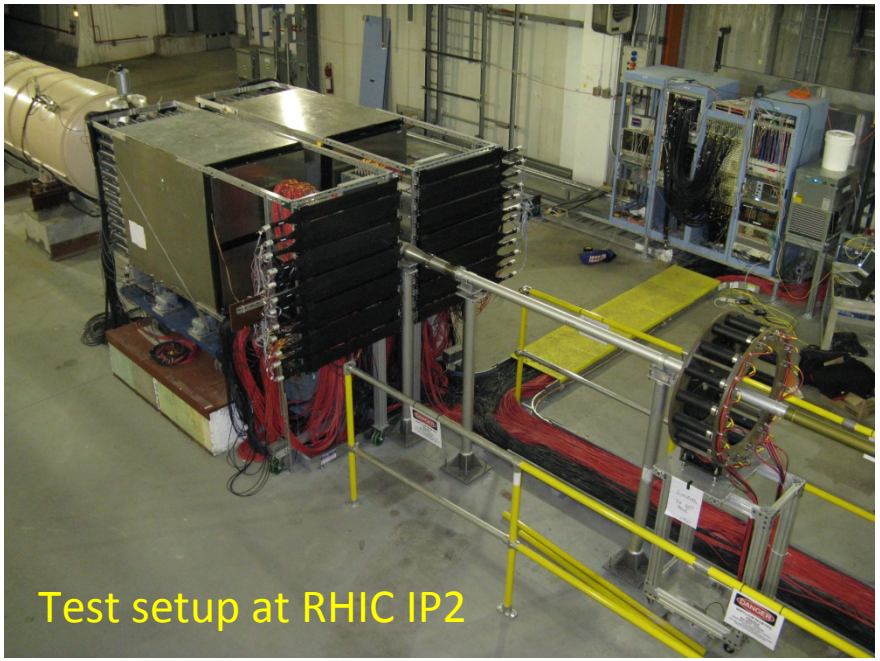
$\Delta\phi \sim 0.15\Delta Z/p_z$

For η~4.0, p_z=100GeV/c, ΔZ=2m, deflect distance ~100μm, FGT-like spatial resolution may work!

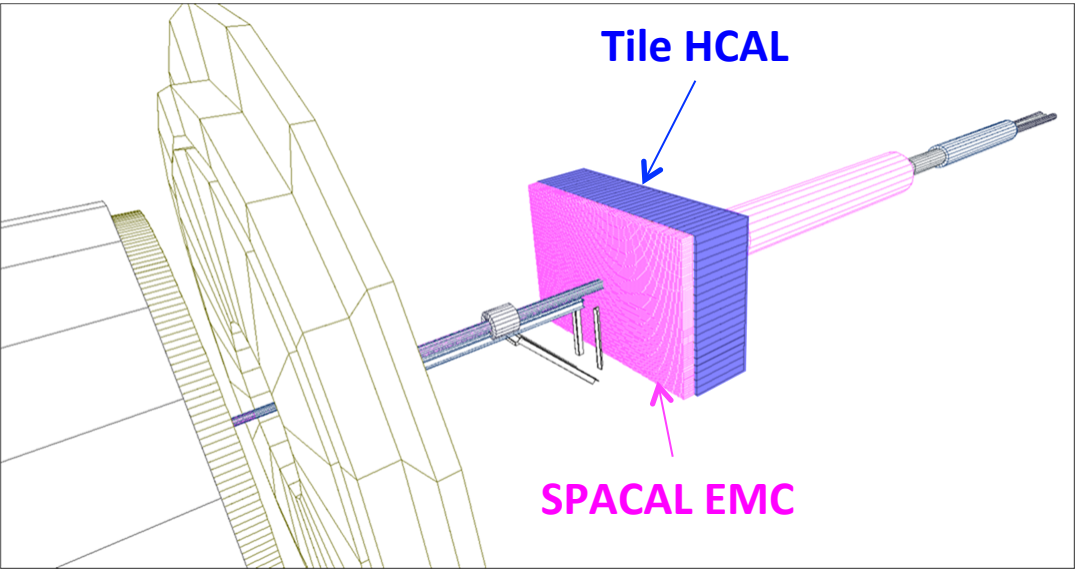
Forward Hadron Calorimeter



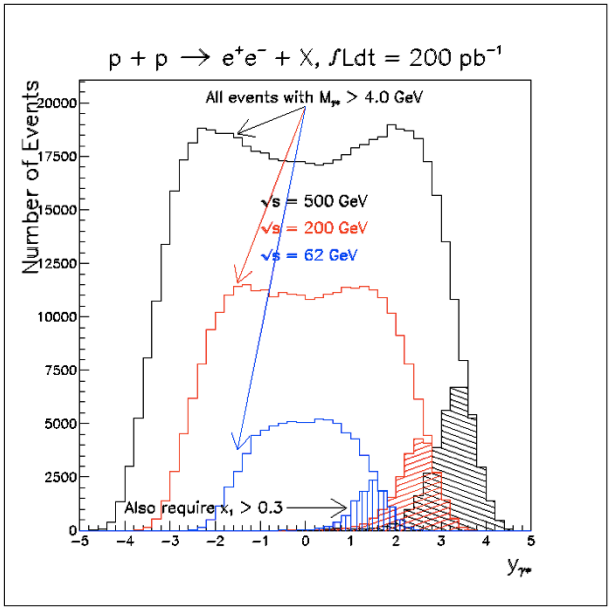
Re-use of E864 hadron calorimeter
Excellent energy resolution demonstrated
Pulse shape analysis to separate electron from hadrons
Pixelation to match ~1.6 cm Moliere radius
Being tested at RHIC IP2 to evaluate its performance



New Calorimeter R&D



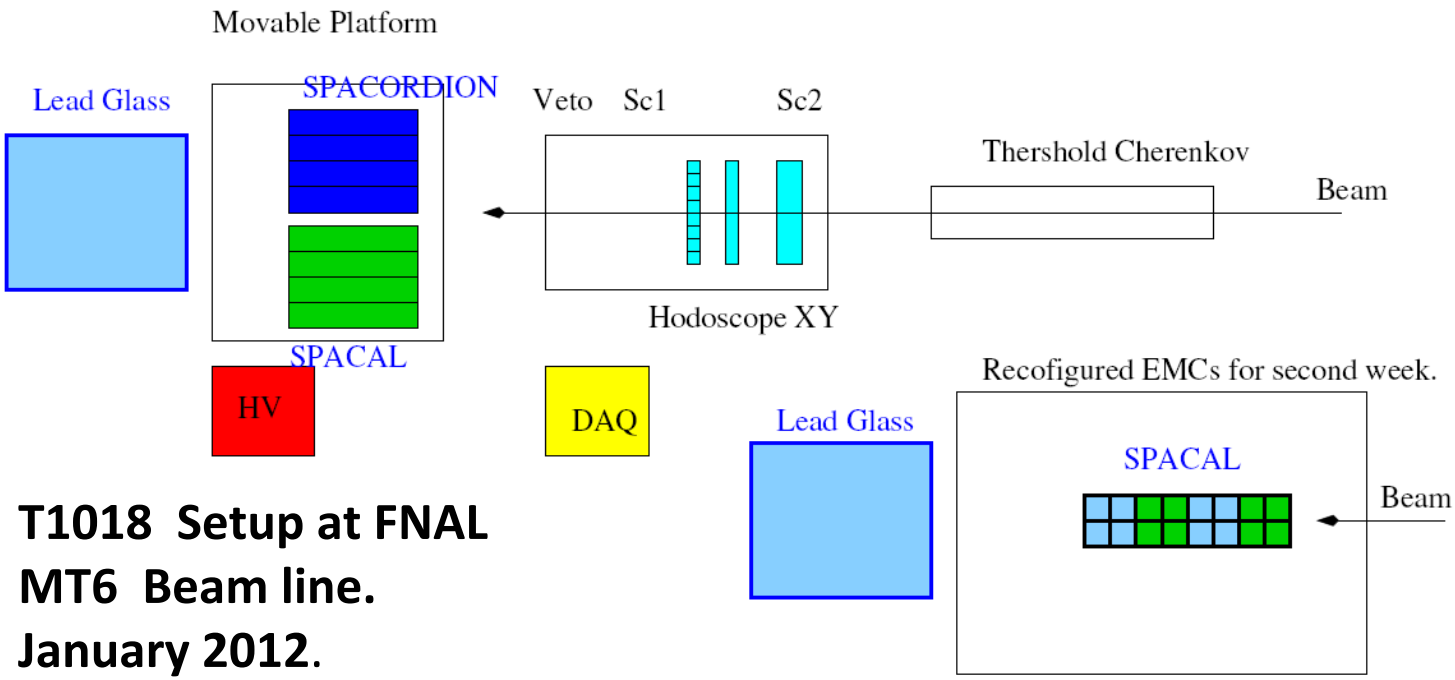
- Requirement:
  - Efficient π^0 reconstruction at 100 GeV.
  - Good γ/π^0 discrimination.
  - Good e/h separation (1000) with high electron efficiency.
  - Reasonable energy



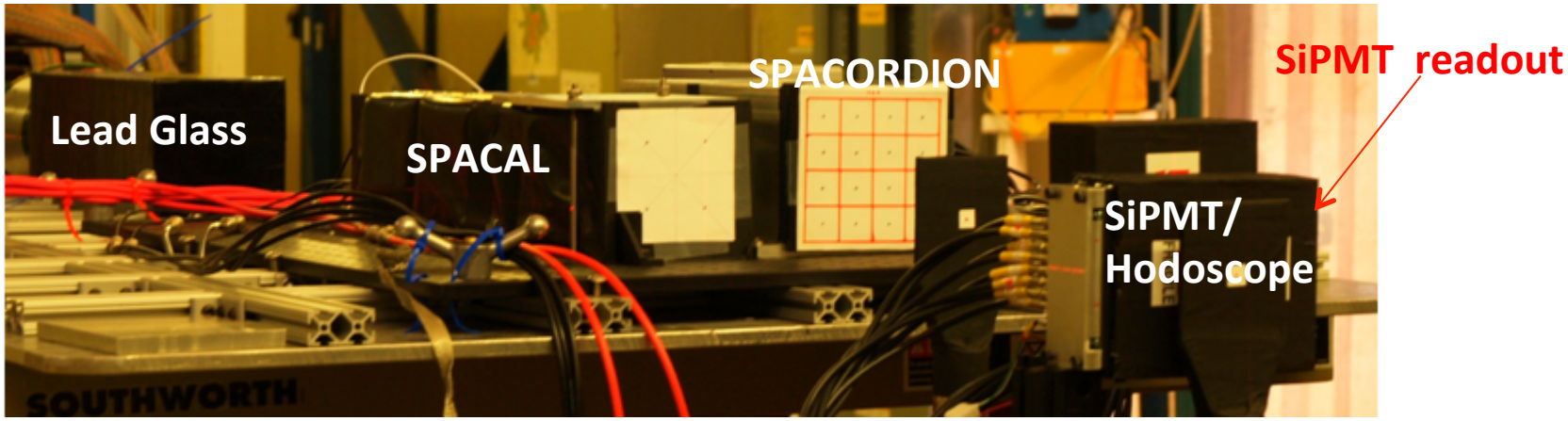
- **Solution:**
  - W powder, fiber readout, compensating (SPACAL) **EMC**
  - compensating tile **HCAL** tail catcher

Forward Calorimeter System- FCS

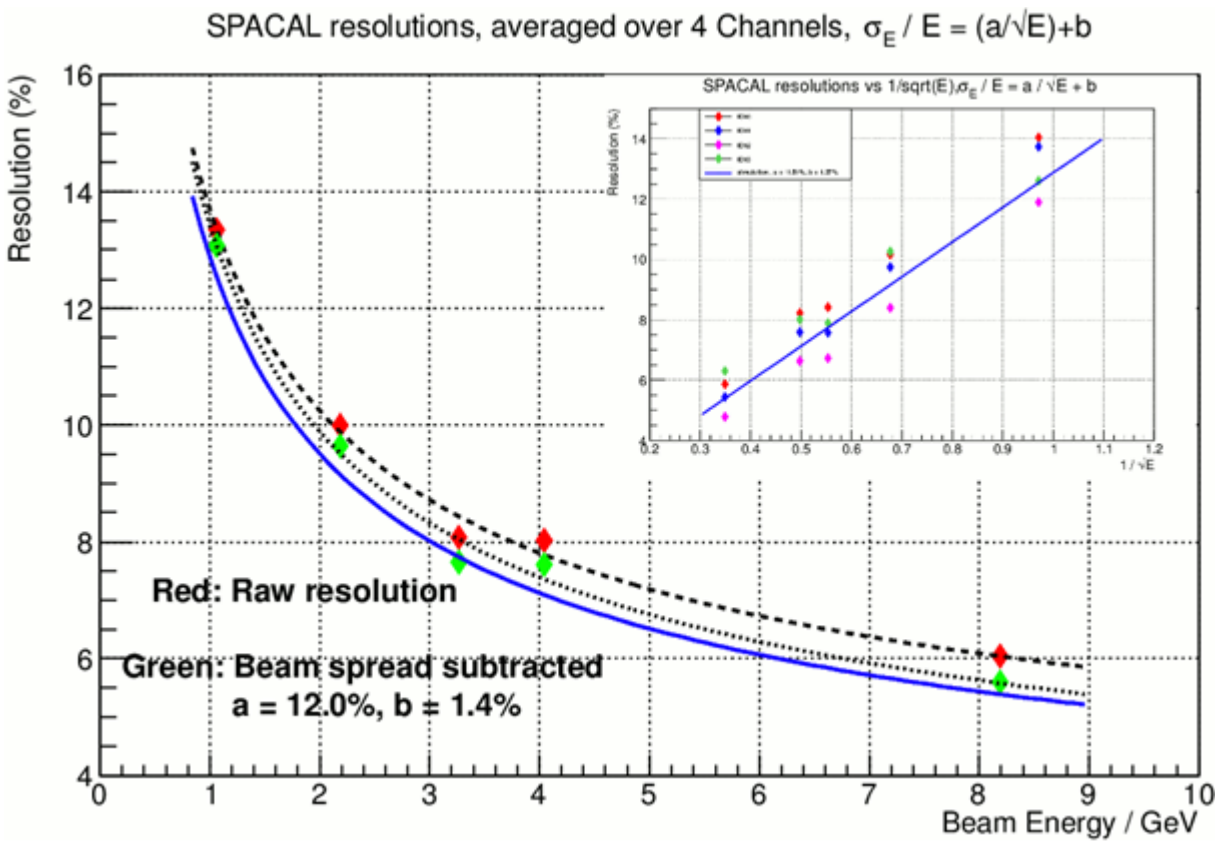
Calorimeter R&D UCLA/TAMU/PSU



T1018 Setup at FNAL MT6 Beam line. January 2012.



Test Results - SPACAL works

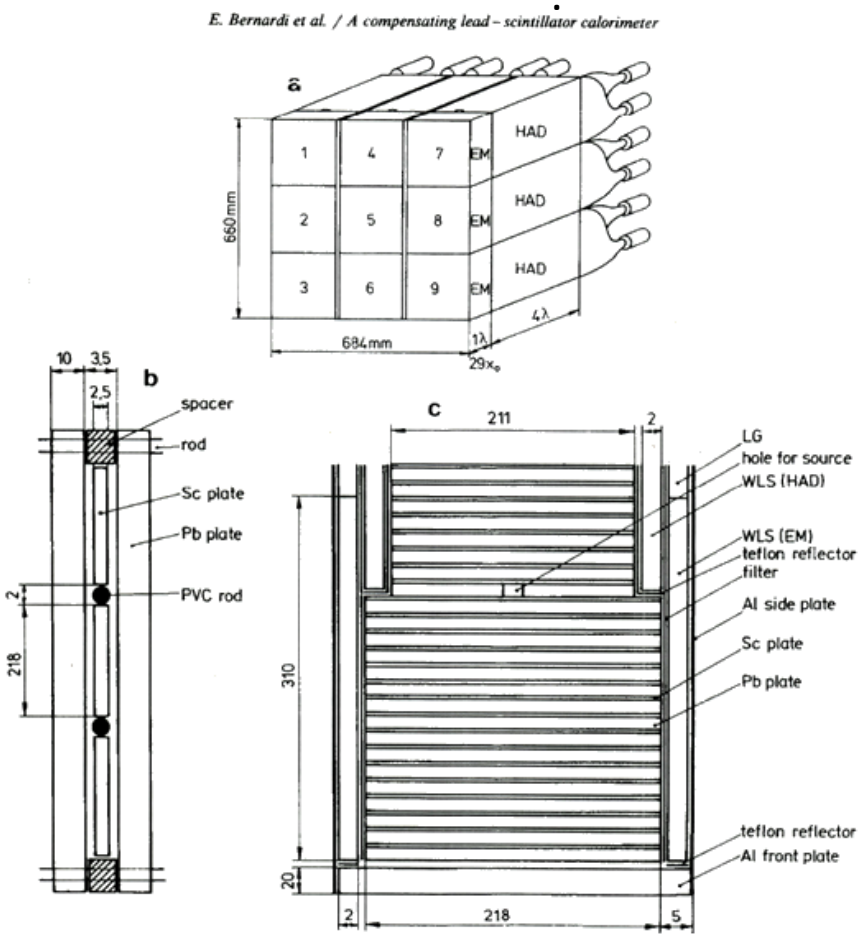


- Also measured:
  - Uniformity of response across the towers.
  - Energy resolution with and without mirror.
  - Perform scans along the towers with electrons and muons.
  - Estimated effects of attenuation and towers non-uniformities on resolution.

Resolution is close to expected (12%@1GeV).
Light yield is very good ~2000 p.e./GeV

Hadronic Calorimeter Upgrade

- **Understand HCAL with simulation**
  - Took ZEUS 1987 experimental data for Pb/Sc tile compensated calorimeter to verify simulation



1. The length of the detector is 5 interaction length. Fit into STAR.
2. It is segmented to EM and Hadronic parts.
3. It is compensated with good energy resolution for hadrons.
4. Experimentally measured longitudinal and transverse shower developments.
5. Geometry is simple.

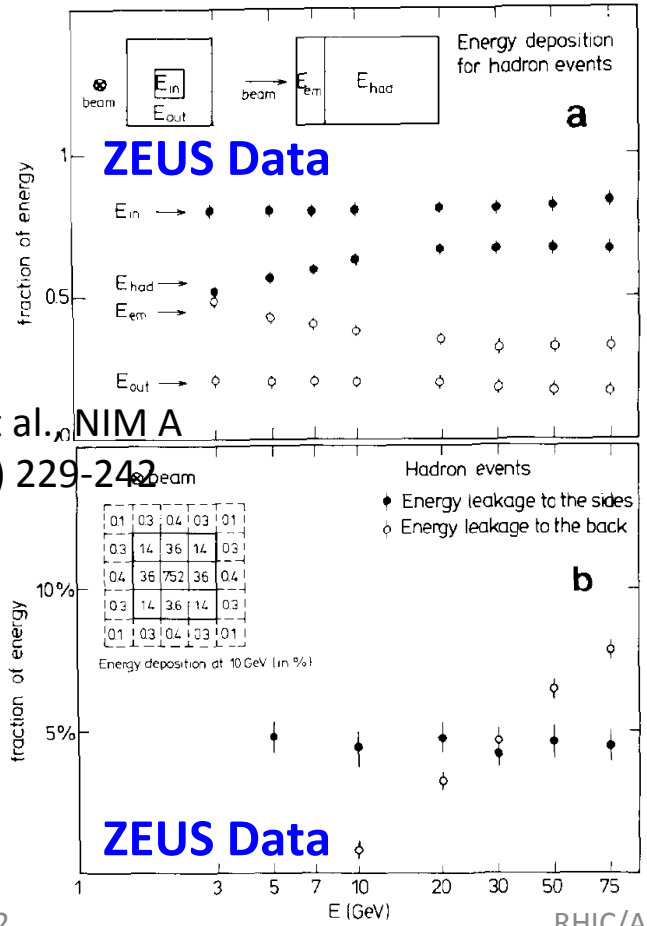
Hadronic Response

Tested 2 possible geant4 physics lists for hadronic physics: QGSP_BERT, LHEP (QGSP_BERT recommended by CALICE collaboration)

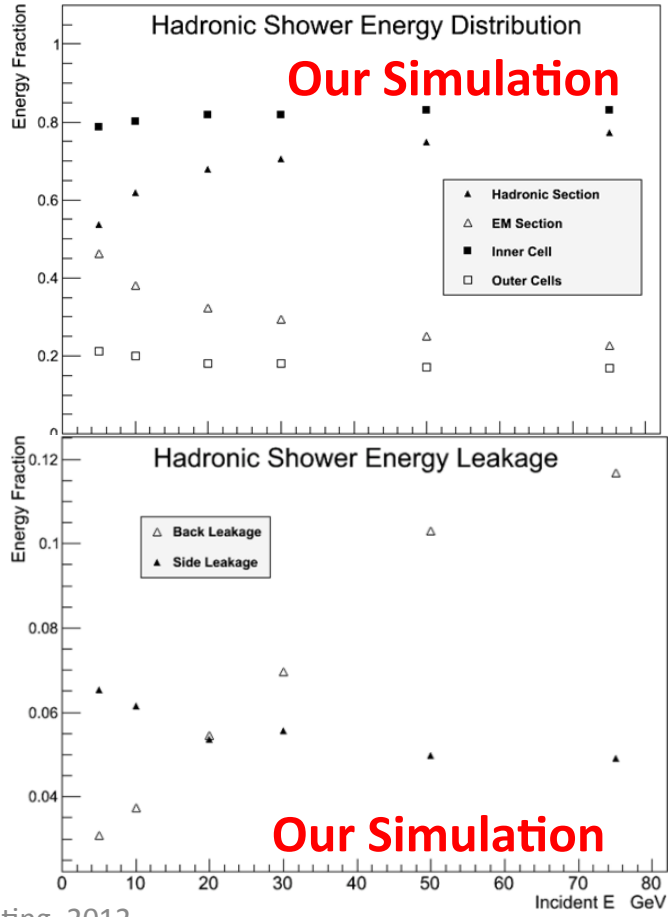
Compared with beam test results for ZEUS calorimeter prototype

QGSP_BERT failed to reproduce the e/h from the ZEUS test

LHEP gives reasonable agreement for hadronic energy resolution, e/h and shower profile



Bernardi et al., NIM A 262, (1987) 229-242



STAR R&D for FCS

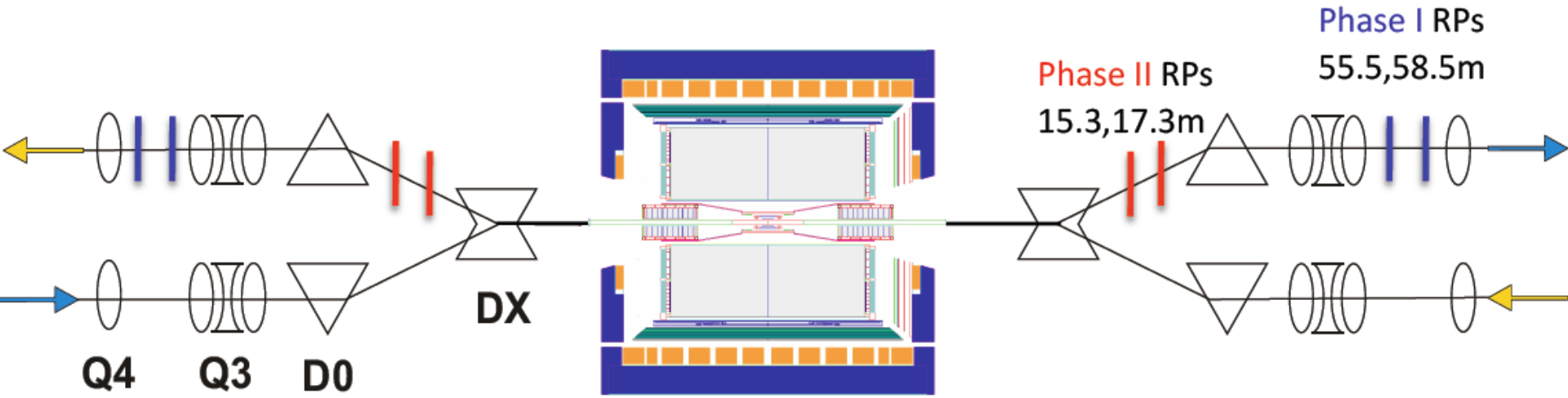
- MC, stand alone GEANT4, done. Compare with Geant3 used in STAR simulation framework?
- Pi0 reconstruction – 80% eff. At 100 GeV
- Energy resolution EM – 12/sqrt(E), constant term ~2%
- Energy resolution for hadrons 50%-60%/sqrt(E), range 10-80 GeV
- e/h rejection few*1000 @ 80 GeV

Need to build a full scale prototype module !

What are the Physics Capability for this Detector?

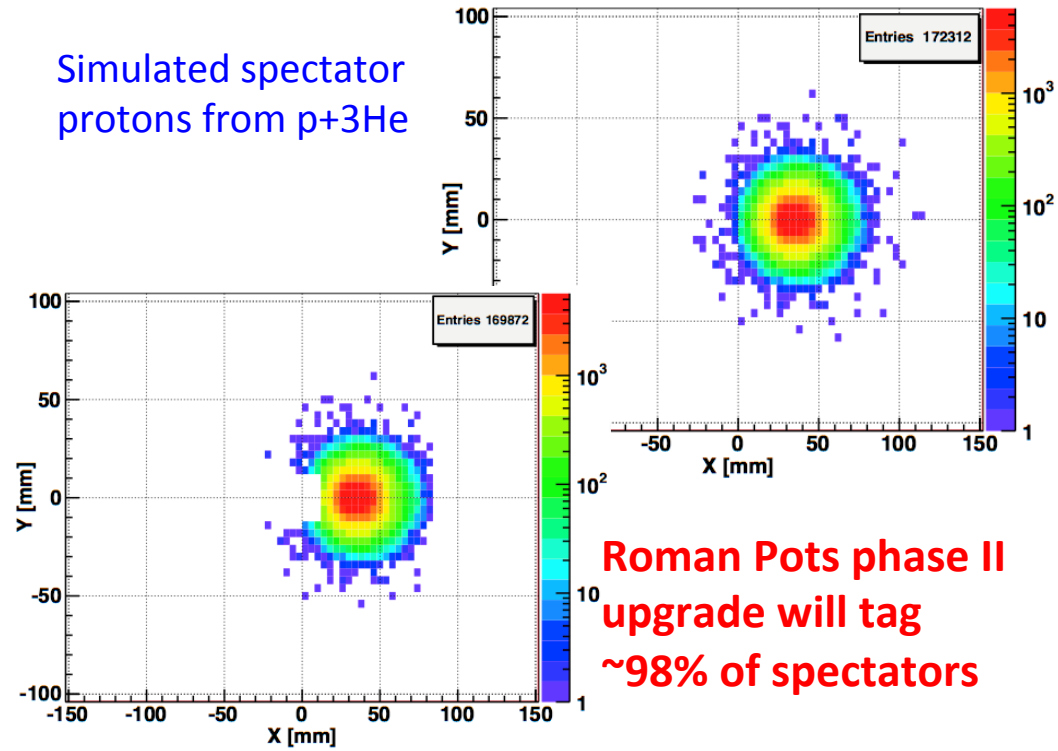
Combined FMS+FHC and FCS, cost vs physics?

Roman Pot Phase II



- Glueball search in the Double Pomeron Exchange (DPE) process
- Search for the Odderon
- Spin dependence of the elastic and diffractive scattering in polarized pp collisions
- Polarized proton on polarized Helium scattering
- Possibility of new physics of sphaleron production in DPE

Simulated spectator protons from p+3He



Roman Pots phase II upgrade will tag ~98% of spectators

Other planned upgrade

- RICH
  - LHCb-like low mass Cherenkov vs. Threshold Cherenkov?
  - Baryon/meson separation for eg. anti_Lambda decay (charged daughter)
  - Charged pion ID
- Pre-shower
  - Lead convertor (2-3 radiation-length) + coarse readout (~1mm) GEM
  - Provide pi0 identification and pi0/γ separation.
  - Charge sign determination

Evolving from STAR into *e*STAR

ToF: π , *K* identification, t_0, electron

ECal: electrons and photons

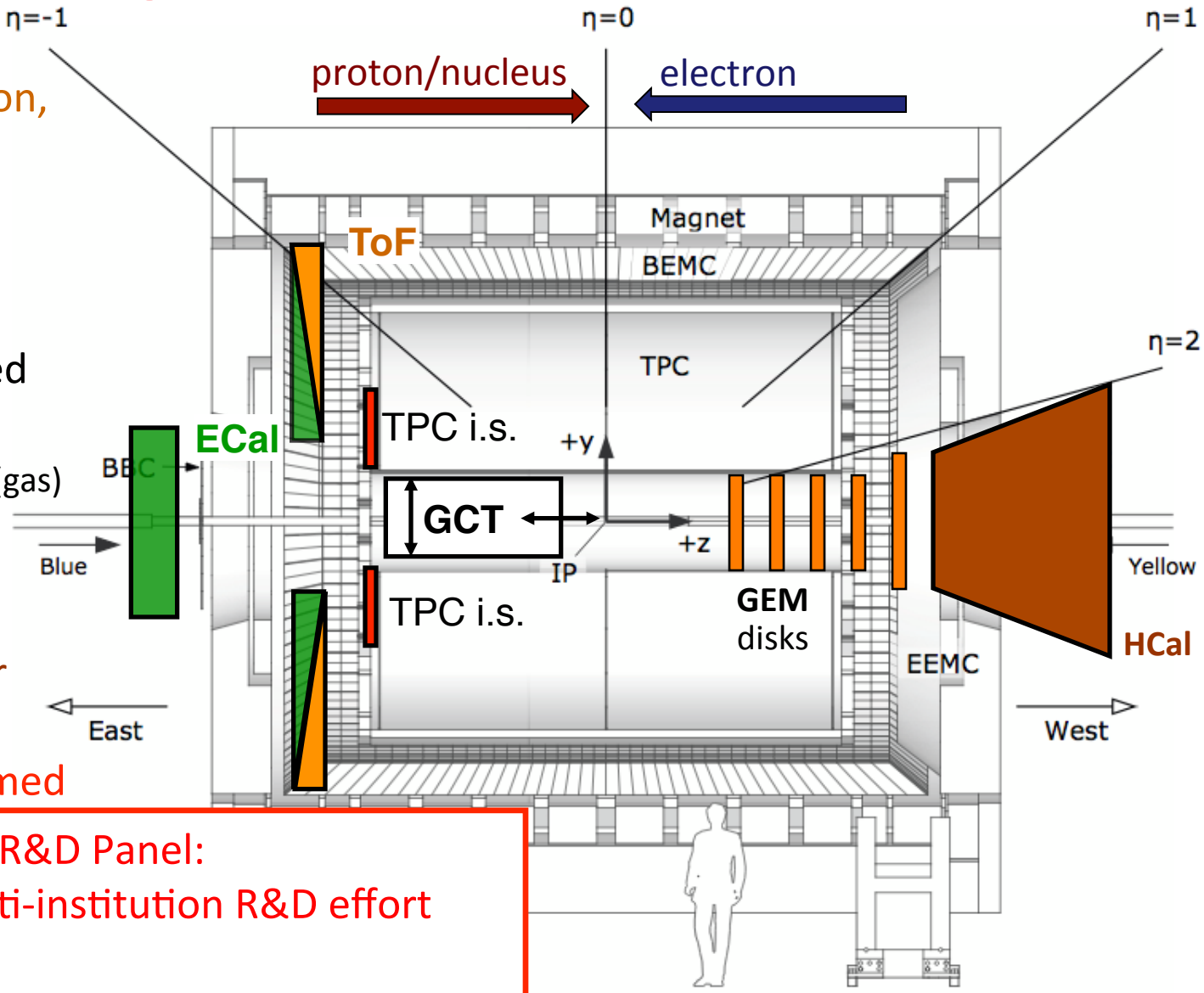
GCT: a compact tracker with enhanced electron capability

-Combine high-threshold (gas) Cherenkov with TPC(-like) tracking

HCal: W powder, spaghetti calorimeter

Simulations ahead

*e*STAR task force formed



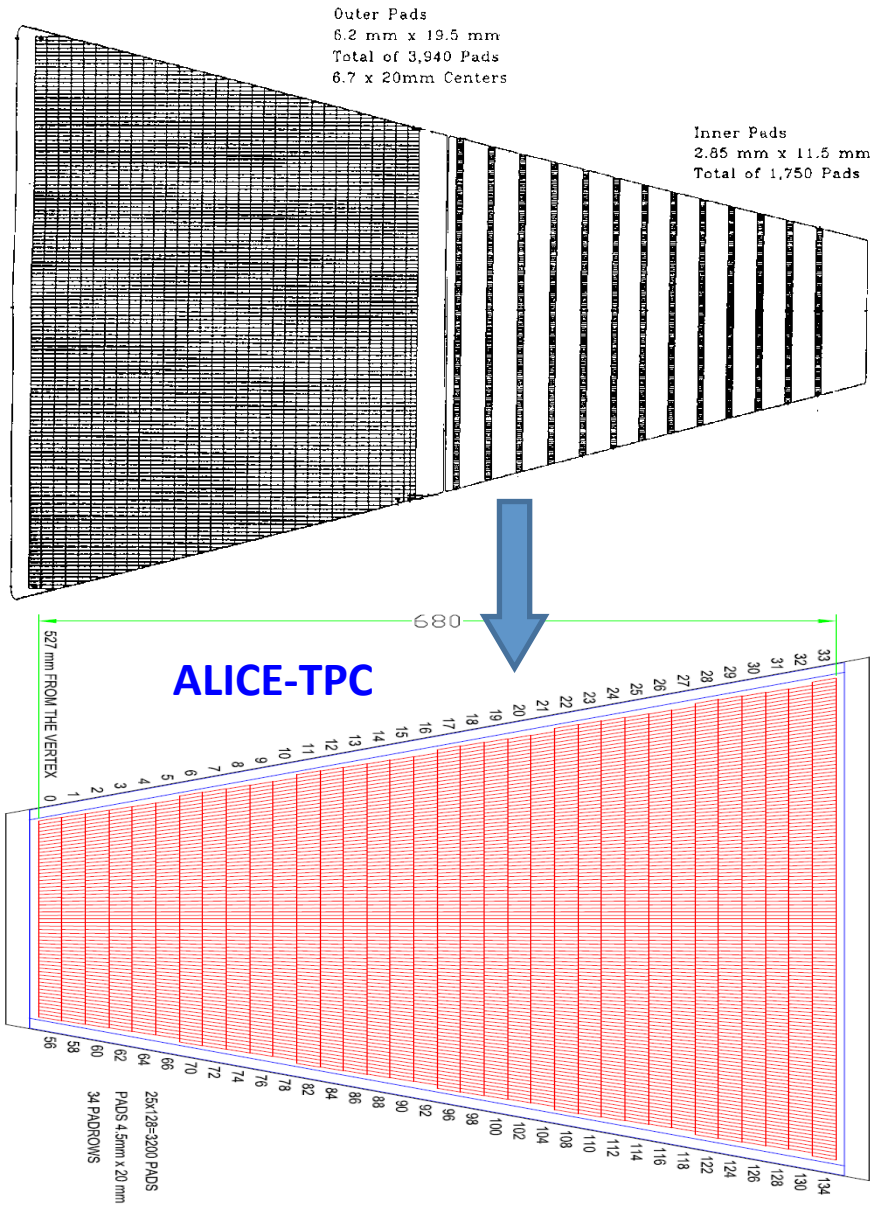
EIC Generic Detector R&D Panel:

GCT: LOI toward multi-institution R&D effort

HCal: R&D proposal

TRD+TOF: R&D proposal

TPC inner sector (iTPC) upgrade



What will benefit from iTPC?

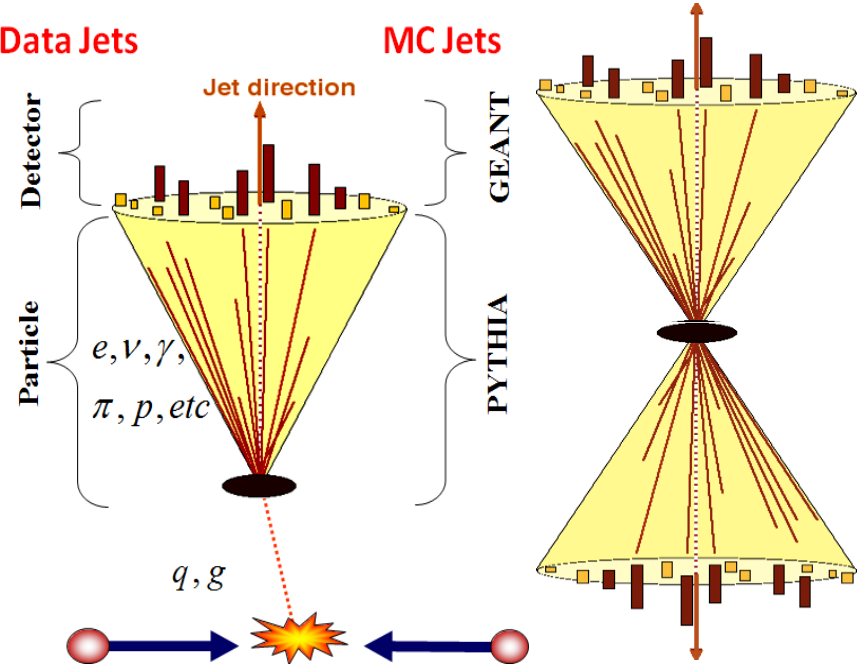
- AA BES-II (fixed-target)
- Electron/hadron ID
- Extended tracking ($1<|\eta|<1.5$-2) and dE/dx capability
- Hyperon/exotic particle reco.

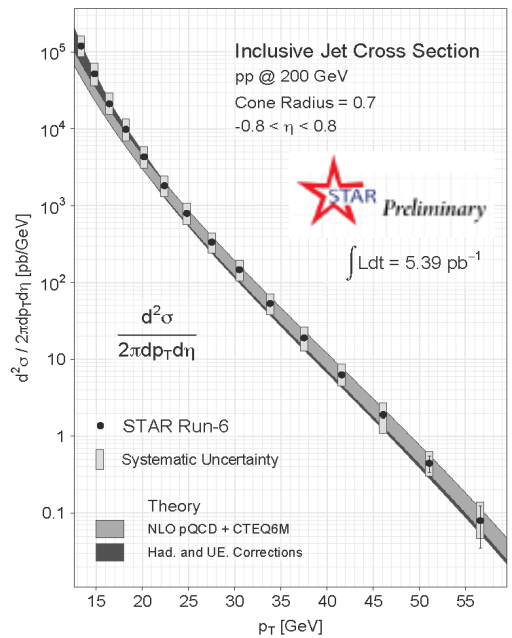
Summary

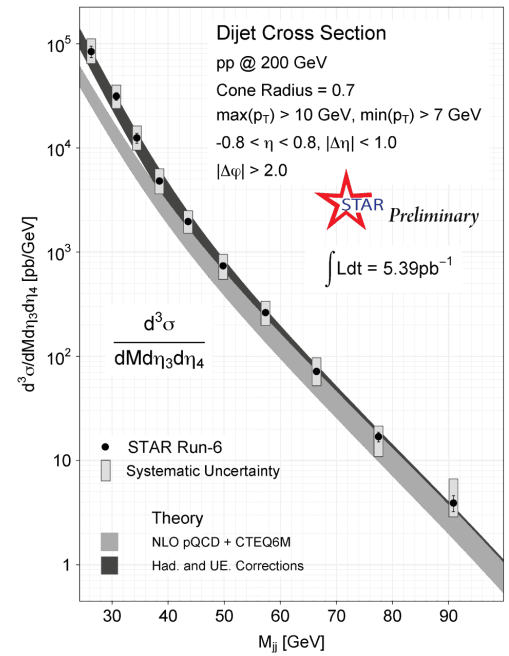
- Forward Detector upgrade at STAR crucial for the (polarized) pp/pA/AA (2017-2020) and future ep/eA program
- Major components (eg. FCS) of forward upgrade progress well. Some upgrade – RICH/pre-shower is currently under consideration/discussion.
- Evolve from conceptual design to more details: physics simulation -> detector requirements, prototype test.

- STAR will go **FORWARD.**

Reconstructing Inclusive and di-Jet at STAR







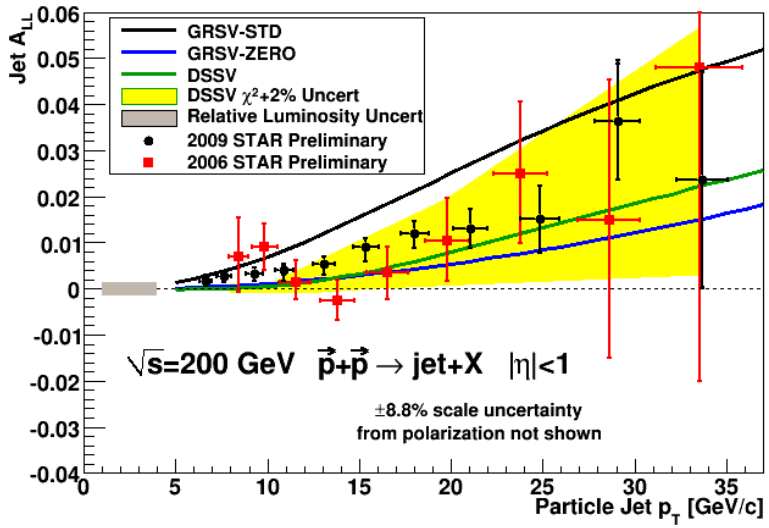
The large acceptance of the STAR detector makes it well suited for jet measurements:

- TPC provides excellent charged-particle tracking and p_T information over broad range in η
- Extensive EM calorimetry over full 2π in azimuth and for $-1 < \eta < 2$
- Sophisticated multi-level trigger on EMC information at tower and patch scale
- Use midpoint cone algorithm

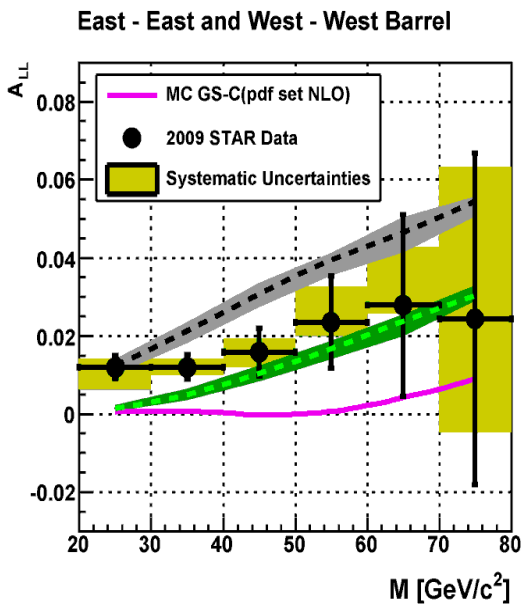
- Data well described by NLO pQCD when including hadronization and underlying event corrections from PYTHIA
- Hadronization and UE corrections more significant at low jet p_T

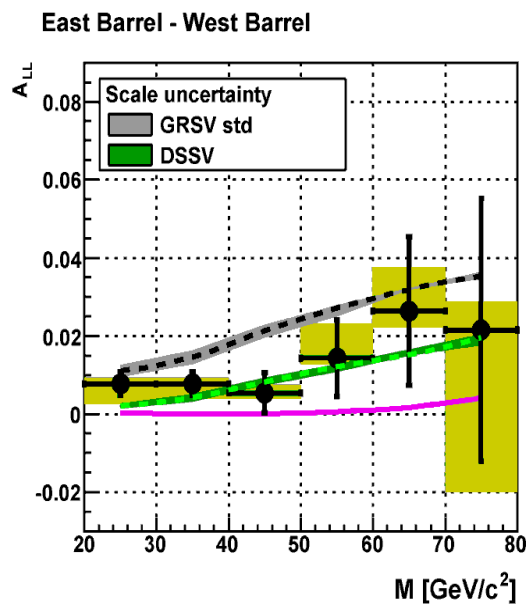
- Reconstructing correlated probes (eg. di-jet, γ-jet) provides information on initial state partonic kinematics at LO
- This allows for constraints on the shape of $\Delta g(x)$

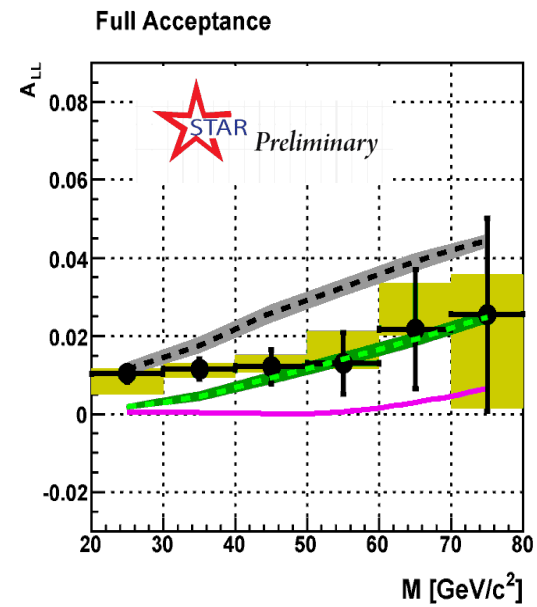
Recent Inclusive and di-Jet A_{LL}



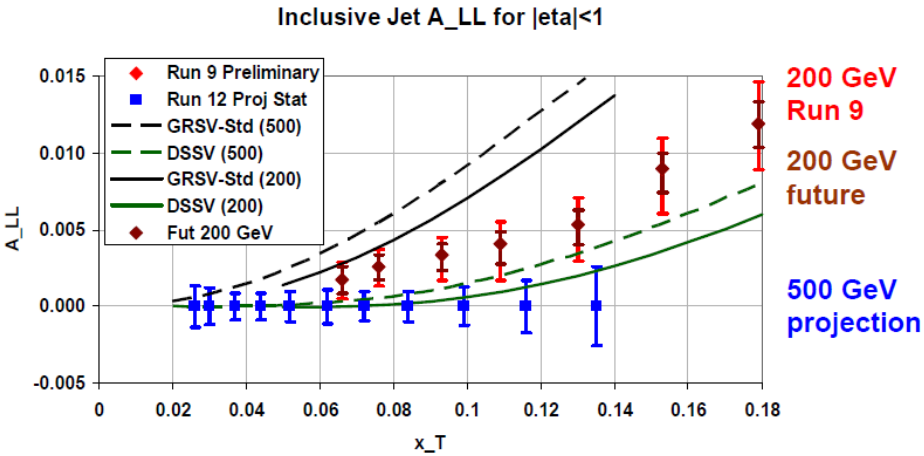
- 2009 results are a factor of 3 or greater more precise than 2006
- Data falls between predictions from **DSSV** and **GRSV-STD**

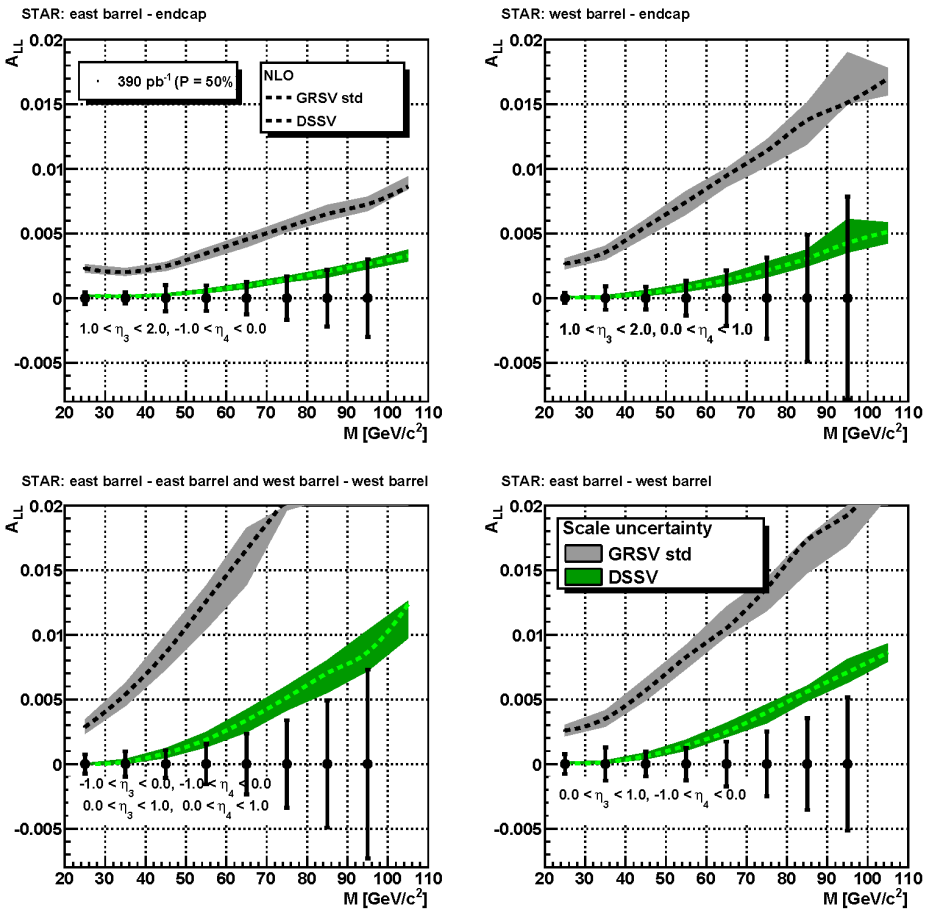






Future Inclusive and di-Jet Sensitivity

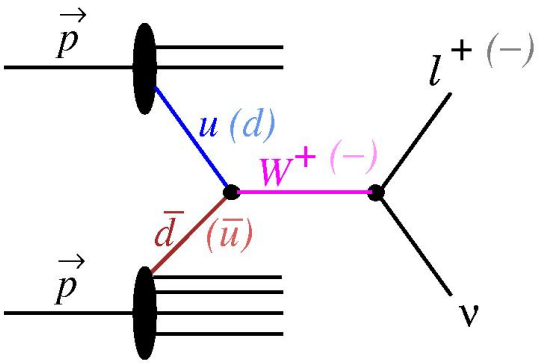




- Future running at 200 GeV expected to significantly reduce uncertainties
- Inclusive and di-jet A_{LL} in 500 GeV
  - Higher energies give access to lower x_g
  - Expect A_{LL} to be smaller than 200 GeV
  - Projections shown are purely statistical
  - Forward jets in EEMC region sensitive to even lower x_g

Projected Stat. Uncertainty: 50% Pol 390 pb^{-1}, 600 pb^{-1} delivered

STAR W A_L - Probing the Sea

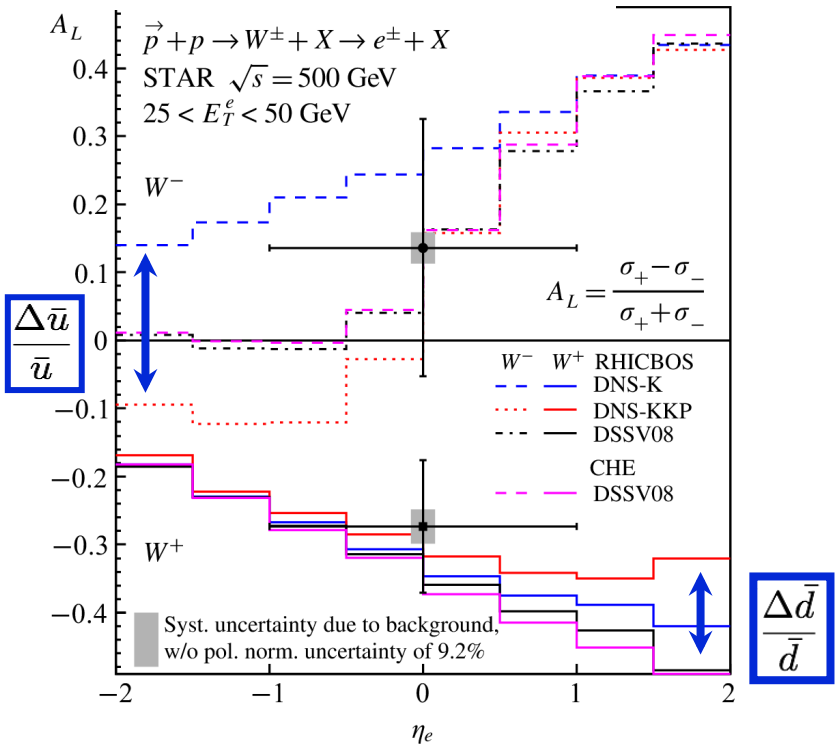


$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu$$

$$\bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu}$$

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

- Detect Ws through e^+/e^- decay channels
- V-A coupling leads to perfect spin separation
- LH quarks and RH anti-quarks
- Neutrino helicity gives preferred direction in decay



STAR Run 9 Result

$$A_L(W^+) = -0.27 \pm 0.10(stat) \pm 0.02(syst)$$

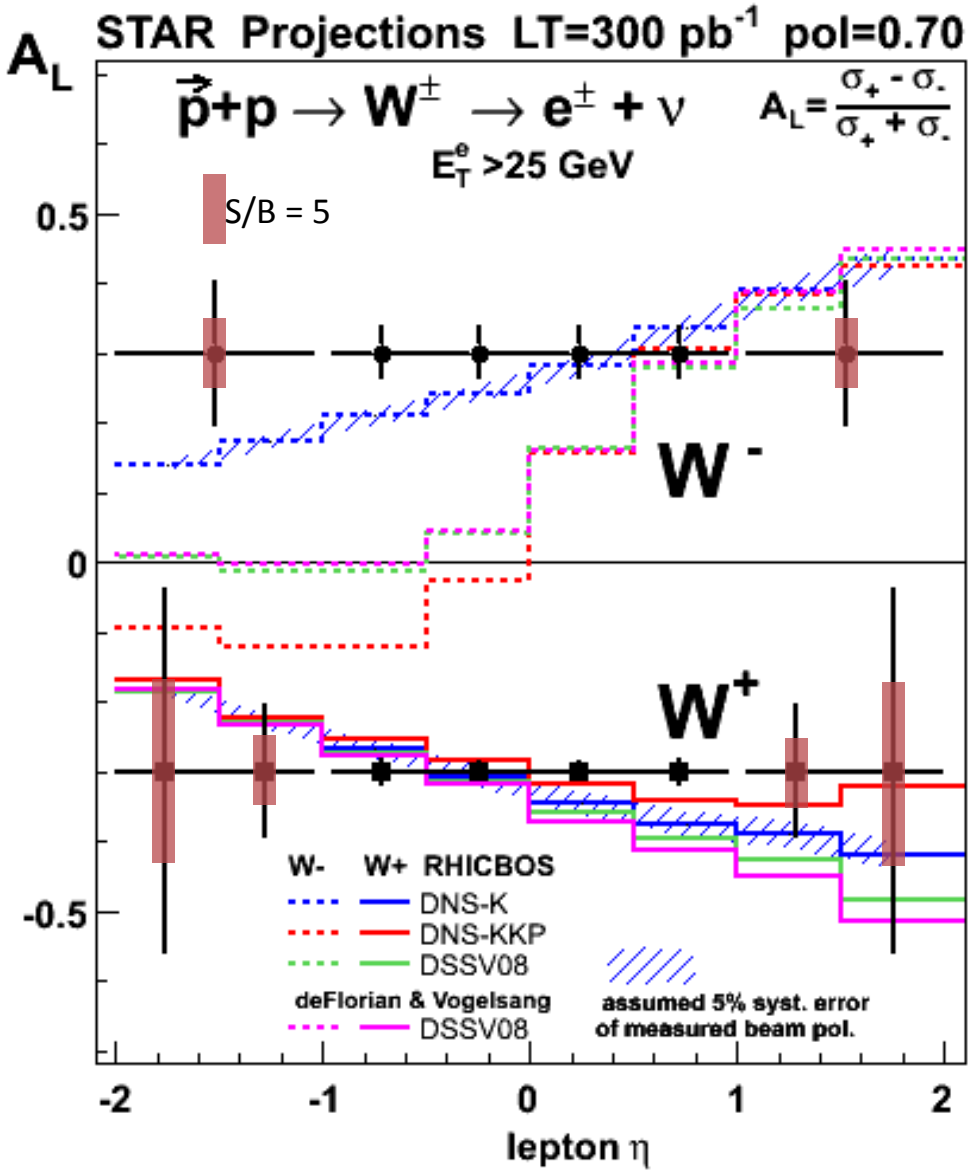
$$A_L(W^-) = 0.14 \pm 0.19(stat) \pm 0.02(syst)$$

PRL **106**, 062002 (2011)

At forward/backward rapidity there is increased sensitivity to single quark flavor

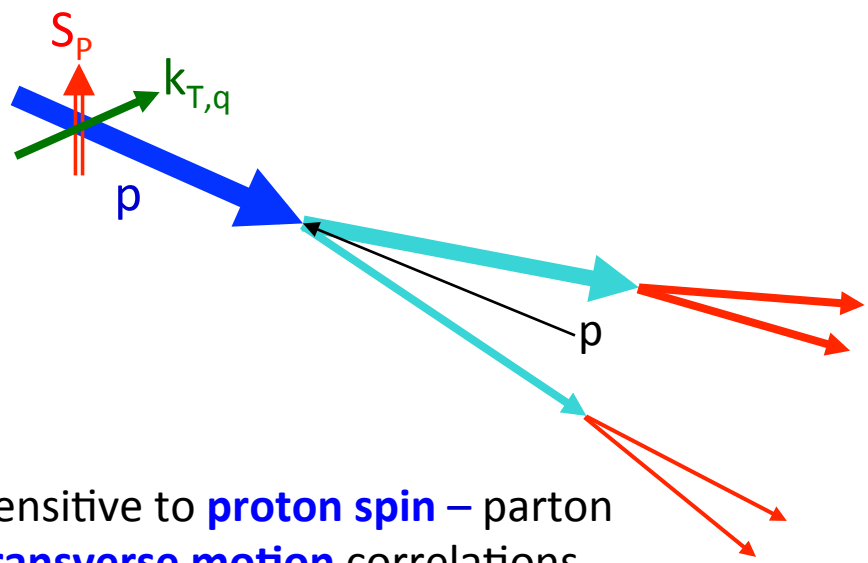
Future STAR W Measurements

- **Forward GEM Tracker upgrade**
  - 6 light-weight triple-GEM disks using industrially produced GEM foils
  - Partial Installation for 2012
- **Multi-year program**
  - L ≈ 300 pb^{-1}
  - P ≈ 70%
  - Significant constraints on the polarized anti-quark sea distributions



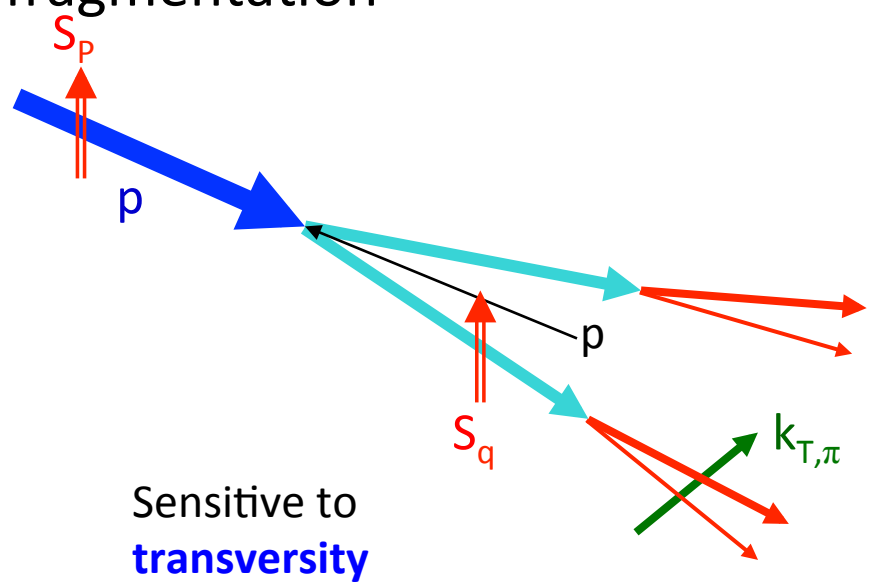
Mechanism for Large Transverse Spin Effects

Sivers mechanism: asymmetry in production of forward jet or γ



Sensitive to **proton spin** – parton **transverse motion** correlations

Collins mechanism: asymmetry in the forward jet fragmentation

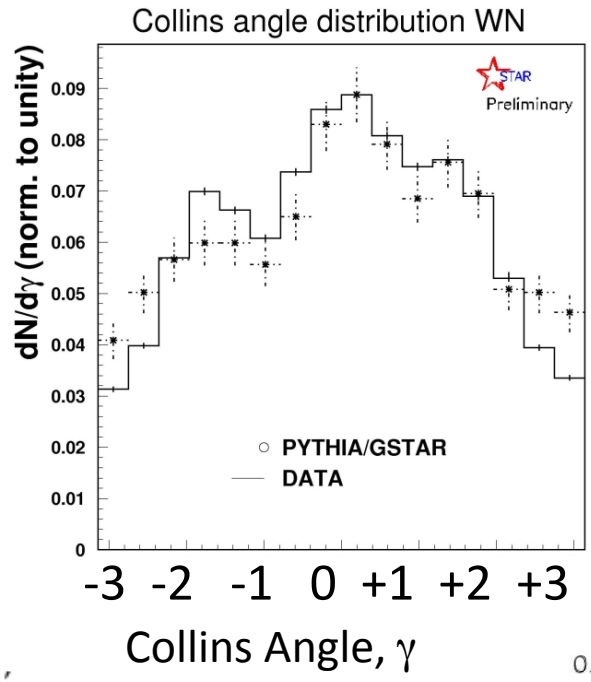


Sensitive to **transversity**

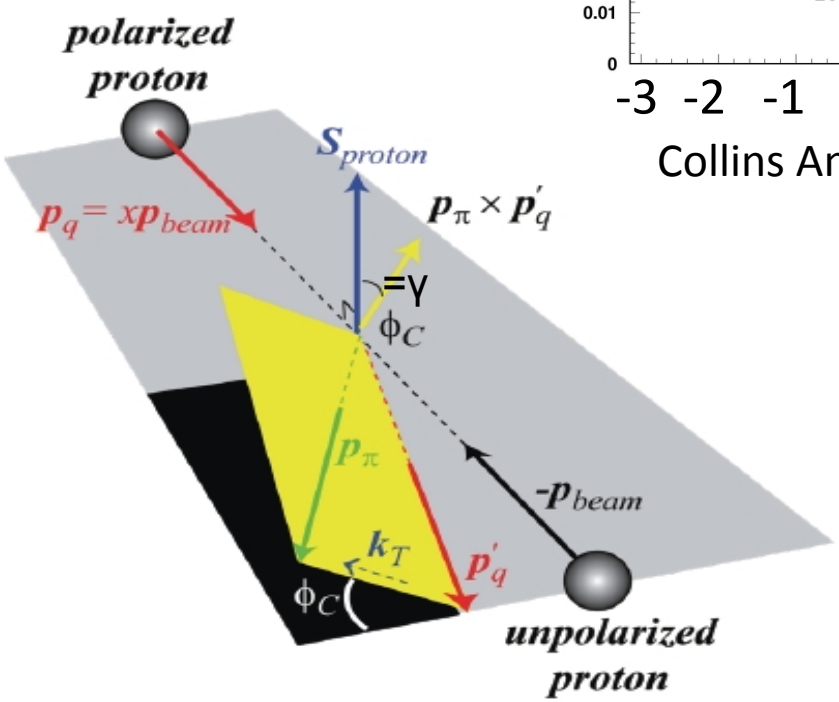
- Need to go beyond inclusive hadron measurements
- Possibilities include jets, direct photons, di-hadron correlations, etc.

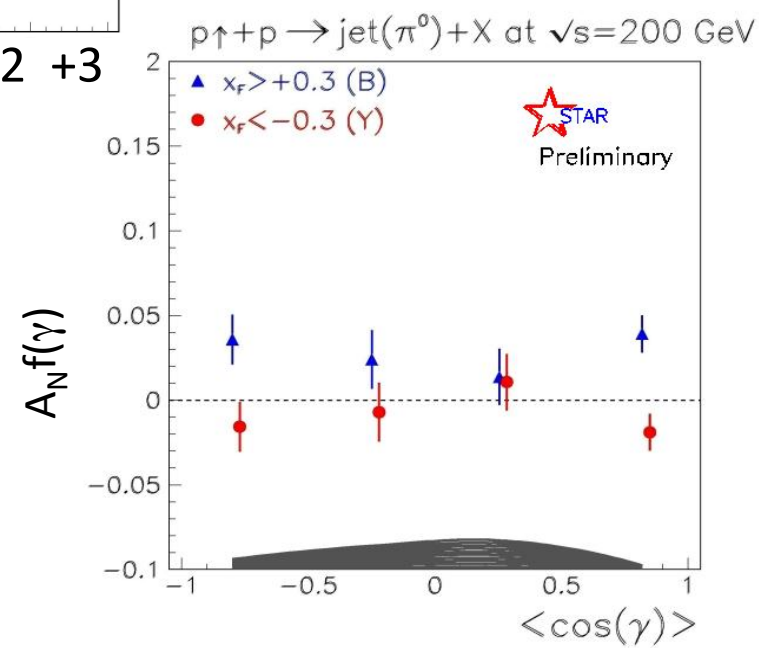
Forward Rapidity Collins Asymmetry

Jet axis and leading pion define plane. Angle between normal to plane and spin is Collins Angle, γ



Collins asymmetry in forward direction slightly positive (consistent with observed pion A_N), but shows no sign of cos(γ) dependence.





Sivers effect sign change

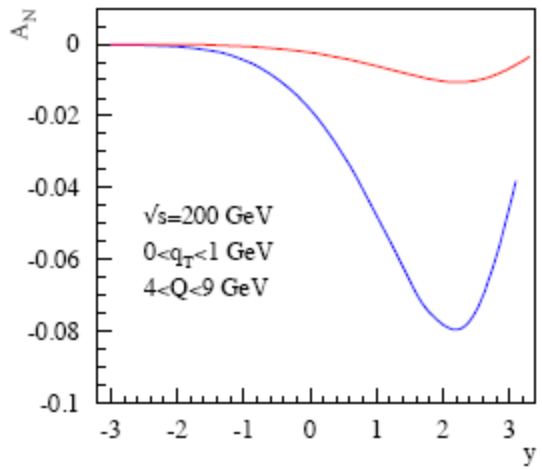
- In **SIDIS**, knock a colored quark out of a color-neutral nucleon
  - Quark was bound to the rest of the nucleon before the interaction
  - Final-state interaction that produces the interference is attractive
- In **Drell-Yan**, a quark in one hadron annihilates with an anti-quark of the same flavor and opposite color from the other hadron
  - The rest of the "other hadron" has the same color charge as the incident quark
  - Initial-state interaction that produces the interference is repulsive
- Leads to **opposite signs for the Sivers effect in the two cases**
  - A **very important test of the TMD approach**

- A_NDY and COMPASS both expect to observe the sign change
  - Assumption: This will be a done deal before STAR (or PHENIX) can perform meaningful Drell-Yan measurements

Sivers effect of DY production at RHIC

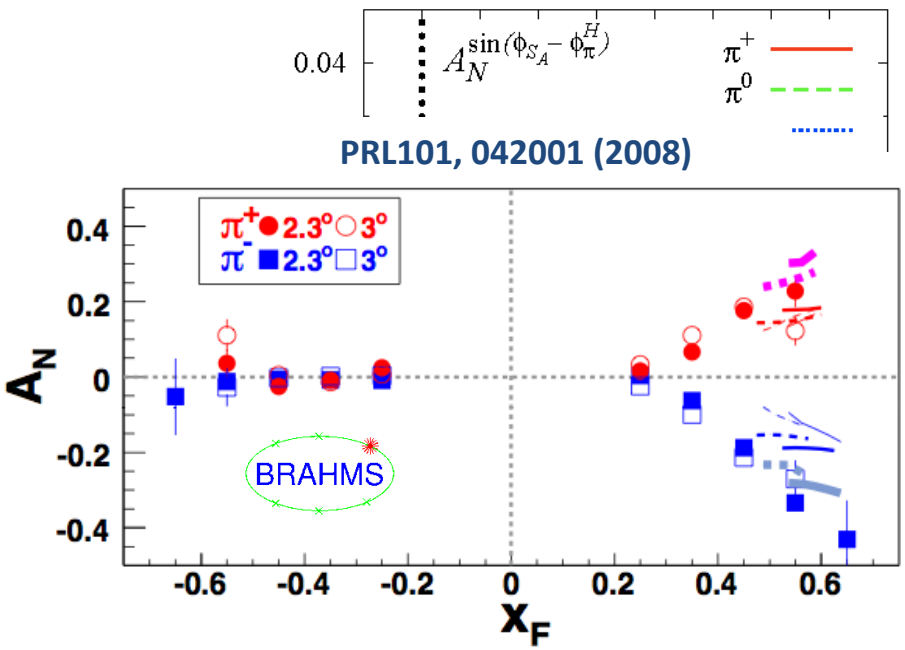
- Blue curve: bare parton model (using Torino TMD with Gaussian ansatz from SIDIS)
- Red curve: resummed formalism (using Torino TMD to calculate $T_F(x, x)$ as the initial input function, then evolve)

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$



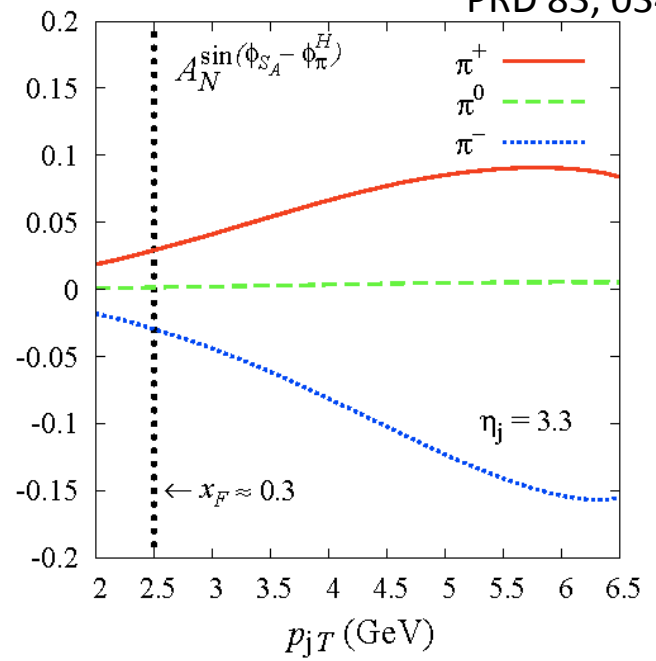
- caution: non-perturbative part could be different for Sivers asymmetry

Pushing transversity even further



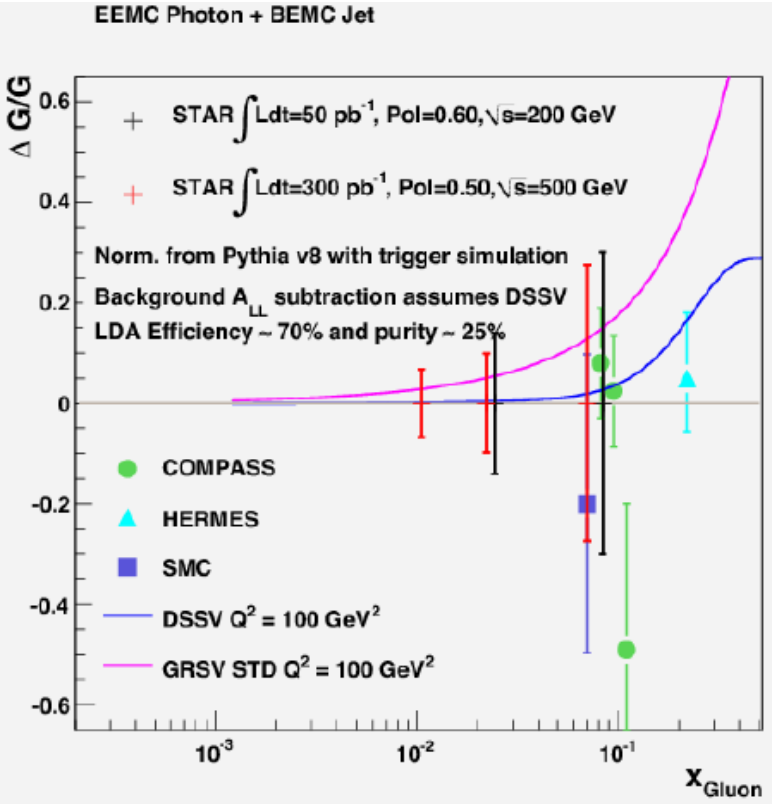
Collins asymmetry in jets

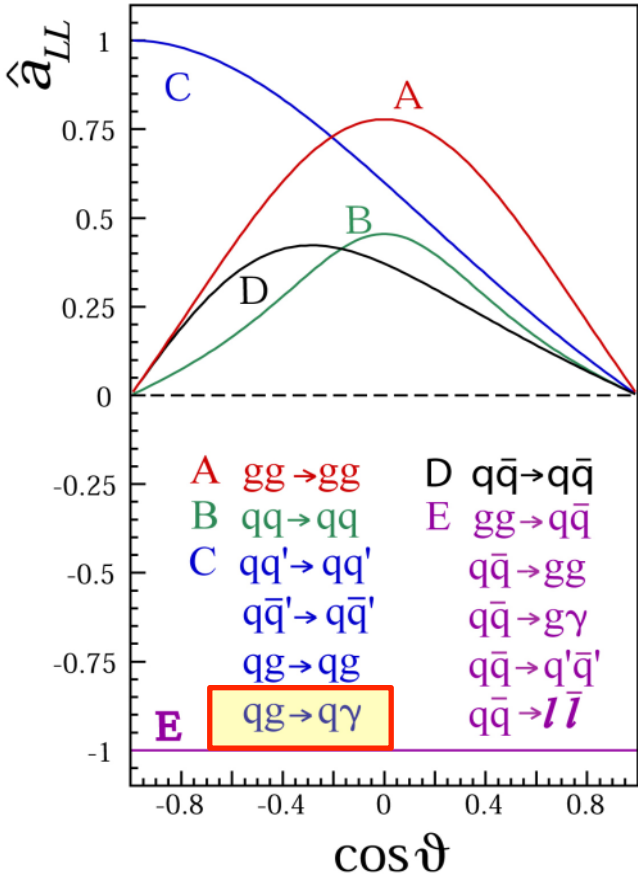
D'Alesio et al, PRD 83, 034021



- Pushing out to the FMS rapidity will probe quark transversity at high *x*
- Need to **trigger on and measure jets** with leading **charged pions**
  - Collins effect for π^0 is expected to be very small
  - Very large, and opposite sign, A_N are observed for inclusive $\pi^\pm$

Future A_{LL} measurement
γ-jet correlation

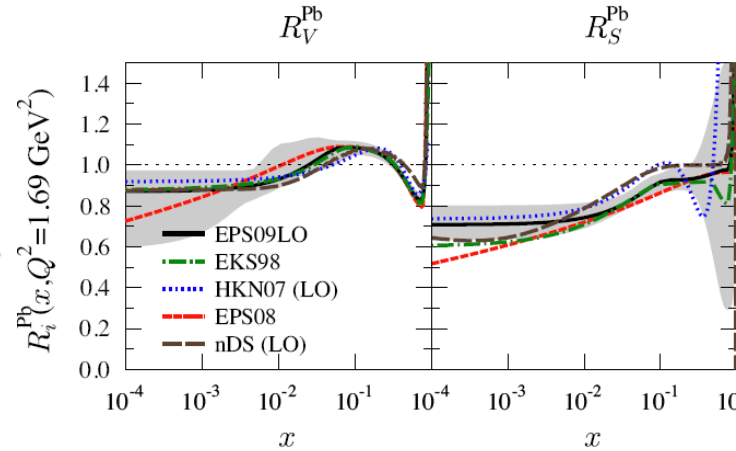


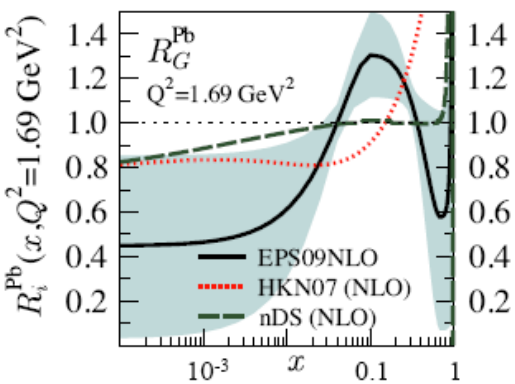


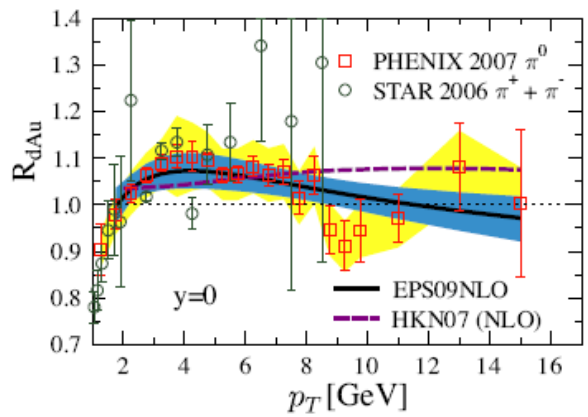
A_{LL} of γ -jet pair access direct leading-order extraction of ΔG(x)/G(x).
Dominate by qg->qγ, process selectivity
Forward γ and full jet capability will extend STAR acceptance

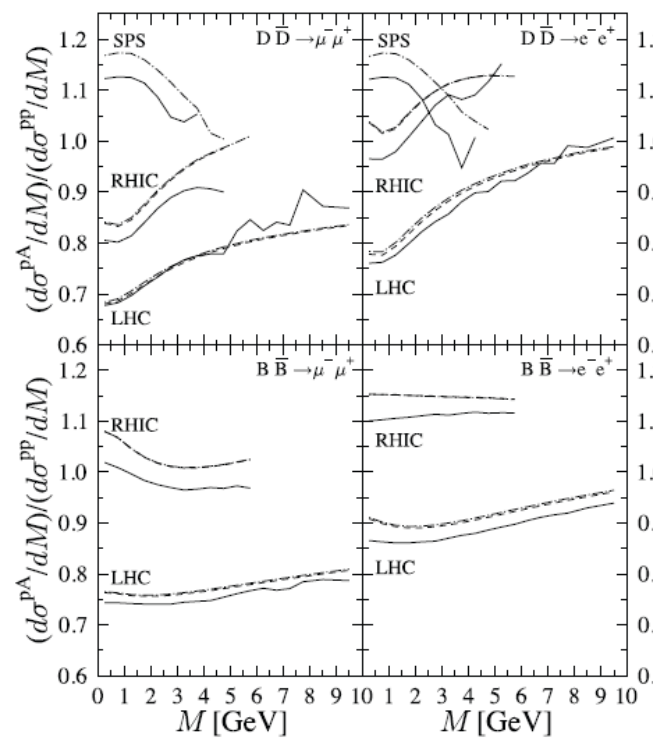
Leading Twist Nuclear Effects in pA

- p: uncertainties from PDF small ⇒ $\delta\sigma/\sigma$ ~ 10%
- A:
  - at x = 10^{-3} uncertainties in R_G ~ 100%
  - no data for x > 0.2, no stringent constraints for x < 0.02
  - RHIC data not yet enough discriminating power





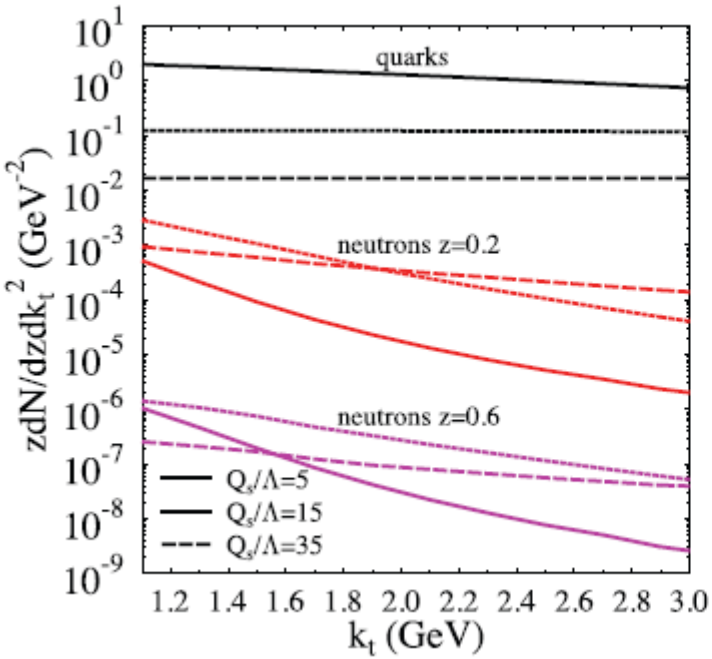


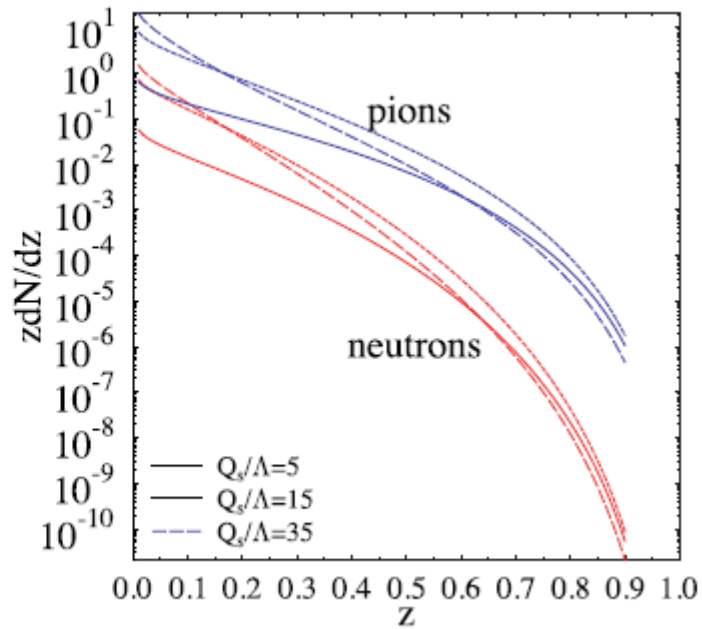


- Important: need constraints at large Q^2 were higher twist effects are small - in pQCD HT ~ $\mathcal{O}(1/Q^2)$

Measurements Constraining nPDFs:
Correlated charm measurements (no long-term upgrade needed)

Baryon Production at large x_F





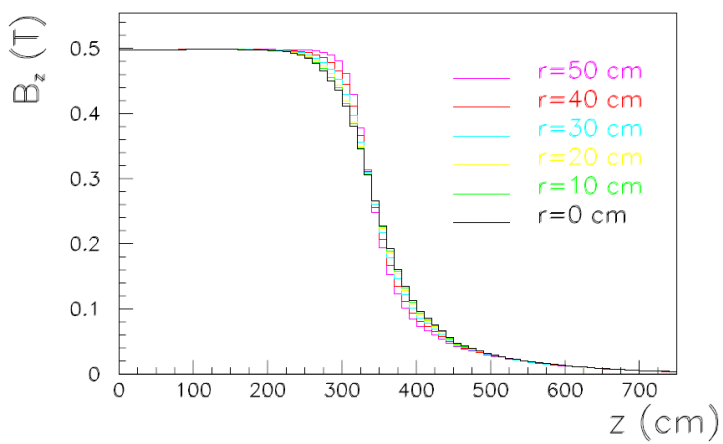
Phys. Rev. Lett. 90, 092301 (2003); 91, 259901 (2003)

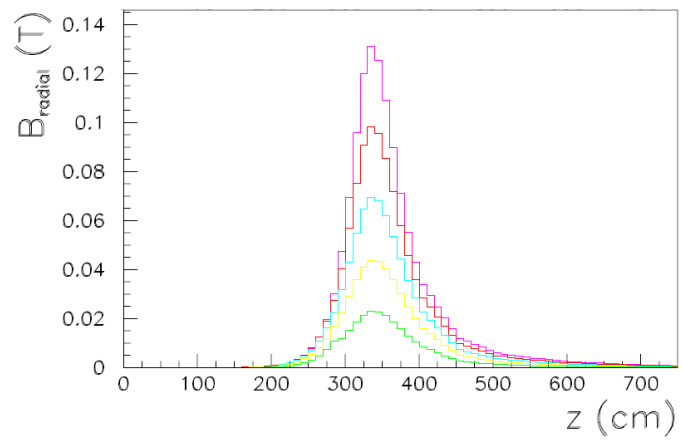
Test baryon stopping scenario at RHIC
Calculable in weak-coupling QCD – intrinsic semi-hard scale Qs
Transverse momentum flatten with increasing energy and A mass
Longitudinal steepen with increasing energy and A mass
Effect more significant for Λ and hyperons

PID challenging at forward !

STAR Magnetic Field

Chris QM09 talk : http://drupal.star.bnl.gov/STAR/files/QM2009_Perkins_v5_0.ppt





- Radial and Azimuthal fields impart impulses in the Φ direction and partially cancel

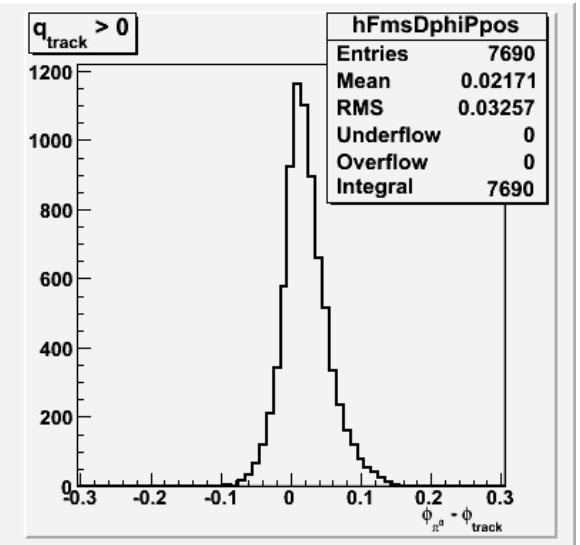
$$\Delta\varphi = \frac{c(\int B_z dr - \int B_r dz)}{P_r}$$

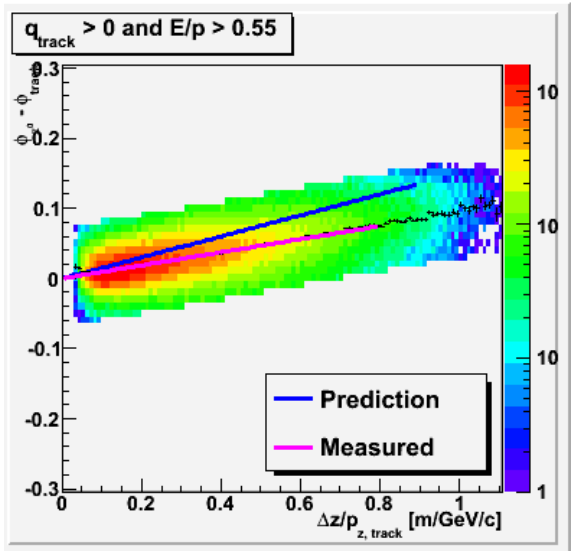
$$\approx \frac{c}{P_r}(0.5T \cdot \frac{P_r}{P_z} 4m - \frac{3.5}{0.4}\frac{P_r}{P_z} 0.1T \cdot 1m)$$

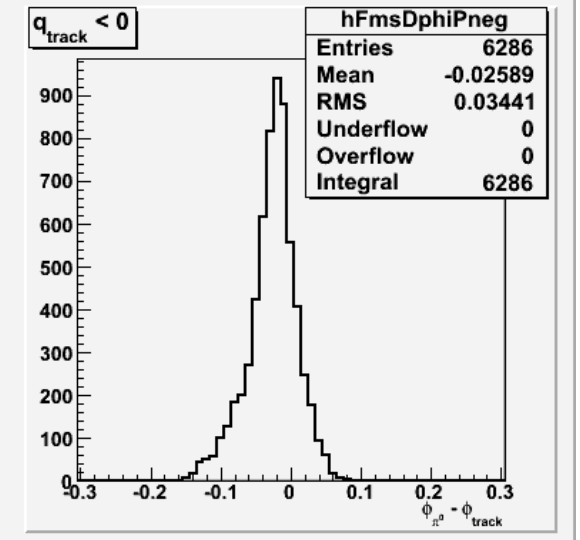
$$\approx \frac{0.6 - 0.26[radian]}{P_z[GeV]} \approx \frac{0.34[radian]}{P_z[GeV]}$$

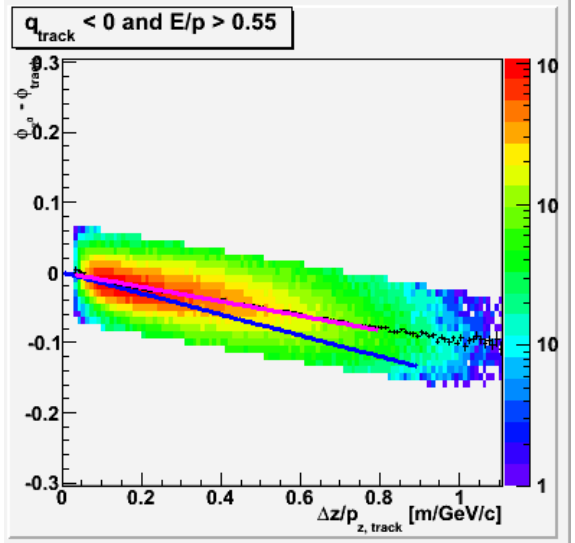
Run8 FMS-FTPC (Jim Drachenberg)

http://www.star.bnl.gov/protected/spin/drach/Run8FMS/FMS-FTPC_correlation/









$\Delta\Phi = 0.1\ \Delta z/p_z$ (Δz=2.5m)
= 0.25 radian / GeV

For 10GeV at y=0 @ FMS
Δy @ x=20cm = 0.5cm
Δy @ x=40cm = 1.0cm
Δy @ x=80cm = 2.0cm

For 50GeV at y=0 @ FMS
Δy @ x=20cm = 0.1cm
Δy @ x=40cm = 0.2cm
Δy @ x=80cm = 0.4cm

FTPC+FMS have done charge separation with STAR magnet at
$2.8<\eta<3.8$
E ~ 10GeV

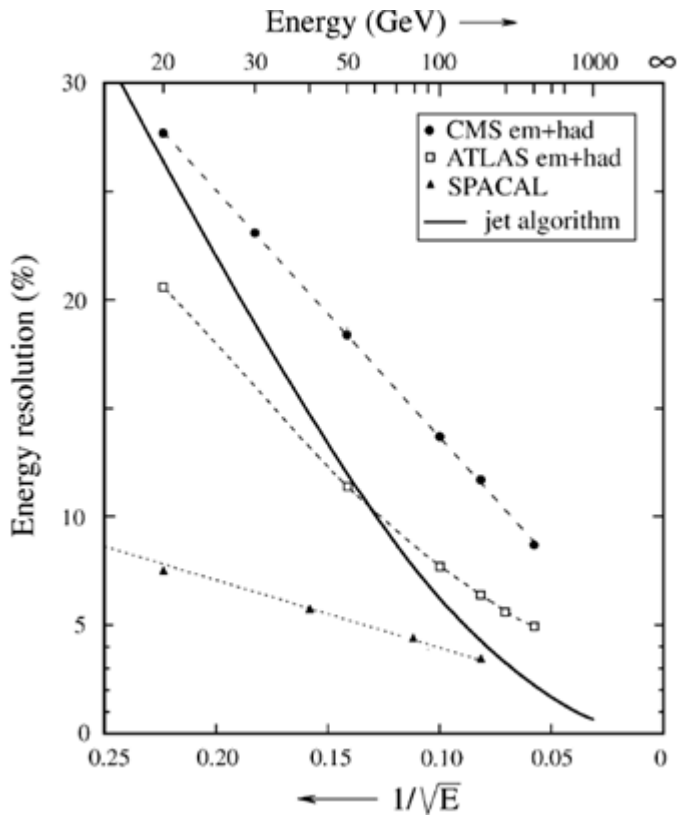
Required kinematic coverage for Drell-Yan

- pp500
  - $y_{pair} = 4$, $M_{pair} = 4.5$ GeV corresponds to $x \sim 0.5$
  - Would like to reach pseudo-rapidities up to ~ 4.3
    - 4.3 would "fill the corners" of the FMS square hole
    - Requires electron detection/identification to >~ 85 GeV
    - Material between IR and FMS grows rapidly beyond $\eta \sim 4.3$

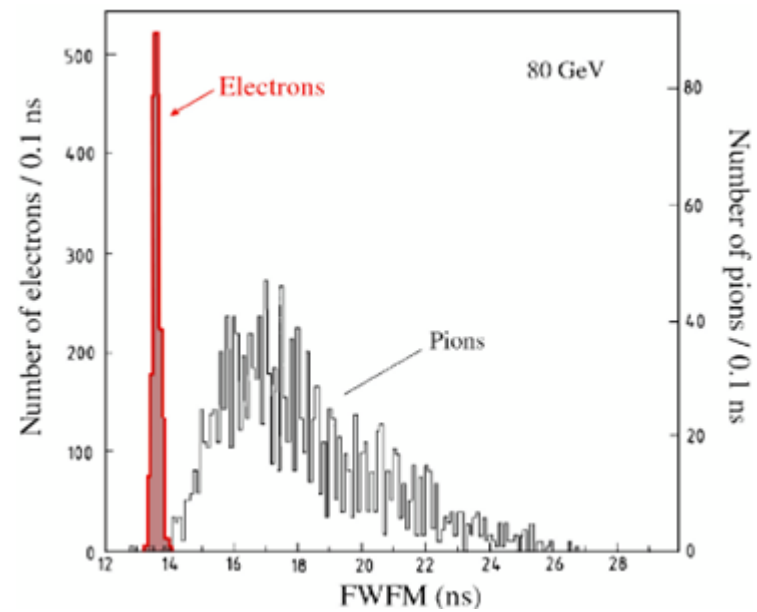
- pA/pp200
  - How close can our acceptance go to the edge of the pole-tip hole at $\eta = 2$?
  - Very little yield beyond $\eta \sim 3$
  - Would like to detect/identify electrons down to ~ 10 GeV

SPACAL

Compensation calorimeter & Fast speed of response



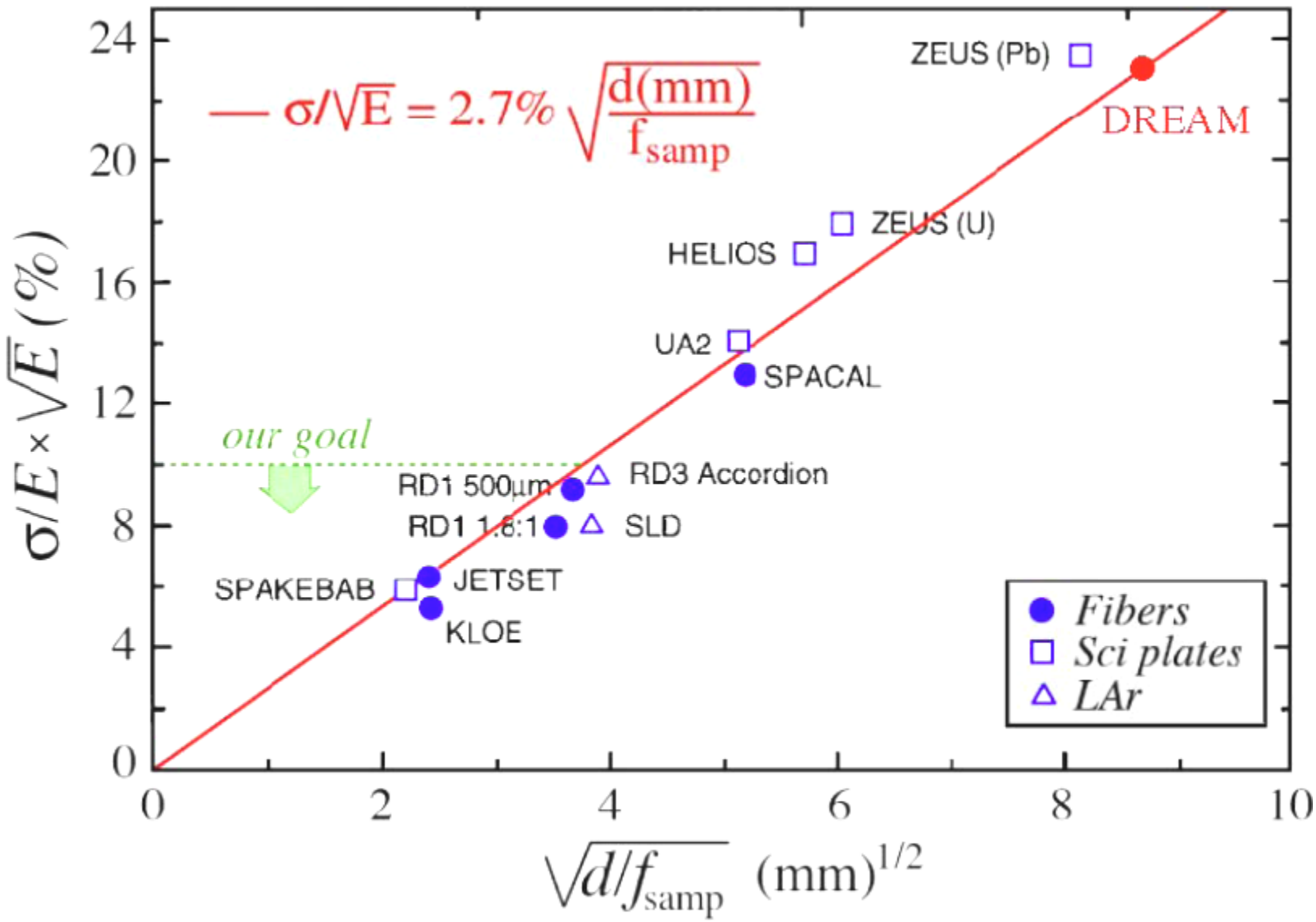
R.Wigmans, NIM A494 (2002) 277-287



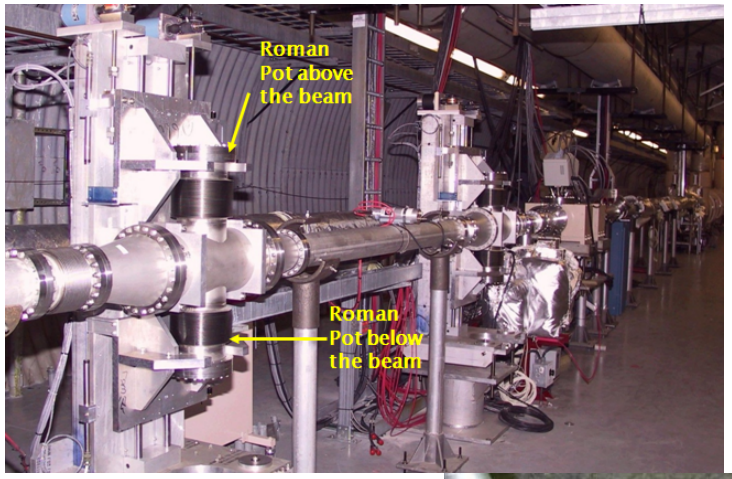
D.Acosta et al., NIM A302 (1991) 36-46

Outstanding hadron energy resolution

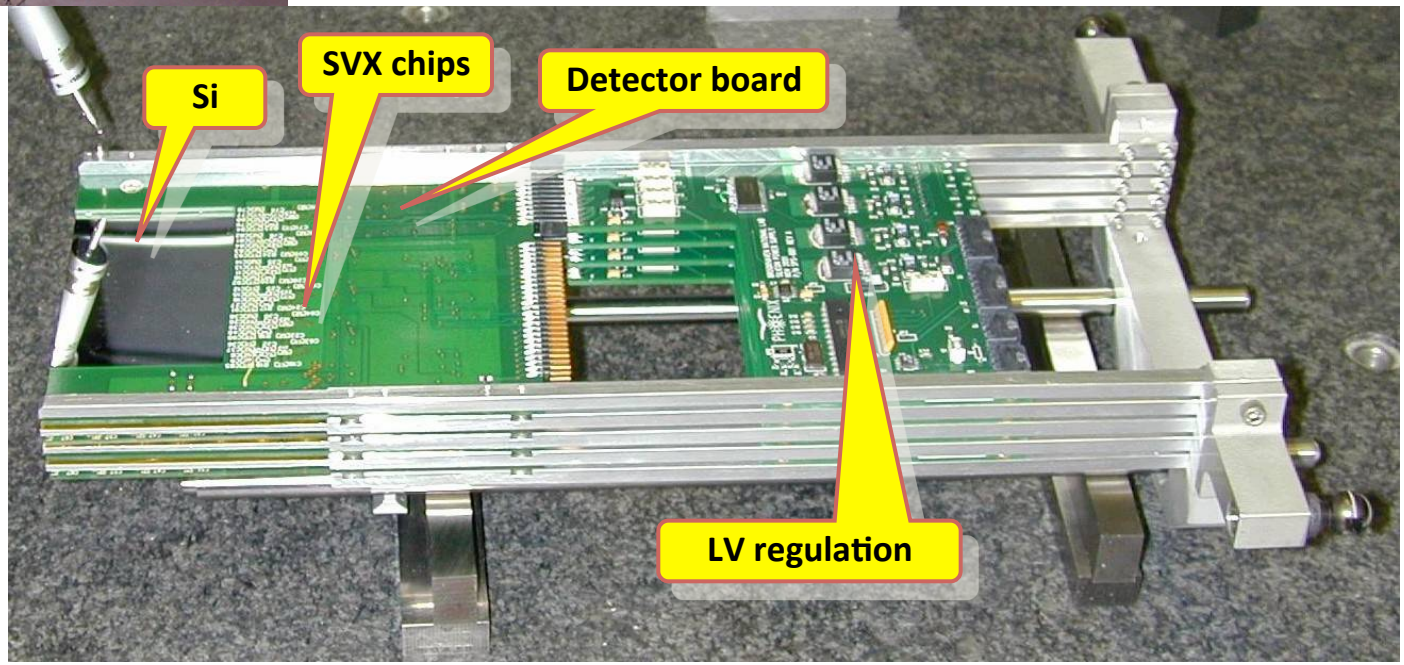
SPACAL had fast (25ns) 'electron' trigger.
e/h rejection ~1000 at 80GeV, electron efficiency ~90%


$\sigma/\sqrt{E} = 2.7\% \sqrt{\frac{d(mm)}{f_{samp}}}$
ZEUS (Pb)
DREAM
ZEUS (U)
HELIOS
UA2
SPACAL
our goal
RD3 Accordion
RD1 500μm
RD1 1.8:1
SLD
SPAKEBAB
JETSET
KLOE
Fibers
Sci plates
LAr
$\sigma/E \times \sqrt{E}$ (%)
$\sqrt{d/f_{samp}}$ (mm)$^{1/2}$
0
4
8
12
16
20
24
0
2
4
6
8
10

Si detector package (RP-I)



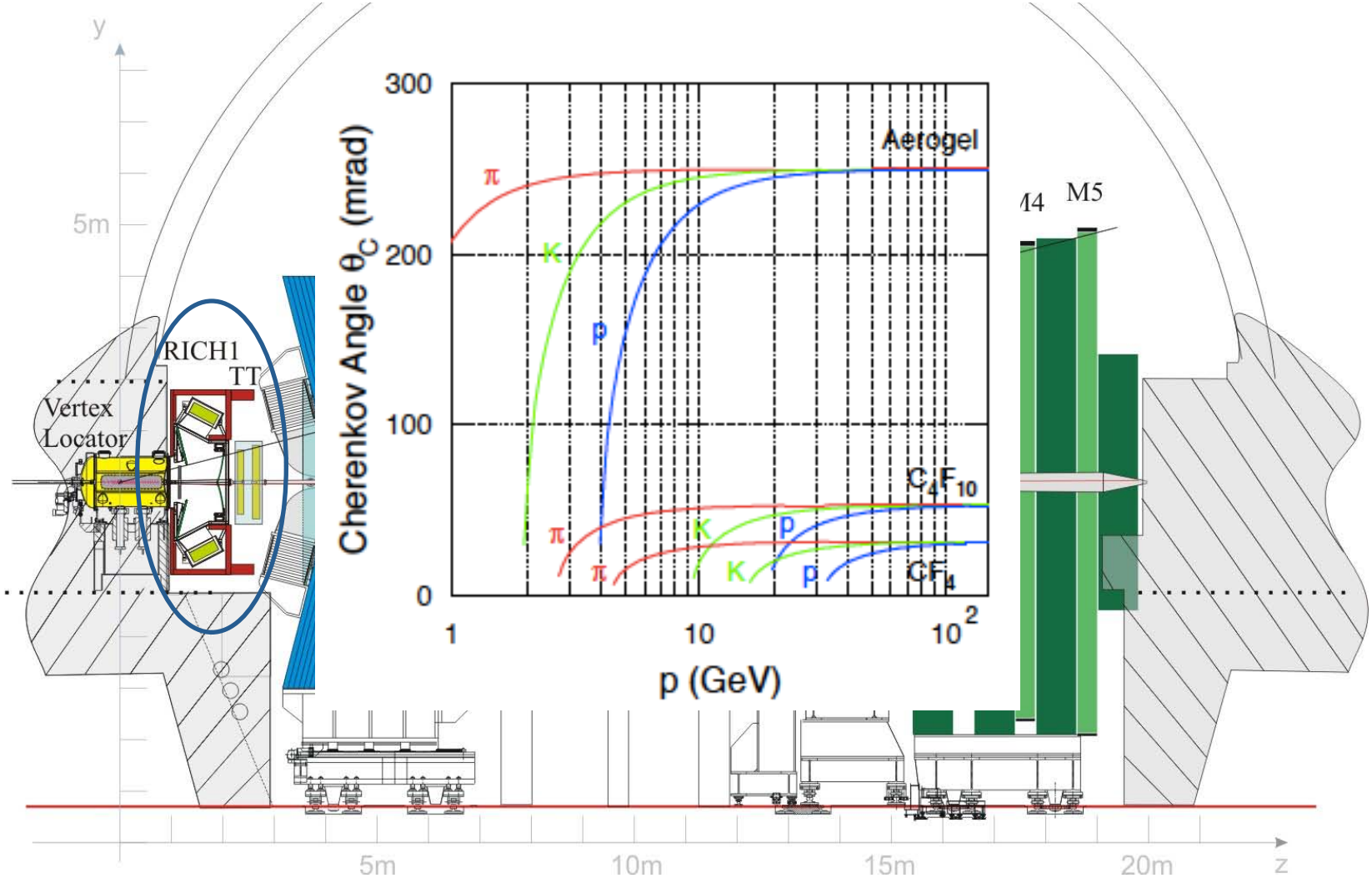
- 4 planes of 400 μm Silicon microstrip detectors:
  - 4.5×7.5 cm^2 sensitive area
  - 100 um pitch => good resolution, low occupancy
  - Redundancy: 2X- and 2Y-detectors in each package
  - Closest proximity to the beam ~10 mm
  - 8 mm trigger scintillator with two PMT readout



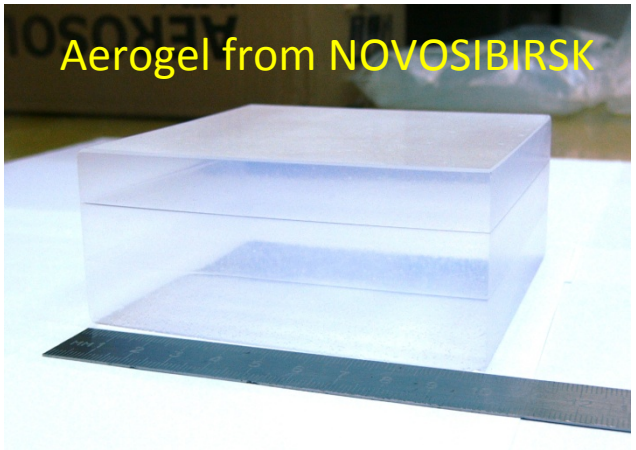
RICH Design for STAR

LHC-b: 2 RICHs with 3 radiators

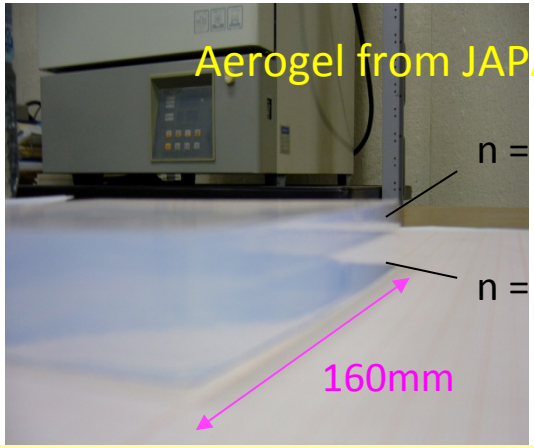
6/28/12



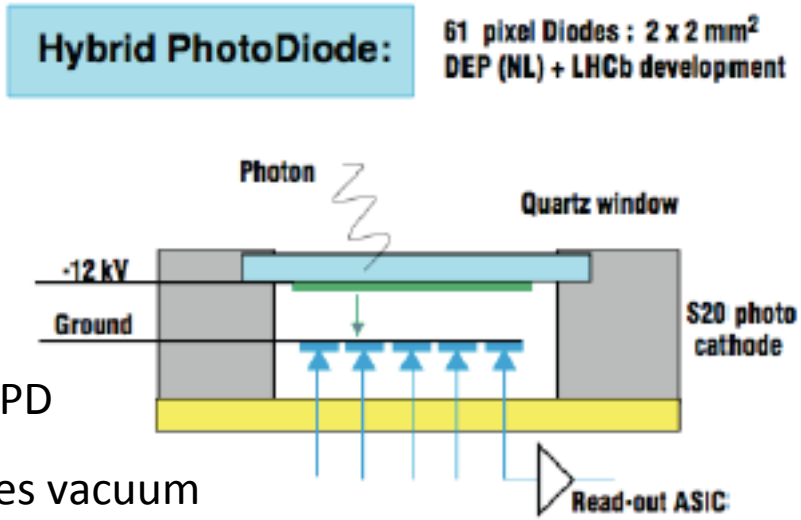
RICH components



High optical parameters
(Lsc≥43mm at 400 nm)

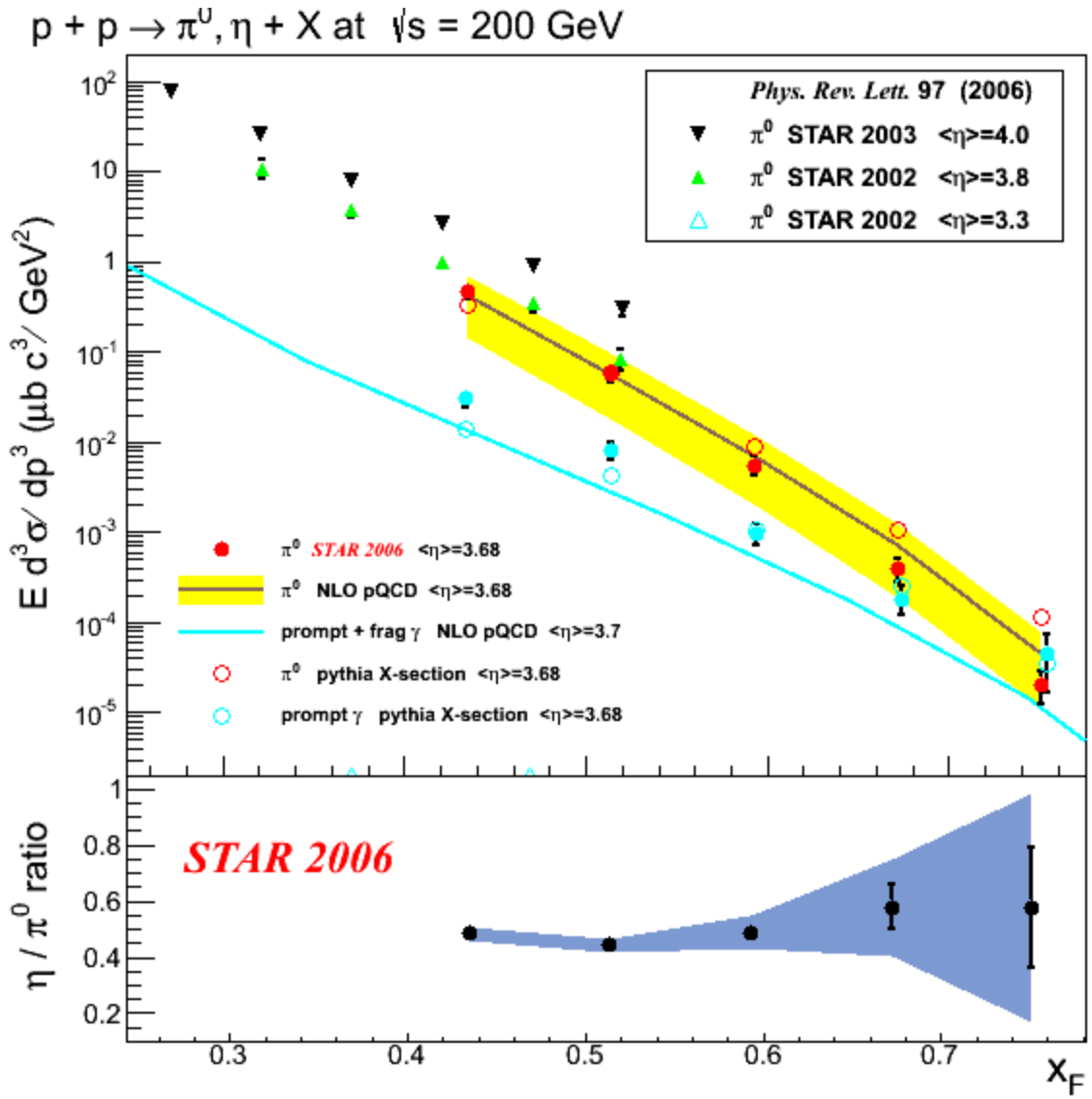


transmission length(400nm): 46mm

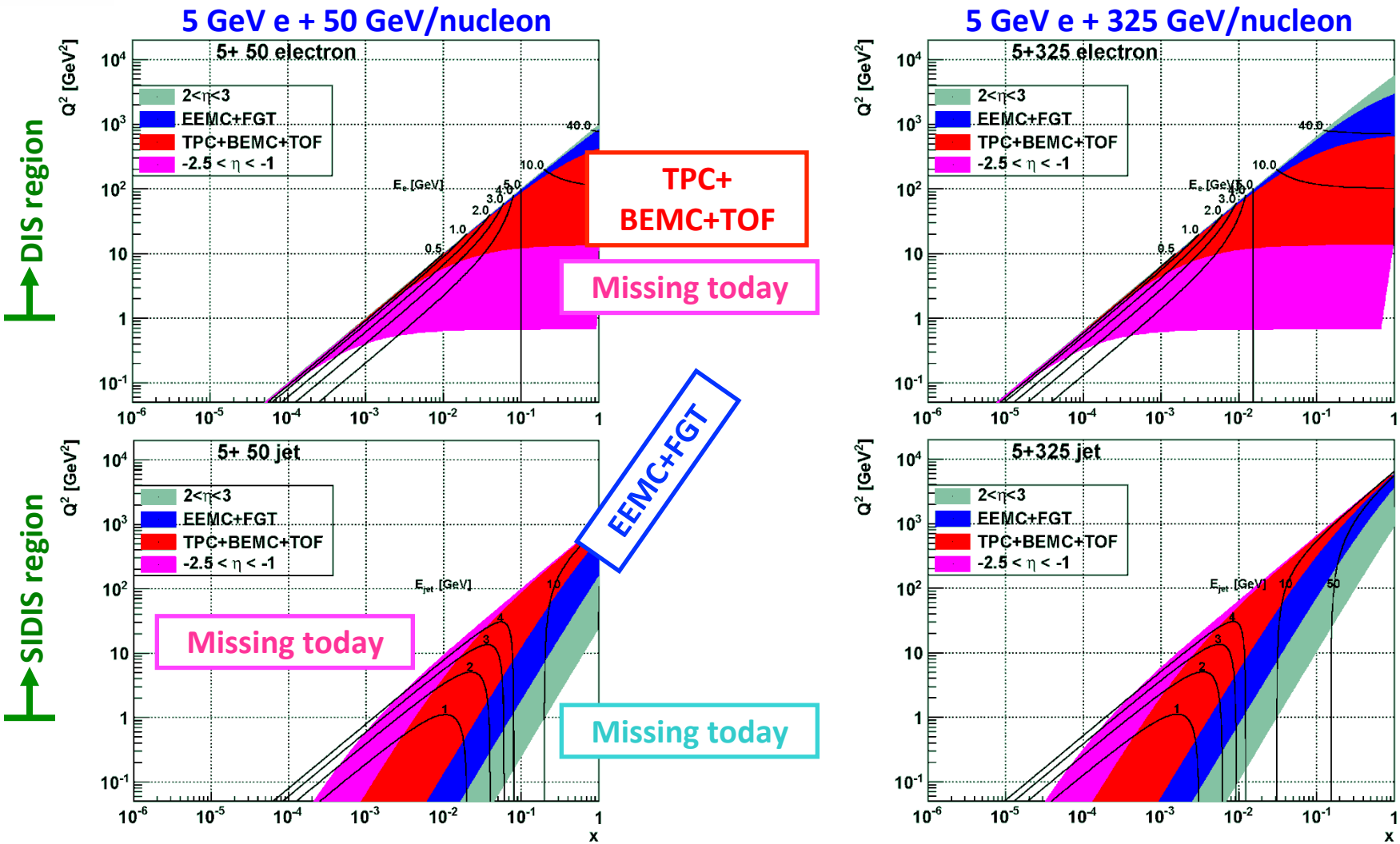


LHC-b HPD

Combines vacuum photo-cathode technology with solid state technology.
Single Photon Sensitivity (200 - 600nm), 30% QE at 200 nm.
Fast signal (rise-fall times of a few ns) and negligeable jitter (<1 ns)


p + p → π⁰, η + X at √s = 200 GeV
Phys. Rev. Lett. 97 (2006)
π⁰ STAR 2003 <η>=4.0
π⁰ STAR 2002 <η>=3.8
π⁰ STAR 2002 <η>=3.3
π⁰ STAR 2006 <η>=3.68
π⁰ NLO pQCD <η>=3.68
prompt + frag γ NLO pQCD <η>=3.7
π⁰ pythia X-section <η>=3.68
prompt γ pythia X-section <η>=3.68
E d³σ/ dp³ (μb c³/ GeV²)
η / π⁰ ratio
STAR 2006
x_F

*e*RHIC phase 1: kinematic range



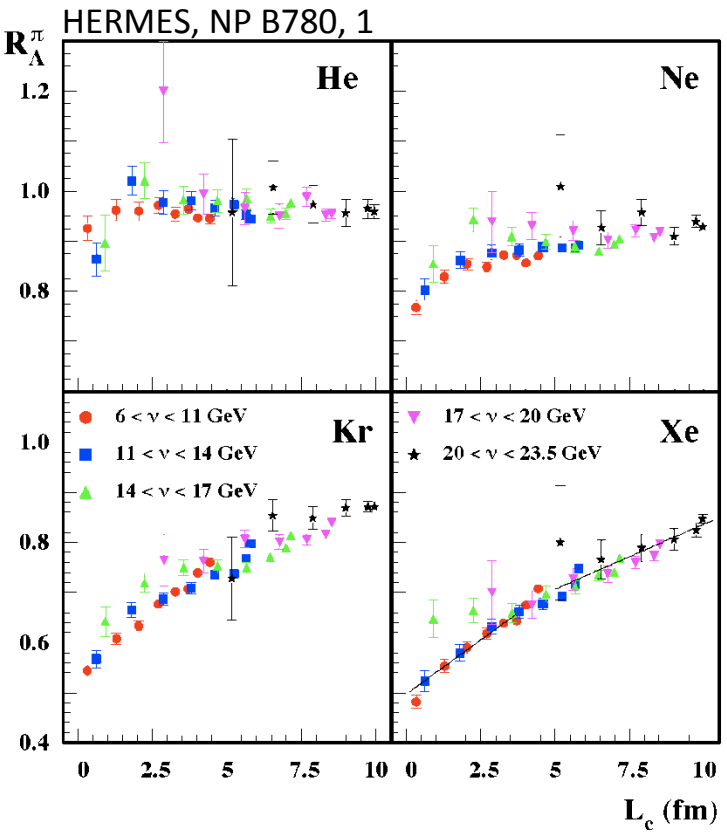
- "Forward" (-2.5 <~ η < -1) **electron acceptance essential** to span deep-inelastic (DIS) regime
- Both **backward** and **forward** **hadron coverage valuable** for semi-inclusive deep-inelastic (SIDIS) scattering

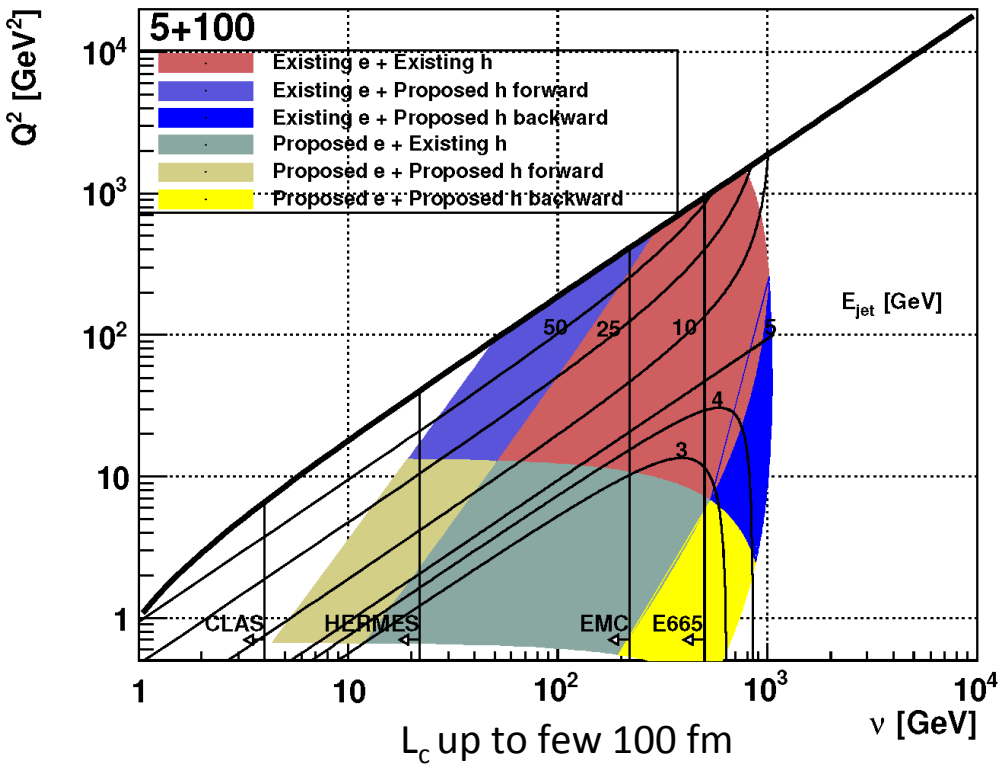
STAR → *e*STAR

Optimizing STAR for e+p and e+A collisions from 5+50 to 5+325 GeV

- Inclusive scattering over the entire deep-inelastic region
  - Key measurements
    - F_L in e+p and e+A: direct measure of gluon densities in nucleons and nuclei
    - g_1 in e+p and e+^{3}He: nucleon spin structure
    - F_2^A/F_2^d: parton distributions in nuclei (including gluons via Q^2 evolution)
  - Need electron detection, ID, and triggering over $-2.5 <\sim \eta < -1$
    - Combined mini-TPC/threshold gas Cherenkov detector
- Semi-inclusive deep-inelastic scattering over a broad (x,Q^2) domain
  - Key measurements
    - Flavor-separated helicity distributions, including strangeness
    - Collins, Sivers, Boer-Mulders, and other transverse spin distributions
    - Flavor-separated parton distributions in nuclei, including strangeness
    - Parton energy loss in cold nuclear matter
  - Need hadron detection and identification beyond the TPC/EEMC
    - Extend TOF to cover $-2 < \eta < -1$
    - GEM disks (from forward instrumentation upgrade) plus hadronic calorimetry in the region $2 < \eta < 3$
- Deeply-virtual Compton scattering
  - Key measurement
    - GPDs
  - Need forward proton and expanded photon detection
    - Roman pots (also valuable for spectator proton tagging in e+^{3}He)
    - EM calorimetry for $-4 < \eta < -1$

Parton energy loss in cold QCD matter





- Complementary tool to investigate partonic energy loss
- HERMES: hadrons can form partially inside the medium
  - Mixture of hadronic absorption and partonic energy loss
- eRHIC: light quark hadrons form well outside the medium
- Heavy quarks: unexplored to date. Low β → short formation time