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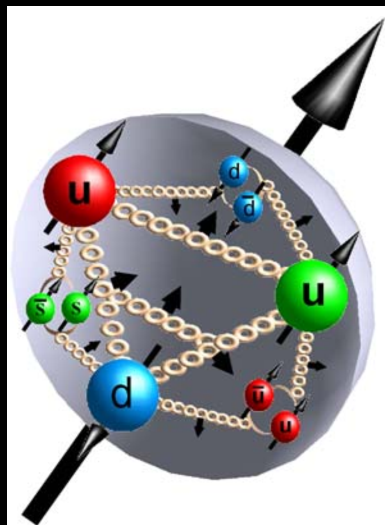
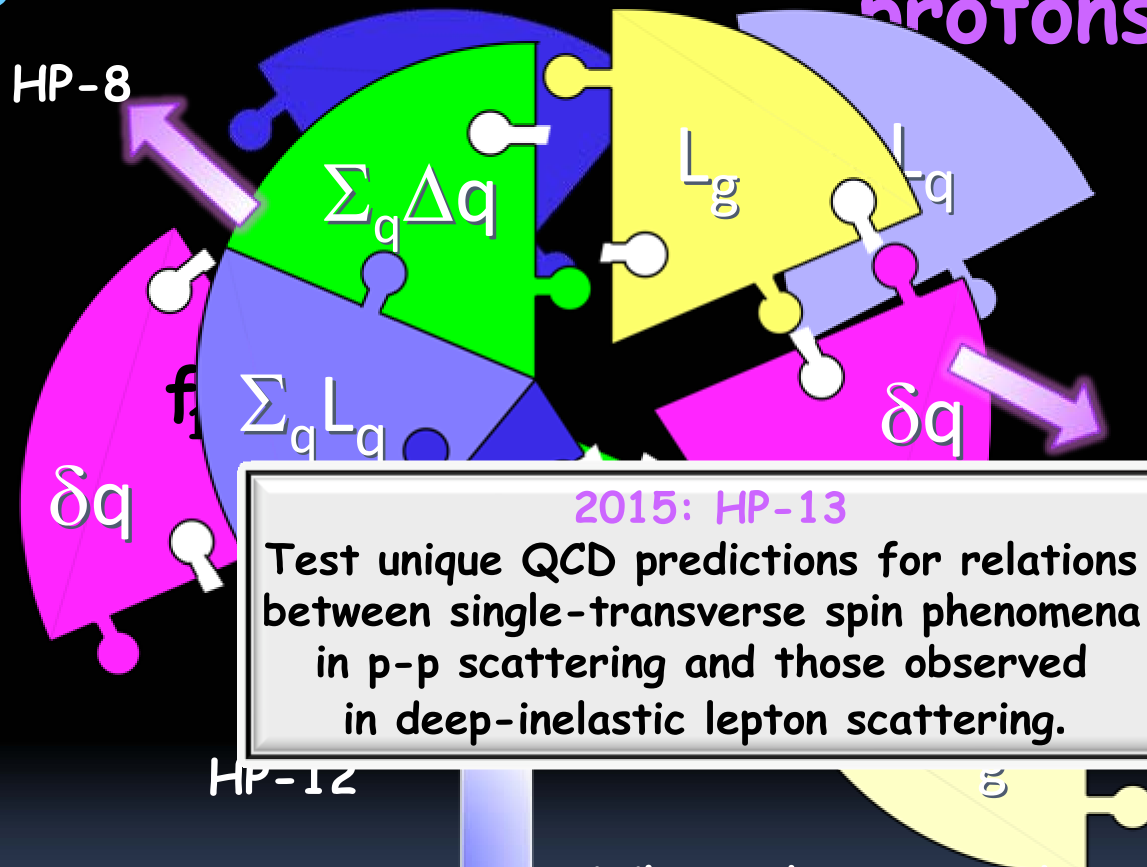
DRELL YAN IN POLARIZED PP COLLISIONS

How do the partons form the spin of protons

Is the proton looking like this?





2015: HP-13

Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering.

"Helicity sum rule"

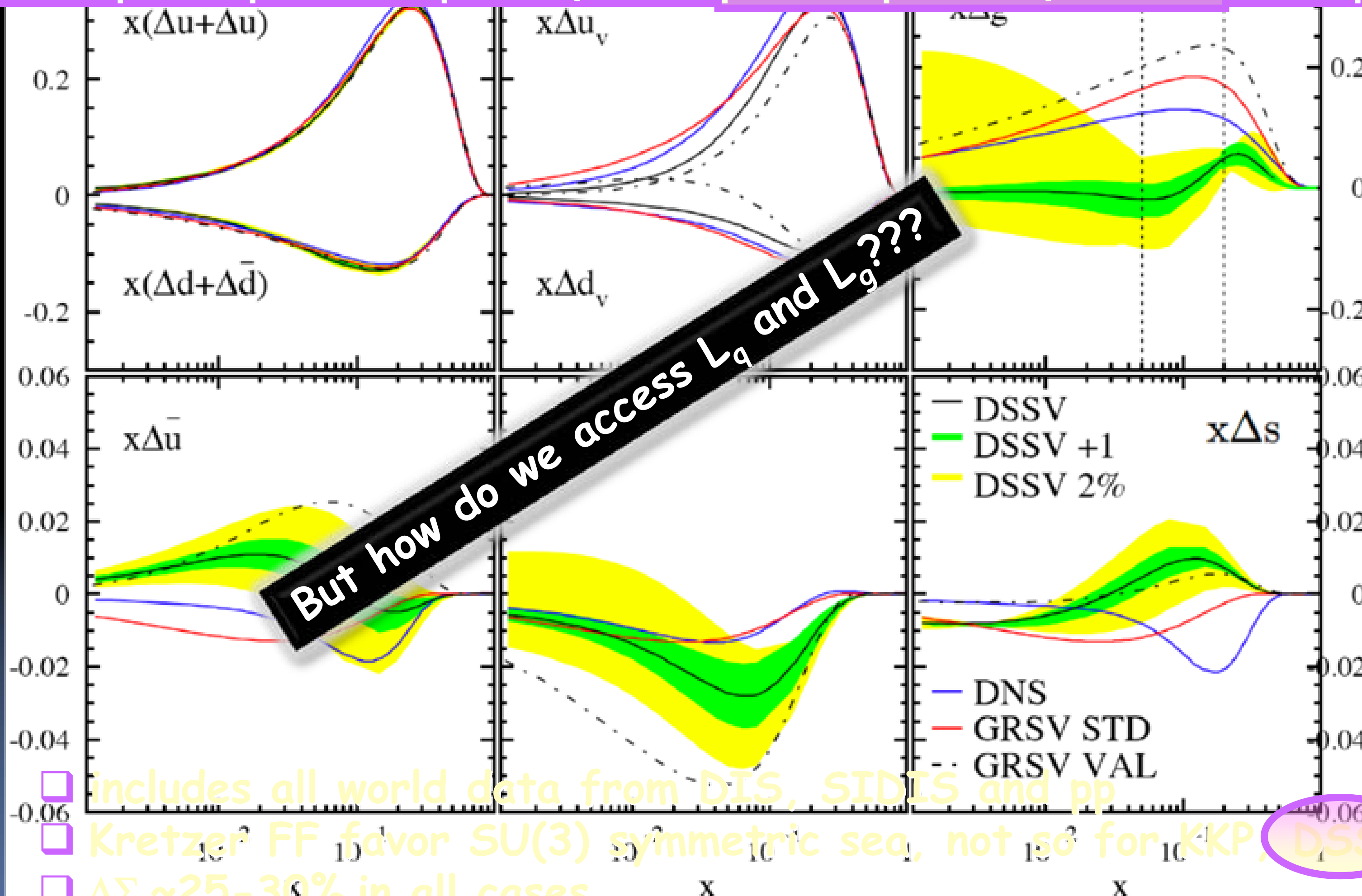
$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2} \middle| J^z_{QCD} \middle| P,\frac{1}{2} \right\rangle = \underbrace{\sum_q \frac{1}{2} S^z_q}_{\text{total u+d+s quark spin}} + \overbrace{S^z_g}^{\text{gluon spin}} + \underbrace{\sum_q L^z_q + L^z_g}_{\text{angular momentum}}$$

Where do we stand solving the "spin puzzle" ?

What do we know: NLO Fit to World Data

D. De Florian et al. arXiv:0804.0422

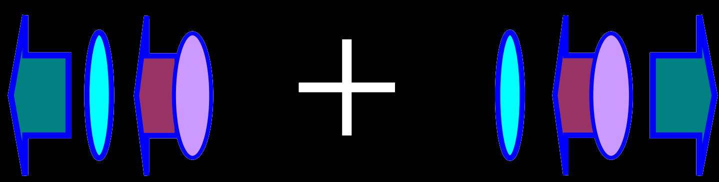
	χ^2_{DIS}	χ^2_{SIDIS}	Δu_v	Δd_v	$\Delta\bar{u}$	$\Delta\bar{d}$	Δs	Δg	$\Delta\Sigma$
DSSV			0.813	–0.458	0.036	–0.115	–0.057	–0.084	0.242



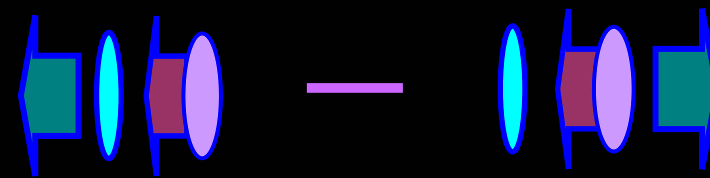
- Includes all world data from DIS, SIDIS and pp
- Kretzer FF favor SU(3) symmetric sea, not so for KKP, DSS
- $\Delta\Sigma$ ~25-30% in all cases

More insights to the proton - TMDs

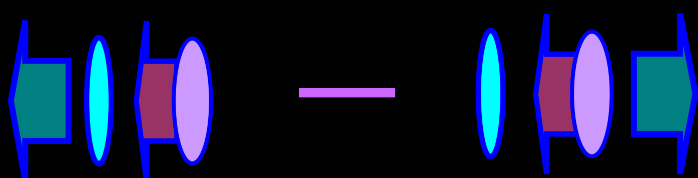
beyond collinear picture
Explore spin orbit correlations



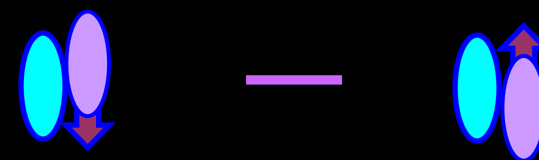
Unpolarized distribution function q(x), G(x)



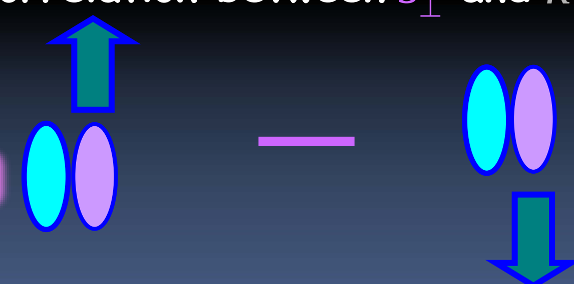
Transversity distribution function δq(x)
Correlation between $\vec{s}_{\perp}^{\,q}$ and $\vec{S}_{\perp}^{\,N}$



Helicity distribution function Δq(x), ΔG(x)



Boer-Mulders distribution function $h_1^{\perp}$
Correlation between $\vec{s}_{\perp}^{\,q}$ and $k_{\perp}^{q}$



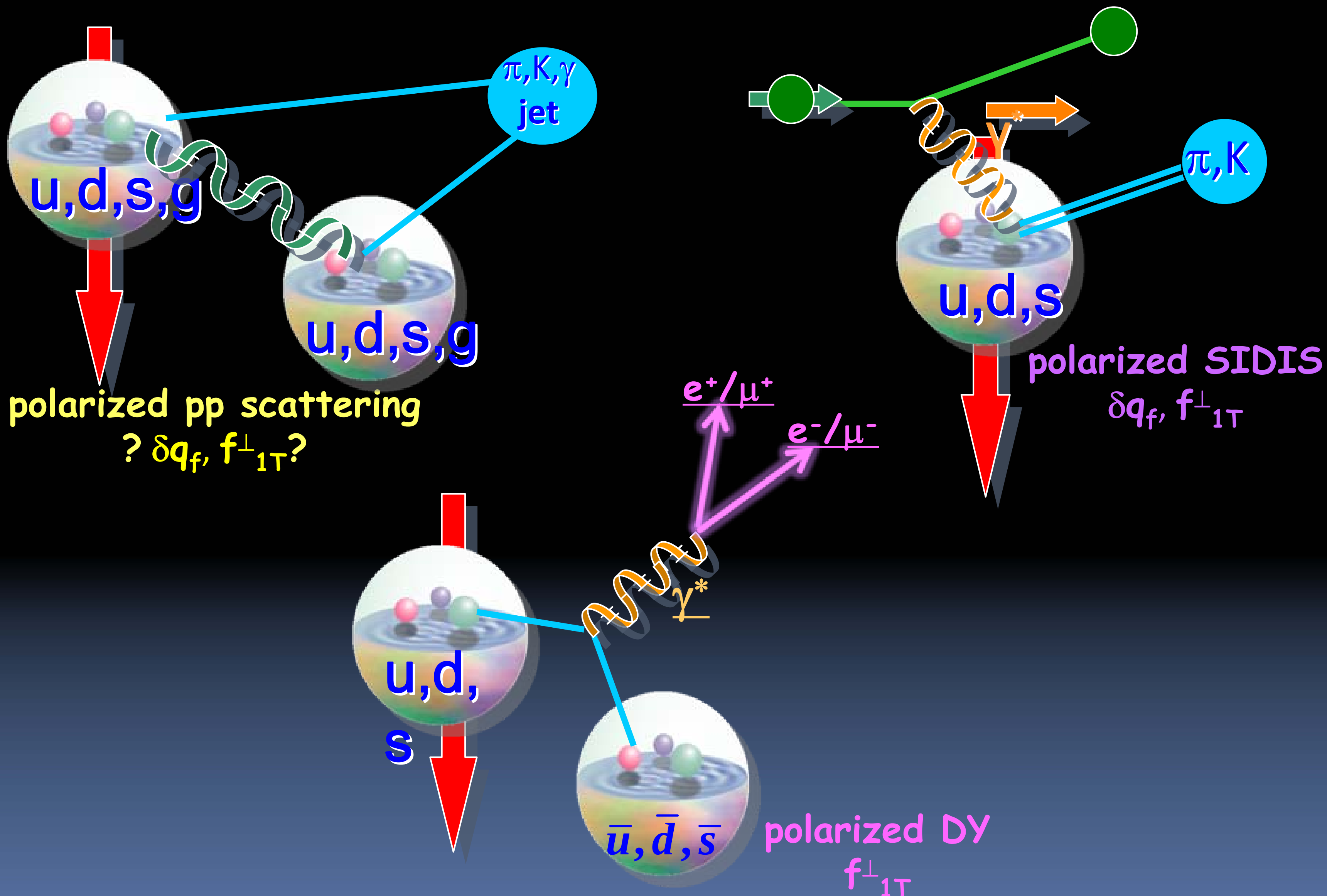
Sivers distribution function $f_{1T}^{\perp}$
Correlation between $\vec{S}_{\perp}^{\,N}$ and $k_{\perp}^{q}$

Single Spin Asymmetries

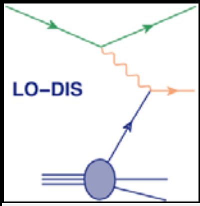
peculiarities of $f^{\perp}_{1T}$

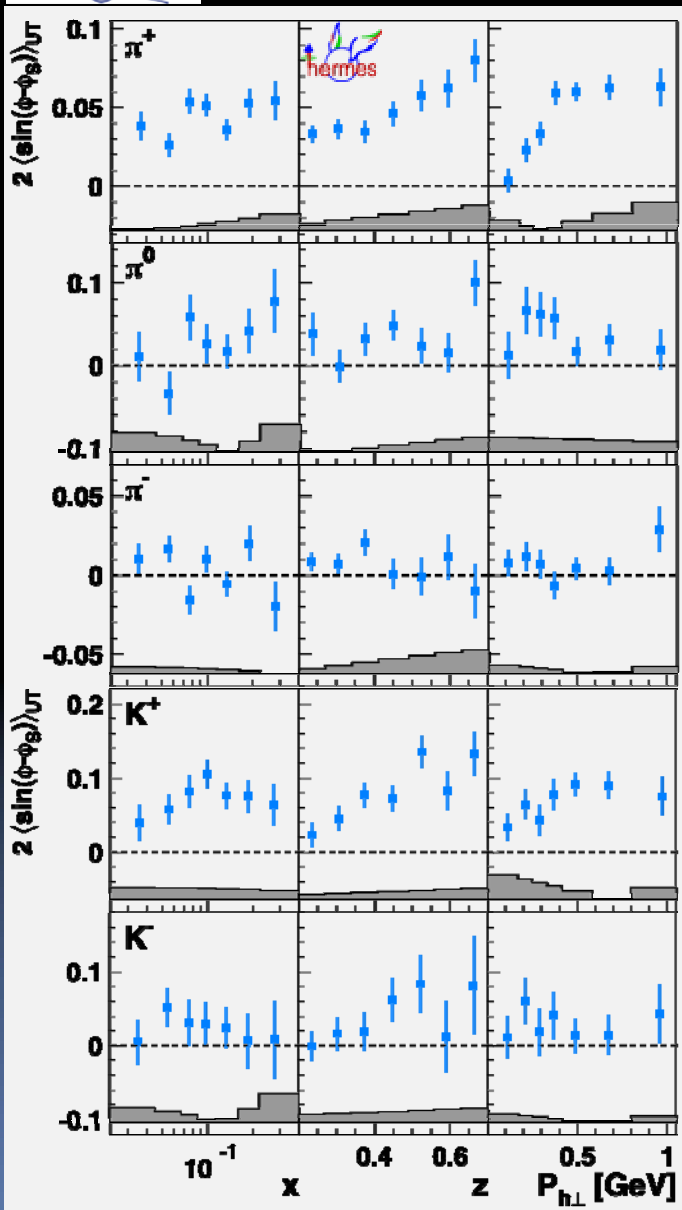
chiral even naïve T-odd DF
related to parton orbital angular momentum
violates naïve universality of PDFs
QCD-prediction: $f^{\perp}_{1T,DY} = -f^{\perp}_{1T,DIS}$

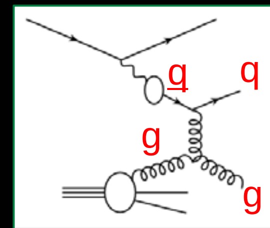
Processes to study Single Spin Asymmetries



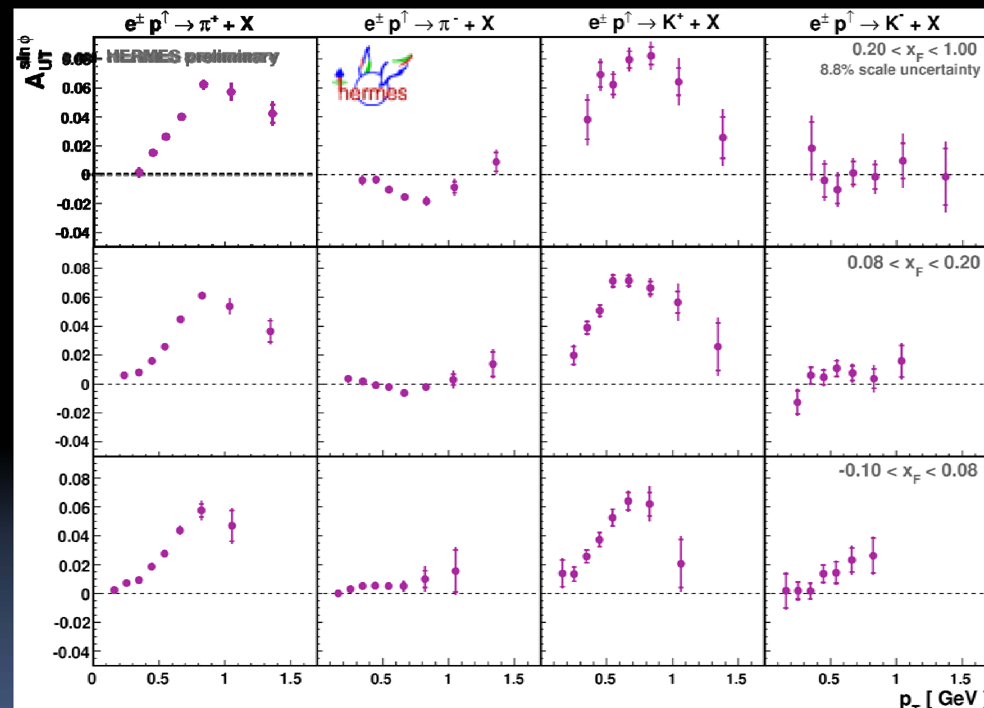
Sivers fct., what do we know?





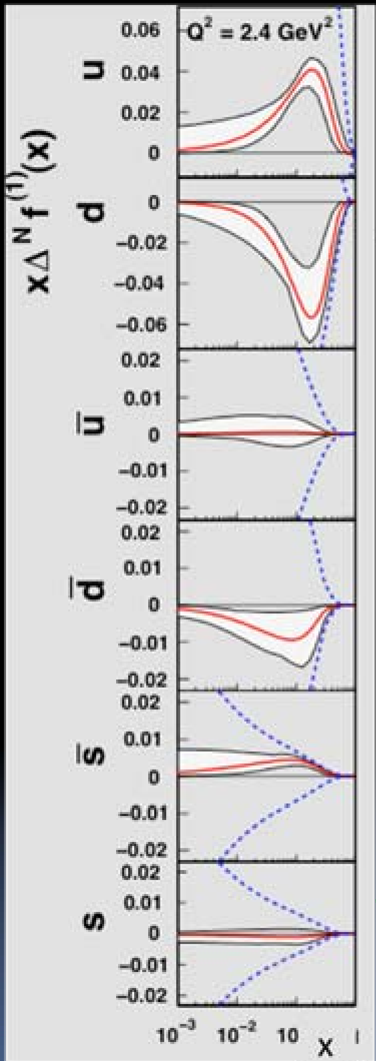


Quasireal Photoproduction
similar to pp



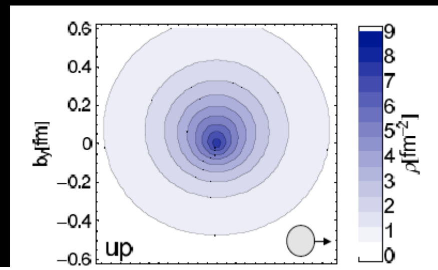
results follow DIS-Sivers
→ asymmetries fall at high p_t
→ as predicted for pp

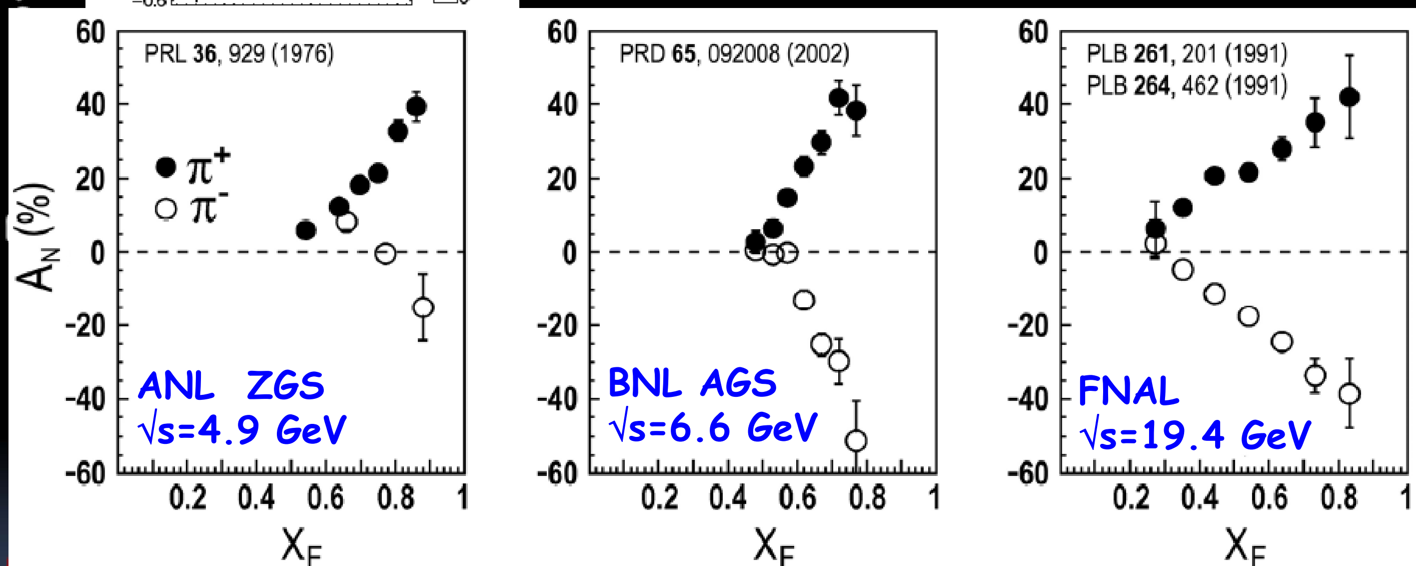
What else do we know



Anselmino et al. arXiv:0809.2677

Sivers f





hermes

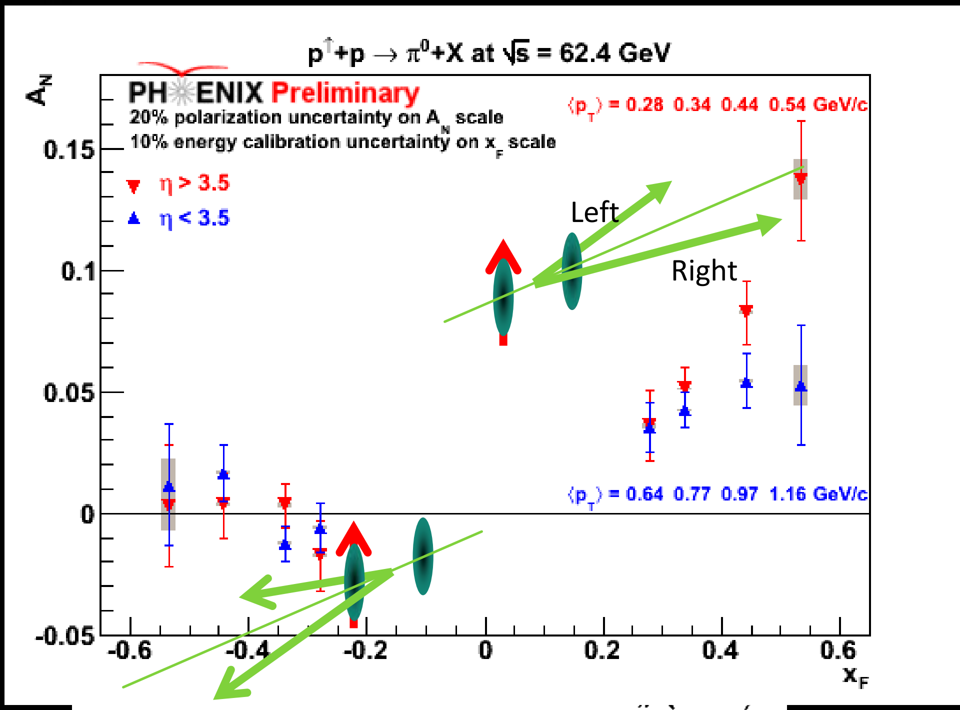
COMPASS

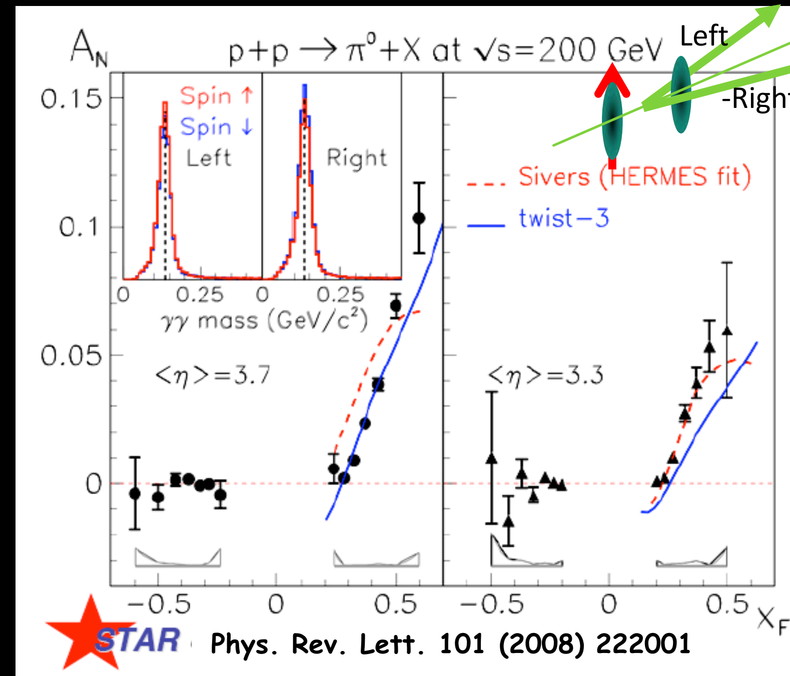
Big single spin asymmetries in p⇑p !!

Naive pQCD (in a collinear picture) predicts $A_N \sim \alpha_s m_q/\mathrm{sqrt}(s) \sim 0$

What is the underlying process?
Do they survive at high $\sqrt{s}$?

Transverse Polarization Effects @ RHIC



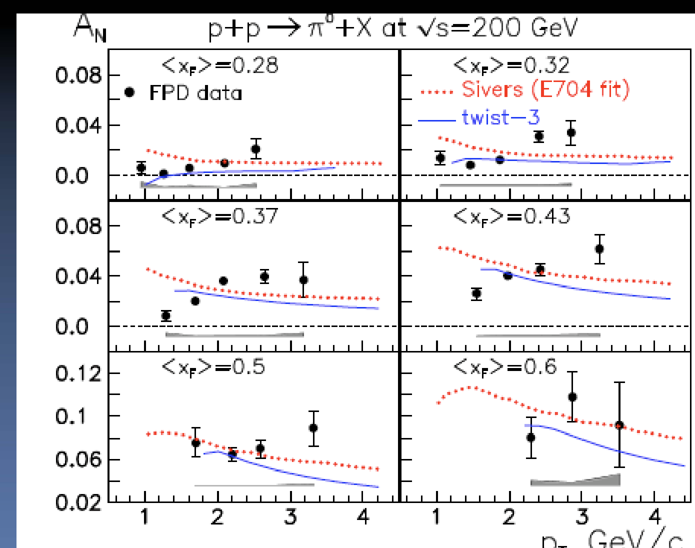


Large A_N observed in forward hadron production from $\sqrt{s}$=5 GeV to $\sqrt{s}$=200 GeV

Proposed mechanisms
- Sivers
- Collins
- twist-3 effect (collinear)
- ...

need other observables to disentangle underlying processes

? Universality ?



The way to HP13

First ideas by theorists to separate underlying processes:

~~A_N for γ-jet → sivers~~

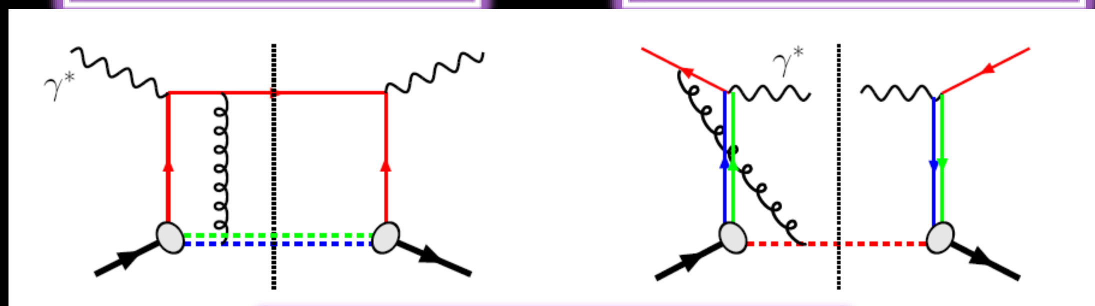
~~A_N for π^0-jet~~ → Collins

→ Universality breaking
Roger, Mulders hep-ph:1001.2977

QCD:

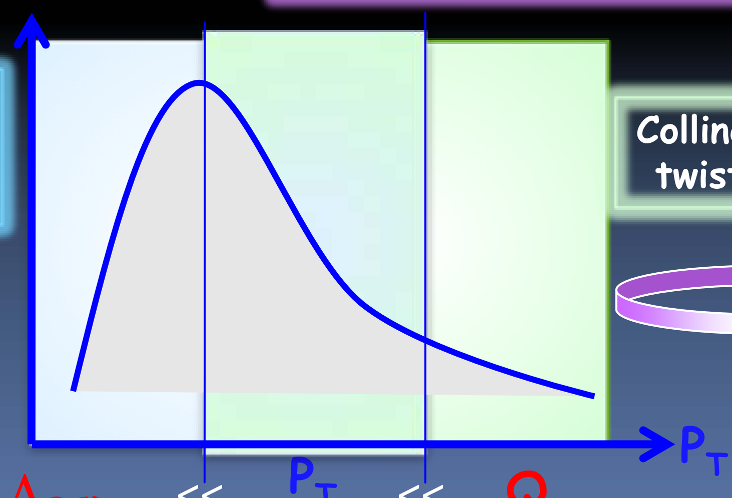
DIS: attractive FSI

Drell-Yan: repulsive ISI



$\text{Sivers}_{DIS} = - \text{Sivers}_{DY}$

Transverse momentum dependent

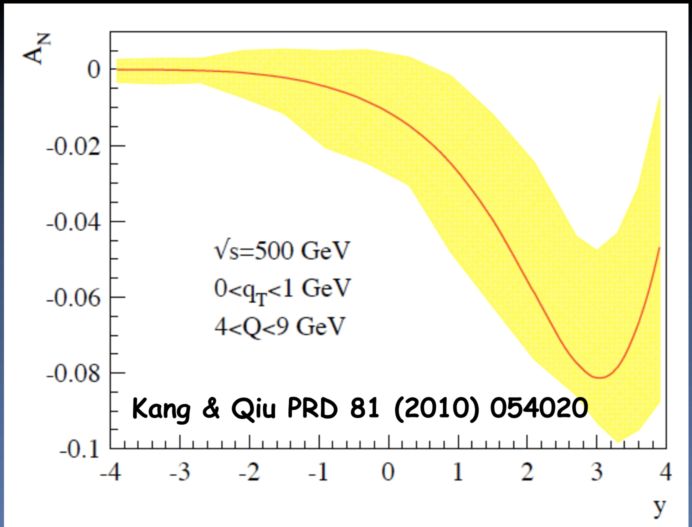


Collinear/ twist-3

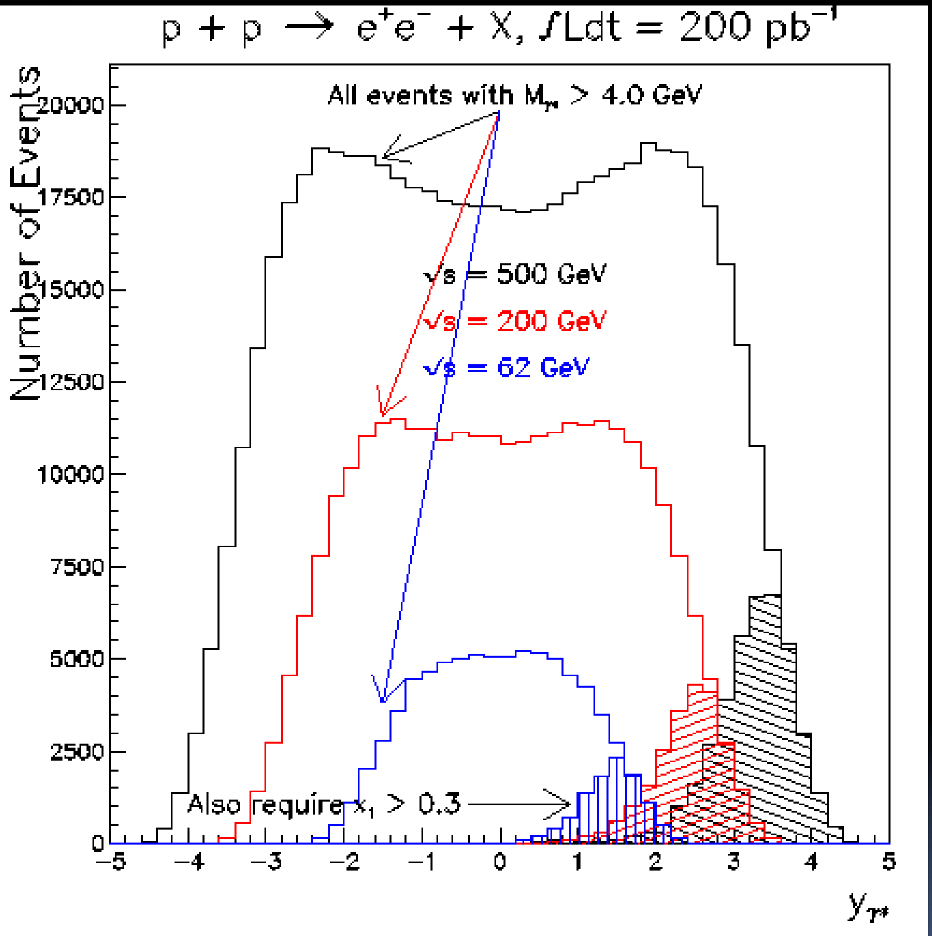
Both models expect sign change

DY Feasibility @ IP-2

- Idea: have DY feasibility test at IP-2
  - staged measurements over 3 years
  - re-use as much detector equipment as possible
    - ✓ keep cost low
  - PheniX and Star need upgrades to measure DY $|\eta|>2$
    - → next decadal plans
- Measurement:
  - why IP-2
    - ✓ always transverse polarization
    - ✓ measure parallel to $\sqrt{s}$ = 500 GeV W-program
      - → more physics output for RHIC
      - → time scale to accomplish HP13 in time and beat COMPASS and lessons learned benefit STAR and PheniX upgrades
  - Kinematic requirements
    - ✓ η > 3, M>4 GeV, $\sqrt{s}$ = 500 GeV
      - → optimizes Signal A_N
      - → optimizes Signal / Background
      - → optimizes DY rate
      - → same kinematic as measured A_N



Collision Energy Dependence of Drell Yan Production



Comments…

- $\bar{q}q \rightarrow \gamma^*$ has $\hat{\sigma} \sim 1/\hat{s}$
- partonic luminosities increase with √s
- net result is that DY grows with √s
- largest √s probes lowest x

⇒ Consider large-x_F DY at √s=500 GeV

$$x \sim \frac{2p_T}{\sqrt{s}} e^{-y}$$

$$x_f = x_1 - x_2$$

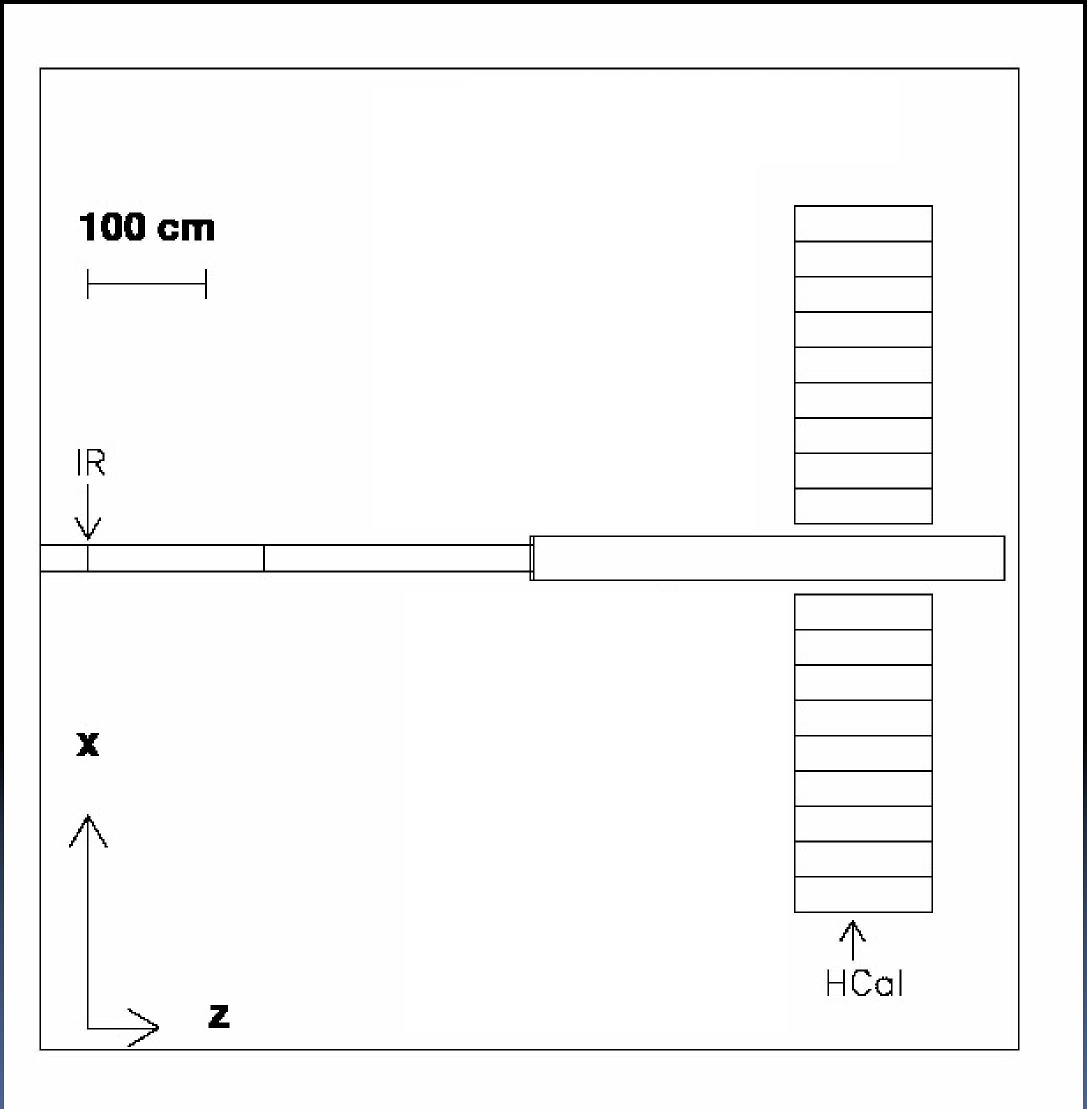
$$M^2 = x_1 x_2 s$$

$$x_2 \sim M^2 / (x_F s)$$

Transverse Spin Drell-Yan Physics at RHIC (2007)

http://spin.riken.bnl.gov/rsc/write-up/dy_final.pdf

Schematic of detector considered @ Run 11



Equipment in place:

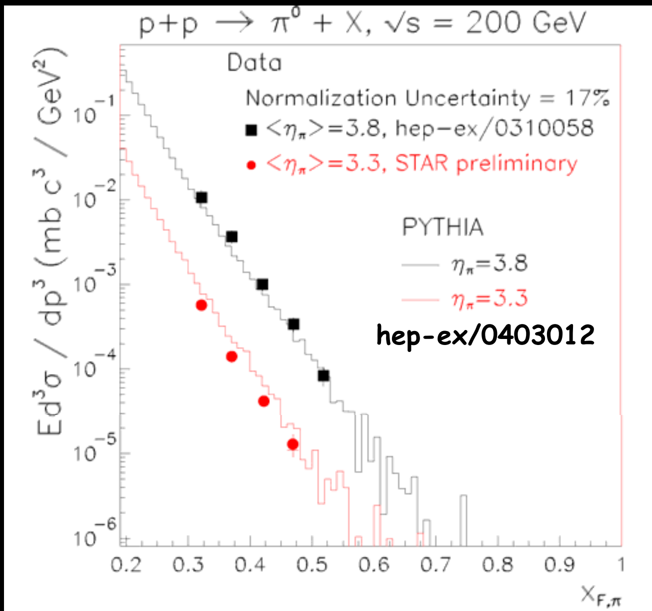
- Hcal is existing 2x9x12 modules from E864 (NIM406,227)
- BBC and ZDC

Goal:

- establish impact of 3 IR operation on PheniX and Star luminosity
- calibrate HCAL
  - absolute Energy scale with ρ, Φ, K_s
  - gains with cosmics
- measure the hadronic background to bench mark MCs further

What do we know about the Backgrounds

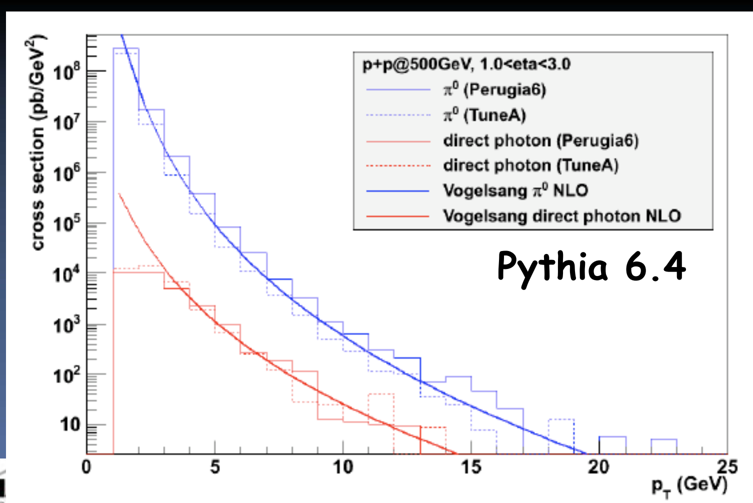
→ Can we trust PYTHIA at forward rapidities

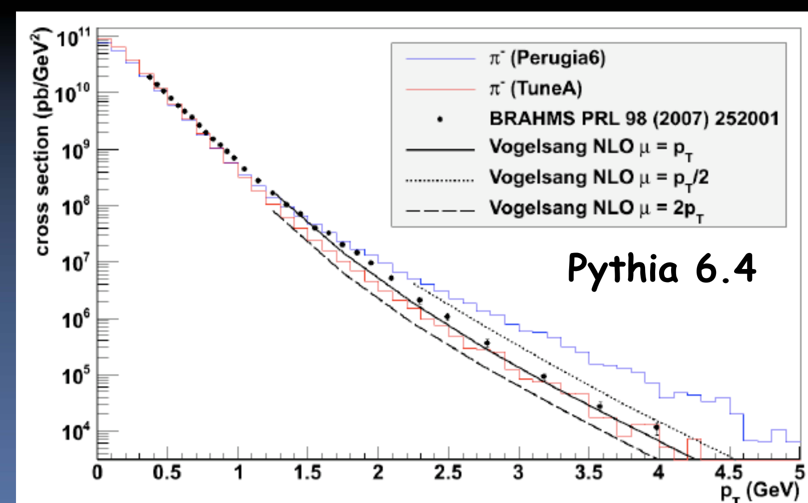


- PYTHIA 5.7 compared well to √s=200 GeV data [PRL 97 (2006) 152302]
- Little change until "underlying event" tunings for LHC created forward havoc
- PYTHIA 6.4 needs a bit more tuning

⇒ but reproduces NLO-pQCD calculations and data

⇒ used PYTHIA 6.222 for simulations

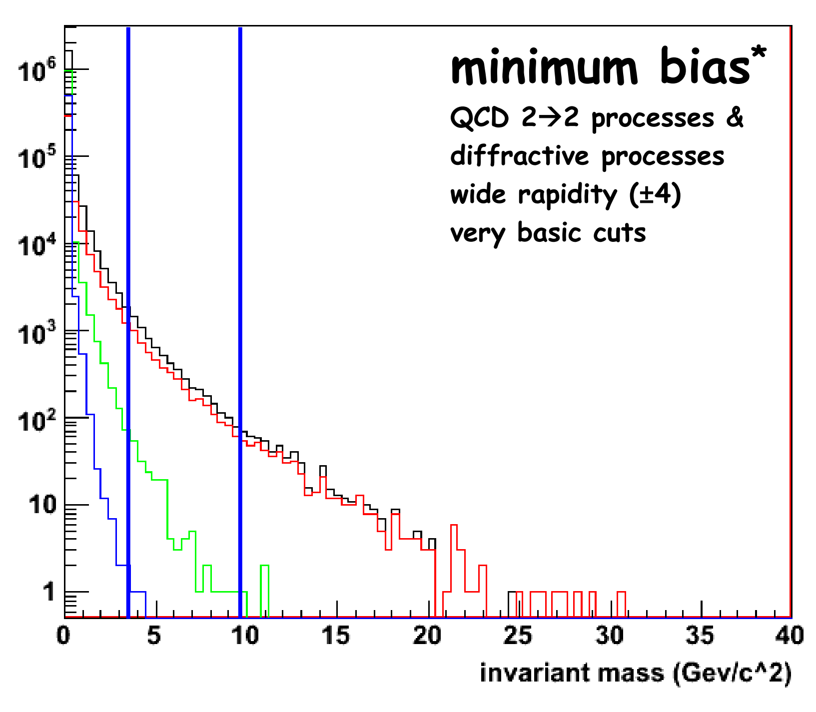


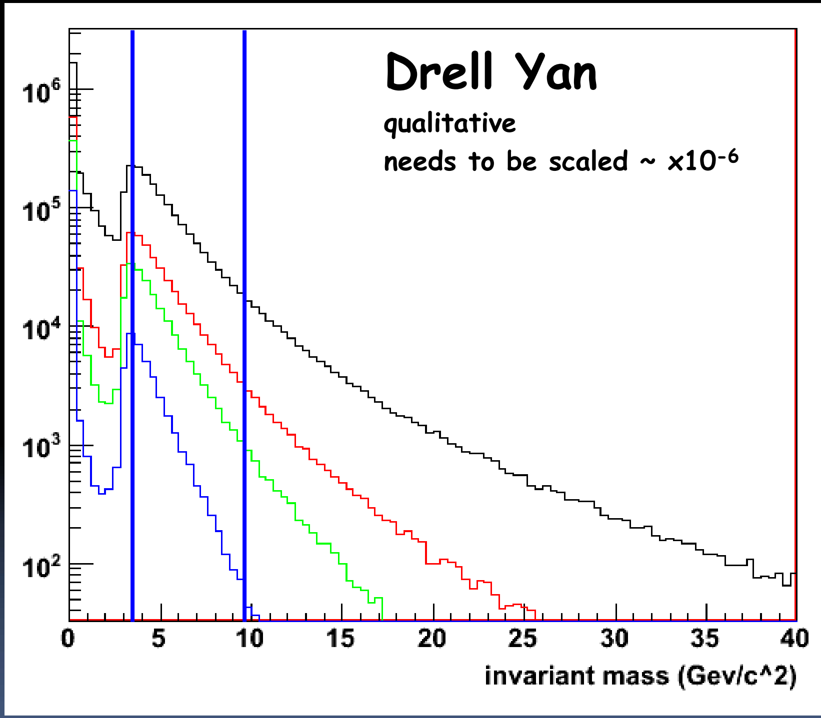


DY Simulation @ 500 GeV

Electron pairs in different rapidity ranges

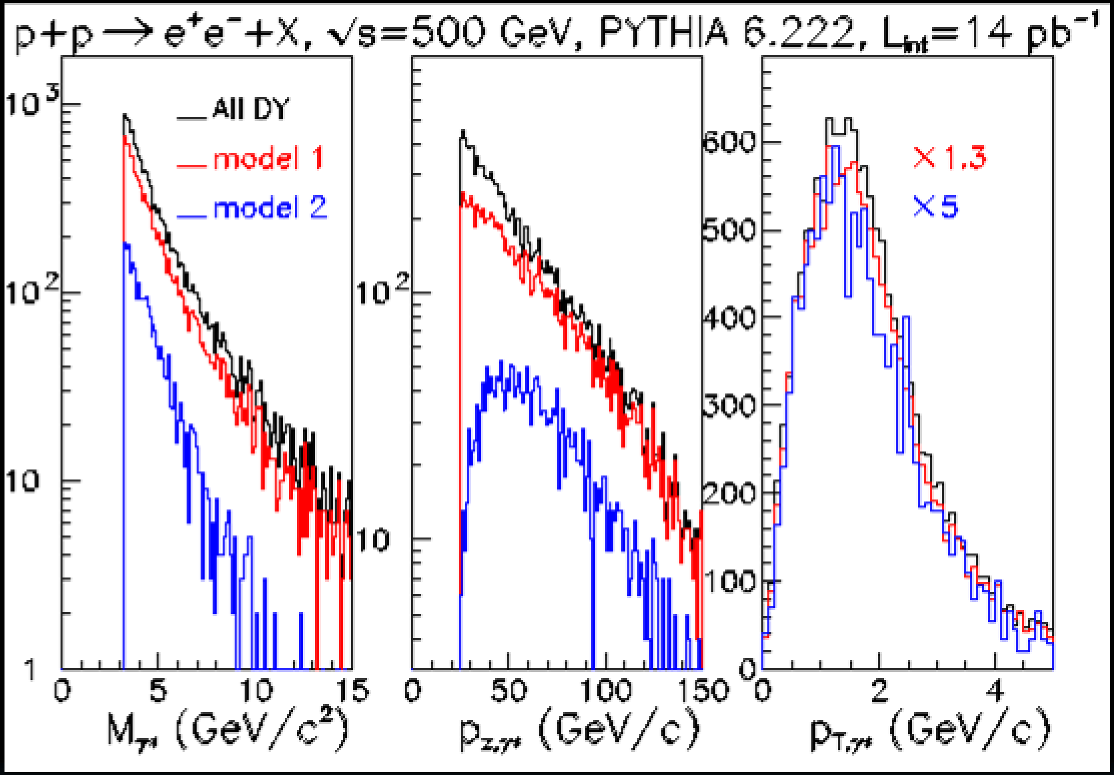
all, central (|y|<1), forward (|y|>2), very forward (|y|>3)





Background decreases faster than signal at forward η

e^+e^- DY expectations at large x_F @ $\sqrt{s}$=500 GeV



Model 1 = EMcal $(2m)^2$ / $(0.2m)^2$ beam hole at 10m / no magnetic field
Model 2 = L/R modular EMcal (0.9mx1.2m) at 5m / no magnetic field
Setup planned for Run 12/13

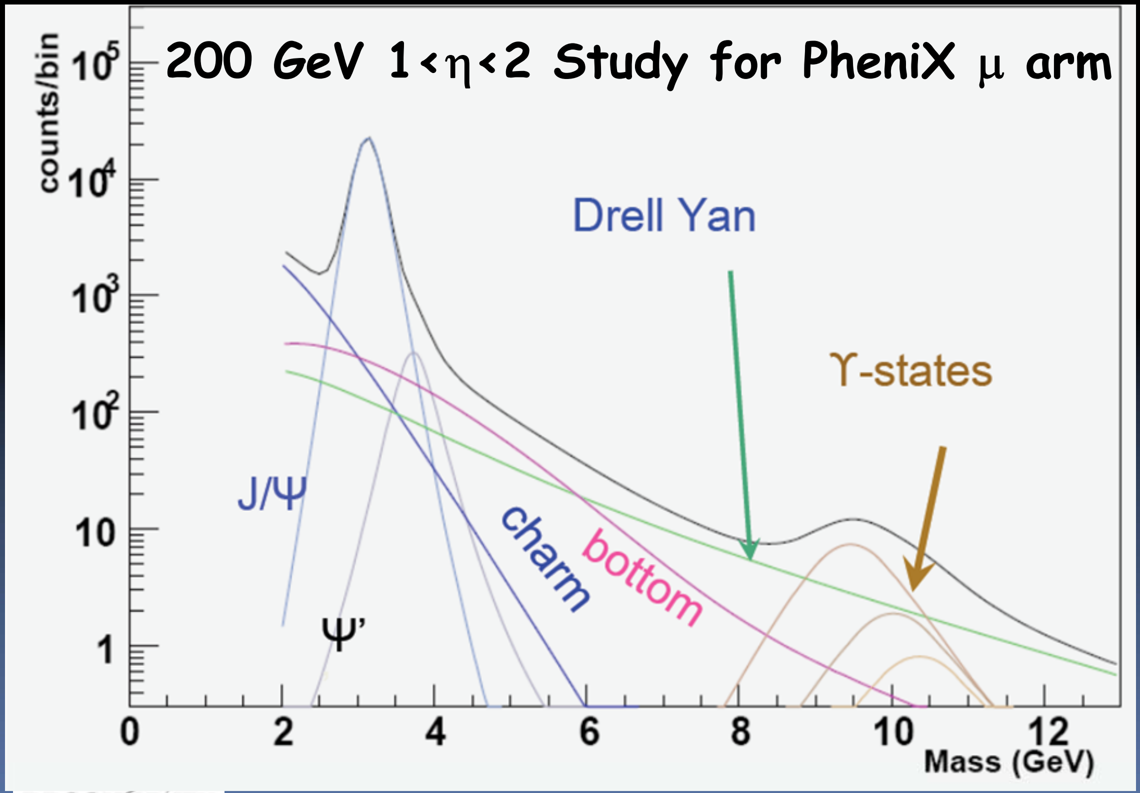
Remarks:

- reasonable efficiency can be obtained for large-x_F DY with existing equipment
- final estimates of DY yield must follow estimates of background rejection
- critical question for decadal planning: is charge sign discrimination required?

What are the biggest background contributions

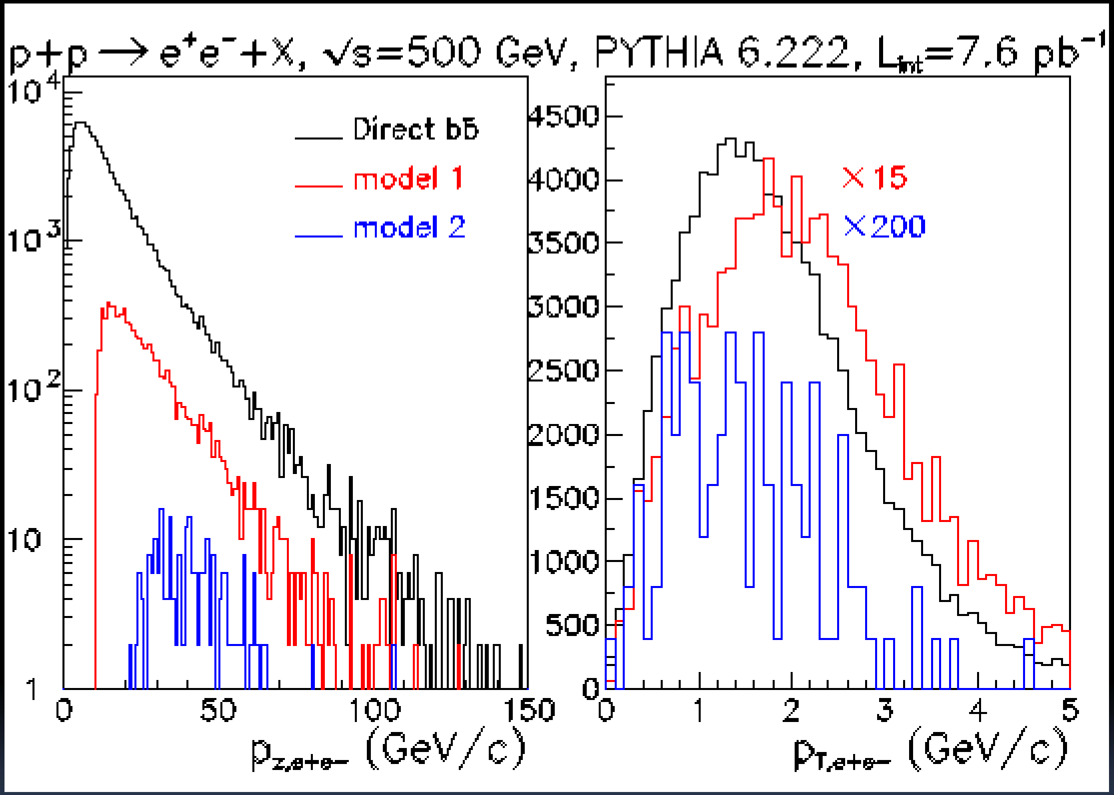
Background to e+e- DY pairs:

- hadronic background from QCD 2→2
  - →$h^{\pm}/e^{\pm}$ discrimination – requires estimates of p+p collisions and EMcal response
  - → charged/neutral discrimination
- photon conversion in beam-pipe and other material
- Open Beauty
- Open Charm



Charm even further reduced going to η > 3

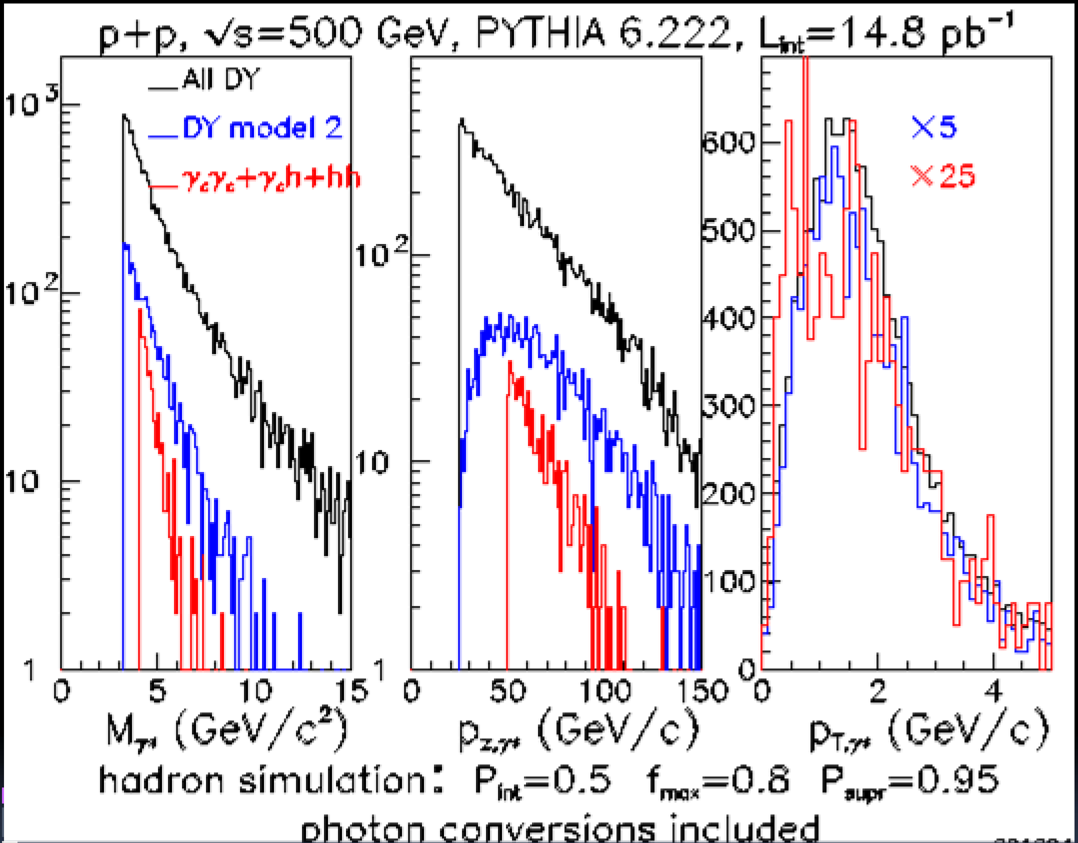
Dileptons from open beauty at large x_F



Remarks:

- direct production of open beauty results in ~15% background at large x_F
- large forward acceptance $1 < \eta < 4$ for the future would require discrimination (isolation)

Background: Di-hadrons and γ



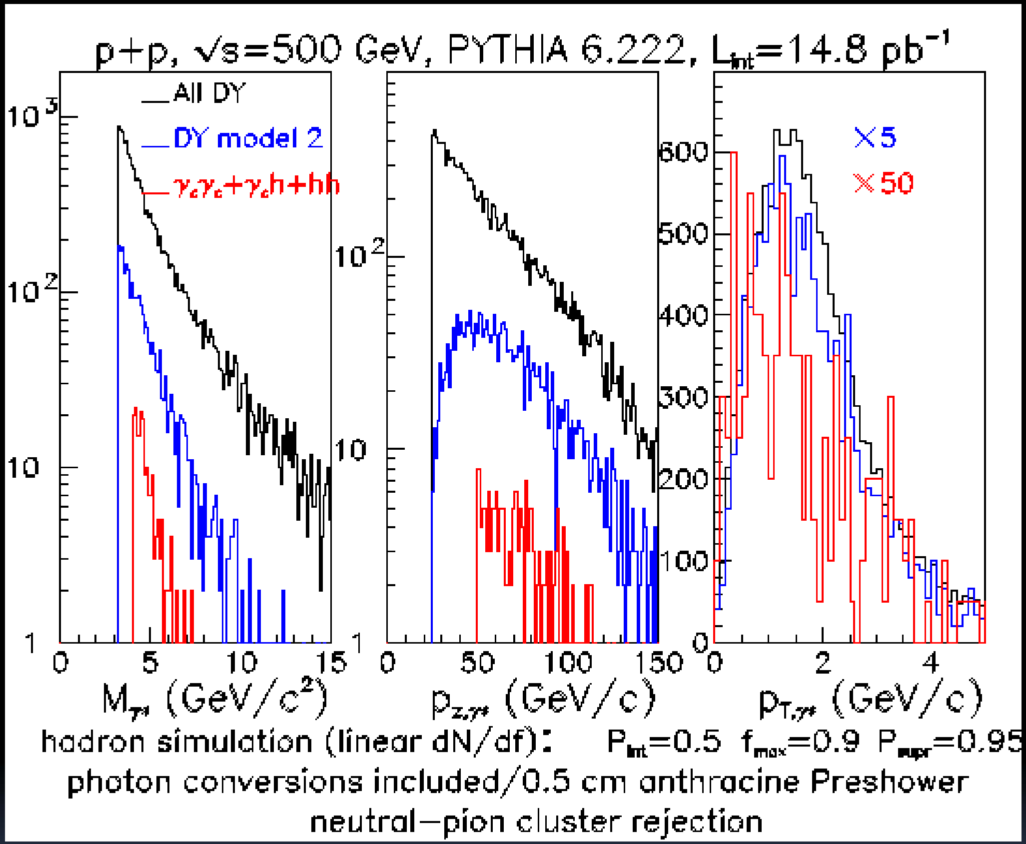
Remarks:

- No cluster simulation and charge sign determination included
- $h^\pm h^\pm$ suppression probability consistent with full GEANT treatment for E=10 GeV π
- dN/df modeled by uniform distribution to f_{max} needs some more sophistication

Remarks:

- ISR low-mass e+e- DY reports limiting background as conversion photons (PLB91,475)
  - → $N(\gamma_c-\gamma_c)=0.25\times N_{back}$ $N(\gamma_c-h^\pm) = 0.47\times N_{back}$ $N(h^\pm-h^\pm) = 0.28\times N_{back}$
- Require $\pi^0\to\gamma\gamma$ suppression

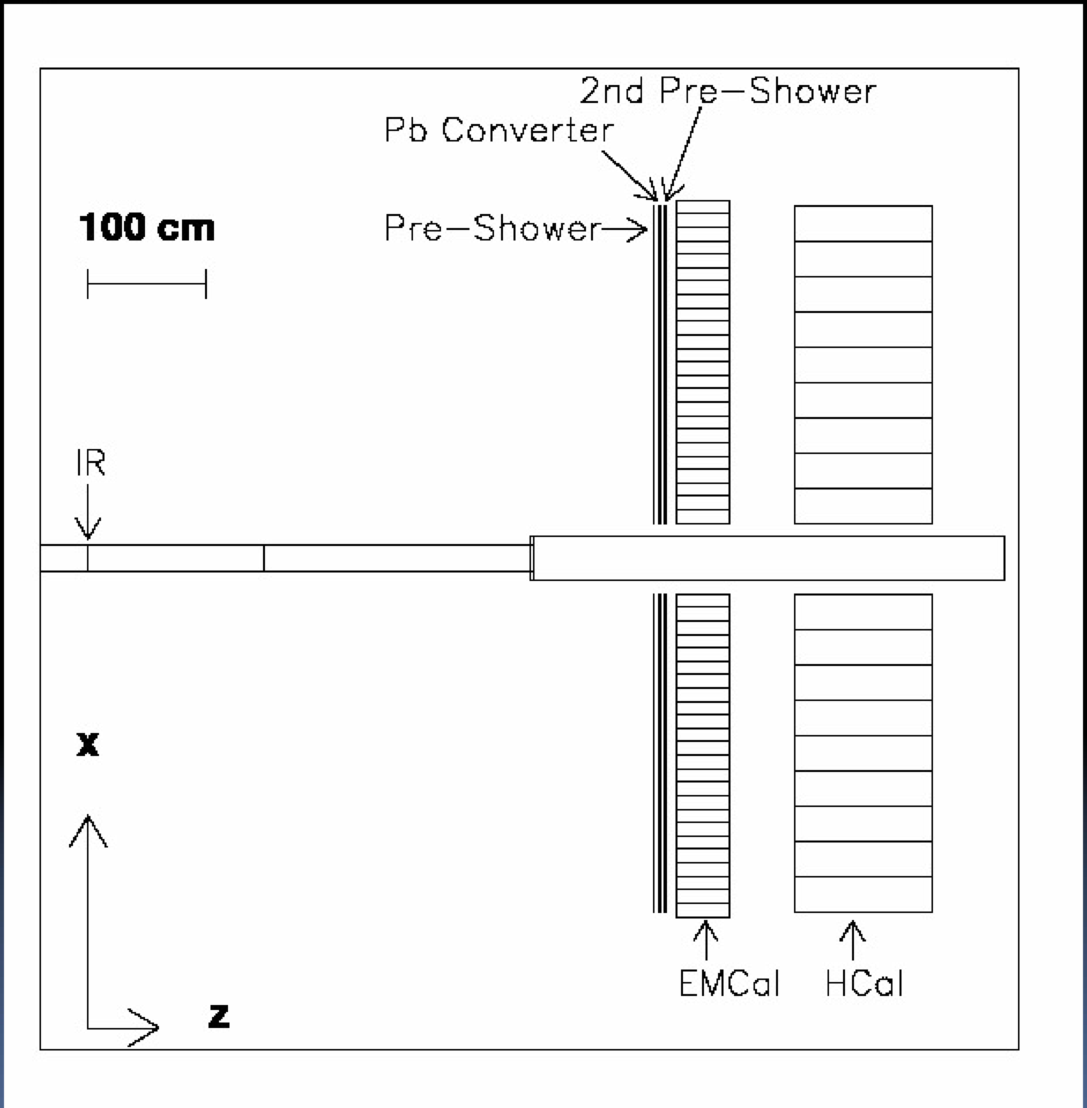
Background: Di-hadrons and γ



- Remarks:

  - Conversion photons significantly reduced by $\pi^0 \rightarrow \gamma\gamma$ veto
  - Preshower thickness tuned, although perhaps is not to critical given photon veto
  - Linearly decreasing dN/df estimates smaller hadronic background
    - $\Rightarrow$ increased sophistication needed for reliable estimates, although hadron interaction model uncertainties in MC could easily dominate
    - $\Rightarrow$ measure hadron background @ Run-11

Schematic of detector considered @ Run 12



http://www.star.bnl.gov/~akio/ip2/topview2.jpeg

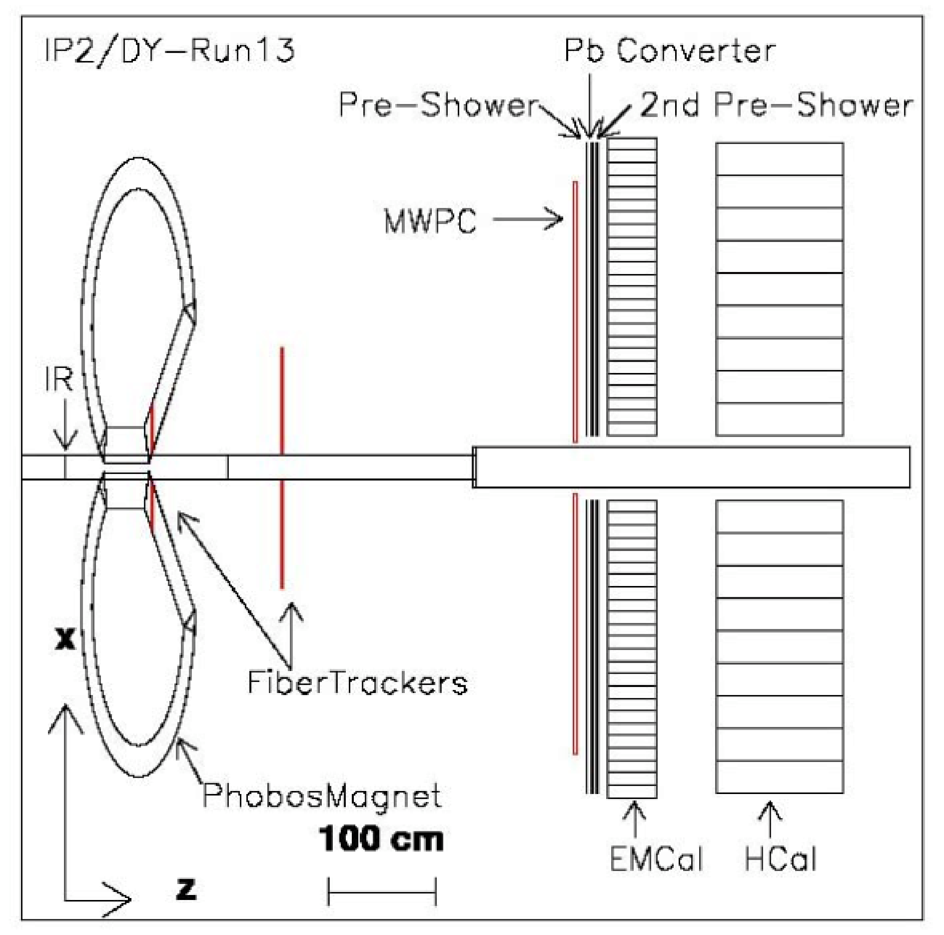
Additional Equipment to Run 11:

- EMcal is modeled as only $(3.8cm)^2 x (45cm)$ lead glass
- Preshower (1cm Pb sandwiched by 0.5cm Scintilator) requires construction
- PHOBOS split-dipole expected to be in place, but not used

Goal:

- establish DY A_N can be measured without charge identification
- 9400 DY-events
  → $|A_N| \sim 0.13$ $\delta A_N \sim 0.02$ with $M_{\gamma*} > 4$ GeV, $p_{z,\gamma*} > 25$GeV, $p_{t,\gamma*} < 2$GeV @ 150pb^{-1}

Schematic of detector considered @ Run 13



Additional Equipment to Run 11/12:

- PHOBOS split-dipole magnetic field in GEANT model used for charge sign determination
- Fiber tracker and MWPC stations require specifications and construction

Goal:

- establish what charge identification adds to DY measurements

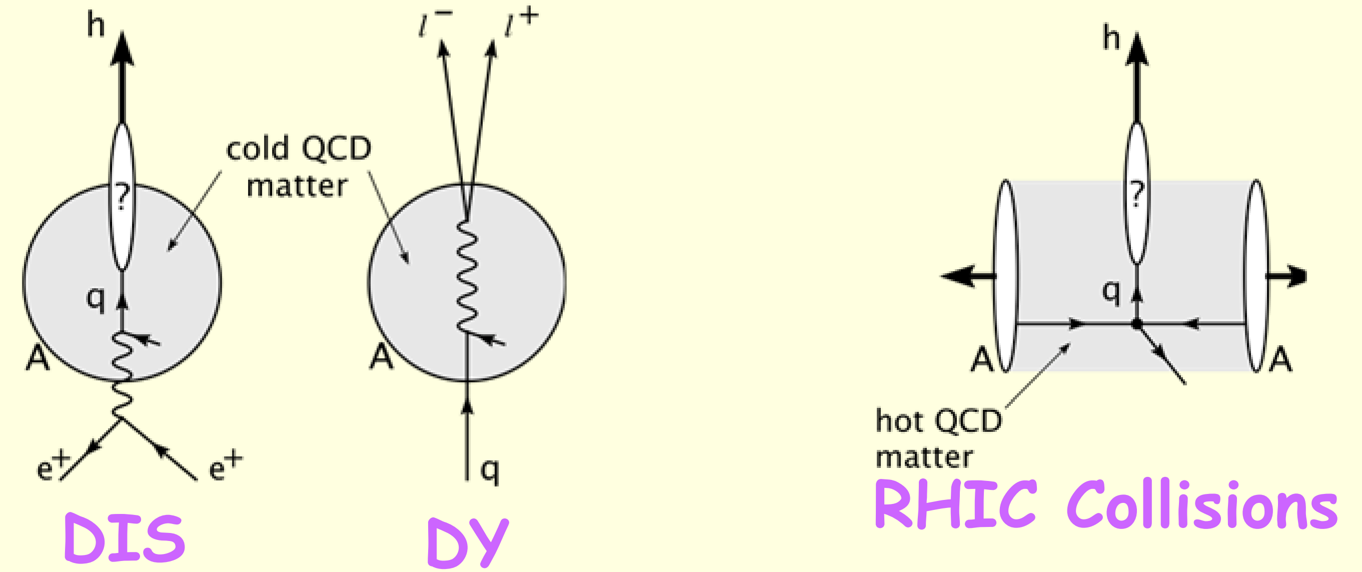
http://www.star.bnl.gov/~akio/ip2/topview3.jpeg

Summary

- DY feasibility test @ IP-2 will provide
  - test of fundamental QCD prediction: $Sivers_{SIDIS} = - Sivers_{DY}$
    - resolve HP-13
    - impact on transverse physics program of EIC
  - timely and cost effective measurement
  - will benchmark requirements for DY upgrades for PHENIX and STAR
    - i.e., charge sign measurement needed or not
  - DY @ RHIC will allow further important measurements; complementary to ep, dA
    - nPDFs
    - parton propagation in nuclear medium
    - more speculative: q-Saturation → EIC → Universality
- Big unknown what is the luminosity impact of 3-IR operation
  - lets measure it in Run-11

What else can DY @ RHIC teach us

Parton Propagation in Nuclear Medium:



eAu:
hadron formation
in-/outside nucl. medium
gluon radiation
→ p_t broadening
due to both effects
→ EIC:
wide ν coverage

dAu / pAu:
no hadron formation
→ p_t broadening
only due to gluon radiation
e+e- DY better resolution
than μ+μ-

What else can DY @ RHIC teach us

Outlook

Saturation:

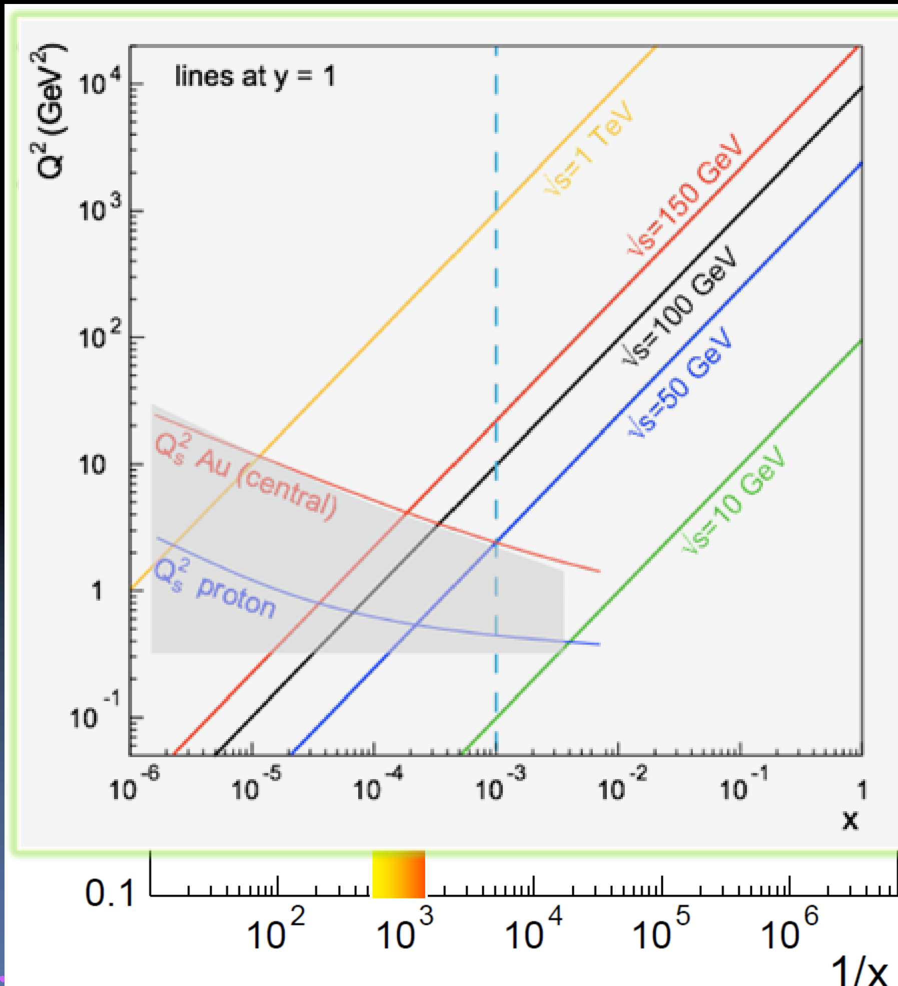
- dAu: Strong hints from RHIC at $x \sim 10^{-3}$
- ep: No (?) hints at Hera up to $x=6.32\cdot10^{-5}$, Q^2 = 1-5 GeV^2

Nuclear Enhancement:

$$Q_s^2(x,A) \sim cQ_0^2\left(\frac{A}{X}\right)^{1/3}$$

EIC Coverage:

- Need lever arm in Q^2 at fixed x to constrain models
- Need Q > Q_s to study onset of saturation
  - eA: √s = 50 GeV is marginal, around √s = 100 GeV desirable
  - low mass DY
    - → access to quark saturation?
    - → universality of saturation

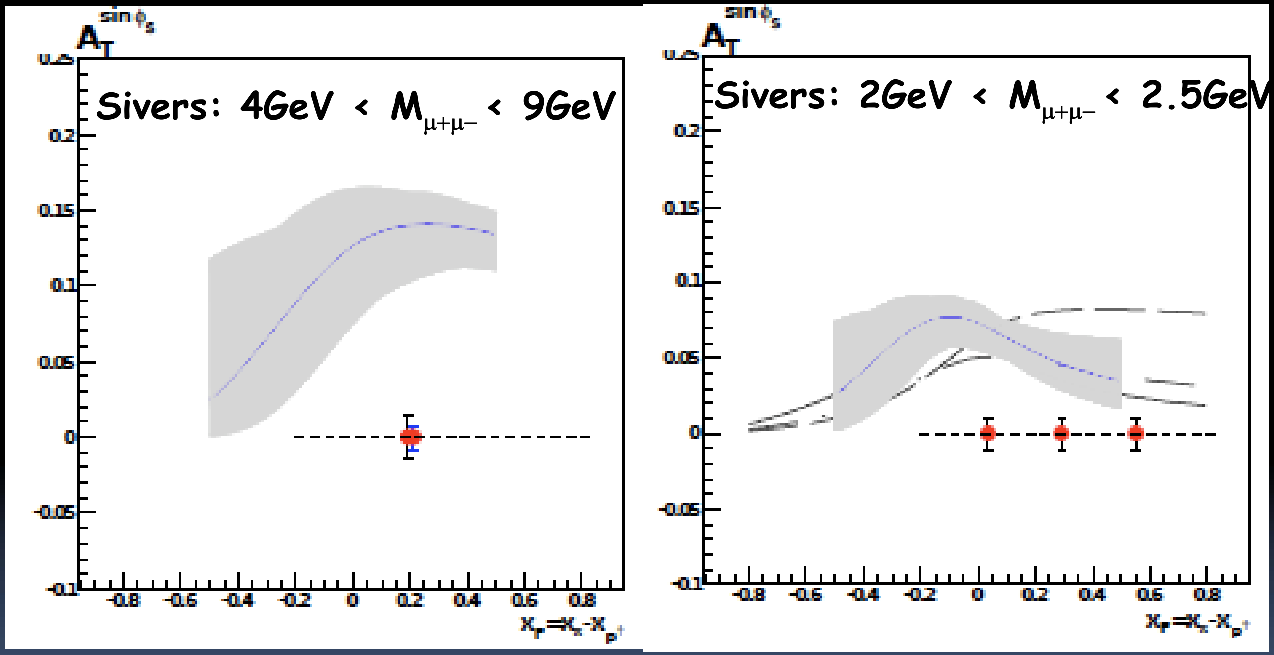


BACKUP

Competing Projects-I

Compass:

- πp @ s = 200GeV², 300GeV², 360GeV², 400GeV²
- 2GeV < $M_{\mu+\mu-}$ < 2.5GeV and 4GeV < $M_{\mu+\mu-}$ < 9GeV
- Target: NH_3 → dilution factor f=0.22

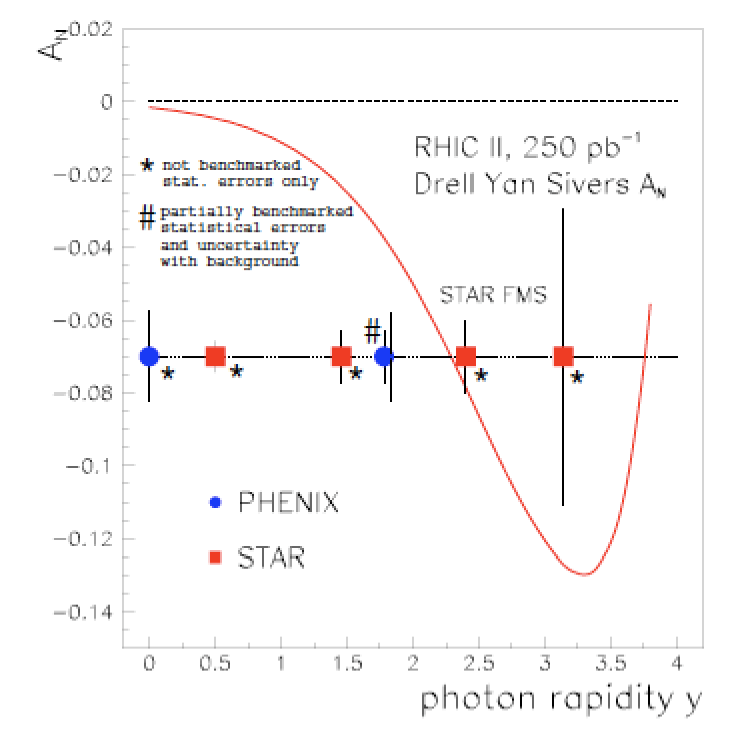


Details: http://wwwcompass.cern.ch/compass/proposal/compass-II_proposal/compass-II_proposal.pdf

Competing Projects-II

PHENIX:

- pp @ $\sqrt{s}$ = 200GeV
- 4GeV < $M_{\mu+\mu-}$ < 9GeV with existing μ-arms 1.2 < $|\eta|$ < 2.4
- not possible in parallel to W-program



STAR:

- pp @ $\sqrt{s}$ = 200GeV
- 4GeV < M_{e+e-} < 9GeV assumed significant hardware upgrade

Details: http://spin.riken.bnl.gov/rsc/write-up/dy_final.pdf

Earlier e+e- DY experiments

p+p DY at ISR, √s=53, 63 GeV
Phys. Lett. B91 (1980) 475

STUDY OF MASSIVE ELECTRON PAIR PRODUCTION AT THE CERN INTERSECTING STORAGE RINGS

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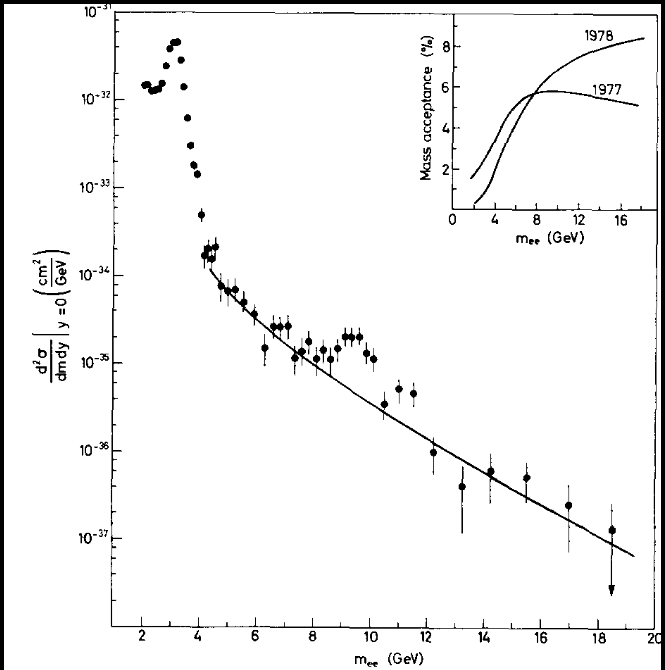
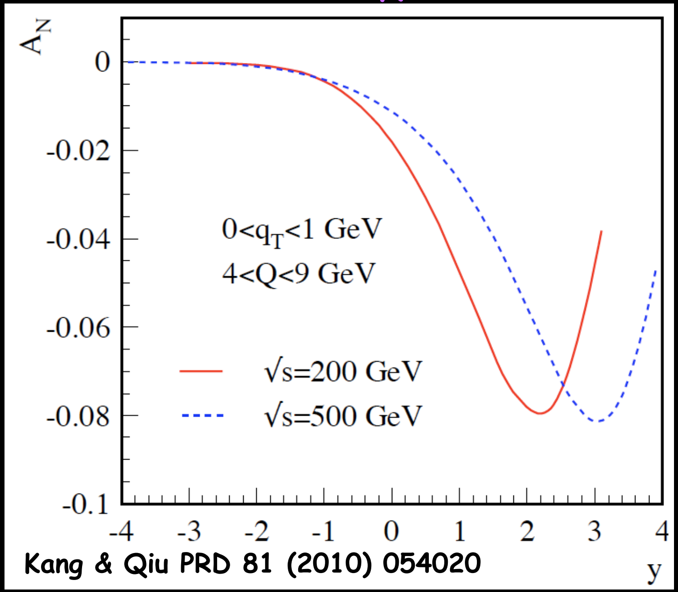


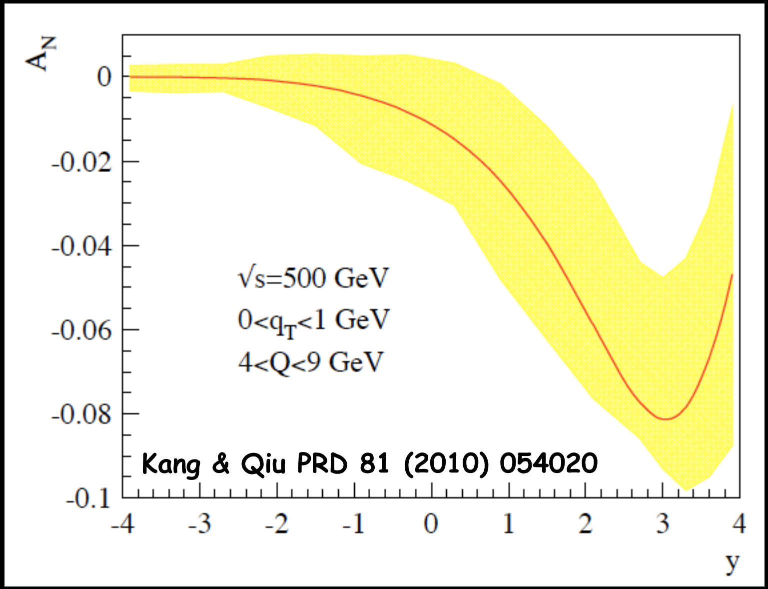
Fig. 1. The cross section $(d^2\sigma/dm\,dy)_{y=0}$ versus mass for the data at $\sqrt{s}$ = 53 and 63 GeV combined. The curve is a result of the fit to the continuum displayed in fig. 2. The inset show the mass acceptance for "1977" and "1978" triggers and geometrical configurations calculated for isotropic decay distributions and production uniform in rapidity with p_T dependence $d\sigma/dp_T^2 \sim \exp(-bp_T)$, where b = 1.4 GeV^{-1}. The mass acceptance changes by ± 15% when the helicity decay distribution follows $dN/d\cos\theta = 1 + \alpha\cos^2\theta$ when α = ± 1, where θ is measured in the s-channel helicity frame.

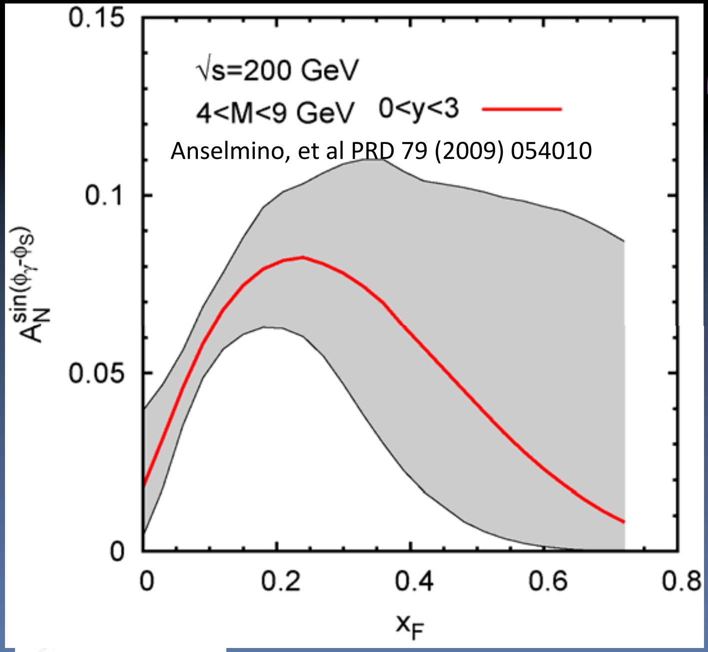
- Comments (note: large x_F at collider breaks new ground)…
- e+e- low-mass DY done at ISR and by UA2 [see review J.Phys. G19 (1993) D1]
- UA2 [PLB275 (1992) 202] did not use magnet / CCOR did [PLB79 (1979) 398]
- most fixed target experiments do μ+μ– DY

Theoretical Predictions for DY in pp

Prediction of A_N in collinear twist-3 approach







Prediction of A_N in TMD approach

- opposite sign of A_N due to different conventi
- √s=500 GeV predictions very similar, since $x_F=x_1-x_2$ is the relevant parameter

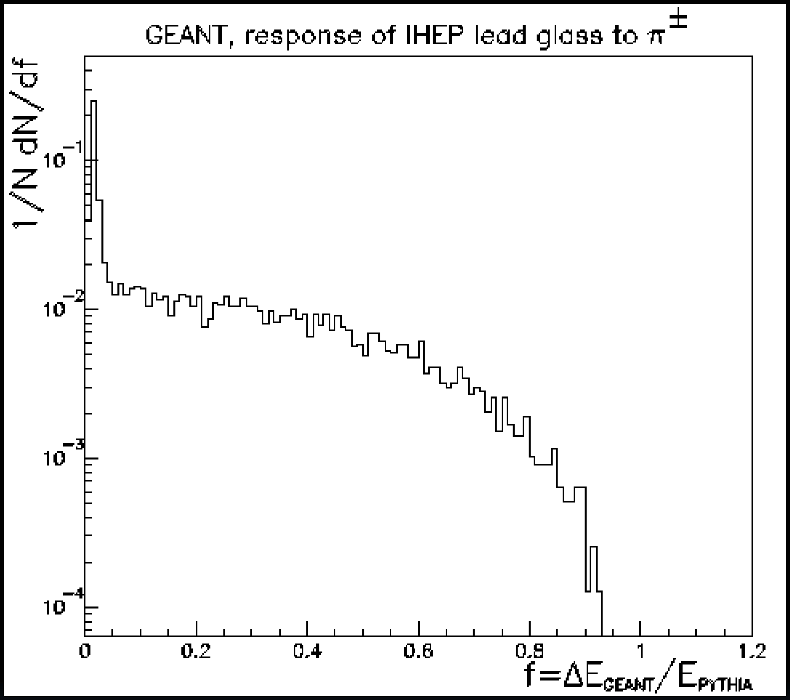
To go very forward ensures to measure non-zero A_N

Big acceptance in η will allow to measure shape of A_N vs η / x_f

DY Feasibility Test

- Staged Experiment
- Assumptions:
  - run in parallel with W-program and keep impact on luminosity for Star and PheniX minimal
- Planned Staging:
  - Hcal + newly constructed BBC at IP2 for RHIC run 11 with goals of establishing impact of 3-IR operation and demonstrate calibration of Hcal to get first data constraints on charged hadron backgrounds
  - Hcal + EMcal + neutral/charged veto + BBC for RHIC run 12 with goals of zero-field data sample with L_{int}~150 / pb and P_{beam}=50% to observe dileptons from J/ψ, Υ and intervening continuum.
  - Hcal + EMcal + neutral/charged veto + BBC + split-dipole for RHIC run 13 with goals data sample with Lint~150 / pb and Pbeam=50% to observe dileptons from J/ψ, Υ and intervening continuum to address whether charge sign discrimination is required
- Lessons learned will be integrated into STAR and PheniX next decadal plan upgrades for DY

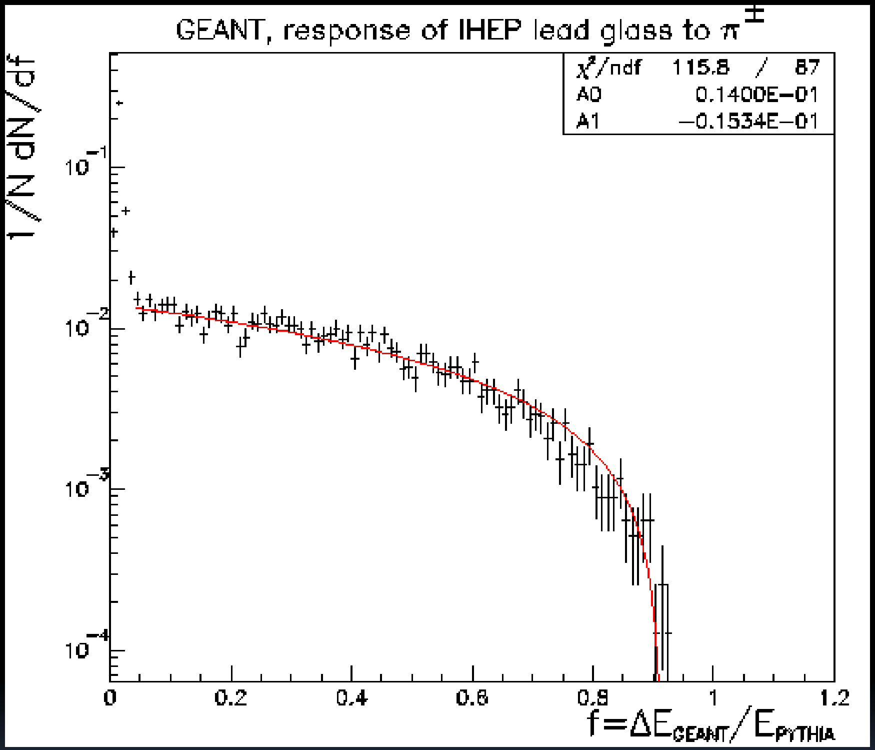
Strategy for detector response estimates



- GEANT simulation of Emcal response to E>15 GeV $\pi^\pm$ from PYTHIA 6.222 incident on $(3.8cm)^2$x45cm lead glass calorimeter

- $\sim 10^{12}$ p+p interactions in 50/pb at $\sqrt{s}$=500 GeV $\Rightarrow$ full PYTHIA/GEANT not practical
- Parameterize GEANT response of EMcal and use parameterized response in fast simulator applied to full PYTHIA events
- Estimate rejection factors from GEANT for hadron calorimeter and preshower detector (both critical to $h^\pm/e^\pm$ discrimination)
- Explicit treatment in fast simulator to estimate pathlength through key elements (beam pipe and preshower), to simulate photon conversion to e+e- pair
- Estimate effects from cluster merging in EMcal ($d < \varepsilon d_{cell}$ / recommended is $\varepsilon \approx 1$)
- Estimate/simulate EMcal cluster energy and position resolutions. $\sigma_E=15\%/\sqrt{E}$ and $\sigma_{x(y)}=0.1d_{cell}$ used to date for $\pi^0 \rightarrow \gamma\gamma$ rejection.

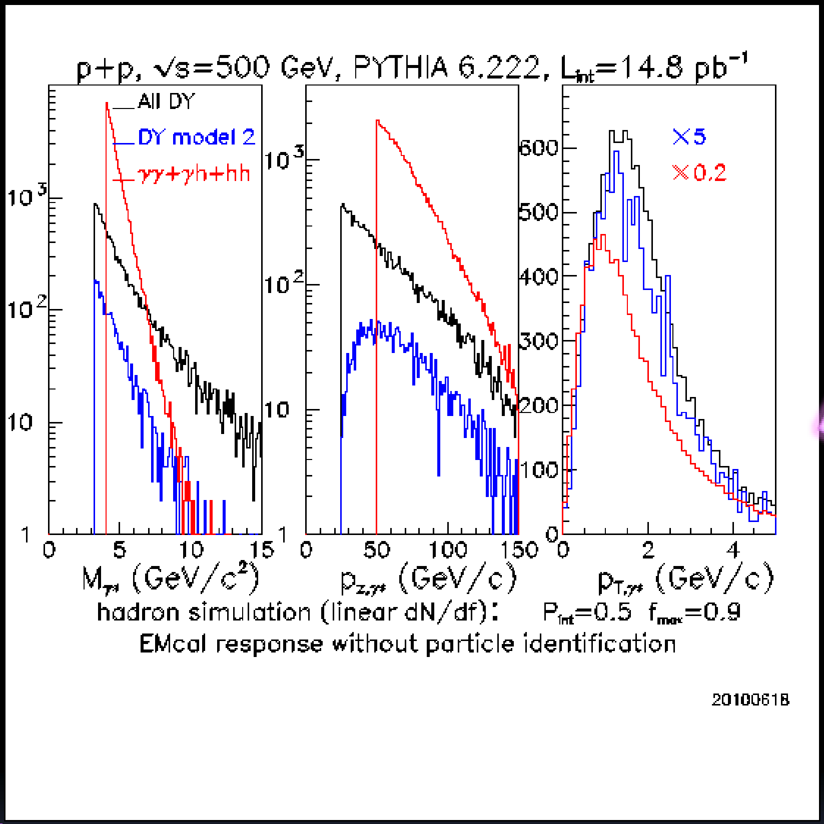
EMcal response to hadrons



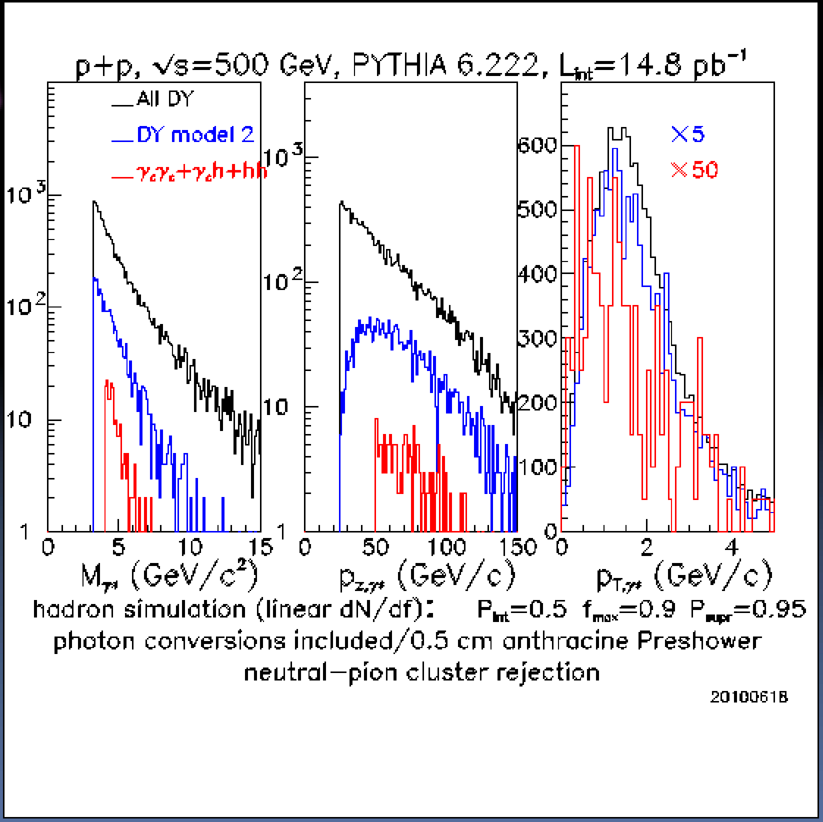
GEANT simulation of EMcal response to E>15 GeV $\pi^{\pm}$ from PYTHIA 6.222 incident on $(3.8cm)^2$x45cm lead glass calorimeter

- Uniform dN/df too simplistic
- GEANT response not so different from 57 GeV pion test beam data from CDF [hep-ex/060808 and presentation file]
- Linear fit to dN/df gives χ^2/DOF=1.3
- Increased sophistication in fast simulator for hadronic response of EMcal still needed

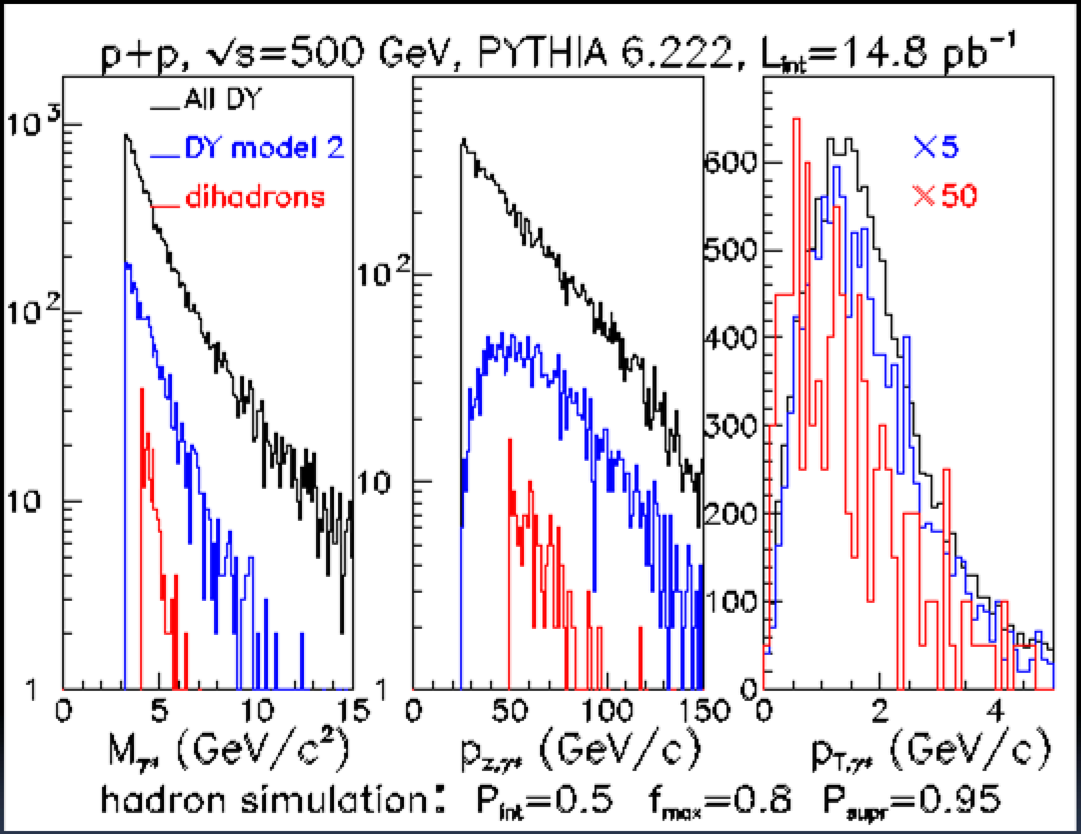
Hadronic Background without and with PID



apply PID



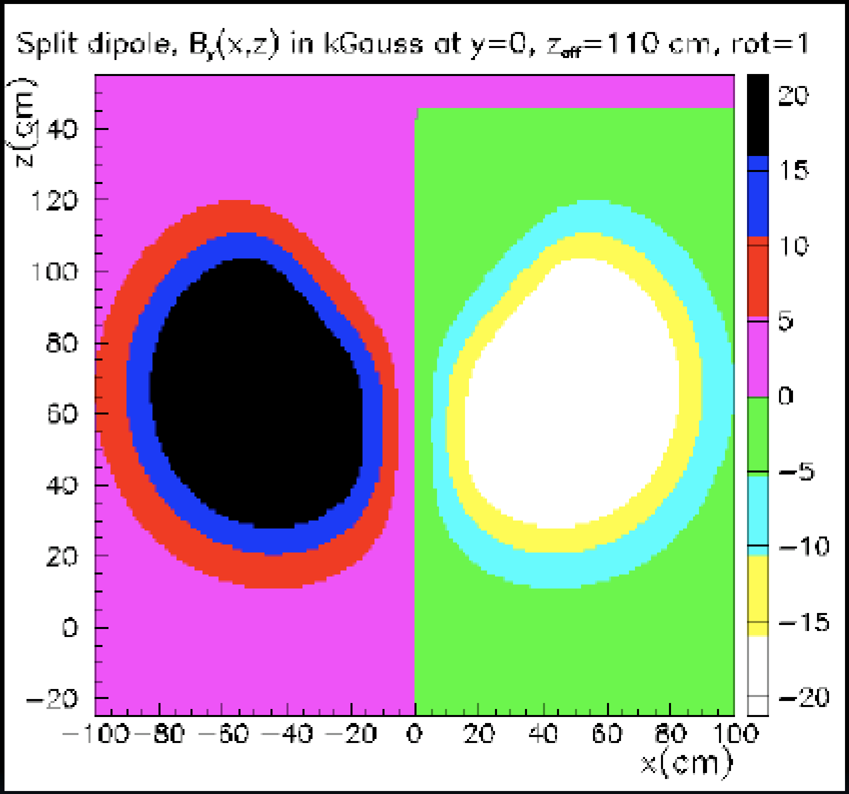
Di-hadron background estimate I

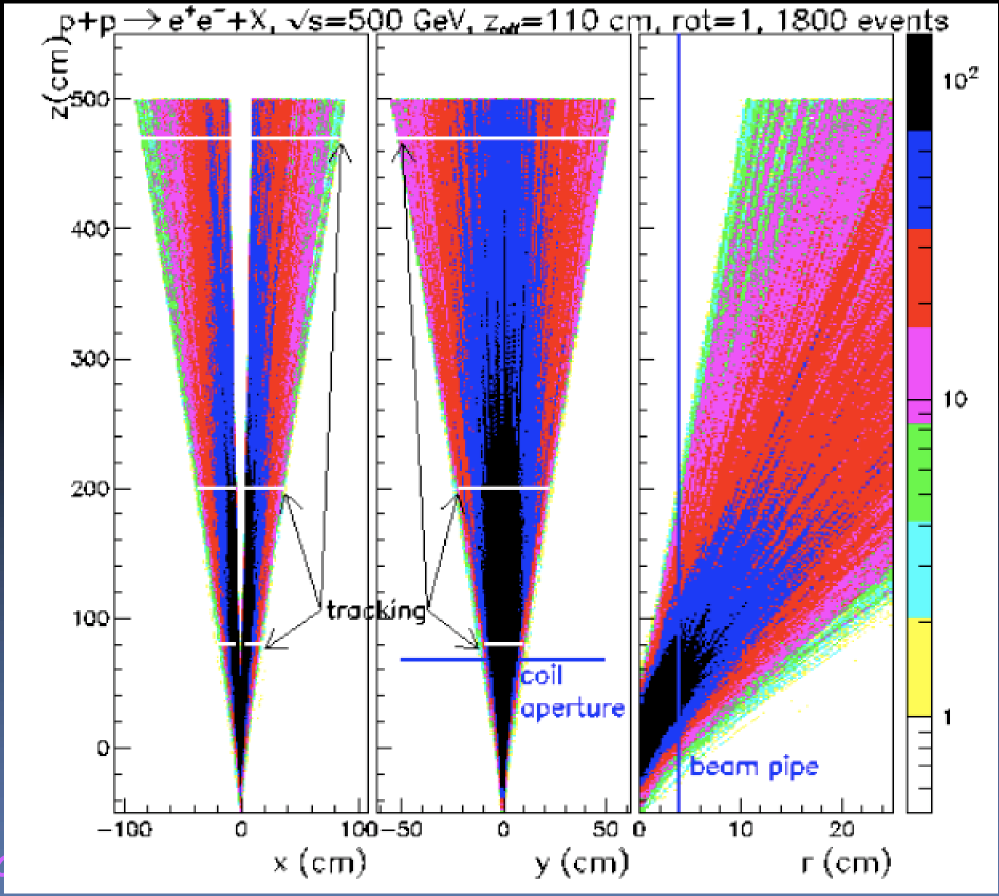


Remarks:

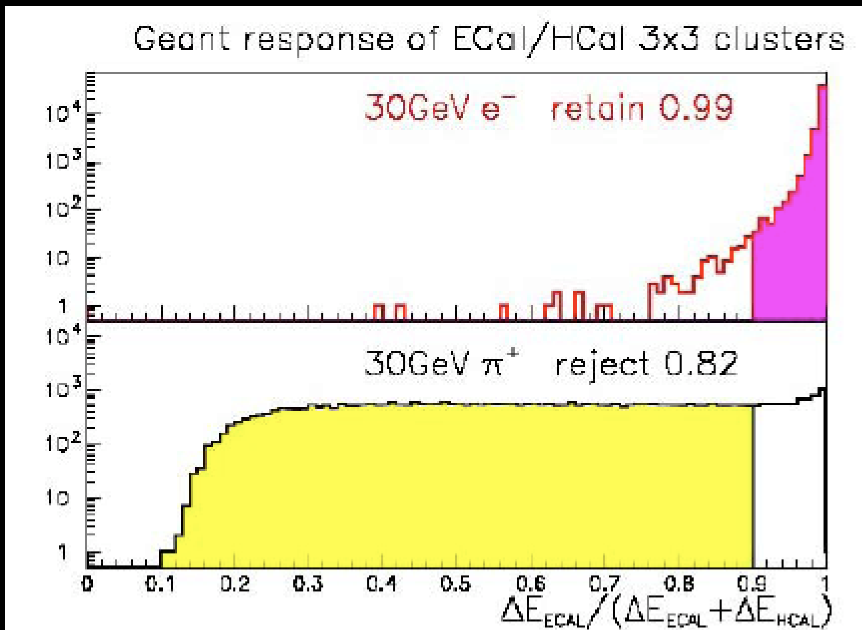
- No cluster simulation and charge sign determination included
- Suppression probability consistent with full GEANT treatment for E=10 GeV π
- dN/df modeled by uniform distribution to f_{max} is too simplistic

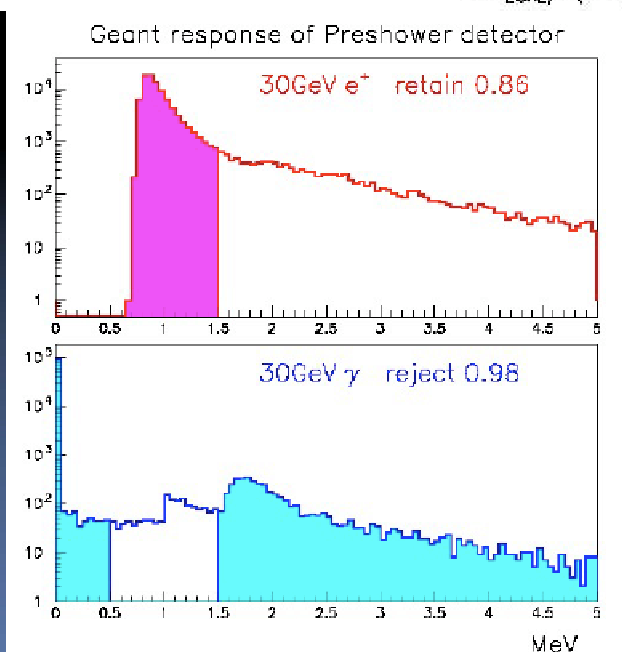
Phobos Split Dipole

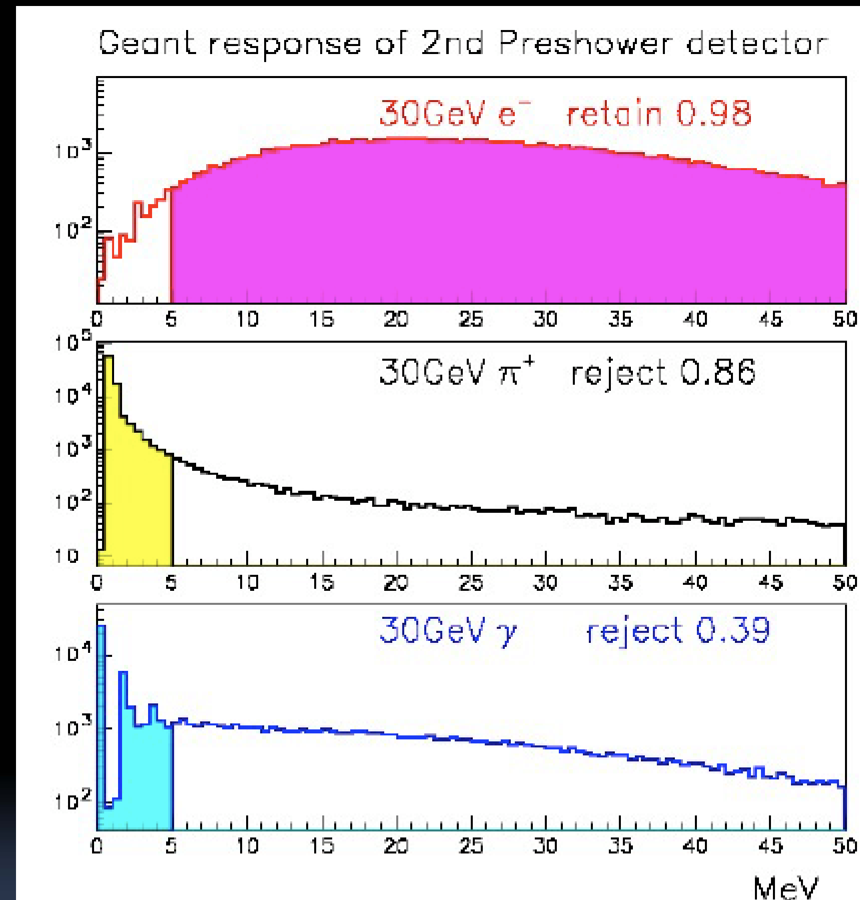




PID response from Geant-3







Cutting on individual detectors very inefficient

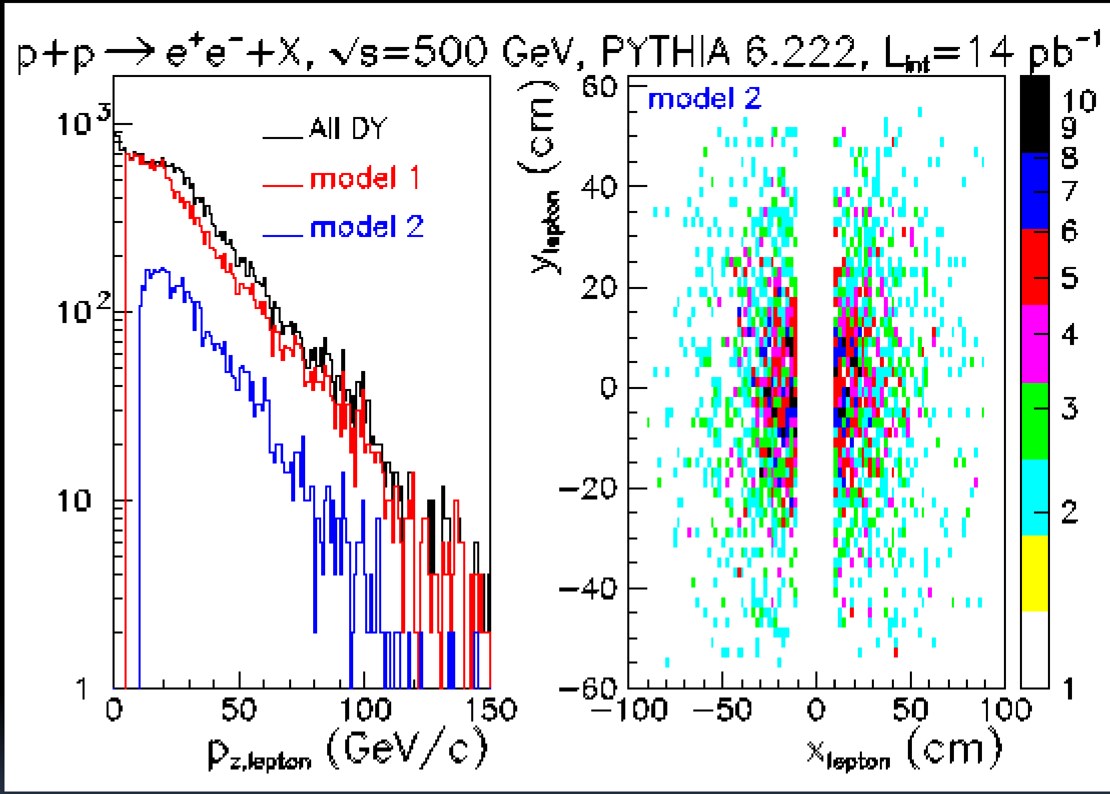
→ convert responses into conditional prob.

→ Bayes theorem → true probabilities

Tracking → reduces conversion e+e-

Clustering → reduces π^0

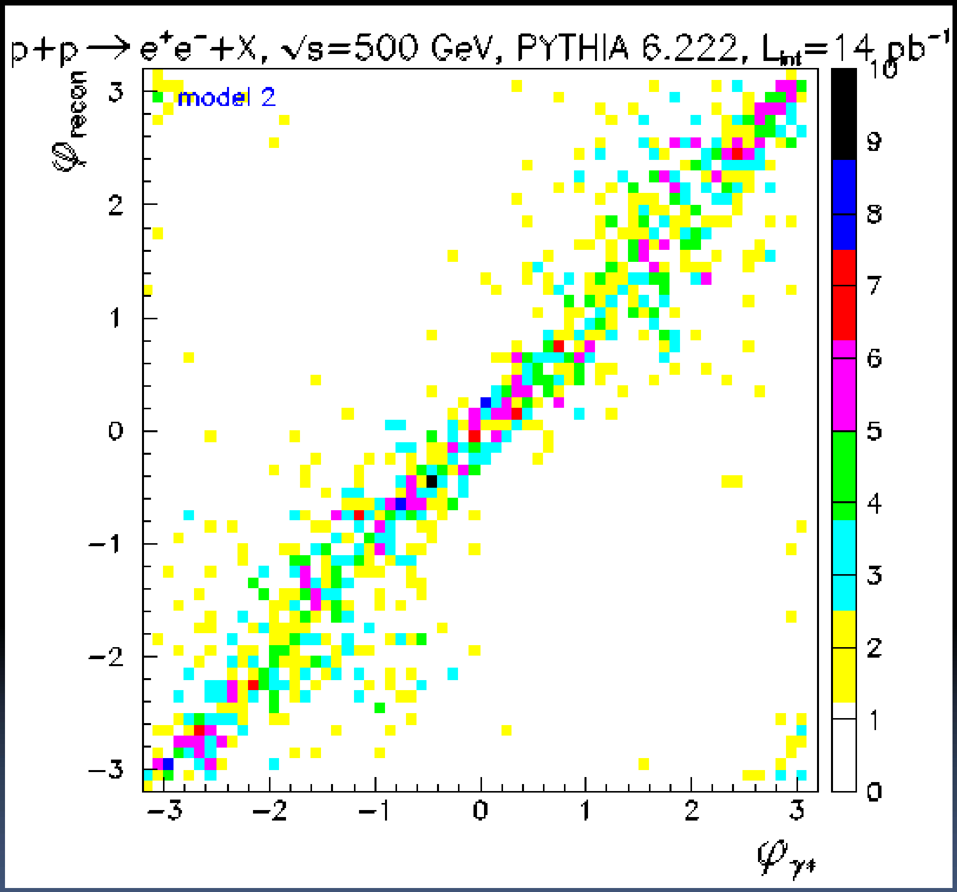
Lepton daughters from γ^*



Most important contributions for γ^* x_F>0.1 at $\sqrt{s}$=500 GeV

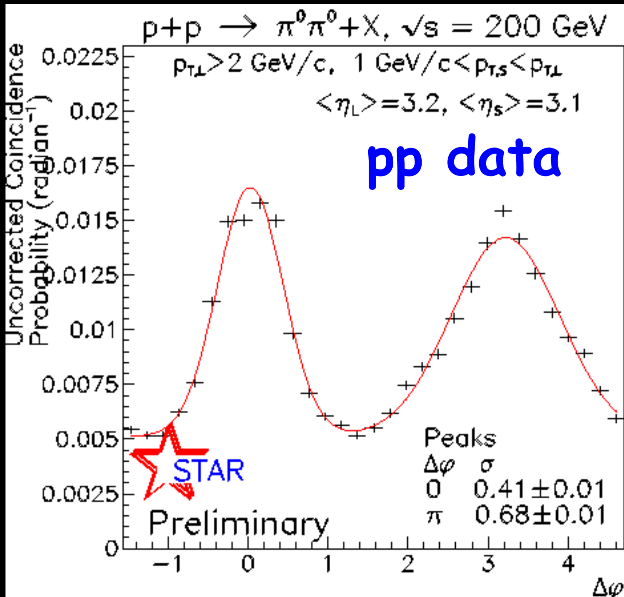
- high energy electrons and positrons (E>10 GeV)
- require detection at very forward angles
- e+e- from γ^* little affected by "modest" isolation (20mr half-angle cone)
- best solution for charge sign would be a dipole magnet (difficult for any collider)

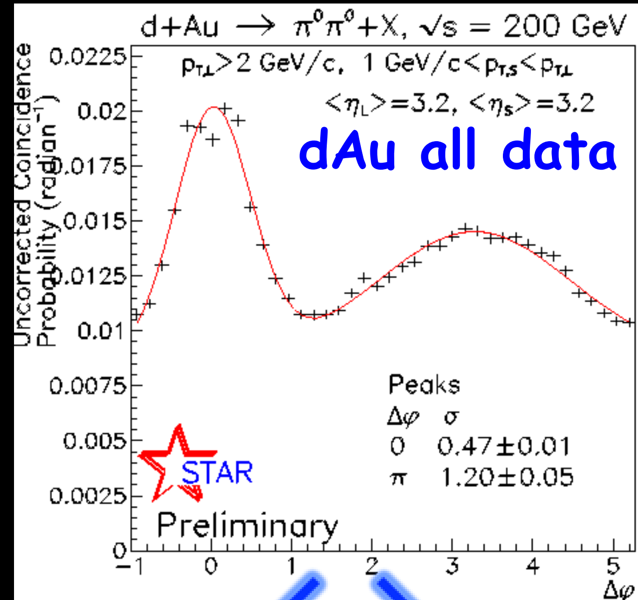
Azimuthal angle for $\gamma^* \rightarrow$ e+e-



- e+ and e- in separate modules except when γ^* has large p_T
- Azimuthal angle required for analyzing power measurement
- Resolution is primarily from measuring energies of e+ and e-
- Model 2 covers full azimuth despite modular coverage

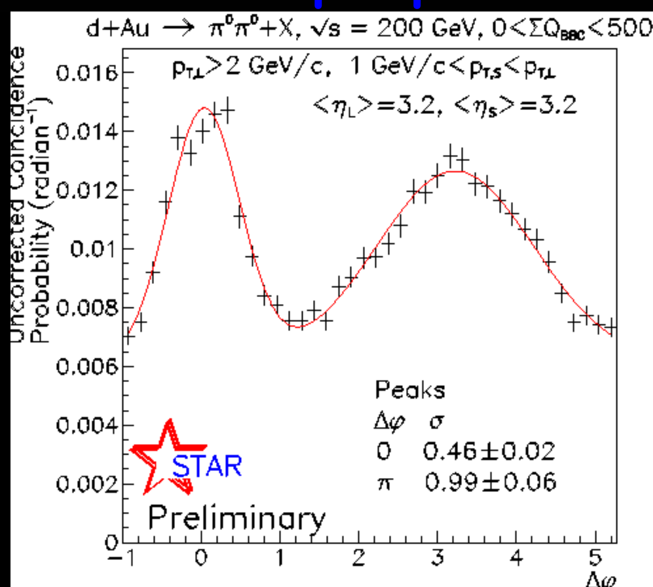
RHIC: Signs of Saturation in dAu

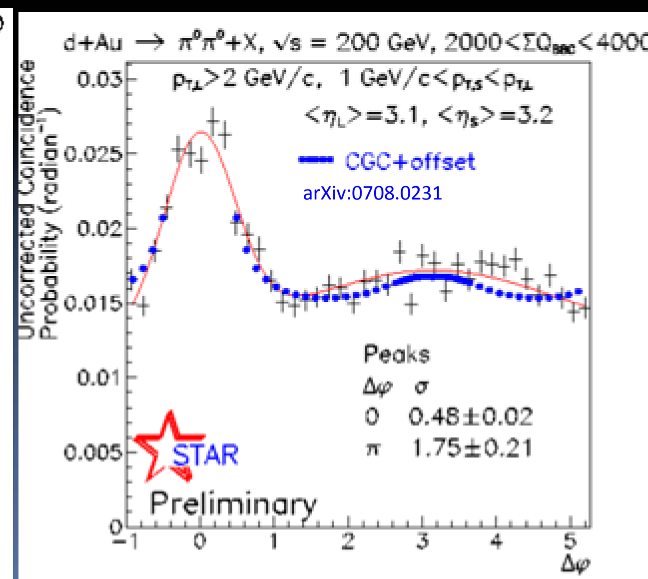




dAu peripheral

dAu Central





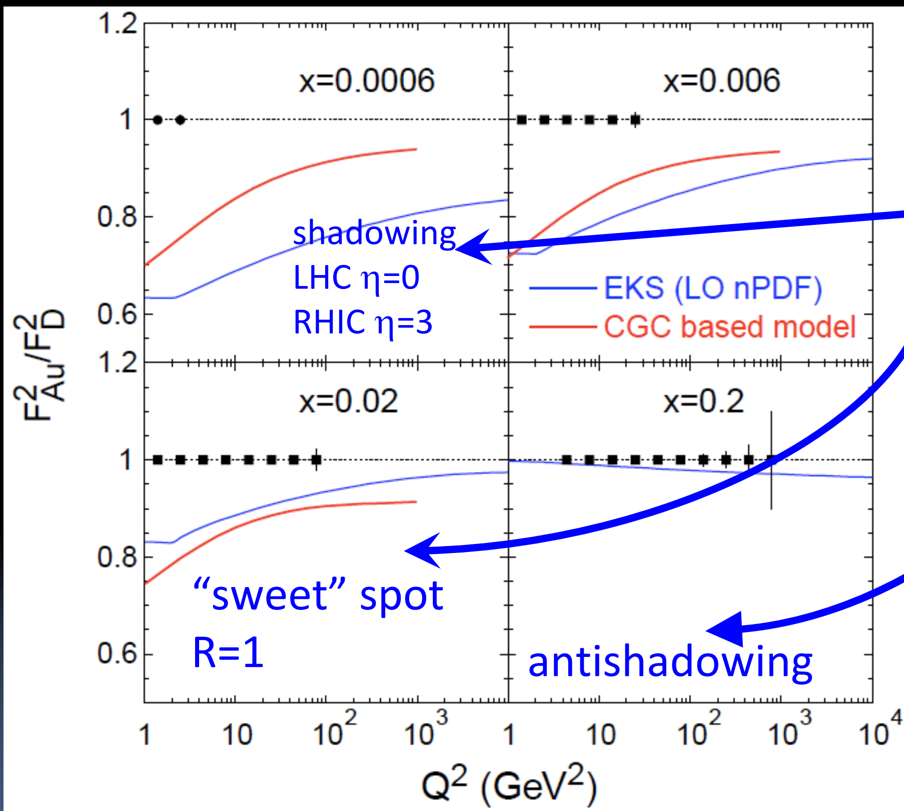
Away-side peaks evident in peripheral dAu and pp.

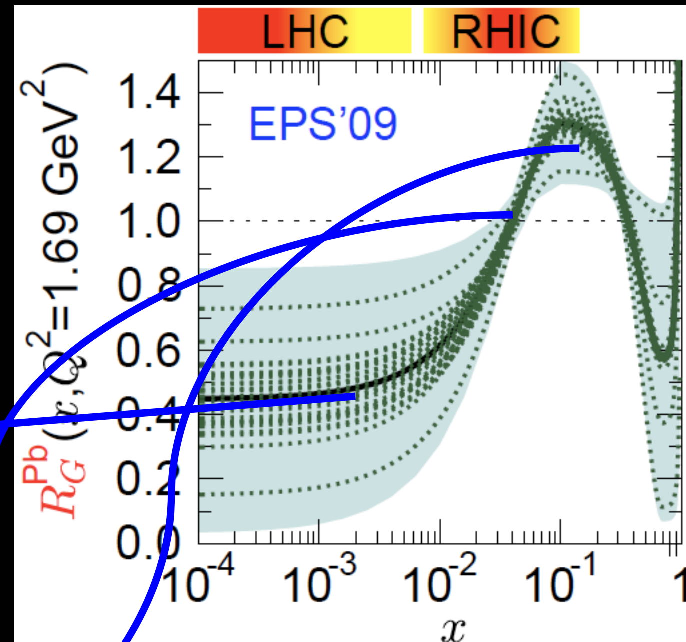
Near side peaks unchanged in dAu for peripheral to central.

Azimuthal decorrelations show significant dependence on centrality

F_2: for Nuclei

$$\frac{d^2\sigma^{NC}_{em\,p}}{dx\,dQ^2} = \frac{2\pi\alpha^2_{em} Y_+}{xQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L \pm \frac{Y_-}{Y_+}xF_3\right)$$





Assumptions:

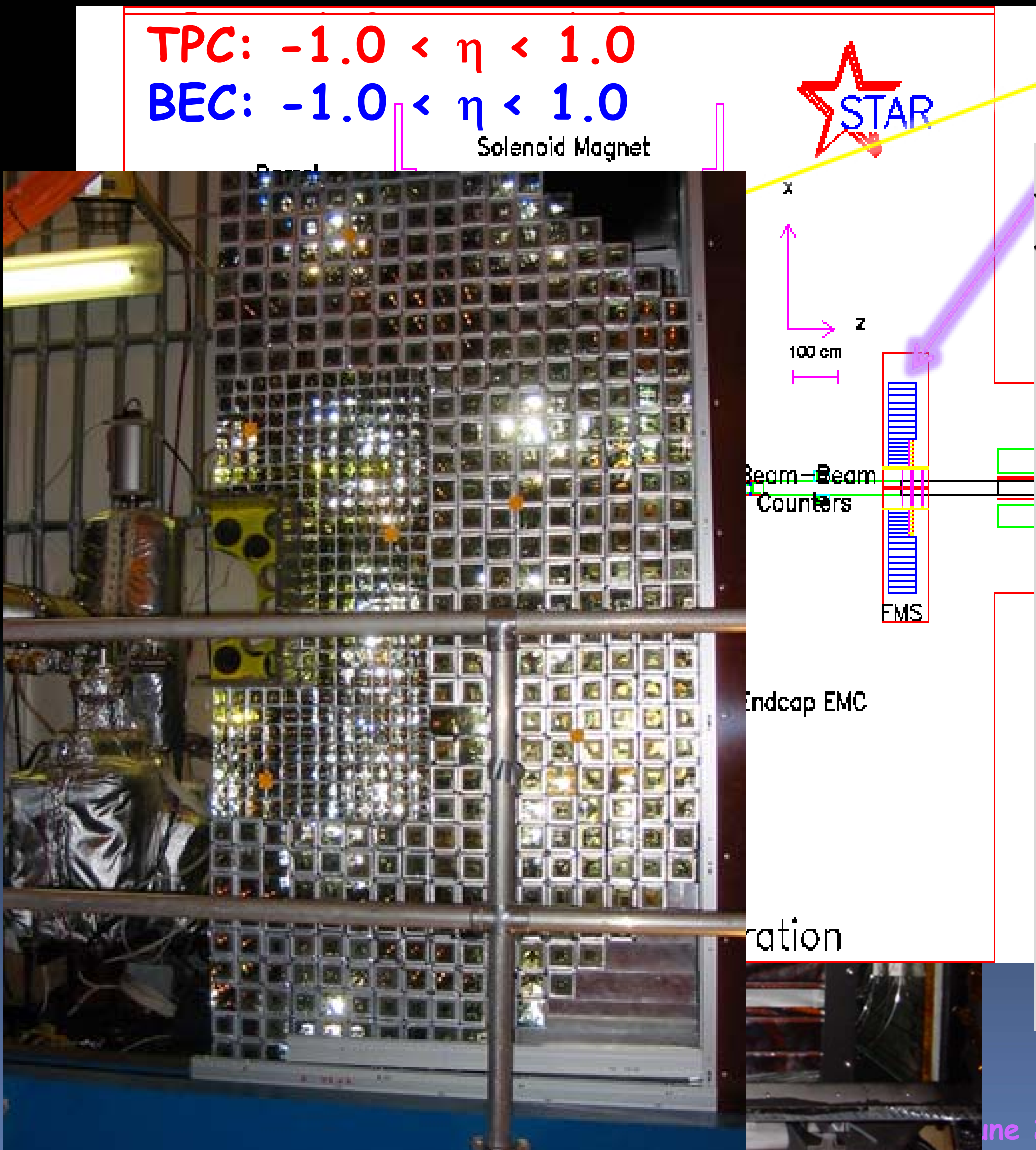
- 10GeV x 100GeV/n
  - $\sqrt{s}$=63GeV
- Ldt = 4/A fb^{-1}
  - equiv to 3.8 10^{33} cm^{-2}s^{-1}
  - T=2weeks; DC:50%
- Detector: 100% efficient
  - Q^2 up to kin. limit sx
- Statistical errors only
  - Note: L~1/A

Star: Forward Physics program

- add electromagnetic calorimetry at forward rapidity

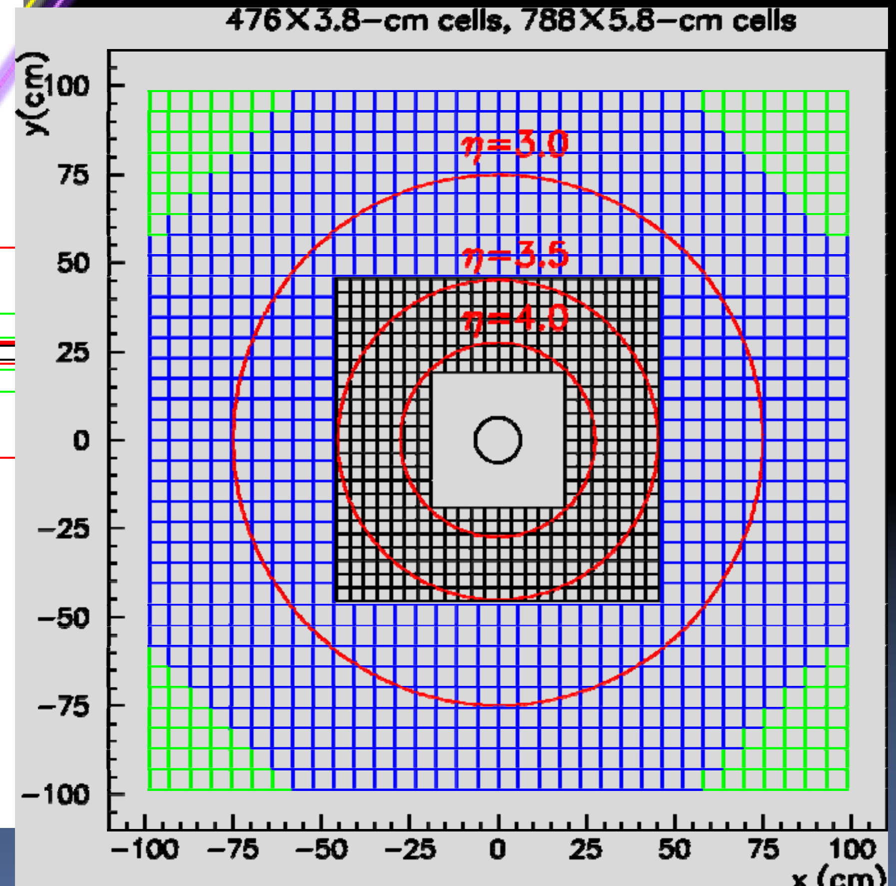
→ access low and high x

$$x \sim \frac{2 p_T}{\sqrt{s}} e^{-y}$$



2003: FPD: 3.3 < η < 4.1

2008: FMS: 2.5 < η < 4.1

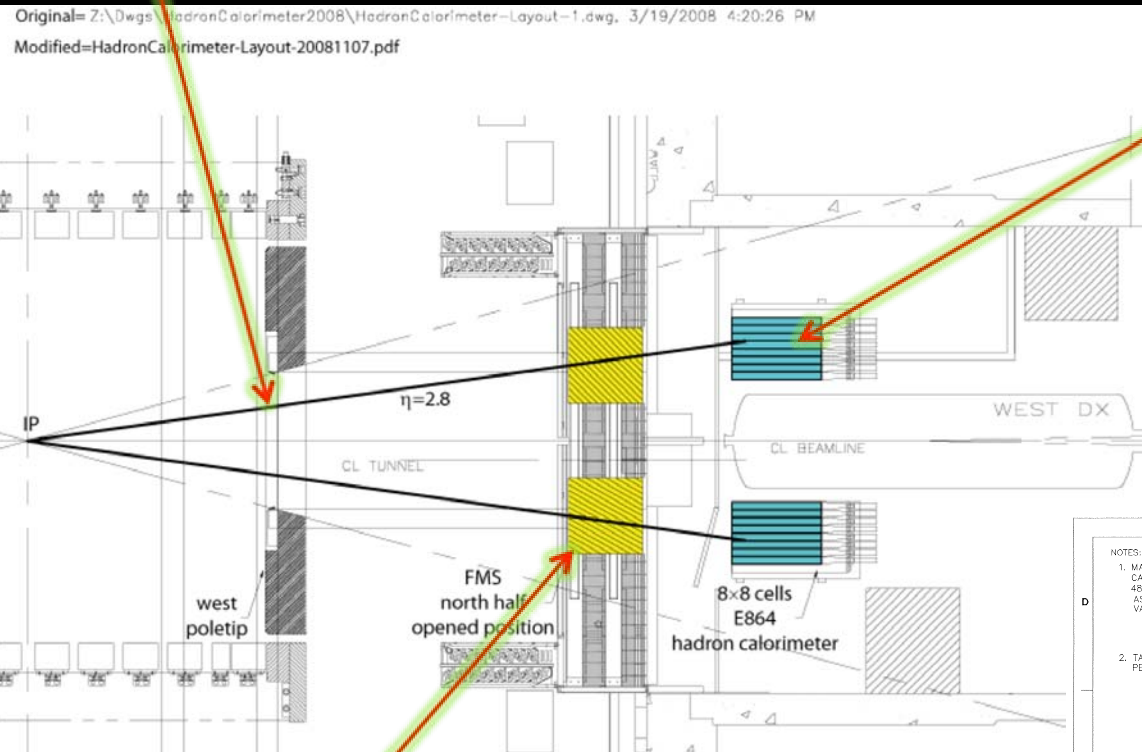


STAR forward detectors

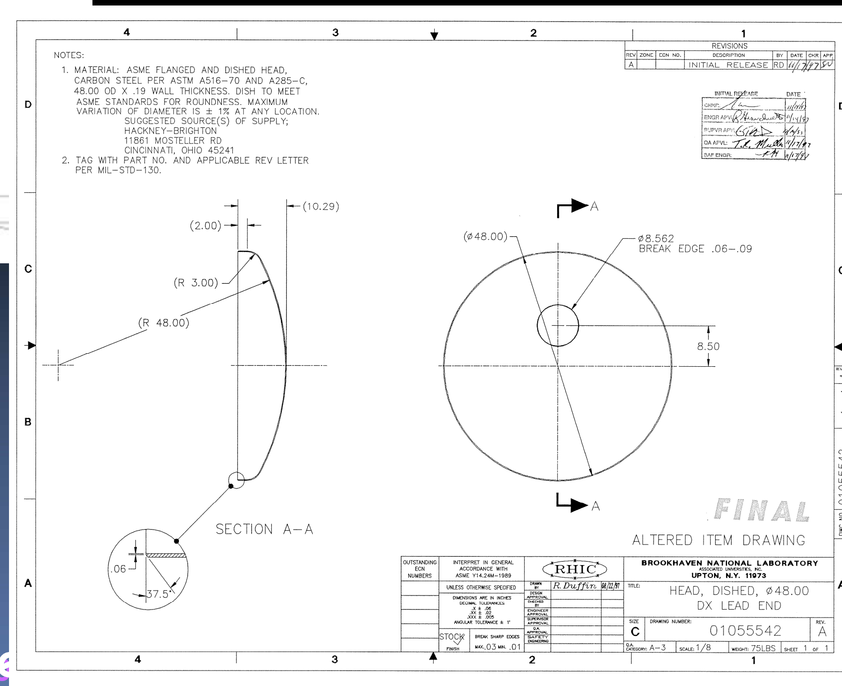
FTPC (to be removed next year)

Proposed FHC
(for jet & lambda)

$\approx$ 6 L_{int} spaghetti calorimeter
10cm x 10cm x 120 cm "cells"



DX shell R ~ 60cm

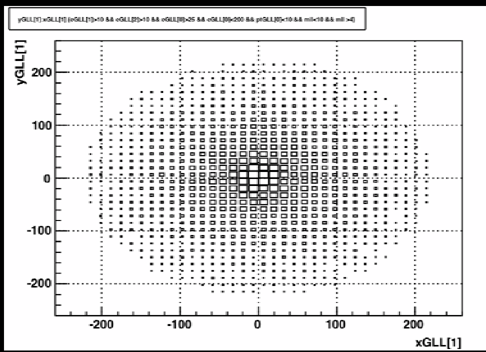


FMS
In open position
x~50cm from beam

No space for FHC near beam
No space in front of FMS neithe

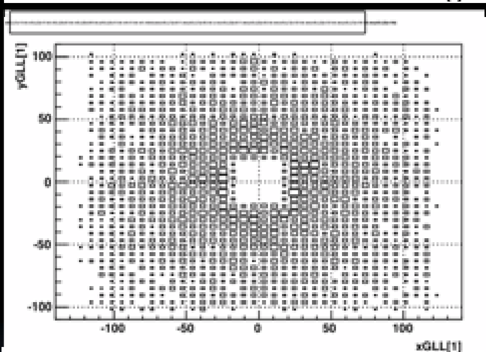
DY Signal

pythia6.222, p+p @ $\sqrt{s}$=500
DY process, 4M events/6.7E^{-05}mb ~ 60/pb
e+/e- energy>10GeV & η>2
x_F>0.1 (25GeV)
4GeV < invariant mass < 10GeV



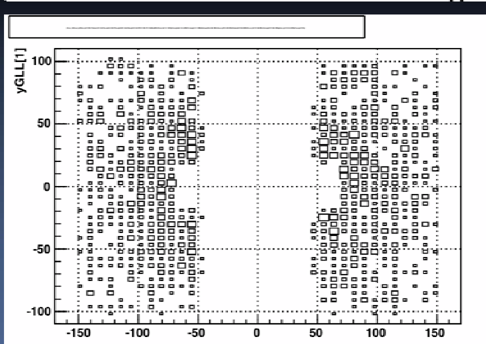
Everything η>2

14799 events



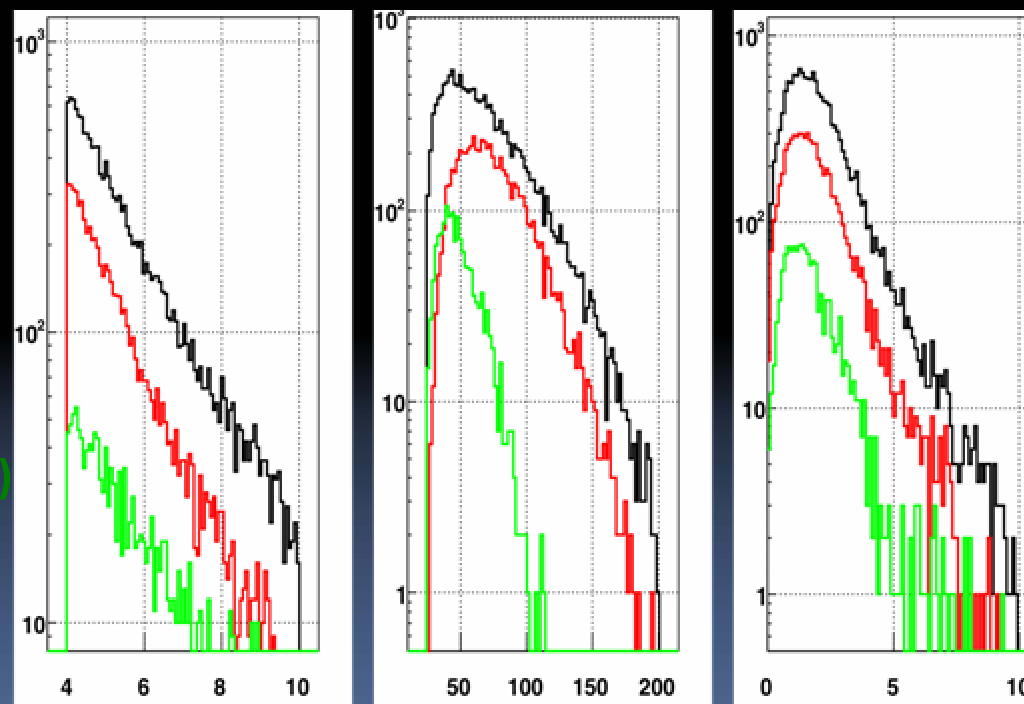
FMS closed
(FHC cannot
be placed due
to DX magnet)

6512 events



FMS open (x=50cm)
+ FHC (x=60cm)

1436 events
(1/5 from closed)



Inv Mass   E p_T

Sivers function and OAM

Extremely Model dependent statement:

M. Burkardt et al.

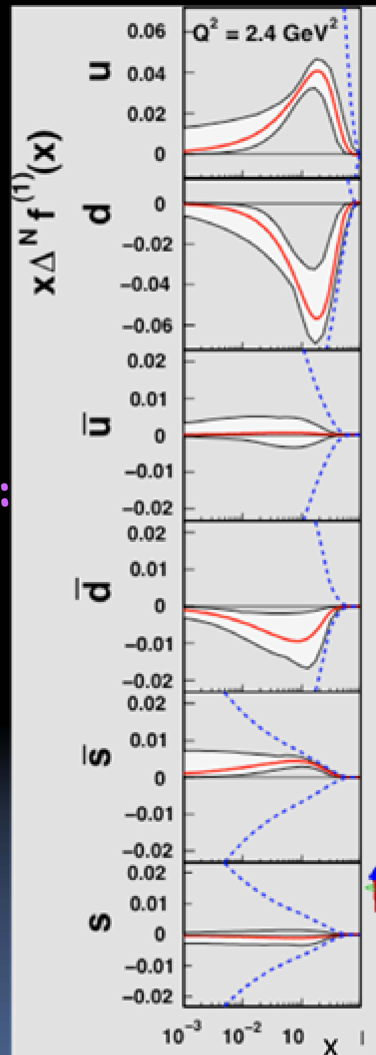
$$(1-x)f_{1T}^{\perp q}(x) = -\frac{3}{2}MC_F\alpha_s E^q(x,0,0)$$

$$\int_0^1 dx(1-x)f_{1T}^{\perp q}(x) = -\frac{3}{2}MC_F\alpha\,\kappa^q$$

anomalous magnetic moment:

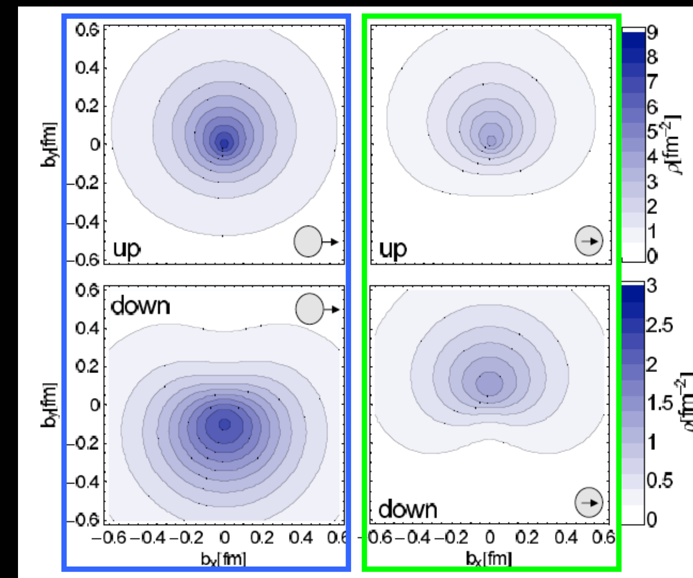
$\kappa^u = +1.67$

$\kappa^d = -2.03$



Sivers fct. from fit to

Anselmino et al. arXiv:0809.2677



Lattice:

QCDSF collaboration

lowest moment of distribution of

unpol. q in transverse pol. proton

and

transverse pol. quarks in unpol. proton