Drell-Yan Production at PHENIX Status and Plan

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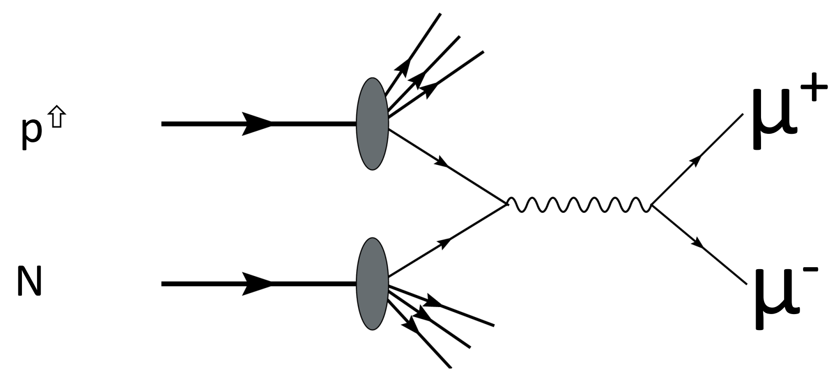
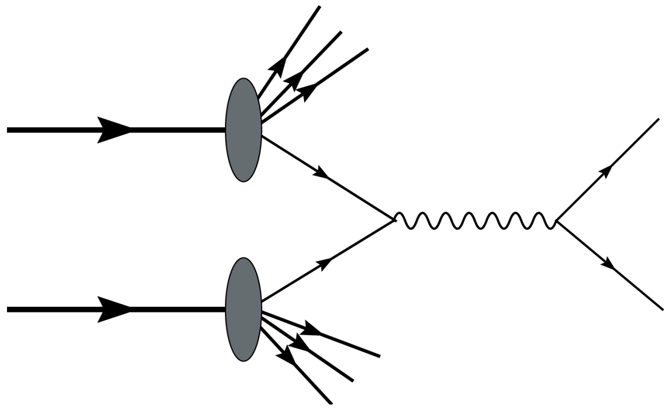
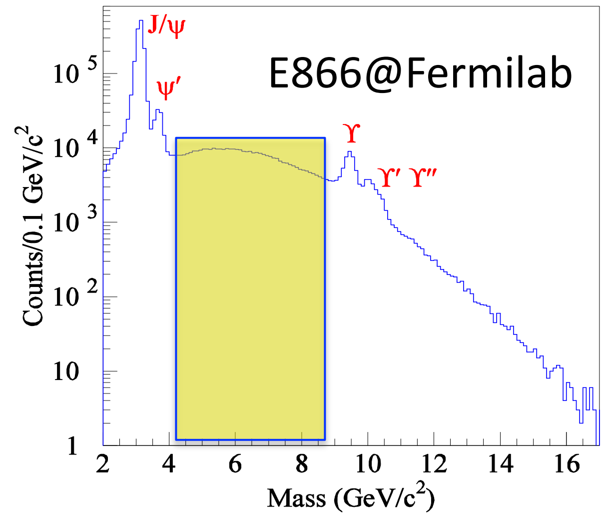
(for the PHENIX Collaboration)



The Drell-Yan Process



- M^2
- p_T



High Mass Low pT Drell-Yan

$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9 s x_1 x_2}\sum_a e_a^2\left[q_a(x_1)\bar{q}_a(x_2)+\bar{q}_a(x_1)q_a(x_2)\right]$$

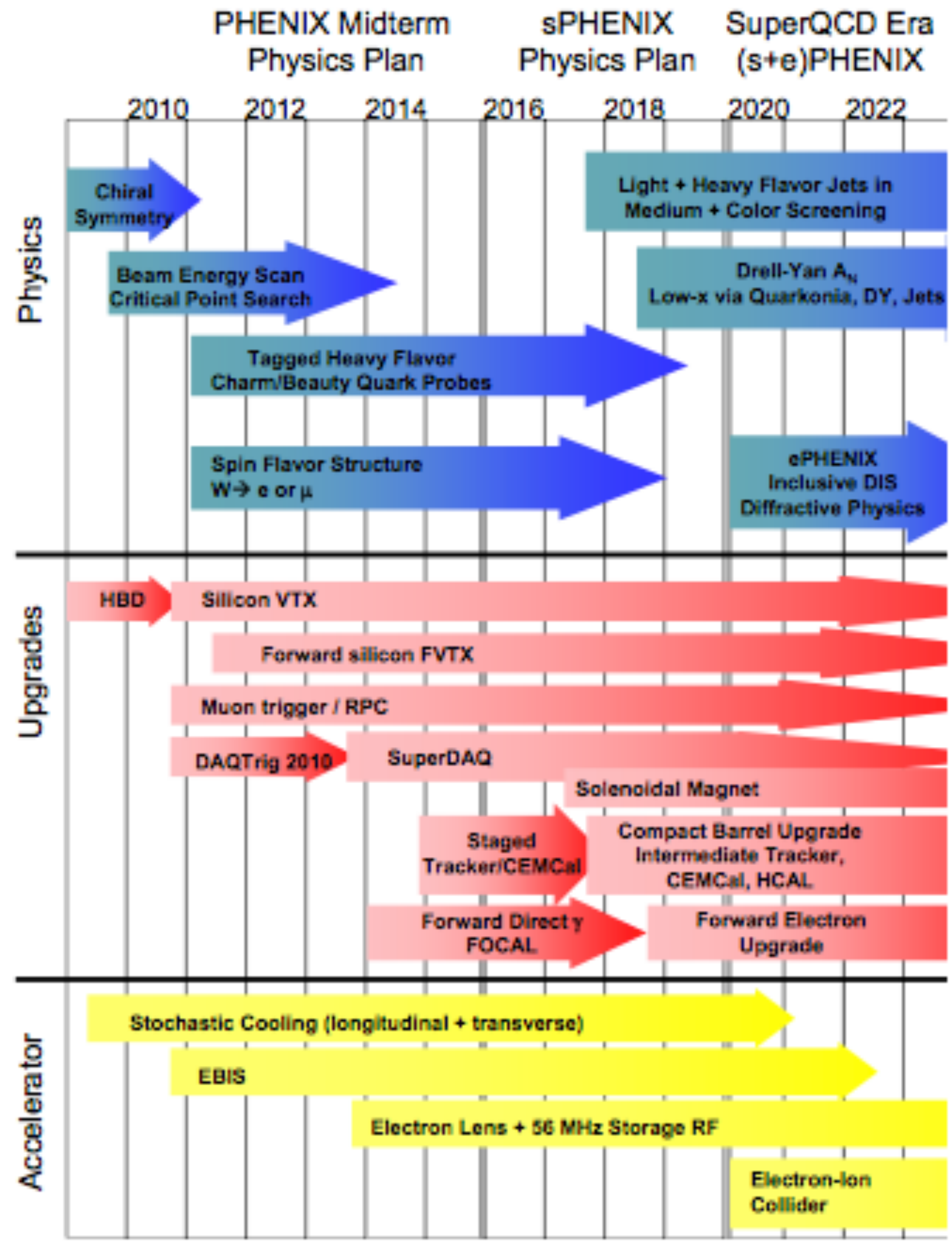
Outline

- Introduction – a hard probe for soft physics
  - Drell-Yan and TMDs in polarized pp collisions
    - NOT going to talk about longitudinal W/Z program
  - Drell-Yan and small-x physics in p(d)+A collisions
  - High msss low pT Drell-Yan @forward rapidity

- Opportunities with PHENIX Experiment
  - PHENIX Current and Near Future (~5 years)
  - sPHENIX proposal and opportunities (>5+ years)

The Timeline

- 2011-2018
  - PHENIX w/upgrades
- 2018-20XX
  - sPHENIX
  - Also ready for eRHIC physics



PHENIX Run Plan 2011-2015

- 500 GeV pp
  - 300 pb-1
- 200 GeV pp
  - 50 pb-1
- 200 GeV dA
  - 260 nb-1
  - 100 pb-1

  (“pp”)

Table B.1: PHENIX run plan for the years 2010–2015. Longitudinal polarization is indicated by (L), transverse by (T).

run	Species	$\sqrt{s_{NN}}$	Wks	$\int$ L dt $\lvert z \rvert < 30$ cm	$\int$ L dt $\lvert z \rvert < 10$ cm	Pol.	Comments
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	Au+Au	200	7		0.8 nb^{-1}		heavy flavor (F/VTX)
	Au+Au	27	1	5.2 μb^{-1}			energy scan
13	$p+p$	500	10	200 pb^{-1}	74 pb^{-1}	60% (L)	W program
	U+U	200	5		0.57 nb^{-1}		} geometry
	Cu+Au	200	5		2.4 nb^{-1}		
14	$p+p$	200	10	34 pb^{-1}	12 pb^{-1}	65% (T)	} HI comp., transv.
	$p+p$	62	3	0.6 pb^{-1}	0.2 pb^{-1}	60% (T/L)	
	d+Au	200	8	260 nb^{-1}	150 nb^{-1}		} CNM/FOCAL
	d+Au	62	2	6.5 nb^{-1}	3.8 nb^{-1}		
15	Au+Au	200	10		2.8 nb^{-1}		High Bandwidth
	Au+Au	62	4		0.13 nb^{-1}		HF vs $\sqrt{s_{NN}}$
	$p+{}^3$He	132	5			(T)	Test Run

Topic (I): Physics of TMDs

Many talks
@this workshop

$$\Phi(x, \boldsymbol{k}_\perp) = \frac{1}{2}\Big[f_1 \not{n}_+ + f_{1T}^\perp \frac{\epsilon_{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu k_\perp^\rho S_T^\sigma}{M} + \Big(S_L g_{1L} + \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_T}{M} g_{1T}^\perp\Big)\gamma^5 \not{n}_+$$

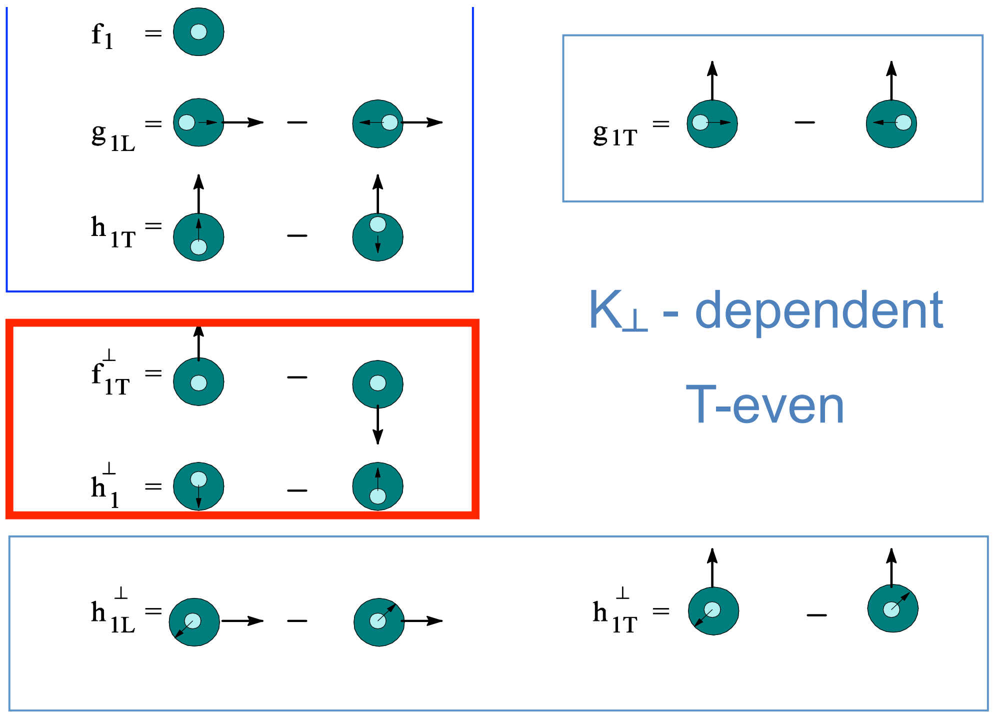
$$+ h_{1T}\, i\sigma_{\mu\nu}\gamma^5 n_+^\mu S_T^\nu + \Big(S_L h_{1L}^\perp + \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_T}{M} h_{1T}^\perp\Big)\frac{i\sigma_{\mu\nu}\gamma^5 n_+^\mu k_\perp^\nu}{M}$$

$$+ h_1^\perp \frac{\sigma_{\mu\nu} k_\perp^\mu n_+^\nu}{M}\Big]$$

No $K_\perp$ dependence

$K_\perp$ - dependent

T-odd



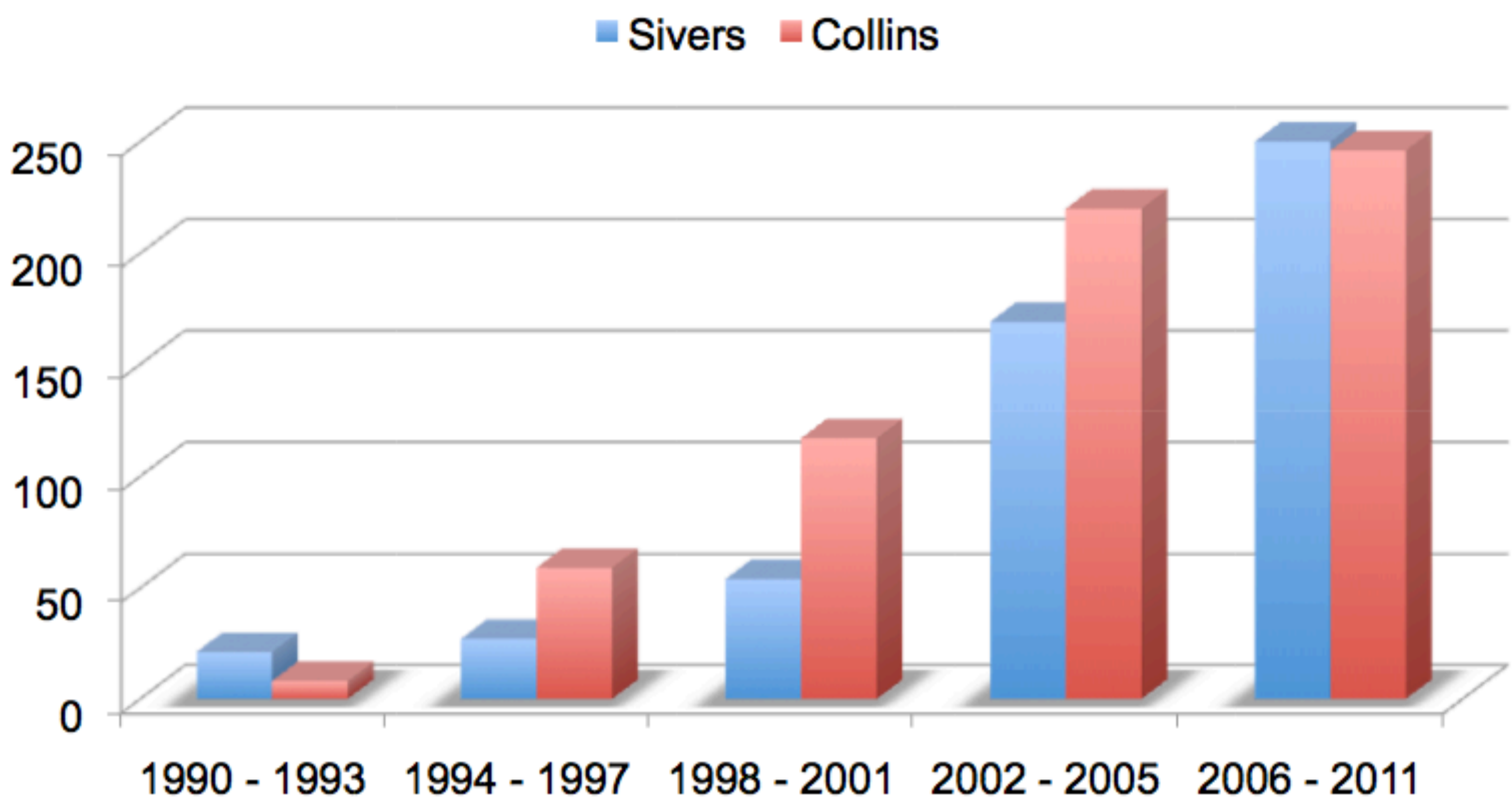
$K_\perp$ - dependent

T-even

The Excitement about Physics of TMDs

- Differential citation for Sivers and Collins functions

Kang's talk



TMDs can be probed via DY

Boer-Mulders functions:

- Unpolarized Drell-Yan: $d\sigma_{DY} \propto h_1^{\perp}\overline{h}_1^{\perp}\cos(2\phi)$

J.C. Peng

Sivers functions:

- Single transverse spin asymmetry in polarized Drell-Yan:

$$A_N^{DY} \propto f_{1T}^{\perp}(x_q)f_{\bar{q}}(x_{\bar{q}})$$

Transversity distributions:

- Double transverse spin asymmetry in polarized Drell-Yan:

$$A_{TT}^{DY} \propto h_1(x_q)h_1(x_{\bar{q}})$$

- Drell-Yan and SIDIS involve different combinations of TMDs
- Drell-Yan does not require knowledge of the fragmentation functions
- T-odd TMDs are predicted to change sign from DIS to DY (Boer-Mulders and Sivers functions)

Remains to be tested experimentally!

Test the Sign Change at PHENIX

Drell-Yan Production @RHIC

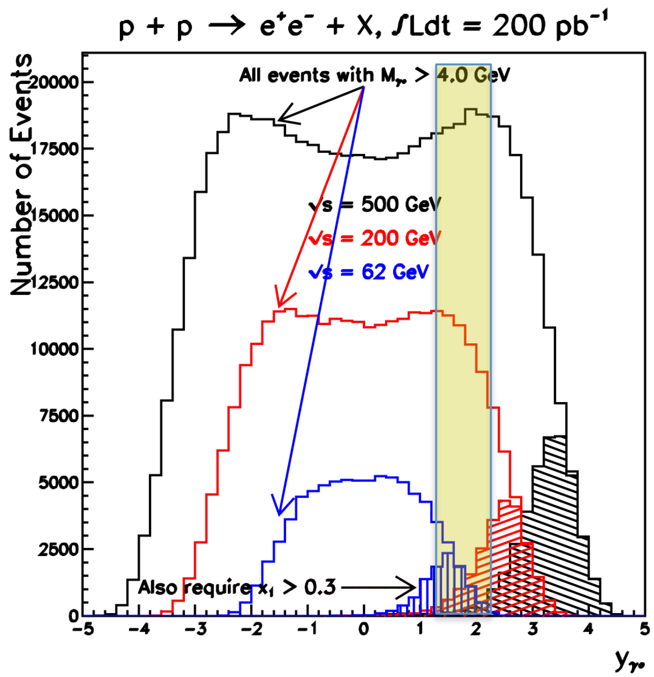


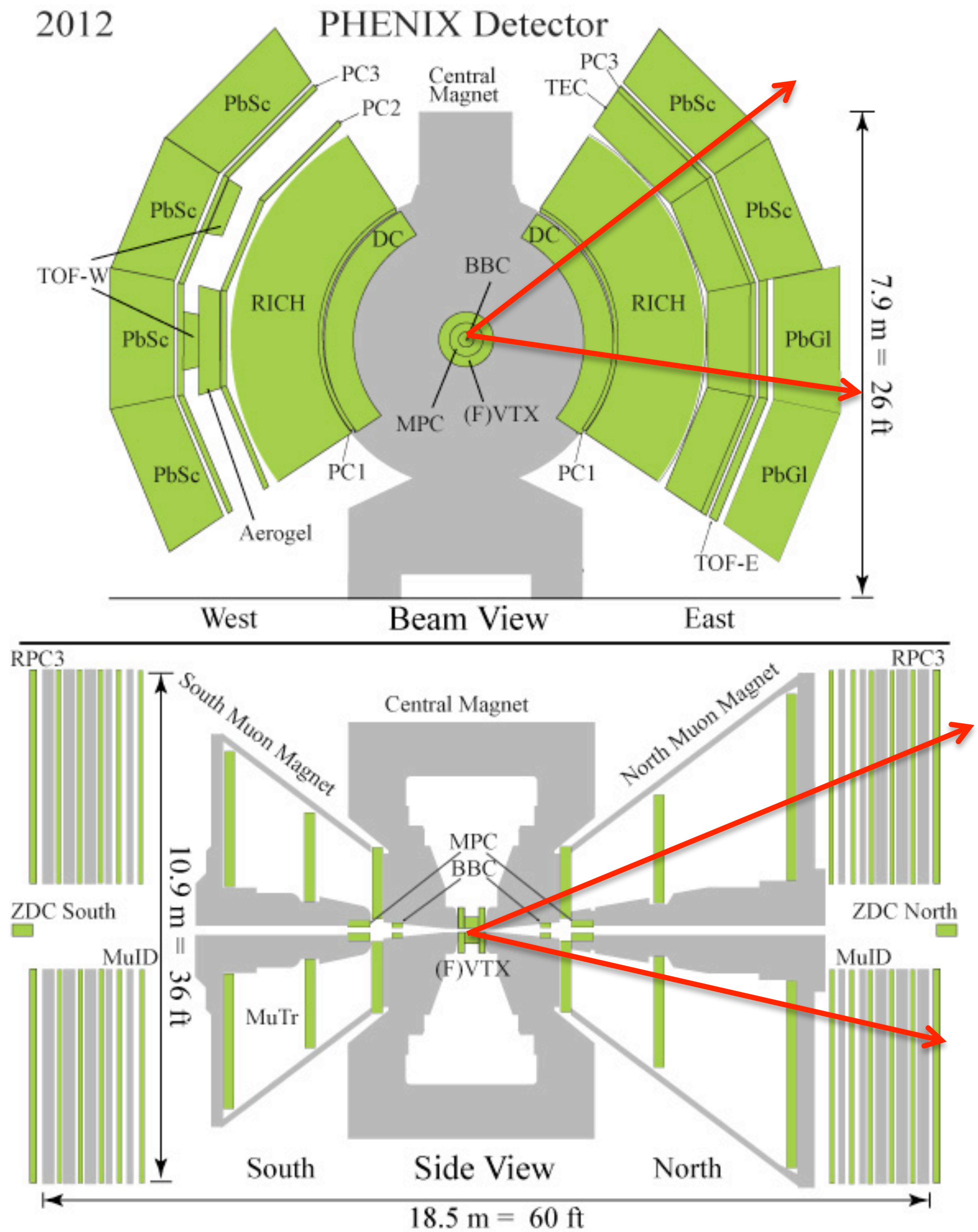
Figure 5: *PYTHIA simulation of the rapidity distribution of* $e^+ e^-$ *dileptons produced through the Drell-Yan process. The importance of large rapidity to probe the valence region is illustrated by selecting events with* $x_1 > 0.3$.

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum_i e_i^2[q_i(x_1)\bar{q}_i(x_2) + \bar{q}_i(x_1)q_i(x_2)]$$

$$\approx \frac{4\pi\alpha^2}{9x_1x_2 s}\sum_i e_i^2[q_i(x_1)\bar{q}_i(x_2)], \quad if\ \ x_1 >> x_2$$

PHENIX: 2011-2018

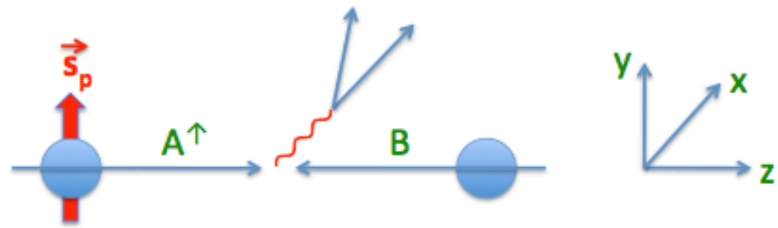
- Multiple upgrades on going
  - MuTrig/RPC (2011)
  - VTX & FVTX (2011)
  - FOCAL
    - proposal, (2014)
- Central Arms
  - |η| < 0.35
  - PID
- Forward Muon Arms
  - 1.2 < |η| < 2.4
  - P > 2.5 GeV



Predictions for Drell-Yan process at RHIC

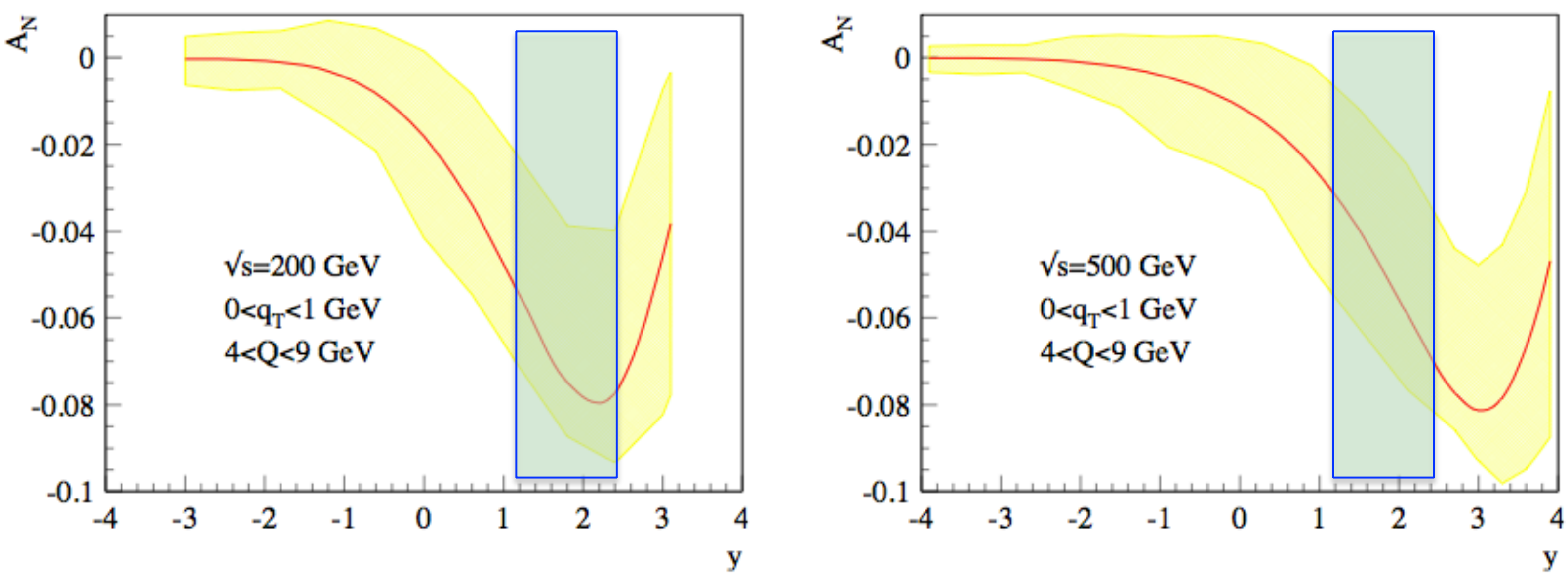
- Reverse the sign of Sivers from SIDIS and make predictions for Drell-Yan production at RHIC

Kang-Qiu, PRD81, 2010



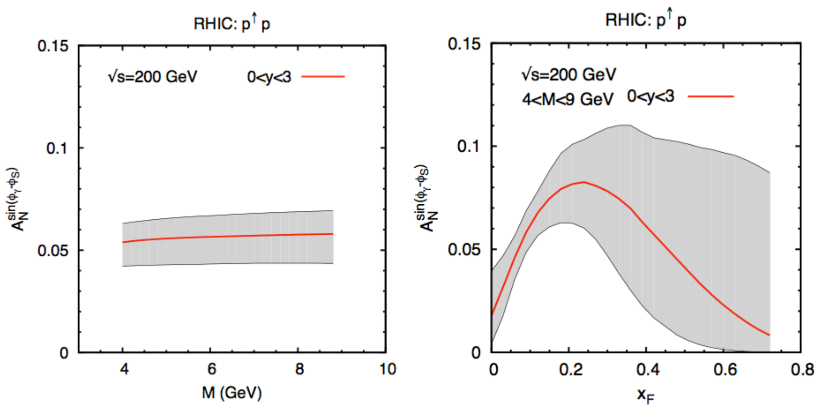
$$A_N \propto \frac{4}{9}\Delta^N u + \frac{1}{9}\Delta^N d < 0$$

- A_N @large XF
- PHENIX dimuons
- 1.2 < |y| <2.4
- muon p > 2.5GeV

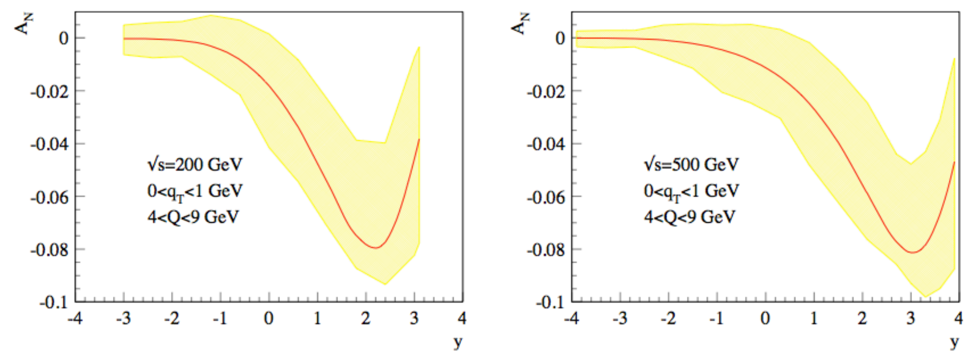


More Predictions of DY Sivers TSSA for RHIC …

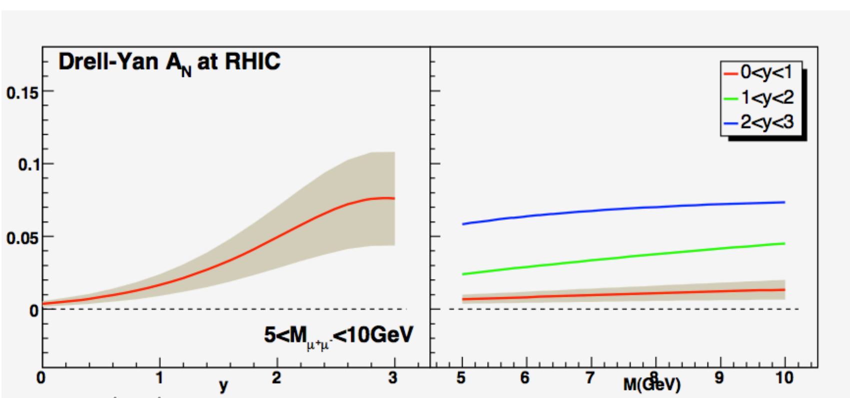
Anselmino et. al. PRD 79, 054010 (2009)



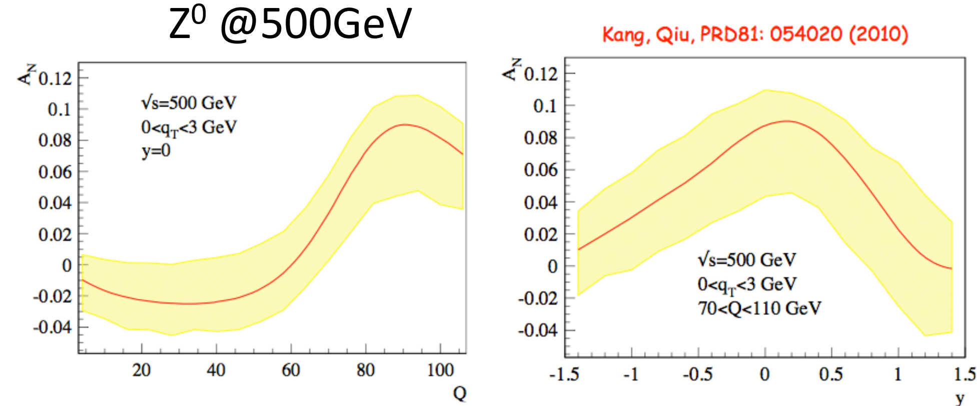
Kang and Qiu, PRD81 054020(2010)



Vogelsang and Yuan PRD72 054028 (2005)



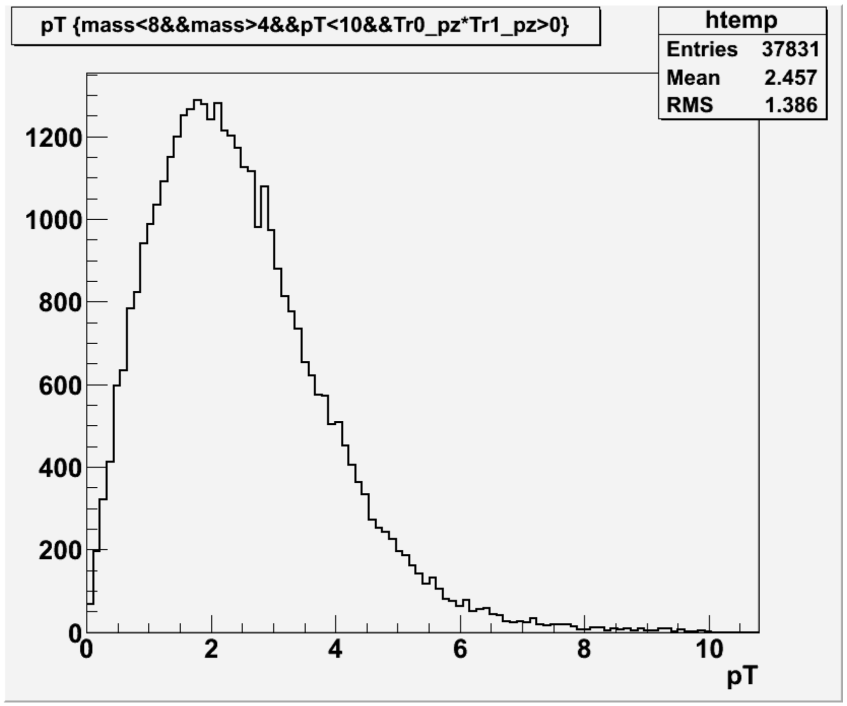
Z^0 @500GeV



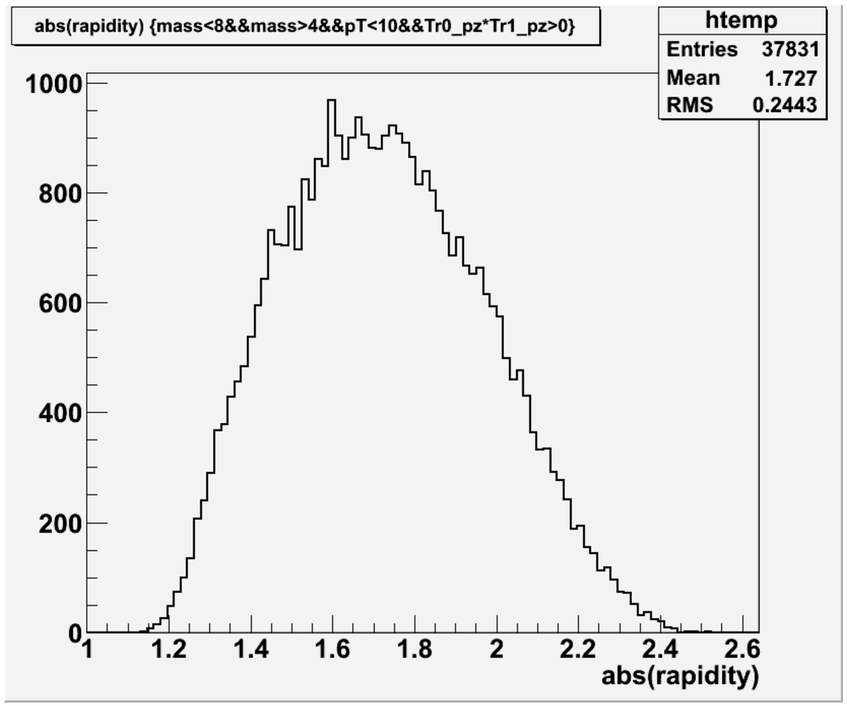
Case Study (I): Drell-Yan pp@200GeV

Accepted Drell-Yan Kinematics in the PHENIX Muon Arms

- pT (GeV)



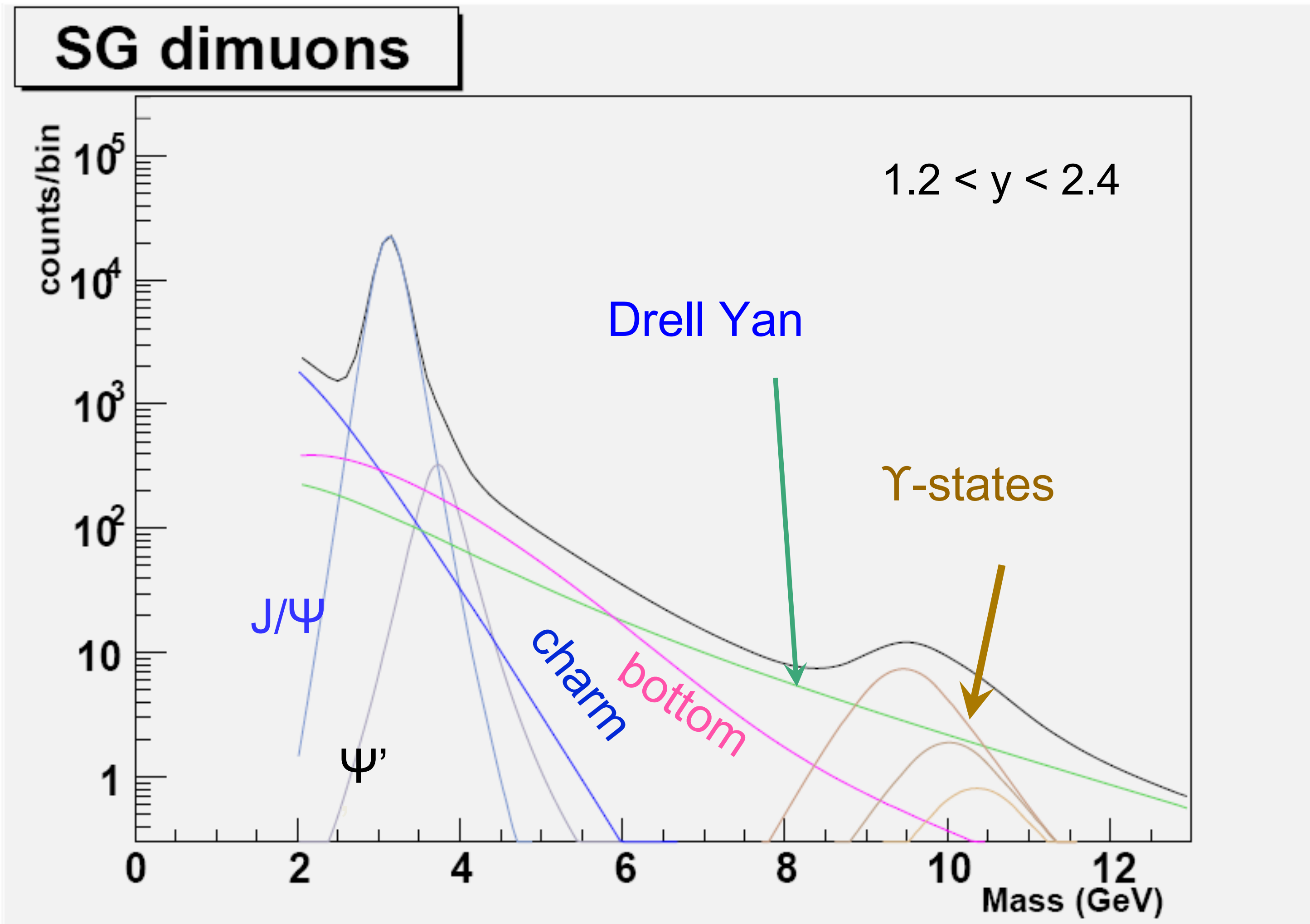
- Rapidity



4 < Mass < 8 GeV

PHENIX Dimuon Cocktails pp@200GeV

(PYTHIA Simulations, DY scaled to NLO)



The Experimental Challenge of Drell-Yan A_N Measurement

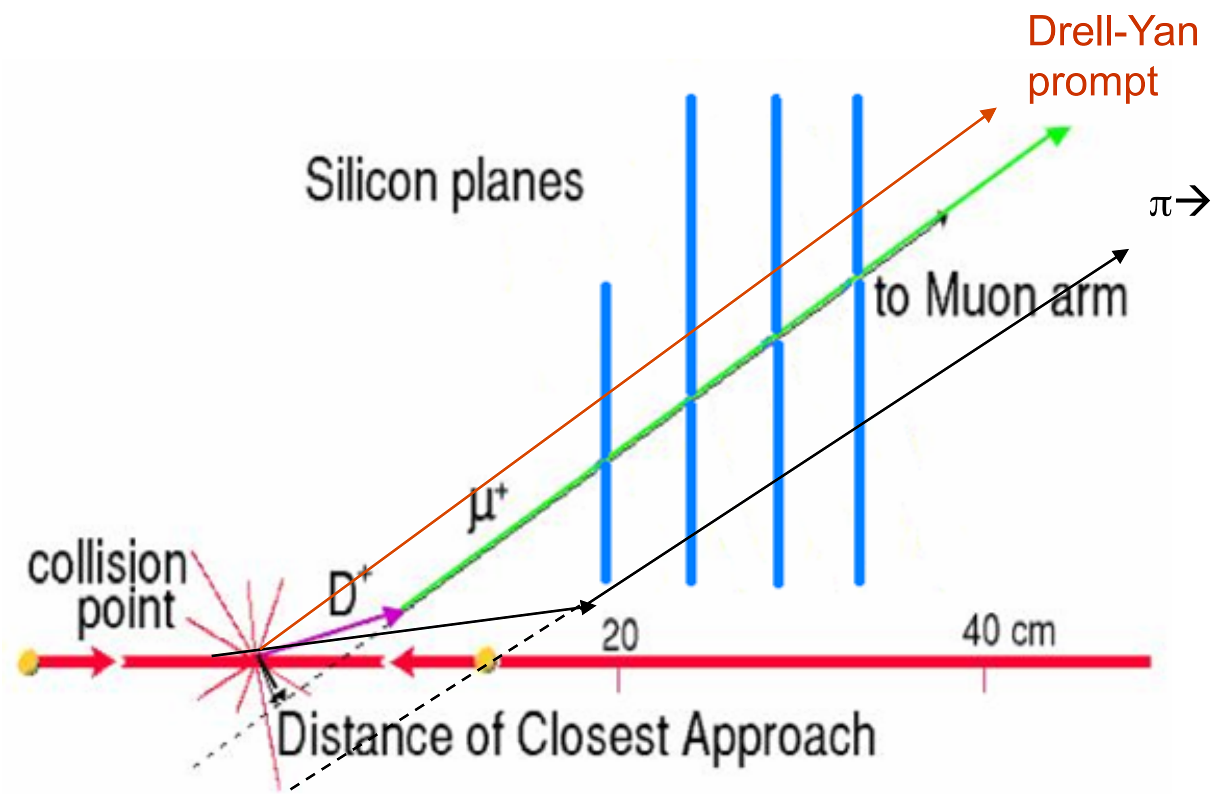
- Need to measure both open heavy and DY
  - Background fraction
  - Background asymmetry
- Silicon VTX - a critical tool

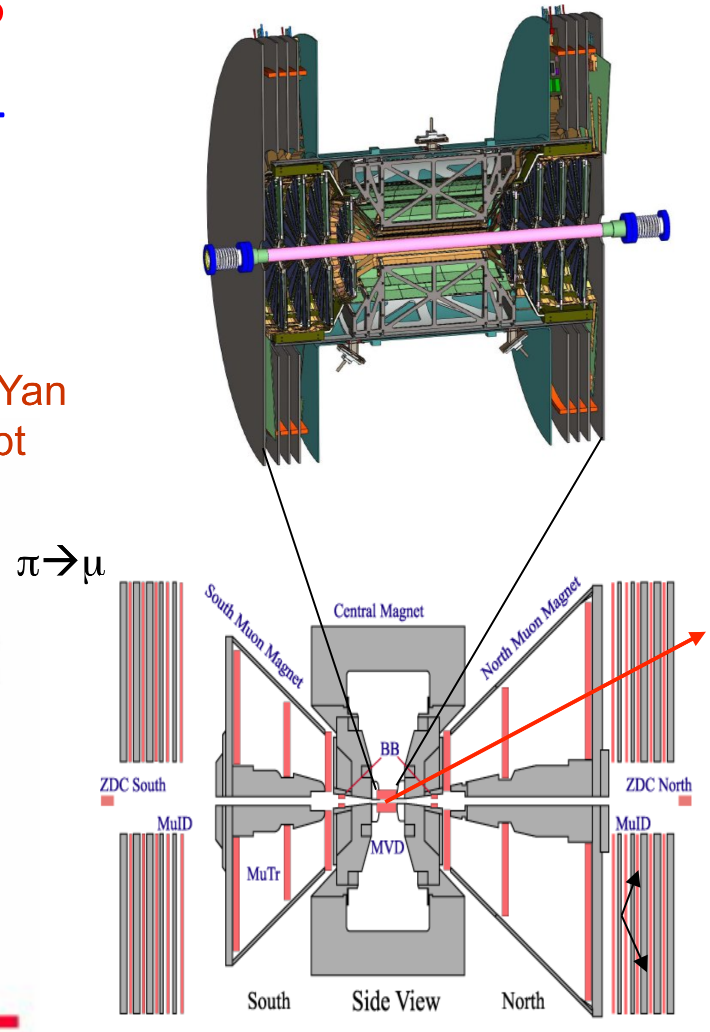
$$A_N^{DY} = \frac{1}{P}\frac{A_N^{incl} - r \cdot A_N^{BG}}{1-r}$$

$$\delta A_N^{DY} \approx \frac{1}{P}\frac{\sqrt{\delta^2 A_N^{incl} + r^2 \cdot \delta^2 A_N^{BG}}}{1-r}$$

PHENIX Silicon VTX Upgrades
– on going, will be completed in 2011

- Precision Charm/Beauty Measurements
- B→J/ψ, Drell-Yan, ψ’

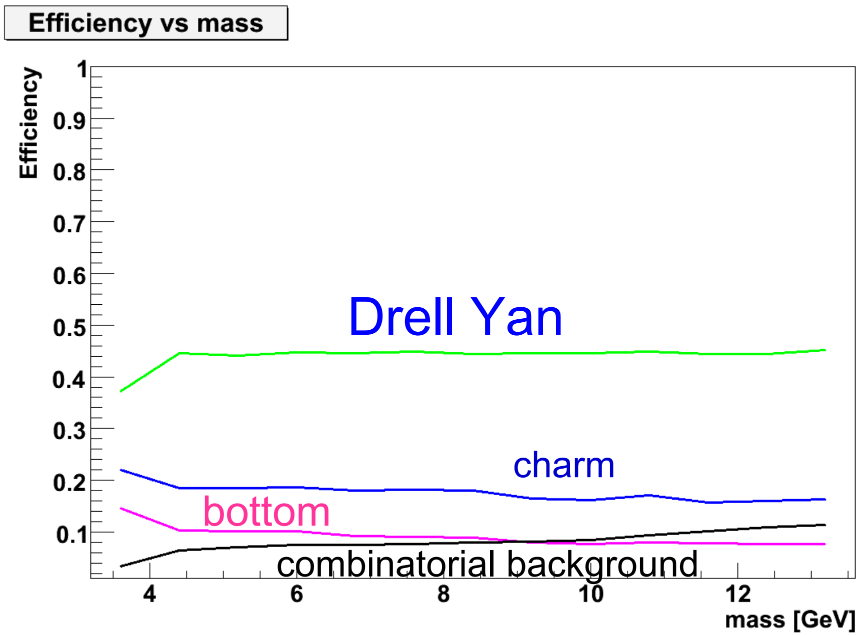




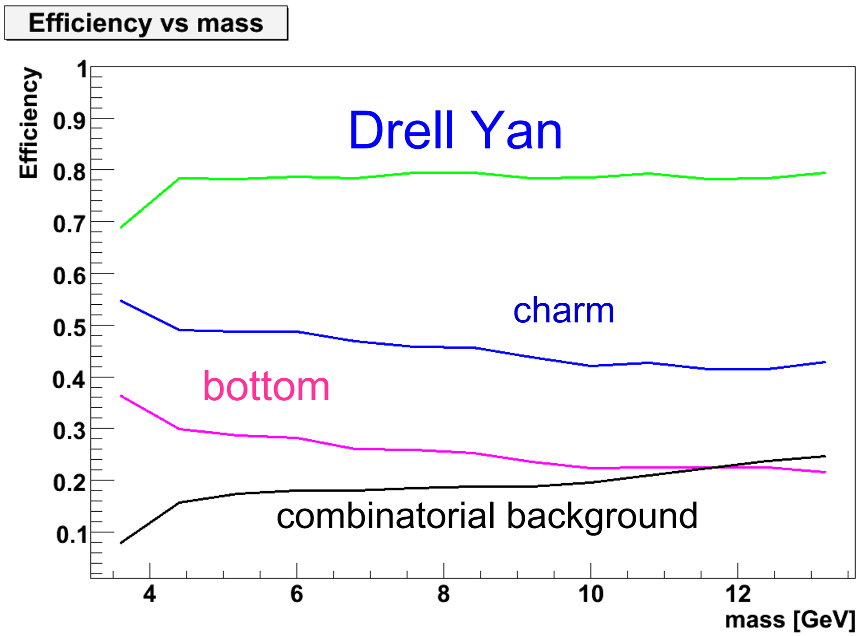
Heavy Quark Background Suppression

- Work in progress

DCA < 1 σ cut:
Increase DY/bb ~ 5



DCA < 2 σ
Increase DY/bb ~ 3



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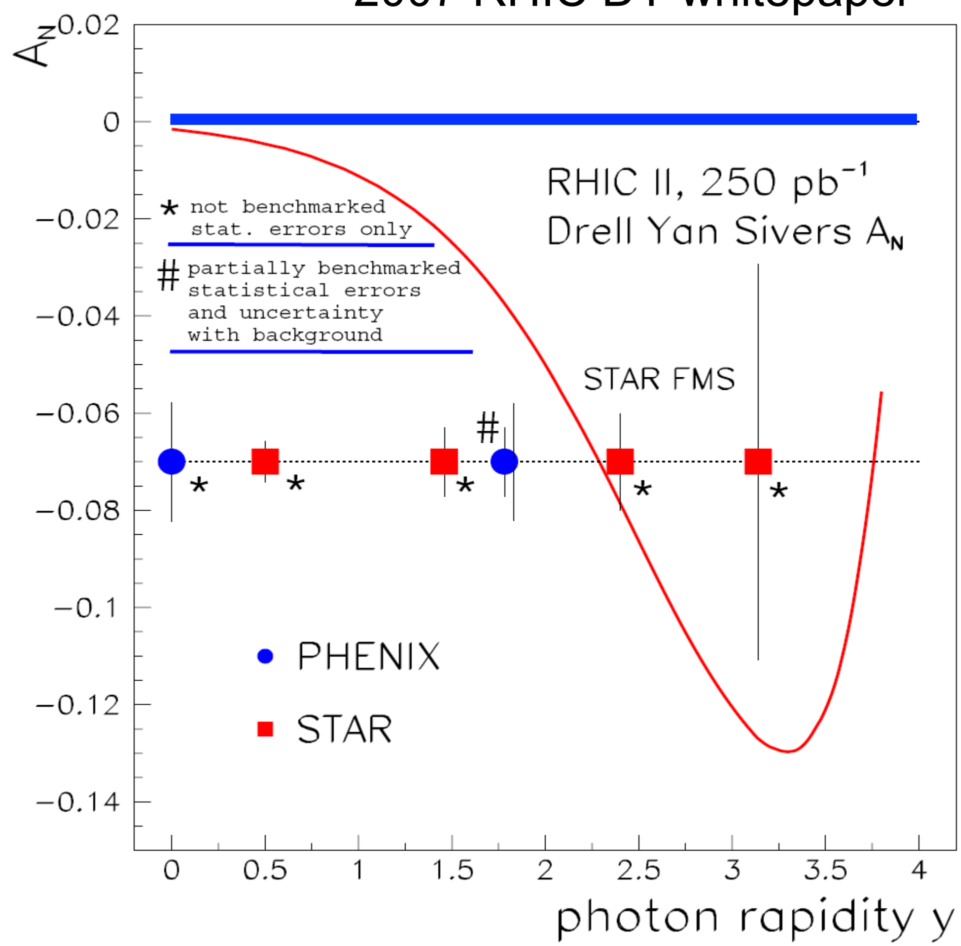
Luminosity Challenged pp@200GeV!

- Expected Luminosity by 2015
  - ~50pb^{-1}
- With upgrade VTX detectors, it is feasible @PHENIX
  - – Drell-Yan X-section OK
  - – A_N statistically limited

– Significant luminosity improvement needed

2007 RHIC DY whitepaper



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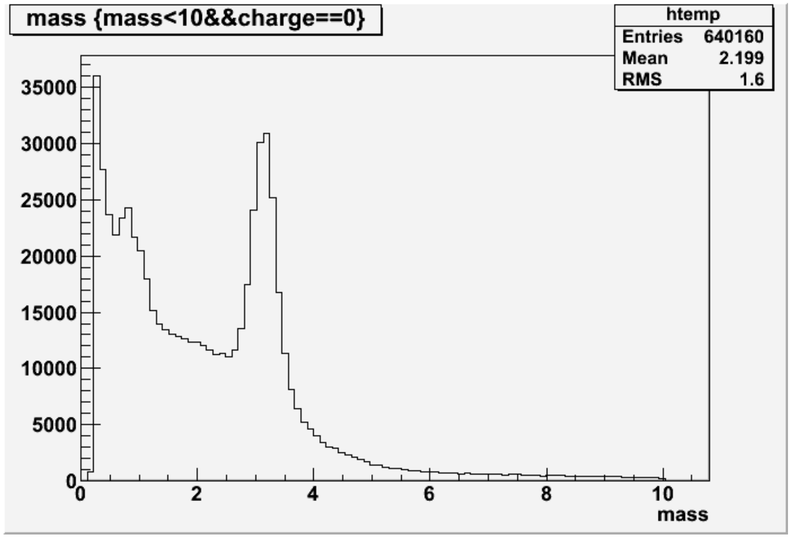
	Au+Au	62	4		0.13 nb^{-1}		HF vs $\sqrt{s_{NN}}$
	p+^{3}He	132	5			(T)	Test Run

Drell-Yan pp@500 GeV 2012-2018

- 500GeV pp runs for "Longitudinal W physics" 2011-2015+
- Can be used to study and benchmark Drell-Yan production in pp@500GeV
  - New VTX/FVTX
  - Central arm di-electrons |y|<0.35
  - Forward arm di-muons
    1.2 < |y| < 2.4
- Possible Boer-Mulders alike asymmetry measurements

Dimuons from Run11 pp@500GeV

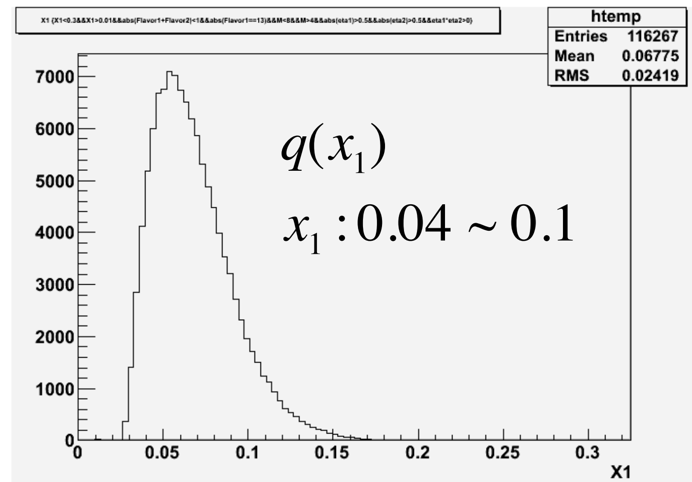


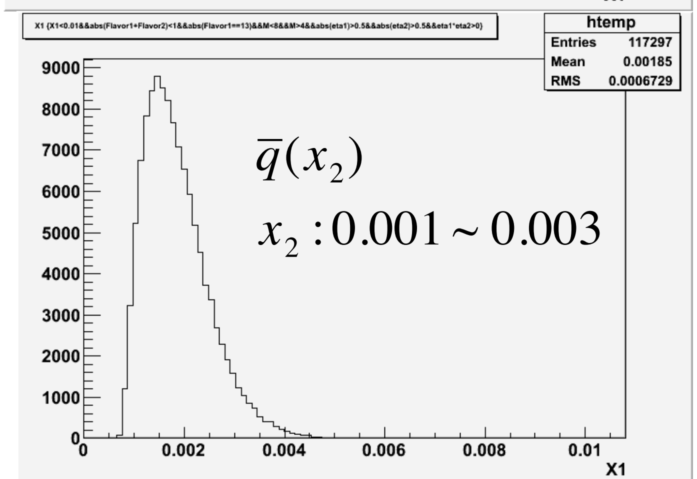
Dimuon mass (GeV)

Forward Drell-Yan Kinematics pp@500 GeV

- Forward DY Dimuons
  - 1.2 < y < 2.4
  - 4<M<8 GeV
- Boer-Mulders asymmetry could be small

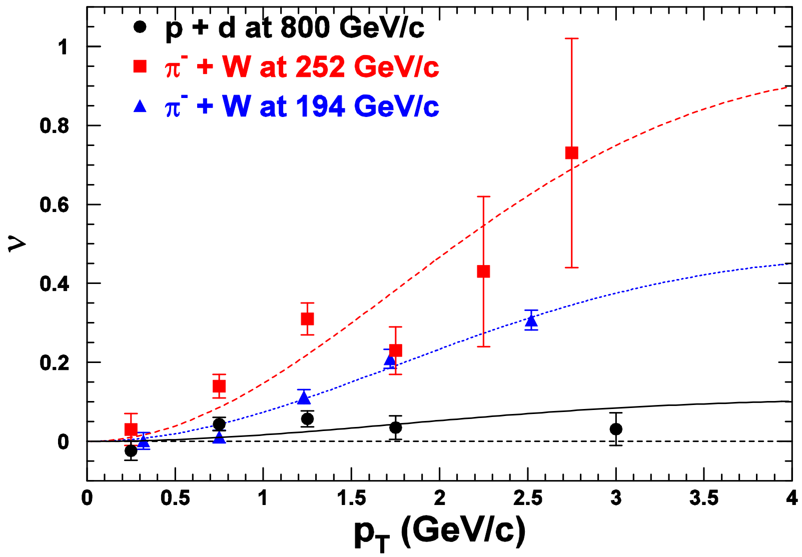
$$\frac{d^2\sigma}{dx_1 dx_2} \approx \frac{\pi\alpha^2}{9M^2}\sum_i e_i^2[q_i(x_1)\bar{q}_i(x_2)]$$





Azimuthal cos2Φ Distribution in Drell-Yan

E866 PRL 99 (2007) 082301; PRL 102 (2009) 182001



Peng's talk

Small ν is observed for p+d and p+p D-Y

$$\nu \propto h_1^{\perp}(x_q) h_1^{\perp}(x_{\bar{q}})$$

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right) = \left[\frac{3}{4\pi}\right]\left[1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi\right]$$

With Boer-Mulders function $h_1^{\perp}$:

$\nu(\pi^- W \to \mu^+\mu^- X) \sim$ [valence $h_1^{\perp}(\pi)$] * [valence $h_1^{\perp}(p)$]

$\nu(pd \to \mu^+\mu^- X) \sim$ [valence $h_1^{\perp}(p)$] * [sea $h_1^{\perp}(p)$]

Sea-quark BM functions are much smaller than valence quarks

More data expected from E906 soon!
Reimer's talk

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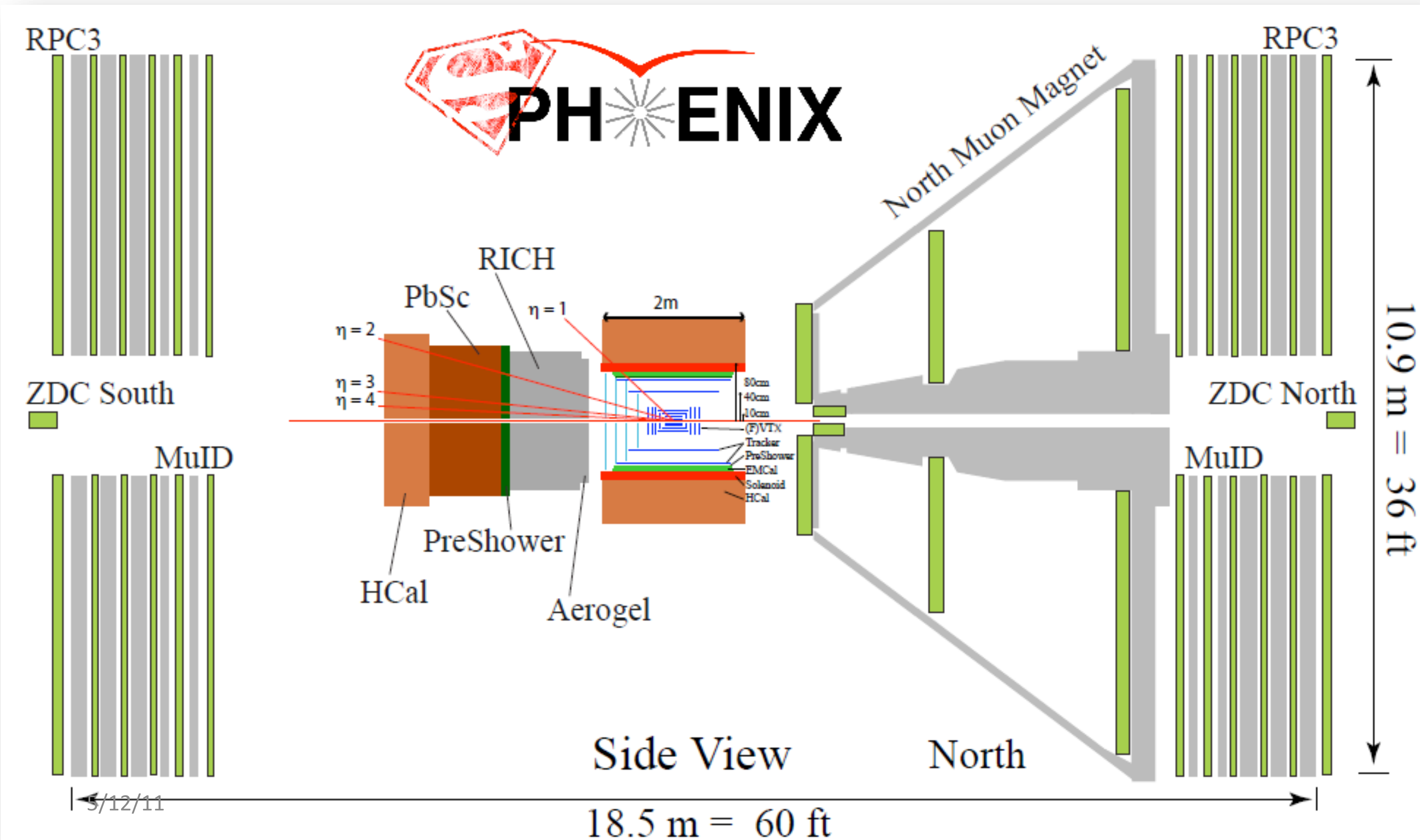
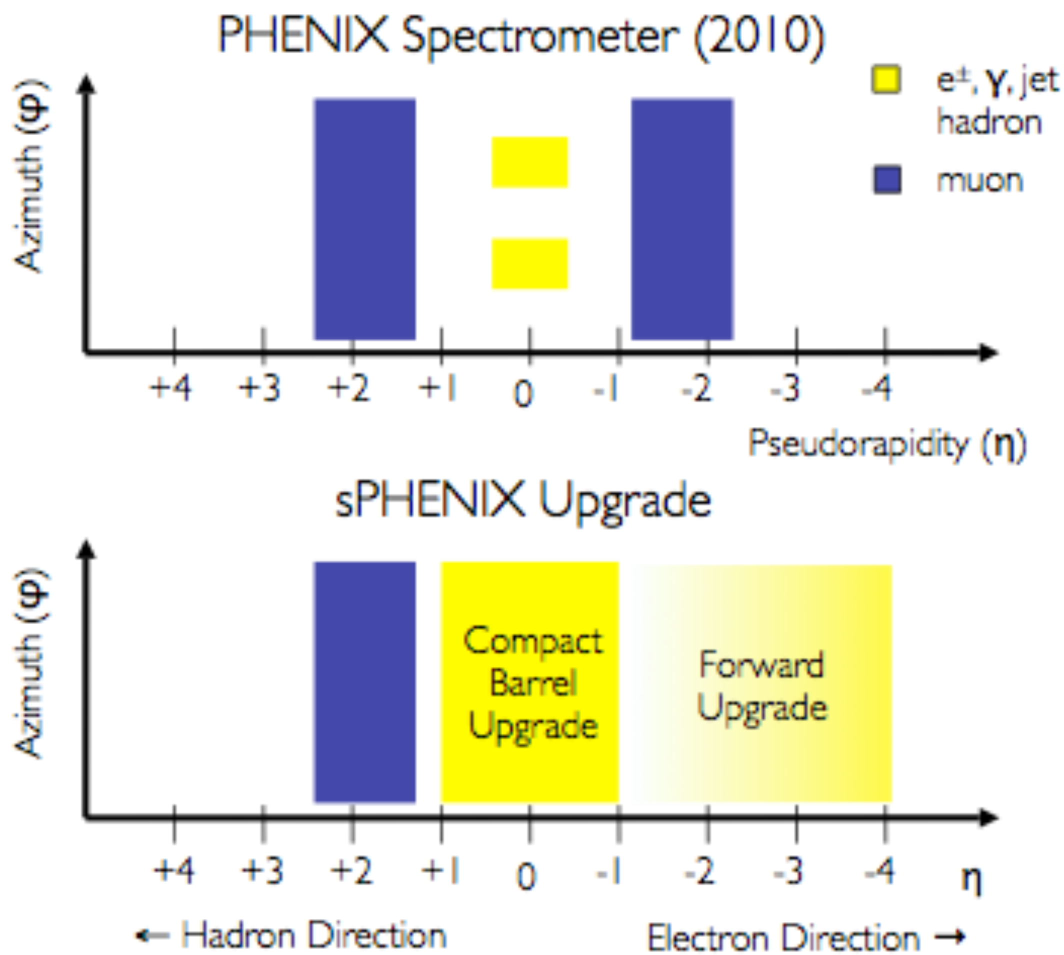
Future Opportunity with sPHENIX 2018 – 20XX

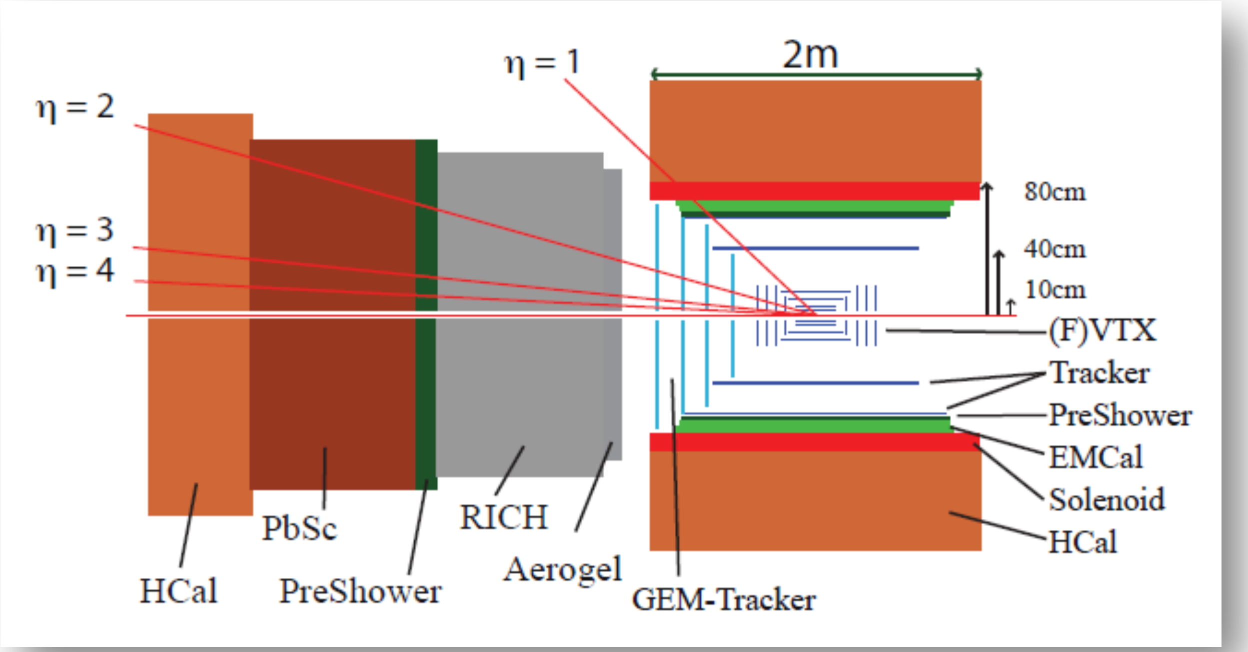


sPHENIX Coverages



sPHENIX Forward Detectors

- Optimized for high energy electrons/photons
  - $2 < \eta < 4$
  - e/photon ID
  - Hadron PID
  - eRHIC ready
    - e+p
    - e+A
  - DY via dielectons @ very forward rapidity

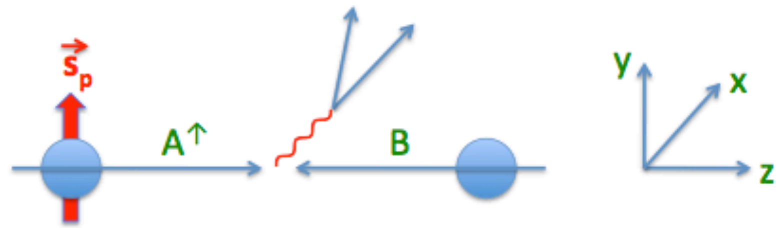


- TRACK has a momentum resolution of $\Delta p/p \approx 2\%$.
- RICH has an electron efficiency of 94% for $p > 10$ GeV/c.
- EMCal has the resolution of the current PHENIX PbGl: $5.95\%/\sqrt{E} + 0.76\%$
- HCAL has the resolution: $50\%/\sqrt{E} + 5\%$ (similar to CMS or LHCb)

Predictions for Drell-Yan process at RHIC

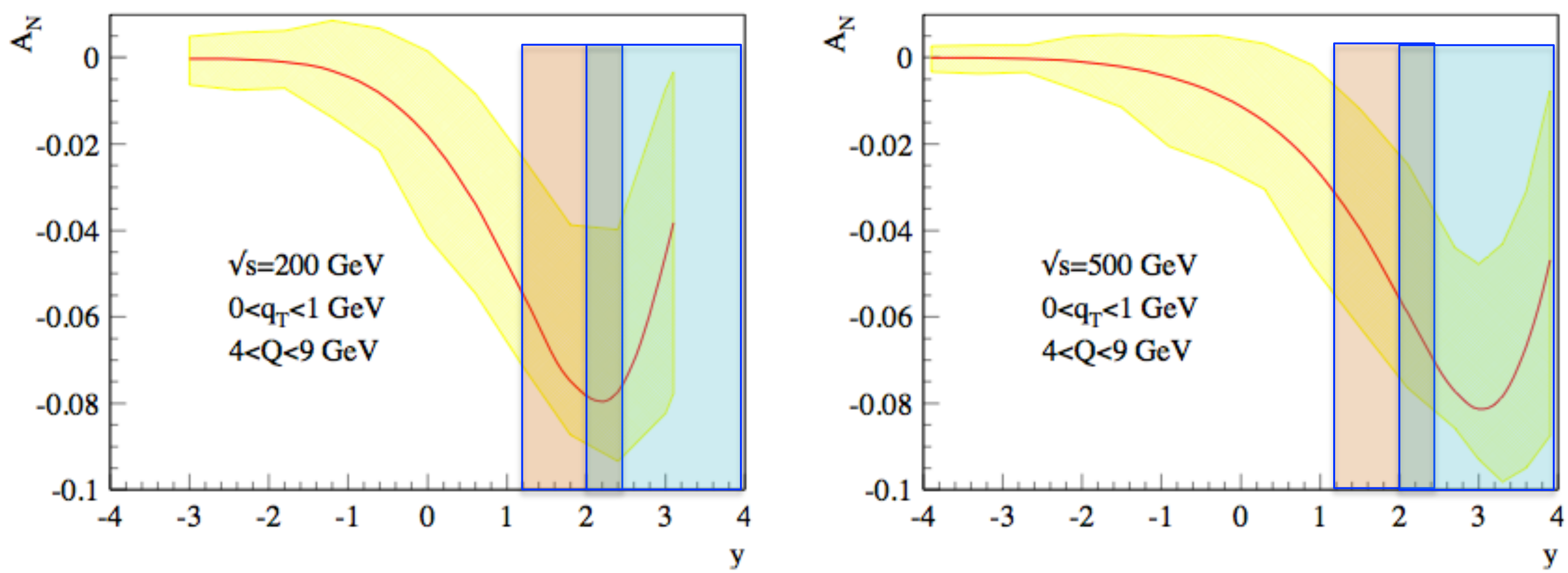
- Reverse the sign of Sivers from SIDIS and make predictions for Drell-Yan production at RHIC

Kang-Qiu, PRD81, 2010

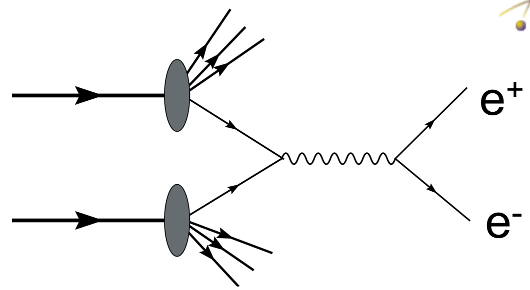


$$A_N \propto \frac{4}{9}\Delta^N u + \frac{1}{9}\Delta^N d < 0$$

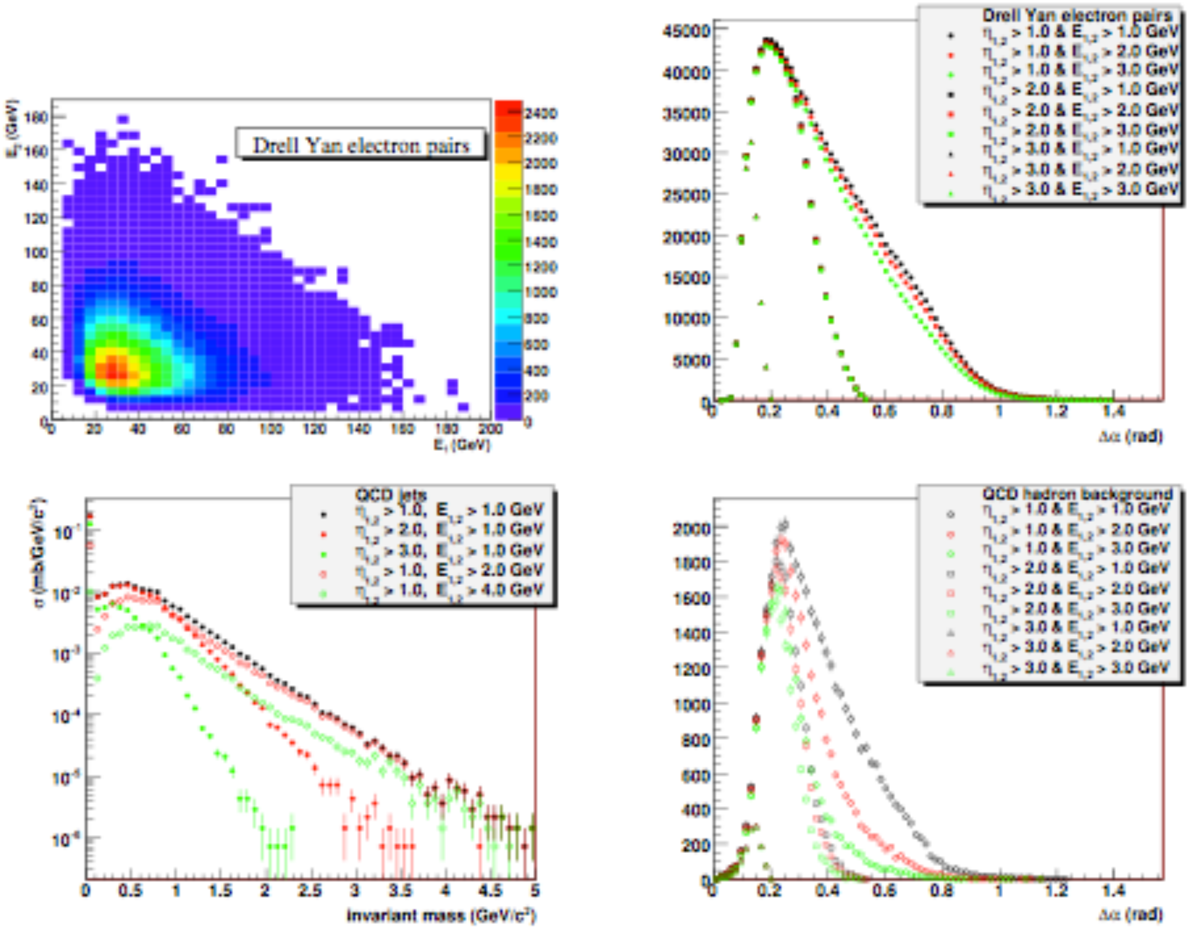
- A_N @large rapidity
- sPHENIX
- 1 < y <4
- DY via dielectrons



Case Study (II): sPHENIX



- Drell-Yan leptons have large energies
  - Expect large A_N @forward
- Background from QCD
  - Decreases with lepton energy
  - Decreases with lepton rapidity

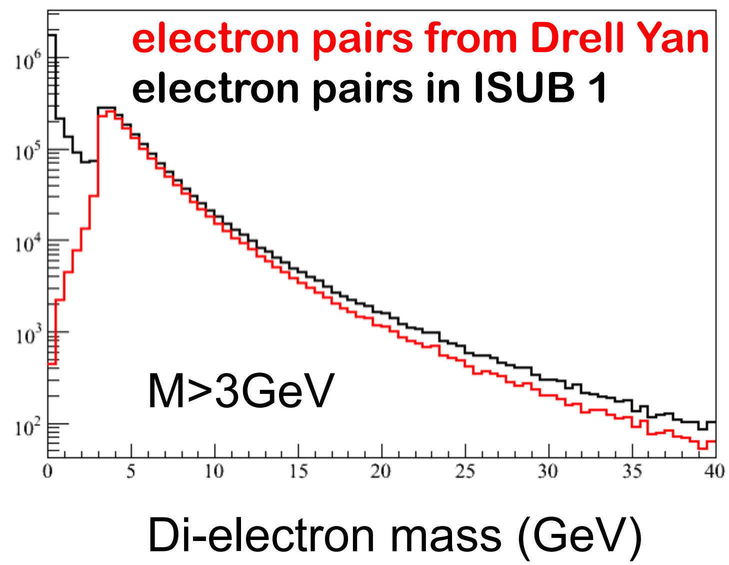


PYTHIA Simulations pp@200/500GeV

- **PYTHIA 6.4**
  - Tune A
  - Drell Yan: ISUB 1
  - QCD jets: ISUBs 11, 12, 13, 28, 53, 68
  - Elastic, diffraction, and low-p_T: ISUBs 91, 92, 93, 94, 95

10M events for Drell Yan
100M+ event for QCD background

- **ISUB 1: γ^* decay modes**



PHENIX

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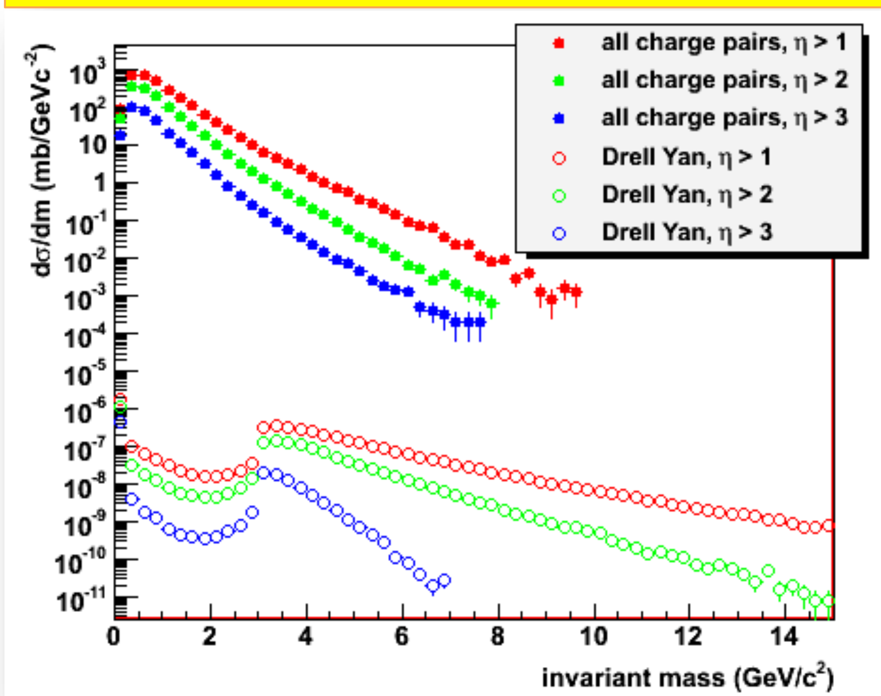
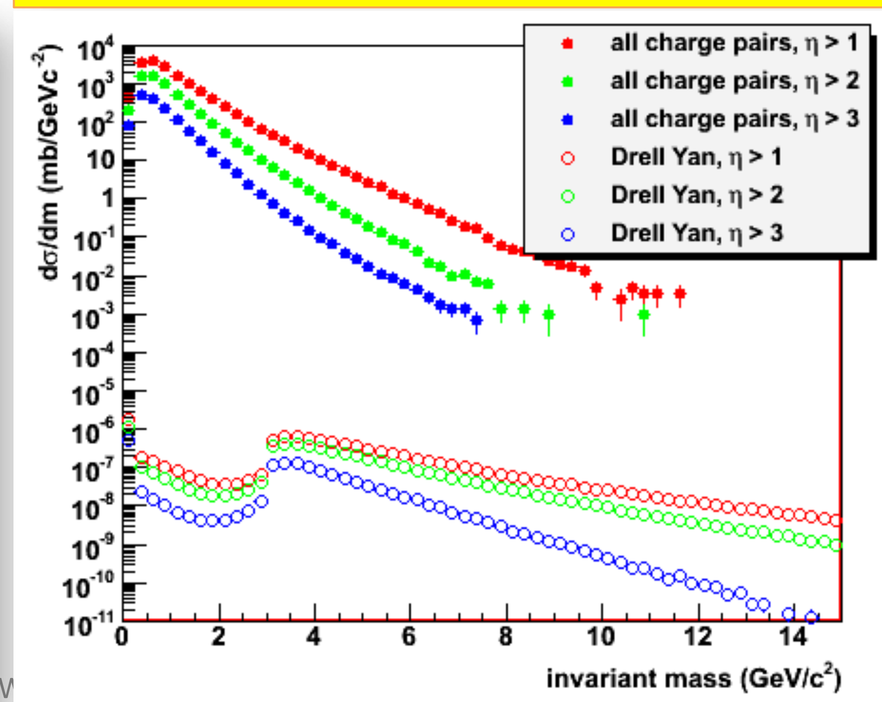
Hadronic Backgrounds

- All charged particle pairs between J/Ψ and Υ
- Hadron suppression 10^3-10^4 needed at 500 GeV
  - Drell Yan yield reduced more in 200 GeV @forward

$\sqrt{s}$ = 200 GeV

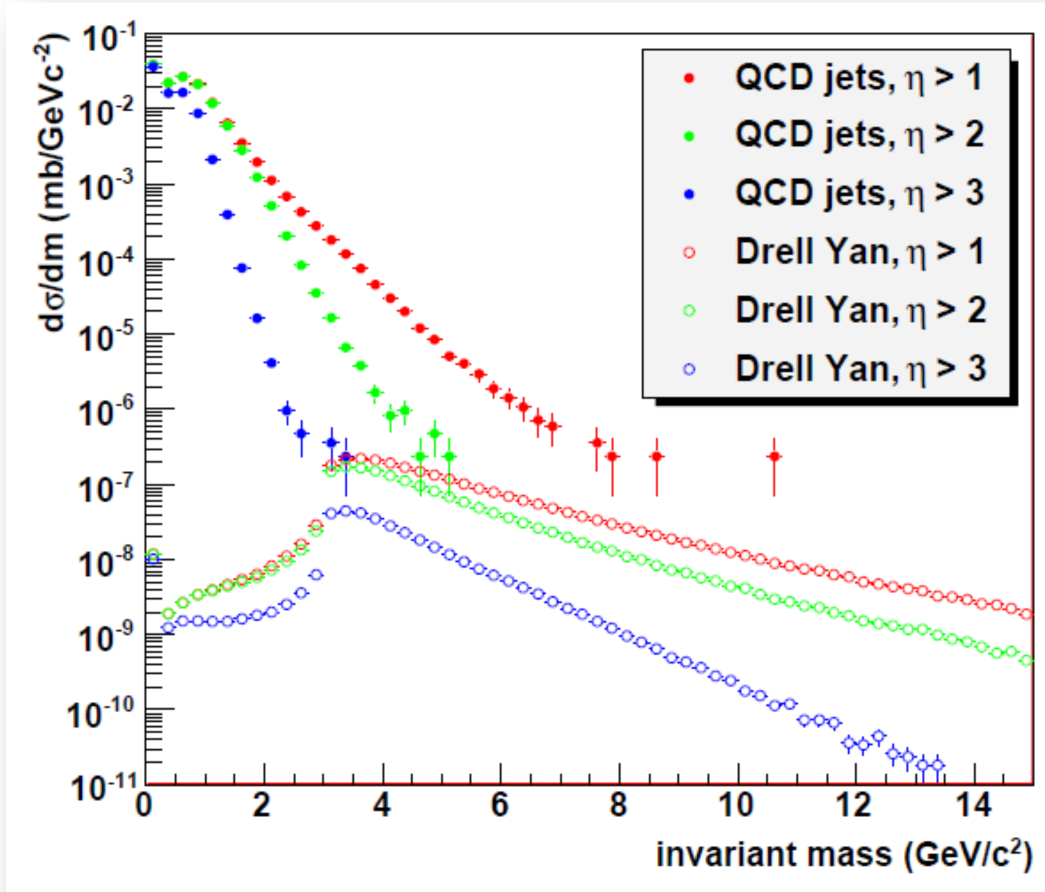


$\sqrt{s}$ = 500 GeV



QCD Jet Backgrounds pp@500GeV

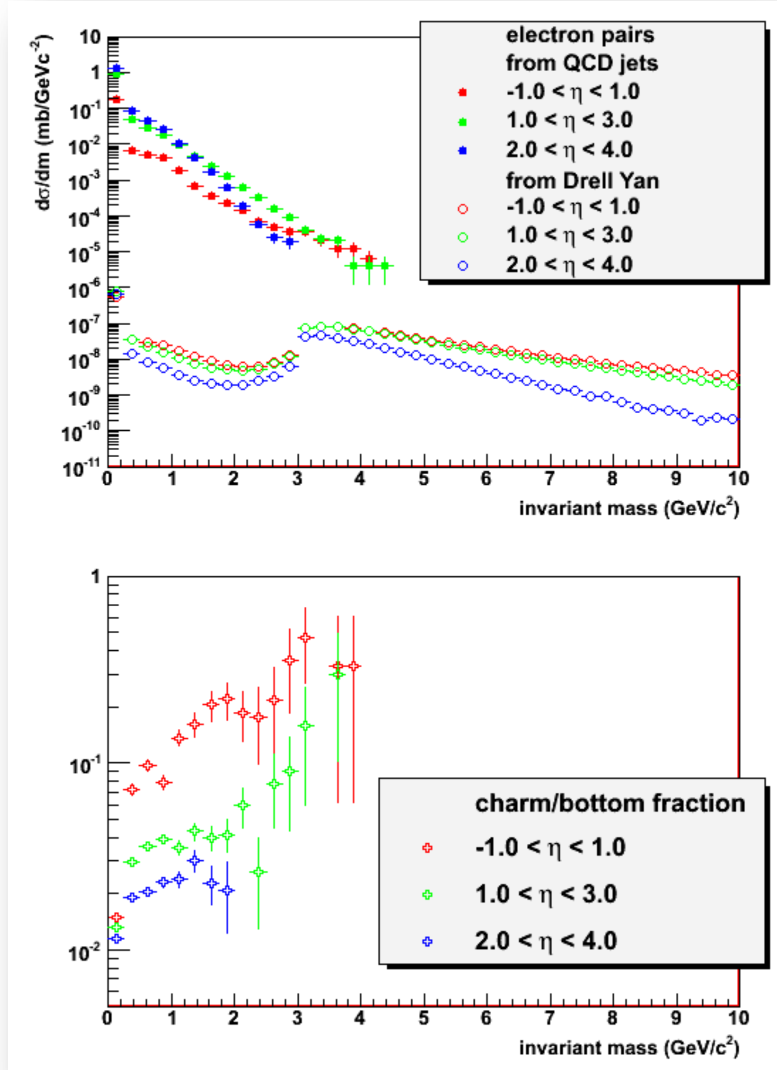
- Samples
  - Drell-Yan dielectrons signal
  - Hard QCDs + Diffratives
- Energy cut
  - $E_{1,2} > 2$ GeV
- Forward rapidities
  - Effectively no background left @η>3
  - Statistically limited



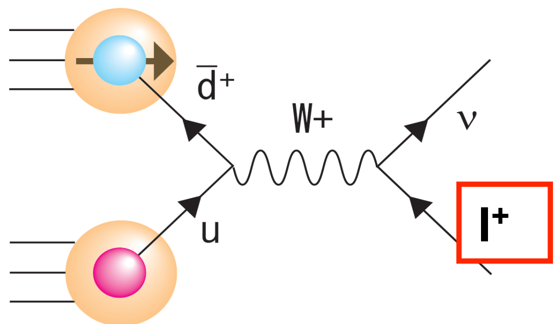
Heavy Flavor Backgrounds

- Charm & bottom contributions increase with m_{inv}
- Less heavy flavor contributions at larger rapidity
- Need designated heavy flavor simulations
  - More statistics

Work in progress …



$W^{+/-}$ Transverse SSA @500GeV ?



Kang & Qiu (2009), Zhou & Metz (2010)

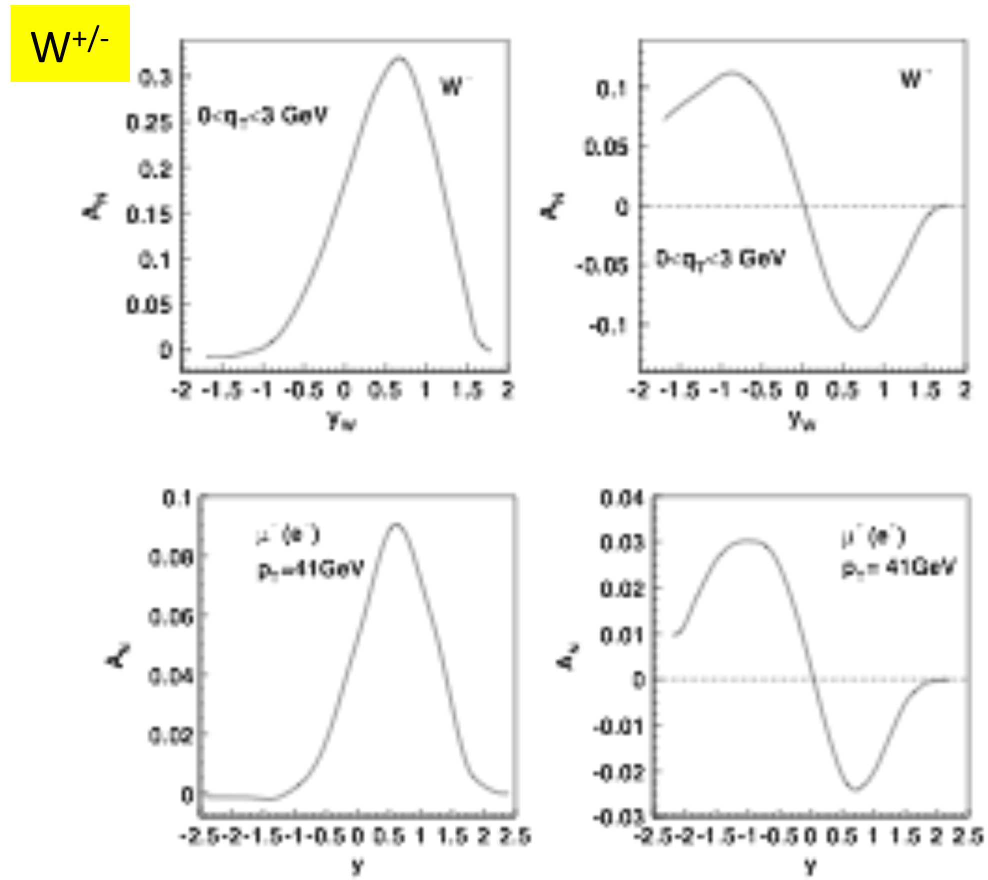


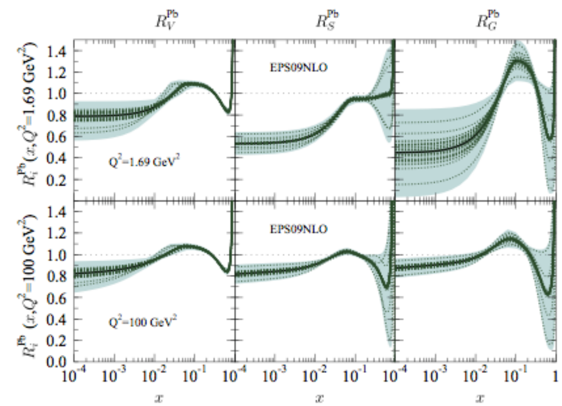
FIG. 3. A_N as a function of lepton rapidity.

- Latest theoretical progress
  - Test time-reversal universality of Sivers functions with W/Z
  - Expect large asymmetry (from DIS fit)
- Flavor-identified Sivers Funs
  - Very large Q^2
- Need high luminosity, ~1fb^{-1} 500GeV
  - $W^{+/-} \rightarrow \mu^{+/-}$ ~20K
  - $Z^0 \rightarrow \mu^+\mu^-$ ~ 1K
  - sPHENIX: wider coverage

Topic (II): Forward Drell-Yan and Sea Quarks @small-x

Reimer, Peng's talks

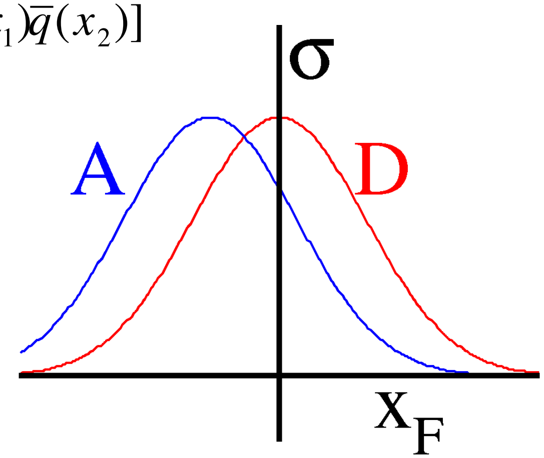
- Sea quark distributions at small-x
  - kT << M
  - Consistency check DIS vs DY
- Parton energy loss vs shadowing effects
  - pT broadening

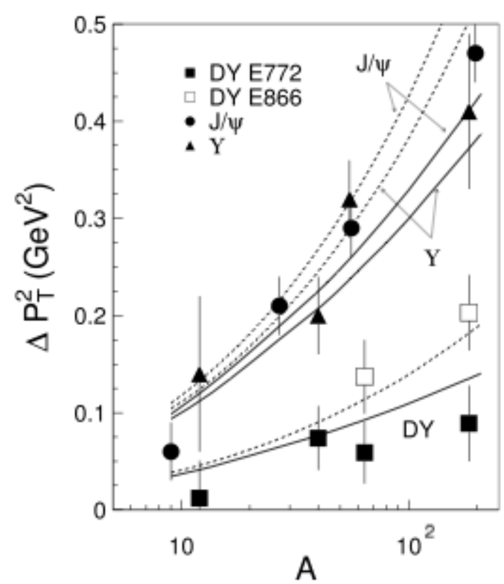


$$\frac{d^2\sigma}{dx_1 dx_2} \approx \frac{4\pi\alpha^2}{9x_1x_2s}\sum e^2[q(x_1)\bar{q}(x_2)]$$

$$x_1 = x'_1 - \delta x_1$$

$$\frac{\Delta E}{E} \sim \frac{\delta x_1}{x_1}$$

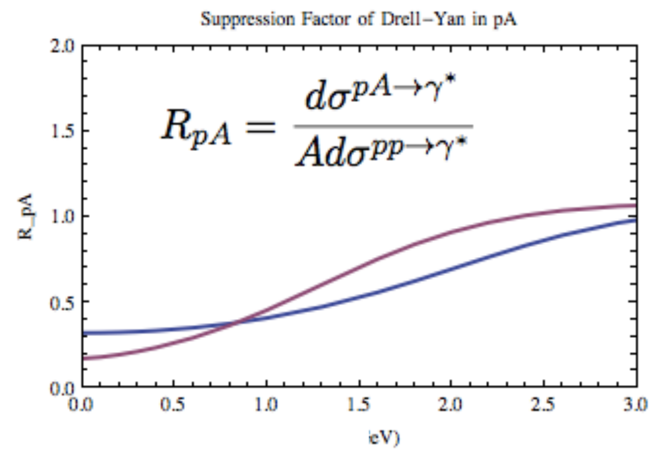


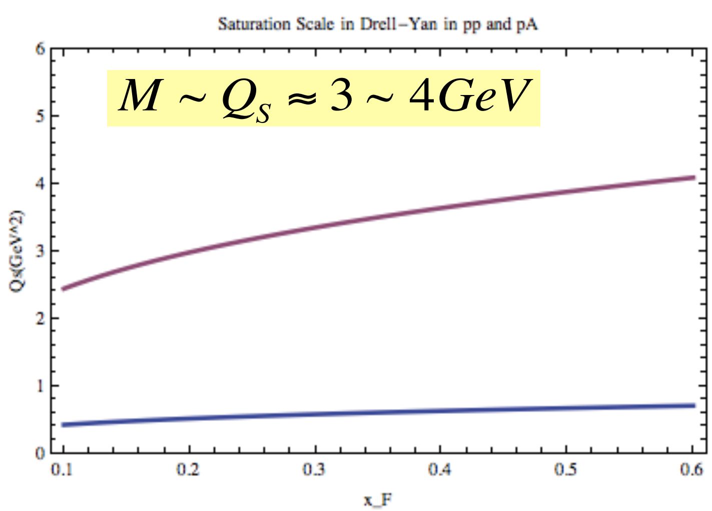


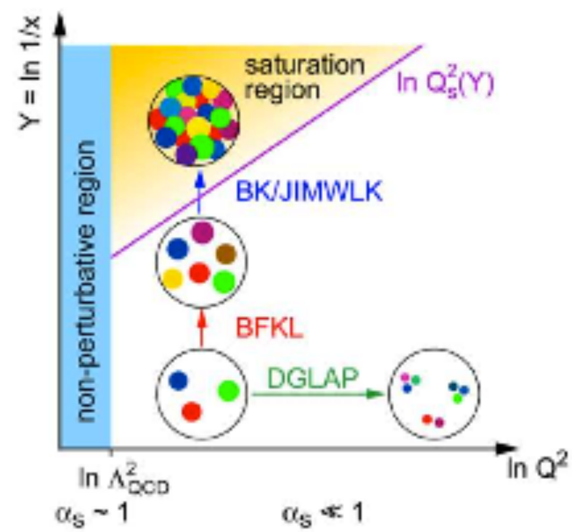
Forward DY and Small-x Saturation Physics

- Forward DY at PHENIX
  - Saturation effects could be important
  - DGLAP probably not enough
  - Muon arms: y = 1.2~2.4
  - sPHENIX: y= 2~4 (2018+)

Feng, Al, Jamal's talks







Summary and Outlook

- PHENIX VTX/FVTX upgrades make Drell-Yan measurements possible
  - Central arms
  - Forward muon arms
  - Boer-Mulders asymmetry measurement possible from upcoming longitudinally polarized pp @500GeV
- Possible Test of Drell-Yan A_N sign change @200GeV and @500GeV after longitudinal W program, ~2017 with forward muon arms
  - much improved luminosity needed
- sPHENIX upgrade (2018+)
  - Extend the coverage to very forward rapidity η = 2~4
  - Test sign change in Drell-Yan A_N via di-electrons at very forward rapidity where significant asymmetry expected
- Explore small-x saturation physics at forward rapidity in p(d)A

PHENIX

Los Alamos NATIONAL LABORATORY

The magic of sign change

Drawing from D. Sivers @Santa Fe Polarized Drell-Yan Workshop 10/31-11/1, 2010

Backup slides

PHENIX

Los Alamos NATIONAL LABORATORY

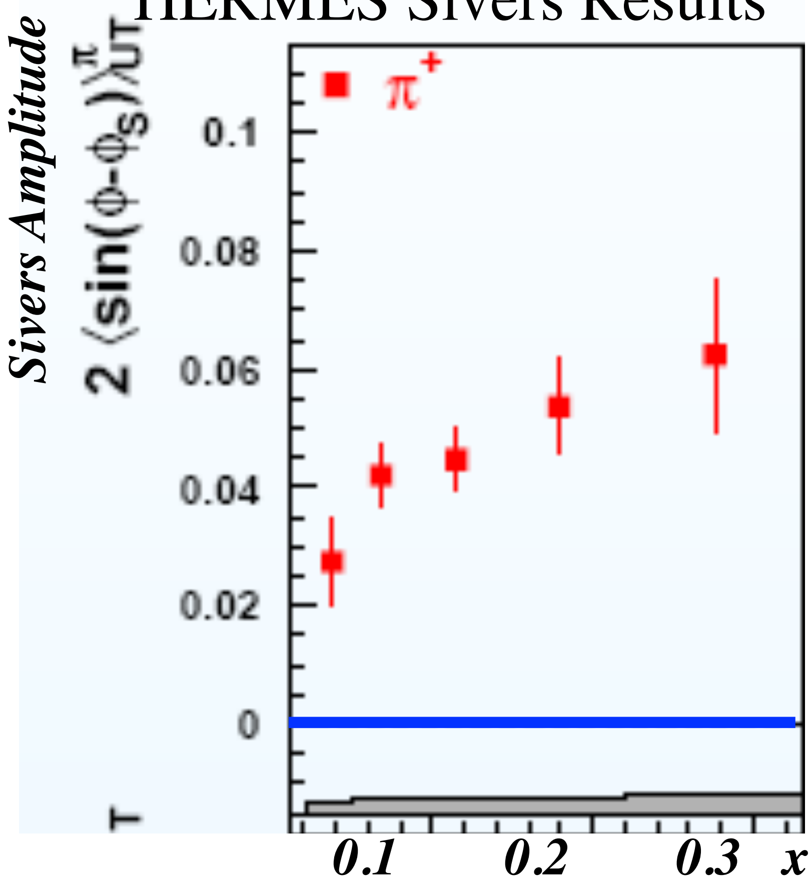
Table B.2: Table of PHENIX Past 10 Years of running (2000-2010) for $|z| < 30$ cm.

run	Species	$\sqrt{s_{NN}}$	$\int$ L dt	Pol.	Comments
1	Au+Au	130	1.0 μb^{-1}	—	first heavy-ion run
2	Au+Au	200	24 μb^{-1}	—	first jet quenching + flow results
	p+p	200	0.15 pb^{-1}	(T)	first p+p spin run
3	d+Au	200	2.7 nb^{-1}	—	first CNM run
	p+p	200	0.35 pb^{-1}	(L)	first π^0 ΔG and J/ψ
4	Au+Au	200	241 μb^{-1}	—	HI high statistics
	Au+Au	62.4	9 μb^{-1}	—	HI energy dependence
5	Cu+Cu	200	3 nb^{-1}	—	HI geometry dependence
	Cu+Cu	62.4	0.2 nb^{-1}	—	} HI geom. + energy dep.
	Cu+Cu	22.5	2.7 μb^{-1}	—	
	p+p	200	3.8 pb^{-1}	(L)	spin running
6	p+p	200	10.7 pb^{-1}	(T&L)	high statistics spin run
	p+p	62.4	0.1 pb^{-1}	(L)	HI comparison, spin lower E
7	Au+Au	200	0.8 nb^{-1}	—	HI high statistics II, RXPN detector
8	d+Au	200	80 nb^{-1}	—	high statistics CNM–MPC correlation, J/ψ suppression
	p+p	200	5.2 pb^{-1}	(T)	spin run
9	p+p	500	14 pb^{-1}	(L) 39%	first W spin run
	p+p	200	16 pb^{-1}	(L) 55%	spin run
10	Au+Au	200	1.3 nb^{-1}	—	} HI dilepton HBD runs
	Au+Au	62.4	0.11 nb^{-1}	—	
	Au+Au	39	40 μb^{-1}	—	HI lower energy + dileptons
	Au+Au	7.7	0.26 μb^{-1}	—	HI lowest energy

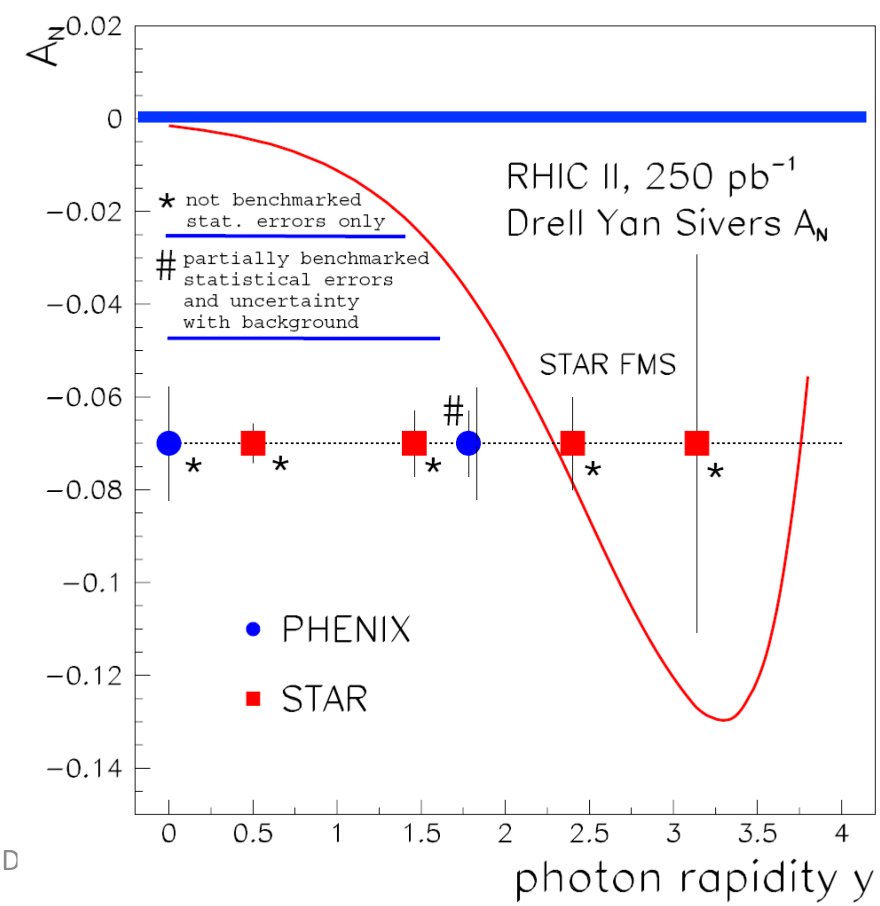
Experiment SIDIS vs Drell Yan: $\text{Sivers}|_{DIS} = -\text{Sivers}|_{DY}$

*** Probes QCD attraction and QCD repulsion ***

HERMES Sivers Results



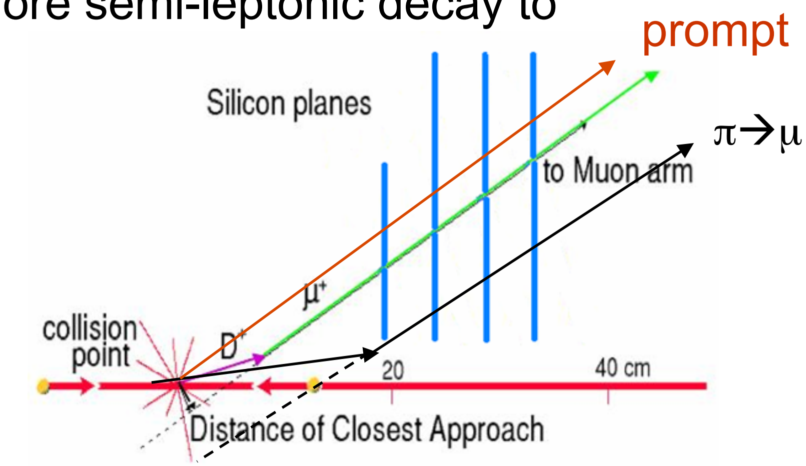
RHIC II Drell Yan Projections

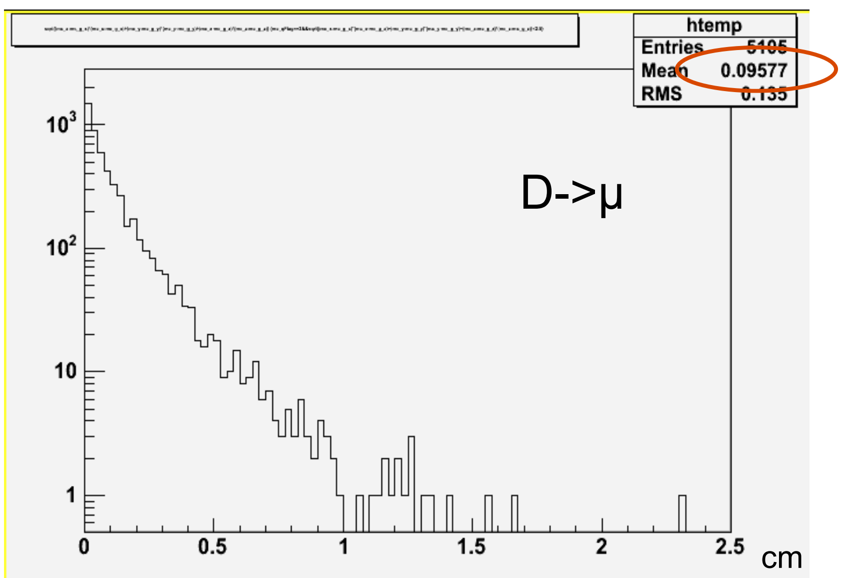


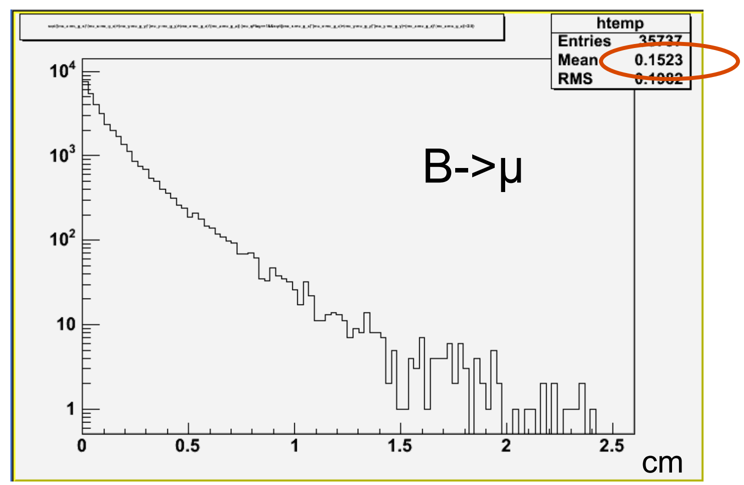
Impact Parameters for muons from D,B and DY

Measuring Charm, Beauty and Drell-Yan

- D, B mesons travel ~1 mm (with boost) before semi-leptonic decay to muons
- By measuring DCA to primary vertex, can separate D and B from prompt particles and long-lived decays like π, K

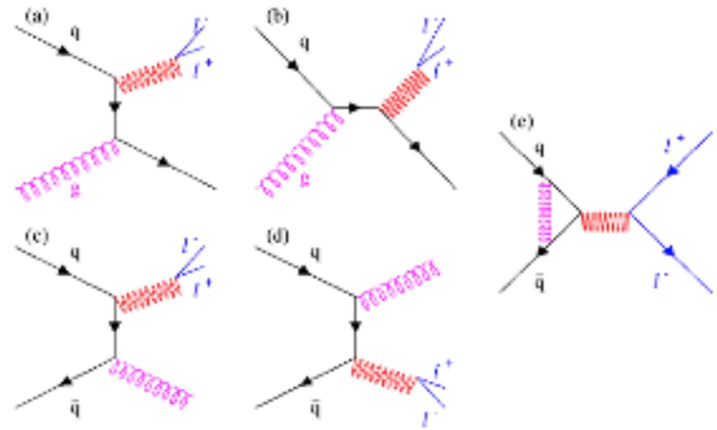






QCD Correction

K factor collection



$$d\sigma^{DY}_{NLO} = K(s, M^2)d\sigma^{DY}_{LO}$$

Group	Beam/target	cm Energy	K
E288	p/Pt	27.4	1.7
E439	p/W	27.4	1.6±0.3
CHFMNP	p/p	44,63	1.6±0.2
AABCSY	p/p	44,63	1.7
NA3	p/Pt	27.4	3.1±0.5±0.3
E537	$\bar{p}$/W	15.3	2.45±0.12±0.20
NA3	(p-$\bar{p}$)/Pt	16.8	2.3±0.4
NA3	π/Pt	16.8	2.49±0.37
		22.9	2.22±0.33
E326	π/W	20.6	2.70±0.08±0.40
NA10	π/W	19.1	2.8±0.1
Goliath	π/Be	16.8,18.1	2.5
Omega	π/W	8.7	2.6±0.5

Table VII..2. *K* Factors for dilepton experiments (Grosso-Pilcher and Shochet, 1986).