$p\bar{p} \rightarrow \mu^+\mu^- X$

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for the PANDA Collaboration

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Scattering and annihilation electromagnetic processes

ECT*, Trento (Italy)
February 18-22, 2013

Overview

- $p\bar{p} \rightarrow \mu^+\mu^- X$
  - Drell-Yan process and background @ PANDA
    - A. Bianconi Drell-Yan generator
    - Cut studies
  - Investigation of Drell-Yan asymmetries

- $p\bar{p} \rightarrow \mu^+\mu^-$
  - Strong and electromagnetic relative phase via J/ψ resonance scan
    - Simulated yelds
    - Energy choice method

- Summary

$$p\bar{p} \rightarrow \mu^{+}\mu^{-}X$$

Motivation

Complete description of the nucleonic structure requires:

- Parton Distribution Functions (PDF)
- Fragmentation Functions (FF)

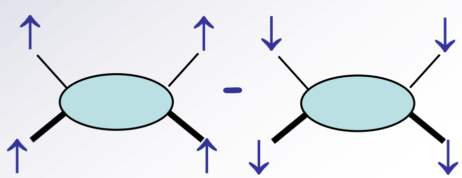
Including k_T dependence

- Transverse Momentum Dependent (TMD) PDF and FF
- Test of Universality $f_{1T}^{\perp f}\,|_{DY} = -\,f_{1T}^{\perp f}\,|_{SIDIS}$

J. C. Collins and D. E. Soper, Nucl. Phys. **B 194**, 445 (1982)

Helicity base

Twist-2 PDFs: $f_1^u(x) \equiv u(x),\ g_1^u(x) \equiv \Delta u(x), h_1^u(x) \equiv \delta u(x)$



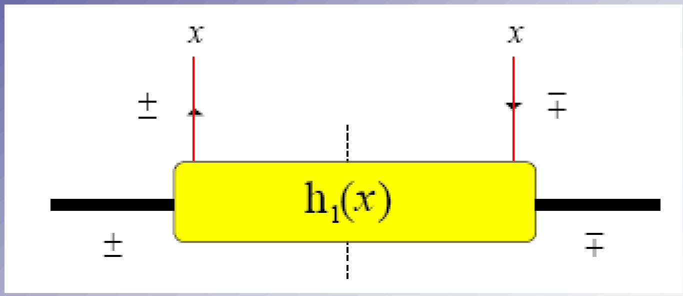
δq(x) helicity flip

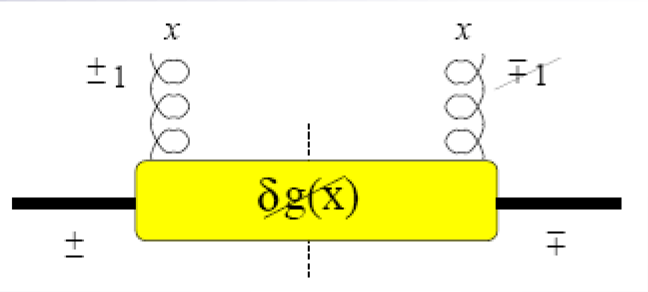
off diagonal in the helicity base

$$u^{\uparrow} = \frac{1}{\sqrt{2}}\left(u_R + u_L\right)$$

$$u^{\downarrow} = \frac{1}{\sqrt{2}}\left(u_R - u_L\right)$$

Transversity





δq(x): a chirally-odd, helicity flip distribution function

δg(x): no gluon transversity distribution; transversely polarised nucleon shows transverse gluon effects at twist-3 (g_2) only

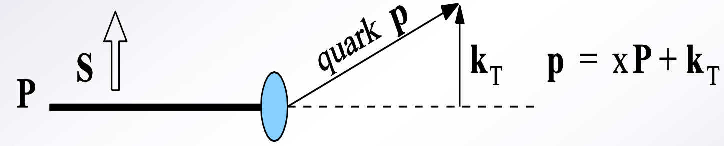
SOFFER INEQUALITY

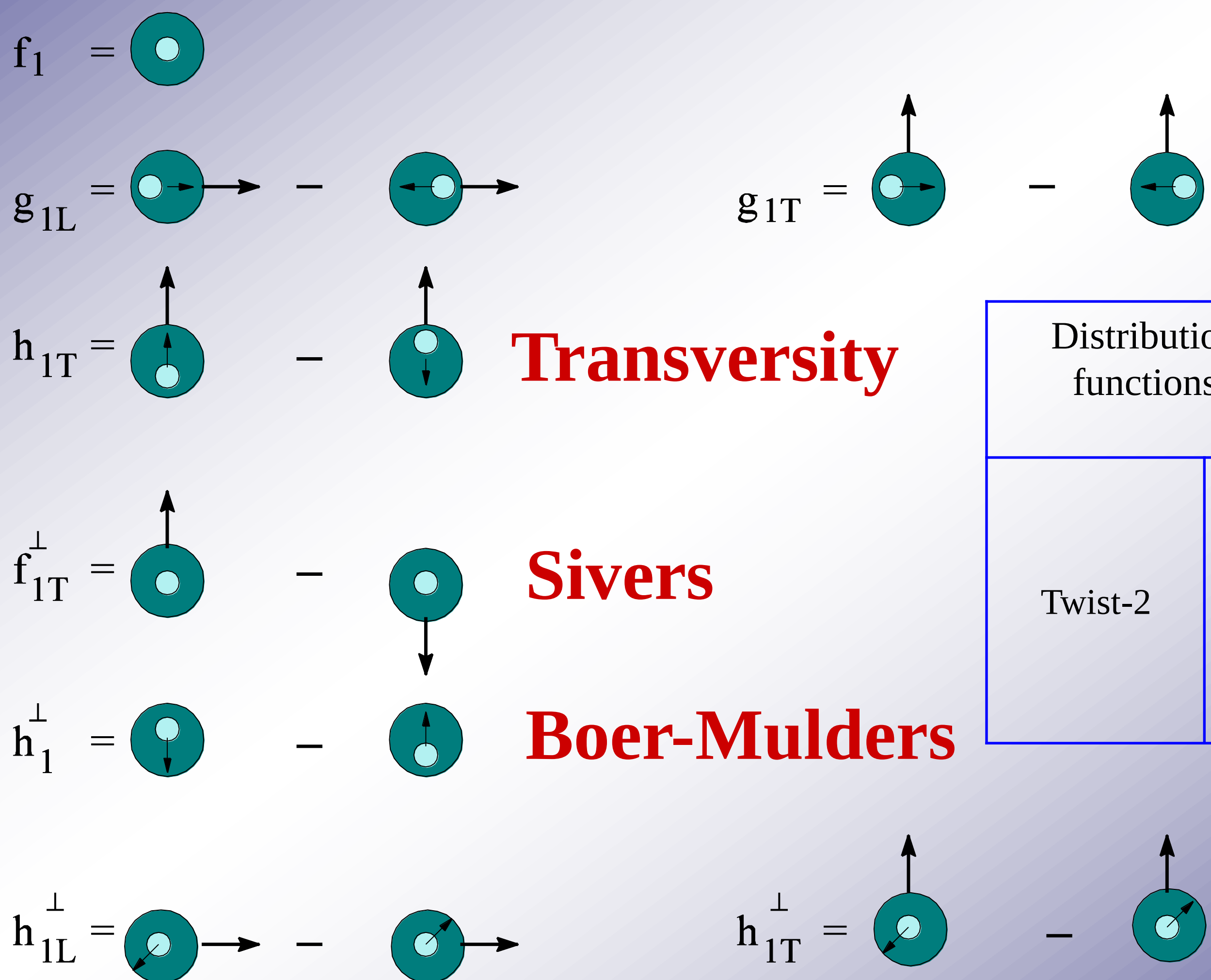
An upper limit: $$\left|h_1(x)\right| \leq \frac{1}{2}\left|f_1(x)+g_1(x)\right|$$

- can be violated by factorisation at NNLO
- inequality preserved under evolution to larger scales only

TMD: K_T-dependent Parton Distributions

Twist-2 PDFs $\quad f_1(x) = \int d^2k_T f_1(x, k_T)$





Distribution functions		Chirality even	Chirality odd
Twist-2	U	f_1	$h_1^{\perp}$
	L	g_1	$h_{1L}^{\perp}$
	T	$f_{1T}^{\perp}, g_{1T}$	$h_1, h_{1T}^{\perp}$

TMD PDF Investigation

Energies

@ FAIR unique energy range

up to $s \sim 30$ GeV^2 with PANDA

up to $s \sim 200$ GeV^2 with PAX

@ much higher energies

→ big contribution from sea-quarks

Process

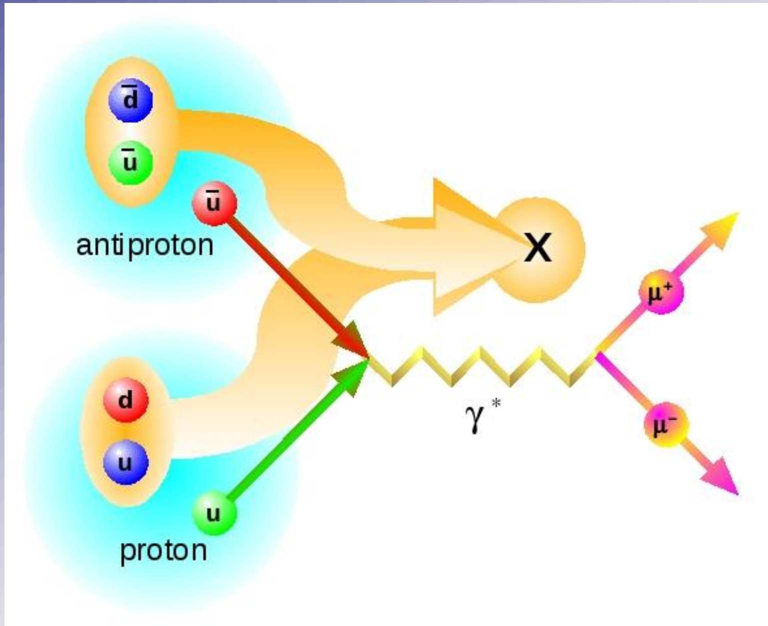
SIDIS → convolution with FF

Drell-Yan → PDF only

$p\bar{p}$ annihilations:
each valence quark can
contribute to the diagram

Drell-Yan Process

- Drell-Yan: $\bar{p}p \rightarrow \mu^+\mu^- X$



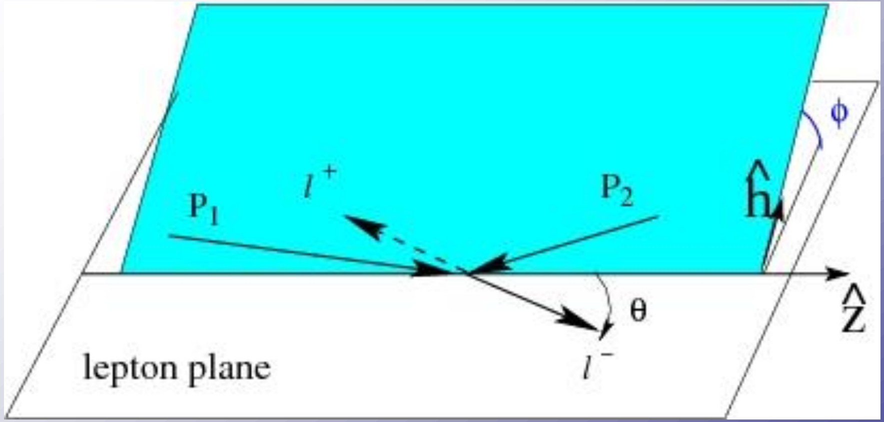
Kinematics

$x_{1,2}$ = mom fraction of $\text{parton}_{1,2}$

$\tau = x_1 \cdot x_2 = M^2/s$

$x_F = x_1 - x_2$

Collins-Soper frame



Collins-Soper frame: Phys. Rev. D16 (1977) 2219.

Drell-Yan Process

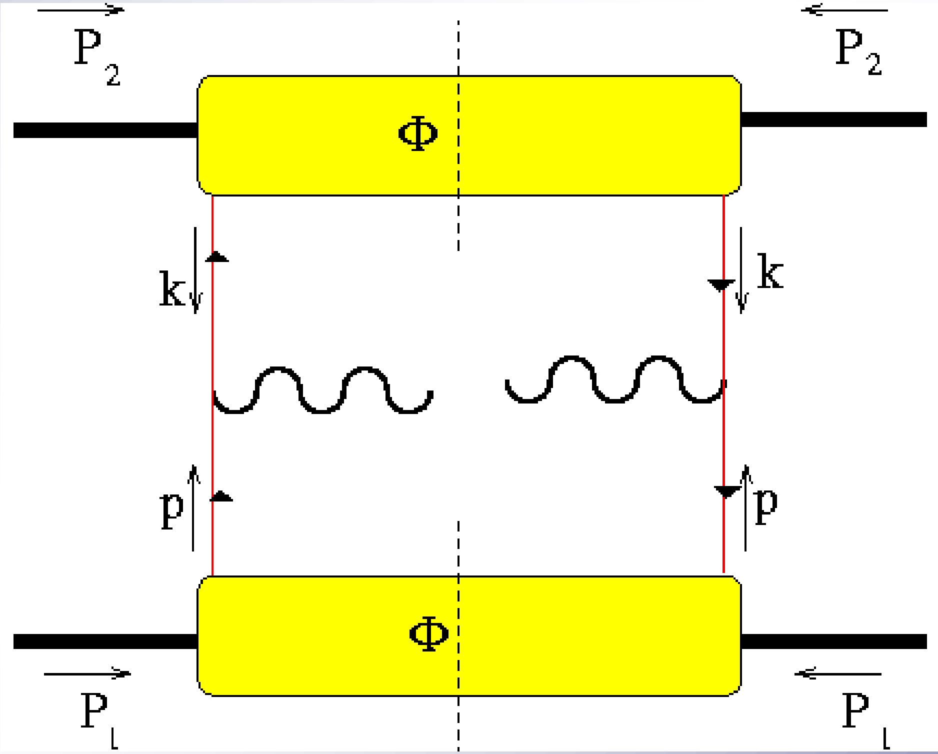
Gives access to chirally odd functions

⇓

Transversity

No convolution with FF

Chirally odd functions are not suppressed (as in DIS)

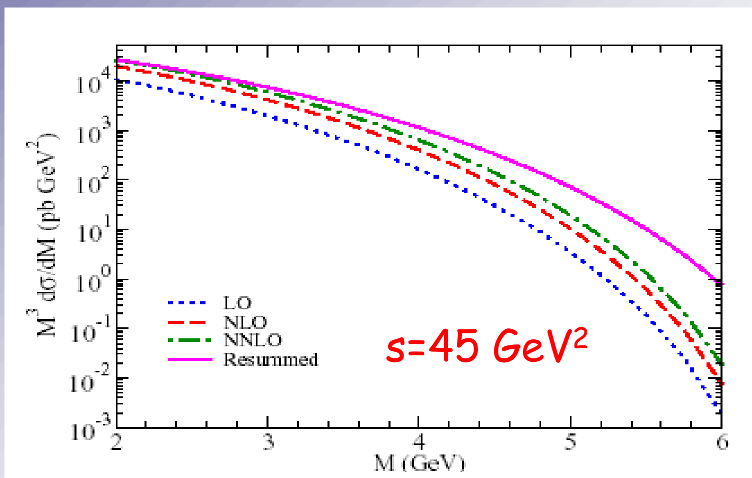


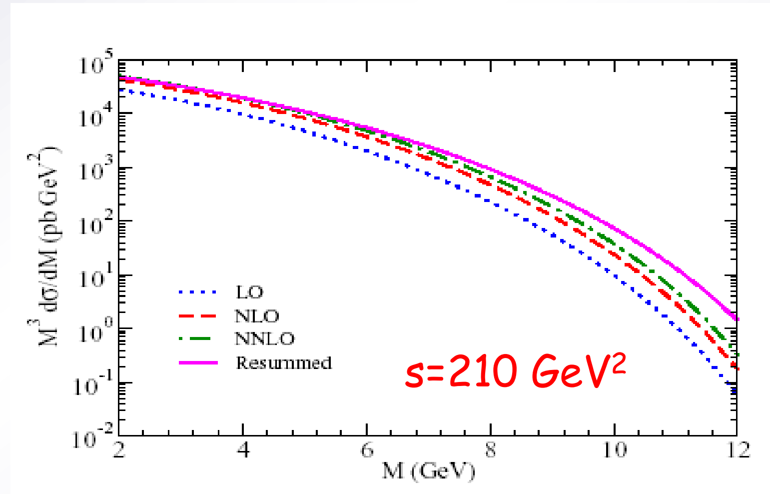
$$A_{LL} = \frac{\sum_a e_a^2 g_1^a(x_1) g_1^{\bar{a}}(x_2)}{\sum_a e_a^2 f_1^a(x_1) f_1^{\bar{a}}(x_2)} \qquad A_{TT} = \frac{\sin^2\theta \cos 2\varphi}{1+\cos^2\theta} \frac{\sum_a e_a^2 h_1^a(x_1) h_1^{\bar{a}}(x_2)}{\sum_a e_a^2 f_1^a(x_1) f_1^{\bar{a}}(x_2)}$$

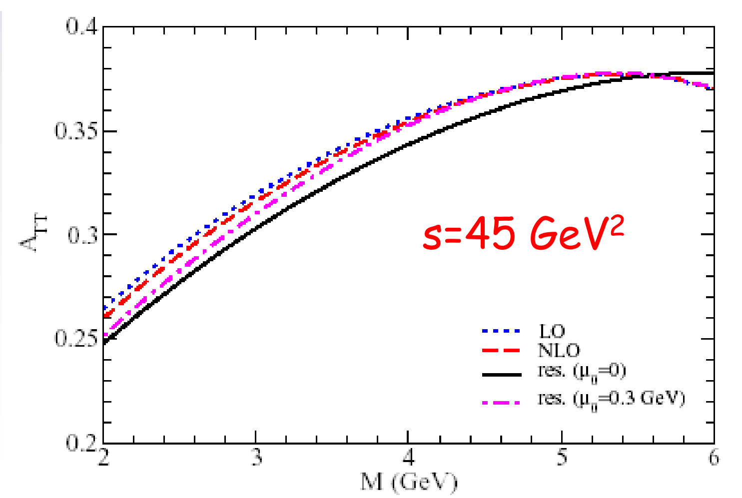
$$A_{LT} = \frac{2\sin 2\theta \cos\varphi}{1+\cos^2\theta} \frac{M}{\sqrt{Q^2}} \frac{\sum_a e_a^2 \left(g_1^a(x_1) x_2 g_T^{\bar{a}}(x_2) - x_1 h_L^a(x_1) h_1^{\bar{a}}(x_2) \right)}{\sum_a e_a^2 f_1^a(x_1) f_1^{\bar{a}}(x_2)}$$

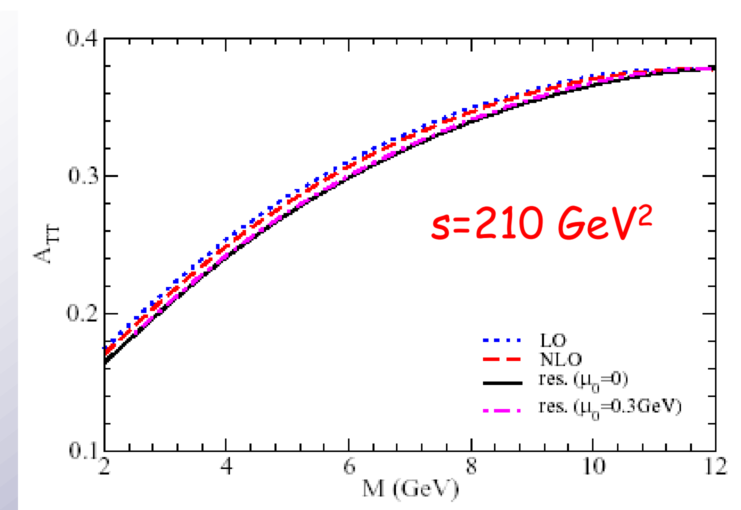
QCD higher order contributions

- cross section affected
- K-factors almost spin independent





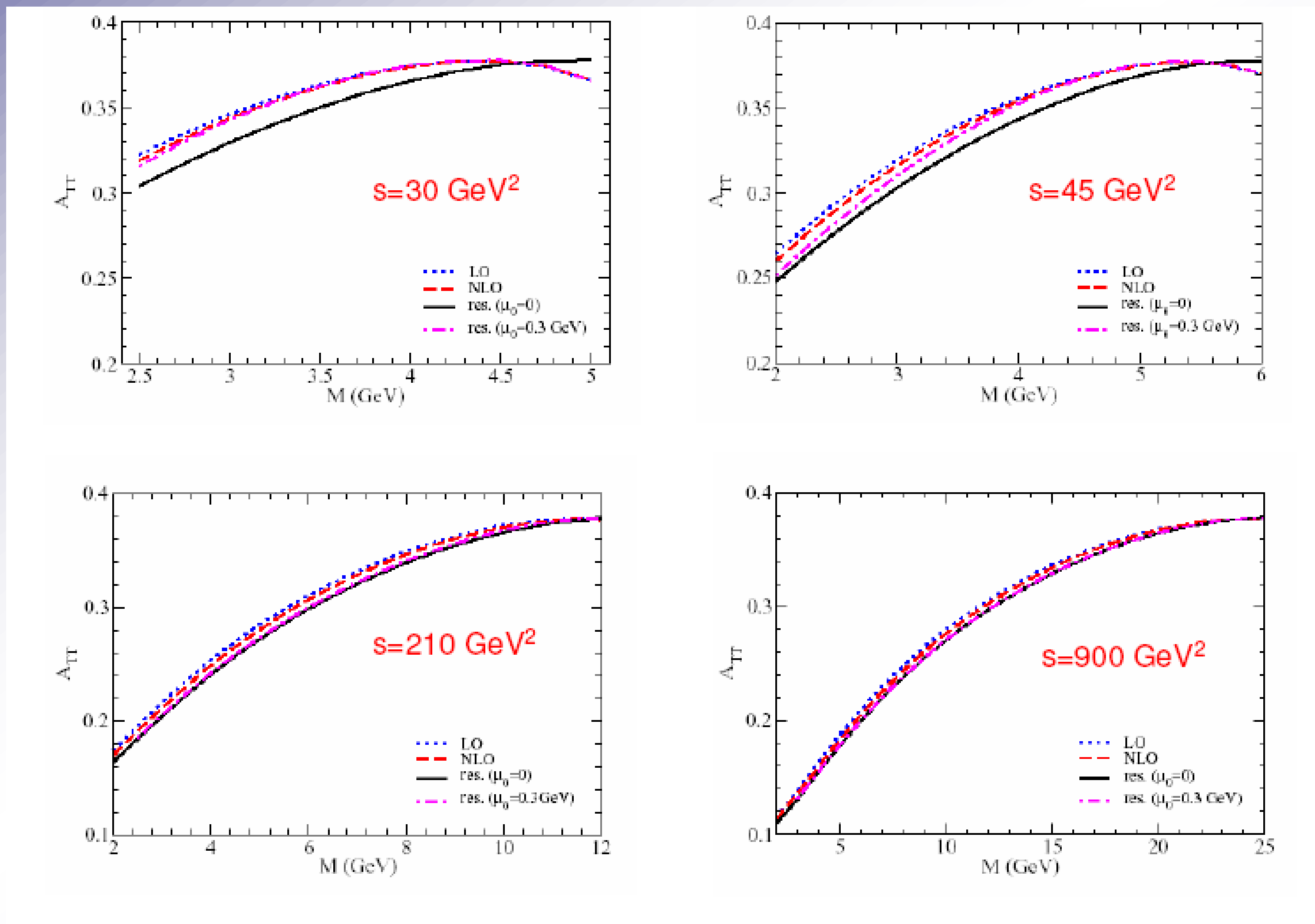




H. Shimizu et al., Phys. Rev. D71 (2005) 114007

QCD contributions to A_{TT}

- Contributions drop increasing the energy[1]

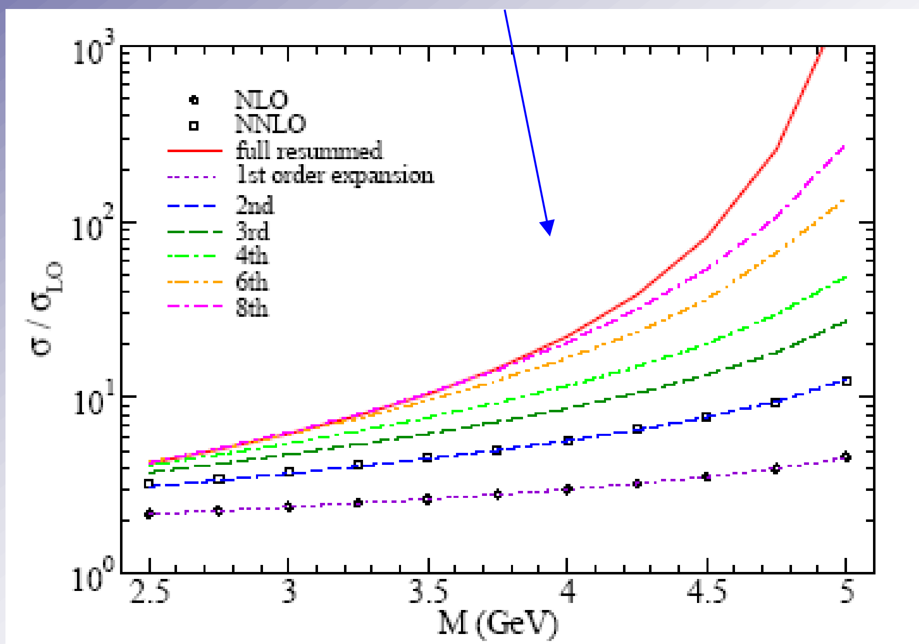


[1]H. Shimizu et al., Phys. Rev. D71 (2005) 114007

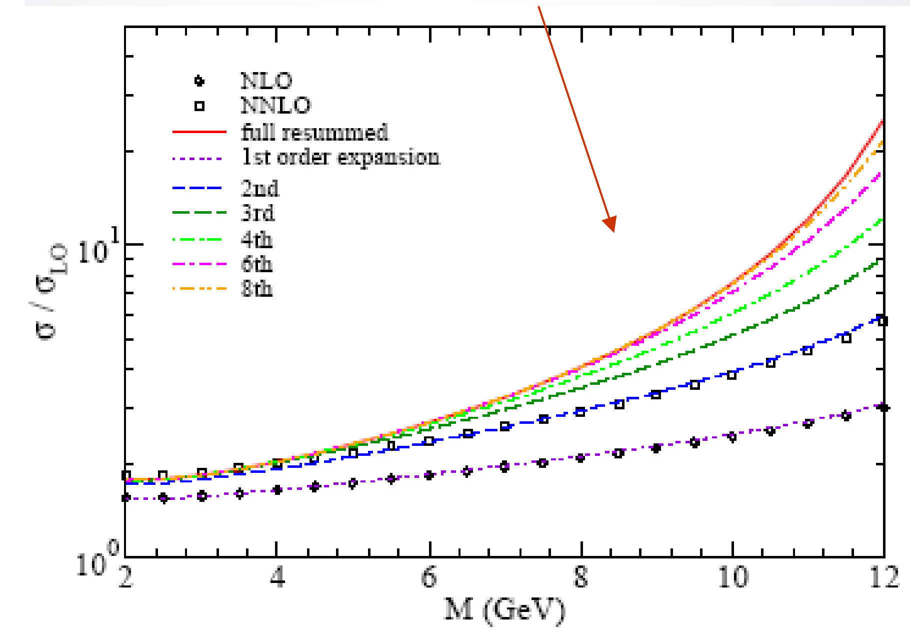
Perturbative Corrections

- Smaller at higher energies[1]

$s = 30\ \text{GeV}^2$



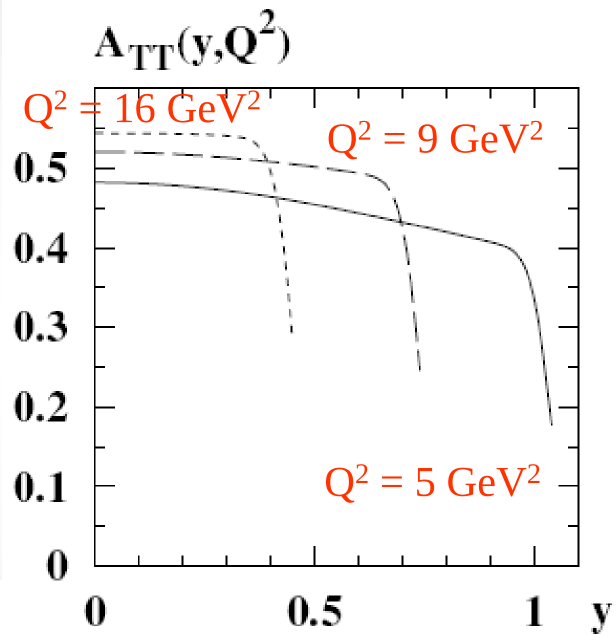
$s = 200\ \text{GeV}^2$



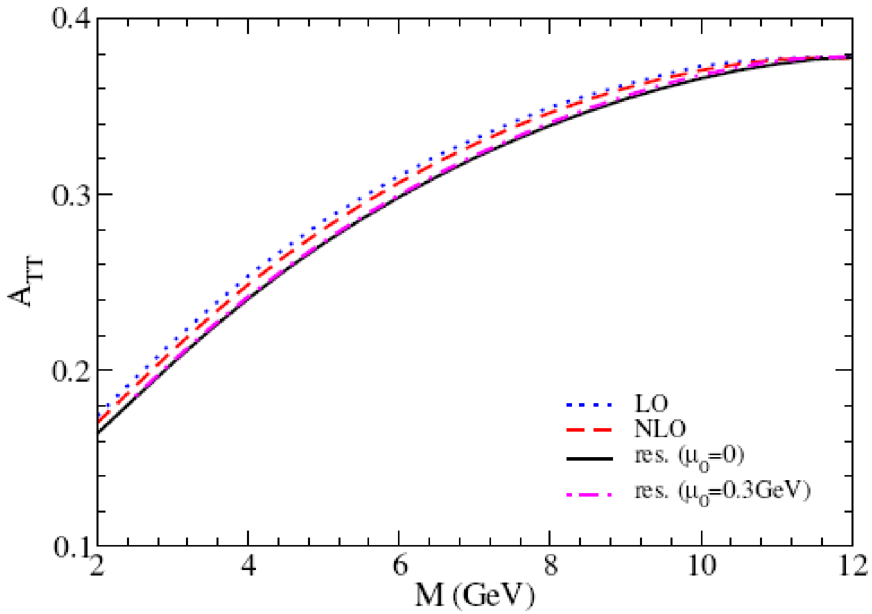
[1]H. Shimizu et al., Phys. Rev. D71 (2005) 114007

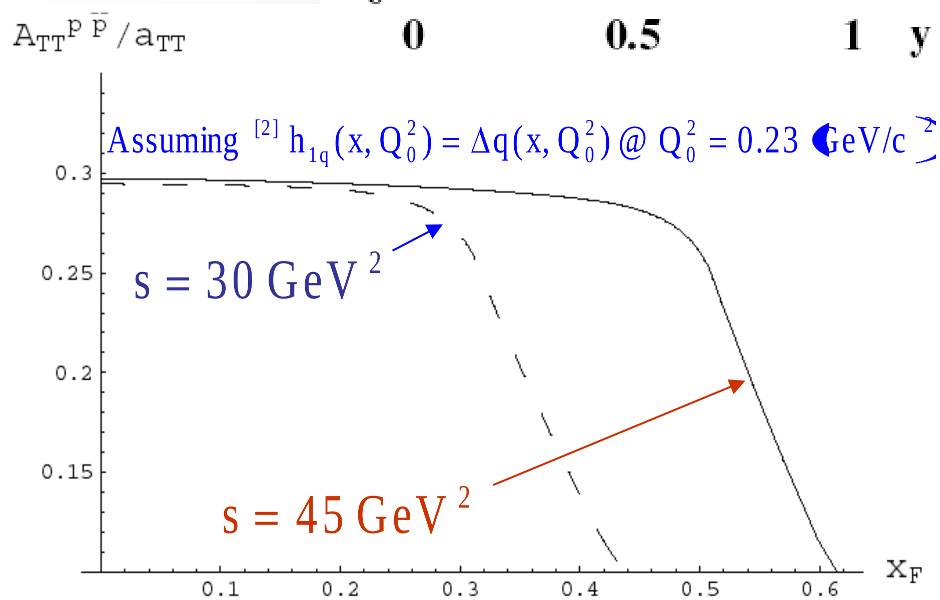
Double Spin Asymmetries @ s = 30, 45 GeV^2

[3] Efremov et al, Eur. Phys. J. C 35 (2004) 207.



- A_{TT} small at large $\sqrt{s}$ and M^2 due to slow evolution of $h_1^a(x,Q^2)$
- Large A_{TT} expected[1] for $\sqrt{s}$ and M^2 not too large and τ not too small





[1] Shimizu et al., Phys.Rev.D 71 (2005) 114007.

[2] M. Anselmino et al., Phys. Lett. B594 (2004) 97.

Drell-Yan Asymmetries

Di-Lepton Rest Frame

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2\theta+\mu\sin^2\theta\cos\varphi+\frac{\nu}{2}\sin^2\theta\cos2\varphi\right)$$

NLO pQCD: $\lambda \sim 1,\ \mu \sim 0,\ \upsilon \sim 0$

Lam-Tung sum rule: $1-\lambda = 2\nu$

- reflects the spin-½ nature of the quarks
- insensitive top QCD-corrections

Experimental data [1]: $\upsilon \sim 30\ \%$

[1] J.S.Conway et al., Phys. Rev. D39 (1989) 92.

Angular distribution in CS frame

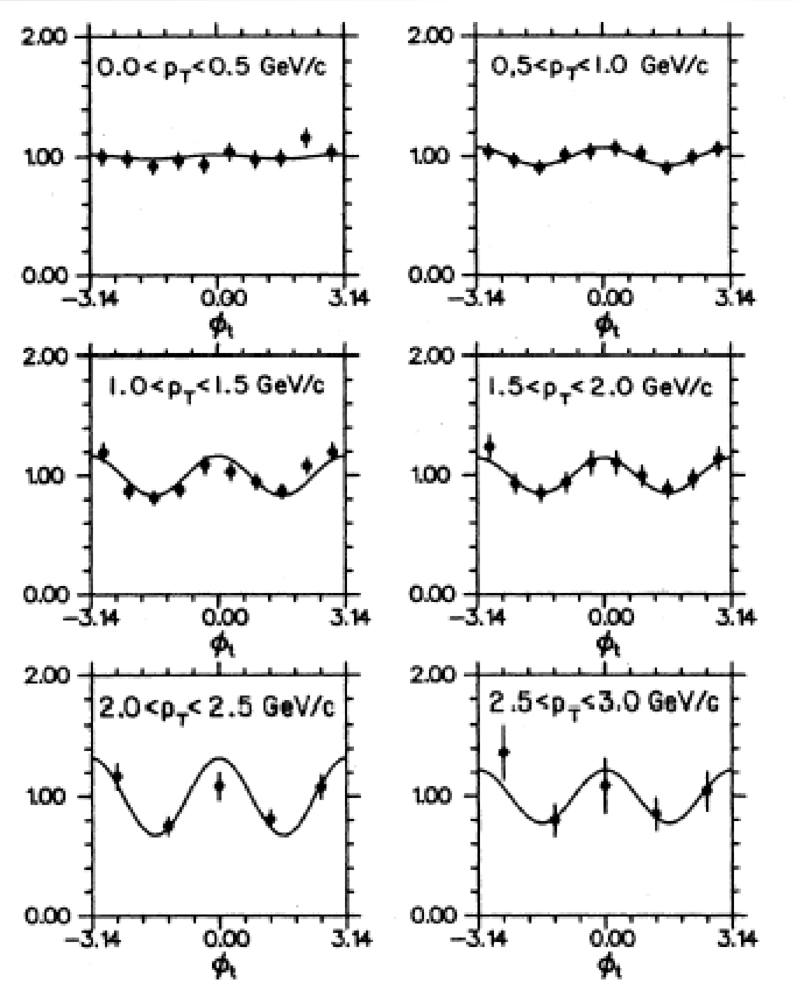
E615 @ Fermilab

π-N $\rightarrow$ $\mu^+\mu^-$X @ 252 GeV/c

$$\frac{d\sigma}{d\Omega} = \sigma_0 (1 + \cos^2 \vartheta)$$

-0.6 < cosϑ < 0.6

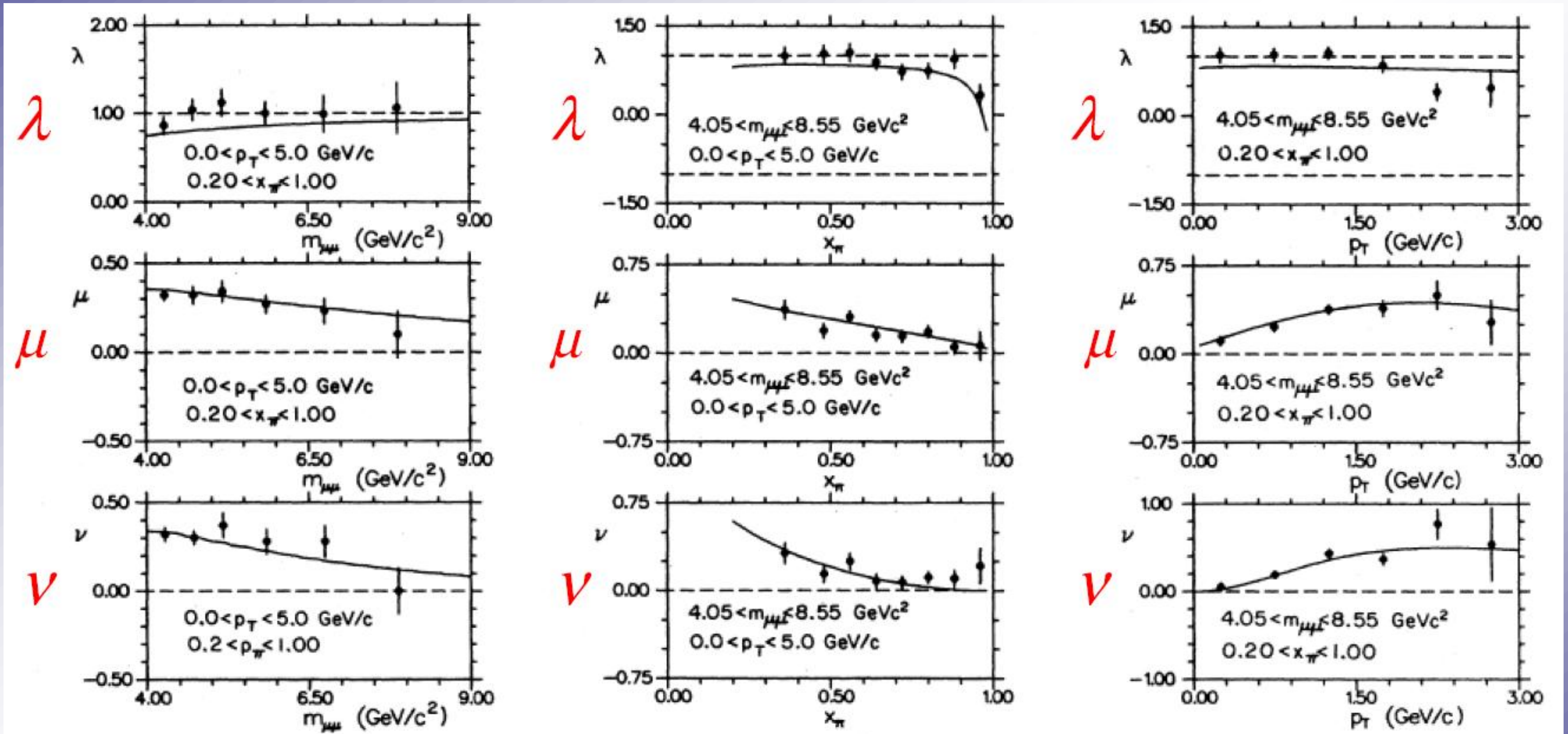
4 < M < 8.5 GeV/c^2



Conway et al, Phys. Rev. D39 (1989) 92

Angular distribution in CS frame

E615 @ Fermilab π-N $\rightarrow$ $\mu^+\mu^- X$ @ 252 GeV/c



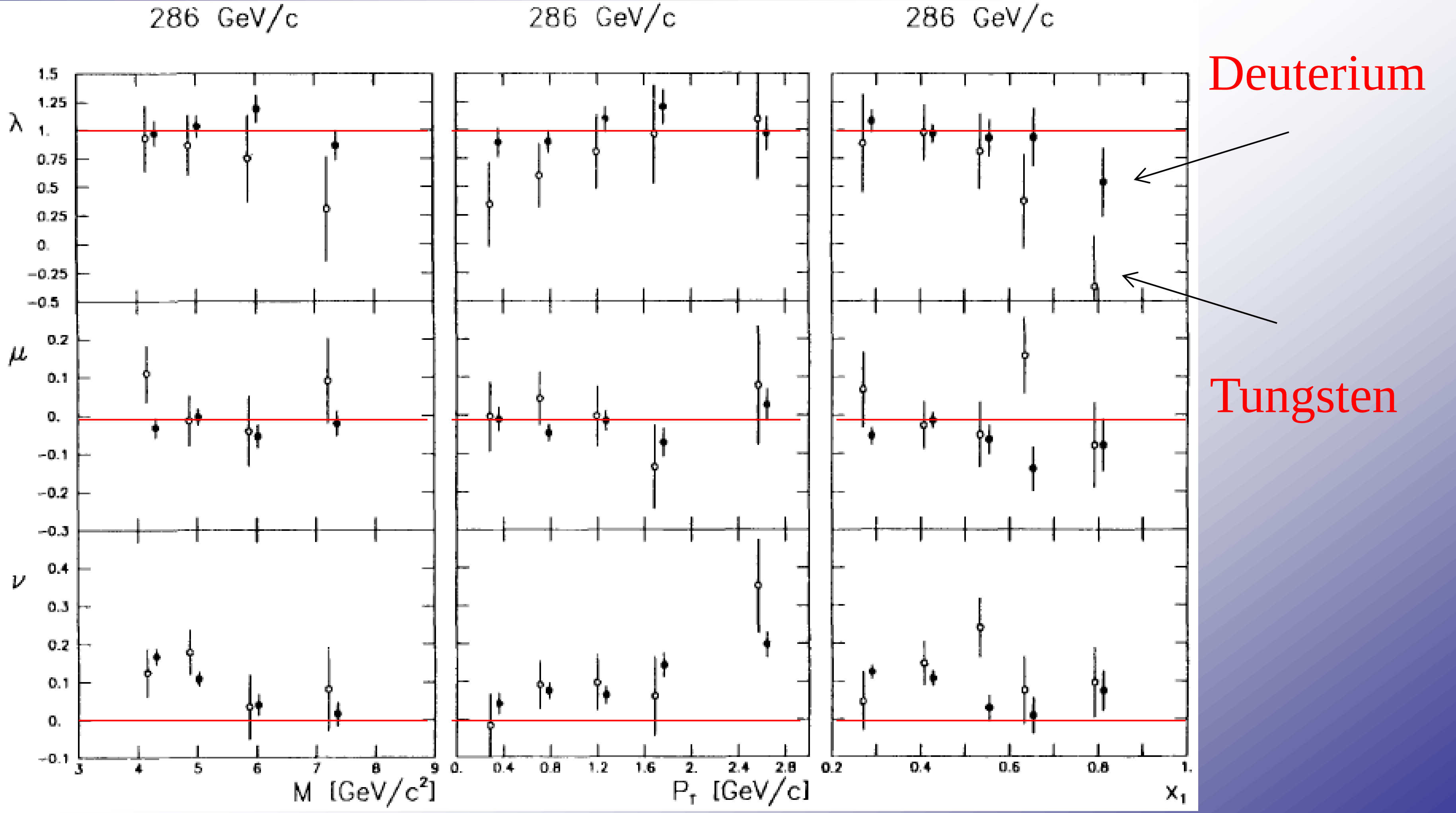
$m_{\mu\mu}$ (GeV/c^2) x_π p_T (GeV/c)

30% asymmetry observed for π^-

Conway et al, Phys. Rev. D39 (1989) 92

Nuclear effects?

NA10 @ CERN π-N $\rightarrow$ $\mu^+\mu^-$X @ 286 GeV/c

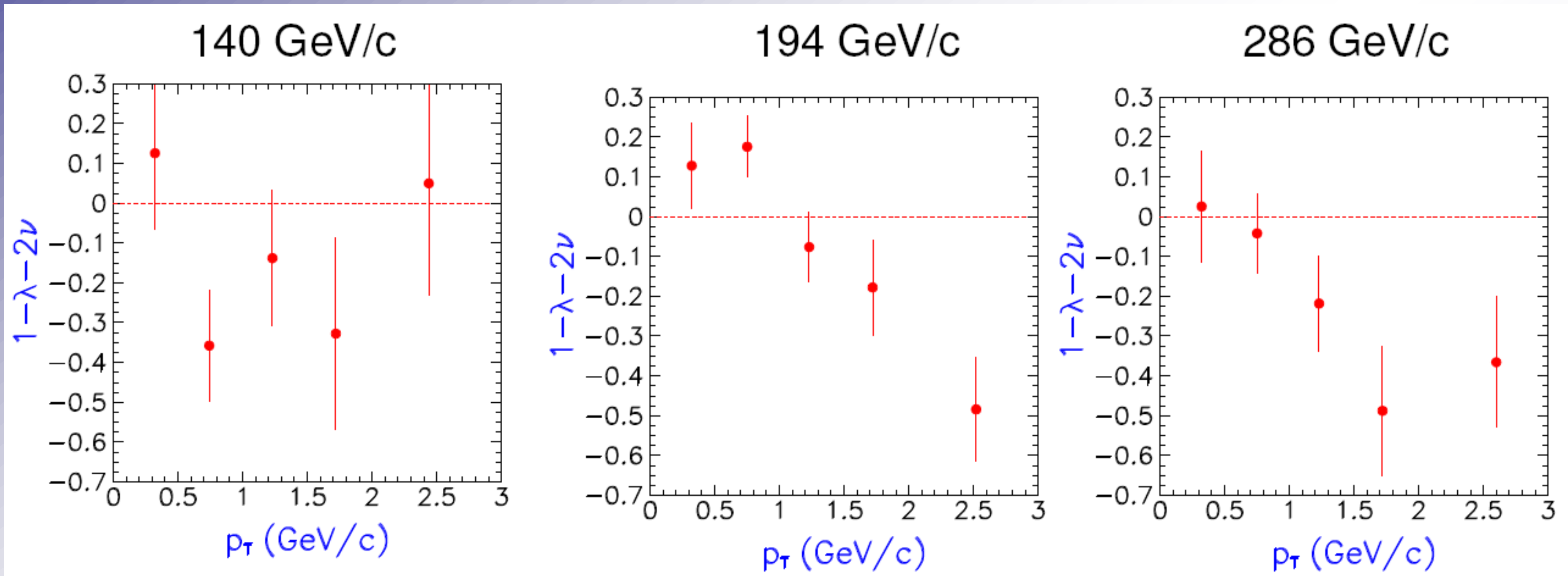


NA10 coll., Z. Phys. C37 (1988) 545

Violation of Lam-Tung sum rule

λ, μ, ν measured in $\pi N \rightarrow \mu^+ \mu^- X$

NA10 @ CERN[1]



υ involves transverse spin effects at leading twist [2]

If unpolarised DY σ is kept differential on k_T ,

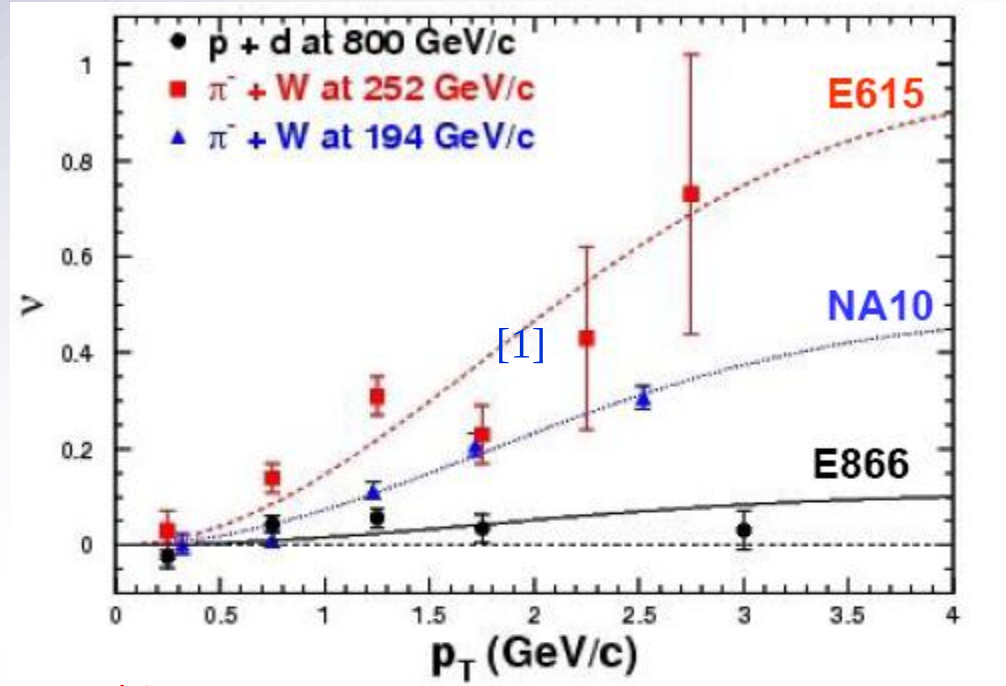
cos2φ contribution to angular distribution provide:

$$h_1^{\perp}(x_{2,}\kappa_{\perp}^2) \times \bar{h}_1^{\perp}(x_1,\kappa_{\perp}'^2)$$

[1] NA10 coll., Z. Phys. C37 (1988) 545

[2] D. Boer et al., Phys. Rev. D60 (1999) 014012.

Drell-Yan Asymmetries



Boer-Mulders

T-odd Chiral-odd TMD

- $\nu > 0 \rightarrow$ valence $h_1^{\perp}$ has same sign in π and N
- $\nu(\pi^- W \rightarrow \mu^+\mu^- X) \sim h_1^{\perp}(\pi)_{valence} \times h_1^{\perp}(p)_{valence}$
- $\nu(pd \rightarrow \mu^+\mu^- X) \sim h_1^{\perp}(p)_{valence} \times h_1^{\perp}(p)_{sea}$
- $\nu > 0 \rightarrow$ valence and sea $h_1^{\perp}$ has same sign, but sea $h_1^{\perp}$ should be significantly smaller

[1] L. Zhu et al, PRL 99 (2007) 082301; [1] D. Boer, Phys. Rew. D60 (1999) 014012.

Drell-Yan Asymmetries

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1+\cos^2\theta+\frac{\nu}{2}\sin^2\theta\cos 2\varphi+\rho\left|S_{1T}\right|\sin^2\theta\sin(\varphi-\varphi_{S_1})+\cdots\right)$$

$\lambda \sim 1,\ \mu \sim 0$

$$A_T=\left|S_{1T}\right|\frac{2\sin 2\theta\sin(\varphi-\varphi_{S_1})}{1+\cos^2\theta}\frac{M}{\sqrt{Q^2}}\frac{\sum_a e_a^2\left[x_1 f_1^{a\perp}(x_1)f_1^{\bar{a}}(x_2)+x_2 h_1^a(x_1)h_1^{\bar{a}\perp}(x_2)\right]}{\sum_a e_a^2 f_1^a(x_1)f_1^{\bar{a}}(x_2)}$$

Even unpolarised $\bar{p}$ beam on polarised p,
or polarised $\bar{p}$ on unpolarised p
are powerful tools
to investigate κ_T dependence of QDF

D. Boer et al., Phys. Rev. D60 (1999) 014012.

Drell-Yan Cross Section

UNPOLARISED

$$\frac{d\sigma^o}{d\Omega dx_1 dx_2 d\mathbf{q}_T} = \frac{\alpha^2}{12Q^2} \sum_f e_f^2 \Big\{ (1+\cos^2\theta)\, \mathcal{F}\left[\bar{f}_1^f\, f_1^f\right]$$
$$+ f\, \sin^2\theta\, \cos 2\phi\, \mathcal{F}\left[\left(2\hat{\mathbf{h}}\cdot\mathbf{p}_{1_T}\,\hat{\mathbf{h}}\cdot\mathbf{p}_{2_T} - \mathbf{p}_{1_T}\cdot\mathbf{p}_{2_T}\right)\frac{\bar{h}_1^{\perp f}\, h_1^{\perp f}}{M_1 M_2}\right]\Big\}$$

SINGLE-POLARISED

$$\frac{d\Delta\sigma^{\uparrow}}{d\Omega dx_1 dx_2 d\mathbf{q}_T} = \frac{\alpha^2}{12sQ^2} \sum_f e_f^2\, |\mathbf{S}_{2_T}| \Big\{ (1+\cos^2\theta)\, \sin(\phi-\phi_{S_2})\, \mathcal{F}\left[\hat{\mathbf{h}}\cdot\mathbf{p}_{2_T}\,\frac{\bar{f}_1^f\, f_{1T}^{\perp f}}{M_2}\right]$$
$$- \sin^2\theta\, \sin(\phi+\phi_{S_2})\, \mathcal{F}\left[\hat{\mathbf{h}}\cdot\mathbf{p}_{1_T}\,\frac{\bar{h}_1^{\perp f}\, h_{1T}^f}{M_1}\right]$$
$$- \sin^2\theta\, \sin(3\phi-\phi_{S_2})\, \mathcal{F}\left[\left(4\hat{\mathbf{h}}\cdot\mathbf{p}_{1_T}\,(\hat{\mathbf{h}}\cdot\mathbf{p}_{2_T})^2 - 2\hat{\mathbf{h}}\cdot\mathbf{p}_{2_T}\,\mathbf{p}_{1_T}\cdot\mathbf{p}_{2_T} - \hat{\mathbf{h}}\cdot\mathbf{p}_{1_T}\,\mathbf{p}_{2_T}^2\right)\frac{\bar{h}_1^{\perp f}\, h_{1T}^{\perp f}}{2M_1\, M_2^2}\right]\Big\}$$

DOUBLE-POLARISED

$$\frac{d\sigma^{\uparrow\uparrow}}{dx_1\, dx_2\, d\Omega} = \frac{\alpha^2}{12q^2}\Big[(1+\cos^2\theta)\sum_f e_f^2\, \bar{f}_1^f(x_1)\, f_1^f(x_2) + \sin^2\theta\, \cos 2\phi\, \frac{\tilde{\nu}(x_1,x_2)}{2}$$
$$+ |\mathbf{S}_{T1}|\, |\mathbf{S}_{T2}|\, \sin^2\theta\, \cos(2\phi-\phi_{S_1}-\phi_{S_2}) \sum_f e_f^2\, \bar{h}_{1T}^f(x_1)\, h_{1T}^f(x_2) + (1\leftrightarrow 2)\Big]$$

R.D. Tangerman and P.J. Mulders, Phys. Rev. D51, 3357-3372 (1995)

Azimuthal Asymmetries

- Unpolarized $\cos 2\varphi$
- Single polarized $\sin(\varphi - \varphi_{S_2}), \sin(\varphi + \varphi_{S_2})$
- Double polarized $\cos(2\varphi - \varphi_{S_1} - \varphi_{S_2})$

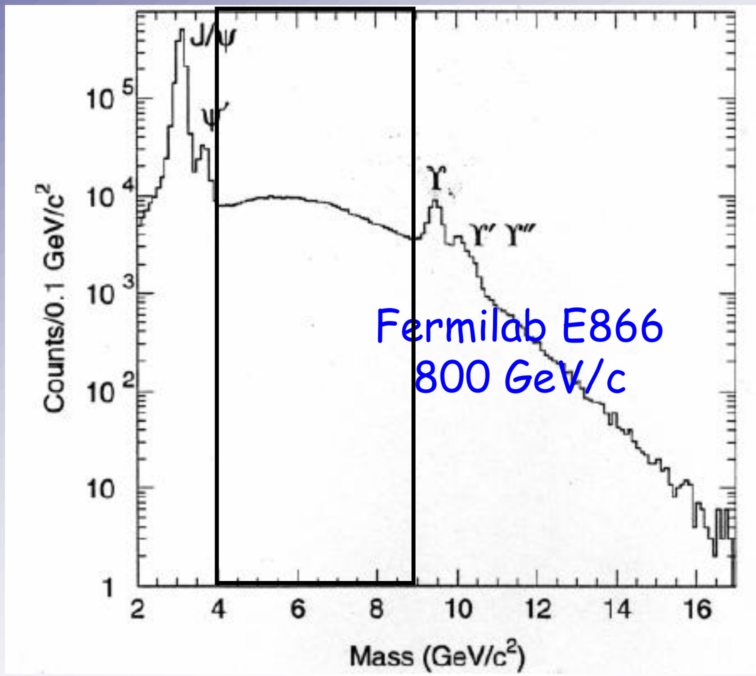
U = N(cos2φ>0)

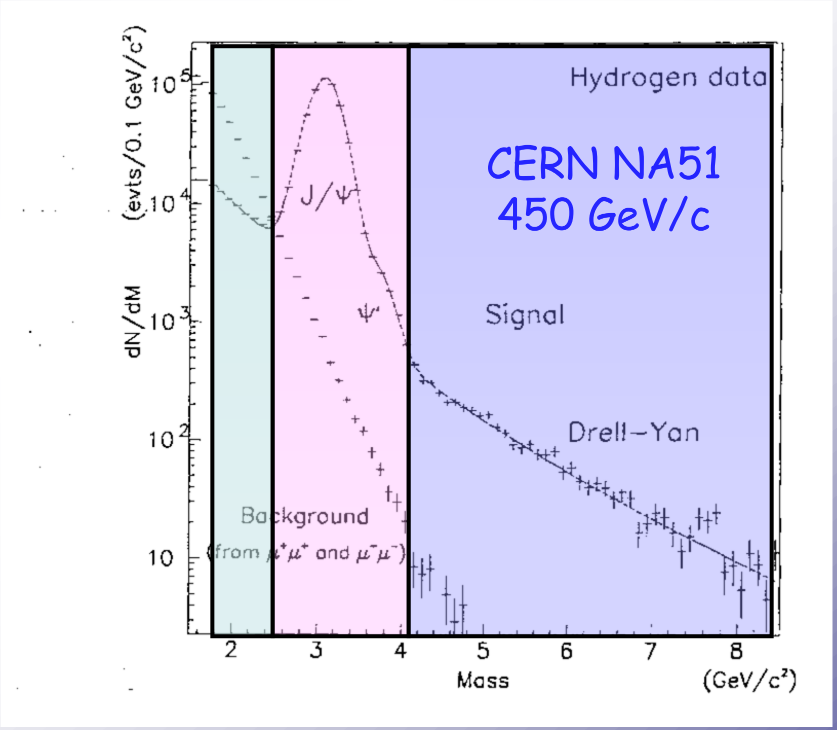
D = N(cos2φ<0)

Asymmetry $A = \frac{U - D}{U + D}$

Di-Lepton Production

$\bar{p}p \rightarrow \ell^+\ell^- X$

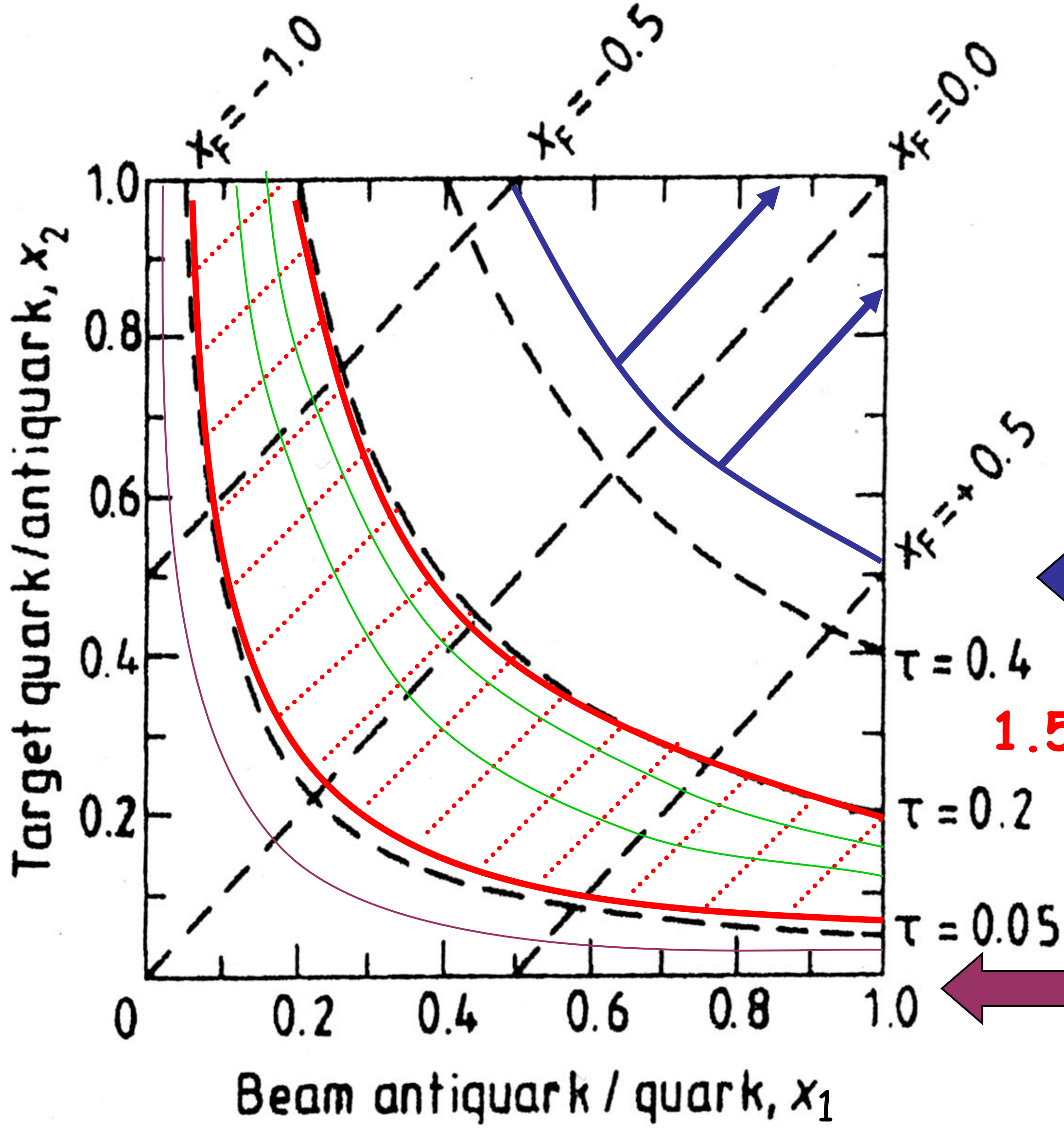




R.S. Towell et al., Phys. Rev. **D 64**, 052002 (2001)

A. Baldit et al., Phys. Lett. **332-B**, 244 (1994)

Phase space for Drell-Yan processes



$x_{1,2}$ = mom fraction of parton$_{1,2}$

$\tau = x_1 \cdot x_2$

$x_F = x_1 - x_2$

τ = const: hyperbolae

x_F = const: diagonal

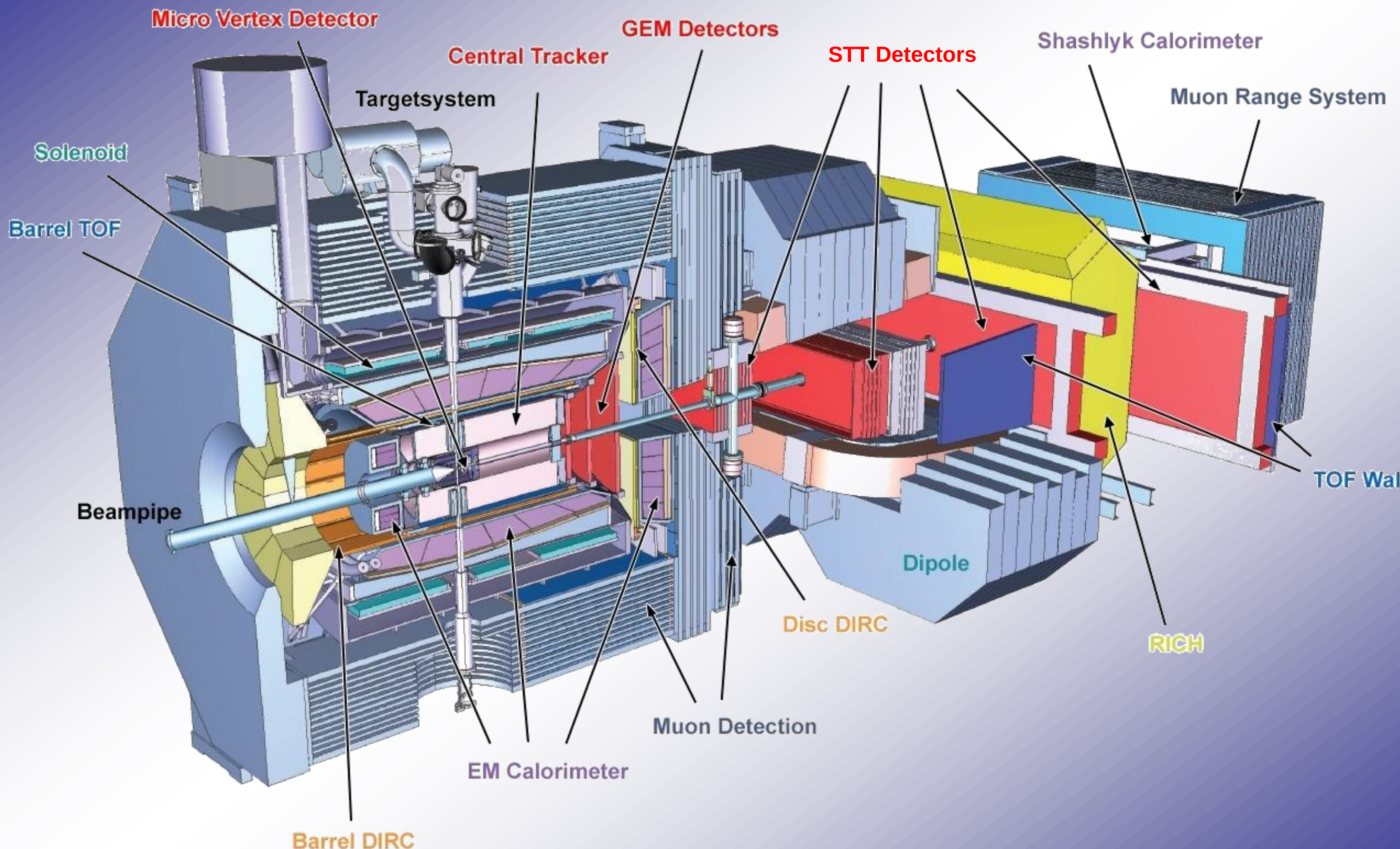
PANDA

$1.5\ \mathrm{GeV}/c^2 \leq M_{\mu\mu} \leq 2.5\ \mathrm{GeV}/c^2$

PAX @ HESR

symmetric HESR collider

The PANDA Detector

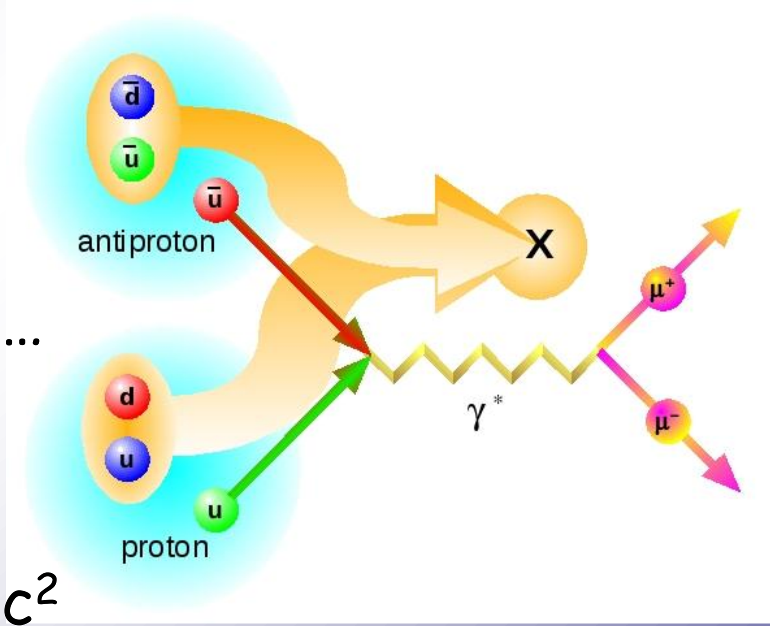


Physics Performance Report for PANDA arXiv:0903.3905

Drell-Yan Process and Background

- Drell-Yan: $\bar{p}p \to \mu^+\mu^- X$

  cross section $\sigma \sim 1$ nb @ $s = 30$ GeV^2



- Background: $\bar{p}p \to \pi^+\pi^- X,\ 2\pi^+2\pi^- X, \ldots\ldots$

  cross section $\sigma \sim 20\text{-}30\ \mu$b

  $m_\mu = 105$ MeV/c^2; m_π 145 MeV/c^2

  average primary pion pairs: ~ 1.5

- Background studies: needed rejection factor of 10^7

A. Bianconi Drell-Yan Generator for $\bar{p}p$

- Antiproton beam
- Polarized/Unpolarized beam and target
- Drell-Yan cross section from experimental data
- Selects event depending on the variables:

$$x_1, x_2, P_T, \vartheta, \varphi, \varphi_S$$

from a flat distribution

- Cross section:

$$\frac{d\sigma}{dx_1 dx_2 dP_T d\Omega} = \frac{K}{S} \cdot S(x_1, x_2) \cdot S'(P_T) \cdot A(\vartheta, \varphi, \varphi_S)$$

A. Bianconi, *Monte Carlo Event Generator DY_AB4 for Drell-Yan Events with Dimuon Production in Antiproton and Negative Pion Collisions with Molecular Targets, internal note (PANDA collaboration)*

A. Bianconi, M. Radici, *Phys. Rev.* **D71**, 074014 (2005) & **D72**, 074013 (2005)

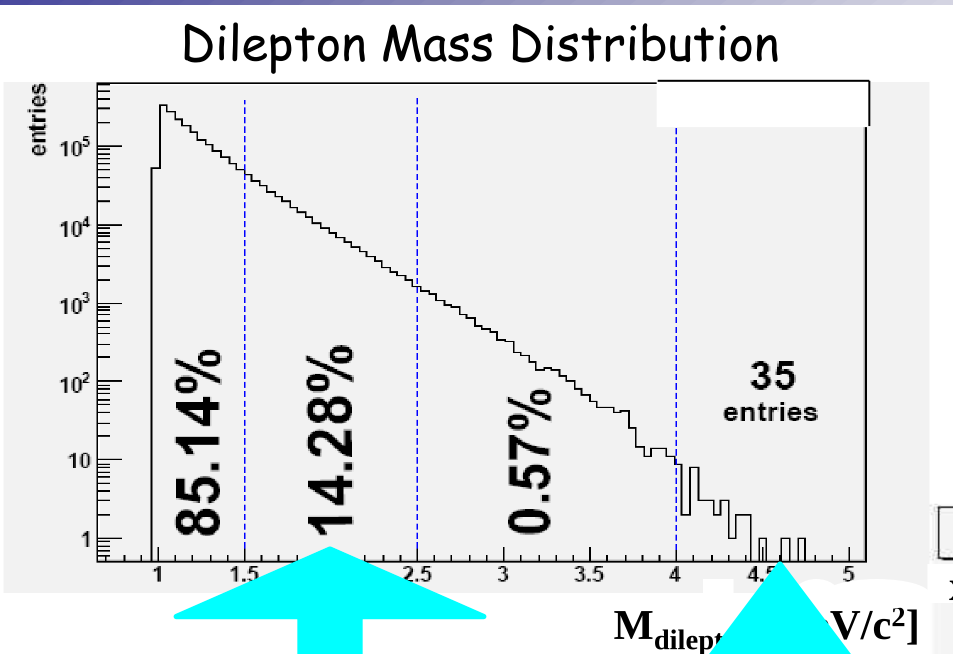
A. Bianconi, Nucl.Instrum.Meth. A593: 562-571, 2008

DY @ 15 GeV/c — $\bar{p}p \to \mu^+\mu^- X$

$\sqrt{s} = 5.5$ GeV

A. Bianconi Drell-Yan Generator [1]

- layout studies for muon id with ABDYG (1.5 MEv)

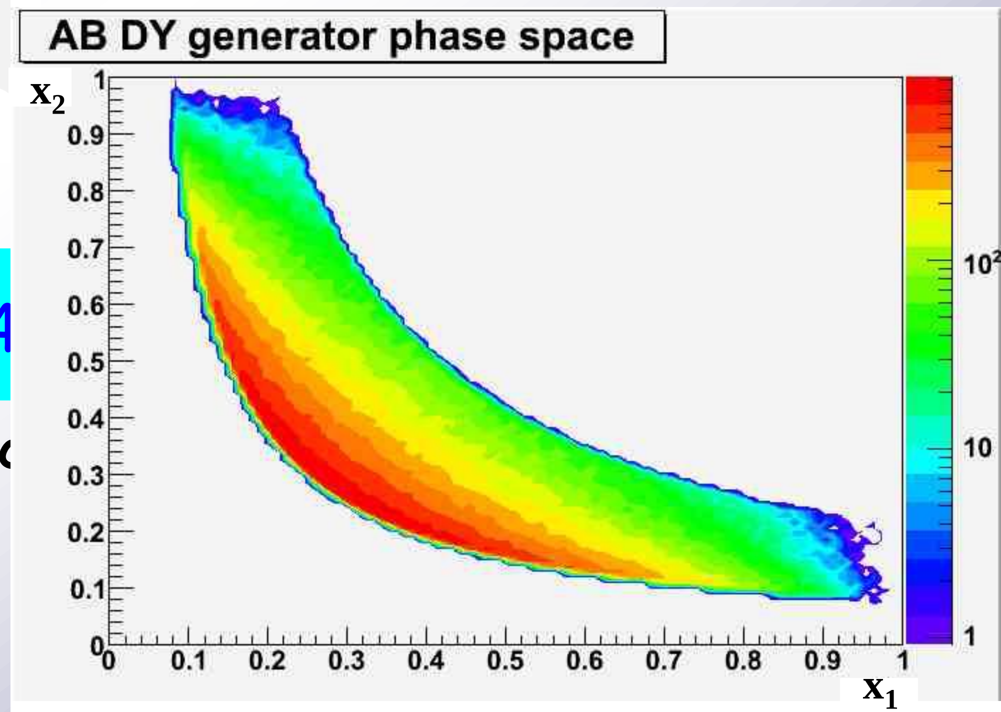


Focus o one

1.5 MEv i 5 < M < 2.5 (GeV/c

$\sigma^0_{4 \leq M \leq 9} \sim 0.4$

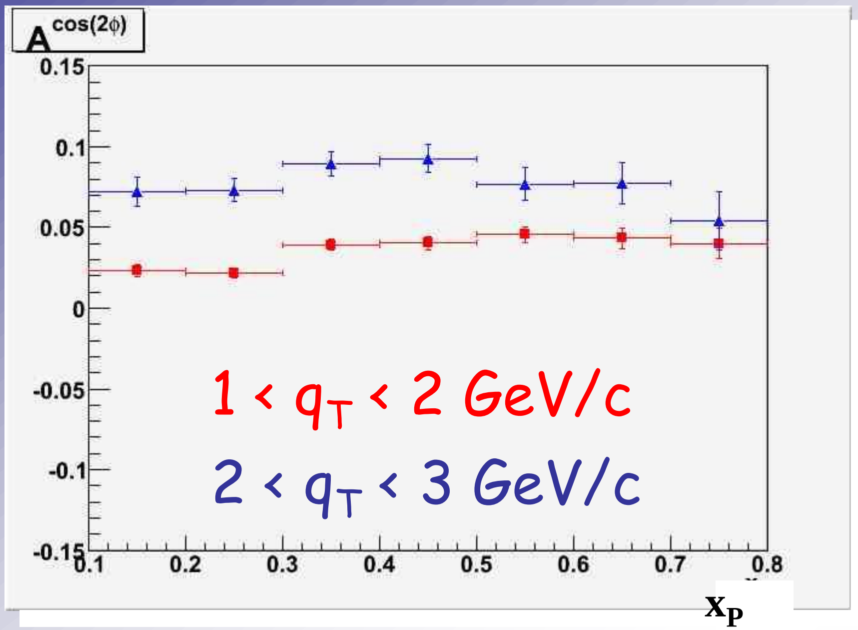
$\sigma^0_{1.5 \leq M \leq 2.5} \sim 0.8$ nb



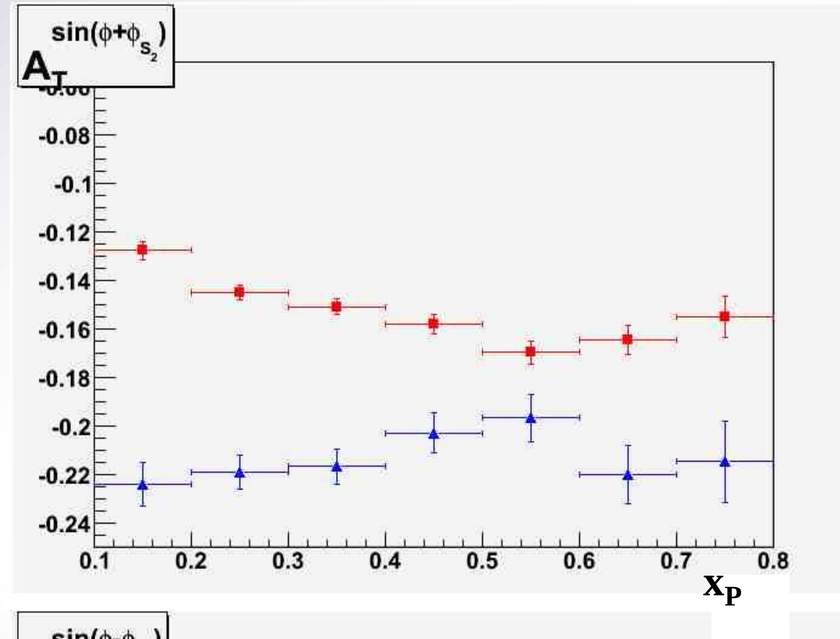
[1] A. Bianconi and M. Radici, Phys. Rev. D71 (2005) 074014

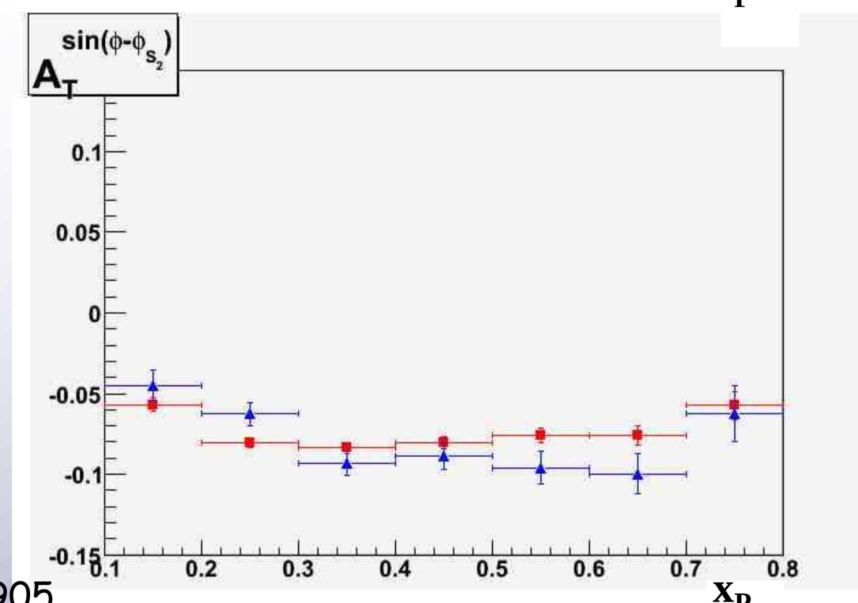
DY Asymmetries @ Vertex

UNPOLARISED



SINGLE-POLARISED





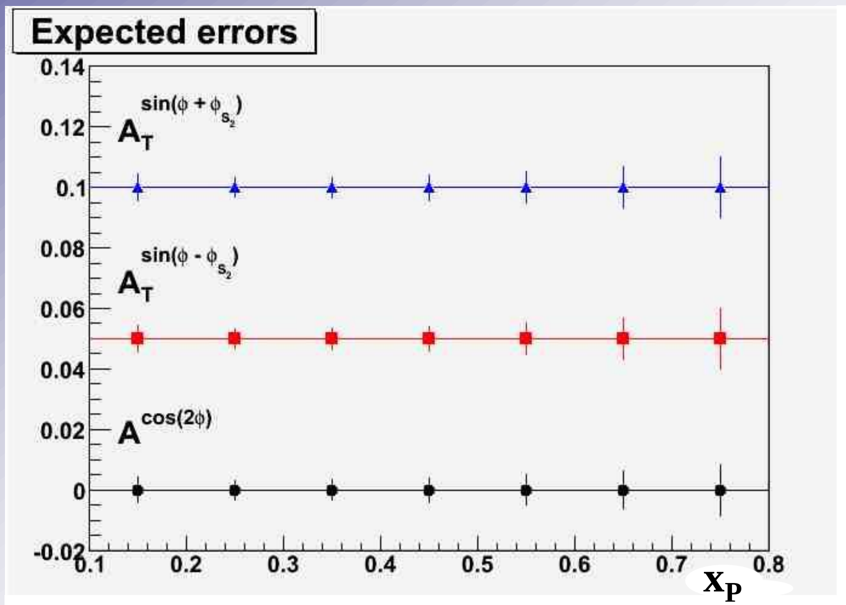
500KEv included in asymmetries

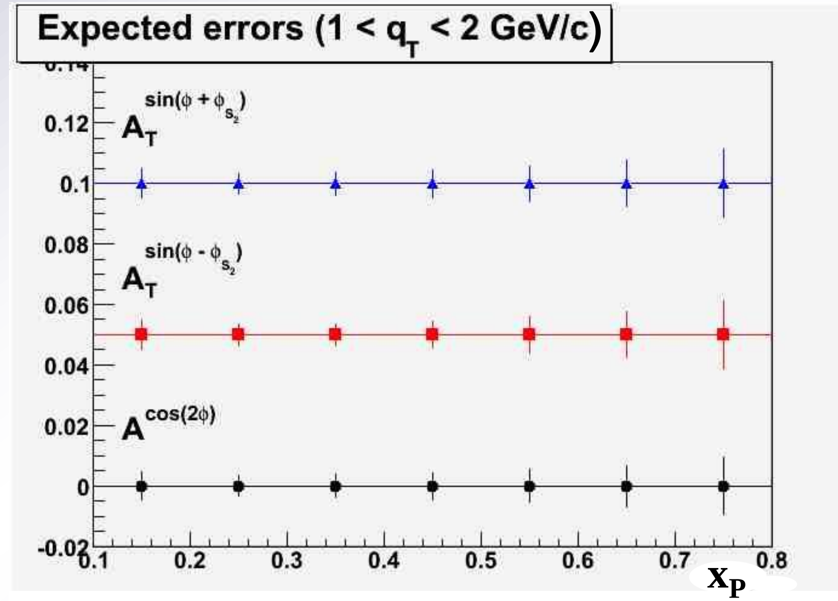
Acceptance corrections crucial!

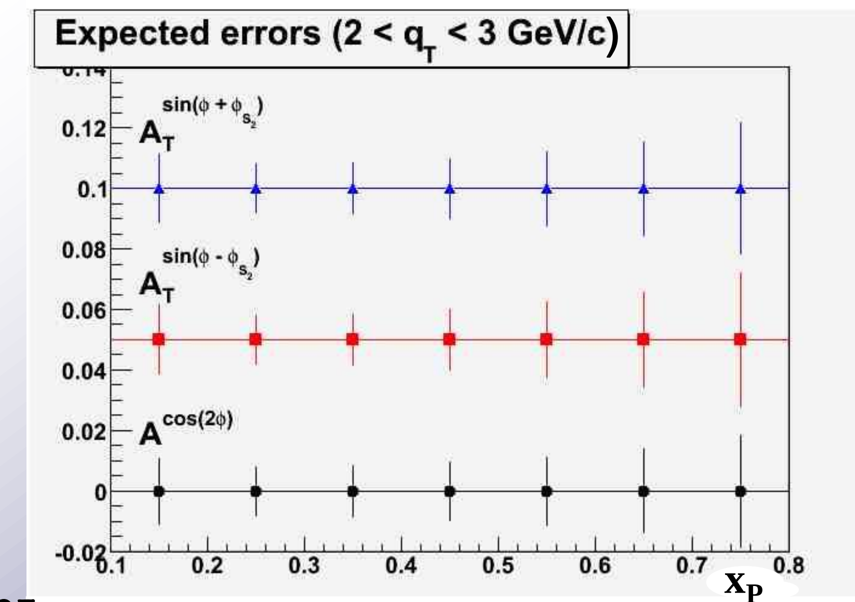
Physics Performance Report for PANDA arXiv:0903.3905

DY Asymmetries @ Vertex

Statistical errors for 500KEv generated







$$R = L \cdot \sigma \cdot \varepsilon$$

$$= 2 \cdot 10^{32} cm^{-2} s^{-1} \times$$

$$\times\ 0.8 \cdot 10^{-33} cm^{2} \times 0.33$$

$$= 0.05\ s^{-1} \sim 130\ \text{Kev/month}$$

Physics Performance Report for PANDA arXiv:0903.3905

$p\bar{p} \rightarrow \mu^+\mu^-$

J/ψ Strong and Electromagnetic Decay Amplitudes

Resonant contributions

$\Gamma_{J/\psi} \sim 93\text{KeV} \;\rightarrow$ pQCD

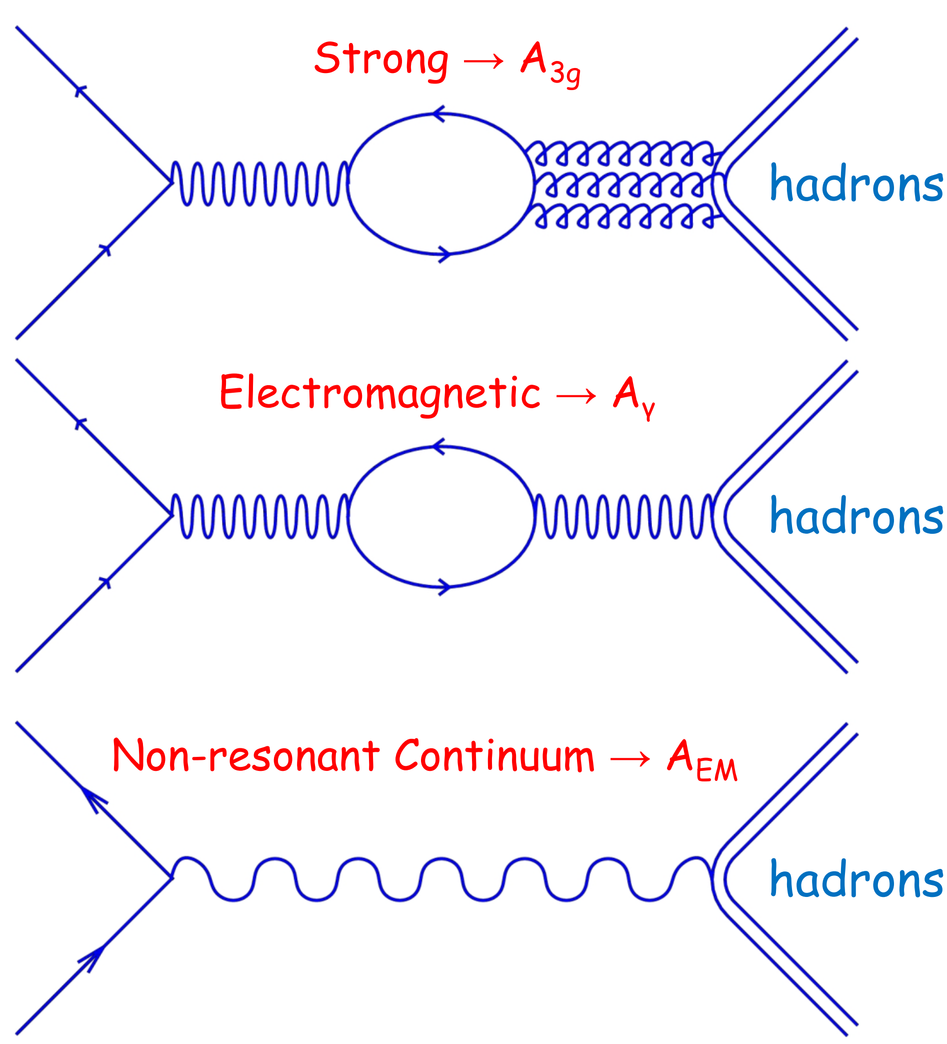
pQCD: all amplitudes almost real [1,2]

QCD -> $\Phi_p \sim 10$ [1]

Non-resonant continuum

pQCD regime

$A_{EM} \in \Re$



[1] J. Bolz and P. Kroll, WU B 95-35.
[2] S.J. Brodsky, G.P. Lepage, S.F. Tuan, Phys. Rev. Lett. 59, 621 (1987).

J/ψ Strong and Electromagnetic Decay Amplitudes

- If both real, they must interfere ($\Phi_p \sim 0°/180°$)
- On the contrary $\Phi_p \sim 90° \rightarrow$ No interference

$J/\psi \rightarrow N\bar{N}$ ($\frac{1}{2}^+\frac{1}{2}^-$) $\Phi_p = 89° \pm 15°$ [1]; $89° \pm 9°$[2]

$J/\psi \rightarrow$ VP (1^-0^-) $\Phi_p = 106° \pm 10°$ [3]

$J/\psi \rightarrow$ PP (0^-0^-) $\Phi_p = 89.6° \pm 9.9°$ [4]

$J/\psi \rightarrow$ VV (1^-1^-) $\Phi_p = 138° \pm 37°$ [4]

- Results are model dependent
- Model independent test:

interference with the non resonant continuum

[1] R. Baldini, C. Bini, E. Luppi, Phys. Lett. B404, 362 (1997); R. Baldini et al., Phys. Lett. B444, 111 (1998)
[2] M. Ablikim et al., Phys. Rev. D 86, 032014 (2012).
[3] L. Kopke and N. Wermes, Phys. Rep. 174, 67 (1989); J. Jousset et al., Phys. Rev. D41,1389 (1990)
[4] M. Suzuki et al., Phys. Rev. D60, 051501 (1999).

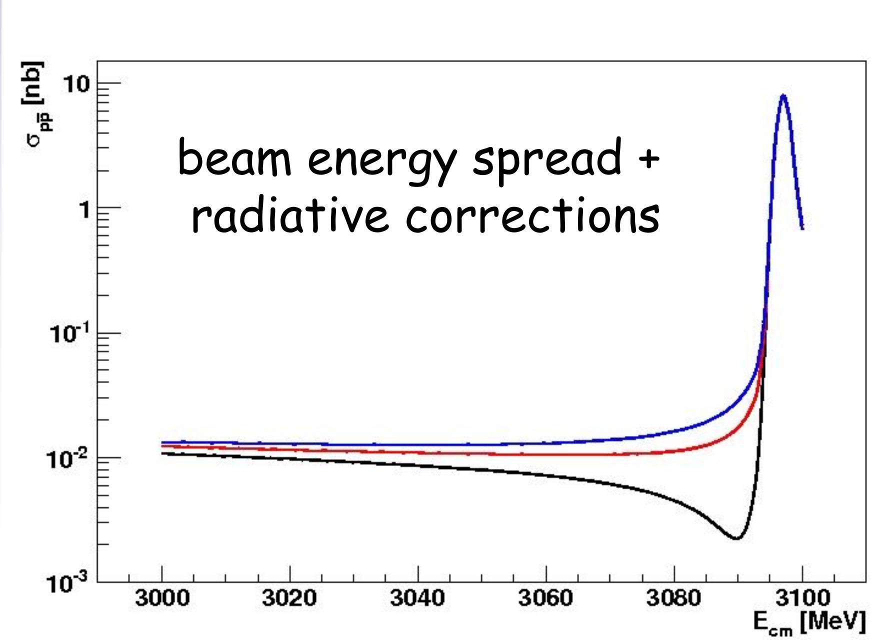
Simulated Yields for $e^+e^- \to p\bar{p}$

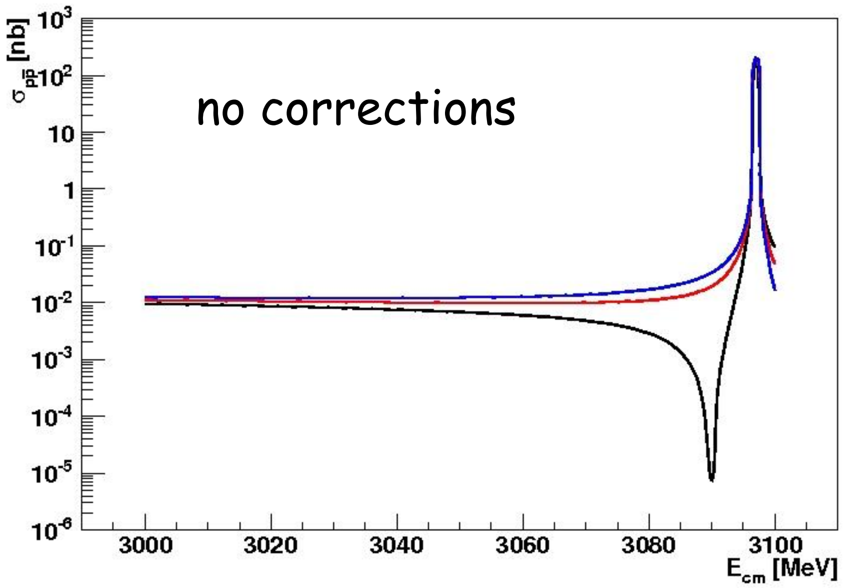
— $\Delta\varphi = 0°$

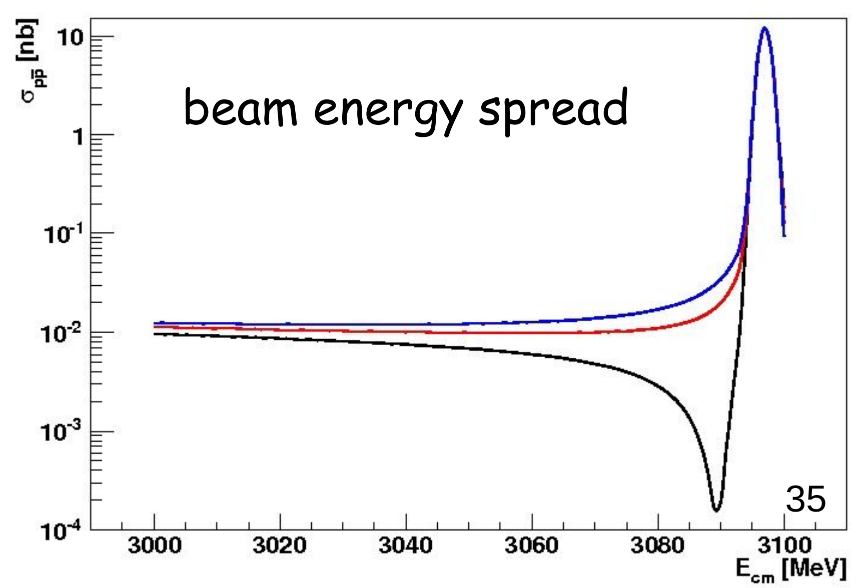
— $\Delta\varphi = 90°$

— $\Delta\varphi = 180°$

continuum reference
$\sigma \sim 11$ pb







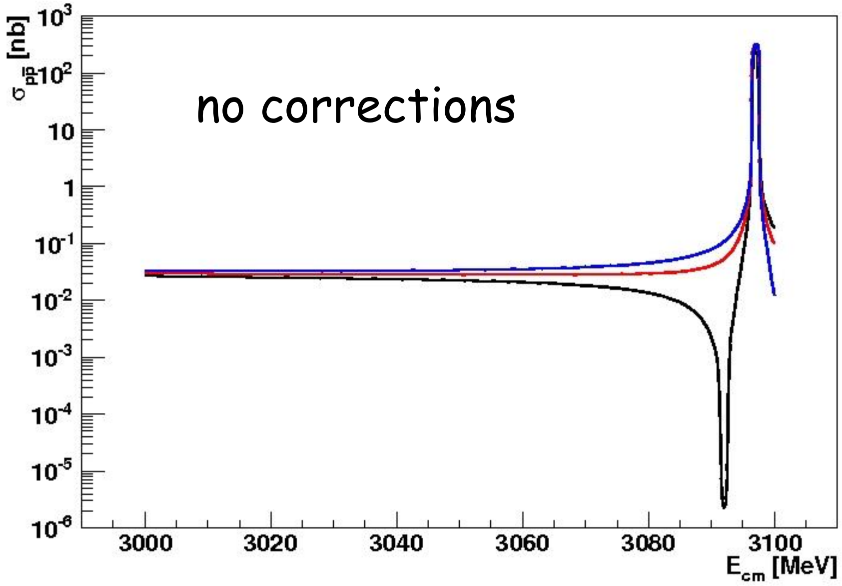
Simulated Yields for $\bar{p}p \rightarrow \mu^+\mu^-$

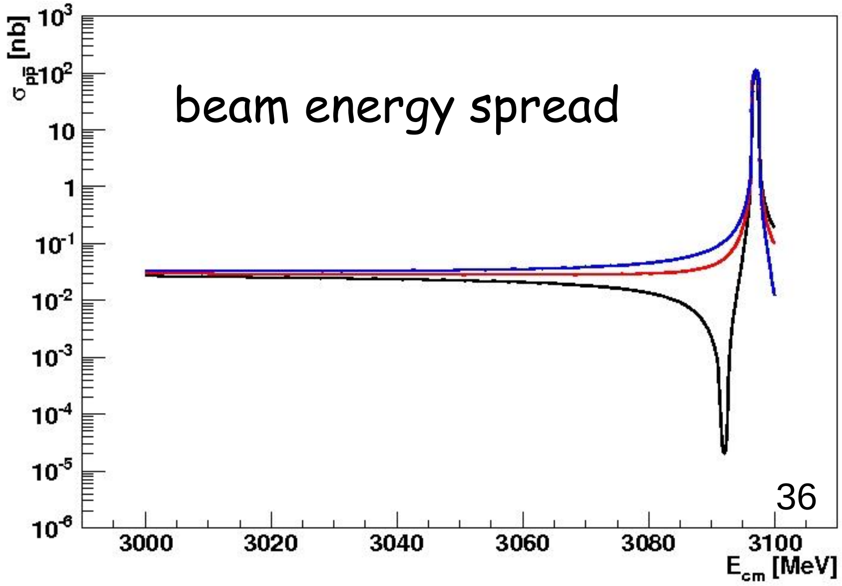
— $\Delta\varphi = 0°$

— $\Delta\varphi = 90°$

— $\Delta\varphi = 180°$

continuum reference
$\sigma \sim 18$ pb

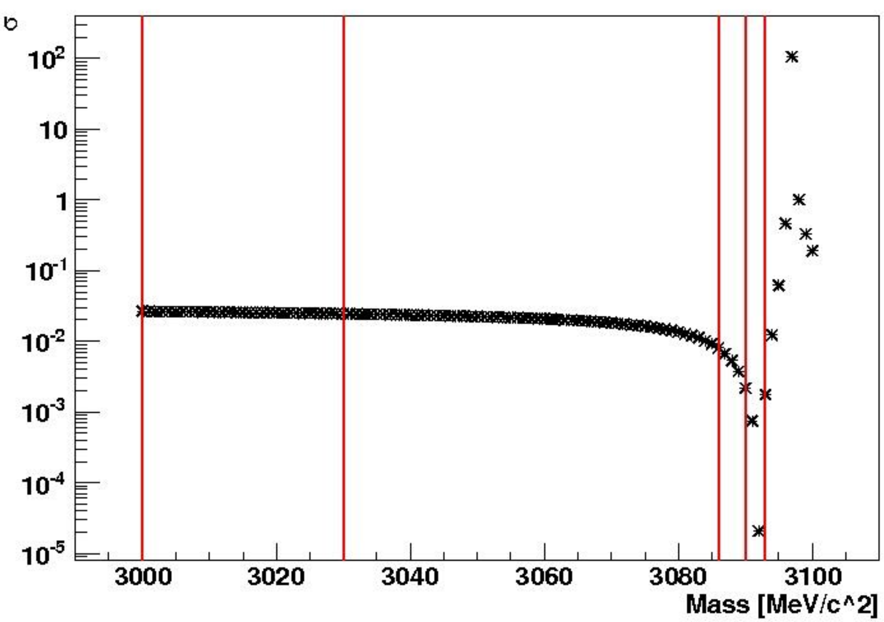




Energy Points Choice

Maximum interference: 0°

- 2 points at low W
  - fit the continuum
  - Student test
  - slope
- Deep position
- Beginning of Breit-Wigner

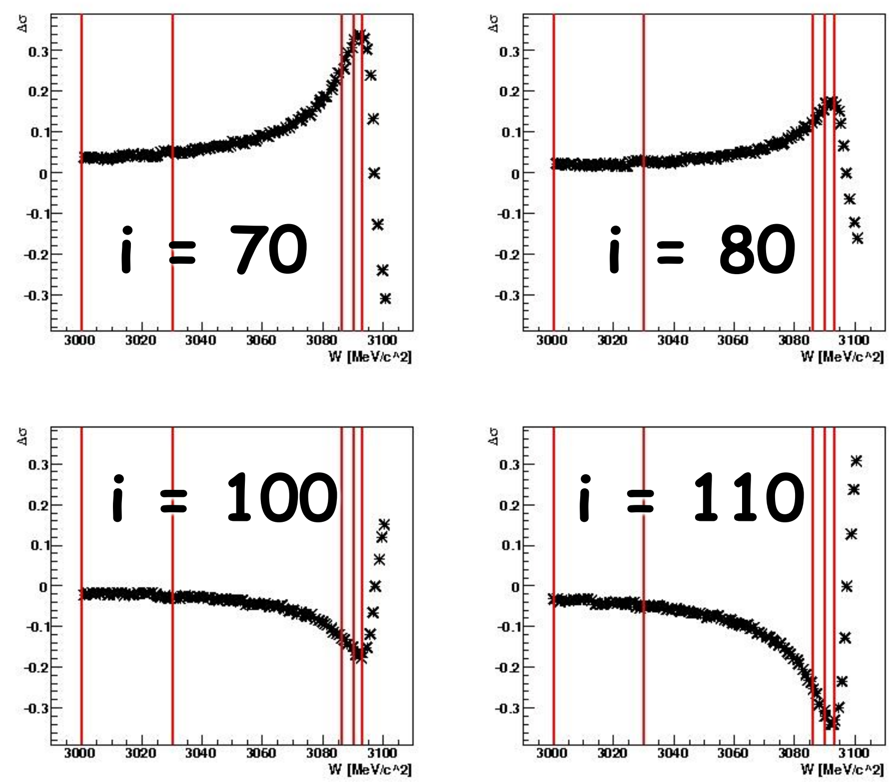


- What happens at 90°

Cross section simulated at

70°, 80°, 90°, 100°, 110°

Gradient $(\sigma_{90}-\sigma_i)/\sigma_{90}$



Summary

- New physics from unpolarized DY
- Wide Single Spin Asymmetry program
- Double Spin Asymmetries, if p can be polarized

• Few months of data taking are enough to:
  - evaluate unpolarised and single-spin asymmetries with good accuracy $\Rightarrow$ investigate their dependence on $q_{T,\mu\mu}$

- Interest on J/ψ decay amplitudes

• Simulation of different phases
• Reasonable energy point choice
• Optimization of the procedure