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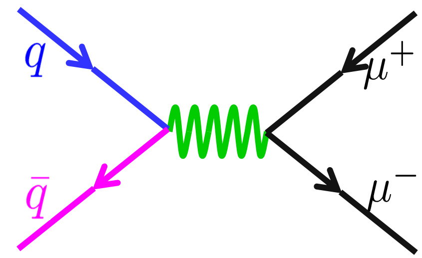
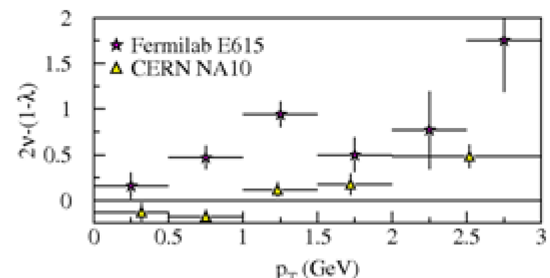
Measurements of Drell-Yan Angular Distributions and the Transverse Boer-Mulders Structure Function



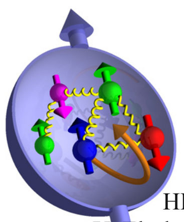
Paul E. Reimer

Argonne National Laboratory

Representing the Fermilab E-866/NuSea collaboration



- *Drell-Yan Angular Distributions and the Lam Tung Relation*
- *Pionic Drell-Yan Angular Distributions*
- *QCD Effects and the Boer-Mulders Distributions*
- *Proton Induced Drell-Yan: Fermilab E-866/NuSea*



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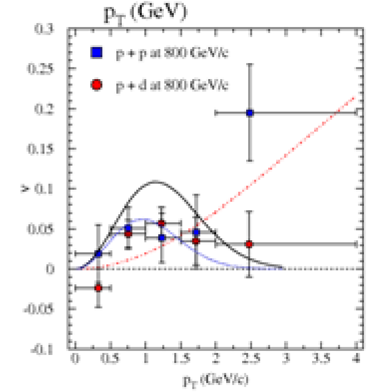
U. Elschenbroich



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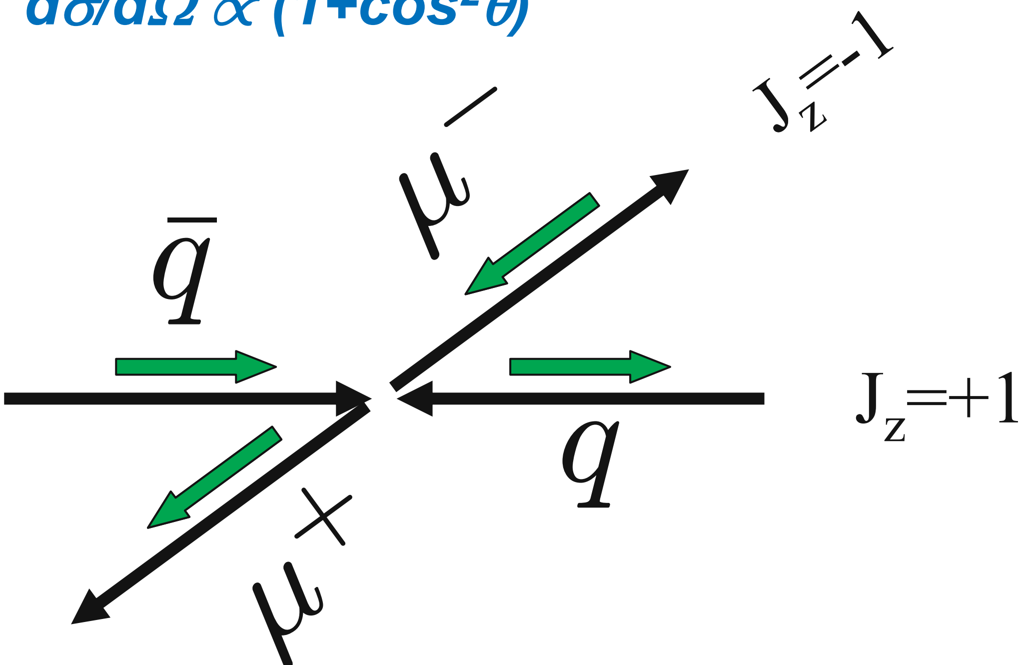
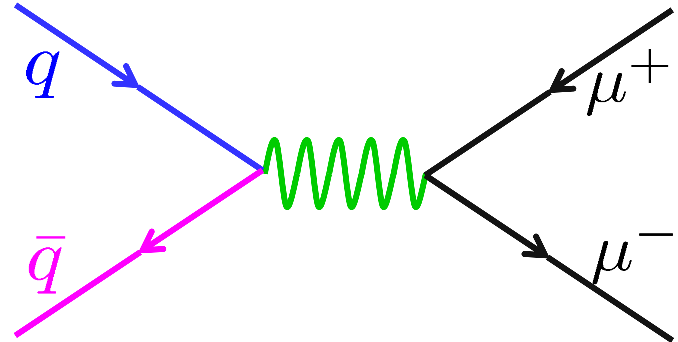
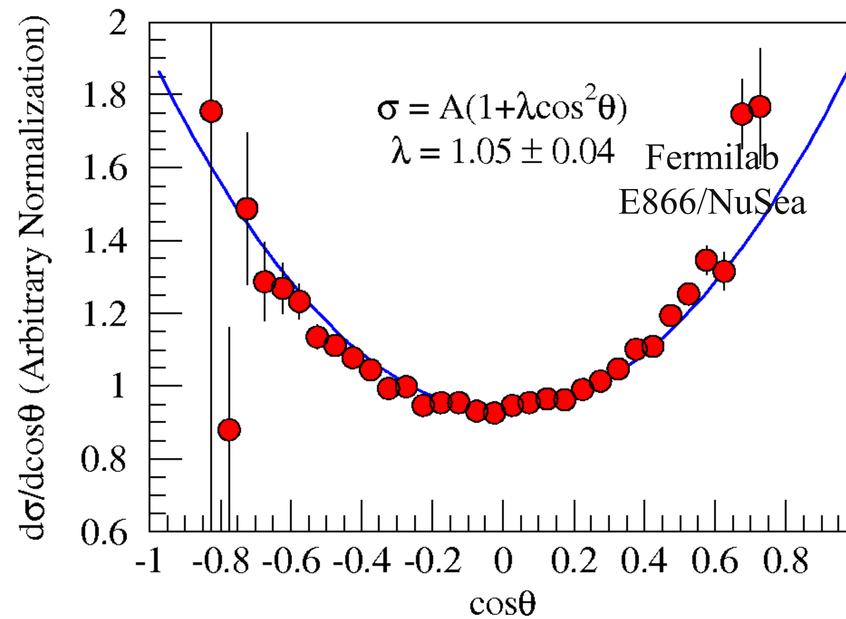
LO Drell-Yan Angular Distributions:

$d\sigma/d\Omega \propto (1+\cos^2\theta)$







$$\mathcal{M} \propto d^j_{\lambda'\lambda}(\theta) = \langle j\lambda' | e^{-i\theta J_y} | j\lambda \rangle$$

$$d^1_{11} = d^1_{-1-1} = \frac{1}{2}(1+\cos\theta)$$

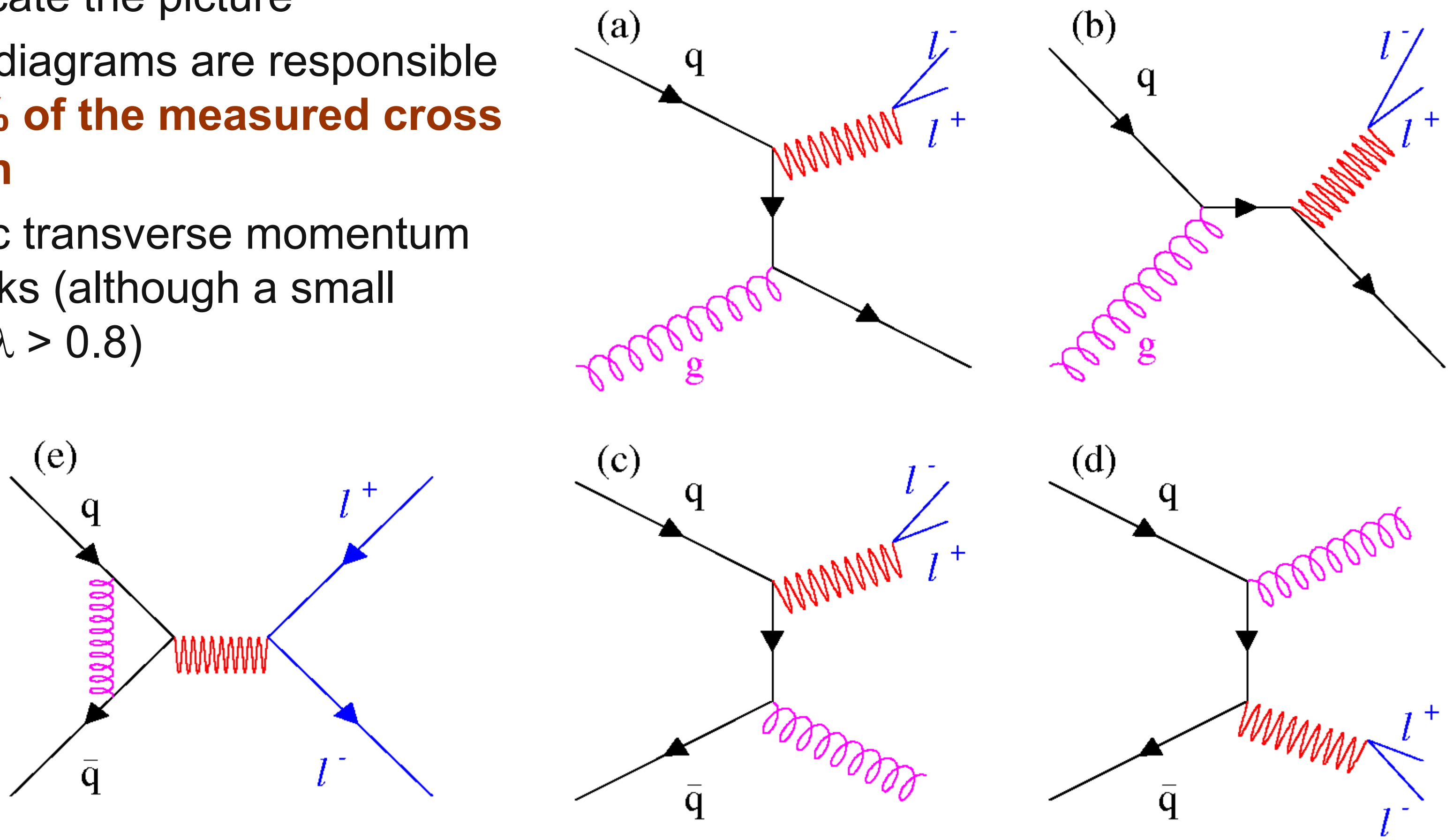
$$d^1_{-11} = d^1_{1-1} = \frac{1}{2}(1-\cos\theta)$$

$$\frac{d\sigma}{d\Omega} \propto \overline{\mathcal{M}^2} \propto (1+\cos^2\theta)$$

Helped to validate the Drell-Yan picture of quark-antiquark annihilation for lepton pair production

Next-to-Leading Order Drell-Yan

- Next-to-leading order diagrams complicate the picture
- These diagrams are responsible for **50% of the measured cross section**
- Intrinsic transverse momentum of quarks (although a small effect, $\lambda > 0.8$)

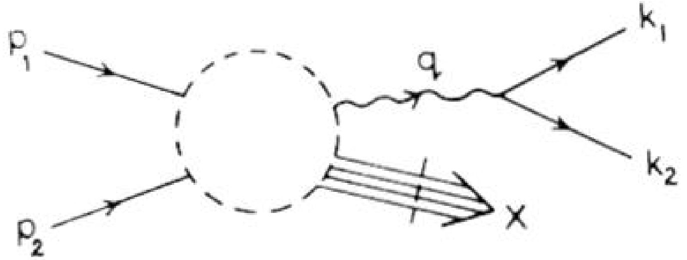


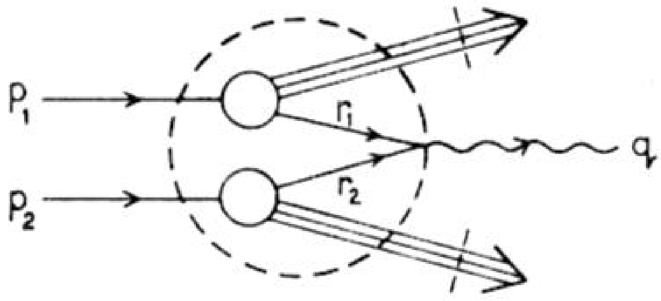
Generalized Angular Distributions

Chi-Sing Lam and Wu-Ki Tung—basic formula for lepton pair production angular distributions PRD **18** 2447 (1978)

$$\frac{d\sigma}{d^4q\; d\Omega_k^*} = \frac{1}{2}\frac{1}{(2\pi)^4}\frac{\alpha^2}{(Ms)^2}\left[W_T\left(1+\cos^2\theta\right) + W_L\left(1-\cos^2\theta\right)\right.$$
$$\left. + W_\Delta \sin 2\theta \cos\phi + W_{\Delta\Delta} \sin^2\theta \cos 2\phi\right]$$

- Structure function formalism
  - Derived in analogy to DIS
  - Independent of Drell-Yan and parton "models"
  - Showed same relations follow as a general consequence of the quark-parton model





PRD 18 2447 (1978)

Lam-Tung Relation *PRD 21 2712 (1980)*

- Lam-Tung Relation

  Direct analogy to the Callan-Gross relation in DIS

$$\frac{d\sigma}{d^4q\ d\Omega_k^*} = \frac{1}{2}\frac{1}{(2\pi)^4}\frac{\alpha^2}{(Ms)^2}\left[W_T\left(1+\cos^2\theta\right) + W_L\left(1-\cos^2\theta\right) + W_\Delta \sin 2\theta\cos\phi + W_{\Delta\Delta}\sin^2\theta\cos 2\phi\right]$$

$$W_L = 2W_{\Delta\Delta}$$

  Normally written as

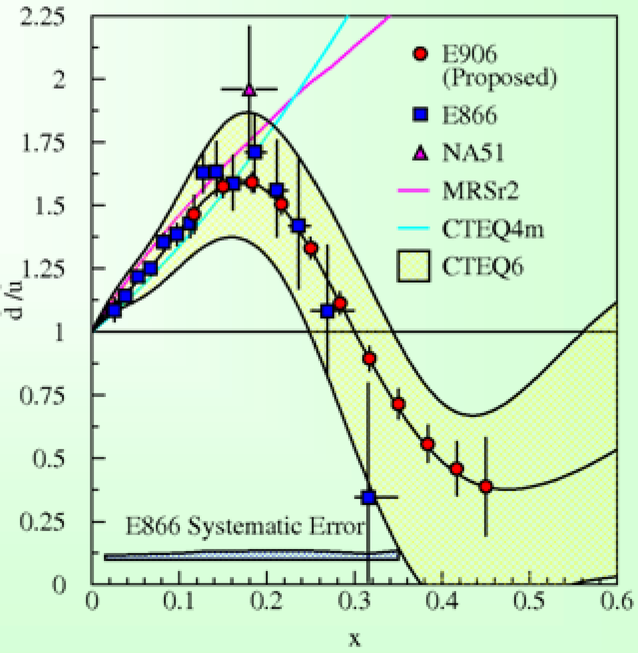
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi$$

$$1-\lambda = 2\nu$$

- Unaffected by $O(\alpha_s)$ (NLO) corrections
- NNLO [$O(\alpha_s^2)$] corrections also small Mirkes and Ohnemus, PRD **51** 4891 (1995)

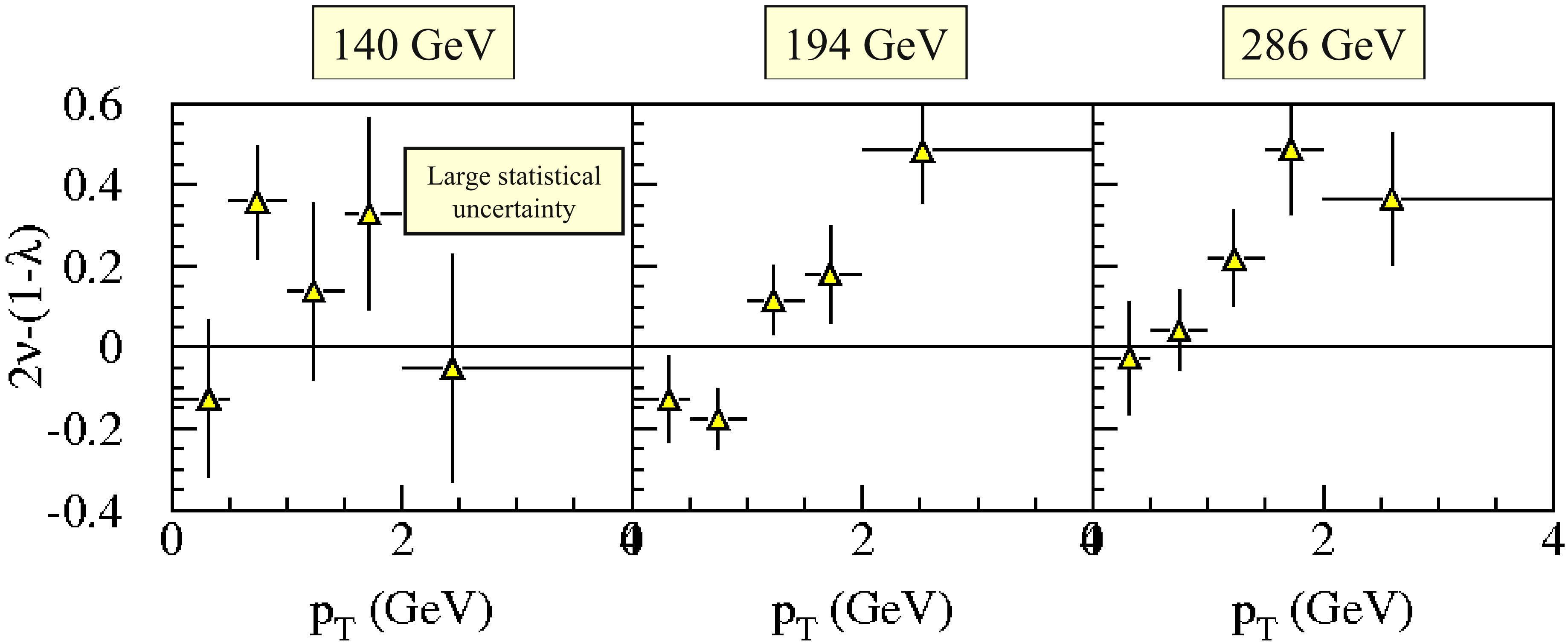
What do the data say?

- Pionic Drell-Yan experiments
  - CERN NA10 Guanziroli *et al.* (NA10) ZPC **37** 545 (1988)
    - *140, 194 and 286 GeV π on tungsten*
  - Fermilab E-615 Conway *et al.* PRD **39** 92 (1989)
    - *252 GeV π on tungsten*



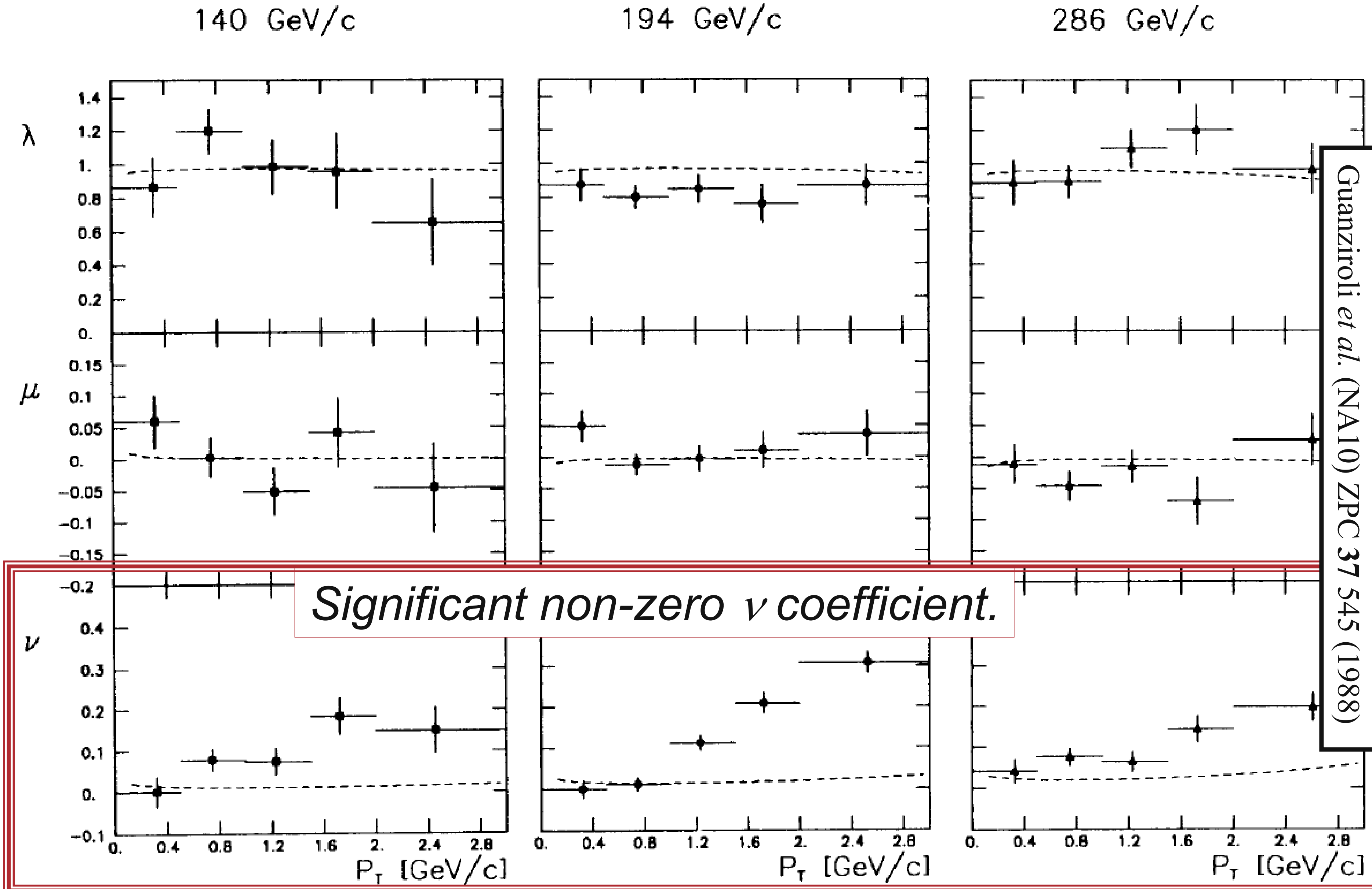
- Proton induced Drell-Yan
  - Fermilab E-866/NuSea
    - *800 GeV proton on proton and deuterium*
    - *Study d-bar/u-bar in proton*

NA10 Lam-Tung Relation vs. p_T



- Violation of Lam-Tung relation as p_T increases in higher momentum data. Statistics poor in 140 GeV data.
- Note: Correlation between λ and ν uncertainties not known.
- Since most data is at low p_T, *on average* the Lam-Tung relationship holds

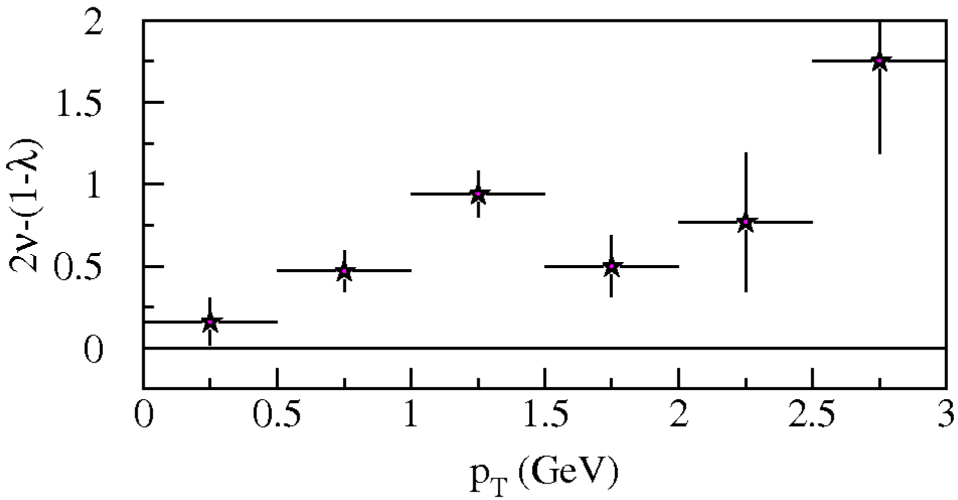
NA10 angular distributions vs. p_T

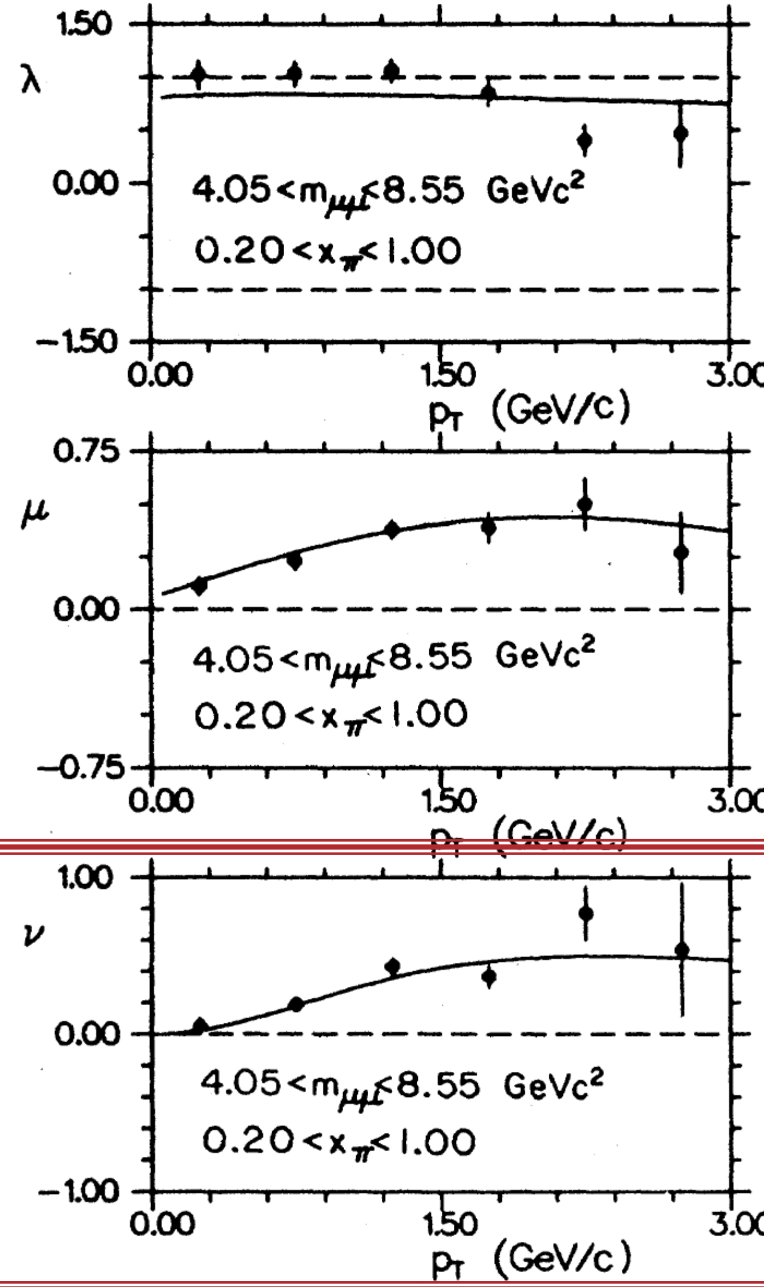


Significant non-zero ν coefficient.

Guanziroli *et al.* (NA10) ZPC **37** 545 (1988)

Pionic Data Fermilab E615





Conway *et al.* PRD **39** 92 (1989)

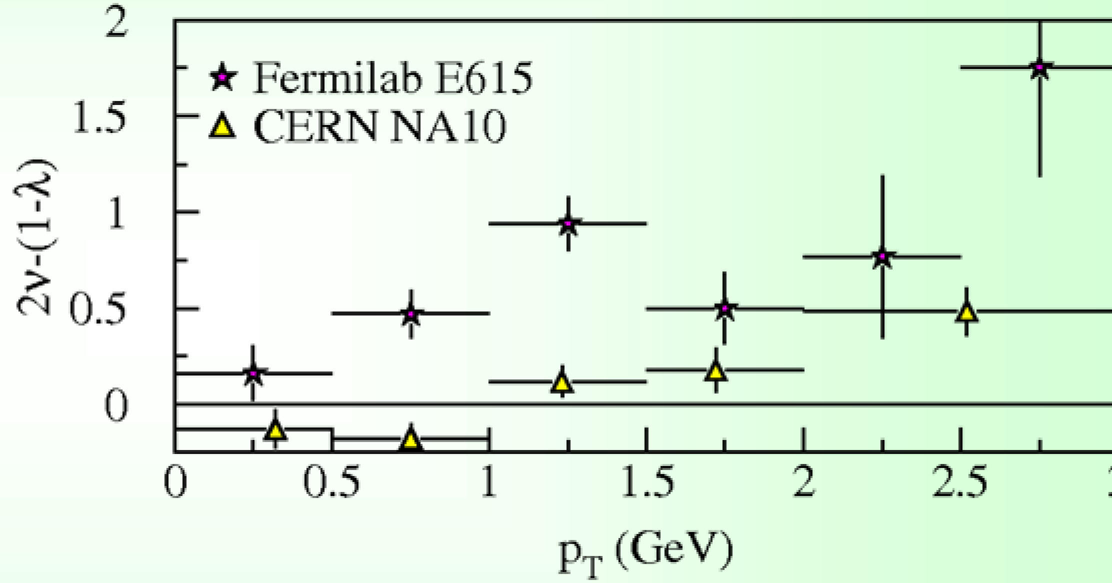
- Clear violation of Lam-Tung Relation vs. p_T.
- *Violation larger than NA10*
- *Significant non-zero ν coefficient*
- Shows other kinematic dependencies

Summary so far

Lam-Tung Relation is theoretically robust

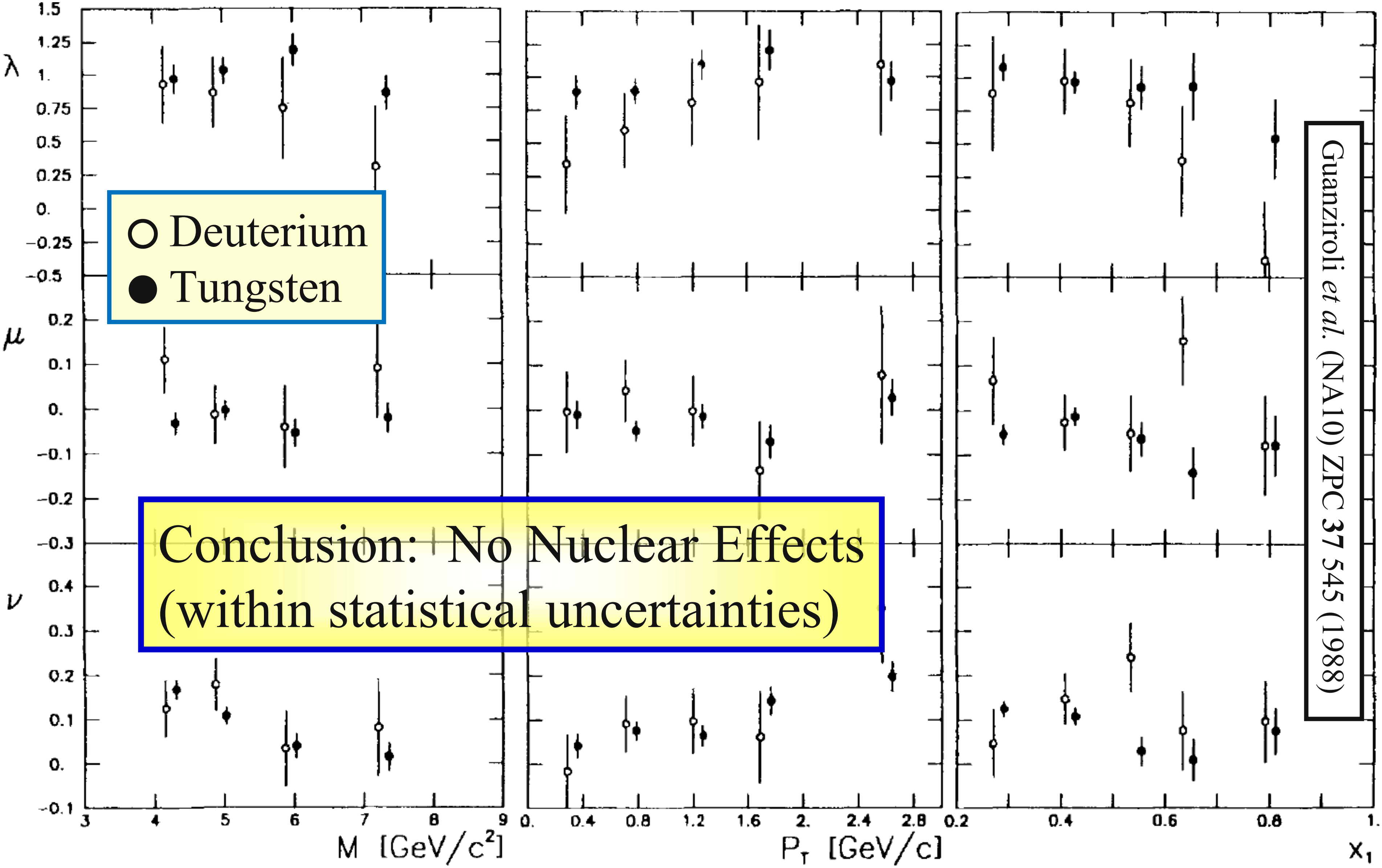
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi \quad 1 - \lambda = 2\nu$$

- Pionic Drell-Yan experiments see a violation which grows as a function of p_T. (Esp. NA10);
- Significant non-zero ν (cos2ϕ) term



- Possible explanations?
  - Nuclear effects
  - Higher-Twist effects from quark-antiquark binding in pion
  - Factorization breaking QCD Vacuum
  - k_T dependent transverse momentum distribution (Boer Mulders $h_1^{\perp}$)

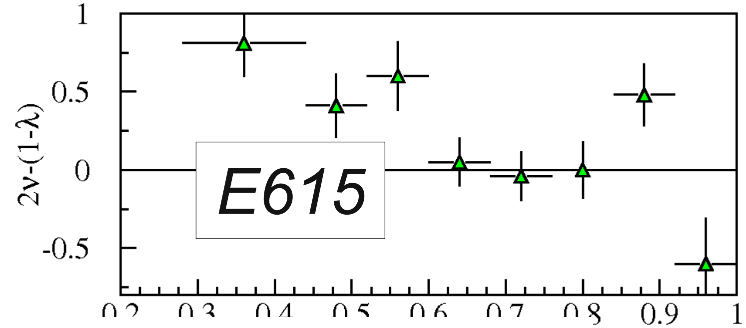
Nuclear Effect? Compare NA10 Deuterium and Tungsten

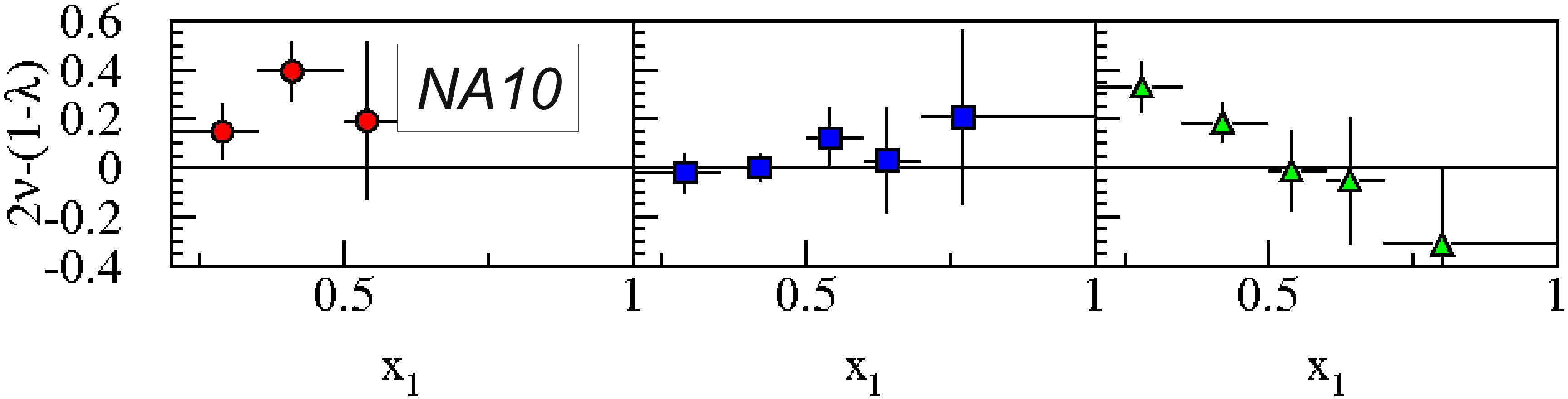


Conclusion: No Nuclear Effects (within statistical uncertainties)

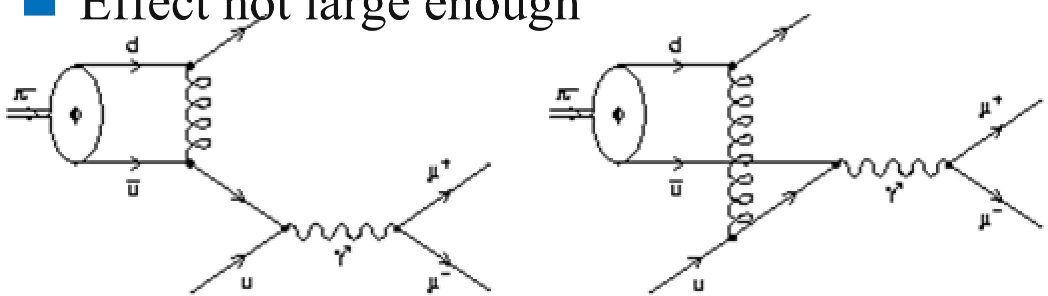
Higher twist/QCD effects in pion

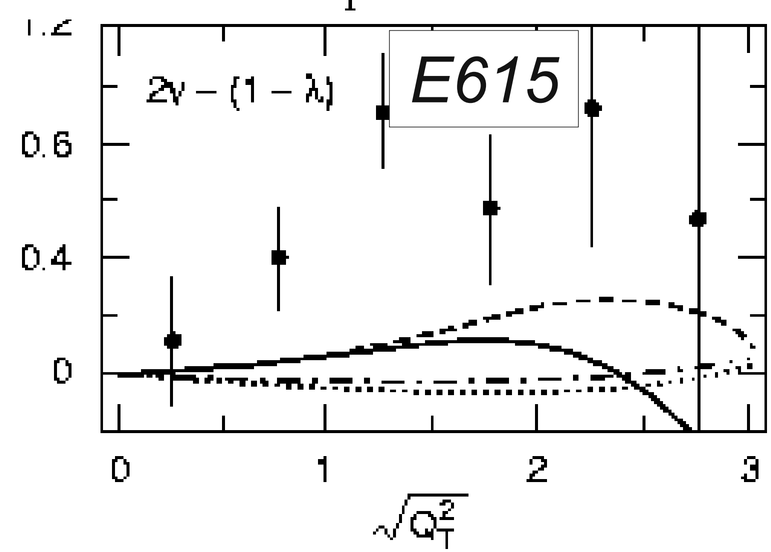
- Expected only as $x_1 \to 1$





- QCD effects in pion—model only applicable for $x_1 > 0.6$ Brandenburg, Brodsky, Khoze and Muller Phys.Rev.Lett.73:939-942,1994
- Effect not large enough



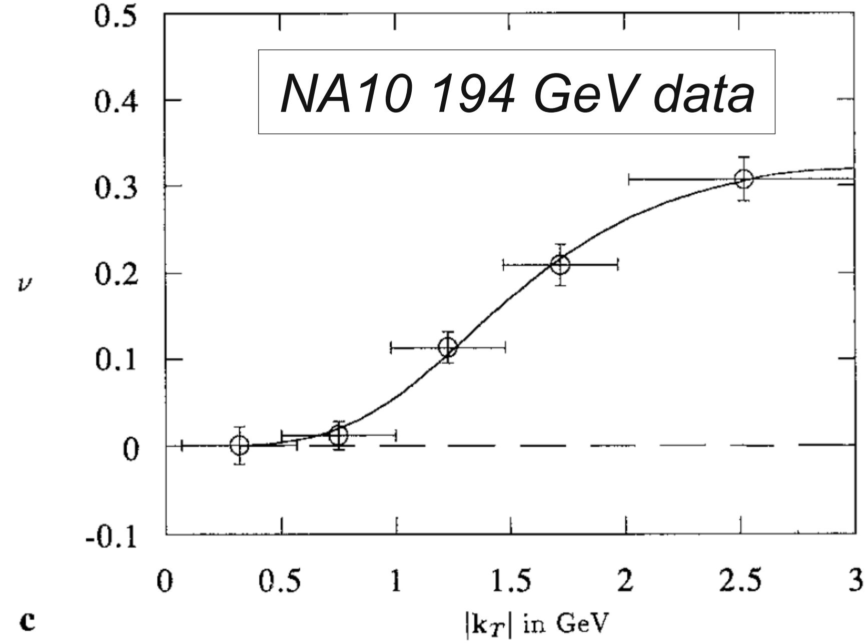


QCD Vacuum Effect

- Factorization breaking Brandenburg, Nachtmann and Mirkes, ZPC **60**, 679 (1993).
  - QCD Vacuum ***may*** correlate the spins and momenta of incoming partons
  - Effect could be instanton-induced Boer, Brandenburg, Nachtmann, Utermann, EPJC 40 55 (2005), Brandenburg, Ringwald, Utermann NPB 754, 107 (2006).

$$\nu \approx 2\mathcal{K} = 2\mathcal{K}_0 \frac{p_T^4}{p_T^4 + m_T^4}$$

$$\lambda \approx 1 \quad \mu \approx 0$$



- Fit NA10:

$\kappa = 0.17$

$m_T = 1.5$

Should be flavor blind and seen in both sea and valence distributions

Boer-Mulders Structure Function

- Relates parton's transverse spin and transverse momentum (k_T) in an unpolarized nucleon.
- Presence in both quark and antiquark in annihilation could form correlation contributing to cos(2ϕ) distribution

$$\nu \propto h^{\perp}_{1,q(\mathrm{beam})}(x_1) h^{\perp}_{1,\bar{q}(\mathrm{target})}(x_2)$$

$$h_1^{\perp}(x, k_T^2) = C_H \frac{\alpha_T}{\pi} \frac{1}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x)$$

$$\nu = 16\ C_1 C_2 \frac{p_T^2 M_C^2}{(p_T^2 + 4M_C^2)^2}$$

$M_C = 2.3 \pm 0.5$ GeV
$16\ C_1 C_2 = 7 \pm 2$

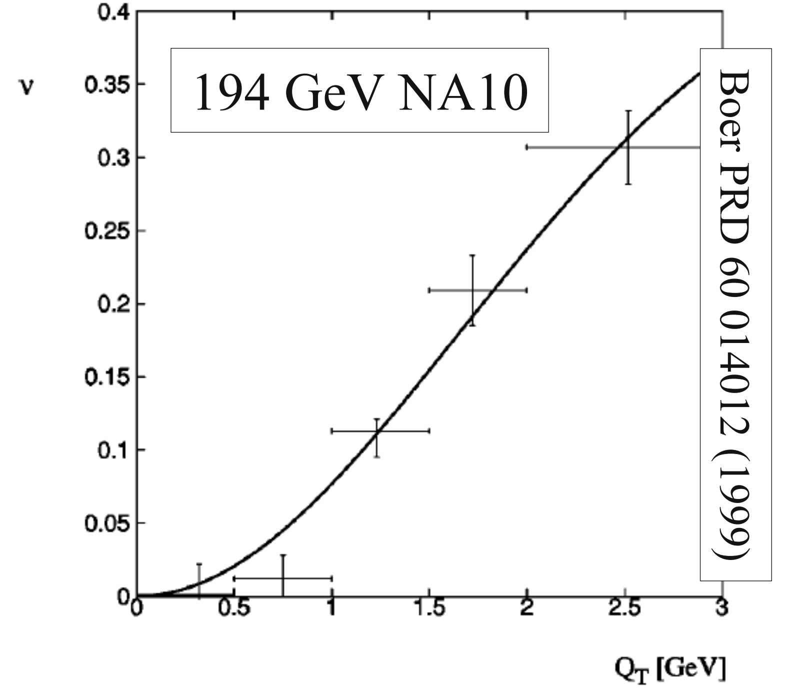


FIG. 4. Data from [3] at 194 GeV and fit [using Eq. (49)] to $\nu = 2\kappa$ as a function of the transverse momentum Q_T of the lepton pair. The fitted parameters are $M_C = 2.3 \pm 0.5$ GeV and $16\kappa_1 = 7 \pm 2$.

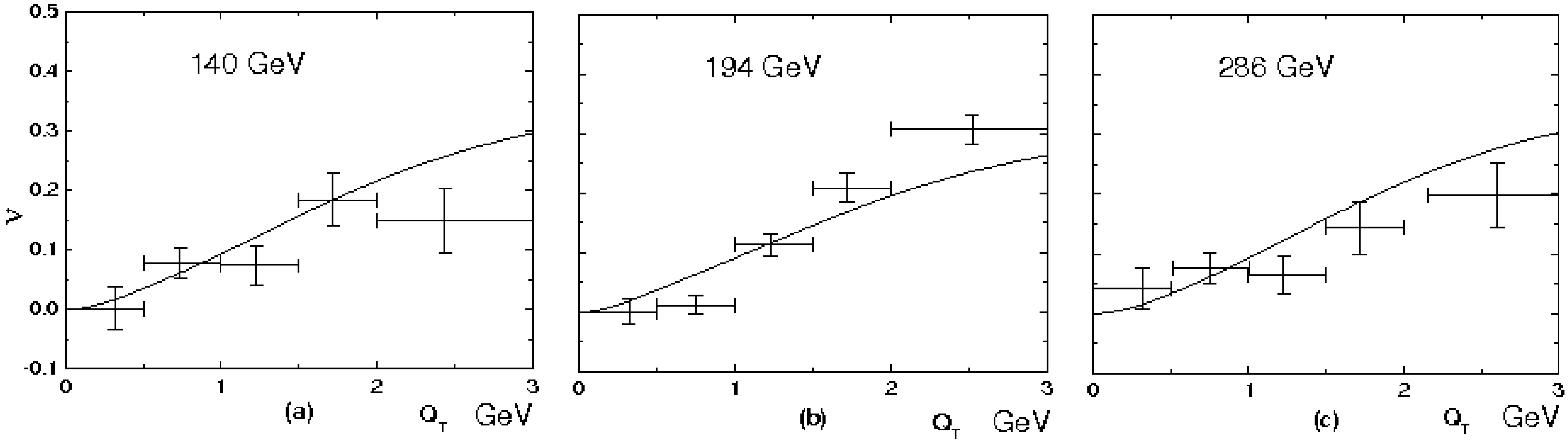
Boer-Mulders Structure Function

- Lu and Ma—quark-spectator-antiquark model

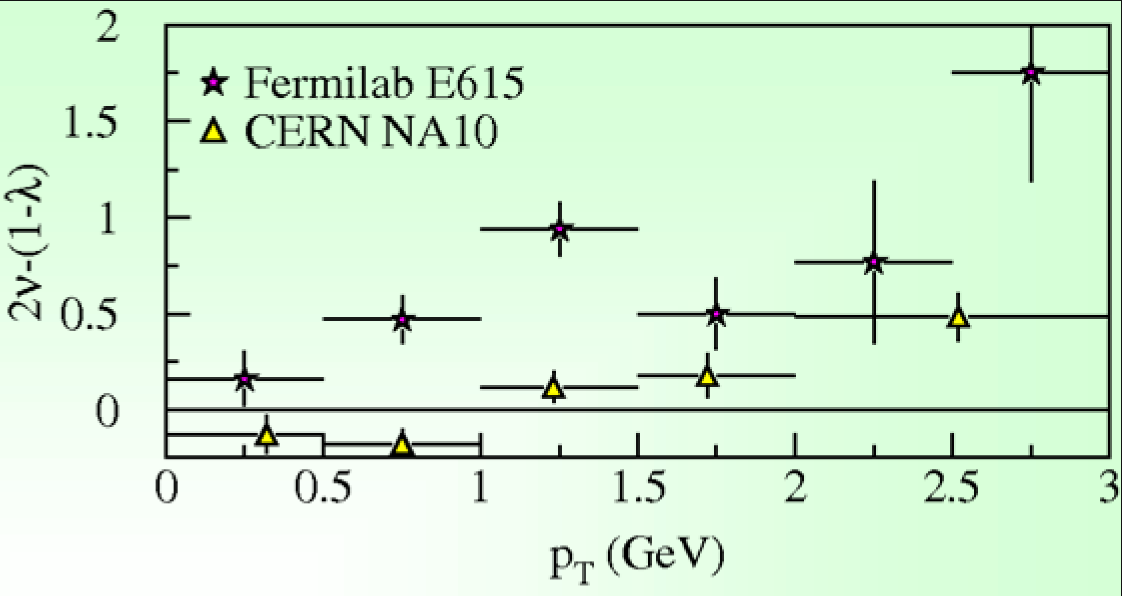
$$h_{1\pi}^{\perp} = \frac{A_\pi(x)}{k_\perp^2 \{k_\perp^2 + B_\pi(x)\}} \ln \frac{k_\perp^2 + B_\pi(x)}{B_\pi(x)}$$

- Fit all three NA10 energies

Lu, Ma, PL**B 615**, 200 (2005)



Summary so far



Lam-Tung Relation is violated in pion induced Drell-Yan

Possible explanations?

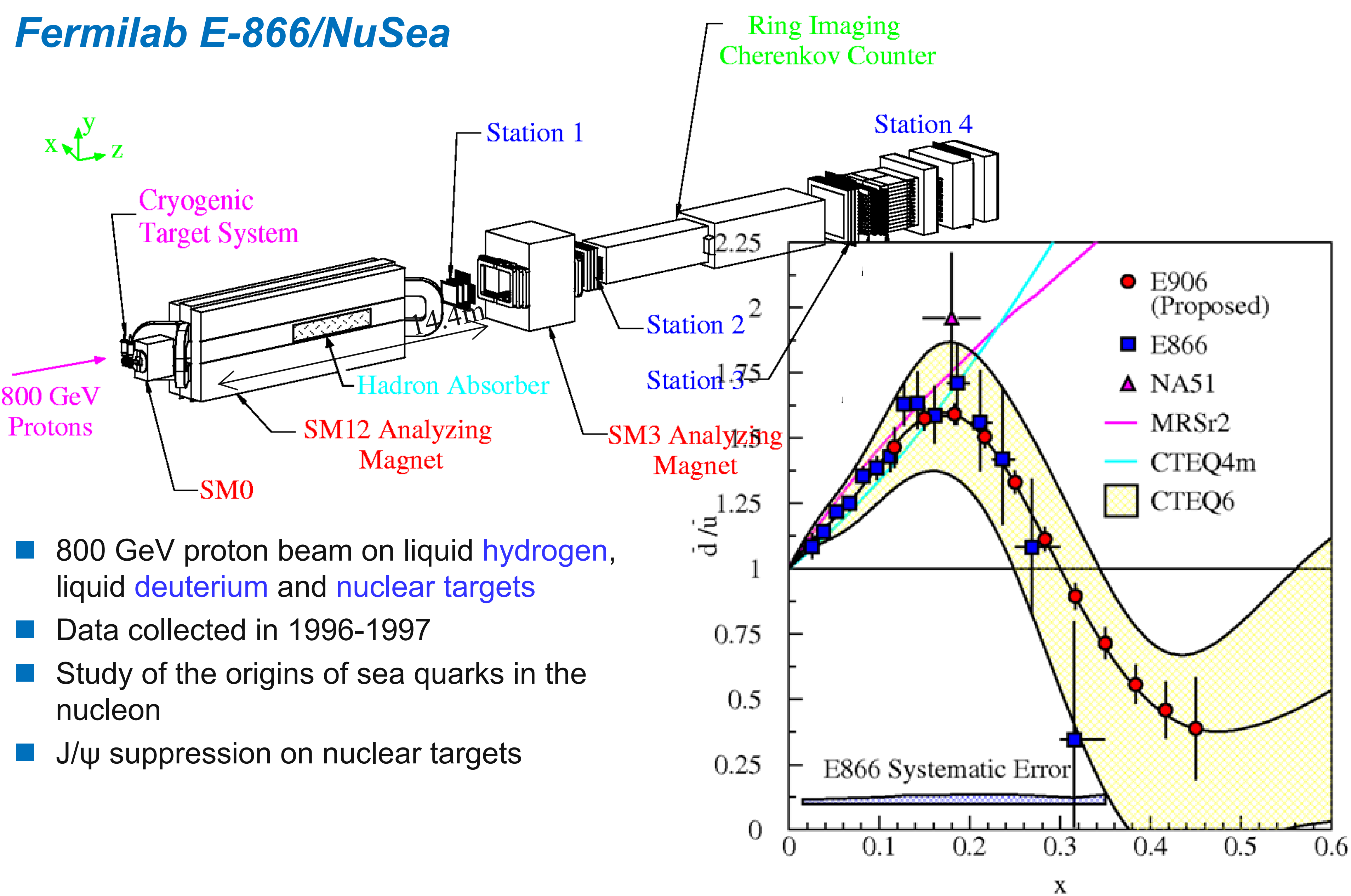
- ~~Nuclear effect~~
- ~~Higher-Twist effects~~ from quark-antiquark binding in pion
- Factorization breaking QCD Vacuum

  Expect same effect for sea and valence

- k_T dependent transverse momentum distribution (Boer Mulders $h_1^{\perp}$)

  Possible difference between valence and sea distributions

Fermilab E-866/NuSea



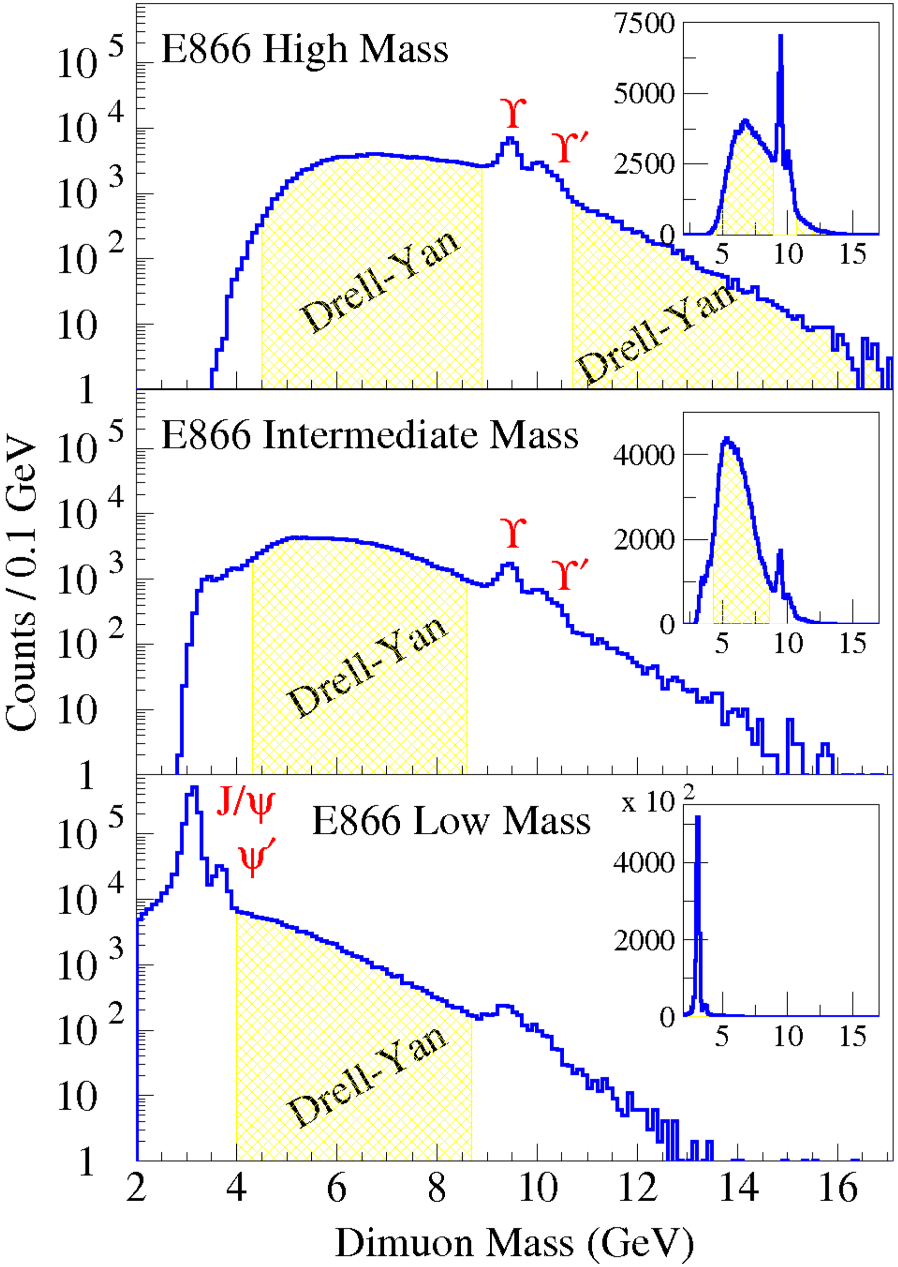
- 800 GeV proton beam on liquid hydrogen, liquid deuterium and nuclear targets
- Data collected in 1996-1997
- Study of the origins of sea quarks in the nucleon
- J/ψ suppression on nuclear targets

Dimuon Mass Distribution

Spectrometer settings

- Data used for cos2φ analysis:
- High Mass:
  - *data set 7-39k (+ polarity)*
  - *data set 8-85k (+ polarity)*
  - *data set 11-25k (- polarity)*
- Low Mass:
  - *data set 5-68k (+ polarity)*

$$\sqrt{s} = 38.8\text{GeV}$$



FNAL E866/NuSea Collaboration

Abilene Christian University
Donald Isenhower, Mike Sadler, Rusty Towell, Josh Bush, Josh Willis, Derek Wise

Argonne National Laboratory
Don Geesaman, Sheldon Kaufman, Naomi Makins, Bryon Mueller, Paul E. Reimer

Fermi National Accelerator Laboratory
Chuck Brown, Bill Cooper

Georgia State University
Gus Petitt, Xiao-chun He, **Bill Lee**

Illinois Institute of Technology
Dan Kaplan

Los Alamos National Laboratory
Melynda Brooks, Tom Carey, Gerry Garvey, Dave Lee, Mike Leitch, Pat McGaughey, Joel Moss, Brent Park, Andrea Palounek, Walt Sondheim, Neil Thompson

Louisiana State University
Paul Kirk, Ying-Chao Wang, Zhi-Fu Wang

New Mexico State University
Mike Beddo, **Ting Chang**, Gary Kyle, Vassilios Papavassiliou, J. Seldon, **Jason Webb**

Oak Ridge National Laboratory
Terry Awes, Paul Stankus, Glenn Young

Texas A & M University
Carl Gagliardi, Bob Tribble, **Eric Hawker**, Maxim Vasiliev

University of Illinois
Jen-Chieh Peng, ***Lingyan Zhu***

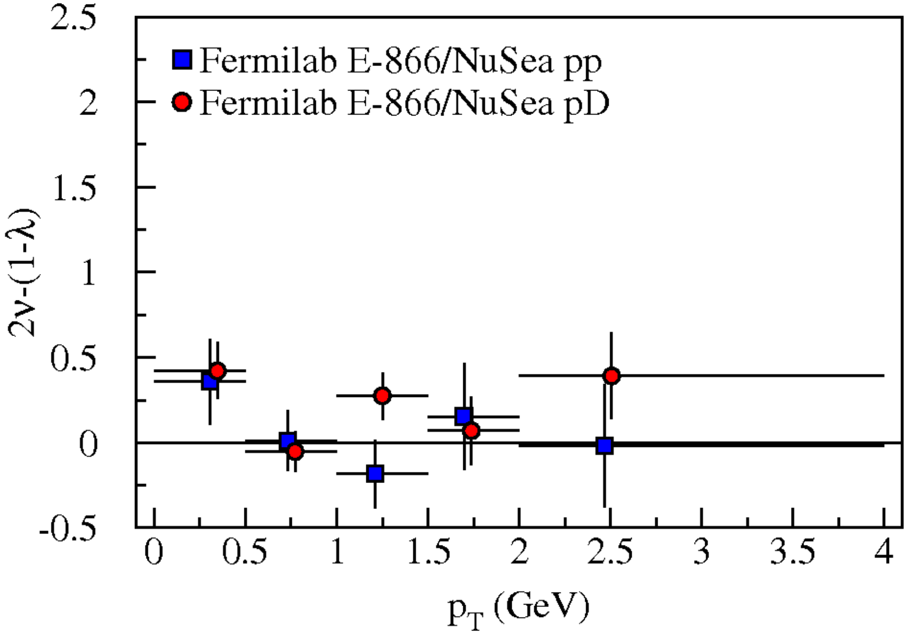
University of New Mexico
Steve Klinksiek

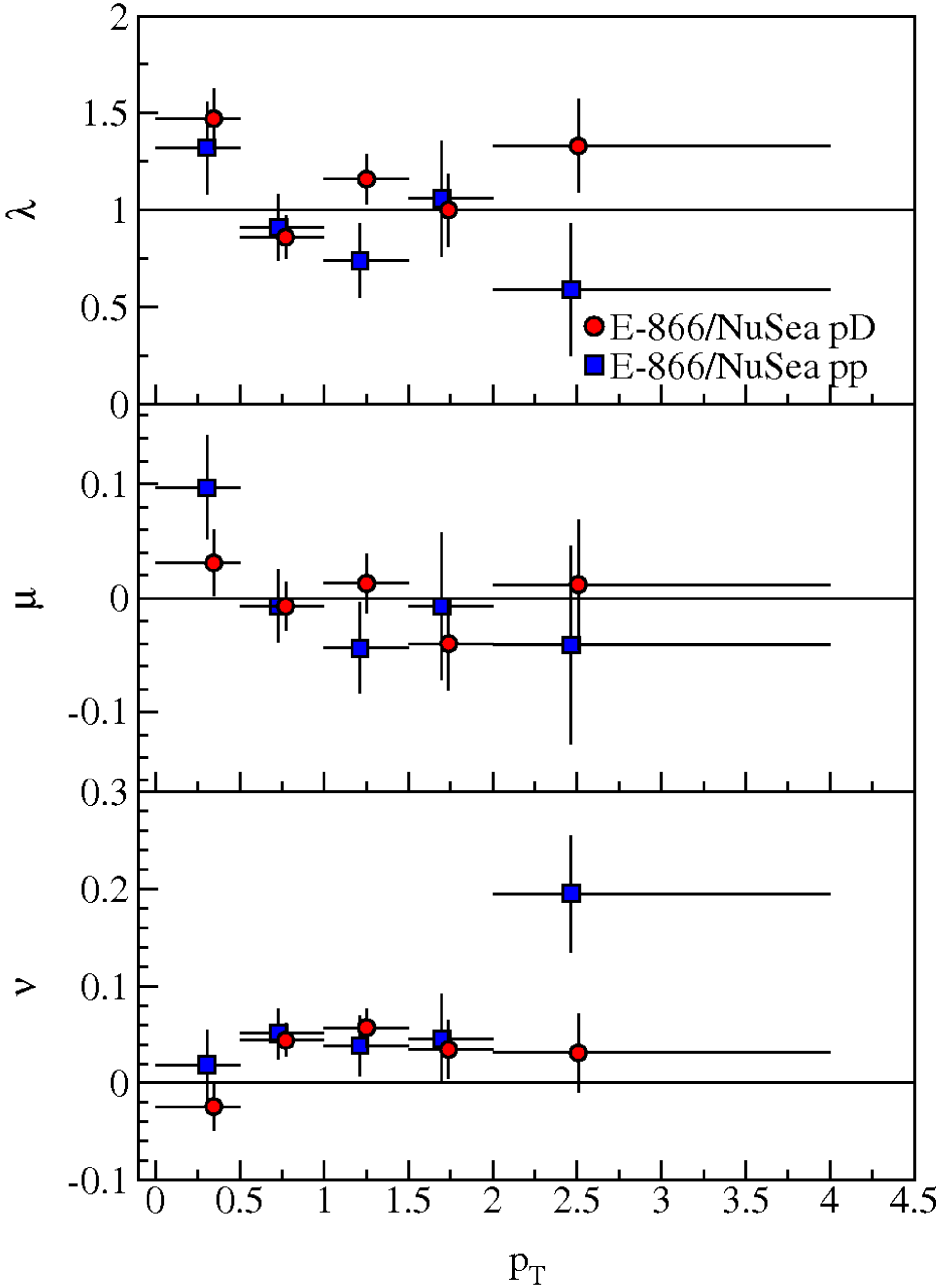
Valparaiso University
Don Koetke, Paul Nord

E-866/NuSea: Angular coefficients

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$

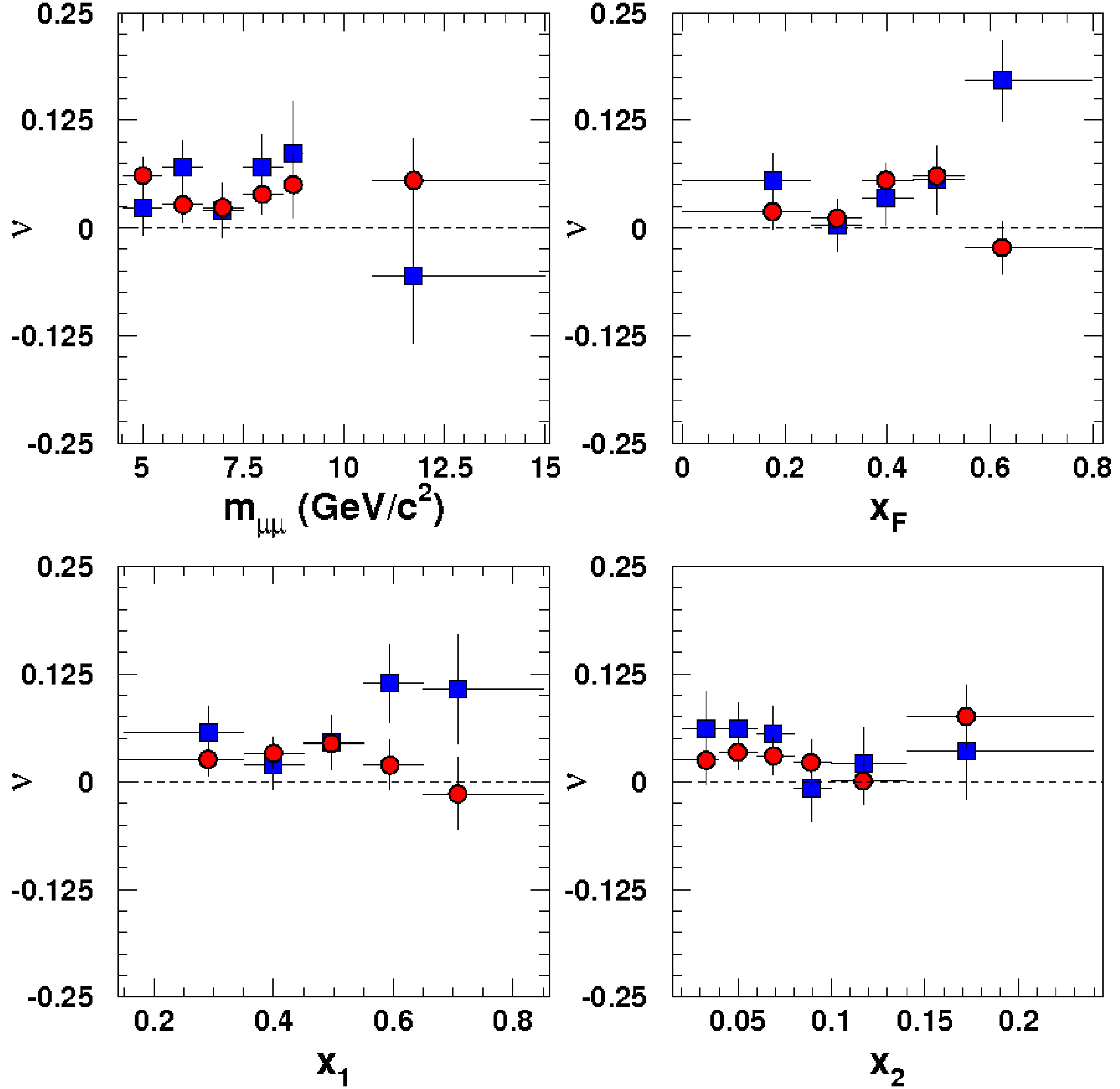
- λ consistent with 1
- μ consistent with 0
- ν consistent with 0 (or slightly positive)





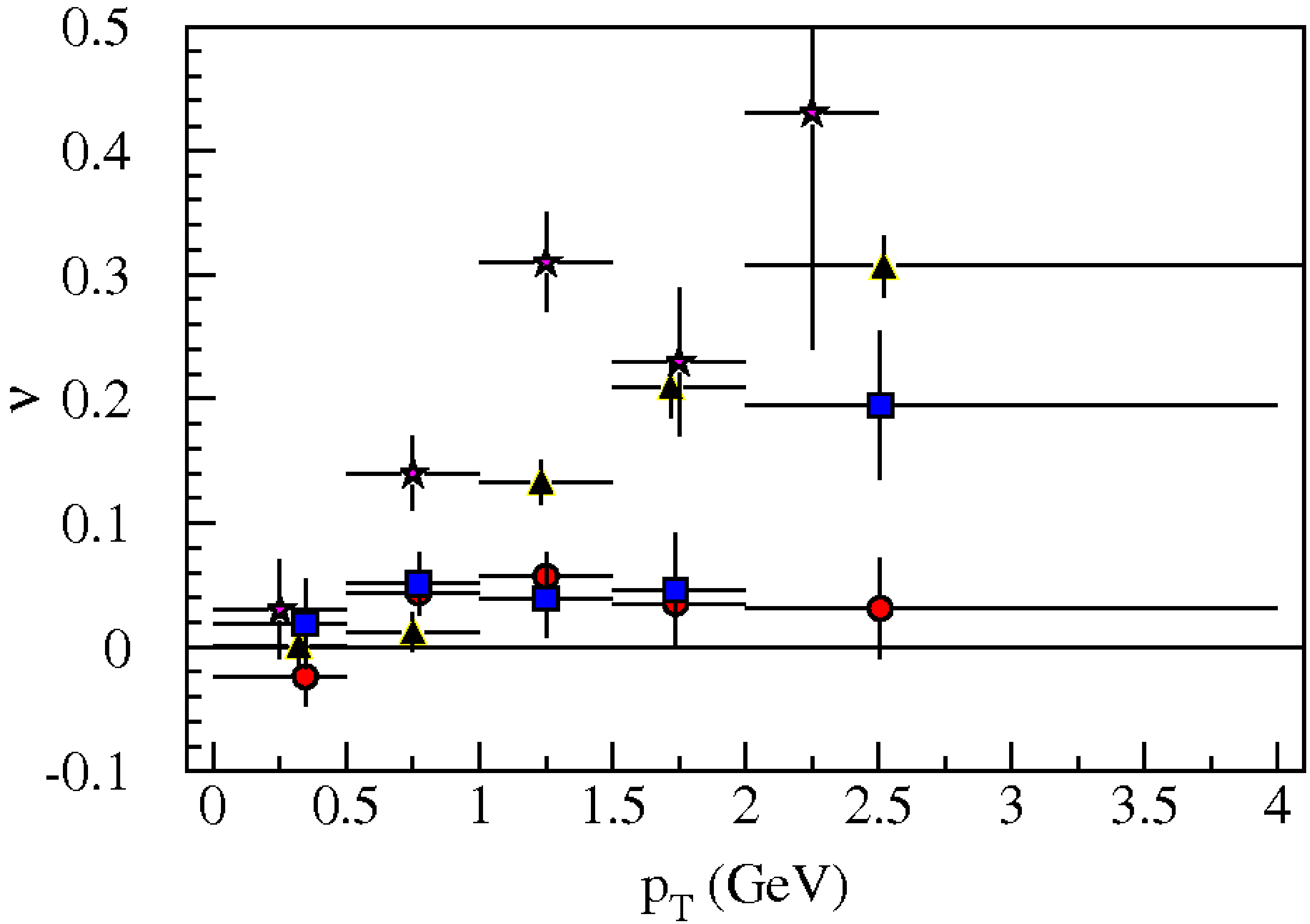
Kinematic Dependencies: *ν*

- ν consistent with 0 or lightly positive
  - for almost all kinematics and
  - both targets



What do the data mean?

- ν coefficient is grows as a function of p_T faster for π^- induced Drell-Yan
- **π^- quark structure has a valence anti-u quark** —sensitive to valence u quark distributions of target



- Proton induced Drell-Yan is sensitive only to sea antiquark structure of the target
- Possible valence vs. sea quark effect?
  - $h^1_\perp$ expected to be small for sea

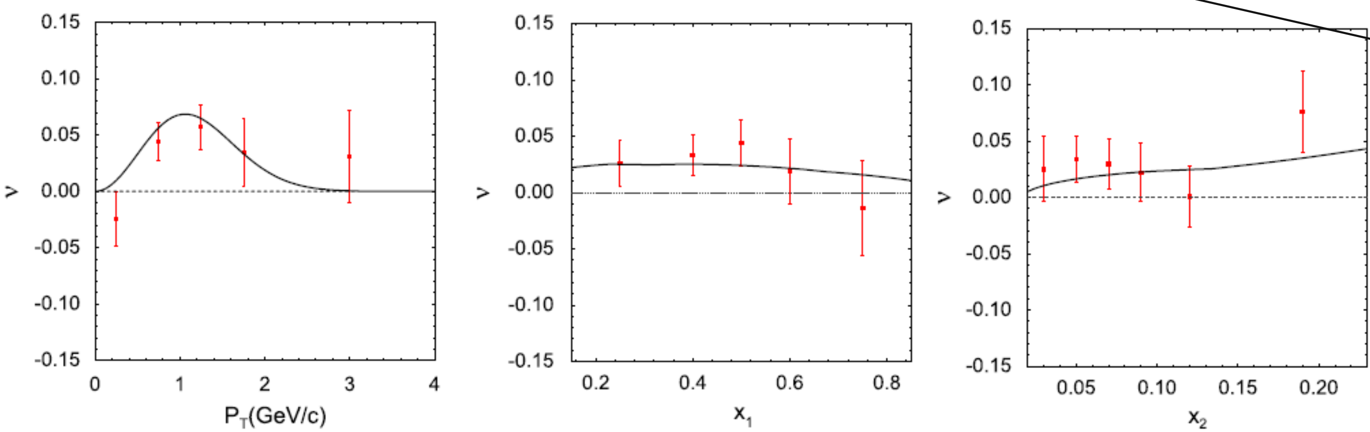
Extraction of Boer-Mulders function from pD Drell-Yan

- Zhang, Lu, Ma, Schmidt, Phys.Rev.**D77**:054011,2008.
- Fit to E866 pD Drell-Yan ν data in p_T, x_1 and x_2
- Extract $h_\perp^{1,q}$. (flavor separation)
- Predict ν for pp Drell-Yan

$$h_1^{\perp,q}(x,p_\perp^2) = H_q x^c (1-x) e^{\left(-p_\perp^2/p_{BM}^2\right)} f_1^q(x)$$

H_u	H_d	$H_{\bar{u}}$	$H_{\bar{d}}$	c	p_{BM}	χ^2/dof
3.99	3.83	0.91	-0.96	0.16	0.45	0.79

Small sea quark $h_1^\perp$



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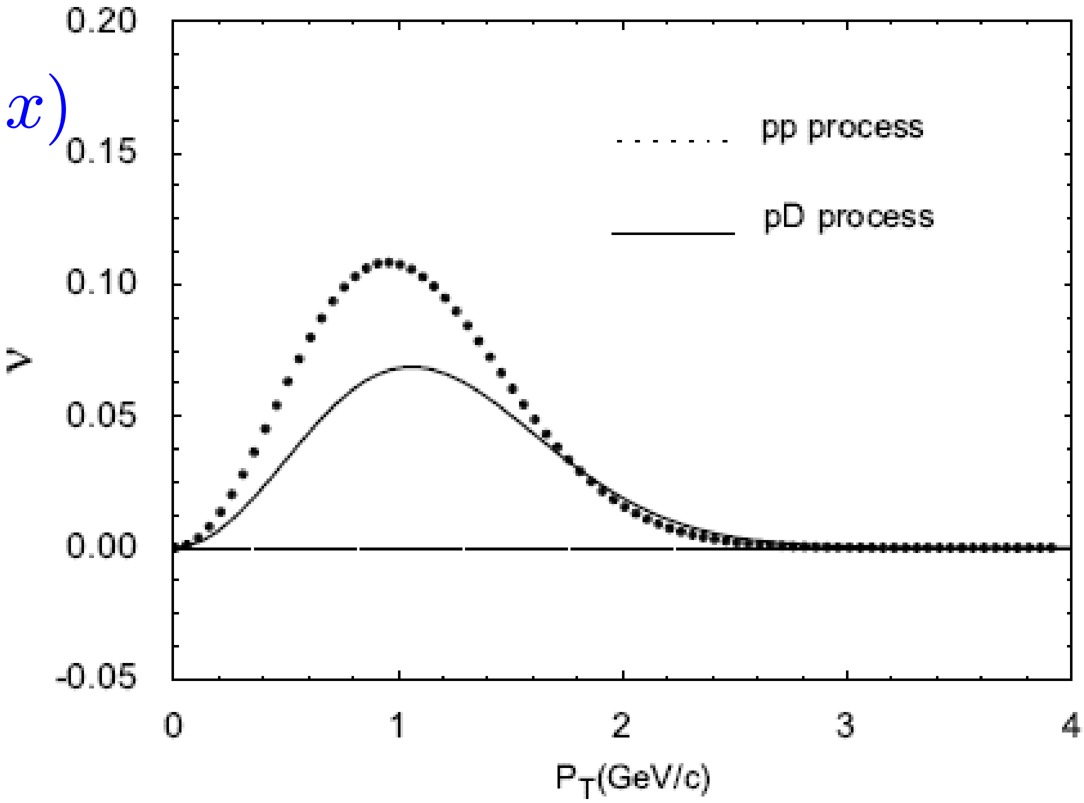
- Predict ν for pp Drell-Yan

$$h_1^{\perp,q}(x,p_\perp^2) = H_q x^c (1-x) \, e^{\left(-p_\perp^2/p_{BM}^2\right)} f_1^q(x)$$

- $\nu(pp) \approx 1.5 \times \nu(pD)$



Boer-Mulders and QCD in p induced Drell-Yan

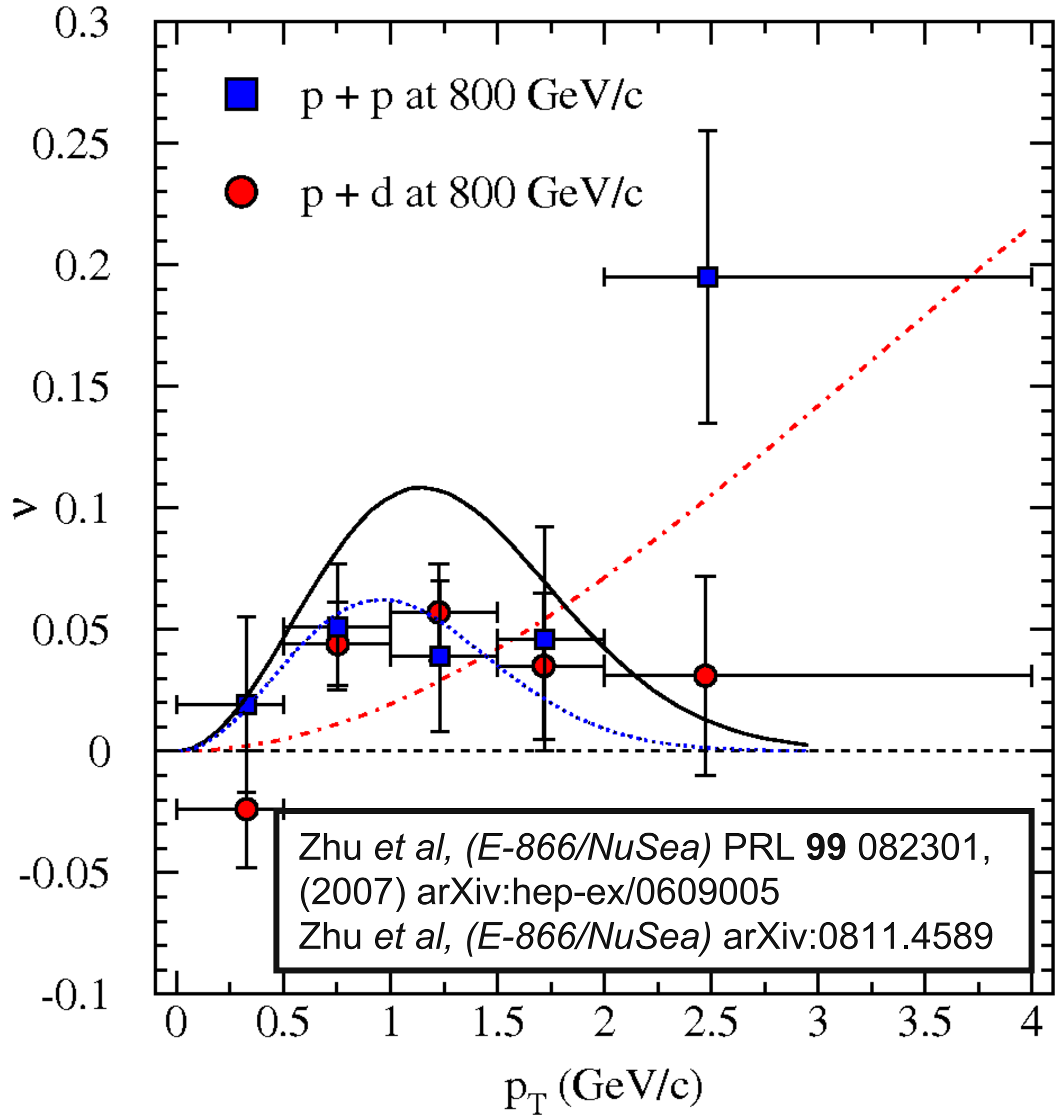
- $\nu(pp) \approx \nu(pD)$
- pp data have a poor χ^2 in ν
  - $\chi^2/5$ dof = 3.5

QCD effects in Drell-Yan

Berger *et al* PRD76,074006 (2007) and Boer *et a*. PRD77, 054011(2008)

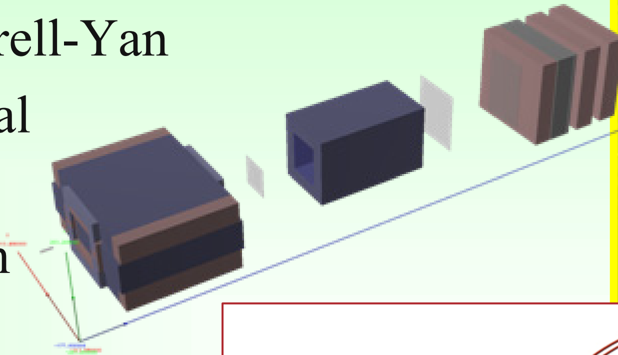
$$\nu = \frac{Q_\perp^2/Q^2}{1 + \frac{3}{2}Q_\perp^2/Q^2}$$

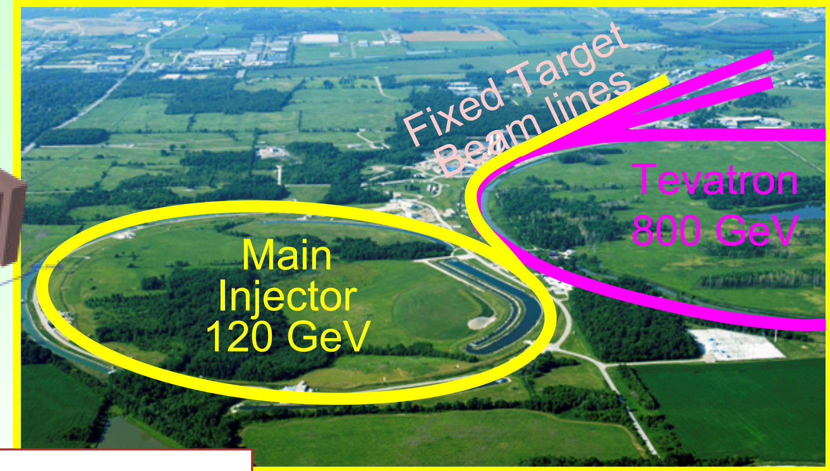
- $\nu(pp) = \nu(pD)$ because of same kinematic coverage



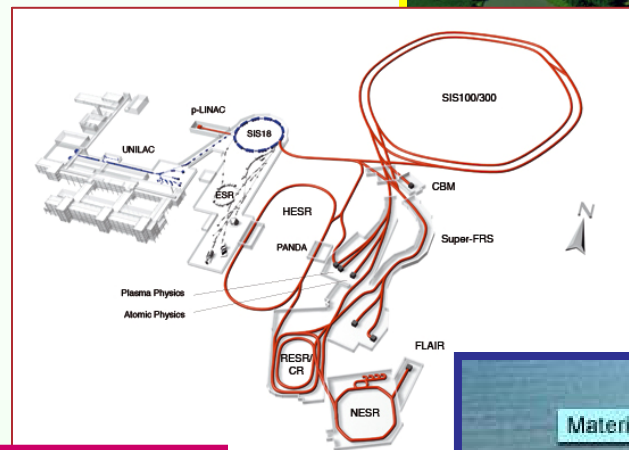
Future experiments

- Fermilab E-906/Drell-Yan
  - Better statistical precision
  - 120 GeV beam





- GSI FAIR program
  - PAX experiment
  - Antiproton beam will sample valence distributions of targets



- J-PARC

- RHIC

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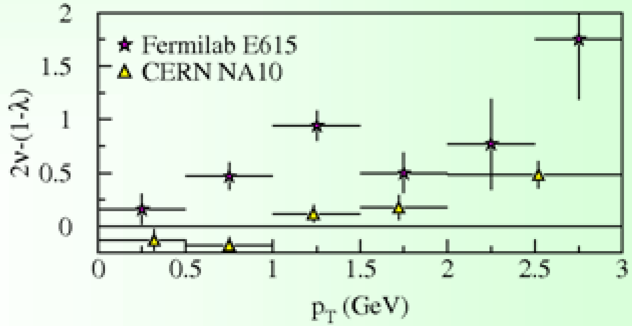
Conclusion

$$1-\lambda = 2\nu$$

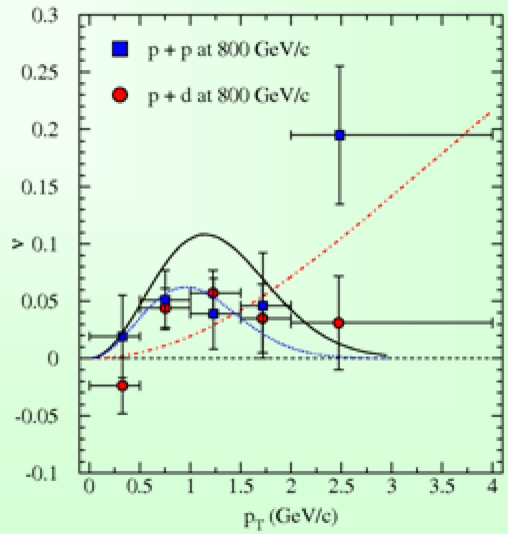
- Lam-Tung Relation provides a useful theoretical framework for studying QCD effects in Drell-Yan Scattering

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$



- Pionic Drell-Yan experiments see a violation which grows as a function of p_T. (Esp. NA10)

- Most plausible explanation based on the $\nu(p_T)$ dependence of the valence (π) and sea (proton) data is the k_T-dependent Boer-Mulders TMD $h^{\perp}_1$ along with QCD effects



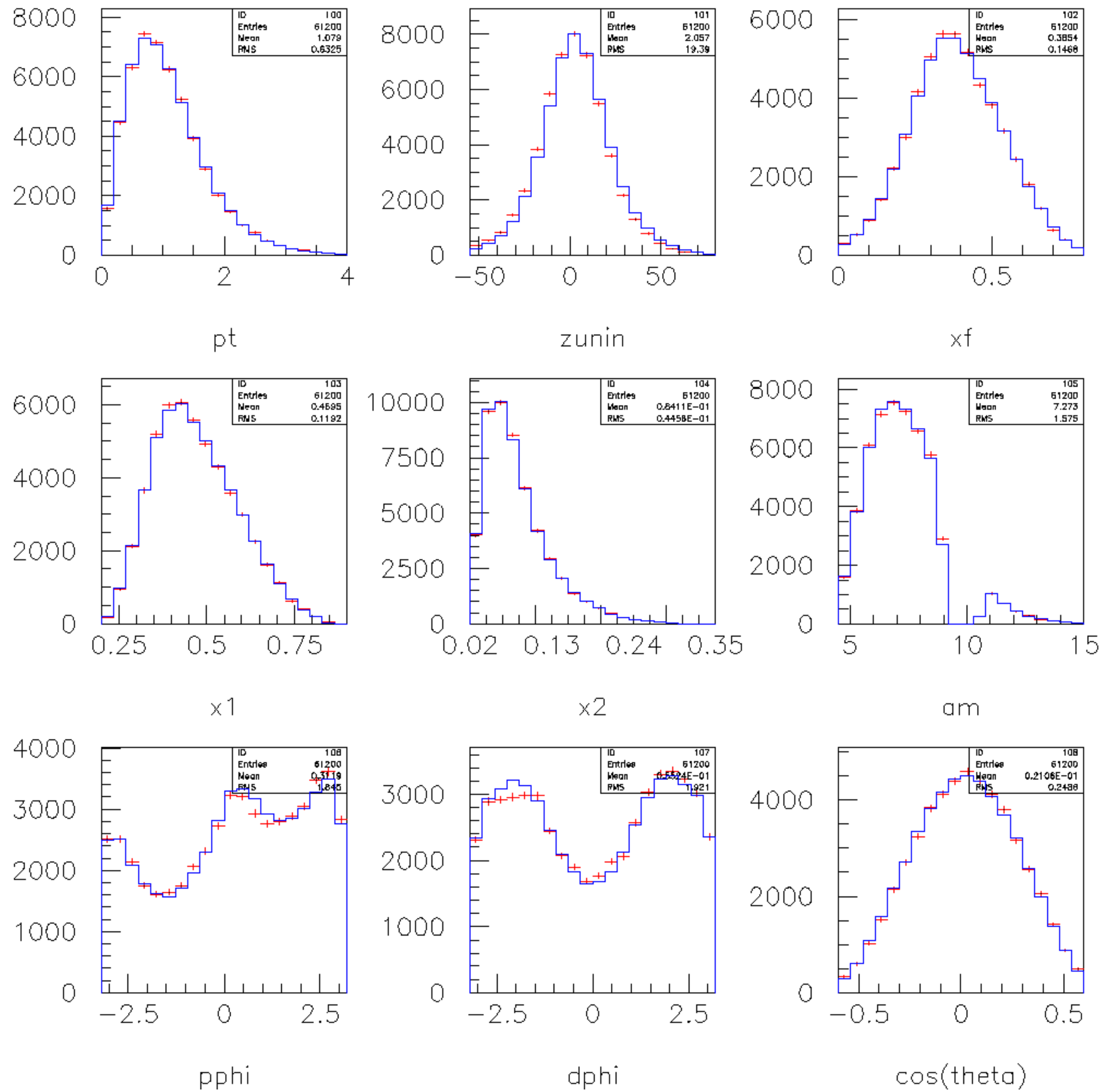
This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

E866: Data/MC comparison

- Blue: Simulation
- Red: Data

- For fit, each bin in p_T was divided into
  - 5 bins in $\cos\theta$
  - 8 bins in ϕ

- $|\cos\theta| < 0.5$



Argonne NATIONAL LABORATORY

Soft Gluon Resummation Effects

- Problem (a general problem for Drell-Yan):
  - At **any fixed order in α_s**, explicit calculations done in the parton model **Drell-Yan cross section diverges** as $(1/Q_\perp)^n$ or as $ln(Q/Q_\perp)$ due to soft and co-linear gluon emission
- Solution:
  - Resummation to all orders in α_s provides expected angular-integrated results

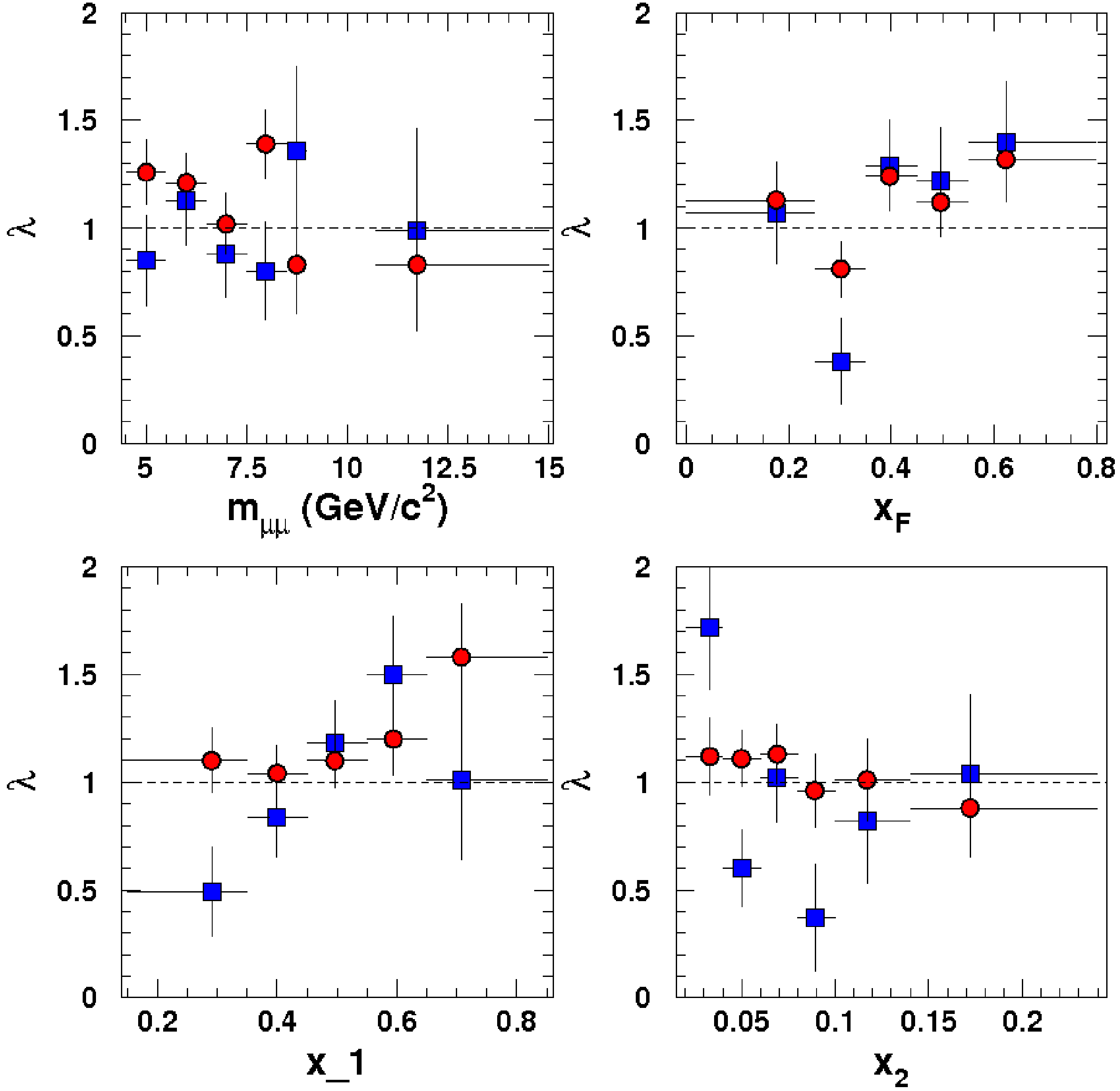
- How does this affect the Lam-Tung relation?
  - W_T, W_L, W_Δ and $W_{\Delta\Delta}$ *are functions of Q_T.*

$$\frac{d\sigma}{d^4q\ d\Omega_k^*} \propto \left[W_T\left(1+\cos^2\theta\right)+W_L\left(1-\cos^2\theta\right) +W_\Delta \sin 2\theta\cos\phi + W_{\Delta\Delta}\sin^2\theta\cos 2\phi\right]$$

  - Deviation from $1+\cos^2\theta$ less than 5% Chiappatta, Bellac, ZPC 32, 521 (1986)

  - Recently Berger, Qiu and Rodrigues-Pedraza showed that **the Lam-Tung relation is preserved** under resummation. arXiv:0707.3150, and PRD **76** 074006 (2007)

Kinematic Dependencies: λ



Kinematic Dependencies: μ