Longitudinal parity-violating asymmetry in W-boson mediated jet pair production

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Based on E. Berger and P. Nadolsky, Phys. Rev. D78, 114010 (2008)

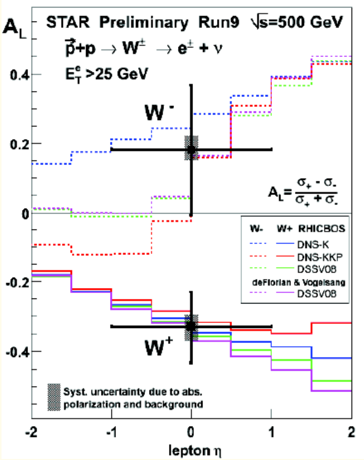
W bosons are observed at RHIC: what is next?

$pp \to W^{\pm}X$ at $\sqrt{s} = 500$ GeV with $\mathcal{L} = 200 - 300$ pb^{-1} provides unique opportunities to explore

- unpolarized $d(x, M_W)/u(x, M_W)$ at $x > 0.1$
- longitudinally polarized $\Delta u(x, M_W)$, $\Delta d(x, M_W)$, $\Delta \overline{u}(x, M_W)$, $\Delta \overline{d}(x, M_W)$

Lepton pair decays in W boson resonant production – **established detection method**

Prospects for observation of a parity-violating asymmetry A_L in the $W \to$ jet + jet mode – **this talk**



J. Balewski, APS meeting, February 2010

Motivation and main message

Rapidity distributions of charged leptons from $W^{\pm}$ decays, $d(\Delta)\sigma(W^{\pm} \to \ell^{\pm}\nu)/dy_{\ell}$, cleanly probe (un)polarized quark PDFs.

However, they have a low event rate and are smeared by final-state spin correlations.

See, e.g., Berger, Halzen, Kim, Willenbrock, PR D40, 83 (1989); Melnitchouk, Peng PL B400, 220 (1997);

P. N. and C.-P. Yuan, NP B666, 31 (2003)

We investigate an alternative process, $p^{\rightarrow} + p \to (W \to \text{jet} + \text{jet}) + X$ at $\sqrt{s}$=500 GeV through all $2 \to 2$ channels, at the fully differential level

Motivation and main message

This calculation leads us to conclude that

- parity-violating hadronic W decays can be systematically distinguished above the large (parity-conserving) QCD background
- a parity-violating $A_L(y)$ of several percent exits in a well-defined kinematic region; no parity violation occurs outside this region, which facilitates the cross checks
- this mode can provide complementary constraints on the polarized PDFs, in particular, on $\Delta\bar{d}(x, M_W)$ that is relatively challenging to constrain in the leptonic mode

Related publications

On-shell W boson production

1. C. Bourrely, J. Soffer, PLB 314, 132 (1993); Nucl.Phys. B423, 329 (1994)
2. A. Weber, Nucl. Phys. B 403, 545 (1993)
3. P. Nadolsky, hep-ph/9503419
4. T. Gehrmann, Nucl. Phys. B534, 21(1998)
5. M. Gluck, A. Hartl, and E. Reya, Eur. Phys. J. C19, 77 (2001)

Leptonic decay mode

1. B. Kamal, Phys. Rev. D57, 6663 (1998)
2. P. Nadolsky and C.-P Yuan, Nucl. Phys. B666, 3 (2003) and B666, 31 (2003)

Dijet mode

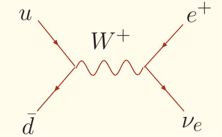
1. H. Haber and G. Kane, Nucl. Phys. B146,109 (1978)
2. F. Paige, T. L. Trueman, T. Tudron, Phys. Rev. D 19, 935 (1979)
3. C. Bourrely, J. P. Guillet, and J. Soffer, Nucl. Phys. B361, 72 (1991)
4. S. Arnold, A. Metz, W. Vogelsang, arXiv:0807.3688; S. Arnold, K. Goeke, A. Metz, P. Schweitzer, W. Vogelsang, Eur.Phys.J.ST 162 (2008)

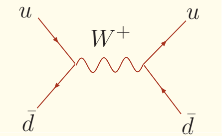
Today's focus is on...

- unpolarized parton distributions: $$f_{a/p}(x,Q) \equiv f_{a/p}^{+/+}(x,Q) + f_{a/p}^{-/+}(x,Q)$$
- longitudinally polarized parton distributions: $$\Delta f_{a/p}(x,Q) \equiv f_{a/p}^{+/+}(x,Q) - f_{a/p}^{-/+}(x,Q)$$
- unpolarized cross sections: $$\sigma = \frac{1}{2}\left[\sigma(p^{\rightarrow}p) + \sigma(p^{\leftarrow}p)\right]$$
- single-spin cross sections ($\neq 0$ if $V-A$ interaction): $$\Delta_L\sigma = \frac{1}{2}\left[\sigma(p^{\rightarrow}p) - \sigma(p^{\leftarrow}p)\right]$$
- single-spin asymmetry as a function of W boson rapidity y: $$A_L(y) \equiv \frac{d\Delta_L\sigma/dy}{d\sigma/dy}$$

Two classes of subprocesses with W bosons

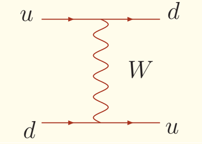
1: Resonant (s-channel) W boson production

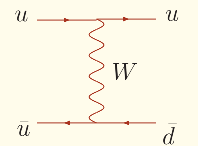


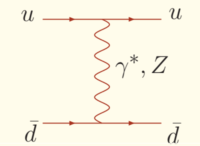


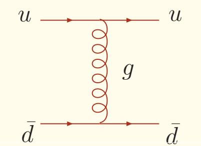
- dominant parity-violating process at $Q \approx M_W$
- Leptonic decays: $\mathrm{Br}(W \rightarrow e\nu_e) \approx 10.8\%$
- Hadronic decays: $\mathrm{Br}(W \rightarrow \mathrm{hadrons}) \approx 67\%$

2: Non-resonant scattering into a dijet final state, mediated by γ^*, W, Z, and g, and interference terms







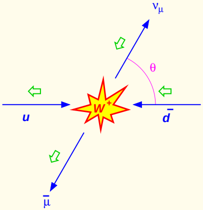


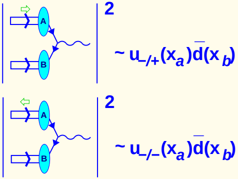
, etc.

Leptonic decay mode

$pp \to (W \to \ell\nu)X$ **at** $\sqrt{s} = 500$ **GeV**

- "Theoretical clean" process
  - mostly $u\bar{d} \to W^+$ or $d\bar{u} \to W^-$; small contributions from s, c, b, g
  - relatively simple QCD and EW higher-order contributions
- Flavor sensitivity through the CKM matrix
- good sensitivity to **quark sea** at scales of order M_W



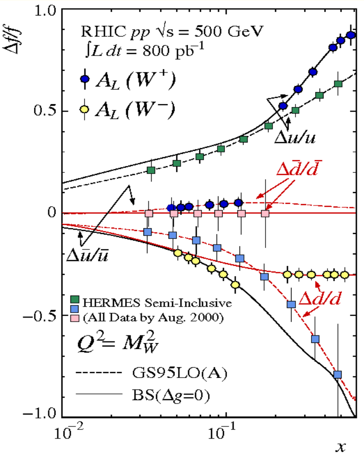


- **single-spin** measurements constrain $\Delta q(x, M_W)$, $\Delta\bar{q}(x, M_W)$
  - complications of low-Q (SI)DIS are avoided

Parity-violating asymmetry $A_L(y)$ at leading order

$$A_L^{W^+}(y) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)} = \begin{cases} -\Delta u(x_a)/u(x_a), \; x_a \to 1 \\ \Delta\bar{d}(x_a)/\,\bar{d}(x_a), \; x_b \to 1 \end{cases}$$

$$A_L^{W^-}(y) = \frac{-\Delta d(x_a)\bar{u}(x_b) + \Delta\bar{u}(x_a)d(x_b)}{d(x_a)\bar{u}(x_b) + \bar{u}(x_a)d(x_b)} = \begin{cases} -\Delta d(x_a)/d(x_a), \; x_a \to 1 \\ \Delta\bar{u}(x_a)/\bar{u}(x_a), \; x_b \to 1 \end{cases}$$



- guaranteed large asymmetries at $x \to 1$
- Fully differential NLO/resummed calculations are available

Unpolarized cross sections and their PDF errors

$pp \to (W^{\pm}, Z^0 \to \ell_1 \bar{\ell}_2)X$ **at** $\sqrt{s} = 500$ **GeV**

$\mathcal{O}(\alpha_s)$ (=NLO), for 1 lepton generation; CTEQ6 PDFs

Boson	σ (pb)
W^+	124 ± 9
W^-	41 ± 4
Z^0	10.0 ± 0.8

$\sigma(W^+) : \sigma(W^-) : \sigma(Z) \approx 1 : 0.33 : 0.08$
(1 : 0.33 : 0.26 in hadronic decays)

W^+ dominates if $W^+/W^-/Z$ contributions are not separated

RHIC-specific challenges for $W \to \ell\nu$

- $\mathcal{O}(\alpha_{EW}^2)$ process at $x \sim 0.1$
  - relatively small cross sections
  - requires substantial luminosity ($\mathcal{L} = 100 - 400$ pb^{-1})
- Neutrino 4-momentum is unknown
  - Q, y, q_T, missing E_T are unknown
  - PDFs must be deduced from $d^2\sigma/(dp_{Te}dy_e)$ within PHENIX/STAR acceptance, accounting for spin correlations in W decay
    - ◇ can be done using available NLO tools (RhicBos, etc.)

$d\sigma/dy_e$ for charged lepton rapidity y_e

At Born level:

$$\frac{d\Delta_L\sigma(W^{\pm}X)}{dy_e} = \frac{2\pi\sigma_0}{S}\int_{y_{\min}(p_{Te}^{\min})}^{y_{\max}(p_{Te}^{\min})} dy\ \sin^2\theta_e$$

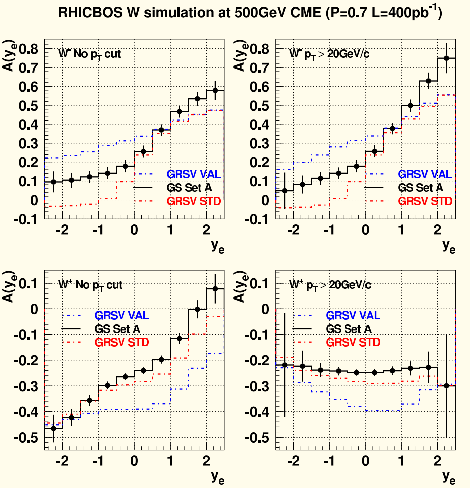
$$\times\left\{-\Delta q(x_a)\bar{q}'(x_b)(1\mp\cos\theta_e)^2 + \Delta\bar{q}'(x_a)q(x_b)(1\pm\cos\theta_e)^2\right\},$$

with $\cos\theta_e = \tanh(y_e - y)$

$W^+ : q = u,\, \bar{q}' = \bar{d}$

$W^- : q = d,\, \bar{q}' = \bar{u}$

$d\sigma/dy_e$ for charged lepton rapidity y_e



- Positrons from $W^+ \to e^+\nu_e$ tend to scatter backwards in the W rest frame $\Rightarrow$
  - sensitivity to $\Delta u(x)$ at $y_e \lesssim 0$, $\Delta\bar{d}(x)$ at $y_e \approx 0$ (at variance with common intuition)
  - manageable, but a bit contrived
  - flavor separation in the global PDF analysis is less direct

Resonant W boson contribution to $pp \to$ jet $+$ jet $+ X$

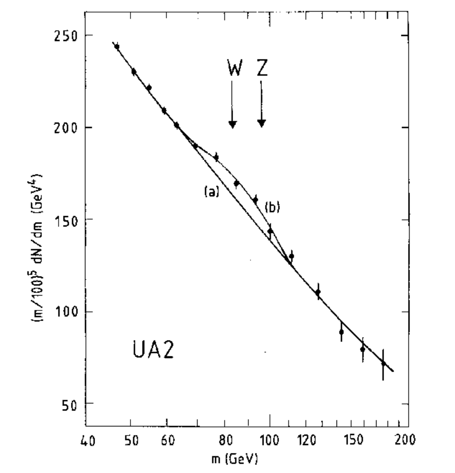
- The hadronic mode is complementary to the leptonic mode:
  - W boson's virtuality Q and rapidity y can be established **approximately** by equating them to the dijet invariant mass and rapidity
  - Contributions mediated by W^+ bosons dominate over W^- and Z^0 contributions; the PDF dependence of $d\sigma/dy$ closely resembles that in W^+ boson production
  - No smearing of PDF dependence by spin correlations in W decays (especially relevant for $\Delta\bar{d}(x,Q)$)

Hadronic mode at RHIC and other colliders

Observation of the hadronic mode at RHIC is much easier than at the Tevatron/LHC, slightly harder than at SppS

- relatively low backgrounds, especially for **parity-violating** A_L
- largest QCD backgrounds are **parity-conserving**; can be subtracted using a side-band technique
- low Q resolution is sufficient (not an electroweak precision measurement as at the Tevatron)

$W \to$ hadrons at SppS *(PLB186, 452 (1987))*



- $p\bar{p} \to WX$, $\sqrt{s} = 630$ GeV, $\mathcal{L} = 0.73$ pb^{-1}; $x \sim 0.13$
- 3σ signal in the dijet mass ($m = Q$) distribution
- background/signal$\gtrsim 20$ (RHIC: $\gtrsim 30$; Tevatron: $\gtrsim 570$)
- background is smooth
- can be interpolated from the sidebands in Q and other variables
- Mass resolution $\delta m = 8 - 9$ GeV
- W and Z peaks are not separated

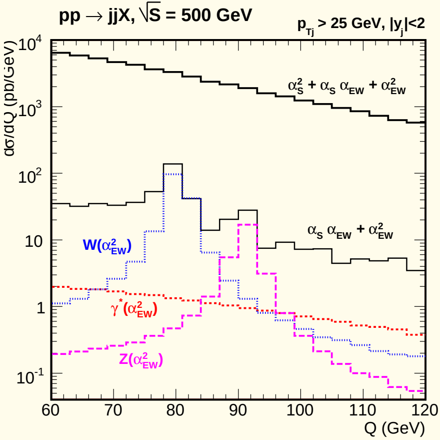
Calculation of the dijet cross sections

- Compute $pp \to \text{jet} + \text{jet} + X$, approximated by $2 \to 2$ exchanges of $V = g, \gamma^*.W^{\pm}, Z^0$ in the $s,\ t,$ and u channels; orders α_{EW}^2, $\alpha_s \alpha_{EW}$, and α_s^2
- Cross sections are fully differential in the momenta of two jets; allow acceptance cuts
- MadGraph for generation of cross sections and MadEvent for phase-space Monte-Carlo integration. Programs operate with helicity-dependent scattering amplitudes, but typically the amplitudes are summed over all helicity combinations to produce spin-averaged cross sections.
  - modified MadEvent to evaluate single-spin cross sections (available upon request)

Calculation of the dijet cross sections

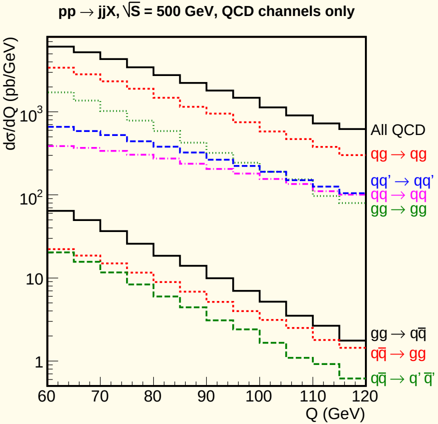
- Include contributions from $u, d, s, c,$ and g
- Factorization and renormalization scales: $\mu_F = \mu_R = Q$
- Impose constraints $p_{Tj} > 25$ GeV and $|y_j| < 2$ to reproduce approximately the acceptance of STAR

Unpolarized dijet mass (Q) distributions



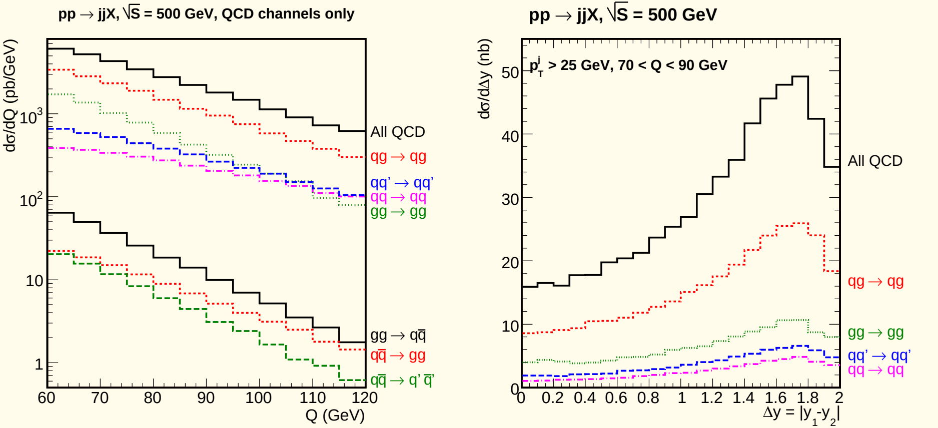
- Continuous event distribution from QCD and electromagnetic scattering (g and γ^*) dominates
- "Signal region" = region in which Q is close to M_W (e.g., $70 \le Q \le 90 - 100$ GeV)
- Even in this region, the spin-averaged W and Z contribution is no more than a few percent of the full event rate

Unpolarized cross section: flavor separation



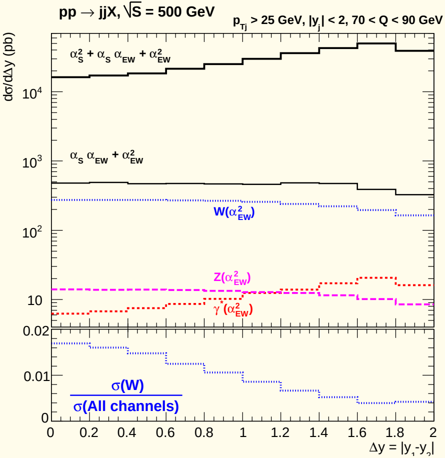
- q stands for both quarks and antiquarks
- qq (qq') stands for scattering of the same (different) quark flavors
- All PV signal has two quark-initiated jets (qq')
- 75% of the background is from $qg \to qg$ and $gg \to gg$ with 1 or 2 gluon-initiated jets

Unpolarized cross section: flavor separation



- $\Delta y \equiv y_1 - y_2$ probes dependence on the decay polar angle θ; $\Delta y = 2\tanh^{-1}(\cos\theta)$ at LO
- $d\sigma/d\cos\theta$ and $d\sigma/d\Delta y$ of the $qg,\ gg$ backgrounds are different from those of the qq' signal

Distributions in Δy - difference of jet rapidities



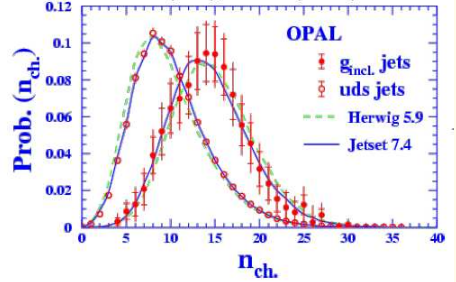
Full $\mathcal{O}(\alpha_s^2 + \alpha_s\alpha_{EW} + \alpha_{EW}^2)$ cross section is peaked strongly at large $|\Delta y|$. The $\mathcal{O}(\alpha_{EW}^2)$ and $\mathcal{O}(\alpha_s\alpha_{EW} + \alpha_{EW}^2)$ cross sections have flatter Δy dependence

Quark-like jets look differently from gluon-like jets

LEP and Tevatron: typical g-like jets have a larger multiplicity and broader jet shapes than u, d, s-like jets

- Similar differences must exist at RHIC
- 75% of the background events contain a g-like jet; $A_L(y)$ is enhanced by a large factor by excluding such events

OPAL (LEP), EPJC11(1999)217

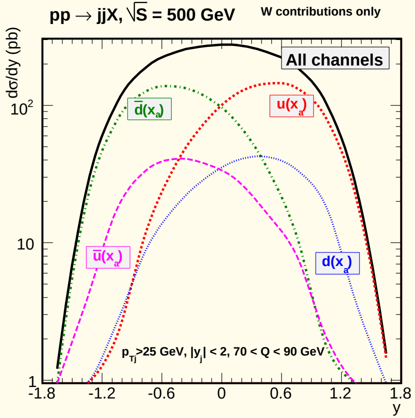


$$\frac{\langle n_{charged}\rangle_{g\ \text{jet}}}{\langle n_{charged}\rangle_{u,d,s\ \text{jet}}} = 1.51 \pm 0.04$$

Further details: B. Gary & N. Varelas at 2009 CTEQ Summer school (http://www.phys.psu.edu/~cteq/schools/summer09/), and refs therein

Quark flavor composition, unpolarized

W^+ and W^- contributions

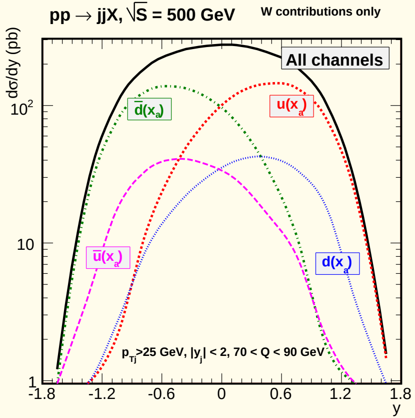


- Figure identifies contributions proportional to $u(x_a)$, $\bar{u}(x_a)$, $d(x_a)$, and $\bar{d}(x_a)$
- The combined $W^{\pm}$ cross section is dominated by
  - $u(x_a)$ contributions at $y > 0$
  - $\bar{d}(x_a)$ contributions at $y < 0$

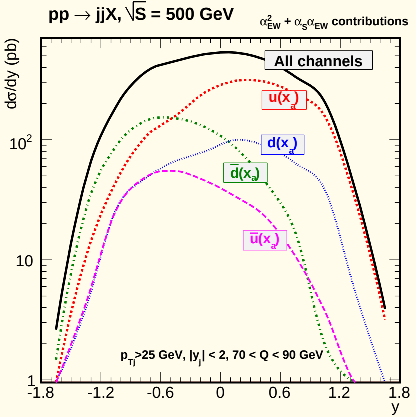
— as in resonant W^+ production

Quark flavor composition, unpolarized

W^+ and W^- contributions



$\mathcal{O}(\alpha_s\alpha_{EW} + \alpha_{EW}^2)$ contributions



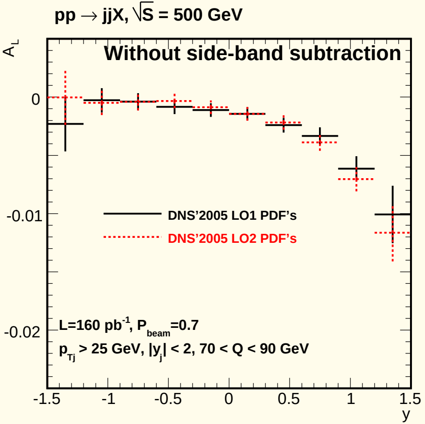
Sensitivity to $\bar{d}$ at $y < 0$ is preserved despite QCD-EW interference, after integration over $70 < Q < 90$ GeV

Spin-dependent dijet production

$$A_L(y) \equiv \frac{d\Delta_L\sigma/dy}{d\sigma/dy} = \frac{N}{D}$$

- Parity violation needed to obtain a non-zero N arises solely from qq contributions with intermediate W and Z bosons
- The magnitude of A_L for $70 < Q < 90$ GeV may be enhanced by applying a "side-band background subtraction" to D
- In this calculation, we approximate the "subtracted" D by the $\mathcal{O}(\alpha_s \alpha_{EW} + \alpha_{EW}^2)$ unpolarized cross section

Spin-dependent dijet production

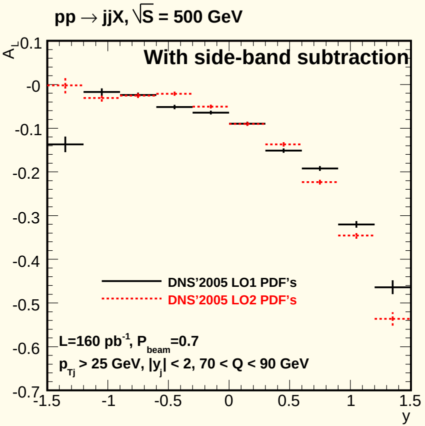


No subtraction

- D is dominated by large $\mathcal{O}(\alpha_s^2)$ terms
- A_L is small
- Different $\Delta f_{a/p}$ cannot be discriminated

Error bars are projected statistical uncertainties for $\mathcal{L} = 160$ pb^{-1}, $P_{beam} = 0.7$

Spin-dependent dijet production



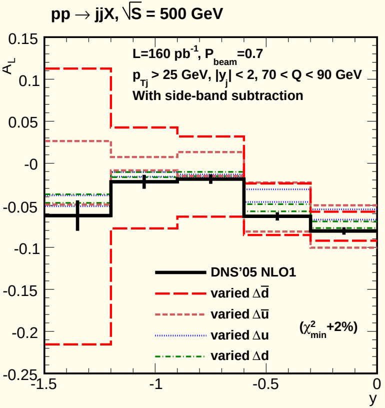
With subtraction

- $\mathcal{O}(\alpha_s^2)$ terms, other non-resonant contributions are measured at $Q < 70$ GeV and $Q > 90$ GeV; interpolated and subtracted from D at $70 < Q < 90$ GeV
- A_L is enhanced; statistical errors remain reasonable
- Sensitivity to $\Delta f_{a/p}$ is improved

Error bars are projected statistical uncertainties for $\mathcal{L} = 160$ pb^{-1}, $P_{beam} = 0.7$

Sensitivity of A_L to $\Delta\bar{q}$

A_L for production of jet pairs, after side-band subtraction



For $y < 0$, pronounced variations in A_L due to the variation of $\Delta\bar{d}(x, Q)$

The black curve corresponds to the DNS2005 NLO PDF set 1. The pairs of other curves contain the ranges of A_L obtained if $\Delta q \equiv \int_0^1 dx\, \Delta q(x, 3.16\ \text{GeV})$ is varied within $\Delta\chi^2/\chi^2_{min} < 2\%$

Discussion

Data-driven search for resonant $W \to$ jet $+$ jet contributions

$A_L(y)$ is most accessible in the signal region:

$$Q = M_W \pm 10 - 15 \text{ GeV},\ p_{Tj} \gtrsim 25 \text{ GeV},\ |y_{1j} - y_{2j}| \lesssim 1$$

The measurement can be based on the following strategy:

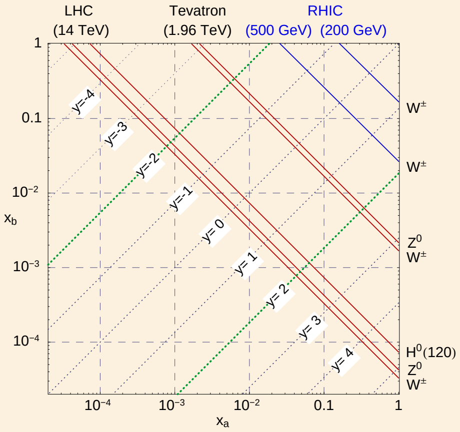
1. Discard events with gluon-like jets (wide, large multiplicity) to the best of one's ability
2. Precisely measure the smooth background outside of the signal region
3. Use this measurement to predict and subtract the background inside the signal region
4. Look for a large $A_L(y)$ at $y > +1$ (driven by a large $\Delta u(x)/u(x)$ at $x \to 1$)
5. Measure moderate $A_L(y)$ at $y < -1$ to constrain $\Delta \bar{d}(x)/\bar{d}(x)$ at $x < 0.1$

Next-to-leading order

- A more precise calculation must include NLO QCD contributions. These increase predicted rates and stabilize hard-scale (μ_F) dependence.
- Backgrounds in the denominator of $A_L(y)$ will be larger
- Comparably large enhancements in the numerator due to $\alpha_s^2 \alpha_W$ terms *(Moretti, Nolten, Ross, Phys. Lett. B643, 86 (2006))*
- Predicted magnitude of A_L could remain largely unaffected
- Could lead to a decrease in δA_L, since $\delta A_L \propto 1/\sqrt{N_{unp}}$

Backup slides

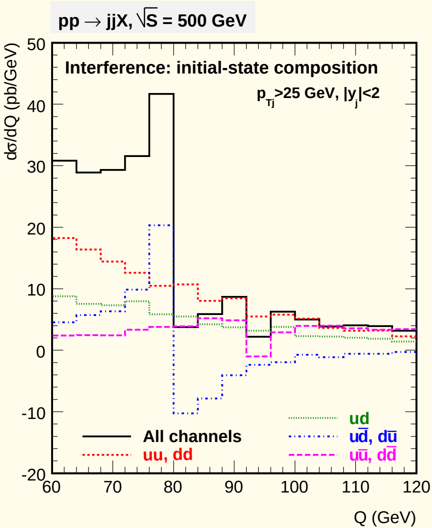
pp and $p\bar{p}$ colliders: accessible momentum fractions



- $W^{\pm}$ at RHIC: access to $x \sim 0.1$ in the experimentally preferred region ($|y| < 2$)
  - valence PDFs at $x \gtrsim 0.1$
  - sea PDFs at $3 \cdot 10^{-2} \lesssim x \lesssim 0.1$

$$x_{a,b} \equiv \frac{M_V}{\sqrt{s}} e^{\pm y}$$

Flavor composition of QCD-EW interference

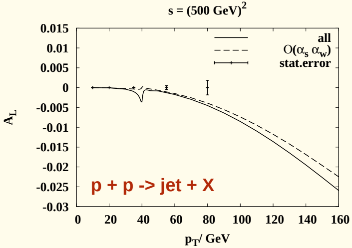


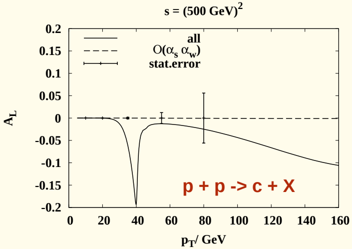
- Large resonant $u\bar{d}$, $d\bar{u}$ contributions cancel when integrated over a Q range centered around M_W
- Smaller non-resonant uu, dd, ud contributions survive

Parity-violating spin asymmetries in polarized pp scattering with hadronic final states

Arnold, Metz, Vogelsang, arXiv:0807.3688; Arnold, Goeke, Metz, Schweitzer, Vogelsang, Eur.Phys.J.ST 162 (2008)

- Focus on **1 jet-inclusive** $d^2\sigma/dy_j dp_{Tj}$ (inclusive in Q, y_{2j}, y)
  - our **2 jet-inclusive** calculation imposes lower cuts both on Q and p_{Tj} (better background rejection)
- Estimates are made without side-band subtraction $\Rightarrow$ $|A_L| < 2-3\%$





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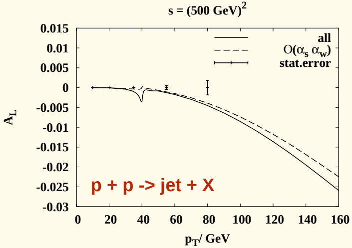
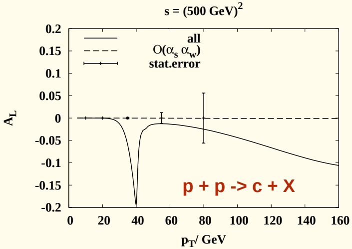
Backgrounds can be suppressed by requiring a final-state c quark

☺ A_L increases

☹ event rate is reduced by experimental charm tagging (not included here)

(?) net effect needs further study

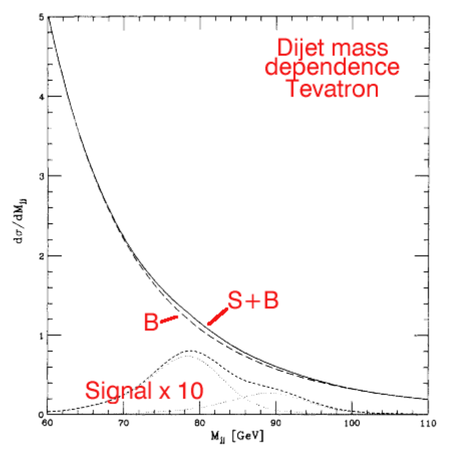




Our MadEvent calculation allows selection of final-state c quarks or other particles (leading pions, etc.) to suppress the QCD background

$W \to$ hadrons at the Tevatron

(J. Pumplin, PRD45, 806 (1992); U. Baur et al., hep-ph/0005226)



- $p\bar{p} \to WX$, $\sqrt{s} = 1.8$ TeV, $x \sim 0.04$
- background/signal$\approx$ 570
- After an angular cut in the$W$ rest frame: background/signal$\approx$255 $QQ/W \approx 22$, $QG/W \approx 101$, $GG/W \approx 132$
- mass resolution $\delta M_{jj} \geq 0.5$ GeV

- of no use for M_W measurement, unless the gluon background is drastically reduced