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)

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:

$$\sigma = \frac{1}{2}\left[\sigma(p^{\rightarrow}p) + \sigma(p^{\leftarrow}p)\right]$$

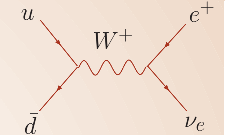
- single-spin cross sections ($\neq 0$ if $V - A$ interaction):

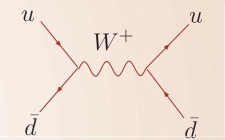
$$\Delta_L\sigma = \frac{1}{2}\left[\sigma(p^{\rightarrow}p) - \sigma(p^{\leftarrow}p)\right]$$

- 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

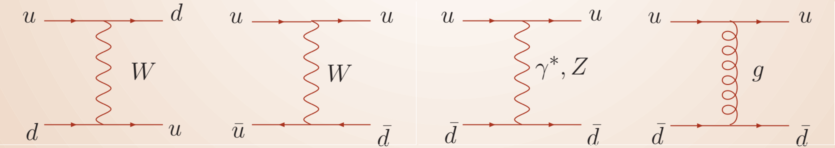




1: Resonant (s-channel) W boson production

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

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



, etc.

Outline

- Role of W boson production at $p\overset{(-)}{p}$ colliders in constraining (un)polarized PDFs
- **Lepton pair decays** in W boson resonant production – **established detection method**
- Fully differential calculation for W-mediated jet pair production and leading background processes – **new result**
- Prospects for observation of a parity-violating A_L in the $W \rightarrow \text{jet} + \text{jet}$ mode – a useful measurement **complementary to 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 and 31 (2003)

Dijet mode

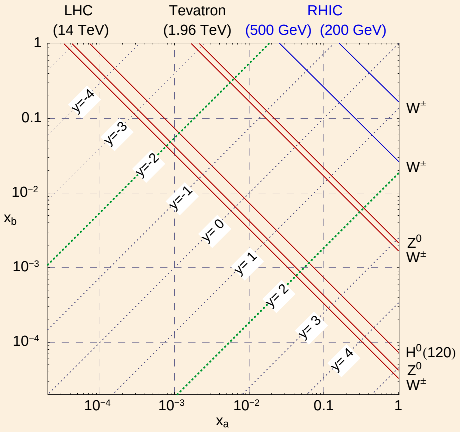
1. H. Haber and G. Kane, Nucl. Phys. B146,109 (1978)
2. F. Paige, T. L. Trueman, T. Tudron, Phys. Rev. D 19, 935 (1979)
3. C. Bourrely, J. P. Guillet, and J. Soffer, Nucl. Phys. B361, 72 (1991)
4. S. Arnold, A. Metz, V. Vogelsang, arXiv:0807.3688; S. Arnold, K. Goeke, A. Metz, P. Schweitzer, W. Vogelsang,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

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

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



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

- $W^{\pm}$ 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 $3 \cdot 10^{-2} \lesssim x \lesssim 0.1$

Unpolarized cross sections and their PDF errors

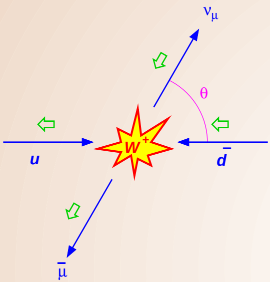
$\mathcal{O}(\alpha_s)$ (=NLO), for 1 lepton generation; CTEQ6 PDFs

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)

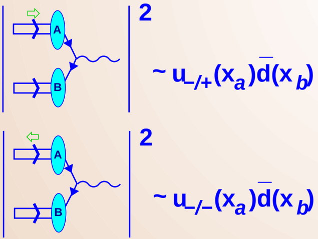
W^+ dominates if $W^+/W^-/Z$ contributions are not separated

$W^{\pm}$ bosons as ideal polarimeters



At Born level:

$$\frac{d\Delta_L \sigma(pp \xrightarrow{W^+} \ell^+ \nu_\ell X)}{dx_a dx_b d\cos\theta d\varphi} \propto$$
$$-\Delta u(x_a)\bar{d}(x_b)\,(1+\cos\theta)^2 +$$
$$+\Delta\bar{d}(x_a)u(x_b)\,(1-\cos\theta)^2$$



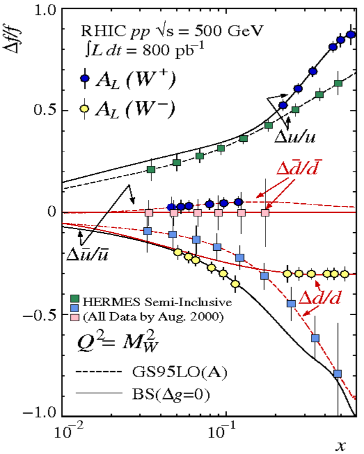
Spin asymmetries in $W^{\pm}$ production are sensitive to the flavor structure of the polarized quark sea

Signature of W boson events: high-p_T charged leptons and $\not{E}_T$

Leading-order $A_L(y)$

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

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



- guaranteed large asymmetries at $x \to 1$

Fully differential resummed NLO cross sections

(RhicBos – P. N., C.-P. Yuan, 2003)

- A fast Monte-Carlo integrator implementing q_T resummation at NNLL/NLO ($A^{(3)}, B^{(2)}, C^{(1)}$ resummed coefficients)
- effects of boson's width and decay, electroweak corrections
- unpolarized, single-spin, and double-spin cross sections
- lepton distributions for realistic acceptance
- available at MSU Q_T resummation portal (http://hep.pa.msu.edu/resum/), together with theory introduction, bibliography, etc.

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:

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

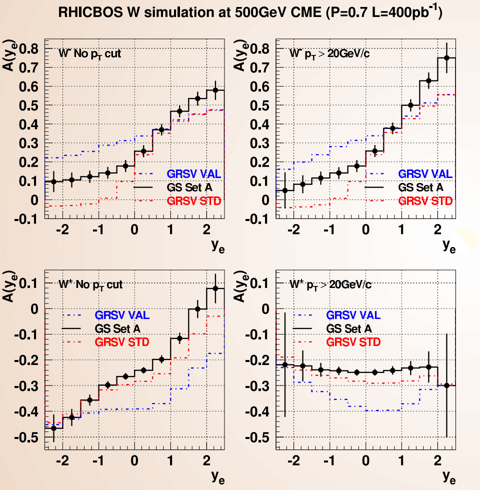
$$\times\left\{-\Delta q(x_a)\bar{q}'(x_b)(1\mp\cos\theta_e)^2 + \Delta\bar{q}'(x_a)q(x_b)(1\pm\cos\theta_e)^2\right\},$$

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⇒
  - 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

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

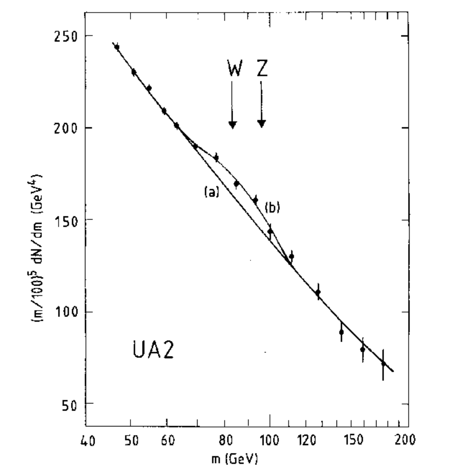
- The $W \to e\nu$ decay is the golden mode at large luminosities ($\mathcal{L} > 300$ pb^{-1})
- The hadronic mode may be competitive at RHIC for lower $\mathcal{L} \approx 100$ pb^{-1} and reduced instrumentation (no lepton charge ID)
- W virtuality Q and rapidity y can be established **approximately** by equating them to dijet invariant mass and rapidity
- No smearing of PDF dependence by spin correlations in W decays (esp. 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
- Mass resolution $\delta m = 8 - 9$ GeV
- W and Z peaks are not separated

Calculation of the dijet cross sections

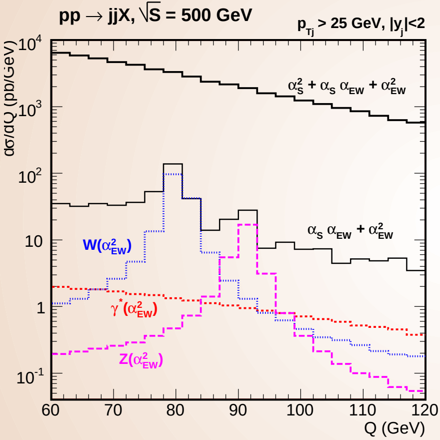
- Compute $pp \to \text{jet} + \text{jet} + X$, approximated by $2 \to 2$ exchanges of $V = g,\ \gamma^*.W^\pm, Z^0$ in the $s,\ t,$ and u channels; orders α_{EW}^2, $\alpha_s \alpha_{EW}$, and α_s^2
- Cross sections are fully differential in the momenta of two jets; allow acceptance cuts
- MadGraph 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

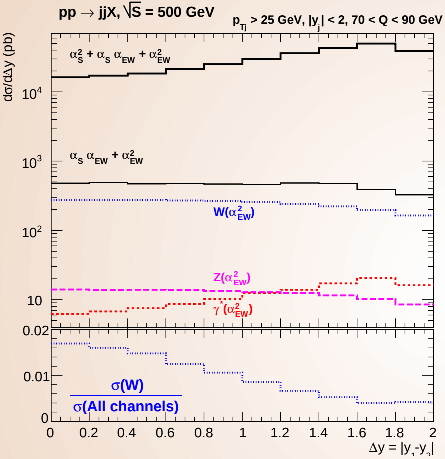
Unpolarized dijet cross sections

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., $70 \leq Q \leq 90 - 100$ GeV)
- Even in this region, the spin-averaged W and Z contribution constitutes at most a few percent of the full event rate

Distributions in Δy - difference of jet rapidities

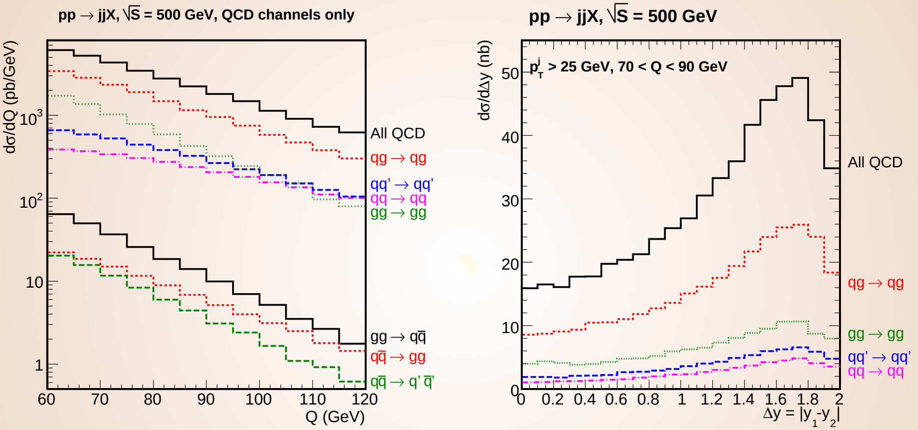


Real-gluon emissions are present in $\mathcal{O}(\alpha_s^2)$ QCD background processes, but not in EW processes

$\Rightarrow$ differences in distributions in $\cos\theta$ or $\Delta y \equiv y_1 - y_2$ ($\Delta y = 2\tanh^{-1}(\cos\theta)$ at LO)

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

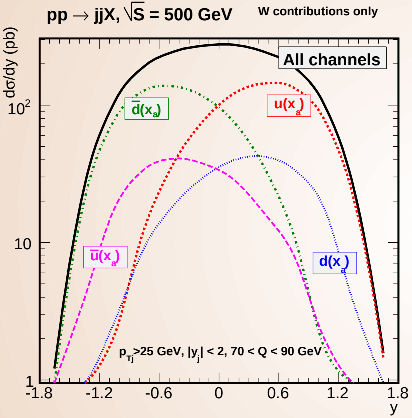
Unpolarized cross section: flavor separation



- q stands for both quarks and antiquarks
- qq (qq') stands for scattering of the same (different) quark flavors
- Two largest contributions, $qg \to qg$ and $gg \to gg$, cancel in $\Delta_L \sigma$

Quark flavor composition, unpolarized

W^+ and W^- contributions

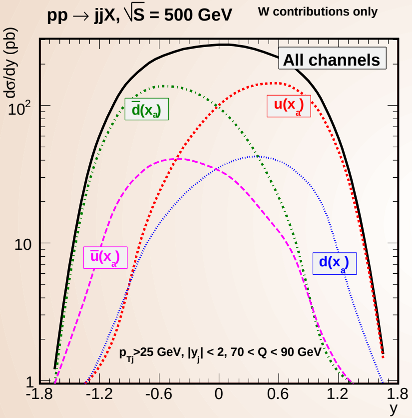


- Figure identifies contributions proportional to $u(x_a)$, $\bar{u}(x_a)$, $d(x_a)$, and $\bar{d}(x_a)$
- The combined $W^\pm$ cross section is dominated by
  - $u(x_a)$ contributions at $y > 0$
  - $\bar{d}(x_a)$ contributions at $y < 0$

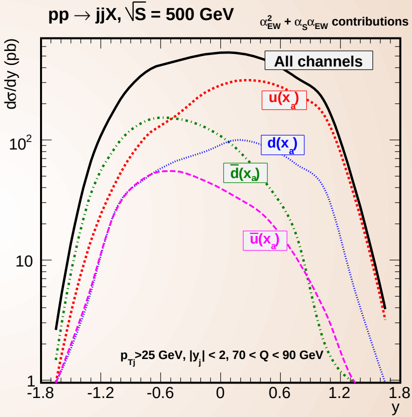
— as in resonant W^+ production

Quark flavor composition, unpolarized

W^+ and W^- contributions

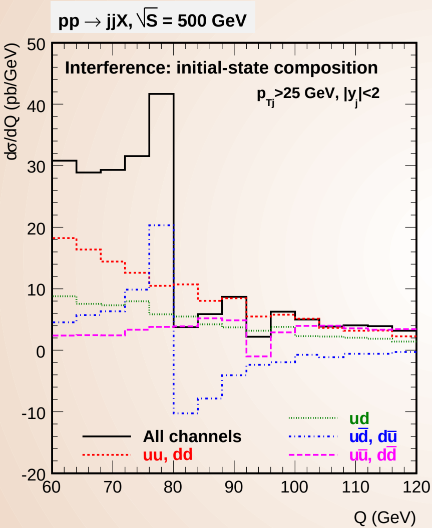


$\mathcal{O}(\alpha_s \alpha_{EW} + \alpha_{EW}^2)$ contributions



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

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

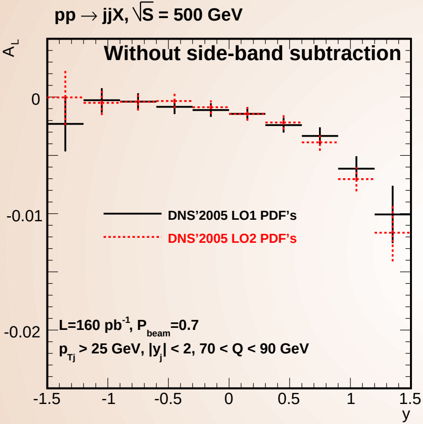
Single-spin asymmetry

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

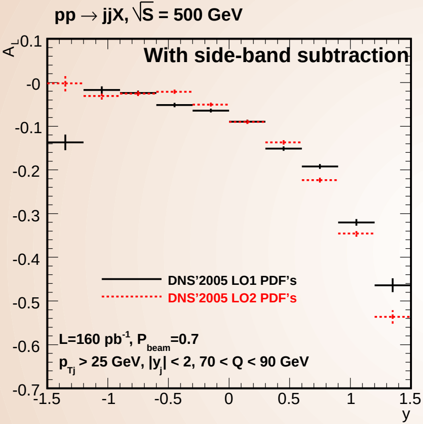


No subtraction

- 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



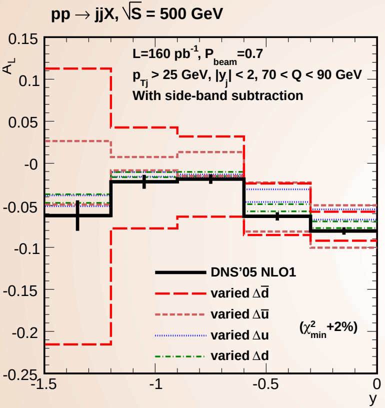
With subtraction

- $\mathcal{O}(\alpha_s^2)$ 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

Our analysis establishes a signal kinematical region where the single-spin asymmetry is most accessible:

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

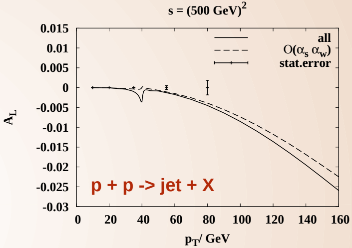
These findings suggest the following experimental strategy:

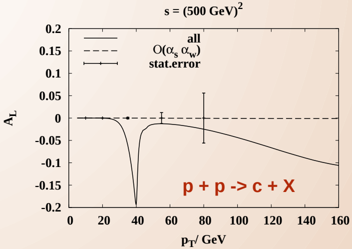
1. Precisely measure the smooth background outside of the signal region
2. Use this measurement to predict and subtract the background inside the signal region
3. Look for a large $A_L(y)$ at $y > +1$ (suggested by JLab measurements+DGLAP evolution; driven by $\Delta u(x)/u(x) \to 1$ at $x \to 1$)
4. Measure moderate $A_L(y)$ at $y < -1$ to constrain $\Delta \bar{d}(x)/\bar{d}(x)$ at $x < 0.1$

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 $\Rightarrow$ $|A_L| < 2 - 3\%$





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

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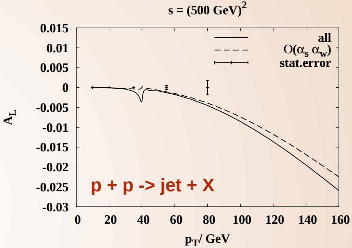
Backgrounds can be suppressed by requiring a final-state c quark

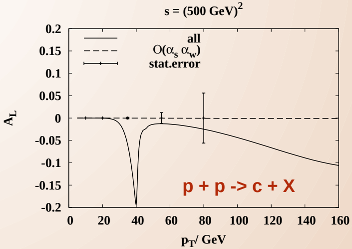
☺ A_L increases

☹ 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





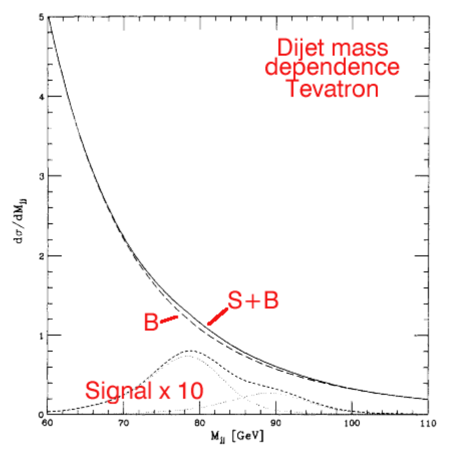
Next-to-leading order

- 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

$W \to$ 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