Single-spin asymmetries in W and Z boson production +RhicBos update

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Big question

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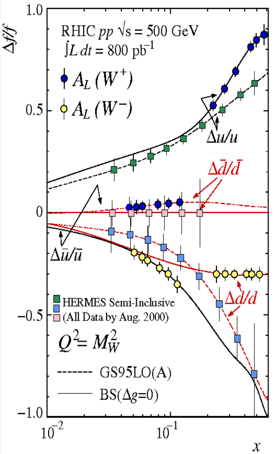
W boson production at RHIC!

- Complements and surpasses polarized SIDIS
- Probes the proton structure in a different kinematical range than the Tevatron and LHC

Leading-order single-spin asymmetries vs. W boson rapidity y_W

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

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



- new Q range
- reliable theory (PQCD)
- guaranteed large asymmetries at $x \to 1$

Large lepton rapidities $(y_\ell \to y_\ell^{max})$

$$W^+ : \left(\frac{\Delta u(x)}{u(x)}\right)_{x\to 1} \qquad W^- : \left(\frac{\Delta d(x)}{d(x)}\right)_{x\to 1}$$

Behavior of valence PDFs at $x \to 1$ is predicted by constituent quark models

- Exact SU(6) symmetry [disfavored]:

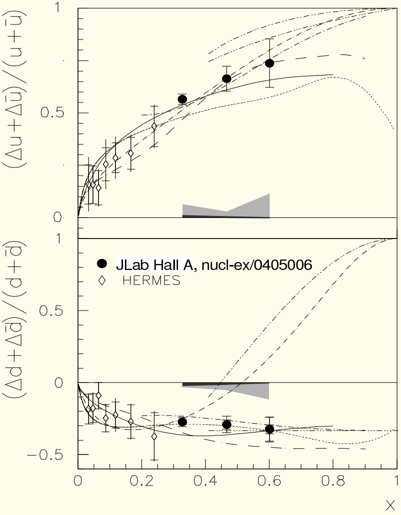
$$\frac{\Delta u(x)}{u(x)} \to \frac{2}{3}, \frac{\Delta d(x)}{d(x)} \to -\frac{1}{3}$$

- Hadron helicity conservation *(Farrar, Jackson;...)* [disfavored]

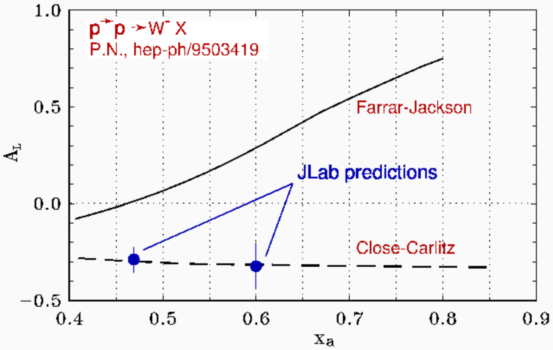
$$\frac{\Delta u(x)}{u(x)} \to 1, \frac{\Delta d(x)}{d(x)} \to 1$$

- Suppression of spin-1 diquarks *(Close; Carlitz;...)*

$$\frac{\Delta u(x)}{u(x)} \to 1, \frac{\Delta d(x)}{d(x)} \to -\frac{1}{3}$$



$A_L(y_W) \approx \Delta d(x)/d(x)$ in W^- boson production



- ❒ If the relationship $\Delta f_q(x, Q_0)/f_q(x, Q_0) \approx$ const for $x > x_0$ holds at some Q_0,
- ❒ and the valence PDFs dominate,

then this relationship holds at all Q [helicity conservation in PQCD radiation off valence quarks]

Beyond the leading order

A realistic model must account for

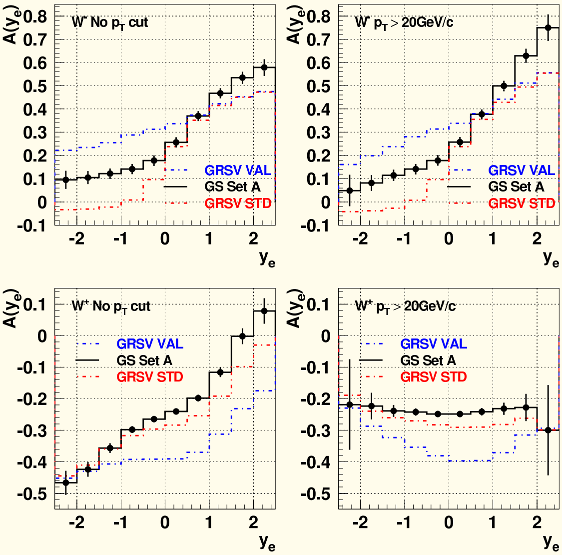
- QCD radiative corrections
- boson decay effects
  - $d\sigma/dy_W$ is often not known; must look at decay particle distributions
  - $W \to e\nu$: clean decay mode; requires large luminosity
  - $W \to$ hadrons: less precise, but may be seen with smaller luminosity
- acceptance of RHIC detectors (no 4π coverage)

RhicBos: resummation program for polarized $W^{\pm}$, Z^0, and γ^* production

(P. N., C.-P. Yuan, Nucl. Phys. B666, 3 (2003); Nucl. Phys. B666, 35 (2003))

- Monte-Carlo integrator with resummation of soft gluons at NNLL/NLO accuracy
- 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.
- new: resummed input grids for de Florian-Sassot (2005), Bourelly-Soffer-Buccella, and other PDF's

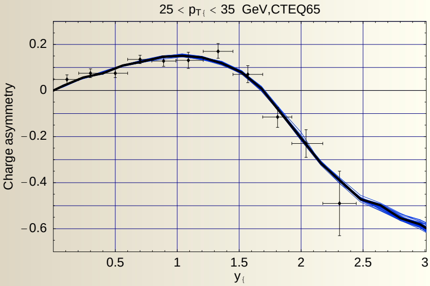
RHICBOS W simulation at 500GeV CME (P=0.7 L=800pb^{-1})

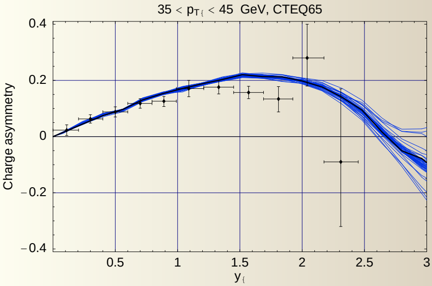


Selection of lepton p_T^e and y_e combinations probes PDF's in different x regions

Example: charged lepton asymmetry in $p\bar{p} \to (W \to \ell\nu)X$ at the Tevatron

- if y_e is large and p_T^e is integrated out, probes $d(x)/u(x)$ at $x \to 1$ (integrated over a substantial x range)
- selection of p_T^e probes constrained ranges of x and Q_T





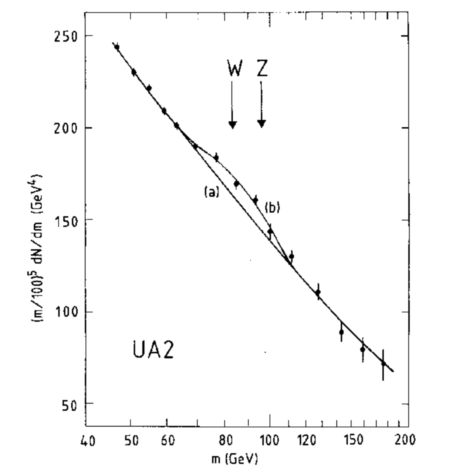
Exploring new opportunities in W and Z production

- A study of sensitivity to quark polarization based on updated (dF-S'2005) PDF's *(B. Surrow and collaborators)*
- Hadronic decays of W and Z bosons
- Spin (in)dependence of resummed power-suppressed corrections in low-Q Drell-Yan and W, Z production

Hadronic decays of W and Z bosons

- The $W \to e\nu$ decay is the golden mode at large luminosities ($\mathcal{L} > 300$ pb^{-1})
- Hadronic decays may be competitive at RHIC for lower $\mathcal{L} \approx 100$ pb^{-1} and reduced instrumentation (no lepton charge ID)
- Hadronic decay mode should be more accessible at RHIC than at the Tevatron or LHC
  - much lower background, especially for parity-violating A_L
  - lower resolution sufficient (not an electroweak precision measurement as at the Tevatron)

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

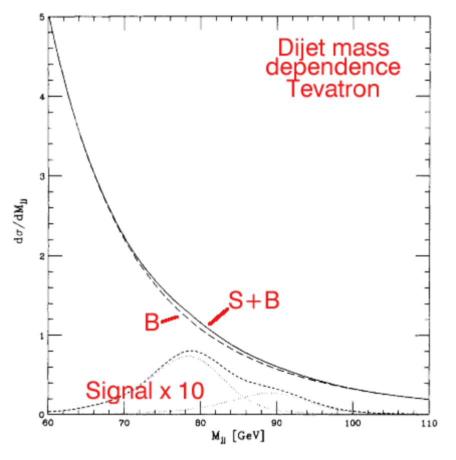


- $p\bar{p} \to WX$, $\sqrt{s} = 630$ GeV, $\mathcal{L} = 0.73$ pb^{-1}; $x \sim 0.13$
- 3σ signal in the dijet mass (m) distribution
- background/signal≈ 20
- background is smooth
- can be extrapolated from the sidebands

- Mass resolution $\delta m = 8 - 9$ GeV
- W and Z peaks are not separated

$W \to$ 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

Hadronic decays: RHIC vs. SPS and Tevatron

☺ smaller $\sqrt{s}$ (500 vs. 630 and 1800 GeV):
gluon background $\downarrow$

☹ pp vs. $p\bar{p}$: gluon background $\uparrow$

$\Rightarrow$ background/signal$\approx$20 for σ_L;
≈ 0 for $\Delta_L^{PV}\sigma$ (false asymmetry only!)

☺ the background can be extrapolated from the sidebands

Hadronic vs. leptonic decays

- ☺ Larger cross sections: $\text{Br}(W \to q_i \bar{q}_j)/\text{Br}(W \to e\nu) \approx 6$
- ☺ Direct measurement of $d\sigma/dy_W$ possible
- ☹ Energy & mass resolution≈ 10 GeV; no charge ID
  W^+, W^- and Z^0 cannot be separated
- ☹ Increased Z^0 contamination: $\text{Br}(Z \to q\bar{q})/\text{Br}(Z \to e^+e^-) \approx 20$

In resonant (s-channel) production:

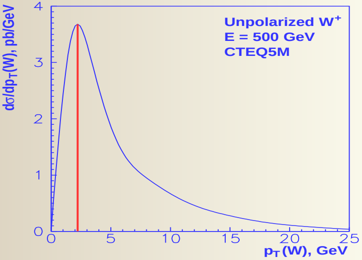
leptonic decays: $\sigma_{W^+} : \sigma_{W^-} : \sigma_{Z^0} = 1 : 0.33 : 0.08$

hadronic decays: $\sigma_{W^+} : \sigma_{W^-} : \sigma_{Z^0} = 1 : 0.33 : 0.26$

- ☹ t, u channel contributions in Z production *(S. Arnold's talk)*
- ☺ The Z^0 component can be reduced by reweighting M_{jj} bins

Spin dependence of nonperturbative resummed contributions

- Processes: unpolarized and polarized $pp \xrightarrow{\gamma^*} \mu^+\mu^- X$, $pp \to W^\pm X$
  - precision test of universality of k_T factorization (Collins-Soper-Sterman resummation)



$Q_T \neq 0$! The shape of $d\sigma/dQ_T$ at $Q_T \to 0$ cannot be described at a finite order of PQCD: calculation of the sum

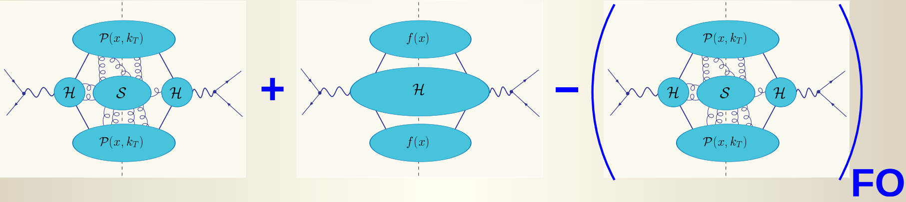
$$\frac{1}{Q_T^2}\sum_{n=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^n \sum_{m=0}^{2n-1} v_{mn}\left(\ln^m \frac{Q^2}{Q_T^2} \quad \text{or} \quad \delta(\vec{q}_{TW})\right)$$

is needed

k_T factorization in impact parameter (b) space

(Collins, Soper, Sterman, 1985)

- is based on a factorization theorem
  (J. Collins, A. Metz; X. Ji, J.-P. Ma, F. Yuan;...)
- applies to Drell-Yan-like processes, SIDIS, and e^+e^- hadroproduction
- resummed $d\sigma/dQ_T$ are given by products of universal functions with perturbative and nonperturbative components



Applications of Q_T resummation

- Tevatron and LHC
  - Precision measurement of W boson mass
  - Higgs boson searches
- Fixed-target Drell-Yan pair production
  - measurement of universal power-suppressed resummed contributions
- SIDIS at HERA, HERMES, COMPASS, JLab
  - energy flow and particle multiplicities in the current fragmentation region ($Q > 3$ GeV); heavy-flavor production
  - k_T factorization for transverse spin asymmetries ($Q \lesssim 2$ GeV!)
- RHIC
  - measurement of polarized parton densities in single-spin W production

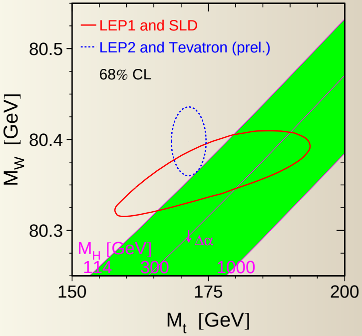
Measurement of W-boson mass M_W at the Tevatron ($p\bar{p} \to WX \to l\nu X$)

- Constrains the **logarithm** of Higgs boson mass M_H in the standard model

- CDF Run-2 result (Jan'07):

$$M_W = 80.413 \pm 0.048 \text{ GeV}$$
$$\left(\delta M_W / M_W = 0.0005\right)$$

- Run-2 goal: reduce δM_W to < 30 MeV per experiment (LHC: $\delta M_W \sim 5 - 15$ MeV)



- M_W is commonly found by measuring $\vec{p}_T$'s of decay leptons

$\Rightarrow Q_T$ of W bosons must be predicted with high precision!

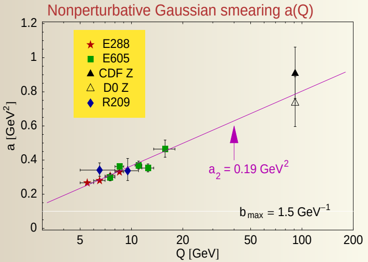
Testing universality of CSS resummation

If universality holds:

- parts of the resummed $d\sigma/dQ_T$ can be "measured" in one set of processes and used to predict other processes
  - global fit of Q_T data is feasible
  - for instance, the low-Q Drell-Yan process at RHIC can constrain predictions for $W, Z, \gamma\gamma, Z'$,... production at the Tevatron and LHC
    - reduce theory error in the measurement of M_W at the Tevatron and LHC
- An important insight would be provided by measuring spin dependence of the leading power-suppressed contribution ("Gaussian k_T-smearing")

Universality of nonperturbative contributions

*A. Konychev, **P. N.**, PLB 633, 710 (2006)*

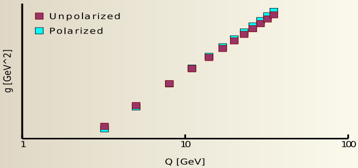


- Q_T factorization: initial-state nonperturbative contributions ($\sim$"intrinsic" $\langle k_T^2 \rangle \equiv a$) follow universal quasi-linear dependence on $\ln Q$; this expectation is confirmed by the global analysis of Drell-Yan and Z boson data
- the observed $\ln Q$ dependence agrees with the renormalon/lattice estimate *(Tafat)*
- at $Q \sim M_Z$, soft NP corrections dominate over collinear NP corrections

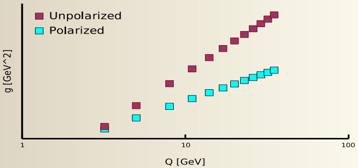
Studies of Gaussian smearing at RHIC

- The new p_T fit supports dominance of soft contributions in $\mathcal{F}_{NP}(b,Q)$ with a nearly linear $\ln Q$ dependence
  - Gaussian $\mathcal{F}_{NP}(b,Q) \approx b^2\,[0.20 + 0.19\ln(Q/3.2) + ...]$
- The $\ln Q$ dependence is expected to be independent of spin
- Polarized Drell-Yan and W, Z Q_T data from RHIC can
  - test $\mathcal{F}_{NP}(b,Q)$ at intermediate $\sqrt{s} = 200$ or 500 GeV
  - test spin independence of $\mathcal{F}_{NP}(b,Q)$

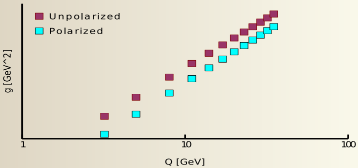
Spin (in)dependence of Gaussian k_T smearing



Universal kT smearing



Spin-dependent Sudakov factor



Spin dependence from the unintegrated PDF's and/or Sudakov factor

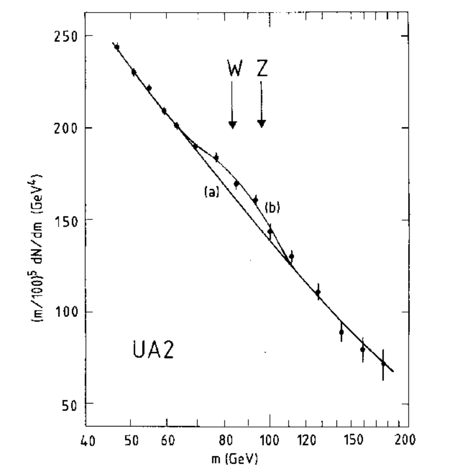
Summary

Single-spin asymmetries in W production provide exciting opportunities

- First measurements to be done in the hadronic decay mode
- Refined measurements in the lepton decay mode
- Possibilities to explore spin dependence of transverse momentum degrees of freedom in the nucleon

Backup slides

$W \rightarrow$ hadrons at SPS *(PLB186, 452 (1987))*



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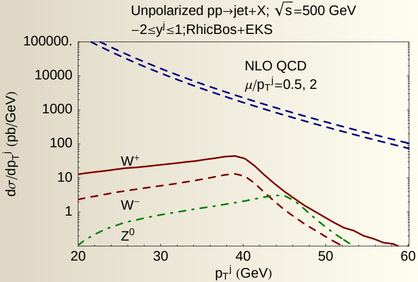
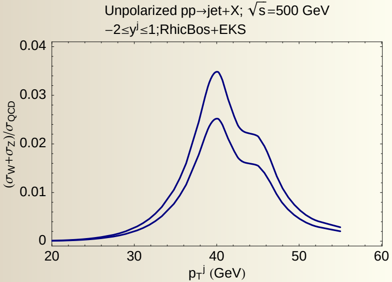
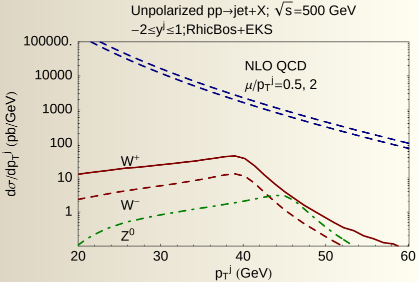
W and Z hadronic decays at RHIC

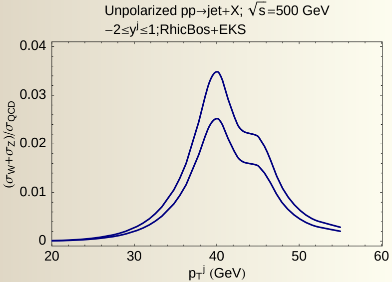




- resonant (s-channel) production only (interference with t, u channels not included)
- $d\sigma/dp_T^{jet}$: less efficient variable than $d\sigma/dM_{jj}$
- background/signal $\gtrsim 30$

W and Z hadronic decays at RHIC





- At $p_T^j \approx M_W/2$, without subtraction of the NLO QCD background, for $\mathcal{L} = 100$ pb^{-1}:
  - $A_L \sim 1\%$; $\delta A_L \sim 1/\sqrt{N_{QCD}}$ evaluated at $p_T^j \approx M_W/2$
- with subtraction:
  - $A_L \gg 1\%$, δA_L is determined by N_{W+Z} at $p_T^j \approx M_W/2$ and N_{QCD} from all p_T^j