BNL Sep. 2000

Drell-Yan Muon Pair Production @ RHIC

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(Regensburg)

- **Drell-Yan process up to NLO QCD**
- **Numerical analysis**:
  - model for transversity densities δq
  - detector angular acceptance (PHENIX)
  - transverse double-spin asymmetries
- **Conclusions**

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together with O. Martin, A. Schäfer, W. Vogelsang

[Phys. Rev. *D57* (1998) 3084; *D60* (1999) 117502]

• Drell-Yan process up to NLO QCD

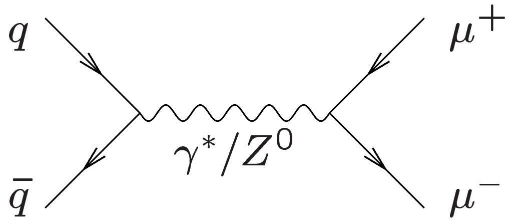
general problem: $\not\exists$ 'transversity' gluons

$\rightsquigarrow$ all asymmetries $A_{TT} = d\delta\sigma/d\sigma$ strongly diluted by gluon induced processes in $d\sigma$

$\rightsquigarrow$ need process *w/o* gluon contribution in LO

best candidate: Drell-Yan process Ralston, Soper; Ji
Cortes, Pire, Ralston; Artru, Mekhfi; Ji; Jaffe

chirality flip ✓
M: dimuon mass
y: dimuon rapidity
ϕ: azimuth [$\phi = 0 \leftrightarrow \uparrow$ spin dir.]



$$\frac{d\delta\sigma}{dM\,dy\,d\phi} = \sum_q \tilde{e}_q^2 \int dx_1 dx_2 \left[\delta q(x_1, \mu_f^2)\delta\bar{q}(x_2, \mu_f^2) + (1 \leftrightarrow 2)\right] \frac{d\delta\widehat{\sigma}}{dM\,dy\,d\phi}$$

$\uparrow$ electroweak effects

$$e_q^2 + e_q G_F \ldots + G_F^2 \ldots$$

γ γZ^0 Z^0

$\nearrow$ defined as

$$(d\widehat{\sigma}^{\uparrow\uparrow} - d\widehat{\sigma}^{\uparrow\downarrow})/2$$

'problem': non-trivial ϕ dependence of $d\delta\widehat{\sigma}$

$$d\delta\widehat{\sigma} \simeq \cos(2\phi) \rightsquigarrow \int_0^{2\pi} d\phi\, d\delta\widehat{\sigma} = 0$$

$\rightsquigarrow$ define $\left(\int_{-\pi/4}^{\pi/4} - \int_{\pi/4}^{3\pi/4} + \int_{3\pi/4}^{5\pi/4} - \int_{5\pi/4}^{7\pi/4}\right) d\phi$

Cortes, Pire, Ralston

In LO:

$$\frac{d\delta\hat{\sigma}^{(0)}}{dM\,dy\,d\phi} = \frac{2\alpha_{em}^2}{9SM}\cos(2\phi)\,\delta(x_1 - \underset{\sqrt{\tau}e^{y}}{\underset{\uparrow}{x_1^{\text{min}}}})\,\delta(x_2 - \underset{\sqrt{\tau}e^{-y}}{\underset{\uparrow}{x_2^{\text{min}}}})$$

where $\tau \equiv M^2/S$

$\rightsquigarrow$ best suited observable: $A_{TT}(M,y)$

y dependence of A_{TT} $\leftrightarrow$ scan of $\delta q(x_1)\delta\bar{q}(x_2)$

$\leftrightarrow$ *shape* of δq

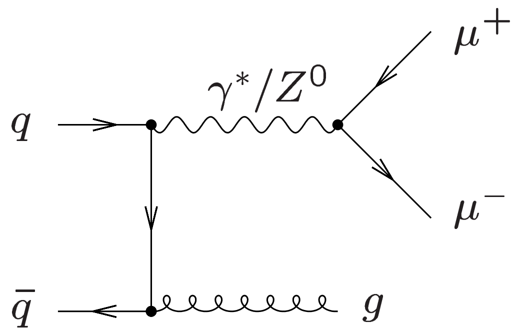
[y integrated $A_{TT}(M)$ 'only' probes very existence of δq]

Why NLO?

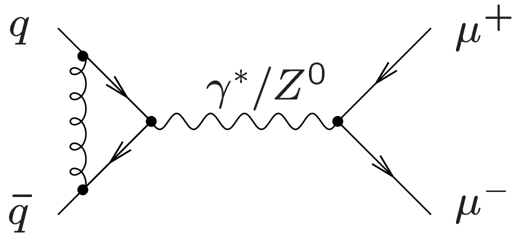
- ▷ Drell-Yan known for sizable K-factor
- ▷ reduced dependence on unphysical scales μ_f, μ_r
- ▷ non-vanishing p_T of muon pair

To do:

real corrections:
[unpol.: also $qg \to q\mu^+\mu^-$]



virtual corrections:



Technical complication:

have to keep azimuthal angle ϕ *un*integrated
[cumbersome when using n *dimensional regularization*]

$\rightsquigarrow$ 1st calculation done with *gluon mass* as regulator
Vogelsang, Weber

available NLO results:

$$\frac{d\delta\hat{\sigma}}{dM\,d\phi} \qquad \frac{d\delta\hat{\sigma}}{dM\,dy\,d\phi} \qquad \frac{d\delta\hat{\sigma}}{dM\,dp_T\,d\phi}$$

$\uparrow$
pheno. less relevant:
LO $q\bar{q} \to \mu^+\mu^-$ does not
contribute ($p_T = 0$)

but NLO splitting functions δP_{qq} are in $\overline{\text{MS}}$
Vogelsang; Koike et al.; Kumano, Miyama

$\rightsquigarrow$ scheme *independence* requires $d\delta\hat{\sigma}$ in $\overline{\text{MS}}$

Transformation off-shell $\to$ $\overline{\text{MS}}$ scheme:

everything can be deduced from

$$(\delta)C_{q\bar{q},\overline{\text{MS}}} - (\delta)C_{q\bar{q},\text{off-shell}}$$

i.e. 'total DY' $d(\delta)\hat{\sigma}/dM\,d\phi$ for the *unpolarized* case
[$C_{q\bar{q},\overline{\text{MS}}}$: Altarelli et al.; Furmanski et al.; $C_{q\bar{q},\text{off-shell}}$: Kubar et al.]

$\rightsquigarrow$ $\overline{\text{MS}}$ results for $d\delta\hat{\sigma}$ $\checkmark$

[2nd calc. of $d\delta\hat{\sigma}$ uses *dimensional reduction* Contogouris et al.
results agree after transformation to $\overline{\text{MS}}$ Kamal; Vogelsang]

• Numerical analysis

Modeling transversity densities δq

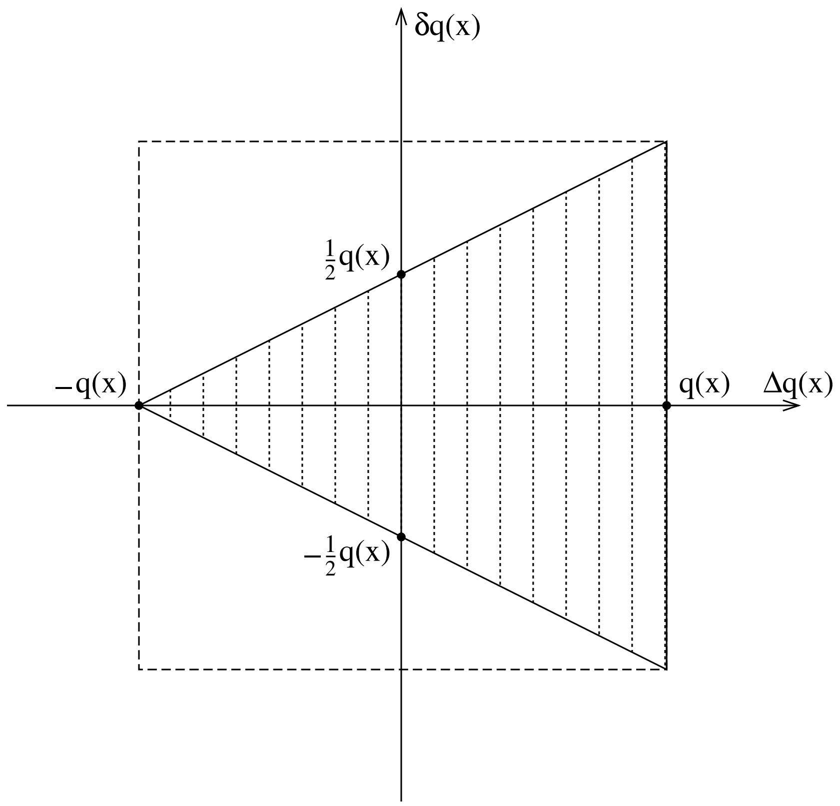
δq unmeasured $\rightsquigarrow$ have to rely on theoretical prejudices

helpful constraint: Soffer inequality

$$\underbrace{\left|\delta q(x,\mu^2)\right|}_{\text{unknown}} \;\le\; \frac{1}{2}\,\underbrace{\left[q(x,\mu^2) + \Delta q(x,\mu^2)\right]}_{\text{known (more or less)}}$$

$\rightsquigarrow$ upper bounds for δq and spin asymmetries A_{TT}

Soffer's inequality is *more restrictive* than $|\delta q| \le q$:



$\rightsquigarrow$ frequently used models based on $\delta q = \Delta q$ at some initial scale $\mu = Q_0$ Scopetta, Vento; Miyama; ...

violate bound if $\Delta q \le -\frac{1}{3} q$

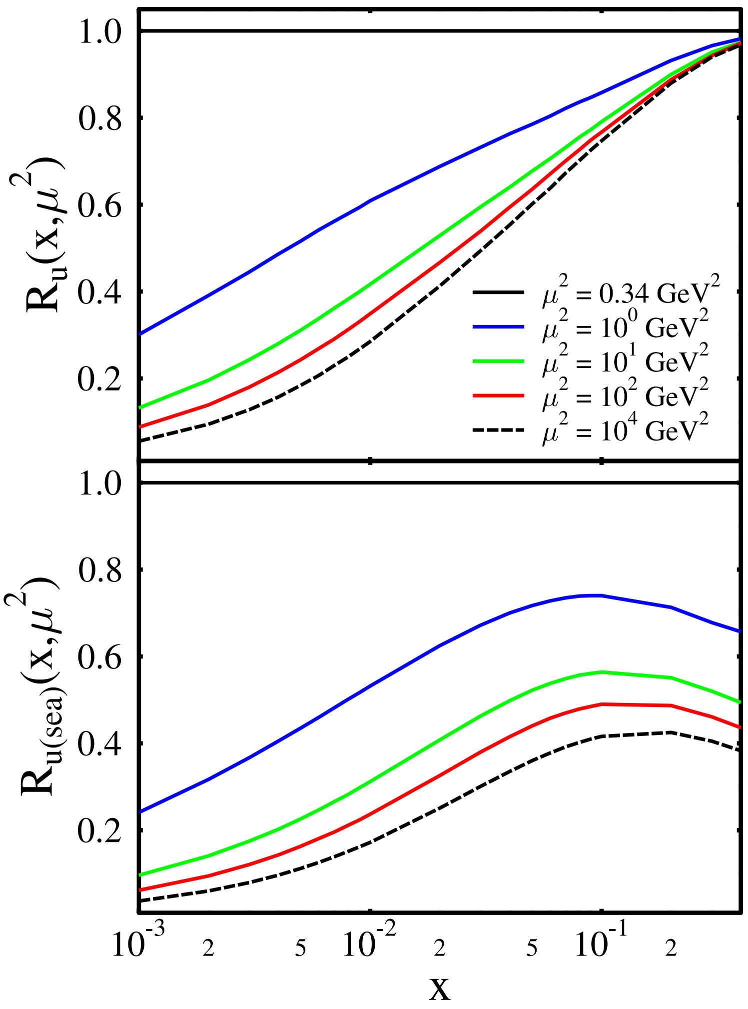
$\rightsquigarrow$ for our estimates of A_{TT} we *saturate* Soffer's ineq. at $Q_0 \simeq 0.6\,\text{GeV}$ using GRV (q) and GRSV (Δq)

Is Soffer's inequality valid *beyond* the leading order?

PDF's are scheme-dependent ($\leftrightarrow$ unphysical) in NLO

$\rightsquigarrow$ constraints on parton level are *not* relevant anymore [similarly: 'positivity' at work for $|\Delta\sigma| \leq \sigma$ *not* $|\Delta f| \leq f$]

However, in $\overline{\text{MS}}$ it *usually* works out ...



[remark: *analytical* proof of the inequality in NLO ($\overline{\text{MS}}$) by Bourrely et al. is flawed: $|\Delta P_{ij}| \leq P_{ij}$ not fulfilled in $\overline{\text{MS}}$ for $q \to g$

$\rightsquigarrow$ $|\Delta f| \not\leq f$ under certain conditions]

Detector angular acceptance for PHENIX

Motivation: theoretical predictions can be misleading if detector effects are not included

Example: Drell-Yan muon pairs @ PHENIX
have to detect *both* muons to get mass M
but only endcaps detect muons: $1.2 \leq |y_{\mu^\pm}| \leq 2.4$

$\rightsquigarrow$ try to include muon acceptance in A_{TT} estimates:
take *fully* differential $d(\delta)\sigma$ [only available in LO so far]
and define acceptance as

$$(\delta)\varepsilon(M,y) \equiv \frac{\int_{\text{detector PS}} dp_T^1 d\phi^1 \; d(\delta)\sigma/dM\,dy\,dp_T^1 d\phi^1}{\int_{\text{full PS}} dp_T^1 d\phi^1 \; d(\delta)\sigma/dM\,dy\,dp_T^1 d\phi^1}$$

important feature: $\delta\varepsilon \neq \varepsilon$

$\rightsquigarrow$ 'distorted' asymmetries: $A_{TT}^{\text{exp}} > A_{TT}$ for $\delta\varepsilon > \varepsilon$
and vice versa

Estimates of statistical errors for A_{TT}:

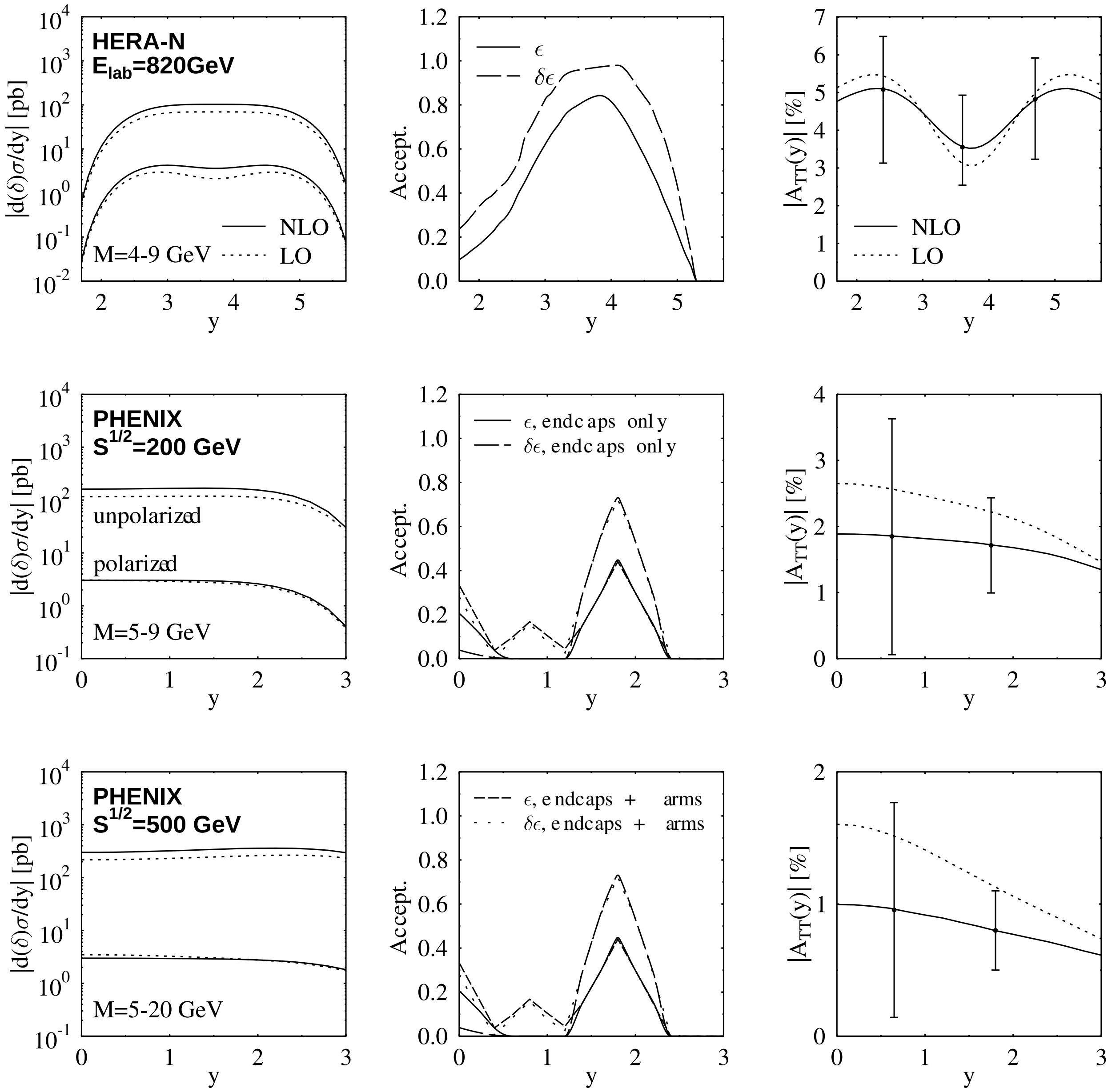
$$\text{stat. error} \simeq \frac{1}{P_A P_B \sqrt{\mathcal{L} \int \varepsilon \, d\sigma}}$$

plus rescaling by $A_{TT}/A_{TT}^{\text{exp}}$

use: $P_A = P_B = 0.7$; $|p_\mu| > 2\,\text{GeV}$ (get rid of background) ;
$\mathcal{L} = 320\ (800)\ \text{pb}^{-1}$ for $\sqrt{S} = 200\ (500)\ \text{GeV}$

Some estimates for A_{TT}

(I) M integrated $\int_{M_1}^{M_2} dM$; differential in y



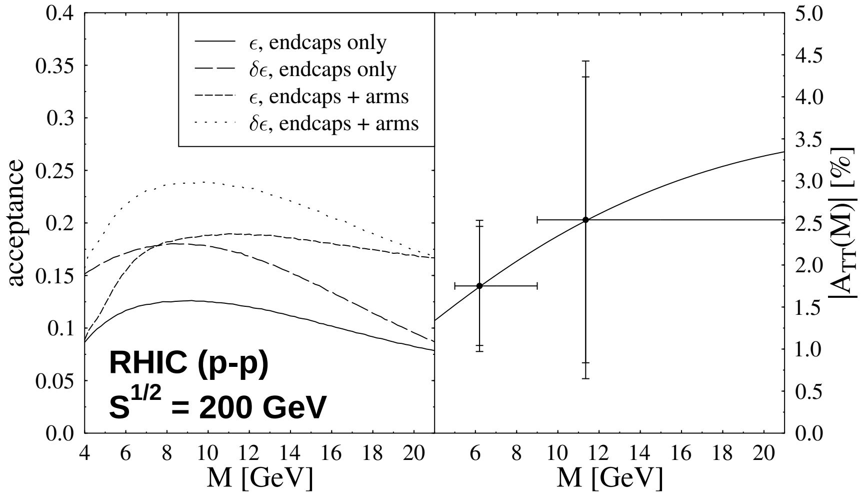
extra 'feature': hypothetical muon arms $|y_{\mu^\pm}| \leq 0.35$

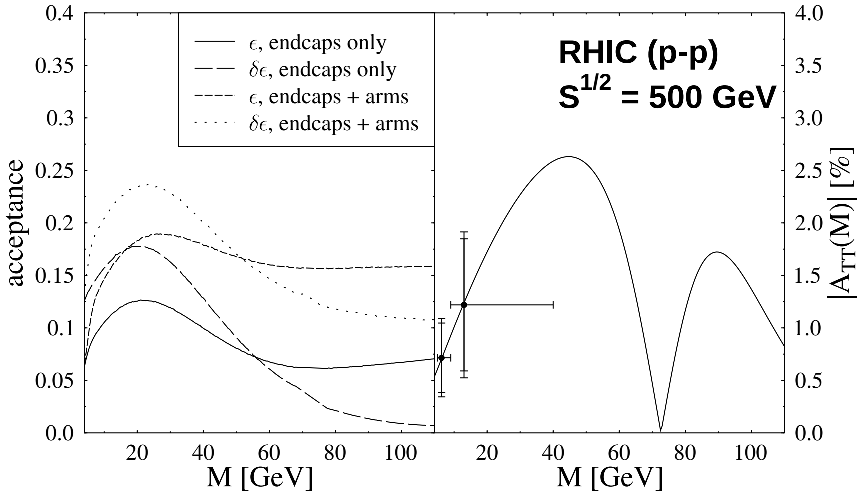
'error bars' for low y bin *with* arms only

HERA-N: possible future *fixed target* exp. at HERA

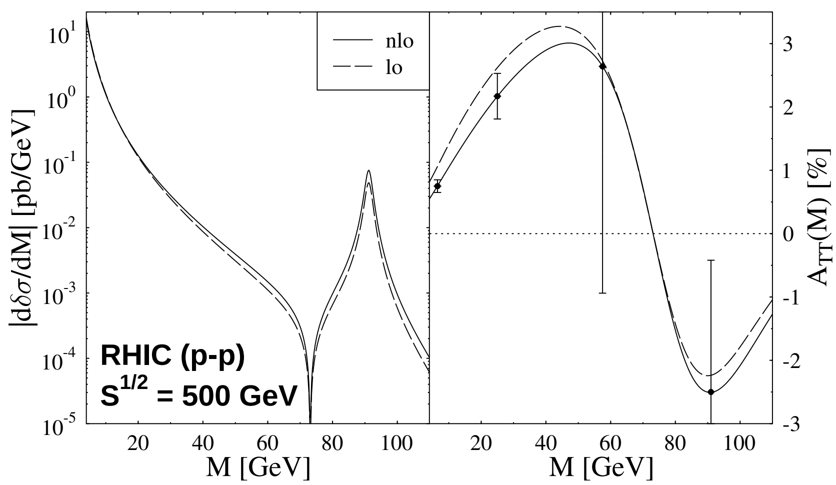
'errors' for $\mathcal{L} = 240\,\mathrm{pb}^{-1}$ Korotkov, Nowak

(II) rapidity y integrated; differential in dimuon mass M





... and for a perfect 4π-detector:



• Conclusions

▷ limited muon acceptance threatens to make a measurement of A_{TT} elusive at PHENIX in particular for $A_{TT}(y, M) \leftrightarrow$ *shape* of δq

▷ $A_{TT}(M)$ still promising $\leftrightarrow$ proves very existence of δq

BUT one should keep in mind that our estimates are upper bounds for A_{TT}, i.e., most optimistic:

▷ if Soffer's inequality is only 50% saturated all A_{TT}'s would be *down* by a factor of four

On the other hand, if saturation takes place at a *higher* scale Q_0 than assumed, all A_{TT}'s would be *up*

▷ for example $A_{TT}(M)$ with $Q_0^2 = 0.34, 0.6, 1\,\text{GeV}^2$: