Hard Scattering and Spin Asymmetries at J-PARC

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Outline

- **motivation**: "the quest for pdfs at large x"
- **theor. framework (I):** pQCD & hard scattering
- **expectations**: pion and photon production @ J-PARC
- **theor. framework (II)**: resummations
- **concluding remarks**

I. Motivation

"the quest for pdfs at large-x"

"counting rules": do they count?

interest in $x \to 1$ behavior of pdfs started some time ago:

Farrar, Jackson; Close, Sivers; Blankenbecler, Brodsky; Brodsky, Gunion; Brodsky, Schmidt; ...

VOLUME 35, NUMBER 21 PHYSICAL REVIEW LETTERS 24 NOVEMBER 1975

Pion and Nucleon Structure Functions near $x = 1$*

Glennys R. Farrar† and Darrell R. Jackson
California Insitute of Technology, Pasadena, California 91125
(Received 4 August 1975)

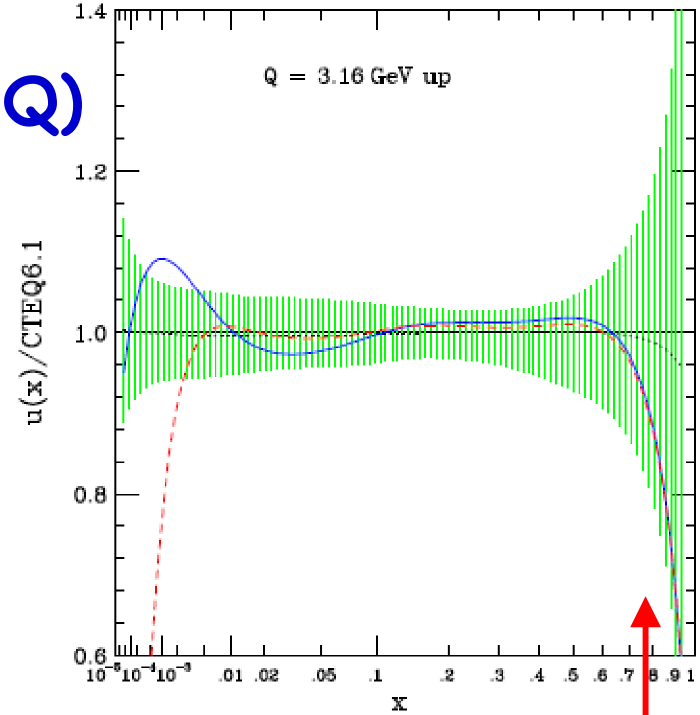
In a colored-quark and vector-gluon model of hadrons we show that a quark carrying nearly all the momentum of a nucleon ($x \approx 1$) must have the same helicity as the nucleon; consequently $\nu W_2^n/\nu W_2^p \to \frac{3}{7}$ as $x \to 1$, not $\frac{2}{3}$ as might naively have been expected. Furthermore as $x \to 1$, $\nu W_2^\pi \sim (1-x)^2$ and $(\sigma_L/\sigma_T)^\pi \sim \mu^2 Q^{-2}(1-x)^{-2} + O(g^2)$; the resulting angular dependence for $e^+e^- \to h^\pm + X$ is consistent with present data and has a distinctive form which can be easily tested when better data are available.

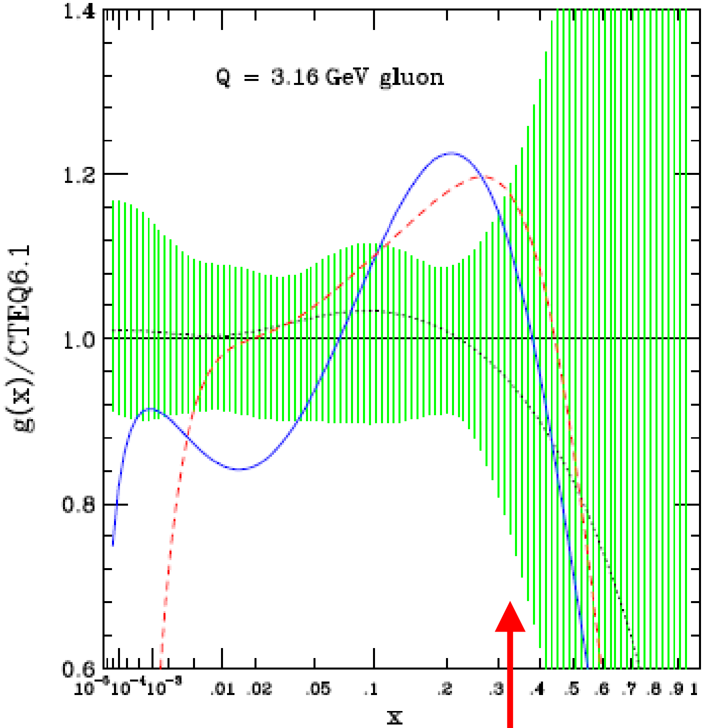
- precise exp. information for $x \to 1$ is still lacking
- rigorous pQCD framework just emerging (fact. theorem) Ji, Ma, Yuan
- extraction of $x \to 1$ behavior complicated
  (presence of potentially large logarithms → resummations)

"counting rules": do they count?

latest global analysis results from CTEQ: Huston, Pumplin, Stump, Tung

u(x,Q)





g(x,Q)

significant uncertainties for $x \gtrsim 0.75$

significant uncertainties for $x \gtrsim 0.3$

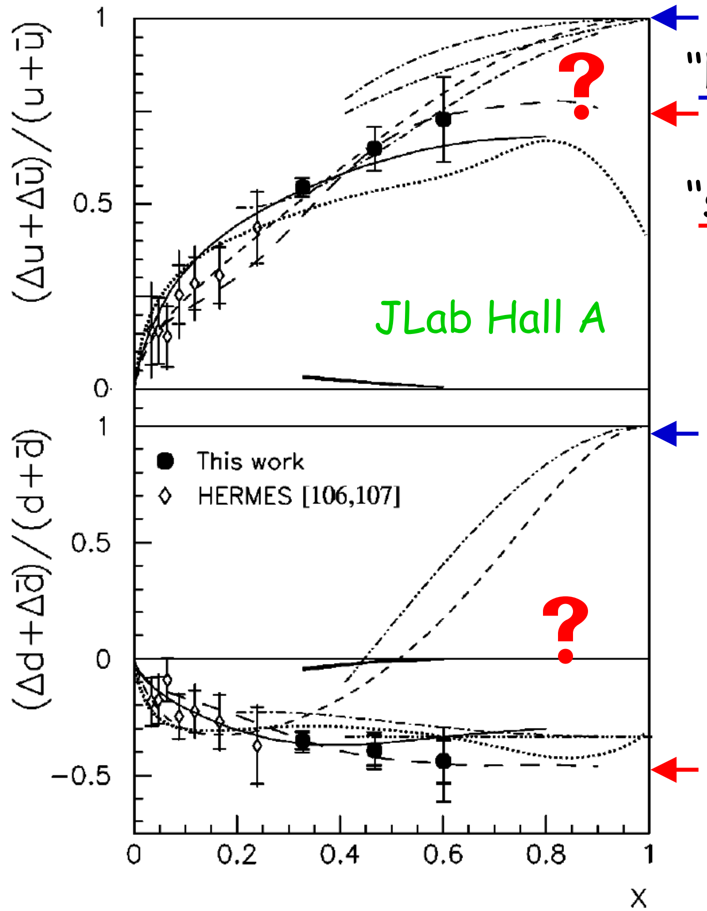
✓ fits always favor $u(x,Q) \sim (1-x)^{3 \div 4}$

$g(x,Q) \sim (1-x)^{0.8 \div 3.6}$ (best fit 1.7) ?

unstable w.r.t. fact. scheme, Q

"counting rules": do they count?

much less is known for helicity-dependent pdfs: $\Delta f(x) \equiv f_+^{N_+}(x) - f_-^{N_+}(x)$

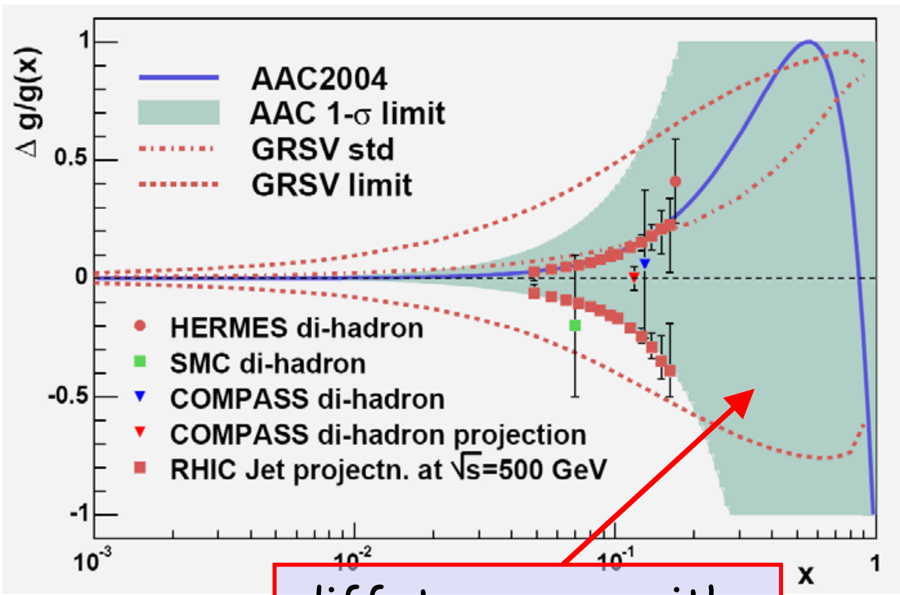


"helicity retention": $(\Delta f/f) \to 1$

Farrar, Jackson; Brodsky, Schmidt; Brodsky, Burkardt, Schmidt

"statist. parton model": $(\Delta u/u) \to 0.75$, $(\Delta d/d) \to -0.5$

Bourrely, Buccella, Soffer



diff. to access with present experiments

the big picture: impact on LHC physics

unpol. pdfs are vital for reliable predictions for new physics signals *and* their background cross sections at the LHC

high precision pdfs are crucial as they can compromise the potential for new physics discovery: Ferrag; ...

- high-x gluon uncertainty: reduces discovery reach in dijets
  5-10 TeV $\rightarrow$ 2-3 TeV
- high-x quark uncertainties: similar for Drell-Yan process

pdf uncertainty relevant for large Higgs masses, $Ht\bar{t}$ prod., ...
Djouadi, Ferrag; ...

ATLAS is looking into their pdf constraining potential

compelling reasons to check what can be done at a high-luminosity but low energy machine like J-PARC

we have to be prepared, however, for complications due to the low c.m.s. energy ...

II. Theoretical framework (i)

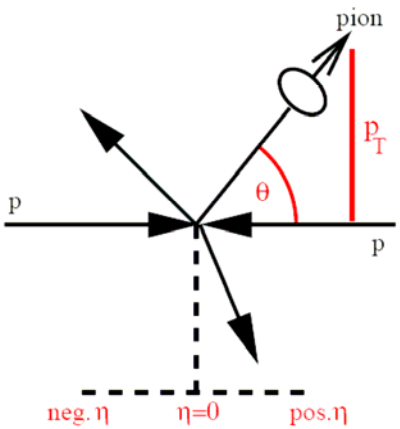
pQCD & hard scattering

the pQCD approach to hard scattering

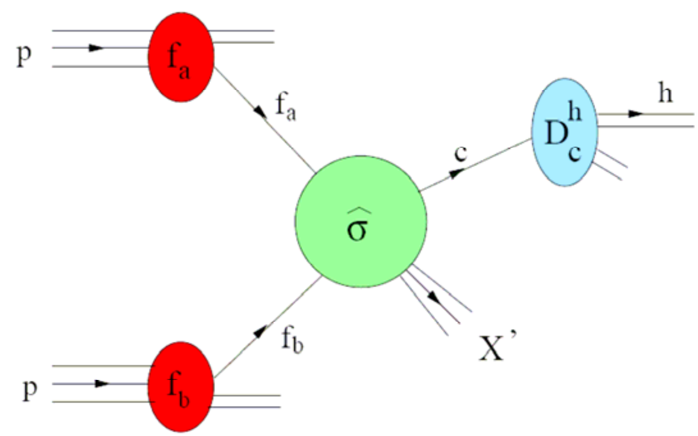
if hardness of probe is large enough ($\alpha_s(Q) \ll 1$), perturbative QCD can be used to make *quantitative predictions*
(exploiting asymptotic freedom of QCD) Gross, Wilczek; Politzer 

starting point: factorization theorem & universality of pdfs
Libby, Sterman; Ellis et al.; Amati et al.; Collins et al.; ...

example : (un)polarized inclusive high-p_T pion production



factorization → theorem



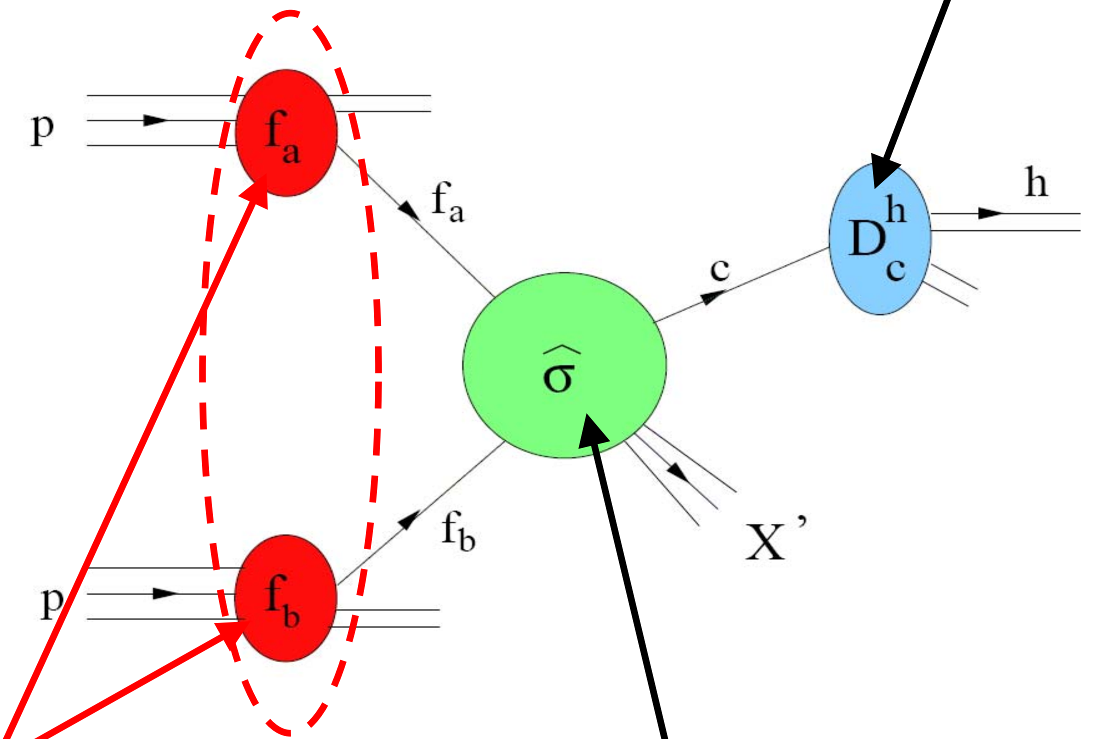
the pQCD approach to hard scattering

the strategy is simple ...

extract from e^+e^- data

measure!

$\mathbf{d(\Delta)\sigma \simeq}$



learn about hadronic/spin structure

compute as a power series in α_s in pQCD

the pQCD approach to hard scattering

in more "mathematical" terms:

long-distance

from exp.; μ-dep.: $d\sigma/d\mu = 0$ (pQCD)

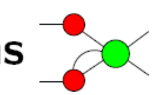
$$\frac{d\Delta\sigma^{\vec{p}\vec{p}\to\pi X}}{dp_T d\eta} = \sum_{abc} \int dx_a\, dx_b\, dz_c\, \Delta f_a(x_a, \mu_f)\, \Delta f_b(x_b, \mu_f)\, D_c^{\pi}(z_c, \mu_f') \times \frac{d\Delta\hat{\sigma}^{ab\to cX'}}{dp_T d\eta}(x_a P_a, x_b P_b, P^{\pi}/z_c, \mu_f, \mu_f', \mu_r) + \mathcal{O}\left(\frac{\lambda}{p_T}\right)^n$$

short-distance

calculable in pQCD: power series in α_s

power corrections

neglected



"features":

- separation between short- and long-dist. not unique (*fact. scheme*)
- theory calculation depends on *unphysical fact./renorm. scales*
- factorized "picture" good up to power corrections

the pQCD approach to hard scattering

the scale dependence is inherent to a pQCD calculation:

- a *measurable* cross section d(Δ)σ has to be *independent* of μ_r and μ_f

$$\frac{d(\Delta)\sigma}{d\ln\mu_{r,f}} = 0$$ → renormalization group eqs. like DGLAP evolution

- if we truncate the series after the first N terms, there will be a residual scale dependence of order (N+1) → theor. error

- there is no such thing like "the right scale" (not even Q in DIS!)

the harder we work, the less the final result should depend on these artificial scales

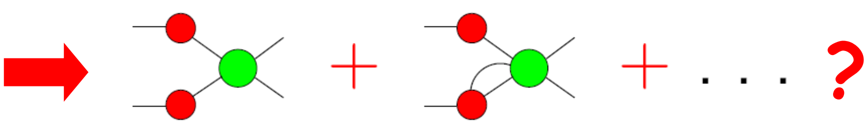
a powerful gauge of the reliability of a pQCD calculation

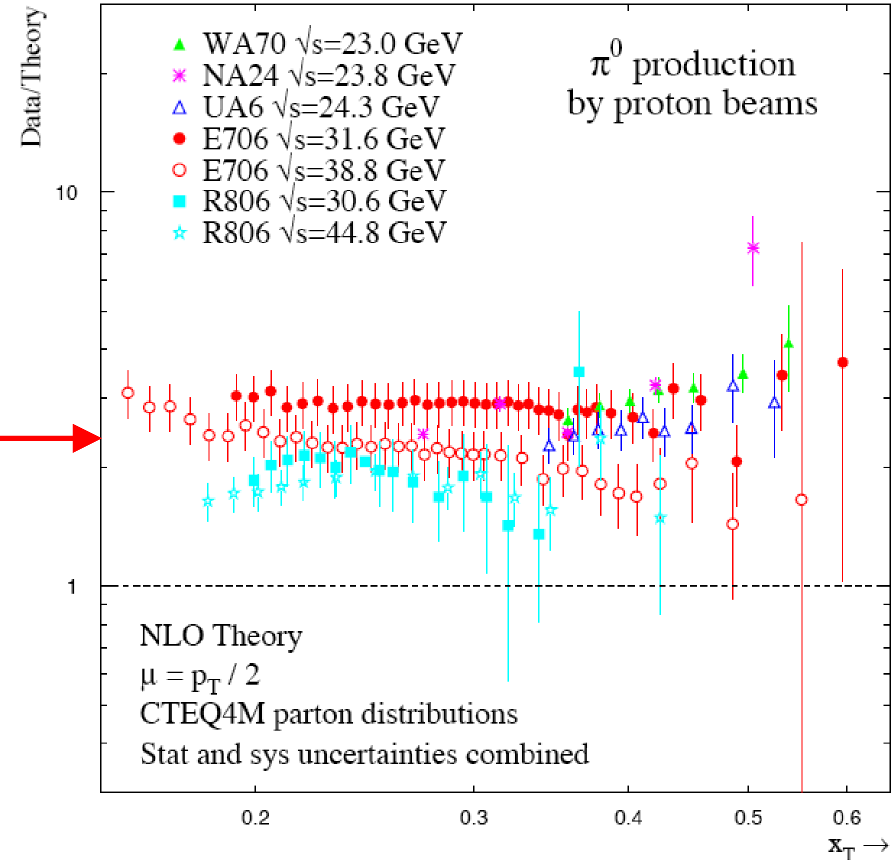
potential problems at fixed-target energies

key question: do we really talk about hard scattering if $\sqrt{S}$ is small ??

a priori we don't know, but

- in pp collisions, hardness is controlled by the observed transverse momentum:
  $p_T^{\mathrm{max}} = \sqrt{S}/[2\cosh(\eta)]$ small !!
- usually NLO pQCD undershoots data
  example: pion producion





Apanasevich et al.; Aurenche et al.; Bourrely, Soffer

not necessarily!

significant improvement after resummation of large logarithms to all orders (later in the talk)

III. Expectations

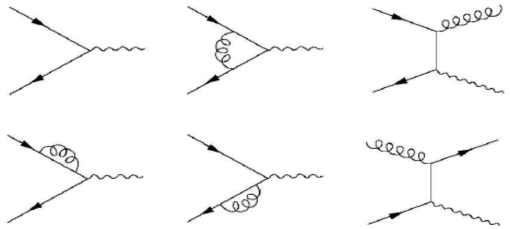
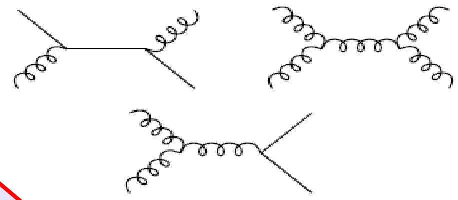
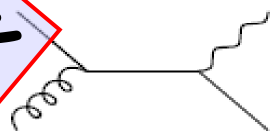
pion and photon production
@ J-PARC

hard processes relevant at J-PARC energies

interesting hard probes: Drell-Yan lepton pairs, inclusive pions, and prompt photons

U: unpolarized
L: long. polarized
T: trans. polarized

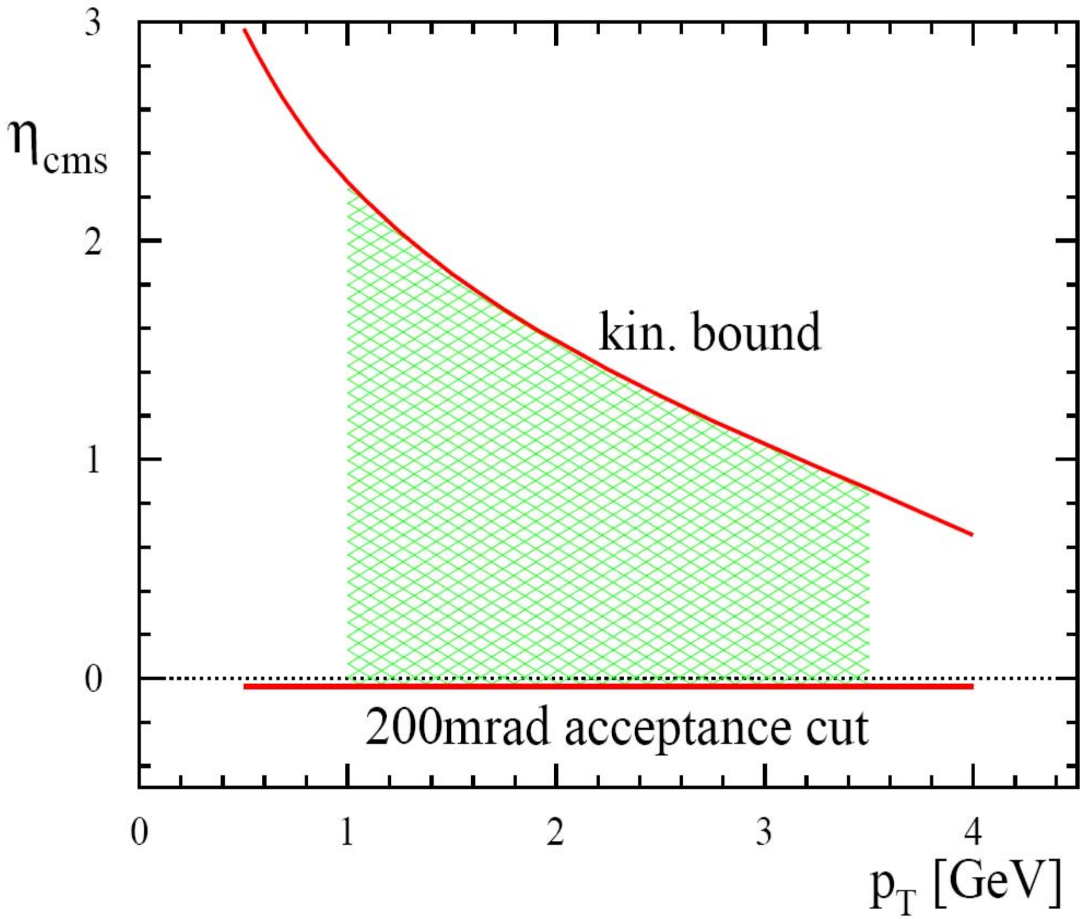
NLO QCD corrections to all reactions are known:

Drell-Yan		see talks by H. Yokoya & H. Kawamura
pions		Aversa et al. (U); de Florian (U,L); Jäger, MS, Vogelsang (U,L); Mukherjee, MS, Vogelsang (T)
prompt photons		Aurenche et al. (U); Baer et al. (U,L); Contogouris et al. (U,L); Gordon, Vogelsang (U,L); Mukherjee, MS, Vogelsang (T)

THIS TALK

inputs to all pQCD calculations

50 GeV proton beam (polarization 75%) on fixed target
target polarization 75%; dilution factor 0.15; integr. luminosity: $10 fb^{-1}$



≈ COMPASS-like angular acceptance: 200mrad

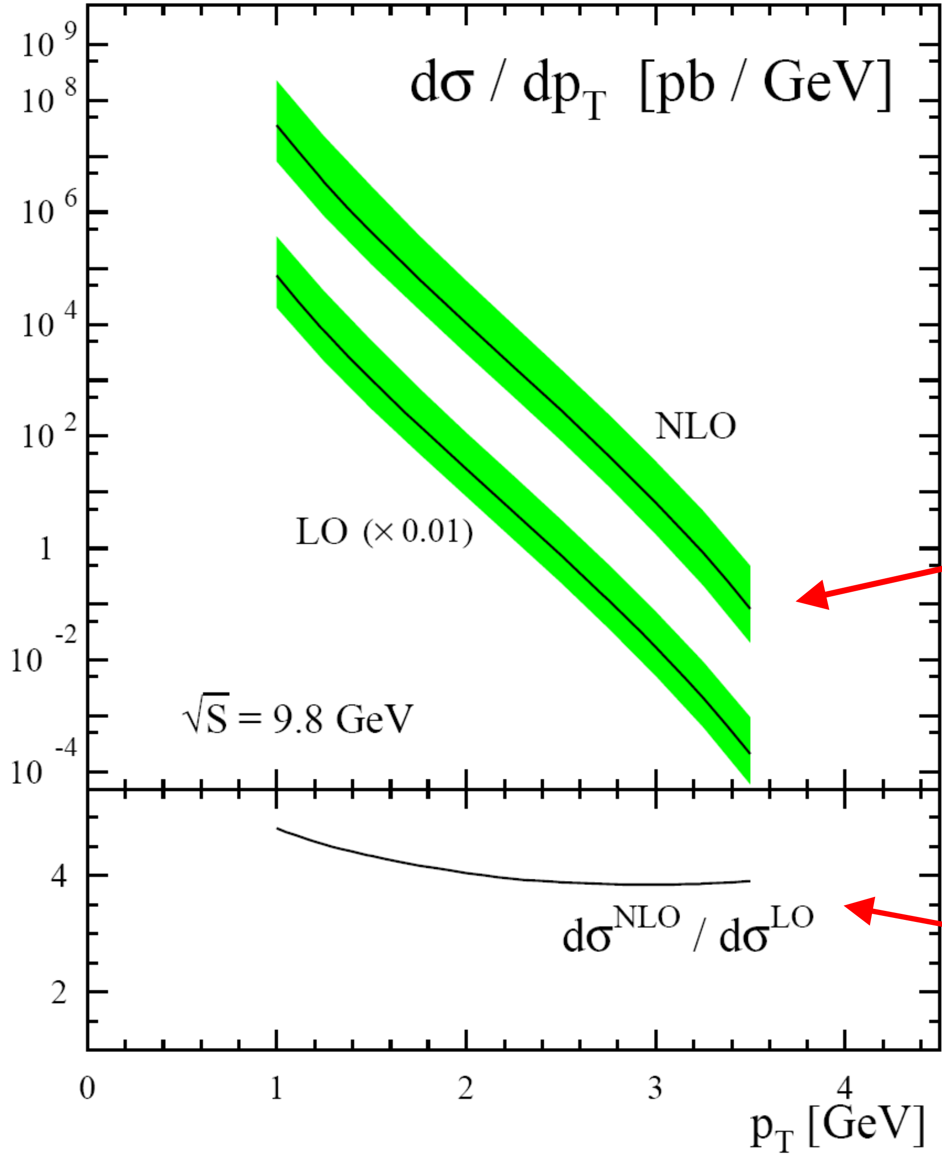
choice of pdfs:

- CTEQ6 (U)
- GRSV (L)
- "Soffer saturated" (T)

choice of frag. fcts.:

- KKP

single-inclusive pion production (unpolarized)

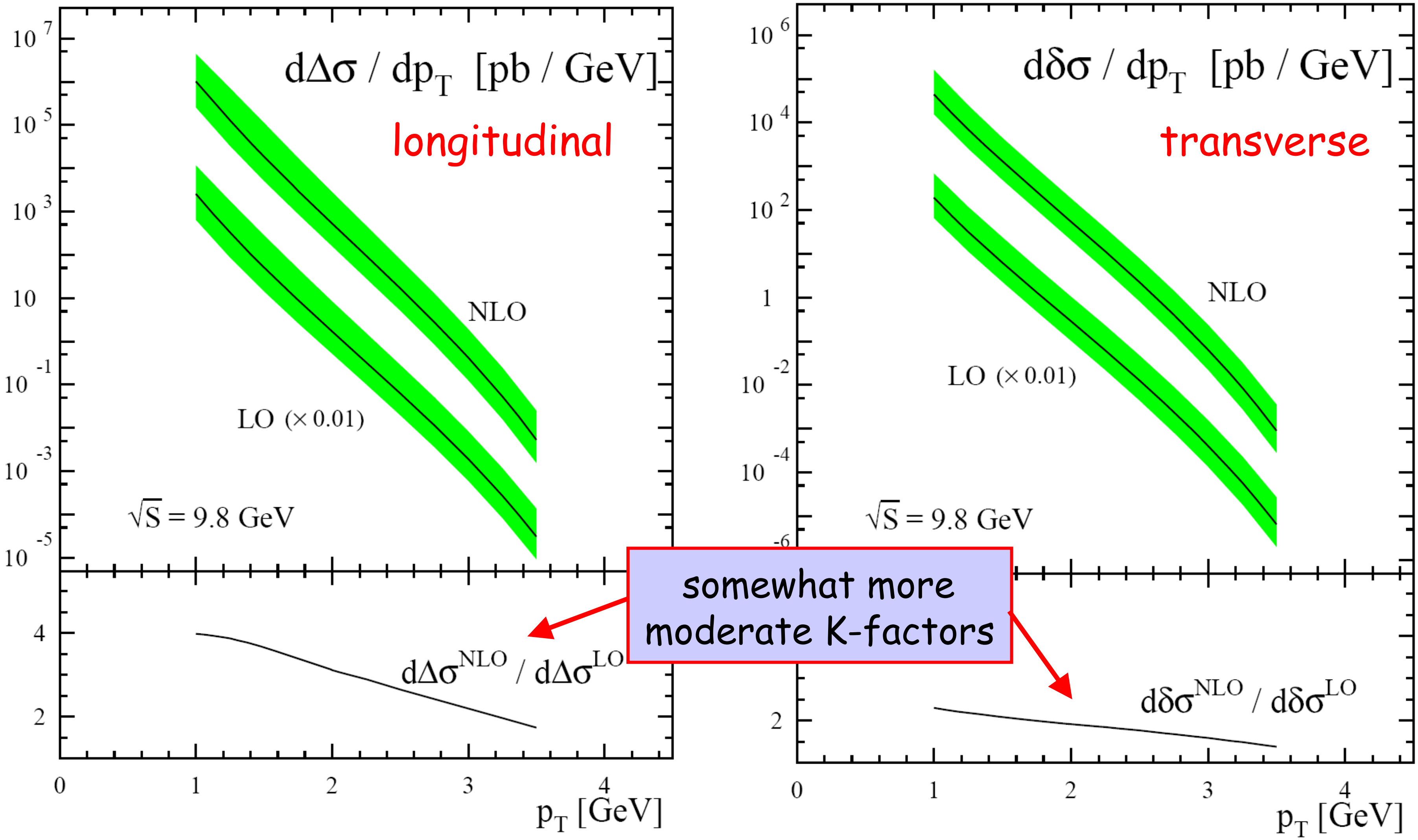


no improvement in scale uncertainty

scales used: $p_T \div 4p_T$

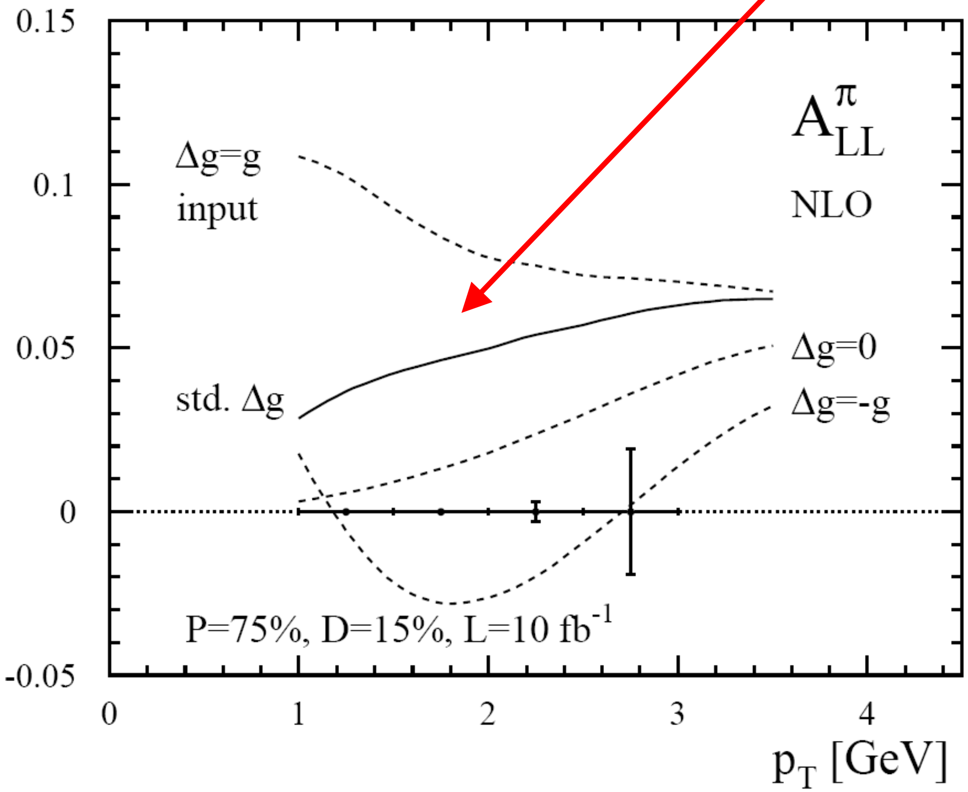
significant NLO corrections

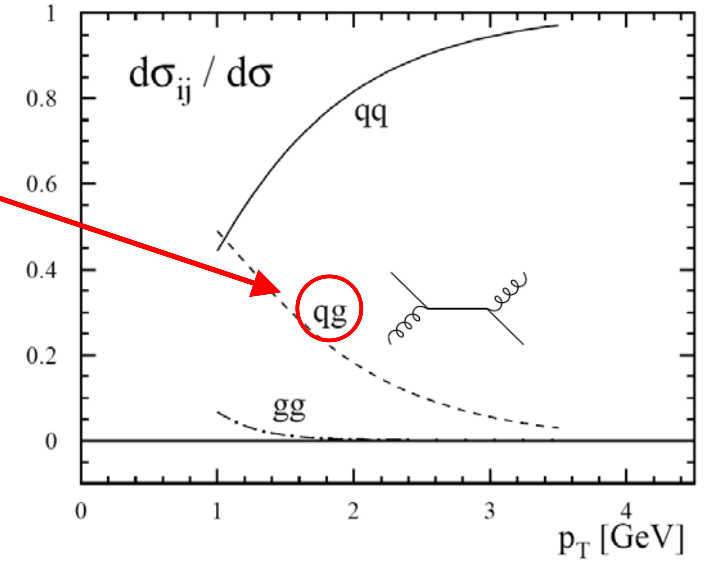
single-inclusive pion production (long./trans. pol.)

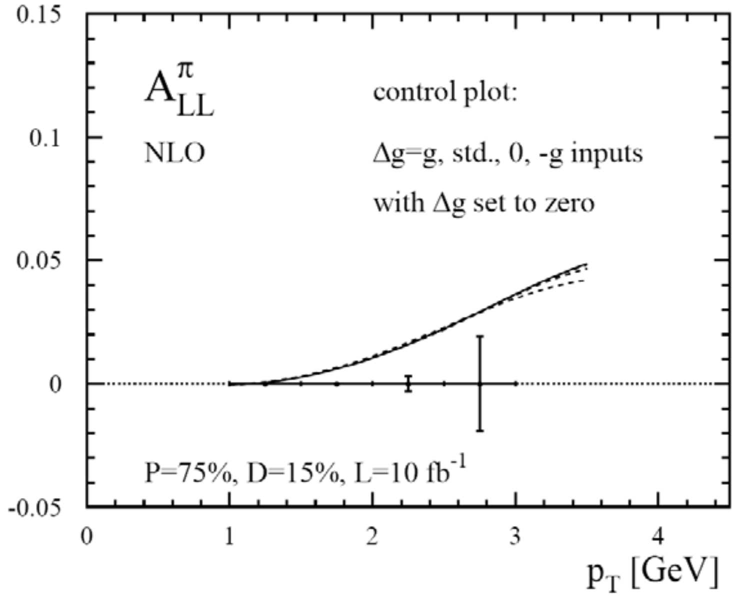


single-inclusive pion production (A$_{LL}$ & subproc.)

sensitivity to Δg through qg-scattering

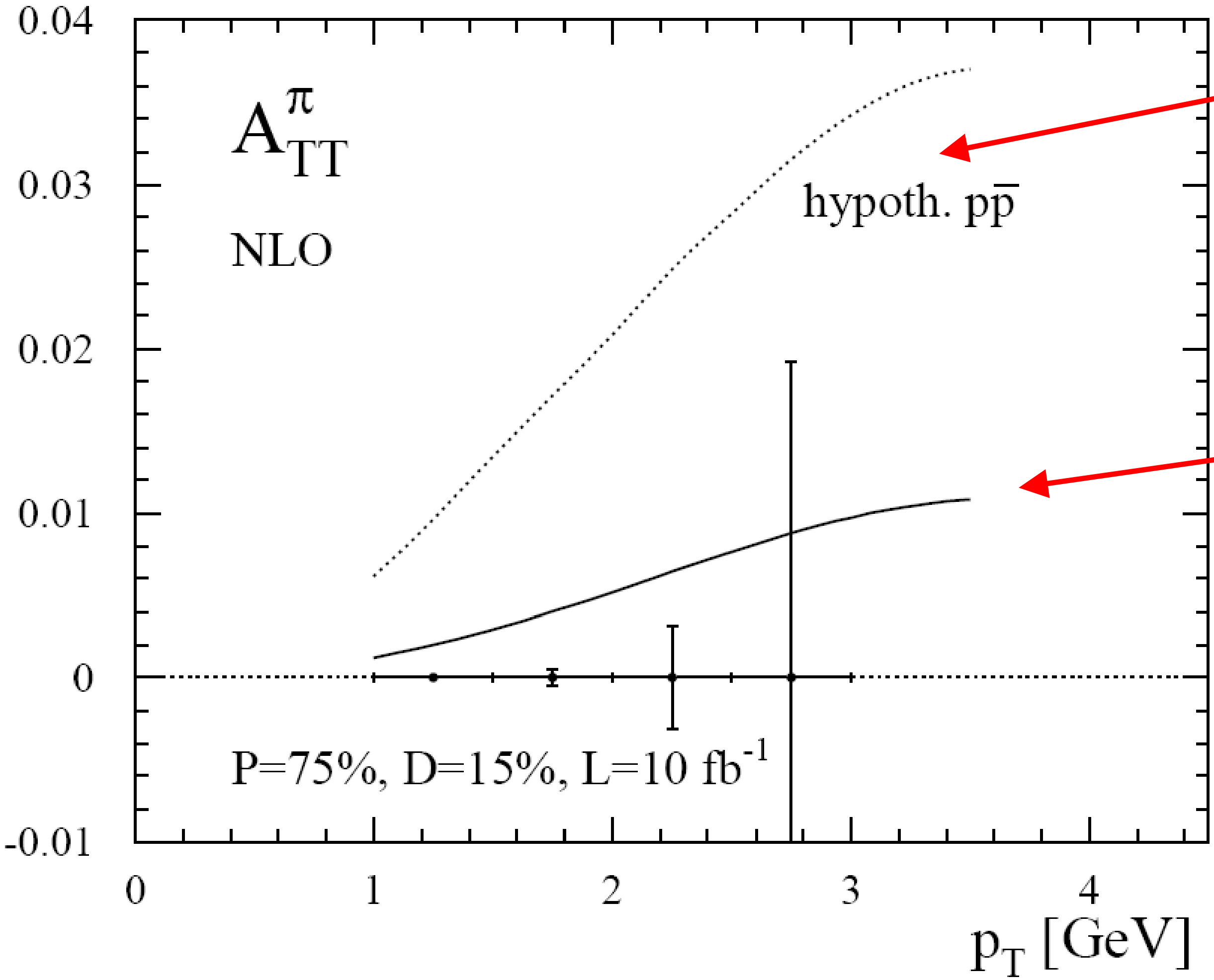






large x probed! 0.2 0.4 0.6 $\frac{2p_T}{\sqrt{S}}$

single-inclusive pion production (A_{TT})



$q\bar{q} \longrightarrow \gamma g$ dominant

$\Rightarrow p\bar{p} \gg pp$

upper bound for A_{TT}

"Soffer inequality"

$$2|\delta q| \leq q + \Delta q$$

saturated Soffer; Sivers

as expected:

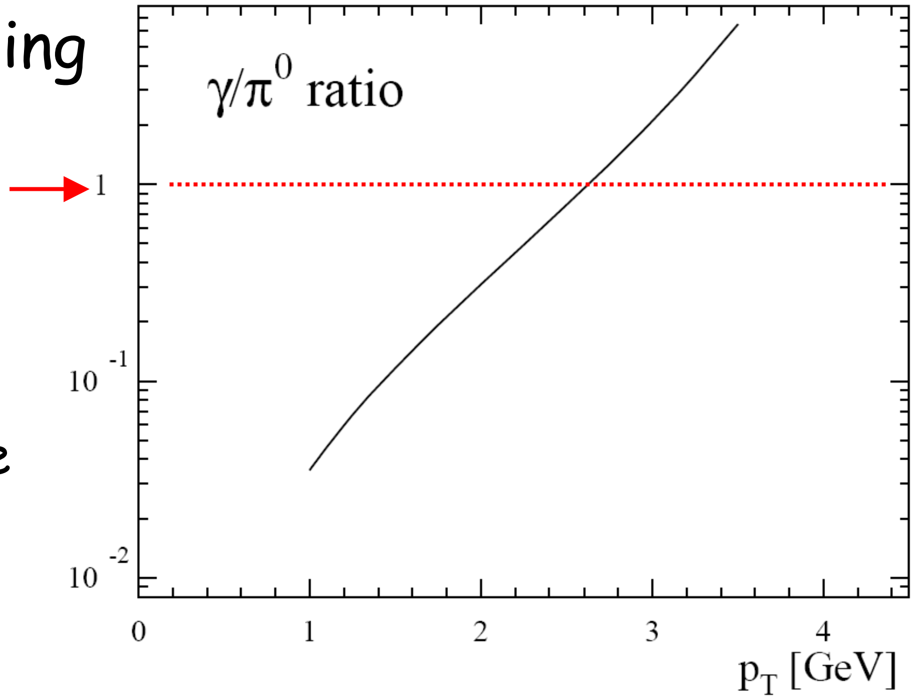
$A_{TT} < A_{LL}$

(lack of gluons)

Jaffe, Saito

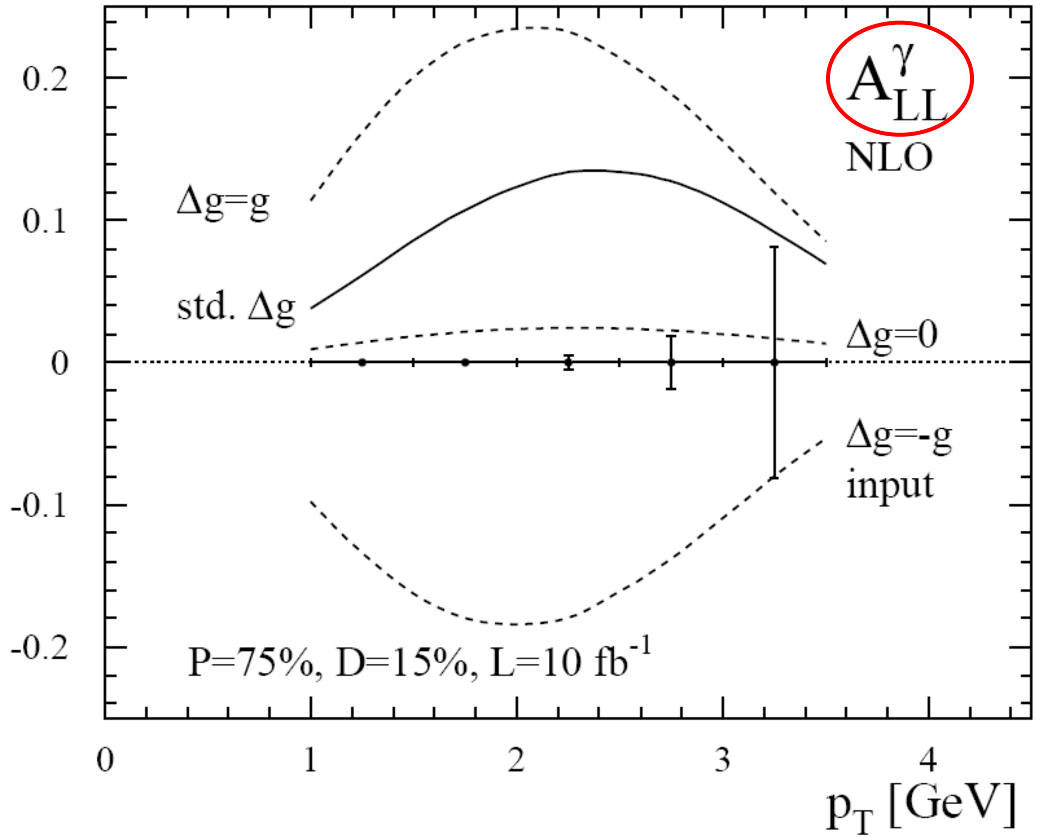
prompt photon production

- the scale dependence and K-factors are equally good/bad as for inclusive pion production (→ focus on A_{LL} & A_{TT})
- we adopt the isolation criterion of Frixione (no fragmentation contr.; R=0.4, ε=1)
- γ/π^0 ratio could be interesting to look at



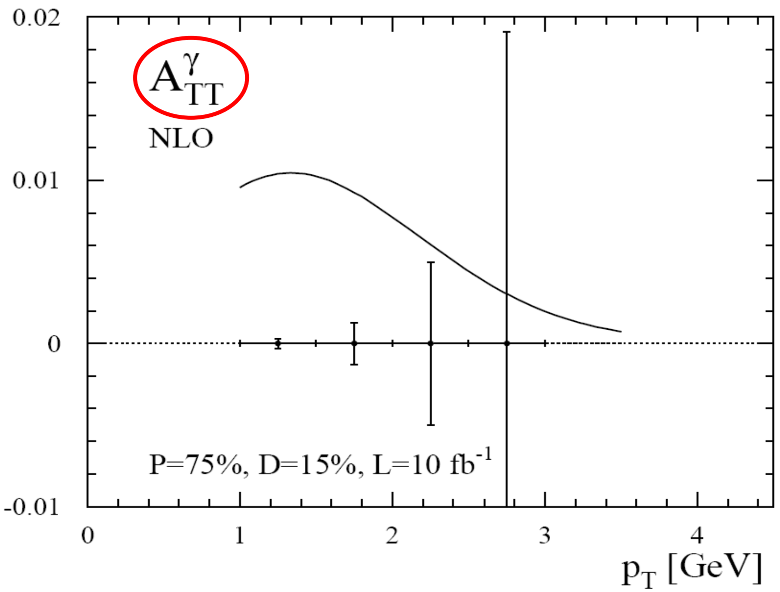
at RHIC we observe a strong rise but γ/π^0 is still less than one

prompt photon production (A_{LL} & A_{TT})



A_{LL}: well-known sensitivity to Δg through $qg \to \gamma q$

A_{TT}: again, this is an *upper* bound



independent of the polarization and the process we observe

- ✘ a large residual scale dependence also in NLO
- ✘ very sizable NLO corrections
- ✓ excellent propects to constrain pdfs at large x

we should work harder to decide whether pQCD is at work or not

IV. Theoretical framework (ii)

resummations

resummations: general idea

fixed order pQCD has many successes but also failures

key question: why problems in fixed-target regime and why near perfect at colliders ??

at partonic threshold:

$$\hat{x}_T = \frac{2p_T}{\sqrt{\hat{s}}} \to 1$$

- just enough energy to produce high-p_T parton
- "inhibited" gluon radiation

→ IR cancellation leaves large logarithms from soft gluons

as $\alpha_s^k \ln^{2k}(1-\hat{x}_T^2)$ at the k[th] order:

$$p_T^3 \frac{d\hat{\sigma}_{ab}}{dp_T} = p_T^3 \frac{d\hat{\sigma}_{ab}^{\text{Born}}}{dp_T} \Big[1 + \underbrace{\mathcal{A}_1\, \alpha_s \ln^2\left(1-\hat{x}_T^2\right) + \mathcal{B}_1\, \alpha_s \ln\left(1-\hat{x}_T^2\right)}_{\text{NLO}}$$

$$+ \ldots + \mathcal{A}_k\, \alpha_s^k \ln^{2k}\left(1-\hat{x}_T^2\right) + \ldots \Big] + \ldots$$

resummations: general idea

resummation of these dominant contributions to the pert. series to all order has reached a high level of sophistication

Sterman; Catani, Trentadue; Laenen, Oderda, Sterman; Catani et al.; Sterman, Vogelsang; Kidonakis, Owens; ...

- worked out for most processes of interest at least to NLL
- well defined class of higher-order corrections
- often of much phenomenological relevance

resummation (=exponentiation !!) occurs when Mellin moments are taken:

$$\alpha_s^k \ln^{2k}(1-\hat{x}_T^2) \rightarrow \alpha_s^k \ln^{2k}(N)$$

$$\Rightarrow \quad \hat{\sigma}(N) \overset{L\equiv\ln(N)}{\propto} \exp\left[\sum_{k=1}^{\infty} \alpha_s^k L^k (a_k L + b_k) + \mathcal{O}(\alpha_s^{k+1} L^k)\right]$$

leading log (LL) $\alpha_s^k L^{2k}$ after expansion

resummations: general structure

(slide from a talk by W. Vogelsang)

Fixed order →

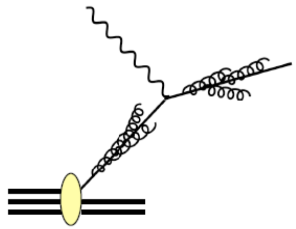
Resummation ↓

	LL	NLL	NNLL		
LO	1				
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s		$+\ldots$
NNLO	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	$+\ldots$
	$\alpha_s^3 L^6$	$\alpha_s^3 L^5$	$\alpha_s^3 L^4$	$\alpha_s^3 L^3$	$+\ldots$
	$\alpha_s^4 L^8$	$\alpha_s^4 L^7$	$\alpha_s^4 L^6$	$\alpha_s^4 L^5$	$+\ldots$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	
$N^k LO$	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$	$\alpha_s^k L^{2k-2}$	$\alpha_s^k L^{2k-3}$	$+\ldots$

resummations: some LL exponents

unobserved parton Sudakov "suppression"

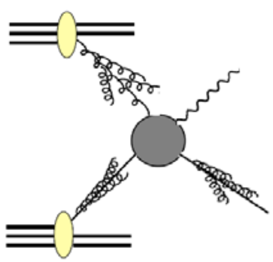
DIS



$$\exp\left[\frac{C_F\,\alpha_s}{\pi}\ln^2(N) - \frac{C_F\,\alpha_s}{\pi}\,\frac{1}{2}\ln^2(N)\right]$$

moderate enhancement

prompt photons

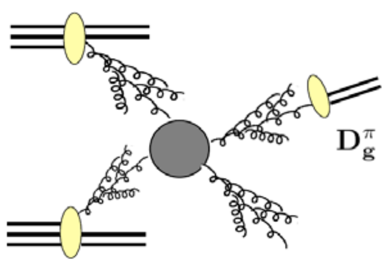


$q\bar{q}\to\gamma g$ $$\exp\left[\left(C_F + C_F - \frac{1}{2}C_A\right)\frac{\alpha_s}{\pi}\ln^2(N)\right]$$

$qg\to\gamma q$ $$\exp\left[\left(C_F + C_A - \frac{1}{2}C_F\right)\frac{\alpha_s}{\pi}\ln^2(N)\right]$$

exponents positive → enhancement

inclusive hadrons



e.g.

observed partons / unobserved

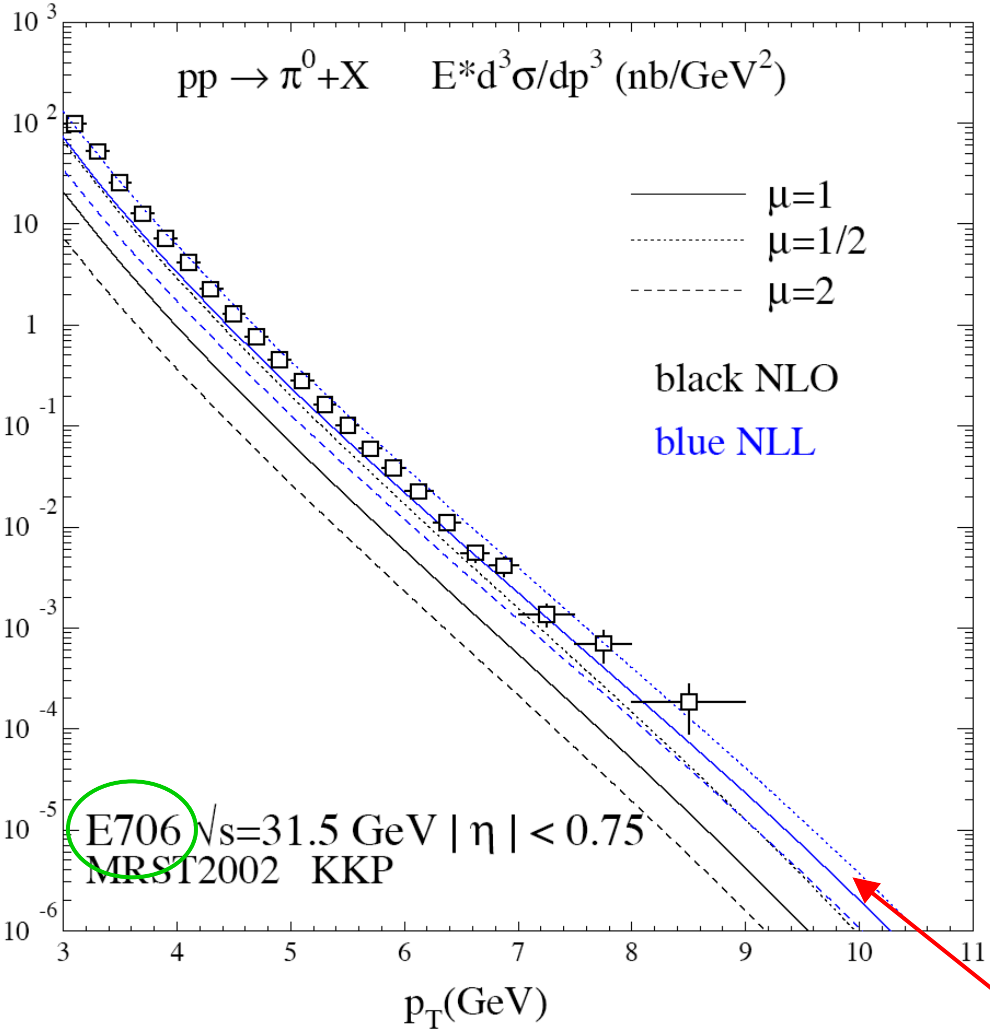
$gg\to gg$ $$\exp\left[\left(C_A + C_A + C_A - \frac{1}{2}C_A\right)\frac{\alpha_s}{\pi}\ln^2(N)\right]$$

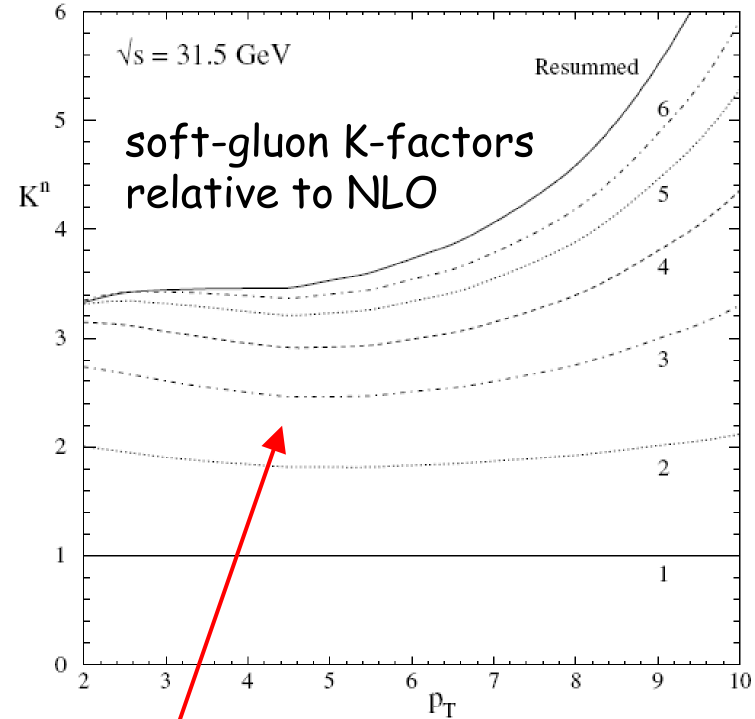
expect much larger enhancement

resummations: phenomenology

$pp \rightarrow \pi^0 X$

de Florian, Vogelsang





- very large enhancement in NLL
- good agreement with data now
- much reduced scale dependence

resummations: J-PARC (to-do list)

resummations seem to be mandatory at fixed-target energies

- ✓ technical framework available
- ✓ well-defined & systematic improvement of pQCD results
- ✓ much reduced uncertainties

bonus: resummations may provide information about power corrections through their sensitivity to strong-coupling regime Sterman, Vogelsang; ...

studies of power corrections/k_T effects prior to resummations do not make very much sense

work in progress: quantitative studies at J-PARC energies; expect:

- significant effects on cross sections
- partial cancellation of soft-gluon effects in A_{LL}
  in particular for prompt photons (simple color structure)
- reduction for A_{TT} (lack of gluons in $d\delta\sigma$)

V. Concluding remarks

scientific opportunities @ J-PARC

scientific opportunities @ J-PARC

two scenarios for hard scattering conceivable: