QCD hard scattering at J-PARC

Marco Stratmann

RIKEN

Outline

- **motivation**
- **theor. framework I:** pQCD & hard scattering
- **expectations**: pion and photon production @ J-PARC
- **theor. framework II**: resummations
  example: Drell-Yan process

I. motivation

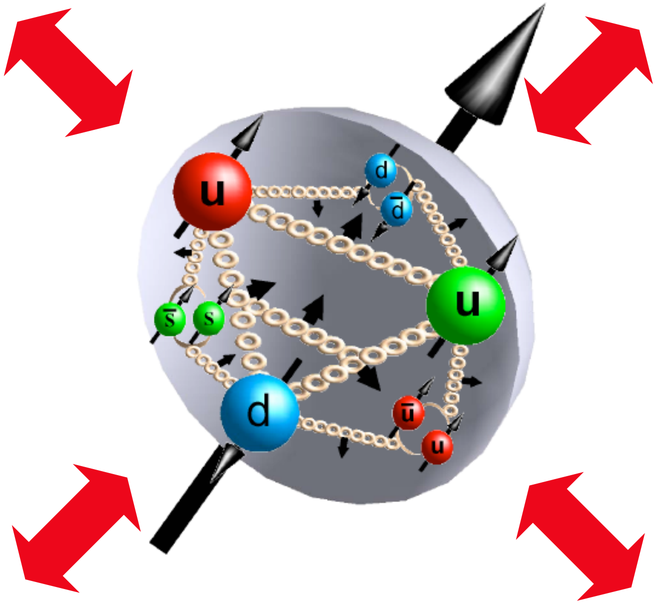
the large x frontier

exploring the limits of pQCD

exploring the nucleon is of fundamental importance

explore and understand QCD:
dynamics, models,
lattice methods

tool for discovery:
RHIC "new state of matter"
LHC Higgs, "new physics"



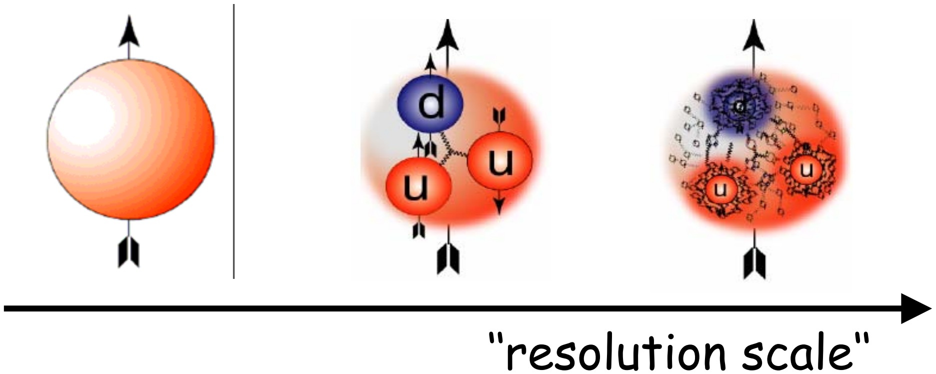
test our ability to use QCD:
asymptotic freedom,
factorization theorems,
phenomenological inputs,
all-order resummations

know what we are made of:
origin of mass,
visible mass of the universe

compelling reasons for hadronic physics @ J-PARC

a great place to test and learn about QCD:

- models for parton densities
- theor. prejudices about $x \to 1$ ("counting rules")
- exploring the limits of perturbative QCD methods
- probing the transition from partonic to hadronic d.o.f.

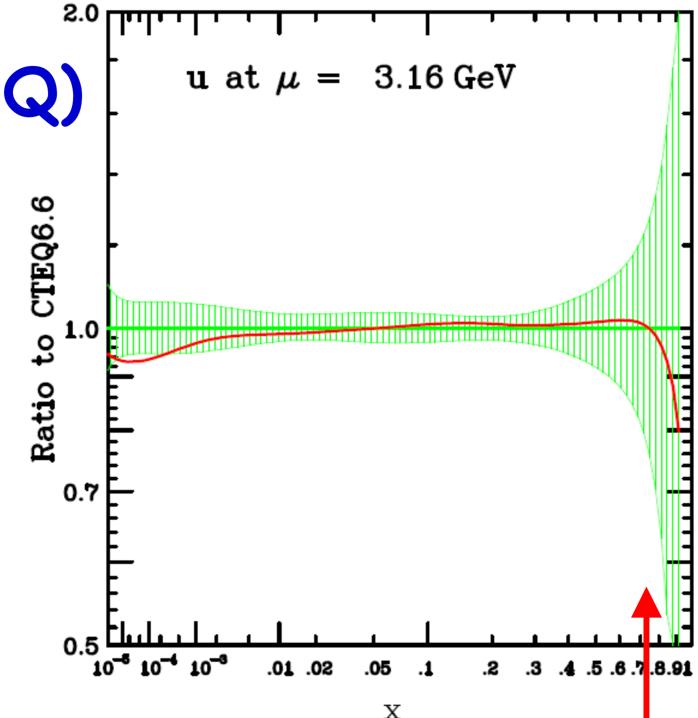


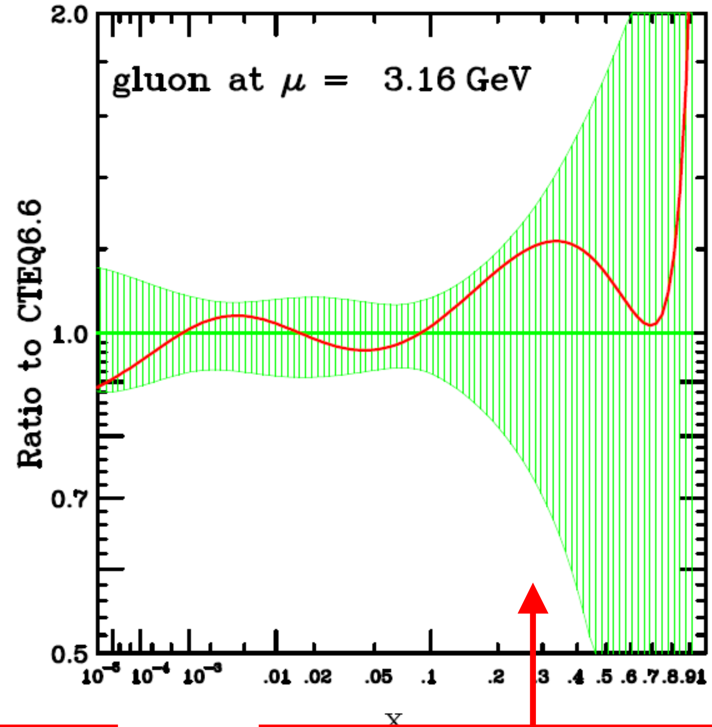
"counting rules": do they count?

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

latest global analysis results from CTEQ arXiv:0802.0007 [hep-ph] :

u(x,Q)





g(x,Q)

significant uncertainties for $x \gtrsim 0.75$

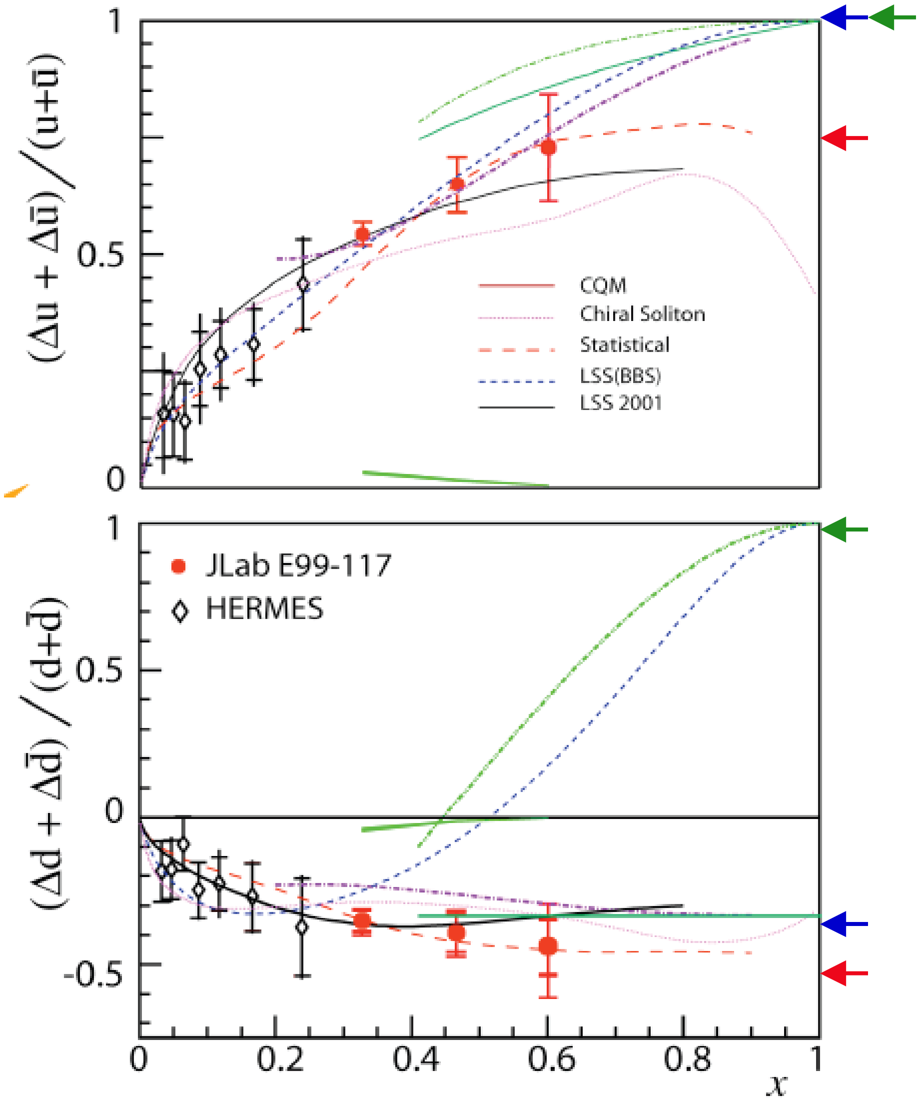
significant uncertainties for $x \gtrsim 0.3$

✓ best fits favor $u(x,Q) \sim (1-x)^{3\div4}$

$g(x,Q) \sim (1-x)^{0.8\div3.6}$?

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

much less is known for helicity-dependent pdfs:



model	$\Delta u/u$	$\Delta d/d$
helicity retention	1	1
stat. parton model	0.75	-0.5
rel. const. quark model	1	-1/3

Farrar, Jackson; Brodsky, Schmidt; Brodsky, Burkardt, Schmidt; Avakian et al.

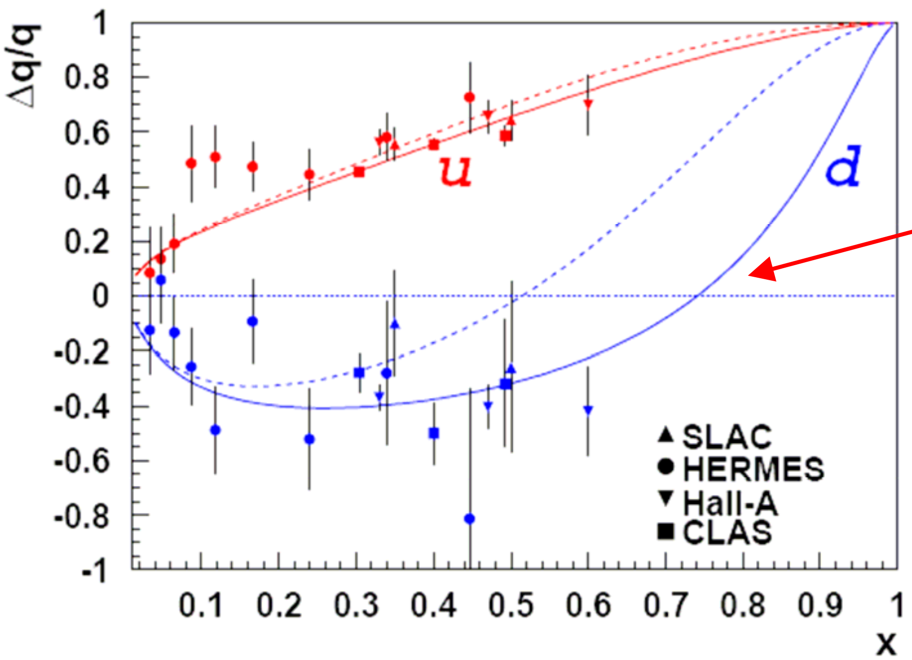
Bourrely, Buccella, Soffer

Isgur, Thomas, Close

conclusions so far: ?

$\Delta d/d \to 1$ a long shot ...

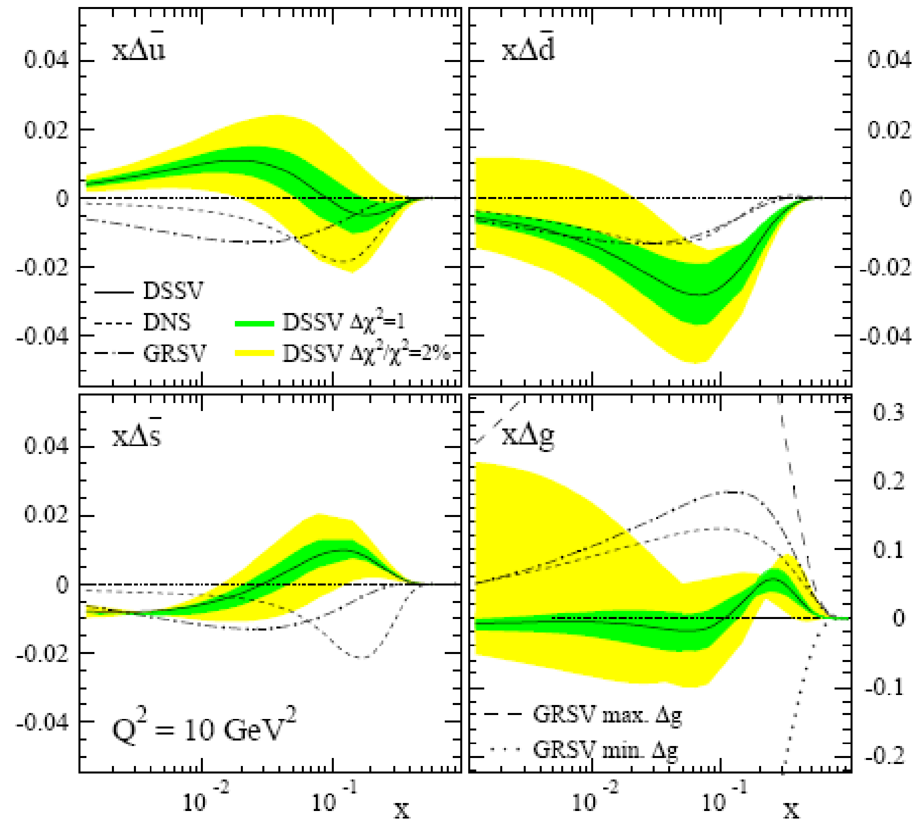
recent developments



non-zero OAM can delay

$\Delta d/d \rightarrow 1$ to $x \simeq 0.75$

Avakian et al., arXiv:0705.1553



1st global analysis: evidence for flavor-**asymmetric** pol. quark-sea

awaits further exp. confirmation

de Florian, Sassot, MS, Vogelsang
arXiv:0804.0422 [hep-ph]

II. theoretical framework (part I)

pQCD & hard scattering

QCD is the theory of strong interactions
– how can we make use of perturbative methods?

confinement

non-perturbative
hadronic structure

e.g. Lattice QCD

asymptotic freedom

Gross, Wilczek; Politzer 

hard scattering
cross sections

perturbative methods

interplay

goal: probe hadronic structure with
weakly interacting quanta of asymptotic freedom

key: **factorization**

perturbative QCD can be used to make *quantitative predictions*

if $\alpha_s(p_T) \ll 1$ (exploiting asymptotic freedom of QCD) Gross, Wilczek; Politzer

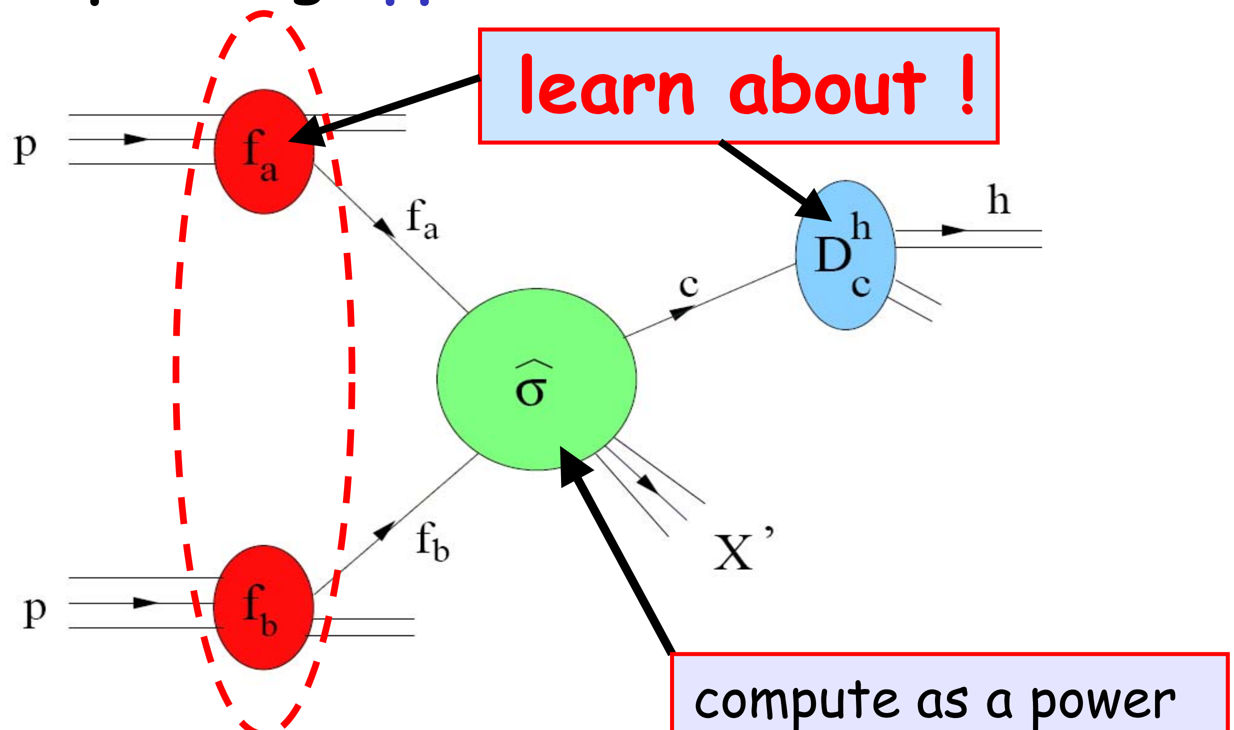
key tool: factorization theorem & universality

Libby, Sterman; Ellis et al.; Amati et al.; Collins et al.; ...

the strategy is simple, e.g. $pp \to \pi X$:

measure

$d\sigma \simeq$



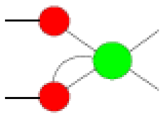
… but the details are not:

long-distance physics
μ–dep. predicted by pQCD

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

short-distance physics
calculable in pQCD as series in α_s

power corrections
usually safely neglected



- factorization requires introduction of **unphysical scales** $\mu_{f,r}$
- pQCD valid only if p_T is “large enough” (α_s small) – but where precisely?
- information on spin/nucleon structure & hadronization is hidden inside complicated convolutions → global analyses

scale dependence inherent to any 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

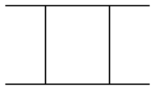
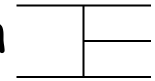
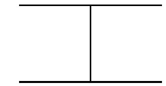
- if we truncate the series after the first N terms, there will be a residual scale dependence of order N+1 → **theoretical error**

- 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

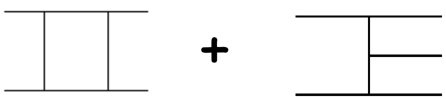
anatomy of a NLO calculation

- need loop  and real emission  corrections to LO  diagrams

- encounter singularities

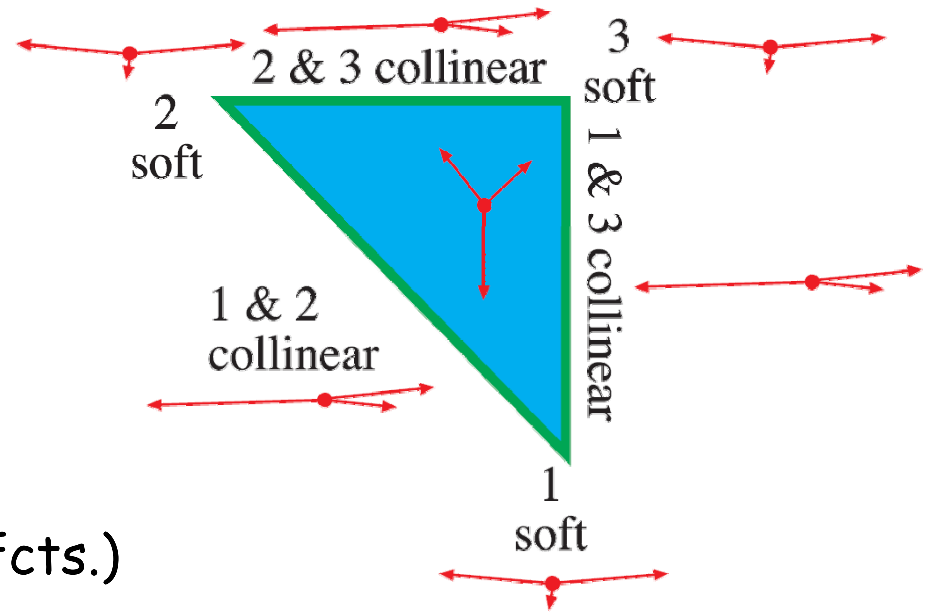
  $\rightarrow$ dimensional regularization, …

  soft: cancel in sum

  collinear: absorb into def.
  of phenomenological inputs
  (parton densities & fragmentation fcts.)

sing. config. of a three parton final-state



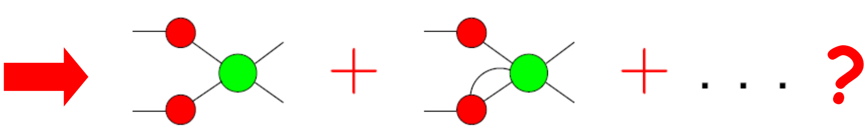
a meaningful observable is insensitive to these long-dist. effects
"infrared – safety"

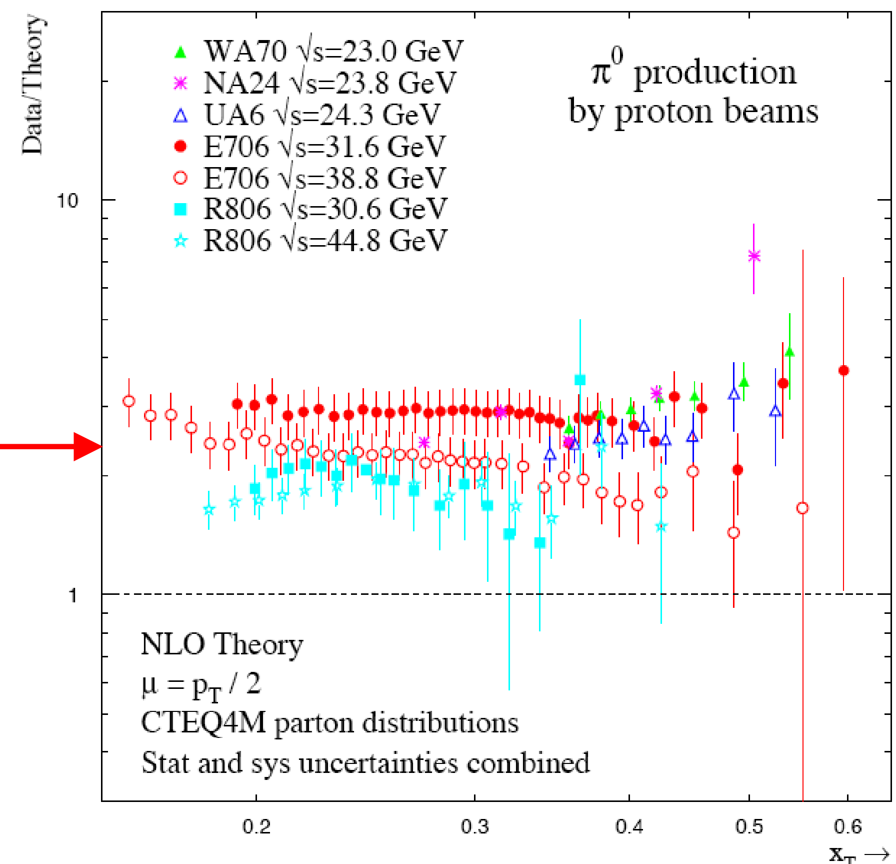
potential problems at fixed-target energies

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: $p_T^{\text{max}} = \sqrt{S}/[2\cosh(\eta)]$ 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

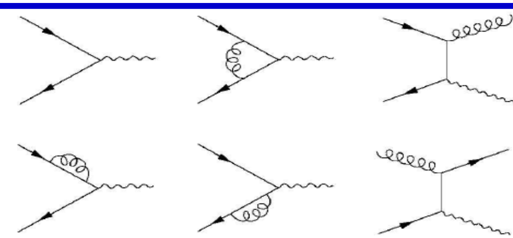
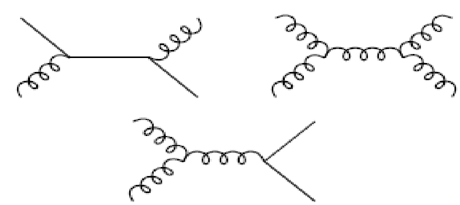
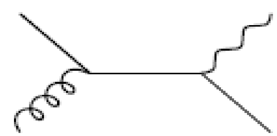
pion and photon production @ J-PARC

potential hard probes at J-PARC energies

Drell-Yan lepton pairs, inclusive pions or prompt photons, and charm

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

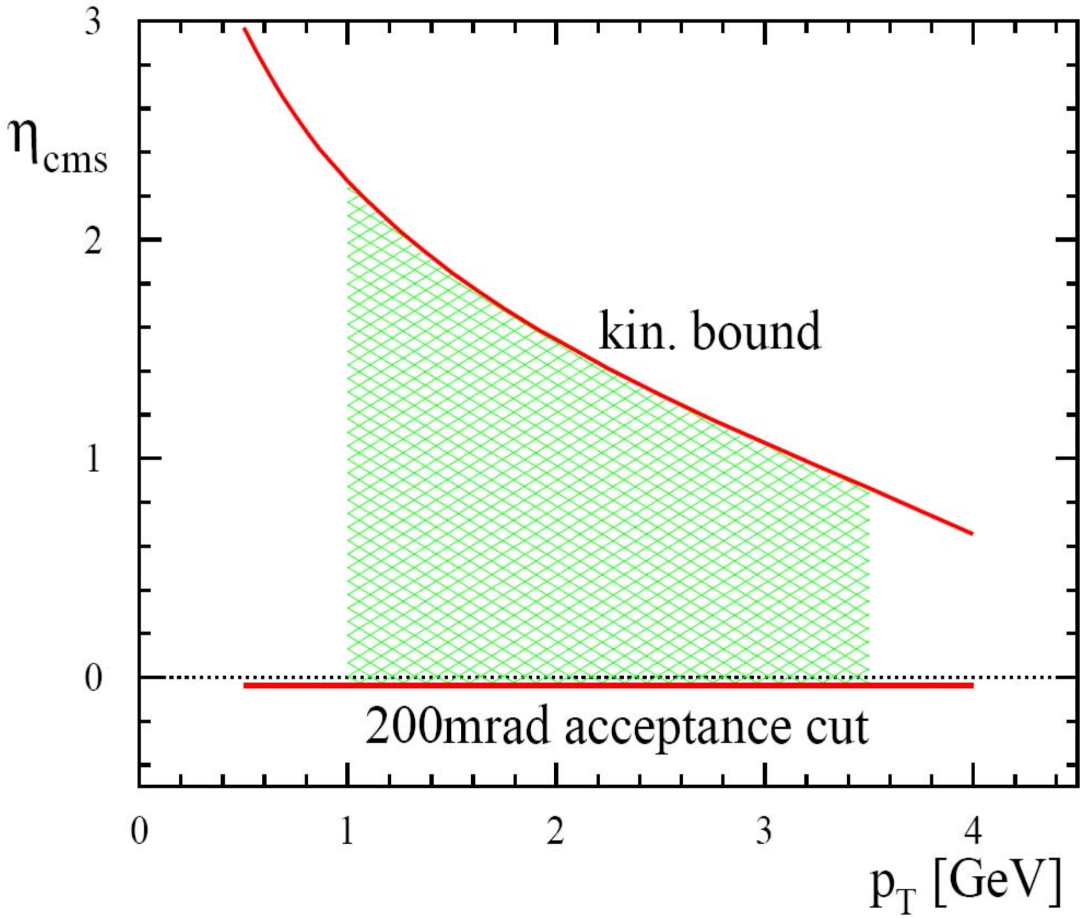
NLO QCD corrections to all reactions are known:

Drell-Yan		many papers (U,L,T) for J-PARC, see: Yokoya et al.; Kawamura et al.
pions		Aversa et al. (U); de Florian (U,L); Jäger et al. (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)

charm production will be discussed in my 2nd talk

input to all pQCD calculations

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



≈ COMPASS-like angular acceptance: 200mrad

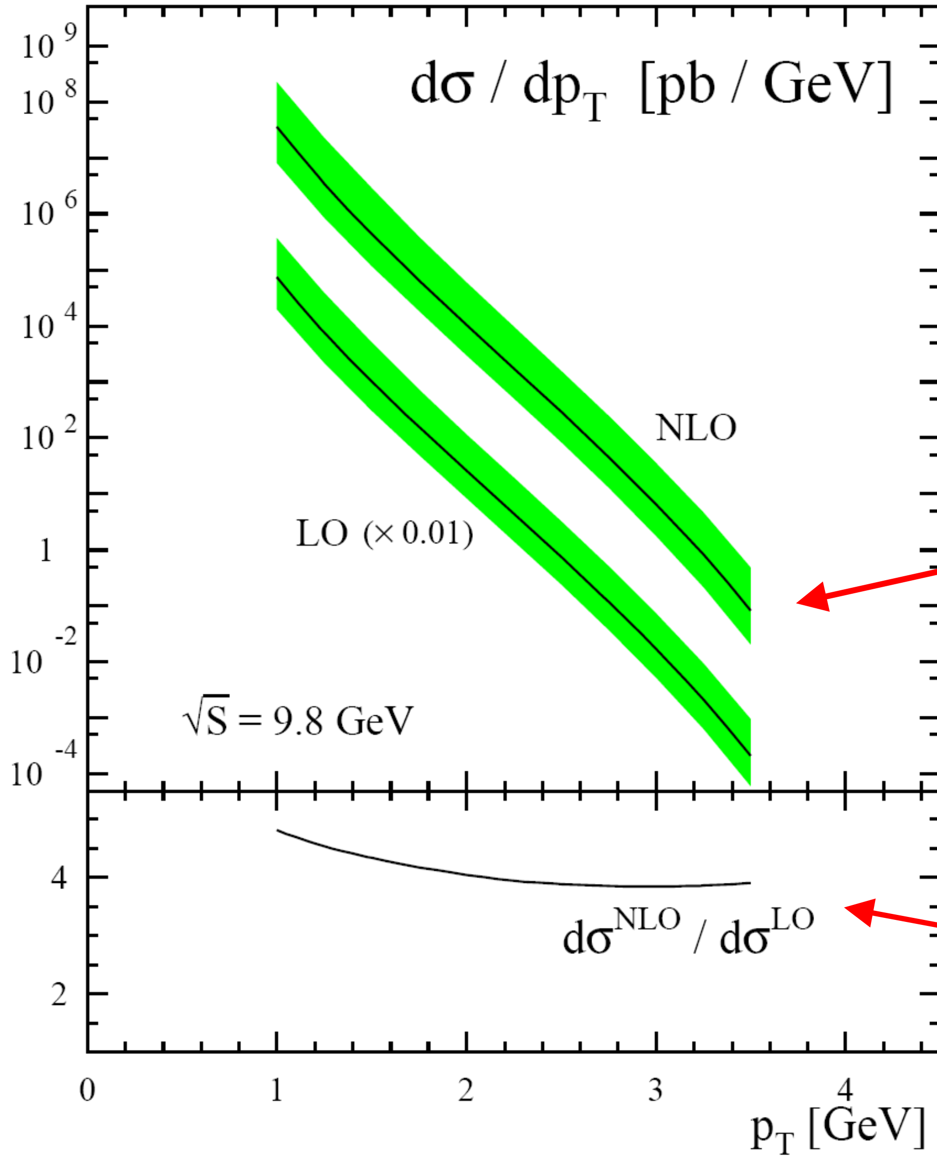
choice of pdfs:

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

choice of frag. fcts.:

- KKP

single-inclusive pion production (unpolarized)

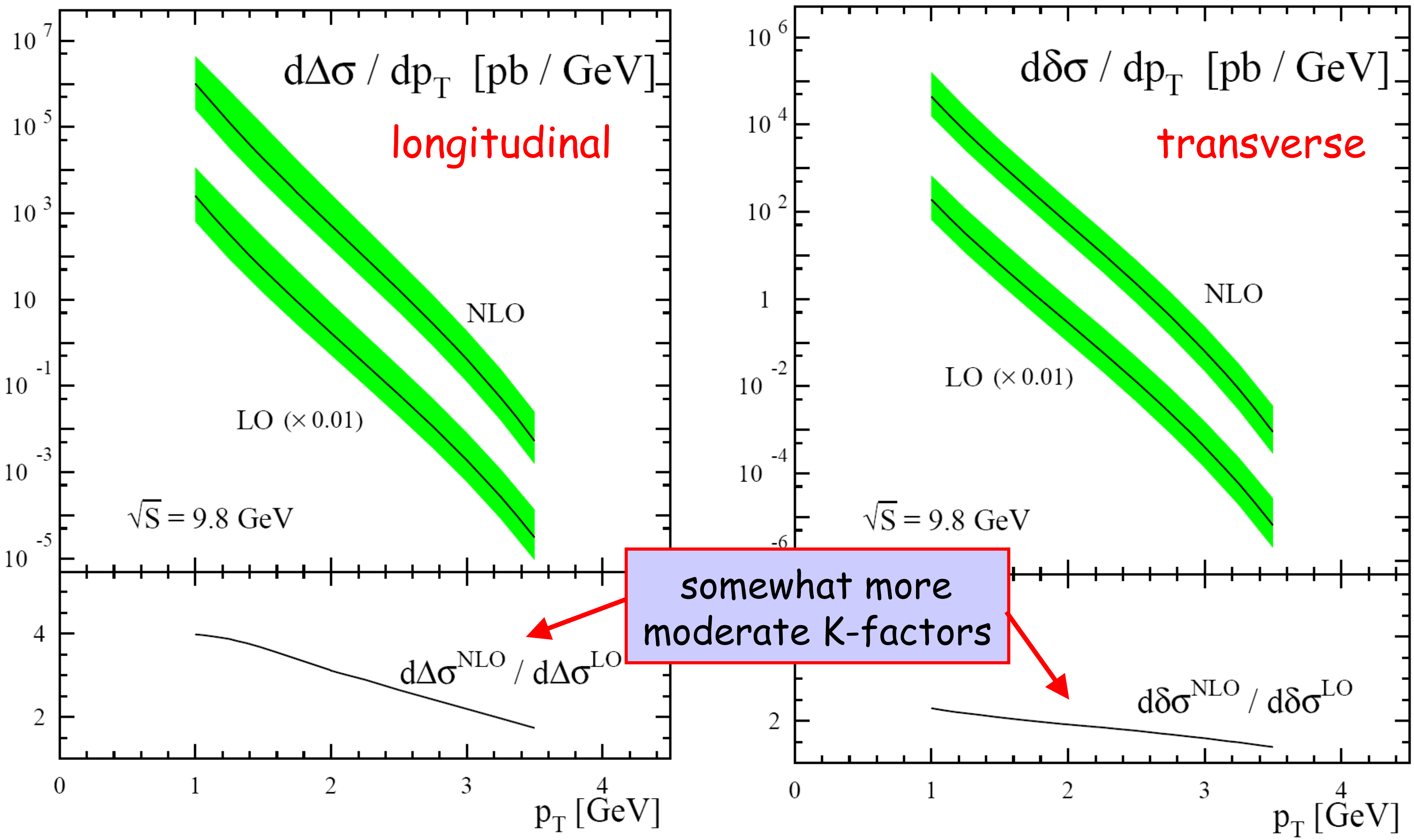


no improvement in scale uncertainty

scales used: $p_T \div 4p_T$

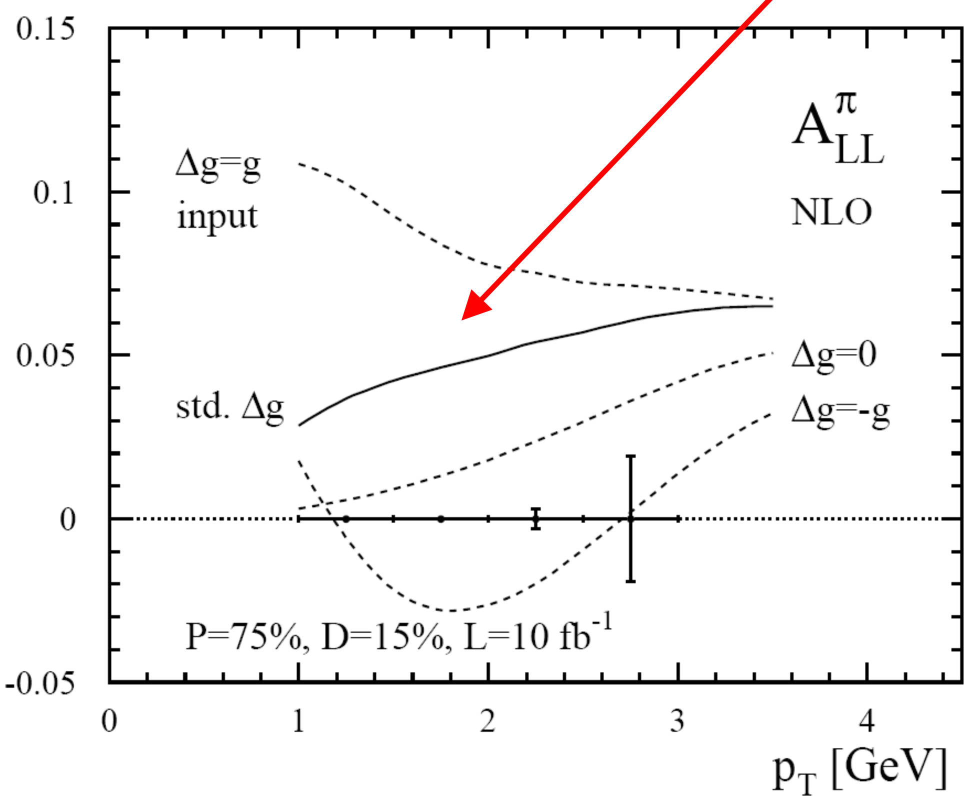
significant NLO corrections

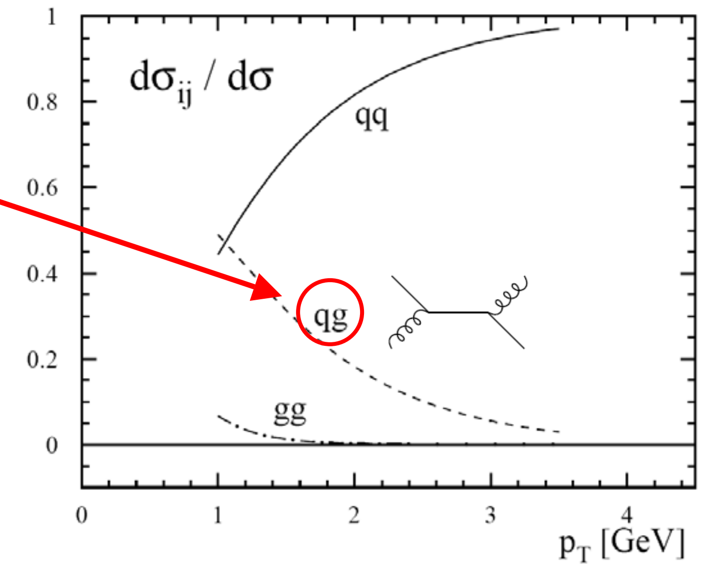
single-inclusive pion production (long./trans. pol.)

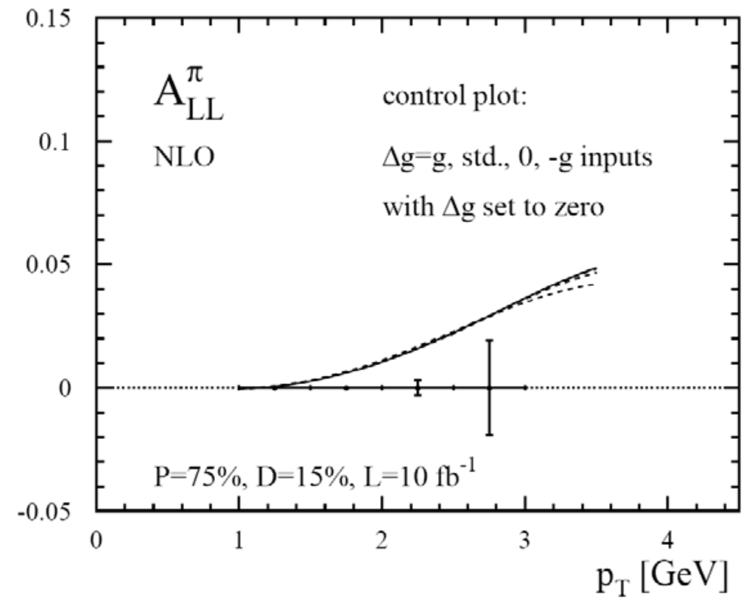


single-inclusive pion production (A_{LL} & subproc.)

sensitivity to Δg through qg-scattering

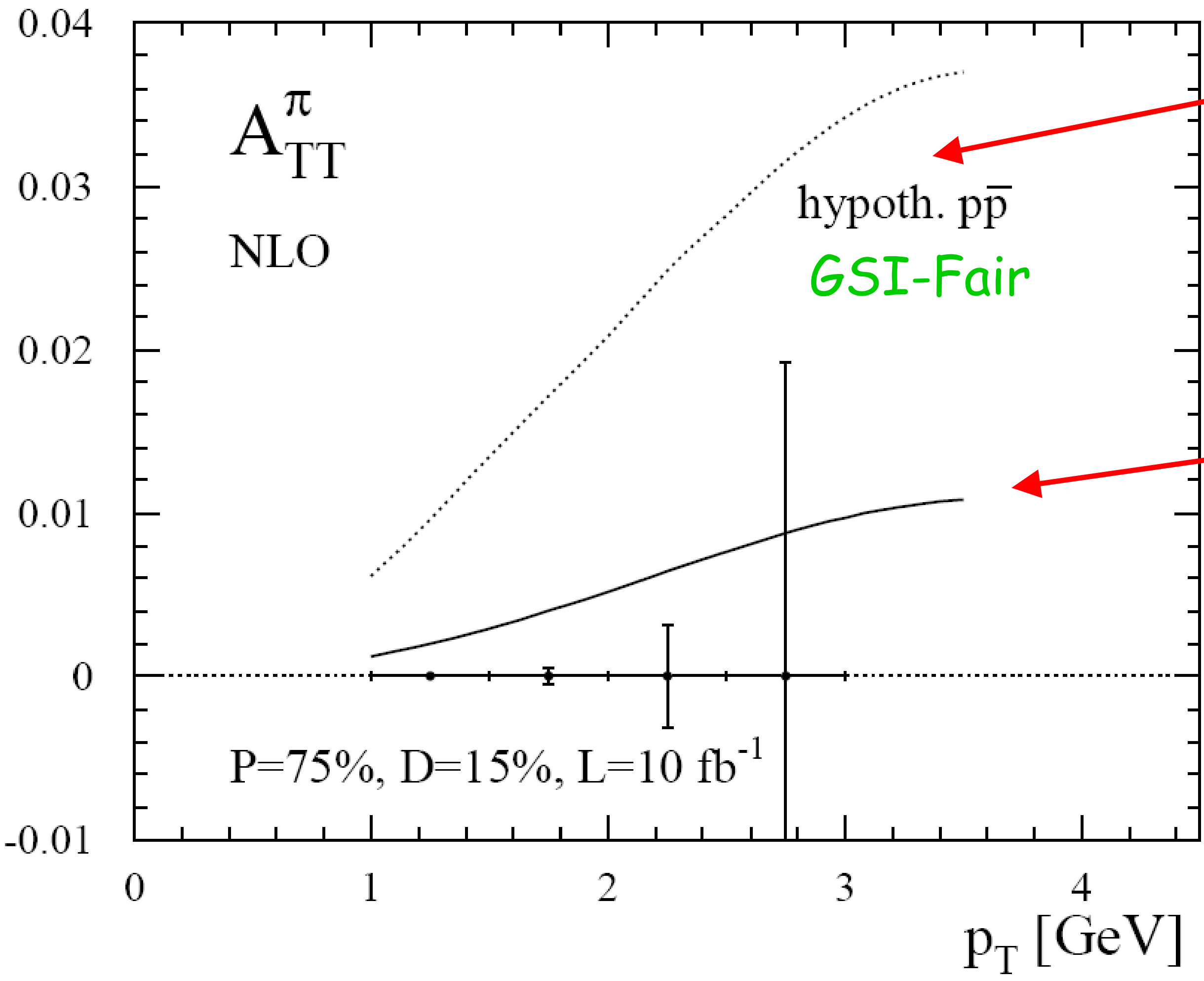






large x probed! → 0.2 0.4 0.6 $\frac{2p_T}{\sqrt{S}}$

single-inclusive pion production (A_{TT})



$q\bar{q}$ proc. dominant

→ $p\bar{p} \gg pp$

"valence-valence"

upper bound for A_{TT}

"Soffer inequality"

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

saturated Soffer; Sivers

as expected:

$A_{TT} < A_{LL}$

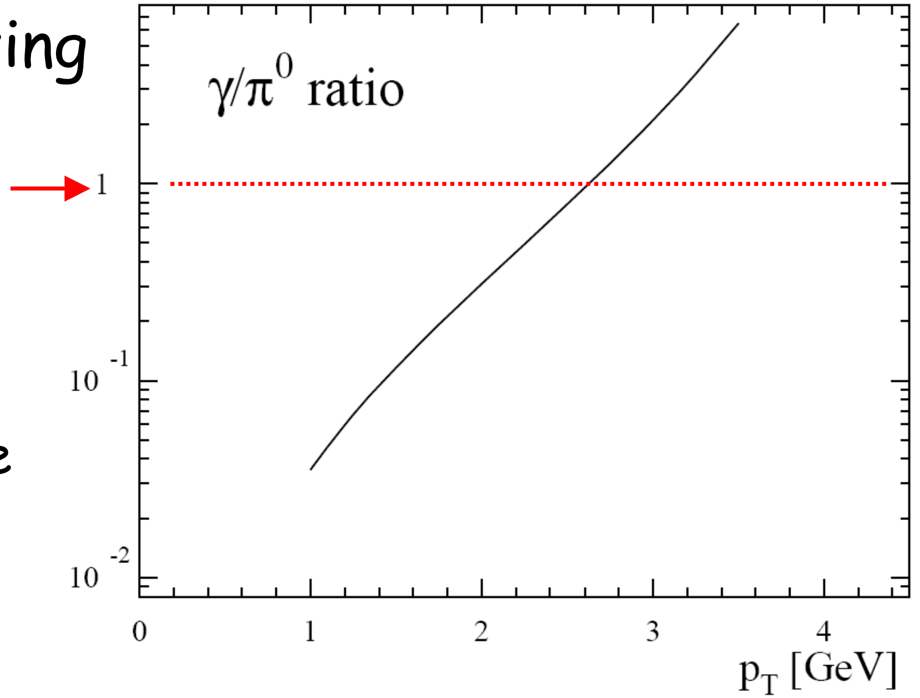
(lack of gluons)

Jaffe, Saito

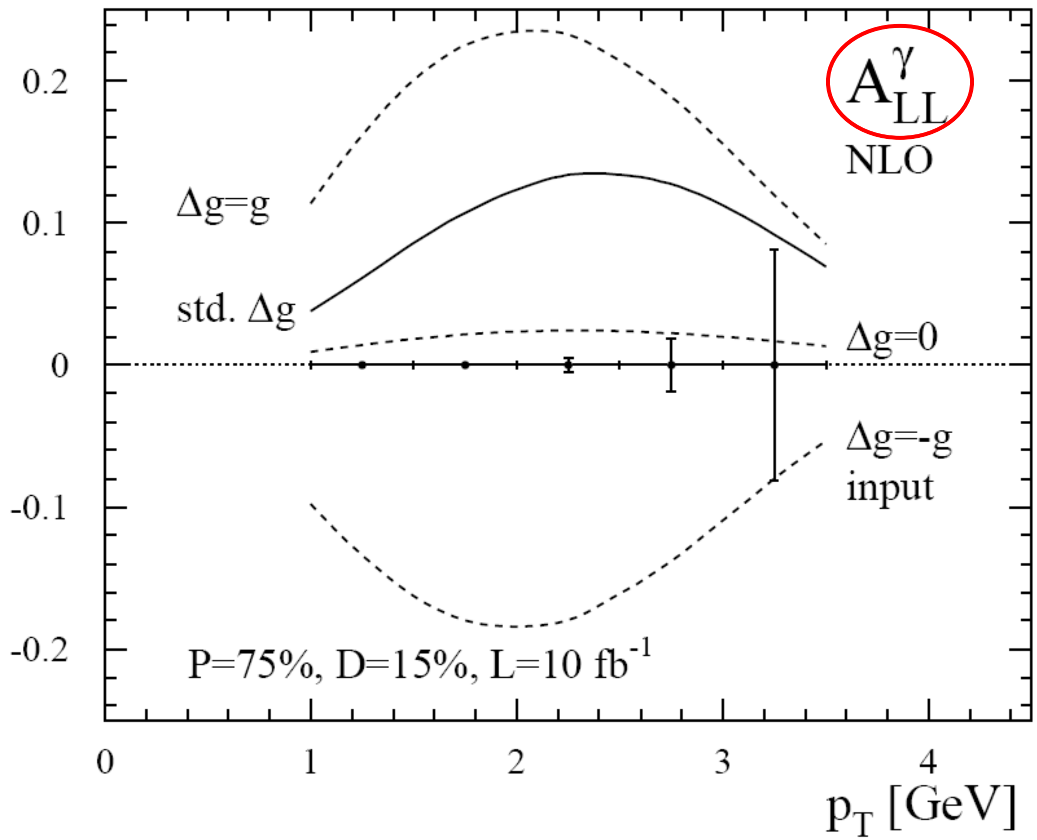
prompt photon production

- 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 contribution; 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

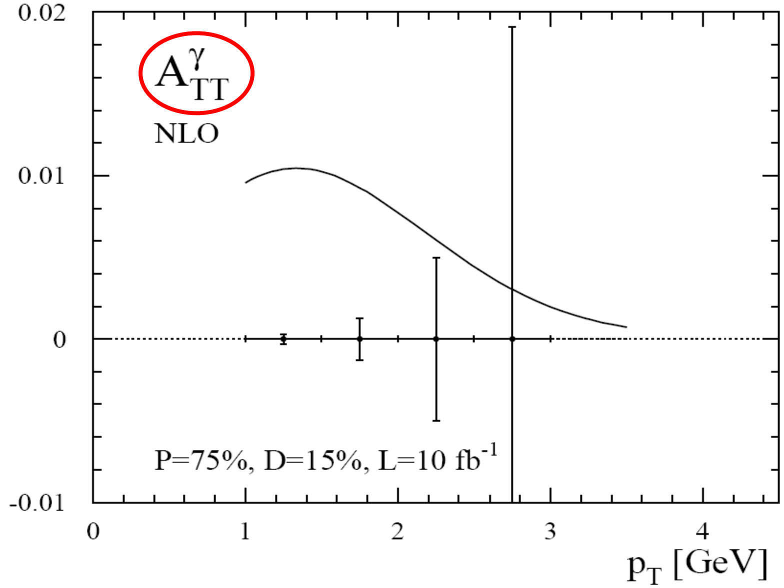


prompt photon production (A_{LL} & A_{TT})



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
- ✓ interesting prospects to constrain pdfs at large x

need to improve pQCD calculations beyond NLO

IV. theoretical framework (part II)

resummations

Drell-Yan process

resummations: why/where relevant

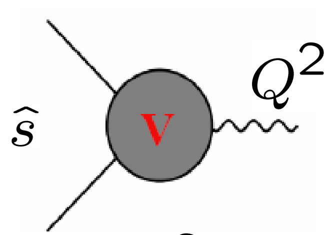
fixed order pQCD has many successes but also failures

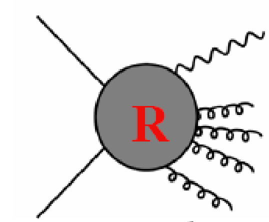
key question: why problems in fixed-target regime and why often near perfect at colliders ??

at partonic threshold / near exclusive boundary:

- just enough energy to produce, e.g., high-p_T parton
- "inhibited" radiation (general phenomenon for gauge theories)

simple example:
Drell-Yan process

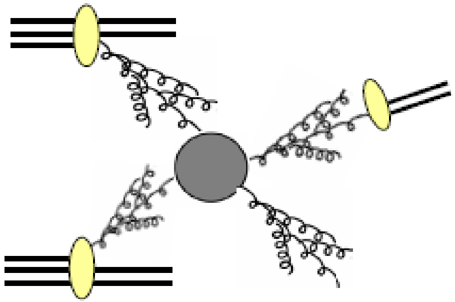




$$z \equiv \frac{Q^2}{\hat{s}} = 1 \qquad \propto \alpha_s^k \, \frac{\ln^{2k-1}(1-z)}{1-z}$$

"imbalance" of real and virtual contributions: IR cancellation leaves larges log's

for single-inclusive pp cross sections:



logarithms related to partonic threshold

$$\hat{\mathbf{x}}_{\mathbf{T}} = \frac{\mathbf{2p_T}}{\sqrt{\hat{\mathbf{s}}}} \rightarrow \mathbf{1}$$

general structure of partonic cross sections at the k[th] order:

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

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

"threshold logarithms"

where relevant? … convolution with steeply falling parton luminosity

$$d\sigma \propto \sum_{a,b} \int_{\tau}^{1} \frac{dz}{z} \mathcal{L}_{ab}\left(\frac{\tau}{z}\right) d\hat{\sigma}_{ab}(z)$$

z = 1 emphasized, in particular as $\tau \rightarrow 1$

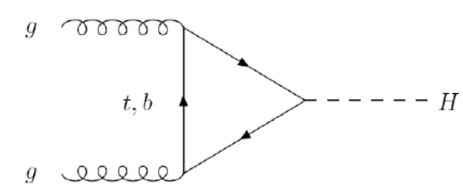
resummations: how it is done

$\alpha_s^k \ln^{2k}(1-\hat{x}_T^2)$ may spoil perturbative series - unless taken into account to all orders

resummation of such terms 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
  even for high mass particle production at the LHC



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

Mellin moments for threshold logs $\alpha_s^k \ln^{2k}(1-\hat{x}_T^2) \rightarrow \alpha_s^k \ln^{2k}(N)$

- fixed order calculations needed to determine "coefficients"
- the more orders are known, the more subleading logs can be resummed

resummations: general structure

(slide from a talk by W. Vogelsang)

Fixed order →

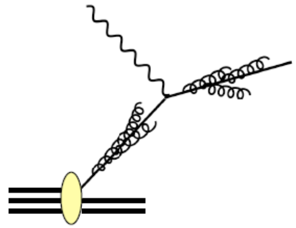
Resummation ↓

	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^kLO	$\alpha_s^k\, L^{2k}$	$\alpha_s^k\, L^{2k-1}$	$\alpha_s^k\, L^{2k-2}$	$\alpha_s^k\, L^{2k-3}$	$+\ \ldots$

resummations: some LL exponents

(assuming fixed α_s)

DIS

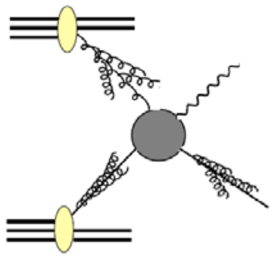


unobserved parton Sudakov "suppression"

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

moderate enhancement, unless x_{Bj} large

prompt photons

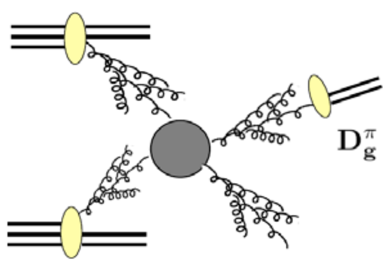


$q\bar{q} \to \gamma g$ $$\exp\left[\left(C_F + C_F - \frac{1}{2}C_A\right)\frac{\alpha_s}{\pi}\ln^2(N)\right]$$

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

exponents positive → enhancement

inclusive hadrons



e.g.

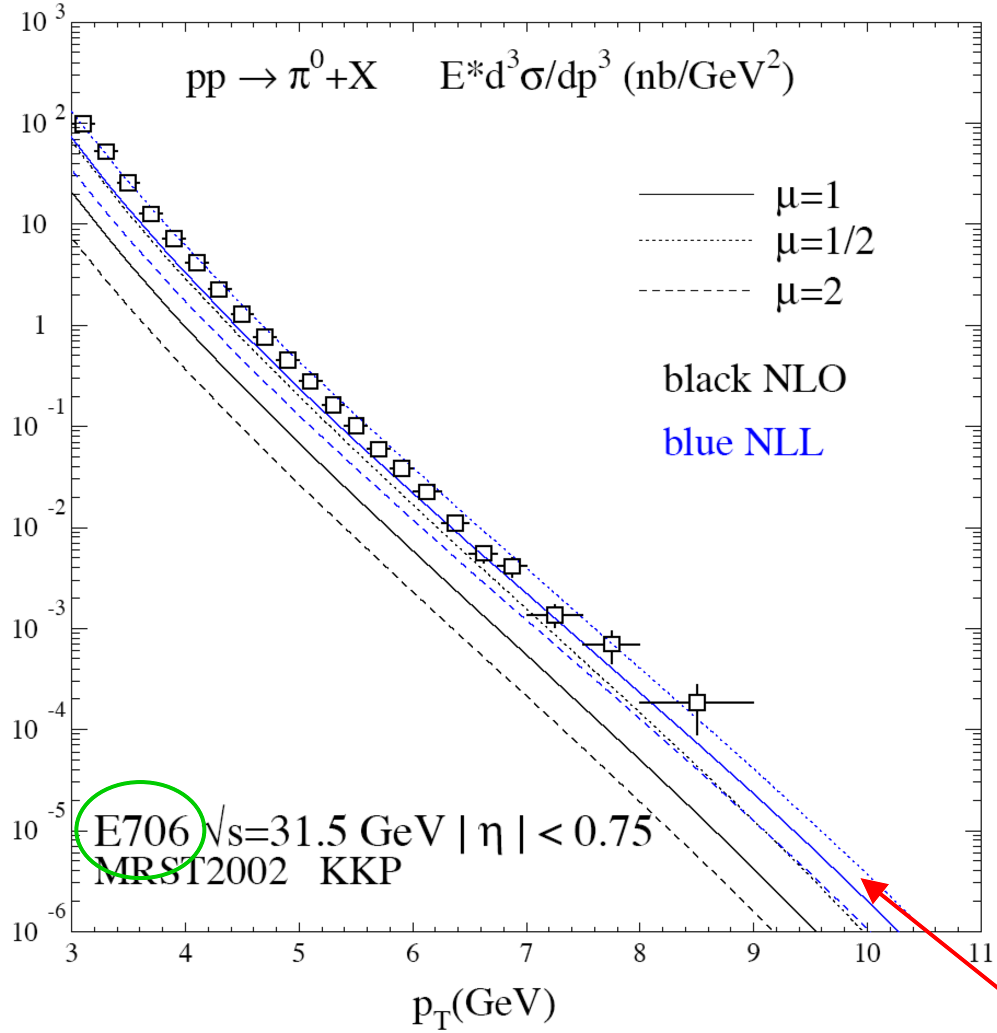
observed partons — unobserved

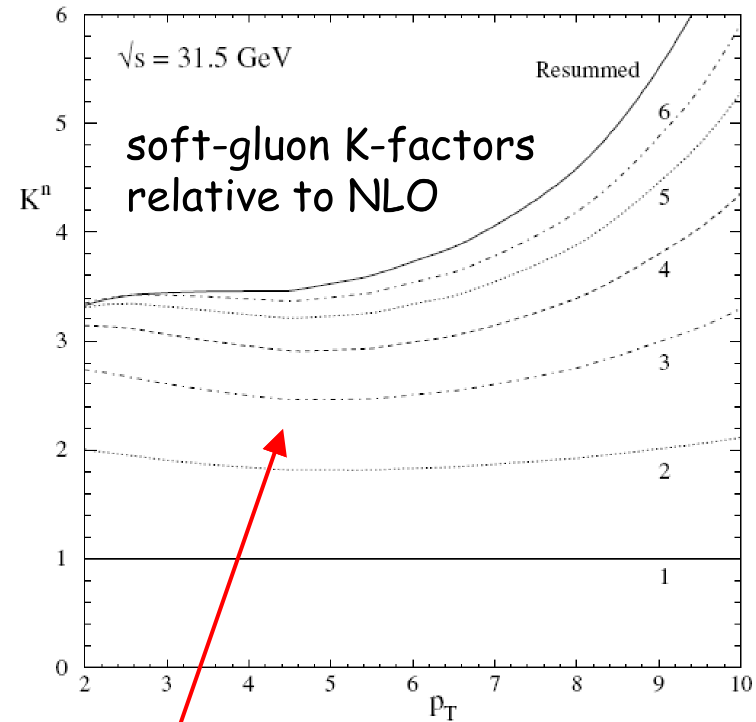
$gg \to gg$ $$\exp\left[\left(C_A + C_A + C_A - \frac{1}{2}C_A\right)\frac{\alpha_s}{\pi}\ln^2(N)\right]$$

expect much larger enhancement

resummations: some phenomenology $pp \to \pi^0 X$

de Florian, Vogelsang





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

resummations: window to the non-pert. regime

important technical issue:

resummations are sensitive to strong coupling regime

→ need some prescription to avoid Landau pole

Catani, Mangano, Nason, Trentadue:

define resummed result such that series is asymptotic
w/o factorial growth associated with power corrections

→ power corrections/k_T effects may be added *afterwards* if phenomenologically needed
studying power corrections prior to resummations makes no sense

window to the non-perturbative regime so far little explored

resummations: J-PARC

resummations seem to be mandatory at fixed-target energies

- ✓ technical framework available
- ✓ well-defined & systematic improvement of pQCD results
- ✓ often much reduced scale uncertainties
- ✓ window to non-perturbative regime

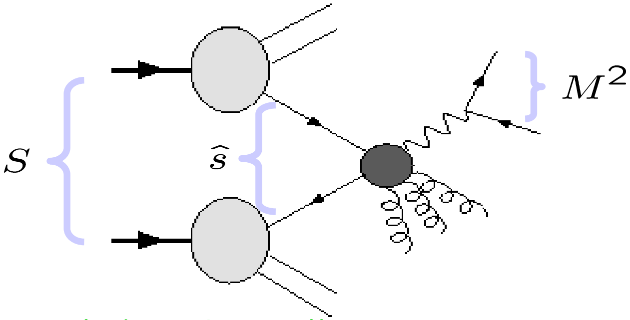
almost no quantitative studies at J-PARC energies yet; expect:

- very 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 $d\delta\sigma$)

notable exception: Drell-Yan process (of much relevance for J-PARC programme)

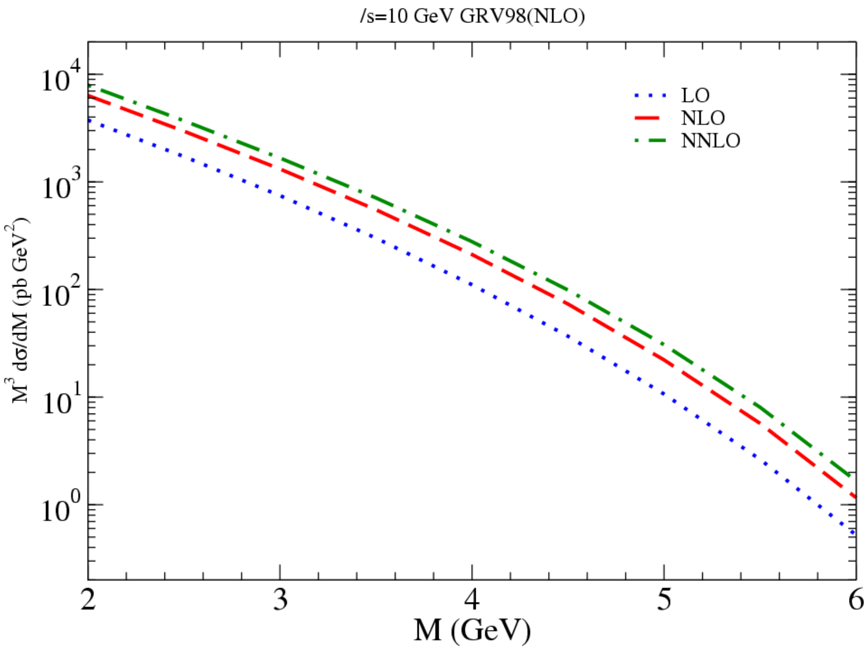
- $d\sigma/dM$, A_{LL}, A_{TT} Yokoya; Shimizu, Sterman, Vogelsang, Yokoya
- $d\sigma/dM/dq_T$, A_{TT} Kawamura, Kodaira, Shimizu, Tanaka

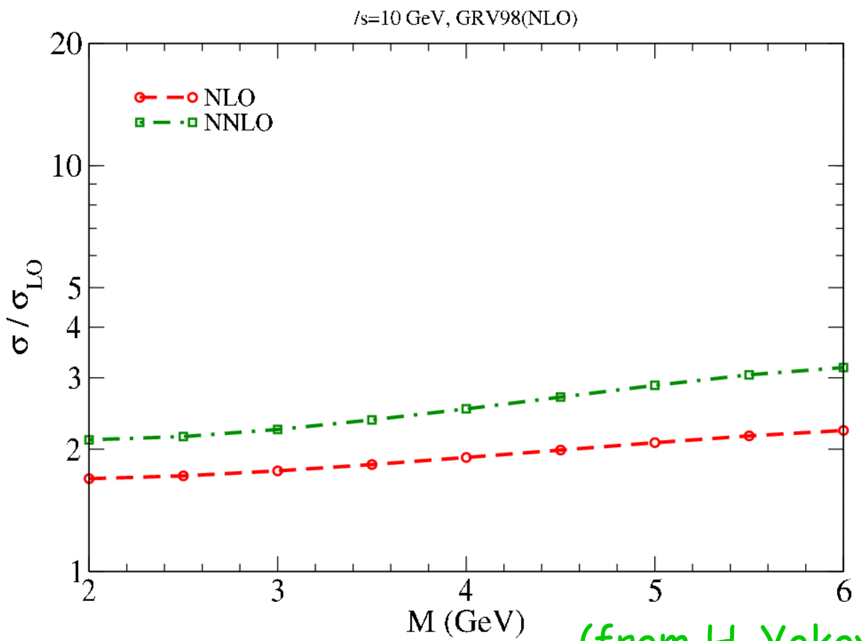
Drell-Yan lepton pairs at J-PARC



fixed order results are known up to **NNLO**

Hamberg, van Neerven, Matsuura; Harlander, Kilgore; Anastasiou, Dixon, Melnikov, Petriello



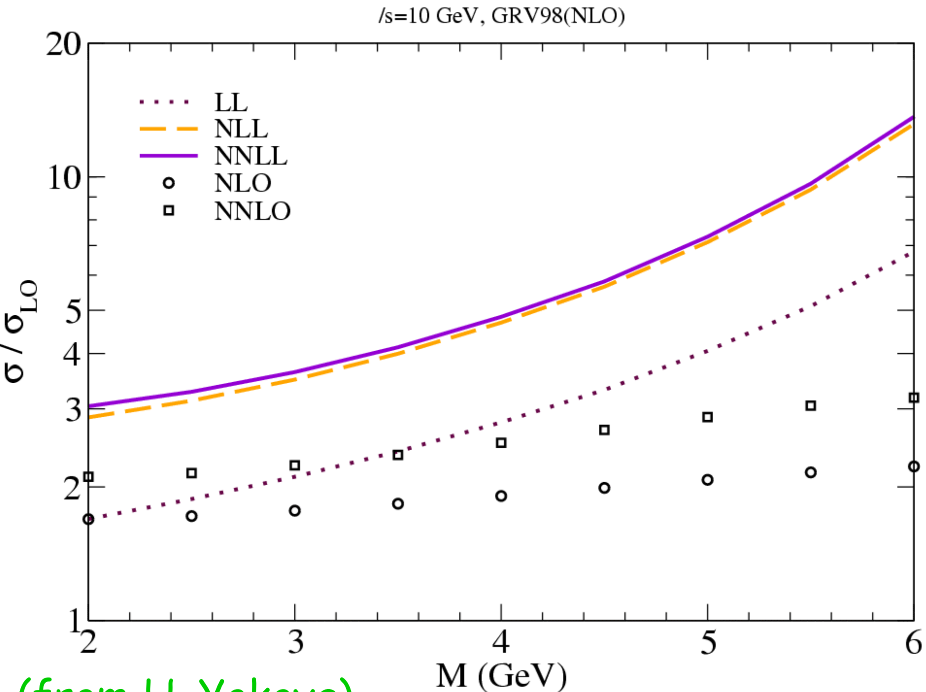


(from H. Yokoya)

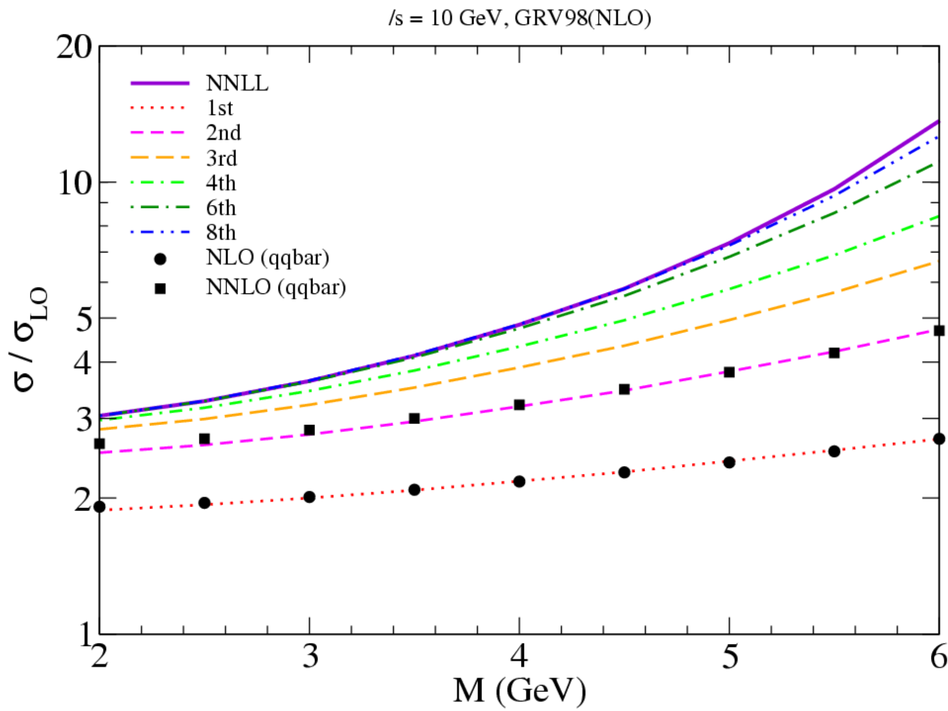
- NNLO corrections still fairly significant
- large corrections stem from near partonic threshold $z \simeq 1$

Drell-Yan process: threshold resummations

first three towers of logs known: **LL, NLL, NNLL**



(from H. Yokoya)



nice convergence
NNLL sufficient

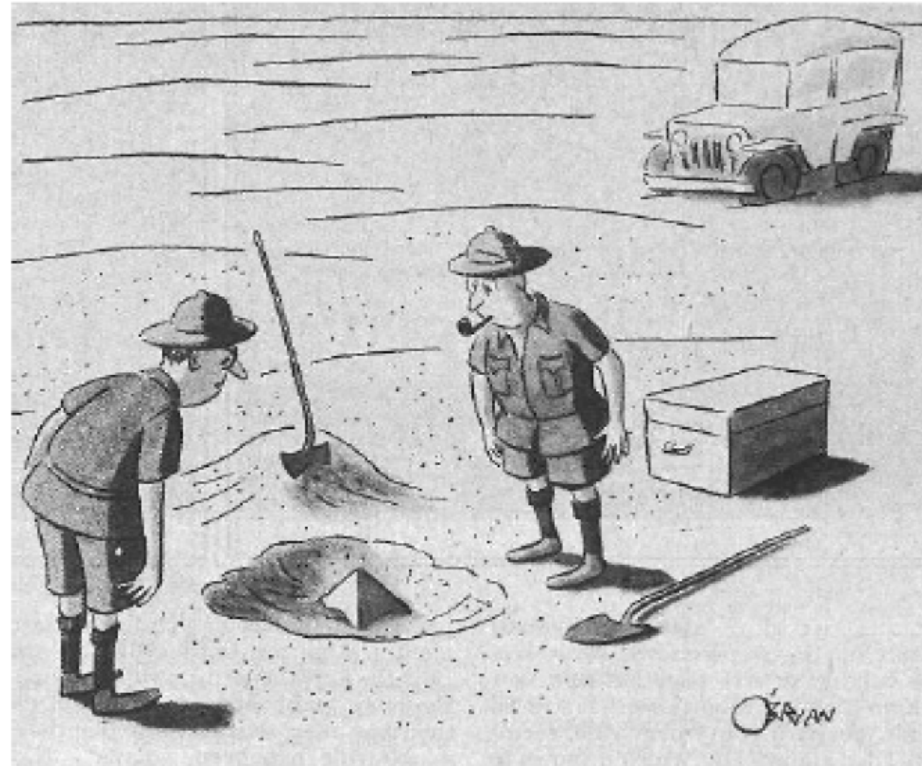
expansion reproduces f.o. results
→ f.o. dominated by threshold logs

V. concluding remarks

scientific opportunities @ J-PARC

ground breaking ceremony
in 2002

2008, almost ready to go



"This could be the discovery of the century. Depending, of course, on how far down it goes."

many avenues for important measurements exploring the limits of pQCD