Heavy Quark Correlations in Polarized pp Collisions

Marco Stratmann

Regensburg / Wűrzburg

Brookhaven National Lab, March 17th, 2010

The Plan

- Heavy Quarks as a QCD Lab
- Anatomy of Heavy Quark Production in pQCD
- Expectations for RHIC: p_T distributions & correlations
- Summary &Outlook

based on

I. Bojak, MS, Phys. Rev. D67 (2003) 034010; J. Riedl, A. Schafer, MS, Phys. Rev. D80 (2009) 114020

Heavy Quarks as a QCD Lab

it makes a difference to be heavy

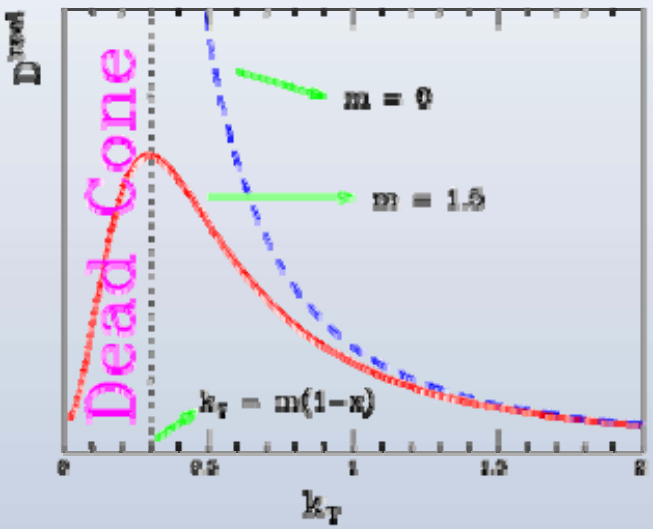
- obesity for quarks starts if $m \gg \Lambda_{QCD}$
- mass sets a hard scale for pQCD calculations
- mass has impact on the gluon spectrum radiated off a (heavy) quark line

$D(x,k_T,m)$

- emission at small k_T suppressed within "dead cone" $\Theta < m/E$

  !**finite total HQ cross sections**

- $m=0$: non-integrable **collinear singularity**



however, "finite" does not necessarily mean "accurate"

many hurdles: multi-scale problem (resummations); hadronization, …

… and you rarely measure a total cross section

a multi-scale problem

pp @ RHIC

s

hard scale

p_T

s/m^2 and/or p_T/m large

large quasi-collinear logs at each order in α_s

can be resummed to all order with "Altarelli-Parisitechniques"

→ pert. HQ FFs, PDFs

not really relevant, often p_T'm

partonic threshold

(details depend on process)

can be resummed to all orders with "Sudakov techniques"

should be looked into

m

quark mass

Λ_{QCD}

hadronic scale

non-perturbative functions (PDFs, FFs) sit here

an ideal heavy quark calculation

can stop here for
total cross section

$$pp \longrightarrow Q \longrightarrow \text{HQ meson} \longrightarrow \text{decay } e, \mu$$

pQCD
+ resummations

non-pert. FF
extracted
from data

MC simulation
(measured decay spectra)

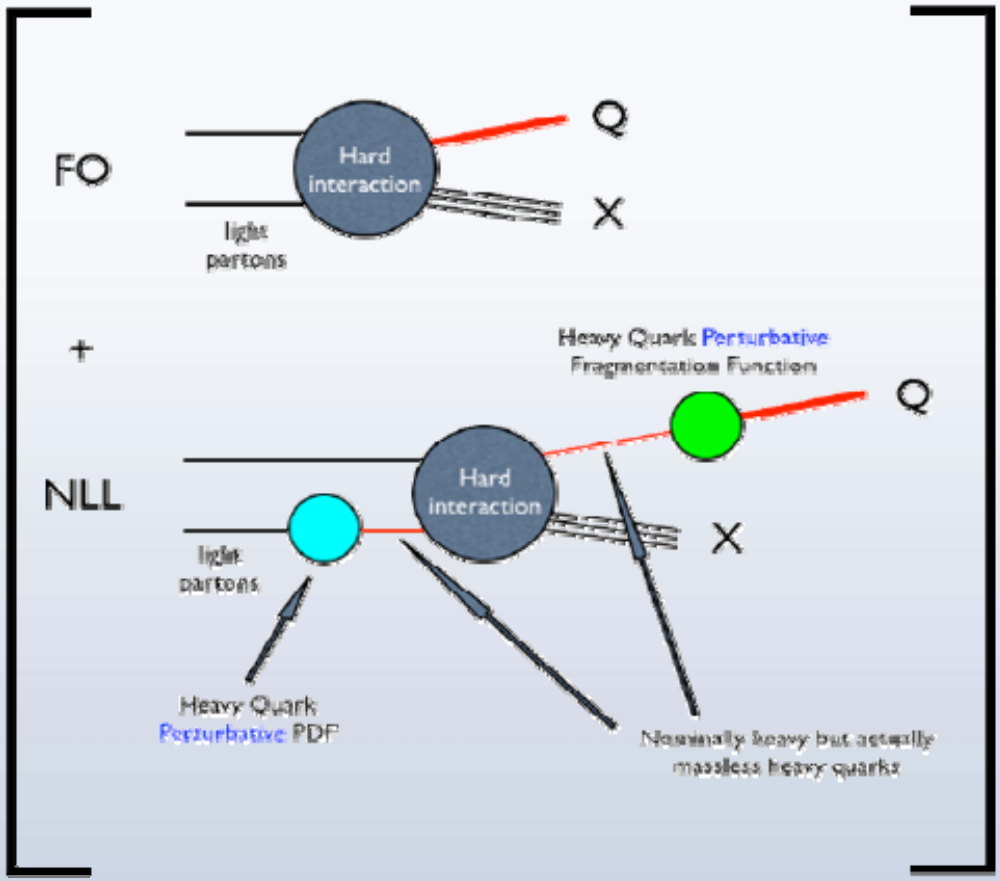
Cacciari et al., … (very important!)

NLO state-of-the-art: Nason et al.; van Neerven et al., … (unpol)
Bojak, MS; Riedl, Schafer, MS (pol)

FONLL: + quasi-coll. logs at NLL Cacciari et al., … (unpol)

threshold effects: NNLO-NNLL Kidonakis et al., …

sketch of a FONLL calculations



cartoon taken from M. Cacciari

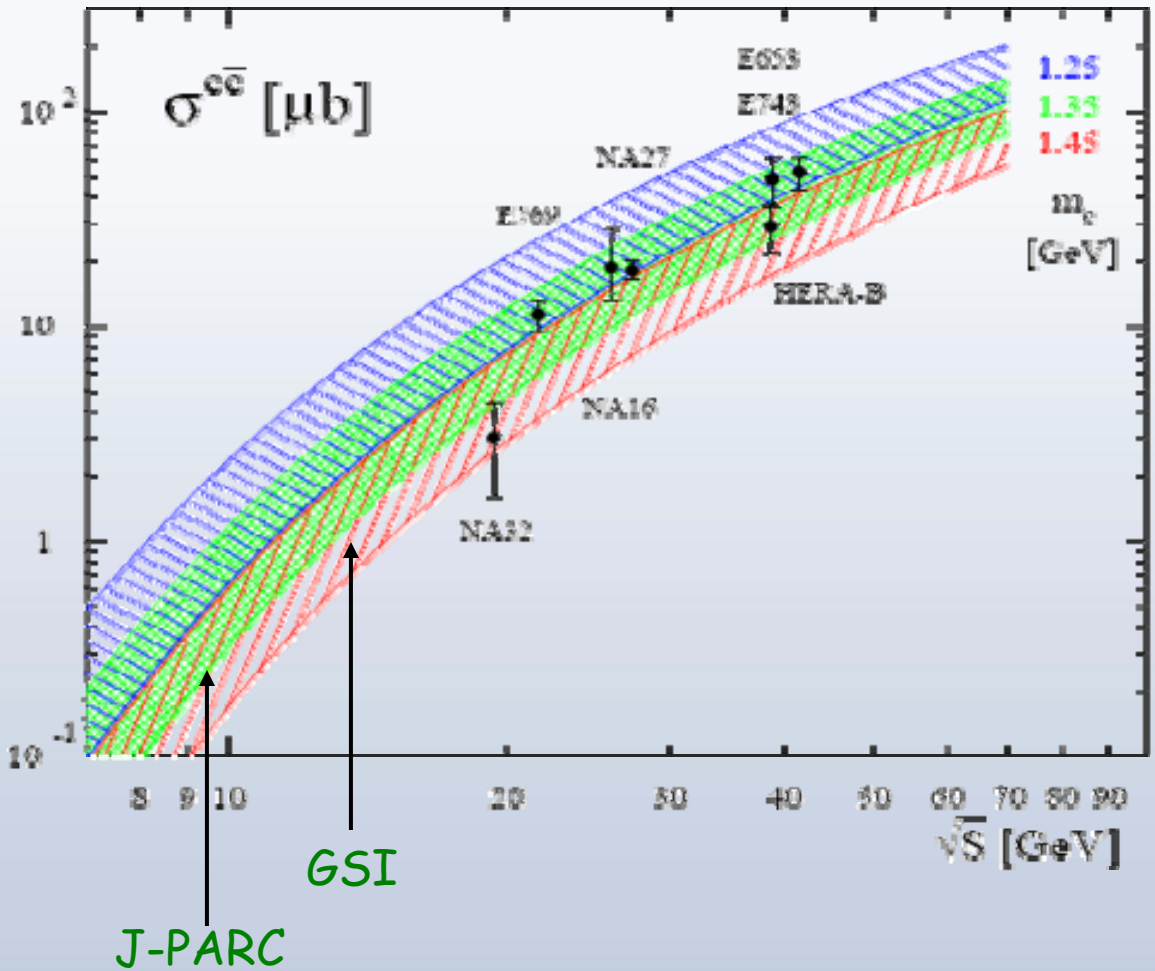
$\otimes \quad D_{Q \to H}$

Fitted to e+e- data in the **same scheme**

- formalism used in analysis of unpol. RHIC data Cacciari, Nason, Vogt, PRL 95 (2005) 122001
- for the time being, we stick to NLO in the polarized case

(measurements of A_{LL} unlikely at $p_T \gg m$ due to lack of statistics)

low energy results: terra incognita



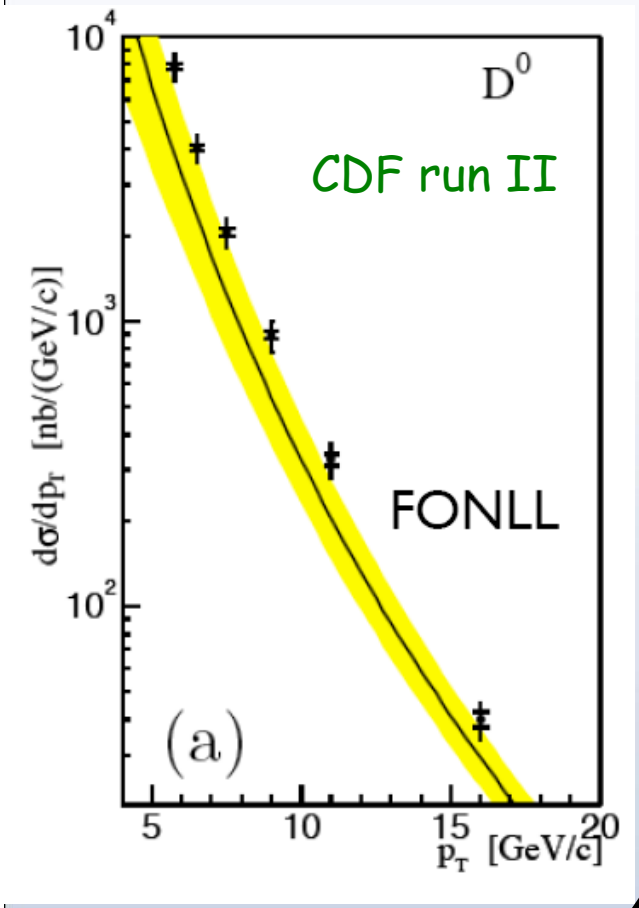
total charm cross section

significant uncertainties:

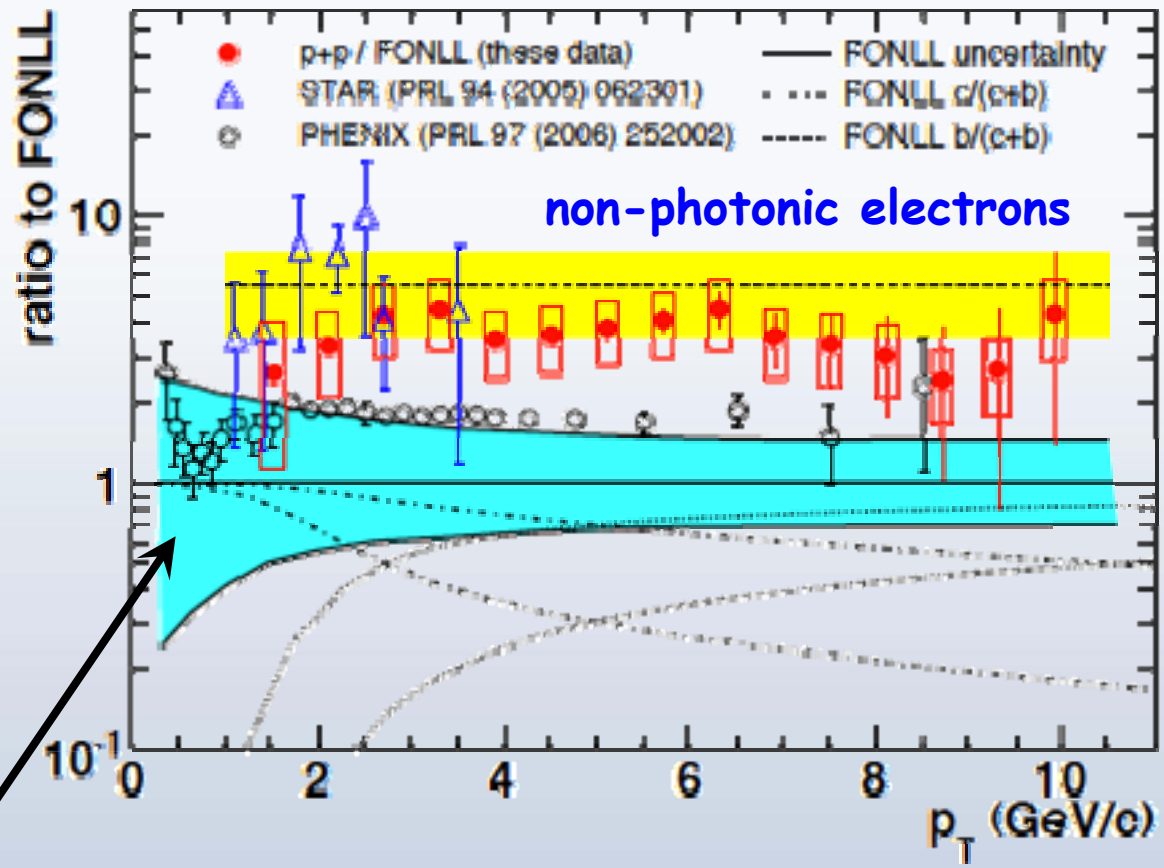
charm mass
choice of scales

$m_c < \mu < 2m_c$

heavy quarks @ colliders: in fairly good shape !?



FONLL calculations: Cacciari et al.



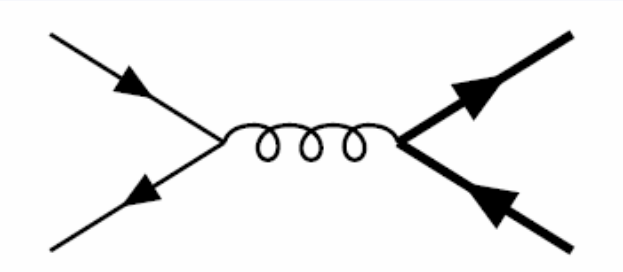
lessons:

- theoretical uncertainties sizable (shaky basis for nuclear modification in HI collisions)
- theory tends to undershoot data
- decay electron (muon) channels probe mixture of charm and bottom

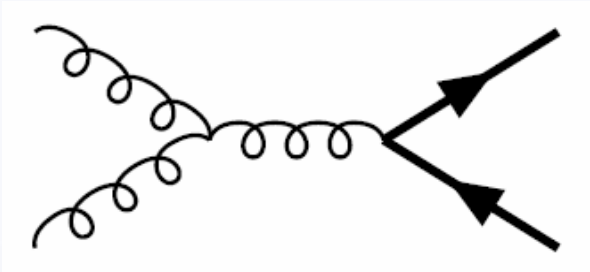
Anatomy of HQ Production

partonicsubprocesses

LO



light quark-antiquark annihilation

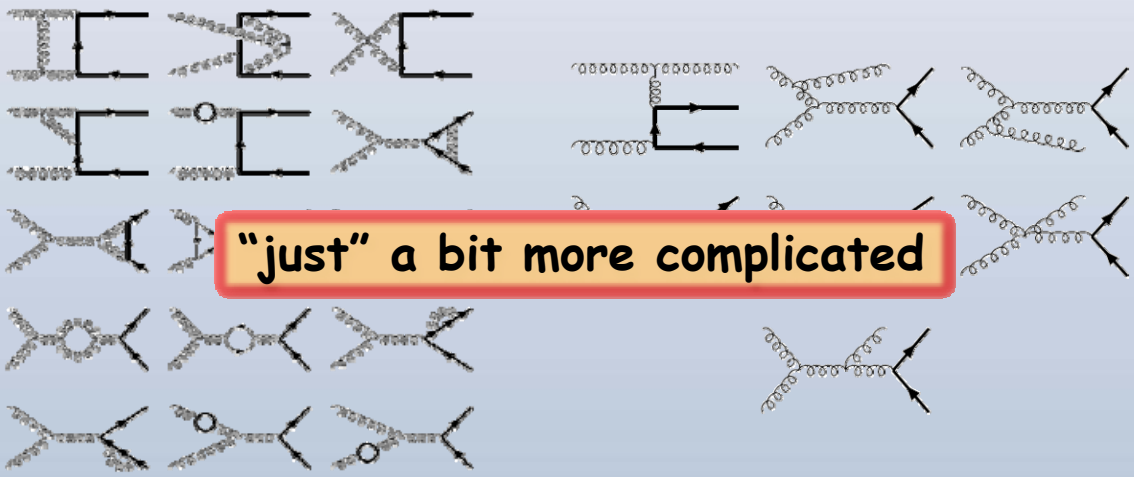


gluon-gluon fusion

by far the dominant mechanism at high energies

not necessarily true in pol. case if Δg small

NLO

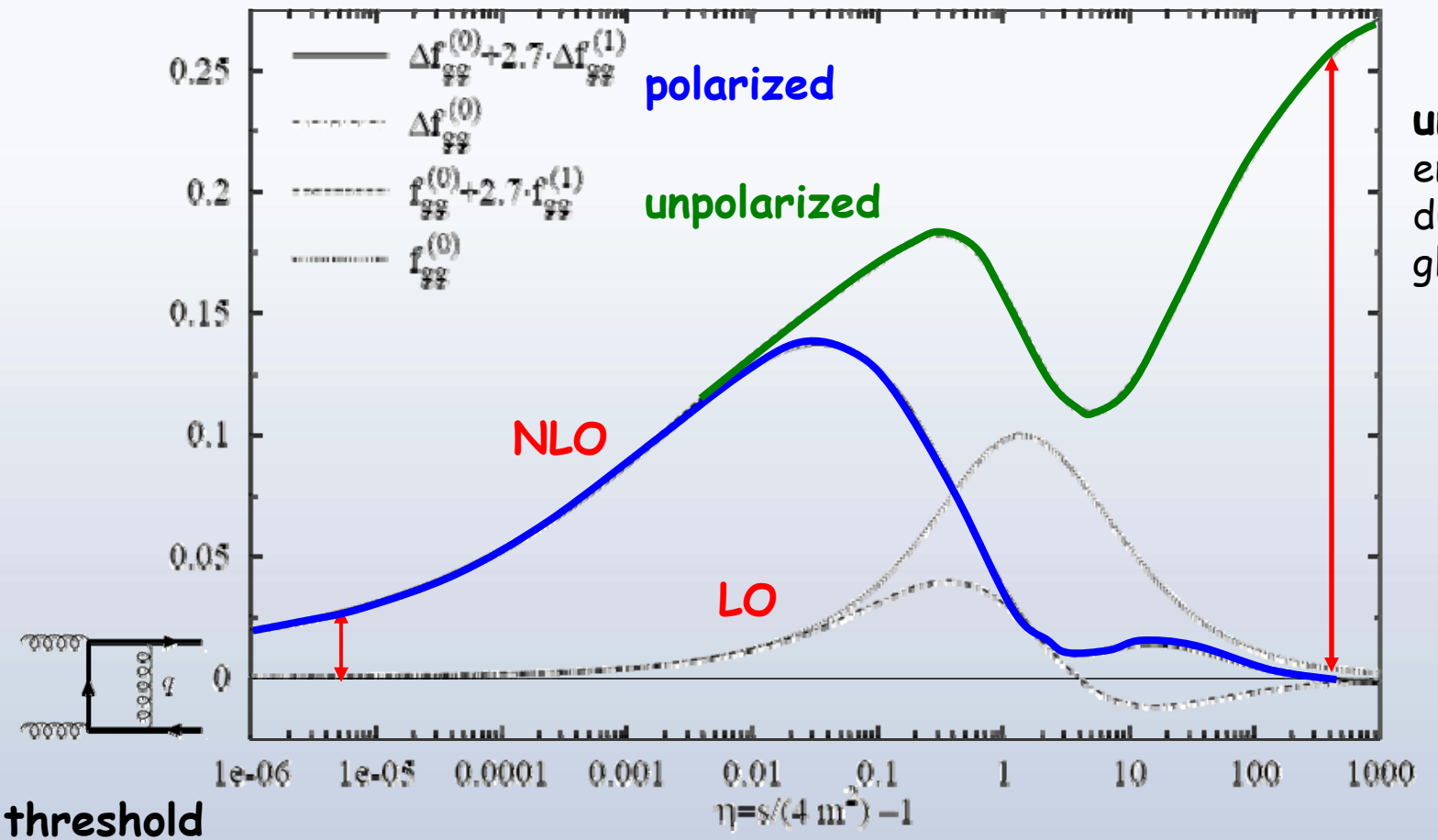


"just" a bit more complicated

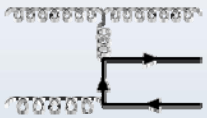
plus
many many
more …

total partonic cross sections

$$\hat{\sigma}_{gg}(\eta) = \frac{\alpha_s^2}{m^2}\left[f_{gg}^{(0)}(\eta) + 4\pi\alpha_s f_{gg}^{(1)}(\eta)\right]$$



unpol:
enhancement due to t-channel gluon exchange



threshold corrections:

"Coulomb sing."
+ soft gluon logs.

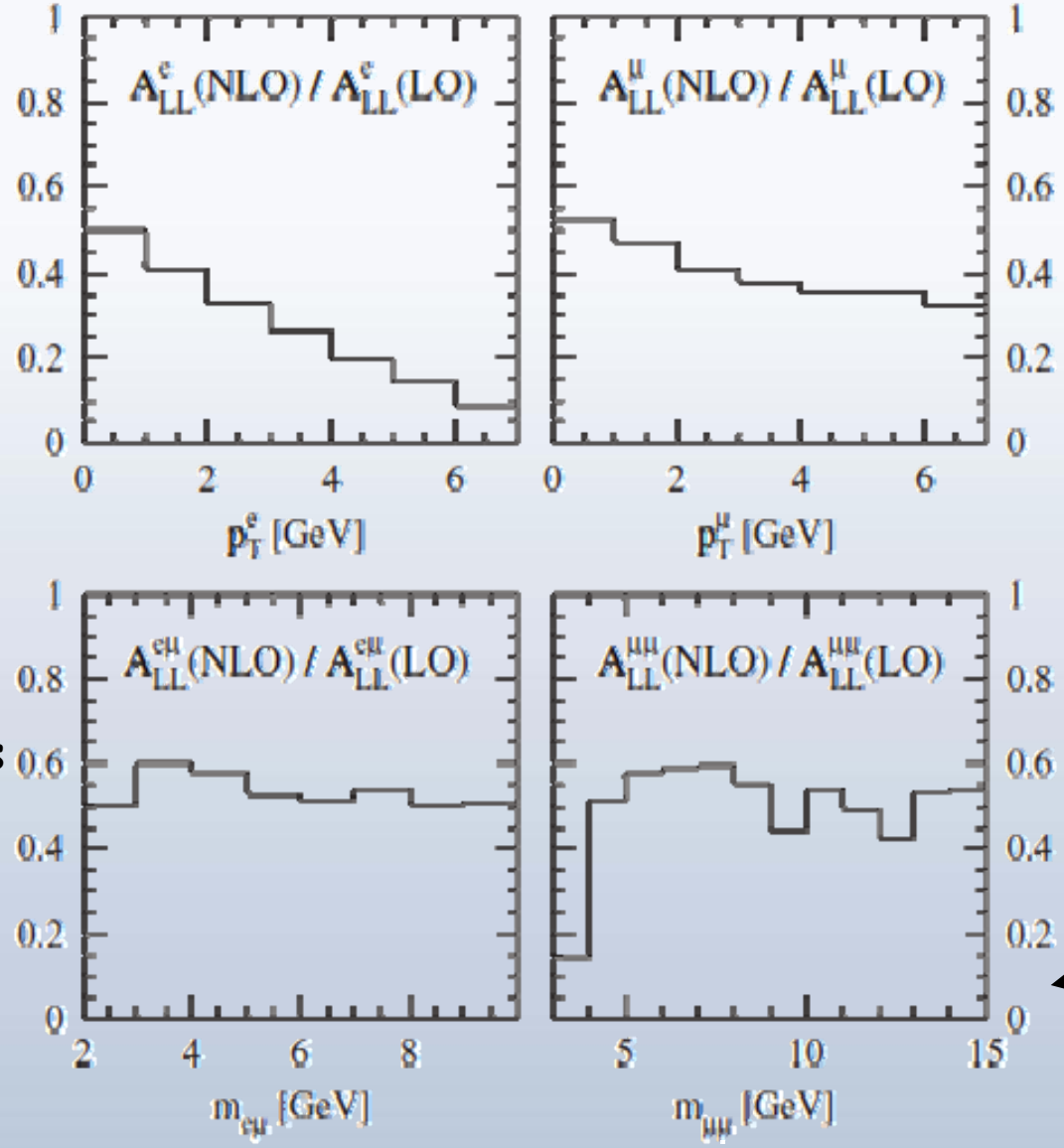
- physical cross section: convolution from $\eta=0$ to η_{max} with PDFs
- expect LARGE corrections to A_{LL}

NLO corrections to A_{LL}

indeed …

single electrons

c,b!e



single muons

c,b!μ

forward-central e-μ coincidences

c,b!e

c,b!μ

forward-backward μ-μ coincidences

c,b!μ

c,b!μ

•correlations more stable w.r.t. NLO corrections; ≈ constant w.r.t. inv. mass

technical aspects in a nutshell

previous calculation: I. Bojak, MS, Phys. Rev. D67 (2003) 034010

phase space calculations done largely analytically; phase space slicing method

→ fast numericalimplementationbutlimited to single-inclusive HQ yields

new calculation: J. Riedl, A. Schafer, MS, Phys. Rev. D80 (2009) 114020

phase space calculations performed numerically; uses available matrix elements

subtraction method for singular regions (a la Mangano, Nason, Ridolfi, NPB373 (1992) 295)

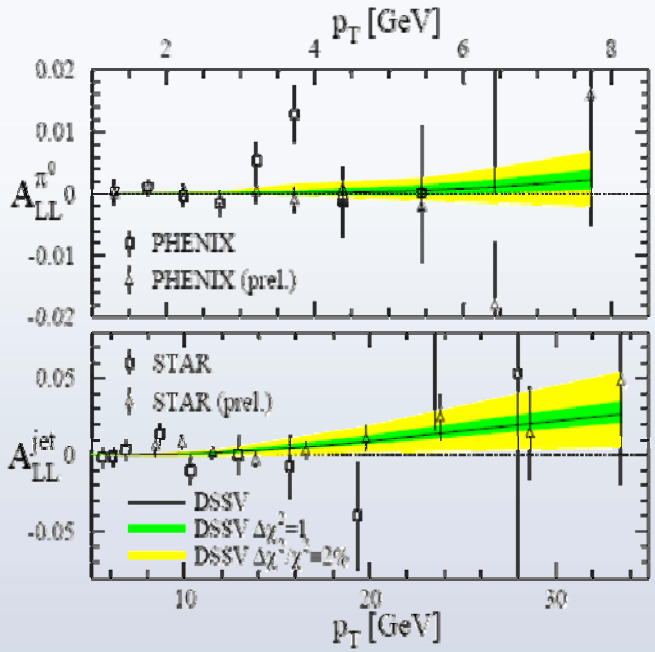
→ no so fast numericalimplementationbutfully flexible:

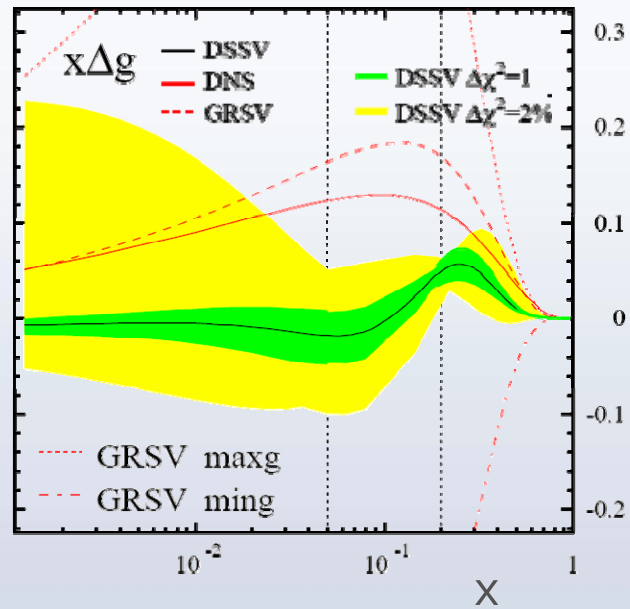
- HQ correlations; HQ-jet correlations (not yet)
- experimental cuts
- HQ decays (so far: semi-leptonically)
- can be easily extended to cover HQ photoproduction at an EIC (soon!)

HQ Production @ RHIC

Why A_{LL} for heavy quarks?

- present knowledge of Δg based on ***single*** class of processes: hadrons & jets





- rare probes (prompt photons, HQs) can be never as significant as jets

but

- ✓different hard scattering dynamics than jets and hadrons
- ✓much smaller number of subprocesses

crucial in understanding spin-dep. QCD hard scattering
test universality and factorization

Phenomenological inputs

largely follow Cacciari, Nason, Vogt (unpolarized HQ production)

$$E_l \frac{d^3(\Delta)\sigma^l}{dp_l^3} = E_Q \frac{d^3(\Delta)\sigma^Q}{dp_Q^3} \otimes D^{Q \to H_Q} \otimes f^{H_Q \to l}$$

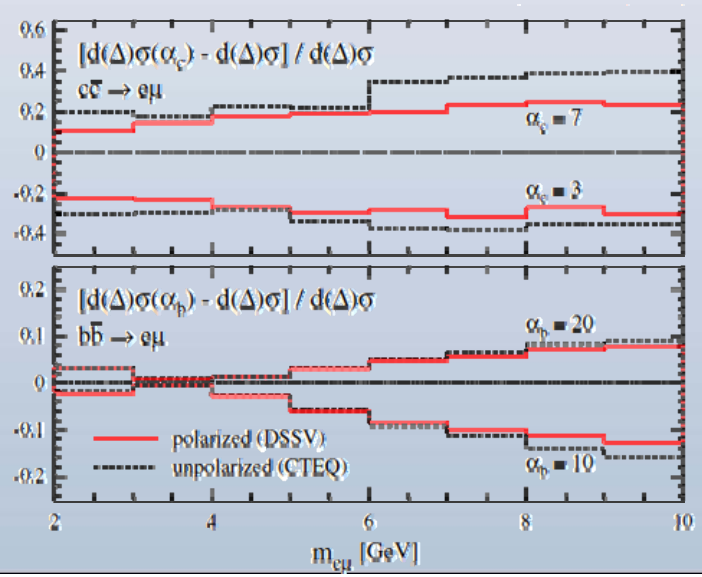
- **hadronization** (various models)

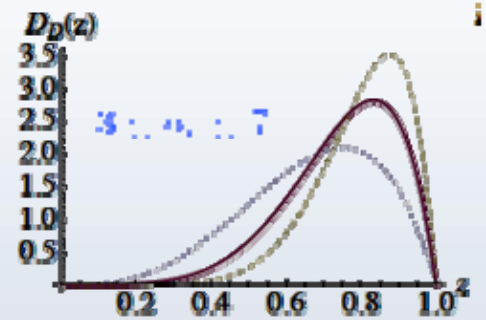
choose $D^{Q \to H_Q}(z) \quad N_Q z^{\alpha_Q}(1-z)$

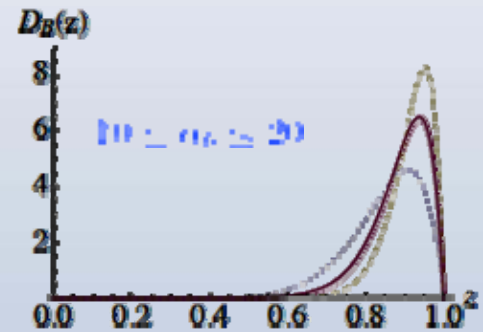
Kartvelishvili, Likhoded, Petrov

N_Q fixed by normalization; scale *independent*;

fitted to e^+e^- data (review: Baines et al.)





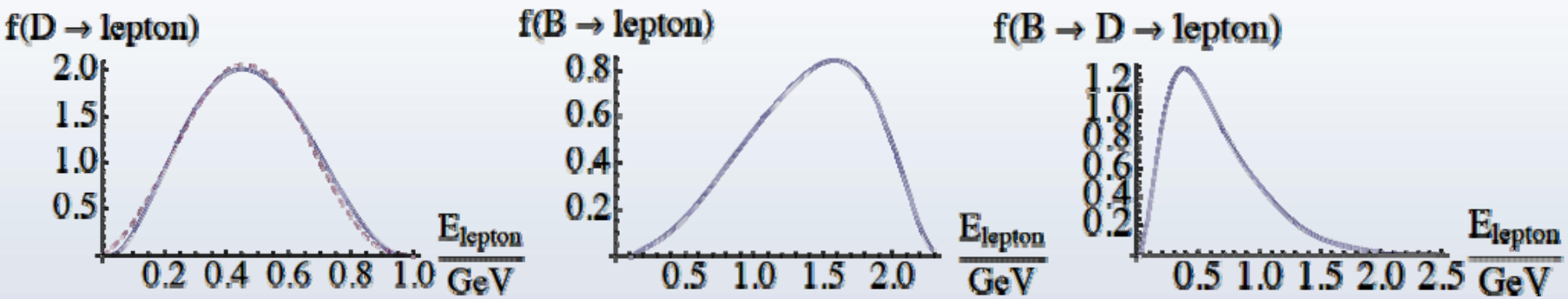


actual choice of $\alpha_{c,b}$ largely cancels in A_{LL}

Phenomenological inputs – cont'd

- **semi-leptonic decay spectrum** $f^{H_Q \to l}$ (taken from Cacciari, Nason, Vogt)

parameterization determined from data (CLEO, BABAR, …)



modeled as $f^{B \to D \to l}$

in general, a small contribution

additional input: appropriate branching fractions: Br(D→e), …

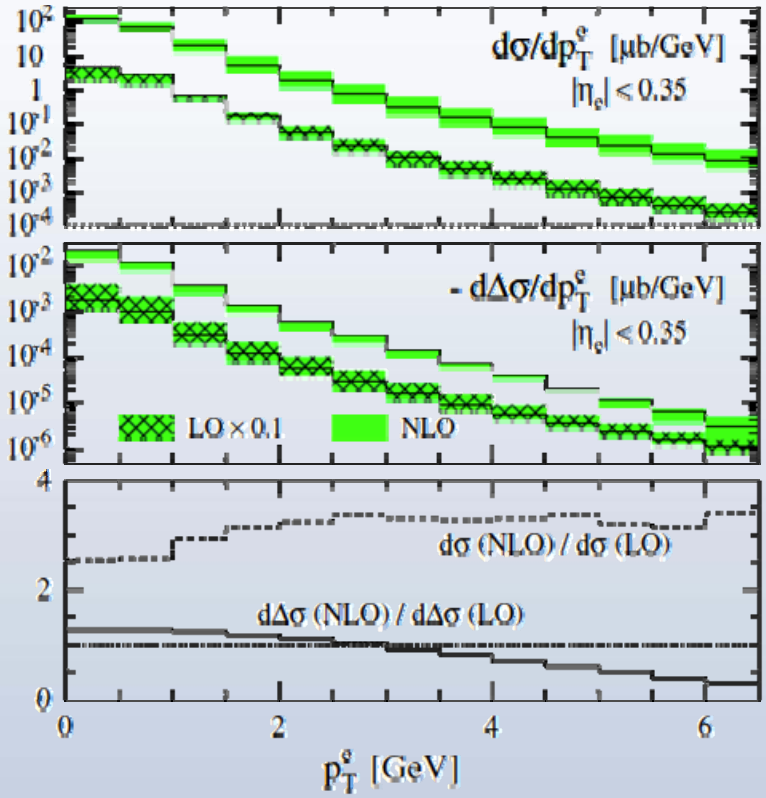
complication:

charm & bottom decays both contribute to lepton spectra

bottom contribution takes over at larger p_T

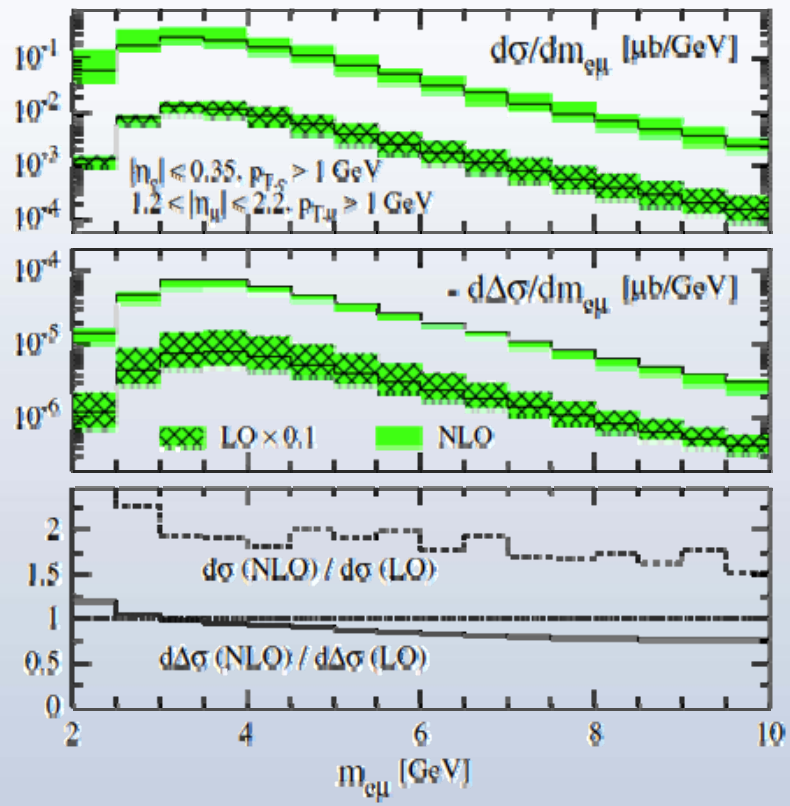
cross sections & scale dependence

single electrons c,b!e



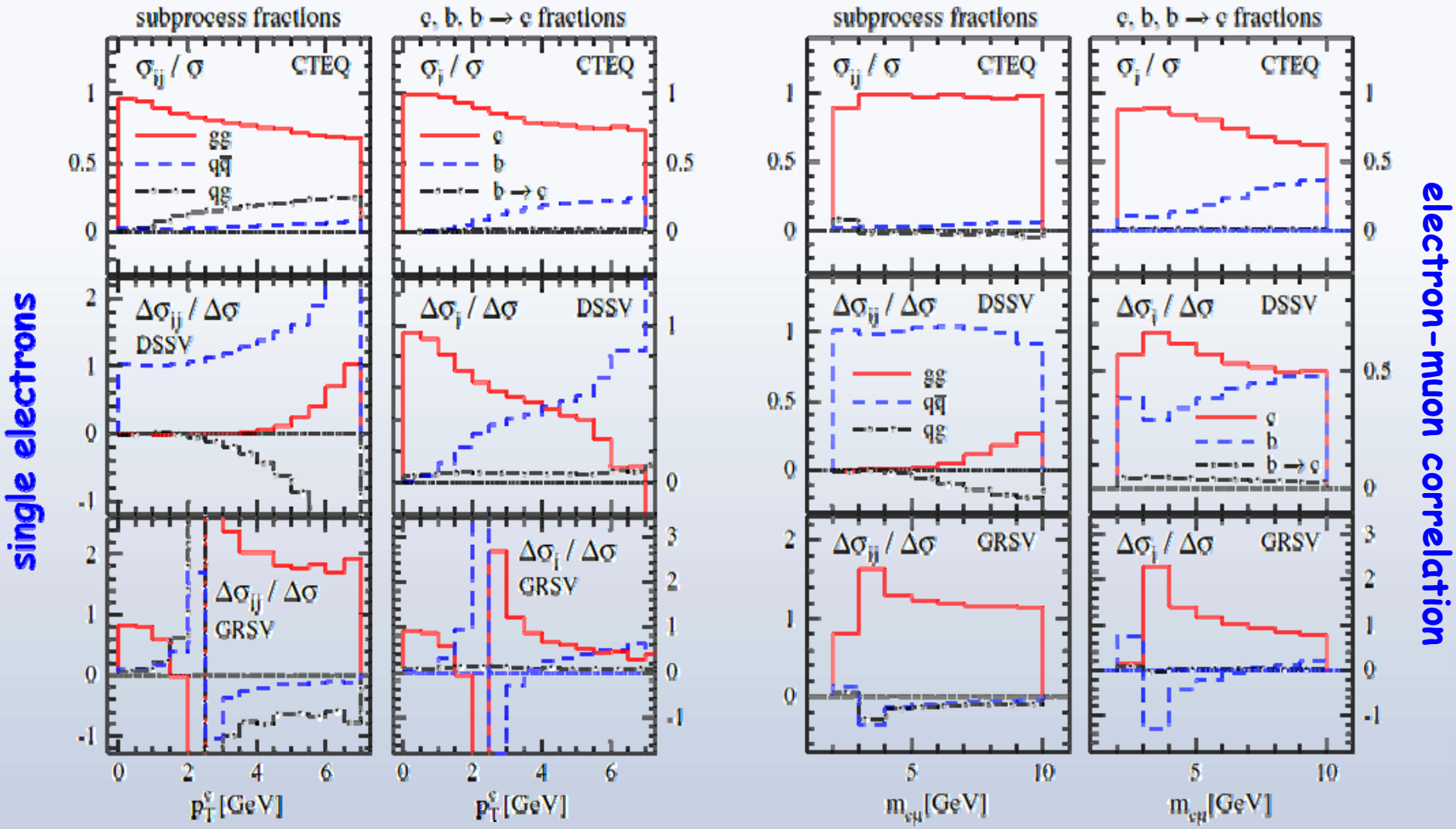
forward-central e-μ coincidences c,b!e

c,b!μ



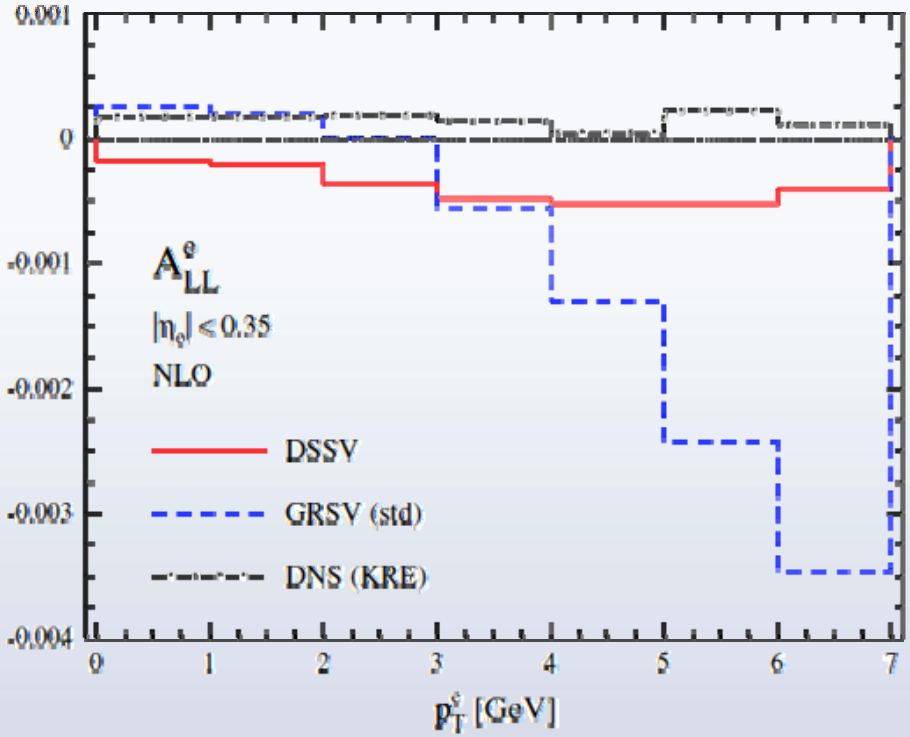
- as often, scale dependence milder in polarized case

subprocess& charm, bottom fractions



- unpol.: gg dominant channel; bottom relevant at higher p_T or $m_{e\mu}$
- pol: cancelations & nodes obscure things a lot ; $q\bar{q}$ relevant if Δg small (like in DSSV !!)
- in general, correlations are better behaved observables

double-spin asymmetries: single-inclusive

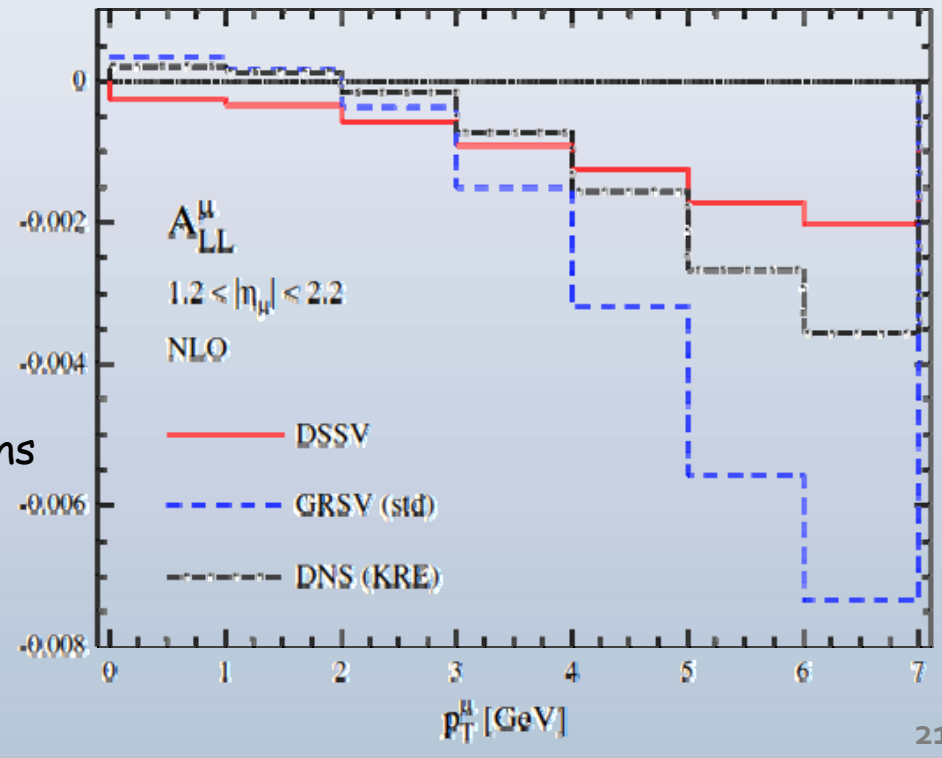


single electrons c,b!e

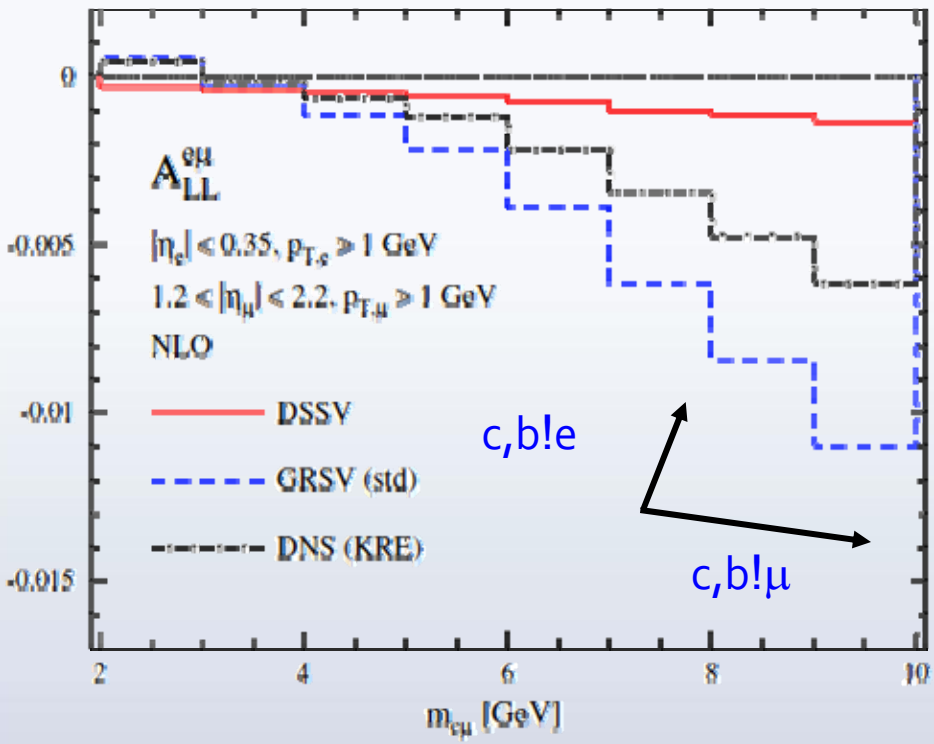
- in general, very small asymmetries
- interpretation of A_{LL} complicated (e.g. cancelations lead to $A_{LL} \approx 0$ for DNS)

single muons c,b!μ

- cancelations less pronounced than for electrons
- better correlation between A_{LL} and Δg
- larger spin asymmetries than for electrons



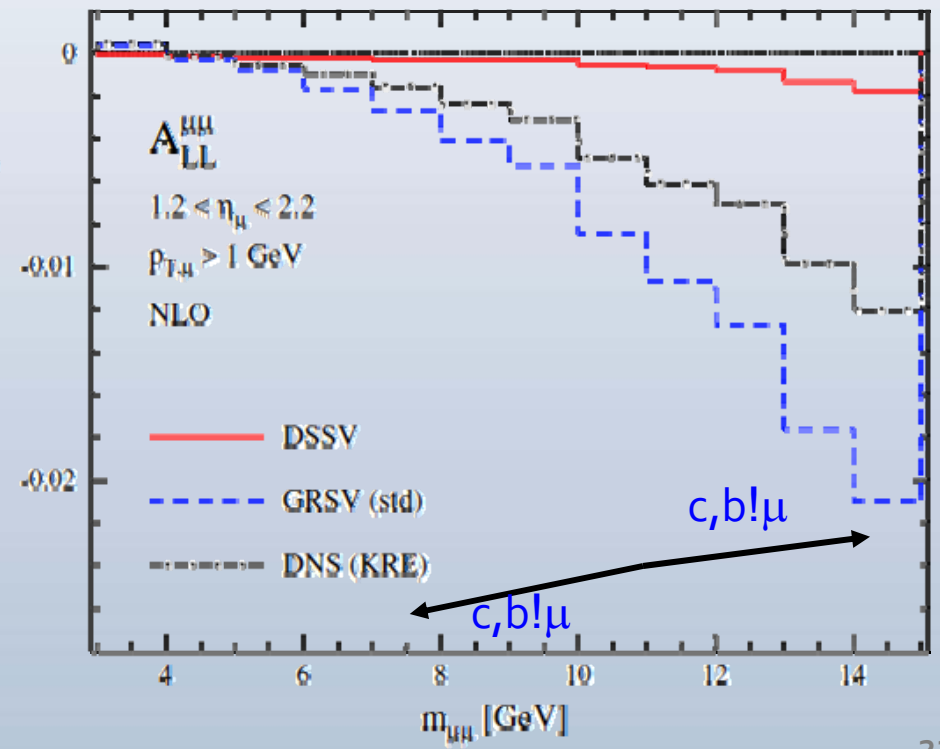
double-spin asymmetries: correlations



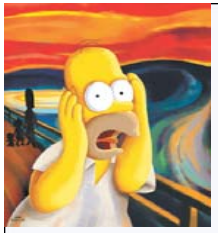
forward-backwardμ-μ coincidences

forward-centrale-μ coincidences

- best suited heavy flavor observables to explore nucleon spin structure
- clear correlation between A_{LL} and Δg

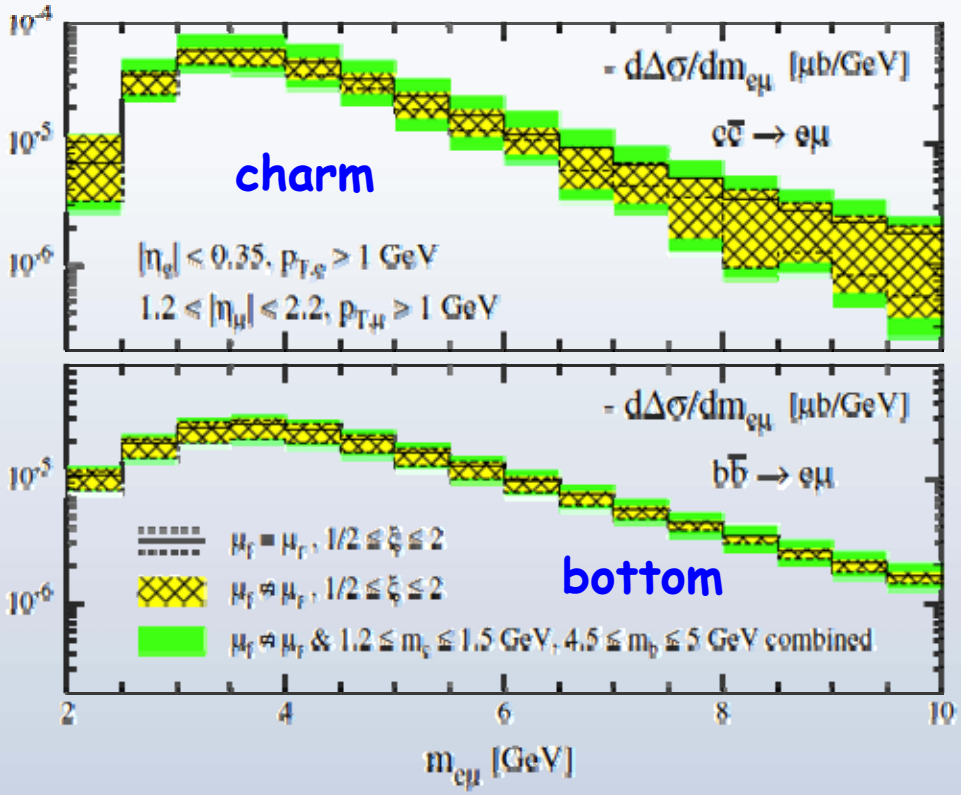


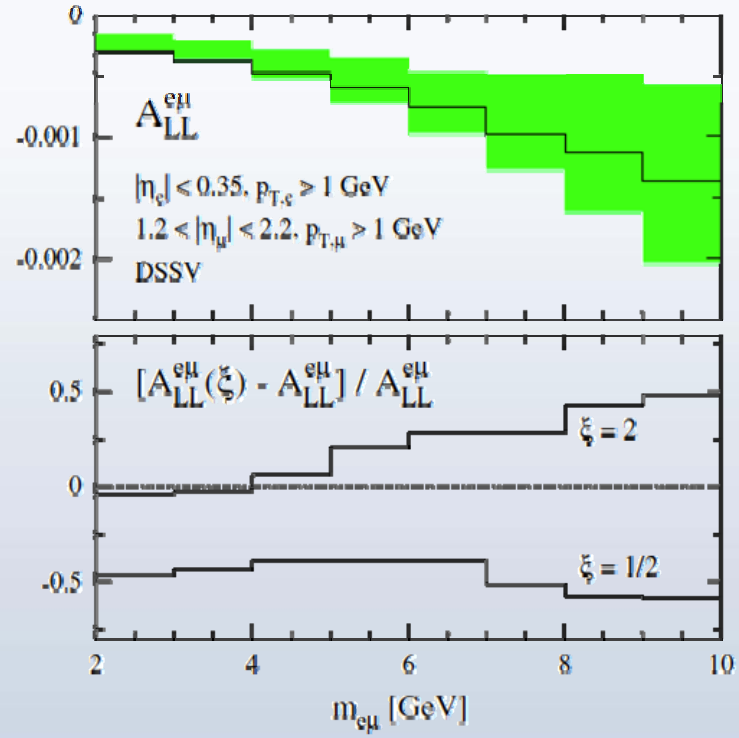
luminosities of a **few hundred pb^{-1}** are requiredfor meaningful measurements at $m_{e\mu,\mu\mu}$ up to 10-15 GeV



uncertainties, uncertainties, uncertainties …

many sources of uncertainties: scales, HQ masses, decay parameters





- varying $\mu_{r,f}$ *independently* can be crucial

  here: $\mu_f = \mu_r$ good approximation
- variations of $m_{c,b}$ add to uncertainty band
- results for bottom much more robust

- scale uncertainties do not cancel in A_{LL} but are smaller than GRSV vs. DSSV vs. DNS
- mass and decay uncertainties do not affect A_{LL} much (some cancellations)

relevant range of momentum fractions

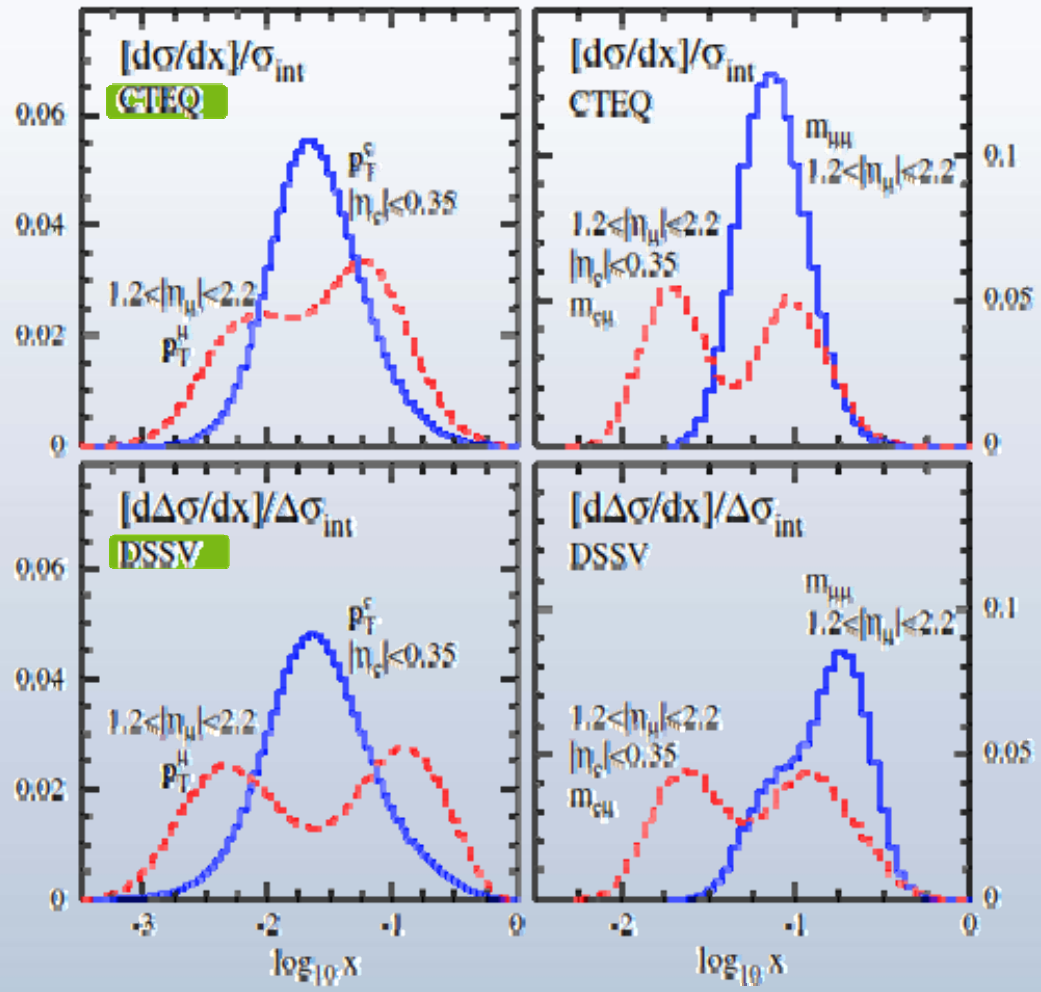
Q: what is the typical range of momentum fractions x probed by HQ observables?

single-inclusive **lepton correlations**

unpolarized

polarized

depends on choice of PDFs

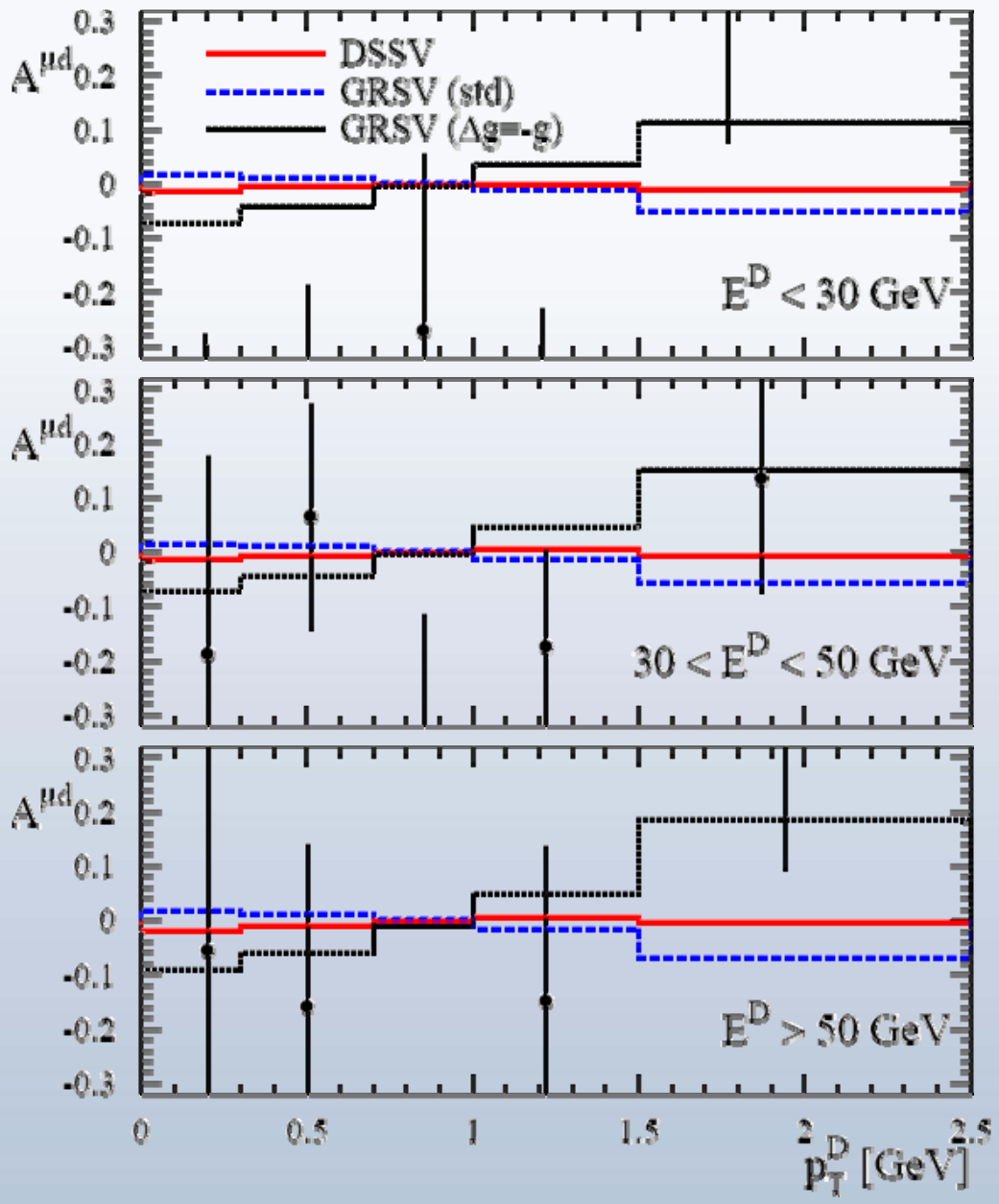


integrated yields within acceptance pp @ 200 GeV

suite of HQ observables can cover a wide range in x similar to jets/pions

sneak preview: charm photoproduction at NLO

Riedl, Schäfer, MS



NLO MC code extended to deal with direct+resolved **photoproduction** at COMPASS &EIC (!)

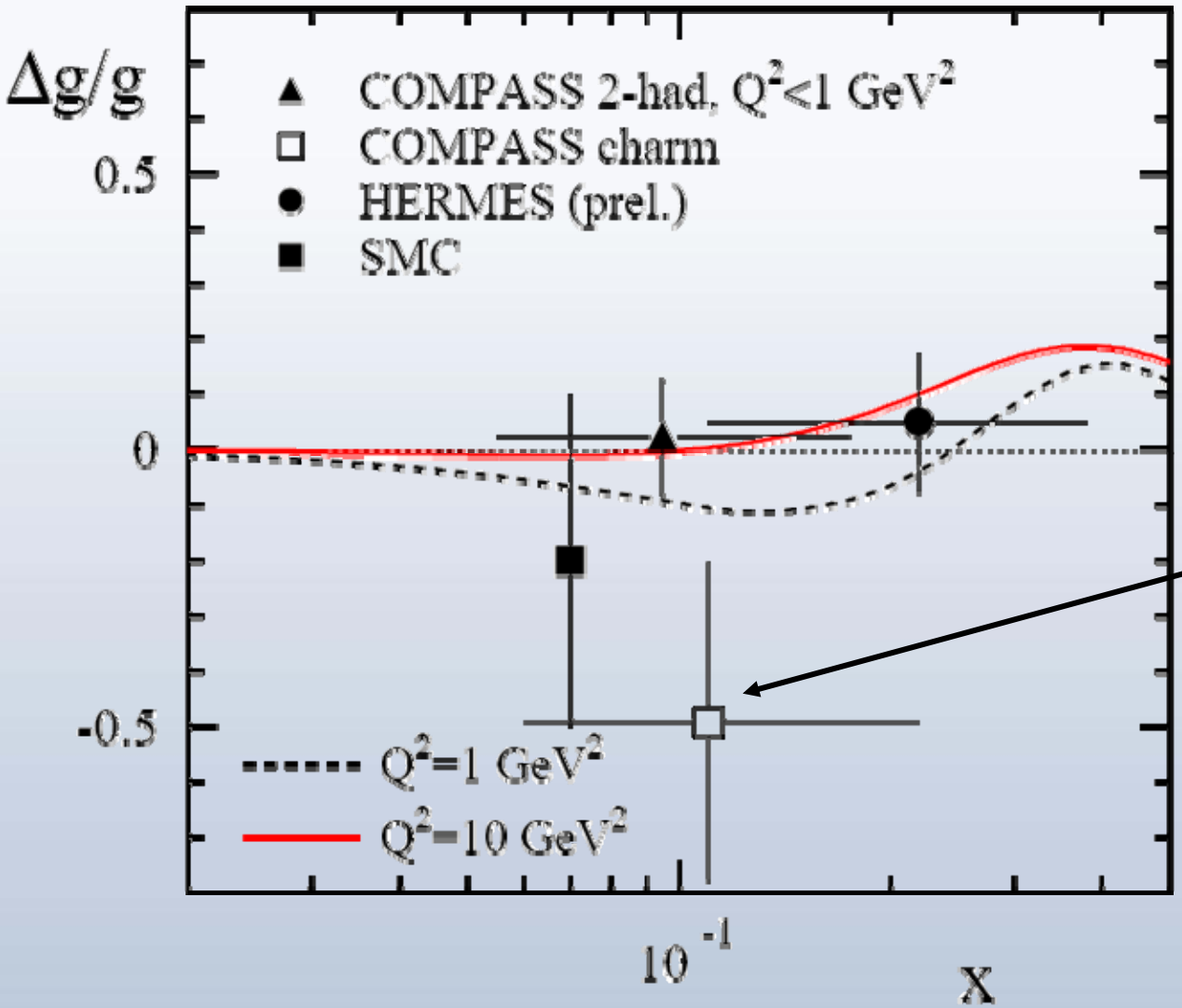
preliminary NLO results:

- for COMPASS kinematics at most 10% from resolved γ
- NLO corrections sizable for spin asymmetry(much smaller!)

some tension with other data constraining Δg

data/bins taken from COMPASS arXiv:0904.3209 [hep-ex]

gluon polarization from fixed target experiments



data not included in DSSVglobal fit

COMPASS (charm)
arXiv:0904.3209 [hep-ex]

at NLO:

smaller analyzing power

→ larger negative Δg/g

things not mentioned

- **prospects for quarkonium production**
  - only rigorous theoretical framework: NRQCD (expansion in α_s and velocity v)

$$d\sigma[H] = \sum_n d\hat{\sigma}^n(\mu)\langle \mathcal{O}_n^H(\mu)\rangle$$

Bodwin, Braaten, Lepage; ..

perturbative
production of $Q\bar{Q}$ pair
with small relative momentum
in a given spin, color, L state n

non-perturbative
NRQCD matrix elements
transition into quarkonium H
determined from data

- NRQCD scorecard: successes & failures

issues: mainly LO so far; considerable uncertainties; slow convergence of series

biggest success: J/Ψ cross section vsTevatron data

Braaten, Fleming; Braaten, Yuan; Kramer

biggest failure: J/Ψ polarization vsp_T

Braaten, Kniehl, Lee

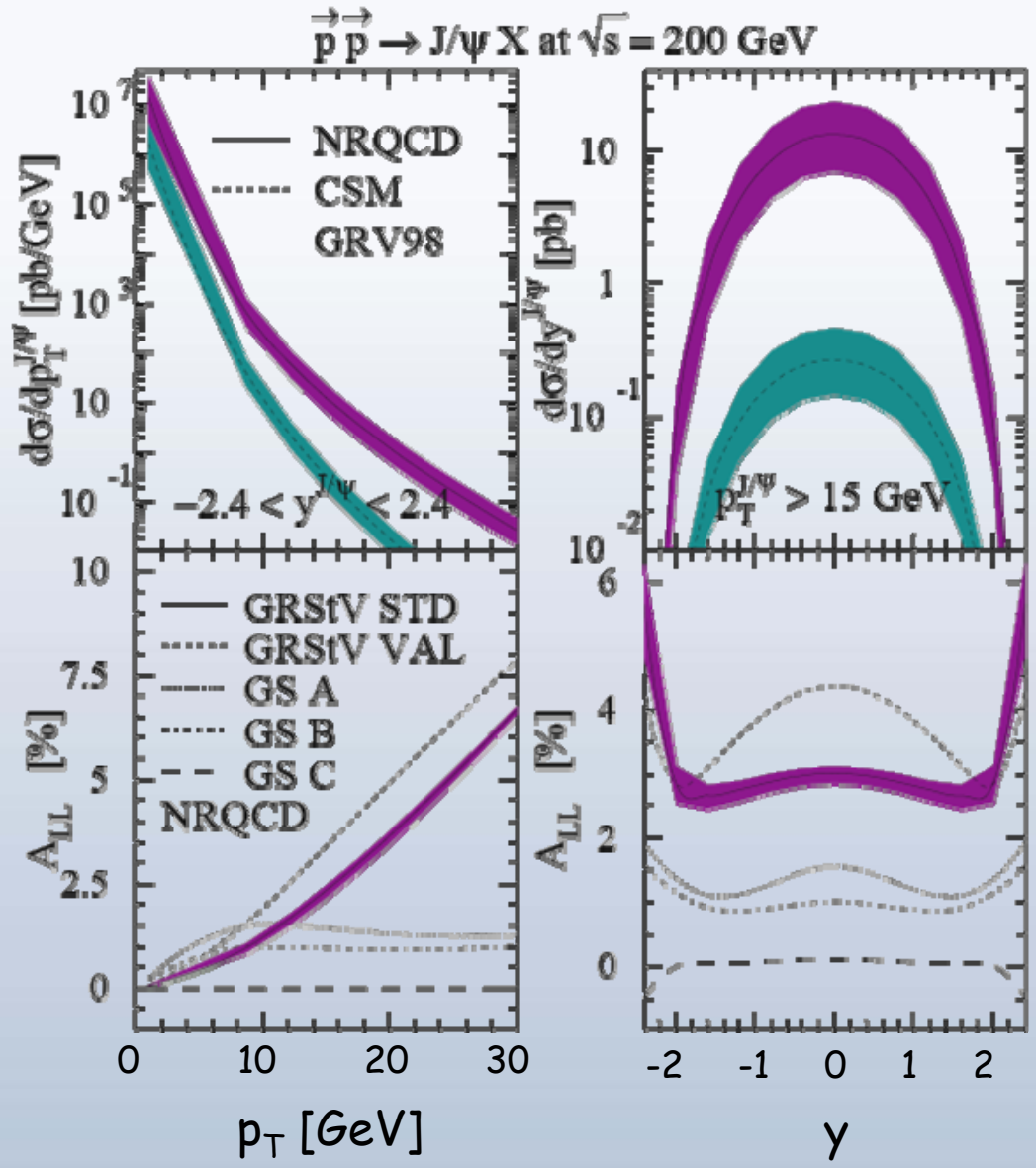
things not mentioned - cont'd

J/Ψproduction in polarized pp collisions at RHIC

LO NRQCD results have been obtained in

Klasen, Kniehl, Mihaila, Steinhauser
hep-ph/0306080; arXiv: 0802.3833

updated results?



Outlook – will it fly?

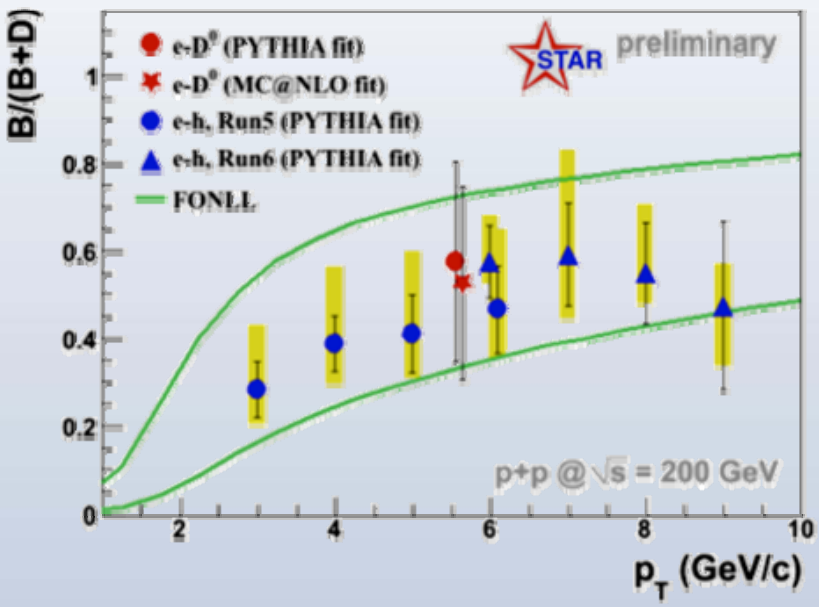
other avenues

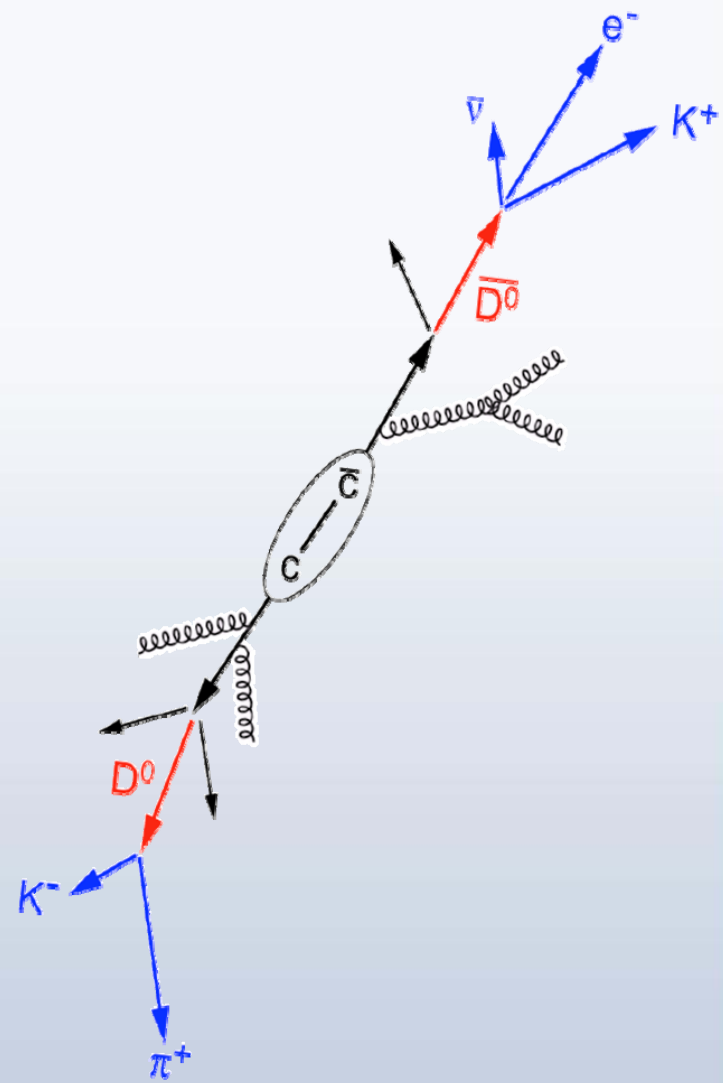
- **hadronic charm & bottom decays**

  e.g. (STAR): look for like sign eK pairs

  far side: mostlycharm

  near side: bottom dominated





  difficult to model in theoretical calculation

  need to interface with PYTHIA for hadronic decays

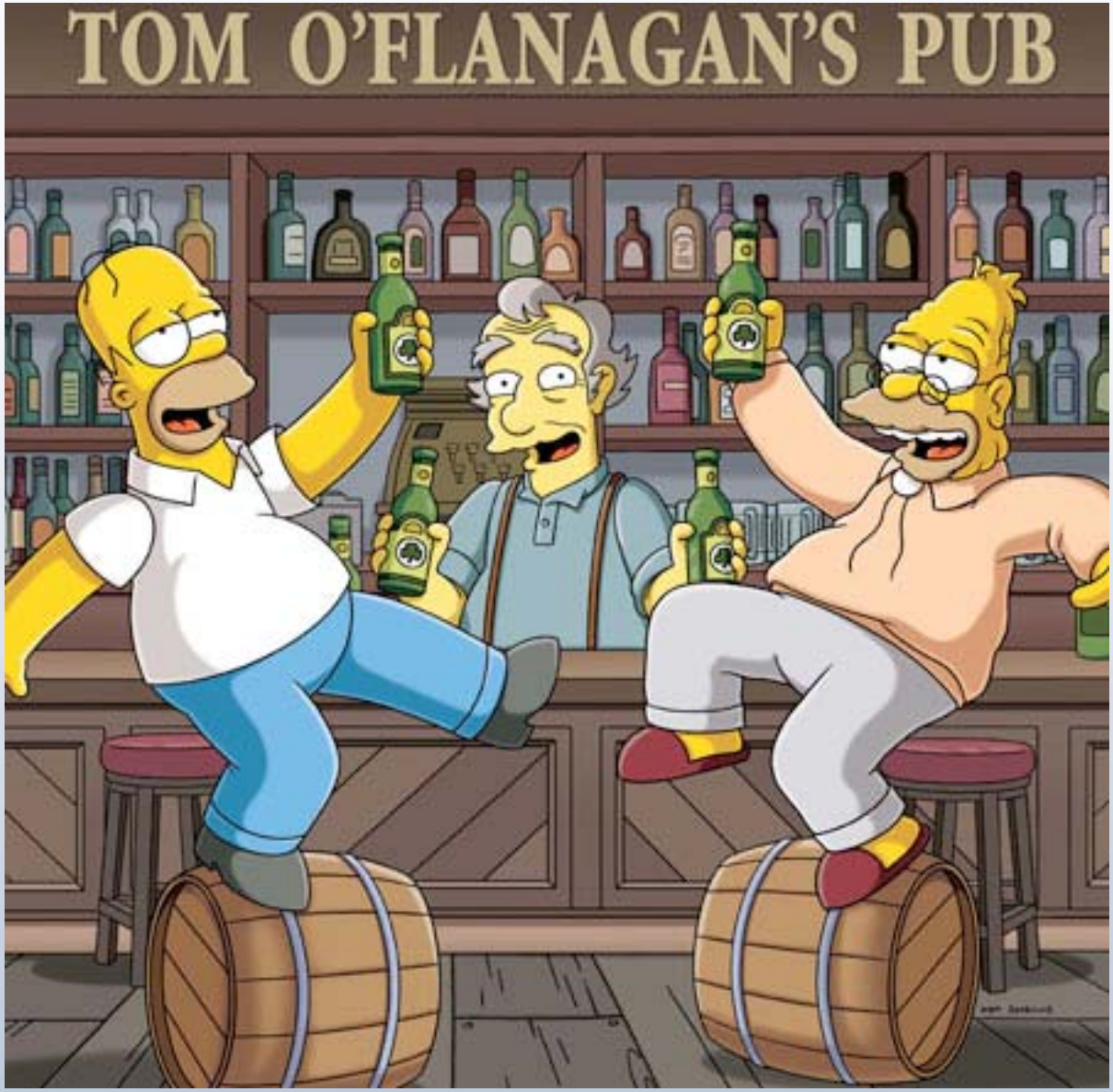
- **secondary vertex reconstruction** → clean sample of charm?

summary

- rare probe but crucial to further our understanding of spin-dep. hard scattering
- newNLO parton-level MC with fragmentation to heavy mesons &leptonic decays
- sizable theor. uncertainties; partly cancel in A_{LL} but not scale ambiguity
- decay lepton correlations are better suited observables than single-incl. leptons
- luminosities of a few hundred pb^{-1} are required for meaningful measurements
- suite of HQ observables can cover a wide range in x

challenging both experimentally & theoretically

heavy flavors often bare surprising results


TOM O'FLANAGAN'S PUB

HAPPY
ST. PATRICK'S
DAY!