July 8th, 2008

Charm @ J-PARC

mainly from a QCD hard scattering perspective

Marco Stratmann

RIKEN

The Plan

- charm as a QCD lab
    - open charm production
        - quarkonium production
            - intrinsic charm

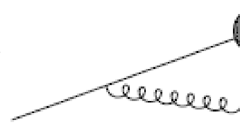
disclaimer: heavy flavor physics has developed into a vast field
can only scratch on the surface in this talk

I. Charm as a QCD lab

charm as a QCD lab

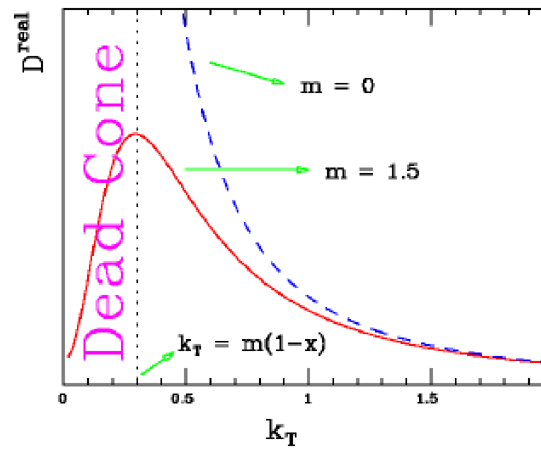
...it makes a difference to be heavy (i.e., $m \gg \Lambda_{QCD}$)

- 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" $\Theta < m/E$
    $\rightarrow$ **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, ...

II. Open charm production

- pQCD framework
- cross sections for GSI, J-PARC
- threshold effects
- spin asymmetries

a multi-scale problem

@ J-PARC

$s^{1/2}$
hard scale
p_T

m
quark mass

Λ_{QCD}
hadronic scale

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-Parisi techniques
→ pert. HQ FFs, PDFs

not really relevant $p_T \simeq m$

partonic threshold
(details depend on process)

can be resummed to all orders with Sudakov techniques

should be included

non-perturbative functions (PDFs, FFs) sit here

an ideal HQ calculation

can stop here for total cross section

$pp \longrightarrow Q \longrightarrow$ HQ meson $\longrightarrow$ decay e, μ

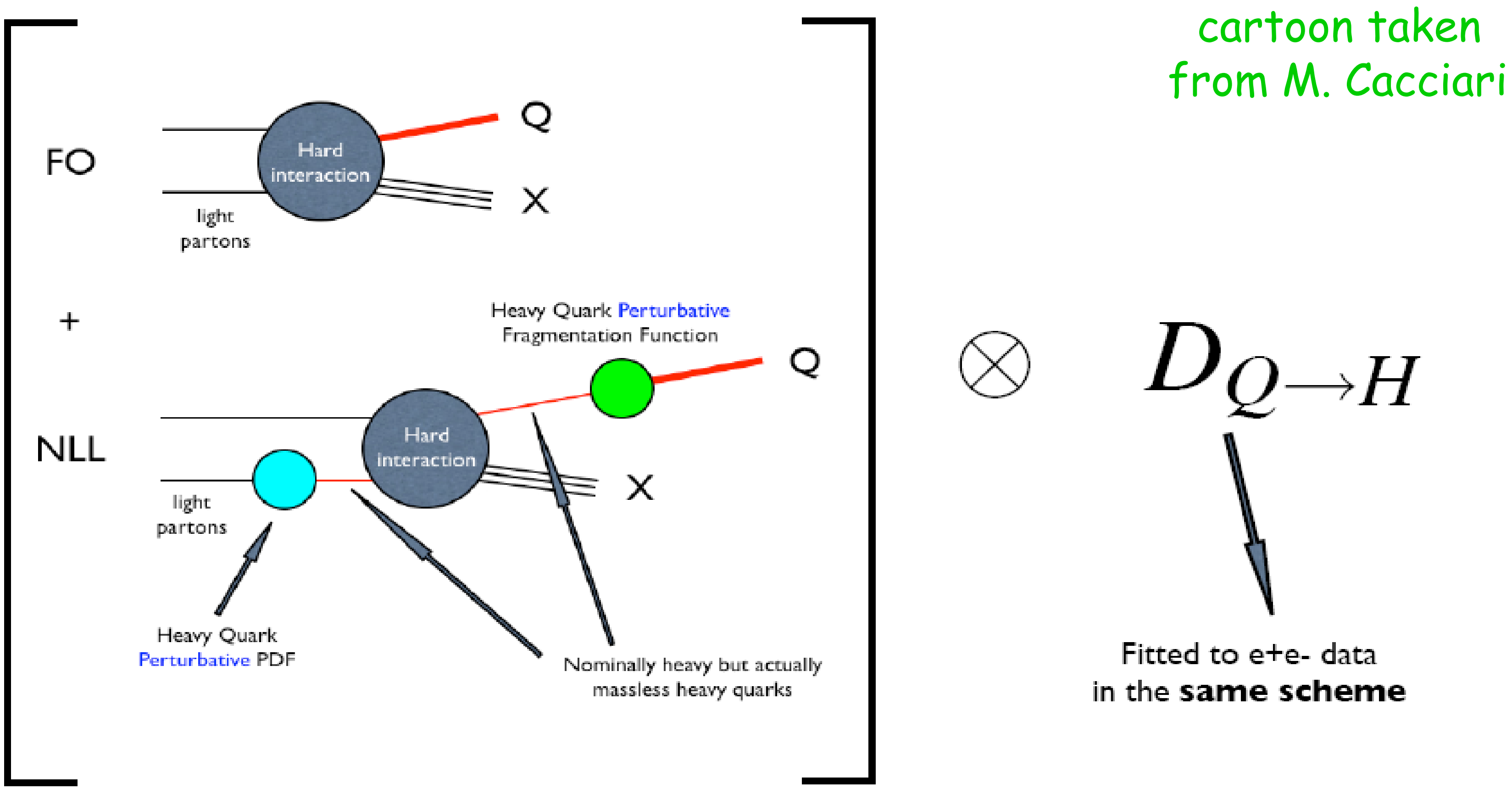
- $pp \to Q$: pQCD + resummations
- $Q \to$ HQ meson: non-pert. FF extracted from data — Cacciari et al., … (very important!)
- HQ meson $\to$ decay: MC simulation

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-NNNLL Kidonakis et al., …

sketch of FONLL HQ calculation

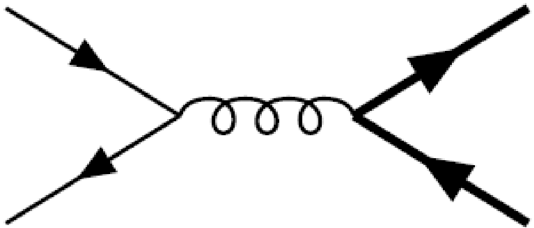


here we stick to NLO [since $p_T/m = O(1)$ for J-PARC]

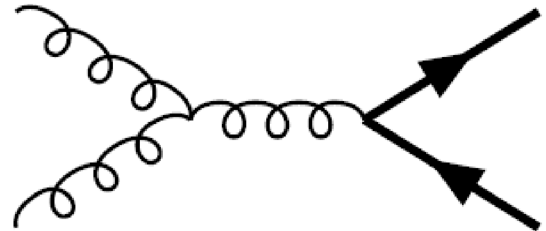
possible effects of threshold resummations will be briefly touched

anatomy of HQ production in pQCD

LO



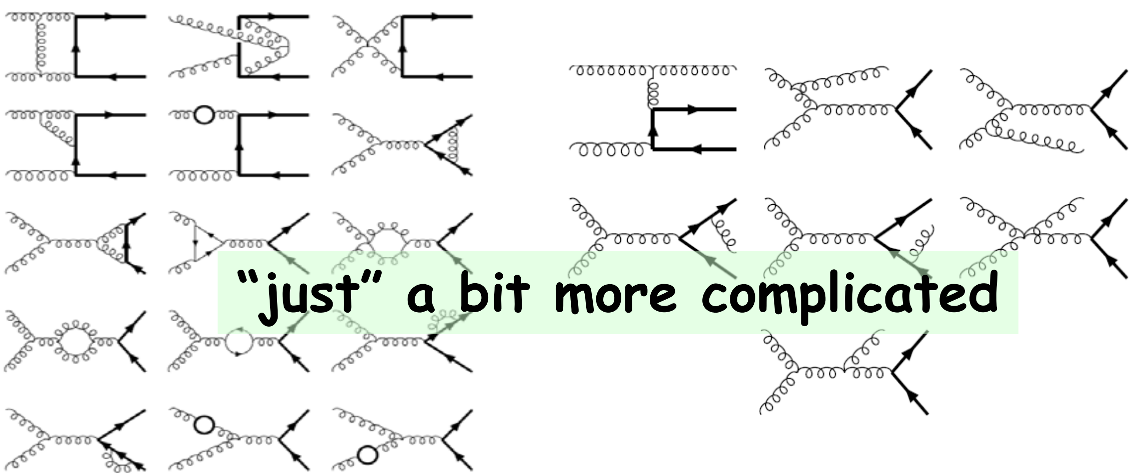
light quark-antiquark annihilation



gluon-gluon fusion

by far the dominant mechnism at high energies
might prevail also at low-energy pp !!

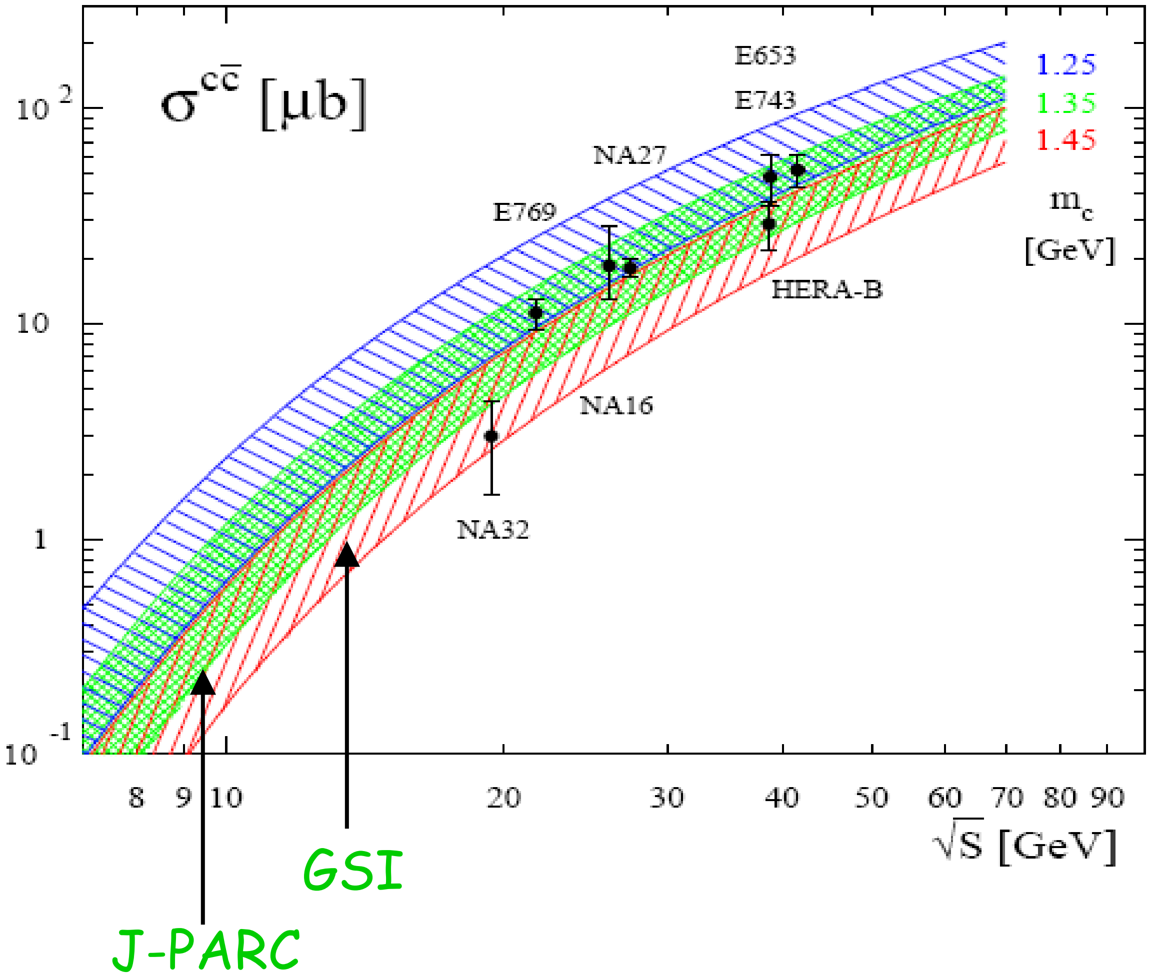
NLO



"just" a bit more complicated

plus many many more …

low energy results: terra incognita



total charm cross section

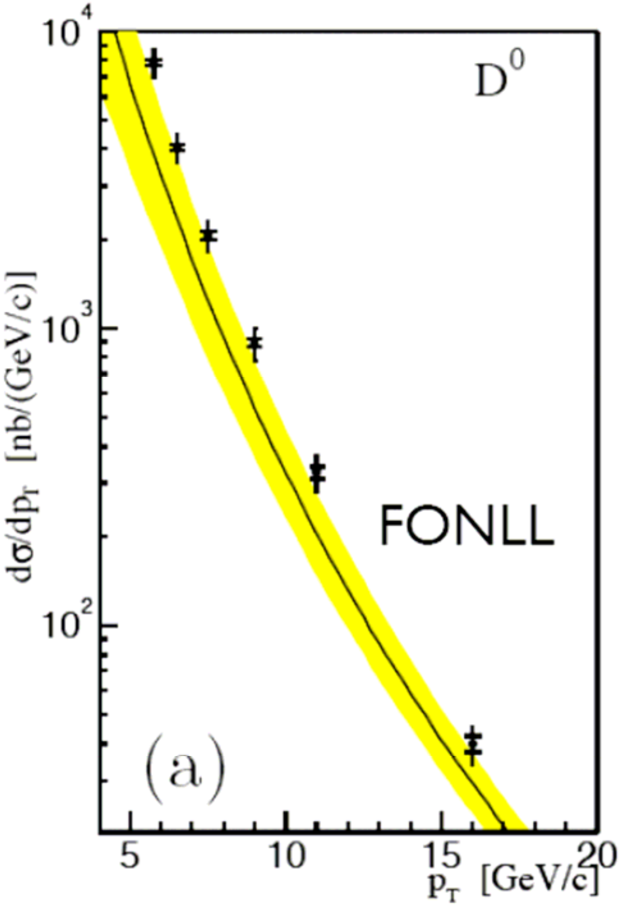
significant uncertainties:

charm mass
choice of scales

$m_c < \mu < 2m_c$

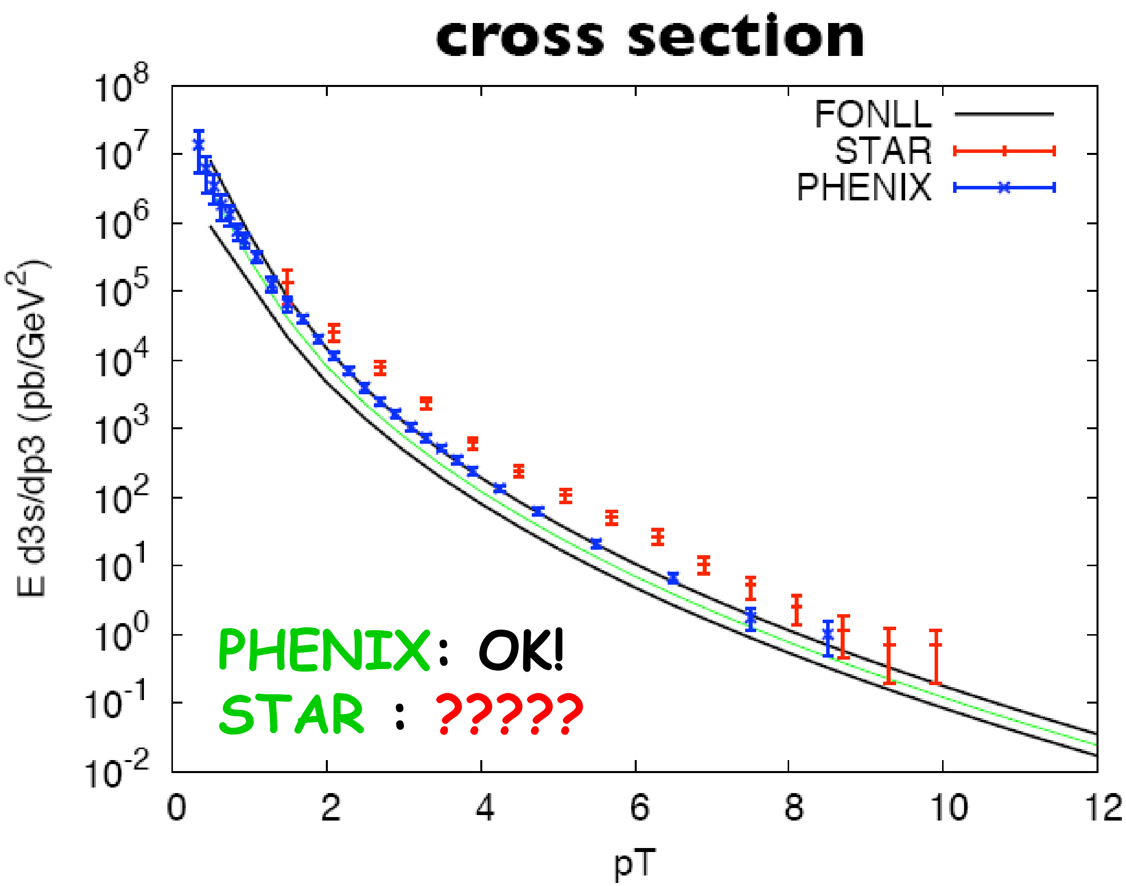
FONLL vs. collider data: in good shape!

CDF run II



FONLL calculation:
Cacciari, Nason

RHIC: PHENIX & STAR



from a talk by M. Cacciari

some predictions for GSI & J-PARC

GSI-FAIR

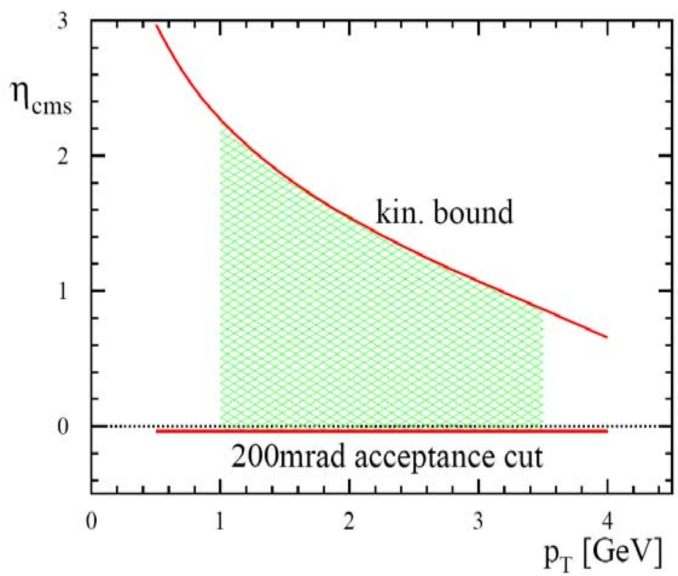
proton (3.5 GeV) – *anti*-proton (15 GeV) collisions

assume PAX detector acceptance:
5 - 130 deg. scattering angles

J-PARC

50 GeV proton beam on fixed target

assume COMPASS-like spectrometer:
200mrad acceptance

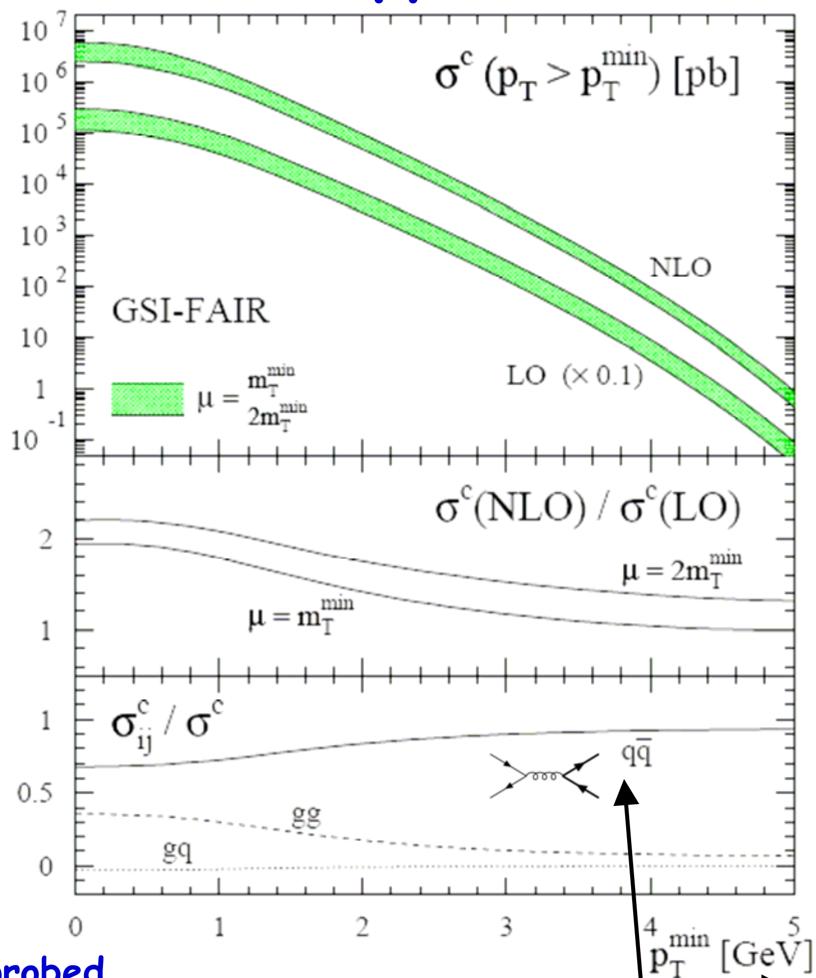


translates into p_T-η-plane

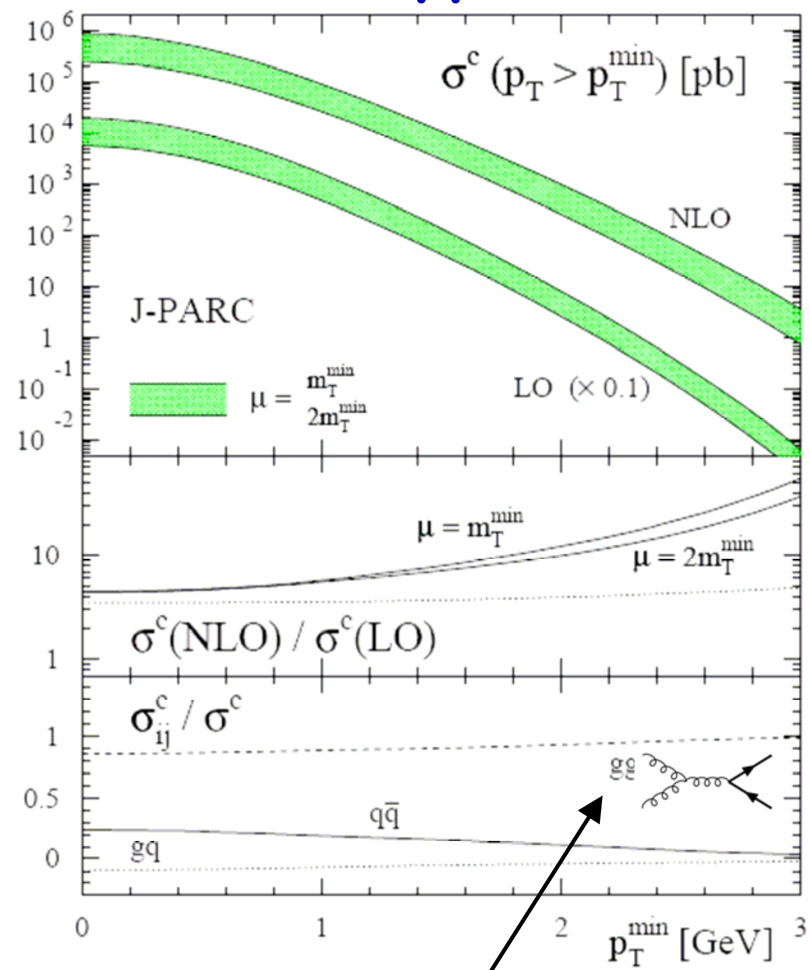
disclaimer:
all calculations NLO
only at HQ – level
(no hadronization, decay)

Riedl, Schafer, MS

$p\bar{p}$



pp



probed x-range (roughly)

x: 0.15 0.3 0.45

x: 0.2 0.4 0.6

mainly valence-valence scattering

still gluon-gluon fusion !!

why still gluon-gluon fusion at 10 GeV?

→ study parton-parton luminosities (relevant for total cross section)

$$\Phi_{ij}(\tau,\mu) = \tau \int_0^1 dx_1 dx_2 \delta(x_1 x_2 - \tau) f_i(x_1,\mu) f_j(x_2,\mu)$$

$$\sigma^{c\bar{c}}(S,m^2) = \sum_{i,j} \int_{4m^2/S}^1 \frac{d\tau}{\tau} \Phi_{ij}(\tau,\mu) \hat{\sigma}_{ij}(\tau S, m^2, \mu)$$

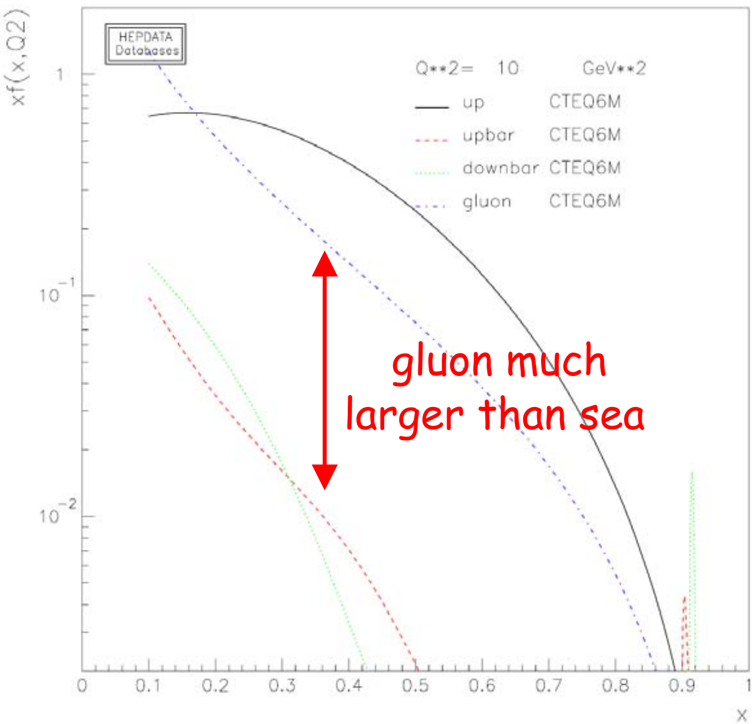
also define distance to partonic threshold η

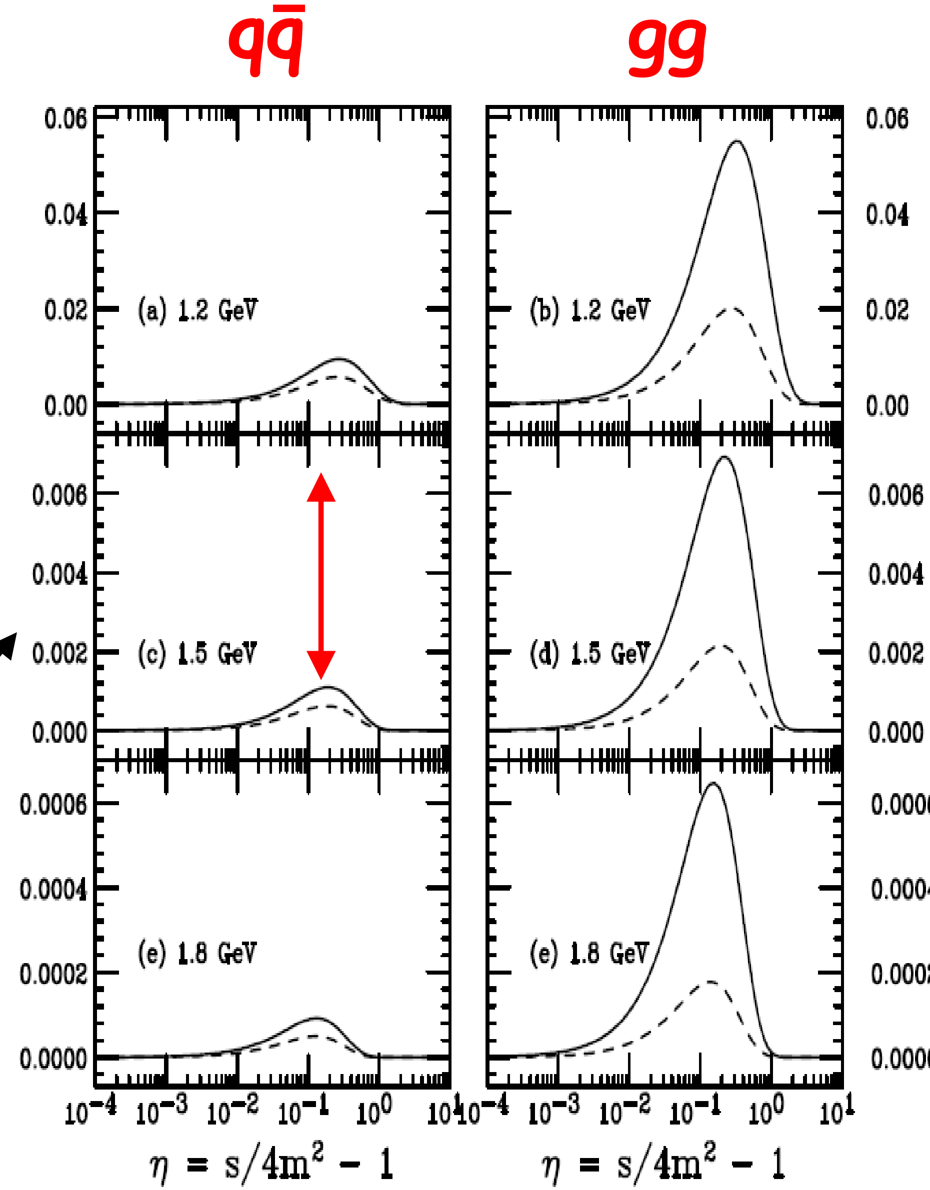
$$\eta = \frac{\hat{s}}{4m^2} - 1 = \frac{\tau S}{4m^2} - 1$$

$\eta \to 0$ partonic threshold

$\eta \to \infty$ high energy limit

physical cross section is always a convolution from η=0 to η_{max}





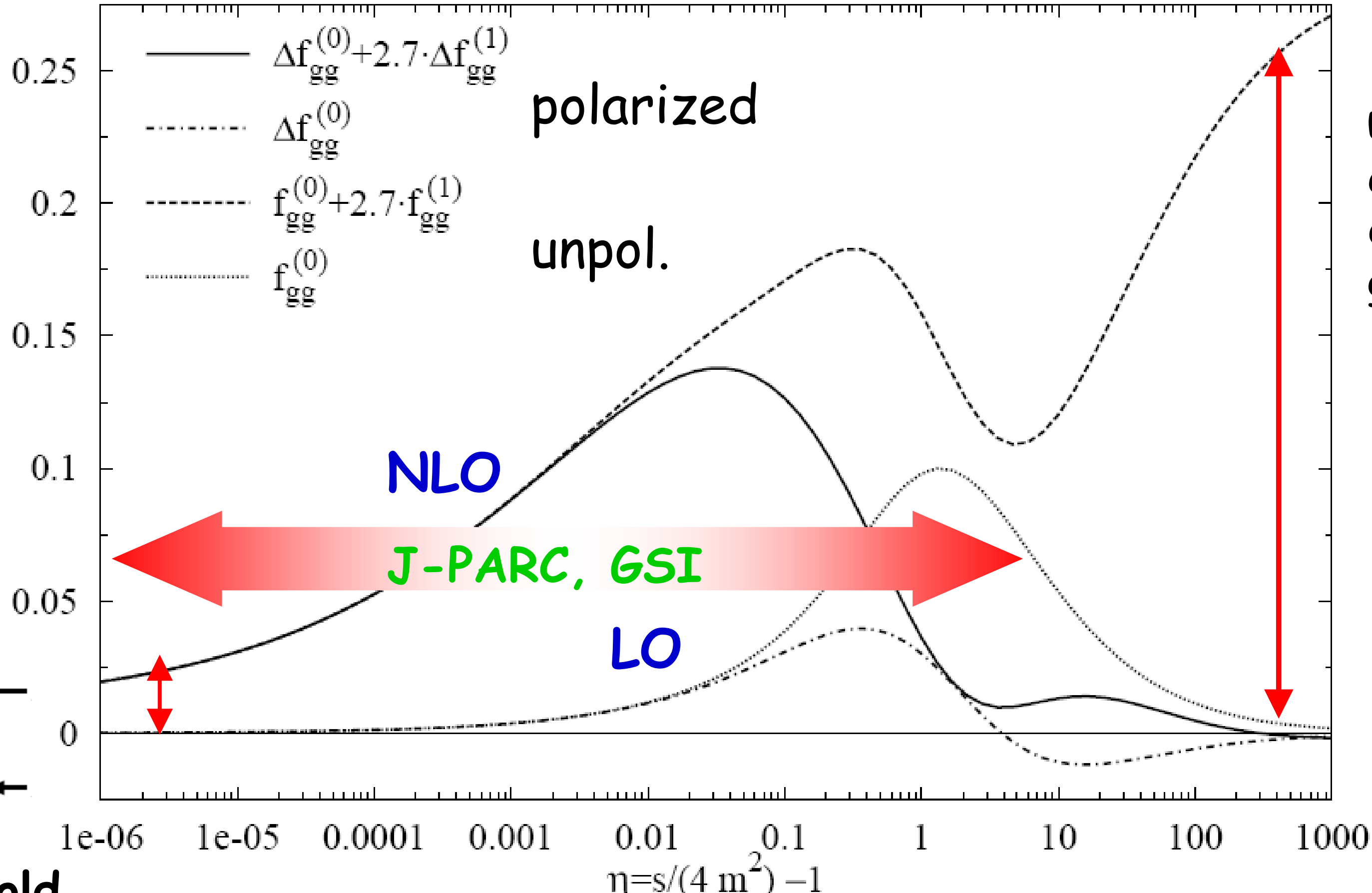
feeds into parton luminosities

→ gluon-gluon fusion prevails in pp down to low energies

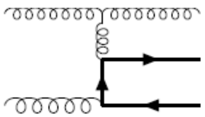
but: recall that $g(x)$ is largely undetermined by data for $x \gtrsim 0.4$

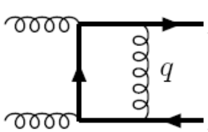
from Kidonakis et al.

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



unpol:
enhancement due to t-channel gluon exchange





threshold corrections:
"Coulomb sing."
+ soft gluon logs.

impact of threshold resummations

at *partonic* threshold:
- just enough energy to produce observed parton
- "inhibited" gluon radiation (no phase space)

→ IR cancellation leaves large logarithms from soft gluons at *each* order in perturbation theory ("Sudakov corrections")

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

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

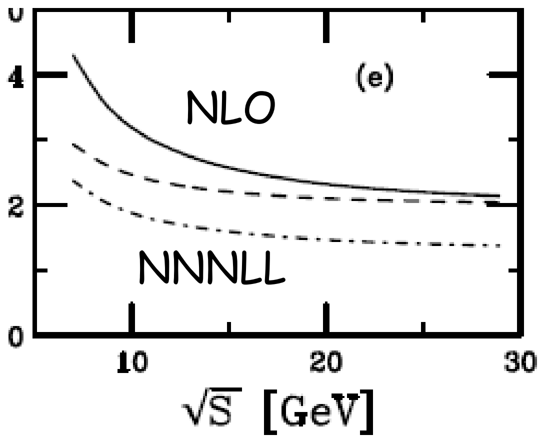
- worked out for most processes of interest at least to NLL
- well defined class of higher-order corrections
- often of much phenomenological relevance, in particular at low energy fixed-target experiments

… some estimates available

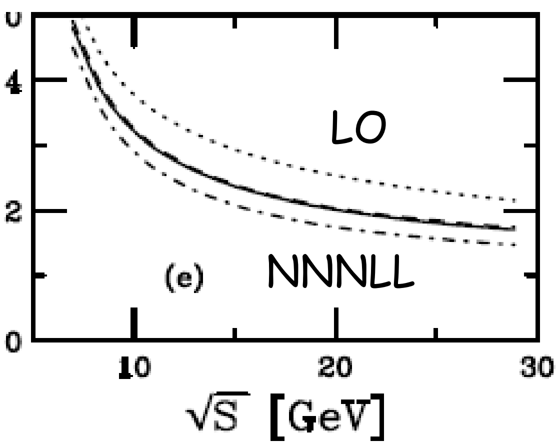
Kidonakis, Laenen, Moch, Vogt;
Kidonakis, Vogt; …

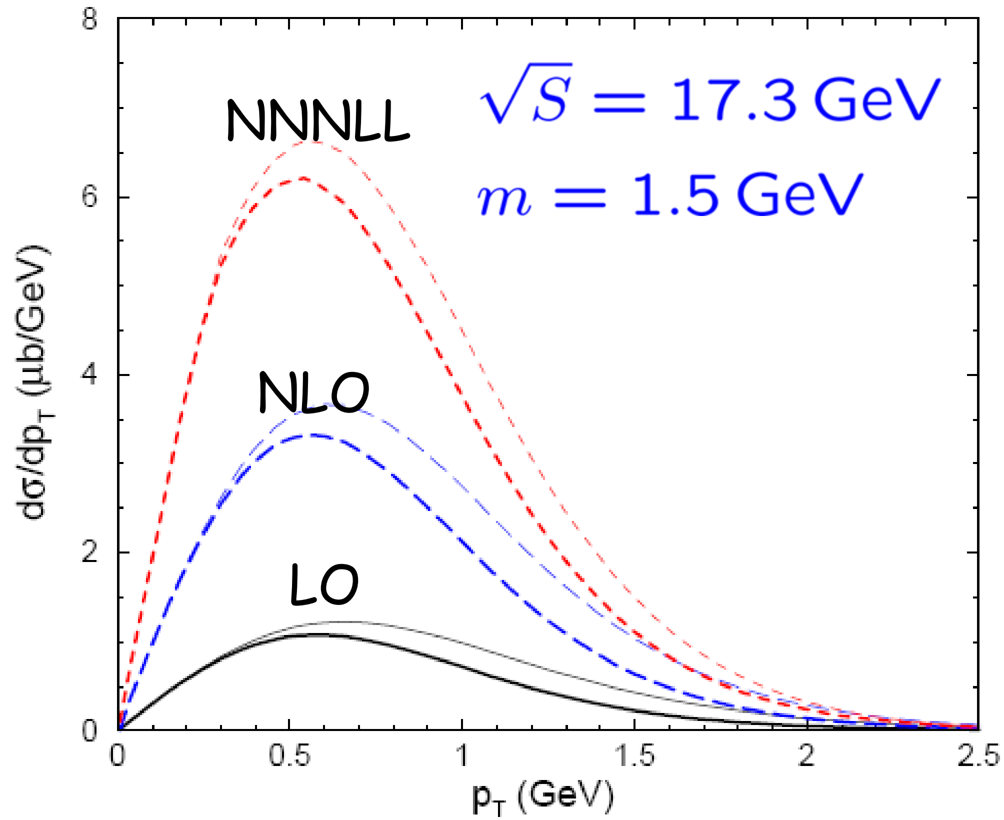
$\sigma^{c\bar{c}}_{\text{tot}}$

K factors



scale uncert.





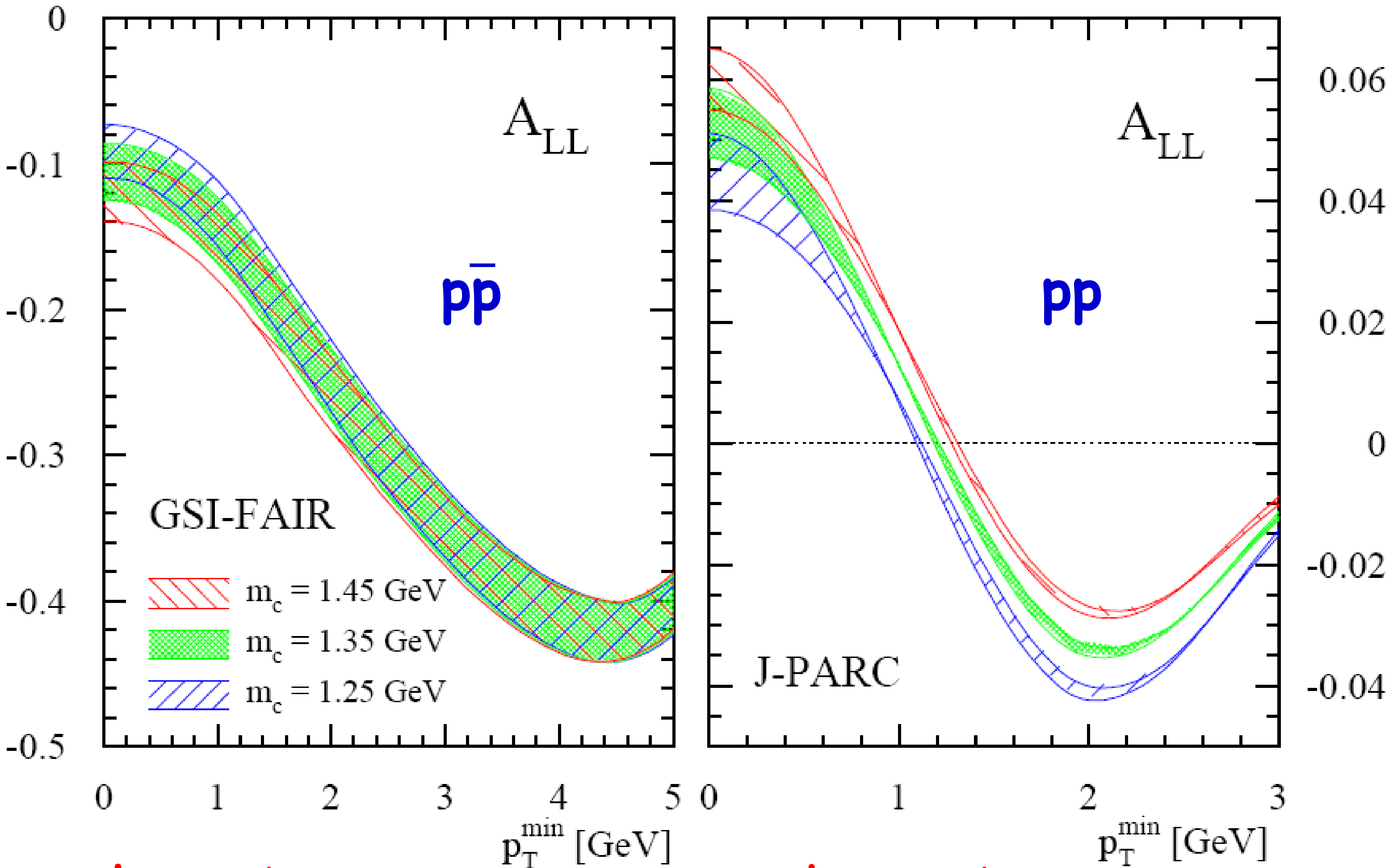
full NNLO result might do a good job
work has started; first partial results

Korner et al.; Czakon et al.; …

spin asymmetries at GSI-FAIR and J-PARC

estimates for NLO spin asymmetries

Riedl, Schafer, MS



large A_{LL}

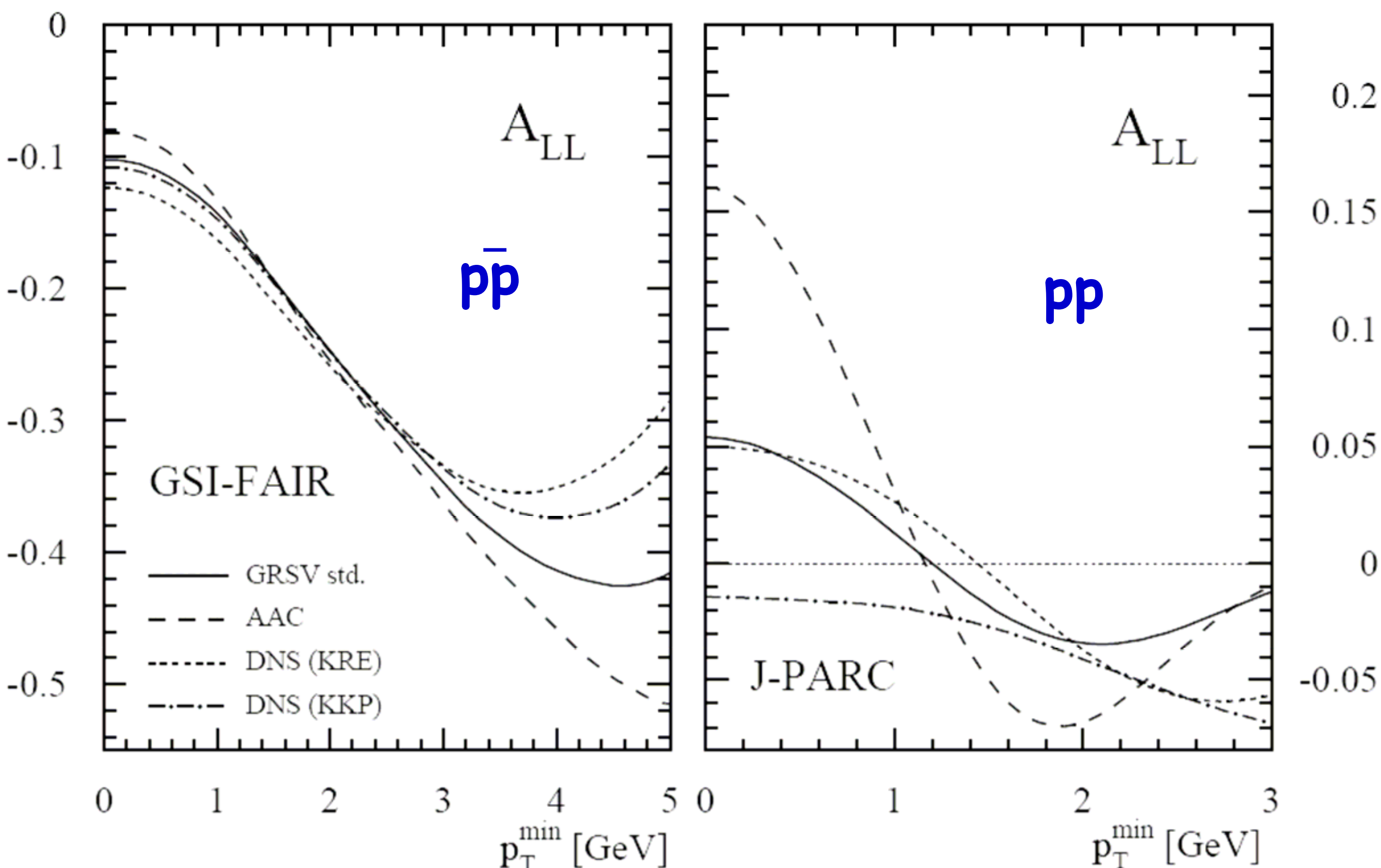
mainly $q\bar{q}$ scattering

moderate A_{LL}

still significant gg scattering

Riedl, Schafer, MS

subprocess fractions leave imprint also in PDF dependence



x

0.15 0.3 0.45 | 0.2 0.4 0.6

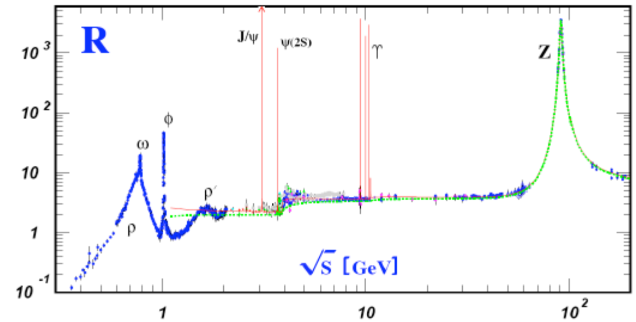
probes mainly Δq_{val} | probes quarks *and* gluons

summary on open charm production

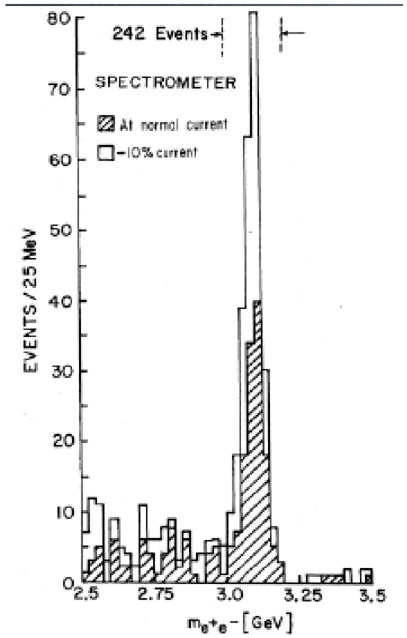
- GSI-FAIR and J-PARC probe complementary aspects of hadron structure
- charm production in pp at c.m.s. energies of O(10 GeV) never explored
  $\rightarrow$ novel effects?
- applicability of pQCD methods is not at all guaranteed
  - large corrections and scale uncertainties
  - close to threshold $\rightarrow$ resummations, non-pert. effects relevant?
  - breakdown of factorization?

however, this cannot be explored without measurements !!

possible window to the non-pert. regime



III. Quarkonium (J/Ψ) production



theoretical framework

some reviews:

M. Kramer, hep-ph/0106120
J.-Ph. Landsberg, hep-ph/0602091
QWG report, hep-ph/0412158 (500 pages!)

general problem

- many different approaches, range of applicability still under debate
- new exp. results often revealed dramatic shortcomings of models
- often predictions are only to leading order accuracy

huge theoretical uncertainties

we only briefly touch two frameworks:

- non-relativistic QCD (NRQCD)
- color evaporation model (CEM)

NRQCD

Bodwin, Braaten, Lepage; ...

idea: make use of the distinct energy scales → factorization

m (mass) mv (momentum) mv^2 (kin. energy)

- the heavy quark mass m sets a (rather) large scale: $\alpha_s(m_c) \simeq 0.35$

→ production of $Q\bar{Q}$ pair is a **short-distance process** at scales $1/m$ or smaller → calculable in pQCD

- potential model + virial theorem, find 2nd "small" parameter: $v_c \simeq 0.6$

→ $Q\bar{Q}$ to quarkonium transition is non-perturbative at **long-distance** scales $1/mv$ (quarkonium size) or larger

this suggests a factorized approach similar to open charm

here it is …

provided that 1/(mv) >> 1/m we can write

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

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
include effects of soft gluons

- double expansion in α_s and relative velocity v
- **rigorous framework** ("effective field theory"), can be systematically improved, resembles full QCD in the limit $\Lambda_{QCD}/m \rightarrow 0$
- a lot of progress on foundations of NRQCD factorization recently
  Nayak, Qiu, Sterman

predictive power?

infinite number of terms $\rightarrow$ have to truncate $\sum_n$ in a controlled way

key: NRQCD power counting plus universality of $\langle \mathcal{O}_n^H \rangle$

consider chromoelectric/magnetic selection rules to estimate

$\Delta L = \pm 1, \Delta S = 0 \qquad \Delta L = 0, \Delta S = \pm 1$

suppression of $|Q\bar{Q}g\rangle, \ldots$ relative to dominant $|Q\bar{Q}\rangle$ (with qu. numbers of H)

find: $$\mathcal{O}^H[{}^{2S+1}L_J^{(1,8)}] \simeq v^{3+2L+2E+4M}$$ (see, review by M. Kramer)

#elec./magn. transitions

- always requires presence of color-singlet *and* octet matrix elements
  the old "color singlet model" is theor. inconsistent (uncanceled IR poles!)

- NRQCD matrix elements fitted from data – considerable uncertainties!

J/Ψ hadroproduction

phenomenological meaningful description requires at least

$$\mathcal{O}^{J/\Psi}[^3S_1^{(1)}] \quad \mathcal{O}^{J/\Psi}[^3S_1^{(8)}] \quad \mathcal{O}^{J/\Psi}[^1S_0^{(8)}] \quad \mathcal{O}^{J/\Psi}[^3P_J^{(8)}]$$

color singlet $\simeq v^3$

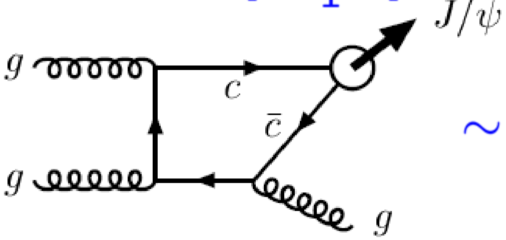
color octet

$\simeq v^7$ but enhanced kinematically !

- relevance of terms also determined by $d\sigma^n$, factors of α_s, m/p_T, …

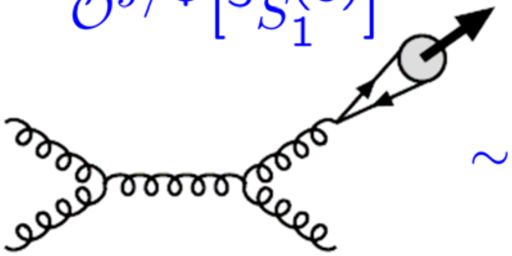
e.g.

$\mathcal{O}^{J/\Psi}[^3S_1^{(1)}]$



$\sim \alpha_s^3 \frac{m^4}{p_T^8}$

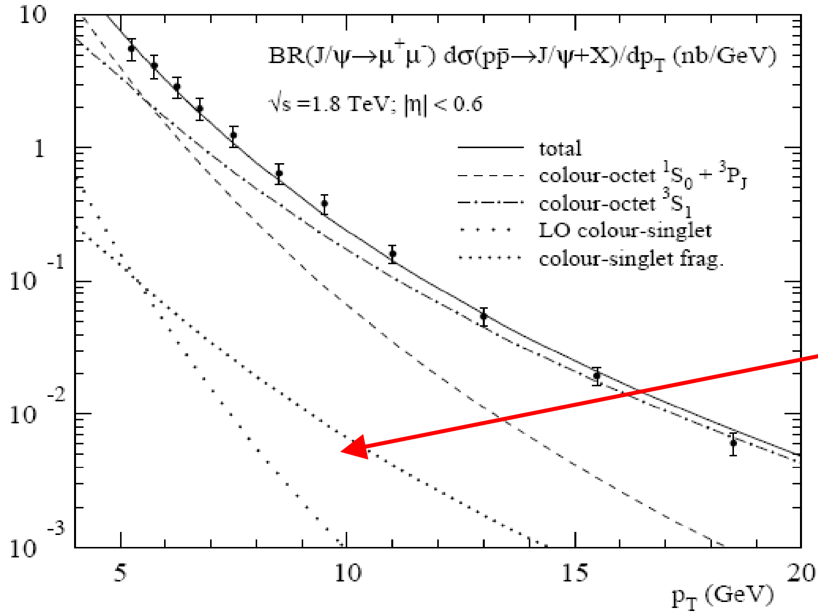
$\mathcal{O}^{J/\Psi}[^3S_1^{(8)}]$



$\sim \alpha_s^3 \frac{v^4}{p_T^4}$

- series in α_s and v often converges slowly → large uncertainties

NRQCD scorecard:



successes

J/Ψ production at the TeVatron

Braaten, Fleming; Braaten, Yuan; Kramer

lashing denial of (inconsistent) CSM

fit consistent with $\mathcal{O}_8^{J/\Psi}/\mathcal{O}_1^{J/\Psi} \simeq v^4$

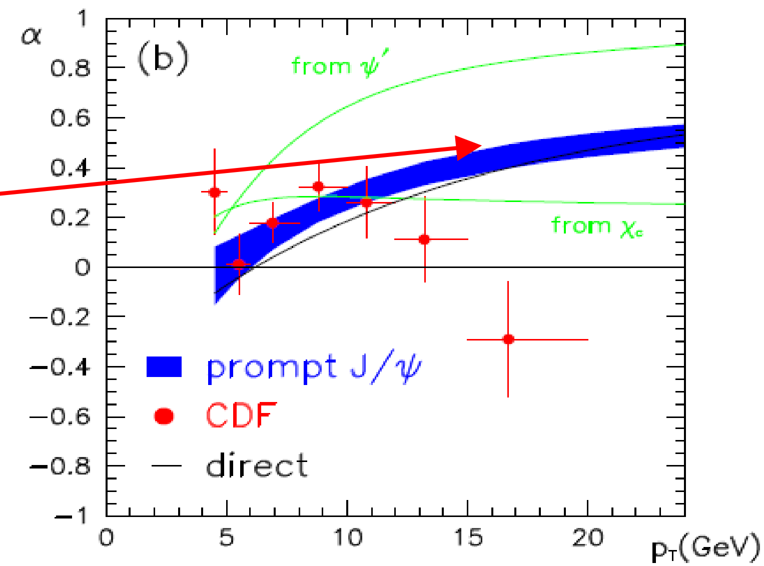
and failures

predictions for J/Ψ polarization

Braaten, Kniehl, Lee

beware! this is only a LO result

[other "problems" have been solved by computing higher order terms]



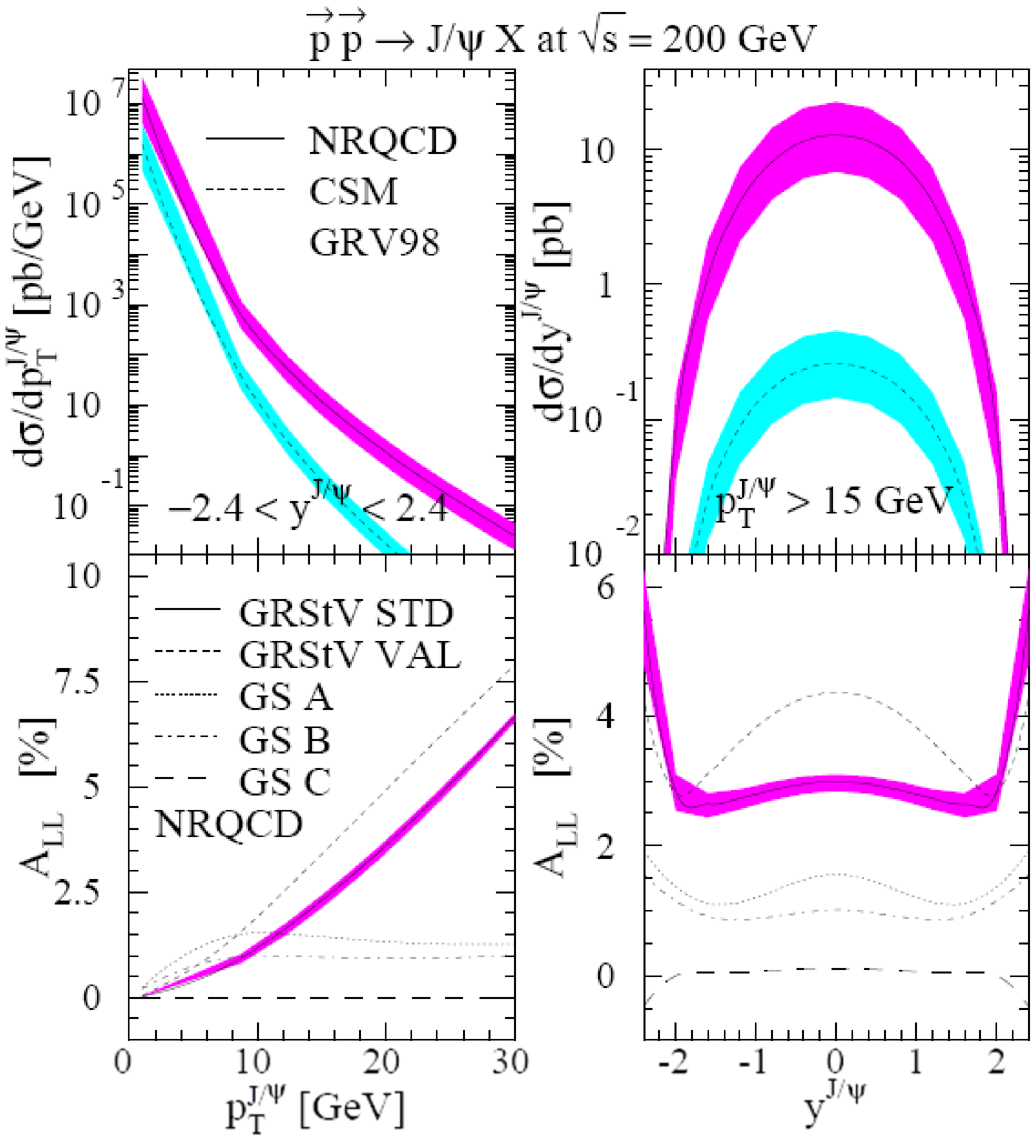
J/Ψ production in polarized pp collisions

LO NRQCD results have been computed

Klasen, Kniehl, Mihaila, Steinhauser
hep-ph/0306080

and applied to RHIC

lower energies ?



color evaporation model (CEM)

Fritzsch; Halzen; …

- most appealing is its simplicity
- assumes that any $Q\bar{Q}$ pair with small v can form quarkonium by emission of soft gluons – no constraints on color/ang. momentum

Qq meson threshold

$$d\sigma^{CEM}(H) = f_H \int_{2m_Q}^{2M_{Qq}} dM_{Q\bar{Q}}\, d\sigma(Q\bar{Q})$$

universal "fraction" to be determined from data

threshold

- early pheno. successes; predictions often at odds with recent data
- revived as soft color interaction (SCI) model

Edin, Ingelman, Rathsman; …

idea: randomly exchange color state of two softly interacting partons can be only implemented in MC models (one parameter)

prospects for quarkonium studies at J-PARC

- NRQCD seems to be (the only) theoretically sound approach
  - factorization; systematic framework
  - limit $\Lambda_{QCD}/m \to 0$ coincides with full QCD

  but there is lot of room for improvement
  - often only LO results; large uncertainties
  - universality of NRQCD matrix elements not really demonstrated
  - issues with quarkonium polarization, NRQCD scaling rules, …

unfortunately, no theory predictions for J-PARC yet

- most likely we have to be prepared for potential problems
  - close to threshold; need for resummations, non-pert. corrections
  - possible breakdown of factorization

a better understanding certainly needs more data

IV. Intrinsic charm

what's the status?

NORDITA-80/18

THE INTRINSIC CHARM OF THE PROTON

S.J. Brodsky*, Stanford Linear Accelerator Center,
Stanford, California 94305

P. Hoyer, C. Peterson and N. Sakai, **
NORDITA, Copenhagen

general idea

Brodsky, Hoyer, Peterson, Sakai **(BHPS)**

see, Pumplin, hep-ph/0508184

- in the light-cone Fock-state picture of the proton it is natural to expect a non-perturbative "intrinsic" charm (IC) component

$$\simeq |uudc\bar{c}\rangle + \ldots$$

- framework not developed to a point to predict its normalization expect a roughly 1% probability for IC

- x-shape can be computed (with assumptions), e.g., BHPS

$$c(x) = \bar{c}(x) = Nx^2 \left[6x(1+x)\ln x + (1-x)(1+10x+x^2)\right]$$

implying (1% norm.): $\langle x \rangle_{c+\bar{c}} = \int_0^1 [c(x) + \bar{c}(x)]\, x\, dx = 0.0057$

$|uudc\bar{c}\rangle$ suppressed by their off-shell distance $\simeq (p_\perp^2 + m^2)/x$

$\rightarrow$ IC concentrated at large x

How to test it?

- proponents of IC often claim EMC F_2^c data as "positive evidence" but it is of no statistical significance

→ **recent attempts by CTEQ to accommodate IC into a full global analysis of PDFs**

- **immediate problem:** light cone ideas are heuristic
  → not clear whether they should be applied in $\overline{MS}$ or some other scheme and at what scale μ_0?

- **CTEQ 6.5** and **6.6 global analyses**:

  hep-ph/0701220; arXiv:0802.0007 [hep-ph]

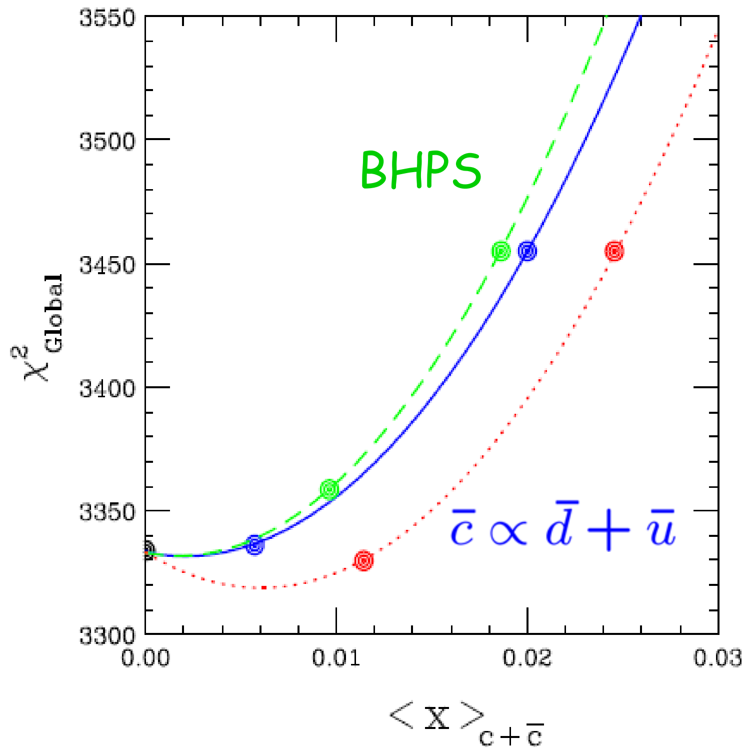
  implement IC at $\mu_0 = m_c = 1.3$ GeV

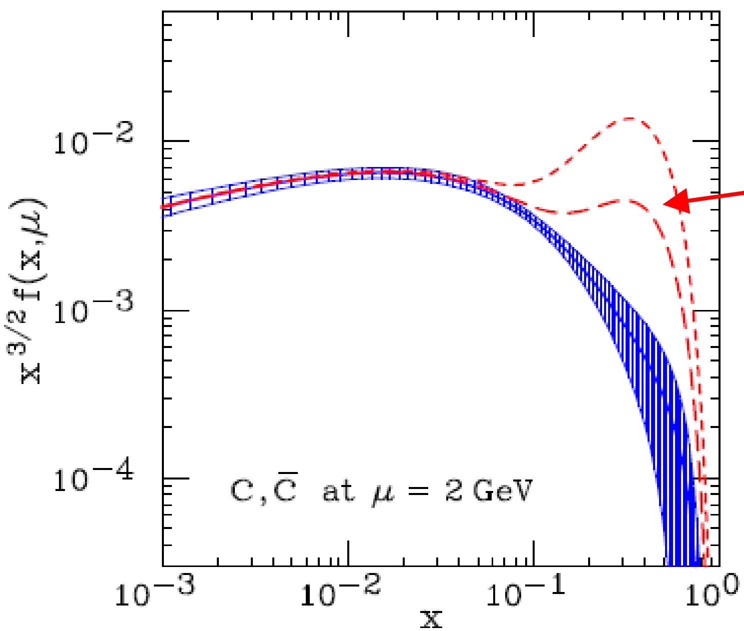
  perform global fits varying the magnitude of IC

  check goodness of fit with Lagrange multiplier for $\langle x \rangle_{c+\bar{c}}$

here is what they find …

- fit very insensitive to $\langle x \rangle_{c+\bar{c}}$
- no evidence either for or against IC up to $\langle x \rangle_{c+\bar{c}} \simeq 0.01$
- $\langle x \rangle_{c+\bar{c}} \gtrsim 0.02$ ruled out





IC can be significant at large x but c(x) still smaller than u(x), d(x), and g(x) !

CTEQ 6.5 and 6.6 sets with IC are available from www.cteq.org !!

V. Concluding remarks

there are many interesting
scientific opportunities at J-PARC
related to charm physics
even if in the end pQCD is not the right framework

in any case it will be challenging
for both experiment and theory