Zeuthen 7/9/2001

Heavy Flavor Production in Polarized pp Collisions

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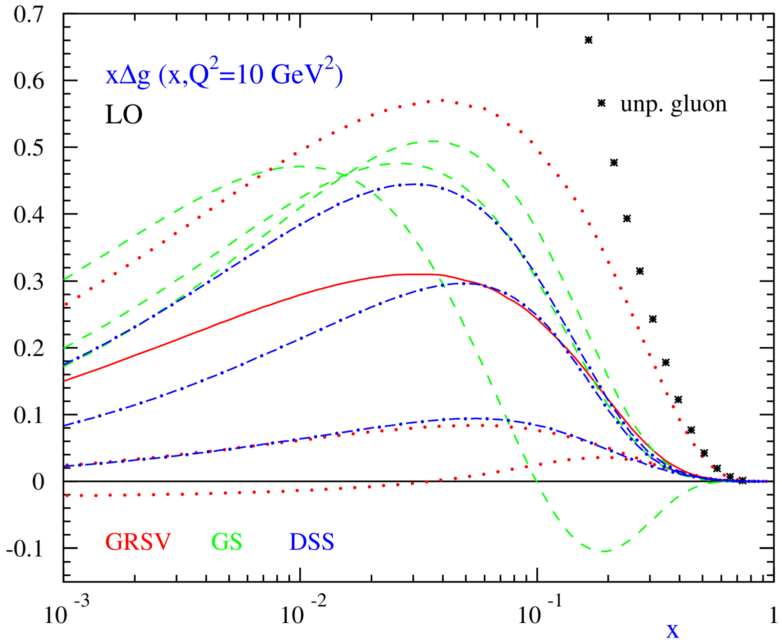
- **Motivation**: Hunting down Δg
- **Open heavy flavor production in NLO QCD**:
  - Why NLO?
  - Sketch of NLO calculation (method, problems)
  - Some results
- **Matching theory and experiment**:
  - Heavy quark decay & detection ('efficiency')
  - Extraction of Δg ('global analysis')
- **Detour**: Do we understand *unpolarized* HQ data?
- **Summary & Outlook**

• Motivation: hunting down Δg

What do we know from QCD analyses of DIS data?



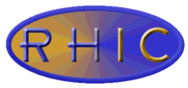
$\rightsquigarrow$ $\Delta g(x, Q^2)$ only weakly constrained by DIS data alone

- lever-arm in Q^2 too small to study scaling violations
- no sum rule which *directly* relates quarks and gluons
  unpol.: mom. sum; pol.: spin sum contains *unknown* $L_z^{q,g}$)

$\rightsquigarrow$ need

- DIS data at *higher* energies ($\to$ EIC, pol. HERA, . . . ??)

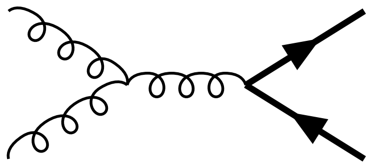
and/or

- direct information on Δg from *other* processes $\to$ 

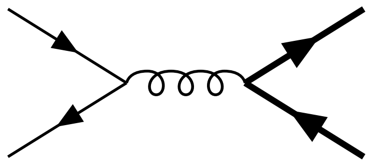
$\Uparrow$

best candidates: processes dominated by Δg in LO

e.g. HQ prod.:



vs.



dominant at small/med. p_T takes over at large p_T

General problem of all QCD analyses so far:

lesson from *unpolarized* fits: CTEQ, GRV, MRST

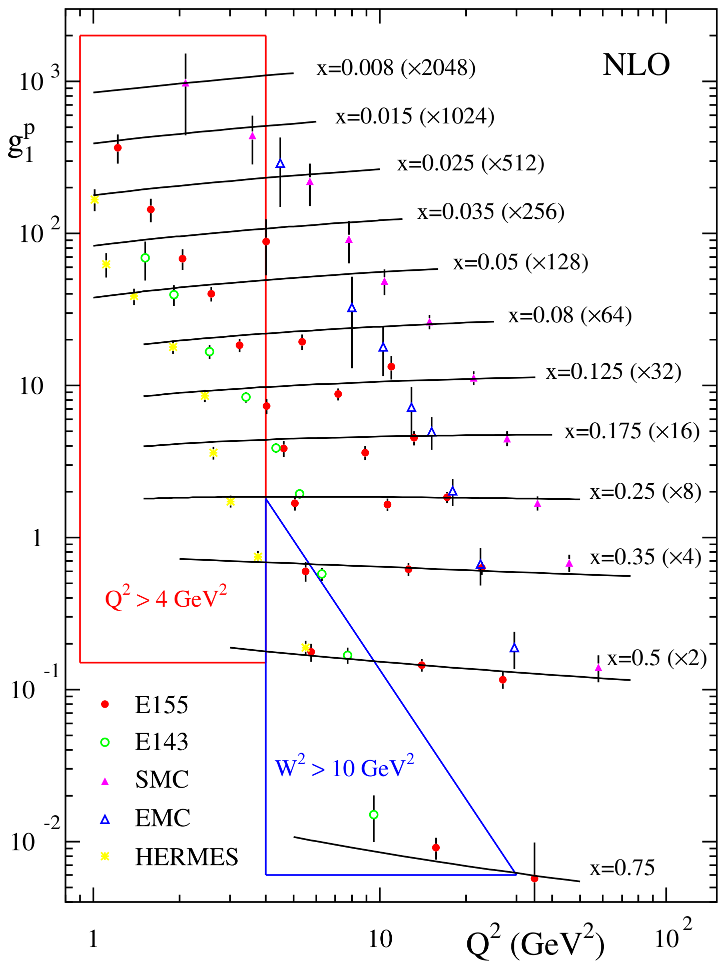
leading twist descr. of F_2 *fails* for low Q^2 and/or high x

$\rightsquigarrow$ impose cuts ($Q^2 \gtrsim 4$, $W^2 \gtrsim 10$ GeV^2) to obtain only the *universal* (twist-2) part of PDF's

we cannot afford similar cuts for g_1:

would loose 'all' data

$\rightsquigarrow$ usually only $Q^2 \gtrsim 1$, $W^2 \gtrsim 4$ GeV^2



$\Rightarrow$ current PDF's *may* suffer from higher twist contrib.

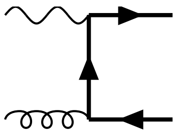
$\Rightarrow$ PDF's have to pass 'consistency check':

measurements at higher ('safer') scales $\leftrightarrow$ RHIC

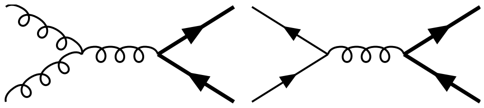
• Open heavy flavor production in NLO QCD

We are interested in the NLO QCD corrections to:

photoproduction:



hadroproduction:



Why NLO? Several reasons ...

▷ experience from unpolarized calculations

Smith, van Neerven, Beenakker et al., Nason et al.

- large corrections near threshold, $S \to 4m^2$
- large corrections for $S \to \infty$

▷ behaviour of perturbation series

- dependence on unphysical scales $\mu_{f,r}$ expected to be reduced

▷ genuine NLO features

- new processes: $g(\gamma)q \to Q\bar{Q}q$ $\leftrightarrow$ may dilute sensitivity to Δg
- angular correlations are trivial in LO ('back-to-back')
- more realistic p_T spectra

▷ features of polarized cross sections

- LO $\Delta\sigma$ can oscillate $\leftrightarrow$ large corrections in vicinity of zero?

Sketch of NLO calculation: together with I. Bojak

Current status:

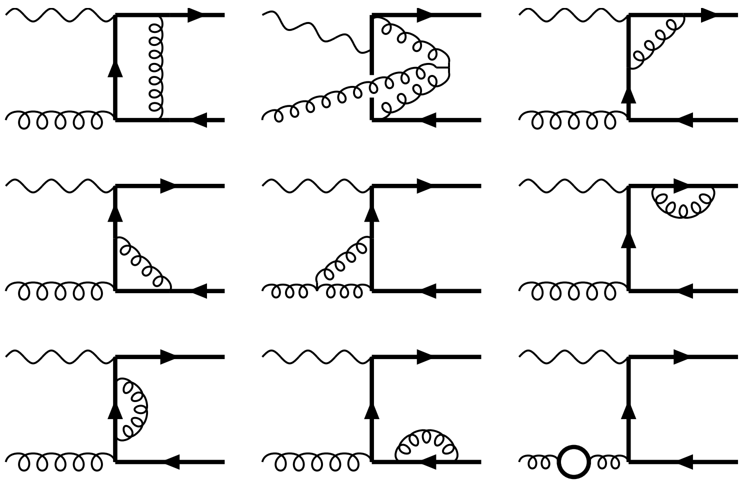
▷ photoproduction: ✓ (PLB433(1998)411; NPB540(1999)345)

▷ hadroproduction: ✓ (just finished; writing up results)

Step I: photoproduction

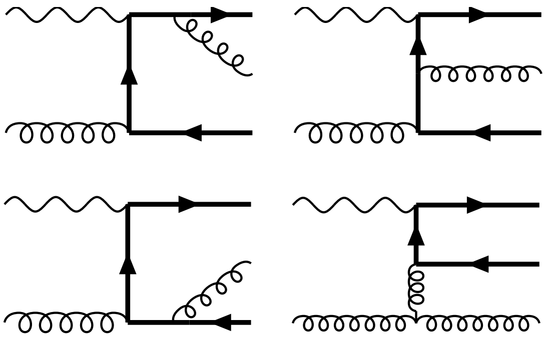
1-loop corrections

to $\gamma g \to Q\bar{Q}$



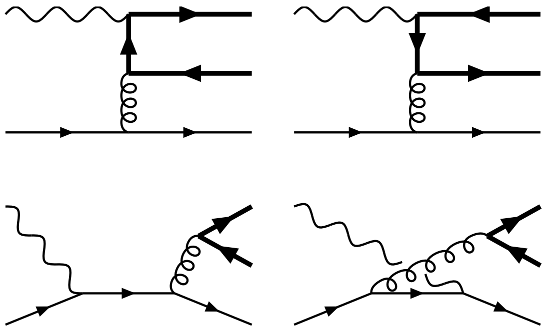
'real' corrections

to $\gamma g \to Q\bar{Q}$



new NLO process

$\gamma q \to Q\bar{Q}q$

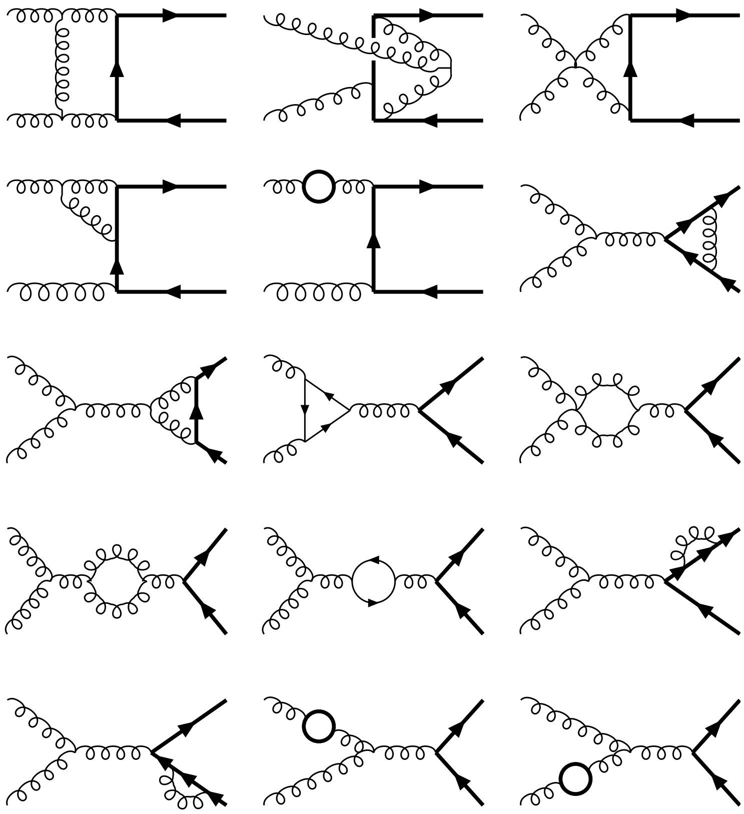


Step II: hadroproduction

very similar, only lots and lots of diagrams ...

1-loop corrections

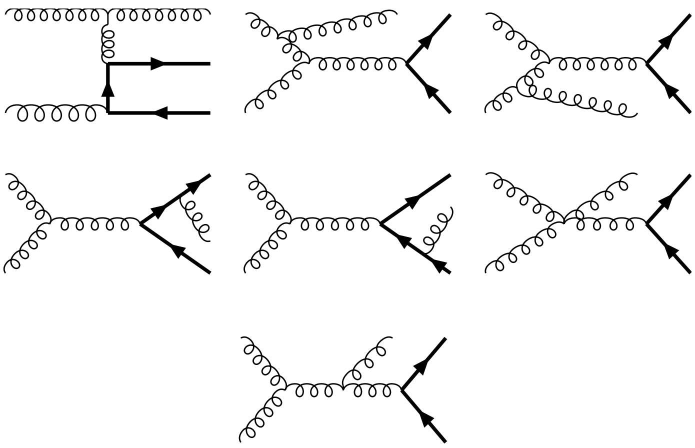
to $gg \to Q\bar{Q}$



$+\ \gamma g$ graphs with $\gamma \to g$

'real' corrections

to $gg \to Q\bar{Q}$



$+\ \gamma g$ graphs with $\gamma \to g$

PLUS NLO corrections ('real' + '1-loop') to $q\bar{q} \to Q\bar{Q}$

new genuine NLO process $gq \to Q\bar{Q}q$

General method/treatment of singularities:

- project onto helicities $\lambda_{1,2} = \pm$ of *incoming* partons using γ_5 and $\epsilon_{\mu\nu\rho\sigma}$

$$\rightsquigarrow \qquad \frac{\Delta\hat{\sigma}}{\hat{\sigma}} \equiv \frac{1}{2}\left[|M(++)|^2 \mp |M(+-)|^2\right]$$

are calculated simultaneously → important check ✓

- cannot use ‘crossing’, e.g., $q\bar{q} \to Q\bar{Q}g \not\leftrightarrow g\bar{q} \to Q\bar{Q}\bar{q}$

- obtain usual bunch of singularities in $(\Delta)\hat{\sigma}$

  $\rightsquigarrow$ work in $n = 4 + \varepsilon$ dimensions (*dim. regularization*)

Then

IR singularities

cancel in sum of 1-loop and ‘real’ contributions

UV singularities

have to be removed by renormalization (mass, α_s)

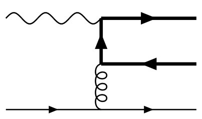
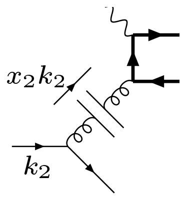
use $\overline{\text{MS}}_Q$ scheme: heavy quark loops decouple

$1/\varepsilon^2$ singularities

when collinear and IR sing. coincide; cancel as for IR

collinear (mass) singularities

have to be removed by factorization

e.g.  $\Rightarrow$ 

$\sim \int dx_2 P_{gq}(x_2)\, d\Delta\hat{\sigma}^{LO}_{\gamma g}(x_2, s, t)$

• <u>1-loop virtual corrections</u>: $[(\gamma)gg \to Q\bar{Q},\ q\bar{q} \to Q\bar{Q}]$

$2 \to 2$ kinematics; only interfer. with Born contributes:

$$d\Delta\hat{\sigma}_{\text{virt}} \sim \ldots \sum \left(\Delta M_{\text{virt}}\, \Delta M^*_{\text{Born}} + c.c.\right)\ \delta(s+t+u)$$

$\updownarrow$

tensor loop-integrals $\sim \int d^n q\, \frac{q^\mu [q^\nu [q^\rho]]}{L_1 L_2 [L_3 [L_4]]}$

handle with (mod.) Passarino-Veltman decomposition

$\rightsquigarrow$ set of n-dim. scalar integrals: A_0, B_0, C_0, D_0

[✓ all integrals agree with results in Beenakker et al.]

final step: renormalization $\rightsquigarrow$ UV finite

• <u>'real' corrections</u>: $[(\gamma)gg \to Q\bar{Q},\ q\bar{q} \to Q\bar{Q}]$

full $2 \to 3$ kinematics (involved due to HQ mass)

use *phase space slicing*: (as in unpol. HQ calc., Smith et al.)

split into hard / soft part: only collinear $1/\varepsilon \to$ factorization; cancels IR, $1/\varepsilon^2$ poles in $d\Delta\hat{\sigma}_{\text{virt}}$

$\uparrow$

$$\underbrace{\int_0^{s_4^{\max}} ds_4 = \underbrace{\int_0^{\Delta} ds_4}_{\substack{\text{soft}\\ 2\to 2}} + \underbrace{\int_{\Delta}^{s_4^{\max}} ds_4}_{\substack{\text{hard}\\ 2\to 3}}}_{}$$

kinematics

The 'Δ-method' is easy and transparent

but $\ln^i(\Delta/m^2)$ (i=1,2) have to cancel *numerically*

$2 \to 3$ phase space integration:

$$d\Delta\hat{\sigma}_{\text{real}} \sim \ldots \int d\theta_1 d\theta_2 \sin^{1-\varepsilon}\theta_1 \sin^{\varepsilon}\theta_2 \, |\Delta M_{\text{real}}|^2$$

we want to calculate *single-inclusive* HQ distributions:

e.g. $gg \to Q \;\; (\bar{Q}g)$

observed   integrated out

calculation requires extensive *partial fractioning* to get

$$I^{(k,l)} = \int \frac{d\theta_1 \; \sin^{1-\varepsilon}\theta_1 \; d\theta_2 \; \sin^{\varepsilon}\theta_2}{(a + b\cos\theta_1)^k (A + B\cos\theta_1 + C\sin\theta_1\cos\theta_2)^l}$$

some $I^{(k,l)}$ are tough: ✓ agree with Beenakker et al.
$I^{(k,l)}$ with $a^2 = b^2$ and/or $A^2 = B^2 + C^2$ can diverge $\rightsquigarrow \frac{1}{\varepsilon}$

- <u>subtlety in pol. calculation</u>: γ_5 in n dimensions

γ_5 (and $\epsilon_{\mu\nu\rho\sigma}$) are 4-dim. $\rightsquigarrow$ use HVBM *prescrip.* in n dim.

price to pay: $(n-4)$-dim. scalar products ('hats') $\widehat{p \cdot k}$

$\rightsquigarrow$ special care in phase space integrations required!!
rewrite $\text{dPS}_3(\theta_1, \theta_2) \to \text{dPS}_3(\theta_1, \theta_2) \times \mathcal{I}(\hat{k}^2)$
$\mathcal{I}(\hat{k}^2) \sim \mathcal{O}(\varepsilon) \rightsquigarrow$ contribute if they pick up $1/\varepsilon$!!

add. compl. due to *artificial helicity viol.*: $\Delta P^n_{qq} \neq P^n_{qq}$
$\to$ add. factorization (Vogelsang)

- <u>final step</u>: factorization; sum soft and virtual $\rightsquigarrow$ finite

- <u>genuine NLO processes</u>: $(\gamma)gq \to Q\bar{Q}q$

straightforward, only collinear poles

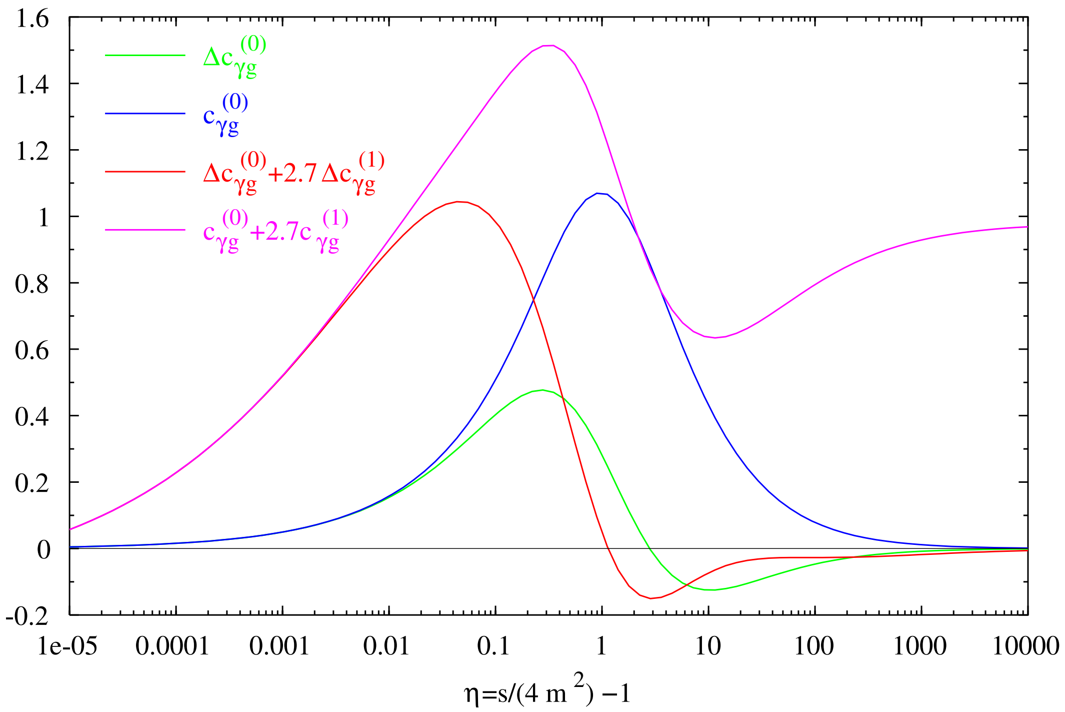
Some results:

total *partonic* γg photoproduction cross section:

[similar features for gg fusion in hadroproduction]

'scales' in $\eta = s/(4m^2) - 1$: [here: $\mu_f = \mu_r$]

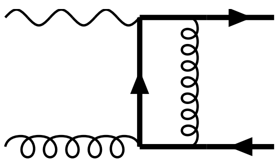
$$\Delta\hat{\sigma}_{\gamma g} = \frac{e_Q^2 \alpha \alpha_s}{m^2} \left[\Delta c_{\gamma g}^{(0)} + 4\pi\alpha_s \left(\Delta c_{\gamma g}^{(1)} + \Delta\bar{c}_{\gamma g}^{(1)} \ln \frac{\mu_f^2}{m^2} \right) \right]$$



$\rightsquigarrow$ large enhancements w.r.t. LO:

<ins>threshold</ins>: η, $\beta = \sqrt{1 - 4m^2/s} \to 0$

(1) 'Coulomb' singularity:



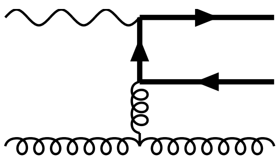
phase space $\sim \beta$

LO ME $\sim 1 \to 0$; NLO ME $\sim 1/\beta \to$ const

(2) 'soft gluons' $\sim \beta \ln^2 8\beta^2 \leftarrow$ can be resummed

<ins>high energy</ins>: $\eta \to \infty$, $\beta \to 1$

't-channel gluon exchange'



cancels in $\Delta\hat{\sigma}$

total hadronic cross section:

physical cross section is convolution of partons and $\Delta\widehat{\sigma}_{ff'}$:

$$s = x_1 x_2 S$$

$$\updownarrow$$

$$\Delta\sigma = \sum_{f,f'} \int_{\frac{4m^2}{S}}^{1} dx_1 \int_{\frac{4m^2}{x_1 S}}^{1} dx_2\, \Delta f(x_1,\mu_f^2)\Delta f'(x_2,\mu_f^2)\Delta\widehat{\sigma}_{ff'}(s,m^2,\mu_r^2,\mu_f^2)$$

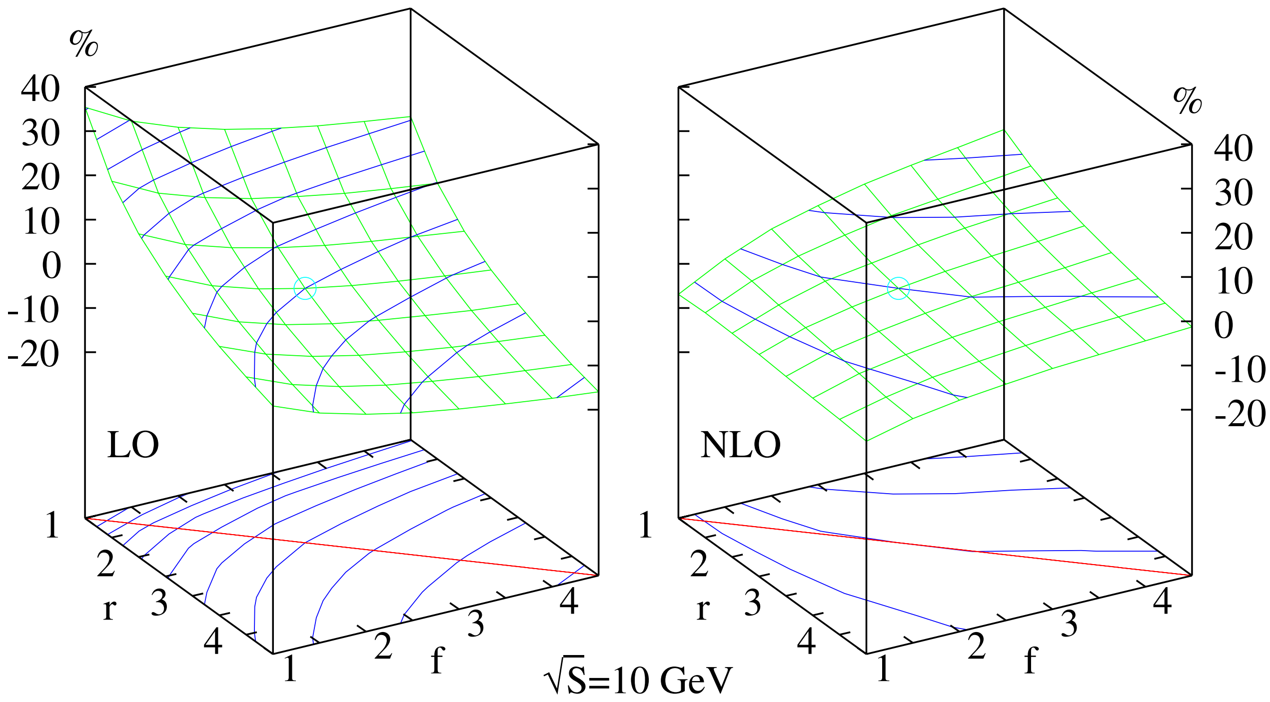
$$\updownarrow$$

γp: $= \delta(1-x_2)$

$\rightsquigarrow$ η dependence of $\Delta\widehat{\sigma}_{ff'}$ is smeared out

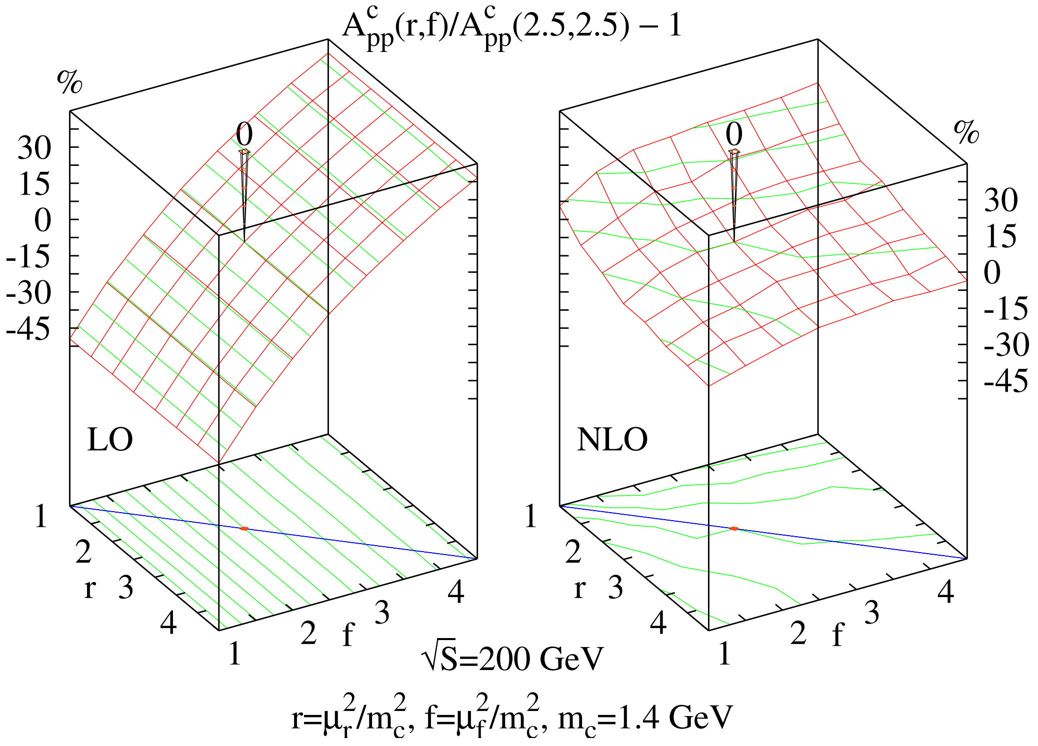
scale dependence of total *charm photo*production $\Delta\sigma$

$r = \mu_r^2/m_c^2$ and $f = \mu_f^2/m_c^2$ using GRSV, $m_c = 1.5$ GeV

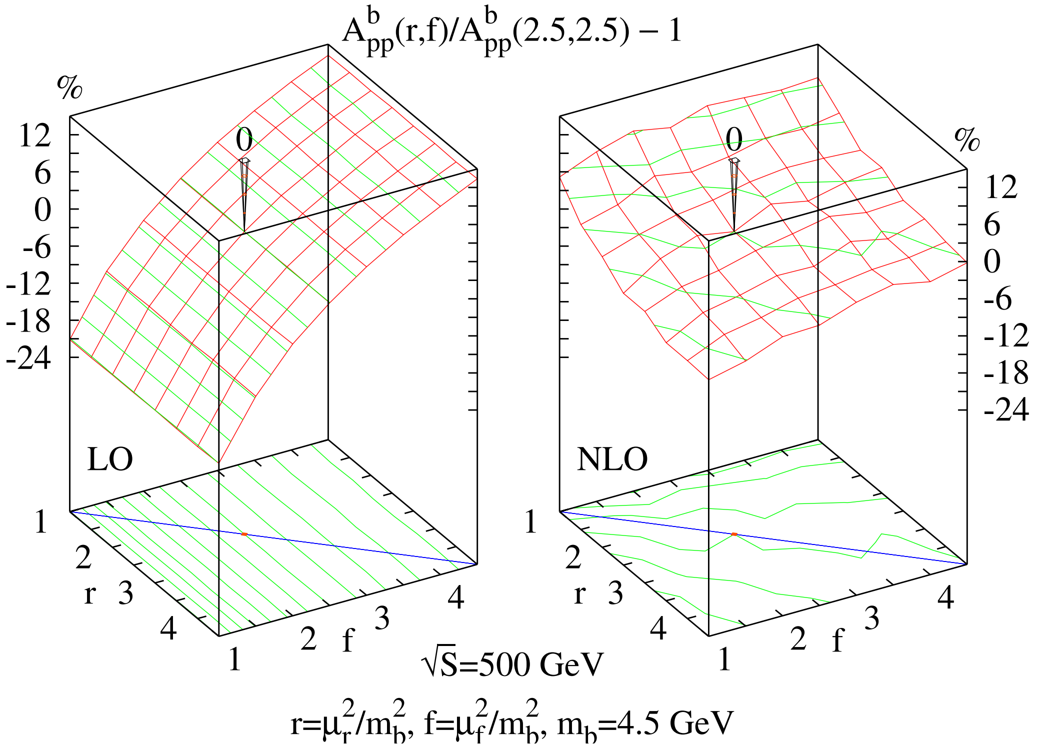


COMPASS

$\rightsquigarrow$ dependence on unphys. scales *largely reduced* in NLO scale dep. of total pp spin asymmetry $A^Q = \mathrm{d}\Delta\sigma^Q/\mathrm{d}\sigma^Q$:

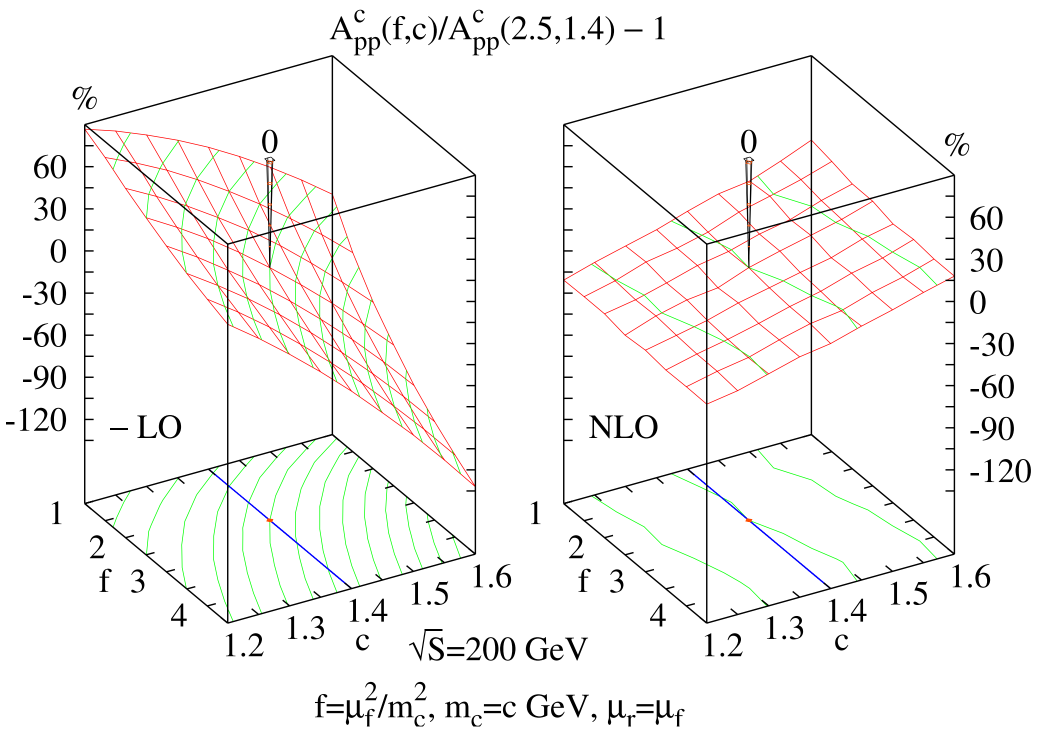


RHIC



RHIC

mass dependence of total pp spin asymmetry:



$\rightsquigarrow$ m_Q is *dominant uncertainty*; better for b production

analytical/numerical checks on our NLO results:

photoproduction

✓ NLO unpolarized — Smith, van Neerven; Ellis, Nason

✓ NLO polarized (abelian part: $\gamma\gamma \to Q\bar{Q}g$) — Contogouris et al.; Jikia, Tkabladze

✓ NLO polarized (seem to agree) — Contogouris, Merebashvili, Grispos

hadroproduction

✓ NLO unpolarized — Beenakker et al.; Nason et al
(agree; num. irrel. typo in HQ-loop of Beenakker et al.)

• Matching theory and experiment

Heavy quark decay & detection:

aim: study *and* optimize sensitivity to Δg for various heavy flavor observables

$\rightsquigarrow$ need *realistic* error estimates for rates and A^Q

problem: calc. assuming a 4π-detector, 100% efficiency, and 'parton = hadron level' are of limited use

- c, b usually not seen directly; c, b decays can have 'multi-body' kinematics
- detector coverage often limited
- non-trivial relation of exp. and theor. variables, e.g., p_T distr. of decay μ's vs. p_T^Q

experimental situation:

hermes: charm production near threshold

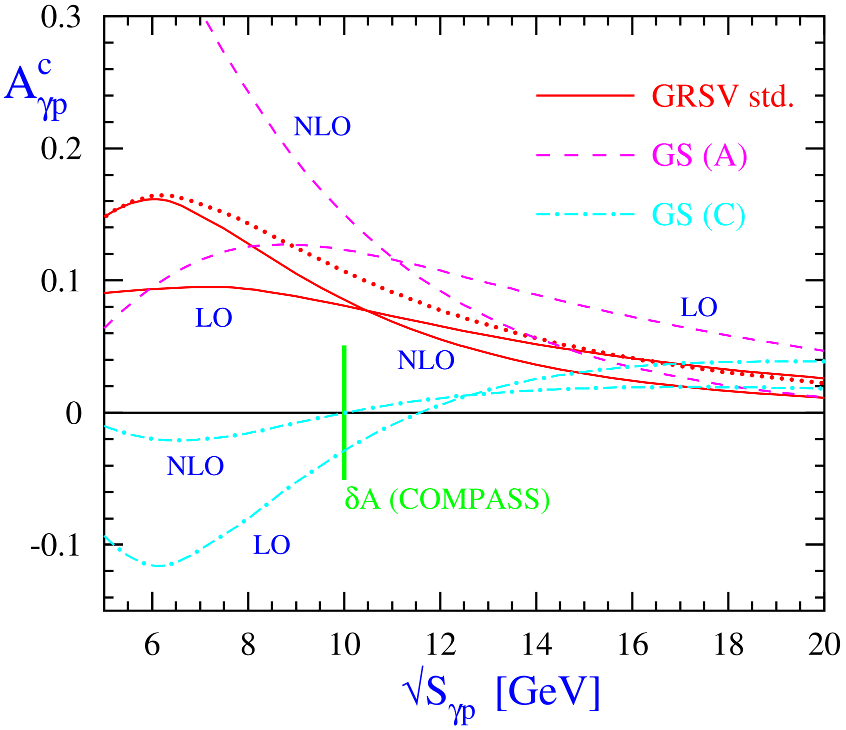
COMPASS: 'only' total charm prod. at $\sqrt{S} = 10\,\text{GeV}$ error estimate given in proposal

RHIC: differential distributions for c and b; different $\sqrt{S}$, channels/strategies to detect heavy quarks

need:

- unpol. *and* pol. NLO parton level MC
- include HQ decay in theor. estimates
- close collab. between theory and experiment

(I) photoproduction of charm @ COMPASS :



✓ some sensitivity to Δg

✓ reduced scale dependence in NLO

✓ 'background' from NLO γq process small

✓ 'background' from *resolved* γ's (e.g., $gg \to c\bar{c}$) small

Vogelsang, MS

$\sqrt{S_{\gamma p}}$ [GeV]	GRSV Δg		large Δg		GSC Δg	
	direct [nb]	resolved [nb]	direct [nb]	resolved [nb]	direct [nb]	resolved [nb]
10	10.2	-0.72	23.0	-0.63	-3.48	-0.70
20	13.9	-0.29	23.2	0.33	19.6	-0.70
100	-4.76	2.09	-9.71	4.00	0.58	2.27

× NLO corrections are sizable

× sizable dependence on m_{charm}

× can extract Δg 'only' for single $\langle x \rangle \sim \mathcal{O}(0.1 \div 0.2)$

(II) hadroproduction of heavy quarks @ RHIC :

Heavy quark tagging at PHENIX via $e^{\pm}$ and/or $\mu^{\pm}$

Lepton detection is limited to

$$\begin{array}{rcl} e^{\pm} & : & |\eta_{e^{\pm}}| \leq 0.35 \\ \mu^{\pm} & : & 1.2 \leq |\eta_{\mu^{\pm}}| \leq 2.4 \end{array}$$

$\rightsquigarrow$ *crucial* to include simulation of HQ-decay in all theory estimates for spin asymmetries

Idea: use PYTHIA to generate *'efficiencies'*

suitable bins in (p_T^e, η_e)

$\updownarrow$

$$\varepsilon_{\text{eff}}^{c,b} \equiv \frac{\#[c, b \text{ in } (p_T, \eta)\text{--bin} \rightarrow e^{\pm} \text{ in 'acceptance'}]}{\#[c, b \text{ in } (p_T, \eta)\text{--bin}]}$$

essential: $\varepsilon_{\text{eff}}^{c,b}$ *independent* of c, b production

$\rightsquigarrow$ $\varepsilon_{\text{eff}}^{c,b}$ give the probability that c, b's in a given (p_T, η)-bin are detected at PHENIX

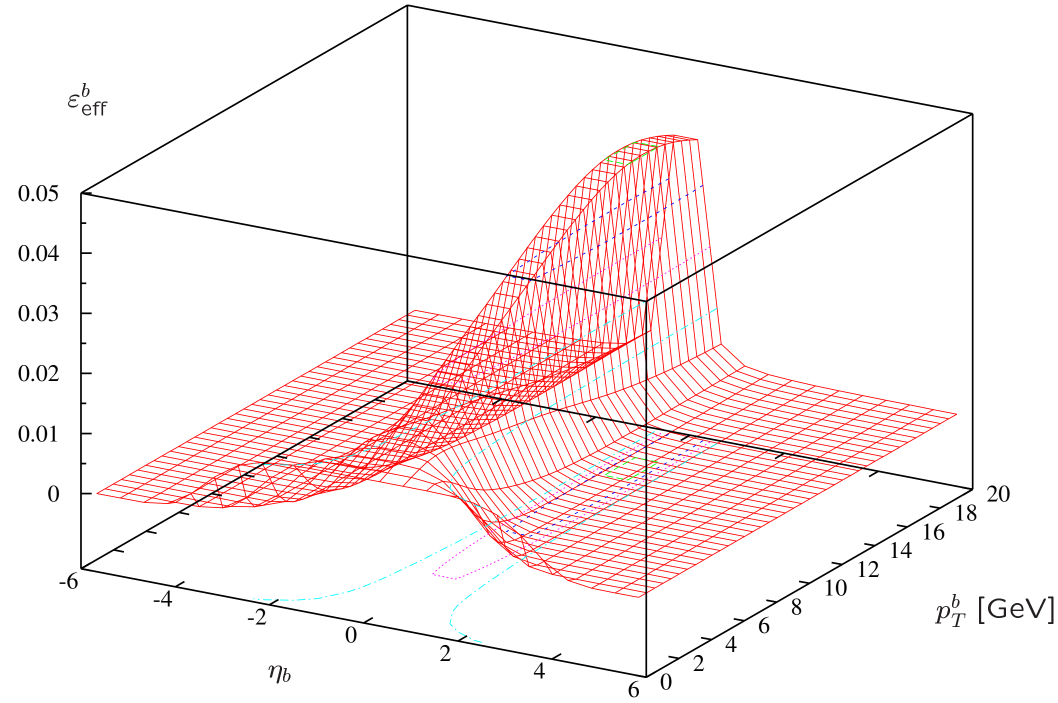
very recently: 1st results for 'single electron tag' $\varepsilon_{\text{eff}}^{c,b}$

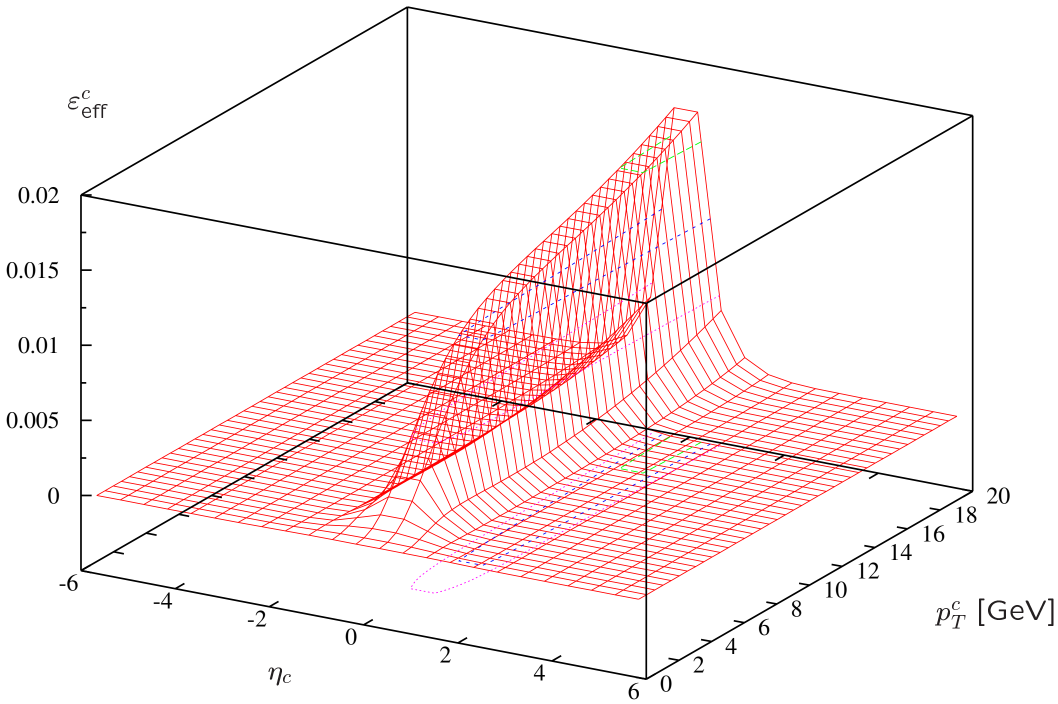
Grosse Perdekamp, Xie, . . .

✓ ready to use for single incl. spin asymmetries in NLO

other promising tags: 'μe coincidences'

× work in progress; spin asymmetries in NLO require MC some typical results for the 'single electron tag' $\varepsilon^{c,b}_{\text{eff}}$





required: $c, b \to e + X$, $p_T^e > 1$ GeV, and $|\eta_e| \leq 0.35$

results for LO/NLO spin asymmetries available soon

Extraction of Δg ('global analysis'):

$\checkmark$ modern evol. codes operate on grids $\leadsto$ very fast

$\times$ NLO calc. of jets, prompt-γ, HQ, ... are based on multi-dim. MC's $\leadsto$ *much too slow for global fitting*

$\Rightarrow$ need a *reliable* and *fast* work-around, e.g.:

- use LO with fudge K-factor (done in unpol. fits)
  $\times$ K-factor may crit. depend on unknown PDF's (pol. PDF's and $\Delta\hat{\sigma}$'s can oscillate!)

- pre-calculate major part of NLO cross sections ('grids')
  $\checkmark$ almost as fast as DIS fits

'Double Mellin transform' technique: Kosower; Vogelsang, MS

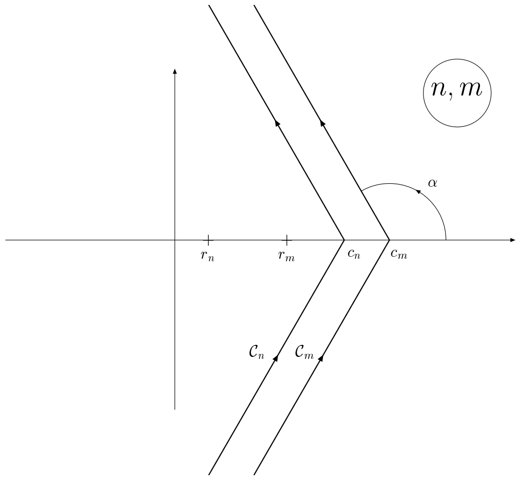
idea: get rid of slow 'double convolutions'

$$d\sigma \simeq \sum_{i,j} \int dx_1\, dx_2\, \underset{\displaystyle \int_{\mathcal{C}_n} dn\, x_1^{-n}\, f_i^n}{\underset{\uparrow}{f_i(x_1)}}\; \underset{\displaystyle \int_{\mathcal{C}_m} dm\, x_2^{-m}\, f_j^m}{\underset{\uparrow}{f_j(x_2)}}\; \hat{\sigma}_{ij}(x_1, x_2)$$

$$= \sum_{i,j} \int_{\mathcal{C}_n} dn \int_{\mathcal{C}_m} dm\; f_i^n\; f_j^m \left[\underbrace{\int dx_1\, dx_2\, x_1^{-n}\; x_2^{-m}\; \hat{\sigma}_{ij}(x_1, x_2)}_{\equiv\, \tilde{\sigma}_{ij}^{n,m}} \right]$$

Then: pre-calculate $\tilde{\sigma}_{ij}^{n,m}$ on a suitable $n \times m$ grid for all subprocesses *and* data pts. *once* before the fit inverse transformation $\int_{\mathcal{C}_n} dn \int_{\mathcal{C}_m} dm$: done on $n \times m$ grids

$\mathcal{C}_n, \mathcal{C}_m$: contours in complex n, m plane to the right of all poles



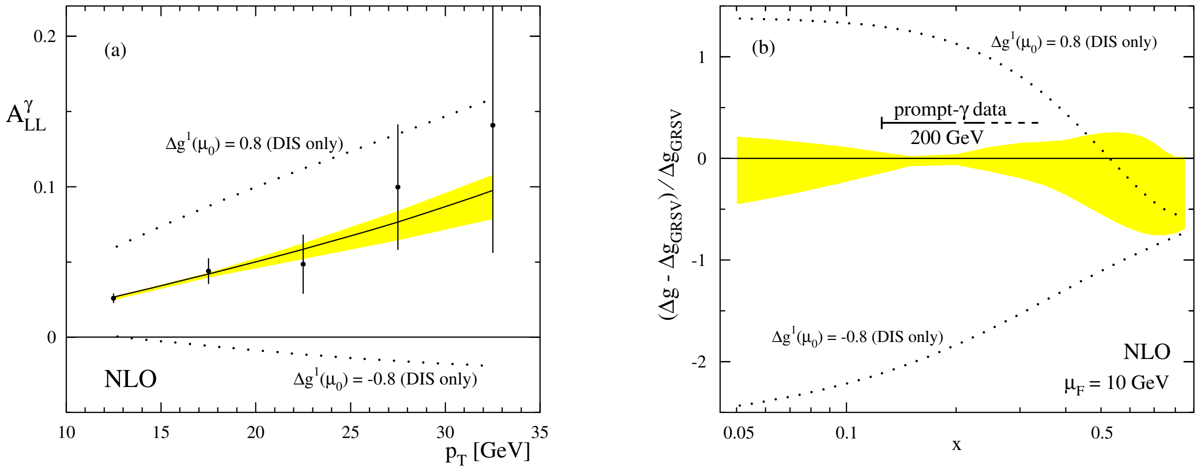
no new poles beyond those already present in $f^{n,m}$

Case study with projected prompt-γ data: Vogelsang, MS

· 64×64 grid gives excellent num. stability

· 1000 calc. of full NLO cross section take $10 \div 15$ sec.!

NLO fits (DIS+γ) with random start values for Δg give: ['data' pts. based on GRSV Δg and Gaussian 1σ-errors]



$\rightsquigarrow$ strong constraint on Δg around $x \simeq 0.15$

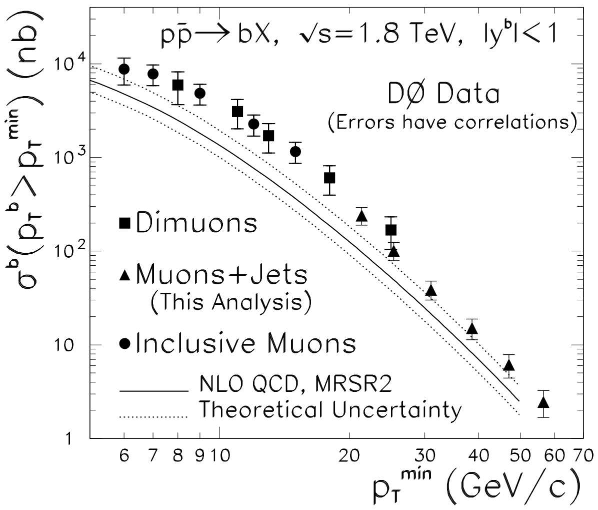
Mellin technique applicable to *all* NLO processes

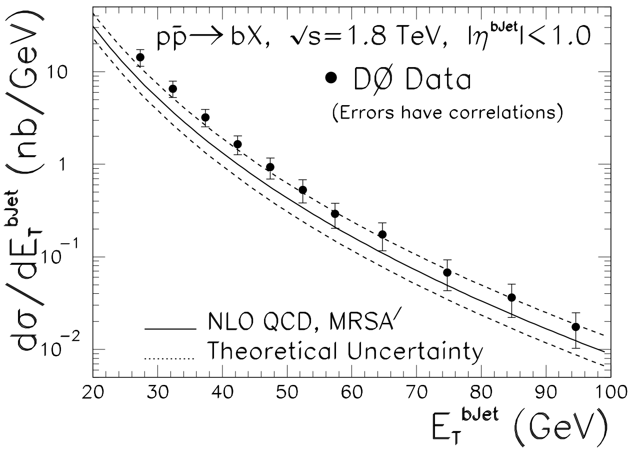
• Detour: do we understand *unpolarized* HQ data?

Prior to Δg meas. one *must* check the unpol. 'status':

$\Rightarrow$ incl. b-rate from QCD too small in $p\bar{p}$, ep, and $\gamma\gamma$!

Latest DØ results: **(I)** 'central' b's: $|y^b| < 1$, $p_T^b > p_T^{\min}$

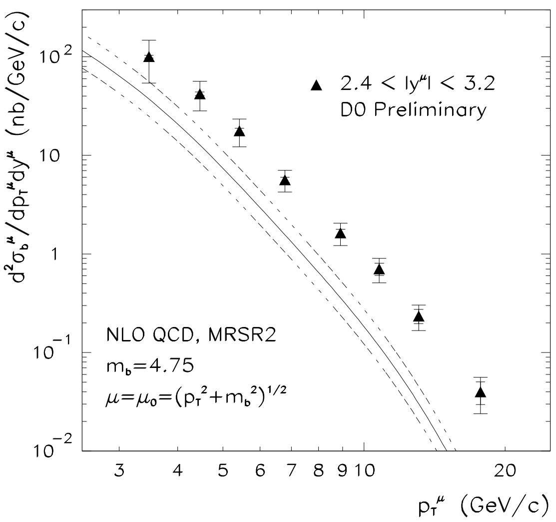


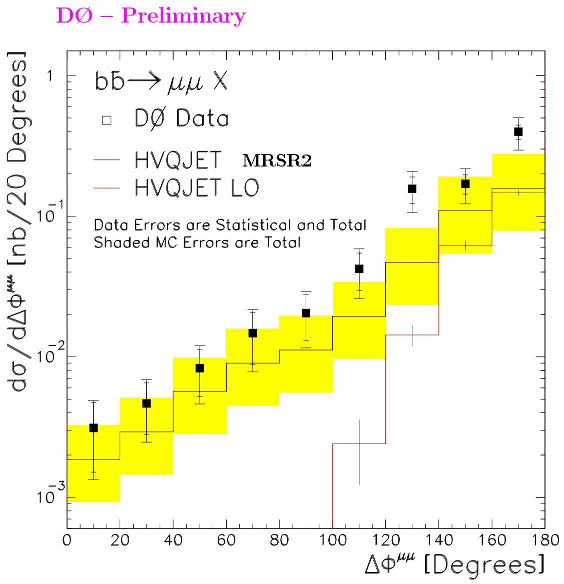


$\rightsquigarrow$ b-jets $\approx$ ✓; otherwise data/theory $\approx 2 \div 2.5$

(II) 'forward' b's

(III) ang. corr. in $b\bar{b} \to \mu\mu$





$\rightsquigarrow$ data/theory $\simeq 4$ data/theory $\simeq 1.8$

Attempts to understand the discrepancy:

Several possibilities have been discussed:

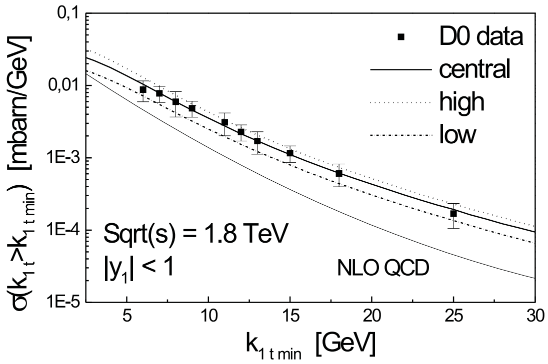
exp. problems, NNLO corrections, modified gluon density, 'intrinsic k_T', resum $\ln p_T/m$, ...

Recently studied/proposed:

- 'BFKL' effects

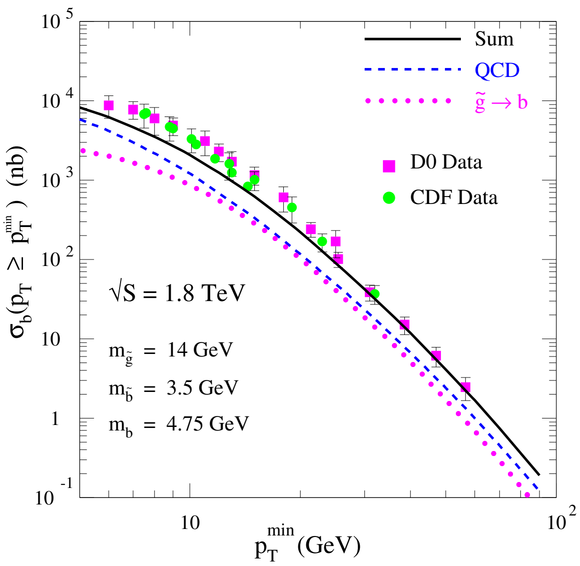
  Hägler, Kirschner, Schäfer, Szymanowski, Teryaev

  - uses: NLL BFKL vtx.; unintegrated gluon; k_T factorization
  - tests: $b\bar{b}$ correlations



- 'SUSY' effects

  Berger, Harris, Kaplan, Sullivan, Tait, Wagner



  - idea: $gg,\, q\bar{q} \to \tilde{g}\tilde{g}$, then $\tilde{g} \to b\tilde{\bar{b}}$
  - claim: consistent with all MSSM constraints
  - tests: bb, $\overline{bb}$ pairs; slower running of α_s

$\rightsquigarrow$ upcoming run II should improve exp. status

a RHIC measurement would be helpful as well

• Summary & Outlook

HAVE

✓ NLO polarized single incl. hadroproduction of HQ's

✓ started close collaboration with RBRC on HQ's

✓ tool for NLO global QCD analyses of PDF's

HAVE TO

- develop polarized NLO parton level MC for HQ's
- improve understanding of unpol. HQ production
- study other HQ observables (jets, ang. corr.)
- study impact of uncertainties on unpol. PDF's on Δg