Open heavy flavor production in pp collisions at the LHC

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Subatech Nantes, 19 February 2015

I. INTRODUCTION

The pQCD formalism

Quantum Chromodynamics (QCD)

QCD: A QFT for the strong interactions

- Statement: Hadronic matter is made of spin-1/2 quarks [$\leftrightarrow SU(3)_{\rm fl}$]
- Baryons like $\Delta^{++} = |u^\uparrow u^\uparrow u^\uparrow\rangle$ forbidden by Pauli exclusion/Fermi-Dirac stat.
  Need additional colour degree of freedom!
- Local SU(3)-color gauge symmetry:

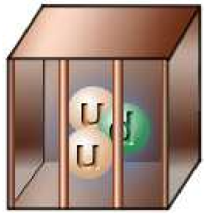
$$\mathcal{L}_{\rm QCD} = \sum_{q=u,d,s,c,b,t} \bar{q}(i\partial\!\!\!/ - m_q)q - g\bar{q}G\!\!\!/q - \frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu} + \mathcal{L}_{gf} + \mathcal{L}_{ghost}$$

- Fundamental d.o.f.: quark and gluon fields
- Free parameters:
  - gauge coupling: g
  - quark masses: $m_u, m_d, m_s, m_c, m_b, m_t$

Quantum Chromodynamics (QCD)

Properties:

- **Confinement and Hadronization:**
  - Free quarks and gluons have not been observed:
    A) They are confined in color-neutral hadrons of size $\sim$ 1 fm.
    B) They hadronize into the observed hadrons.



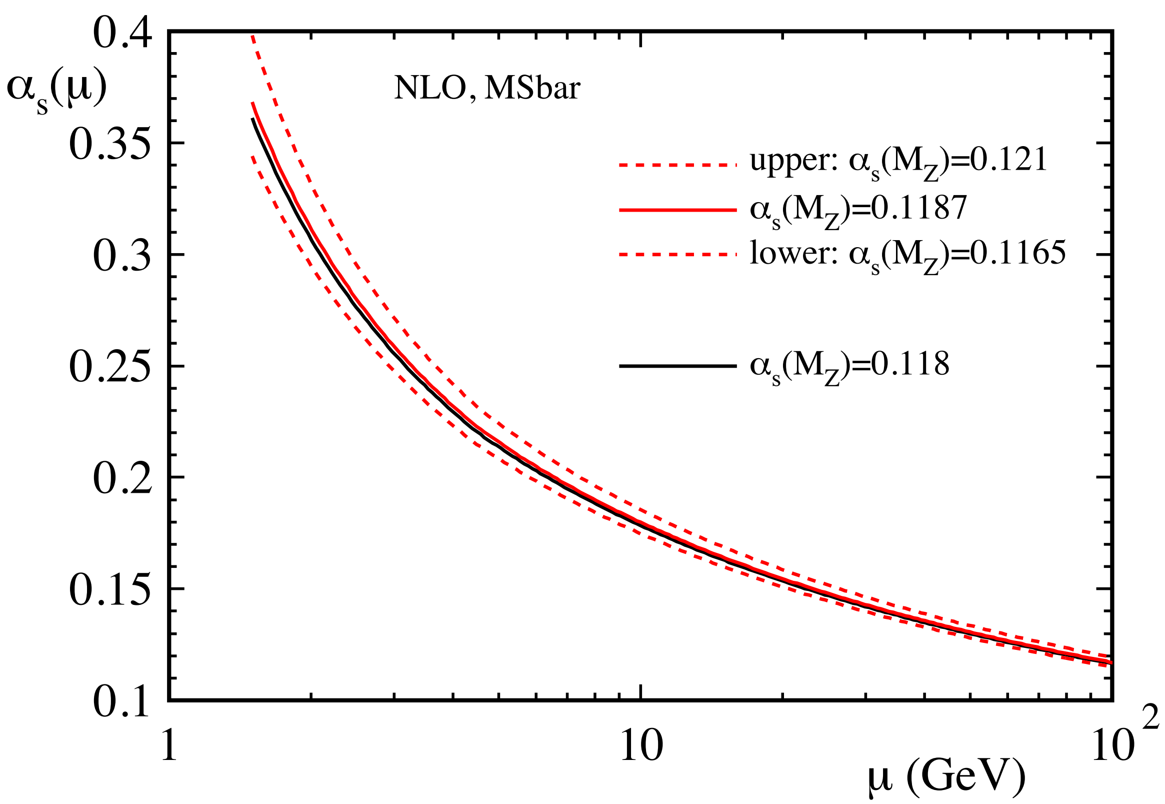
  - Hadronic energy scale: a few hundred MeV [1 fm $\leftrightarrow$ 200 MeV]
  - Strong coupling large at long distances ($\gtrsim$ 1 fm): 'IR-slavery'
  - Hadrons and hadron masses enter the game

- **Asymptotic freedom:**
  - Strong couling small at short distances: perturbation theory
  - Quarks and gluons behave as free particles at asymptotically large energies

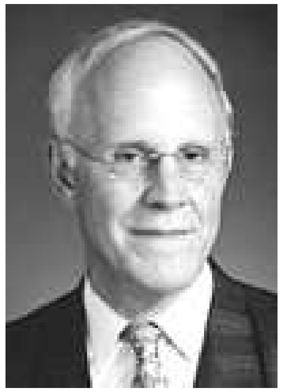
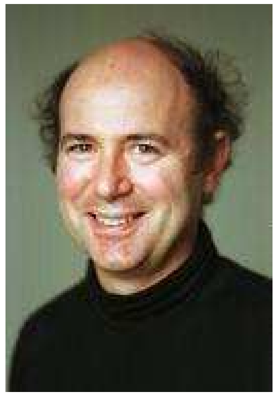
Asymptotic Freedom

Renormalization of UV-divergences:
Running coupling constant $a_s := \alpha_s/(4\pi)$

$$a_s(\mu) = \frac{1}{\beta_0 \ln(\mu^2/\Lambda^2)}$$



- Gross, Wilczek ('73); Politzer ('73)


Non-abelian gauge theories:
negative beta-functions

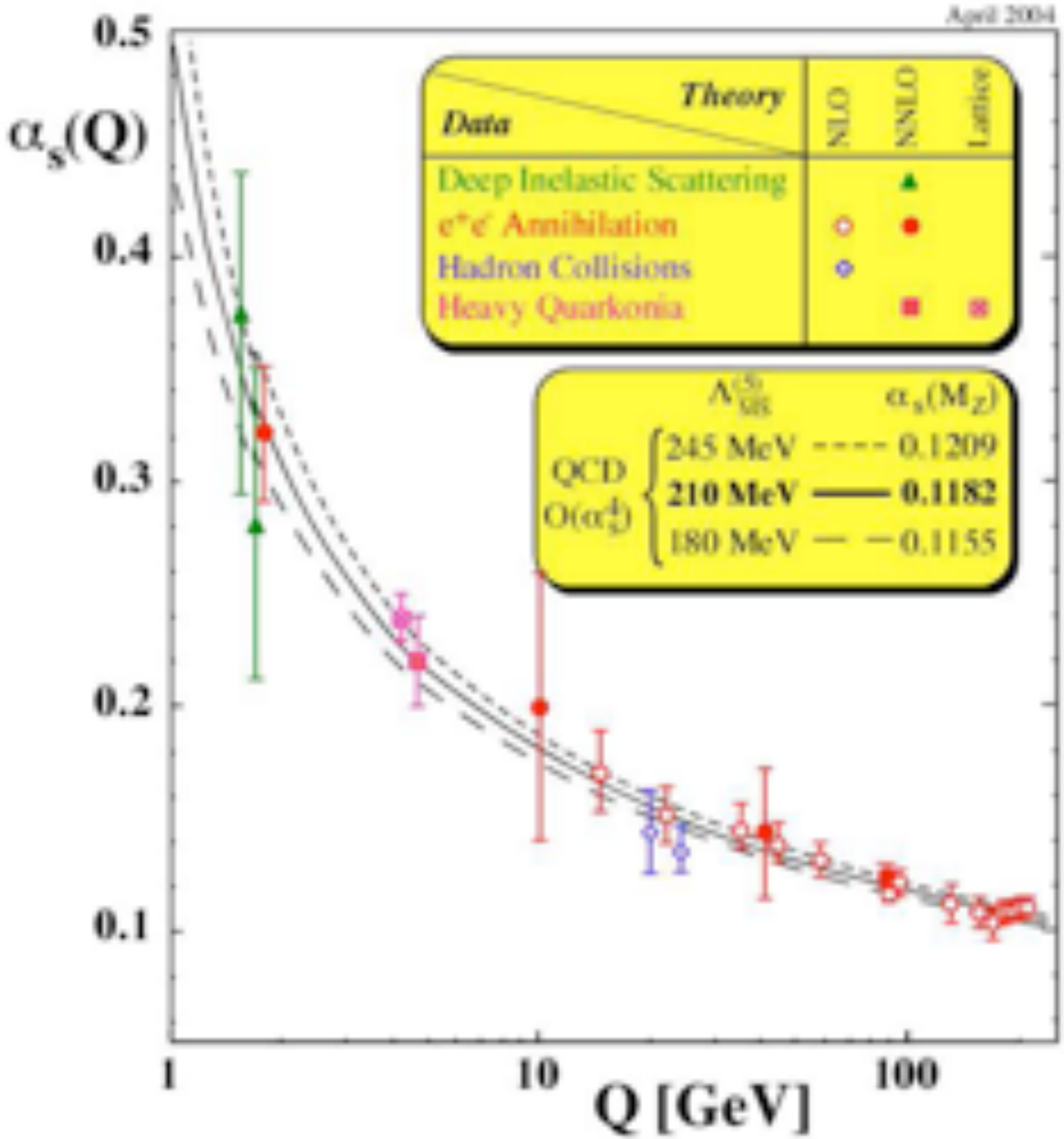
$$\frac{da_s}{d \ln \mu^2} = -\beta_0 a_s^2 + \dots$$

where $\beta_0 = \frac{11}{3} C_A - \frac{2}{3} n_f$

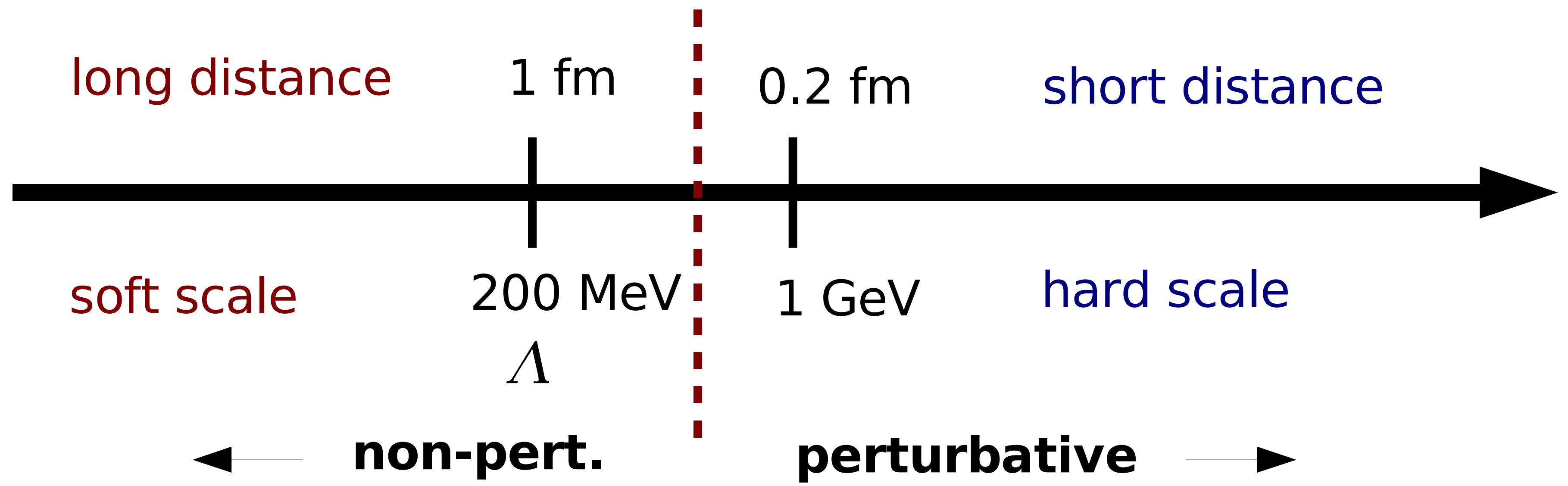
$\Rightarrow$ asympt. freedom: $a_s \searrow$ for $\mu \nearrow$

- Nobel Prize 2004

Running strong coupling constant



Perturbative QCD (pQCD)



Asympt. freedom → pQCD possible if **all** scales hard

Factorisation → Possible to **separate** hard and soft scales

soft part : **universal**

hard part : **perturbative**

The pQCD formalism

QCD factorization theorems:

$$\mathrm{d}\sigma \quad = \quad \mathrm{PDF} \otimes \mathrm{d}\hat{\sigma} + \mathrm{remainder}$$

- PDF:
  - Proton composed of partons = quarks, gluons
  - Structure of proton described by parton distribution functions (PDF)
  - Factorization theorems provide field theoretic definition of PDFs
  - PDFs universal $\rightarrow$ **PREDICTIVE POWER**
- Hard part $\mathrm{d}\hat{\sigma}$:
  - depends on the process
  - calculable order by order in perturbation theory
  - Factorization theorems prescribe how to calculate $\mathrm{d}\hat{\sigma}$:
    "$\mathrm{d}\hat{\sigma} =$ partonic cross section - mass factorization"
- Statement about error: remainder suppressed by hard scale

Original factorization proofs considered massless partons

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The pQCD formalism is ***essential*** *for the physics program at the LHC!*

- Harc
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Original factorization proofs considered massless partons

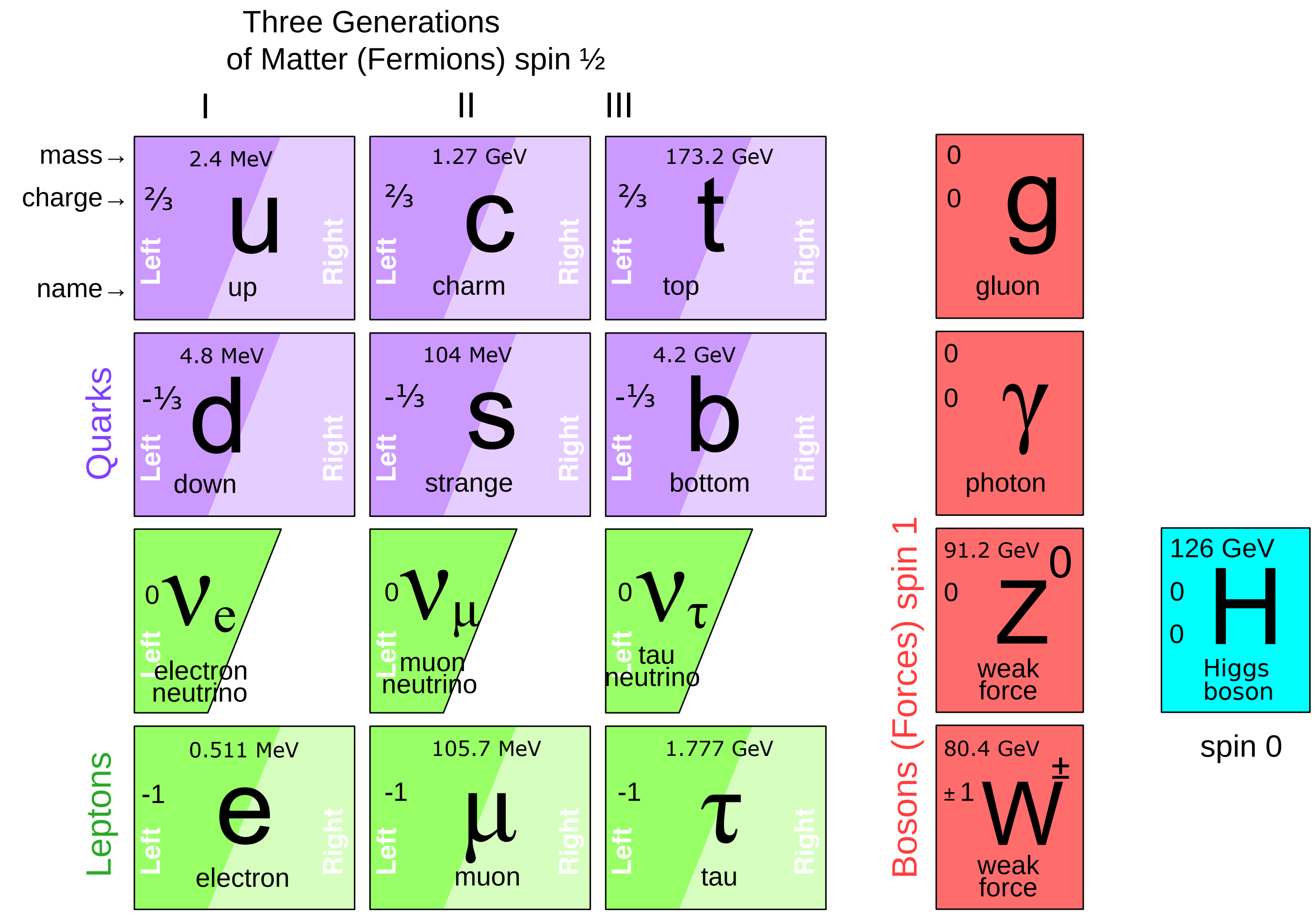
The Large Hadron Collider

- World records: Largest collider, highest energy, ...
- Main experiments: ATLAS, CMS, ALICE, LHCb
- p-p, p-Pb, Pb-Pb collisions

Heavy quarks

Heavy quarks

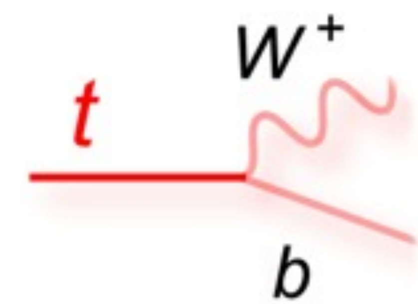
Particle content of the SM



Mass scales in QCD

- Light quarks: m_u~2 MeV, m_d~5 MeV, m_s~100 MeV
- Λ_{QCD}~200 MeV
- **Heavy quarks**: m_c~1.3 GeV, m_b~4.5 GeV, m_t~175 GeV

Heavy quarks



$$\Gamma(t \to W^+ b) \simeq 1.5 \text{ GeV}$$

$$\tau \simeq 4.36 \times 10^{-25} \text{ s}$$

$$\Gamma(t \to W^+ b) = \frac{G_F}{8\pi\sqrt{2}} m_t^3 |V_{tb}|^2 (1 - m_W^2/m_t^2)^2 (1 + 2m_W^2/m_t^2)$$

- The top quark is special: it decays before it could hadronize!
- The charm quark hadronizes into D, D*, Lambdac, ...
- The bottom quark hadronizes into B mesons, etc

Heavy quarks in pQCD

Heavy Quarks: $h = c, b, t$

- $m_u, m_d, m_s \lesssim \Lambda_{\rm QCD} \ll m_c, m_b, m_t$
- $m_h \gg \Lambda_{\rm QCD} \Rightarrow \alpha_s(m_h^2) \propto \ln^{-1}(\frac{m_h^2}{\Lambda_{\rm QCD}^2}) \ll 1$ (asymptotic freedom)
- m_h sets hard scale; acts as long distance cut-off $\rightarrow$ pQCD

How to incorporate heavy quark masses into the pQCD formalism?

Requirements:

(1) $\mu \ll m$: Decoupling of heavy degrees of freedom

(2) $\mu \gg m$: IR-safety

(3) $\mu \sim m$: Correct threshold behavior

Heavy flavor schemes

Heavy flavor schemes

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(3) $\mu \sim m$: Correct threshold behavior

Problem:

- Multiple hard scales: m_c, m_b, m_t, μ
- Mass-independent factorization/renormalization schemes like $\overline{\rm MS}$
- A single $\overline{\rm MS}$ scheme cannot meet requirements (1) and (3) (is unphysical).

Way out: Patchwork of $\overline{\rm MS}$ schemes S^{n_f, n_R}

- Variable Flavor-Number Scheme (VFNS): $S^{3,3} \to S^{4,4} \to S^{5,5}$
- Fixed Flavor-Number Scheme (FFNS): $S^{3,3} \to S^{3,4} \to S^{3,5}$ (3-FFNS)
- **Masses reintroduced** by backdoor: threshold corrections (=matching conditions)

Variable Flavor Number Scheme

- Effective theory with N_F active partons (N_F=N_R)

$$S^{(N_F)}$$

- RGE's for PDFs (DGLAP) and α_s (for μ_R = μ_F= μ)

$$\frac{\partial}{\partial \ln \mu_2} f_i(x, \mu^2, N_F) = P_{ij}(x, \mu^2, N_F) \otimes f_j(x, \mu^2, N_F)$$

$$\frac{da_s(\mu^2, N_F)}{d \ln \mu^2} = \beta(a_s, N_F)$$

- Flavor thresholds: matching scales

$$\mu_M^{(4)} \simeq m_c, \mu_M^{(5)} \simeq m_b, \mu_M^{(6)} \simeq m_t$$

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Variable Flavor Number Scheme

- Flavor thresholds: matching conditions at $\mu = \mu_M$

$$f_i(x,\mu^2,N_F+1) = A^{ij} \otimes f_j(x,\mu^2,N_F)$$

$$A^{ij} = \delta^{ij} + \frac{\alpha_s}{2\pi}\left(a_1^{ij} + P_0^{ij}\ln\left[\frac{\mu^2}{m^2}\right]\right) + \left(\frac{\alpha_s}{2\pi}\right)^2\left(a_2^{ij} + \left\{P_1^{ij} + P_0^{ij}\otimes a_1^{ij} - \beta_0 a_1^{ij}\right\}\ln\left[\frac{\mu^2}{m^2}\right] + \frac{1}{2}\left\{P_0^{ij}\otimes P_0^{ij} - \beta_0 P_0^{ij}\right\}\ln^2\left[\frac{\mu^2}{m^2}\right]\right) + \ldots$$

(hep-ph/9601302, 9612398)

$$\alpha_s(\mu^2,N_F+1) = \alpha_s(\mu^2,N_F)\left[1+\sum_{k=1}^{\infty}\sum_{l=0}^{k} c_{kl}[\alpha_s(\mu^2,N_F)]^k \ln^l\left(\frac{\mu^2}{m^2}\right)\right]$$

$$c_{10}^{\overline{MS}} = 0,\; c_{20}^{\overline{MS}} \neq 0$$

(hep-ph/9706430)

Using $\mu = m$ and restricting to $O\left(\alpha_s^3\right)$ terms

$$\alpha_s(m^2,N_F+1) = \alpha_s(m^2,N_F) + c_{20}\alpha_s^3(m^2,N_F)$$

Variable Flavor Number Scheme

- Transition scales: change of scheme for **observables**

$$O(N_F) \to O(N_F + 1) \quad \text{at} \quad \mu_T^{(NF+1)}$$

- **Standard VFNS**: $\mu_M = m$, $\mu_T = m$
  - user has to change the scheme at the heavy quark mass

- **Hybrid VFNS** (H-VFNS): $\mu_M = m$, $\mu_T > m$
  - μ_T can depend on kinematic variables, e.g., $\mu_T = \mu_T(x,Q)$ in DIS
  - requires knowledge of PDFs $f_i(x, mu_F, N_F)$ and $\alpha_s(\mu, N_F)$ up to μ_T
  - user can freely choose where to change the scheme

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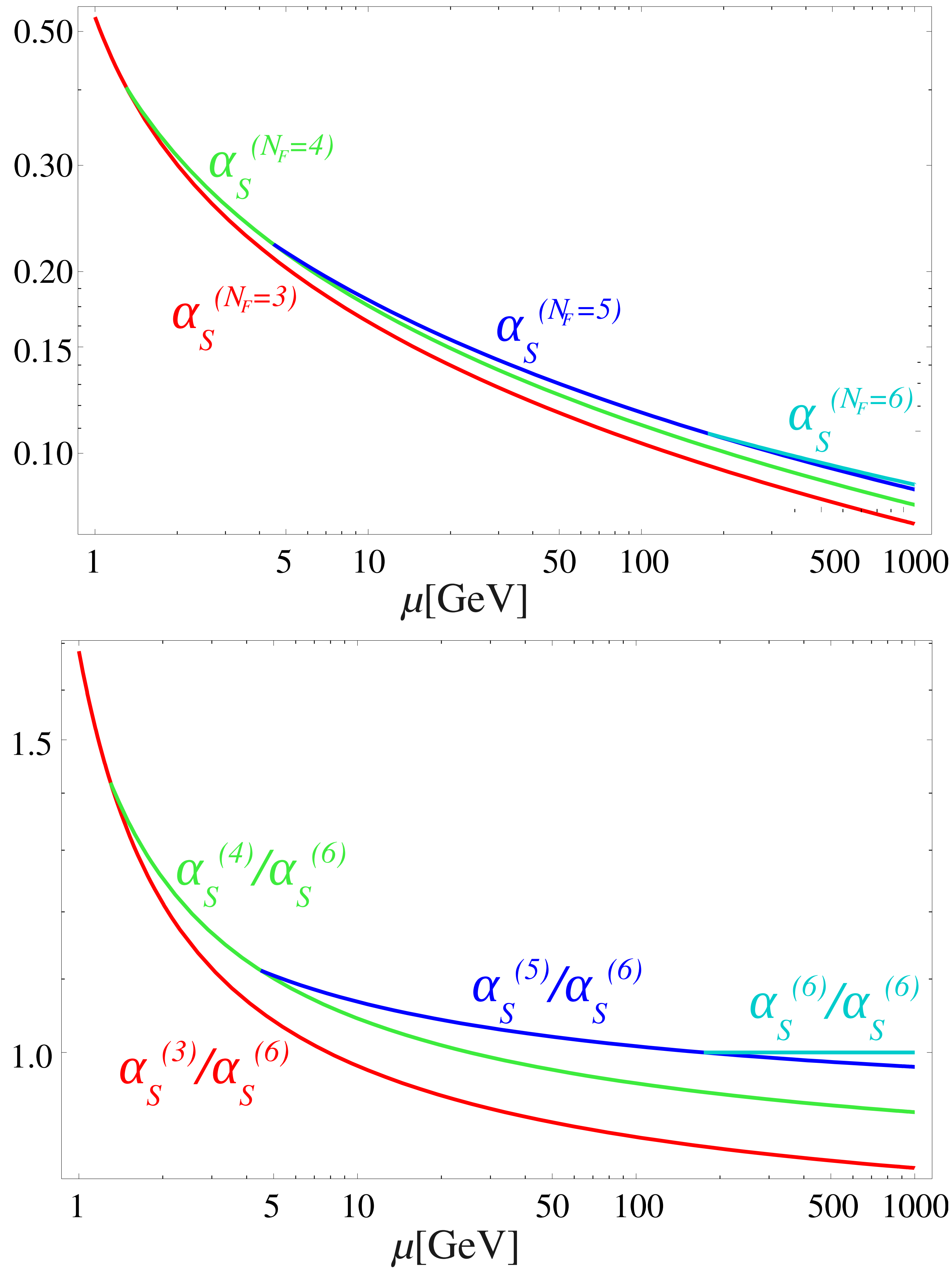
arXiv:1306.6553



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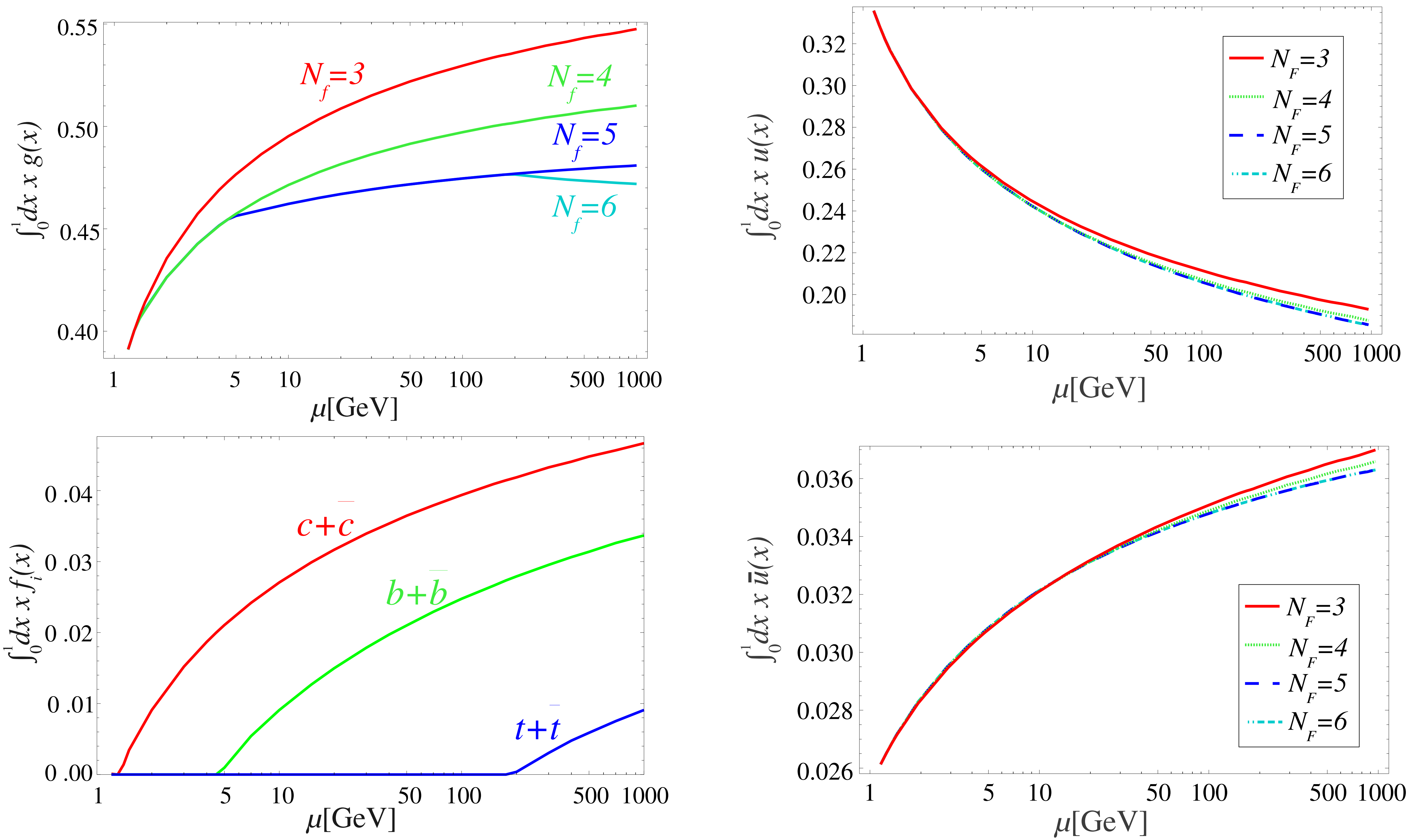

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FFNS vs VFNS: Pros and Cons

Heavy flavor schemes: FFNS

3-FFNS

- charm is not a parton, appears only in final state
- no collinear divergences from $c \to c + g$
  but terms $\propto \log(\mu/m)$ with $\mu = Q, p_T, \ldots$ the hard scale
- Collinear logarithms $\log(\mu/m)$ kept in fixed order perturbation theory

+ correct threshold behavior
+ finite charm mass terms m/μ exactly taken into account

– not IR-safe: does not meet requirement (2)
– How to include possible intrinsic charm?

The 3-FFNS should fail when $\alpha_s \ln(\mu/m)$ becomes large [or $a_s \ln(\mu/m)$?]

Phenomenological question: When need to resum collinear log's?
$\to$ Not unambigously answered yet! A lot of handwaving . . .

Heavy flavor schemes: VFNS

VFNS

- charm is a parton for $\mu \gtrsim m$
- mass singularities absorbed in PDFs (and FFs)
  - if $m = 0$: $1/\varepsilon$ poles $\rightarrow \overline{\mathrm{MS}}$ subtraction
  - if $m \neq 0$: $\log(\mu/m)$ + finite $\rightarrow \overline{\mathrm{MS}}$ subtraction
- QCD prediction: DGLAP (RG) evolution resums large logarithms $\log(\mu/m)$

\+ Requirements (1), (2) satisfied

\+ finite mass terms m/μ can be taken into account: massive VFNS (GM-VFNS) (otherwise: massless VFNS (ZM-VFNS) which is the original parton model)

– Requirement (3) **problematic point**:

  - In DIS slow-rescaling prescriptions (ACOT-χ) good approximation of exact threshold kinematics: $c(x) \rightarrow c(\chi)$ where $\chi = x(1 + 4m^2/Q^2)$
  - What to do in hadron–hadron collisions?
  - What to do in 1-particle inclusive production?

- Intrinsic charm natural to incorporate

Heavy flavor schemes: VFNS

VFNS

- Factorization proof with massive quarks for inclusive DIS: Collins '98
  Remainder $\sim \mathcal{O}(\Lambda^2/Q^2)$ not $\sim \mathcal{O}(m^2/Q^2)$
- Many incarnations of VFNS (ACOT, ACOT-χ, TR): Freedom to shift finite m-terms without spoiling IR-safety
- S-ACOT scheme: incoming heavy quarks massless ($\leftrightarrow$ scheme choice) more complex at NNLO
- Massive quarks can be described by massless evolution kernels ($\leftrightarrow$ scheme choice)
- Matching $n \to n+1$: PDFs, α_s, masses
- At NLO matching continuous at $\mu = m$: $f_i^{n_f} = f_i^{n_f+1}$
- At higher orders matching discontinuos:
  - for PDFs discontinuous at $\mathcal{O}(\alpha_s^2)$
  - for α_s discontinuous at $\mathcal{O}(\alpha_s^3)$
- Observable discontinuous: $\sigma^{n_f} = \sigma^{n_f+1} + \mathcal{O}(\alpha_s^{K+1})$

Termes in the perturbation series

$L = \ln (m/p_T)$
$a = \alpha_s/(2\pi)$

Resummed ↓

Fixed Order →

	LL	NLL	NNLL	...
LO	1			
NLO	aL	a		
NNLO	$(aL)^2$	$a(aL)$	a^2	
...	...	...	...	...

FFNS/Fixed Order NLO

Resummed ↓

Fixed Order →

	LL	NLL	NNLL	...
LO m≠0	1			
NLO m≠0	aL	a		
NNLO	$(aL)^2$	a(aL)	a^2	
...	...	...	...	...

ZM-VFNS/Resummed NLO

Resummed ↓

Fixed Order →

	LL m=0	NLL m=0	NNLL	...
LO	1			
NLO	aL	a		
NNLO	$(aL)^2$	a(aL)	a^2	
...	...	...	...	...

GM-VFNS/FONLL (NLO+NLL)

Resummed ↓

Fixed Order →

	LL	NLL	NNLL	...
LO	1 m≠0			
NLO	aL m≠0	a m≠0		
NNLO	$(aL)^2$ m=0	a(aL) m=0	a^2	
...	... m=0	... m=0	...	...

II. OPEN HEAVY FLAVOR HADROPRODUCTION

Why interesting?

Why open heavy flavor production is interesting

- Provides important probes for (our understanding of) QCD
- m_h acts as long distance cut-off: pQCD applicable down to $p_T \sim 0$,
  σ_{tot} calculable
- multi-scale problem (m, p_T): $p_T < m$, $p_T \sim m$, $p_T >> m$ confronted to data!

  testing ground for other multi-scale problems:
  production of W/Z/Higgs, BSM processes
- Heavy flavor production sensitive to gluon, heavy quark PDFs
  pp and pA collisions: constraints on these PDFs
- AA collisions: heavy flavors important probes of the QGP
- Solid understanding of charm production needed in cosmic ray and neutrino astrophysics

Theoretical approaches:
Fixed Flavor Number Scheme
(FFNS)

FFNS/Fixed Order

Factorization formula for inclusive heavy quark (Q) production:

PDFs

$$d\sigma^Q \simeq \sum_{a,b} f_a^A \otimes f_b^B \otimes d\tilde{\sigma}_{ab\to Q+X}$$

sum over all possible partonic subprocesses

Calculable short distance cross section; log(pT/m) terms kept in **fixed order**

FFNS/Fixed Order

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Inclusive heavy-flavored hadron (H) production:

$$d\sigma^H = d\sigma^Q \otimes D_Q^H(z)$$

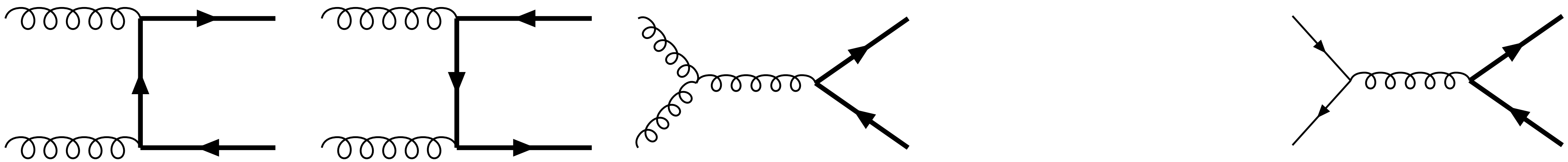
Convolution with a **scale-independent** FF

* non-perturbative
* describes hadronization
* not based on a fact. theorem

Leading Order (LO)

Leading order subprocesses:

1. $gg \to Q\bar{Q}$
2. $q\bar{q} \to Q\bar{Q} \quad (q = u, d, s)$



- The gg-channel is dominant at the LHC ($\sim$ 85% at $\sqrt{S} = 14$ TeV).
- The total production cross section for heavy quarks is fi nite.
  The minimum virtuality of the t-channel propagator is m^2. Sets the scale in α_s.
  Perturbation theory should be reliable.
- Note: For $m^2 \to 0$ total cross section would diverge.

[See M. Mangano, hep-ph/9711337; Textbook by Ellis, Stirling and Webber]

Next-to-leading Order (NLO)

Next-to-leading order (NLO) subprocesses:

1. $gg \to Q\bar{Q}g$
2. $q\bar{q} \to Q\bar{Q}g \quad (q = u, d, s)$
3. $gq \to Q\bar{Q}q$, $g\bar{q} \to Q\bar{Q}\bar{q}$ [new at NLO]
4. Virtual corrections to $gg \to Q\bar{Q}$ and $q\bar{q} \to Q\bar{Q}$

NLO corrections for $\sigma_{\rm tot}$ and differential cross sections $d\sigma/dp_T dy$ known since long:

- Nason, Dawson, Ellis, NPB303(1988)607; Beenakker, Kuif, van Neerven, Smith, PRD40(1989)54 [$\sigma_{\rm tot}$]
- NDE, NPB327(1989)49; (E)B335(1990)260; Beenakker *et al.*,NPB351(1991)507 [$d\sigma/dp_T dy$]

Well tested by recalculations and zero-mass limit:

- Bojak, Stratmann, PRD67(2003)034010 [$d\sigma/dp_T dy$ (un)polarized]
- Kniehl, Kramer, Spiesberger, IS, PRD71(2005)014018 [$m \to 0$ limit of diff. x-sec]
- Czakon, Mitov, NPB824(2010)111 [$\sigma_{\rm tot}$, fully analytic]

Next-to-leading Order (NLO)

- Fixed order NLO calculation also useful to obtain predictions of heavy quark correlations!

  Mangano,Nason,Ridolfi ('92)

Next-to-next-to-leading Order (NNLO)

Channels: $q\bar{q}$, gg, qg

- Two-loop virtual most difficult $\quad M_2^{(0)} + M_2^{(1)} + M_2^{(2)}$
  - Analytic approach: Bonciani, Ferroglia, Gehrmann, Maitre, Studerus, von Manteuffel ('08-'10)
  - Numeric approach: Czakon, Mitov et al.
- Virtual + Real $\quad M_3^{(0)} + M_3^{(1)}$
  Dittmaier, Uwer, Weinzierl ('08)
- Subtraction method for IR singularities in double real $\quad M_4^{(0)}$
  Czakon ('10-'11)

Next-to-next-to-leading Order (NNLO)

- Available now for top pair production!
- Total cross section — Czakon, Mitov, PRL110(2013)252004
- Differential distributions — Czakon, Mitov, arXiv:1411.3007
- Analytic approach not yet complete

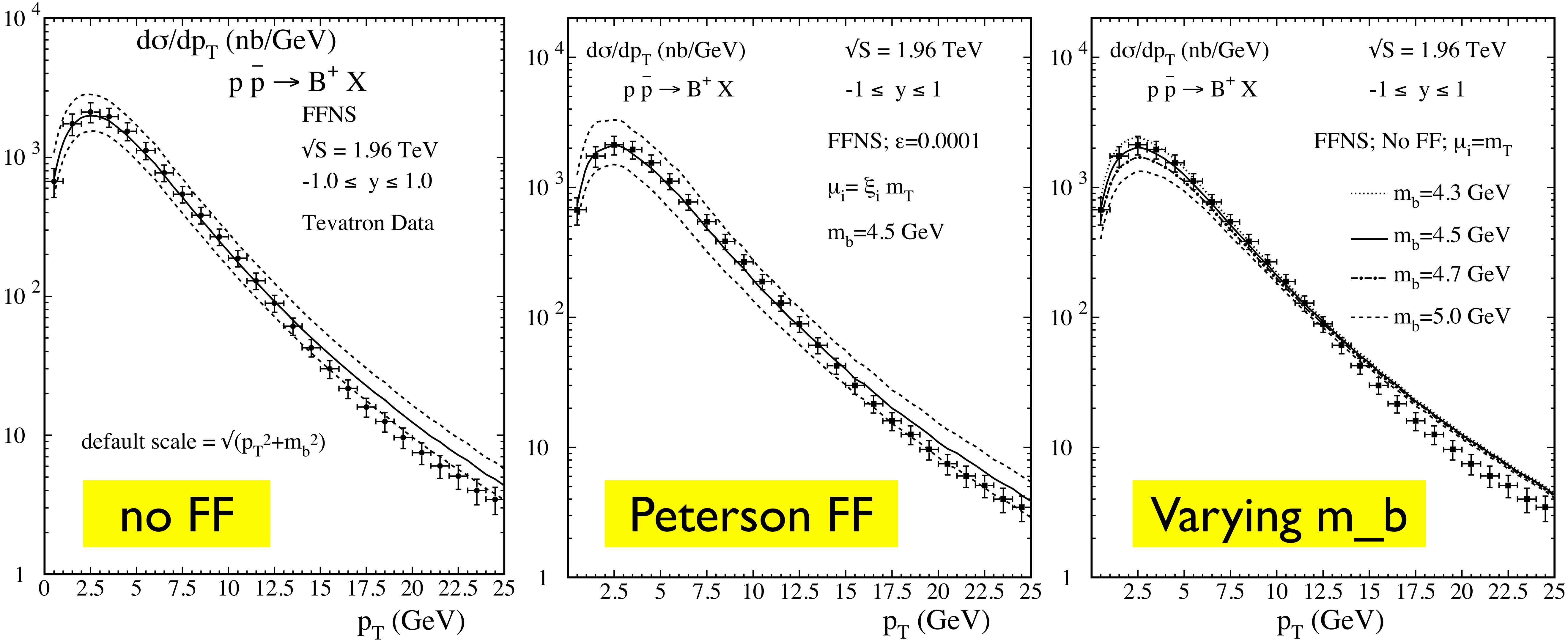
  [Bonciani et al.]

Very large scale uncertainties at NLO in c,b production

NNLO will be crucial to make progress!

Some NLO results for B-meson production

NLO FFNS works very well for pT up to roughly 5m



Remarks:

- Fixed order theory in reasonable agreement with Tevatron data up to $p_T \simeq 5 m_b$
- At $p_T \lesssim m_b$ factorization less obvious. Depends on defi nition of convolution variable z: $p_B = z p_b$ or $p_T^B = z p_T^b$ or $p_B^+ = z p_b^+$ or $\vec{p}_B = z \vec{p}_b$
- Less hadronization effects than originally believed:
  ϵ-parameter small corresponding to a hard fragmentation function.
  Harder FF $\rightarrow$ harder p_T-spectrum
- Larger $\alpha_s(M_Z) \rightarrow$ harder p_T-spectrum
- Mass dependence imortant for $p_T \lesssim m$ (peak) $\rightarrow \sigma_{tot}$
- Only the 4th or 5th Mellin-moment of the FF is relevant for large p_T [M. Mangano]:
  $d\sigma^b/dp_T(b) \simeq A/p_T(b)^n$ with $n \simeq 4, \ldots, 5$

  $d\sigma^B/dp_T(B) = \int dz/z\, D(z)\, d\sigma^b/dp_T(b)[p_T(b) = p_T(B)/z] =$
  $A/p_T(B)^n \times \int dz\, z^{n-1}\, D(z)$

Theoretical approaches:
Zero Mass Variable Flavor Number Scheme (ZM-VFNS)

ZM-VFNS/RS

Factorization formula for inclusive heavy quark (Q) production:

$$d\sigma^{H+X} \simeq \sum_{a,b,c} \int_0^1 dx_a \int_0^1 dx_b \int_0^1 dz \; f_a^A(x_a, \mu_F) f_b^B(x_b, \mu_F) d\hat{\sigma}_{ab\to c+X} D_c^H(z, \mu_F') + \mathcal{O}(m^2/p_T^2)$$

- Same factorization formula as for inclusive production of pions and kaons
- Quark mass neglected in kinematics and the short distance cross section
- Allows to compute p_T spectrum for $p_T >> m$
- Needs **scale-dependent** FFs of quarks and gluons into the observed heavy-flavored hadron (H)

List of subprocesses in the ZM-VFNS

Massless NLO calculation: [Aversa,Chiappetta,Greco,Guillet,NPB327(1989)105]

1. $gg \to qX$
2. $gg \to gX$
3. $qg \to gX$
4. $qg \to qX$
5. $q\bar{q} \to gX$
6. $q\bar{q} \to qX$
7. $qg \to \bar{q}X$
8. $qg \to \bar{q}'X$
9. $qg \to q'X$
10. $qq \to gX$
11. $qq \to qX$
12. $q\bar{q} \to q'X$
13. $q\bar{q}' \to gX$
14. $q\bar{q}' \to qX$
15. $qq' \to gX$
16. $qq' \to qX$

$\oplus$ charge conjugated processes

Fragmentation functions

Approach I: Perturbative FFs (PFFs)

Caccciari, Greco, ...

$$D_i^H(z,\mu_F') = D_i^Q(z,\mu_F') \otimes D_Q^H(z)$$

PFF evolved with DGLAP;
short distance;
boundary condition calculable

Non-pert., scale-independent FF describing hadronization of heavy quark Q into heavy hadron H

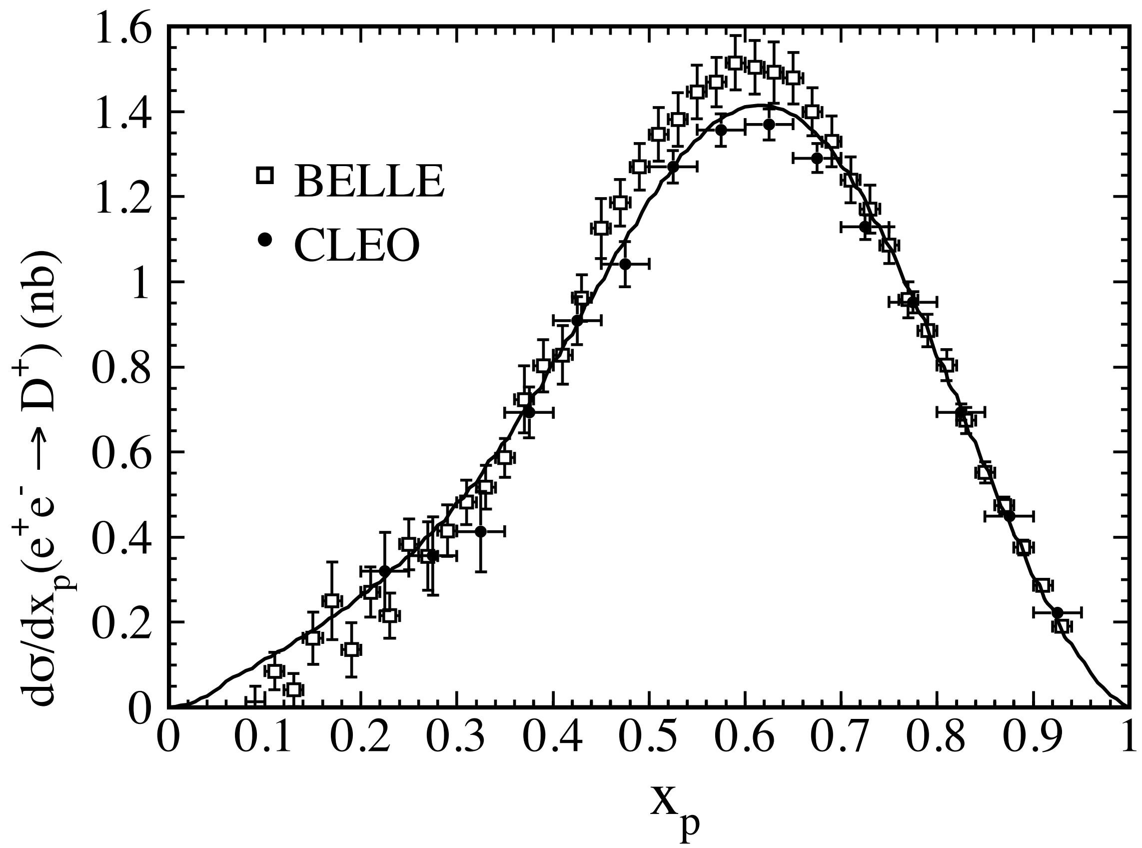
Mellin-moments of $D_Q^H(z)$ determined from e^+e^- data

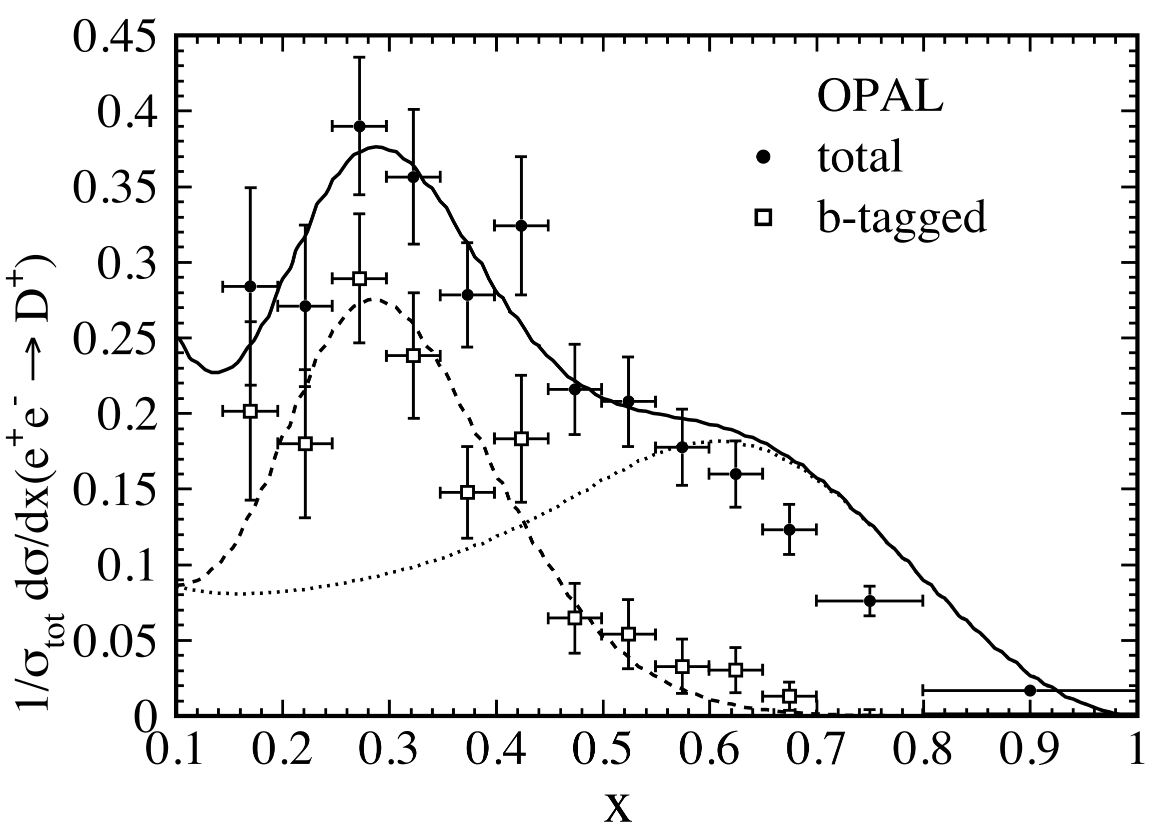
Approach II: treat FFs into H in the same way as FFs into pions or kaons

Binnewies, Kniehl, Kramer, ...

Non-pert. boundary conditions $D_i^H(z,m)$ from fit to e^+e^- data;
Determine FFs directly in x-space; evolved with DGLAP

FFs into D mesons





FF for $c \to D^*$
from fitting to e^+e^- data

2008 analysis based on GM-VFNS
$\mu_0 = m$

global fit: data from
ALEPH, OPAL, BELLE, CLEO

BELLE/CLEO fit

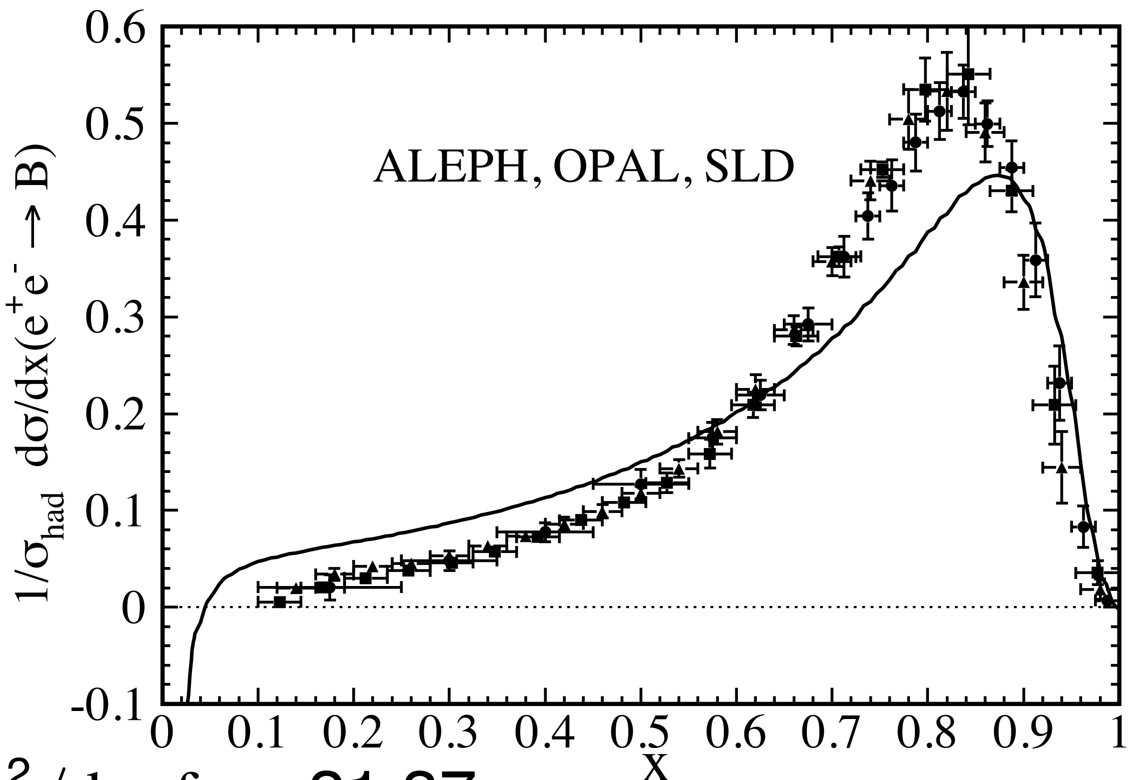
[KKKS: Kneesch, Kramer, Kniehl, IS
NPB799 (2008)]

tension between low and high energy data sets $\to$ speculations about non-perturbative (power-suppressed) terms

FFs into B mesons [1] from LEP/SLC data [2]

Petersen

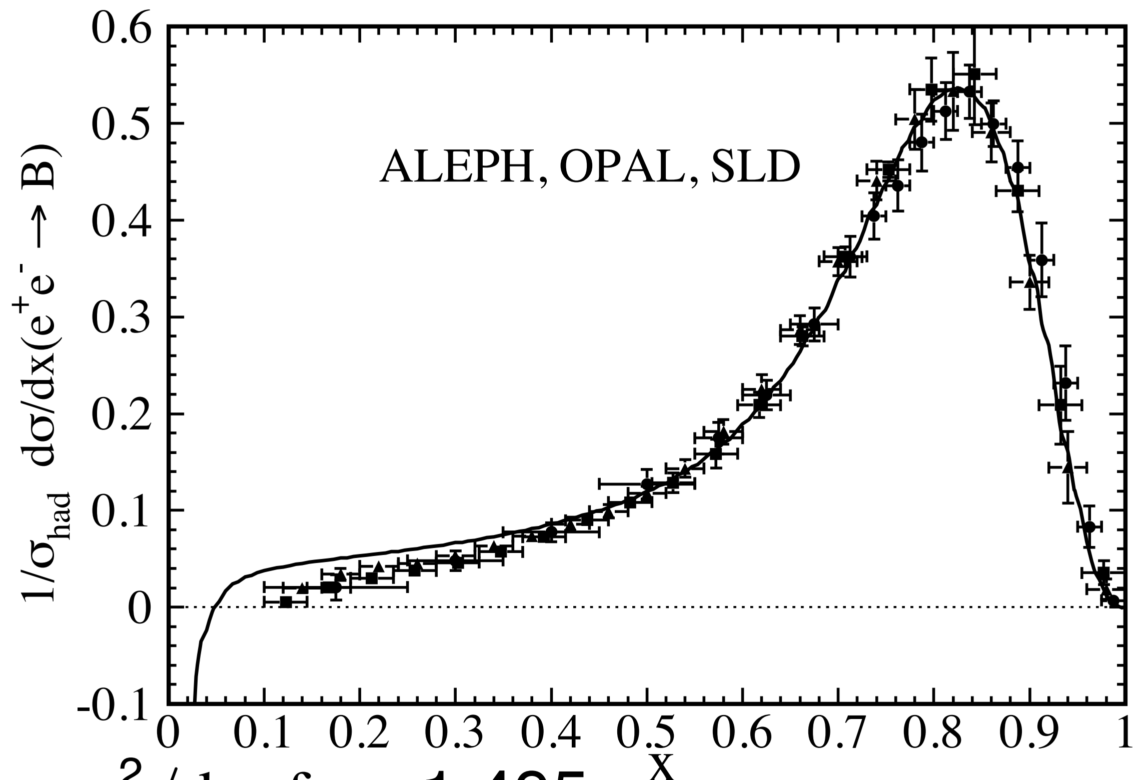
$$D(x,\mu_0^2) = N\frac{x(1-x)^2}{[(1-x)^2+\epsilon x]^2}$$



$\chi^2/\text{d.o.f.} = 21.37$

Kartvelishvili-Likhoded

$$D(x,\mu_0^2) = Nx^{\alpha}(1-x)^{\beta}$$



$\chi^2/\text{d.o.f.} = 1.495$

[1] Kniehl,Kramer,IS,Spiesberger,PRD77(2008)014011

[2] ALEPH, PLB512(2001)30; OPAL, EPJC29(2003)463; SLD, PRL84(2000)4300; PRD65(2002)092006

Theoretical approaches:
General Mass Variable Flavor Number Scheme (GM-VFNS)

GM-VFNS

Factorization Formula: [1]

$$d\sigma(p\bar{p} \to D^\star X) = \sum_{i,j,k} \int dx_1\, dx_2\, dz\, f_i^p(x_1)\, f_j^{\bar{p}}(x_2) \times$$
$$\mathrm{d}\hat{\sigma}(ij \to kX)\, D_k^{D^\star}(z) + \mathcal{O}(\alpha_s^{n+1}, (\tfrac{\Lambda}{Q})^p)$$

Q: hard scale, $p = 1, 2$

- $\mathrm{d}\hat{\sigma}(\mu_F, \mu'_F, \alpha_s(\mu_R), \frac{m_h}{p_T})$: hard scattering cross sections free of long-distance physics $\longrightarrow$ m_h kept
- PDFs $f_i^p(x_1, \mu_F)$, $f_j^{\bar{p}}(x_2, \mu_F)$: $i, j = g, q, c$ $\quad [q = u, d, s]$
- FFs $D_k^{D^\star}(z, \mu'_F)$: $k = g, q, c$

$\Rightarrow$ need short distance coefficients including heavy quark masses

---

[1] J. Collins, 'Hard-scattering factorization with heavy quarks: A general treatment', PRD58(1998)094002

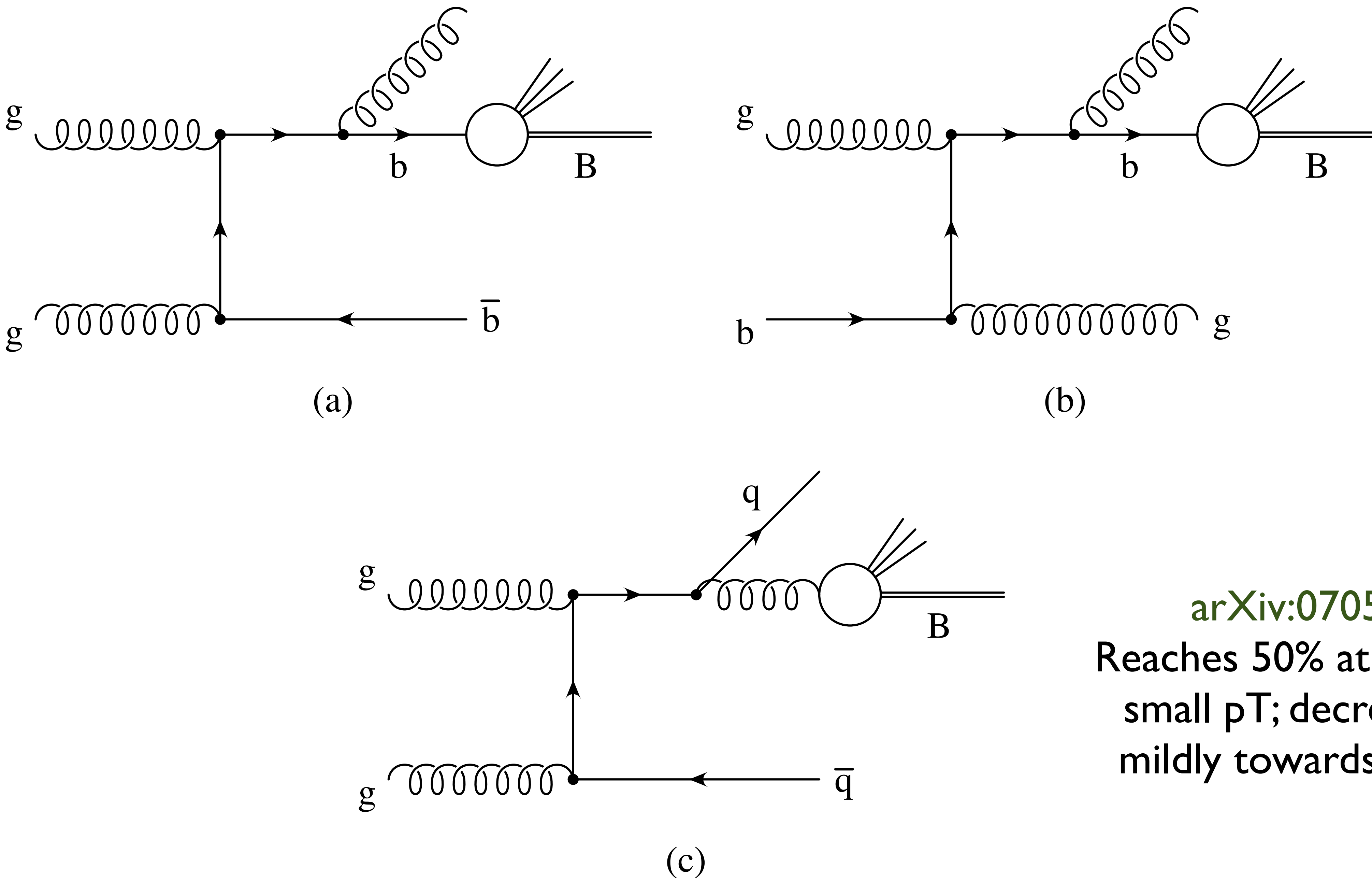
List of subprocesses in the GM-VFNS

	Only light lines	Heavy quark initiated ($m_Q = 0$)	Mass effects: $m_Q \neq 0$
1	$gg \to qX$	-	$gg \to QX$
2	$gg \to gX$	-	-
3	$qg \to gX$	$Qg \to gX$	-
4	$qg \to qX$	$Qg \to QX$	-
5	$q\bar{q} \to gX$	$Q\bar{Q} \to gX$	-
6	$q\bar{q} \to qX$	$Q\bar{Q} \to QX$	-
7	$qg \to \bar{q}X$	$Qg \to \bar{Q}X$	-
8	$qg \to \bar{q}'X$	$Qg \to \bar{q}X$	$qg \to \bar{Q}X$
9	$qg \to q'X$	$Qg \to qX$	$qg \to QX$
10	$qq \to gX$	$QQ \to gX$	-
11	$qq \to qX$	$QQ \to QX$	-
12	$q\bar{q} \to q'X$	$Q\bar{Q} \to qX$	$q\bar{q} \to QX$
13	$q\bar{q}' \to gX$	$Q\bar{q} \to gX$, $q\bar{Q} \to gX$	-
14	$q\bar{q}' \to qX$	$Q\bar{q} \to QX$, $q\bar{Q} \to qX$	-
15	$qq' \to gX$	$Qq \to gX$, $qQ \to gX$	-
16	$qq' \to qX$	$Qq \to QX$, $qQ \to qX$	-

$\oplus$ charge conjugated processes

Example diagrams

m ≠ 0   m = 0 (S-ACOT)



arXiv:0705.4392

Reaches 50% at Tevatron at small pT; decreases only mildly towards larger pT

FIG. 2: Examples of Feynman diagrams leading to contributions of (a) class (i), (b) class (ii), and (c) class (iii).

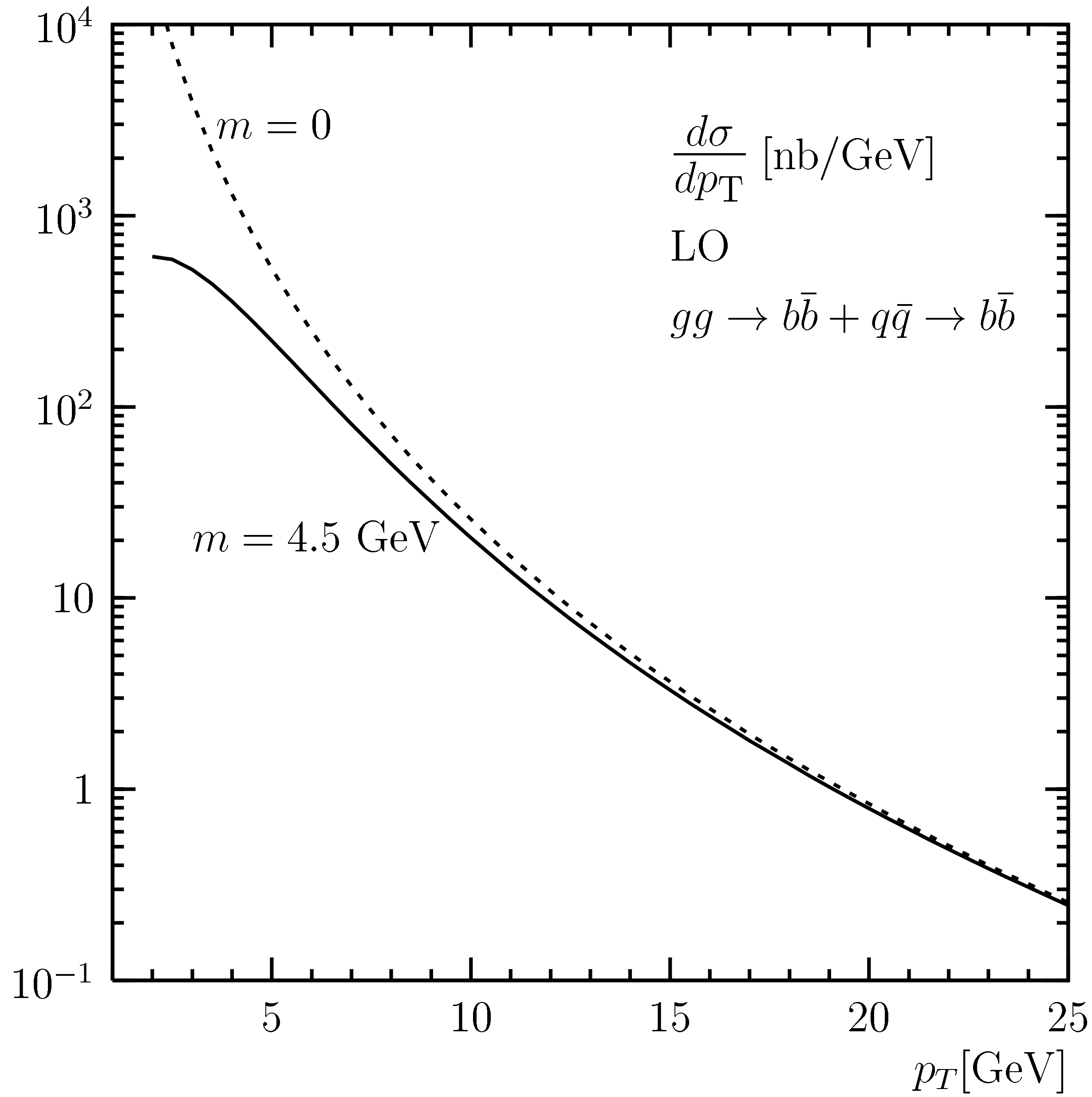
Limiting cases

- **GM-VFNS → ZM-VFNS for $p_T >> m$**
  (this is the case by construction)

- **GM-VFNS → FFNS for $p_T \sim m$**
  (formally this can be shown; numerically problematic in the S-ACOT scheme)

The GM-VFNS at low p_T

LO: m=0 case diverges at pT=0



Problem: current implementation in S-ACOT scheme
b+g channel with m=0 diverges at small p_T!

The GM-VFNS at low p_T

Problem can be solved by suitable scale choice

arXiv:1502.01001

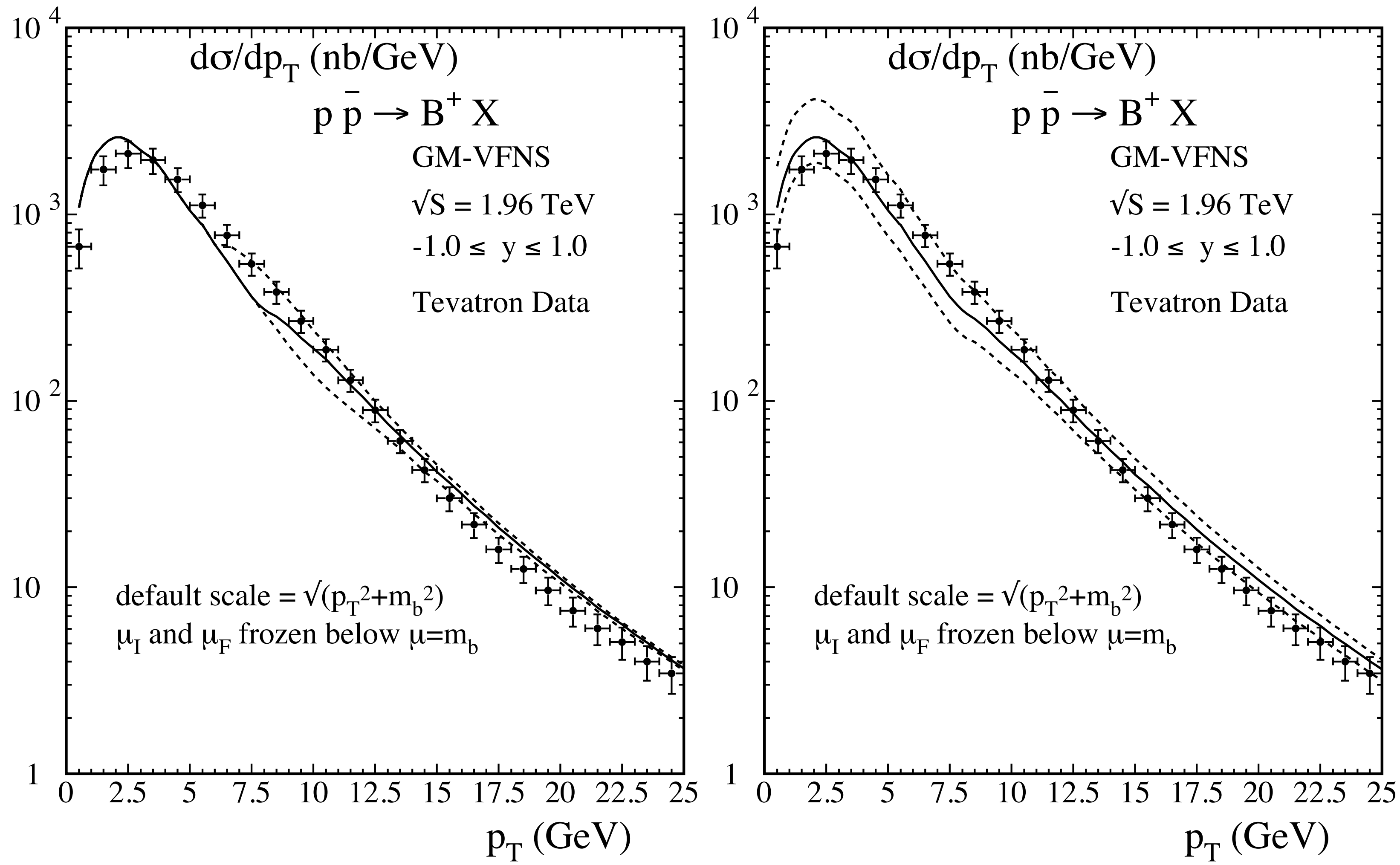


Figure 5: $d\sigma/dp_T$ for $p\bar{p} \to B^+ + X$ at $\sqrt{S} = 1.96$ TeV, $|y| < 1.0$, in the GM-VFNS (data from CDF [6]). Left panel: $\xi_R = 1$, $\xi_I = 0.5$ and $\xi_F = 0.5$ (full curve), $\xi_F = 0.6$ (upper dashed curve), $\xi_F = 0.4$ (lower dashed curve). Right panel: $\xi_i = (1, 0.5, 0.5)$ for the central curve; upper curve: $\xi_R = 0.5$, lower curve: $\xi_R = 2$.

The GM-VFNS at low p_T

Comparison with LHCb data

arXiv:1502.01001

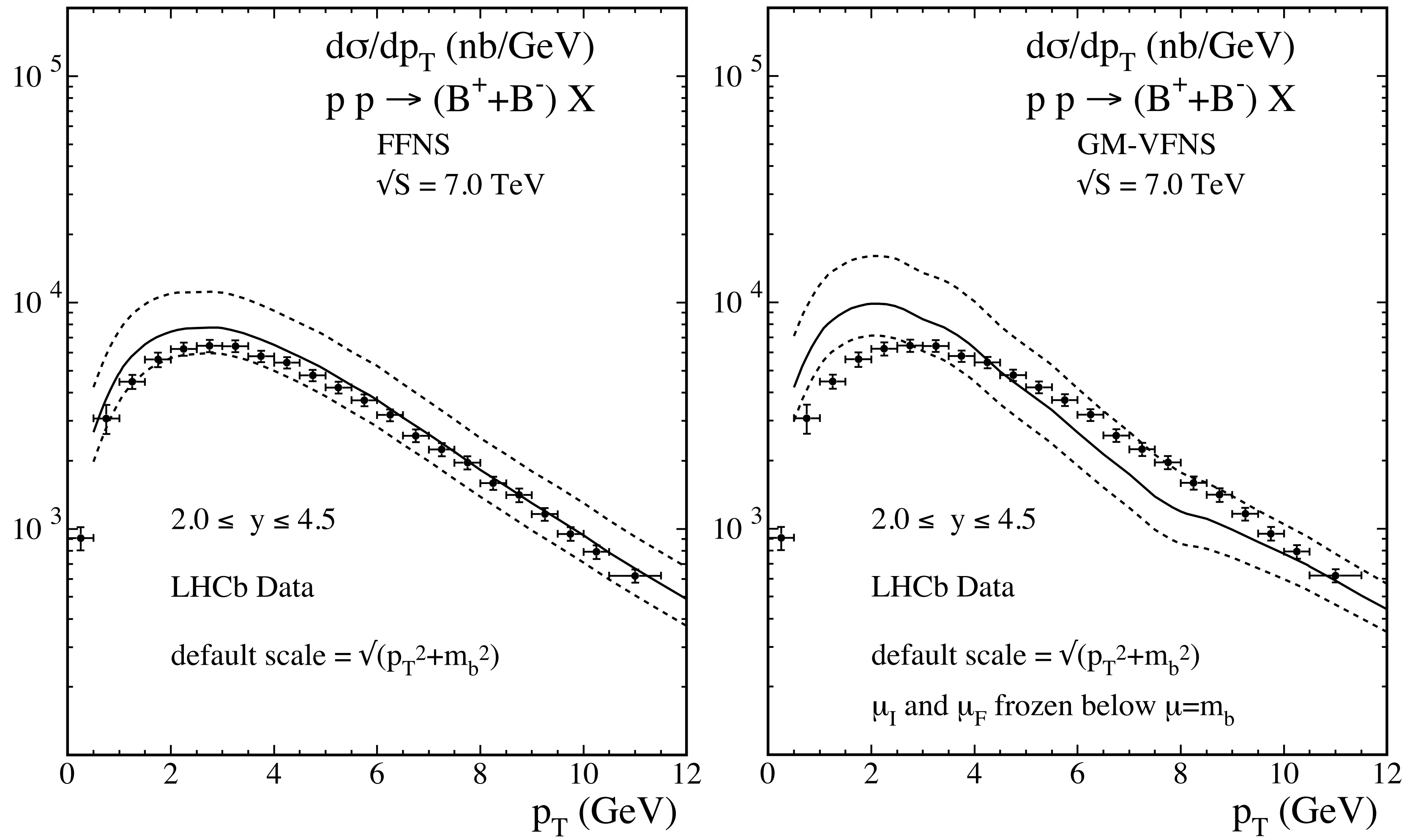


Figure 6: $d\sigma/dp_T$ for $pp \to B^+ + B^- + X$ at $\sqrt{S} = 7$ TeV with $2.0 < y < 4.5$, compared with results from the FFNS (left) and the GM-VFNS (right). $\xi_{R,I,F} = (1,\ 0.5,\ 0.5)$. The error band is obtained from variations by factors 2 up and down (maximum: $\xi_R = 0.5$, minimum: $\xi_R = 2$). The factorization scale parameters are frozen below $\mu_{I,F} = m_b$. Data points are taken from [15].

GM-VFNS: Comparison with ATLAS data

arXiv:1502.01001

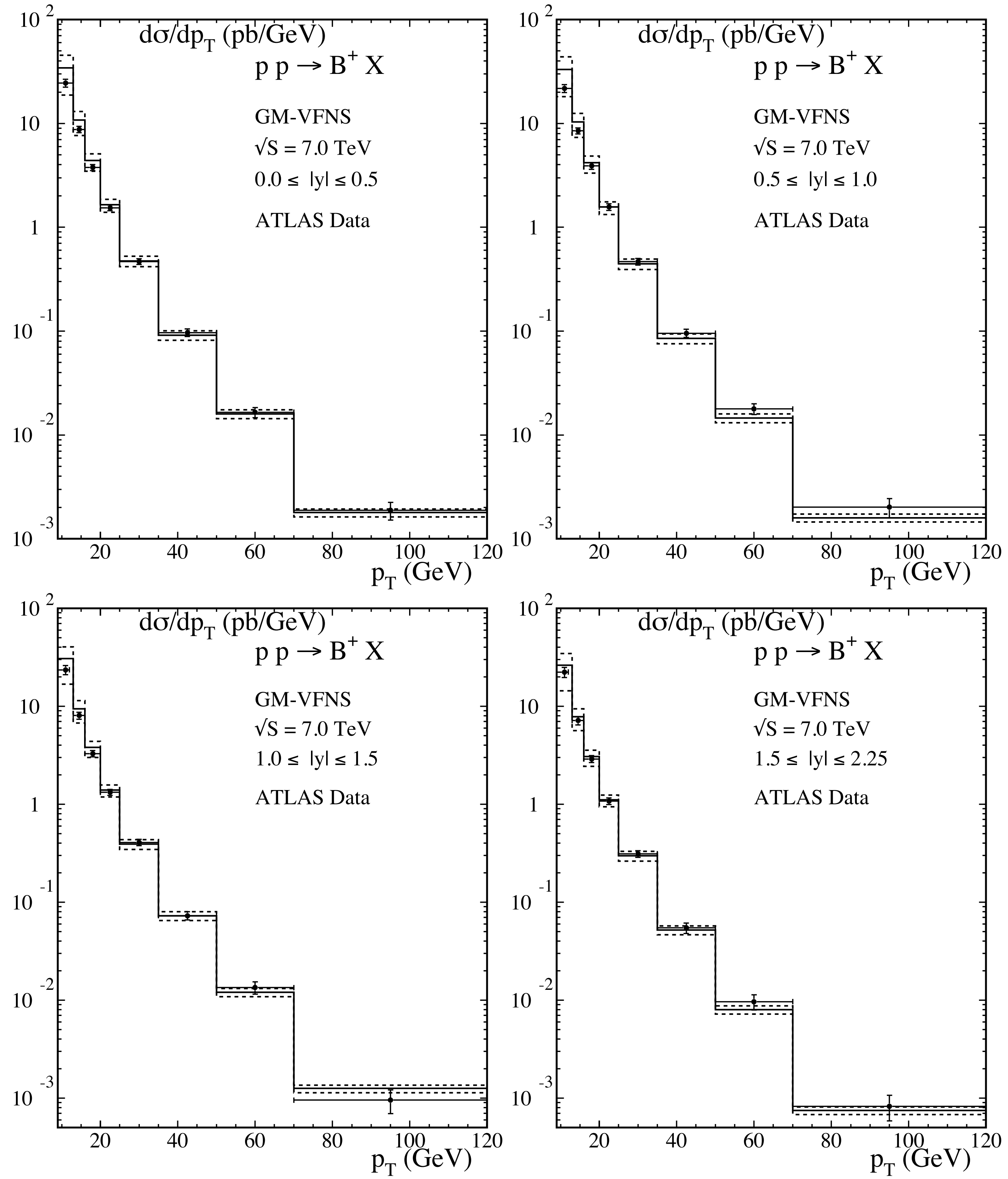


Figure 9: $pp \to B^+ + X$ at $\sqrt{S} = 7$ TeV in the GM-VFNS compared with data from ATLAS [13]. $\mu_{I,F}$ are frozen below m_b and $\xi_i = (1,\ 1,\ 1)$.

GM-VFNS

- FFs in x-space in the BKK approach

- Heavy-quark initiated contributions (Q+g → Q+X, ...) get very large at small p_T in the massless case:

  (i) switch off heavy-quark PDF sufficiently quickly
  OR
  (ii) calculate these subprocesses with mass

- Error bands: μ_R , μ_F , μ_F' varied independently

- Predictions for D and B prod. at Tevatron, RHIC, LHC:
  arXiv:1502.01001, 1202.0439, 1109.2472, 0901.4130, 0705.4392, hep-ph/0508129, ph/0502194, ph/0410289

- Predictions including D-decay and B-decay:
  arXiv: 1310.2924, 1212.4356

Theoretical approaches:
Fixed Order plus Next-to-Leading Logarithms (FONLL)

FONLL=FO+NLL [1]

$$\mathrm{FONLL} = \mathrm{FO} + (\mathrm{RS} - \mathrm{FOM0})\mathrm{G}(\mathrm{m}, \mathrm{p_T})$$

FO: Fixed Order; FOM0: Massless limit of FO; RS: Resummed

$$G(m, p_T) = \frac{p_T^2}{p_T^2 + 25m^2} \simeq \begin{cases} 0.04 & : \quad p_T = m \\ 0.25 & : \quad p_T = 3m \\ 0.50 & : \quad p_T = 5m \\ 0.66 & : \quad p_T = 7m \\ 0.80 & : \quad p_T = 10m \end{cases}$$

$$\Rightarrow \mathrm{FONLL} = \begin{cases} \mathrm{FO} & : \quad \mathrm{p_T} \lesssim 3\mathrm{m} \\ \mathrm{RS} & : \quad \mathrm{p_T} \gtrsim 10\mathrm{m} \end{cases}$$

[1] Cacciari, Greco, Nason, JHEP05(1998)007

FONLL

- FFs in N-space in the PFF approach
- RS-FOM0 gets very large at small p_T:

  $G(m,p_T) = p_T^2/(p_T^2 + a^2 m^2)$ with **a=5**

  needed to suppress this contribution sufficiently rapidly
- Central scale choice for FO, RS, FOM0: m_T
- Error bands: $\mu_F = \mu_F'$ (only two scales varied)
- Predictions for LHC7 in arXiv:1205.6344

NLO Monte Carlo generators:
MC@NLO and POWHEG

NLO MC generators

- MC@NLO, POWHEG: hep-ph/0305252, arXiv:0707.3088
  consistent matching of NLO matrix elements with parton showers (PS)

- Flexible simulation of hadronic final state
  (PS, hadronization, detector effects)

  Note: FONLL and GM-VFNS only one-particle inclusive observables

- High accuracy: NLO+LL*
  (FONLL and GM-VFNS have NLO+NLL accuracy)

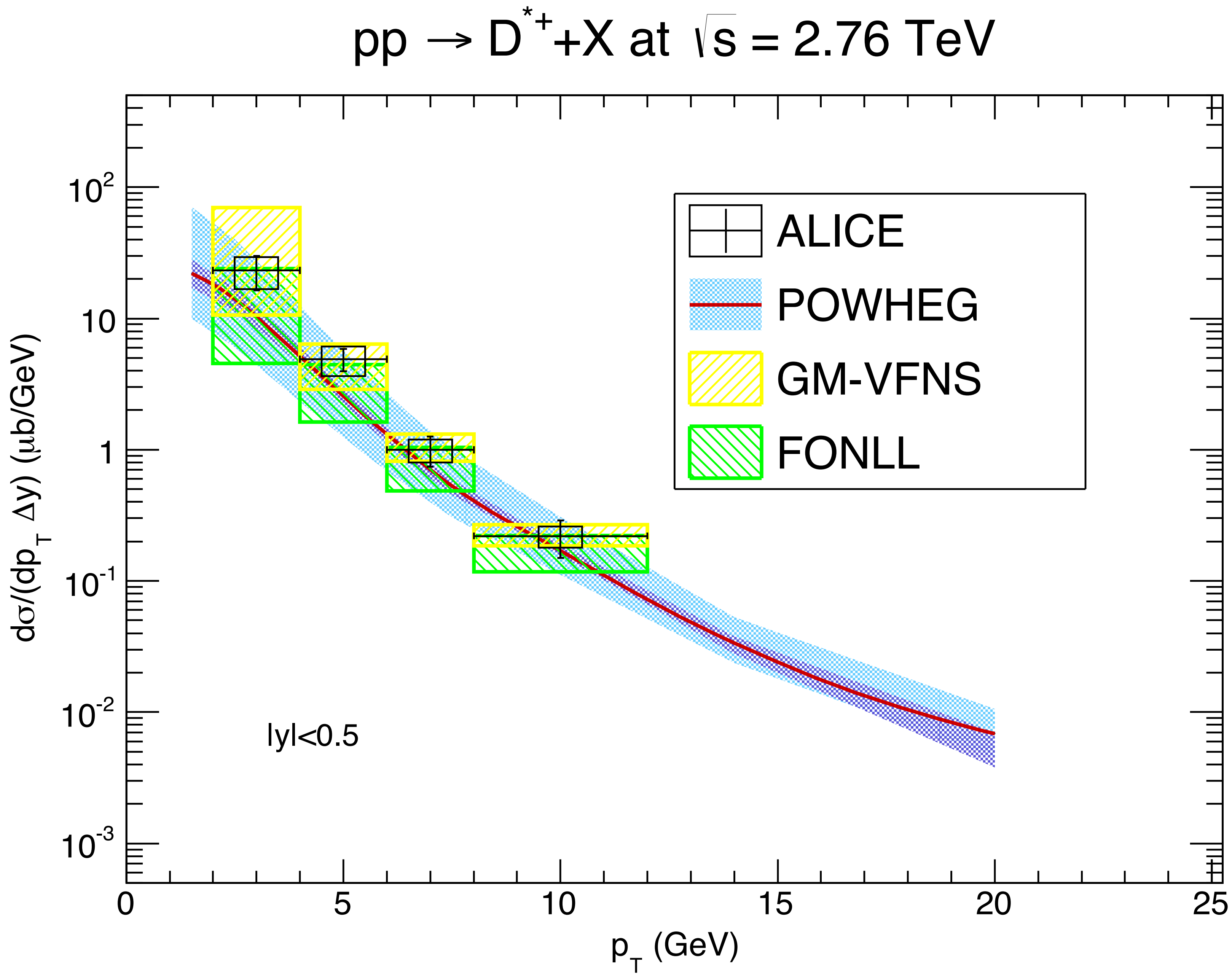
- Simulation of hadronic final state involves tuning;
  NOT a pure theory prediction!

Theoretical approaches:
k_T factorization

III. COMPARISON OF GM-VFNS, FONLL, POWHEG with ALICE DATA

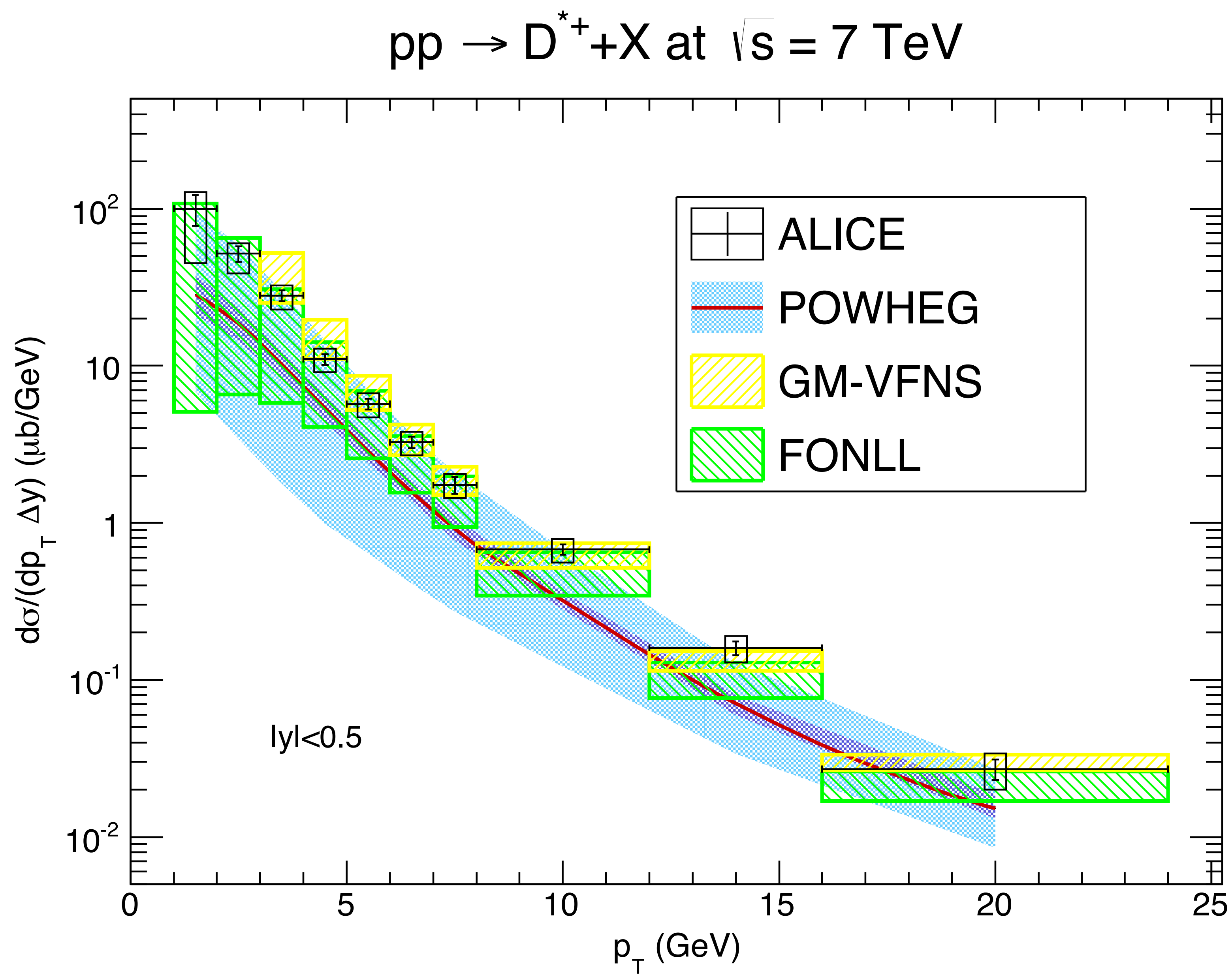
Comparison with ALICE data

arXiv:1405.3083



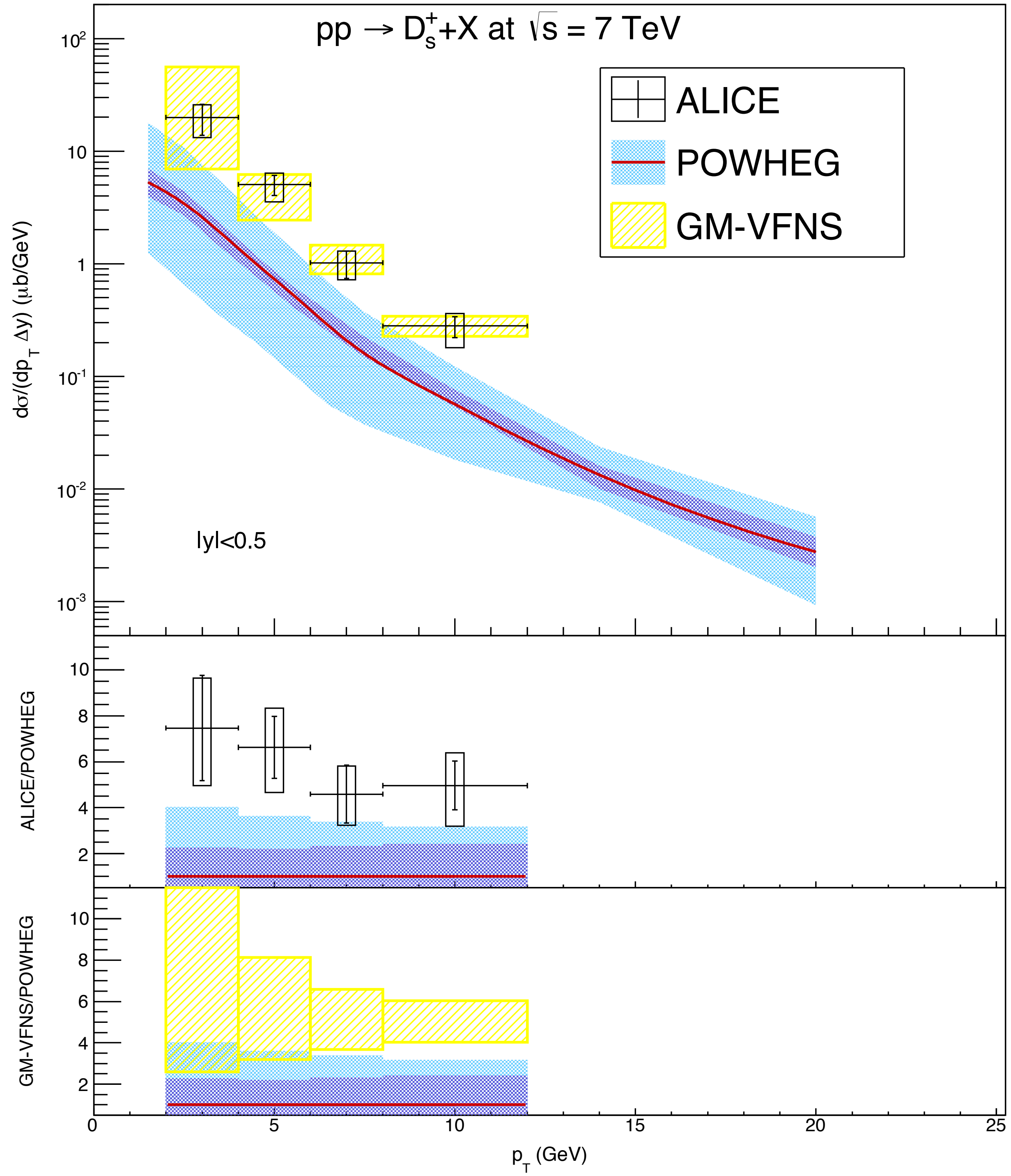
Comparison with ALICE data

arXiv:1405.3083

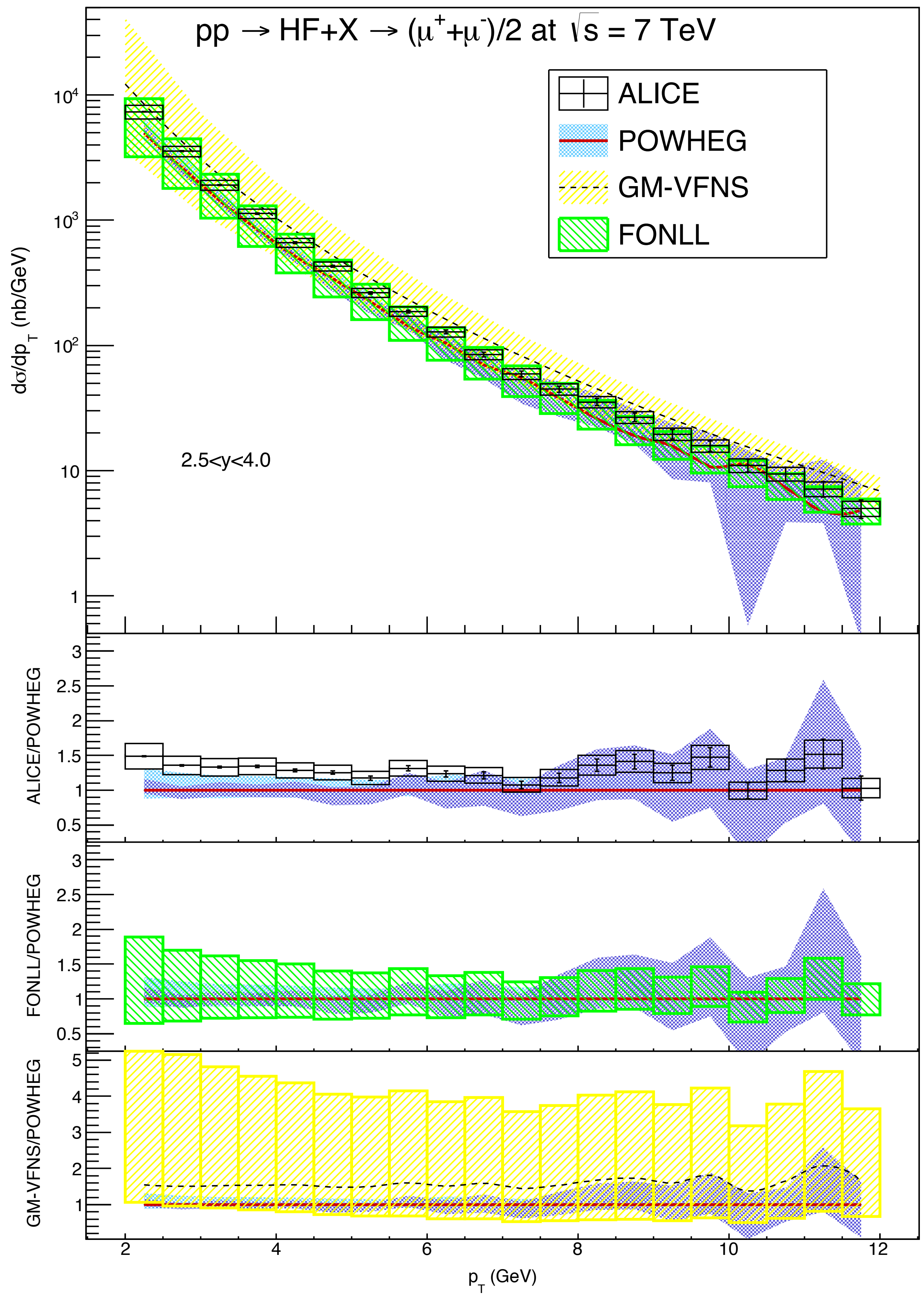


Comparison with ALICE data

arXiv:1405.3083



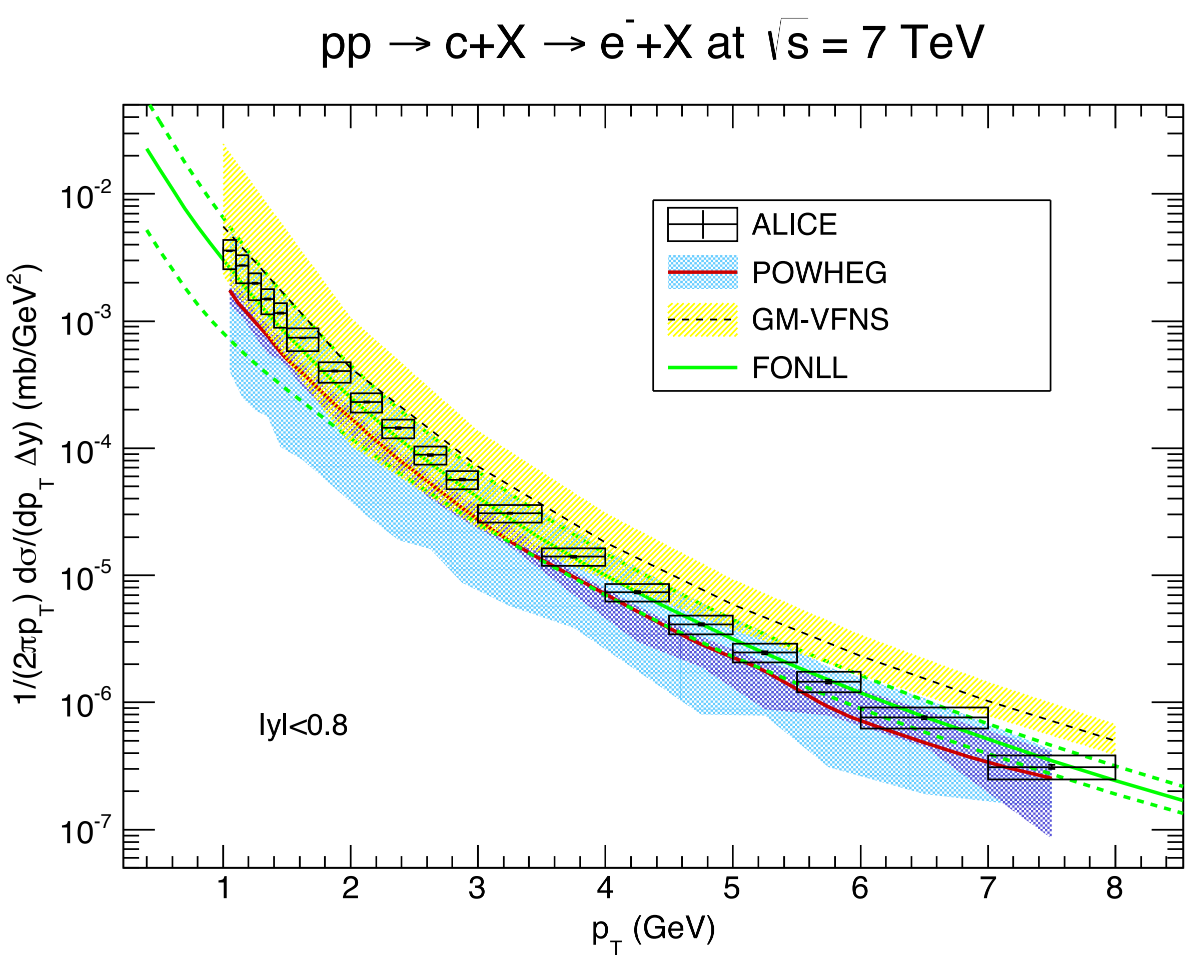
Comparison with ALICE data

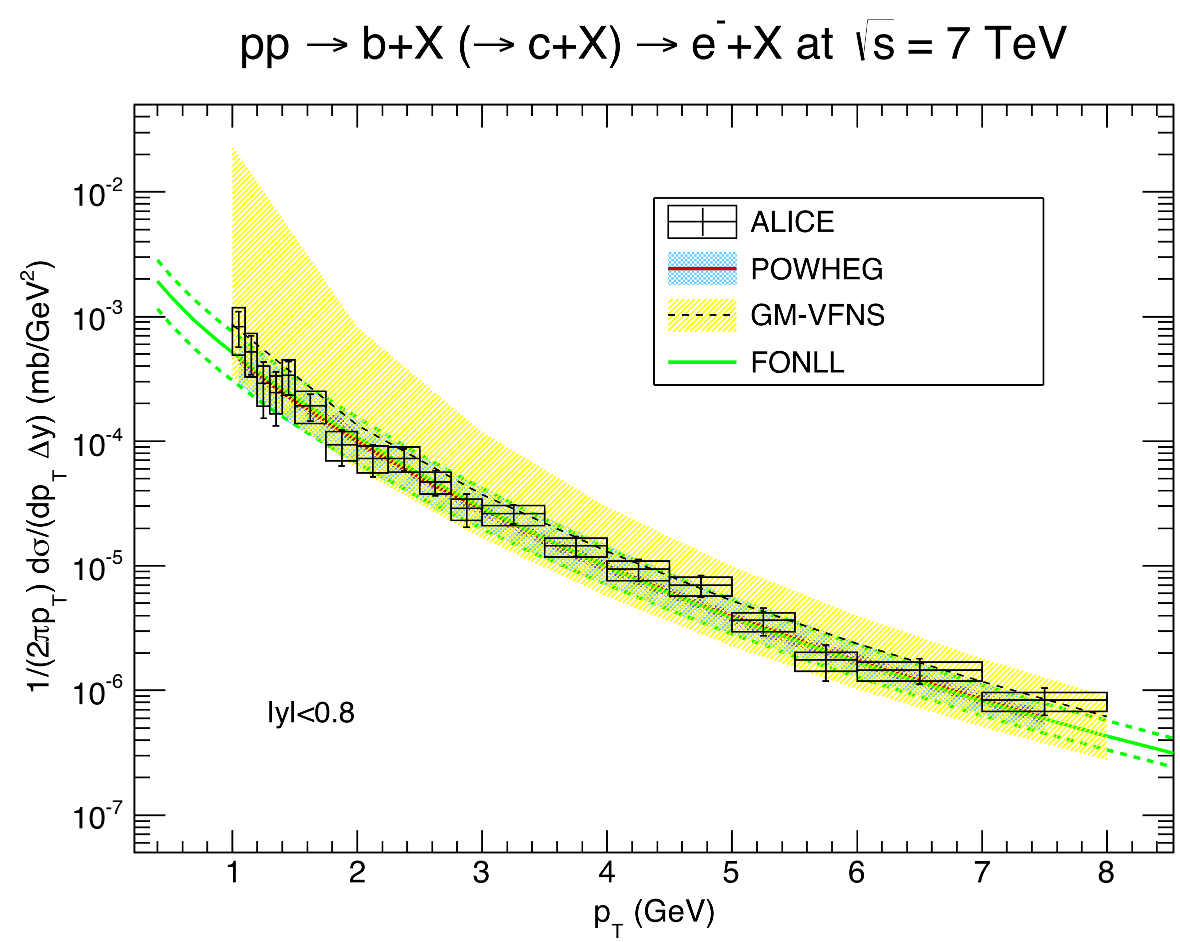


arXiv:1405.3083

Comparison with ALICE data

arXiv:1405.3083





IV. SUMMARY

Summary

- Discussed different theoretical approaches to open heavy flavor hadroproduction
- GM-VFNS, FONLL, POWHEG in good agreement with data within large uncertainties!
- GM-VFNS at low p_T improved; more work in progress
- Need NNLO to reduce scale uncertainties!

Back up slides

Mass terms contained in the hard scattering coeffi cients:

$$d\hat{\sigma}(\mu_F, \mu_{F'}, \alpha_s(\mu_R), \frac{m}{p_T})$$

Two ways to derive them:

(1) Compare massless limit of a massive fi xed-order calculation
with a massless $\overline{\mathrm{MS}}$ calculation
to determine subtraction terms

[Kniehl,Kramer,IS,Spiesberger,PRD71(2005)014018]

OR

(2) Perform mass factorization using partonic PDFs and FFs

[Kniehl,Kramer,IS,Spiesberger,EPJC41(2005)199]

▸▸ skip details

- Compare limit $m \to 0$ of the massive calculation (Merebashvili et al., Ellis, Nason; Smith, van Neerven; Bojak, Stratmann; ...) with massless $\overline{\mathrm{MS}}$ calculation (Aurenche et al., Aversa et al., ...)

$$\lim_{m\to 0} \mathrm{d}\tilde{\sigma}(m) = \mathrm{d}\hat{\sigma}_{\overline{\mathrm{MS}}} + \Delta\mathrm{d}\sigma$$

$\Rightarrow$ Subtraction terms

$$\mathrm{d}\sigma_{\mathrm{sub}} \equiv \Delta\mathrm{d}\sigma = \lim_{m\to 0} \mathrm{d}\tilde{\sigma}(m) - \mathrm{d}\hat{\sigma}_{\overline{\mathrm{MS}}}$$

- Subtract $\mathrm{d}\sigma_{\mathrm{sub}}$ from massive partonic cross section while keeping mass terms

$$\mathrm{d}\hat{\sigma}(m) = \mathrm{d}\tilde{\sigma}(m) - \mathrm{d}\sigma_{\mathrm{sub}}$$

$\to$ $\mathrm{d}\hat{\sigma}(m)$ short distance coeffi cient including m dependence

$\to$ allows to use PDFs and FFs with $\overline{\mathrm{MS}}$ factorization $\otimes$ massive short distance cross sections

- Treat contributions with charm in the initial state with $m = 0$
- Massless limit: technically non-trivial, map from phase-space slicing to subtraction method

Mass factorization

Subtraction terms are associated to mass singularities:
can be described by
partonic PDFs and FFs for collinear splittings $a \to b + X$

- initial state:

$$f^{(1)}_{g\to Q}(x,\mu^2) = \frac{\alpha_s(\mu)}{2\pi} P^{(0)}_{g\to q}(x) \ln \frac{\mu^2}{m^2}$$

$$f^{(1)}_{Q\to Q}(x,\mu^2) = \frac{\alpha_s(\mu)}{2\pi} C_F \left[\frac{1+z^2}{1-z}\left(\ln \frac{\mu^2}{m^2} - 2\ln(1-z) - 1\right)\right]_+$$

$$f^{(1)}_{g\to g}(x,\mu^2) = -\frac{\alpha_s(\mu)}{2\pi} \frac{1}{3} \ln \frac{\mu^2}{m^2} \delta(1-x)$$

- fi nal state:

$$d^{(1)}_{g\to Q}(z,\mu^2) = \frac{\alpha_s(\mu)}{2\pi} P^{(0)}_{g\to q}(z) \ln \frac{\mu^2}{m^2}$$

$$d^{(1)}_{Q\to Q}(z,\mu^2) = C_F \frac{\alpha_s(\mu)}{2\pi} \left[\frac{1+z^2}{1-z}\left(\ln \frac{\mu^2}{m^2} - 2\ln(1-z) - 1\right)\right]_+$$

- Other partonic distribution functions are zero to order α_s

[Mele, Nason; Kretzer, Schienbein; Melnikov, Mitov]

(2) Subtraction terms via $\overline{\text{MS}}$ mass factorization: $a(k_1)b(k_2) \to Q(p_1)X$ [1]

Sketch of kinematics:

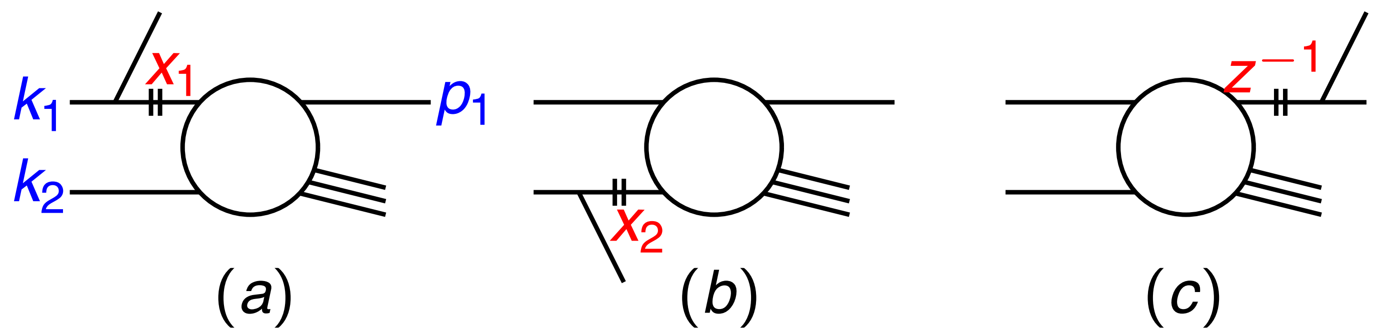


Fig. (a):

$$d\sigma^{\text{sub}}(ab \to QX) = \int_0^1 dx_1\, f^{(1)}_{a\to i}(x_1, \mu_F^2)\, d\hat{\sigma}^{(0)}(ib \to QX)[x_1 k_1, k_2, p_1]$$
$$\equiv f^{(1)}_{a\to i}(x_1) \otimes d\hat{\sigma}^{(0)}(ib \to QX)$$

Fig. (b):

$$d\sigma^{\text{sub}}(ab \to QX) = \int_0^1 dx_2\, f^{(1)}_{b\to j}(x_2, \mu_F^2)\, d\hat{\sigma}^{(0)}(aj \to QX)[k_1, x_2 k_2, p_1]$$
$$\equiv f^{(1)}_{b\to j}(x_2) \otimes d\hat{\sigma}^{(0)}(aj \to QX)$$

Fig. (c):

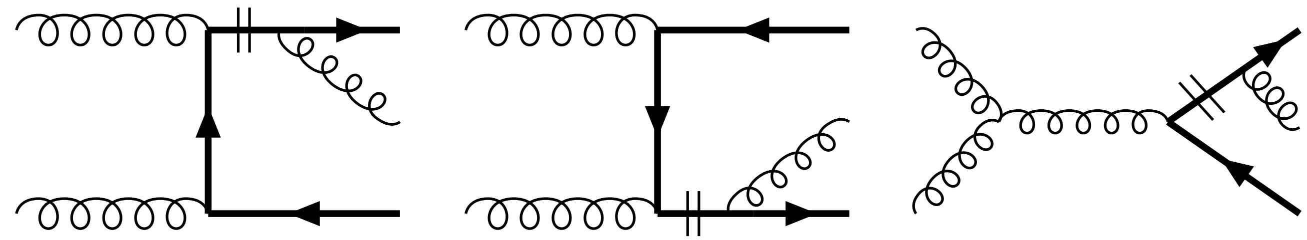
$$d\sigma^{\text{sub}}(ab \to QX) = \int_0^1 dz\, d\hat{\sigma}^{(0)}(ab \to kX)[k_1, k_2, z^{-1} p_1]\, d^{(1)}_{k\to Q}(z, \mu_F'^2)$$
$$\equiv d\hat{\sigma}^{(0)}(ab \to kX) \otimes d^{(1)}_{k\to Q}(z)$$

---

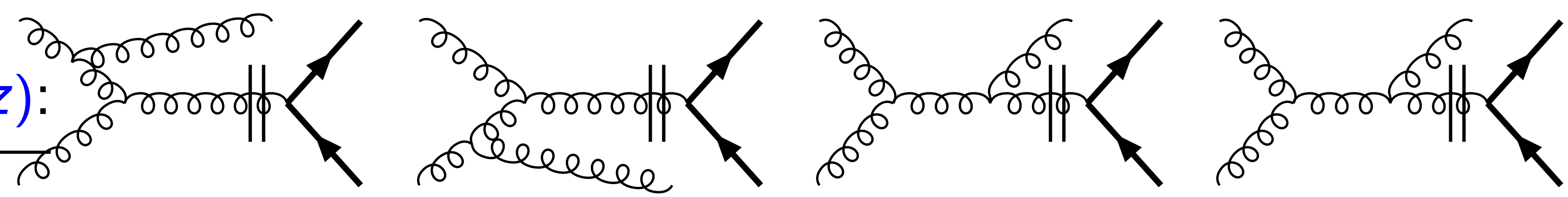
[1] Kniehl, Kramer, I.S., Spiesberger, EPJC41(2005)199

GRAPHICAL REPRESENTATION OF SUBTRACTION TERMS FOR $gg \to Q\bar{Q}g$

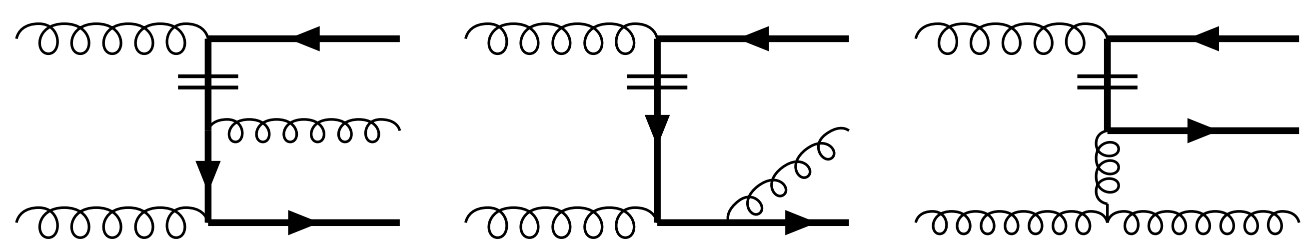
$d\hat{\sigma}^{(0)}(gg \to Q\bar{Q}) \otimes d^{(1)}_{Q\to Q}(z)$:



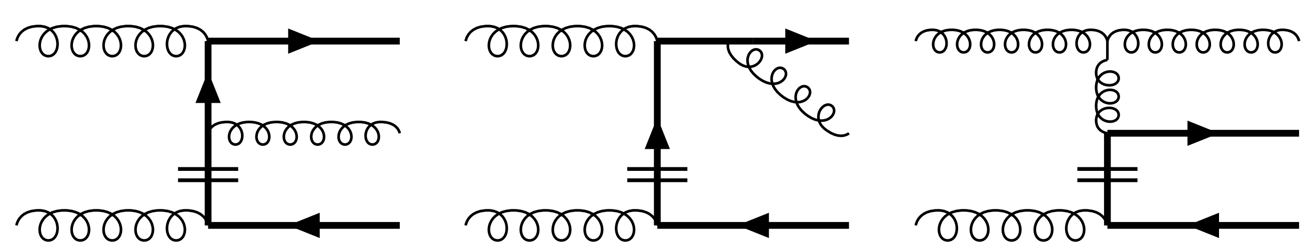
$d\hat{\sigma}^{(0)}(gg \to gg) \otimes d^{(1)}_{g\to Q}(z)$:



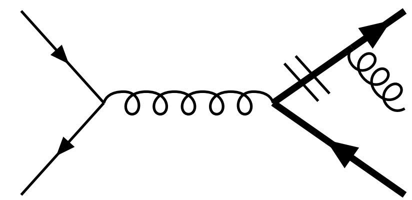
$f^{(1)}_{g\to Q}(x_1) \otimes d\hat{\sigma}^{(0)}(Qg \to Qg)$:



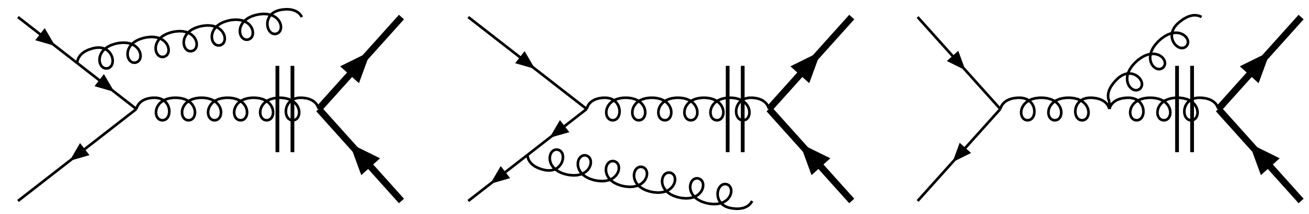
$f^{(1)}_{g\to Q}(x_2) \otimes d\hat{\sigma}^{(0)}(gQ \to Qg)$:



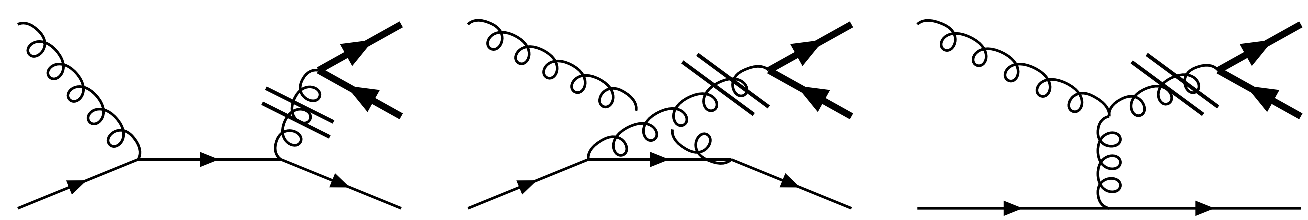
$\mathrm{d}\hat{\sigma}^{(0)}(q\bar{q} \to Q\bar{Q}) \otimes d^{(1)}_{Q\to Q}(z)$:



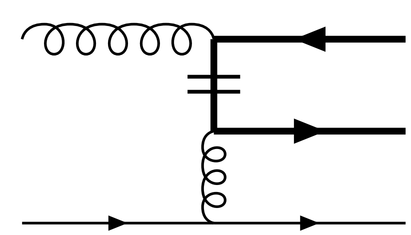
$\mathrm{d}\hat{\sigma}^{(0)}(q\bar{q} \to gg) \otimes d^{(1)}_{g\to Q}(z)$:



$\mathrm{d}\hat{\sigma}^{(0)}(gq \to gq) \otimes d^{(1)}_{g\to Q}(z)$:

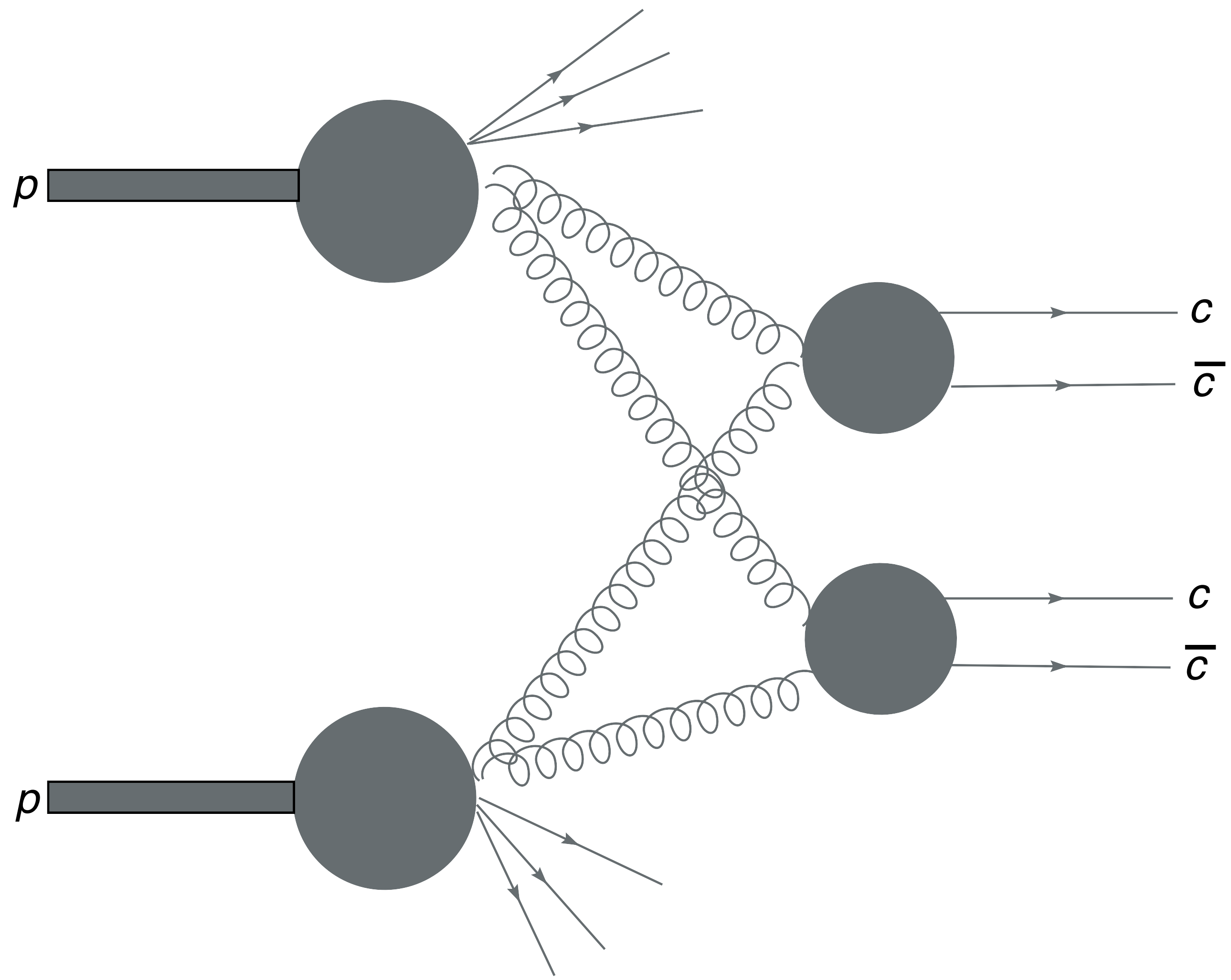


$f^{(1)}_{g\to Q}(x_1) \otimes \mathrm{d}\hat{\sigma}^{(0)}(Qq \to Qq)$:



Production of two $c\bar{c}$ pairs in double-parton scattering

Consider two hard (parton) scatterings



Not consider so far in the literature

Luszczak, Maciula, Szczurek, arXiv:1111.3255

Formalism

Consider reaction: $pp \to c\bar{c}c\bar{c}X$

Modeling double-parton scattering

Factorized form:

$$\sigma^{DPS}(pp \to c\bar{c}c\bar{c}X) = \frac{1}{2\sigma_{eff}} \sigma^{SPS}(pp \to c\bar{c}X_1) \cdot \sigma^{SPS}(pp \to c\bar{c}X_2).$$

The simple formula can be generalized to include differential distributions

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1t} dy_3 dy_4 d^2p_{2t}} = \frac{1}{2\sigma_{eff}} \cdot \frac{d\sigma}{dy_1 dy_2 d^2p_{1t}} \cdot \frac{d\sigma}{dy_3 dy_4 d^2p_{2t}} .$$

σ_{eff} is a model parameter (12-15 mb)

Formalism

$$d\sigma^{DPS} = \frac{1}{2\sigma_{eff}} F_{gg}(x_1, x_2, \mu_1^2, \mu_2^2) F_{gg}(x_1' x_2', \mu_1^2, \mu_2^2)$$
$$d\sigma_{gg\to c\bar{c}}(x_1, x_1', \mu_1^2) d\sigma_{gg\to c\bar{c}}(x_2, x_2', \mu_2^2)\; dx_1 dx_2 dx_1' dx_2' \,.$$

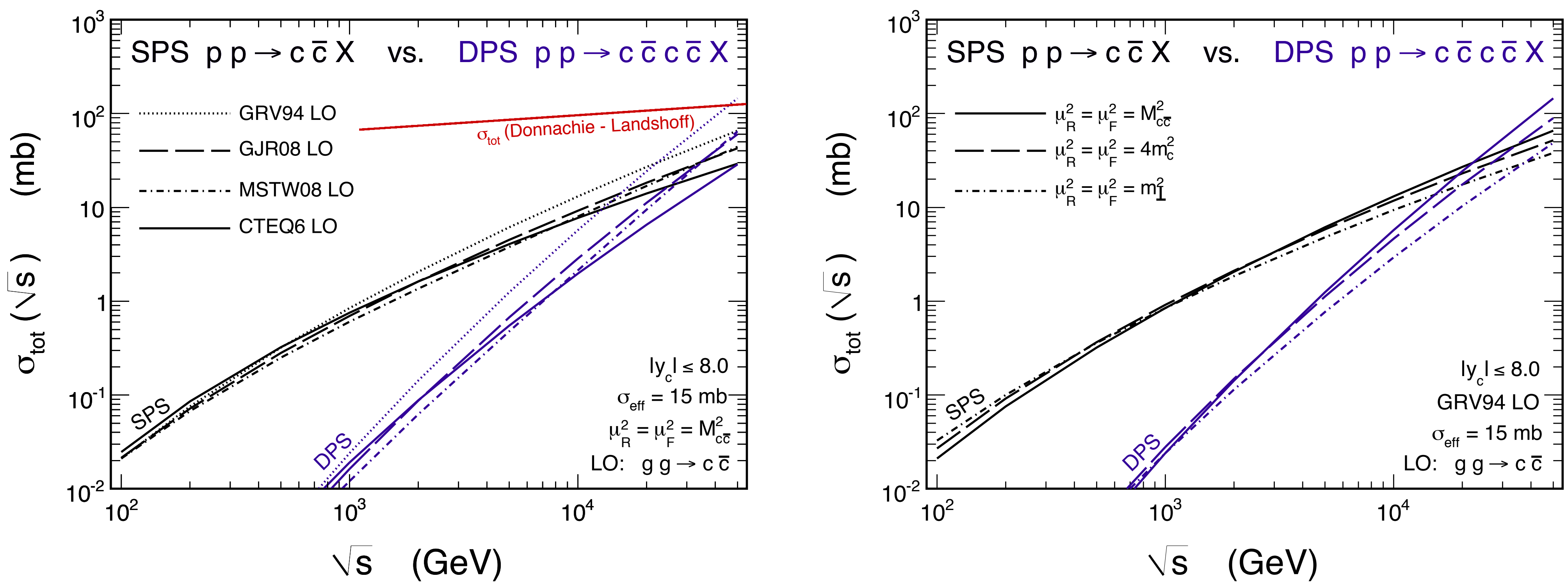
$F_{gg}(x_1, x_2, \mu_1^2, \mu_2^2)$, $F_{gg}(x_1' x_2', \mu_1^2, \mu_2^2)$
are called double parton distributions

dPDF are subjected to special evoultion equations

single scale evolution: Snigireev

double scale evolution: Ceccopieri, Gaunt-Stirling

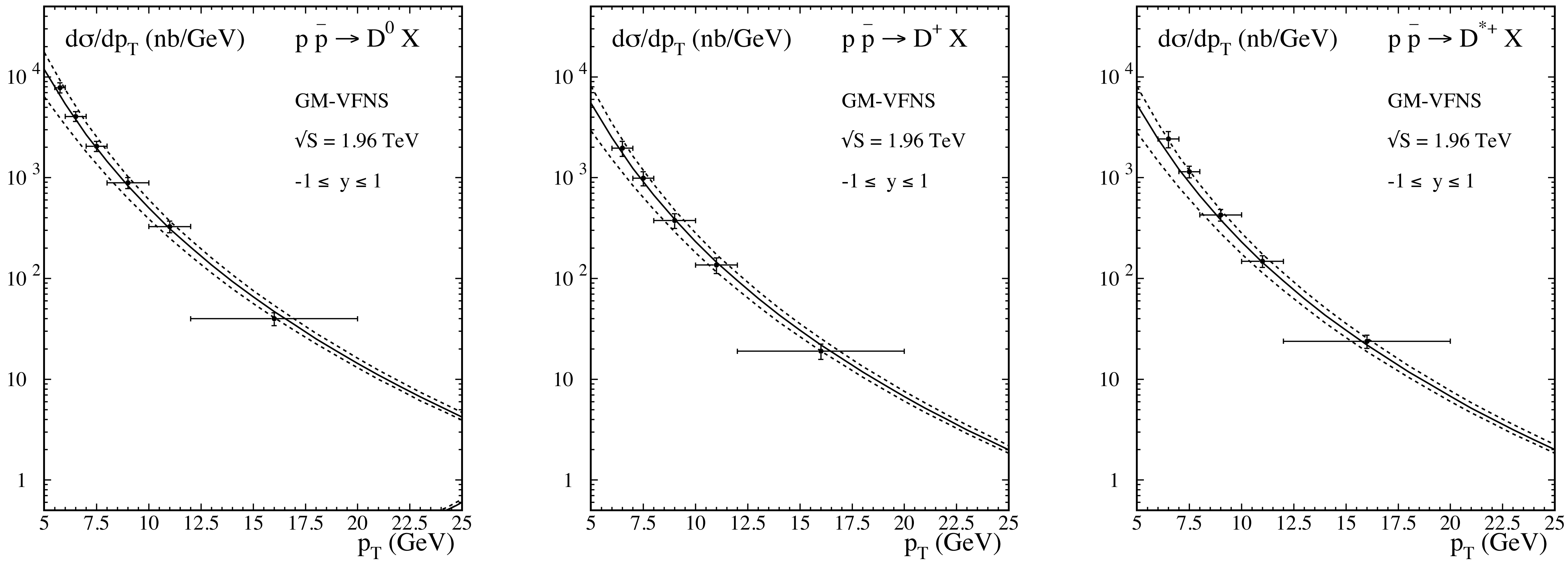
DPS results



Inclusive cross section more difficult to calculate

$$\sigma_{SS}, 2\sigma_{DS} < \sigma_c^{inclusive} < \sigma_{SS} + 2\sigma_{DS}$$

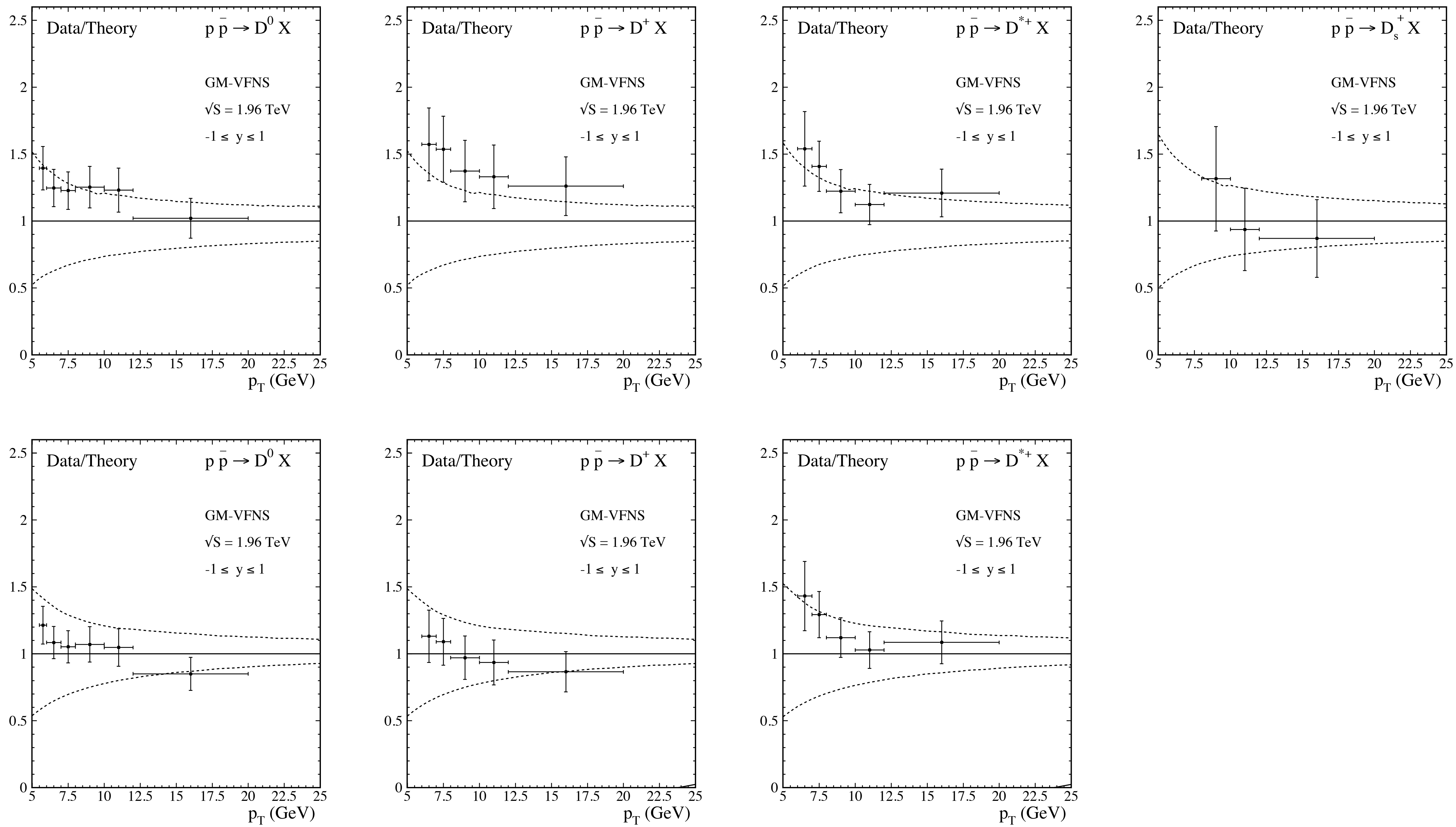
Hadroproduction of D^0, D^+, D^{*+}, D_s^+
GM-VFNS results w/ KKKSc FFs [1]



- $d\sigma/dp_T$ [nb/GeV] $|y| \leq 1$ prompt charm
- Uncertainty band: $1/2 \leq \mu_R/m_T, \mu_F/m_T \leq 2 \quad (m_T = \sqrt{p_T^2 + m_c^2})$
- CDF data from run II [2]
- GM-VFNS describes data within errors

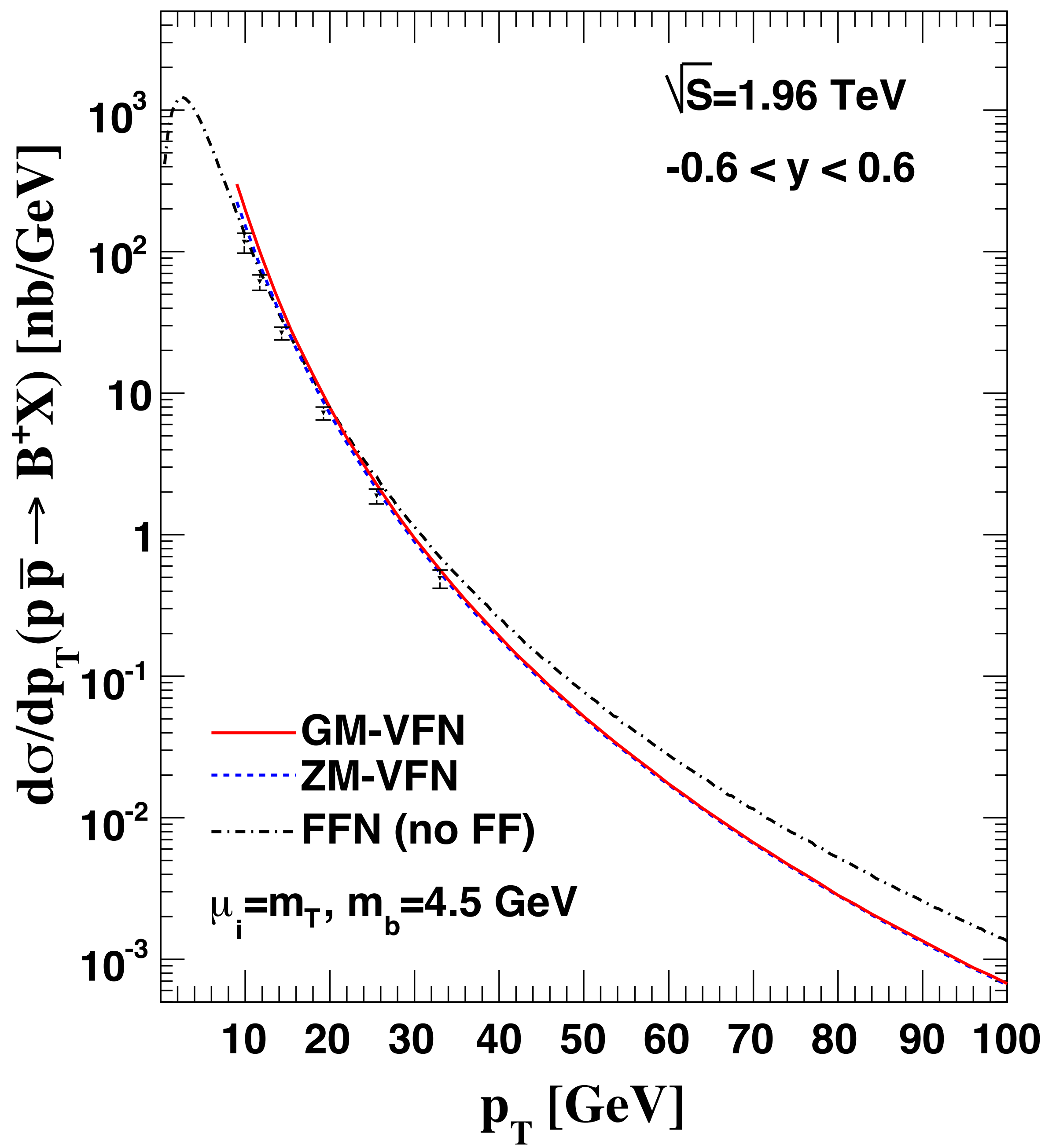
[1] Kniehl,Kramer,IS,Spiesberger, arXiv:0901.4130[hep-ph], PRD(to appear)

[2] Acosta et al., PRL91(2003)241804



- New KKKSc FFs improve agreement w/ CDF data.

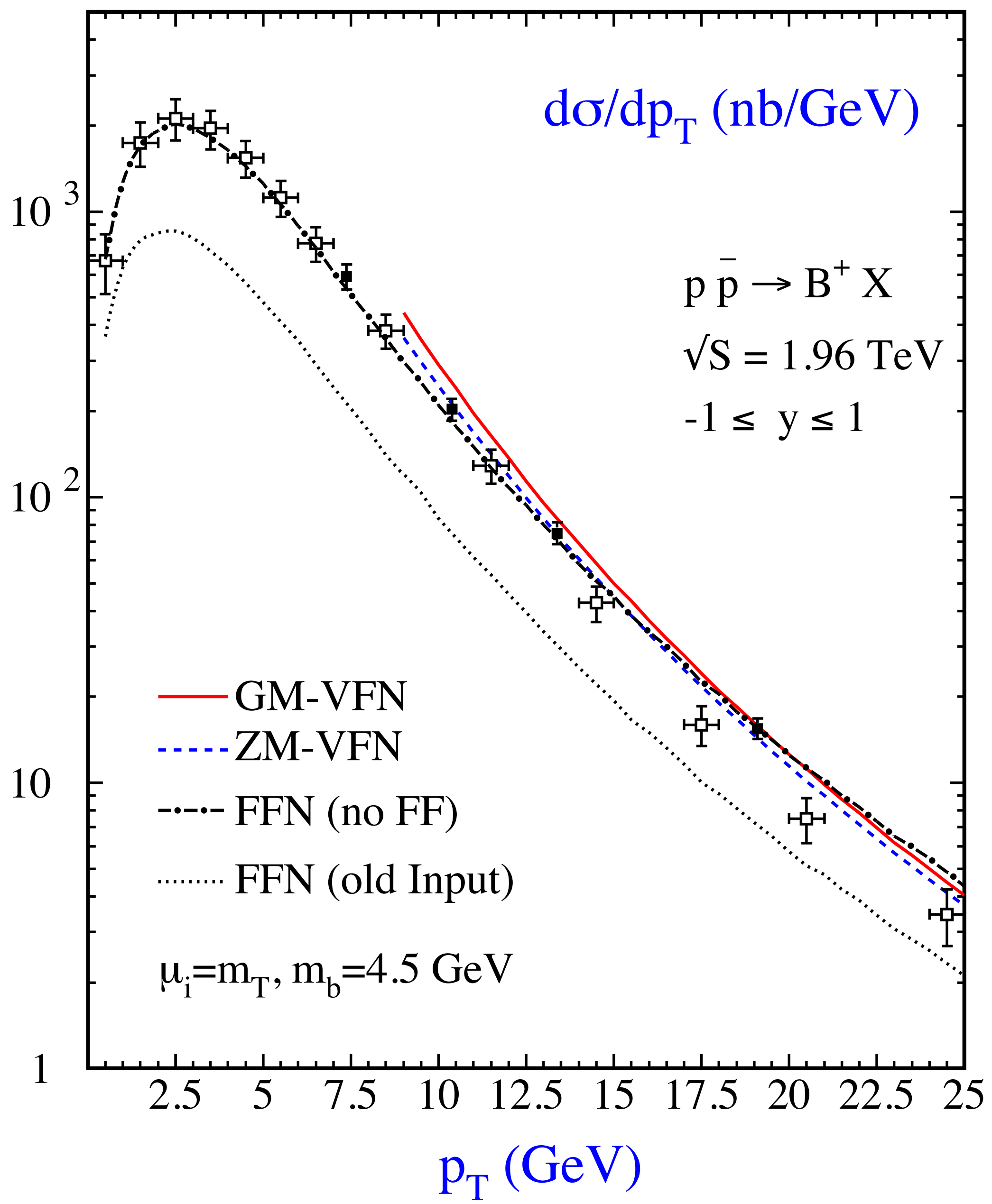
[1] Kniehl,Kramer, PRD74(2006)037502



- CDF II (preliminary) [1]
- $\mu_R = \mu_F = m_T$
- for $p_T \gg m_b$:
  - GM-VFN merges w/ ZM-VFN
  - FFN breaks down
- data point in bin [29,40] favors GM-VFN

[1] Kraus, FERMILAB-THESIS-2006-47; Annovi, FERMILAB-CONF-07-509-E

FFN vs. CDF II [1]

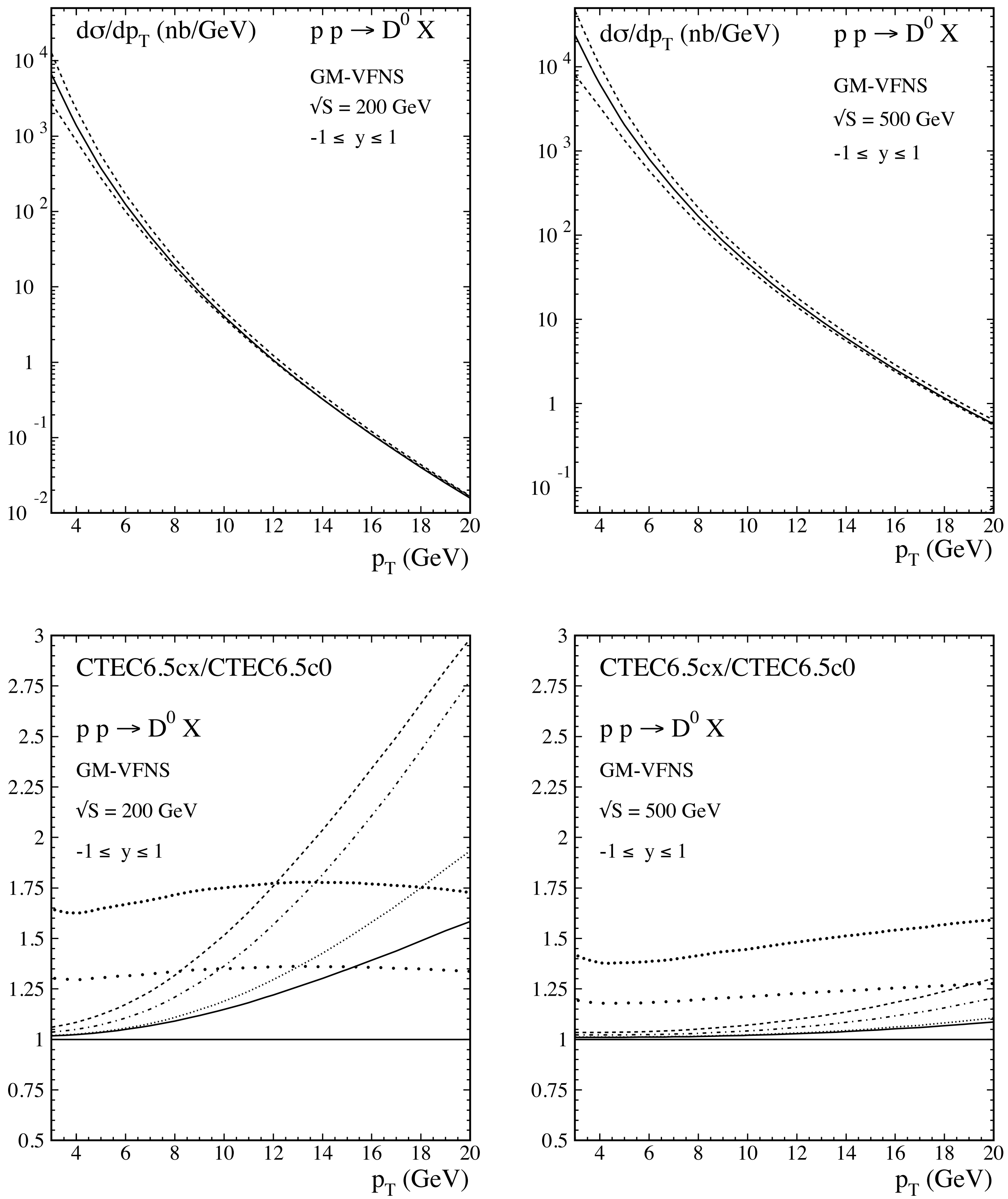


- obsolete FFN as above
- up-to-date FFN evaluated with
  - CTEQ6.1M PDFs
  - $m_b = 4.5$ GeV
  - $\Lambda^{(5)}_{\overline{\rm MS}} = 227$ MeV $\rightsquigarrow \alpha_s^{(5)} = 0.1181$
  - $D(x) = B(b \to B)\delta(1-x)$ with $B(b \to B) = 39.8\%$

[1] Kniehl,Kramer,IS,Spiesberger,PRD77(2008)014011

INTRINSIC CHARM IN THE PROTON

D-MESONS AT RHIC



$(\mathrm{d}\sigma/\mathrm{d}p_T)(pp \to D^0 + X)$
$\sqrt{s} = 200, 500$ GeV
$|y| < 1$

IC Model	moderate	marginal
BHPS	solid	dashed
Meson-cloud	densely dotted	dot-dashed
Sealike	scarsely dotted	dotted