

Heavy Flavour WG – Theory Summary

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6₊₂ Contributions

- ✓ Two-loop massive OMEs and HFL production in DIS
 - J. Blümlein (+ I. Bierenbaum, S. Klein)
- ✓ Heavy-quark mass effects in pQCD and HFL PDFs
 - W.K. Tung (+ H.L. Lai, J. Pumplin)
- ✓ HFL production in DGLAP improved saturation model
 - S. Sapeta (+ K. Golec-Biernat)
- ✓ Quarkonium production in the Regge limit of QCD
 - V.A. Saleev (+ B.A. Kniehl, D.V. Vasin)
- ✓ Heavy quarkonium decay on and off the lattice
 - A. Hart
- ✓ Light and heavy multiquark spectroscopy
 - J.M. Richard

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 - J. Blümlein (SPIN-1, HFL-2, SF-4, HFS-8) ←
- Heavy-quark mass effects in Heavy talk fragmentation ?
 - W.K. Tung (SF-2, HFL-2) ←
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 - S. Sapeta → Summary of diffractive WG
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2-loop massive OMEs and HFL production in DIS

Bierenbaum, Blümlein, Klein, hep-ph/0702265, hep-ph/0703285

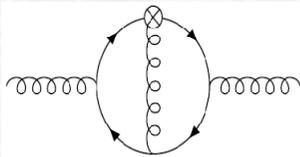
HFL part of structure fcts.:

$$F_2^{Q\bar{Q}}(N, Q^2) = \sum_{k=1}^{n_f} e_k^2 [f_{k-\bar{k}}(N, \mu^2) H_{2,q}^{NS}\left(N, \frac{Q^2}{m^2}, \frac{Q^2}{\mu^2}\right)] \\ + e_Q^2 [\Sigma(N, \mu^2) H_{2,q}^{PS}\left(N, \frac{Q^2}{m^2}, \frac{Q^2}{\mu^2}\right) + G(N, \mu^2) H_{2,g}^S\left(N, \frac{Q^2}{m^2}, \frac{Q^2}{\mu^2}\right)]$$

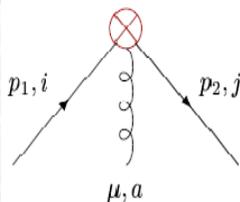
Process independent OMEs:

$$H_{(2,L),i}^{S,NS}\left(\frac{Q^2}{\mu^2}, \frac{m^2}{\mu^2}\right) = \underbrace{A_{k,i}^{S,NS}\left(\frac{m^2}{\mu^2}\right)}_{\text{massive OMEs}} \otimes \underbrace{C_{(2,L),k}^{S,NS}\left(\frac{Q^2}{\mu^2}\right)}_{\text{light Wilson coefficients}}$$

Example diagram:



Operator insertion, light cone:



$$gt_{ji}^a \Delta^\mu \mathbb{A} \gamma_\perp \sum_{j=0}^{N-2} (\Delta \cdot p_1)^j (\Delta \cdot p_2)^{N-j-2}$$

Simple analytical results:

Hypergeometric functions

$$I = \frac{S_2^2(\Delta p)^{N-2}}{(4\pi)^4 (m^2)^{1-\epsilon}} \exp\left\{\sum_{l=2}^{\infty} \frac{\zeta_l}{l} \epsilon^l\right\} \frac{2\pi}{N \sin(\frac{\pi}{2}\epsilon)} \sum_{j=1}^N \left\{ \binom{N}{j} (-1)^j + \delta_{j,N} \right\} \\ \times \left\{ \frac{\Gamma(j)\Gamma(j+1-\frac{\epsilon}{2})}{\Gamma(j+2-\epsilon)\Gamma(j+1+\frac{\epsilon}{2})} - \frac{B(1-\frac{\epsilon}{2}, 1+j)}{j} {}_3F_2\left[1-\epsilon, \frac{\epsilon}{2}, j+1; 1, j+2-\frac{\epsilon}{2}; 1\right] \right\} \\ = \frac{S_2^2(\Delta p)^{N-2}}{(4\pi)^4 (m^2)^{1-\epsilon}} \left\{ \frac{4}{N} \left[S_2(N) - \frac{S_1(N)}{N} \right] + \frac{\epsilon}{N} \left[-2S_{2,1}(N) + 2S_3(N) + \frac{4N+1}{N} S_2(N) \right. \right. \\ \left. \left. - \frac{S_1^2(N)}{N} - \frac{4}{N} S_1(N) \right] \right\} + O(\epsilon^2)$$

Basis: $\{S_1, S_2, S_3, S_{-2}, S_{-3}\}, S_{-2,1}$

Numerical checks:

Mellin-Barnes integrals

Existing calculation:

van Neerven et al., 1996/7

Integration by parts, 48 fcts.

Heavy-quark mass effects in pQCD and HFL PDFs

Lai, Pumplin, Tung et al., hep-ph/0701220, hep-ph/0702268

Strange PDFs:

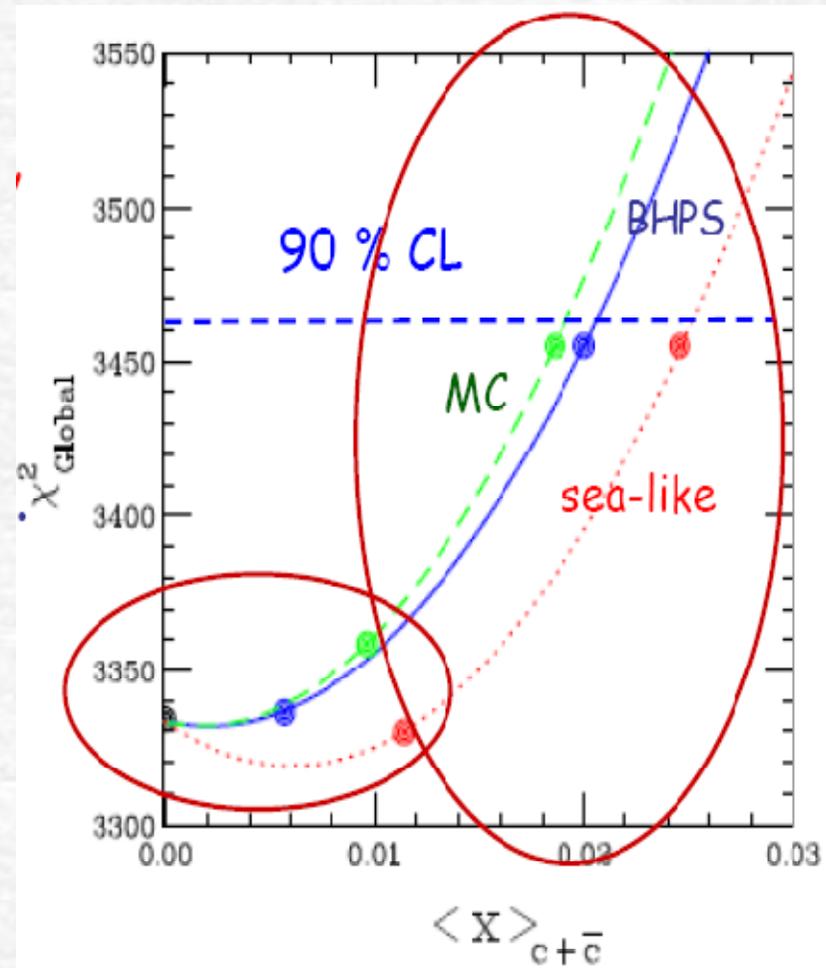
- Traditional: $s(x) = \bar{s}(x) = r(\bar{u}(x) + \bar{d}(x))/2$
- SF-2: $\nu : W_+ s \rightarrow c$
- HERA c-data eq. well descr.

Charm in the proton:

- $|uud\rangle, |uudcc\rangle$ (Brodsky) ?
- Upper bound on mom. fract.

HQ mass in PDFs:

- $c(x, Q)$ rad. gen. @ m_c
- Pole/ $\overline{\text{MS}}$ /"global" mass?
- Fit prefers 1.3 over 1.5 GeV
- Difference mostly from F_2^c



Heavy-quark mass effects in pQCD and HFL PDFs

Special discussion session (Blümlein, Kniehl, Tung, Vogt, ...)

Inclusive charm at HERA:

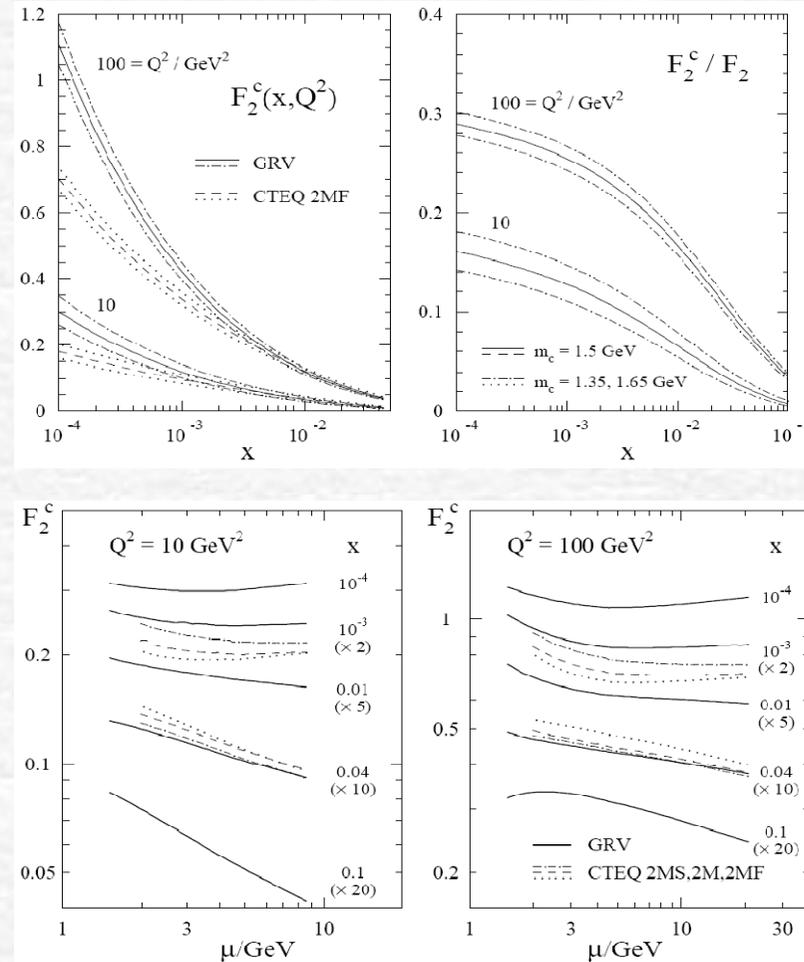
- ☞ m_c dependence clearly visible
- ☞ Scale dep. small (phys. qu.)

Ideas:

- ☞ Propose set with varying m_c
- ☞ Fit m_c, ε_h with HVQDIS

$$D_{H/h}(x) = \frac{N}{x[1 - 1/x - \varepsilon_h/(1-x)]^2}$$

- ☞ Problem: FF not universal
- ☞ Take m_c from lattice



Inclusive heavy-meson production in GM-VFNS

Kniesl, Kramer, Schienbein, Spiesberger, PRL 96 (2006) 012001, hep-ex/0608042, ...

Traditional methods:

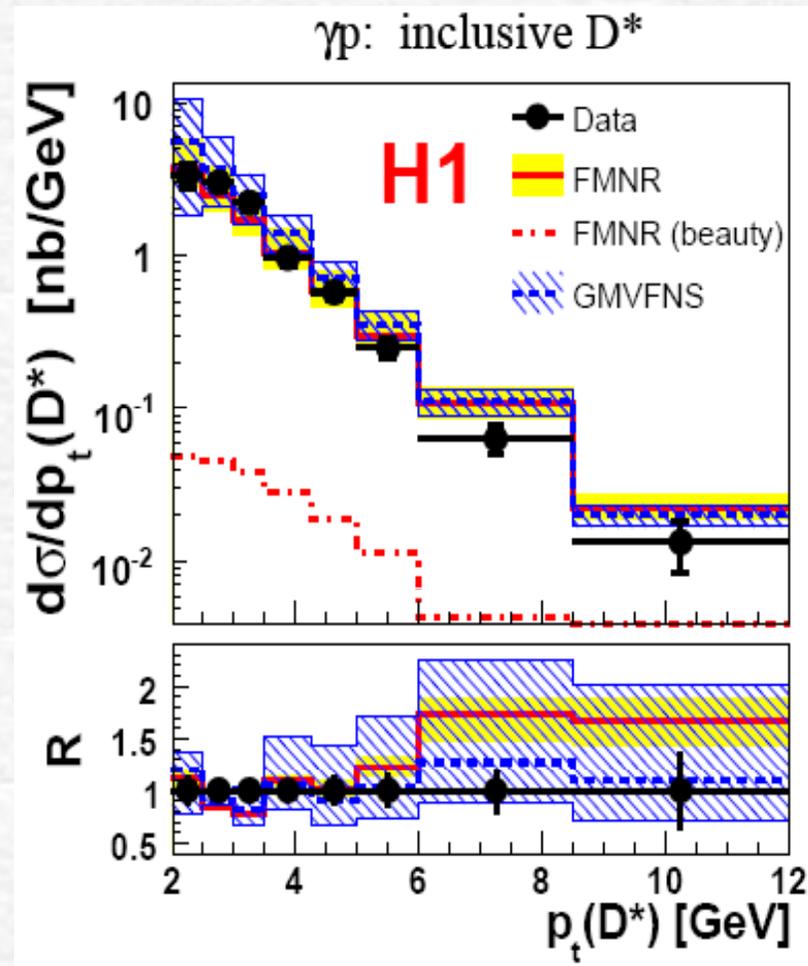
- FFNS (Cacciari et al.)
- ZM-FVNS (Kniesl et al.)

FONLL:

- $\ln(\mu/m_h) \rightarrow$ perturbative FF
- Boundary cond. \rightarrow evolution

GM-VFNS:

- Subtr. $\ln(\mu/m_h)$ from MEs
- Difference massive \leftrightarrow \overline{MS}
- Subtr. mass-ind. finite terms
- Keep mass-dep. finite terms
- Match with XKK FFs



QCD corrections to J/Ψ and Υ production

Campbell, Maltoni, Tramontano, hep-ph/0703113

γγ in CSM:

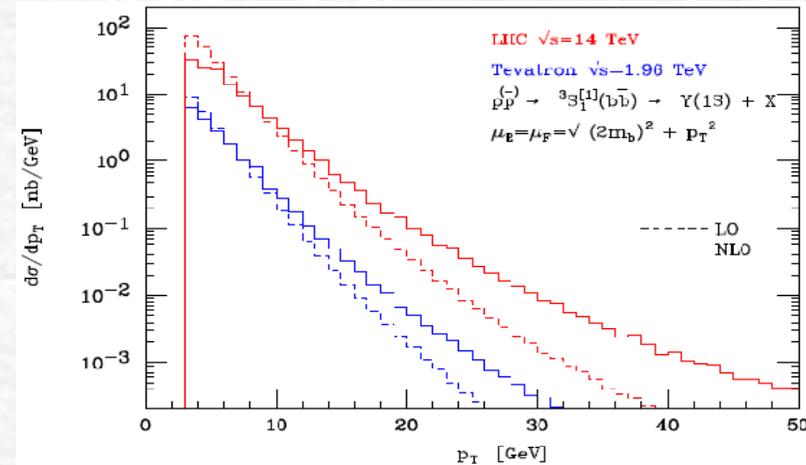
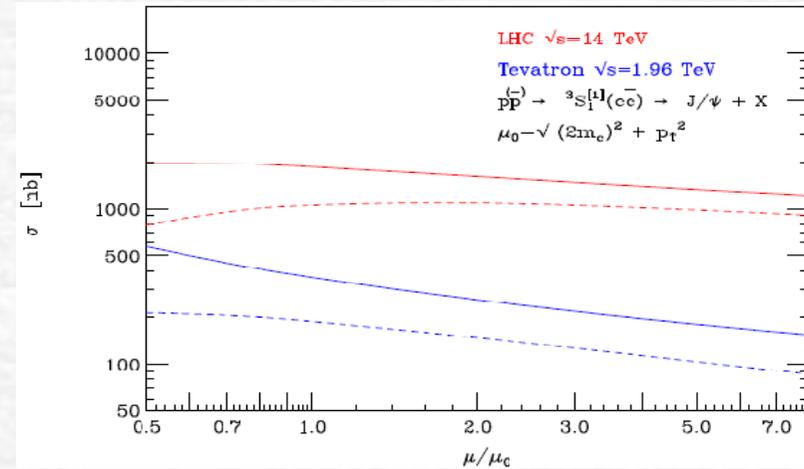
- ☞ Krämer, Zunft, Steegborn, Zerwas
PLB 348 (1995) 657.

γγ in NRQCD:

- ☞ MK, Kniehl, Mihaila, Steinhauser,
NPB 713 (05) and PRD 71 (05).
- ☞ NLO/LO ≈ 10 (J/Ψ+jet, DD ↔ SR)

pp in CSM:

- ☞ Campbell, Maltoni, Tramontano,
hep-ph/0703113.
- ☞ Same diagrams as J/Ψ → hadrons
- ☞ Confirm Mackenzie/Lepage (81)
- ☞ Helicity amplitudes and J/Ψ → ll
- ☞ Color sums → only 1/6 survive
- ☞ Subtraction method a la MCFM



Quarkonium production in Regge limit of QCD (1)

Kniehl, Saleev, Vasin, PRD 73 (2006) 074022; PRD 74 (2006) 014024

Quasi-multi Regge kinematics:

Initial gluon momentum, polarisation: $k_1^\mu = x_1 P_1^\mu + k_{1T}^\mu$, $\varepsilon^\mu(k_T) = \frac{k_T^\mu}{|k_T|}$

Cross section:
$$d\sigma^{\text{KT}}(p + p \rightarrow \mathcal{H} + X, S) = \int \frac{dx_1}{x_1} \int d|\mathbf{k}_{1T}|^2 \int \frac{d\varphi_1}{2\pi} \Phi(x_1, |\mathbf{k}_{1T}|^2, \mu^2) \\ \times \int \frac{dx_2}{x_2} \int d|\mathbf{k}_{2T}|^2 \int \frac{d\varphi_2}{2\pi} \Phi(x_2, |\mathbf{k}_{2T}|^2, \mu^2) d\hat{\sigma}(R + R \rightarrow \mathcal{H} + X, \mathbf{k}_{1T}, \mathbf{k}_{2T}, \hat{s})$$

Large μ , not too small x : $xG(x, \mu^2) = \int_0^{\mu^2} d|\mathbf{k}_T|^2 \Phi(x, |\mathbf{k}_T|^2, \mu^2)$

Unintegrated gluon PDFs:

BFKL: J. Blümlein

CCFM: Jung, Salam; Kimber, Martin, Ryskin

NRQCD fit to Tevatron p_T -spectra:

Intrinsic k_T leads to harder p_T -spectrum

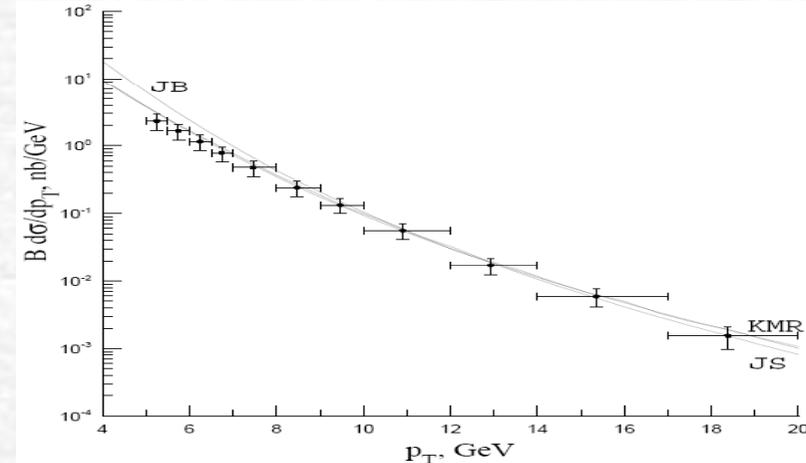
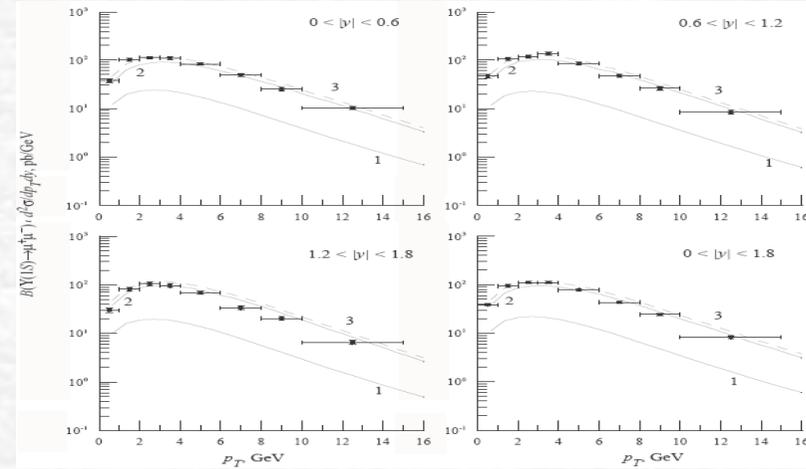
Color-octet MEs reduced

Quarkonium production in Regge limit of QCD (2)

Kniehl, Saleev, Vasin, PRD 73 (2006) 074022; PRD 74 (2006) 014024

NME	PM	Fit JB	Fit JS	Fit KMR
$\langle \mathcal{O}^{J/\psi} [^3S_1^{(1)}] \rangle / \text{GeV}^3$	1.3	1.3	1.3	1.3
$\langle \mathcal{O}^{J/\psi} [^3S_1^{(8)}] \rangle / \text{GeV}^3$	$4.4 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$6.1 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$
$\langle \mathcal{O}^{J/\psi} [^1S_0^{(8)}] \rangle / \text{GeV}^3$	$4.3 \cdot 10^{-2}$	$6.6 \cdot 10^{-3}$	$9.0 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$
$\langle \mathcal{O}^{J/\psi} [^3P_0^{(8)}] \rangle / \text{GeV}^5$	$2.8 \cdot 10^{-2}$	0	0	0
$\langle \mathcal{O}^{\psi'} [^3S_1^{(1)}] \rangle / \text{GeV}^3$	$6.5 \cdot 10^{-1}$	$6.5 \cdot 10^{-1}$	$6.5 \cdot 10^{-1}$	$6.5 \cdot 10^{-1}$
$\langle \mathcal{O}^{\psi'} [^3S_1^{(8)}] \rangle / \text{GeV}^3$	$4.2 \cdot 10^{-3}$	$3.0 \cdot 10^{-4}$	$1.5 \cdot 10^{-3}$	$8.3 \cdot 10^{-4}$
$\langle \mathcal{O}^{\psi'} [^1S_0^{(8)}] \rangle / \text{GeV}^3$	$6.9 \cdot 10^{-3}$	0	0	0
$\langle \mathcal{O}^{\psi'} [^3P_0^{(8)}] \rangle / \text{GeV}^5$	$3.9 \cdot 10^{-3}$	0	0	0
$\langle \mathcal{O}^{\chi_{c0}} [^3P_0^{(1)}] \rangle / \text{GeV}^5$	$8.9 \cdot 10^{-2}$	$8.9 \cdot 10^{-2}$	$8.9 \cdot 10^{-2}$	$8.9 \cdot 10^{-2}$
$\langle \mathcal{O}^{\chi_{c0}} [^3S_1^{(8)}] \rangle / \text{GeV}^3$	$4.4 \cdot 10^{-3}$	0	$2.2 \cdot 10^{-4}$	$4.7 \cdot 10^{-5}$
$\chi^2/\text{d.o.f}$	—	2.2 (*)	4.1	3.0

n / n	PM	Fit JB	Fit JS	Fit KMR
$\langle \mathcal{O}^{\Upsilon(1S)} [^1S_0^{(8)}] \rangle, \text{GeV}^3$	$1.4 \cdot 10^{-1}$	0.0	0.0	0.0
$\langle \mathcal{O}^{\Upsilon(1S)} [^3S_1^{(1)}] \rangle, \text{GeV}^3$	$1.1 \cdot 10^1$	$1.1 \cdot 10^1$	$1.1 \cdot 10^1$	$1.1 \cdot 10^1$
$\langle \mathcal{O}^{\Upsilon(1S)} [^3S_1^{(8)}] \rangle, \text{GeV}^3$	$2.0 \cdot 10^{-2}$	$5.3 \cdot 10^{-3}$	0.0	0.0
$\langle \mathcal{O}^{\Upsilon(1S)} [^3P_0^{(8)}] \rangle, \text{GeV}^5$	0.0	0.0	0.0	$9.5 \cdot 10^{-2}$
$\langle \mathcal{O}^{\chi_{b0}(1P)} [^3S_1^{(8)}] \rangle, \text{GeV}^3$	$1.5 \cdot 10^{-2}$	0.0	0.0	0.0
$\langle \mathcal{O}^{\chi_{b0}(1P)} [^3P_0^{(1)}] \rangle, \text{GeV}^5$	2.4	2.4	2.4	2.4
$\langle \mathcal{O}^{\Upsilon(2S)} [^1S_0^{(8)}] \rangle, \text{GeV}^3$	0.0	0.0	0.0	0.0
$\langle \mathcal{O}^{\Upsilon(2S)} [^3S_1^{(1)}] \rangle, \text{GeV}^3$	4.5	4.5	4.5	4.5
$\langle \mathcal{O}^{\Upsilon(2S)} [^3S_1^{(8)}] \rangle, \text{GeV}^3$	$1.6 \cdot 10^{-1}$	0.0	0.0	$3.3 \cdot 10^{-2}$
$\langle \mathcal{O}^{\Upsilon(2S)} [^3P_0^{(8)}] \rangle, \text{GeV}^5$	0.0	0.0	0.0	0.0
$\langle \mathcal{O}^{\chi_{b0}(2P)} [^3S_1^{(8)}] \rangle, \text{GeV}^3$	$8.0 \cdot 10^{-3}$	$1.1 \cdot 10^{-2}$	0.0	0.0
$\langle \mathcal{O}^{\chi_{b0}(2P)} [^3P_0^{(1)}] \rangle, \text{GeV}^5$	2.6	2.6	2.6	2.6
$\langle \mathcal{O}^{\Upsilon(3S)} [^1S_0^{(8)}] \rangle, \text{GeV}^3$	$5.4 \cdot 10^{-2}$	0.0	0.0	0.0
$\langle \mathcal{O}^{\Upsilon(3S)} [^3S_1^{(1)}] \rangle, \text{GeV}^3$	4.3	4.3	4.3	4.3
$\langle \mathcal{O}^{\Upsilon(3S)} [^3S_1^{(8)}] \rangle, \text{GeV}^3$	$3.6 \cdot 10^{-2}$	$1.4 \cdot 10^{-2}$	$5.9 \cdot 10^{-3}$	$1.1 \cdot 10^{-2}$
$\langle \mathcal{O}^{\Upsilon(3S)} [^3P_0^{(8)}] \rangle, \text{GeV}^5$	0.0	$2.4 \cdot 10^{-2}$	$3.4 \cdot 10^{-3}$	$5.2 \cdot 10^{-2}$
$\chi^2/\text{d.o.f}$	—	2.9	$2.7 \cdot 10^1$	$4.9 \cdot 10^{-1}$

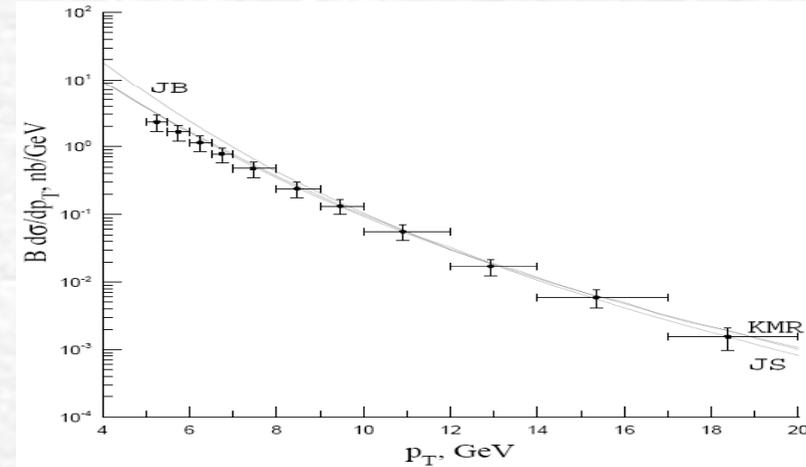
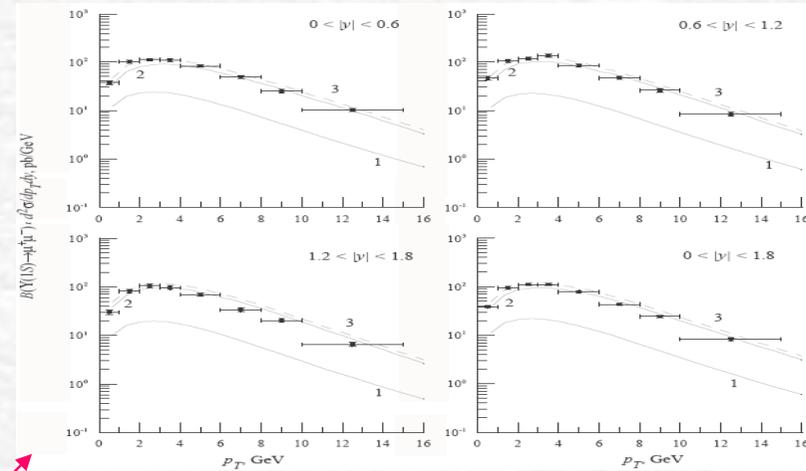


Quarkonium production in Regge limit of QCD (2)

Kniehl, Saleev, Vasin, PRD 73 (2006) 074022; PRD 74 (2006) 014024

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$\langle \mathcal{O}^{J/\psi} [^3P_0^{(8)}] \rangle / \text{GeV}^5$	$2.8 \cdot 10^{-2}$	0	0	0
$\langle \mathcal{O}^{\psi'} [^3S_1^{(1)}] \rangle / \text{GeV}^3$	$6.5 \cdot 10^{-1}$	$6.5 \cdot 10^{-1}$	$6.5 \cdot 10^{-1}$	$6.5 \cdot 10^{-1}$
$\langle \mathcal{O}^{\psi'} [^3S_1^{(8)}] \rangle / \text{GeV}^3$	$4.2 \cdot 10^{-3}$	$3.0 \cdot 10^{-4}$	$1.5 \cdot 10^{-3}$	$8.3 \cdot 10^{-4}$
$\langle \mathcal{O}^{\psi'} [^1S_0^{(8)}] \rangle / \text{GeV}^3$	$6.9 \cdot 10^{-3}$	0	0	0
$\langle \mathcal{O}^{\psi'} [^3P_0^{(8)}] \rangle / \text{GeV}^5$	$3.9 \cdot 10^{-3}$	0	0	0
$\langle \mathcal{O}^{\chi_{c0}} [^3P_0^{(1)}] \rangle / \text{GeV}^5$	$8.9 \cdot 10^{-2}$	$8.9 \cdot 10^{-2}$	$8.9 \cdot 10^{-2}$	$8.9 \cdot 10^{-2}$
$\langle \mathcal{O}^{\chi_{c0}} [^3S_1^{(8)}] \rangle / \text{GeV}^3$	$4.4 \cdot 10^{-3}$	0	$2.2 \cdot 10^{-4}$	$4.7 \cdot 10^{-5}$
$\chi^2/\text{d.o.f}$	—	2.2 (*)	4.1	3.0

n / n	PM	Fit JB	Fit JS	Fit KMR
$\langle \mathcal{O}^{\Upsilon(1S)} [^1S_0^{(8)}] \rangle, \text{GeV}^3$	$1.4 \cdot 10^{-1}$	0.0	0.0	0.0
$\langle \mathcal{O}^{\Upsilon(1S)} [^3S_1^{(1)}] \rangle, \text{GeV}^3$	$1.1 \cdot 10^1$	$1.1 \cdot 10^1$	$1.1 \cdot 10^1$	$1.1 \cdot 10^1$
$\langle \mathcal{O}^{\Upsilon(1S)} [^3S_1^{(8)}] \rangle, \text{GeV}^3$	$2.0 \cdot 10^{-2}$	$5.3 \cdot 10^{-3}$	0.0	0.0
$\langle \mathcal{O}^{\Upsilon(1S)} [^3P_0^{(8)}] \rangle, \text{GeV}^5$	0.0	0.0	0.0	$9.5 \cdot 10^{-2}$
$\langle \mathcal{O}^{\chi_{b0}(1P)} [^3S_1^{(8)}] \rangle, \text{GeV}^3$	$1.5 \cdot 10^{-2}$	0.0	0.0	0.0
$\langle \mathcal{O}^{\chi_{b0}(1P)} [^3P_0^{(1)}] \rangle, \text{GeV}^5$	2.4	2.4	2.4	2.4
$\langle \mathcal{O}^{\Upsilon(2S)} [^1S_0^{(8)}] \rangle, \text{GeV}^3$	0.0	0.0	0.0	0.0
$\langle \mathcal{O}^{\Upsilon(2S)} [^3S_1^{(1)}] \rangle, \text{GeV}^3$	4.5	4.5	4.5	4.5
$\langle \mathcal{O}^{\Upsilon(2S)} [^3S_1^{(8)}] \rangle, \text{GeV}^3$	$1.6 \cdot 10^{-1}$	0.0	0.0	$3.3 \cdot 10^{-2}$
$\langle \mathcal{O}^{\Upsilon(2S)} [^3P_0^{(8)}] \rangle, \text{GeV}^5$	0.0	0.0	0.0	0.0
$\langle \mathcal{O}^{\chi_{b0}(2P)} [^3S_1^{(8)}] \rangle, \text{GeV}^3$	$8.0 \cdot 10^{-3}$	$1.1 \cdot 10^{-2}$	0.0	0.0
$\langle \mathcal{O}^{\chi_{b0}(2P)} [^3P_0^{(1)}] \rangle, \text{GeV}^5$	2.6	2.6	2.6	2.6
$\langle \mathcal{O}^{\Upsilon(3S)} [^1S_0^{(8)}] \rangle, \text{GeV}^3$	$5.4 \cdot 10^{-2}$	0.0	0.0	0.0
$\langle \mathcal{O}^{\Upsilon(3S)} [^3S_1^{(1)}] \rangle, \text{GeV}^3$	4.3	4.3	4.3	4.3
$\langle \mathcal{O}^{\Upsilon(3S)} [^3S_1^{(8)}] \rangle, \text{GeV}^3$	$3.6 \cdot 10^{-2}$	$1.4 \cdot 10^{-2}$	$5.9 \cdot 10^{-3}$	$1.1 \cdot 10^{-2}$
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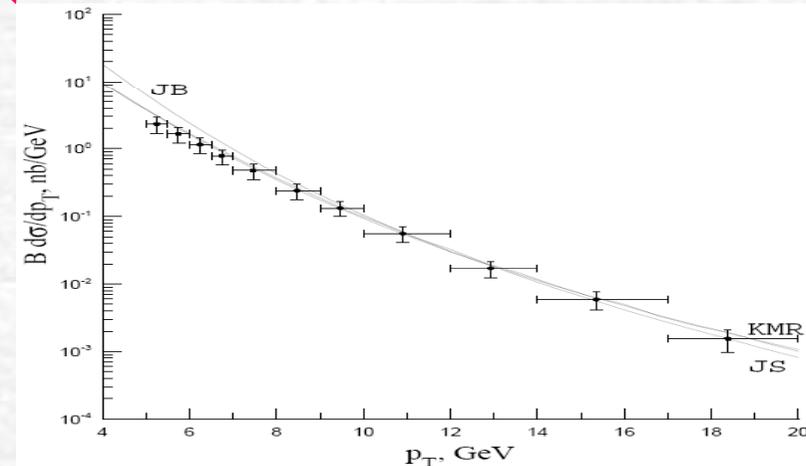
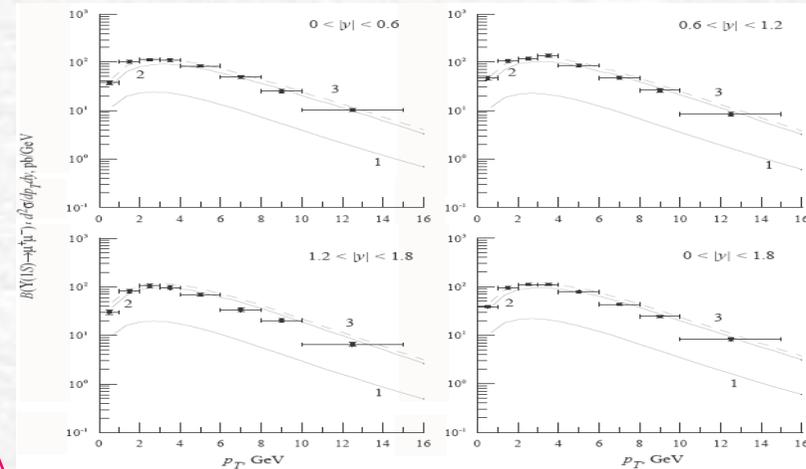


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$\langle \mathcal{O}^{\psi'} [^3S_1^{(1)}] \rangle / \text{GeV}^3$	$6.5 \cdot 10^{-1}$	$6.5 \cdot 10^{-1}$	$6.5 \cdot 10^{-1}$	$6.5 \cdot 10^{-1}$
$\langle \mathcal{O}^{\psi'} [^3S_1^{(8)}] \rangle / \text{GeV}^3$	$4.2 \cdot 10^{-3}$	$3.0 \cdot 10^{-4}$	$1.5 \cdot 10^{-3}$	$8.3 \cdot 10^{-4}$
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$\langle \mathcal{O}^{\psi'} [^3P_0^{(8)}] \rangle / \text{GeV}^5$	$3.9 \cdot 10^{-3}$	0	0	0
$\langle \mathcal{O}^{\chi_{c0}} [^3P_0^{(1)}] \rangle / \text{GeV}^5$	$8.9 \cdot 10^{-2}$	$8.9 \cdot 10^{-2}$	$8.9 \cdot 10^{-2}$	$8.9 \cdot 10^{-2}$
$\langle \mathcal{O}^{\chi_{c0}} [^3S_1^{(8)}] \rangle / \text{GeV}^3$	$4.4 \cdot 10^{-3}$	0	$2.2 \cdot 10^{-4}$	$4.7 \cdot 10^{-5}$
$\chi^2/\text{d.o.f}$	—	2.2 (*)	4.1	3.0

n / n	PM	Fit JB	Fit JS	Fit KMR
$\langle \mathcal{O}^{\Upsilon(1S)} [^1S_0^{(8)}] \rangle, \text{GeV}^3$	$1.4 \cdot 10^{-1}$	0.0	0.0	0.0
$\langle \mathcal{O}^{\Upsilon(1S)} [^3S_1^{(1)}] \rangle, \text{GeV}^3$	$1.1 \cdot 10^1$	$1.1 \cdot 10^1$	$1.1 \cdot 10^1$	$1.1 \cdot 10^1$
$\langle \mathcal{O}^{\Upsilon(1S)} [^3S_1^{(8)}] \rangle, \text{GeV}^3$	$2.0 \cdot 10^{-2}$	$5.3 \cdot 10^{-3}$	0.0	0.0
$\langle \mathcal{O}^{\Upsilon(1S)} [^3P_0^{(8)}] \rangle, \text{GeV}^5$	0.0	0.0	0.0	$9.5 \cdot 10^{-2}$
$\langle \mathcal{O}^{\chi_{b0}(1P)} [^3S_1^{(8)}] \rangle, \text{GeV}^3$	$1.5 \cdot 10^{-2}$	0.0	0.0	0.0
$\langle \mathcal{O}^{\chi_{b0}(1P)} [^3P_0^{(1)}] \rangle, \text{GeV}^5$	2.4	2.4	2.4	2.4
$\langle \mathcal{O}^{\Upsilon(2S)} [^1S_0^{(8)}] \rangle, \text{GeV}^3$	0.0	0.0	0.0	0.0
$\langle \mathcal{O}^{\Upsilon(2S)} [^3S_1^{(1)}] \rangle, \text{GeV}^3$	4.5	4.5	4.5	4.5
$\langle \mathcal{O}^{\Upsilon(2S)} [^3S_1^{(8)}] \rangle, \text{GeV}^3$	$1.6 \cdot 10^{-1}$	0.0	0.0	$3.3 \cdot 10^{-2}$
$\langle \mathcal{O}^{\Upsilon(2S)} [^3P_0^{(8)}] \rangle, \text{GeV}^5$	0.0	0.0	0.0	0.0
$\langle \mathcal{O}^{\chi_{b0}(2P)} [^3S_1^{(8)}] \rangle, \text{GeV}^3$	$8.0 \cdot 10^{-3}$	$1.1 \cdot 10^{-2}$	0.0	0.0
$\langle \mathcal{O}^{\chi_{b0}(2P)} [^3P_0^{(1)}] \rangle, \text{GeV}^5$	2.6	2.6	2.6	2.6
$\langle \mathcal{O}^{\Upsilon(3S)} [^1S_0^{(8)}] \rangle, \text{GeV}^3$	$5.4 \cdot 10^{-2}$	0.0	0.0	0.0
$\langle \mathcal{O}^{\Upsilon(3S)} [^3S_1^{(1)}] \rangle, \text{GeV}^3$	4.3	4.3	4.3	4.3
$\langle \mathcal{O}^{\Upsilon(3S)} [^3S_1^{(8)}] \rangle, \text{GeV}^3$	$3.6 \cdot 10^{-2}$	$1.4 \cdot 10^{-2}$	$5.9 \cdot 10^{-3}$	$1.1 \cdot 10^{-2}$
$\langle \mathcal{O}^{\Upsilon(3S)} [^3P_0^{(8)}] \rangle, \text{GeV}^5$	0.0	$2.4 \cdot 10^{-2}$	$3.4 \cdot 10^{-3}$	$5.2 \cdot 10^{-2}$
$\chi^2/\text{d.o.f}$	—	2.9	$2.7 \cdot 10^1$	$4.9 \cdot 10^{-1}$



Heavy quarkonium decay on/off the lattice (1)

Hart, Horgan, von Hippel, PRD 75 (2007) 014008: Matching QCD/NRQCD for $Y \rightarrow \ell\bar{\ell}$

$\eta_c, \chi_{c,0} \rightarrow \gamma\gamma$: Quenched LQCD

[Dudek, Edwards, hep-ph/0607140]

- Relativistic valence quarks
- Pert. exp. of γqq -coupling
- γ = superpos. of QCD states

Results:

$\Gamma_{\gamma\gamma}/\text{keV}$	D & E	(stat)	(disc)	(quench)	PDG
η_c	2.65	(26)	(80)	(53)	7.14 (2.49)
χ_{c0}	2.41	(58)	(72)	(48)	2.87 (0.40)

Problems:

- Incorrect running of $\alpha_s \rightarrow$
Depleted wave fct. at origin
- Only 1 lattice spacing \rightarrow
Discretization error ?

$\eta_{c,b} \rightarrow \gamma\gamma$: Static appr. with HQSS

[Lansberg, Pham, hep-ph/0603113, hep-ph/0609268]

- Binding energy in propag.s
- 1S: $f_{\eta_c} = f_{J/\psi}$, relates $\Gamma_{\gamma\gamma}(\eta_c)$ to $\Gamma_{\ell\bar{\ell}}(J/\psi)$
- 2S: $f_{\eta'_c} = f_{\Psi'} \Rightarrow \Gamma_{\gamma\gamma}(\eta'_c) = \Gamma_{\gamma\gamma}(\eta_c) \left(\frac{f_{\Psi'}}{f_{J/\psi}}\right)^2 + \text{"B.E."}$

Results:

f_η	L&P	$\Gamma_{\gamma\gamma}^{\text{expt}}/\text{keV}$	f_η	L&P
η_c	7.5 – 10	$7.4 \pm 0.9 \pm 2.1$ (PDG)	η_b	0.560
η'_c	3.5 – 4.5	1.3 ± 0.6 (CLEO)	η'_b	0.269
			η''_b	0.208

Problems:

- Dudek, Edwards:

$$\begin{array}{l} f_{\Psi'} \quad 143 (81) \\ f_{\eta'_c} \quad 56 (21) (3) \end{array} \rightarrow f_{\eta'_c} \simeq \frac{1}{3} f_{\Psi'}$$

- Non-static effects ?

Heavy quarkonium decay on/off the lattice (2)

Hart, Horgan, von Hippel, PRD 75 (2007) 014008: Matching QCD/NRQCD for $Y \rightarrow ll$

Radiative decays (open/bound):

[Gao, Zhang, Chao, hep-ph/0606170, 0607278, ...]

- 1-loop pQCD + QED contr.
- Cuts: $p_T^{\text{jet}} > 1 \text{ GeV}$, $\theta > 37$
- OMEs fixed by vel. scal. rules

Results:

$J/\psi \rightarrow \gamma X:$	$f_0(980)$	$f_1(1285)$	$f_2(1270)$	$f_1'(1420)$	$f_2'(1525)$
$BR_{th} \times 10^4$	1.6	7.0	8.7	1.8	2.0
$BR_{ex} \times 10^4$		6.1 ± 0.8	13.8 ± 1.4	7.9 ± 1.3	$4.5^{+0.7}_{-0.4}$

- $\Upsilon \rightarrow \chi_{cJ}\gamma, \Upsilon \rightarrow f_J\gamma$
- $\chi_{bJ} \rightarrow J/\psi\gamma, \chi_{bJ} \rightarrow \rho(\omega, \phi)\gamma$
- $\eta_b \rightarrow J/\psi\gamma$

- Light mesons = CS NR WF

Radiative decays (open/bound):

[Oliveira, Coimbra, hep-ph/0603046]

- Class. Solutions: only $l=0$
- Conf. potential, fit to qLQCD

Leptonic widths:

- 1S: sets scale
- 2S: good, very robust
- 3S, 3D: disaster

Two-photon widths:

- $\eta_c \rightarrow \gamma\gamma$: sets scale
- $\Gamma_{\gamma\gamma}(\chi_{c0}) = 4.06 \text{ keV}$ vs. PDG: 2.87 (40) keV

Gluon widths: poor

Predictions for exotic states

Light and heavy multiquark spectroscopy

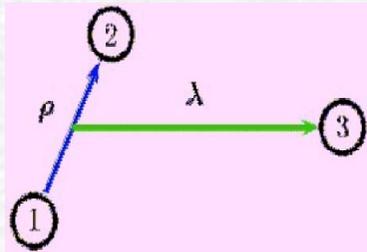
J.M. Richard, hep-ph/0508043, hep-ph/0608297

Pentaquark: $uudds$ ($+$)

Baryons: cqq (B-factories)

☞ BaBar $M=2940$, $\Gamma \approx 17$ MeV

☞ Potential models:



☞ 3-body dynamics ?

Baryons: ccq (Selex 3520 ?)

☞ NRQCD

☞ Diquarks (too many states)

Baryons: ccc ("Ultimate goal")

Mesons: $c\bar{c}g$ -hybrids

☞ BO appr./class. const. gluons

☞ $X(3940)$ a 1^{-+} candidate

Mesons: Multiquarks

☞ Potential models:

☞ c, b : $H\{q_i\} = \sum t_i + \sum \tilde{\lambda}_i^{(c)} \cdot \tilde{\lambda}_j^{(c)} v_{ij}$

☞ q : $H_{SS} = -C \sum \vec{\sigma}_i \cdot \vec{\sigma}_j \tilde{\lambda}_i^{(c)} \cdot \tilde{\lambda}_j^{(c)} \delta^{(3)}(\vec{r}_{ij})$

☞ Flavour-spin: $H_{SS} \propto \sum \vec{\sigma}_i \cdot \vec{\sigma}_j \vec{\tau}_i \cdot \vec{\tau}_j$

☞ QCD sum rules:

☞ Duality of 2-point corr. fct.

☞ $X(3872)$: $cc\bar{c}q$ @ 3925 127

☞ Lattice QCD:

☞ Resonance or artefact ?

☞ Complex energy scaling

Summa summarum

Wide spectrum of topics:

- ☛ Inclusive SF, open prod., bound state prod. & decay

New calculations:

- ☛ NLO: CSM for direct J/Ψ hadroproduction, need more
- ☛ NNLO: Difficult (massive 2-loop massive OPEs)
- ☛ Lattice: Quenched \rightarrow staggered \rightarrow dynamical

Prospects:

- ☛ Correct treatment of HQs very important for LHC
- ☛ Workshop “Flavor in the era of the LHC” just ended
- ☛ “Flavor day” at Les Houches: 16 june 2007