Конференция Confinement 08.
Обзор основных результатов.

Майнц (Германия), 1 6 Сентября 2008

Эффективные теории

Quarkonium Production: NRQCD Confronts Experiment

Geoffrey Bodwin, Argonne

- Nonrelativistic QCD (NRQCD)
  - Heavy-Quarkonium: A Multi-Scale Problem
  - NRQCD
- The NRQCD Factorization Approach in Quarkonium Production
  - Factorization: a Separation of Scales
  - Factorization of the Inclusive Quarkonium Production Cross Section
  - Status of Proofs of Factorization

Nonrelativistic QCD (NRQCD)

Heavy-Quarkonium: A Multi-Scale Problem

- Heavy quarkonium: a bound state of a heavy quark Q and heavy antiquark $\bar{Q}$ (charmonium, bottomonium).
- There are many important scales in a heavy quarkonium:
  - m, the heavy-quark mass;
  - mv, the typical heavy-quark momentum;
  - mv^2, the typical heavy-quark kinetic energy and binding energy.
- v is the typical heavy-quark velocity in the quarkonium CM frame.
  - $v^2 \approx 0.3$ for charmonium.
  - $v^2 \approx 0.1$ for bottomonium.

- In theoretical analyses, it is useful to treat the physics at each of these scales separately.
  - $\alpha_s(m_c) \approx 0.25$ and $\alpha_s(m_b) \approx 0.18$, so we can treat physics at the scales m_c and m_b perturbatively.
  - Approximate symmetries (*e.g.* heavy-quark spin symmetry) can be exploited at some scales.
  - Analytic calculations simplify when they involve only one scale at a time.
  - Lattice calculations can encompass only a limited range of scales, and so become more tractable after scale separation.
- Effective field theories provide a convenient way to separate scales.
  - Basic idea: construct an effective theory that describes the low-momentum degrees of freedom in the original (full) theory.
  - Do this by integrating out the high-momentum degrees of freedom in the original theory.
  - The high-momentum degrees of freedom are no longer manifest in the effective theory, but their effects on the low-momentum degrees of freedom are taken into account through the local interactions in the effective theory.

- For the heavy-quark sector
  - diagonalize interactions in terms of the Q and $\bar{Q}$ parts of the Dirac field (Foldy-Wouthuysen tx.),
  - set the Q and $\bar{Q}$ energies to zero at zero three-momentum.
- Leading terms in $p/m = v$ are just the Schrödinger action:

$$\mathcal{L}_0 = \psi^\dagger \left(iD_t + \frac{\mathbf{D}^2}{2m} \right) \psi + \chi^\dagger \left(iD_t - \frac{\mathbf{D}^2}{2m} \right) \chi.$$

$$D_t = \partial_t + igA_0. \qquad \mathbf{D} = \boldsymbol{\partial} - ig\mathbf{A}.$$

  - ψ is the Pauli spinor field that annihilates Q.
  - χ is the Pauli spinor field that creates $\bar{Q}$.

- To reproduce QCD completely, we would need an infinite number of interactions. For example, at next-to-leading order in v^2 we have

$$\begin{aligned}\delta\mathcal{L}_{\text{bilinear}} &= \frac{c_1}{8m^3}\left[\psi^\dagger(\mathbf{D}^2)^2\psi \;-\; \chi^\dagger(\mathbf{D}^2)^2\chi\right] \\ &+ \frac{c_2}{8m^2}\left[\psi^\dagger(\mathbf{D}\cdot g\mathbf{E} - g\mathbf{E}\cdot\mathbf{D})\psi + \chi^\dagger(\mathbf{D}\cdot g\mathbf{E} - g\mathbf{E}\cdot\mathbf{D})\chi\right] \\ &+ \frac{c_3}{8m^2}\left[\psi^\dagger(i\mathbf{D}\times g\mathbf{E} - g\mathbf{E}\times i\mathbf{D})\cdot\boldsymbol{\sigma}\psi + \chi^\dagger(i\mathbf{D}\times g\mathbf{E} - g\mathbf{E}\times i\mathbf{D})\cdot\boldsymbol{\sigma}\chi\right] \\ &+ \frac{c_4}{2m}\left[\psi^\dagger(g\mathbf{B}\cdot\boldsymbol{\sigma})\psi \;-\; \chi^\dagger(g\mathbf{B}\cdot\boldsymbol{\sigma})\chi\right].\end{aligned}$$

- In practice, work to a given precision in v.
- The c_i are called short-distance coefficients.
  - They can be computed in perturbation theory by matching amplitudes (on-shell) in full QCD and NRQCD.
  - By design, all of the low-scale physics is contained in the explicit NRQCD interactions.
  - The c_i contain the effects from momenta $> \Lambda$.

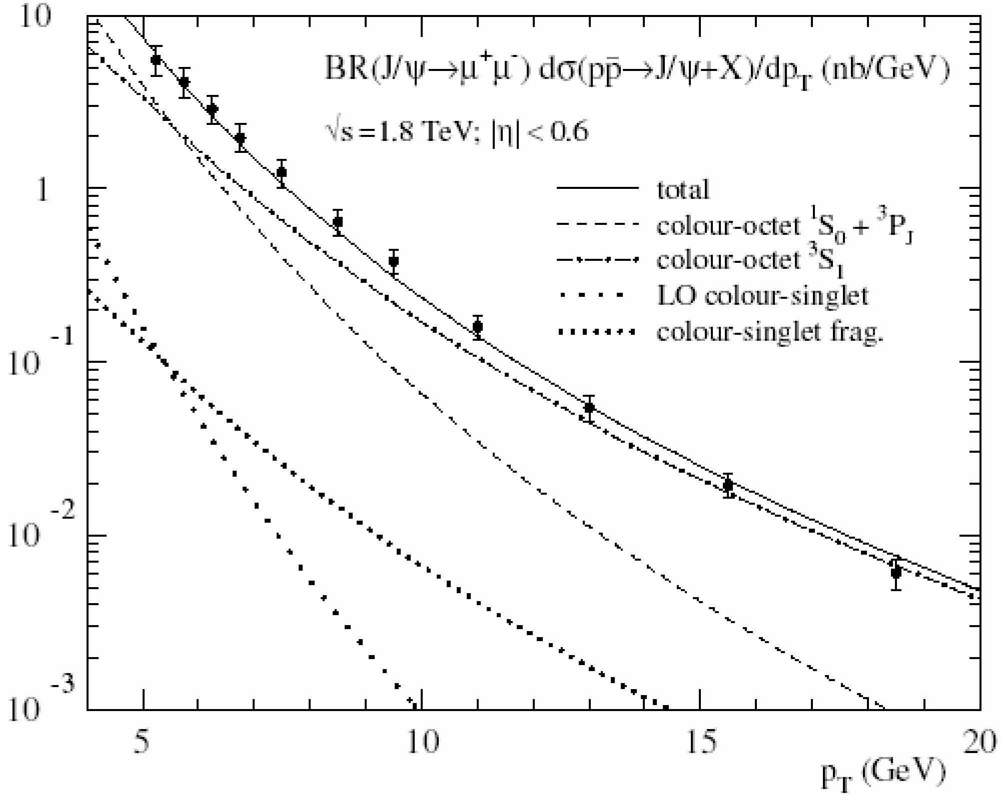
- Conjecture (GTB, Braaten, Lepage (1995)):
  The inclusive cross section for producing a quarkonium at large momentum transfer (p_T) can be written as hard-scattering cross section convolved with an NRQCD matrix element.

$$\sigma(H) = \sum_n F_n(\Lambda) \langle 0 | \mathcal{O}_n^H(\Lambda) | 0 \rangle .$$

- The "short-distance" coefficients $F_n(\Lambda)$ are essentially the process-dependent partonic cross sections to make a $Q\bar{Q}$ pair convolved with the parton distributions.
  - They have an expansion in powers of α_s.
- The operator matrix elements are universal (process independent).
  - Only the color-singlet production matrix elements are simply related to the decay matrix elements.
  - The matrix elements have a known scaling with v.

Comparisons of NRQCD Factorization with Experiment

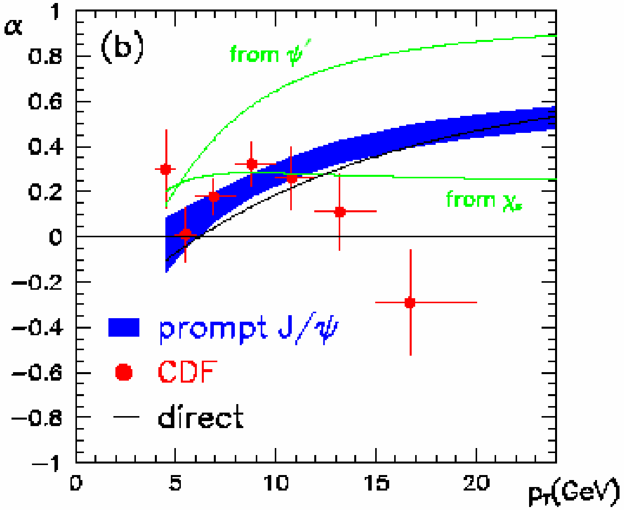
Quarkonium Production at the Tevatron



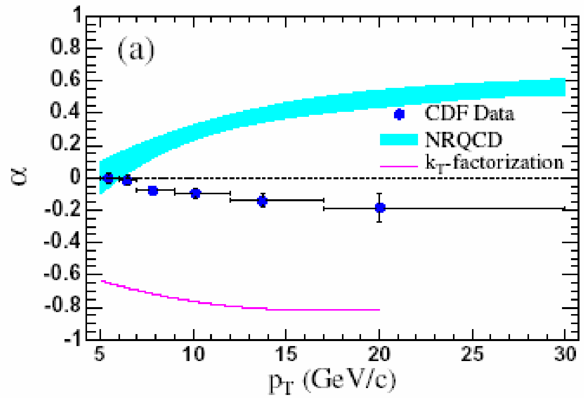
- Data are more than an order of magnitude larger than the predictions of the color-singlet model.
- p_T distributions are consistent with NRQCD, but not with the LO color-singlet model.
- Color-octet matrix elements are determined from fits to the data.
- Satisfactory fits can be obtained for J/ψ, ψ', Υ production.

J/ψ Polarization

Run I:



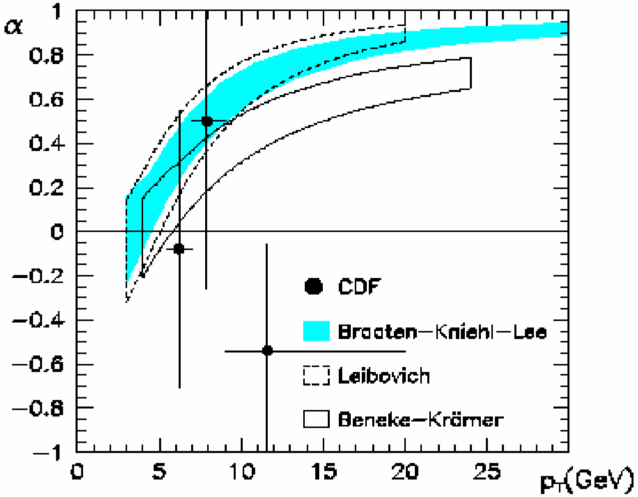
Run II:



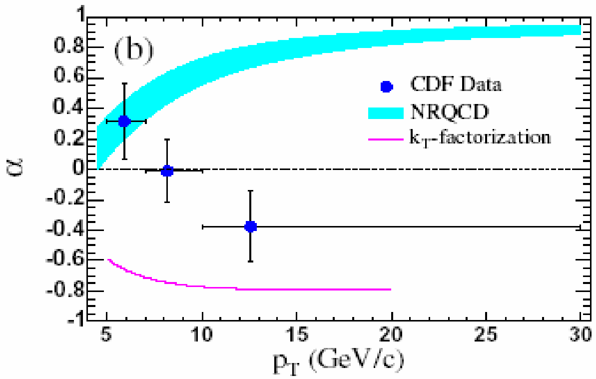
- NRQCD prediction from Braaten, Kniehl, Lee (1999).
  - Feeddown from χ_c states is about 30% of the J/ψ sample and dilutes the polarization.
  - Feeddown from $\psi(2S)$ is about 10% of the J/ψ sample and is largely transversely polarized.
- $d\sigma/d(\cos\theta) \propto 1 + \alpha\cos^2\theta$.
  - $\alpha = 1$ is completely transverse;
  - $\alpha = -1$ is completely longitudinal.
- Run I results are marginally compatible with the NRQCD prediction.
- Run II results are inconsistent with the NRQCD prediction.
- Also, inconsistent with Run I results.
  CDF was unable to track down the source of the Run I-Run II discrepancy.

$\psi(2S)$ Polarization

Run: I



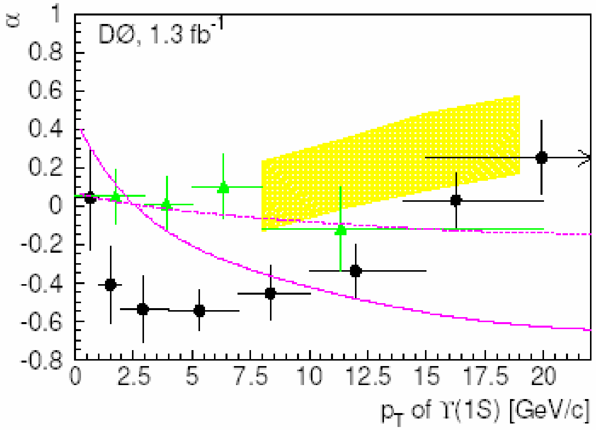
Run: II



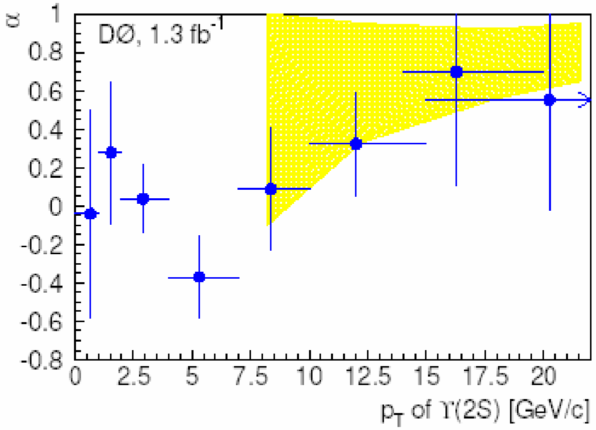
- The Run II data are incompatible with the NRQCD prediction.

Υ Polarization

$\Upsilon(1S)$ Polarization:



$\Upsilon(2S)$ Polarization:



- In the $\Upsilon(1S)$ case, the D0 results (black) are incompatible with the CDF results (green).
- The CDF results are compatible with the NRQCD prediction (yellow).
- The D0 results are marginally incompatible with the NRQCD prediction.
- The curves are the limiting cases of the k_T-factorization prediction.
- In the $\Upsilon(2S)$ case, the theoretical and experimental error bars are too large to make a stringent test.

Exclusive Double Charmonium Production at Belle and BABAR

$$e^+e^- \to J/\psi + \eta_c$$

- Experiment

  Belle (2004): $\sigma[e^+e^- \to J/\psi + \eta_c] \times B_{>2} = 25.6 \pm 2.8 \pm 3.4$ fb.

  BABAR (2005): $\sigma[e^+e^- \to J/\psi + \eta_c] \times B_{>2} = 17.6 \pm 2.8^{+1.5}_{-2.1}$ fb.

- NRQCD at LO in α_s and v

  Braaten, Lee (2003): $\sigma[e^+e^- \to J/\psi + \eta_c] = 3.78 \pm 1.26$ fb.

  Liu, He, Chao (2003): $\sigma[e^+e^- \to J/\psi + \eta_c] = 5.5$ fb.

  The two calculations employ different choices of m_c, NRQCD matrix elements, and α_s.

  Braaten and Lee include QED effects.

- Exclusive process: the color-octet contribution is suppressed as v^4.
- The color-singlet matrix elements are determined from $\eta_c \to \gamma\gamma$ and $J/\psi \to e^+e^-$.

Inclusive Double $c\bar{c}$ Production at Belle

- Belle:

$$
\begin{aligned}
&\sigma(e^+e^- \to J/\psi + c\bar{c} + X)/\sigma(e^+e^- \to J/\psi + X) \\
&\quad = 0.82 \pm 0.15 \pm 0.14 \\
&\quad > 0.48 \text{ (90\% confidence level)}
\end{aligned}
$$

- pQCD plus color-singlet model (Cho, Leibovich (1996); Baek, Ko, Lee, Song (1997); Yuan, Qiao, Chao (1997)):

$$\sigma(e^+e^- \to J/\psi + c\bar{c} + X)/\sigma(e^+e^- \to J/\psi + X) \approx 0.1.$$

Including Relativistic and α_s Corrections to $e^+e^- \to J/\psi + \eta_c$

- Relativistic corrections $\sigma[e^+e^- \to J/\psi + \eta_c]$ can come from two sources:
  - Direct corrections to the process $e^+e^- \to J/\psi + \eta_c$ itself,
  - Indirect corrections that enter through the matrix element of leading order in v. Appear when $\Gamma[J/\psi \to e^+e^-]$ is used to determine the matrix element because of relativistic corrections to the theoretical expression for $\Gamma[J/\psi \to e^+e^-]$.
- Relativistic corrections depend on matrix elements of higher order in v.
- GTB, Kang, Lee (2006): Determine matrix elements of higher order in v by making use of a potential model.
  - If the static $Q\bar{Q}$ potential is known exactly, then the uncertainty is of relative order v^2.
  - First determination of these matrix elements with small enough uncertainties to be useful.
- GTB, Chung, Kang, Kim, Lee, Yu (2006): Corrections at NLO in α_s plus relativistic corrections may bring theory into agreement with experiment.
- Confirmed by He, Fan, Chao (2007).
- GTB, Chung, Kang, Lee (2007): New determination of the matrix elements of LO and NLO in v.

- New Calculation of $\sigma[e^+e^- \to J/\psi + \eta_c]$
  (GTB, Chung, Kang, Lee, Yu (2007))
  - Makes use of the matrix elements from GTB, Chung, Kang, Lee (2007).
  - Resums a class of relativistic corrections.
    Includes all corrections that arise from the potential-model $Q\bar{Q}$-Fock-state wave function, up to the UV cutoff of NRQCD.
  - Uses the results of Zhang, Gao, and Chao (2005) for the corrections of NLO in α_s.
  - Includes the interference between the relativistic corrections and the corrections of NLO in α_s.
  - Includes a detailed error analysis

$$\sigma_{\text{tot}} = 17.6^{+0.8+5.3+0.7+3.9+0.7+2.8+1.6+1.4+1.9+1.32+1.89}_{-0.9-3.7-0.7-3.0-0.7-2.9-1.5-1.1-2.0-1.32-1.89}\ \text{fb} = 17.6^{+8.1}_{-6.7}\ \text{fb}$$

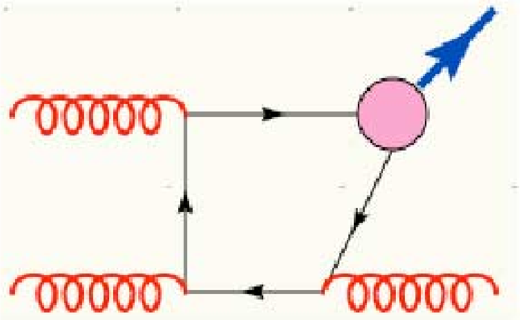
- Uncertainty in the NRQCD factorization formula: $\sim m_H^2/(s/4) \approx 34\%$.

- The Numerator: Experiment and theory also disagree.
  - Belle (2002): $\sigma(e^+e^- \to J/\psi + c\bar{c} + X) = 0.87^{+0.21}_{-0.19} \pm 0.17$ pb.
  - Leading-Order Theory (Color-Singlet): $\sigma(e^+e^- \to J/\psi + c\bar{c} + X) =$ 0.10–0.27 pb.
    Large renormalization-scale dependence.
- New NLO Calculation of the Numerator
  (Zhang and Chao (2007))
  - Find a K factor of about 1.8.
  - Taking into account QED corrections, two-photon processes, feeddown from $\psi(2S)$ (the largest effect) and χ_{cJ}, and color-octet corrections, they obtain
    $\sigma(e^+e^- \to J/\psi + c\bar{c} + X) = 0.53^{+0.59}_{-0.23}$ pb. ($\mu = \sqrt{s}/2$)
    The uncertainties come from m_c.
  - Resolves the discrepancy between theory and experiment, but the theoretical uncertainties are large.
- He, Fan, Chao (2007): Direct relativistic corrections to the numerator are only about $+31\%$.
- Nayak, Qiu, and Sterman: there could be a nonperturbative enhancement to production of $J/\psi + c\bar{c}$ when the c or the $\bar{c}$ is co-moving with the J/ψ.
  This effect can't be calculated reliably in perturbation theory.
  Its size must be determined experimentally.

A Possible Resolution of the Conflicts Between Theory and Experiment

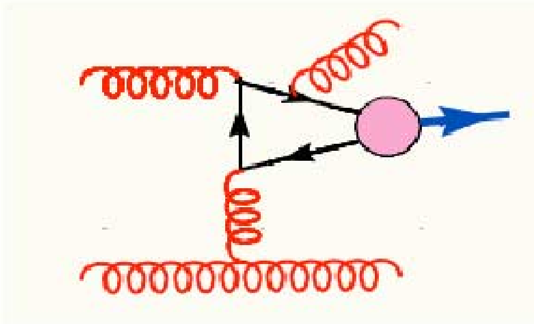
- Campbell, Maltoni, Tramontano(2007); Artoisenet, Lansberg, Maltoni (2007): Higher-order corrections to color-singlet quarkonium production at the Tevatron can be unexpectedly large.
- See the talk by Pierre Artoisenet in Parallel Session C.
- At high p_T, higher powers of α_s can be offset by a less rapid fall-off with p_T.

LO:

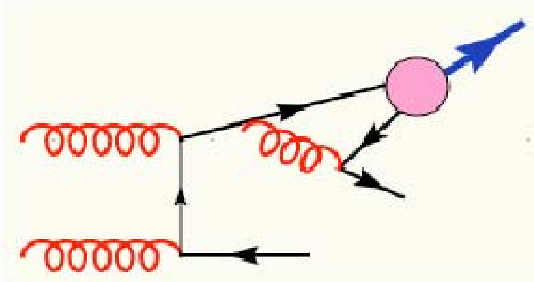


$$\sim \alpha_s^3 \frac{(2m_c)^4}{p_T^8}$$

NLO:

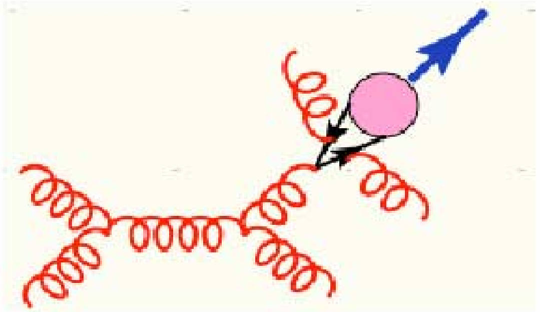


$$\sim \alpha_s^4 \frac{(2m_c)^2}{p_T^6}$$



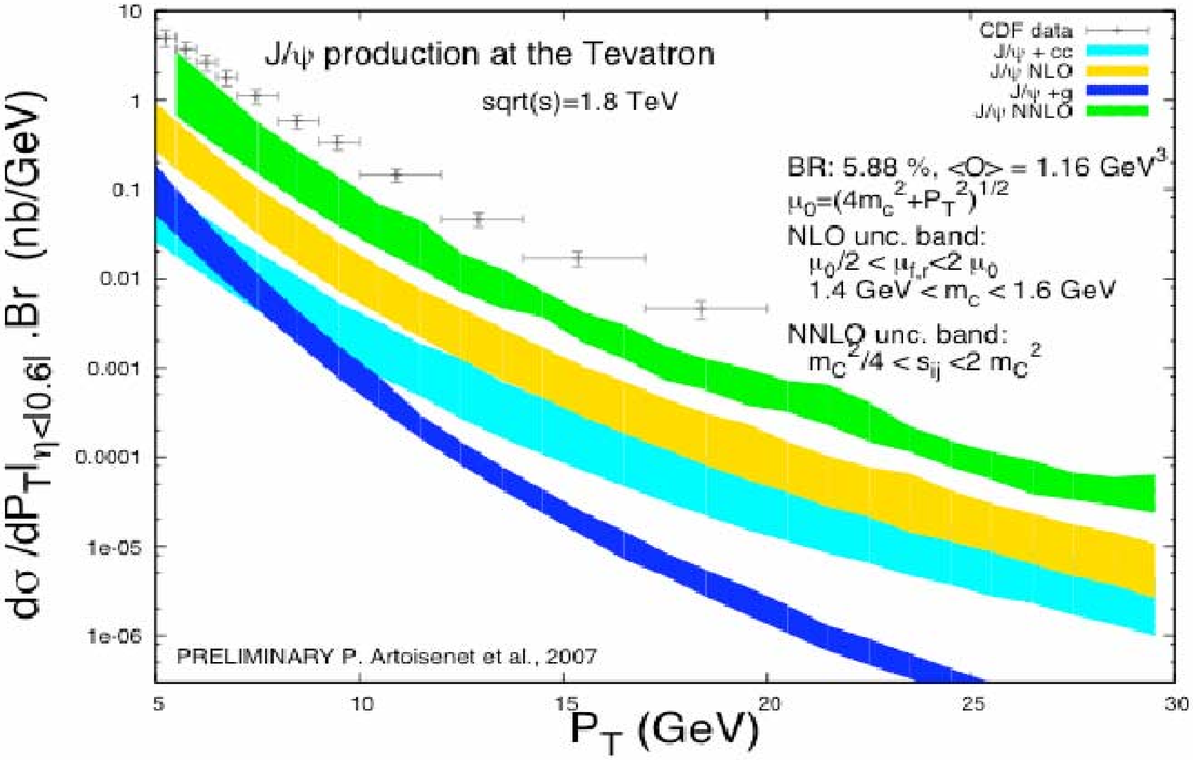
$$\sim \alpha_s^4 \frac{1}{p_T^4}$$

NNLO:



$$\sim \alpha_s^5 \frac{1}{p_T^4}$$

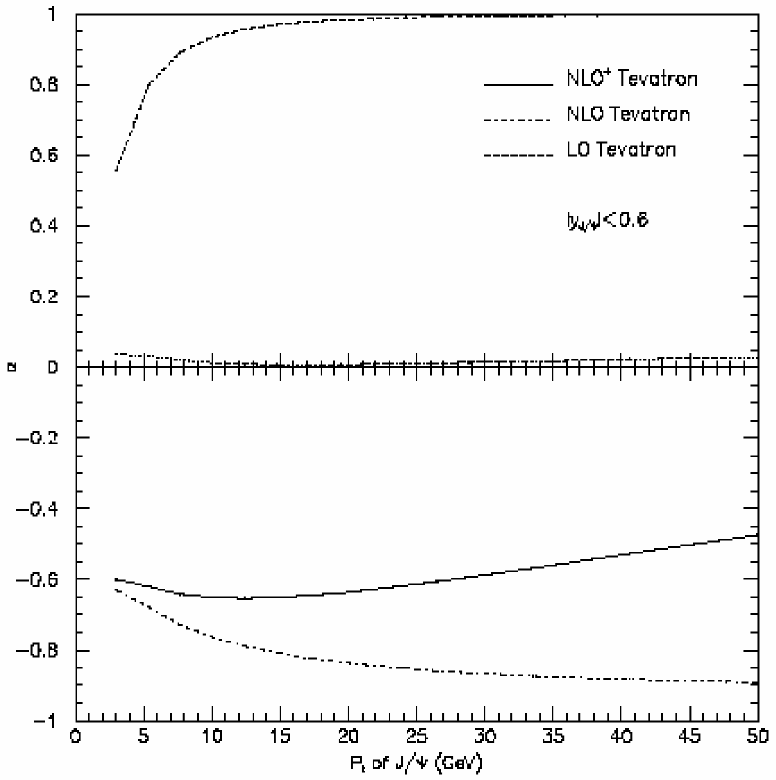
Color-singlet J/ψ production:



- The NNLO calculation is an estimate based on real-emission contributions only.
- There is still room for a color-octet contribution, but its size is greatly reduced from previous estimates.

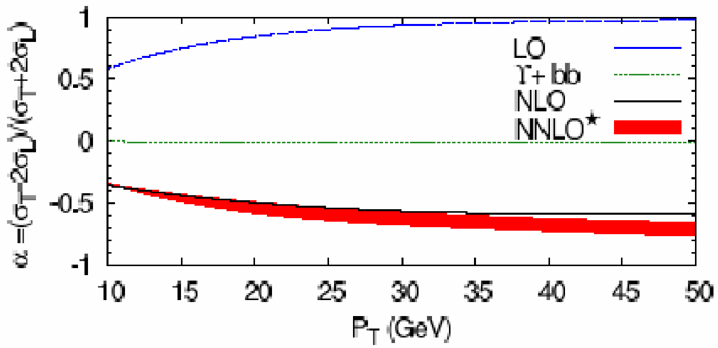
  Affects the matrix elements used to compute all other processes.

- Gong and Wang (2008) find a large longitudinal polarization in color-singlet J/ψ production at the Tevatron in NLO.



- NLO$^+$ includes $gg \to J/\psi c\bar{c}$.

- Artoisenet, Campbell, Lansberg, Maltoni, Tramontano (2008) find a large longitudinal polarization in color-singlet Υ production at the Tevatron in NLO and NNLO.



Improved predictions for J/ψ and Υ hadroproduction

Confinement 8

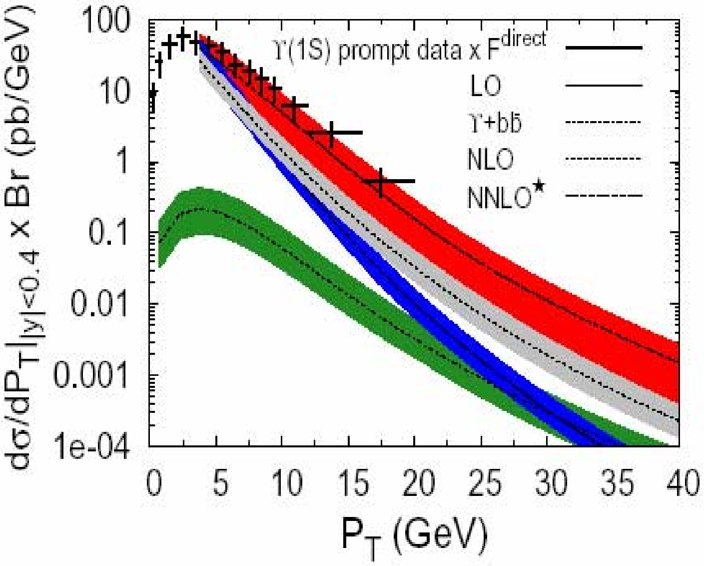
04 September 2008

Pierre Artoisenet

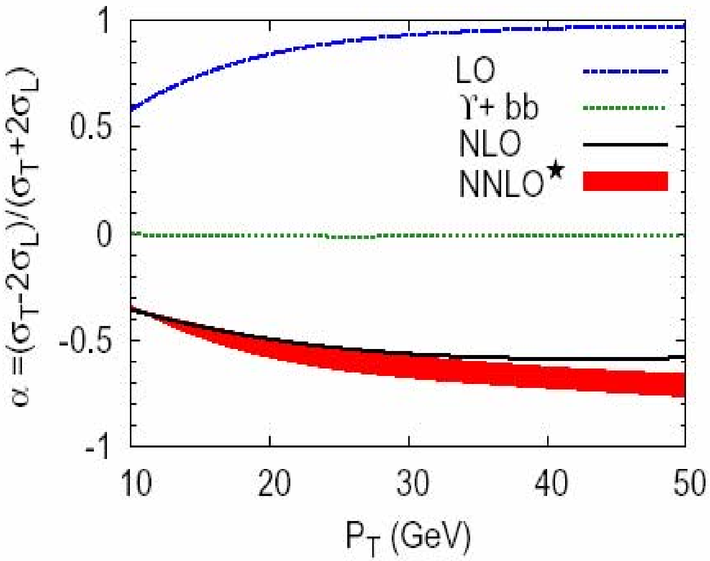
Université Catholique de Louvain

CP3

Υ production - comparison with the CDF data

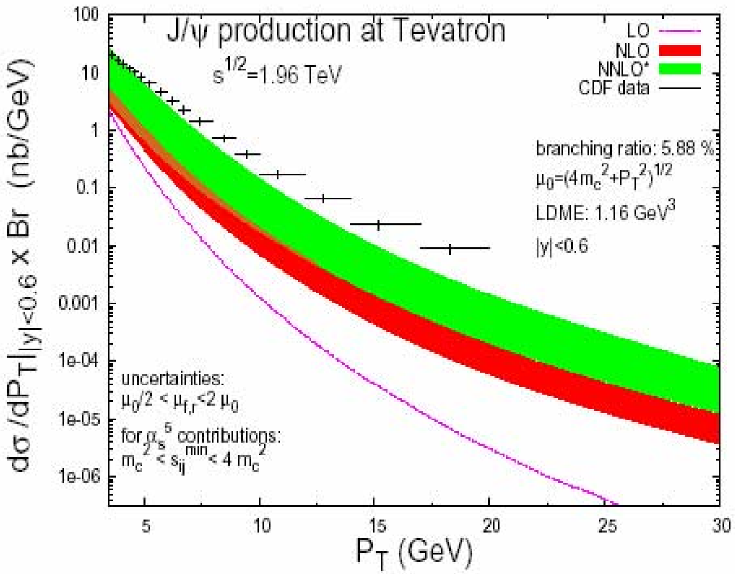


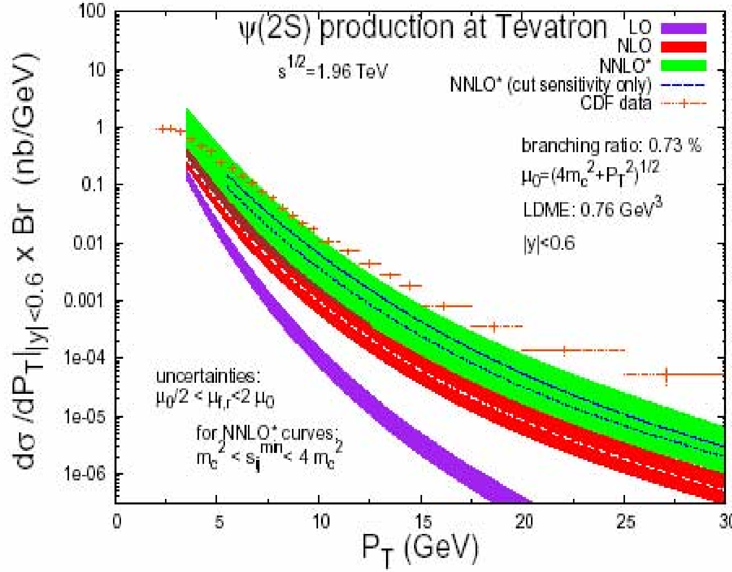
α_s^5 contributions to Υ production bring the CS cross section in agreement with the data (large uncertainties)



QCD corrections lower dramatically the polarization parameter α

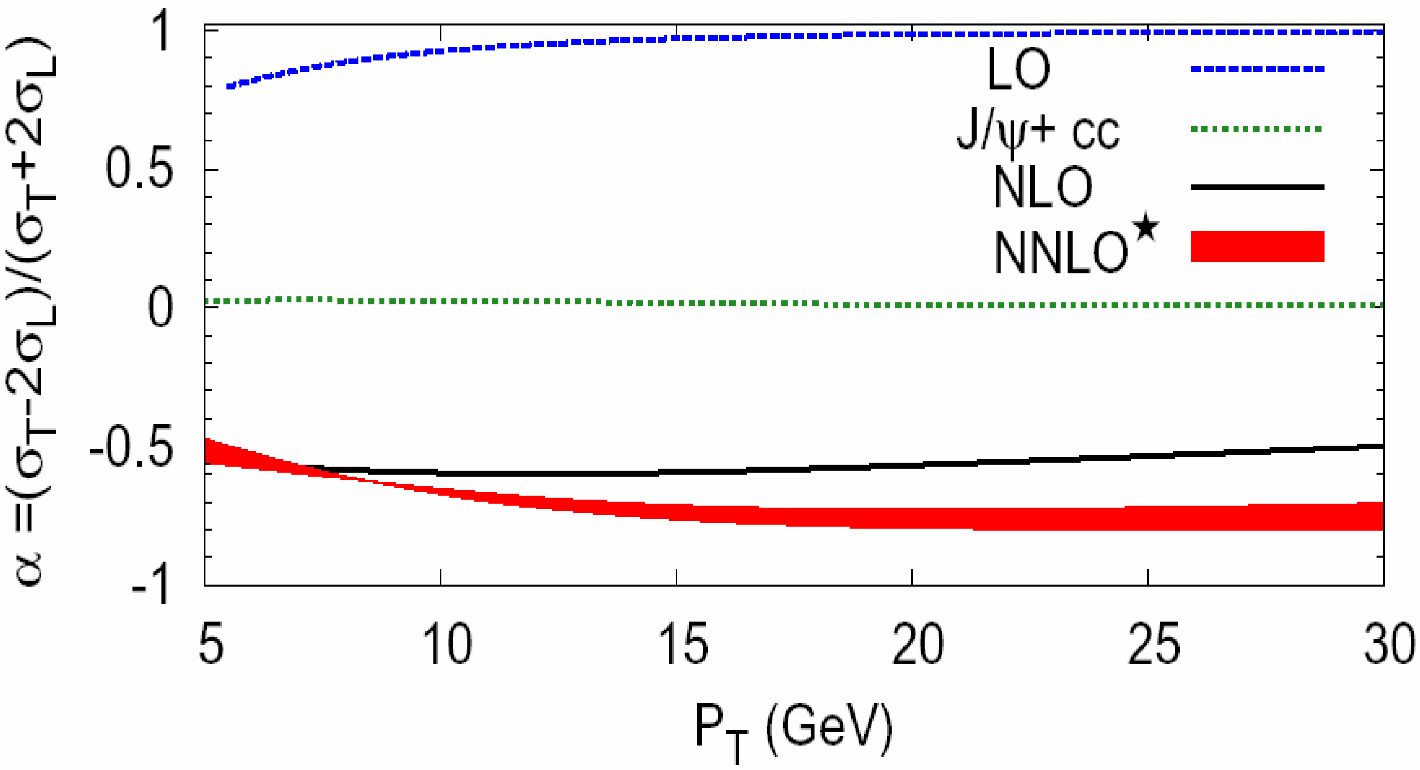
- J/ψ **and** $\psi(2S)$ **differential cross sections - comparison with the preliminary CDF data**





α_s^5 contributions to J/ψ and $\psi(2S)$ production reduces the gap between the CS yield and the data, though a discrepancy remains ...

J/ψ polarization (CS, direct)

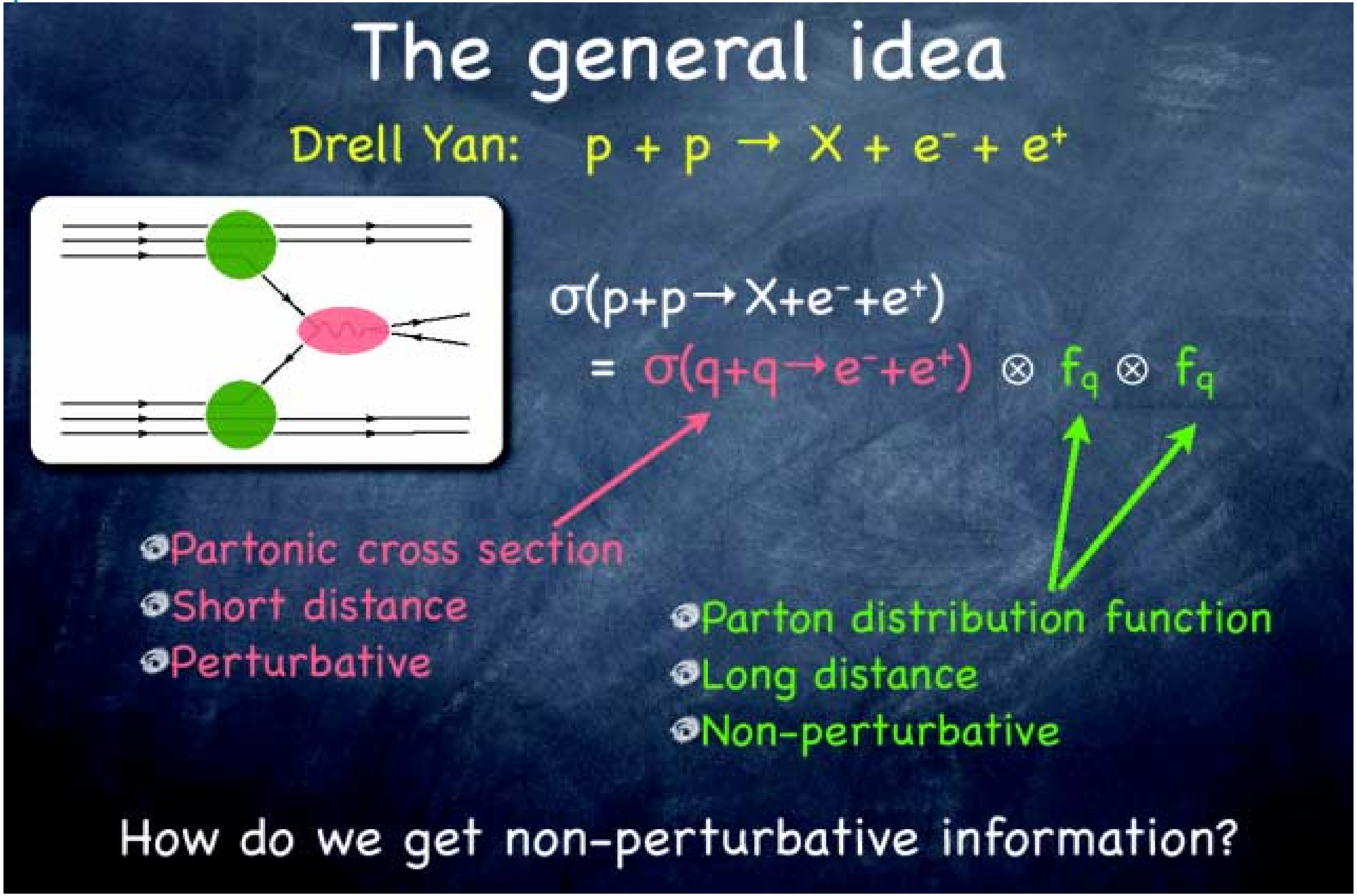


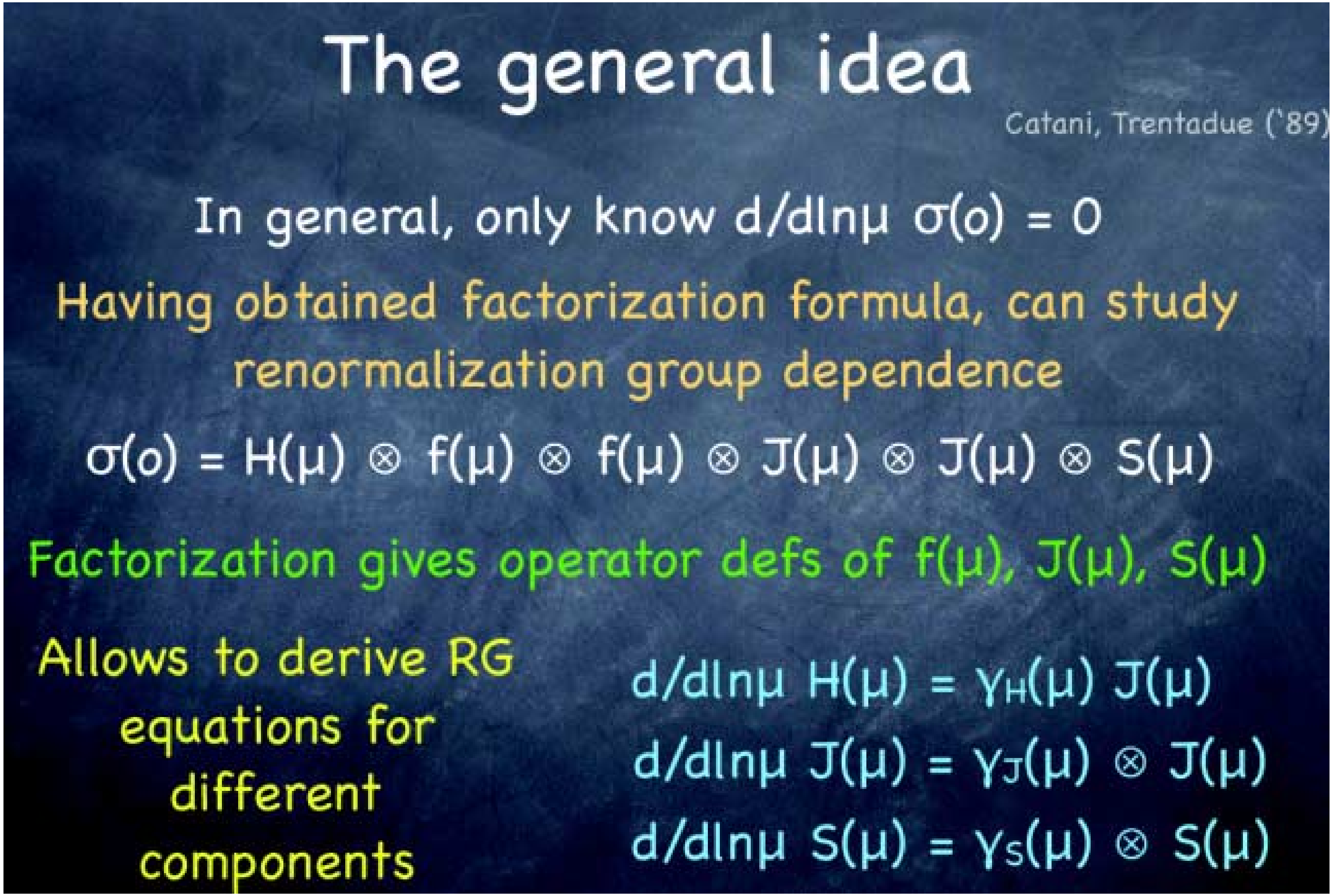
SCET applications in collider physics

Christian Bauer
LBNL/UC Berkeley

Questions that need answers

- How to deal with hadronization effects?
  - Factorize perturbative from non-perturbative physics, and write non-perturbative physics in terms of universal matrix elements
- How to obtain the best perturbative predictions?
  - Use renormalization group evolution resum large logarithmic terms

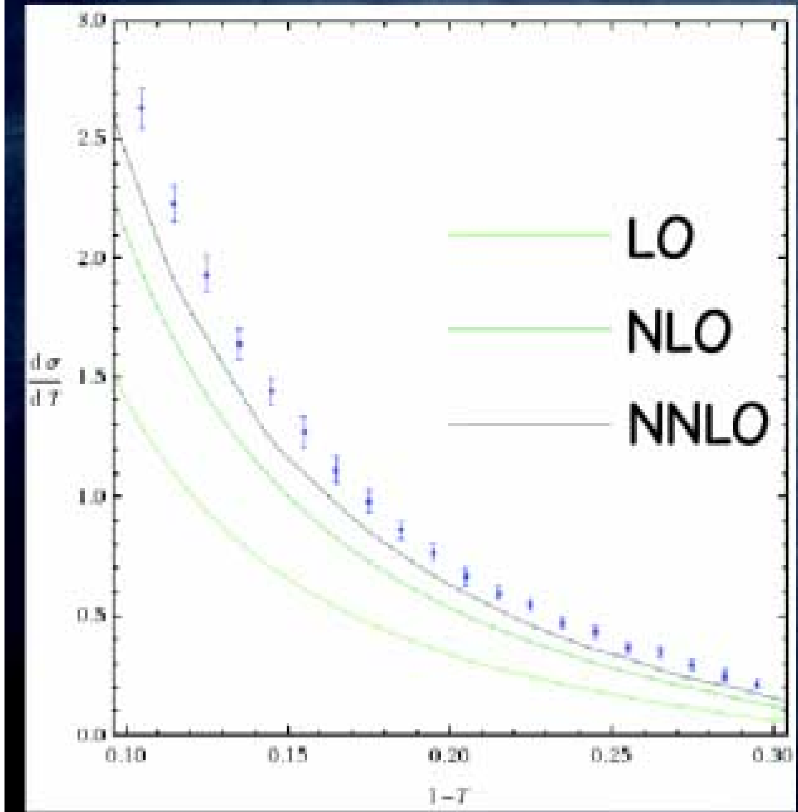

The general idea
Drell Yan: p + p → X + e⁻ + e⁺
σ(p+p→X+e⁻+e⁺)
= σ(q+q→e⁻+e⁺) ⊗ f_q ⊗ f_q
Partonic cross section
Short distance
Perturbative
Parton distribution function
Long distance
Non-perturbative
How do we get non-perturbative information?


The general idea
Catani, Trentadue ('89)
In general, only know d/dlnμ σ(o) = 0
Having obtained factorization formula, can study renormalization group dependence
σ(o) = H(μ) ⊗ f(μ) ⊗ f(μ) ⊗ J(μ) ⊗ J(μ) ⊗ S(μ)
Factorization gives operator defs of f(μ), J(μ), S(μ)
Allows to derive RG equations for different components
d/dlnμ H(μ) = γH(μ) J(μ)
d/dlnμ J(μ) = γJ(μ) ⊗ J(μ)
d/dlnμ S(μ) = γS(μ) ⊗ S(μ)

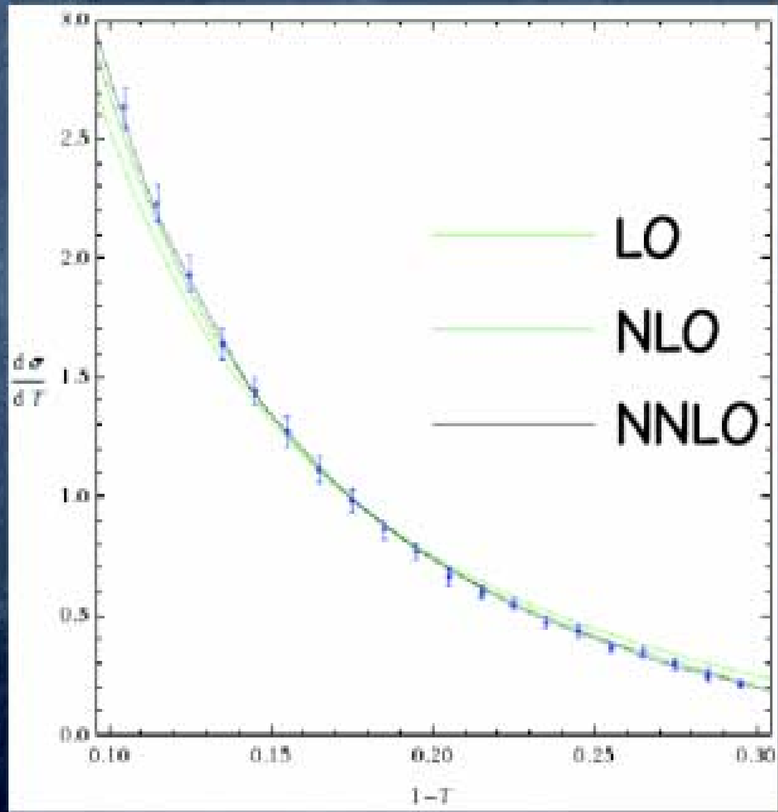
Effect of resumation

Becher, Schwartz, (0803.0342)

fixed order



EFT resummed



STATUS OF CHIRAL PERTURBATION THEORY

Gerhard Ecker

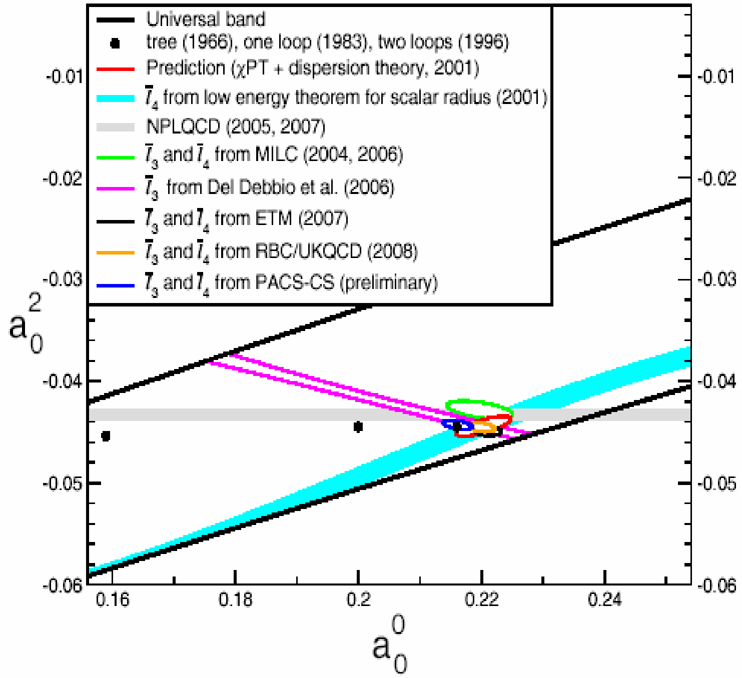
Univ. Wien

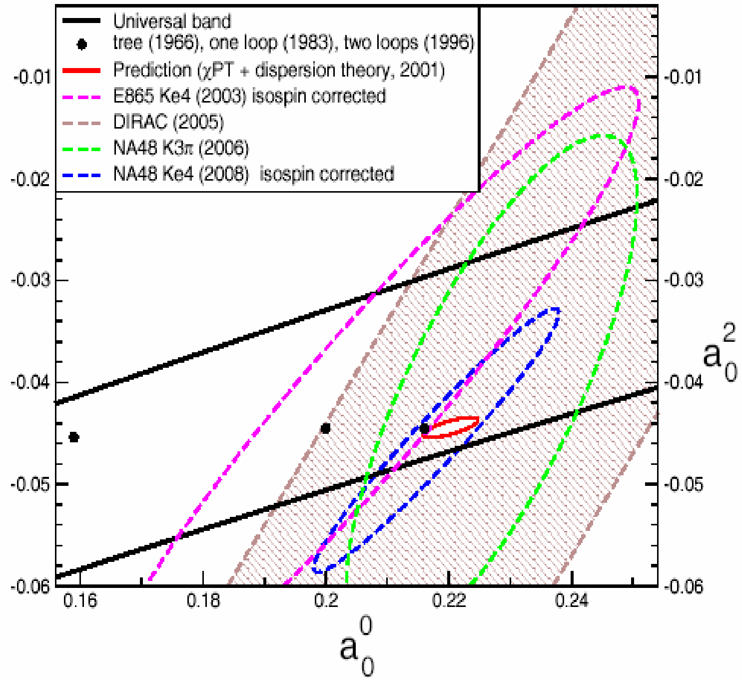
Quark Confinement and the Hadron Spectrum

Mainz, Sept. 1 - 6, 2008

Theoretical and experimental status of scattering lengths

(courtesy of Heiri Leutwyler)





Semileptonic K decays

rich field for CHPT: $K_{l2}, K_{l3}, K_{l4}, \ldots$

K_{l3} decays

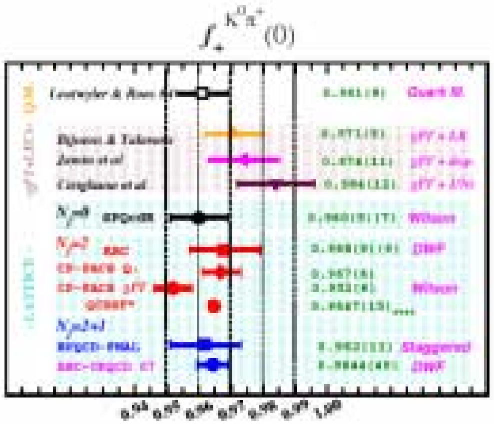
best source for CKM matrix element V_{us} at present

collaboration theory + exp. $\longrightarrow$ $|V_{us}| f_+(0) = 0.21661(47)$

FLAVIANet Kaon WG

some spread in predictions for vector form factor $f_+(t)$ at $t = 0$

dominated by lattice results (agreeing with 1984 prediction of Leutwyler, Roos)



$f_+(0) = 0.964(5)$ (UKQCD/RBC)

yields

$$|V_{us}| = 0.2246(12)$$

perfect agreement with CKM unitarity

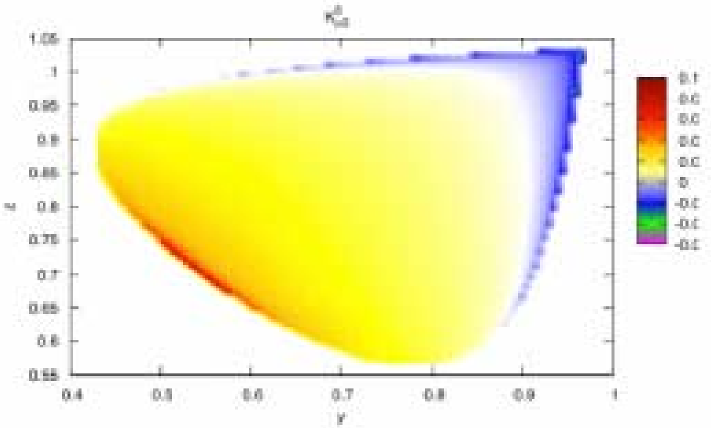
(with V_{ud} from nuclear β decays)

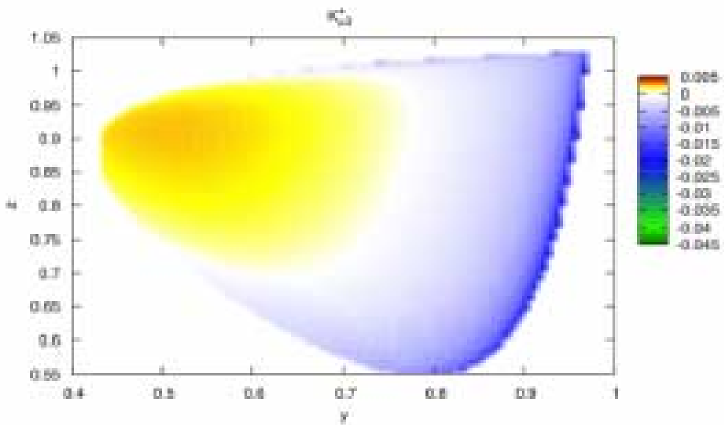
recent determinations		$\lambda_0 \cdot 10^4$
dispersive approach	Bernard, Oertel, Passemar, Stern	150(8)
standard CHPT	Kastner, Neufeld	$139(^{13}_{4})(4)$
exp.	NA48	117 (7)(1)

N.B.: state-of-the-art radiative corrections for $K_{\mu 3}$ remain to be applied

Cirigliano, Gianotti, Neufeld (July 2008)

Dalitz plot of relative radiative corrections





$\Gamma(P \to e\nu_e)/\Gamma(P \to \mu\nu_\mu) \quad (P = \pi, K)$

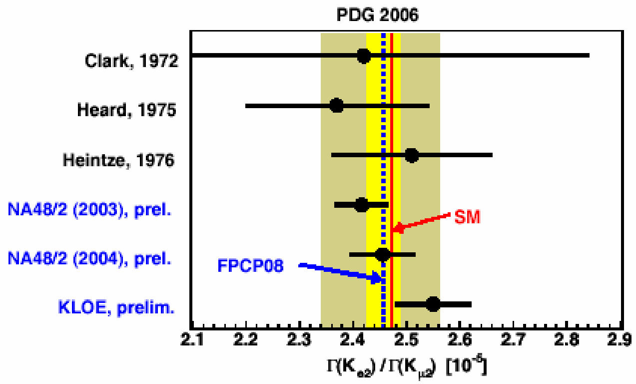
$V - A$ structure of charged currents $\longrightarrow$

$$R_{e/\mu}^{(P)} = \Gamma(P \to e\nu_e[\gamma])/\Gamma(P \to \mu\nu_\mu[\gamma])$$ **helicity suppressed**

$\longrightarrow$ **sensitive probe for new physics**

(charged Higgs exchange, violation of lepton universality, ...)

	PDG '08	Marciano, Sirlin 1993	Finkemeier 1996
$R_{e/\mu}^{(\pi)} \cdot 10^4$	1.230 ± 0.004	1.2352 ± 0.0005	1.2354 ± 0.0002
$R_{e/\mu}^{(K)} \cdot 10^5$	2.45 ± 0.11		2.472 ± 0.001



FLAVIANet fit

$$R_{e/\mu}^{(K)} \cdot 10^5 = 2.457(32)$$

Nonleptonic K decays

big impact of CHPT also for nonleptonic K decays

However: in contrast to semileptonic decays

incomplete knowledge of LECs already at NLO $O(G_F p^4)$

theorists' favourites:

decays without LECs at NLO $\longrightarrow$ completely predicted to $O(G_F p^4)$

but estimates of NNLO contributions required

discuss here 2 early examples (2nd half of 80s)

$K_S \to \gamma\gamma$ and $K_L \to \pi^0\gamma\gamma$

N.B.: **recent progress purely experimental**

recall theoretical status at $O(G_F p^4)$

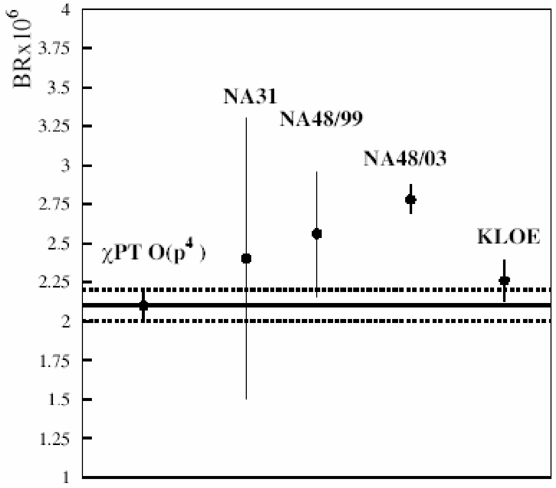
$K_S \to \gamma\gamma$ D'Ambrosio, Espriu; Goity

$K_L \to \pi^0\gamma\gamma$ E., Pich, de Rafael; Cappiello, D'Ambrosio

$K_S \to \gamma\gamma$

puzzling result of NA48 (2003):
rate much bigger than CHPT result

welcome resolution (?):
new KLOE measurement (2008)
$B(K_S \to \gamma\gamma) = 2.26(12)(06) \times 10^{-6}$
plot: courtesy of Matteo Martini



$\longrightarrow$ **perfect agreement with CHPT**

experimental situation only settled this year

☛ **excellent agreement between theory and experiment for both rate and spectrum**

$$B(K_L \to \pi^0\gamma\gamma)\cdot 10^6 = \begin{cases} 1.36 \pm 0.03 \pm 0.03 \pm 0.03 & \text{NA48 (2002)} \\ 1.29 \pm 0.03 \pm 0.05 & \text{KTeV (2008)} \end{cases}$$

$$a_V = \begin{cases} -0.46 \pm 0.03 \pm 0.04 & \text{NA48 (2002)} \\ -0.31 \pm 0.05 \pm 0.07 & \text{KTeV (2008)} \end{cases}$$

Conclusions

- significant progress along several directions
- $\pi\pi$ scattering

  impressive precision by combining CHPT with dispersion theory

  impressive experimental confirmation
- progress in kaon physics closely related to CHPT
  - $K_{l3} \quad \longrightarrow \quad V_{us}$
  - $\Gamma(P \to e\nu_e)/\Gamma(P \to \mu\nu_\mu)$ to $O(e^2p^4)$

    $\longrightarrow$ small theor. uncertainties challenge for experiment
  - sometimes patience is needed: $K_S \to \gamma\gamma, K_L \to \pi^0\gamma\gamma, \ldots$
- CHPT only reliable method for isospin violating and elm. corrections
- progress in determination of LECs $\longrightarrow$ Silvia Necco, Toni Pich
- CHPT: precision physics at low energies

  significant tests of the SM

Правила сумм КХД

How reliable are hadron parameters obtained from QCD sum rules?

Dmitri Melikhov

HEPHY, Vienna and SINP, Moscow State University

We discuss the extraction of the parameters of the individual bound states from dispersive sum rules, making use of the exactly solvable quantum-mechanical harmonic-oscillator model. In this model, (i) the bound-state parameters are known (ii) the analytic expressions for the relaveant correlators are known precisely.

We apply the standard sum-rule machinery and compare the parameters extracted from the sum rule with the true known values. We show that the existing criteria do not allow one to provide realistic error estimates of bound-state parameters (such as decay constants and form factors) extracted from sum rules.

Based on work with Wolfgang Lucha and Silvano Simula

1. MODEL

$H = H_0 + V(r), \quad H_0 = \vec{p}^2/2m, \quad V(r) = \frac{m\omega^2\vec{r}^2}{2}, \quad G(E) = (H - E)^{-1}.$

2. TWO–POINT SUM RULE

Polarization operator $\Pi(E)$ is defined through the full Green function $G(E)$:

$$\Pi(E) = (2\pi/m)^{3/2} \langle \vec{r}_f = 0 | G(E) | \vec{r}_i = 0 \rangle,$$

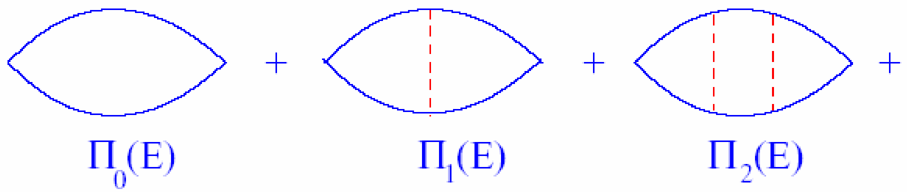
The Borel transformed $\Pi(\mu)$ is the evolution operator in imaginary time $\tau = 1/\mu$ is known:

$$\boxed{\Pi(\mu) = (2\pi/m)^{3/2} \langle \vec{r}_f = 0 | \exp(-H/\mu) | \vec{r}_i = 0 \rangle = \left(\frac{\omega}{\sinh(\omega/\mu)} \right)^{3/2}.}$$

OPE: expanding in inverse powers of μ gives the OPE series for $\Pi(\mu)$ to any order:

$$\Pi_{\rm OPE}(\mu) \equiv \Pi_0(\mu) + \Pi_1(\mu) + \Pi_2(\mu) + \cdots = \mu^{3/2} \left[1 - \frac{\omega^2}{4\mu^2} + \frac{19}{480} \frac{\omega^4}{\mu^4} - \frac{631}{120960} \frac{\omega^6}{\mu^6} + \cdots \right].$$

Each term may be calculated from the series



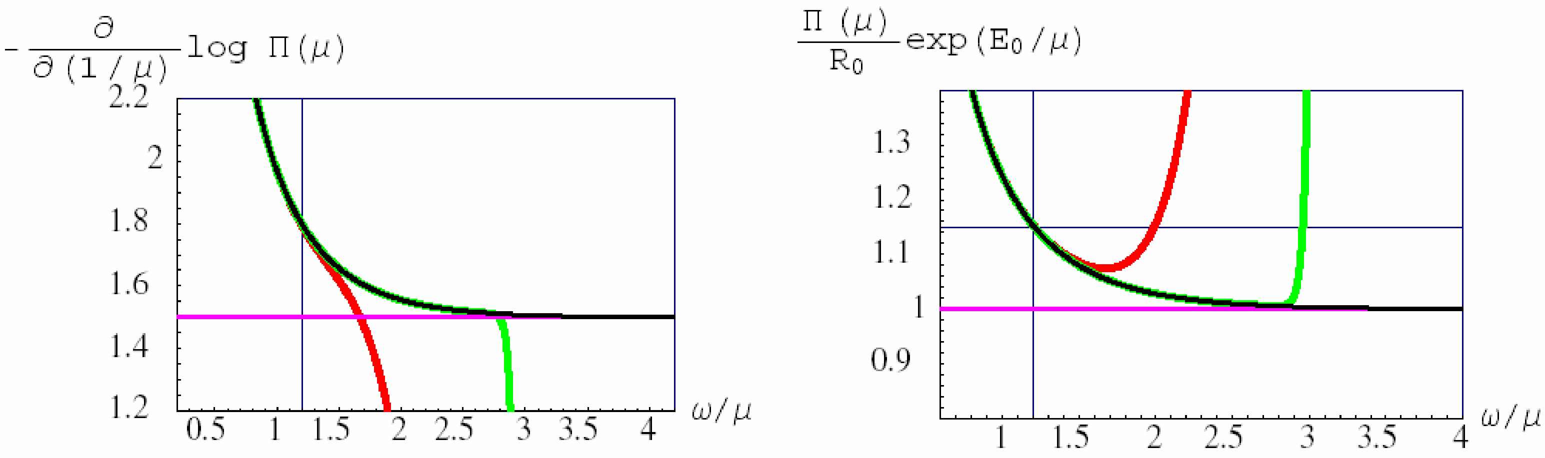
The "phenomenological" representation for $\Pi(\mu)$ - in the basis of hadron eigenstates:

$$\Pi(\mu) = \sum_{n=0}^{\infty} R_n \exp(-E_n/\mu),$$

E_n **- energy of the** n**-th bound state,** $R_n = (2\pi/m)^{3/2}|\Psi_n(\vec{r}=0)|^2$.

$$E_0 = \tfrac{3}{2}\omega, \quad R_0 = 2\sqrt{2}\omega^{3/2}, \qquad E_1 = \tfrac{7}{2}\omega, \quad R_1 = 3\sqrt{2}\omega^{3/2}.$$

How to calculate E_0 and R_0 from $\Pi(\mu)$ known numerically?



Black - exact $\Pi(\mu)$; Red - OPE with 4 power corrections, Green - OPE with 100 power corrections.

SUM RULE:

The equality of the correlator calculated in the "hadron" basis (l.h.s.) and in the "quark" basis (r.h.s.):

$$R_0 e^{-E_0/\mu} + \int_{z_{\rm cont}}^{\infty} dz \rho_{\rm phen}(z) e^{-z/\mu} = \int_0^{\infty} dz \rho_0(z) e^{-z/\mu} + \mu^{3/2}\left[-\frac{\omega^2}{4\mu^2} + \frac{19}{480}\frac{\omega^4}{\mu^4} + \cdots\right].$$

Effective continuum threshold $z_{\rm eff}(\mu)$

$$\int_{z_{\rm cont}}^{\infty} dz\, \rho_{\rm phen}(z) \exp(-z/\mu) = \int_{z_{\rm eff}(\mu)}^{\infty} dz\, \rho_0(z) \exp(-z/\mu), \qquad \rho_0(z) = \frac{2}{\sqrt{\pi}}\sqrt{z}$$

Rewrite sum rule in the form

$$R_0 \exp(-E_0/\mu) = \Pi(\mu, z_{\rm eff}(\mu)) \equiv \frac{2}{\sqrt{\pi}} \int_0^{z_{\rm eff}(\mu)} dz\, \sqrt{z} \exp(-z/\mu) + \mu^{3/2}\left[-\frac{\omega^2}{4\mu^2} + \frac{19}{480}\frac{\omega^4}{\mu^4} - \cdots\right].$$

The cut correlator $\Pi(\mu, z_{\rm eff}(\mu))$ **satisfies the equation:**

$$E(\mu) \equiv -\frac{d}{d(1/\mu)} \log \Pi(\mu, z_{\rm eff}(\mu)) = E_0.$$

The cut correlator governs the extraction of the ground-state parameters.

We must impose constraints on $z_{\text{eff}}(\mu)$ to obtain predictions. A widely used procedure:

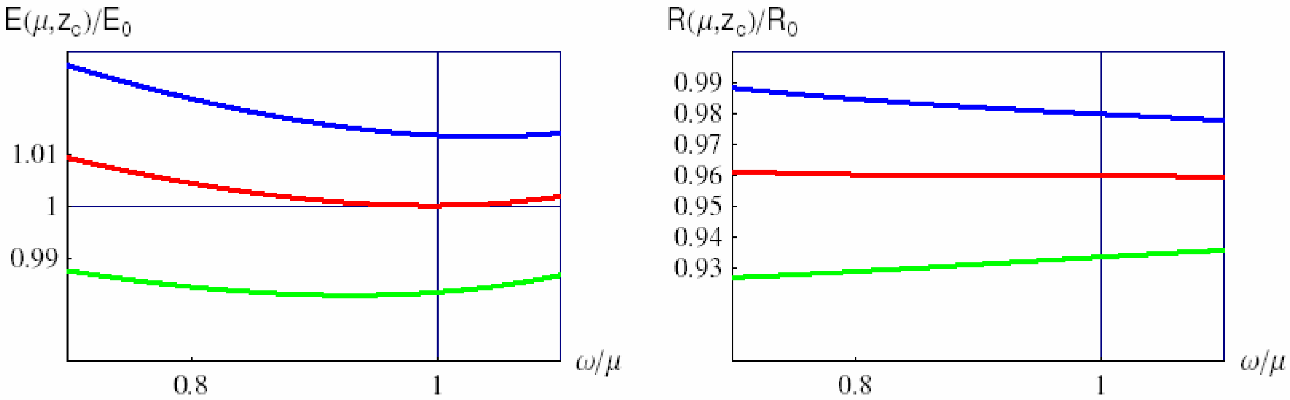
1. ANSATZ: $z_{\text{eff}}(\mu) \to z_c = \text{const}$.

2. Impose a criterion for fixing z_c: e.g. one calculates

$$E(\mu, z_c) = -\frac{d}{d(1/\mu)} \log \Pi(\mu, z_c).$$

This now depends on μ due to approximating $z_{\text{eff}}(\mu)$ with a constant. Then, one determines μ_0 and z_c as the solution to the system of equations

$$E(\mu_0, z_c) = E_0, \qquad \frac{\partial}{\partial\mu} E(\mu, z_c)|_{\mu=\mu_0} = 0,$$



$z_c = 2.4\omega$ (green); $z_c = 2.454\omega$ (red); $z_c = 2.5\omega$ (blue).

The sum-rule estimate for R is obtained as follows:
The "right" values: $z_c = 2.454\omega$ (red), $\mu = \mu_0 = \omega \quad \Rightarrow \quad R = R(z_c, \mu_0)$.

3. THREE−POINT SUM RULE

The basic object is the following correlator

$$\Gamma(E_2, E_1, q^2) = \langle \vec{r}_f = 0|(H - E_2)^{-1} J(\vec{q})(H - E_1)^{-1}|\vec{r}_i = 0\rangle, \qquad q^2 \equiv \vec{q}^{\,2},$$

and its double Borel transform $E_1 \to \tau_1$ **and** $E_2 \to \tau_2$

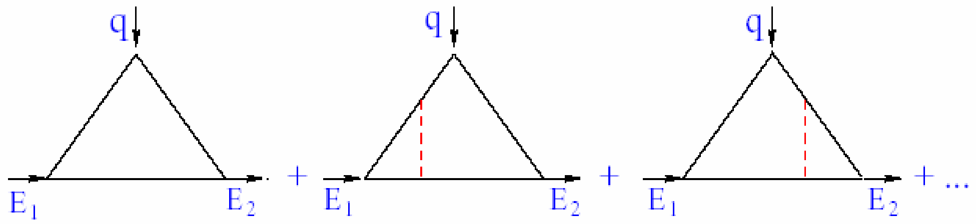
$$\Gamma(\tau_2, \tau_1, q^2) = \langle \vec{r}_f = 0| \exp(-H\tau_2) J(\vec{q}) \exp(-H\tau_1)|\vec{r}_i = 0\rangle.$$

For large τ_1 **and** τ_2**:**

$$\Gamma(\tau_2, \tau_1, q^2) \to |\psi_{n=0}(r = 0)|^2 e^{-E_0(\tau_1+\tau_2)} F_0(q^2) + \dots$$

In HO model the exact analytic expression for $\Gamma(\tau_2, \tau_1, q)$ **is known → OPE to any order.**

Alternatively, OPE may be obtained from the diagrams



Present results for $\tau_1 = \tau_2 = \frac{1}{2}T$**, denote** $\Gamma(T, q^2) \equiv \Gamma(\frac{1}{2}T, \frac{1}{2}T, q^2)$**.**

To construct OPE for $\Gamma(T, q^2)$**, we calculate the first diagram** Γ_0 **(without interaction) and add power corrections up to** $O(T^9)$ **[which we obtain from the exact expression].**

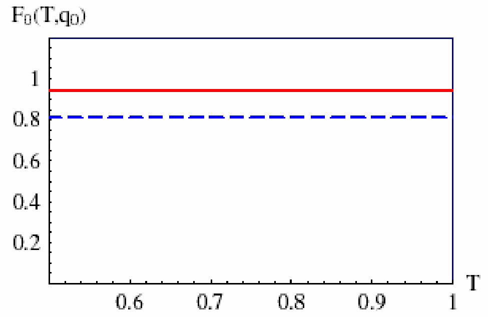
The extraction of ground-state form factor

The form factor of the ground state in HO is known:

$$F_0(q^2) = \exp\left(-\frac{q^2}{4m\omega}\right)$$

To obtain the form factor from the sum rule, we cut the double spectral representation for Γ_0 in z and z' at $z_{\rm eff}$ [which now depends on T, q^2, and the shape of the duality region]. Let us assume $z_{\rm eff} = z_c$, as a trial take the same value as in two-point sum rule.

Then, for $m = \omega = 1\,GeV$ and e.g. for $q_0 = 0.5\,GeV$ we extract the following form factor $F_0(q_0^2)$



Red - exact form factor, blue - as obtained from sum rule.

Notice:

1. the extracted form factor is extremely stable in the Borel window;

2. however, its value is about 15% smaller than the true form factor.

On duality violations in hadronic tau decay

Santi Peris, IFAE - U.A. Barcelona

Mainz 2008

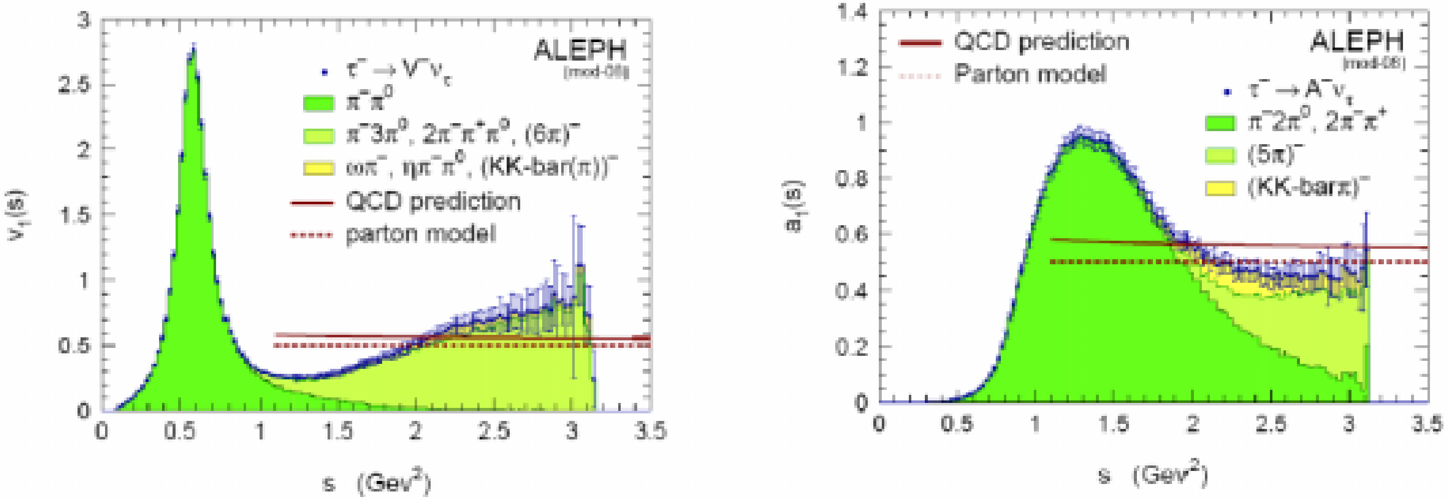
Ongoing work done in collaboration with

Oscar Catà, Maarten Golterman and Matthias Jamin

Introduction

$$R_\tau = \frac{\Gamma(\tau \to \nu_\tau \text{hadrons})}{\Gamma(\tau \to \nu_\tau e \overline{\nu}_e)}$$

$$= 12\pi \, S_{EW} |V_{ud}|^2 \int_0^{m_\tau^2} \frac{ds}{m_\tau^2} \left(1 - \frac{s}{m_\tau^2}\right)^2 \left[\left(1 + 2\frac{s}{m_\tau^2}\right) \text{Im}\Pi^{(1)}(s) + \text{Im}\Pi^{(0)}(s)\right]$$



Duality Violations

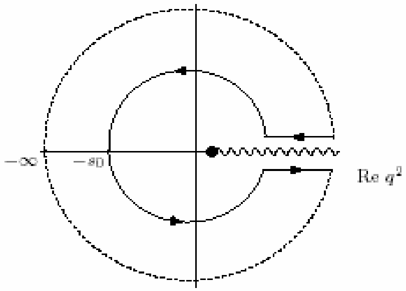
What do we know about duality violations:

(Shifman '00)

$$\Delta(s) = \Pi(s) - \Pi^{OPE}(s) \quad ?$$

Almost nothing.
Let us assume:

- $\Delta(s) \to 0$ as $|s| \to \infty$. Then:



$$\mathcal{D}^P(m_\tau^2) \simeq - \int_{m_\tau^2}^{\infty} ds \; P(s) \; \frac{1}{\pi} \mathrm{Im}\Delta(s)$$

(Catà, Golterman, S.P. '05)

- A model with Regge behavior, $\Gamma_R \sim \frac{1}{N_c} M_R$, analyticity, etc... suggests

(Blok et al. '98; Bigi et al. '99; Catà et al. '08; Davier et al. '08)

$$(s \text{ large}) \qquad , \qquad \frac{1}{\pi}\mathrm{Im}\Delta(s) \sim \kappa \; e^{-\gamma s} \; \sin(\alpha + \beta s)$$

Fit to exp. data to extract κ, γ, α and β.

Results

Taking

$$\mathcal{D}^P(M_\tau^2) \simeq -\int_{m_\tau^2}^{\infty} ds\ P(s)\ \frac{1}{\pi}\mathrm{Im}\Delta(s)$$

we find

$$\frac{\delta R_\tau^V}{R_\tau^V} \simeq -1.5\% \quad \Longrightarrow \quad \delta\alpha_s(M_\tau^2)|_{th} \simeq 0.01$$

$$\frac{\delta R_\tau^A}{R_\tau^A} \simeq 0$$

Pion form factor from local – duality QCD sum rule

Dmitri Melikhov

HEPHY, Vienna & SINP, Moscow State University, Moscow

We present the analysis of the pion elastic form factor from a local-duality (LD) three-point sum rule (a Borel sum rule in the limit of an infinite Borel parameter). Our calculation includes the $O(1)$ and $O(\alpha_s)$ contributions and is therefore applicable in a broad range of spacelike momentum transfers.

We compare the result from the LD version of QCD sum rules with the existing results from light-cone sum rules and discuss the uncertainties in both approaches.

Based on V.Braguta, W.Lucha, D.M., PLB 661, 354 (2008) and work in progress W.Lucha, D.M., S.Simula

The standard Borel sum rules for the pion decay constant:

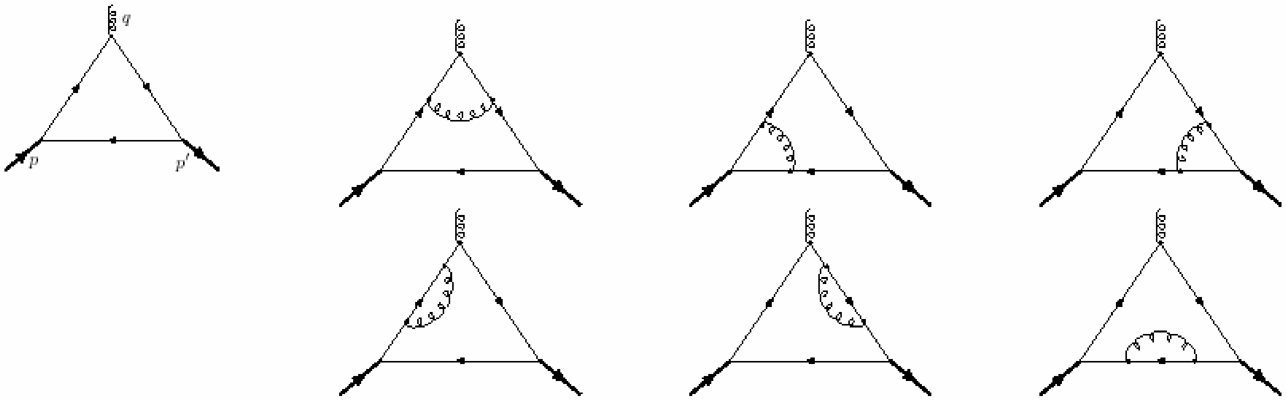
$$f_\pi^2 = \frac{1}{4\pi^2}\int_0^{\bar{s}_{\rm eff}} ds \exp\left(-s/M^2\right)\left(1+\frac{\alpha_s}{\pi}+O(\alpha_s^2)\right)+\frac{\langle\alpha_s G^2\rangle}{12\pi M^2}+\frac{176\pi\alpha_s\langle\bar{q}q\rangle^2}{81M^4}+\cdots,$$

and for the pion form factor:

$$f_\pi^2 F_\pi(Q^2) = \Gamma(Q^2, M^2, M^2|s_{\rm eff}) + \frac{\langle\frac{\alpha_s}{\pi}G^2\rangle}{24M^2}+\frac{4\pi\alpha_s\langle\bar{q}q\rangle^2}{81M^4}\left(13+\frac{Q^2}{M^2}\right).$$

Here $\Gamma(Q^2, M^2, M^2|s_{\rm eff})$ is the cut perturbative contribution obtained from the $\langle AVA\rangle$ correlator:

$$\Gamma(Q^2, M_1^2, M_2^2|s_{\rm eff}) = \frac{1}{\pi^2}\int^{s_{\rm eff}} ds_1 \int^{s_{\rm eff}} ds_2 e^{-s_1/2M^2} e^{-s_2/2M^2}\left[\Delta^{(0)}(Q^2, s_1, s_2)+\alpha_s\Delta^{(1)}(Q^2, s_1, s_2)\right].$$



The Local – duality (LD) limit is M → ∞. Then ALL power corrections vanish.

$$F_\pi(Q^2) = \frac{\frac{1}{\pi^2}\int_0^{s_0} ds_1 \int_0^{s_0} ds_2 \left[\Delta^{(0)}(s_1, s_2, Q^2) + \alpha_s \Delta^{(1)}(s_1, s_2, Q^2)\right]}{\frac{1}{\pi}\int_0^{s_0} ds \left[\rho^{(0)}(s) + \alpha_s \rho^{(1)}(s)\right]}, \qquad s_0 = \frac{4\pi^2 f_\pi^2}{1 + \alpha_s/\pi}.$$

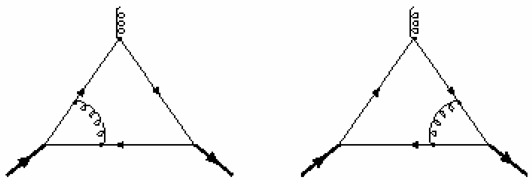
(i) The normalization condition $F_\pi(Q^2 = 0) = 1$ due to the vector Ward identity:

$$\lim_{Q^2\to 0} \Delta^{(i)}(s_1, s_2, Q^2) = \pi\rho^{(i)}(s_1)\delta(s_1 - s_2), \qquad \rho^{(0)}(s) = \frac{1}{4\pi}, \qquad \rho^{(1)}(s) = \frac{1}{4\pi^2}.$$

For consistency take into account rad corrections to the same order in 2- and 3-point correlators.

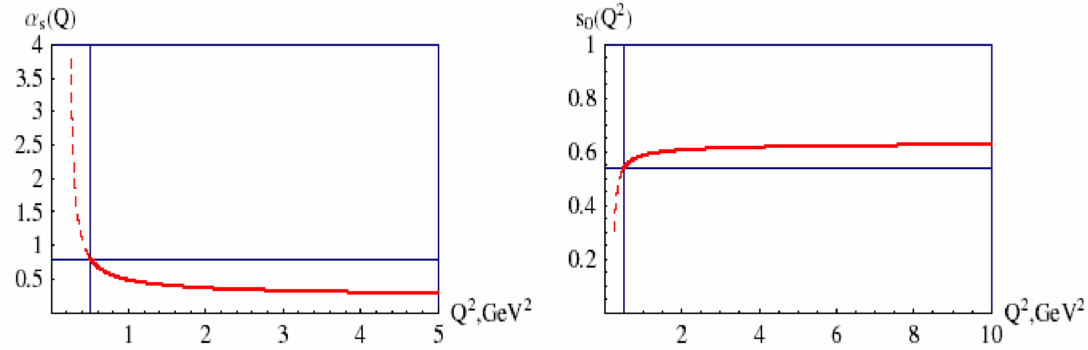
(ii) The correct pQCD large-Q^2 asymptotics of the pion form factor (up to the running of α_s):

$$F_\pi(Q^2) = \frac{8\pi f_\pi^2 \alpha_s}{Q^2} + \frac{96\pi^4 f_\pi^4}{Q^4} + O\left(\alpha_s f_\pi^4/Q^4\right) + O\left(\alpha_s^2\right).$$

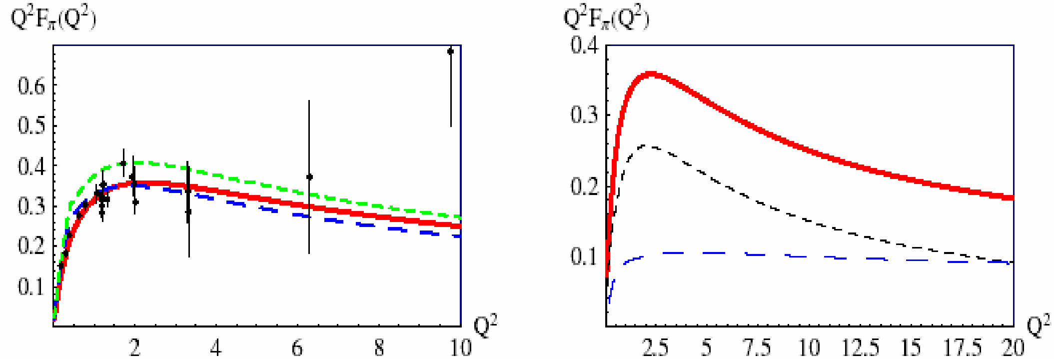


Where this representation for the form factor may be applied?

NUMERICAL RESULTS

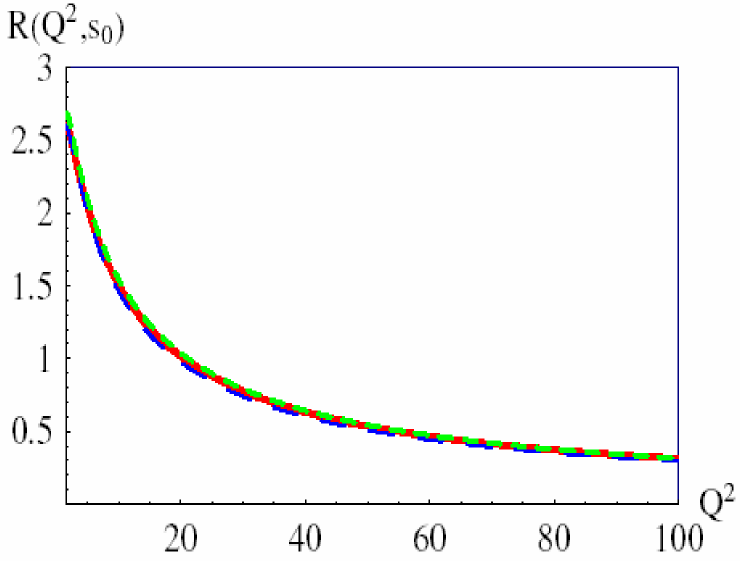


The perturbative $\alpha_s(Q)$ (a) and the corresponding effective threshold $s_0(Q^2)$ (b). Dashed lines show these quantities outside our working region.



Red line: the result for Q^2-dependent effective threshold. (a) Green line: the form factor obtained with constant $s_0 = 0.65$ GeV^2; blue line: $s_0 = 0.6$ GeV^2. (b) Black line: the $O(1)$ contribution, blue line: the $O(\alpha_s)$ contribution.

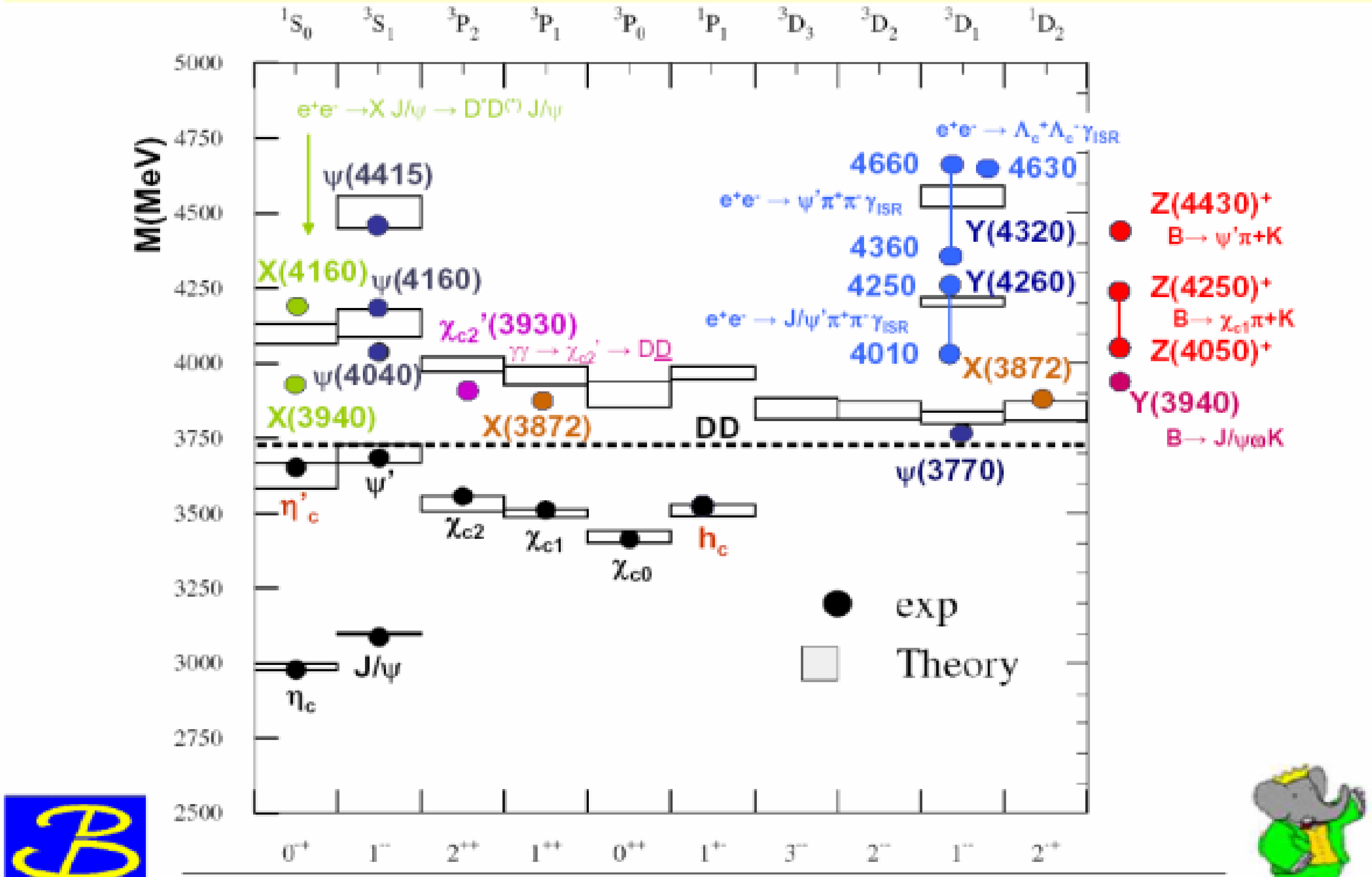
The ratio of the $O(1)/O(\alpha_s)$ contributions to the pion form factor may be predicted to a very good accuracy:



Red line: the result of the calculation with the effective continuum threshold $s_0(Q^2)$**, green line:** $s_0 = 0.65$ **GeV**^{2}**, blue line:** $s_0 = 0.6$ **GeV**^{2}**.**

Obviously, one cannot neglect the $O(1)$ contribution to the form factor at $Q^2 \leq 100$ GeV^2!

Экзотические мезоны



V.Balagura, 3 Sep 2008, Mainz

Review and interpretation of the new heavy states discovered at the B factories

M. Nielsen

Instituto de Física - USP

Quark Confinement and the Hadron Spectrum

Mainz 1-6/September 2008

QCD sum rules calculation for $X(3872)$

tetraquark state (PRD75 (2007) 014005)

$$j^X = [cq]_{S=1}[\bar{c}\bar{q}]_{S=0} + [cq]_{S=0}[\bar{c}\bar{q}]_{S=1}$$

$$m_X = (3.92 \pm 0.13)\ \text{GeV}$$

molecular state (arXiv:0803.1168)

$$j^X = D^{*0}\bar{D}^0 + \bar{D}^{*0}D^0$$

$$m_X = (3.87 \pm 0.07)\ \text{GeV}$$

Better agreement with the molecular model

Exotic states?

charmonium hybrids:
- Lattice (PRL82(99)): $M \sim 4200$ MeV
- flux tube (Barnes et al. (PRD52(95)) $M \sim 4200$ MeV

Maiani et al. (PRD72 (05)) tetraquark $J^{PC} = 1^{--}$ states:

$$Y(4260) = ([cs]_{S=0}[\bar{c}\bar{s}]_{S=0})_{\text{P-wave}}$$

They arrive at $M_Y = 4160$ MeV+ orbital term = (4330 ± 70) MeV

Other Possibilities

$$Y = ([cs]_{S=0}[\bar{c}\bar{s}]_{S=1} + [cs]_{S=1}[\bar{c}\bar{s}]_{S=0}) \text{ or } s \leftrightarrow q$$

molecule
- $D_s^*(2110)\bar{D}_{s0}(2317)$ ($m_{thres} \sim 4430$ MeV)
- $D^*(2007)\bar{D}_0(2310)$ ($m_{thres} \sim 4320$ MeV)
- $D(1865)\bar{D}_1(2420)$ ($m_{thres} \sim 4285$ MeV)

QCD sum rules calculation for $Y(J^{PC} = 1^{--})$

tetraquark state (arXiv:0804.4817)

$$j^Y = [cs]_{S=1}[\bar{c}\bar{s}]_{S=0} + [cs]_{S=0}[\bar{c}\bar{s}]_{S=1}$$

$m_Y = (4.65 \pm 0.10)$ GeV in good agreement with $Y(4660)$

molecular state (arXiv:0804.4817)

$$j^Y = D_0\bar{D}^* + \bar{D}_0 D^*$$

$m_Y = (4.27 \pm 0.10)$ GeV in good agreement with $Y(4260)$

other states:

- $D_s^*\bar{D}_{s0} \Rightarrow m = (4.42 \pm 0.10)$ GeV
- $D\bar{D}_1 \Rightarrow m = (4.12 \pm 0.09)$ GeV
- $[cq]_{S=0}[\bar{c}\bar{q}]_{S=1} \Rightarrow m = (4.49 \pm 0.11)$ GeV

QCD sum rules calculation for $Z^+(4430)$

tetraquark states with $J^P = 0^-,\ 1^-$ (arXiv:0807.3275)

$$j_Z(1^-) = [cu]_{S=1}[\bar{c}\bar{d}]_{S=0} + [cu]_{S=0}[\bar{c}\bar{d}]_{S=1}$$

$$m_Z = (4.84 \pm 0.14)\ \text{GeV}$$

$$j_Z(0^-) = [cu]_{S=0}[\bar{c}\bar{d}]_{S=0}$$

$$m_Z = (4.52 \pm 0.09)\ \text{GeV}$$

molecular state with $J^P = 0^-$ (PLB661(2008)28)

$$j_Z = D_1^0 D^{*+} + D_1^+ D^{*0}$$

$m_Z = (4.40 \pm 0.10)$ GeV in good agreement with $Z^+(4430)$

Better agreement with the molecular model

Other Multiquark states

$X(3872)$, $Y(4260)$, $Y(4660)$, $Z^+(4430)$, $Z_2^+(4250)$ molecules $\Rightarrow$
many other molecules should exist!

$$\mathrm{B}^+ \to \pi^+(\mathrm{J}/\psi\pi^-\mathrm{K}^+) \begin{cases} \text{similar to } B^+ \to K^+(J/\psi\pi^+\pi^-) \\ (J/\psi\pi^-K^+) \Rightarrow (D_s\bar{D}^*) \text{ molecule} \\ J^P = 1^+ \end{cases}$$

QCD sum rule study $D_s\bar{D}^*$ molecule (arXiv:0803.1168)

$$m_{D_s D^*} = (3.97 \pm 0.08)\ \text{MeV}$$

~ 100 MeV bigger than $X(3872)$ mass
very close to the $D_s\bar{D}^*$ threshold: ~ 3980 MeV