FPCP 2003: Theory Summary

Patricia Ball

IPPP, Durham

University of Durham

Excellent talks on

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  - CPV and Cosmology: Branco

Time is short – restrict report to

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New Physics

G. Hiller: New Phys. & Flavour Viol.

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An excursion into the realm of free-roaming imagination. . .

- NP (with extended scalar sector) often induces a plethora of new sources of flavour violation
- models can be classified acc. to the amount of FV:
  - minimal flavour violation (MFV): the same FV as in the SM (Yukawa couplings → quark mixing via CKM matrix)
  - non-MFV: new sources of FV

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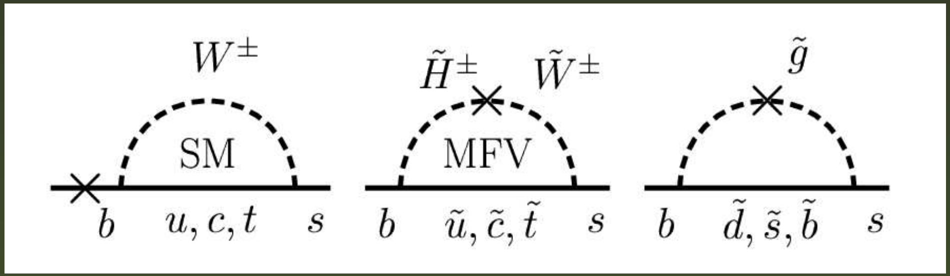

- Ex.: $b \longrightarrow s\gamma$
  - in MFV (e.g. MSSM with flavour-blind SUSY breaking): all diagrams with CKM factors $\sim V_{tb}V_{ts}^*$
  - in non-MFV (e.g. MSSM with flavour-dep. soft SUSY breaking terms): gluino-loops with non-flavour diagonal squark-propagators: no CKM factors, α_s enhanced

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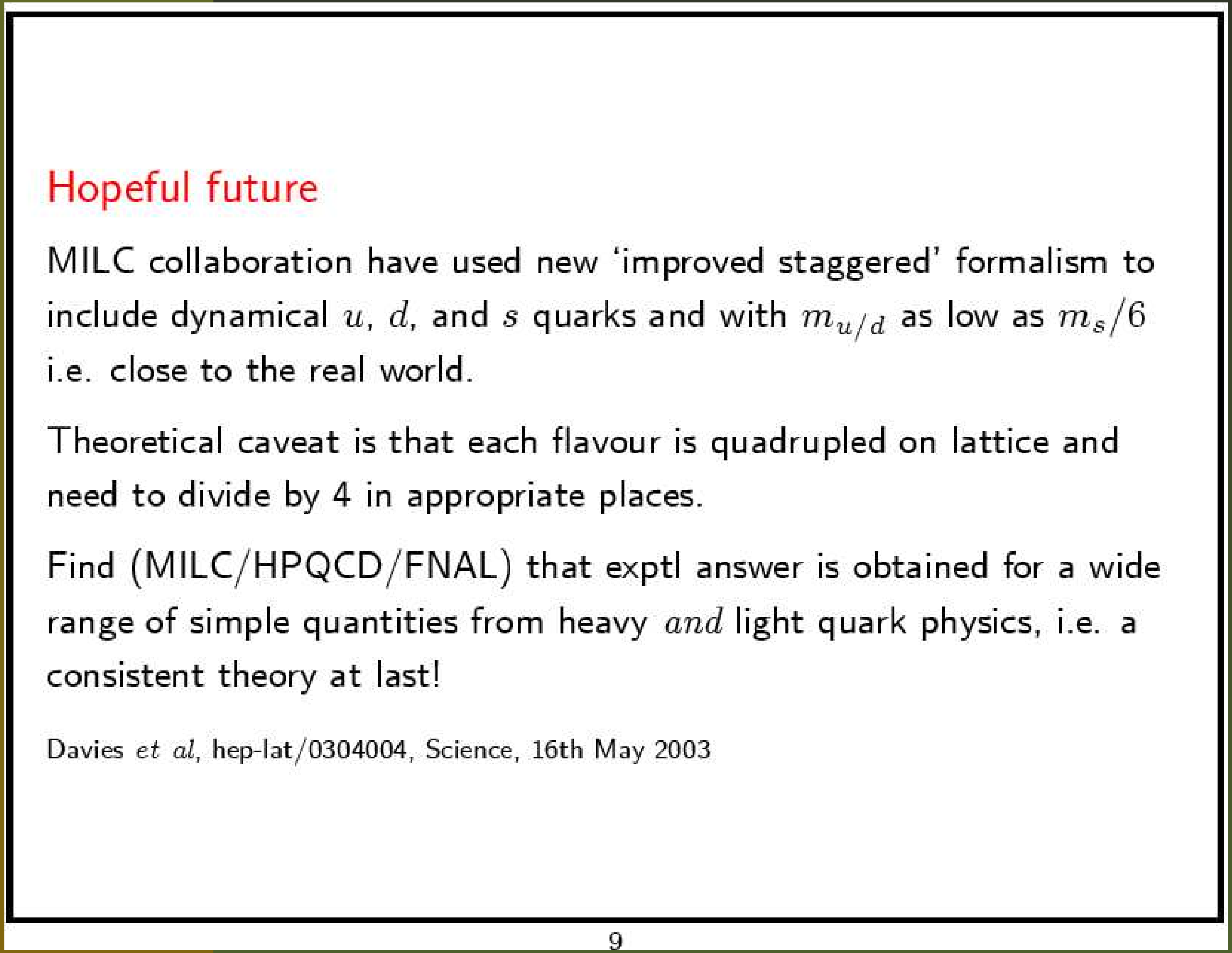
- non-MFV can induce patterns of BRs and CP-violation which completely differ from the SM: large B_s mixing phase, non-CKM phase in $b \longrightarrow s\bar{s}s$ etc.
- bottom-up approach for SUSY model-builders: constrain squark-mass matrix from observed flavour-changing processes, distinguish between MFV and non-MFV SUSY-breaking scenarios: complementary to direct searches at the LHC

Lattice

C. Davies: Breakthrough in LQCD

Generic problem of lattice calculations:
lights quarks at physical masses very expensive

C. Davies: Breakthrough in LQCD



Hopeful future

MILC collaboration have used new ‘improved staggered’ formalism to include dynamical u, d, and s quarks and with $m_{u/d}$ as low as $m_s/6$ i.e. close to the real world.

Theoretical caveat is that each flavour is quadrupled on lattice and need to divide by 4 in appropriate places.

Find (MILC/HPQCD/FNAL) that exptl answer is obtained for a wide range of simple quantities from heavy *and* light quark physics, i.e. a consistent theory at last!

Davies *et al*, hep-lat/0304004, Science, 16th May 2003

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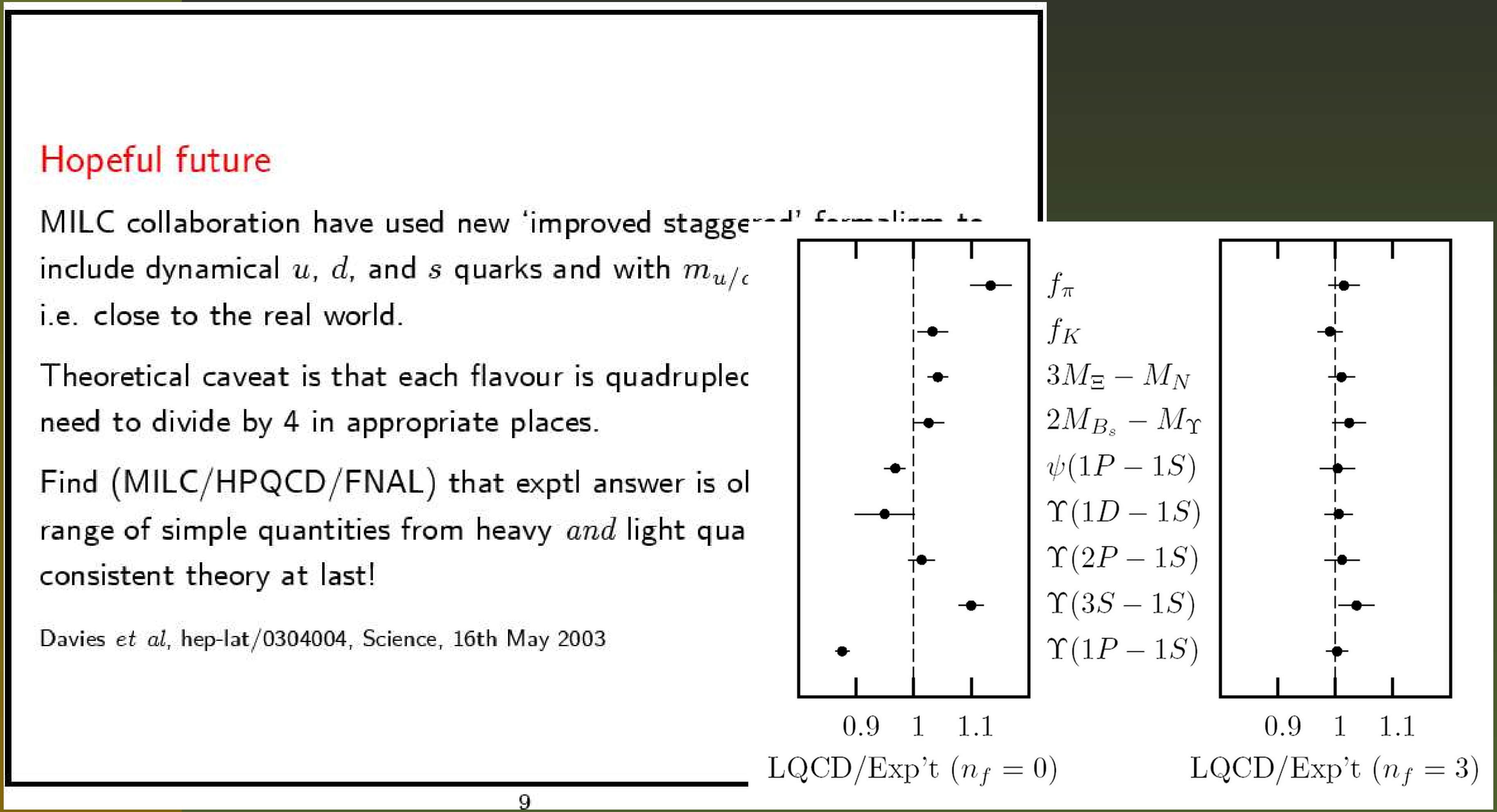

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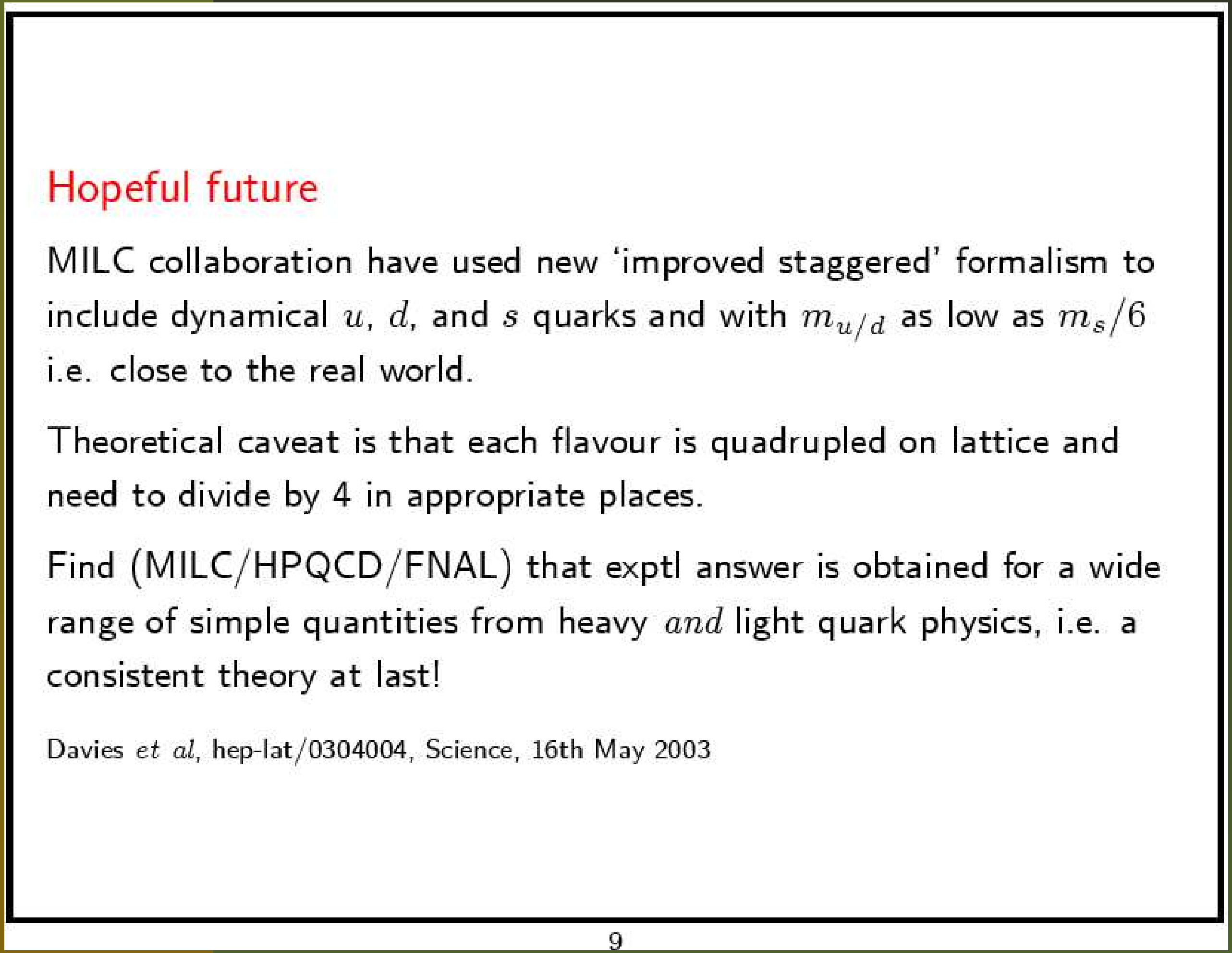

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Caveat may be problematic: correct by taking 4th root of fermion determinant: sign???

D. Becirevic: Heavy Meson FFs

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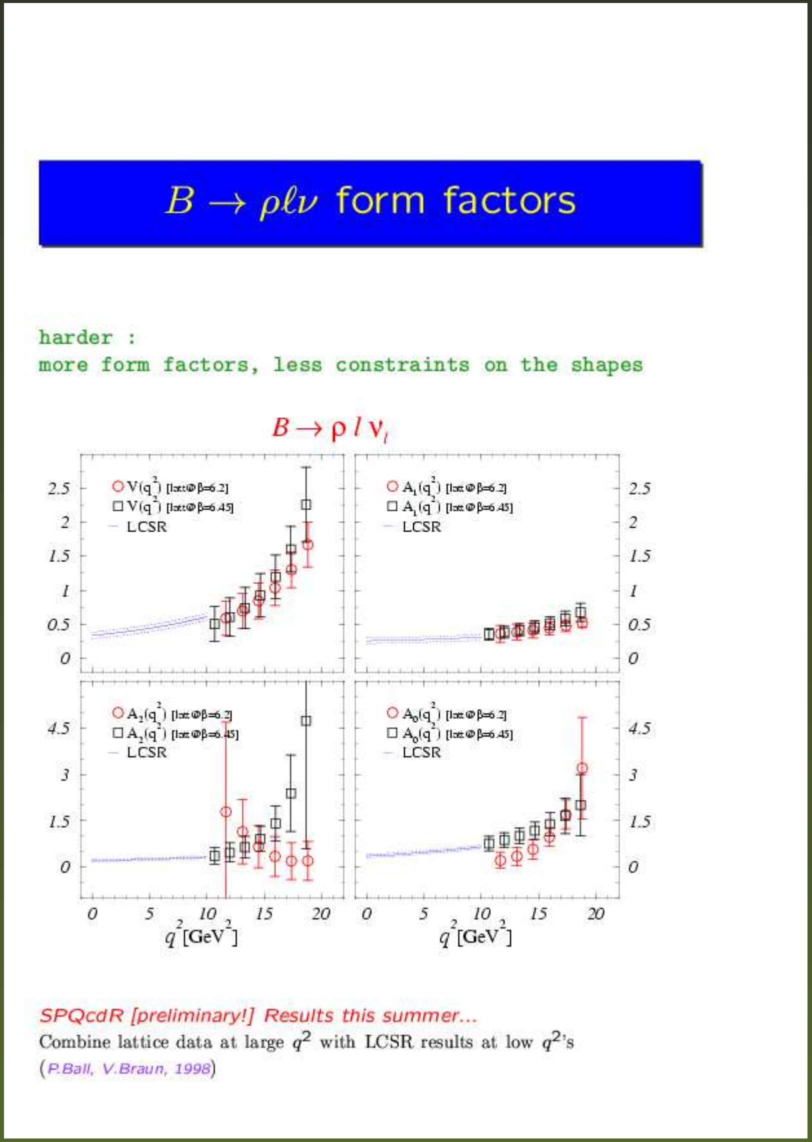


$B \to \rho \ell \nu$ form factors

harder :
more form factors, less constraints on the shapes

SPQcdR [preliminary!] Results this summer…

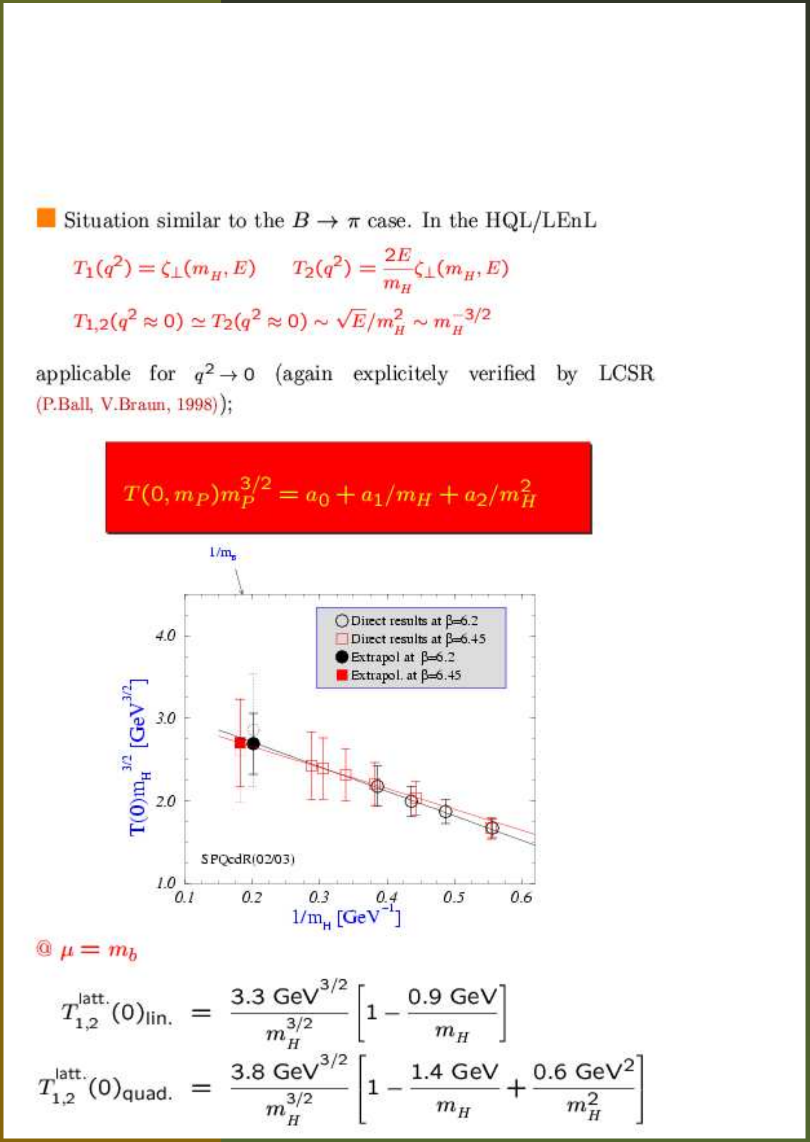
Combine lattice data at large q^2 with LCSR results at low q^2's

(*P.Ball, V.Braun, 1998*)

D. Becirevic: Heavy Meson FFs

Alternative:
fix momentum transfer q^2 and extrapolate in m_b

D. Becirevic: Heavy Meson FFs



- Situation similar to the $B \to \pi$ case. In the HQL/LEnL

$$T_1(q^2) = \zeta_\perp(m_H, E) \qquad T_2(q^2) = \frac{2E}{m_H}\zeta_\perp(m_H, E)$$

$$T_{1,2}(q^2 \approx 0) \simeq T_2(q^2 \approx 0) \sim \sqrt{E}/m_H^2 \sim m_H^{-3/2}$$

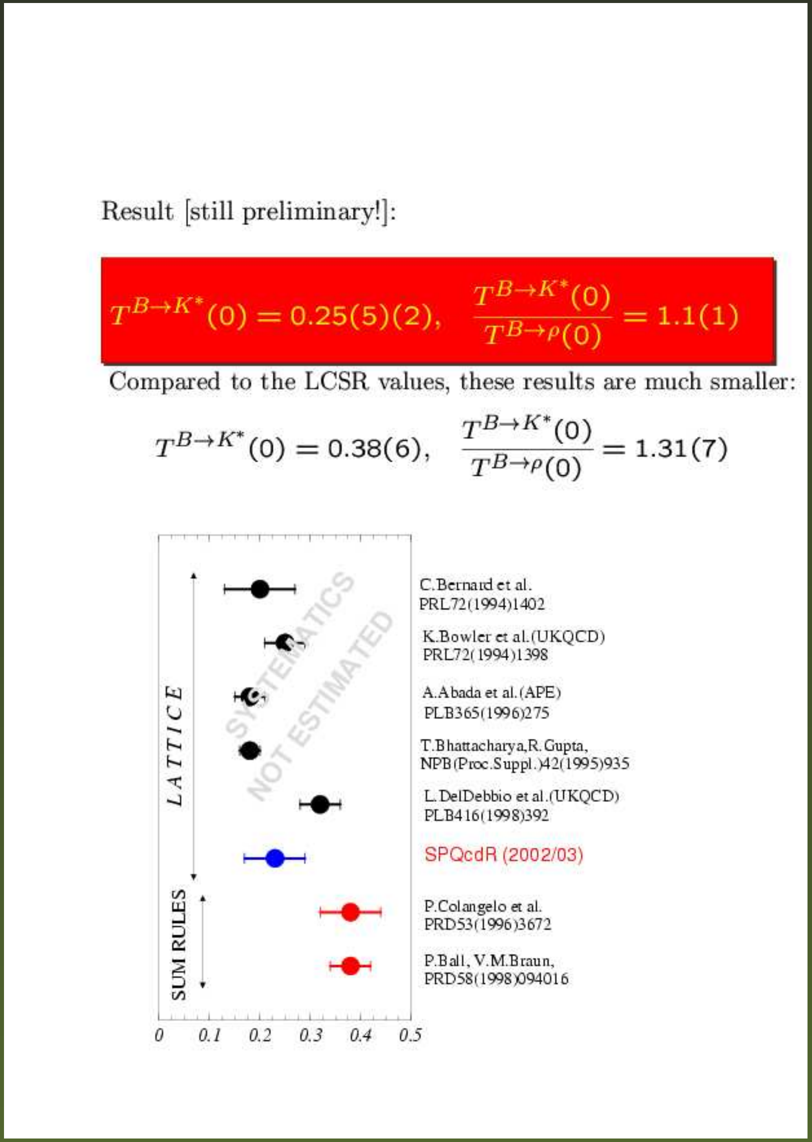
applicable for $q^2 \to 0$ (again explicitely verified by LCSR (P.Ball, V.Braun, 1998));

$$\boxed{T(0, m_P)m_P^{3/2} = a_0 + a_1/m_H + a_2/m_H^2}$$

@ $\mu = m_b$

$$T_{1,2}^{\text{latt.}}(0)_{\text{lin.}} = \frac{3.3\ \text{GeV}^{3/2}}{m_H^{3/2}}\left[1 - \frac{0.9\ \text{GeV}}{m_H}\right]$$

$$T_{1,2}^{\text{latt.}}(0)_{\text{quad.}} = \frac{3.8\ \text{GeV}^{3/2}}{m_H^{3/2}}\left[1 - \frac{1.4\ \text{GeV}}{m_H} + \frac{0.6\ \text{GeV}^2}{m_H^2}\right]$$



Result [still preliminary!]:

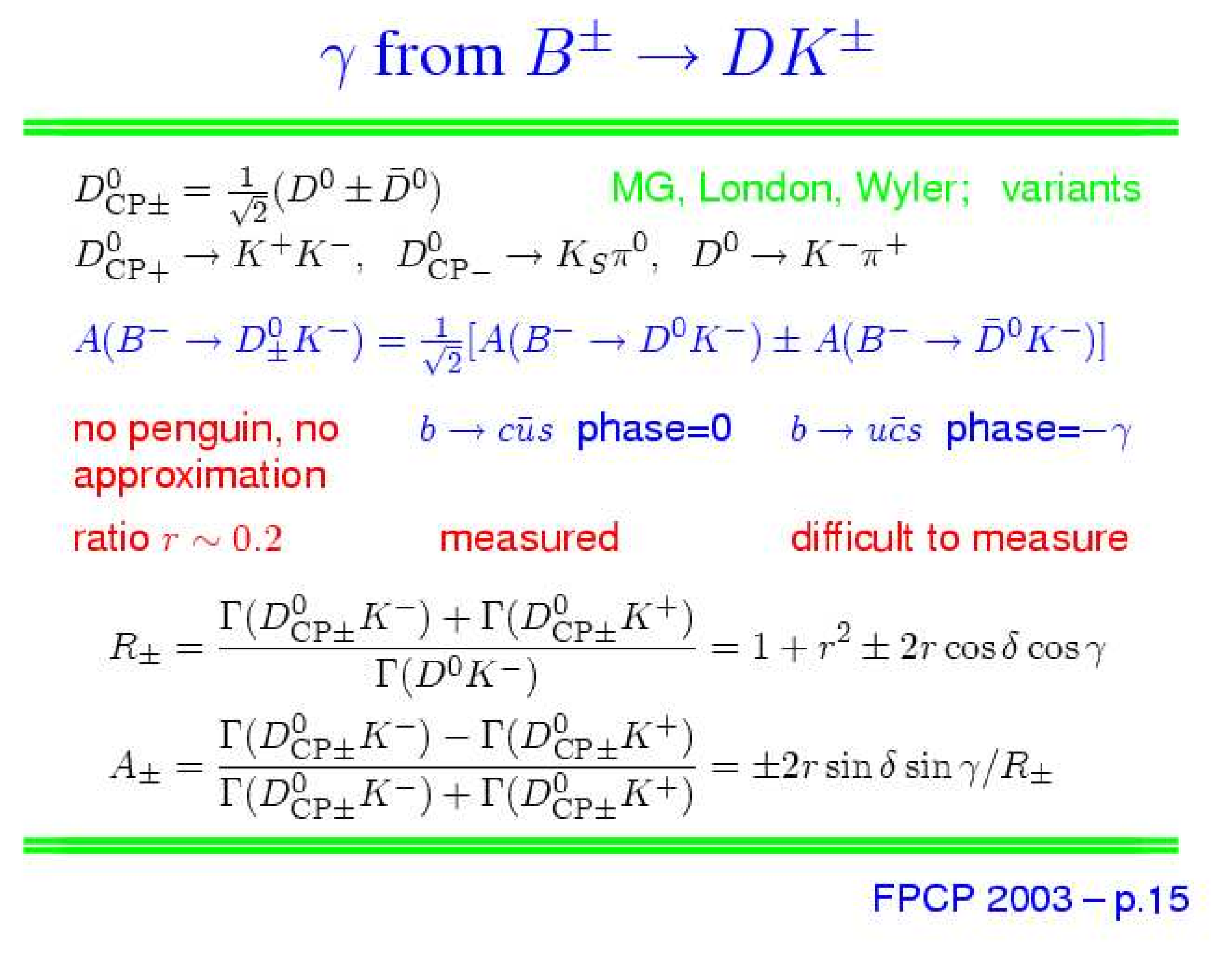
$$\boxed{T^{B\to K^*}(0) = 0.25(5)(2), \quad \frac{T^{B\to K^*}(0)}{T^{B\to\rho}(0)} = 1.1(1)}$$

Compared to the LCSR values, these results are much smaller:

$$T^{B\to K^*}(0) = 0.38(6), \quad \frac{T^{B\to K^*}(0)}{T^{B\to\rho}(0)} = 1.31(7)$$

Phenomenological Methods

M. Gronau: CPV beyond $B \to J/\psi K_S$



γ from $B^\pm \to DK^\pm$

$D^0_{\rm CP\pm} = \frac{1}{\sqrt{2}}(D^0 \pm \bar{D}^0)$ MG, London, Wyler; variants

$D^0_{\rm CP+} \to K^+K^-, \quad D^0_{\rm CP-} \to K_S\pi^0, \quad D^0 \to K^-\pi^+$

$$A(B^- \to D^0_\pm K^-) = \frac{1}{\sqrt{2}}[A(B^- \to D^0K^-) \pm A(B^- \to \bar{D}^0K^-)]$$

no penguin, no approximation	$b \to c\bar{u}s$ phase=0	$b \to u\bar{c}s$ phase=$-\gamma$
ratio $r \sim 0.2$	measured	difficult to measure

$$R_\pm = \frac{\Gamma(D^0_{\rm CP\pm}K^-) + \Gamma(D^0_{\rm CP\pm}K^+)}{\Gamma(D^0K^-)} = 1 + r^2 \pm 2r\cos\delta\cos\gamma$$

$$A_\pm = \frac{\Gamma(D^0_{\rm CP\pm}K^-) - \Gamma(D^0_{\rm CP\pm}K^+)}{\Gamma(D^0_{\rm CP\pm}K^-) + \Gamma(D^0_{\rm CP\pm}K^+)} = \pm 2r\sin\delta\sin\gamma/R_\pm$$

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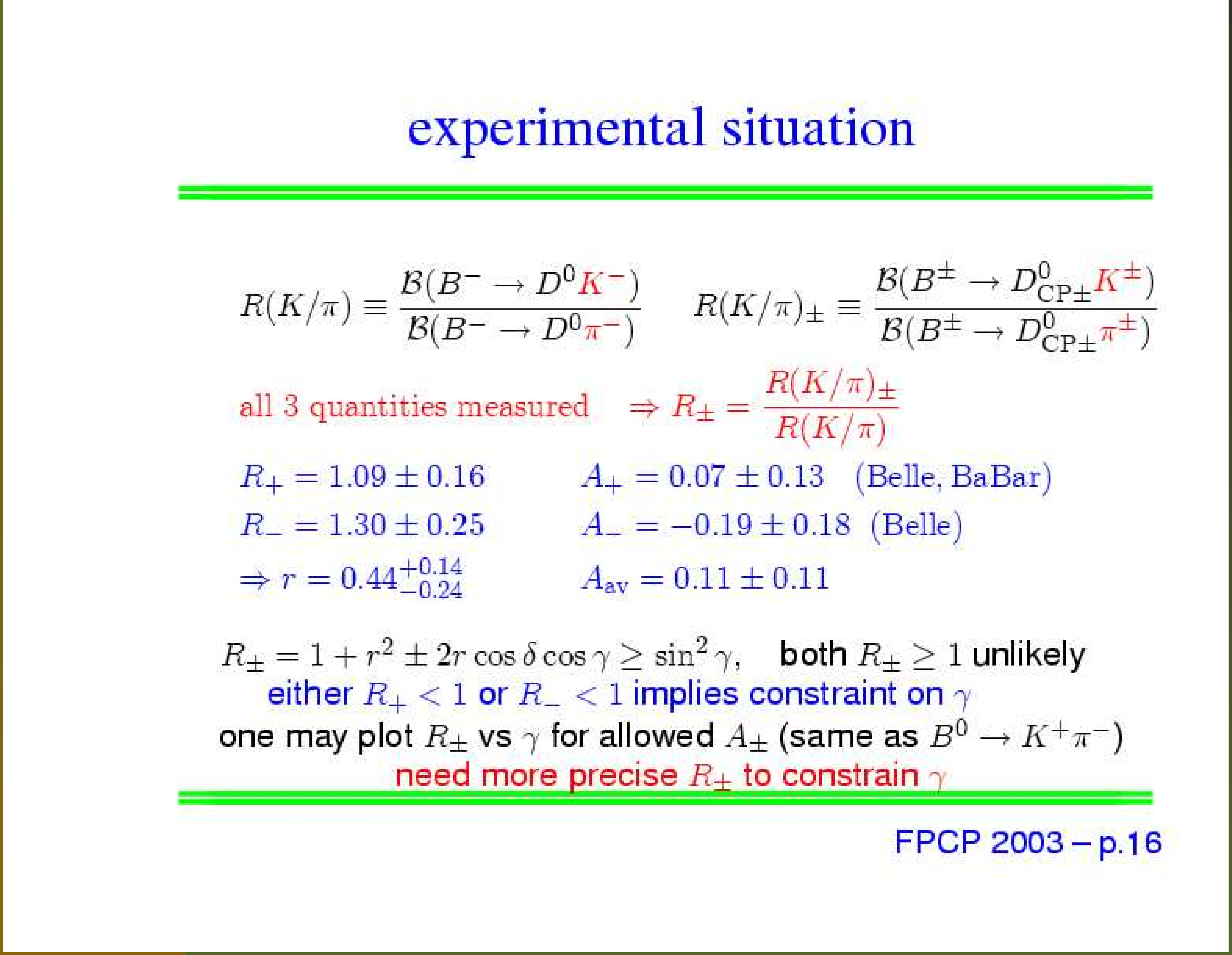

experimental situation

$$R(K/\pi) \equiv \frac{\mathcal{B}(B^- \to D^0 K^-)}{\mathcal{B}(B^- \to D^0 \pi^-)} \qquad R(K/\pi)_\pm \equiv \frac{\mathcal{B}(B^\pm \to D^0_{\mathrm{CP}\pm} K^\pm)}{\mathcal{B}(B^\pm \to D^0_{\mathrm{CP}\pm} \pi^\pm)}$$

all 3 quantities measured $\Rightarrow R_\pm = \dfrac{R(K/\pi)_\pm}{R(K/\pi)}$

$R_+ = 1.09 \pm 0.16$ $\qquad A_+ = 0.07 \pm 0.13$ (Belle, BaBar)

$R_- = 1.30 \pm 0.25$ $\qquad A_- = -0.19 \pm 0.18$ (Belle)

$\Rightarrow r = 0.44^{+0.14}_{-0.24}$ $\qquad A_{\mathrm{av}} = 0.11 \pm 0.11$

$R_\pm = 1 + r^2 \pm 2r\cos\delta\cos\gamma \geq \sin^2\gamma$, both $R_\pm \geq 1$ unlikely

either $R_+ < 1$ or $R_- < 1$ implies constraint on γ

one may plot $R_\pm$ vs γ for allowed $A_\pm$ (same as $B^0 \to K^+\pi^-$)

need more precise $R_\pm$ to constrain γ

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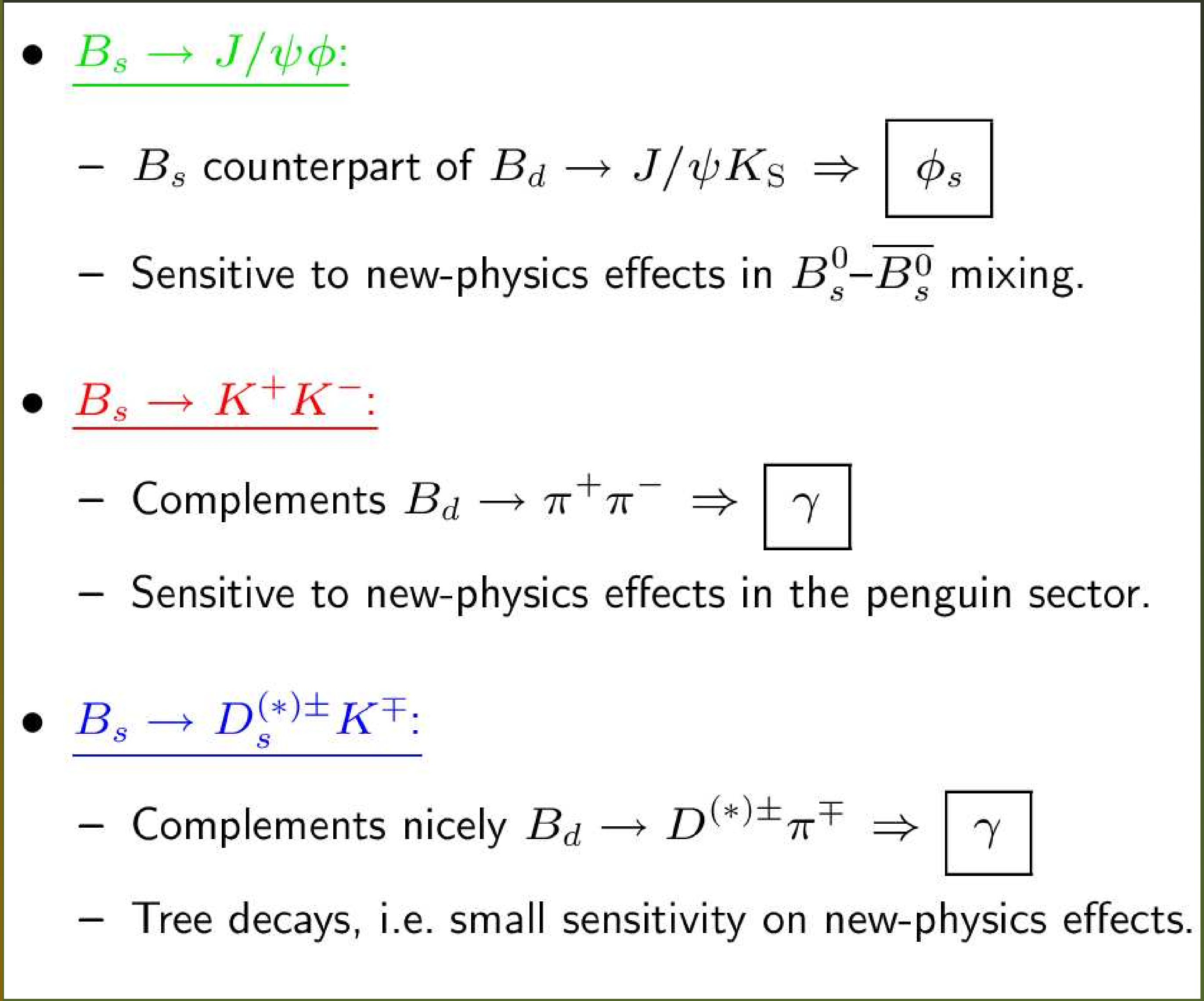
R. Fleischer: Strategies in El Dorado



- $B_s \to J/\psi\phi$:
  - B_s counterpart of $B_d \to J/\psi K_S \Rightarrow \boxed{\phi_s}$
  - Sensitive to new-physics effects in B_s^0–$\overline{B_s^0}$ mixing.
- $B_s \to K^+K^-$:
  - Complements $B_d \to \pi^+\pi^- \Rightarrow \boxed{\gamma}$
  - Sensitive to new-physics effects in the penguin sector.
- $B_s \to D_s^{(*)\pm}K^{\mp}$:
  - Complements nicely $B_d \to D^{(*)\pm}\pi^{\mp} \Rightarrow \boxed{\gamma}$
  - Tree decays, i.e. small sensitivity on new-physics effects.

D. London: 3xProd. & CPV in $B \to VV$

- Angular analysis in $B \to V_1 V_2$: measure triple-product correlations $(\vec{\epsilon_1}^T \times \vec{\epsilon_2}^T) \cdot \vec{p}$

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- CPV signal to be found in $B \to V_1 V_2 + \bar{B} \to \bar{V}_1 \bar{V}_2$:

$$\mathcal{A}_T \propto \sin\phi \cos\delta$$

(i.e. maximal in naive and BBNS factorisation)

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- In the SM, all triple products involving light mesons either vanish or are very small
→ good place to watch out for NP

Factorisation and All That

A Longstanding Problem...

$$A(B^0 \to \pi^+\pi^-) = |T| \exp(i\gamma) + |P| \exp(i\delta)$$

- want weak phase γ

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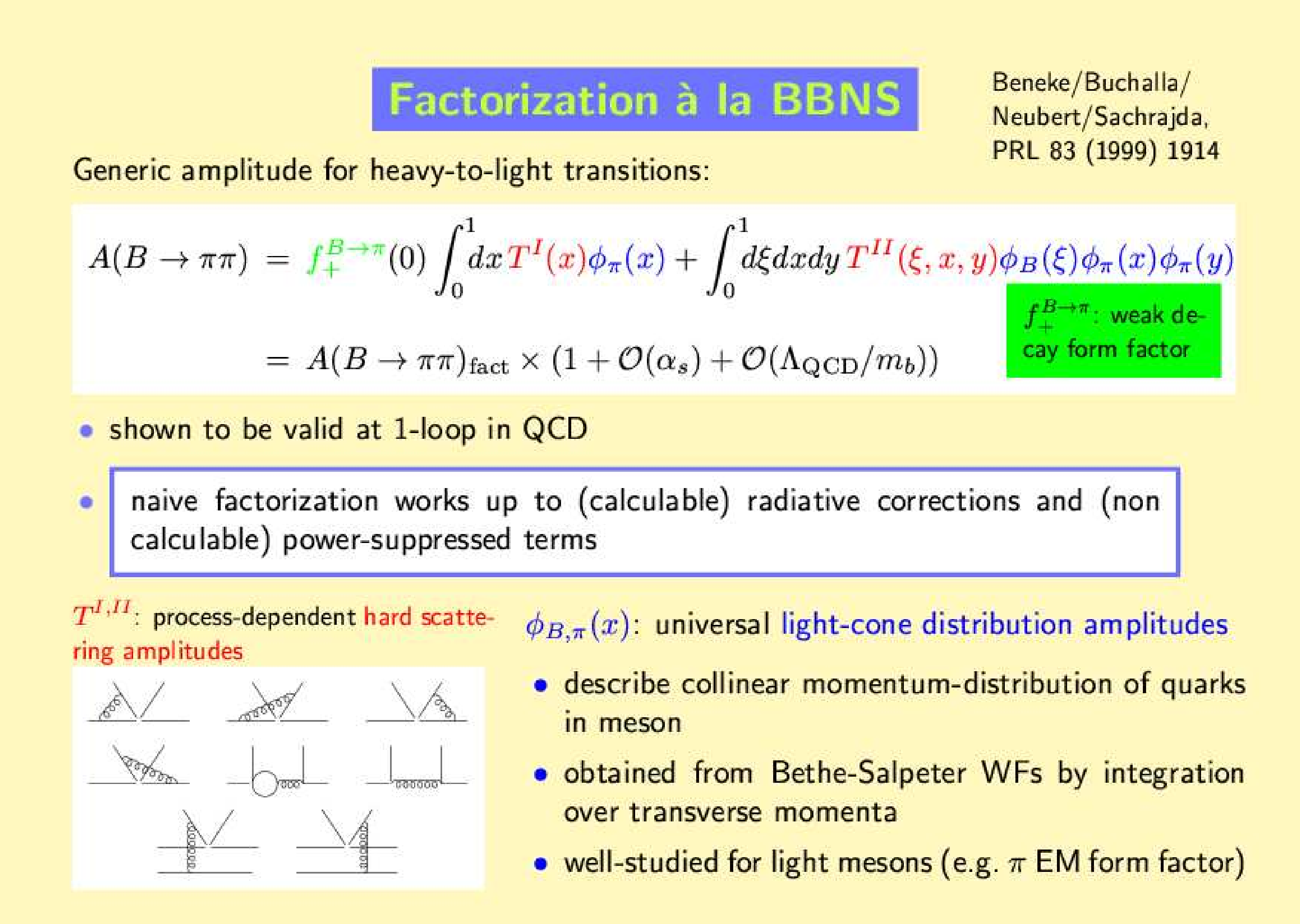
  - calculation from first principles & in a model-independent way
- historically: quark models & naive factorisation
- since 1999: various methods of improved factorisation

Part I of the Story: BBNS



Factorization à la BBNS

Beneke/Buchalla/
Neubert/Sachrajda,
PRL 83 (1999) 1914

Generic amplitude for heavy-to-light transitions:

$$A(B \to \pi\pi) = f_+^{B\to\pi}(0) \int_0^1 dx\, T^I(x)\phi_\pi(x) + \int_0^1 d\xi dx dy\, T^{II}(\xi, x, y)\phi_B(\xi)\phi_\pi(x)\phi_\pi(y)$$

$$= A(B \to \pi\pi)_{\text{fact}} \times (1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\Lambda_{\text{QCD}}/m_b))$$

$f_+^{B\to\pi}$: weak decay form factor

- shown to be valid at 1-loop in QCD
- naive factorization works up to (calculable) radiative corrections and (non calculable) power-suppressed terms

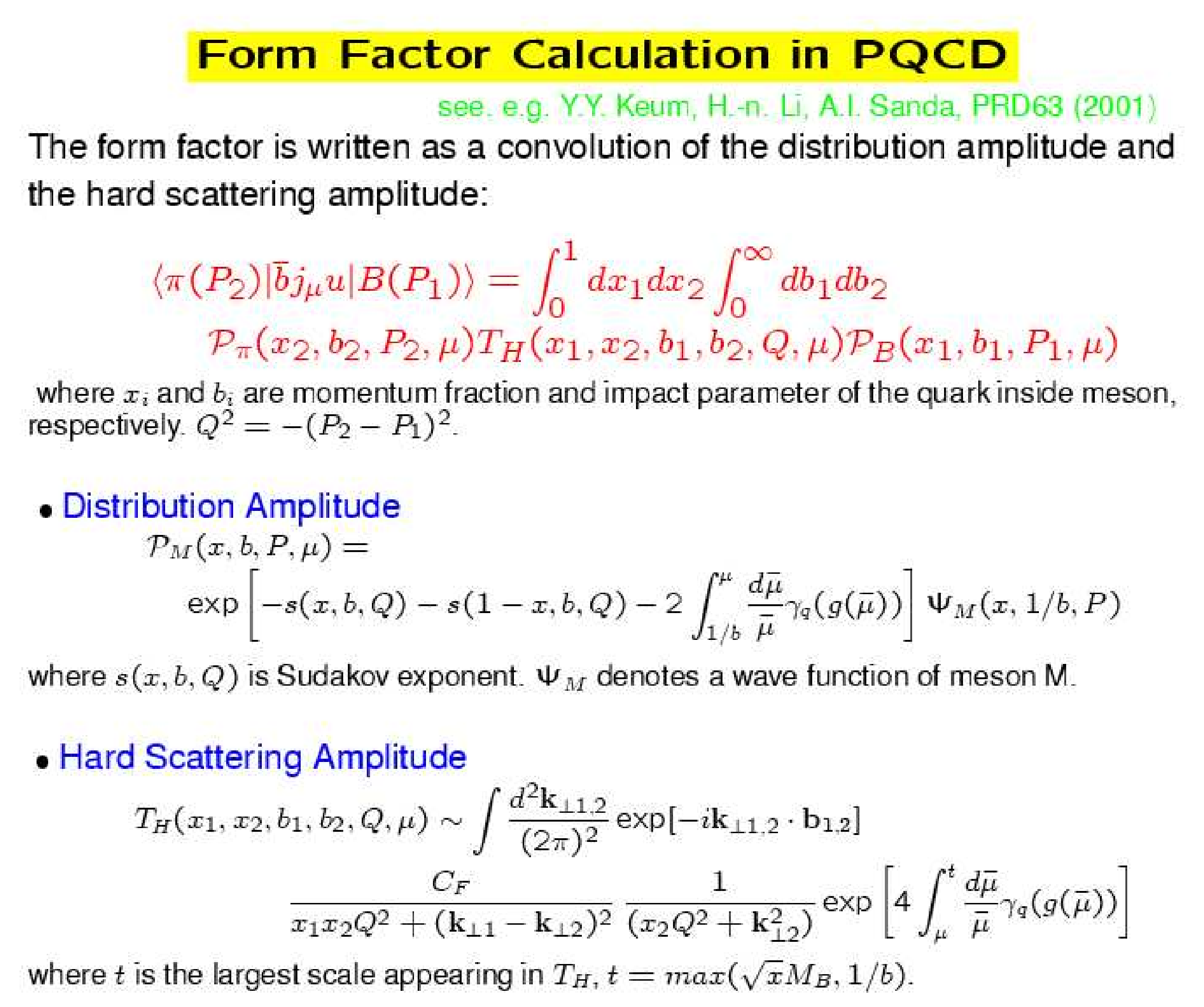
$T^{I,II}$: process-dependent hard scattering amplitudes

$\phi_{B,\pi}(x)$: universal light-cone distribution amplitudes

- describe collinear momentum-distribution of quarks in meson
- obtained from Bethe-Salpeter WFs by integration over transverse momenta
- well-studied for light mesons (e.g. π EM form factor)

(slide courtesy of P. Ball)

Part II: E. Kou: pQCD Factorisation



Form Factor Calculation in PQCD

see. e.g. Y.Y. Keum, H.-n. Li, A.I. Sanda, PRD63 (2001)

The form factor is written as a convolution of the distribution amplitude and the hard scattering amplitude:

$$\langle \pi(P_2)|\bar{b}j_\mu u|B(P_1)\rangle = \int_0^1 dx_1 dx_2 \int_0^\infty db_1 db_2$$
$$\mathcal{P}_\pi(x_2, b_2, P_2, \mu) T_H(x_1, x_2, b_1, b_2, Q, \mu) \mathcal{P}_B(x_1, b_1, P_1, \mu)$$

where x_i and b_i are momentum fraction and impact parameter of the quark inside meson, respectively. $Q^2 = -(P_2 - P_1)^2$.

- **Distribution Amplitude**

$$\mathcal{P}_M(x, b, P, \mu) =$$
$$\exp\left[-s(x, b, Q) - s(1-x, b, Q) - 2\int_{1/b}^{\mu} \frac{d\bar{\mu}}{\bar{\mu}} \gamma_q(g(\bar{\mu}))\right] \Psi_M(x, 1/b, P)$$

where $s(x, b, Q)$ is Sudakov exponent. Ψ_M denotes a wave function of meson M.

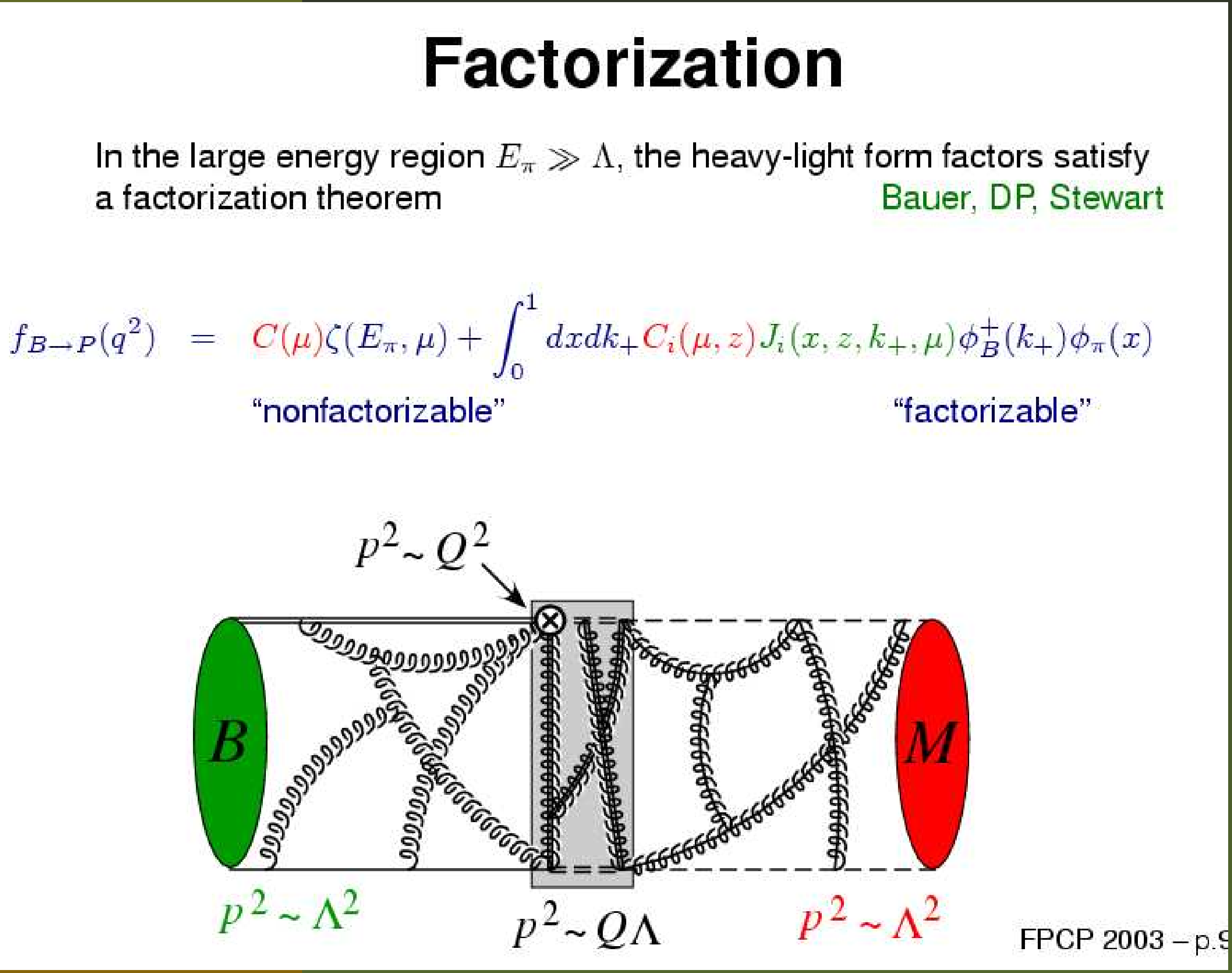
- **Hard Scattering Amplitude**

$$T_H(x_1, x_2, b_1, b_2, Q, \mu) \sim \int \frac{d^2\mathbf{k}_{\perp 1,2}}{(2\pi)^2} \exp[-i\mathbf{k}_{\perp 1,2} \cdot \mathbf{b}_{1,2}]$$
$$\frac{C_F}{x_1 x_2 Q^2 + (\mathbf{k}_{\perp 1} - \mathbf{k}_{\perp 2})^2} \frac{1}{(x_2 Q^2 + \mathbf{k}_{\perp 2}^2)} \exp\left[4\int_\mu^t \frac{d\bar{\mu}}{\bar{\mu}} \gamma_q(g(\bar{\mu}))\right]$$

where t is the largest scale appearing in T_H, $t = max(\sqrt{x} M_B, 1/b)$.

and similarly for nonlep. decays

Part III: S. Fleming/D. Pirjol: SCET



Factorization

In the large energy region $E_\pi \gg \Lambda$, the heavy-light form factors satisfy a factorization theorem

Bauer, DP, Stewart

$$f_{B\to P}(q^2) \quad = \quad C(\mu)\zeta(E_\pi,\mu) + \int_0^1 dx dk_+ C_i(\mu,z) J_i(x,z,k_+,\mu)\phi_B^+(k_+)\phi_\pi(x)$$

"nonfactorizable"

"factorizable"

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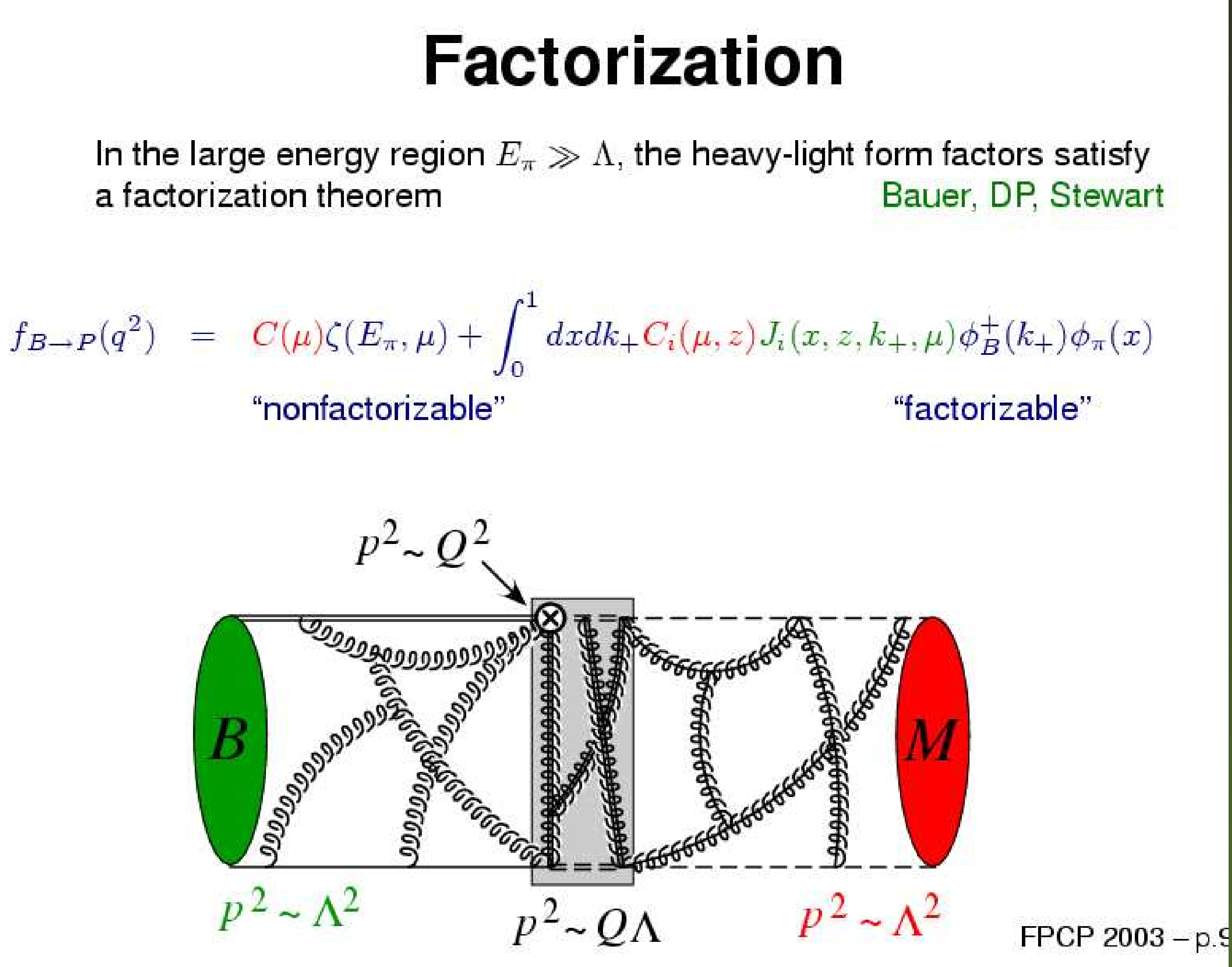

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"nonfactorizable" "factorizable"

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- two large scales m_b & $\sqrt{m_b\Lambda_{\rm QCD}}$, separated by eff. field theory techniques
- large logs resummed by RG methods
- systematic expansion in $1/m_b$ of Lagrangian and states (not yet done)

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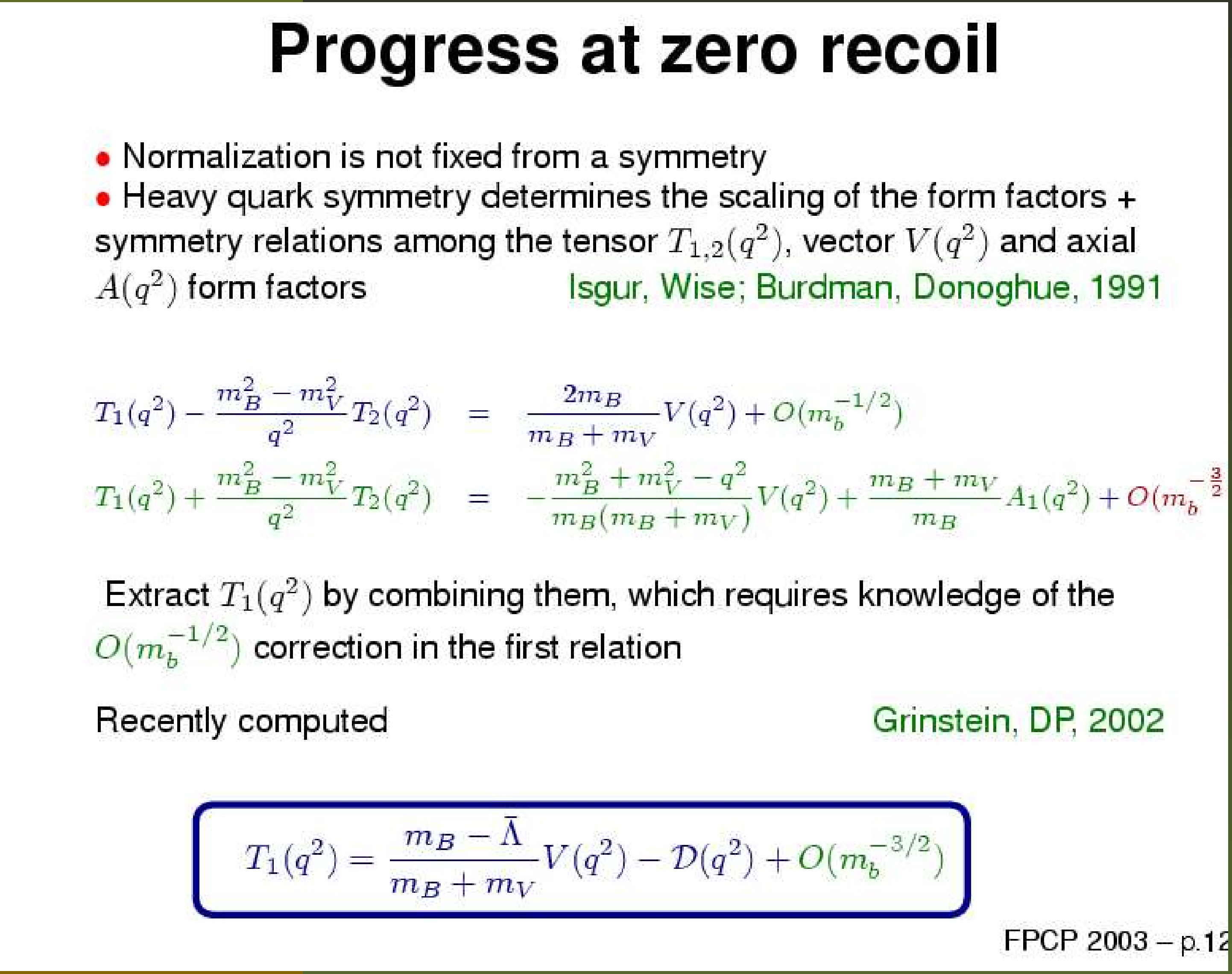

Progress at zero recoil

- Normalization is not fixed from a symmetry
- Heavy quark symmetry determines the scaling of the form factors + symmetry relations among the tensor $T_{1,2}(q^2)$, vector $V(q^2)$ and axial $A(q^2)$ form factors Isgur, Wise; Burdman, Donoghue, 1991

$$T_1(q^2) - \frac{m_B^2 - m_V^2}{q^2} T_2(q^2) = \frac{2m_B}{m_B + m_V} V(q^2) + O(m_b^{-1/2})$$

$$T_1(q^2) + \frac{m_B^2 - m_V^2}{q^2} T_2(q^2) = -\frac{m_B^2 + m_V^2 - q^2}{m_B(m_B + m_V)} V(q^2) + \frac{m_B + m_V}{m_B} A_1(q^2) + O(m_b^{-\frac{3}{2}}$$

Extract $T_1(q^2)$ by combining them, which requires knowledge of the $O(m_b^{-1/2})$ correction in the first relation

Recently computed Grinstein, DP, 2002

$$\boxed{T_1(q^2) = \frac{m_B - \bar{\Lambda}}{m_B + m_V} V(q^2) - \mathcal{D}(q^2) + O(m_b^{-3/2})}$$

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- two large scales m_b & $\sqrt{m_b \Lambda_{\text{QCD}}}$, separated by eff. field theory techniques
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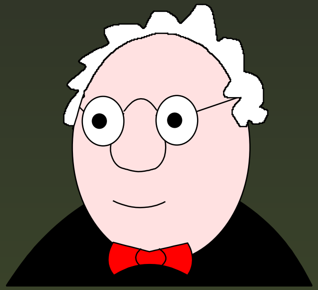
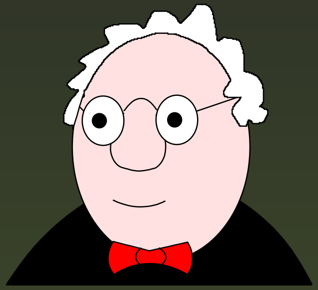
What the Pandit has to Say



A few words of caution…

- use of symmetries (like heavy-quark symmetry) has proven to be very useful in high-energy physics

What the Pandit has to Say



A few words of caution. . .

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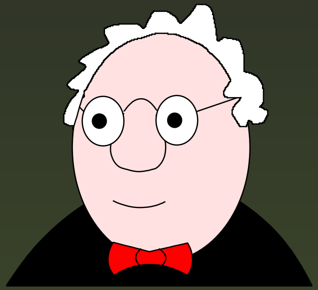

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- BBNS: OK in heavy quark limit – breaks down in $O(1/m_b)$

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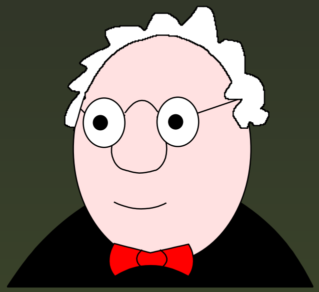

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- pQCD: all nonfactorisable terms suppressed? Systematic expansion in QCD pert. th.? Criticism by Descotes-Genon/Sachrajda (hep-ph/0109260) conc. Sudakov-resummation?

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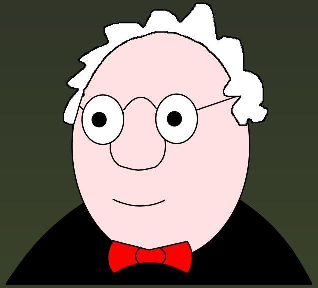

A few words of caution…

- use of symmetries (like heavy-quark symmetry) has proven to be very useful in high-energy physics – if they are not too badly broken ☹
- SCET: good for all-order factorisation proofs – to leading order in $1/m_b$
  useful phenomenological tool? For the moment – no numbers!
  $B \longrightarrow \pi$ FF: beware of economy in nonpert. input: need ζ & ϕ_π & ϕ_B

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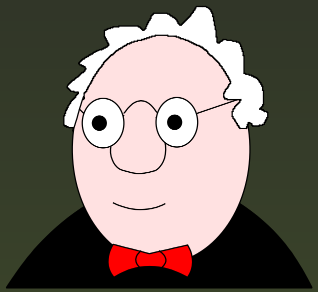

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- use of symmetries (like heavy-quark symmetry) has proven to be very useful in high-energy physics – if they are not too badly broken ☹
- ϕ_B: weird properties under renormalization: evolution with μ causes ϕ_B to diverge!

(Lange/Neubert, hep-ph/0303082)

Only $\int_0^\infty \phi_B(k,\mu)/k$ has meaningful evolution.

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- let it be a mutually fruitful competition!
- my apologies to Alexey, Kolia, Zoltan et al.: beautiful talks, beautiful results: alas, 30min not enough to give proper appreciation to everybody's contribution