Nonperturbative QCD Calculations: *Status and Prospects*

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Amsterdam

An Idiosyncratic Overview

rather than an encyclopedic review

- Focus on hadronic matrix elements from Lattice QCD
- CKM unitarity
- B_s mixing
- Rare B decays
- Beautiful baryons

Lattice QCD

- Nonperturbative regulator of quantum field theories
- Quantifiable and improvable uncertainties
- No time for a pedagogic introduction, but
- Reminder of sources of lattice uncertainties . . .

Lattice QCD

Lattice QCD

in 1 minute

Lattice QCD

in 1 minute

a silent film
by Matthew Wingate

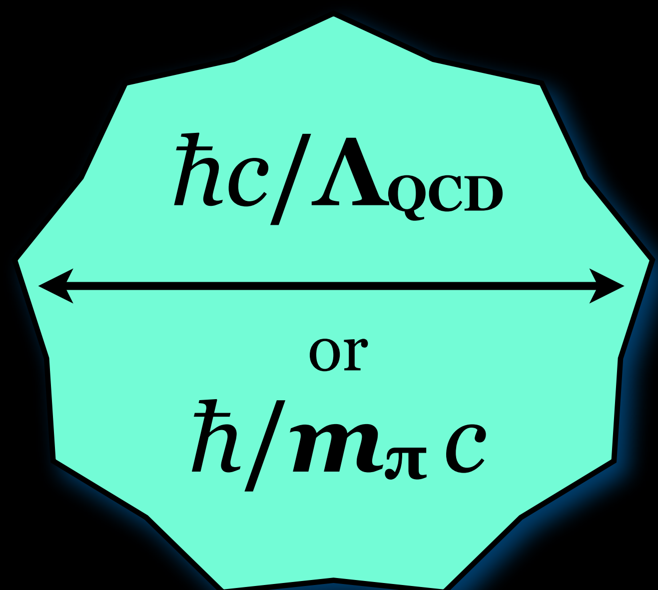
finite box

L^3

finite imaginary time

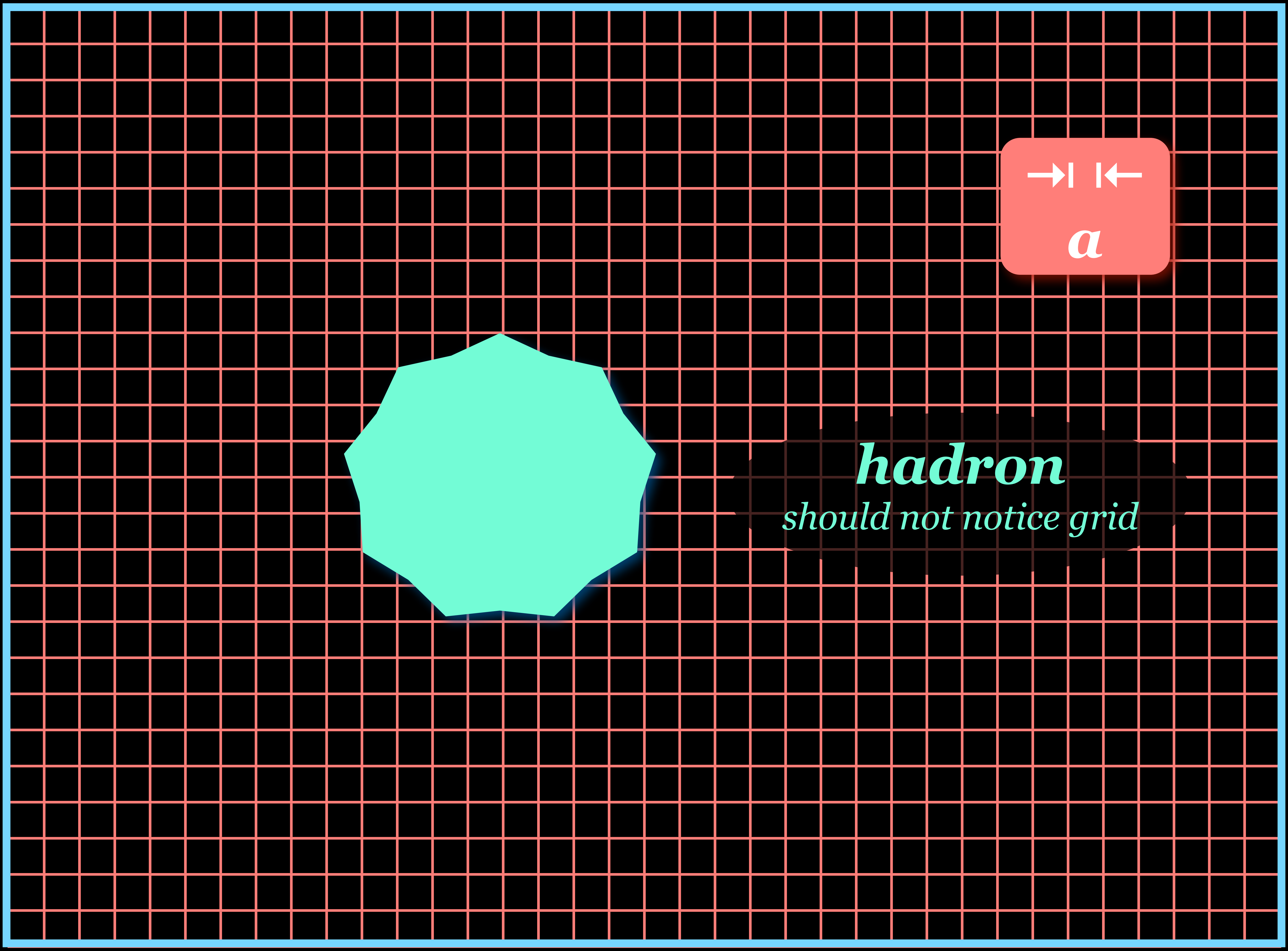
L_τ

$\therefore$ ***evolution operator:*** $\exp(-\hat{H}\tau)$

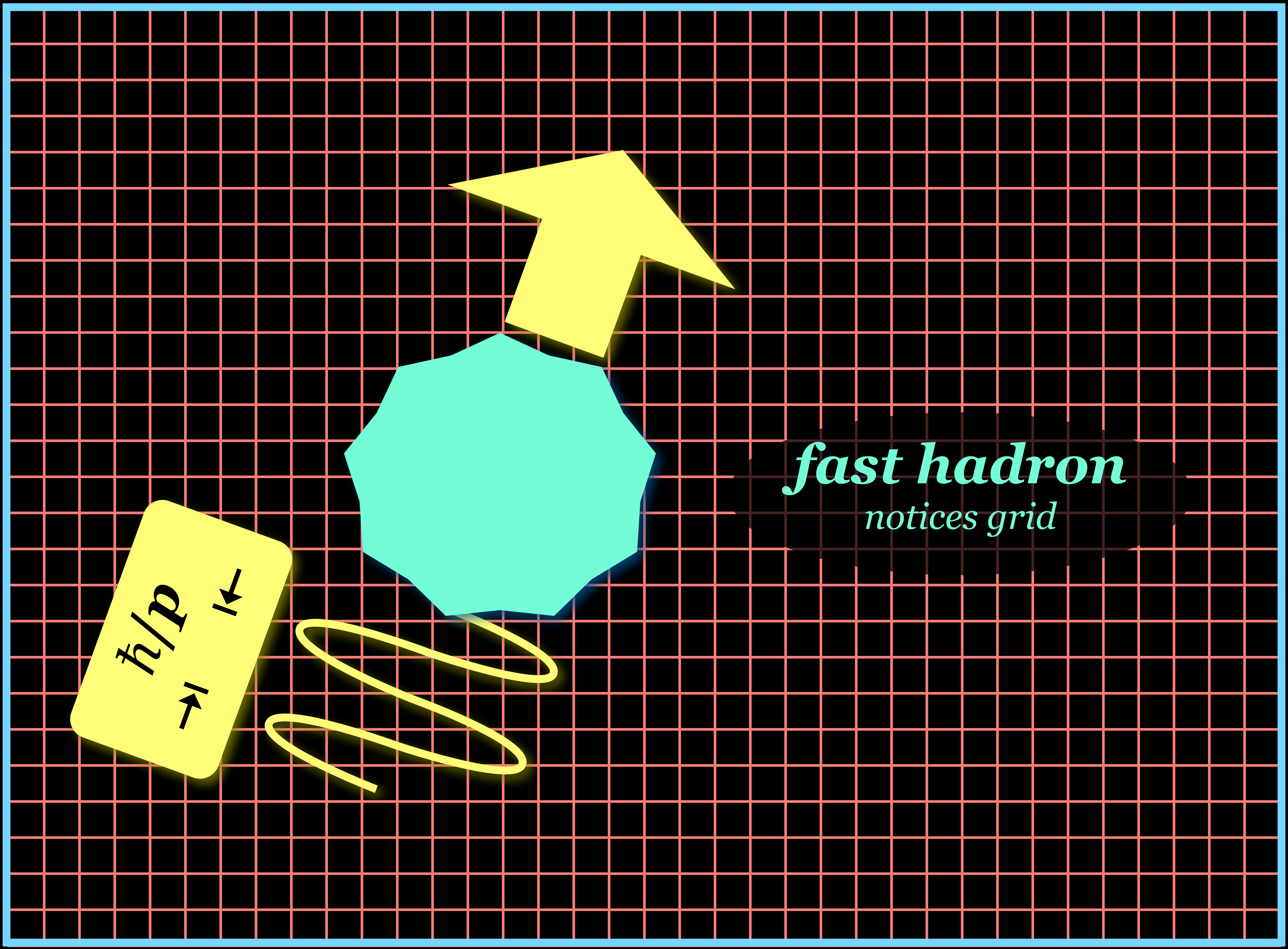


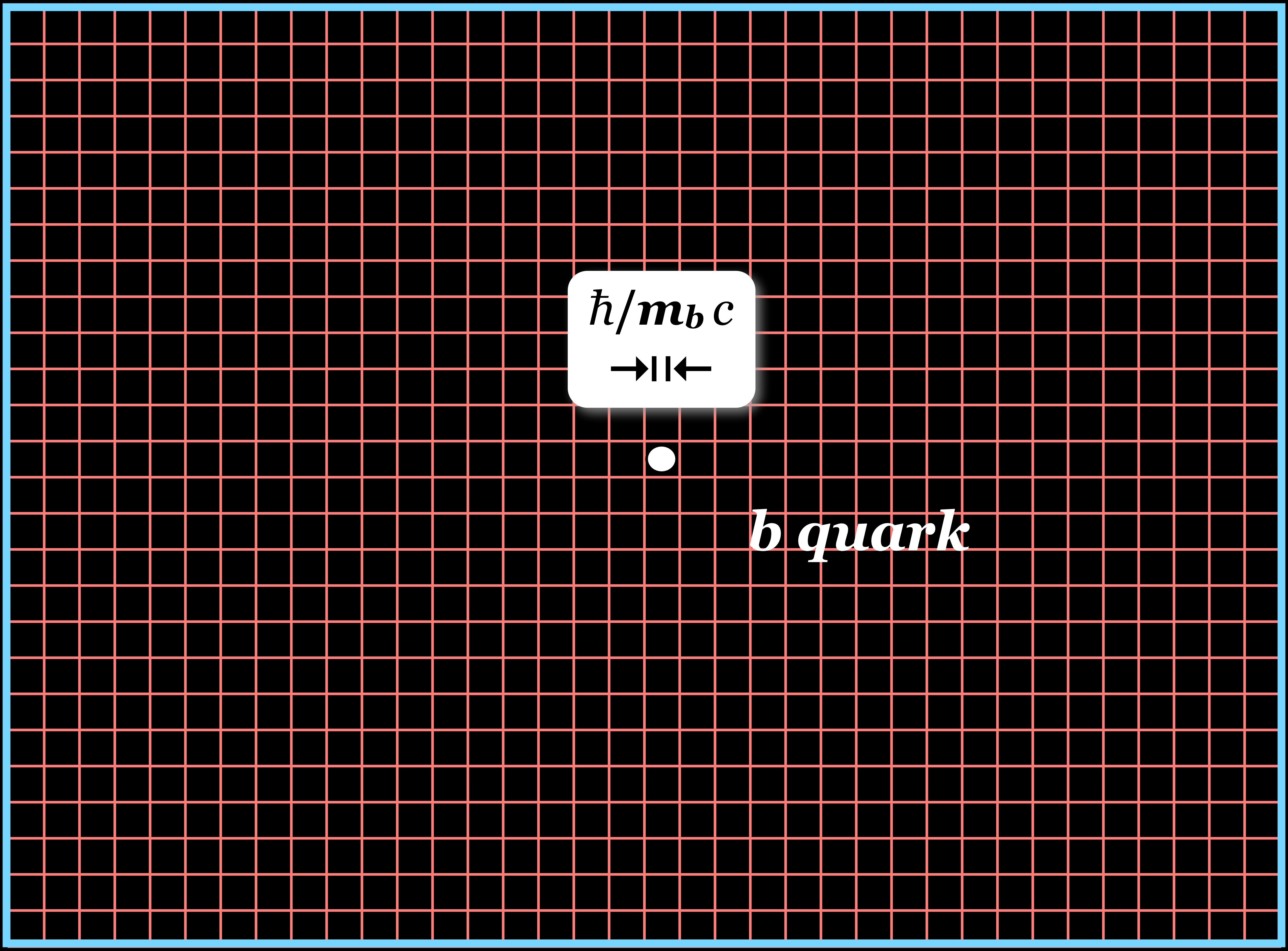
hadron

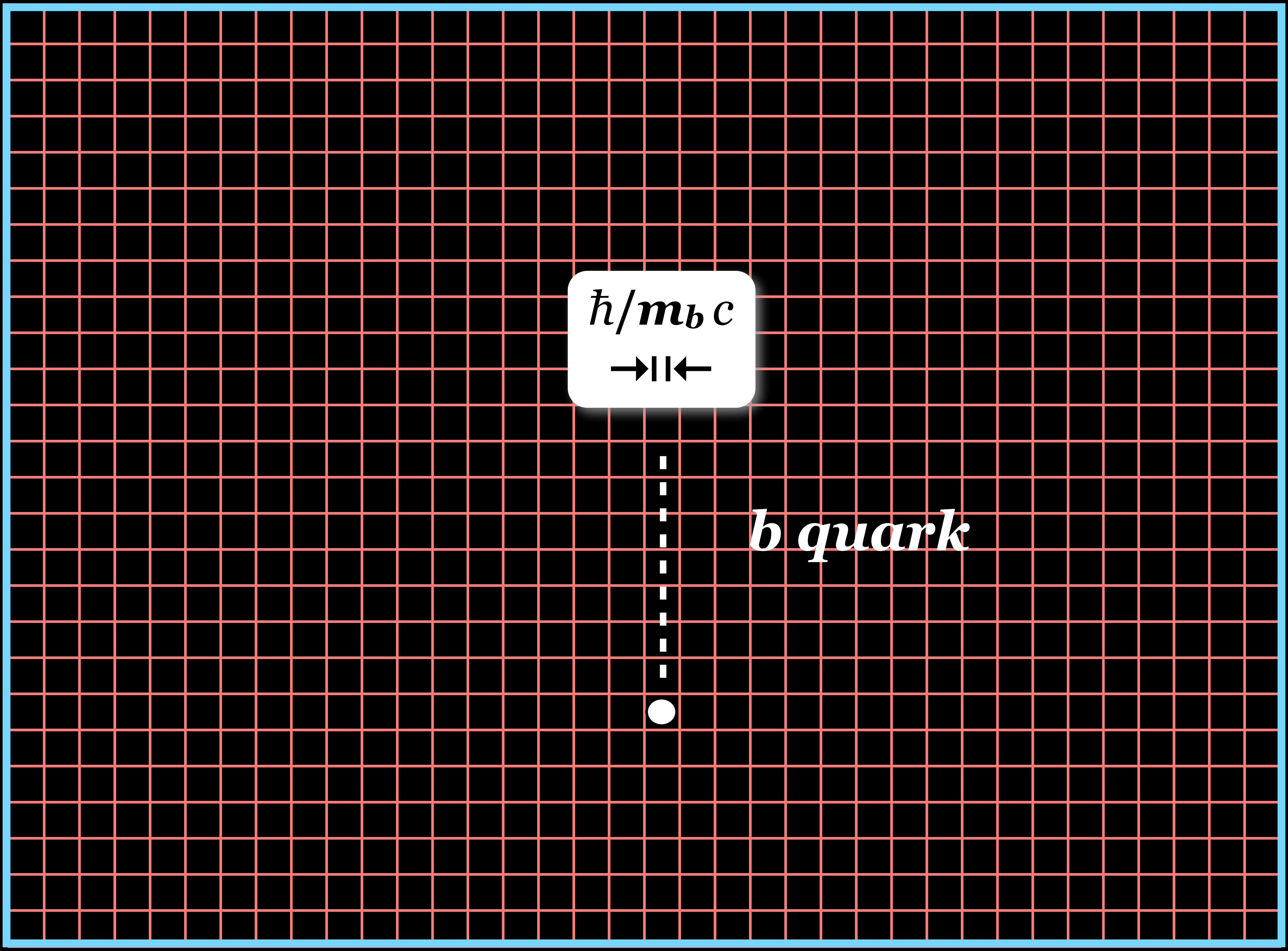
should be smaller than box

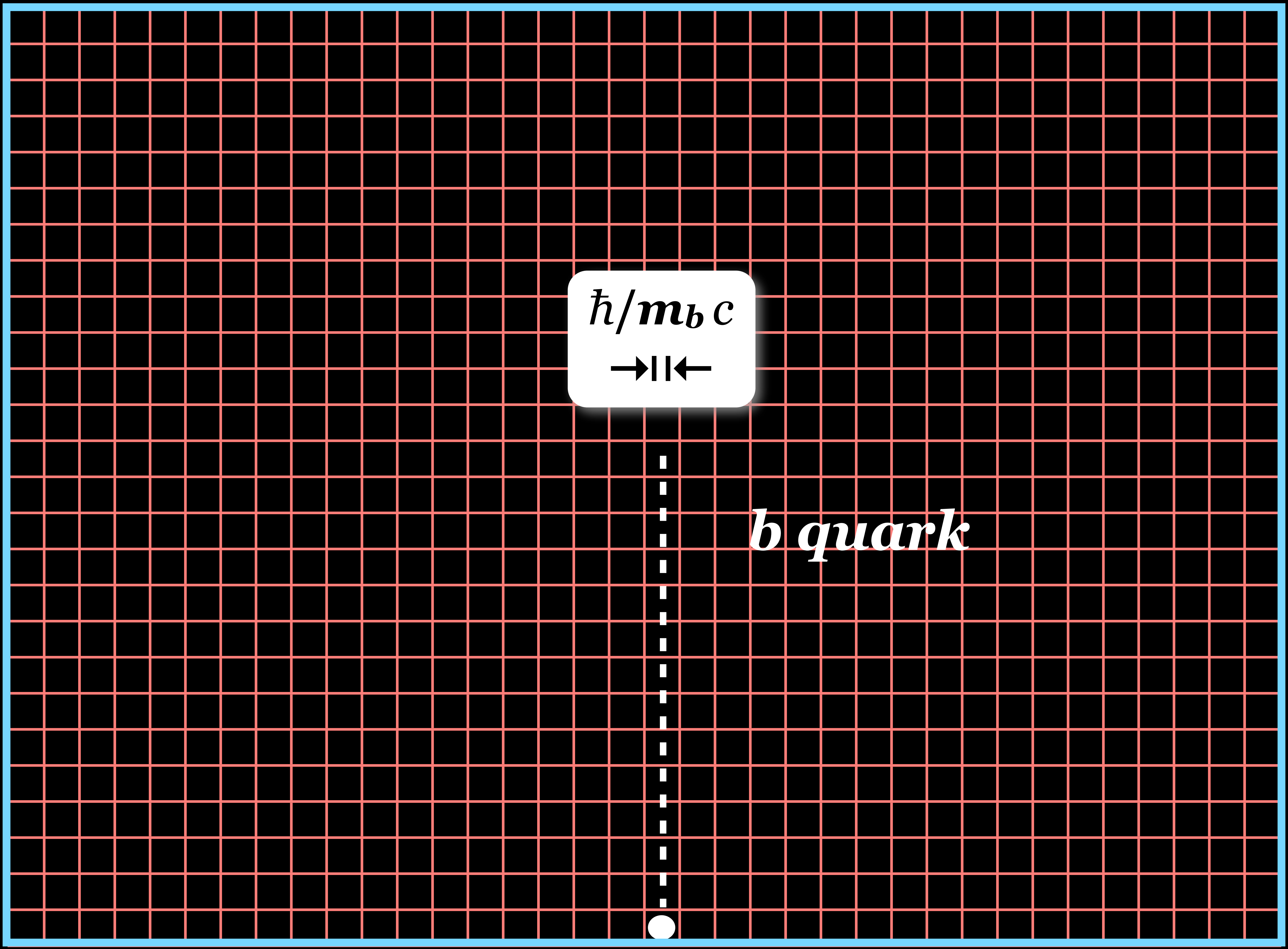


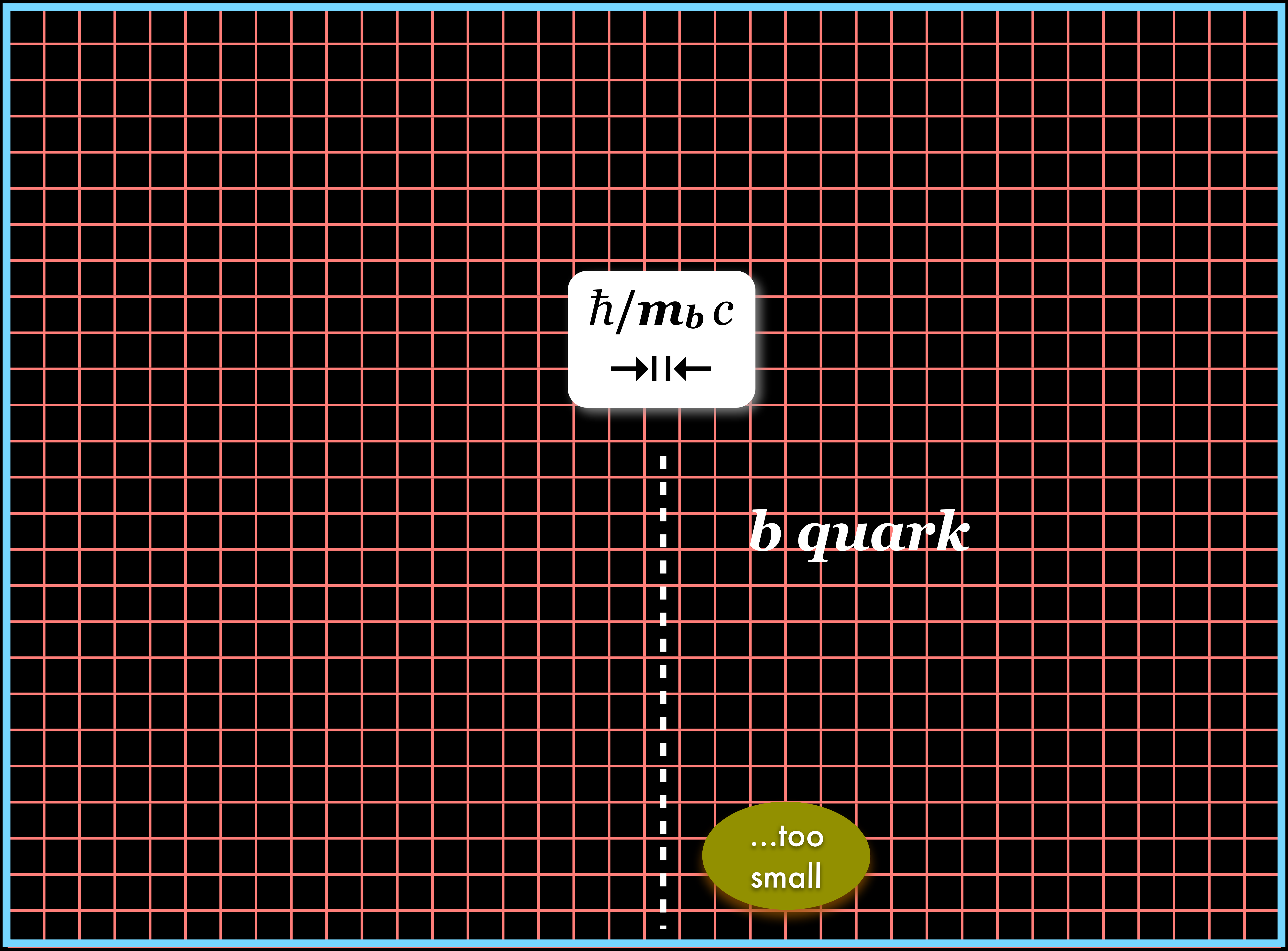
→| |←
a
hadron
should not notice grid


fast hadron
notices grid
ħ/p


$\hbar/m_b c$
b quark

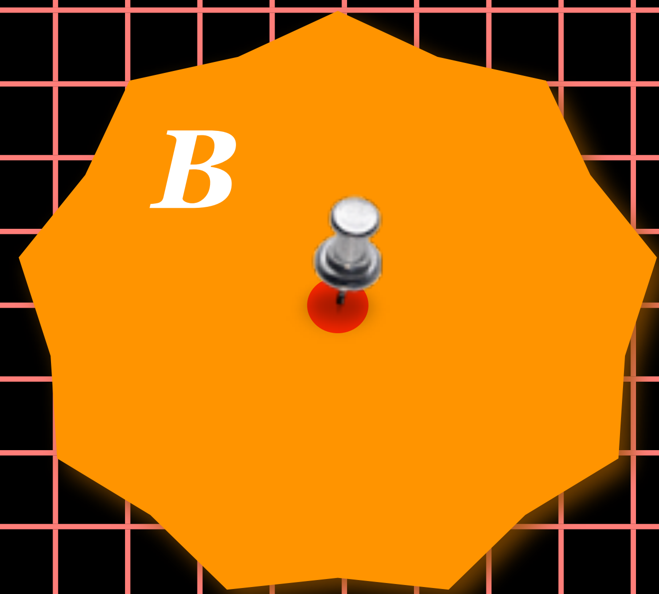

$\hbar/m_b c$
b quark


$\hbar/m_b c$
b quark



$\hbar/m_b c$
b quark
...too
small

HQET (NRQCD) *to the rescue!*



b as static color source

hadronic physics as “brown muck”

einde

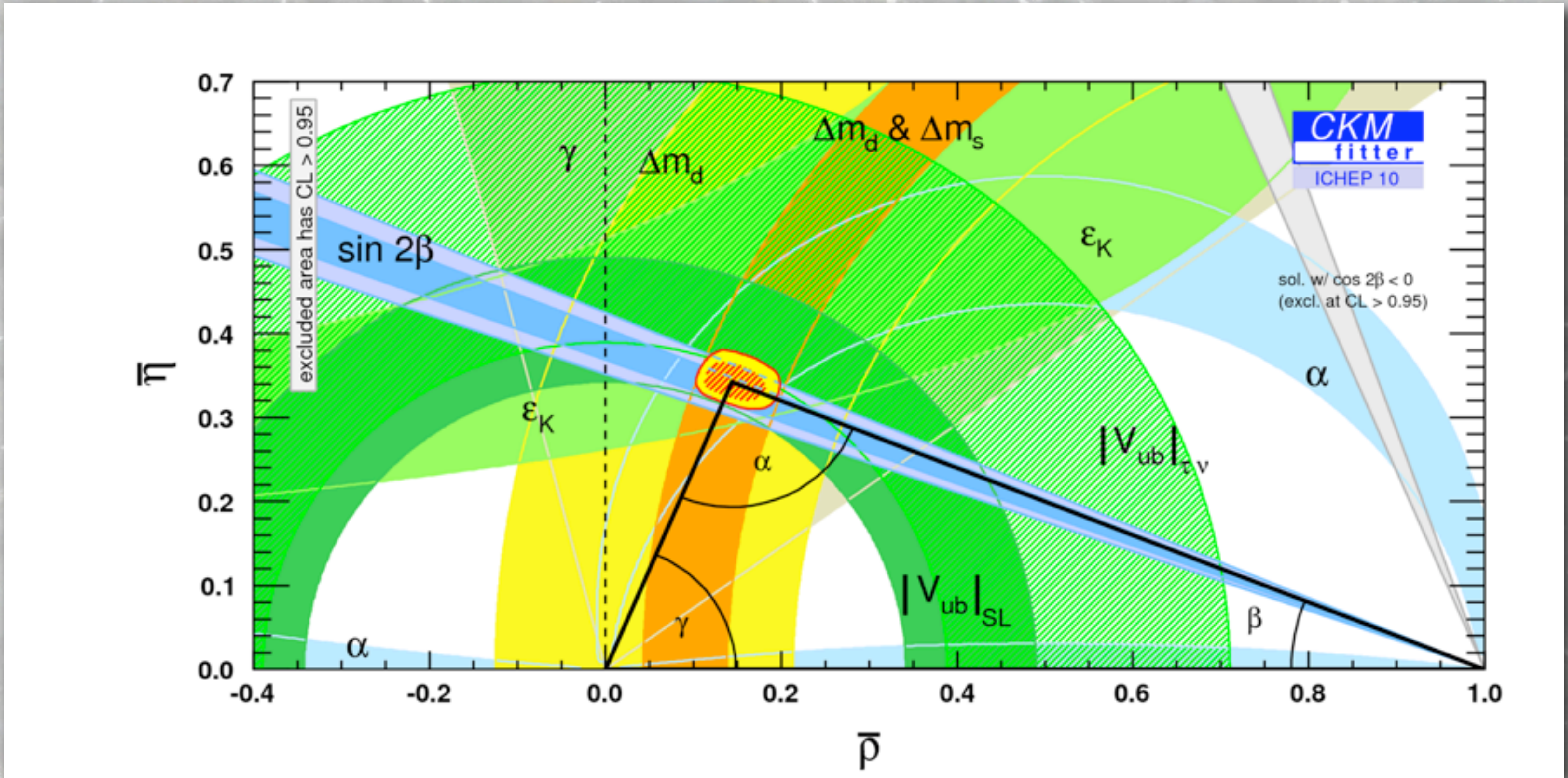
Salient points

- Need clean separation of scales
- Physical point still too expensive

$$a \ll \; m_b^{-1} \sim m_\pi^{-1} \; \ll L$$

- Effective theories (HQET, chiral PT) used to treat heavy quark effects, extrapolate in light quark mass
- Both lattice spacing and use of HQET restrict kinematics
- Imaginary time ⇒ at most 1 hadron init/final state
- Statistical errors (physical reasons why some quantities have larger errors than others), another 5-minute film…

Global fits to CKM parameters



CKMfitter: Bona *et al.*, ICHEP 2010
Talk by Heiko Lacker, Friday

Global fits to CKM parameters

Results of the SM analysis

preliminary Summer '10

SM determination of the Unitarity Triangle

$R_u\, e^{i\gamma} + R_t\, e^{-i\beta} = 1$

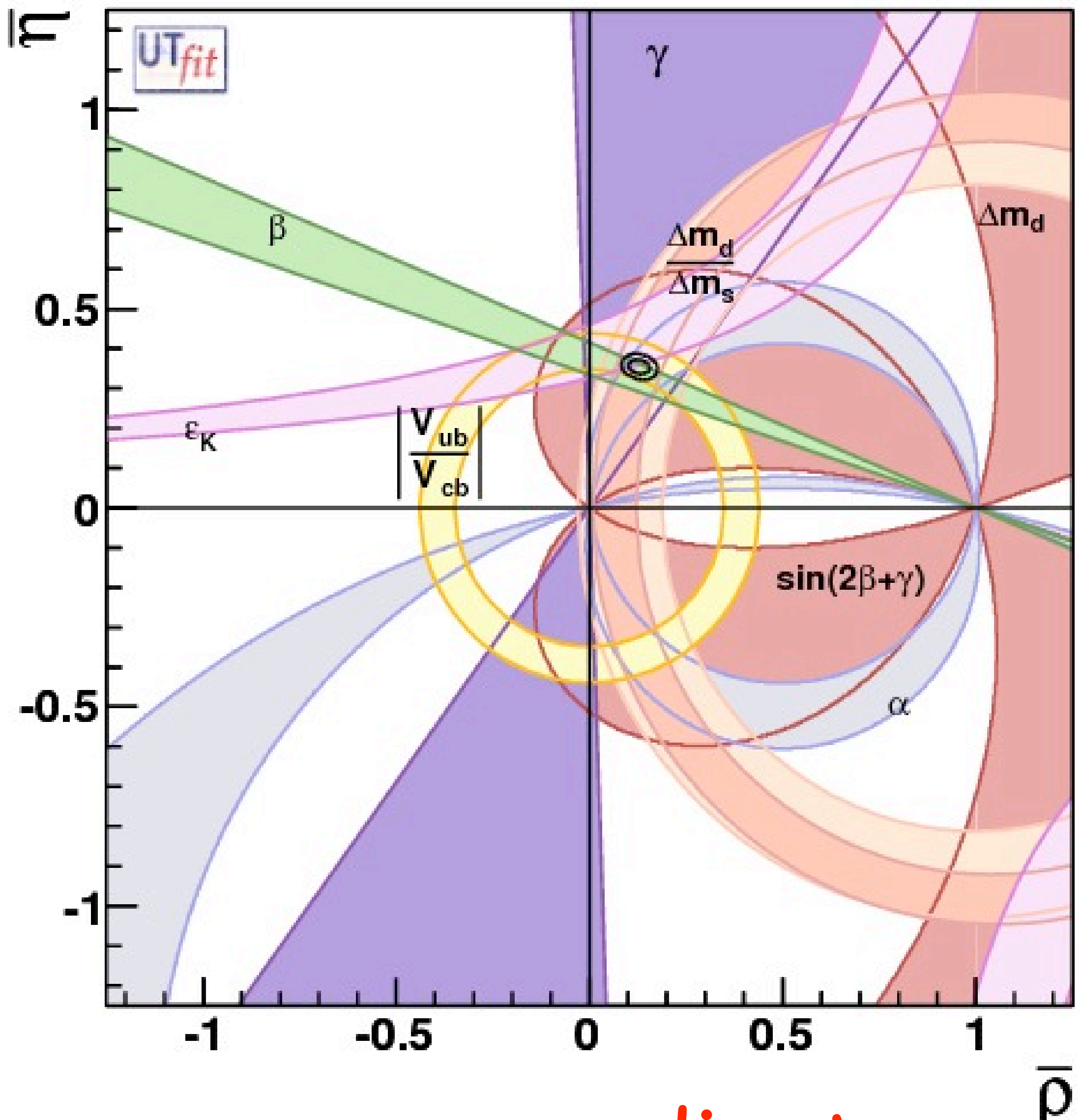
$R_u = 0.379 \pm 0.013$

$R_t = 0.939 \pm 0.021$

$\gamma = (69.8 \pm 3.1)°$

$\beta = (22.15 \pm 0.75)°$

$\alpha = (87.8 \pm 3.0)°$



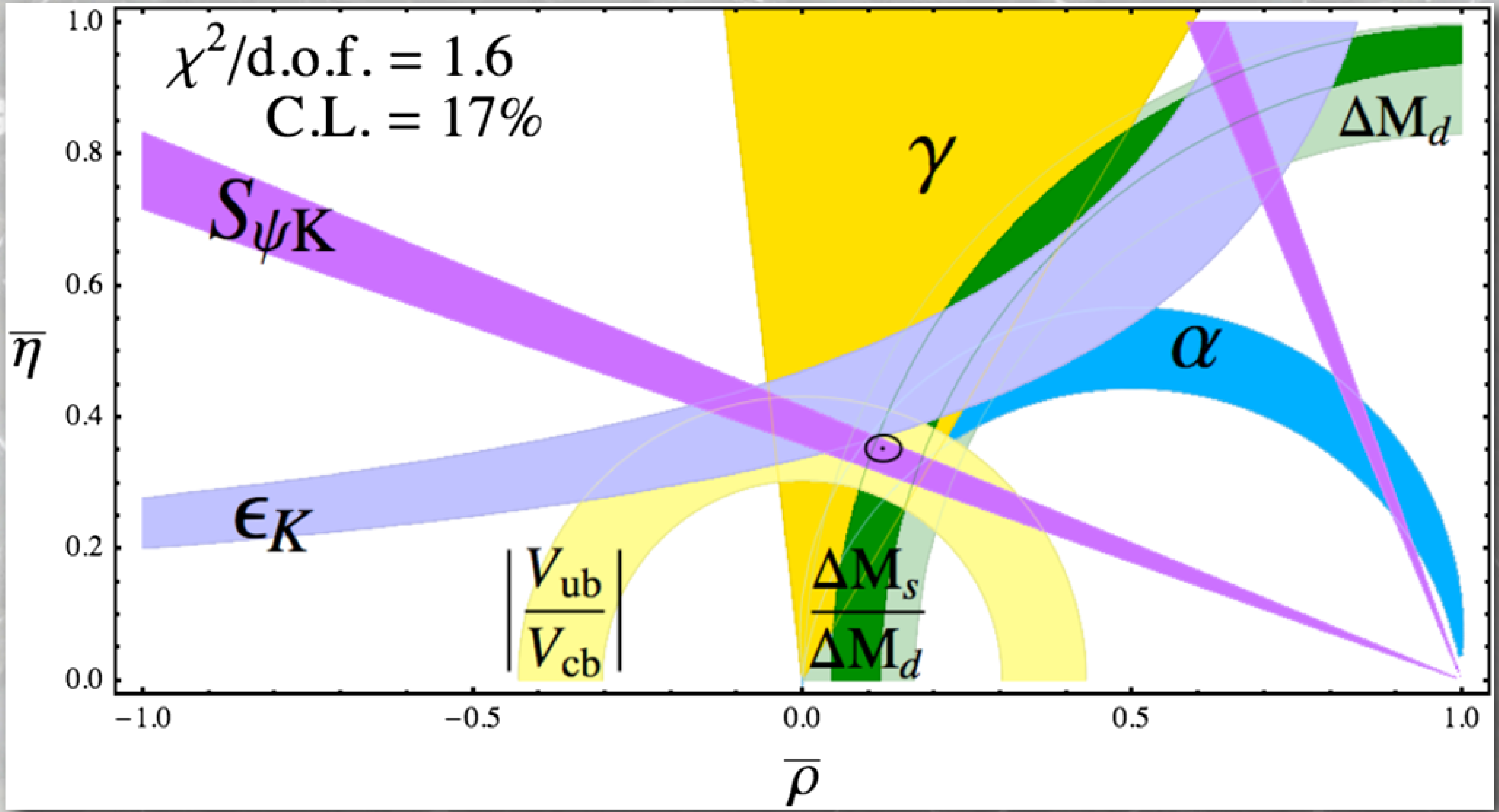
apex coordinates

$\bar{\rho} = 0.130 \pm 0.021$

$\bar{\eta} = 0.355 \pm 0.013$

UTfit, Ciuchini et al., Capri 2010

Global fits to CKM parameters



Laiho, Lunghi, Van de Water, Phys. Rev. D **81** (2010)

$$\langle \overline{K^0} | Q_{\Delta S=2} | K^0 \rangle \quad \langle \pi | \bar u \gamma^\mu b | B \rangle \quad \langle \overline{B}_q | Q_{\Delta B=2} | B_q \rangle \quad \langle 0 | \bar u \gamma^\mu \gamma^5 b | B \rangle$$

$$B_K \quad f_+(q^2) \quad f_{B_q}^2 B_{B_q} \quad f_B$$

$$\langle D | \bar c \gamma^\mu b | B \rangle \quad \langle D^* | \bar c \gamma^\mu b | B \rangle$$

$$\mathcal{F}_{B\to D}(1) \quad \mathcal{F}^{B\to D^*}(1) \quad f_\pi, f_K, \langle \pi | \bar u \gamma^\mu s | K \rangle$$

Fitters: LQCD averages and errors

- **CKMfitter (Charles, et al.)** (arXiv:0905.1572)
  - 2 and 2+1 flavor LQCD results
  - Rfit (Gaussian + flat components to syst. errors)
  - Systematic errors added linearly
- **UTfit (Bona, et al.)** (arXiv:0807.4605)
  - 0 (??), 2 and 2+1 flavor LQCD results
  - Bayesian
- **Laiho, Lunghi, Van de Water** (PRD 81, 034503, 2010)
  - 2+1 flavor LQCD results
  - Frequentist, systematic errors as Gaussian
  - Systematic errors added quadratically

Fitters: LQCD averages

e.g. $\hat{B}_K$

- **CKMfitter (Charles, et al.)** (arX
  - 2 and 2+1 flavor LQCD results
  - Rfit (Gaussian + flat components to
  - Systematic errors added linearly

$0.721(5)_{stat}(40)_{sys}$

- **UTfit (Bona, et al.)** (L & T, arXiv:0
  - 0 (??), 2 and 2+1 flavor LQCD result
  - Bayesian

0.750(70)

- **Laiho, Lunghi, Van de Water**
  - 2+1 flavor LQCD results
  - Frequentist, systematic errors as Ga
  - Systematic errors added quadratical

0.725(27)

Snapshot of recent work

f_B, f_{B_s}

ETM, PoS(LAT2009);
HPQCD, PRL 92 (2004);
FNAL/MILC, PoS(LAT2008);
HPQCD, PRD 80 (2009)

B_{B_d}, B_{B_s}

HPQCD, PRD 76 (2007);
RBC-UKQCD, PoS(LAT2007);
HPQCD, PRD 80 (2009);
RBC-UKQCD, PRD 82 (2010)

$f_+^{B\to\pi}(q^2)$

HPQCD, PRD 73 (2006);
FNAL/MILC, PRD 79 (2009) 054507;
FNAL/MILC, PRD 80 (2010)

$\mathcal{F}^{B\to D}(1)$

FNAL/MILC, NPB Proc Suppl (2005)

$\mathcal{F}^{B\to D^*}(1)$

FNAL/MILC, PRD 79 (2009) 014506

$\hat{B}_K$

JLQCD, PRD 77 (2008);
HPQCD, PRD 73 (2006);
RBC-UKQCD, PRL 100 (2008);
Aubin et al., PRD 81 (2010)

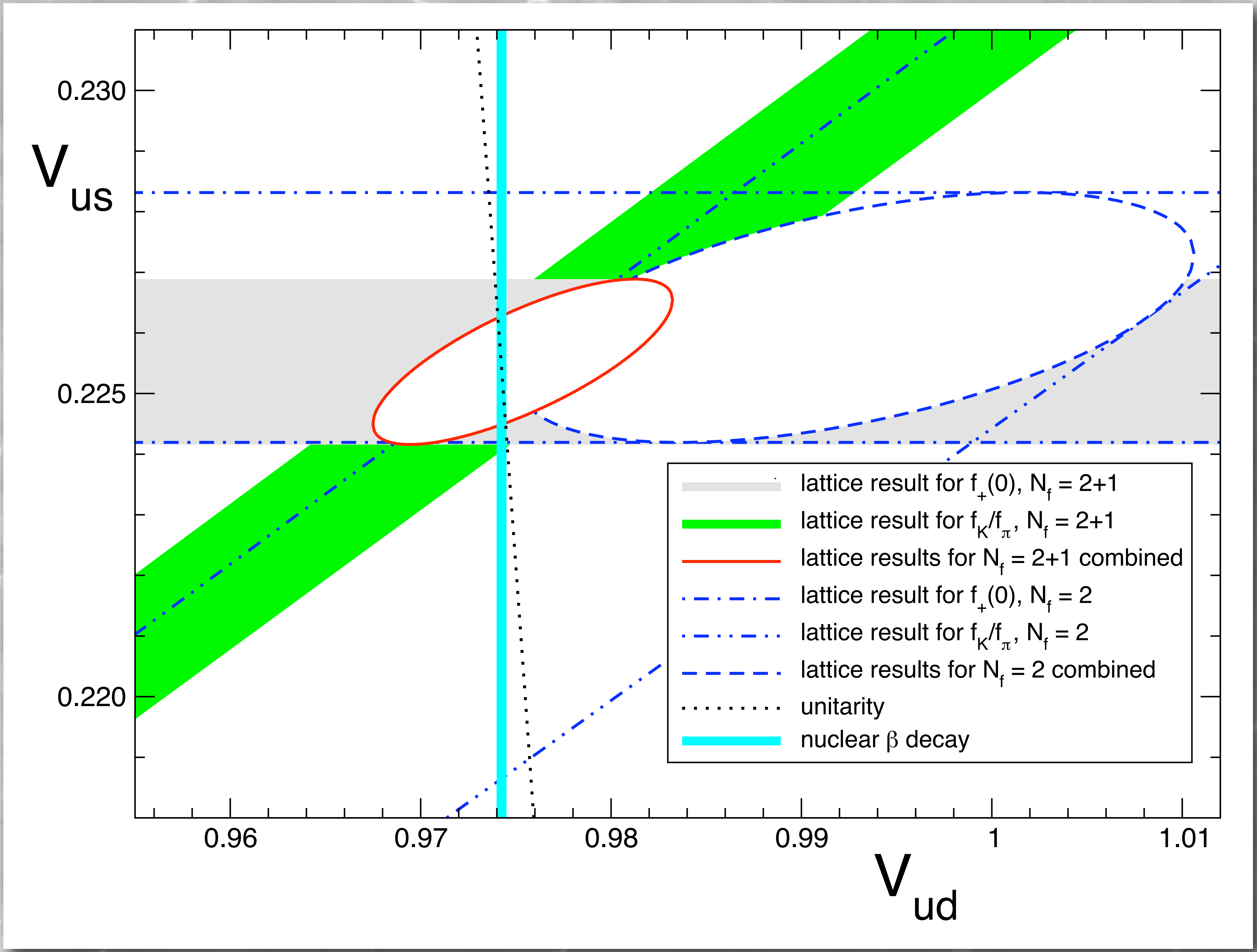
$f_+^{K\to\pi}(0)$

RBC-UKQCD, PRL 100 (2008);
ETM, PRD 80 (2009);
RBC-UKQCD, EPJ C69 (2010)

f_π, f_K

NPLQCD, PRD 75 (2007);
HPQCD, PRL 100 (2008);
QCDSF, PoS(LAT2007);
PACS-CS, PoS(LAT2008);
PACS-CS, PRD 79 (2009);
RBC-UKQCD, PRD 78 (2008);
Aubin et al., PoS(LAT2008);
MILC, PoS(CD09);
MILC, RMP 82 (2010);
JLQCD/TWQCD, PoS(LAT2009);
ETM, JHEP 07 (2009);
BMW, PRD 82 (2010)

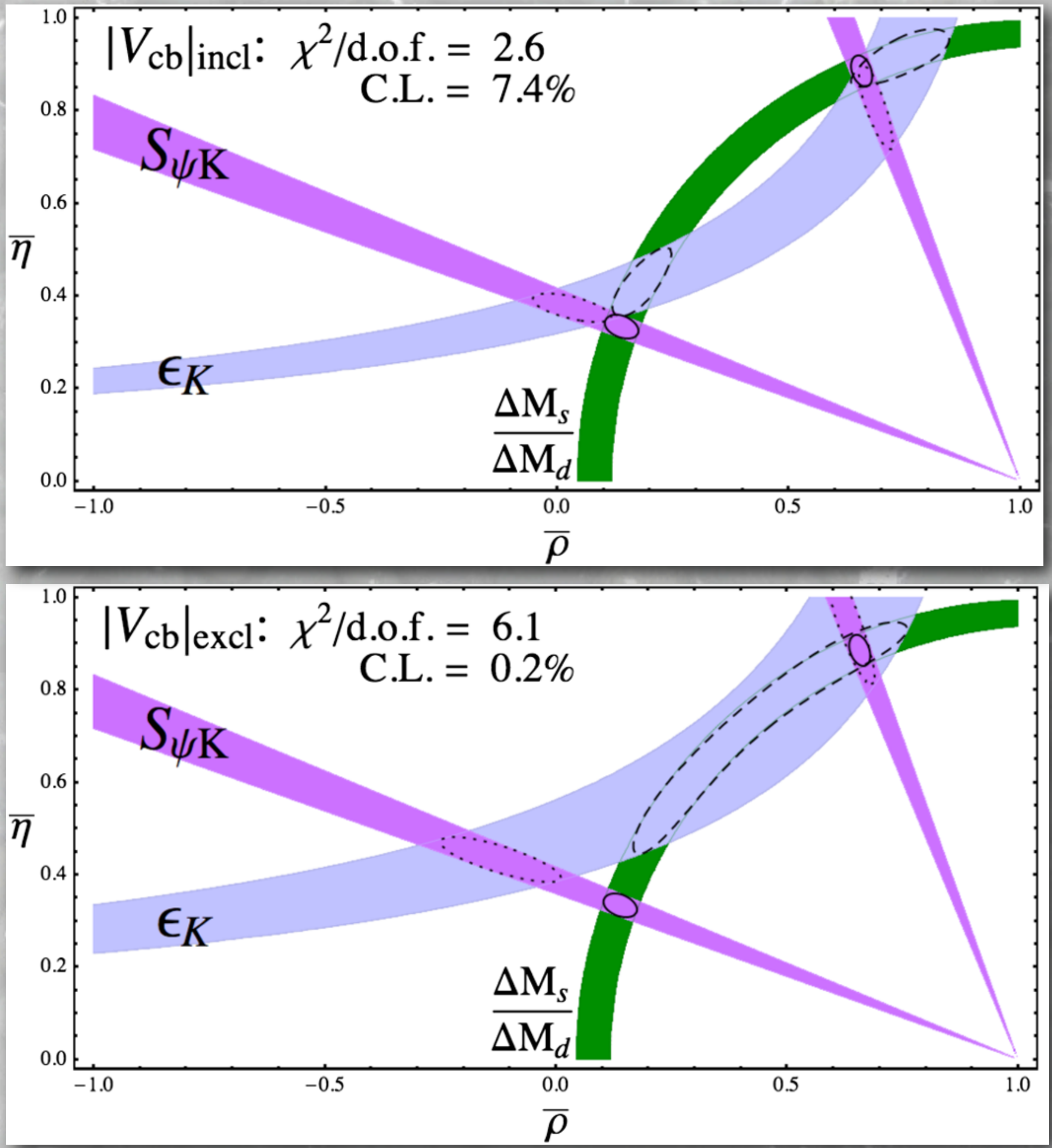
Cabibbo angle



From, FLAG working group of FLAVIANET, arXiv:1011.4408

Tensions

- ✤ Uncertainty in V_{cb} affects ε_K
- ✤ Inclusive/exclusive tension in V_{cb}
- ✤ As with V_{ub}, exclusive "check" of inclusive result has exposed interesting "features"



Laiho, Lunghi, Van de Water, Phys. Rev. D **81** (2011)

B_s mixing

Anomalous like-sign di-muon asymmetry

$$\begin{aligned} A_{SL}^{\mathrm{D0}} &= (-9.6 \pm 2.5 \pm 1.5) \times 10^{-3} \\ A_{SL}^{\mathrm{LN}} &= (-0.20 \pm 0.03) \times 10^{-3} \end{aligned}$$

A discrepancy of ~3σ

$$\begin{aligned} A_{SL} &= (0.506 \pm 0.043)\, a_{\mathrm{fs}}^{d} + (0.494 \pm 0.043)\, a_{\mathrm{fs}}^{s} \\ a_{\mathrm{fs}}^{d} &= (-4.1 \pm 0.6) \times 10^{-4} \end{aligned}$$

$a_{\mathrm{fs}}^{s,\mathrm{SM}}$	L&N, '11	L&N, '07
Central Value	$2.11 \cdot 10^{-5}$	$2.06 \cdot 10^{-5}$
$\delta(\lvert V_{ub}/V_{cb}\rvert)$	11.6%	19.5%
$\delta(\mu)$	8.9%	12.7%

Tables from Lenz & Nierste, arXiv:1102.4274 (cf. L&N, JHEP **0706** (2007))

B_s mixing

- LQCD progress reducing f_{Bs} error by more than half
- Still dominant uncertainty in ΔM_s
- Full NLO calculation requires dedicated effort

ΔM_s^{SM}	L&N, '11	L&N, '07
Central Value	$17.3\,\mathrm{ps}^{-1}$	$19.3\,\mathrm{ps}^{-1}$
$\delta(f_{B_s})$	13.2%	33.4%
$\delta(V_{cb})$	3.4%	4.9%
$\delta(\mathcal{B}_{B_s})$	2.9%	7.1%

$\Delta\Gamma_s^{\mathrm{SM}}$	L&N, '11	L&N, '07
Central Value	$0.087\,\mathrm{ps}^{-1}$	$0.096\,\mathrm{ps}^{-1}$
$\delta(\mathcal{B}_{\tilde{R}_2})$	17.2%	15.7%
$\delta(f_{B_s})$	13.2%	33.4%
$\delta(\mu)$	7.8%	13.7%

$$R_{2/\tilde{2}} = \frac{1}{m_b^2}[\bar{s}_\alpha \overleftarrow{D}_\rho \gamma^\mu (1-\gamma_5) D^\rho b_{\alpha/\beta}][\bar{s}_{\beta/\alpha}\gamma_\mu(1-\gamma_5)b_\beta]$$

Tables from Lenz & Nierste, arXiv:1102.4274 (cf. L&N, JHEP **0706** (2007))

From Status to Prospects

- Checks w/ alt. LQCD formulations (actions, etc.)
- Reduction of errors will occur via
  - Further-improved actions (*e.g.* NRQCD/HISQ for $B \rightarrow D$)
  - Nonperturbative operator matching
  - Fine enough lattices for relativistic b

Rare B decays

- Talk by David Straub yesterday
- At large q^2 hadronic physics is determined by $B \to K^{(*)}$ form factors (Buchalla & Isidori; Grinstein & Pirjol; Beylich, Buchalla, Feldmann)
- LQCD calculations of the relevant 10 form factors are being completed (Meinel, Liu, *et al*)
- Permits SM tests with more observables, those where form factors do *not* cancel (Bobeth, Hiller, van Dyk)

Beautiful baryon spectrum

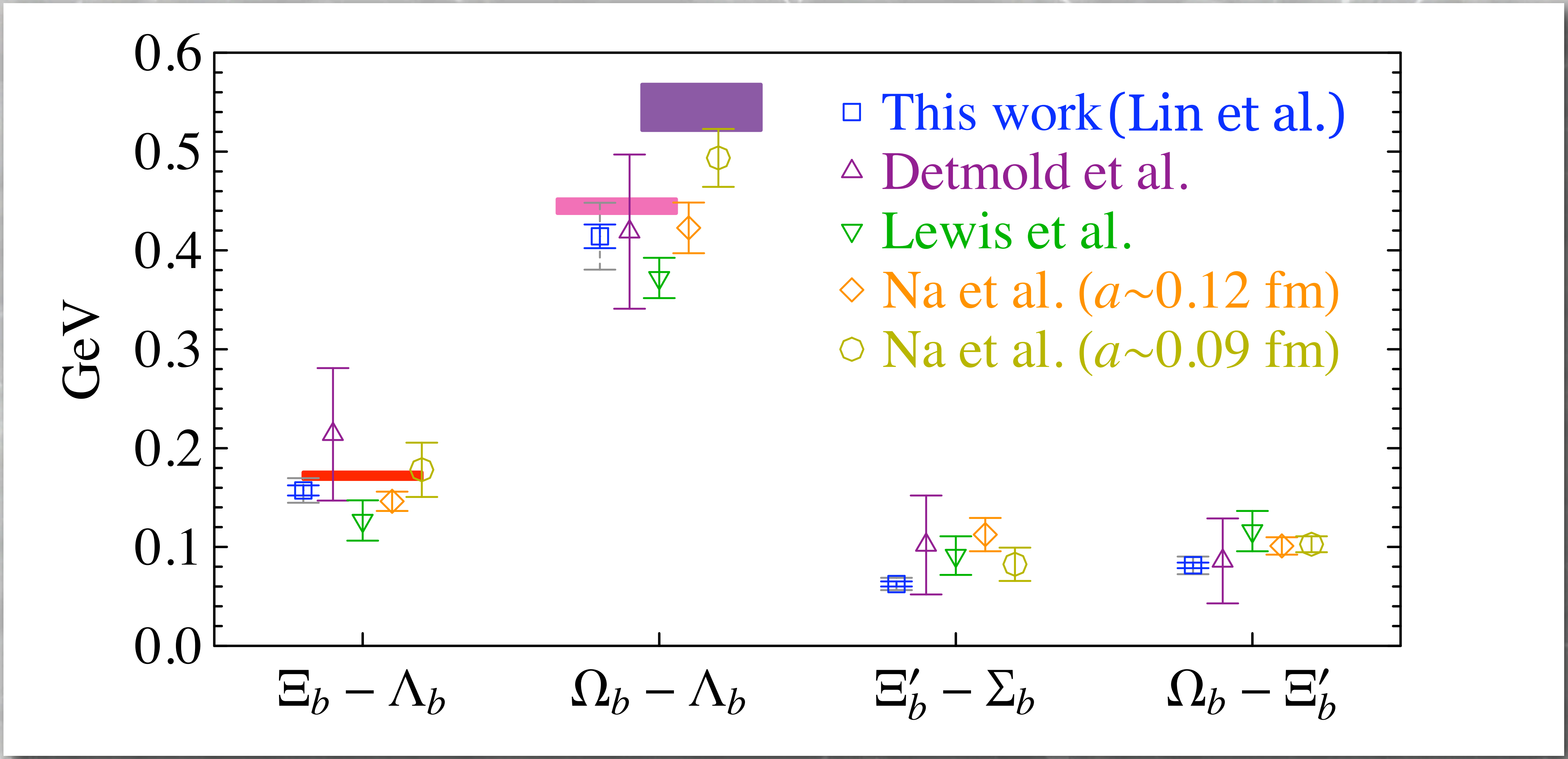


Figure from Lin, Cohen, Mathur, Orginos (2009)
LQCD data also from: Lewis & Woloshyn, PRD **79** (2009); Detmold, Lin, Wingate, NPB (2009); Na & Gottlieb, PoS (2008)
Experimental bands: PDG (red), CDF (pink), D0 (purple)

Rare Λ_b decay

$$\boldsymbol{\Lambda_b \to \Lambda\, \ell^+ \ell^-}$$

In the static limit, the 12 form factors reduce to only 2 form factors

$$\langle \boldsymbol{\Lambda}(p)|\bar{s}\,\boldsymbol{\Gamma}\,b|\boldsymbol{\Lambda}_b(p+q)\rangle \;=\; \bar{u}_{\boldsymbol{\Lambda}}(p)\Big[F_1(q^2) + \not{p}\,F_2(q^2)\Big]\boldsymbol{\Gamma}\,u_{\boldsymbol{\Lambda}_b}(p+q)$$

Mannel, Roberts, Ryzak, Nucl. Phys. B **355**, 38 (1991)

- ✤ Future LQCD calculation of f.f. at large Q^2
- ✤ Baryons noiser than mesons, esp. pseudoscalars
- ✤ Hard to imagine ever calculating $1/m$ corrections

Conclusions

CKM unitarity

- Recent progress due to light quarks, use of EFT
- Further reduction of errors, relativistic *b*
- Meantime: other choices to confirm or expose hidden systematics

FCNC

- B_s mixing
- Rare decays
- *b* baryons

In our quest to discover and understand non-SM physics, we must . . .

leave no stone unturned!