# Theory Summary


Sebastian Jäger, 26 July 2014

University of Sussex

An excellent summary of the state & motivation of flavour physics was given in the opening talk by Jernej Kamenik...

SM phenomenologically very successful

Kamenik

Most likely just (experimentally accessible) effective theory

Baryogenesis

Unification of interactions

Dark matter?

$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{gauge}}(A_a, \psi_i) + D_\mu \phi^\dagger D^\mu \phi - V_{\mathrm{eff}}(\phi, A_a, \psi_i)$$

$$V_{\mathrm{eff}} = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 + Y^{ij} \psi_L^i \psi_R^j \phi + \frac{y^{ij}}{\Lambda} \psi_L^{iT} \psi_L^j \phi^T \phi + \ldots$$

EW scale stabilization

Origin of flavor

$m_\nu$

Need to understand/constrain size of additional terms in series



... followed by nearly 30 specialised theory summaries ...

... on precision probes of BSM physics, theoretical techniques, assessing uncertainties and interpreting the data, and providing suggestions for future experimental (and theoretical) directions.

# Why and what BSM physics?

The discovery of a Higgs scalar has, in my view, **strengthened** the naturalness argument: If there is a physical scale M above $M_Z$, as suggested by near-unification of gauge couplings, baryon asymmetry, neutrino masses, gravity, then the weak scale is unstable to quantum corrections unless $M \sim M_Z$

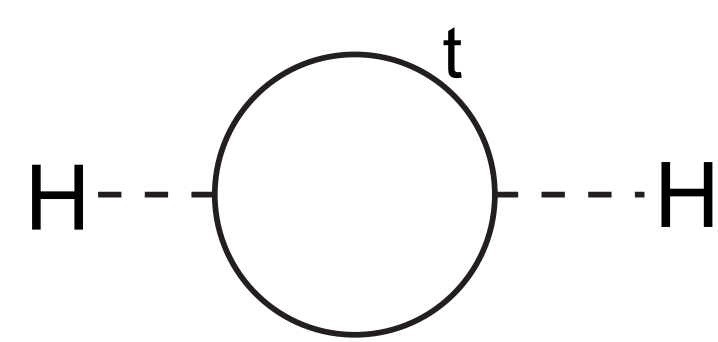
$SU(3)^5$ flavour symmetric kinetic/gauge terms

EW scale setting

$$\mathcal{L}_{\rm SM} = \sum_f \bar{\psi}_f \gamma^\mu D_\mu \psi_f - \sum_{i,a} \frac{1}{4} g_i F^{ia}_{\mu\nu} F^{ia\mu\nu}$$
$$-\bar{u}_R Y_U \phi^{c\dagger} Q_L - \bar{d}_R Y_D \phi^\dagger D_L - \bar{e}_R Y_E \phi^\dagger E_L - \mu^2 \phi^\dagger \phi - \frac{\lambda}{2} (\phi^\dagger \phi)^2$$

flavour-breaking fermion masses and Higgs couplings

Naturalness problem is (mostly) caused by top Yukawa, a flavour-breaking term




Physics addressing naturalness should be flavourful, too

This happens in supersymmetry, extra dim/composite Higgs, ...

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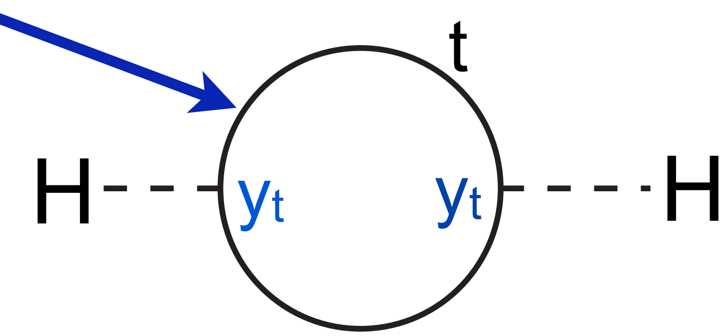


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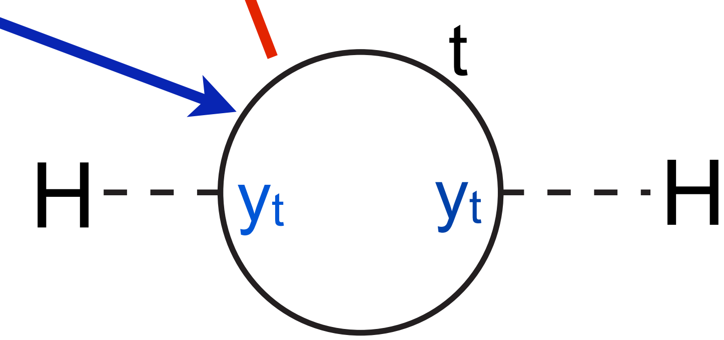
flavour-breaking fermion masses and Higgs couplings

$\propto y_t^2 M^2$

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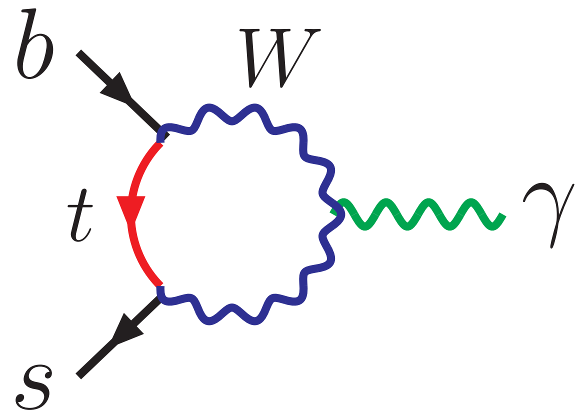
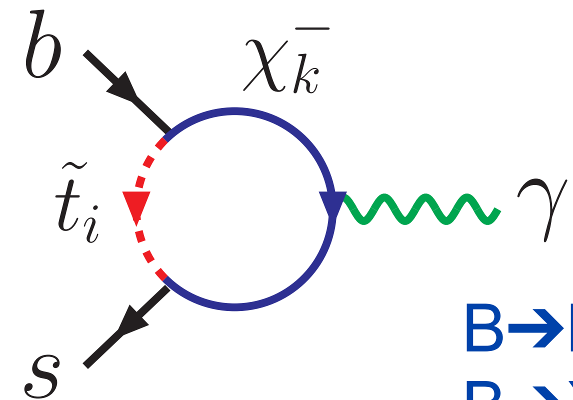
# BSM flavour

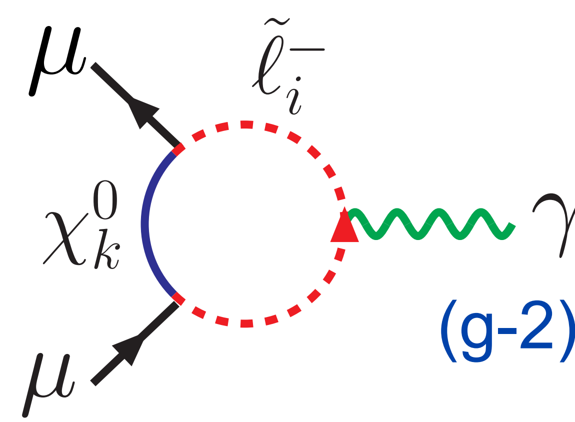
New particles addressing naturalness will at least have CKM-like flavour violations (minimal flavour violation), so will always affect rare decays. E.g.,




$B \to K^* \gamma$
$B \to X_s \gamma$

Of course BSM particles will mediate flavour-*conserving* processes, too.




$(g\text{-}2)_{muon}$

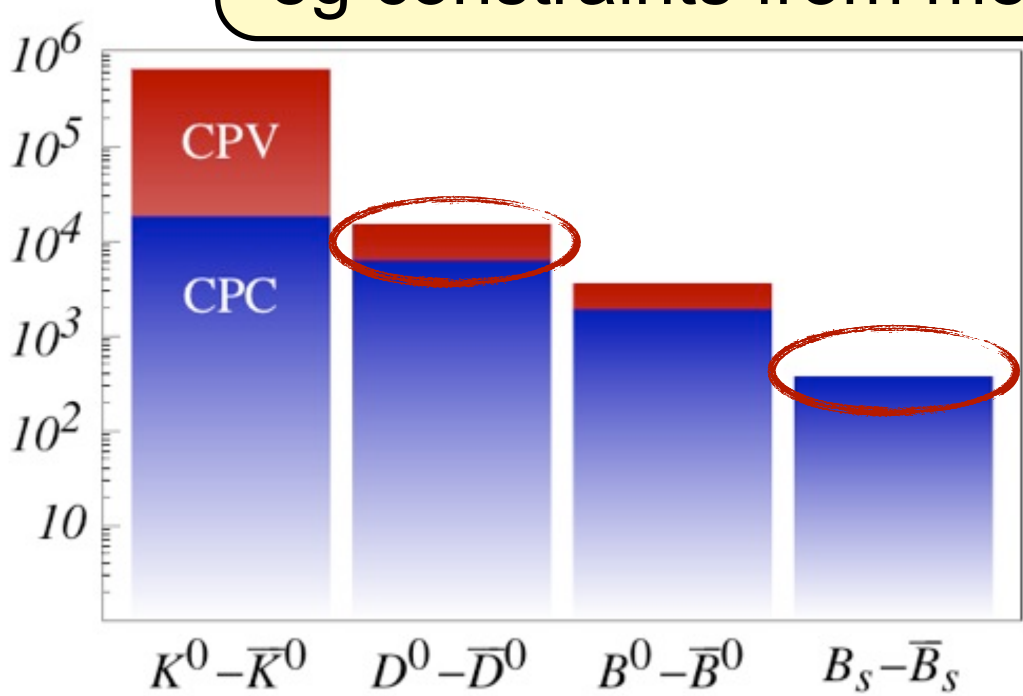
The absence of BSM particle discoveries so far challenges theoretical paradigms (eg CMSSM) and strengthens the importance of indirect, precision probes. They may provide the leading avenue to physics beyond the Standard Model.

# Twofold role of flavor physics

Kamenik

(1) Indirect probe of BSM physics beyond direct reach

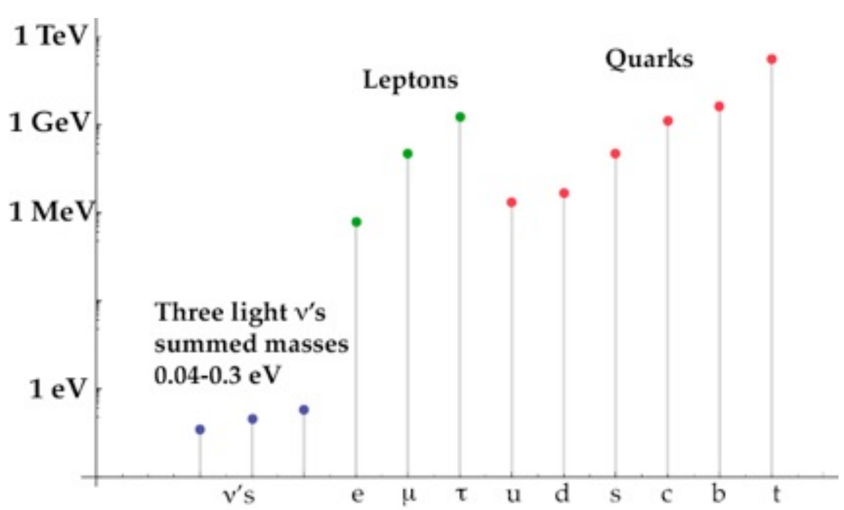
eg constraints from meson mixing



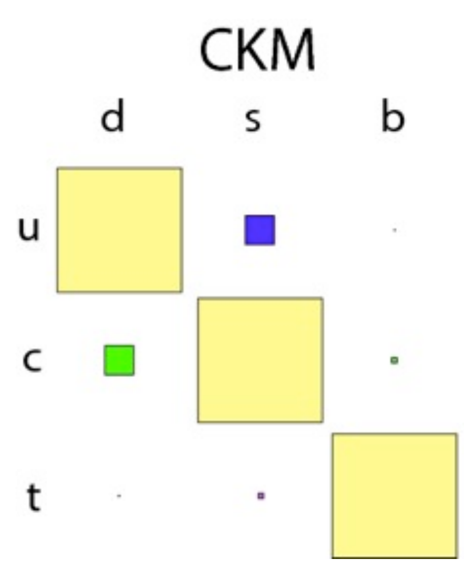

CPV in D, $B_s$ only constraints not (yet) theory limited
⇒ effective null-tests within SM

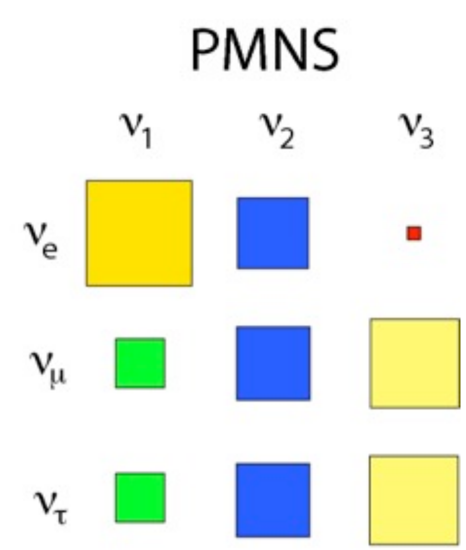
(2) Test sources of flavor symmetries & their violation

Suggestive pattern of masses and mixings




S. Stone, 1212.6374




Accidental? Dynamics? Symmetries?

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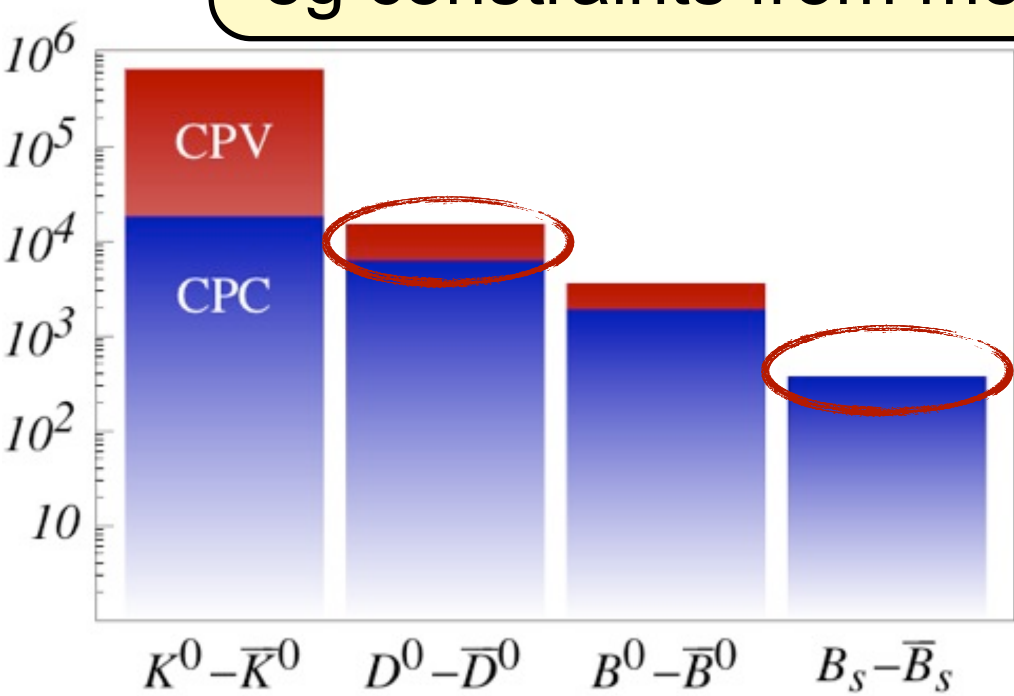


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**This could improve with better theory!**
Christ, Juttner

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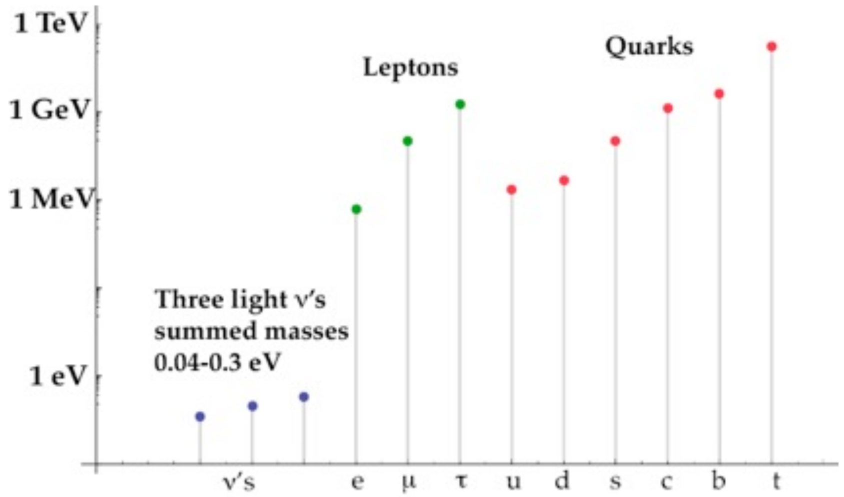


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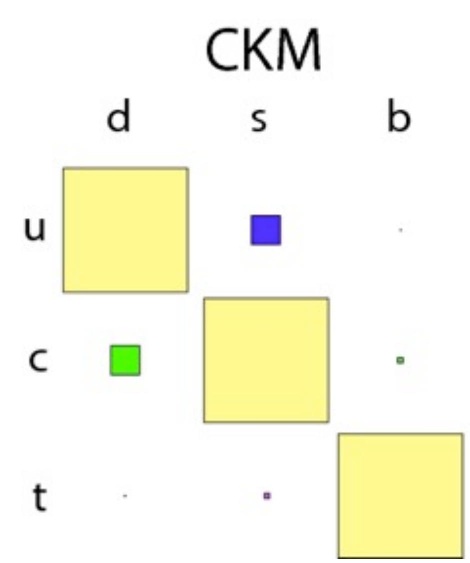


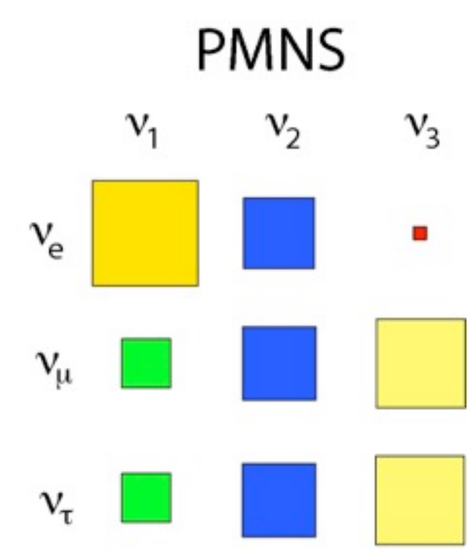


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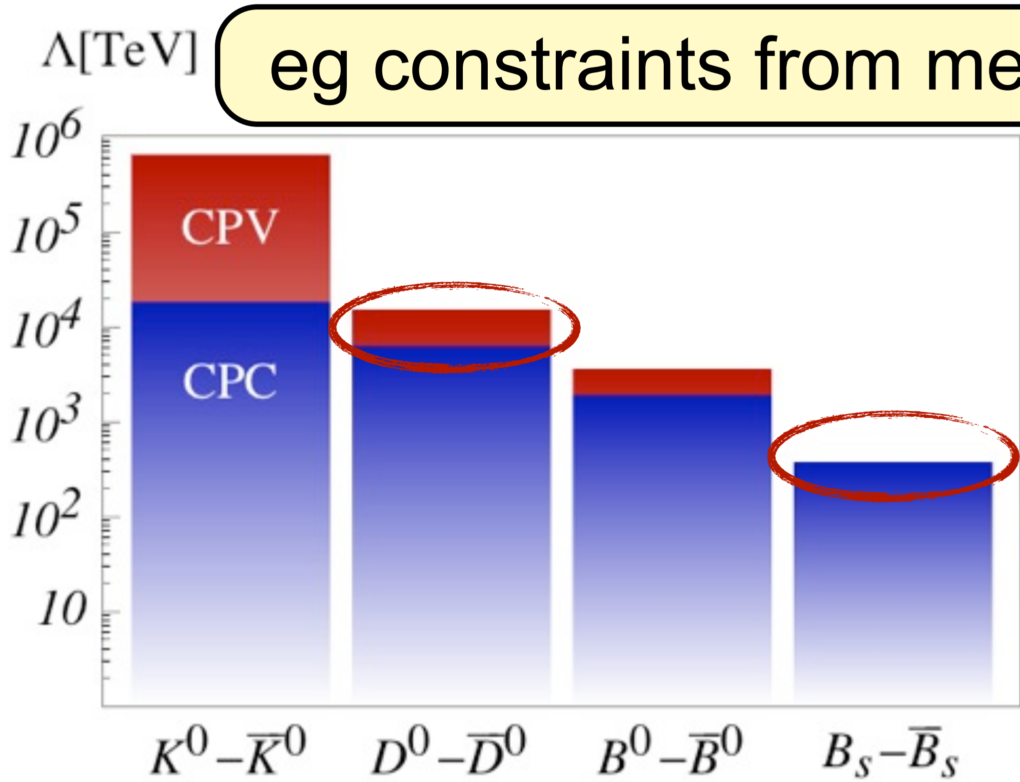


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Little discussion of models at BEACH 2014: focus is on precision theory and interpreting data.

Although this is in part due to the experimental focus of the conference, it reflects a broader trend in the theory community toward a more bottom-up, data-driven approach to modelling of constraints and anomalies.

This may go on for some time. Requires ingenuity and work in exploiting existing and identifying new experimental probes of the unknown.

# What BSM effects?

Heavy physics with mass scale M described by local effective Lagrangian at energies below M (many incarnations)

Effective Lagrangian dimension-5,6 terms describes **all** BSM physics to O($E^2/M^2$) accuracy. **Systematic & simple**. E.g.

Buchmuller, Wyler 1986
Grzadkowski, Misiak, Iskrzynski, Rosiek 2010

| | |
|---|---|
| $Q_{ll}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$ |

operators (vertices) are catalogued for arbitrary (heavy) new physics

Only trace of BSM physics is in their (Wilson) coefficients

Higgs physics (production & decay) probes 19 operators

B physics O(100) operators (more if lepton flavour violation)

Lepton flavour violation O(100)

eg Crivellin, Najjari, Rosiek 2013

Top physics in principle many more, most of them 4-quark operators mediating 3-body hadronic decays.

# Scales, techniques, observables

$>m_t$ — new physics? SU(2)xU(1) covariant SM | energy frontier

$m_W \sim m_t$ — Wilson coefficient matching | W,top,Z physics

RGE

$m_b$

HQET, NRQCD

SCET

Bottomonium spectroscopy

K,B,D mixing

rare K,B,D decays

$m_c$

Charmonium spectroscopy

$\Lambda_{QCD}$

lattice QCD

QCD phase diagram

K, pi, hyperon decays

$m_\pi \sim \Lambda^{1/2} m_q^{1/2}$ — chi PT

Will discuss roughly in order of increasing energy (leptons later)

Key issue disentangling strong QCD and short-distance physics

# Kaons, pions, their weak decays

semileptonic K decays, K->ππ, K mixing, rare K decay

traditional tool: chiral PT

increasingly accurate results from lattice QCD

Pich

**Short-distance dynamics encoded in Low-Energy Couplings**

**$O(p^2)$ $\chi$PT:** Goldstone interactions $(\pi, K, \eta)$ $\Phi \equiv \frac{1}{\sqrt{2}} \vec{\lambda}\,\vec{\varphi}$

$$\mathcal{L}_2^{\Delta S=1} = G_8\, F^4\, \mathrm{Tr}(\lambda L_\mu L^\mu) + G_{27}\, F^4 \left( L_{\mu 23} L^\mu_{11} + \frac{2}{3} L_{\mu 21} L^\mu_{13} \right)$$

$$G_R \equiv -\frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* \, g_R \quad ; \quad L_\mu = -iU^\dagger D_\mu U \quad ; \quad \lambda \equiv \tfrac{1}{2}\lambda_{6-i7} \quad ; \quad U \equiv \exp\left\{ i\sqrt{2}\,\Phi/F \right\}$$

**Loop corrections ($\chi$PT logarithms) unambiguously predicted**

**LECs can be determined at $N_C \to \infty$ (matching)**

**$O(p^2)$ LECs ($G_8$, $G_{27}$) can be phenomenologically determined**

EFT valid up to few hundred MeV
systematic perturbative calculations

First-principles treatment of low-energy, non-perturbative QCD. Christ

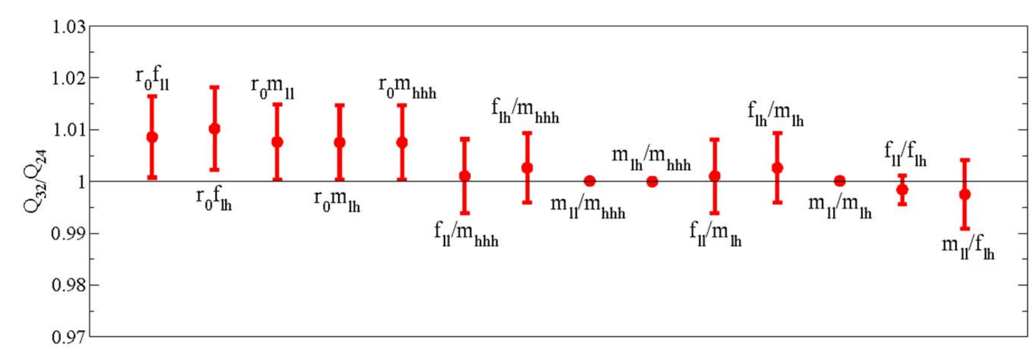
All approximations understood and controlled:

- Non-zero lattice spacing: $a \to 0$.
- Finite volume: $L \to \infty$

At low energy $E << 1/a$, 5-D DWF theory looks like a chiral 4-D theory (QCD) with small chiral asymmetry:

- Leading, dim-3 operator: $m_{res}\, \overline{q}\, q$ (mass term)
- Next leading dim-5 operator: $m_{res}\, \overline{q}\, \sigma^{\upsilon\nu} F^{\upsilon\nu} q$ (clover term)

Very small discretization errors:




Ratios of dimensionless combinations of physical quantities computed using $1/a$ = 1.73 and 2.28 GeV.

can now simulate chiral light quarks with physical mass values cutoff far above $\Lambda_{QCD}$

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rapid progress in accuracy for phenomenology

2012 (elaborate chiral fit): $f_\pi = 127(3)_{stat}(3)_{sys}$ MeV

2013 ($m_\pi$=135 MeV): $f_\pi = 130.0(0.3)_{stat}$ MeV (40 confgs.)

Experiment: $f_\pi = 130.4(0.04)(0.2)$ MeV

# Hadronic K decays

ΔI=1/2 rule - 50 year old theoretical puzzle

$$\frac{A(K\to\pi\pi)_{I=0}}{A(K\to\pi\pi)_{I=2}} \approx 22$$

chi PT picture

Pich

**Short-distance:** $\frac{1}{N_C}\log(M_W/\mu)$ → $\begin{cases} g_8^\infty = 1.13 \pm 0.05_\mu \pm 0.08_{L_5} \pm 0.05_{m_s} \\ g_{27}^\infty = 0.46 \pm 0.01_\mu \end{cases}$

**Long-distance ($\chi$PT):** $\frac{1}{N_C}\log(\mu/m_\pi)$ $g_8^{\mathrm{NLO}} = 3.6$

**Isospin Violation:** $g_{27}^{\mathrm{NLO}} = 0.297$

**A large $\log(M_1/M_2)$ compensates a $1/N_C$ suppression**

uncertainties?

CP violation in K->ππ decays

$$\epsilon' = \frac{i\,e^{\delta_2-\delta_0}}{\sqrt{2}}\left|\frac{A_2}{A_0}\right|\left(\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2}-\frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right)$$ Christ

$$\epsilon_K = \frac{i}{2}\left\{\frac{\mathrm{Im}M_{0\bar{0}}-\frac{i}{2}\mathrm{Im}\Gamma_{0\bar{0}}}{\mathrm{Re}M_{0\bar{0}}-\frac{i}{2}\mathrm{Re}\Gamma_{0\bar{0}}}\right\}+i\frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}$$

strong BSM sensitivity
theory limited at the moment

$$\mathrm{Re}\,(\epsilon'/\epsilon)_{\mathrm{SM}} = \left(19 \pm 2\,^{+9}_{-6} \pm 6\right)\cdot 10^{-4}$$ Pich

Pallante-Pich-Scimemi

chi PT calc

$$(16.8 \pm 1.4)\cdot 10^{-4}$$ expt

## big lattice advances

Christ

Theoretical advances allow rescattering effects to be correctly computed in Euclidean space (so far only for low energy $\pi\text{–}\pi$ states).

- $48^3$ x 96, $1/a$=1.73 GeV
- $64^3$ x 128, $1/a$=2.28 GeV

Many critical quantities can now be computed:

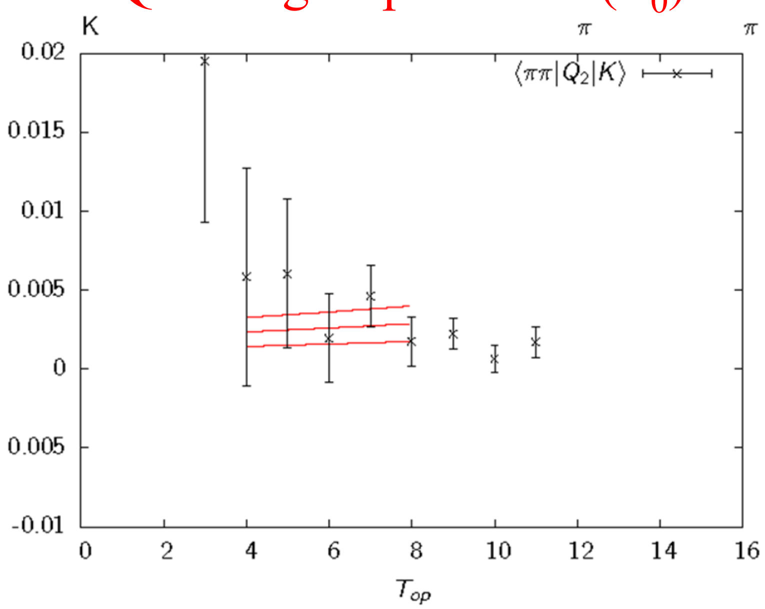
- $K \to \pi\pi$ , $\Delta I$=3/2 and 1/2, $\varepsilon'/\varepsilon$
- $m_{K_L} - m_{K_S}$, long dist. contribution to $\varepsilon$
- $K \to \pi l \bar{l}$, $K \to \pi \nu\bar{\nu}$

First continuum results, (preliminary):

- $\mathrm{Re}(A_2) = (1.583 \pm 0.067_{stat})\times10^{-8}$ GeV
- $\mathrm{Im}(A_2) = -\,(7.51 \pm 27_{stat})\times10^{-13}$ GeV

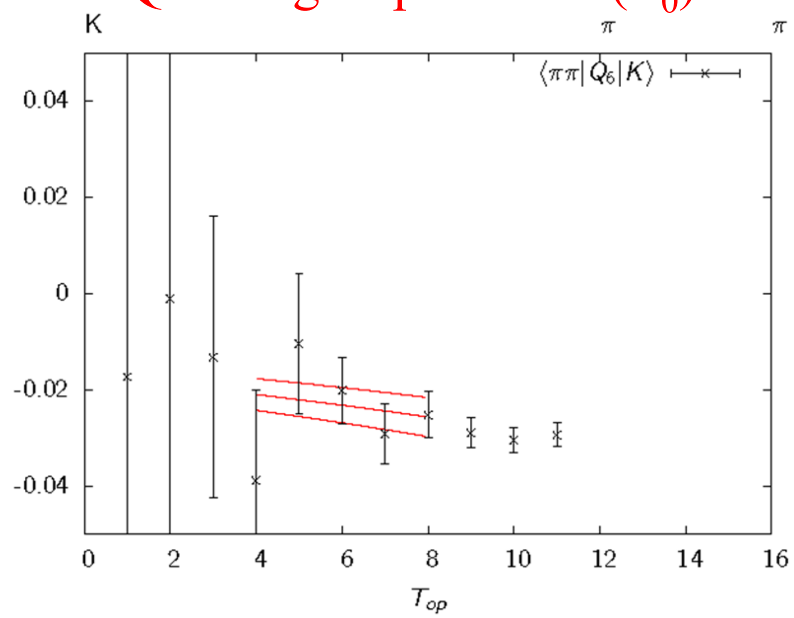
Experiment: $\mathrm{Re}(A_2) = 1.479(4)\ 10^{-8}$ GeV

Q2 - largest part of $\mathrm{Re}(A_0)$



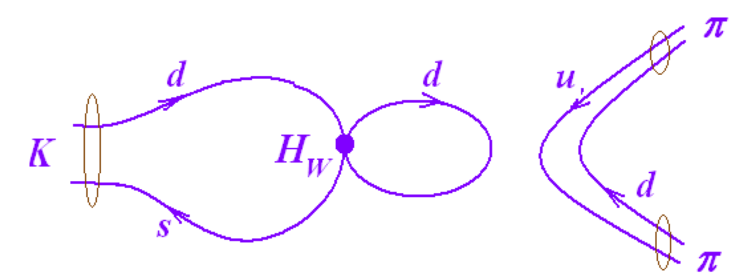

$\langle \pi\pi_{I=0}|Q_2|K\rangle = (1.92 \pm 0.75)\times10^{-3}$

Q6 - largest part of $\mathrm{Im}(A_0)$




$\langle \pi\pi_{I=0}|Q_6|K\rangle = (-1.71 \pm 0.27)\times10^{-3}$

Made much more difficult by disconnected diagrams:

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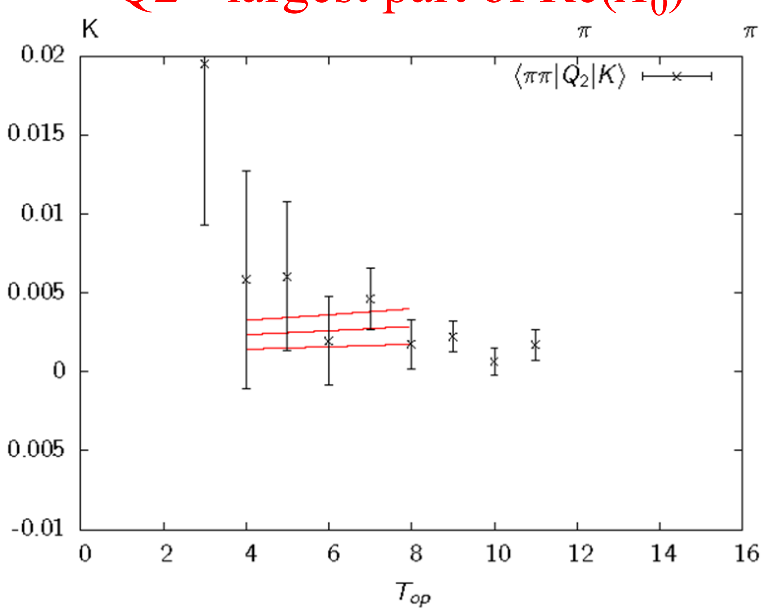


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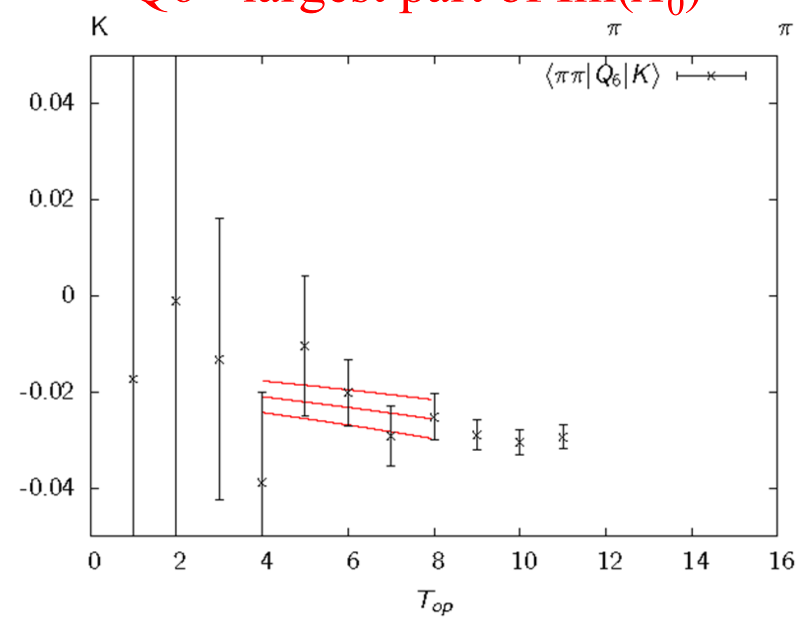


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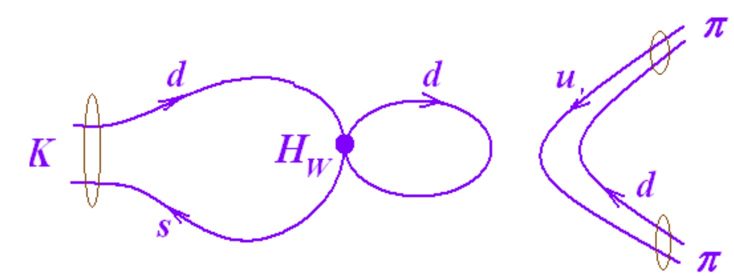



Goal is a 20% calculation of $\varepsilon'/\varepsilon$ with all errors controlled

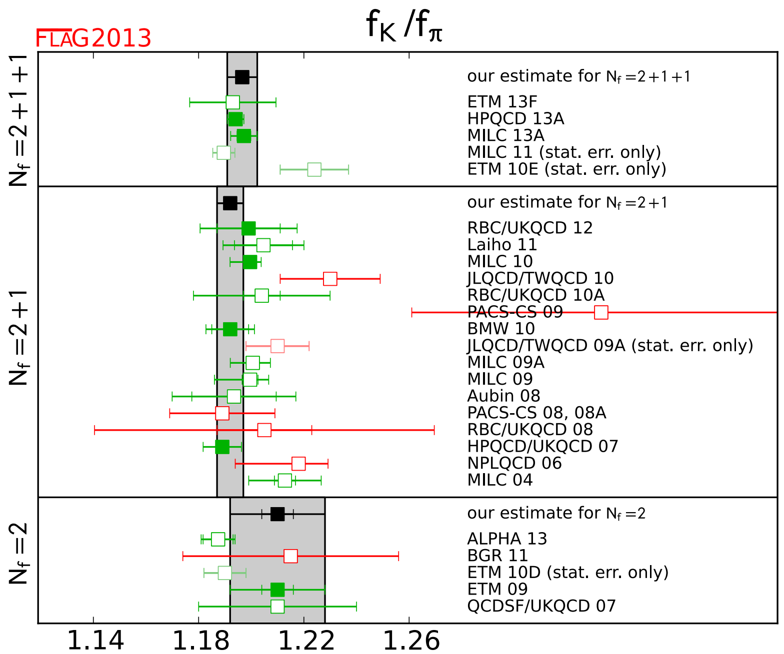
A 20% theory error on ε'/ε would give a precise constraint/signal of BSM physics. (Expt: 8% error)

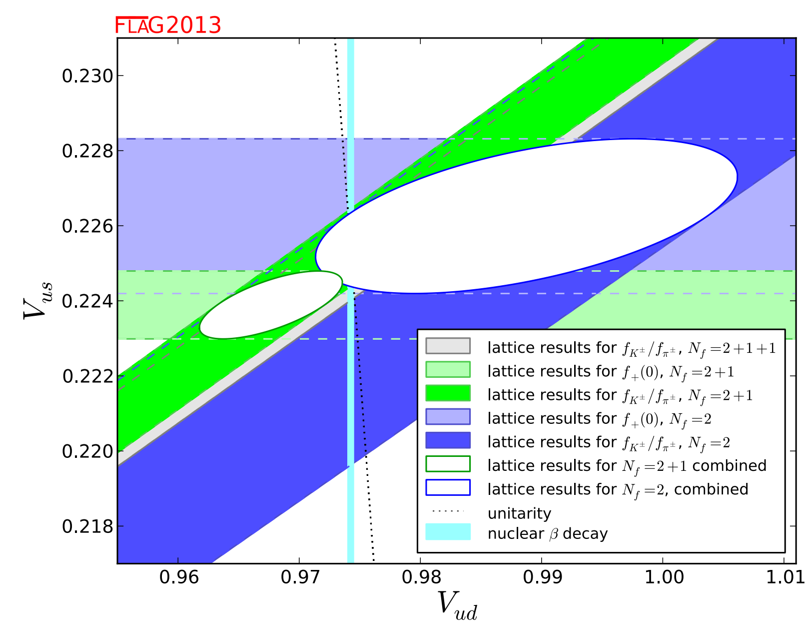
# CKM determination

Pich

$\Gamma(K^+ \to \mu^+ \nu_\mu)/\Gamma(\pi^+ \to \mu^+ \nu_\mu)$:

$$\frac{|V_{us}\, f_K|}{|V_{ud}\, f_\pi|} = 0.2763 \pm 0.0005 \quad \rightarrow \quad \frac{|V_{us}|}{|V_{ud}|} = 0.2314 \pm 0.0011$$




$$|V_{ud}| = 0.97425 \pm 0.00022 \quad , \quad |V_{us}| = 0.2245 \pm 0.0007$$

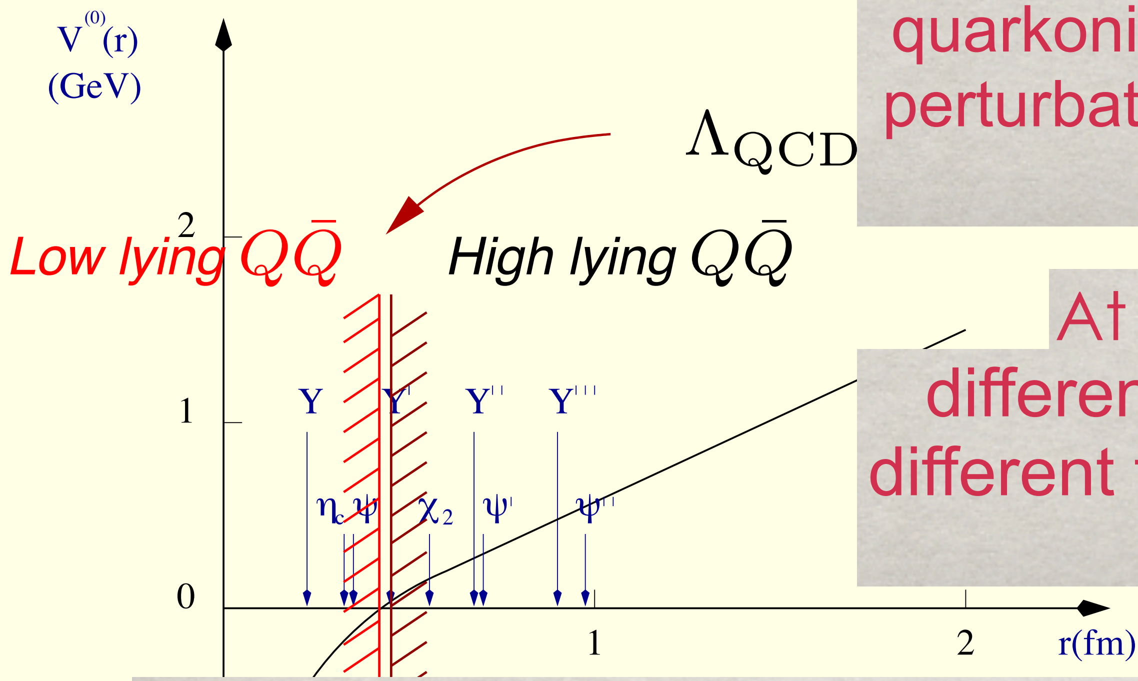
$$\Delta_{\rm CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0004 \pm 0.0007$$

many more results, see talk slides for details

# Quarkonium spectroscopy

Brambilla

The different quarkonium radii provide different measures of the transition from a Coulombic to a confined bound state.



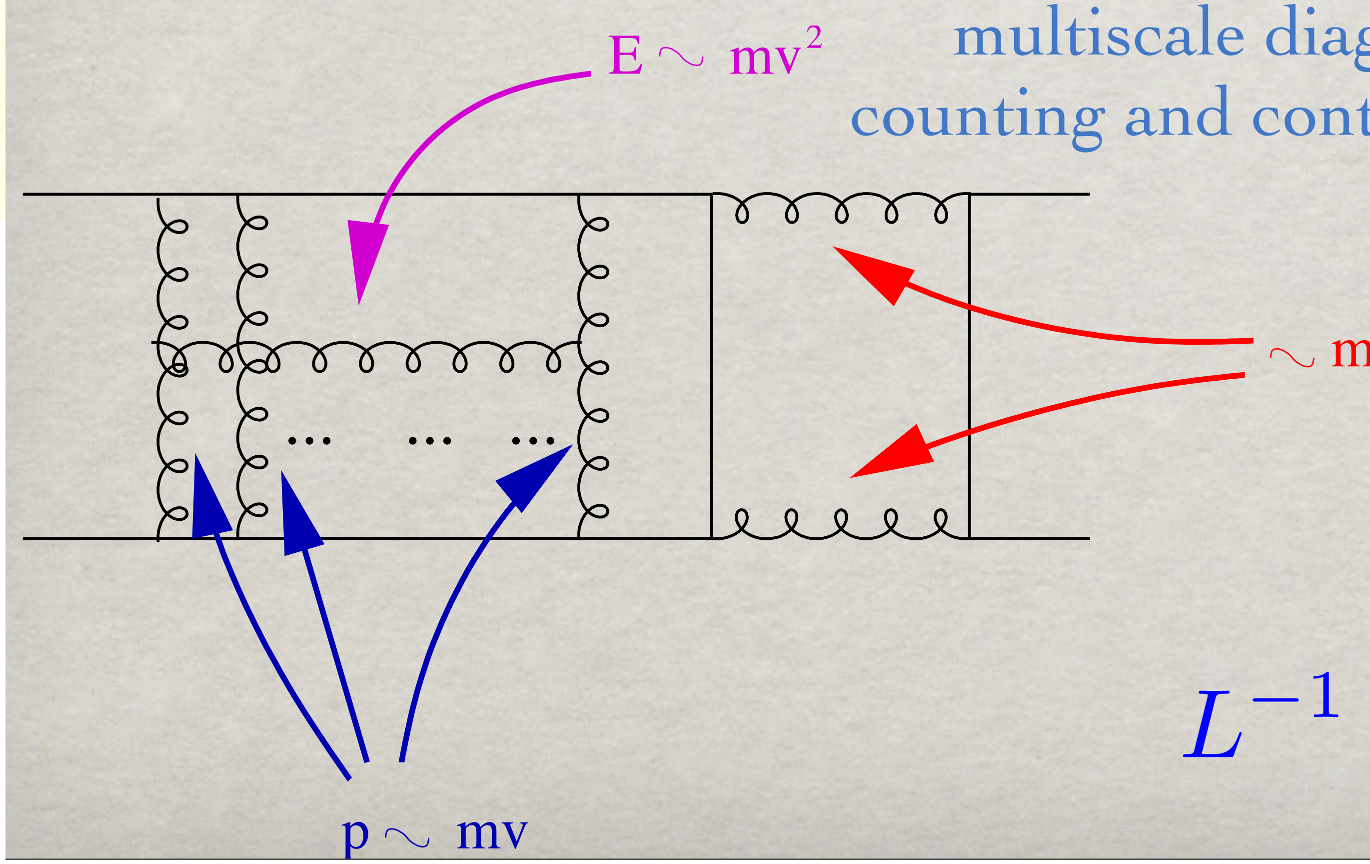

At zero temperature

quarkonia probe the perturbative (high energy) and non perturbative region (low energy) as well as the transition region in dependence of their radius r

At finite temperature ( in heavy ion collisions)

different quarkonia will dissociate in the medium at different temperatures providing a thermometer for the hot QCD plasma

multiscale diagrams have a complicate power counting and contribute to all orders in the coupling



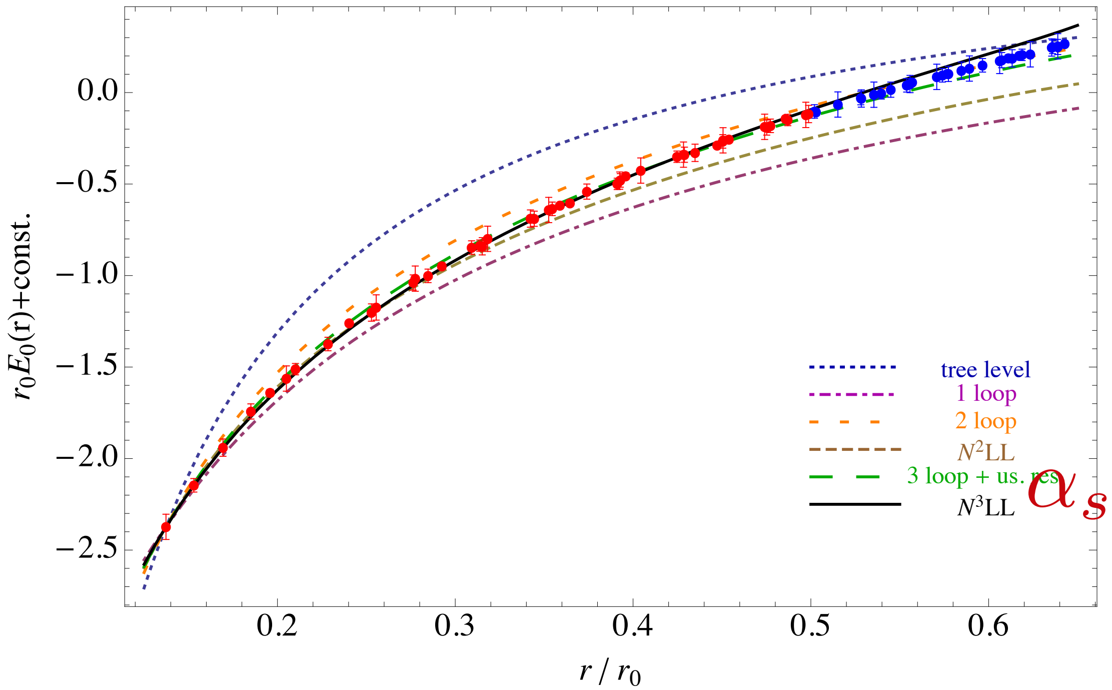

Difficult also for the lattice!

$$L^{-1} \ll \lambda \ll \Lambda \ll a^{-1}$$

## low-lying charmonia

At short distances the potential is well described by PT up to NNNLL accuracy.

Brambilla




○ Bazavov Brambilla Garcia i Tormo Petreczky Soto Vairo PRD 86 (2012) 114031

$$\alpha_s(M_z, n_f = 5) = 0.1156^{+0.0021}_{-0.0022}$$

**$\alpha_s$ determination**

## high-lying charmonia

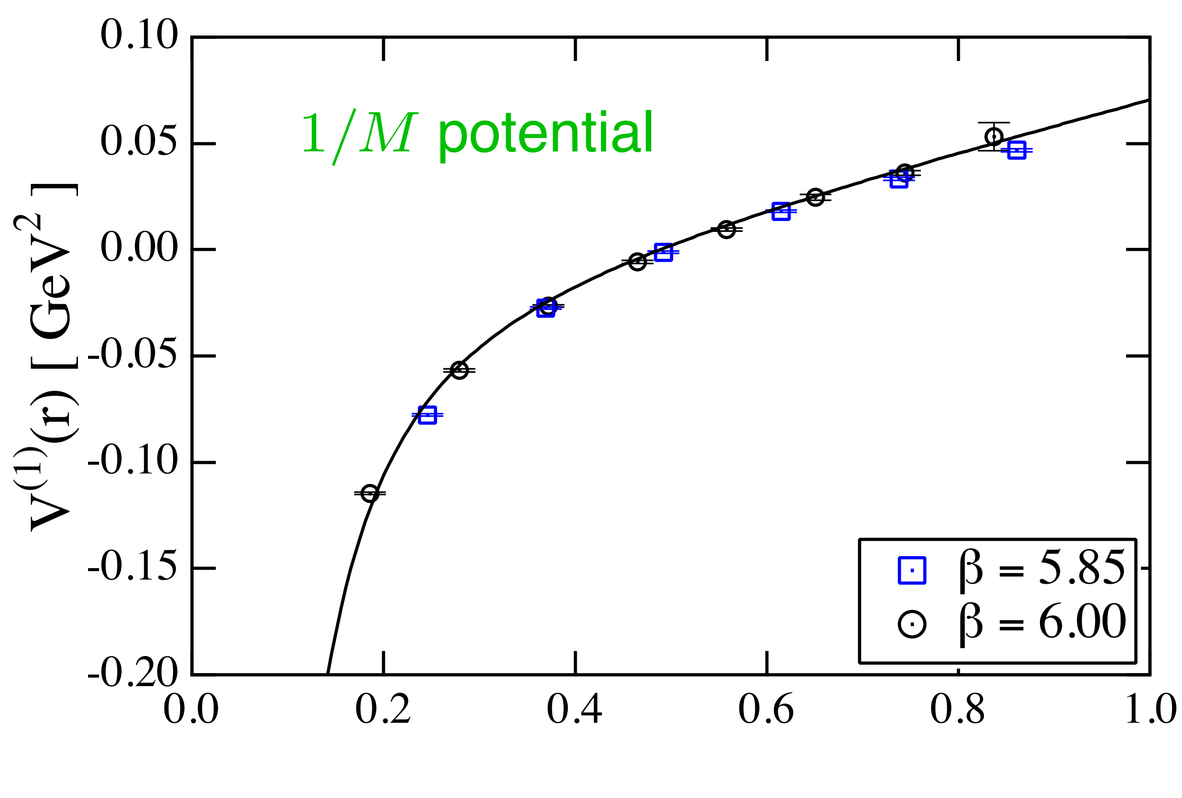
Lattice provides a non-perturbative determination of the potentials

$$V = V_0 + \frac{1}{m}V_1 + \frac{1}{m^2}(V_{SD} + V_{VD})$$

**still 1/M expansion, spin symmetry good description of data, eg**

$$M_{h_b(2P)} = 10259.76 \pm 0.64^{+1.43}_{-1.03}\ \text{MeV}$$ [Babar]

$$M_{\text{c.o.g.}}(2P) = 10260.06 \pm 0.24 \pm 0.50\ \text{MeV}$$



close to/above threshold: many degrees of freedom, molecular states, ...

Brambilla
Nieves

The $X(3872)$, with a mass of $m_X = 3871.57 \pm 0.25\,\mathrm{MeV}$, **is extremely close to the $D^{0*}\bar{D}^0$ threshold** $(m_{D^0} + m_{D^{*0}} = 3871.85 \pm 0.20\,\mathrm{MeV})$
$\Rightarrow$ **molecule?**

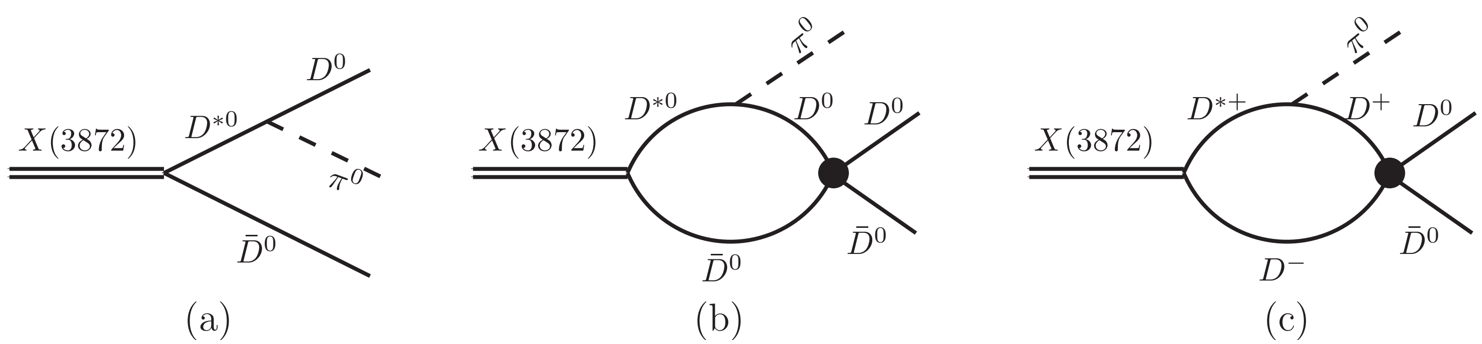
$X(3872) \sim D^0\bar{D}^{*0}\ \&\ D^+\bar{D}^{*-}$ **bound state** $(D\bar{D}^* - hc$ **with C-parity=+)**

For such a small binding energy, the mass difference **(8 MeV)** between neutral and charged channels plays a role $(m_{D^+} + m_{D^{*-}} = 3879.91 \pm 0.20\,\mathrm{MeV})$ and the **mass term breaks isospin invariance!**

employ HQ spin symmetry

Nieves

$X(3872) \to D^0\bar{D}^0\pi^0$



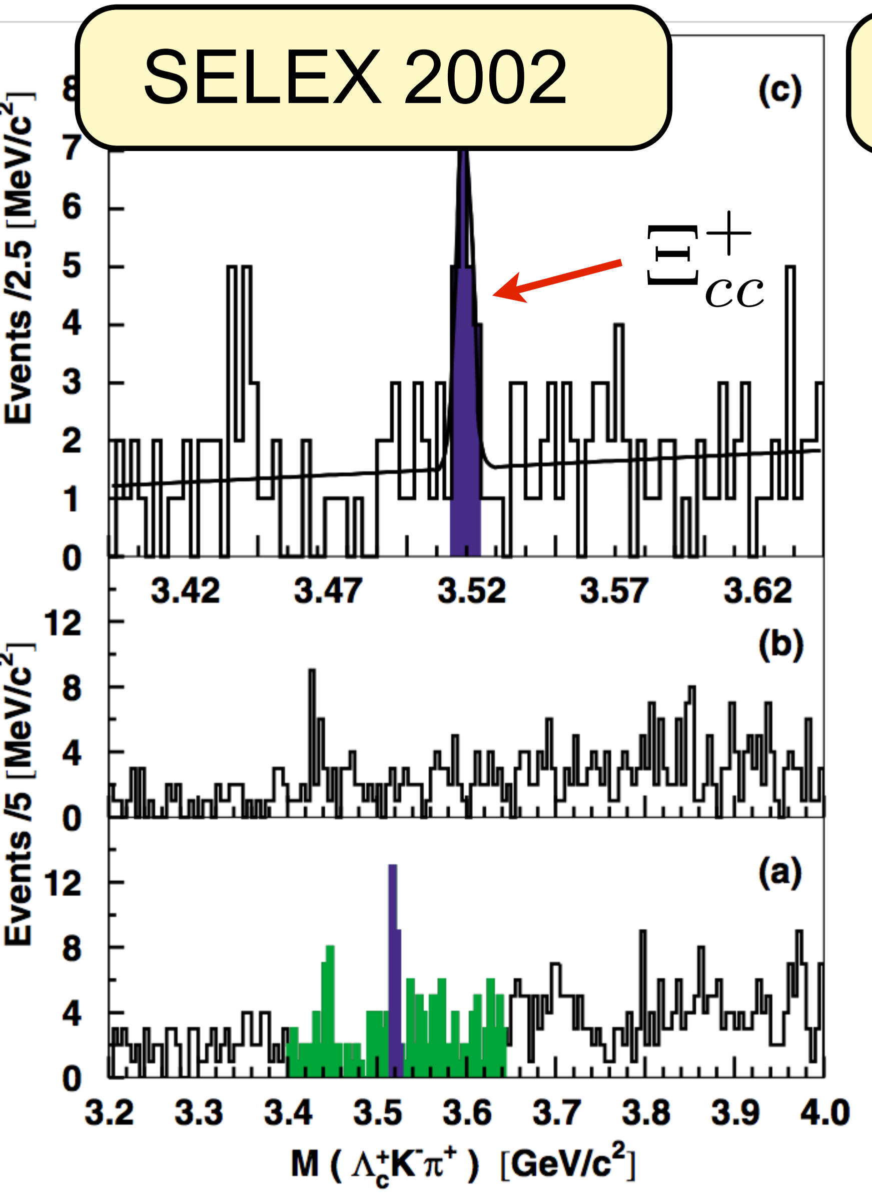

$\sim \Psi(\vec{p}_{D^0})$
**sensitive also to $D\bar{D}^*$ long-distance dynamics!**
$g_0[X(3872)\bar{D}^0 D^{*0}]$
$g_c[X(3872)D^- D^{*+}]$
$T[D^0\bar{D}^0 \to D^0\bar{D}^0]$
$T[D^+D^- \to D^0\bar{D}^0]$

$$\mathbf{\Gamma(X(3872) \to D^0\bar{D}^0\pi^0)_{tree}} = \underbrace{44.0^{+2.4}_{-7.2}}_{\mathbf{\Lambda=0.5}\ \mathrm{GeV}} \left(\underbrace{42.0^{+3.6}_{-7.3}}_{\mathbf{\Lambda=1}\ \mathrm{GeV}}\right)\ \mathrm{keV}$$

In addition to HQSS, HFS and HADS can be used to predict new heavy meson molecules and triply heavy pentaquarks

# Heavy baryons (one or more c or b)

SELEX 2002

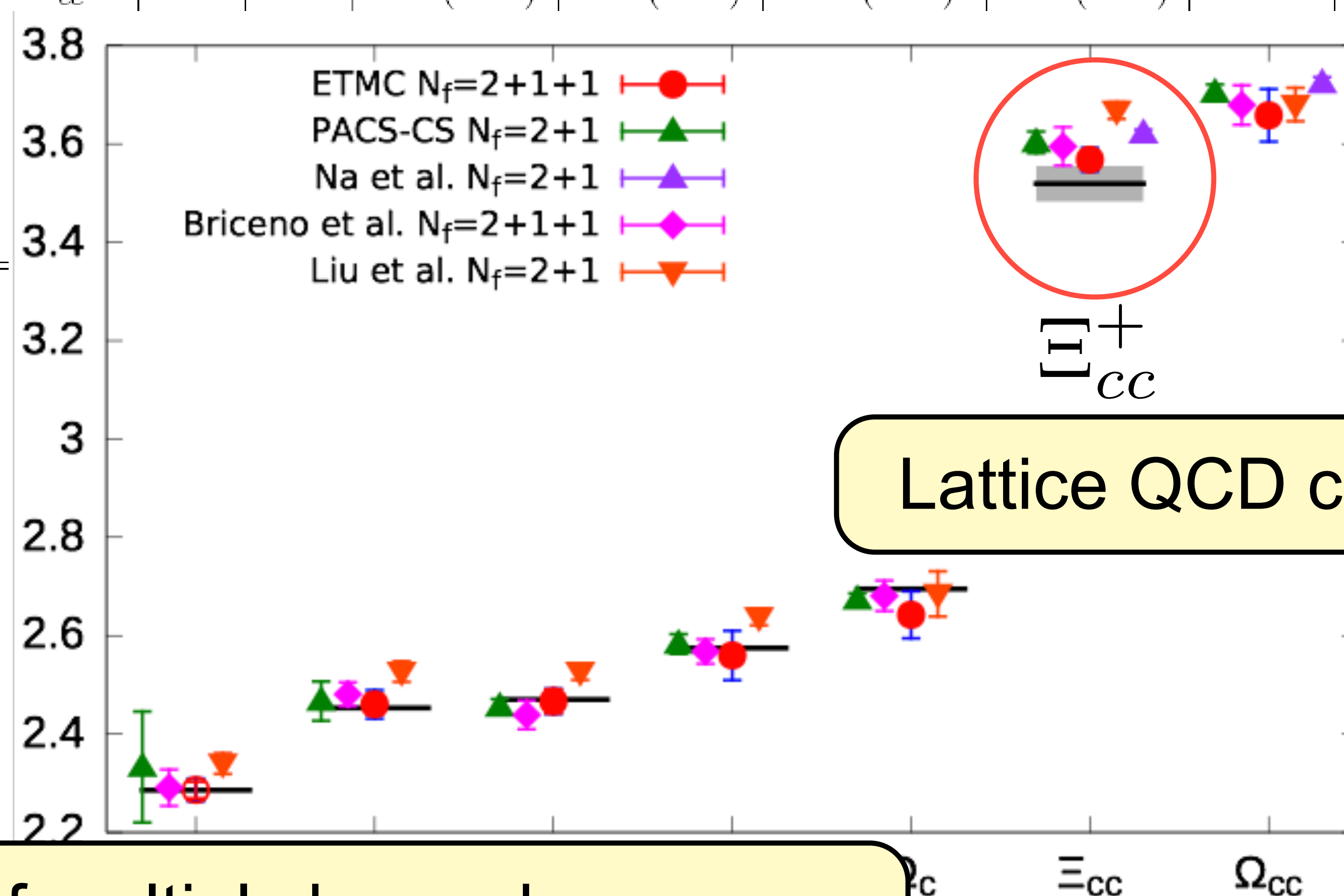



Light-cone sum rule calculation

Azizi

QCDSR, Ioffe — Quark model

| Baryon | $M^2$ | $\sqrt{s_0}$ | This work | [11] | [12] | [13] | [6] | [19] | Exp [20] |
|---|---|---|---|---|---|---|---|---|---|
| $\Xi_{bb}$ | 11.0 | 10.9 | 9.96(0.90) | 9.78(0.07) | 10.17(0.14) | 9.94(0.91) | 10.202 | – | – |
| $\Omega_{bb}$ | 11.0 | 10.9 | 9.97(0.90) | 9.85(0.07) | 10.32(0.14) | 9.99(0.91) | 10.359 | – | – |
| $\Xi_{bc}$ | 8.0 | 7.5 | 6.72(0.20) | 6.75(0.05) | – | 6.86 | 6.933 | 7.053 | – |
| $\Omega_{bc}$ | 8.0 | 7.5 | 6.75(0.30) | 7.02(0.08) | – | 6.864 | 7.088 | 7.148 | – |
| $\Xi_{cc}$ | 5.0 | 4.6 | 3.72(0.20) | 4.26(0.19) | 3.57(0.14) | 3.52(0.06) | 3.620 | 3.676 | 3.5189(0.0009) |
| | | | | | | | | 787 | – |
| | | | | | | | | 062 | – |
| | | | | | | | | 151 | – |




Lattice QCD comparison

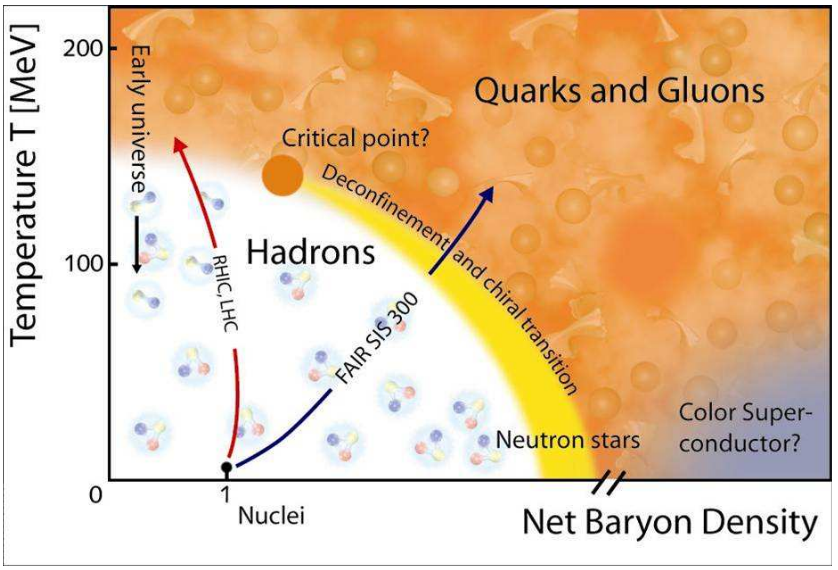
Erkol

also, find compact sizes of multiply heavy baryons

Erkol

# Phase diagram

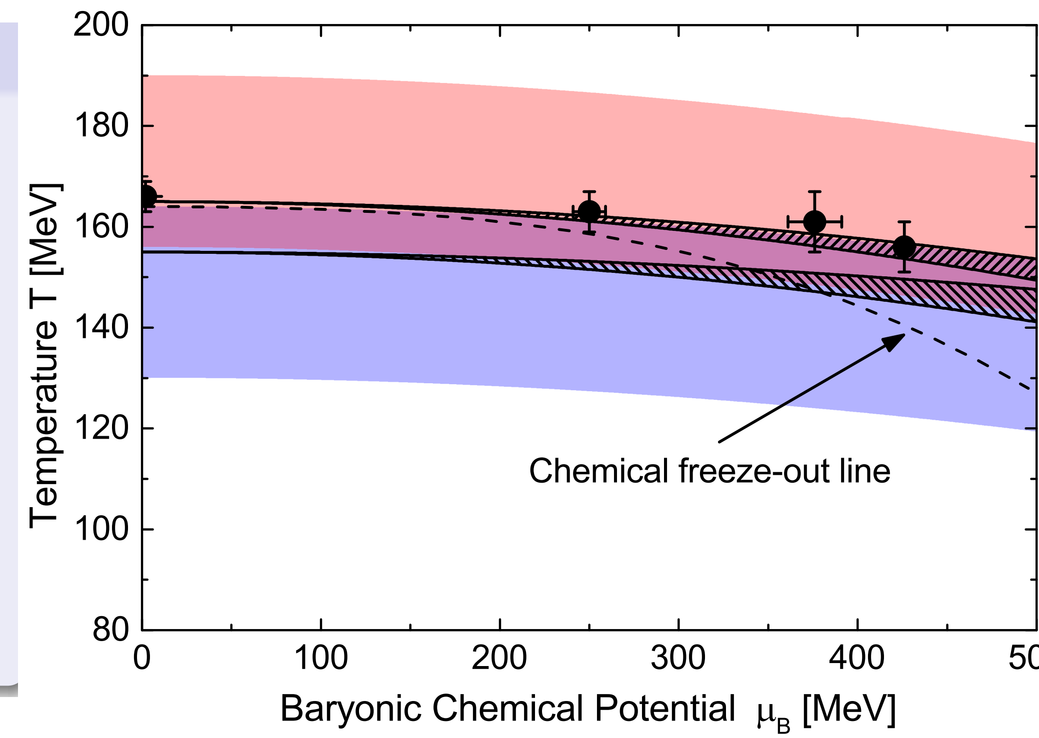
probed through heavy-ion collisions



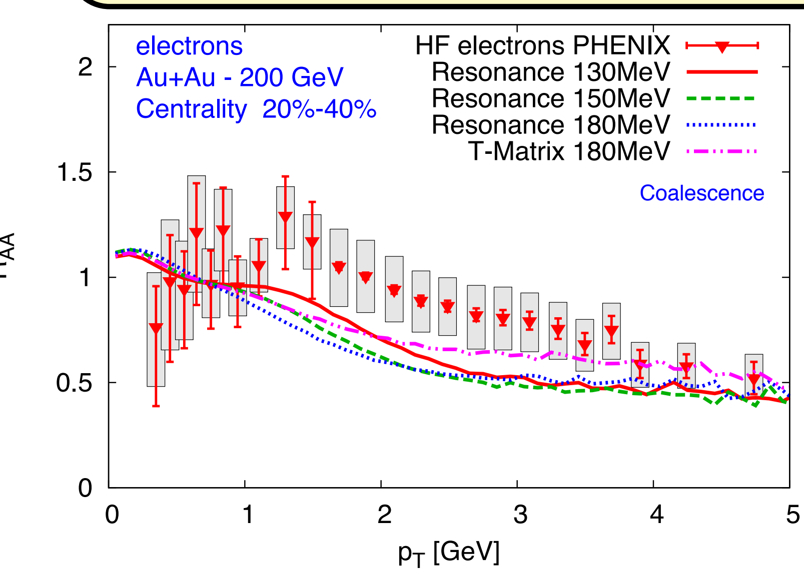

Main Questions for HI Physics:

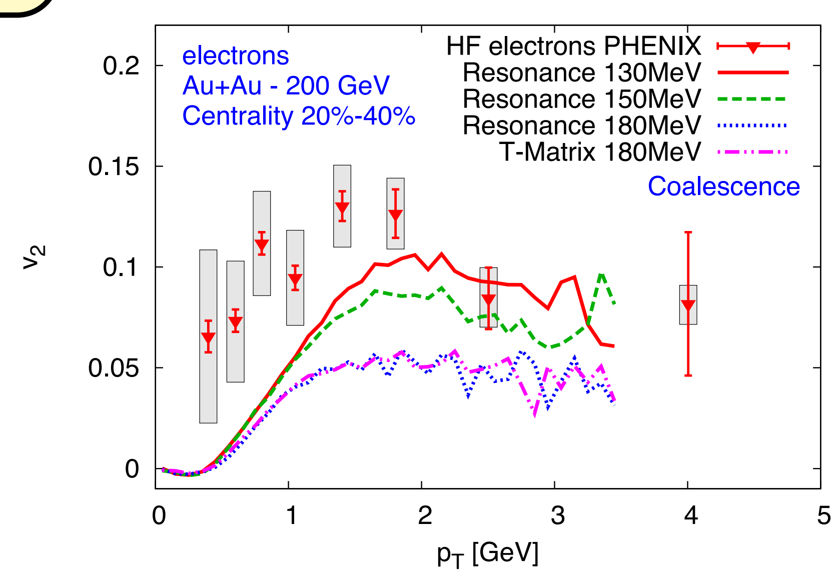
- What is the phase structure of QCD?
- Locate the Onset of deconfinement/hadronization!
- Is it a phase transition or crossover?
- What are the matter properties in the different phases?

Steinheimer




charm transport in QGP




Lesson Learned

(Hadronization) we need to understand hadronic LHC.

Hydro model + Langevin transport + coalescence + low decoupling temperature seems to work for D mesons ar RHIC.

Need to understand hadronic interactions of charmed quarks.

# Charm mixing

$$x_D = \frac{M_2 - M_1}{\Gamma_D}, \; y_D = \frac{\Gamma_2 - \Gamma_1}{2\Gamma_D}$$

Petrov

★ ...can be calculated as real and imaginary parts of a correlation function

$$y_{\rm D} = \frac{1}{2M_{\rm D}\Gamma_{\rm D}} \, {\rm Im} \, \langle \overline{D^0} | \, i \int {\rm d}^4 x \, T \left\{ \mathcal{H}_w^{|\Delta C|=1}(x) \, \mathcal{H}_w^{|\Delta C|=1}(0) \right\} | D^0 \rangle$$

bi-local time-ordered product

$$x_{\rm D} = \frac{1}{2M_{\rm D}\Gamma_{\rm D}} \, {\rm Re} \left[ 2\langle \overline{D^0} | H^{|\Delta C|=2} | D^0 \rangle + \langle \overline{D^0} | \, i \int {\rm d}^4 x \, T \left\{ \mathcal{H}_w^{|\Delta C|=1}(x) \, \mathcal{H}_w^{|\Delta C|=1}(0) \right\} | D^0 \rangle \right]$$

local operator (b-quark, NP): small?

bi-local time-ordered product

★ Theoretically, $y_D$ is dominated by long-distance SM-dominated effects

★ CP-violating phases can appear from subleading local SM or NP operators

★ Comparing to experimental value of x, obtain constraints on NP models

- assume x is dominated by the New Physics model
- assume no accidental strong cancellations b/w SM and NP

New Physics is either at a very high scales

tree level: $\Lambda_{NP} \geq (4-10) \times 10^3$ TeV

loop level: $\Lambda_{NP} \geq (1-3) \times 10^2$ TeV

or have highly suppressed couplings to charm!

$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu) Q_i'$$

$$\begin{aligned} Q_1^{cu} &= \bar{u}_L^\alpha \gamma_\mu c_L^\alpha \bar{u}_L^\beta \gamma^\mu c_L^\beta, \\ Q_2^{cu} &= \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta, \\ Q_3^{cu} &= \bar{u}_R^\alpha c_L^\beta \bar{u}_R^\beta c_L^\alpha, \end{aligned} + \left\{ \begin{array}{c} L \\ \updownarrow \\ R \end{array} \right\} + \begin{aligned} Q_4^{cu} &= \bar{u}_R^\alpha c_L^\alpha \bar{u}_L^\beta c_R^\beta, \\ Q_5^{cu} &= \bar{u}_R^\alpha c_L^\beta \bar{u}_L^\beta c_R^\alpha, \end{aligned}$$

Gedalia, Grossman, Nir, Perez
Phys.Rev.D80, 055024, 2009

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
Phys. Rev. D76:095009, 2007

# CPV in charm decay

★ Experiment: the difference of CP-asymmetries: $\Delta a_{CP} = a_{CP,KK} - a_{CP,\pi\pi}$

Petrov

Fajfer

Earlier results (before 2013):

| Experiment | $\Delta A_{CP}$ |
|---|---|
| LHCb | $(-0.82 \pm 0.21 \pm 0.11)\%$ |
| CDF | $(-0.62 \pm 0.21 \pm 0.10)\%$ |
| Belle | $(-0.87 \pm 0.41 \pm 0.06)\%$ |
| BaBar | $(+0.24 \pm 0.62 \pm 0.26)\%$ |

· results (after 2013):

$$\Delta a_{CP} = (+0.14 \pm 0.16(\text{stat}) \pm 0.08(\text{syst}))\,\%$$
$$a_{CP,KK} = (-0.06 \pm 0.15(\text{stat}) \pm 0.10(\text{syst}))\,\%$$
$$a_{CP,\pi\pi} = (-0.20 \pm 0.19(\text{stat}) \pm 0.10(\text{syst}))\,\%$$

LHCb arXiv:1405.2797

CPV no longer significant
sizable U-spin breaking?

future: lattice QCD for
charm DCPV?

Can these methods be generalized to D-decays?

- make D-meson slightly lighter, $m_D < 4\, m_\pi$
- assume G-parity and consider scattering of two pions and two kaons in a box with SM scattering energy

$$2m_\pi < 2m_K < E^* < 4m_\pi$$

Hansen, Sharpe
PRD86, 016007 (2012)

- only four possible scattering events: $\pi\pi\to\pi\pi$, $\pi\pi\to KK$, $KK\to\pi\pi$, $KK\to KK$
- couple the two by adding weak part to the strong Hamiltonian $\mathcal{H}(x) \to \mathcal{H}(x) + \lambda\mathcal{H}_W(x)$

# Rare charm decay

generic issue:

Fajfer

- LD dominates decay rates. Main issue: how to observe NP “screened” by LD contribution:

# Rare charm decay

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Fajfer

- LD dominates decay rates. Main issue: how to observe NP "screened" by LD contribution:
  - charm quark not heavy enough for HQET;
  - charm mesons are having masses above scale $\chi$PT.

No adequate theoretical framework!

# Rare charm decay

Fajfer

generic issue:

- LD dominates decay rates. Main issue: how to observe NP "screened" by LD contribution:
  - charm quark not heavy enough for HQET;
  - charm mesons are having masses above scale χPT.

CP violation in rare charm decays

nework!

| Mode | CP violating observable | Size (2014) | reference |
|---|---|---|---|
| $D \to \rho/\omega\gamma$ | $\not{CP}$ asymmetry | < 3% | 1205.3164; 1210.6546 |
| $D \to K^+K^-\gamma$ | $\not{CP}$ asymmetry (<$m_\varphi$,>$m_\varphi$) | < 0.7%(<2%) | 1205.3164 |
| $D \to hh\mu^+\mu^-$ | $\not{CP}$ asymmetry (on φ res.) | ~ 0.7% | 1209.4235 |
| $D \to \pi\mu^+\mu^-$ | $\not{CP}$ asymmetry (on φ res.) | ~3 % (0.7%) | 1208.0795 |
| $D \to X_u l^+ l^-$ | $\not{CP}$ asymmetry | ~ 5% | |

see talk slides for a comprehensive literature review

- LD + SD contributions are reinvestigated within SM and NP (CPC and CPV) ;
- Lattice QCD should help in understanding hadronic inputs;
- New observables have been suggested to test CP violation, or NP;
- In these decays CP violating asymmetries are on the 1% level;
- NP effects in B, K and LHC physics are correlated with NP effects in charm physics.

# B mesons: lattice

b quark sufficiently heavy that expansion in $\Lambda_{QCD}/m_b$ phenomenologically useful. Already discussed heavy quarkonia

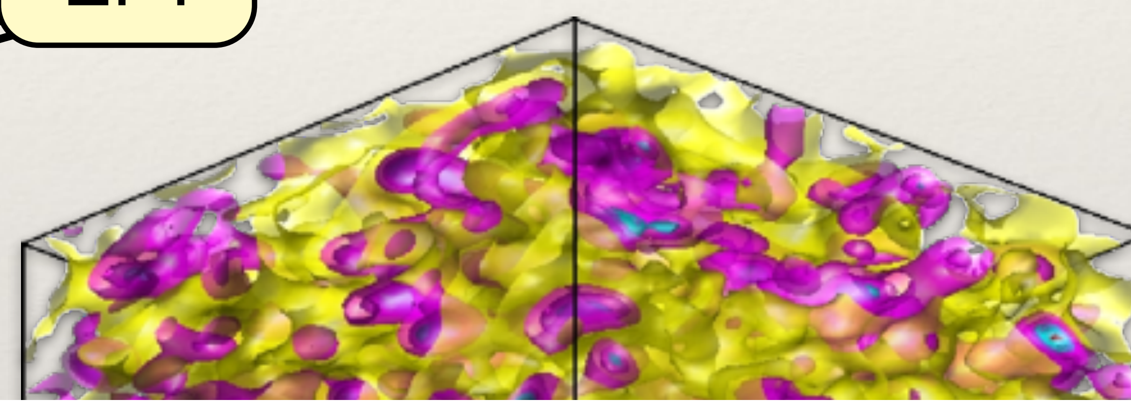
Lattice:

Jüttner

## What we can do

- mass degenerate up and down quarks at their physical point
- physical strange and charm quarks ($\rightarrow N_f = 2,\ 2+1,\ 2+1+1$ QCD)
- bottom needs special treatment
- cut-off $a^{-1} \leq 4\text{GeV}$
- volume $L \leq 6fm$

EFT



**Standard:** single incoming and/or outgoing pseudo-scalar states

- $\pi, K, D_{(s)}, B_{(s)} \rightarrow \text{QCD} - \text{vacuum}$
- $\pi \rightarrow \pi, K \rightarrow \pi, D \rightarrow K, B \rightarrow \pi, \ldots$
- $B_K, (B_D), B_B$

heavy quark quantities still pose considerable technical challenges and results are less mature

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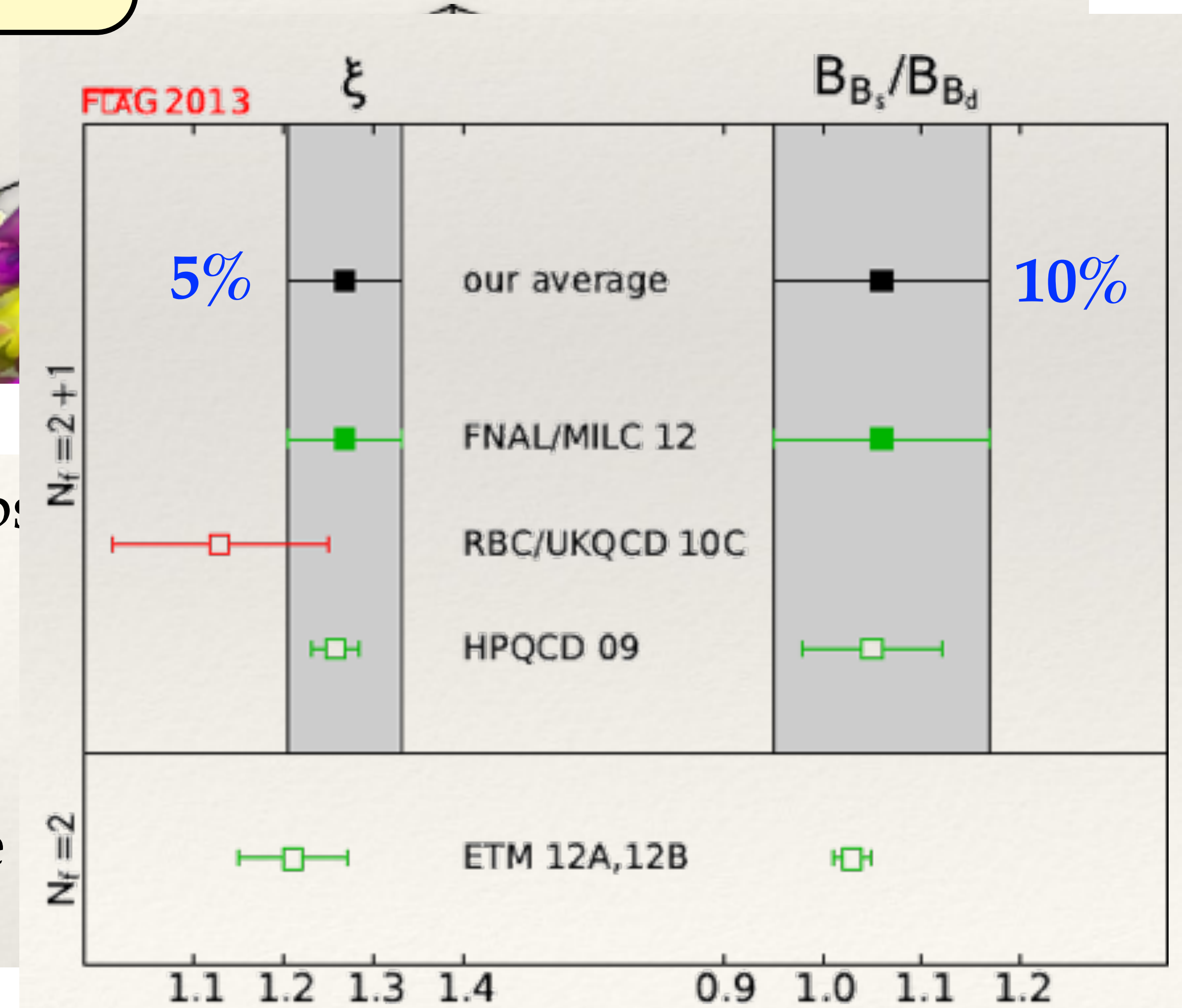


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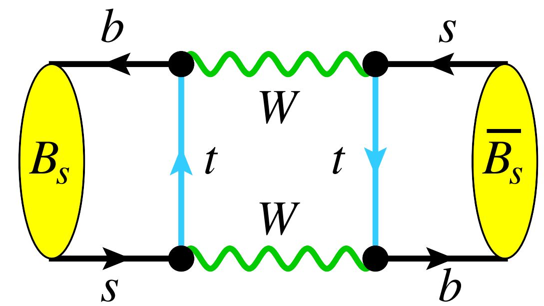
# B mixing and new physics

Bobeth

## Theory predictions of $M_{12}^q \longrightarrow \Delta M_q = 2\,|M_{12}^q|$

Short-distance (decoupling of $W$'s and top's in box diagrams) + local matrix element

$$M_{12}^q = \frac{G_F^2}{12\pi^2}\left(V_{tb}V_{tq}^*\right)^2 M_W^2 S_0(x_t)\hat{\eta}_B B_{B_q} f_{B_q}^2 M_{B_q}$$




- Short-distance under control

  1-loop result $S_0(x_t = m_t^2/m_W^2)$ [Inami/Lim Prog.Theor.Phys. 65 (1981) 297]
  2-loop QCD corrections $\hat{\eta}_B$ [Buras/Jamin/Weisz Nucl.Phys. B347 (1990) 491]
  2-loop EW corrections tiny (usually neglected) [Gambino/Kwiatkowski/Pott hep-ph/9810400]

- Hadronic matrix element $\left\langle \overline{B}_q|(\bar{b}q)_{V-A}(\bar{b}q)_{V-A}|B_q\right\rangle = \frac{8}{3} B_{B_q} f_{B_q}^2 M_{B_q}$

  ⇒ preciser Lattice results become available (talk A. Jütter) [averages from FLAG arXiv:1310.8555]

| [MeV] | $N_f = 2+1$ | $\delta(\Delta M_q)$ | | $N_f = 2+1$ | $\delta(\Delta M_q)$ |
|---|---|---|---|---|---|
| $f_{B_s}$ | $227.7 \pm 4.5$ | 4.0% | $\hat{B}_{B_s}$ | $1.33 \pm 0.06$ | 4.5% |
| $f_{B_d}$ | $190.5 \pm 4.2$ | 4.4% | $\hat{B}_{B_d}$ | $1.27 \pm 0.10$ | 7.9% |

- and CKM we would like to determine from experiment . . .
  . . . and confront with tree-fit (semileptonic, $B \to D^{(*)}K$) results

  ⇒ however, when taking UTfit tree-fit (pre-Moriond 2013): [www.utfit.org]
  rel. err. on $V_{ts}$ ($V_{td}$) about 2.5% (6%) induces 5% (12%) uncertainty on $\Delta M_s$ ($\Delta M_d$)

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Bobeth

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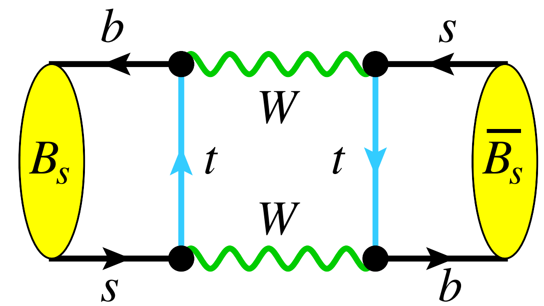


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[Inami/Lim Prog.Theor.Phys. 65 (1981) 297]
[Buras/Jamin/Weisz Nucl.Phys. B347 (1990) 491]
[Lenz/Nierste/CKMfitter 1203.0238v2 and update FPCP 2013]

- Hadronic matrix element

  $\Rightarrow$ preciser Lattice results become available (ta

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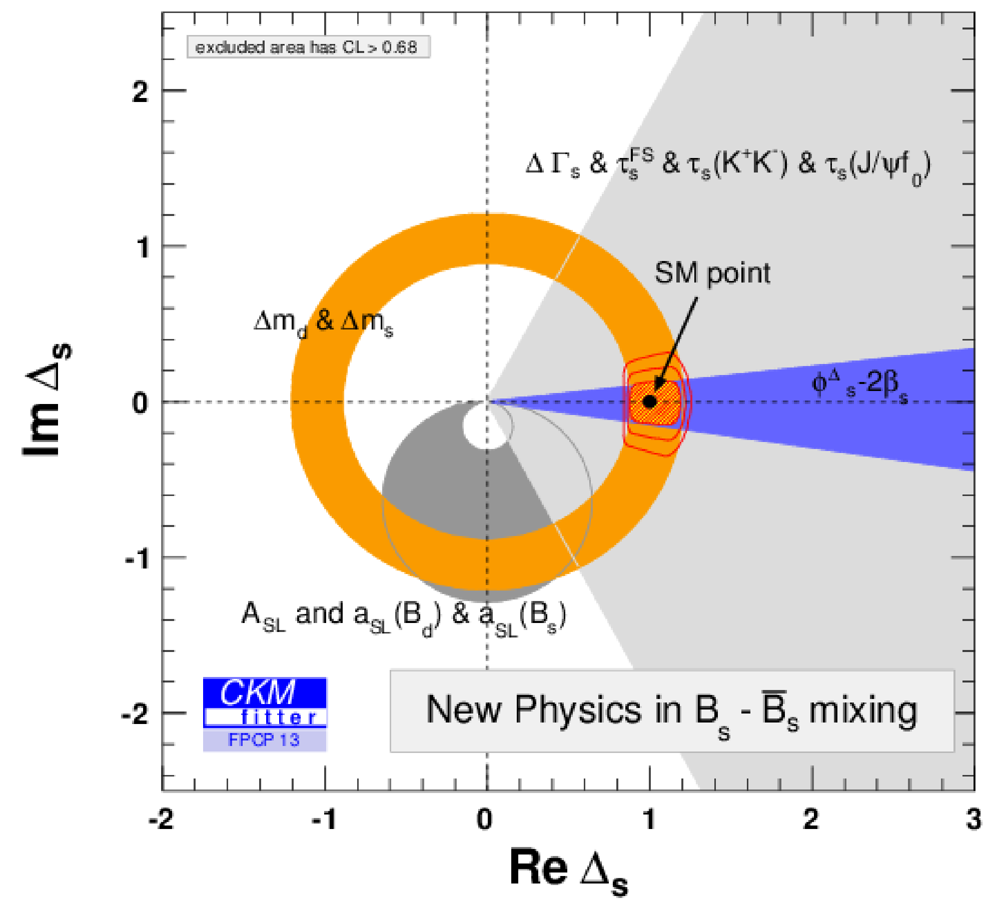
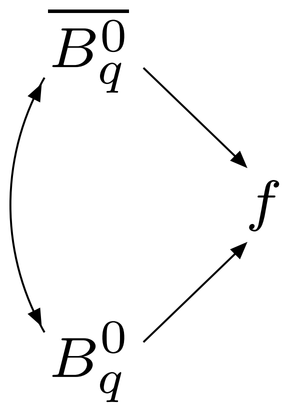


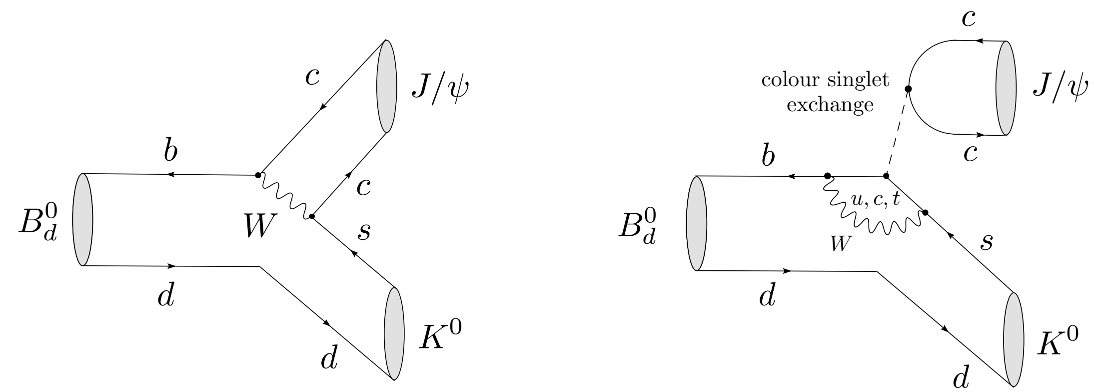
# Mixing phase measurement accuracy

## The Decay $B_d \to J/\psi K_S$

Fleischer

Interference effects through $B_q^0$–$\overline{B_q^0}$ mixing:



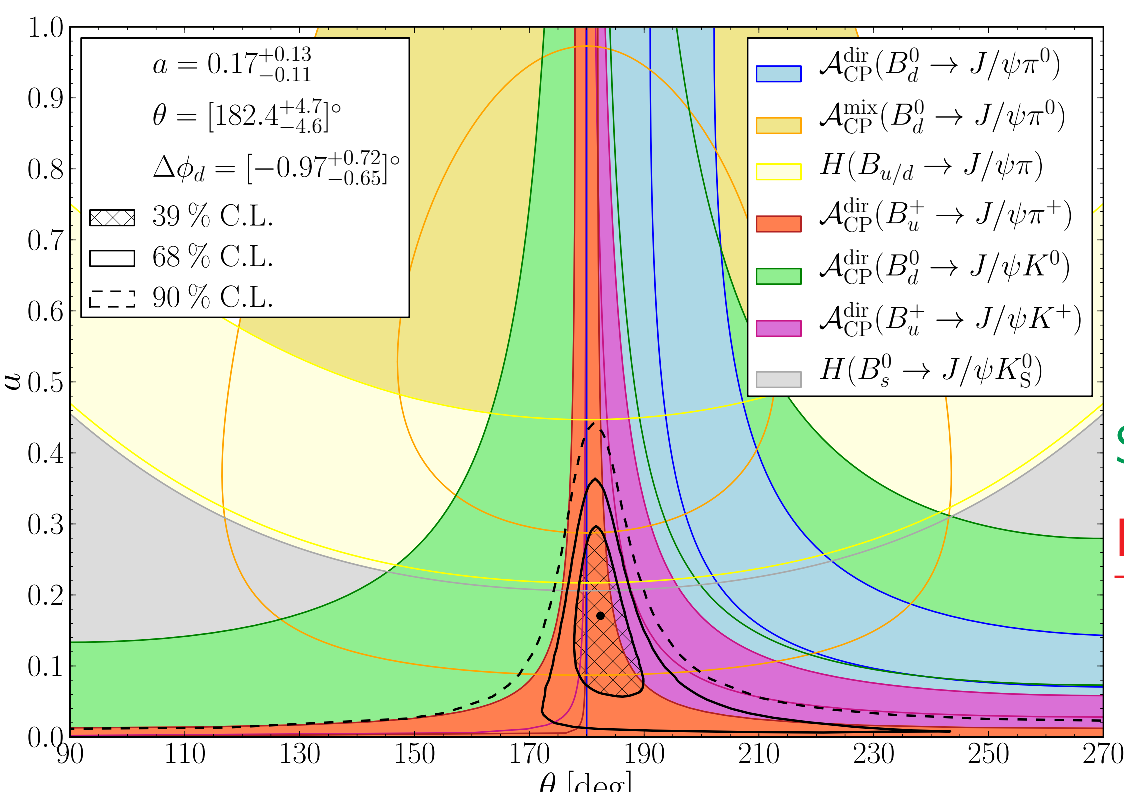




Uncertainties from doubly Cabibbo-suppressed *penguin* contributions.

$$\tan \Delta\phi_d = \frac{2\epsilon a' \cos\theta' \sin\gamma + \epsilon^2 a'^2 \sin 2\gamma}{1 + 2\epsilon a' \cos\theta \cos\gamma + \epsilon^2 a'^2 \cos 2\gamma} \qquad a' e^{i\theta'} \sim R_b \left[\frac{\text{“pen”}}{\text{“tree”}}\right]$$

using U(spin) related data to constrain incalculable a’,θ’

work in progress with Kristof De Bruyn [See also Ciuchini, Pierini & Silvestrini (’05); Faller, R.F., Jung & Mannel (’08); Jung




obtain $\Delta\phi_d = (-0.97^{+0.72}_{-0.65})^\circ$

$$\phi_d = (42.7 \pm 1.7|_S \pm 0.7|_{\Delta\phi_d})^\circ = (43.0 \pm 1.8)^\circ$$

Situation is similar in the extraction of $\phi_s$ from $B_s \to J/\psi\phi$ ...

LHCb strategy document [arXiv:1208.3355]:

$\to$ theory uncertainty of $\phi_s$ measurement quoted as $\sim 0.003 = 0.17^\circ$!?

# B mixing and new physics (2)

analysis of DØ 10.4 fb$^{-1}$ [DØ arXiv:1310.0447]

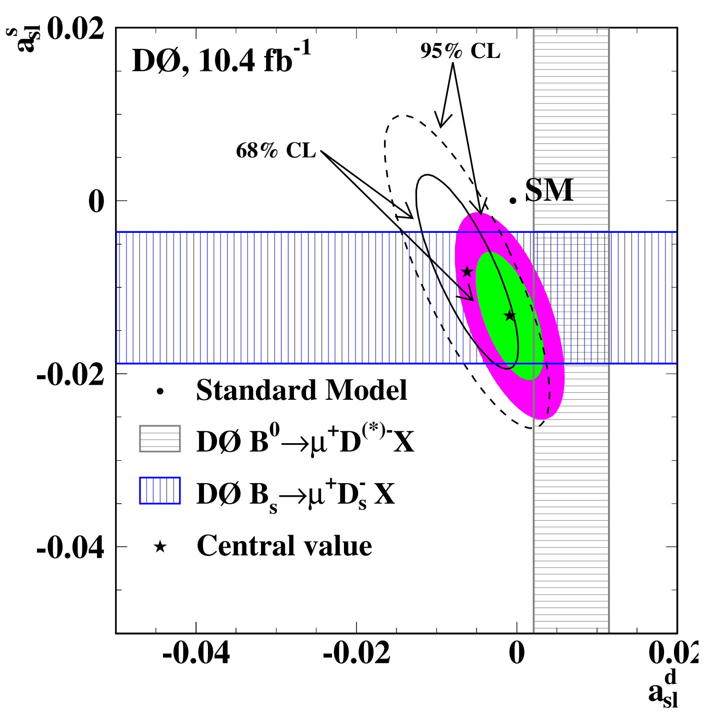
complex analysis of $A_{\rm CP}$ and $a_{\rm CP}$ in several bins of $\mu$-impact pmr. (IP)

allows for combined fit of $a^d_{\rm fs}$, $a^s_{\rm fs}$ and $\Delta\Gamma_d$

$$a^d_{\rm fs} = (0.62 \pm 0.43)\%, \quad a^s_{\rm fs} = (-0.82 \pm 0.99)\%, \quad \Delta\Gamma_d/\Gamma_d = (0.50 \pm 1.38)\%$$

$\Rightarrow$ 3.0$\sigma$ away from SM

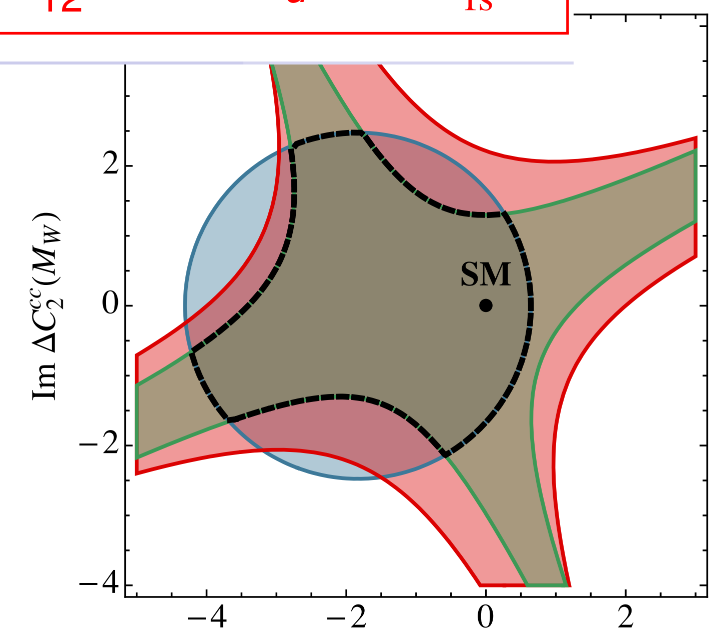
$\Rightarrow$ How well can we constrain NP to $\Gamma^d_{12} \longrightarrow \Delta\Gamma_d$ and $a^d_{\rm fs}$?




fitting also $\Delta\Gamma_d/\Gamma_d$

Model-independently, $\Delta B = 1$ dim-6 opera

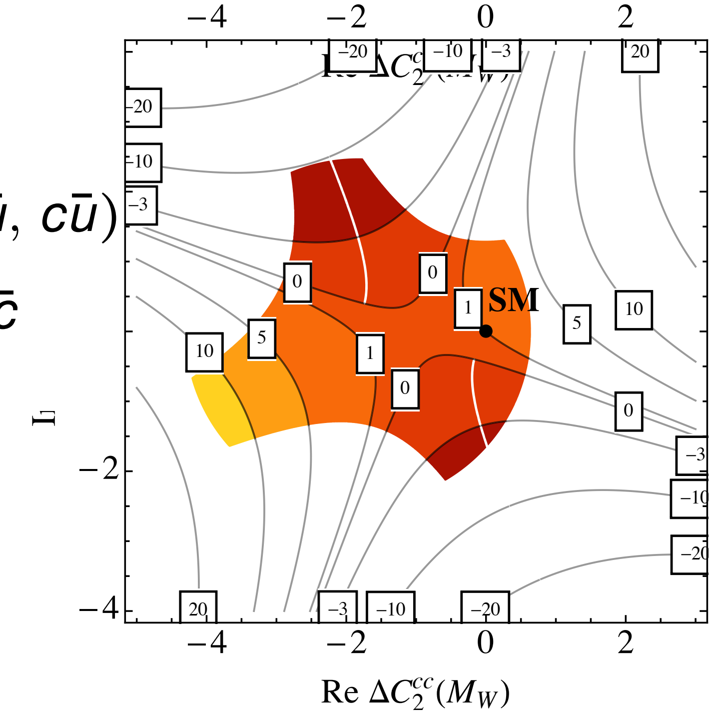
$b \to d + (u\bar{u},\, c\bar{u},\, c\bar{c})$




used experimental constraints from
$B \to \pi\pi,\ \rho\pi,\ \rho\rho,\ D^*\pi,\ X_d\gamma$ and $\sin 2\beta$

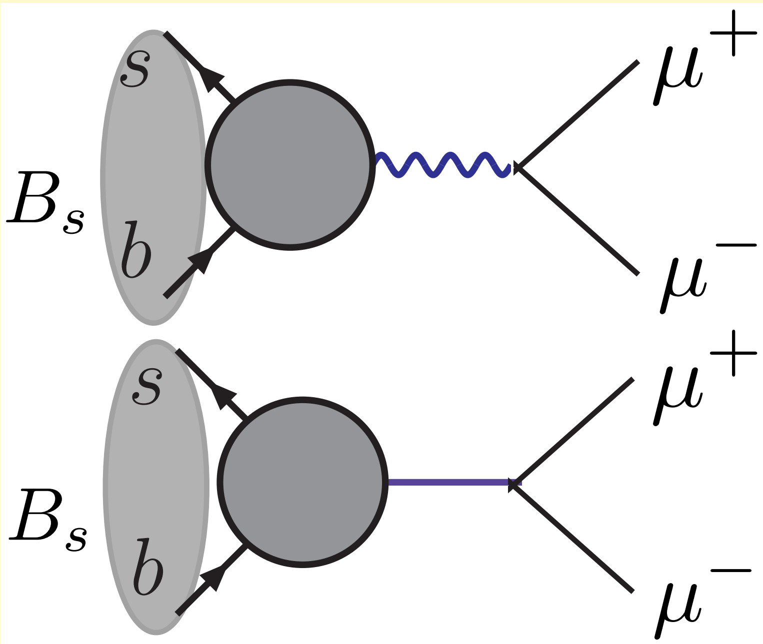
$\Delta\Gamma_d/\Delta\Gamma^{\rm SM}_d \in [-1.0, 1.4]$ for $b \to d + (u\bar{u},\, c\bar{u})$

huge effects of several 100% in $b \to d\, c\bar{c}$
can not be ruled out



# Rare leptonic B decays

Steinhauser




very NP sensitive (EW penguin, helicity suppression)

- NLO QCD corrections [Buchalla,Buras'93'99; Misiak,Urban'99]
- leading-$m_t$ NLO electroweak corrections [Buchalla,Buras'98]
- uncertainty (from higher orders): $\approx 7\%$

exp uncertainty will match this within a few years

- NNLO QCD
- NLO EW

[Bobeth,Gorbahn,Hermann,Misiak,Stamou,Steinhauser'13]

**missing** $\mathcal{O}(\alpha_{em})$

- no enhancement factor (like $\frac{1}{\sin^2\theta_W}$, $\frac{m_t^2}{M_W^2}$ or $\ln^2\frac{M_W^2}{\mu_b^2}$)
- soft Bremsstrahlung: $B_s \to \mu^+\mu^- + (n\gamma)$ $(n = 0, 1, 2, \ldots)$
- Can QED corrections ($\alpha_{em}/\pi \approx 2\times 10^{-3}$) remove helicity suppression factor ($m_\mu^2/M_{B_s}^2 \approx 10^{-4}$)?

Conclusion after careful analysis:

helicity suppression remains

$$\overline{\mathcal{B}}_{s\mu} = (3.65 \pm 0.06)\, R_{t\alpha}\, R_s \times 10^{-9} = 3.65 \pm 0.23 \times 10^{-9}$$

$$\overline{R}_{ql} = \frac{\overline{\mathcal{B}}_{ql}}{(\overline{\mathcal{B}}_{ql})_{\rm SM}} = \frac{1 + \mathcal{A}^{ll}_{\Delta\Gamma}\, y_q}{1 + y_q}\left(|S|^2 + |P\right.$$

$$R_s = \left(\frac{f_{B_s}[\mathrm{MeV}]}{227.7}\right)^2 \left(\frac{|V_{cb}|}{0.0424}\right)^2 \left(\frac{|V_{tb}^\star V_{ts}/V_{cb}|}{0.980}\right)^2 \frac{\tau_H^s\,[\mathrm{ps}]}{1.615}$$

# B physics: light-cone sum rules (LCSR)

- predict heavy-light form factors in the large recoil region
- provide "soft" form factors and power suppressed terms

for the QCD factorization theorems

Khodjamirian

- accuracy at 10-15 % level;

quark-hadron duality - an important issue

- applications to nonlocal hadronic matrix elements in

$b \to s\ell\ell$ exclusive transitions

e.g. for B->pi form factors at large recoil (lattice cannot do at present)

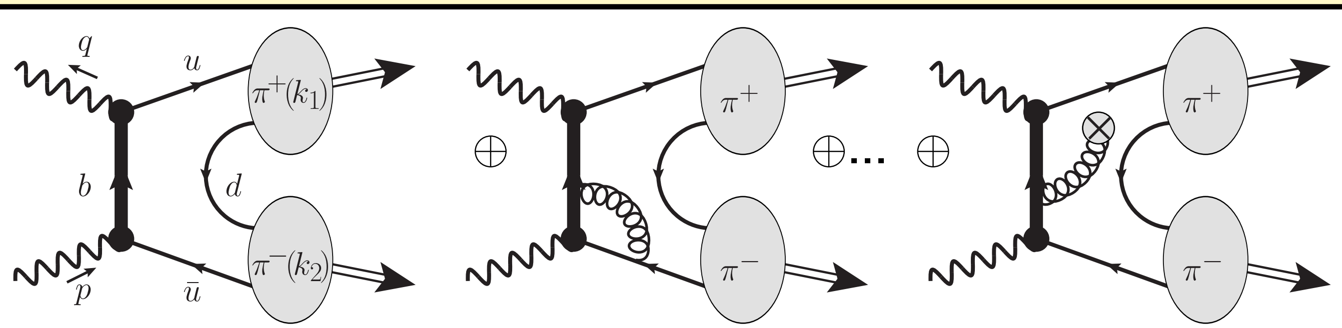
$$[F((p+q)^2, q^2)]_{OPE} = \frac{m_B^2 f_B f_{B\pi}^+(q^2)}{m_B^2 - (p+q)^2} + \int_{s_0^B}^{\infty} ds \frac{[\mathrm{Im} F(s, q^2)]_{OPE}}{s-(p+q)^2}$$

$\Uparrow$ $\overline{m}_b, \alpha_s, \varphi_\pi^{(t)}(u)$, t=2,3,4;

$\Uparrow$ QCD SR for $f_B$

$\Uparrow$ quark-hadron duality

new application: B->pi pi form factors (avoid narrow-width approximation




new nonperturbative input: timelike pion form factors

# B form factors in improved quark model

Hernandez

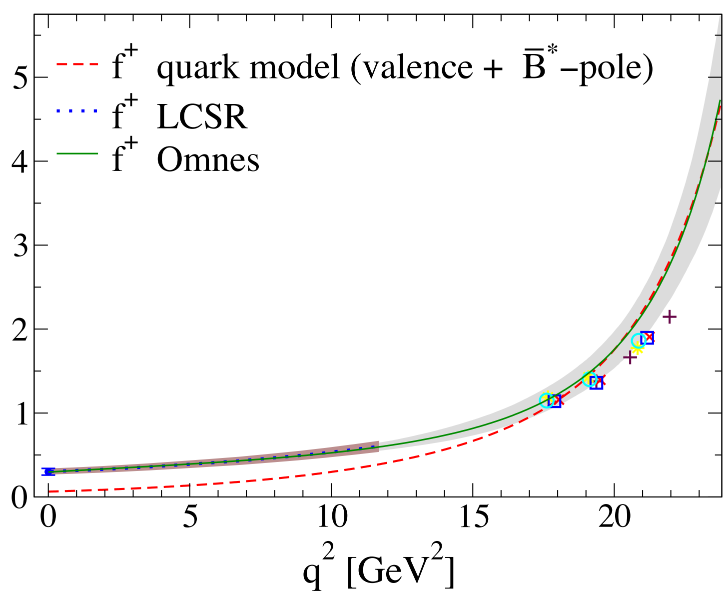
Motivated by "$V_{ub}$ crisis"

$|V_{ub}| = (4.41 \pm 0.15^{+0.15}_{-0.17}) \times 10^{-3}$ Inclusive

$|V_{ub}| = (3.23 \pm 0.31) \times 10^{-3}$ Exclusive ($B \to \pi$ dominated)

Any new determination of $|V_{ub}|$ is relevant.

In particular the $\bar{B}_s \to K^+ \ell^- \bar{\nu}_\ell$ decay channel is expected to be observed at LHCb and Belle.




$$
\begin{aligned}
f^+(0) &= 0.297 \pm 0.027, \\
f^+(q^2_{\max}/3) &= 0.461 \pm 0.025, \\
f^+(2\,q^2_{\max}/3) &= 0.902 \pm 0.100, \\
f^+(q^2_{\max}) &= 4.738 \pm 0.998
\end{aligned}
$$

The form factor thus obtained has been used to evaluate the decay width for which we get $\Gamma(\bar{B}_s \to K^+ \ell^- \bar{\nu}_\ell) = (5.47^{+0.54}_{-0.46})|V_{ub}|^2 \times 10^{-9}\,\mathrm{MeV}$.

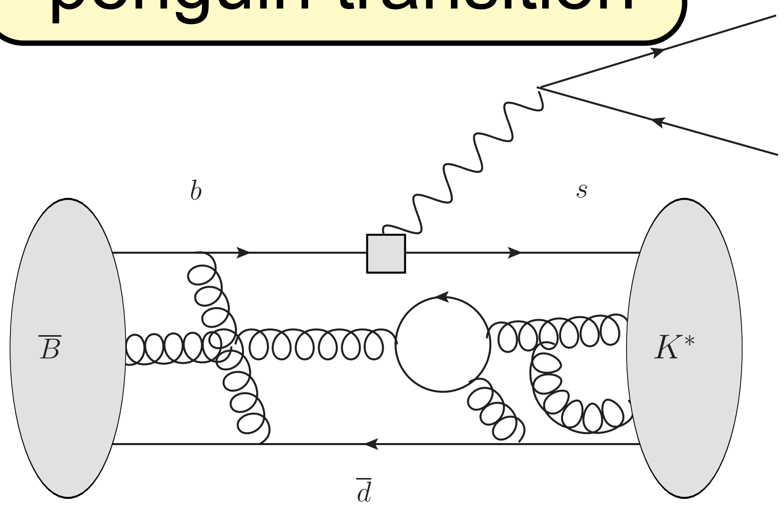
The result for the decay width can be used to obtain $|V_{ub}|$ with a theoretical error of the order of 3%.

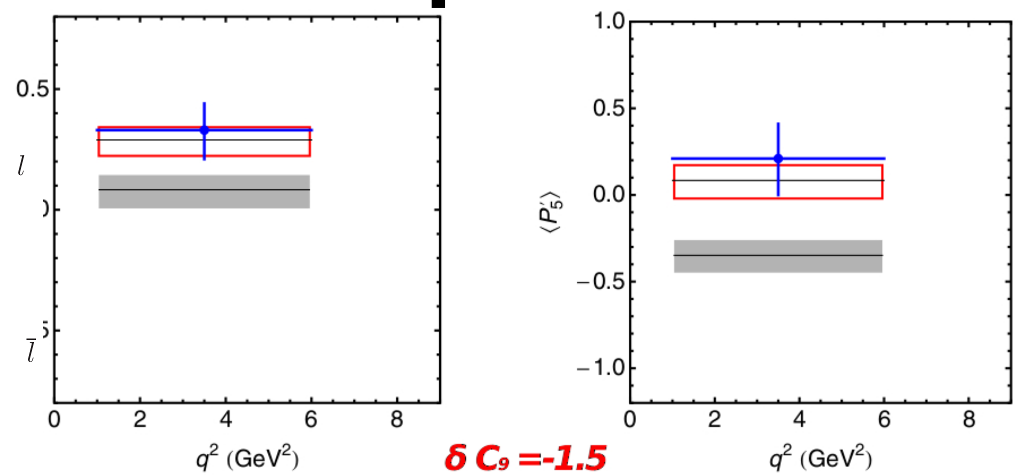
How are the "theory systematics" of the model estimated?

# Rare semileptonic B decays

Martin Camalich

NP sensitive EW penguin transition




$\delta C_9$ =-1.5

Descotes-Genon *et al.* PRD88,074002,hep-ph 1311.3876

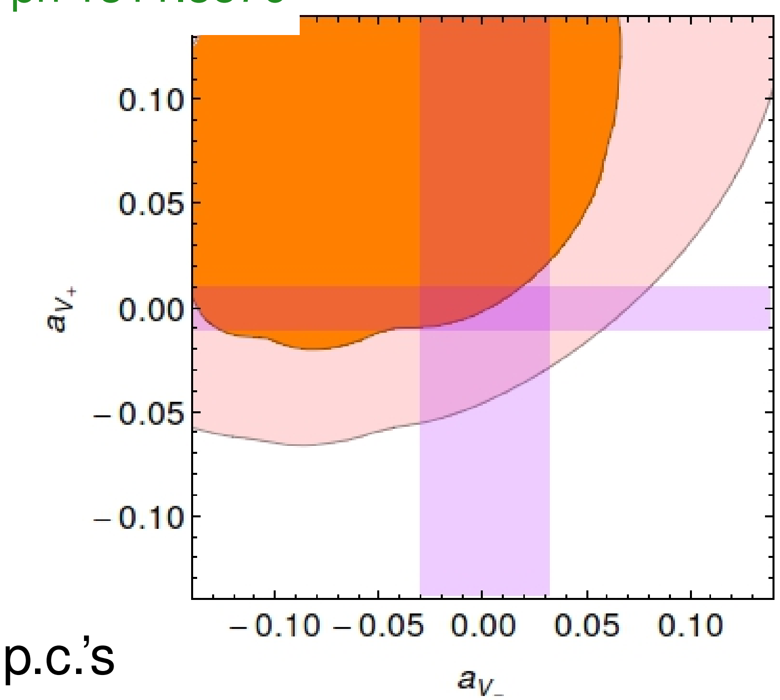
Anomaly in the angular decay distribution, can be explained as BSM

Largely calculable in heavy-quark limit

However, sensitivity to $\Lambda_{QCD}/m_b$ power corrections

Jäger and JMC, JHEP 1305 (2013) 043

SJ, J Martin Camalich, w.i.p.




The anomaly could be *largely* accommodated in the SM through p.c.'s

$$H_V^- \sim \left\{ C_9 \left( V_-^{\mathrm{QCDf}} + a_{V_-} \right) - \frac{m_B^2}{q^2} \left[ \frac{2\,\hat{m}_b}{m_B} C_{7\gamma} T_-^{\mathrm{QCD}} - 16\pi^2 h_- \right] \right\}$$

Charm contribution in $h_\lambda$ could also play a role

At present, anomaly inconclusive, but promising with more data and modes

R. Alonso, B. Grinstein, JMC, in preparation

# Rare semileptonic B decays

Martin Camalich

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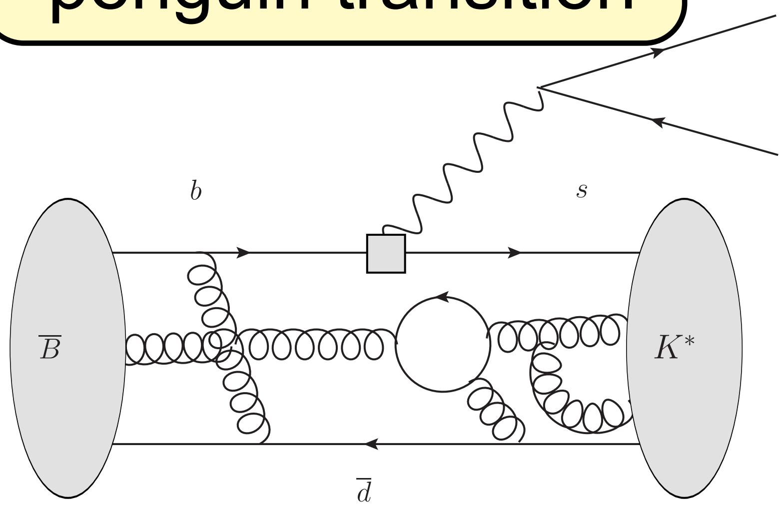


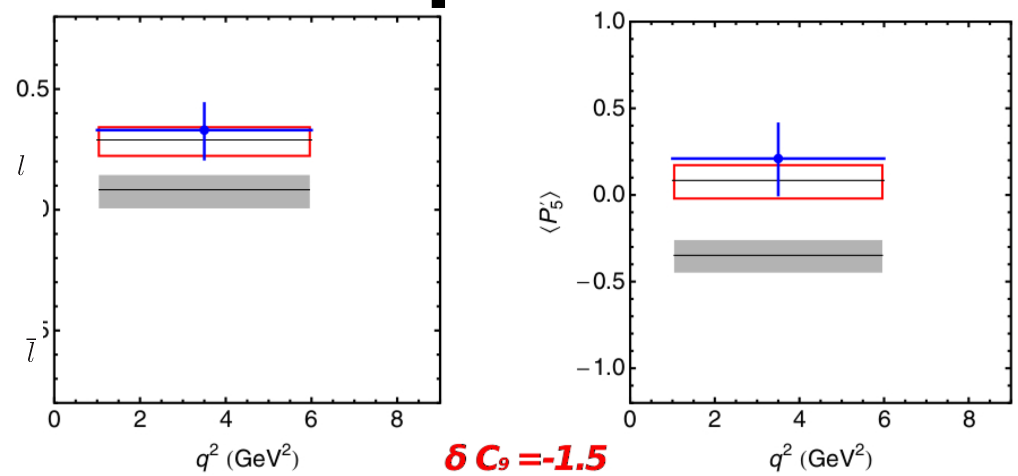


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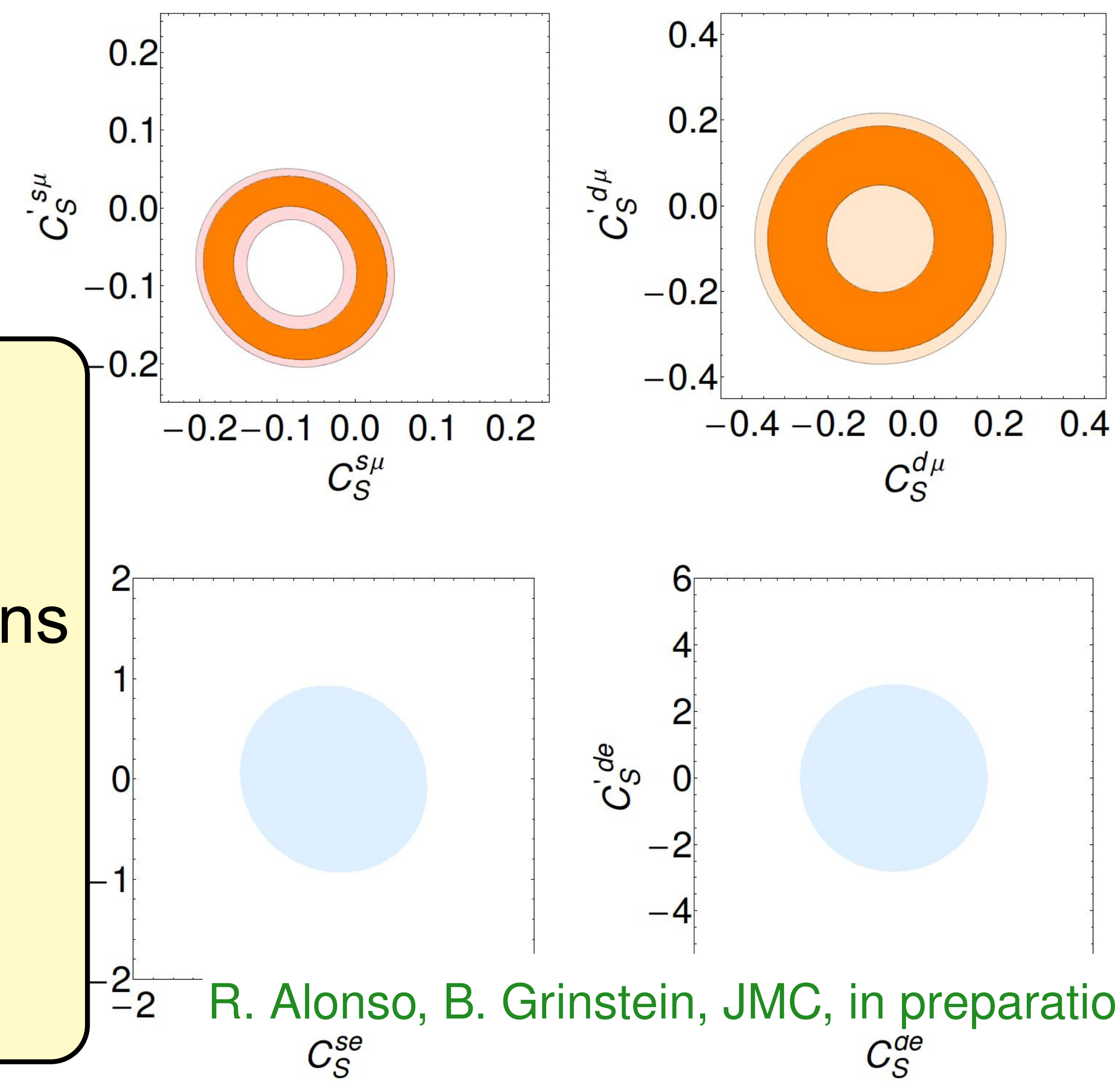
Jäger and JMC, JHE
SJ, J Martin



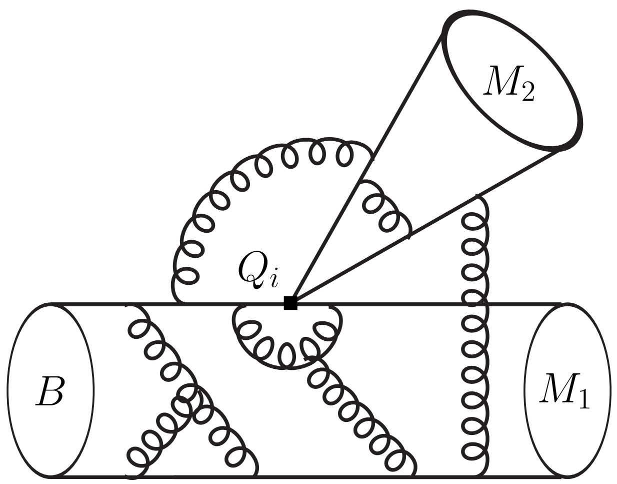

R. Alonso, B. Grinstein, JMC, in preparation

Observation (Martin Camalich): Heavy NP should respect $SU(2)_L xU(1)_Y$ (cf intro). Implies *no* tensor operators and two relations between Wilson coefficients in weak Hamiltonian.
Can use *leptonic decay* to rule out "scalar" interpretation of anomaly!

# Charmless B decays: QCDf

Bell

The challenge:

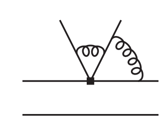
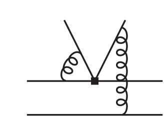
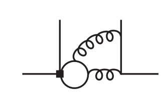
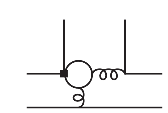


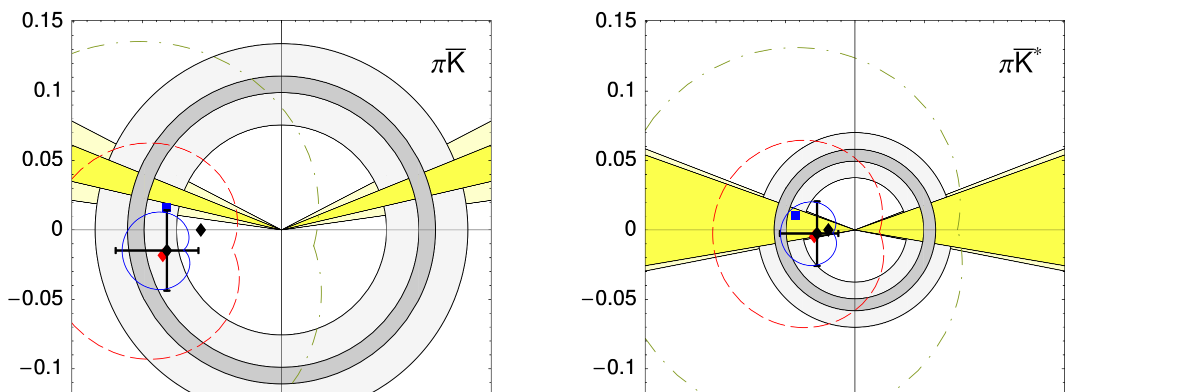

Hadronic matrix elements factorise in heavy quark limit $m_b \gg \Lambda_{QCD}$

$$\langle M_1 M_2 | Q_i | B \rangle \simeq F^{BM_1}(0) \int du \, T_i^I(u) \, \phi_{M_2}(u) + \int d\omega \, du \, dv \, T_i^{II}(\omega, u, v) \, \phi_B(\omega) \, \phi_{M_1}(v) \, \phi_{M_2}(u)$$

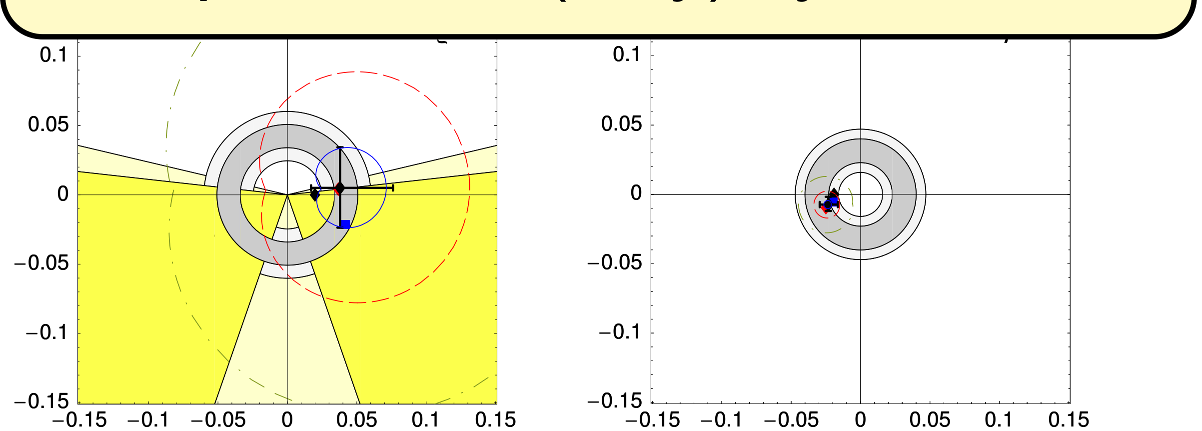
- strong phases from final-state interactions $\sim \mathcal{O}(\alpha_s)$

$\Rightarrow$ NNLO is first correction for direct CP asymmetries!

| Status | 2-loop vertex corrections ($T_i^I$) | 1-loop spectator scattering ($T_i^{II}$) |
|---|---|---|
| Trees |  [GB 07, 09] [Beneke, Huber, Li 09] |  [Beneke, Jäger 05] [Kivel 06] [Pilipp 07] |
| Penguins |  [in progress] |  [Beneke, Jäger 06] [Jain, Rothstein, Stewart 07] |




Observed hierarchies in the date are predicted (only) by QCDF



[figures from Beneke, Jäger 06]

Very substantial perturbative QCD calculation ongoing - see talk for much more detail (and numbers)

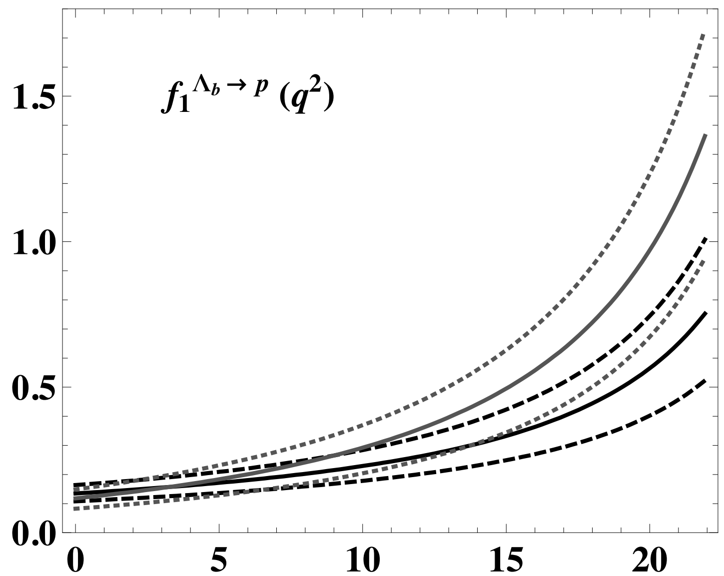
# B baryon decays

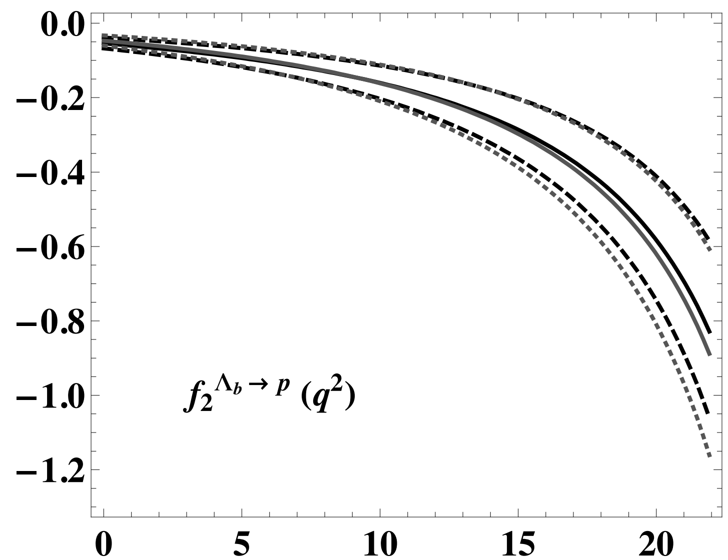
## Light-cone sum rules of $\Lambda_b \to p$ form factors

Wang

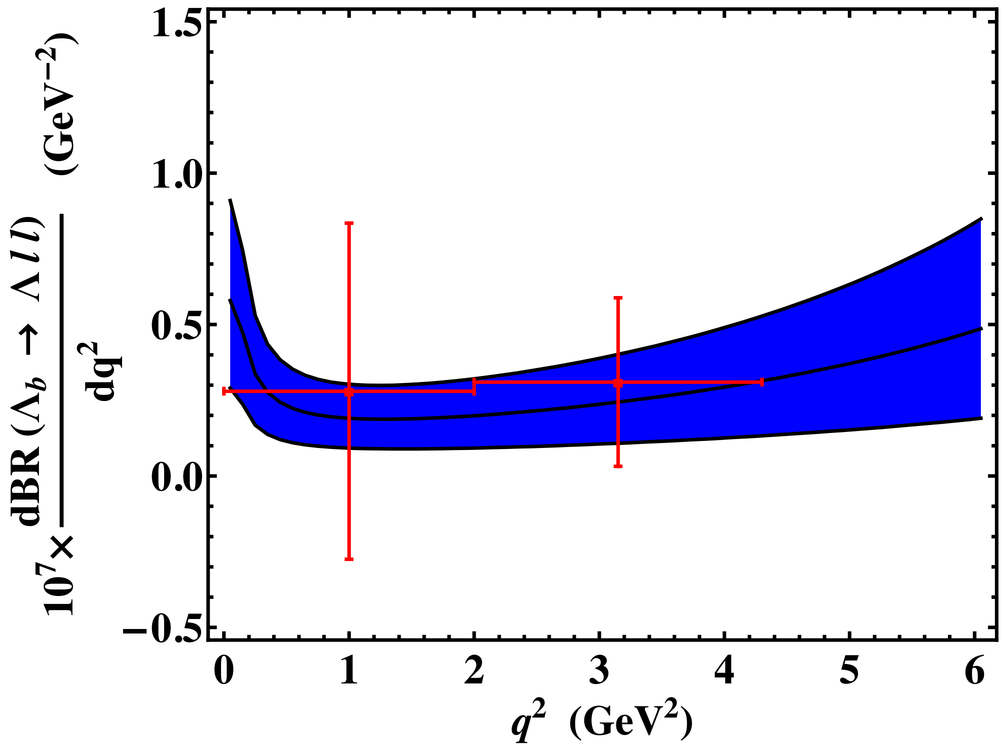
Method outlined earlier

- Form factors from LCSR at $q^2 \leq 11$ GeV $^2$ and extrapolated to larger $q^2$ using the series-parametrization:



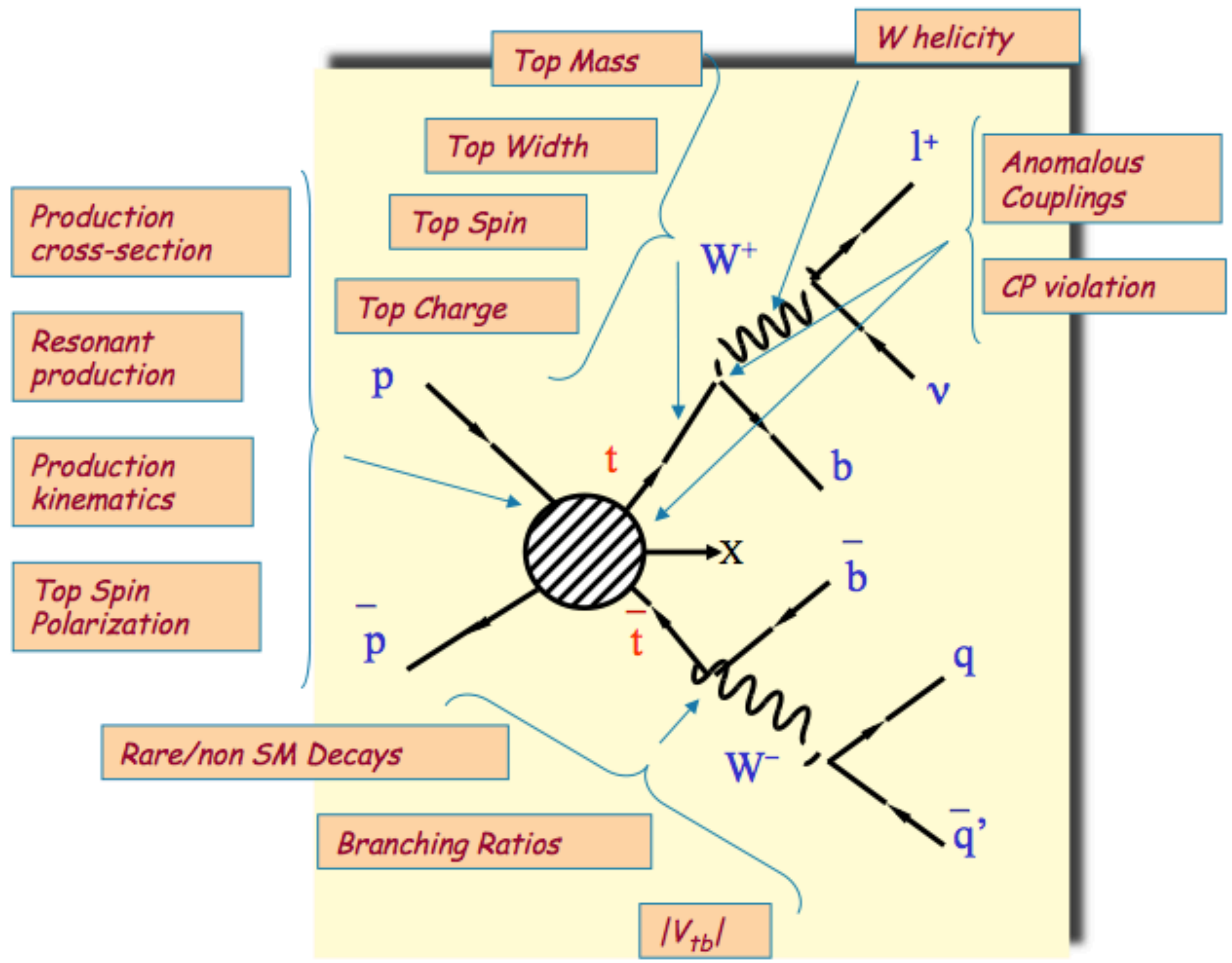

- Differential branching ratio [YMW, Li and Lü, 2009; LHCb, 2013]:




- Experimental data from LHCb rather uncertain, CDF 2011 data are more uncertain.
- Precision measurement will be crucial to understand the QCD dynamics.
- Theory predictions can be improved due to the recently known subleading corrections to $\Lambda$-baryon LCDAs [Liu, Cui and Huang, 2014].

# Top production and decay

THE ASSEMBLY LINE OF TOP PROPERTIES    Pecjak



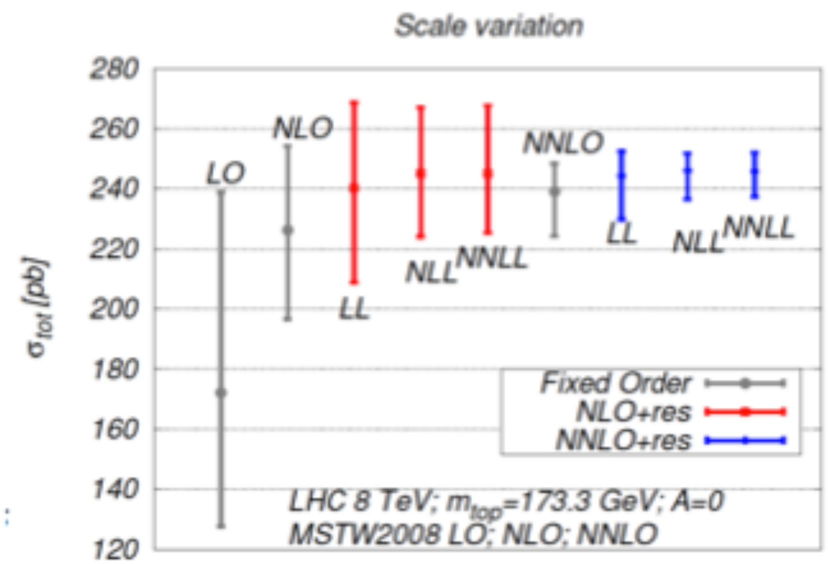

[Ferroglia, Marzani, BP, Yang '13]

# Top production and decay

**The assembly line of top properties** Pecjak


Total inclusive cross section now known (numerically) at NNLO!!!

[Baernreuther, Fiedler, Mitov, Czakon '13]




Concurrent uncertainties:

| | |
|---|---|
| Scales | ~ 3% |
| pdf (at 68%cl) | ~ 2-3% |
| $\alpha_s$ (parametric) | ~ 1.5% |
| $m_{top}$ (parametric) | ~ 3% |

Soft gluon resummation makes a difference:

5% -> 3%

- first ever NNLO calculation for 2→2 process

[Ferroglia, Marzani, BP, Yang '13]

# Top production and decay

## Finding boosted tops: jet substructure and tagging

PERTIES

Pecjak

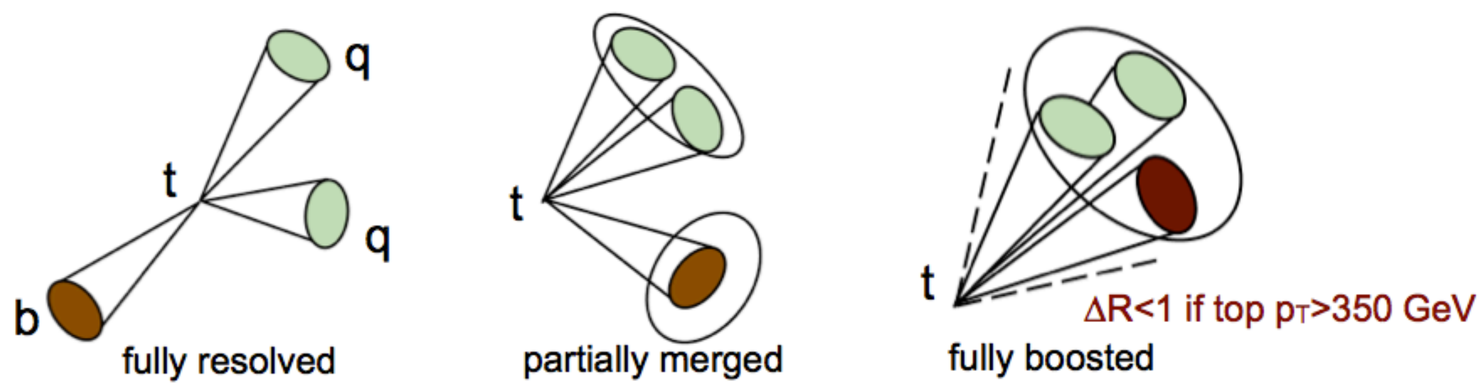
Anomalous Couplings

CP violation

T

[I

- In high $p_T$ regime, decay products of top are collimated
  *(overlapped objects, reduced combinatorics, large-area jets wi*
- New techniques of identifying/reconstructing top are needed




ıce:

- To the observer, a high-$p_T$ top is a fat jet
- Inside, we can see substructure specific to top decays, use as tagger

- first ever NNLO calculation for 2→2 process

$|V_{tb}|$

[Ferroglia, Marzani, BP, Yang '13]

# Top production and decay

## Finding boosted tops: jet substructure and tagging

PERTIES

Pecjak

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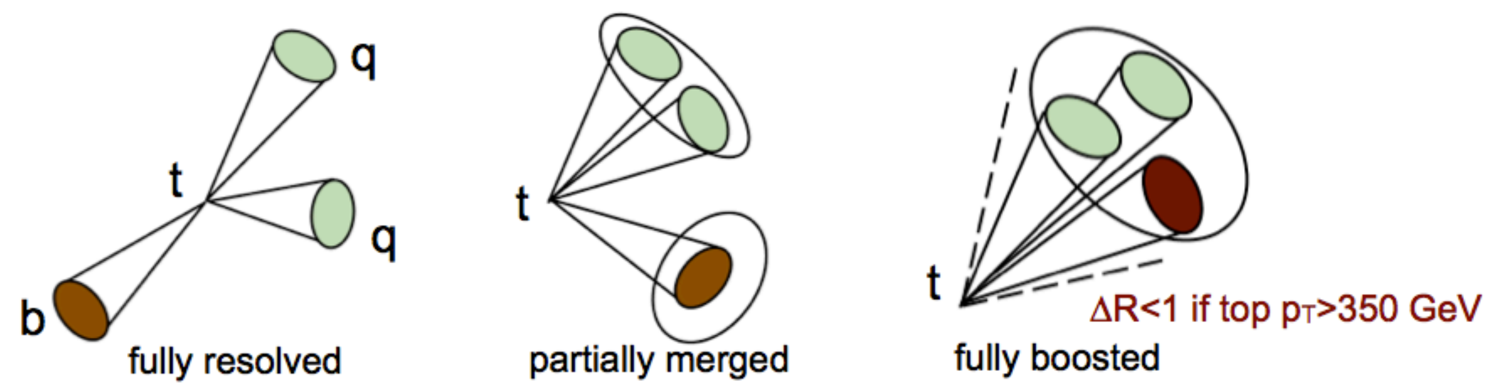


Anomalous Couplings

CP violation

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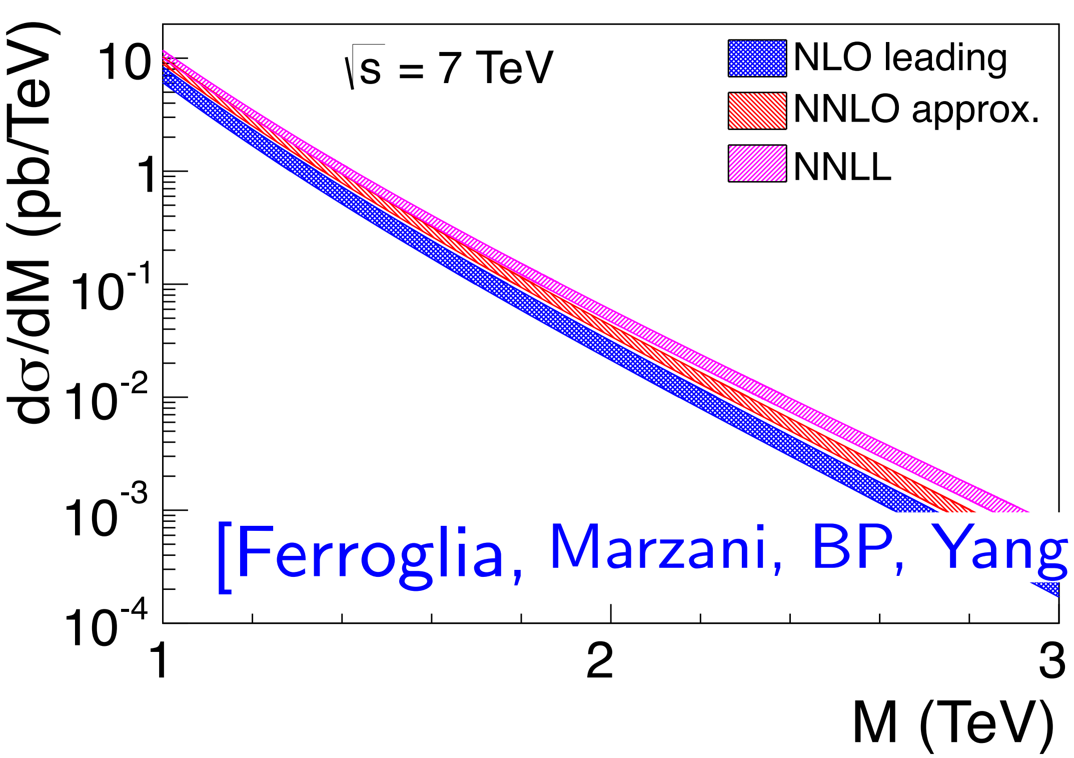
top decays, use as tagger

s

$|V_{tb}|$




[Ferroglia, Marzani, BP, Yang '13]

# Top production and decay

FINDING BOOSTED TOPS: JET SUBSTRUCTURE AND TAGGING

...PERTIES

Pecjak

Anomalous Couplings

CP violation

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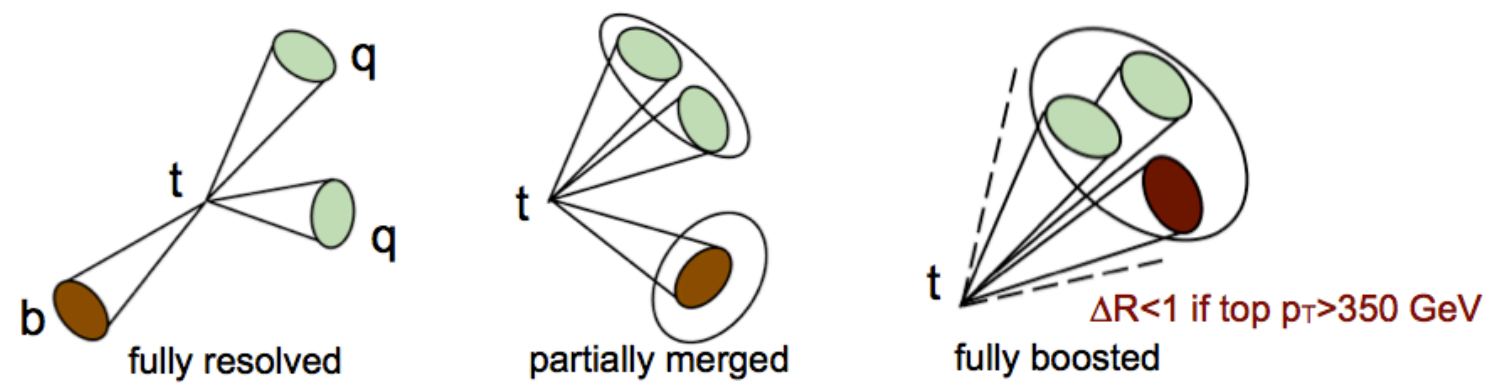


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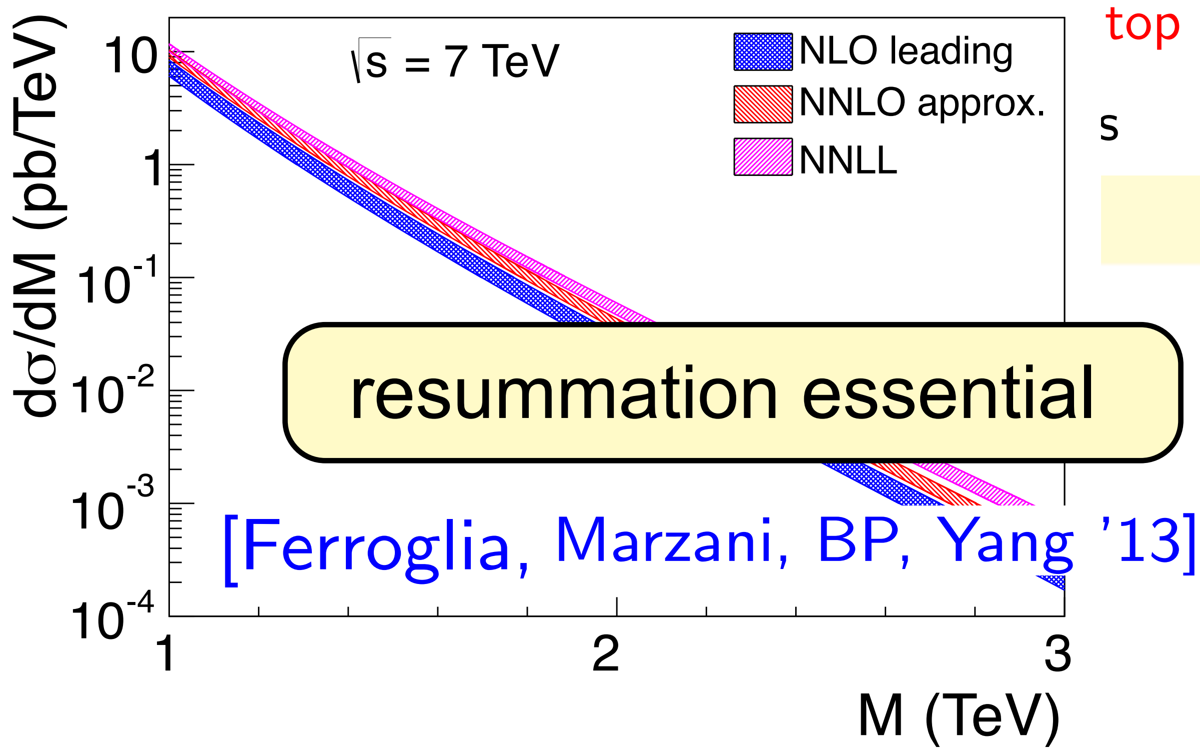
s

$|V_{tb}|$




resummation essential

[Ferroglia, Marzani, BP, Yang '13]

# Top production and decay

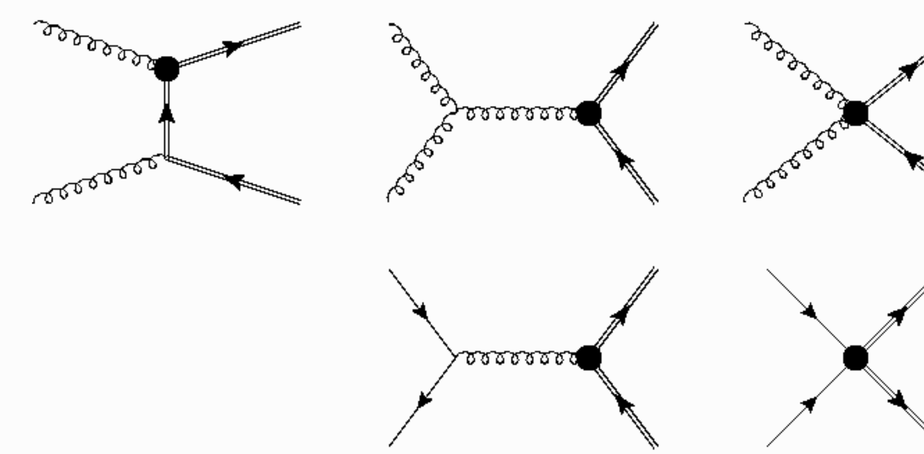
Indirectly, probe NP through virtual effects, in precision measurements.

- Need effective theories.
- Flavor physics falls in this category.
- As the top quark physics develops into precision phy on NP being pushed higher and higher, now top qua belongs to this category.
  - *W helicity fractions in top quark decay, top quark FCNC processes*

Zhang

Systematic, SU(2)xU(1)$_Y$ covariant formalism

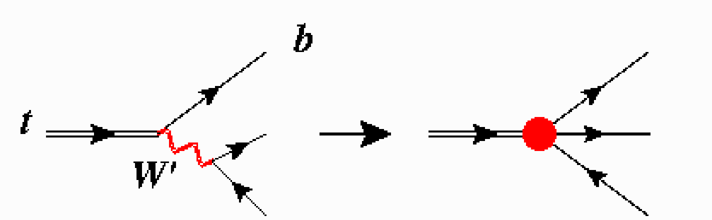
$pp \to t\bar{t}$ at LO:



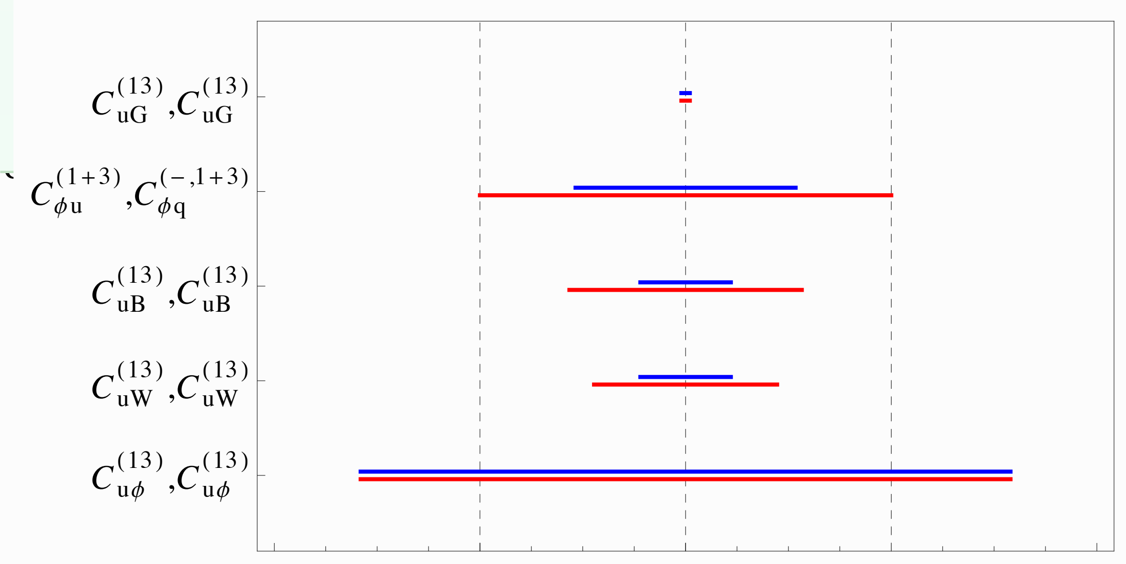
The helicity fractions will be modified by dim-6 operators.

- Operators involving *Wtb* vertex are computed at NLO in QCD.
- Top-color dipole operator, i.e. *gtt* vertex, contributes only at NLO.
- 4-fermion operators are also considered at NLO. (May change $F_+$.)

$$O_{qQ}^{(1,3)} = \left(\bar{q}\gamma_\mu \tau^I q\right)\left(\bar{Q}\gamma^\mu \tau^I Q\right)$$




Limits on each operator




One can constrain some two-fermion operators using thes example, for $O_{tW}$ (setting other operator coefficients to zer

$$\frac{C_{tW}}{\Lambda^2} = -0.08 \pm 0.55\,\mathrm{TeV}^{-2}$$

# Neutrinos, CPV

Pakvasa

Nice review (Pakvasa) of the historical discovery record of flavour physics. (Flavour mixing, charm, ...) Template for the future?

## Conclusions / Outlook

Some hints that $\delta \neq 0$ (but no CPV seen).

Future LBL experiments will hunt for CPV in neutrino oscillations

Ongoing search for $\nu$-less $\beta\beta$ decay →

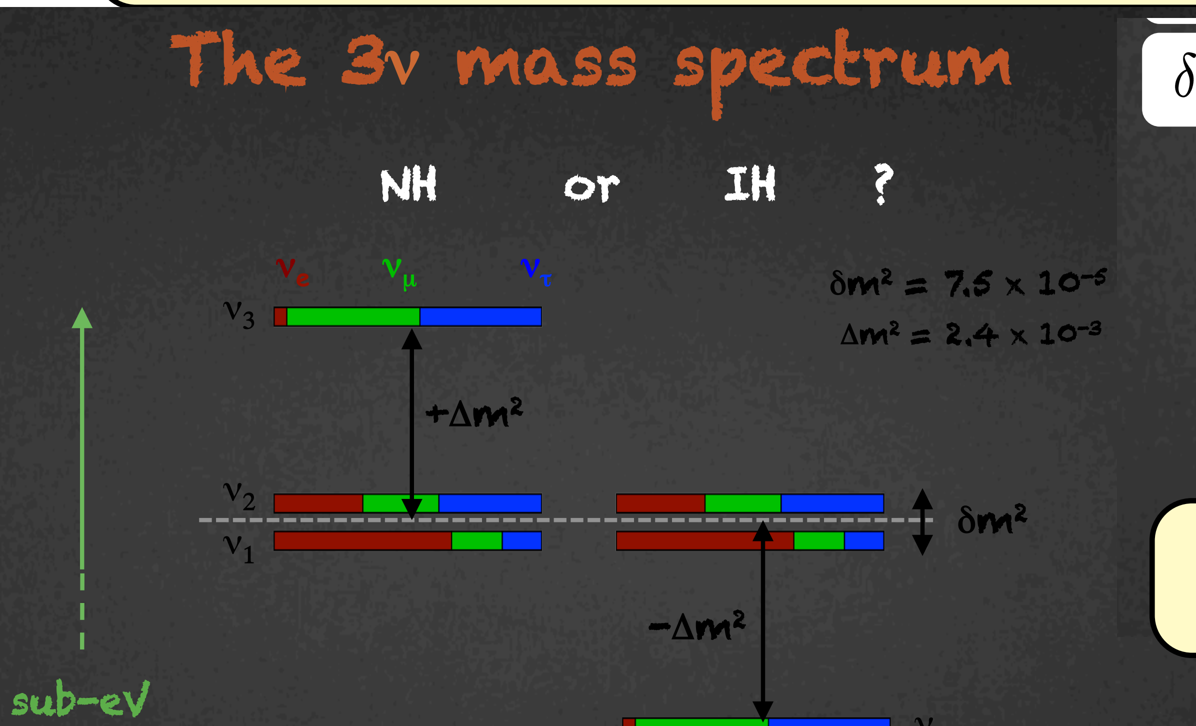
- if observed
- & if $\delta$ observed

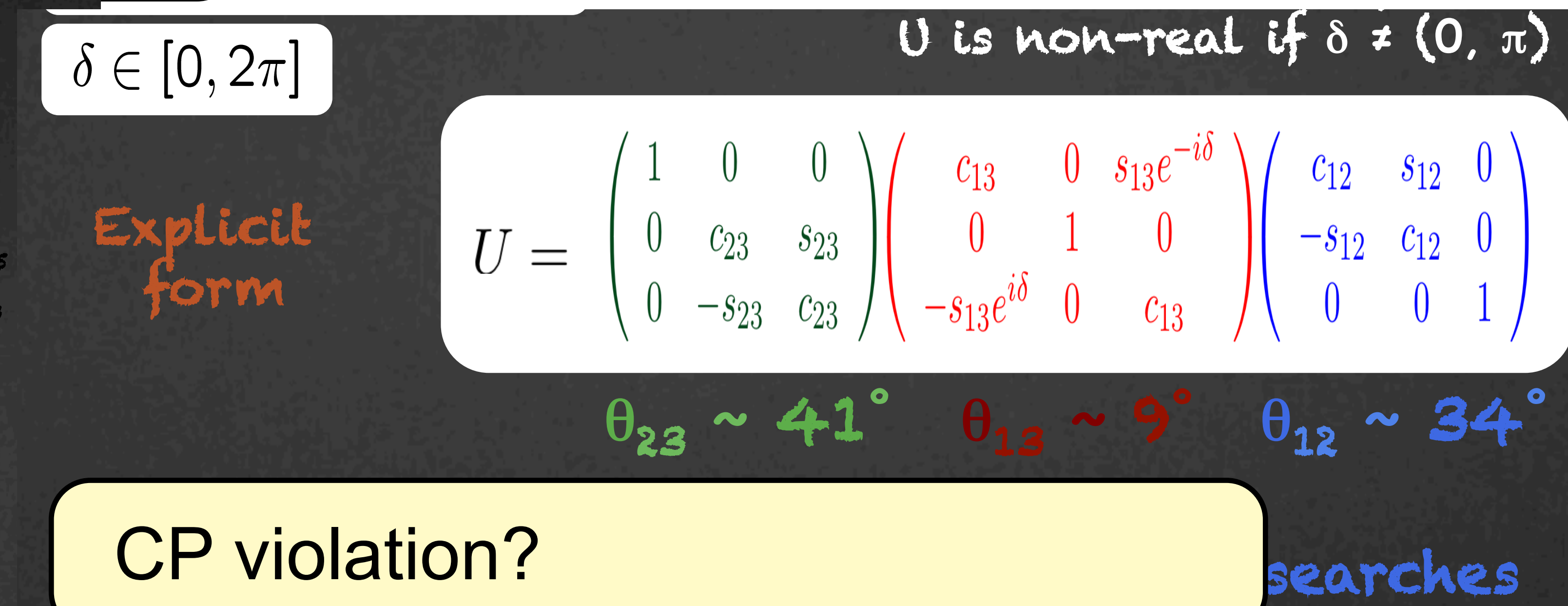
} ⟹ offer support for idea of

# Neutrinos: oscillations and sterile

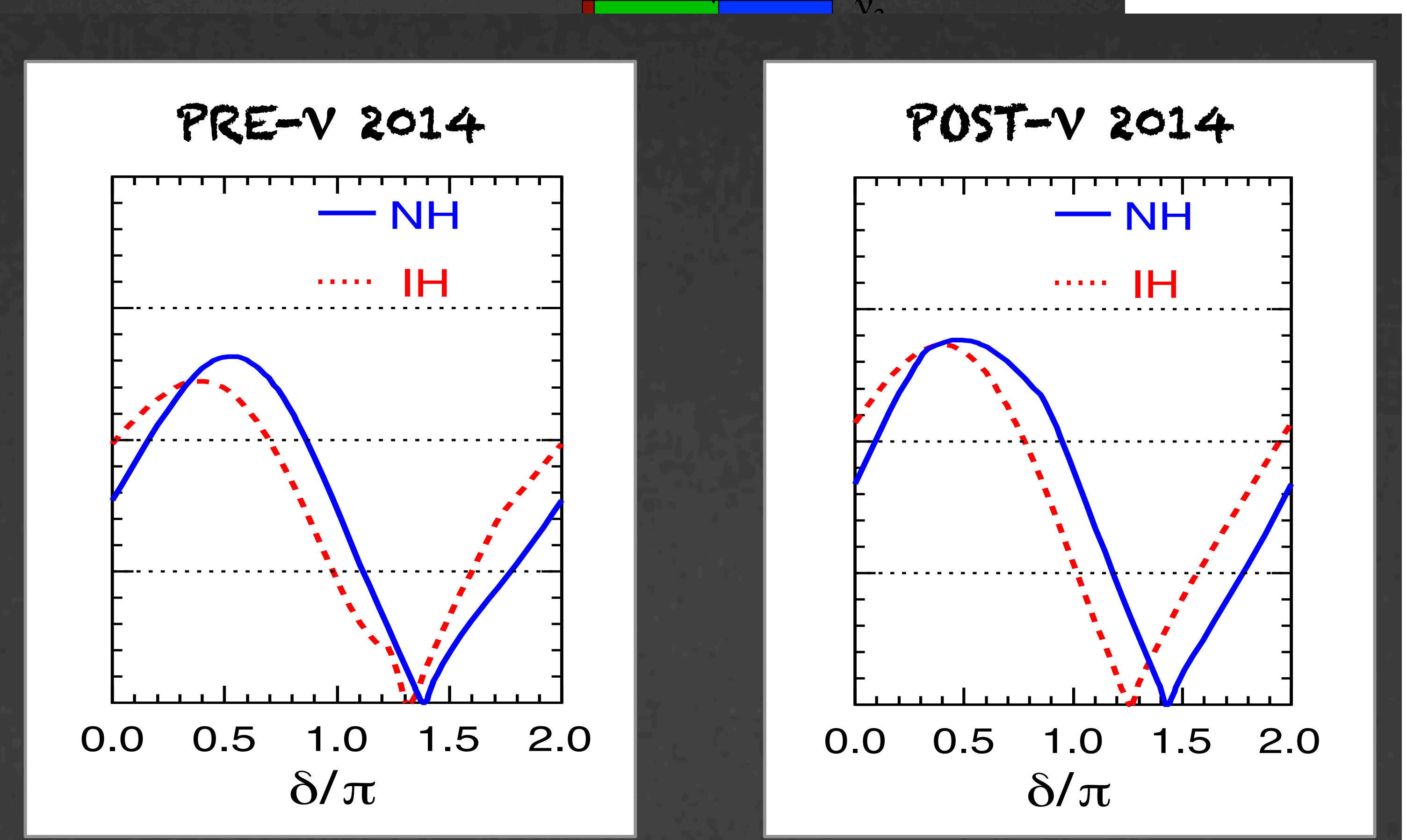
key question: neutrino hierarchy?

Palazzo




CP violation?



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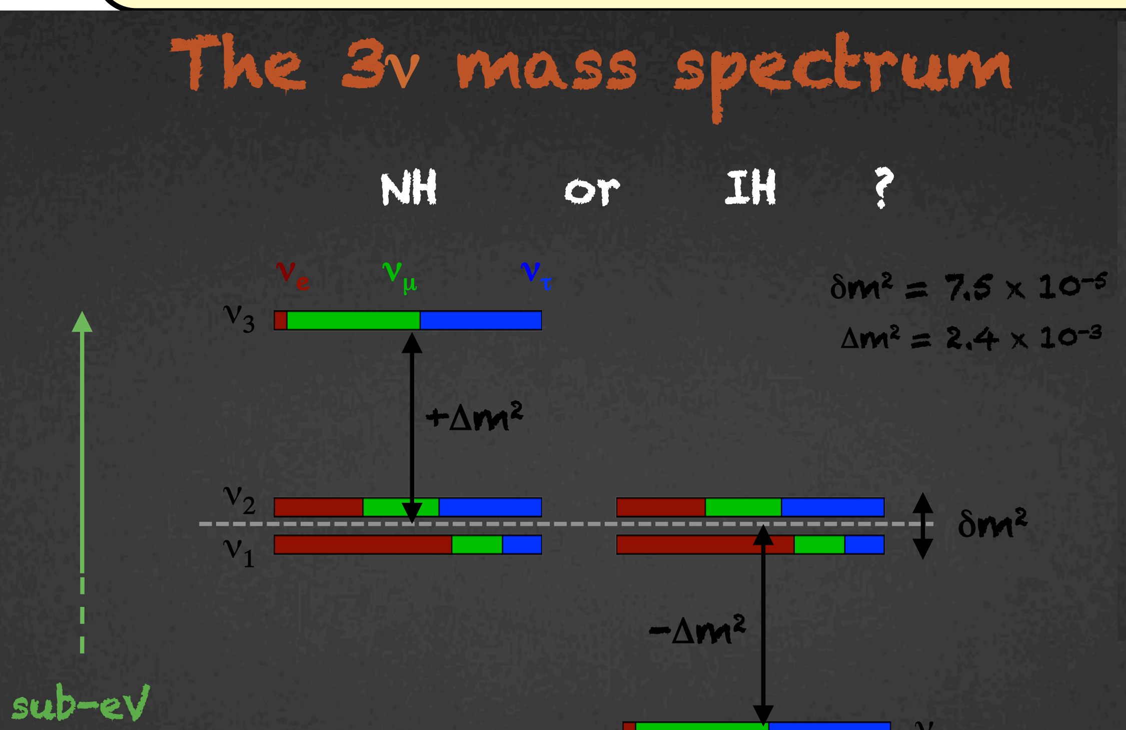


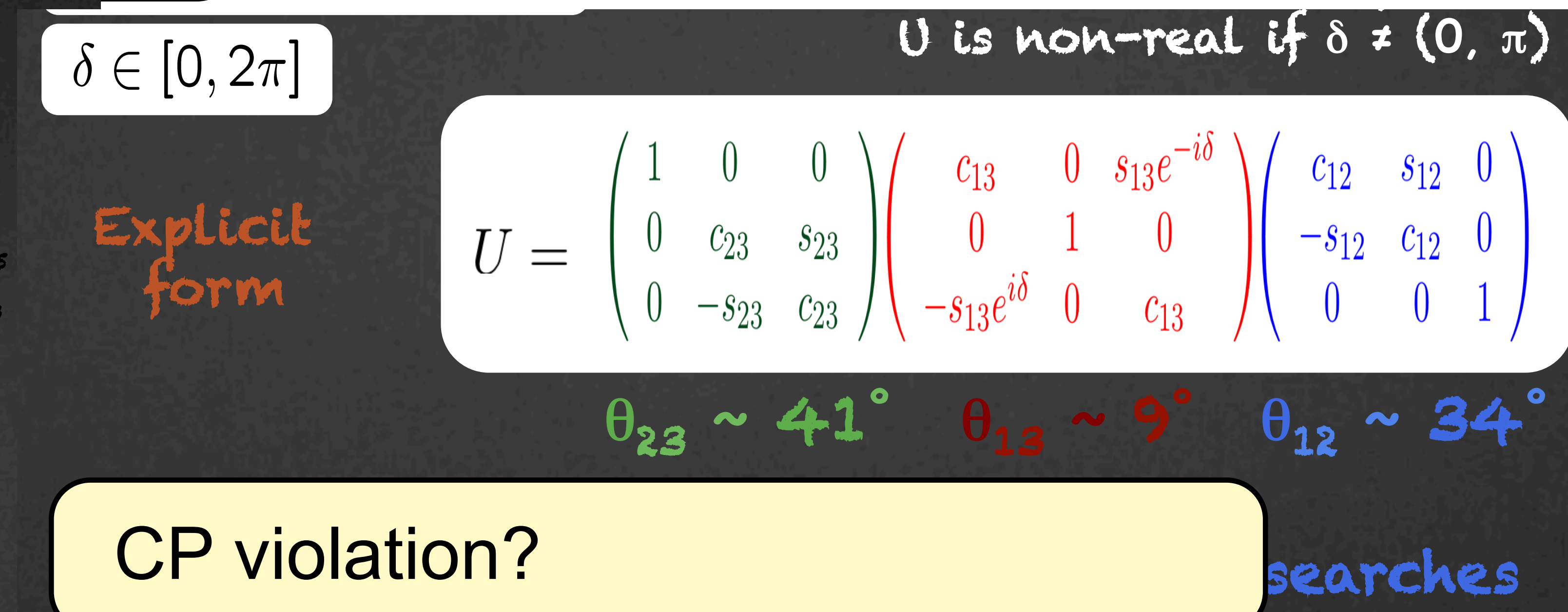


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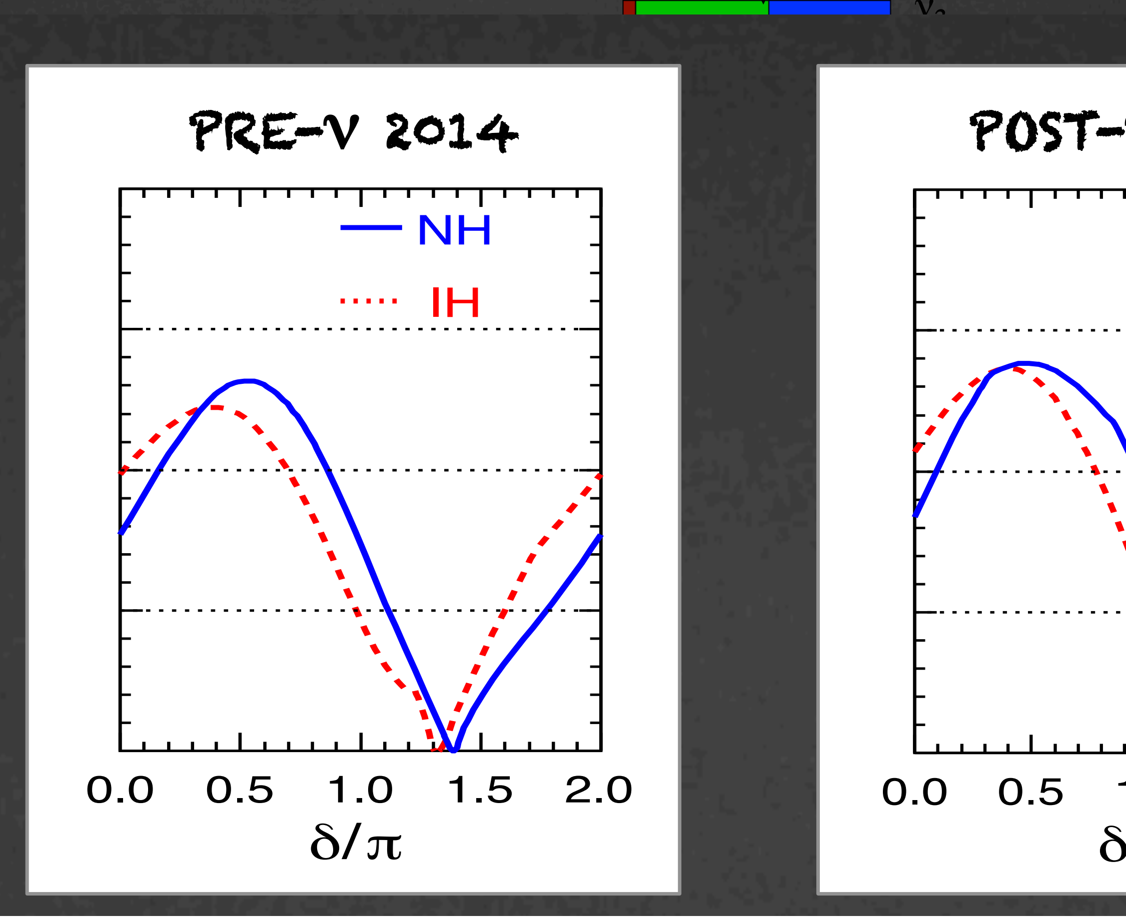
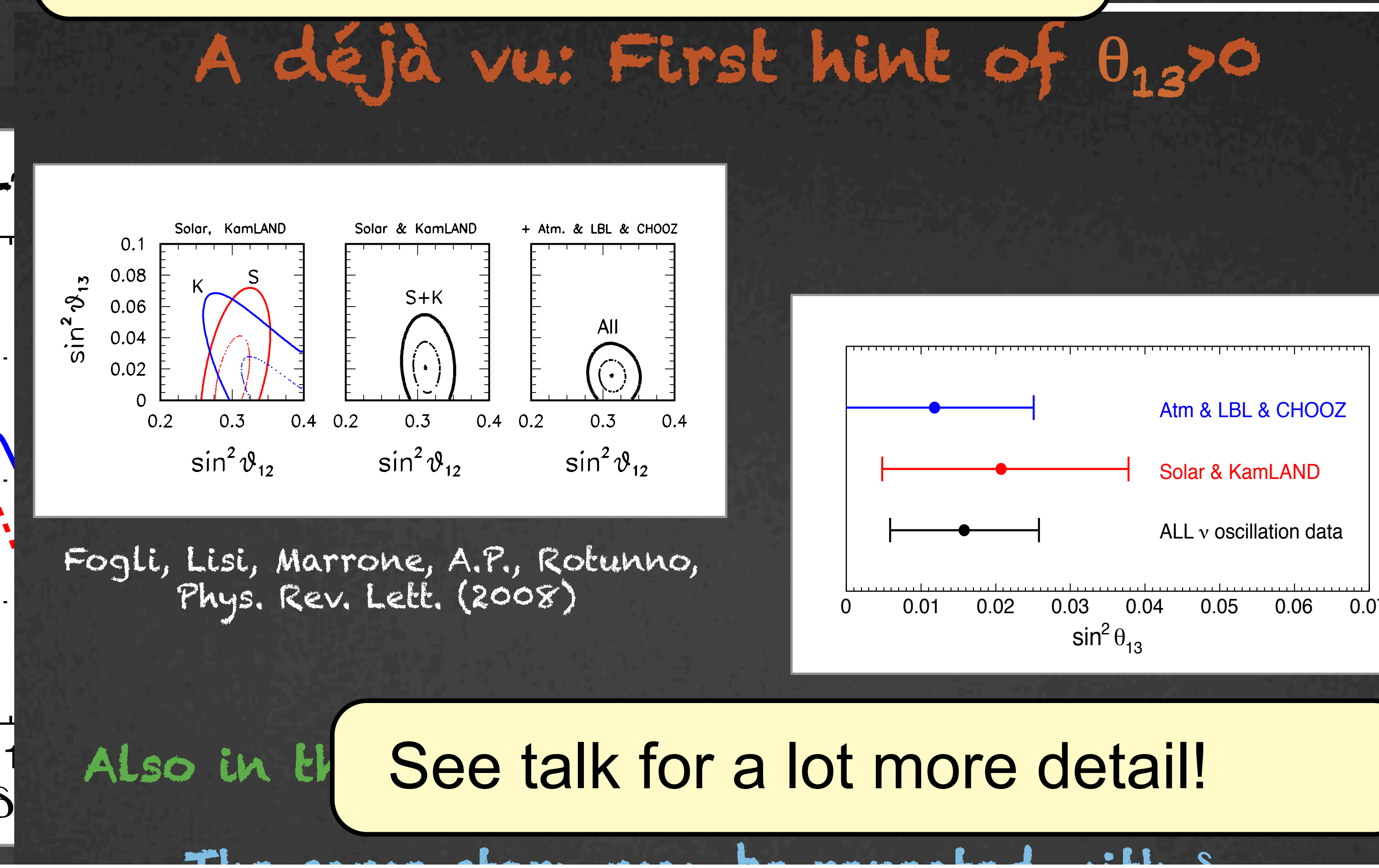


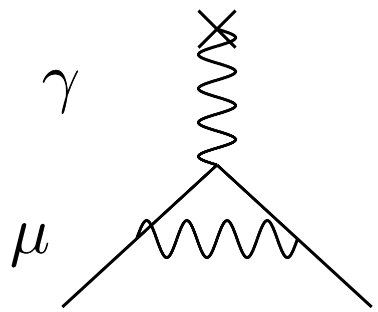




See talk for a lot more detail!

# g-2

Velasco-Sevilla

The anomaly $a_\ell = \frac{g_\ell - 2}{2}$ arises from quantum fluctuations



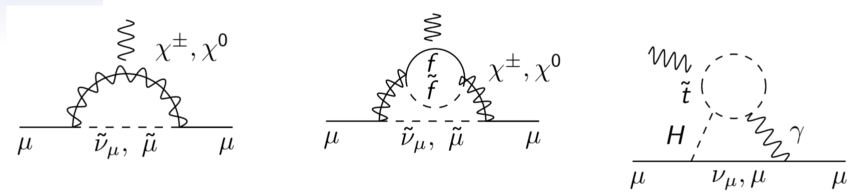

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had.}$$

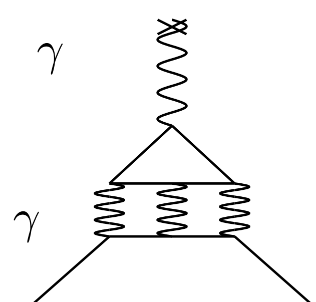
Largest contribution comes from the $1\ell$ diagram QED, but EW and Hadronic crucial to determine departure from SM

Arguably the best hint of physics BSM

$a_\mu^{HLbL}$

Must be determined using hadronic models that reproduce QCD properties



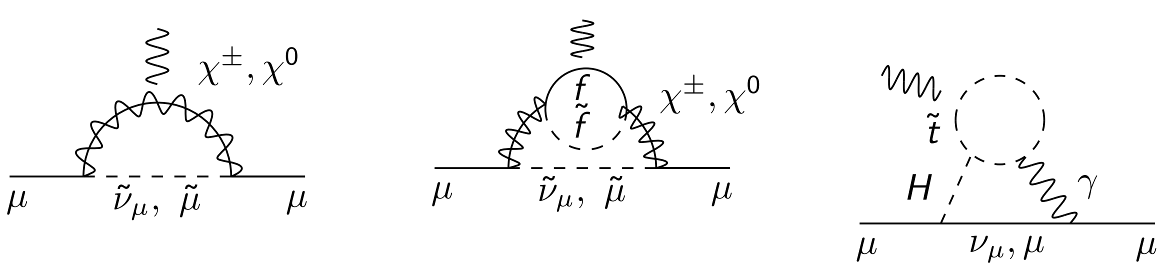

$$a_\mu^{E821} = (116592089 \pm 63) \times 10^{-11} \longrightarrow$$

3.3 to 3.6 $\sigma$ difference

$$\Delta a_\mu(E821 - SM) = (287 \pm 80) \times 10^{-11}$$
$$= (261 \pm 80) \times 10^{-11}$$

Computations done in two limits: long and short distanc

In SUSY:



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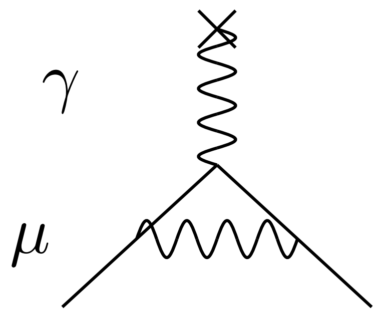


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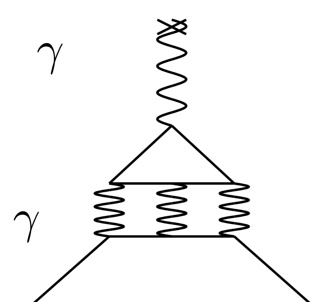
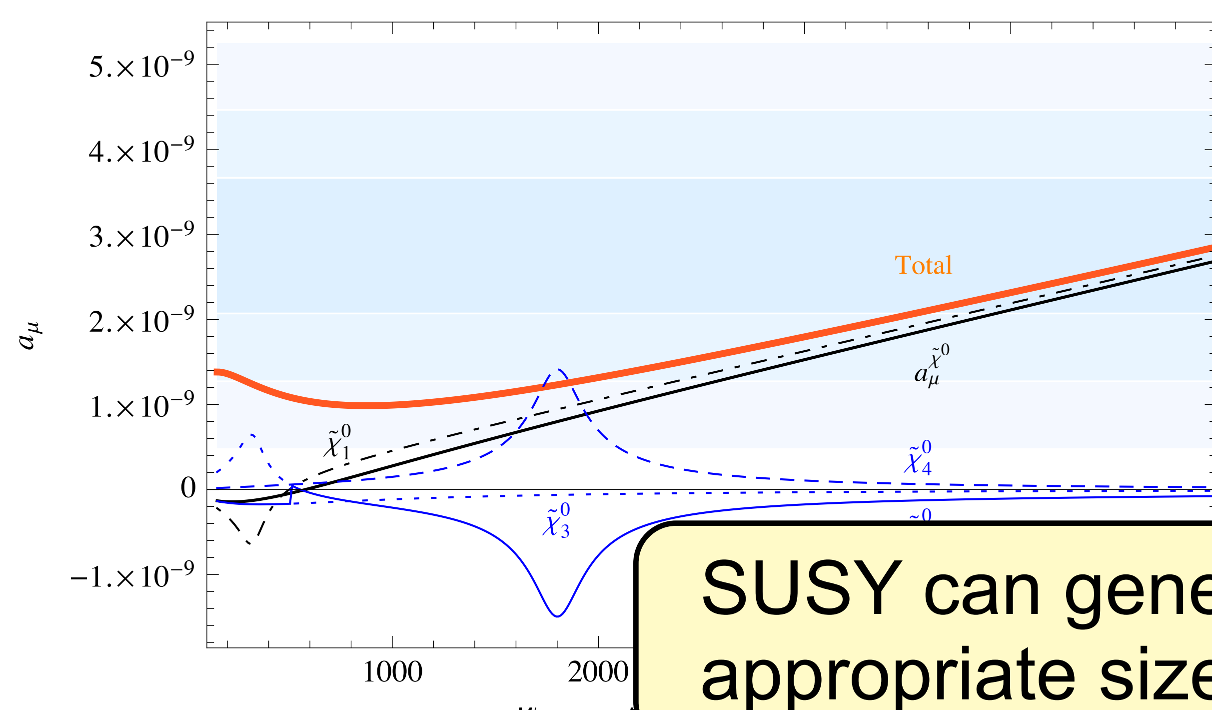



Computations done in two limits: lor

Example [VS et. al. 2014]

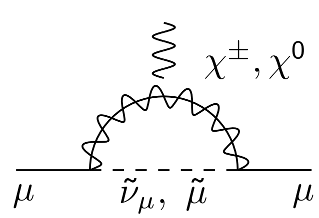



$63) \times 10^{-11} \longrightarrow$

$87 \pm 80) \times 10^{-11}$

$61 \pm 80) \times 10^{-11}$

In SUSY:




SUSY can generate the appropriate size of effect

# Charged lepton flavour violation

| LFV process | Experiment | Future limits | Year (expected) |
|---|---|---|---|
| $\mathrm{BR}(\mu \to e\gamma)$ | MEG | $\mathcal{O}(10^{-13})$ | $\sim 2013$ |
| | Project X | $\mathcal{O}(10^{-15})$ | $> 2021$ |
| $\mathrm{BR}(\mu \to eee)$ | Mu3e | $\mathcal{O}(10^{-15})$ | $\sim 2017$ |
| | Mu3e | $\mathcal{O}(10^{-16})$ | $> 2017$ |
| | MUSIC | $\mathcal{O}(10^{-16})$ | $\sim 2017$ |
| | Project X | $\mathcal{O}(10^{-17})$ | $> 2021$ |
| $\mathrm{CR}(\mu \to e)$ | COMET | $\mathcal{O}(10^{-17})$ | $\sim 2017$ |
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| $\mathrm{BR}(\tau \to \mu\mu\mu)$ | Belle II | $\mathcal{O}(10^{-10})$ | $> 2020$ |
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Table: Future sensitivities of next-generation experiments.

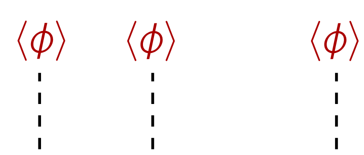
Paradisi

charged lepton flavour violation is present in many BSM sceanrios (eg general MSSM)

and is *generic* in SUSY GUTs.

Can the SM and NP flavour problems have a common explanation?

**Froggat-Nielsen '79: Hierarchies from SSB of a Flavour Symmetry**




$$\epsilon = \frac{\langle\phi\rangle}{M} \ll 1 \Rightarrow Y_{ij} \propto \epsilon^{(a_i+b_j)}$$

interesting model-independent relations between radiative

$\mathrm{BR}(\ell_i \to \ell_j\gamma)$ **vs.** $(g-2)_\mu$

$$\mathrm{BR}(\mu \to e\gamma) \approx 3 \times 10^{-13}\left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{e\mu}}{10^{-5}}\right)^2 ,$$

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[Giudice, P.P., & Passera, '12]

# Charged lepton flavour violation

| LFV process | Experiment | Future limits | Year (expected) |
|---|---|---|---|
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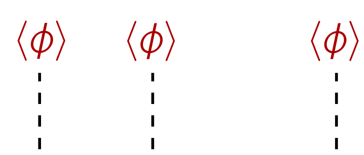


int
rel

## $BR(\ell_i \to \ell_j\gamma)$ vs. $(g-2)_\mu$

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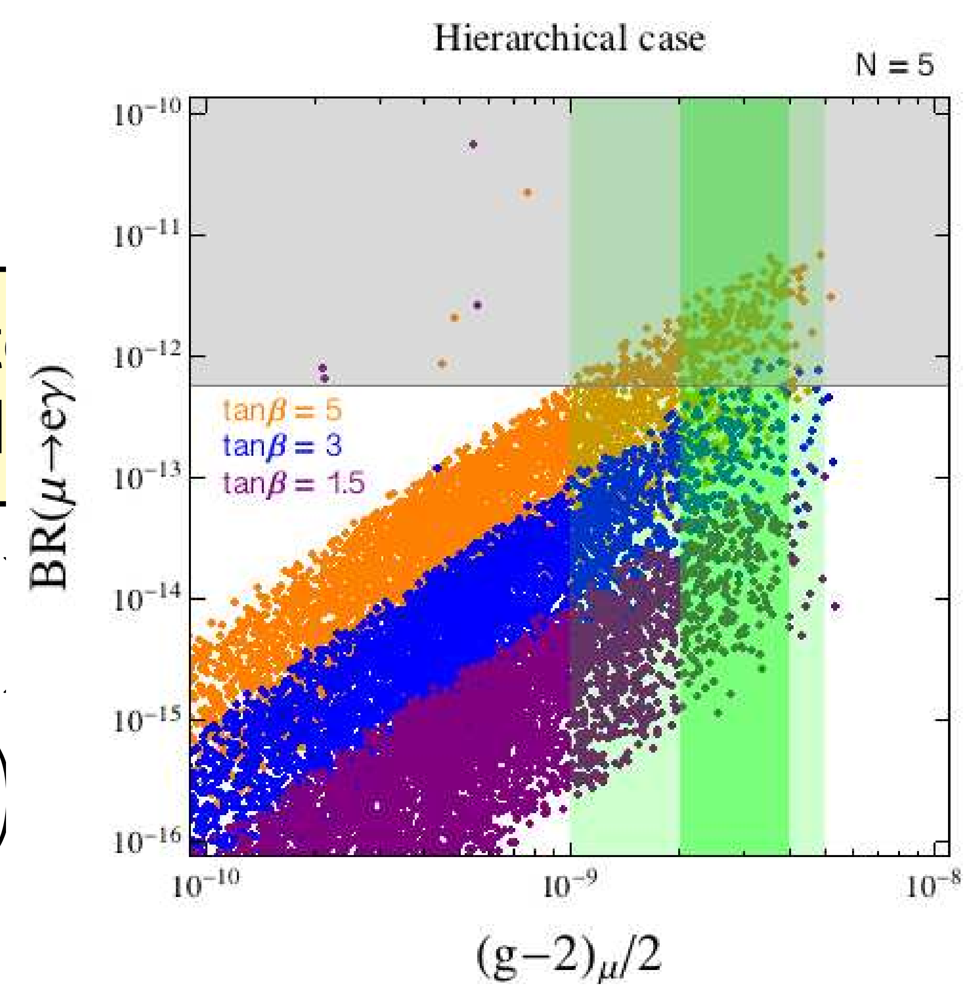
[Giudice, P.P., & Passera, '12]



# Origin of matter

From BBN and CMB!

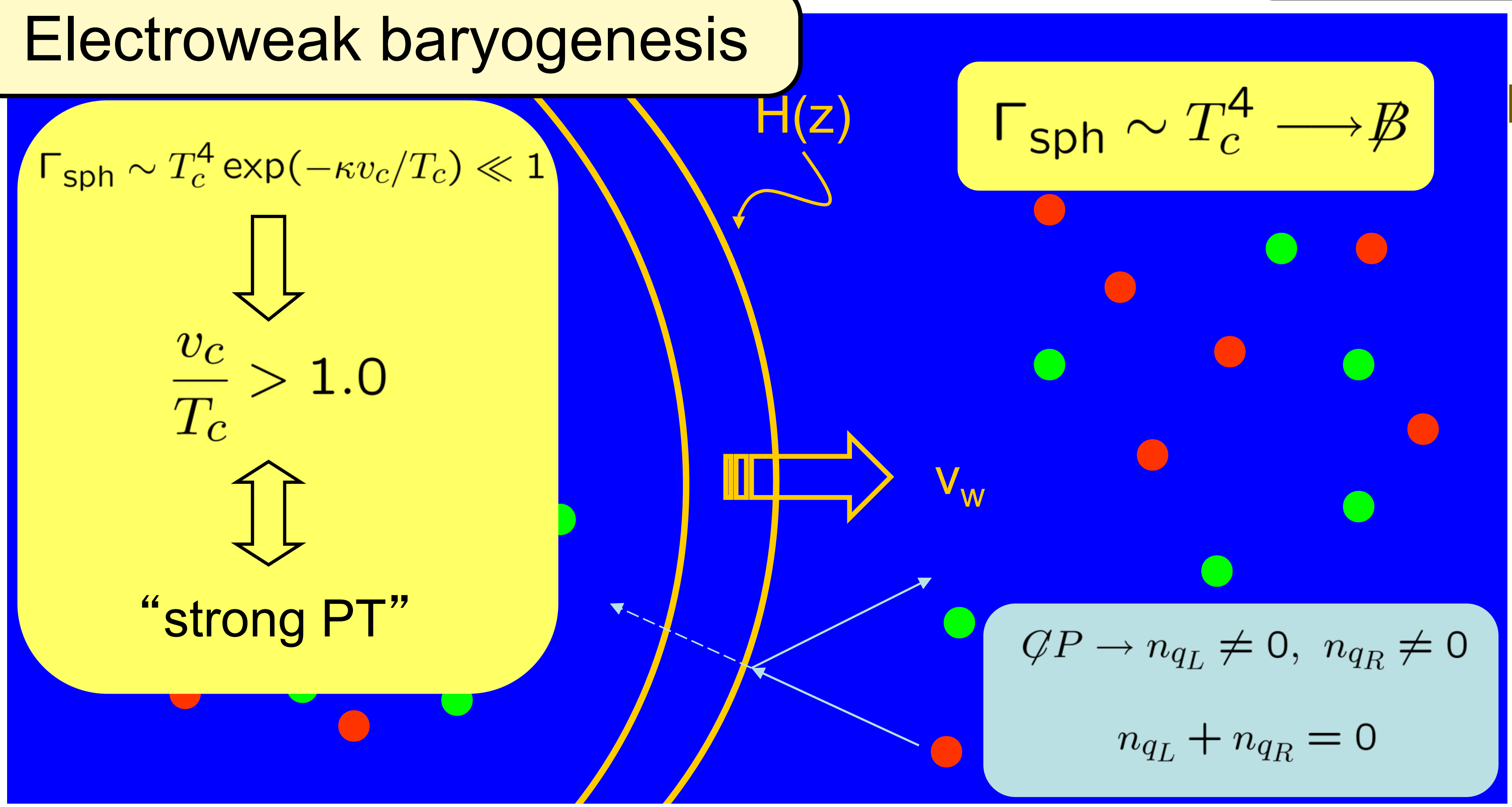
Schwaller

$$Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s} = (8.75 \pm 0.23) \times 10^{-11}$$

- Sakharov's conditions: SM
  - **B** violation ✔
  - CP violation ✔
  - Departure from thermal equilibrium ✘ In SM: Requires $m_h \lesssim (40-80)$ GeV

need more degrees of freedom for 1st order phase transition

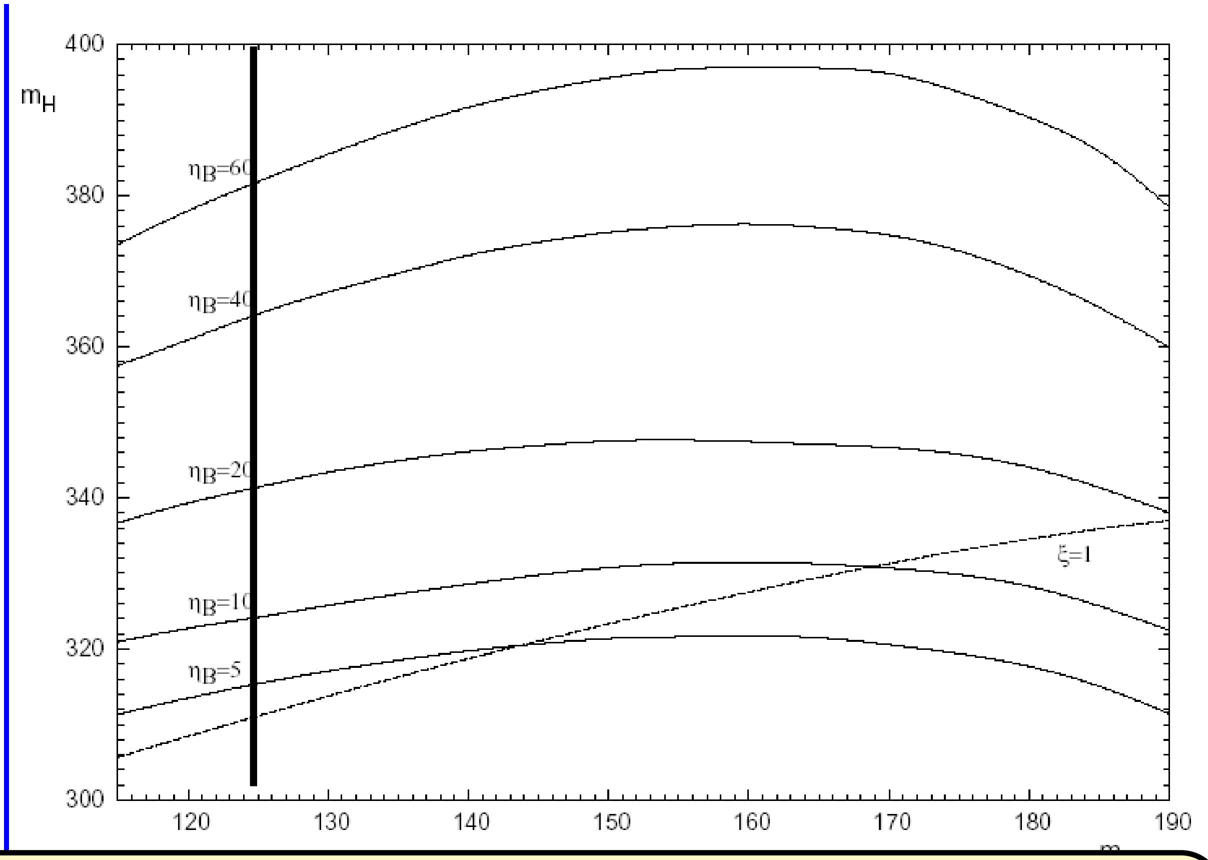
Electroweak baryogenesis




Huber

# EW baryogenesis

Huber

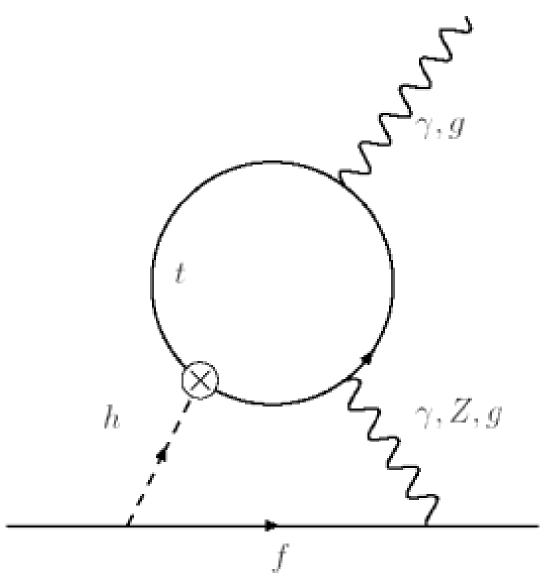



in a CPV 2HDM

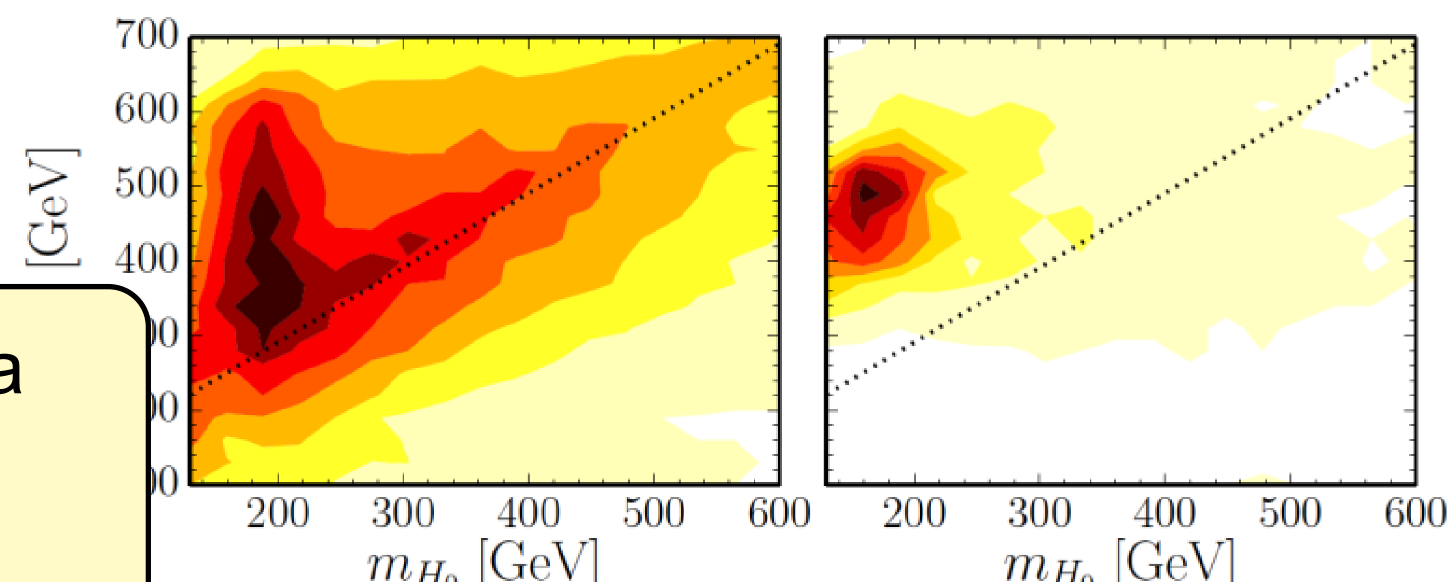
Constraints: rho-parameter

B→ s γ, B-Bbar mixing

correlates with EDMs and B physics




scan of a general 2HDM




[Dorsch, S.H., Mimasu, No '14]

# Leptogenesis

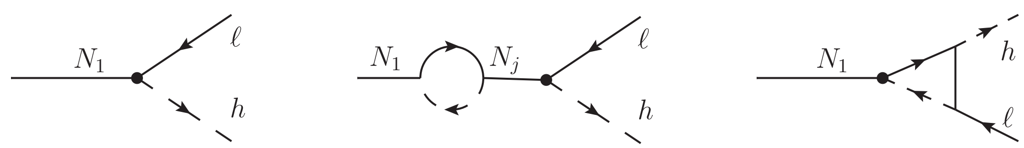
Schwaller

- Extend SM with right-handed neutrinos:

$$\mathcal{L} \supset -\tfrac{1}{2} M_i \bar{N}_i^c N_i - Y_{i\alpha} \bar{N}_i H \ell_\alpha + \text{h.c.}$$

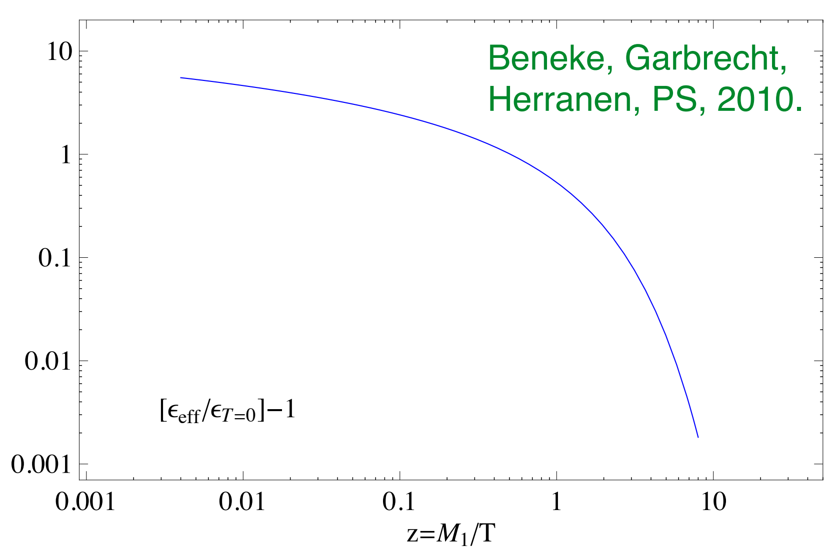
- Explicit **L** (and **B-L**) violation

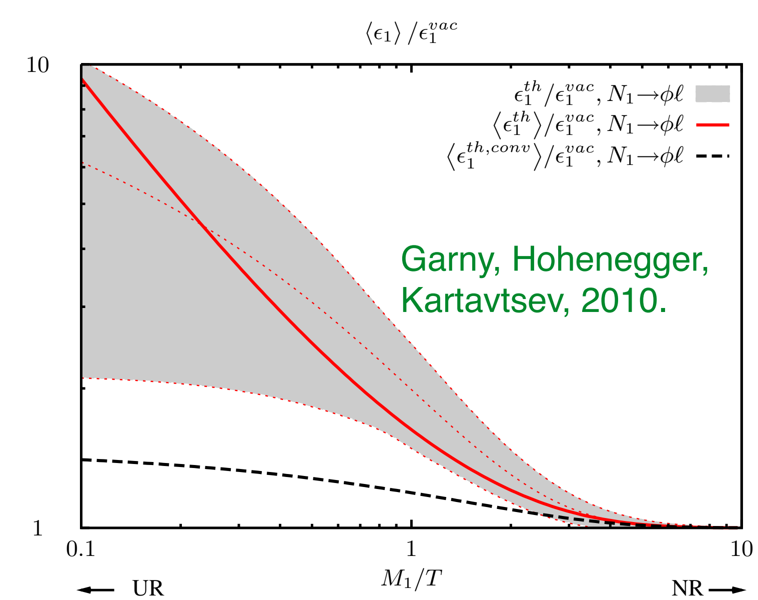
- CPV from phases in $Y$




$$\epsilon = \frac{\Gamma(N_1 \to H\ell) - \Gamma(N_1 \to H^\dagger \bar{\ell})}{\Gamma(N_1 \to H\ell) + \Gamma(N_1 \to H^\dagger \bar{\ell})} \propto \frac{\Im m[(YY^\dagger)^2_{1j}]}{(YY^\dagger)_{11}} \frac{M_1}{M_j}$$

- Thermal corrections to CPV



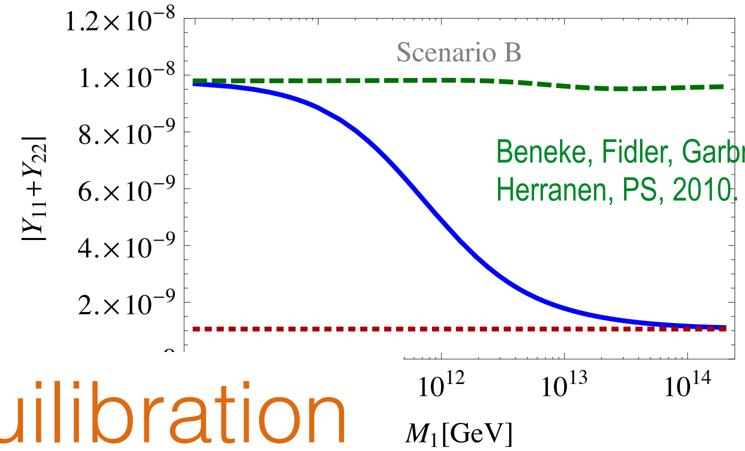




also Anisimov, Buchmuller, Drewes, Medizabal, 2010;
and earlier work by Riotto, de Simone, 2007; Giudice, Notari et al, 2004; Covi et al, 1997.

- For $T \lesssim 10^{12}$ GeV: Tau Yukawa in equilibrium

Schwaller

  - Different washout for different flavours, increase final asymmetry
  - No oscillations!



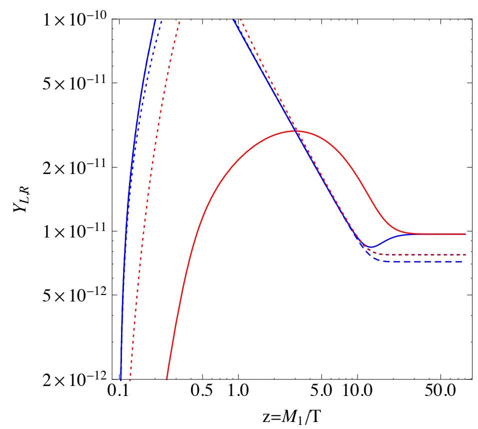

# Partial tau Yukawa equilibration

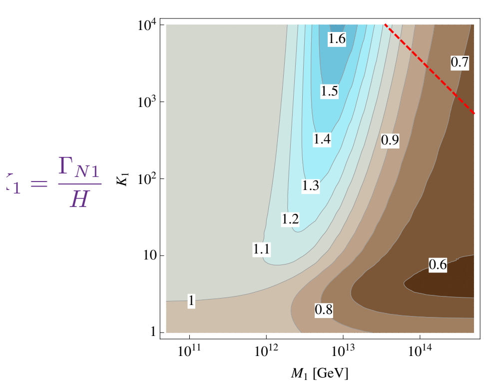
Garbrecht, PS, 1404.2915

- Evolution equations

$$\frac{d}{dt}Y_\ell = S - WY_\ell - \gamma^{\rm fl} h_\tau^2 (Y_\ell - Y_R)$$
$$\frac{d}{dt}Y_R = -\gamma^{\rm fl} h_\tau^2 (Y_R - Y_\ell)$$

- Asymmetry hidden in $Y_R$




- Up to 60% enhancement compared to old approach
- $\Gamma_\tau^{\rm fl}/H = 1$ at $T_\tau \approx 3.7\times10^{11}$ GeV

Lots of progress in theoretical description - some work still to do, sizeable effects can still appear in some parameter regions, but predictions are getting more solid!

Maybe best candidate theory to explain baryon asymmetry. Possible connection with neutrino CP phase, neutrinoless double beta decay, but a full test seems very difficult

# Conclusions

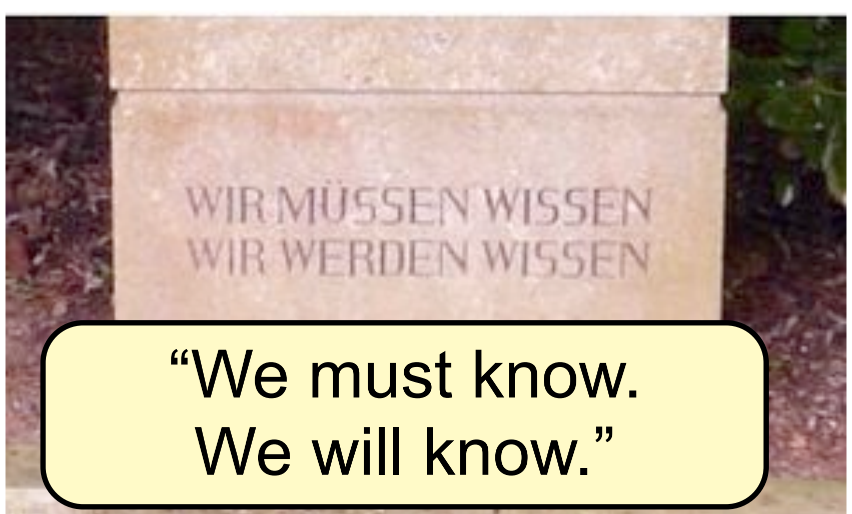

“Getting at high scales can be hard.”

Discoveries of BSM particles have not (yet) happened, unlike expected by many.

There is now a very strong case for indirect searches at low and high $p_T$.

Flavour plays a key role in probing fundamental scales.

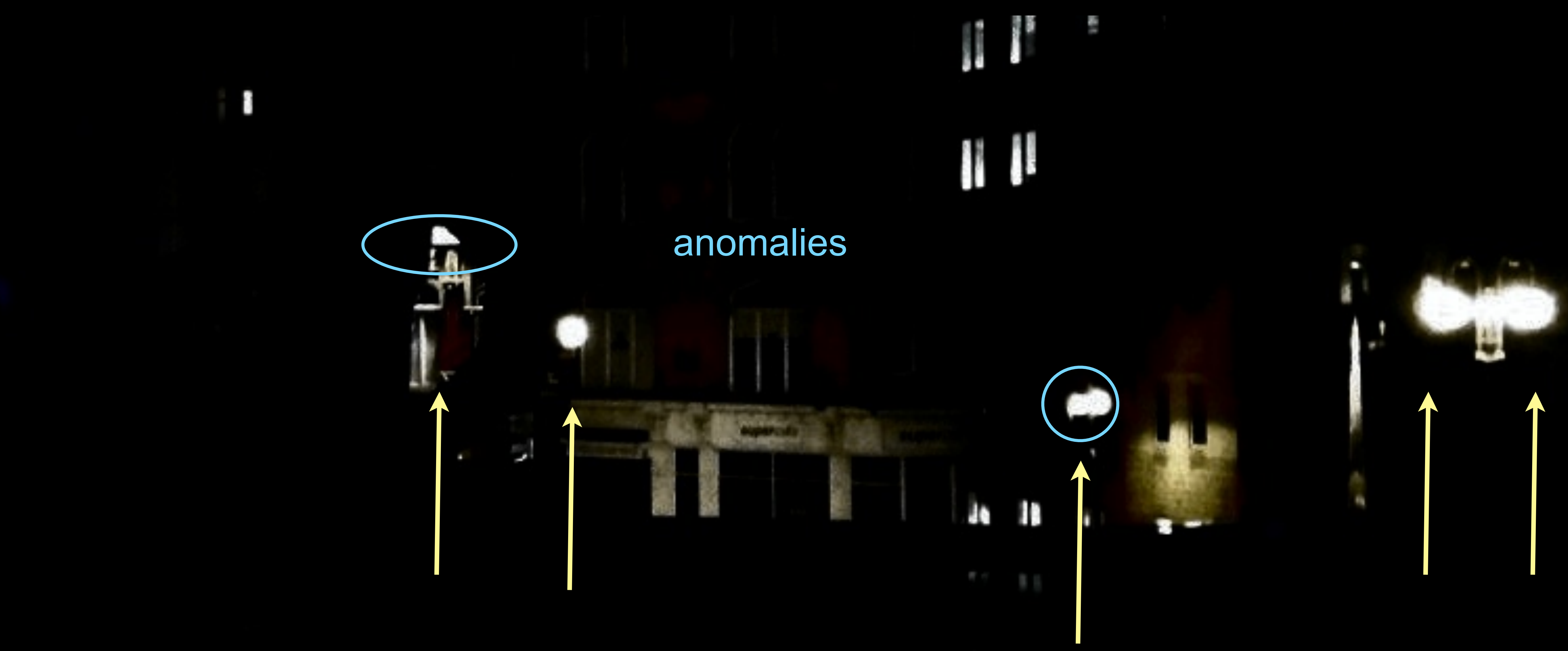
Intriguing anomalies are being rapidly scrutinised and interpreted by theorists. Fresh data, new theoretical techniques, and new precision experiments will soon provide new sources of light to be shed on the physics at the TeV scale and beyond.




“We must know. We will know.”

Success is not guaranteed, but this is (usually) the nature of frontier research...

Five anonymous precision experiments represented at this conference

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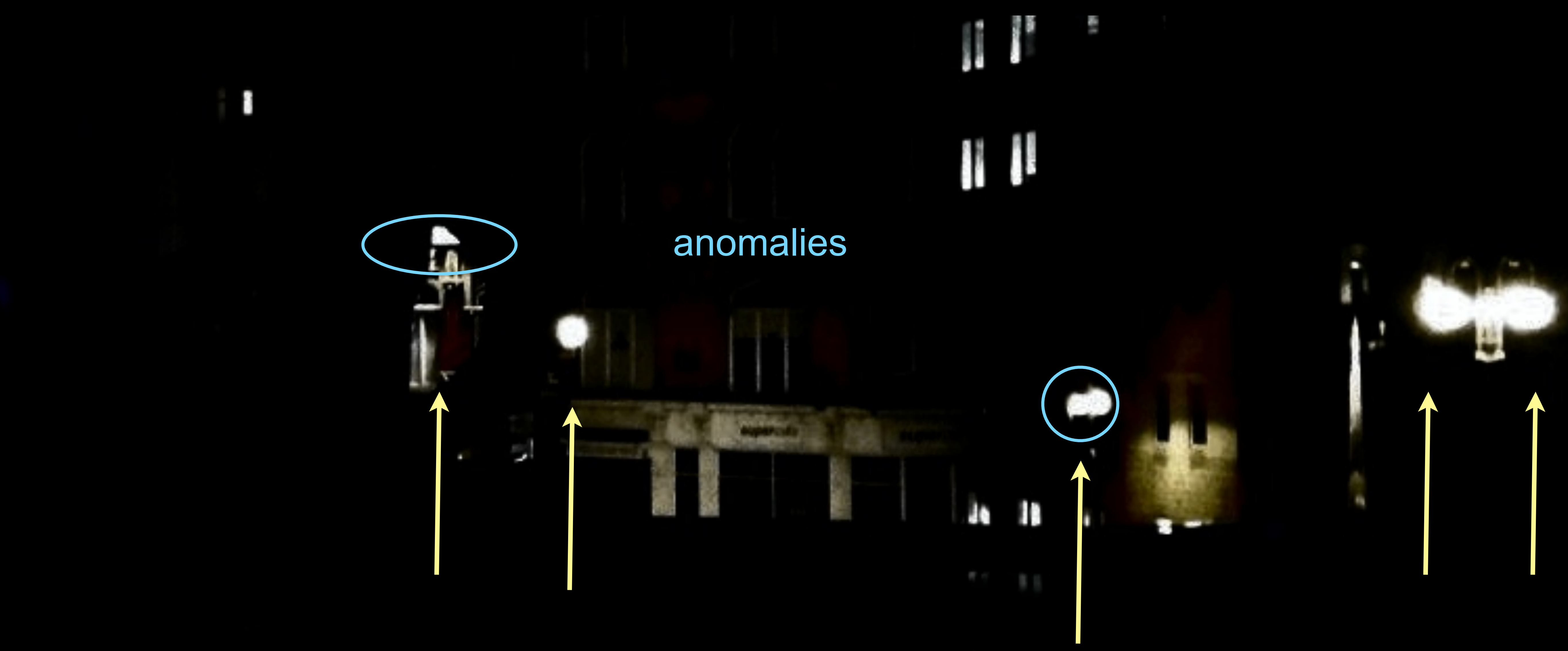


Five anonymous precision experiments represented at this conference

Is it QCD?

Fluctuations?

Systematics?

SUSY?


with increased luminosity...
... increasing
backgrounds...


**The River**
Sat in the upper pool, is a monumental female figure representing the life force. The figure has been nicknamed 'The Floozie in the Jacuzzi' and weighs 1.75 tonnes. The River is also a fountain - one of the largest in Europe - with a flow of 3,000 gallons per minute. [http://www.birmingham.gov.uk]


Big thank you to the organisers for a wonderful BEACH (and the great weather, too).

thanks to Alexey Petrov for providing photographs