Beijing, August 2005

Flavour Dynamics & ~~C~~P in the SM*: A Tale of Great Successes, Little Understanding -- and Promise for the Future!

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Lecture VI (6)

Searching for a New Paradigm 2005 & Beyond
Following Samuel Beckett's Dictum

Recap from Lectures I -- IV

CKM has scored novel successes in the last few years that have to be viewed as amazing due to its very peculiar structure

`We know a lot -- yet understand so little!"
i.e., these successes do not invalidate the general arguments in favour of the SM being incomplete

But -- based on these successes -- we cannot count on massive manifestations of New Physics in flavour dynamics

➥ must combine high accuracy with high sensitivity in studies of flavour dynamics

➻ goal can be achieved combining robust theory with detailed & comprehensive data

S. Beckett: "Ever tried? Ever failed?

No matter.

Try again. Fail again. Fail better.

Cheer up -- we know there is New Physics -- we will not fail forever!

A. Masiero: "You have to be lucky to find New Physics."

Napoleon:"Being lucky is part of the job description for my generals!"

SM with CKM very successful in describing
(though not necessarily explaining) earthly data, except for:

the `Strong CP Problem' of QCD

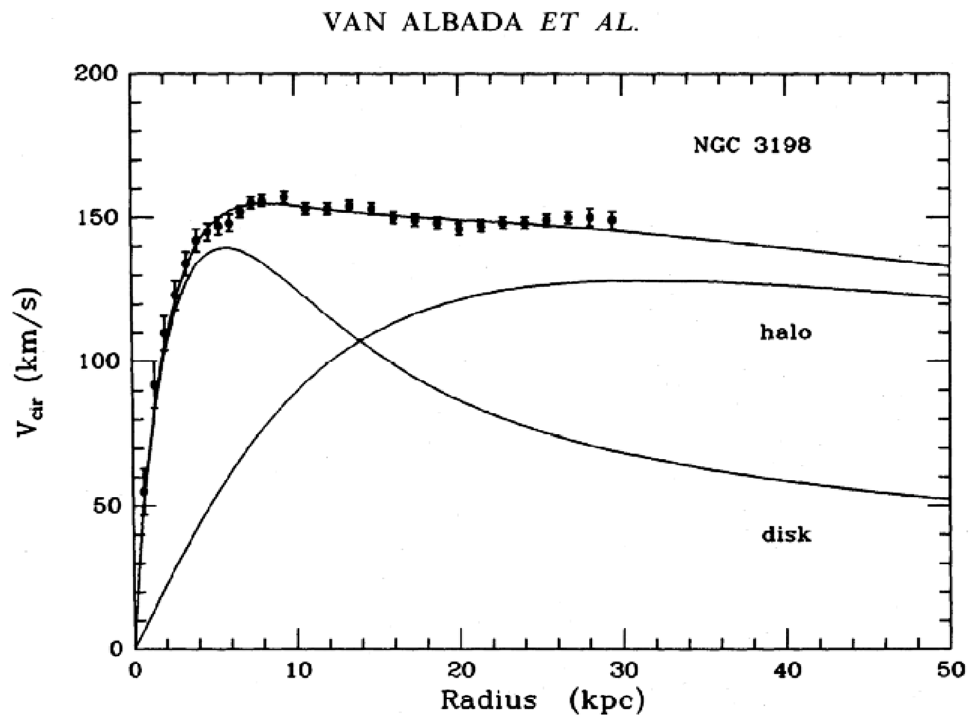
Evidence for ν oscillations from KAMLAND & K2K

Yet `heavenly' evidence is quite unequivocal

compelling evidence from astrophysics & cosmology
that Standard Model is incomplete!

- baryon # of Universe
  - 😐 *standard* CKM irrelevant for baryon number of universe
  - ☺ New Physics exists!
  - ☺ New CP Paradigm: ~~CP~~ phases can be large

❑ Dark Matter

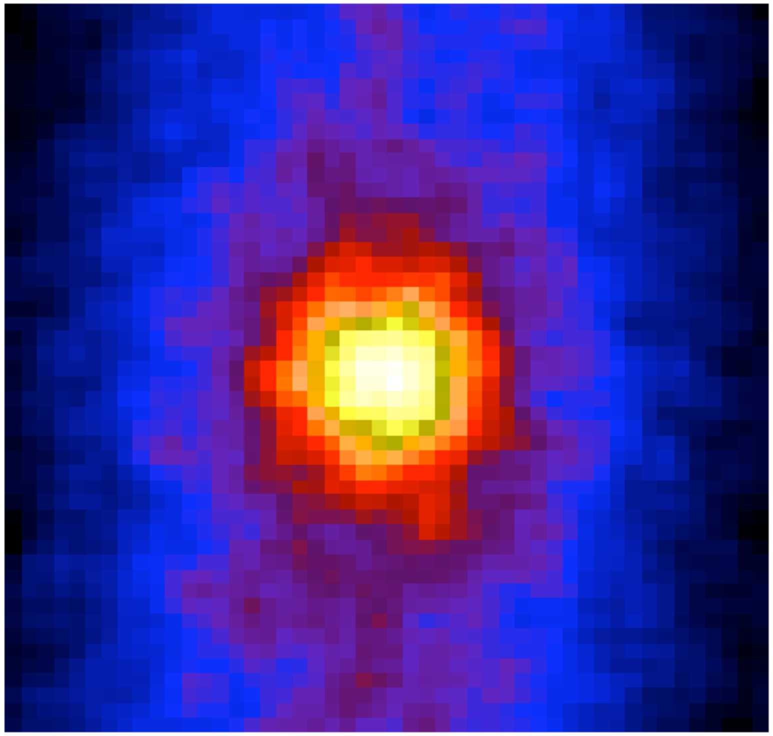


A lot more `stuff' --

i.e. gravitating agents -- out there than meets the eye!

- about 1/4 of gravitating agents in the Universe are `dark matter', mostly non-baryonic
  - ☞ Standard Model has no candidates for it!

- Solar & atmospheric ν `anomalies'



From R. Svoboda

Our sun seen by Super-K in the `light' of neutrinos -- it looks paler than it should: ν_e disappear by changing their identity!

ν_μ produced in the earth's atmosphere `disappear' as well

Dark Energy

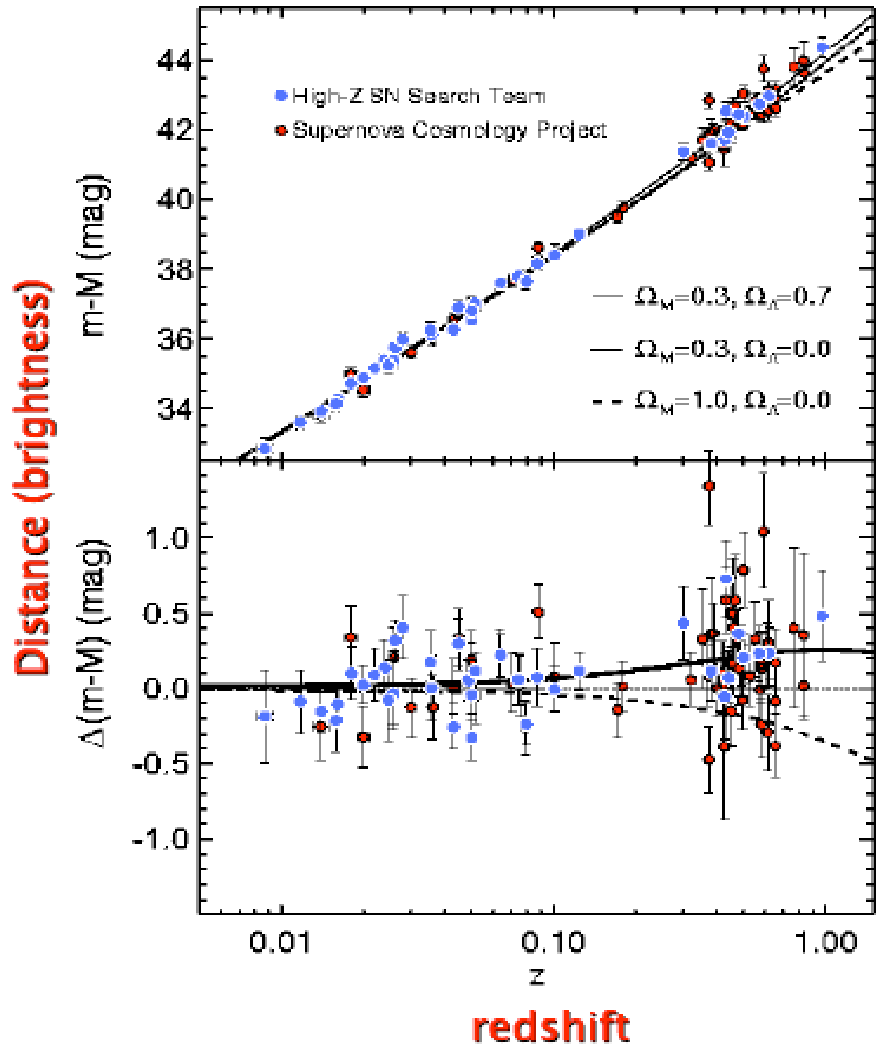
In 1998 2 teams searched for SN 1a (=`standard candles')

~5 billion LY away;

found them fainter than expected from deceleration:

➥ acceleration!

P. Garnavich



Menu for Lecture V

I $\Delta S \neq 0$ -- the `Established Hero'

II The `King Kong Scenario' for New Physics Searches

III τ Decays -- the Next Hero Candidate

IV Future HEP landscape - a Call to ~~Arms~~ well-reasoned Action

I $\Delta S \neq 0$ -- the `Established Hero'

Memento $\Delta S \neq 0$ dynamics:

- $\tau - \theta$ puzzle $\Rightarrow$ $\cancel{P}$!
- production rate >> decay rate $\Rightarrow$ families !
- no $\Delta Fl \neq 0$ NC $\Rightarrow$ charm !
- $K_L \to \pi\pi$ $\Rightarrow$ $\cancel{CP}$, top !

All New Physics at that time

-- yet now pillars of the SM!

- the `dark horse'

$Pol_\perp(\mu)$ in $K_{\mu 3}$ decays

$\boxed{K \to \mu^+ \nu \pi}$

$Pol_\perp(\mu) = \langle \mathbf{s}_\mu \cdot (\mathbf{p}_\mu \times \mathbf{p}_\pi) / |\mathbf{p}_\mu \times \mathbf{p}_\pi| \rangle$ -- T odd moment

$K^+ \to \mu^+ \nu \pi^0$

$Pol_\perp(\mu) = (-1.7 \pm 2.3 \pm 1.1) \times 10^{-3}$ vs. $Pol_\perp^{SM}(\mu) < 10^{-6}$

→ a clean search for $\cancel{CP}$ via Higgs dyn. (need enhanced coupling to leptons to makke it viable)

- various radiative K decays -- $K \to \pi\gamma\gamma$, $\pi\pi\gamma$ -- to probe χpert. th. & possibly get better treatment of long distance contrib. to $\Delta I = 1/2$ rule, Δm_K & ε'

- `heresy'

  $K^+ \to \pi^+\pi^0$ vs. $K^- \to \pi^-\pi^0$ CPT test on 10^{-3} level ?

- the `Second Trojan War' (described in the Iliad):

  - $\boxed{K^+ \to \pi^+\nu\nu}$

    theoret. uncertainty [m_c] ~ 7 % (I think can be cut to 4 - 5 %)

  - $\boxed{K_L \to \pi^0\nu\nu}$ = $\cancel{CP}$!

    theoret. uncertainty ~ 2 %

    - `standard candles' of SM
    - should aim for ~ $\mathcal{O}(1000)$ events

II The `King Kong Scenario' for New Physics Searches

"One might be unlikely to encounter King Kong;
yet once it happens there will be no doubt that one
has come across something out of the ordinary!"

as with historical precedent of strange hadrons search for a qualitative discrepancy between data & expectation,
i.e. discrepancies by orders of magnitude!

II.1 $\cancel{CP}$ in leptodynamics

Compelling impetus to search for $\cancel{CP}$ in leptodynamics

- to complete `demystification' of CP
- baryogenesis due to primary leptogenesis (?)

ν oscillations

no worry about hadronization, yet … probe ν oscillations

… disentangle matter enhancements …

ancient Greek wisdom:

"If the gods want to really harm you, they fulfill your wishes."

Electric dipole moments

static quantities

energy shift $\Delta\mathcal{E}$ of system inside electric field $\boldsymbol{E}$:

$$\Delta\mathcal{E} = d_i E_i + d_{ij} E_i E_j + \ldots$$

linear in E $\quad$ $\mathbf{d} \propto \mathbf{s} \Rightarrow \mathbf{d} \neq 0 \Leftrightarrow$ T violation !

$d_N < 0.63 \times 10^{-25}$ ecm $\quad$ vs. $\quad$ $d_N^{CKM} < 10^{-30}$ ecm (except strong CP)

from ultracold neutrons

$d_e = (0.07 \pm 0.07) \times 10^{-26}$ ecm $\quad$ vs. $\quad$ $d_e^{CKM} < 10^{-32}$ ecm

from atomic EDM

✍ New Physics scenarios can yield ~ 10^{-26} - 10^{-28} ecm

II.2 Charm Decays

S. Bianco et al., `A Cicerone for the Physics of Charm', hep-ex/0309021, La Rivista d. N. C.

Common feeling: charm physics -- great past, *no* future!

- drove paradigm shift: quarks as *real* entities
  essential support for acceptance of QCD
- electroweak SM phenomenolgy for $\Delta C \neq 0$ `dull'
  - CKM parameters `known'
  - D^0 - D^0 oscillations very slow
  - ~~CP~~ very small
  - loop driven decays extremely rare

`I have come to praise C. -- not to bury it!'

charm dynamics full of challenges -- & promises

triple motivation for further dedicated studies

❶ *QCD (& `beyond')*: understanding nonperturb. dynamics & establishing theoretical control over it

❷ *B dynamics*: calibrating theoret. tools for B studies

❸ *New Physics*: charm transitions a novel window onto New Physics

❶ & ❷ will not be addressed here

❸ *New Physics*

only up-type quark allowing full range of probes for New Phys.

☞ top quarks do not hadronize

☞ up quarks: no π^0-π^0 oscillations possible

CP asymmetries basically ruled out by CPT

basic contention:
charm transitions are a unique portal for obtaining a novel access to the flavour problem with the experimental situation being a priori favourable (apart from absence of Cabibbo suppression)!

D^0-$\bar{D}^0$ oscillations

- case for New Physics based on x_D uncertain

D^0-D^0 oscillations `slow' in the SM

How `slow' is `slow'?

$$x_D = \frac{\Delta m_D}{\Gamma_D} \quad y_D = \frac{\Delta\Gamma_D}{2\Gamma_D}$$

$$x_D, \quad y_D \sim \cancel{SU(3)}_{Fl} \cdot 2\sin^2\theta_C < \text{few} \cdot 0.01$$

on-shell transitions

off-shell transitions

➥ *conservative* bound: x_D, $y_D \sim \mathcal{O}(0.01)$

Data: $x_D < 0.03$, $y_D \sim 0.01 \pm 0.005$

"game" has just begun!

It is not the quark box diagram, stupid!

sobering lesson: case for New Physics based on x_D uncertain!

➥ search for $\cancel{C}P$ in D^0-$\bar{D}^0$ oscillations

Caveat en passant:

- $\Delta\Gamma(B_s)$ vulnerable to violations of local duality!

remember when extracting $|V(td)|$ from $\Delta m(B_d)/ \Delta\Gamma(B_s)$

- definitive measurement:

  x_D, y_D down to 0.001

CP Violation

- ☺ baryon # of Universe implies/requires NP in ~~CP~~ dynamics
- ☺ within SM:
  - ☞ highly diluted weak phase in 1x Cabibbo supp. Modes $V(cs) = 1 \dots + i\lambda^4$
  - ☞ no weak phase in Cab. favoured & 2 x Cab. supp. modes (except for $D^\pm \to K_S h^\pm$)
- ☺ CP asymmetry linear in NP amplitude
- ☺ final state interactions large
- ☺ BR's for CP eigenstates large
- ☹ D^0-D^0 oscillations at best slow

✍ B factories can contribute

☞ challenge to LHCb: can you?
$D^{*+} \to D^0(t) \to K^+\pi^-$ vs. $D^{*-} \to D^0(t) \to K^-\pi^+$

time integrated *partial widths*

final state interact.

- ☹ necessary evil
- ☺ cannot fake signal
- ☺ ~ large in charm

☺ in Cabibbo favoured (CF) modes

possible only with New Physics (except *)

☹ in singly Cabibbo supp. modes (SCS)

possible with KM -- benchmark: $O(\lambda^4) \sim O(10^{-3})$

New Physics models: $O(\%)$ conceivable

☺ in doubly Cabibbo supp. modes (DCS)

possible only with New Physics (except *) exception *: $D^{\pm} \to K_{S[L]}\, \pi^{\pm}$ interference between

$D^+ \to K^0 \pi^+$ (CF) and $D^+ \to \bar{K}^0 \pi^+$ (DCS)

in KM only effect from $\cancel{CP}$ in $K^0 - \bar{K}^0$

asymmetry $A_{S,L} = [+]_{S,L} - [-]_{S,L} = -3.3 \times 10^{-3}$

with NP in DCS amplitude could reach $O(1\%)$ of either sign and $A_S = - A_L$

$\boxed{\textit{Final state distributions: Dalitz plots, T-odd moments}}$

final state interact.
- ☹ not necessary
- ☹ a nuissance: can fake signal
- ☺ can be disentangled

very promising -- most effective theoretical tools not developed yet for small asymmetries

$\cancel{CP}$ involving D^0-D^0 oscillations: `indirect' $\cancel{CP}$

$D^0 \to K_S\,\phi/\pi^0$ vs. $D^0 \to K_S\,\phi/\pi^0$

$D^0 \to K^+K^-/\pi^+\pi^-$ vs. $D^0 \to K^+K^-/\pi^+\pi^-$

$D^0 \to K^+\pi^-$ vs. $D^0 \to K^-\pi^+$

CP asymmetry given by $\boxed{\sin\Delta m_D t}$ $\boxed{\mathrm{Im}(q/p)\,\rho(D \to f)}$

small [each ~ $\mathcal{O}(10^{-3})$]

in SM with KM

➥ strong case for New Physics!

asymmetry is linear in x_D whereas r_D is quadratic

➥ could be first signal of oscillations!

Benchmarks

for definitive measurements must aim at:

- x_D, y_D down to $\mathcal{O}(10^{-3}) \Leftrightarrow r_D \sim \mathcal{O}(10^{-6} - 10^{-5})$
- time dependant CP asymmetries in

  $D^0 \to K^+K^-, \pi^+\pi^-, K_S\phi$ down to $\mathcal{O}(10^{-4})$;

  $D^0 \to K^+\pi^-$ down to $\mathcal{O}(10^{-3})$.

- direct $\cancel{CP}$ in partial widths of

  $D^\pm \to K_{S[L]}\pi^\pm$ down to $\mathcal{O}(10^{-3})$;

  in a host of SCS channels down to $\mathcal{O}(10^{-3})$.

- direct $\cancel{CP}$ in the final state distributions:

  Dalitz plots, T-odd correlations etc. down to $\mathcal{O}(10^{-3})$.

III τ Decays -- the Next Hero Candidate

SM forbidden τ decays

$\tau \to \mu/e\,\gamma$

$\tau \to 3\,l$

if New Physics in $b \to sss \approx$ New Physics in $\tau \to \mu\mu\mu$

then $BR(\tau \to \mu\mu\mu) \sim 10^{-8}$

$\cancel{CP}$ in τ decays

most promising channels: $\tau \to \nu K \pi$

- most sensitive to Higgs dynamics

- CP asymmetries possible also in final state distributions rather than integrated rates

- unique opportunity for $e^+e^- \to \tau^+\tau^-$
  pair produced with spins aligned:
  1 τ decays can `tag' the spin of the other
  ➥ can probe spin-dependent $\cancel{CP}$ with unpolarized beams!

- confidently predicted $\cancel{CP}$:

  0.0033 in $\Gamma(\tau^+ \to \nu K_S \pi^+)$ vs. $\Gamma(\tau^- \to \nu K_S \pi^-)$

  -- due to K_S's preference for antimatter

IV Future HEP landscape - a Call to ~~Arms~~ well-reasoned Action

Sketch situation through 7 statements

❶ *SM nontrivially consistent with all data* -- except for

- ν oscillations
- probably the Universe's baryon #, dark energy/matter
- possibly the *strong CP problem*
- maybe -- just maybe ~~*CP*~~ in $B \to \phi K_S$

☞ *New dimension due to findings of 1999-2001*

first decisive tests of the CKM description of ~~*CP*~~ --

- $B \to \psi K_S$: first observation of ~~*CP*~~ outside K_L decays
- it is huge -- as predicted!

➥ CKM a tested theory rather than an ansatz

❷ flavour dynamics even more intriguing due to emergence of neutrino oscillations

CKM matrix ≠ P-MNS matrix

do not understand | do not understand

we do understand | Majorana ν's, `see-saw'

F. Mauriac & his love for 2 Germanies

❸ `Grand Challenge' after dynamics behind electro-weak phase transition: ~~CP~~ in lepton sector!

❹ "Know so much, yet understand so little!"

The SM's success in describing flavour transitions not matched by an understanding of the origin of flavour.

It *resolves none of the deep mysteries of the*
SM in the heavy flavour sector: masses & CKM parameters.

➥ SM incomplete: `strongly suspected' NP= *ssNP*

❺ New Physics driving electroweak phase transition
confidently expected ~ TeV scale: *cpNP*

☞ this is the justification for the LHC

SUSY an organizing principle, not a theory!

➼ LHC (TEVATRON ?) is likely to uncover New Physics

☞ LHC (TEVATRON) is primarily a discovery machine

☞ Linear Collid. a surgical probe of the New Physics

❻ The *cpNP* unlikely to shed light on the *ssNP* behind flavour puzzle of SM (though it could);

- ☞ instead studies of flavour transitions might elucidate salient features of the *cpNP*
- ☞ New Physics around TeV scale could affect flavour transitions significantly

➥ Heavy flavour decays provide probe for New Physics that is complementary to the TEVATRON, LHC & Linear Collider -- and actually necessary!

☞ heavy flavour studies

- ❑ are of fundamental importance;
- ❑ its lessons cannot be obtained any other way;
- ❑ cannot become obsolete.

i.e., no matter what studies of high p_t physics at FNAL & LHC will or will not show -- comprehensive & detailed studies of flavour dynamics will remain crucial in our efforts to reveal Nature's Grand Design

❼ Crucial manifestations of New Physics likely to be subtle

➥ precision in interpretation of data essential!

3 scenarios for the next 5 - 8 years out

A -- the optimal one:

new physics observed at high p_t (FNAL/LHC)

➥ must study their impact on flavour dynamics

☺ some features -- mass scale etc. known !

B -- the intriguing one

deviations from SM established in heavy flavour decays

C -- the frustrating one

no deviation from SM prediction identified

➻ none of these scenarios weakens the role of flavour studies being essential for coming to grips with nature's `Grand Design'

- handful of even perfectly measured processes not enough
  -- comprehensive body of accurate data essential

Super-B factory = asymmetric e^+e^- collider
near $\Upsilon(4S)$ with $L \sim$ few x 10^{35} cm^{-2} s^{-1}

- up to 10^{10} B mesons/year

  [vs. LHC-b with 20×10^{11} beauty hadrons/year]

- in a clean environment

appears peerlessly able to provide required data base

Wind on the Hill

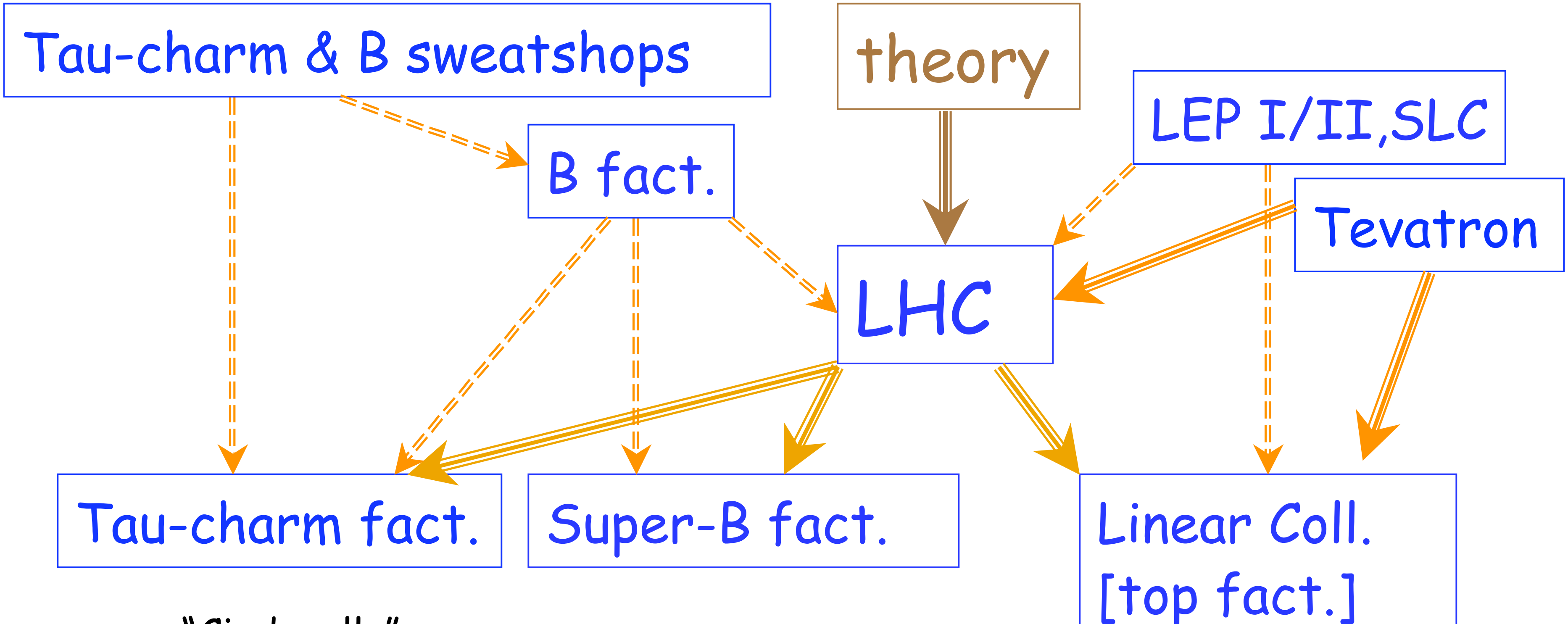
No one can tell me
    Nobody knows
Where the wind comes from,
    Where the wind goes.

But if I stopped holding
    The string of my kite,
It would blow with the wind
    For a day and a night.

And then when I found it,
    Wherever it blew,
I should know that the wind
    Had been going there, too.

So then I could tell them
    Where the wind goes …
But where the wind comes from
    Nobody knows.

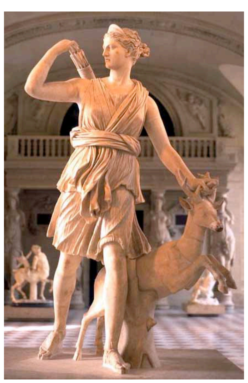
A.A. Milne
[Winnie-the-Pooh 1926]
(with thanks to T.D. Lee)



"Cinderella"

"the beautiful daughter"

"the straight daughter"



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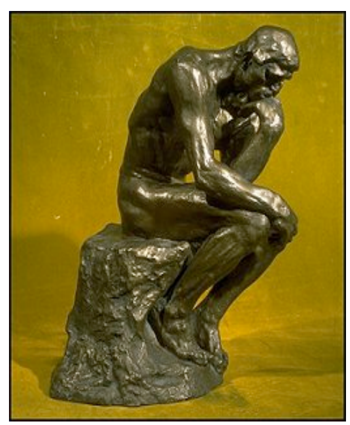

beginning of an exciting adventure …

and we are most privileged to participate!