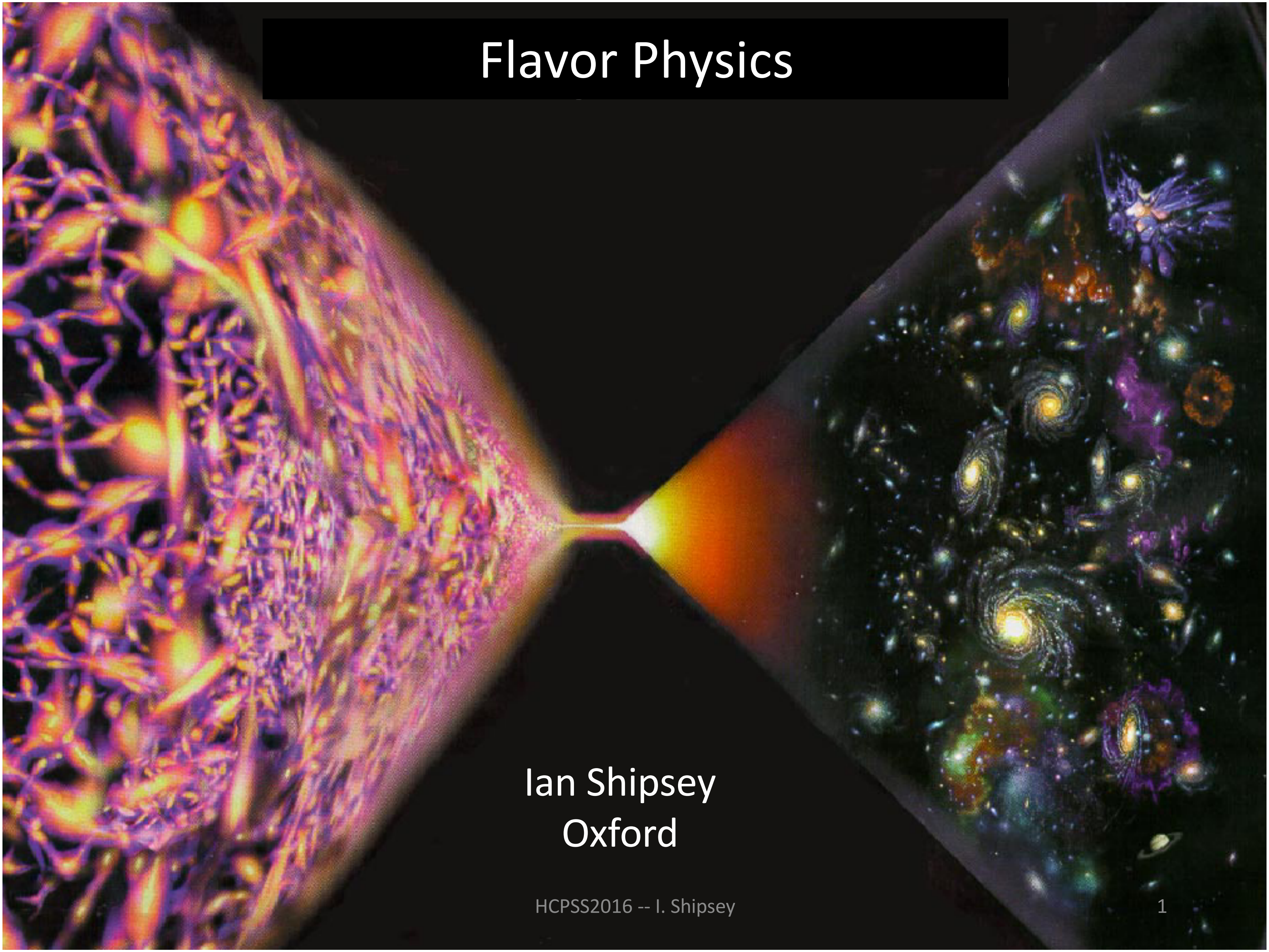
Flavor Physics



Ian Shipsey
Oxford

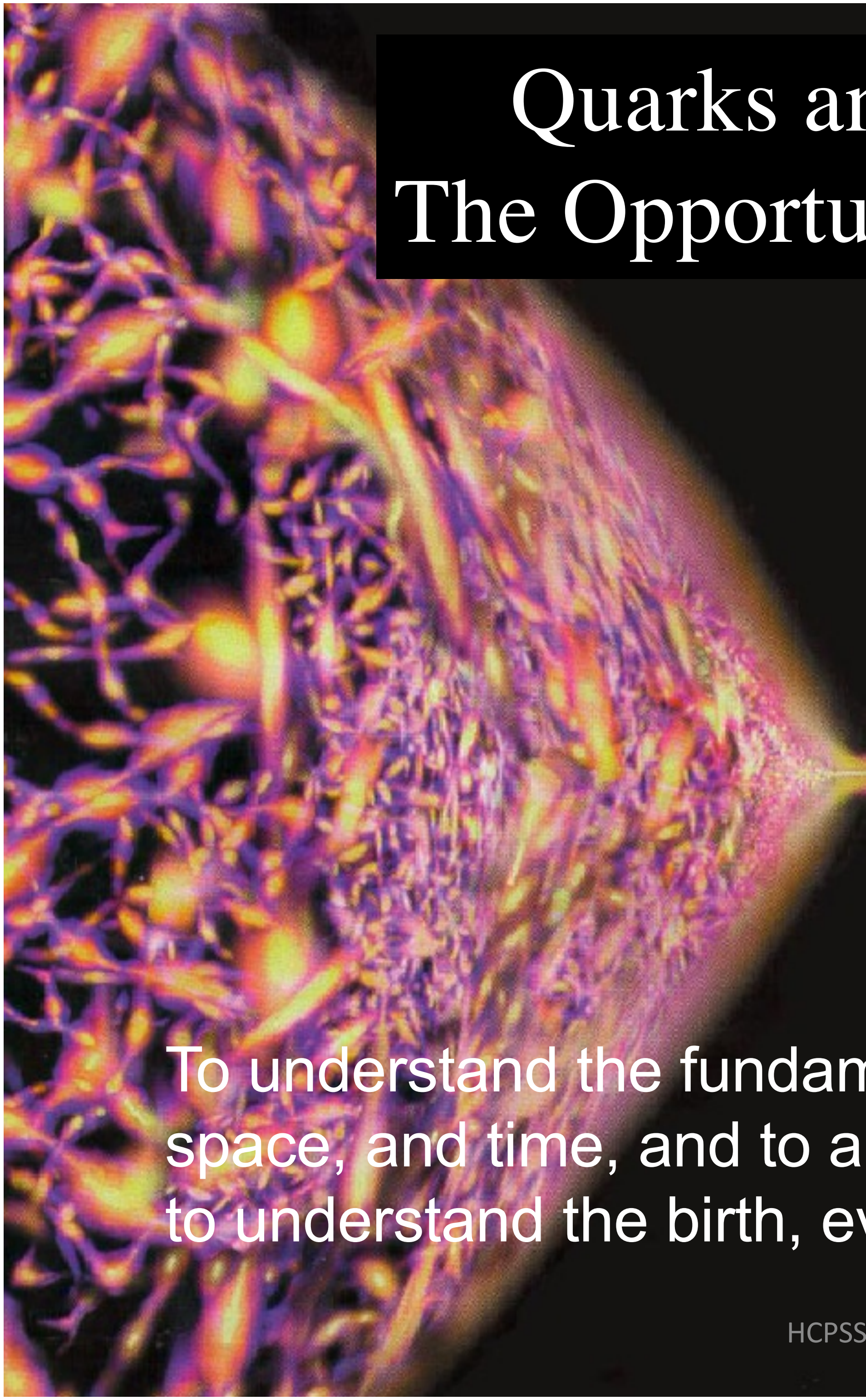
OUTLINE

The Big Picture

Role of flavor physics in the Big Picture

Flavor Physics past and present

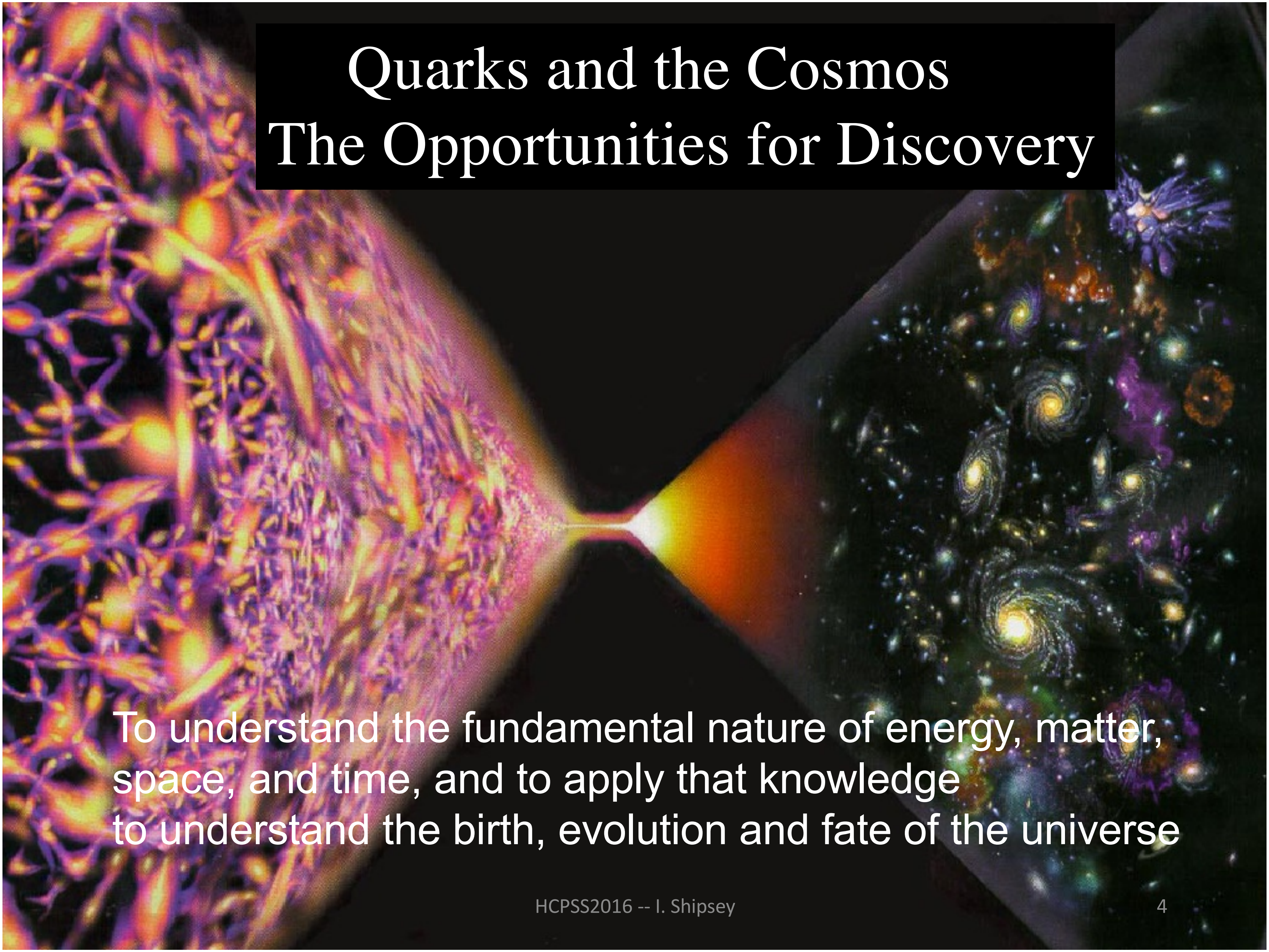
Opportunities for achieving “transformational or paradigm-altering” scientific advances: *great discoveries*.



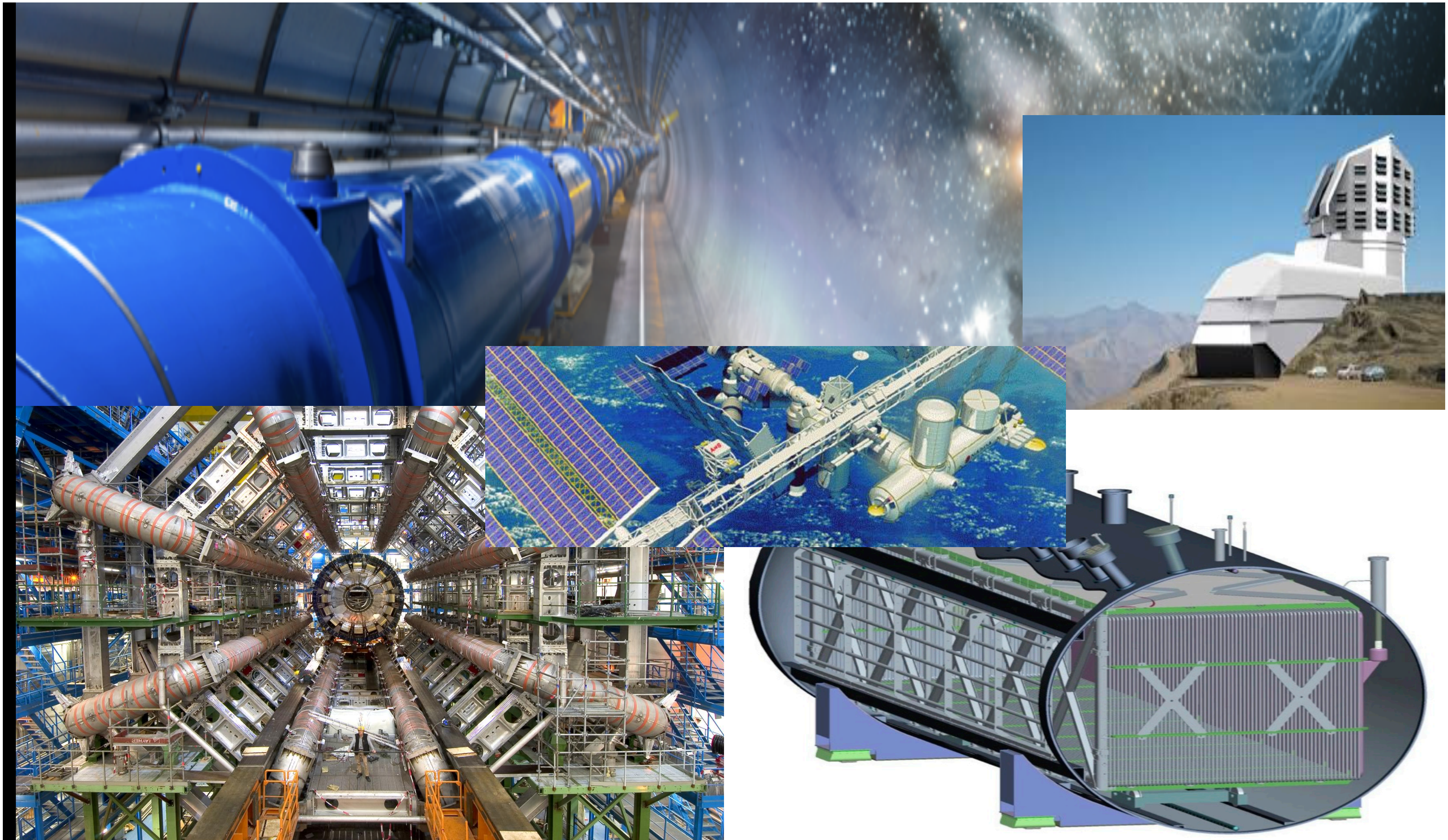
Quarks and the Cosmos
The Opportunities for Discovery

To understand the fundamental nature of energy, matter, space, and time, and to apply that knowledge to understand the birth, evolution and fate of the universe

Quarks and the Cosmos
The Opportunities for Discovery



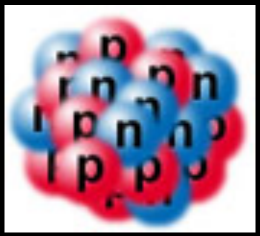
To understand the fundamental nature of energy, matter, space, and time, and to apply that knowledge to understand the birth, evolution and fate of the universe



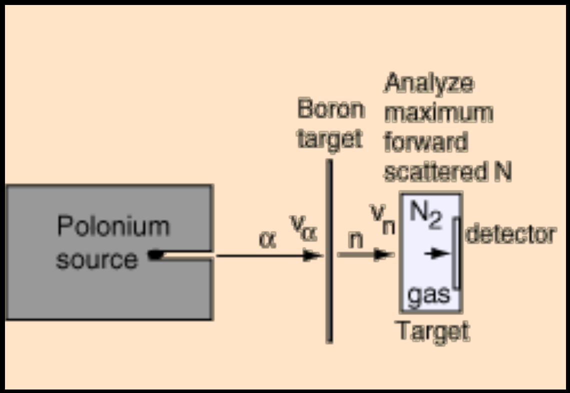
Our scope is broad and we use many tools: accelerator, non-accelerator & cosmological observations all have a critical role to play

A work a century in the making

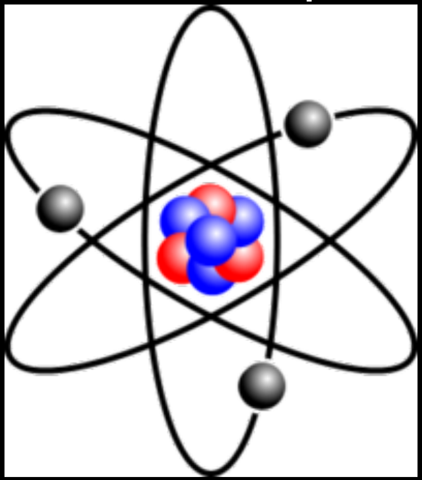
From the discovery of the electron in 1896, the nucleus in 1911 to



the neutron in 1932

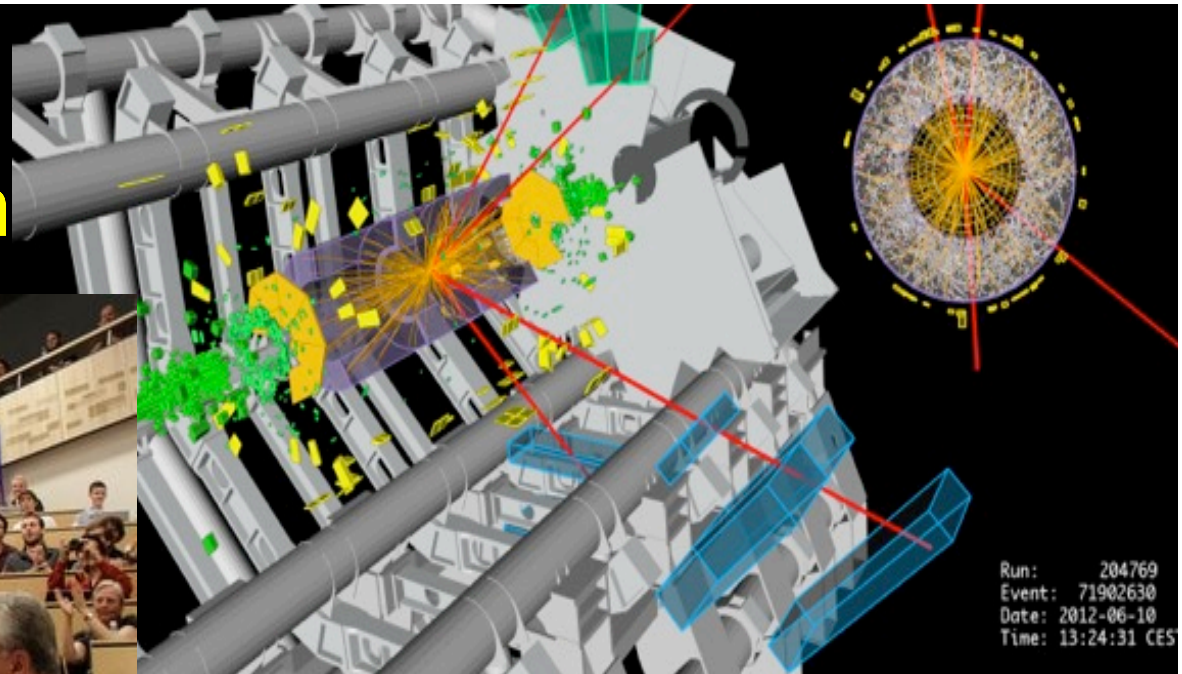


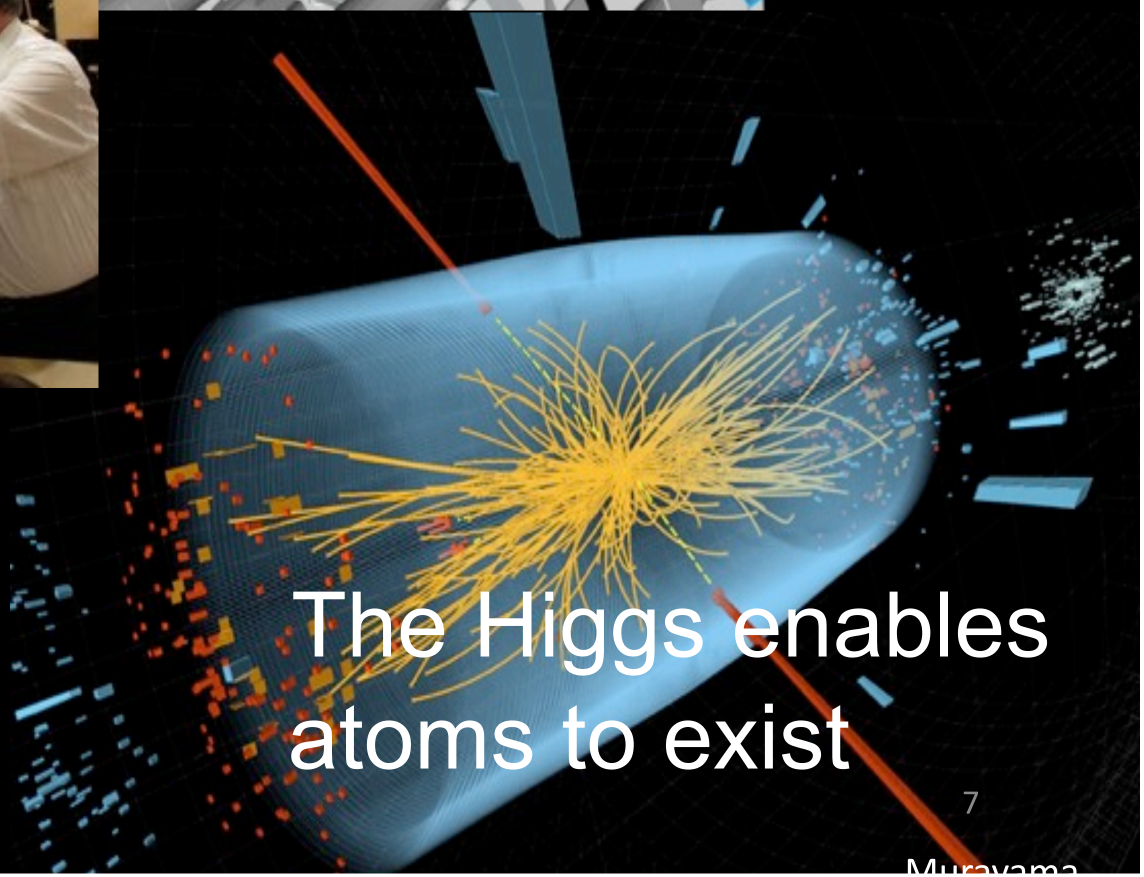
the particles that compose an atom



2012.7.4

discovery of Higgs boson





theory：1964

design：1984

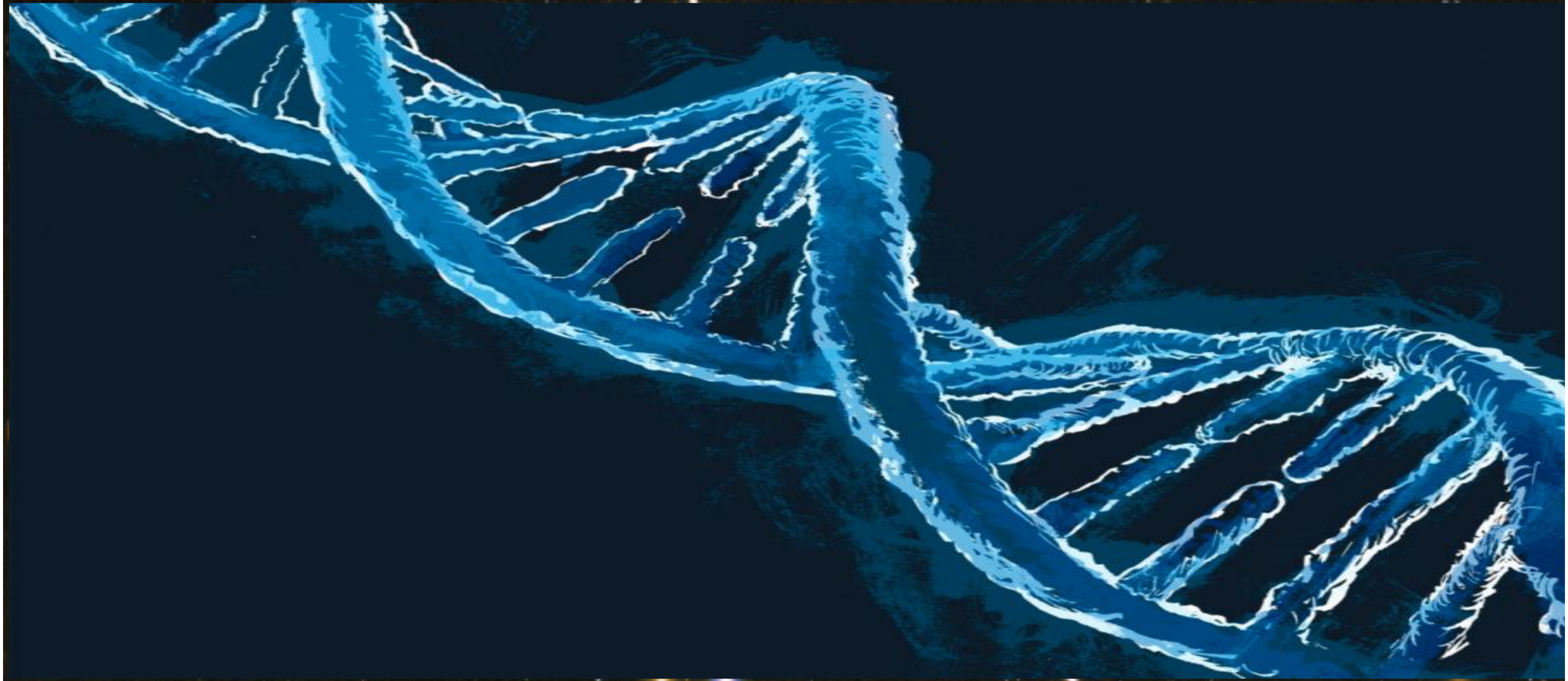
construction：1998

The Higgs enables atoms to exist

Murayama

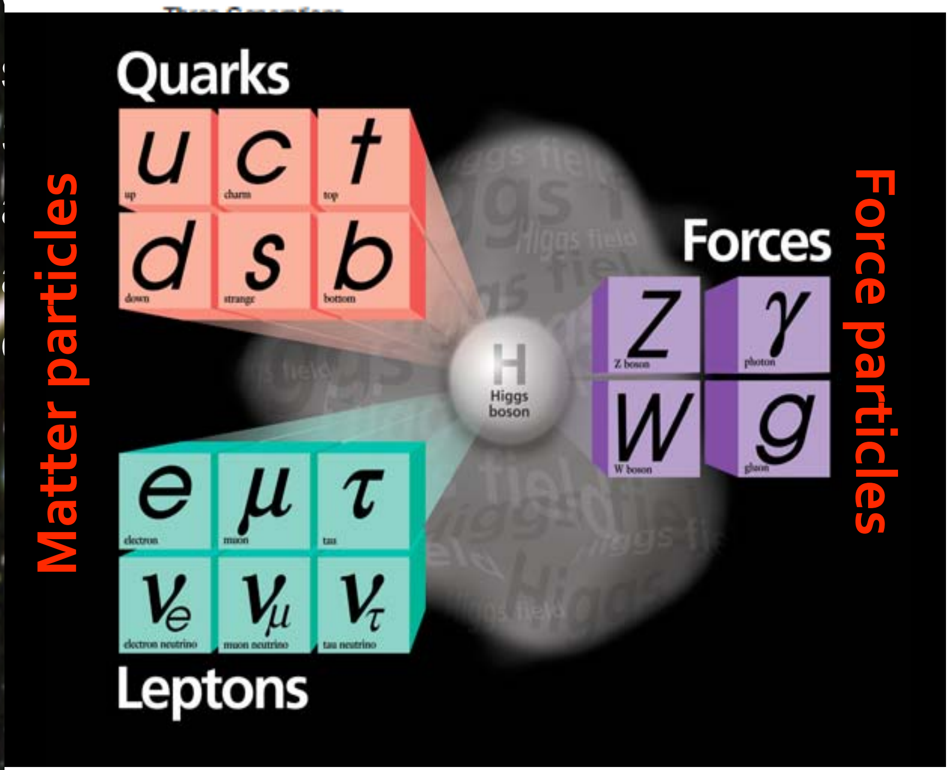
BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Our community has revolutionized human understanding of the Universe – its underlying code, structure and evolution

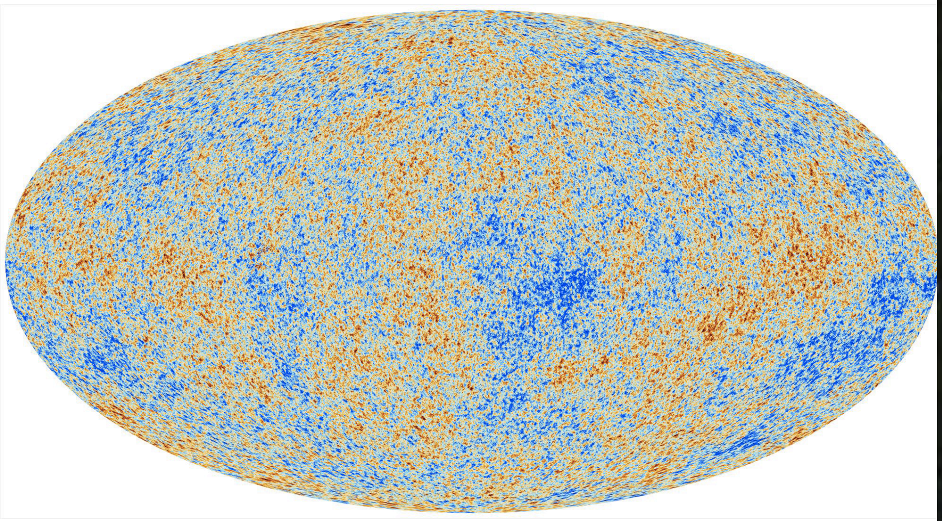


BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

- **PARTICLE STANDARD MODEL**



- **COSMOLOGY STANDARD MODEL**



ΛCDM + "SIMPLE" INFLATION

BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

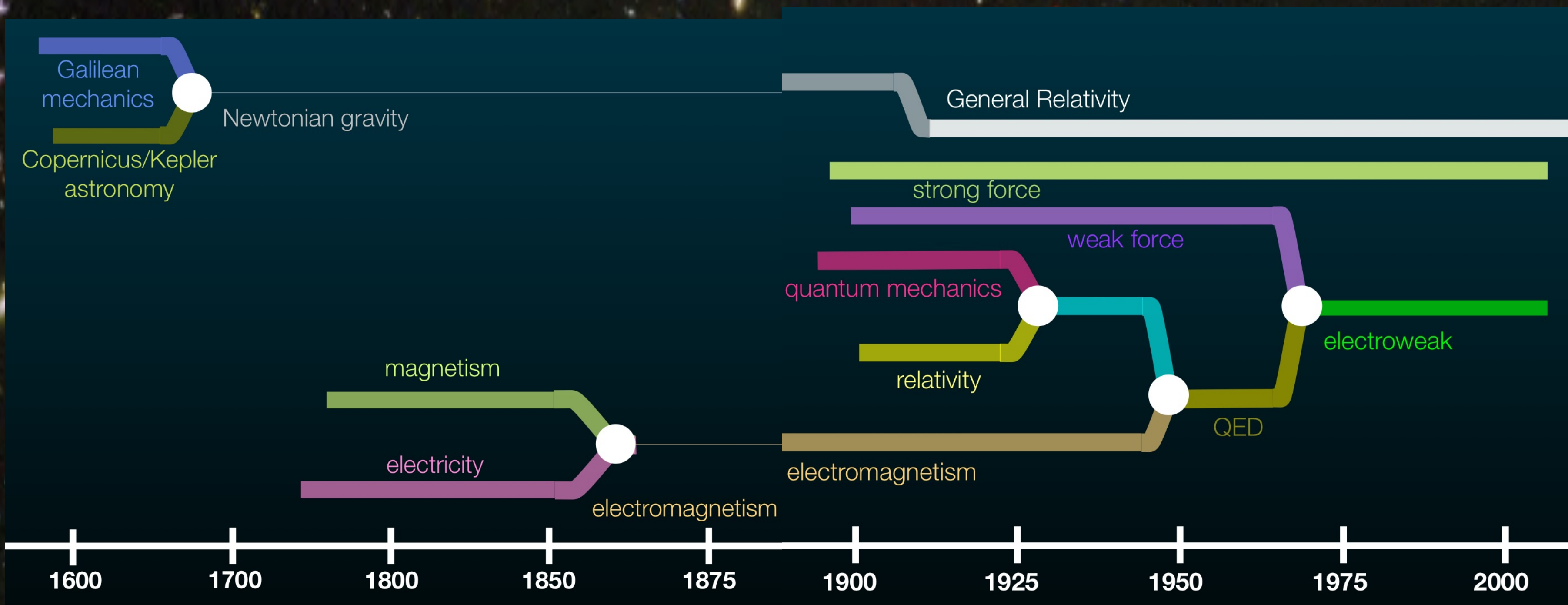
…..that are highly predictive and have been rigorously tested in some cases to 1 part in 10 billion

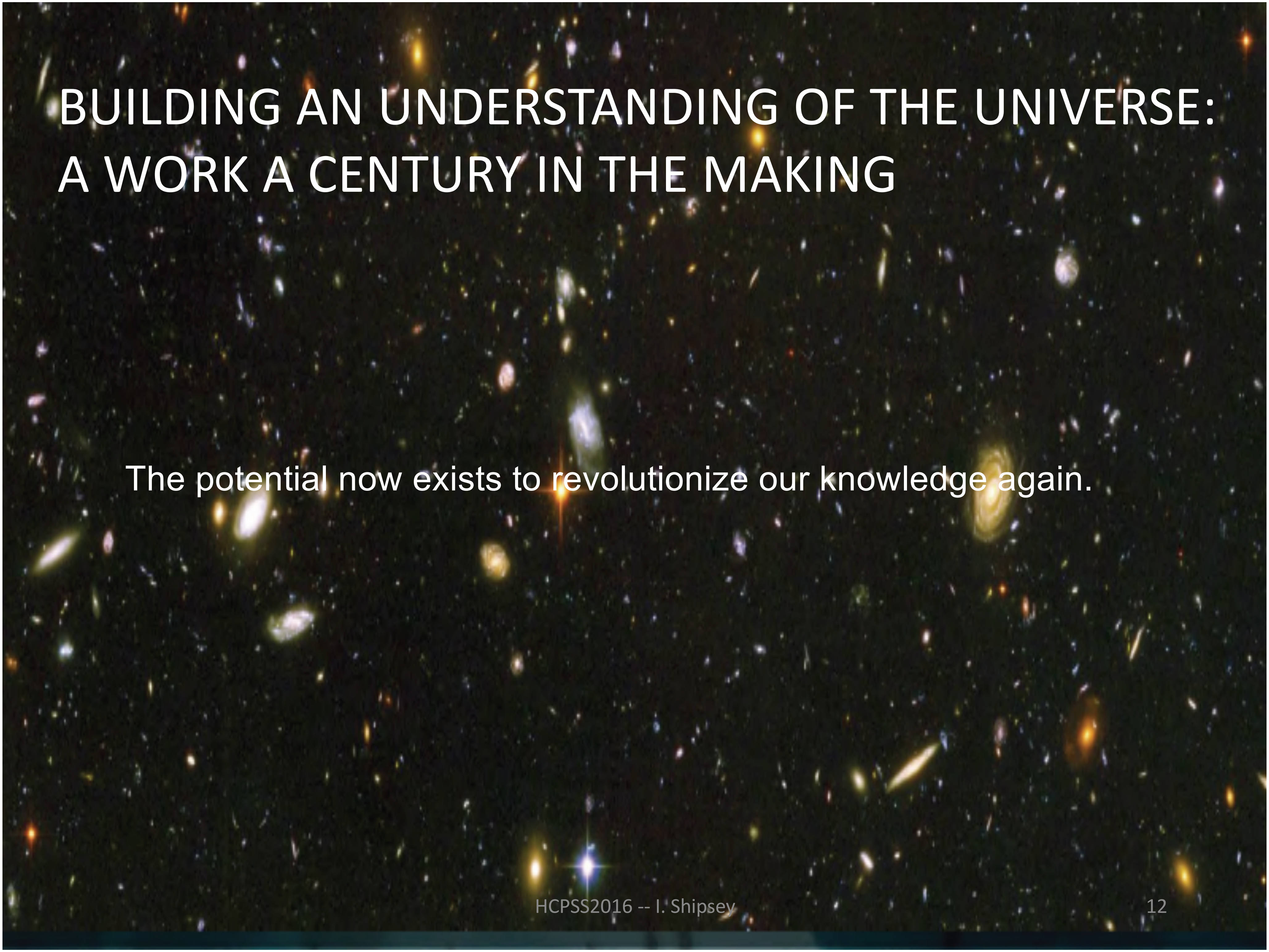
Quantity	Value	Standard Model	Pull	Dev.
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1	0.0
Γ_Z [GeV]	2.4952 ± 0.0023	2.4961 ± 0.0010	−0.4	−0.2
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7426 ± 0.0010	—	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.69 ± 0.06	—	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.005 ± 0.015	—	—
σ_{had}[nb]	41.541 ± 0.037	41.477 ± 0.009	1.7	1.7
R_e	20.804 ± 0.050	20.744 ± 0.011	1.2	1.3
R_μ	20.785 ± 0.033	20.744 ± 0.011	1.2	1.3
R_τ	20.764 ± 0.045	20.789 ± 0.011	−0.6	−0.5
R_b	0.21629 ± 0.00066	0.21576 ± 0.00004	0.8	0.8
R_c	0.1721 ± 0.0030	0.17227 ± 0.00004	−0.1	−0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01633 ± 0.00021	−0.7	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.4	0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5	1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1034 ± 0.0007	−2.6	−2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0739 ± 0.0005	−0.9	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1035 ± 0.0007	−0.5	−0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23146 ± 0.00012	0.8	0.7
	0.23200 ± 0.00076		0.7	0.6
	0.2287 ± 0.0032		−0.9	−0.9
A_e	0.15138 ± 0.00216	0.1475 ± 0.0010	1.8	2.1
	0.1544 ± 0.0060		1.1	1.3
	0.1498 ± 0.0049		0.5	0.6
A_μ	0.142 ± 0.015		−0.4	−0.3
A_τ	0.136 ± 0.015		−0.8	−0.7
	0.1439 ± 0.0043		−0.8	−0.7
A_b	0.923 ± 0.020	0.9348 ± 0.0001	−0.6	−0.6
A_c	0.670 ± 0.027	0.6680 ± 0.0004	0.1	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	−0.4	− 0.4

Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	173.4 ± 1.0	173.5 ± 1.0	−0.1	−0.3
M_W [GeV]	80.420 ± 0.031	80.381 ± 0.014	1.2	1.6
	80.376 ± 0.033		−0.2	0.2
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0474 ± 0.0005	1.3	1.3
$Q_W(\text{Cs})$	-73.20 ± 0.35	-73.23 ± 0.02	0.1	0.1
$Q_W(\text{Tl})$	-116.4 ± 3.6	-116.88 ± 0.03	0.1	0.1
τ_τ [fs]	291.13 ± 0.43	290.75 ± 2.51	0.1	0.1
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.07 \pm 0.77) \times 10^{-9}$	$(4508.70 \pm 0.09) \times 10^{-9}$	3.0	3.0

BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

These are among the highest intellectual achievements in the history of our species, they will be part of our legacy to future generations for eternity



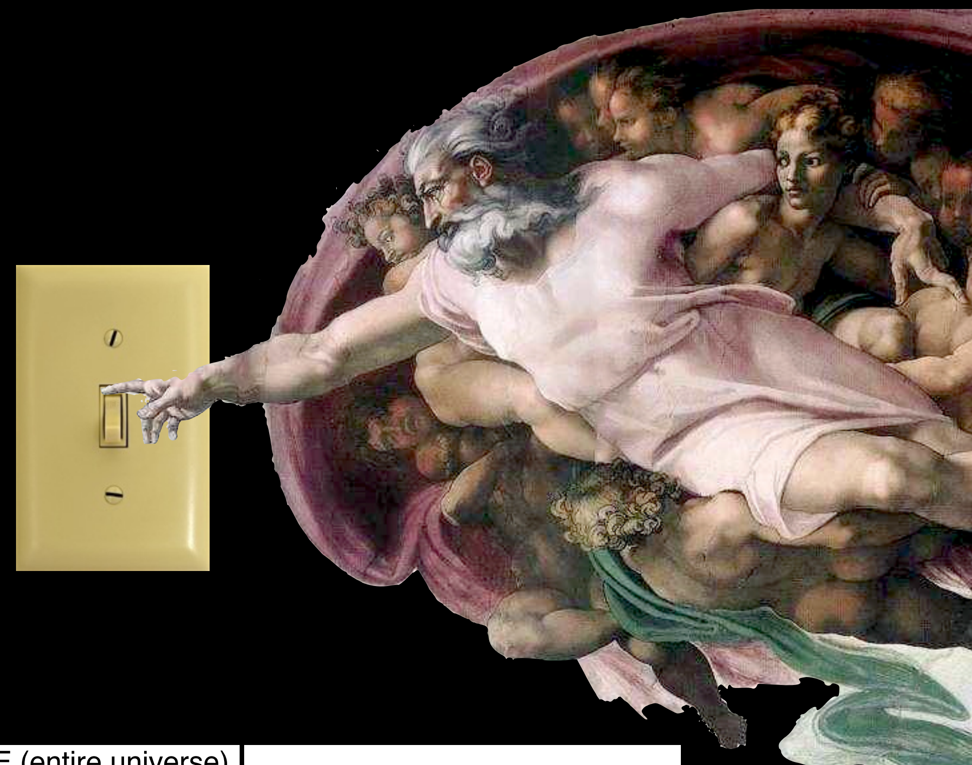


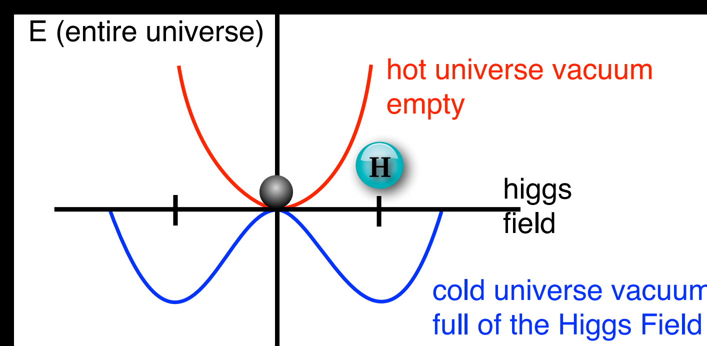
BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

The potential now exists to revolutionize our knowledge again.

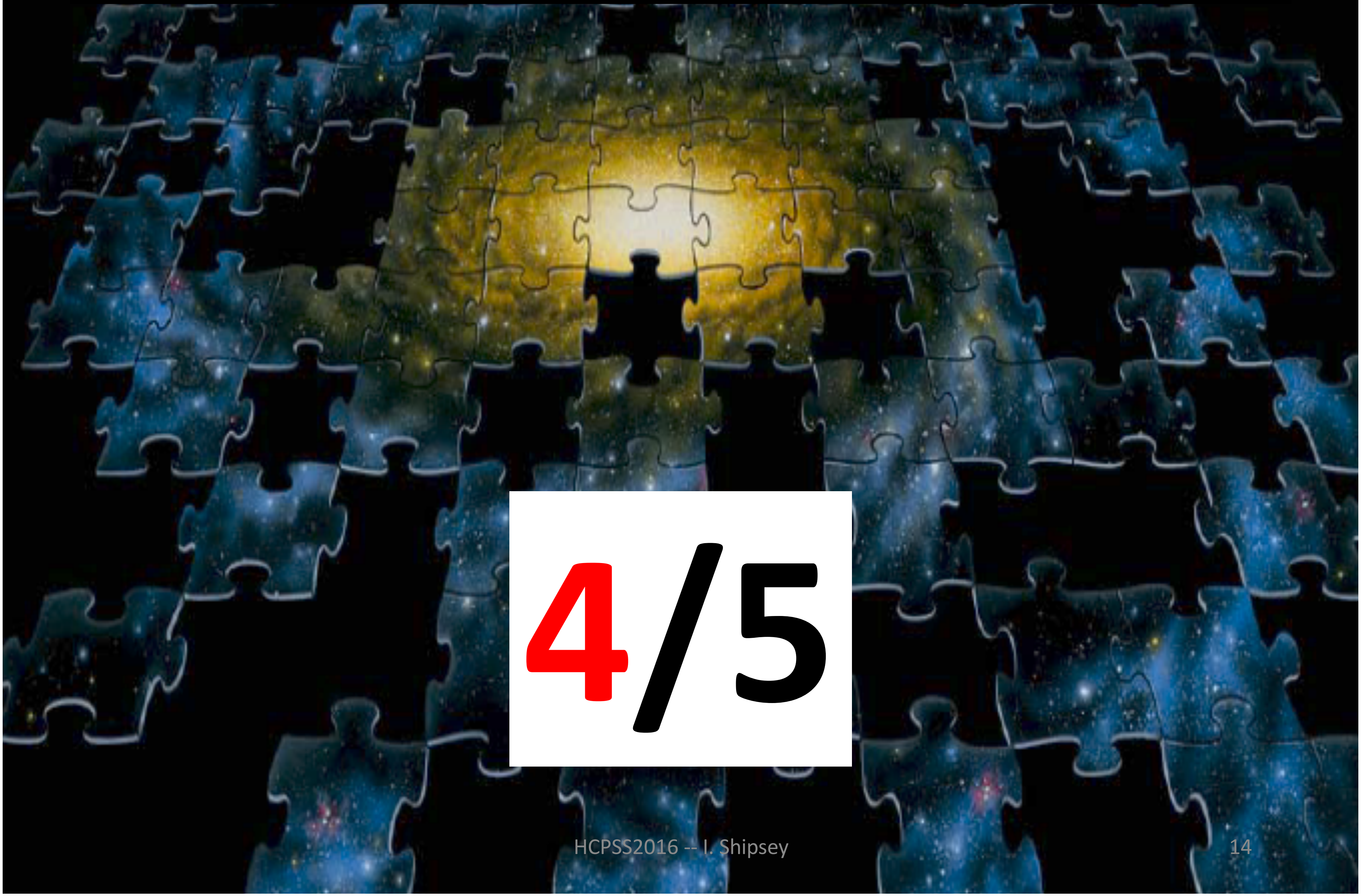
Mystery: The Higgs

That Spin 0 Boson
Changes Everything

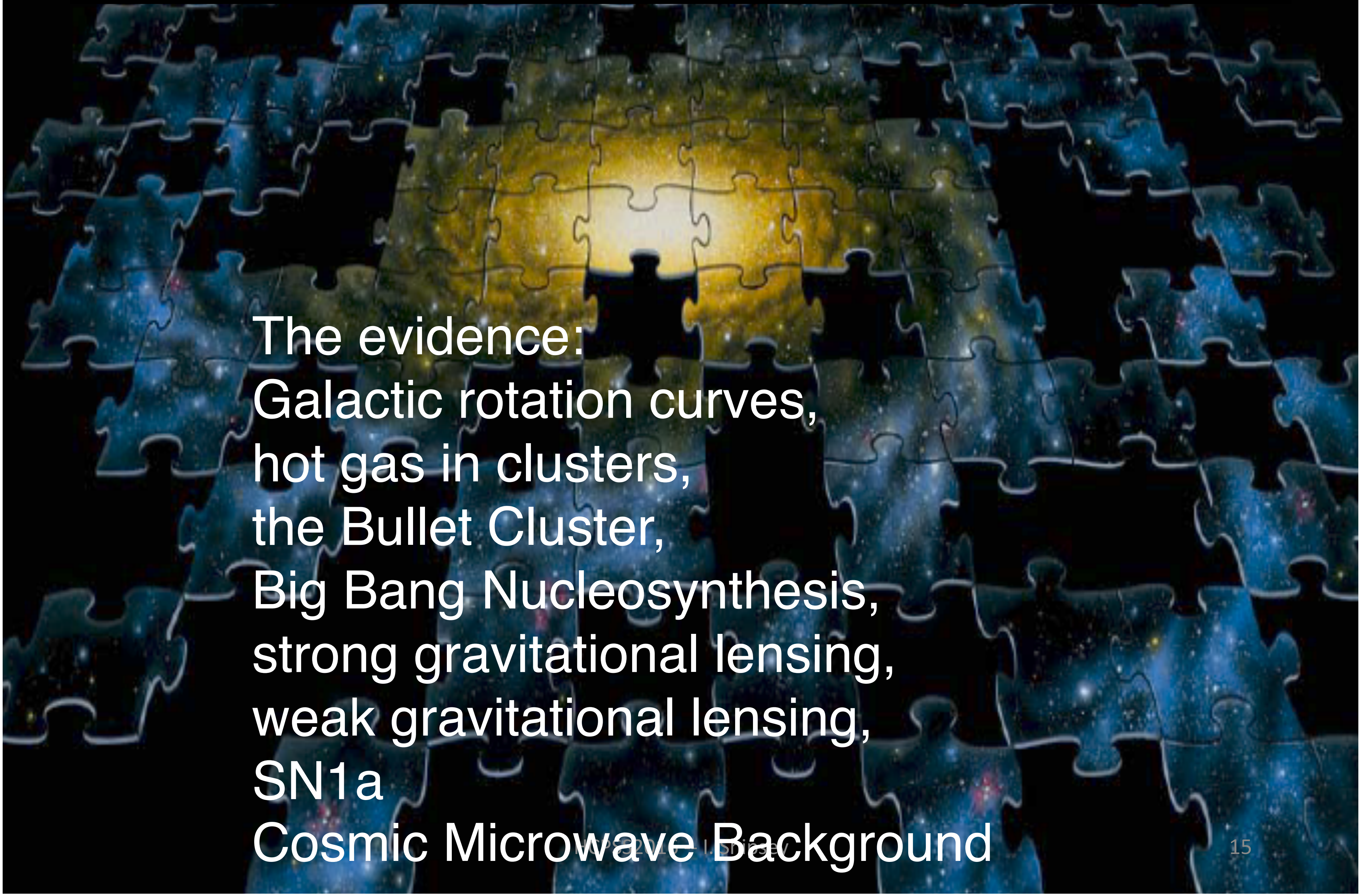




Mystery: Dark Matter

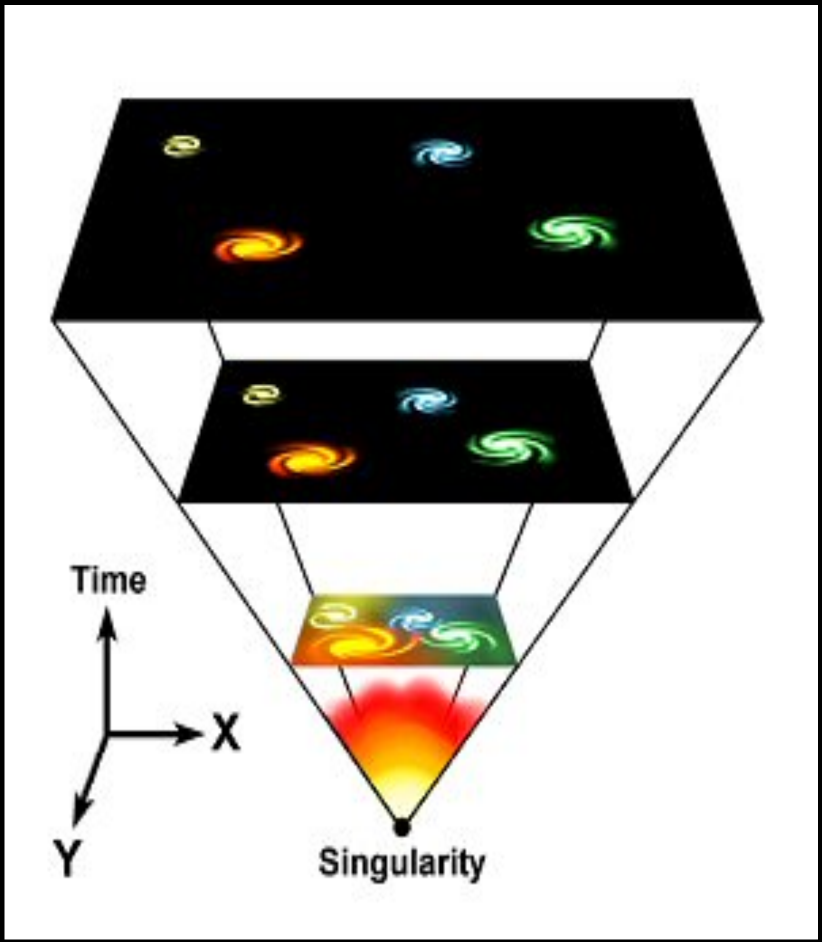


Mystery: Dark Matter



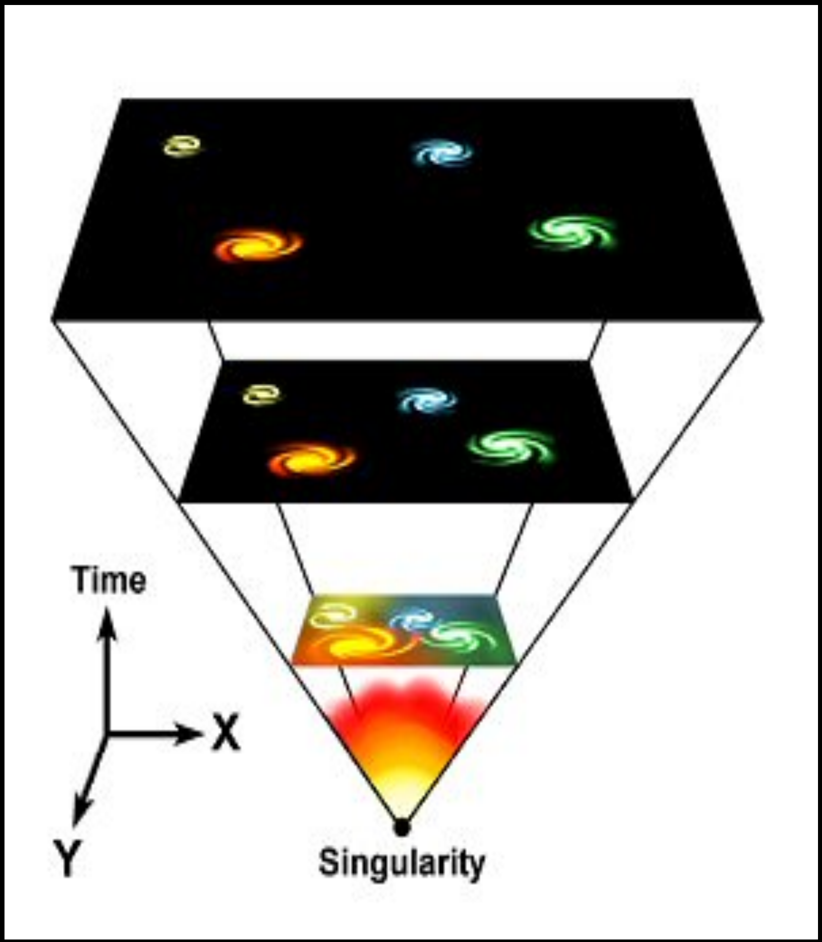
The evidence:
Galactic rotation curves,
hot gas in clusters,
the Bullet Cluster,
Big Bang Nucleosynthesis,
strong gravitational lensing,
weak gravitational lensing,
SN1a
Cosmic Microwave Background

Mystery: Dark Energy



The evidence
SN1a
BAO in the galaxy distribution
Cosmic Microwave Background

Mystery: Dark Energy



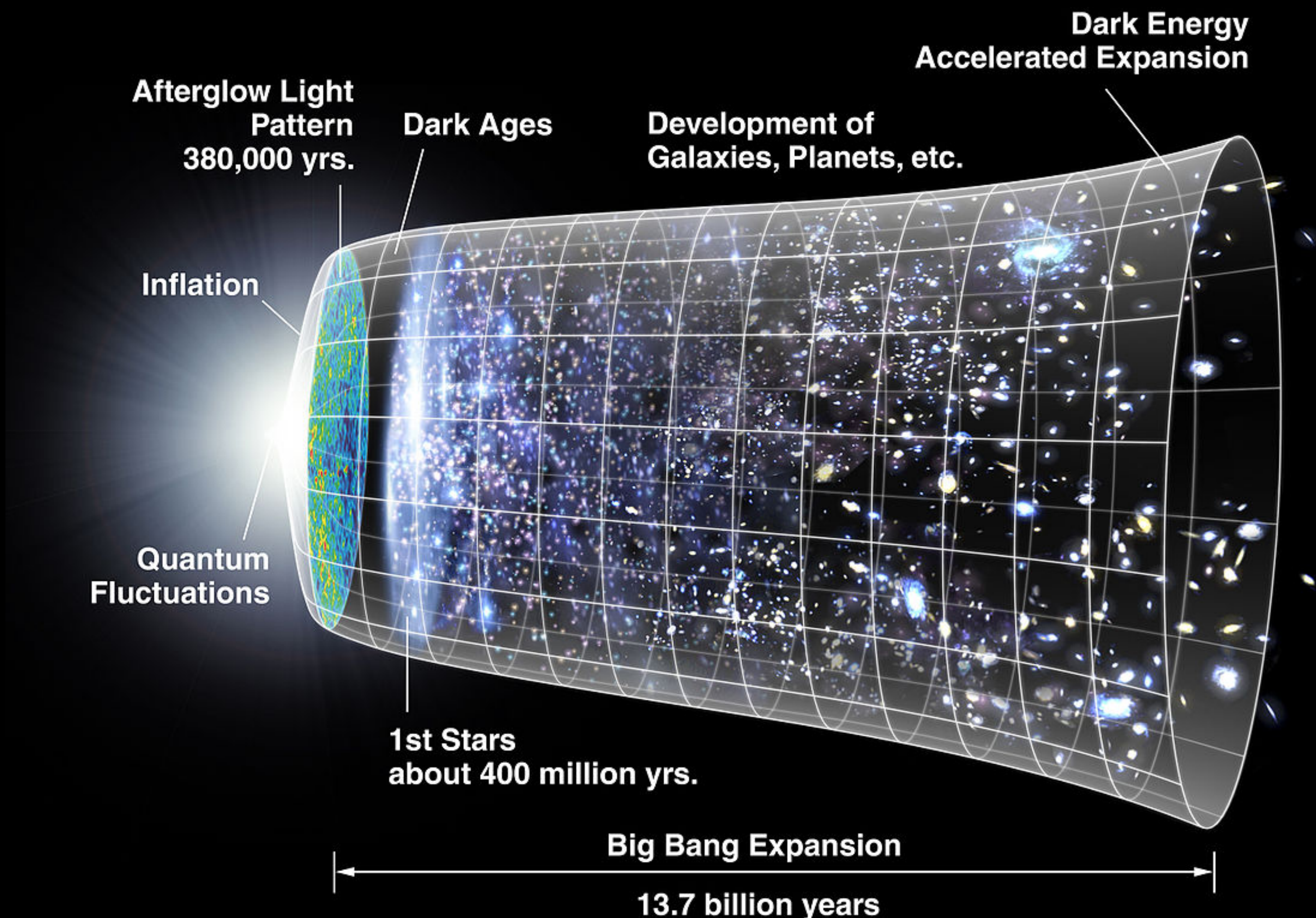
What we know: just the tip of the iceberg.

Mystery: how did matter survive the birth of the universe?

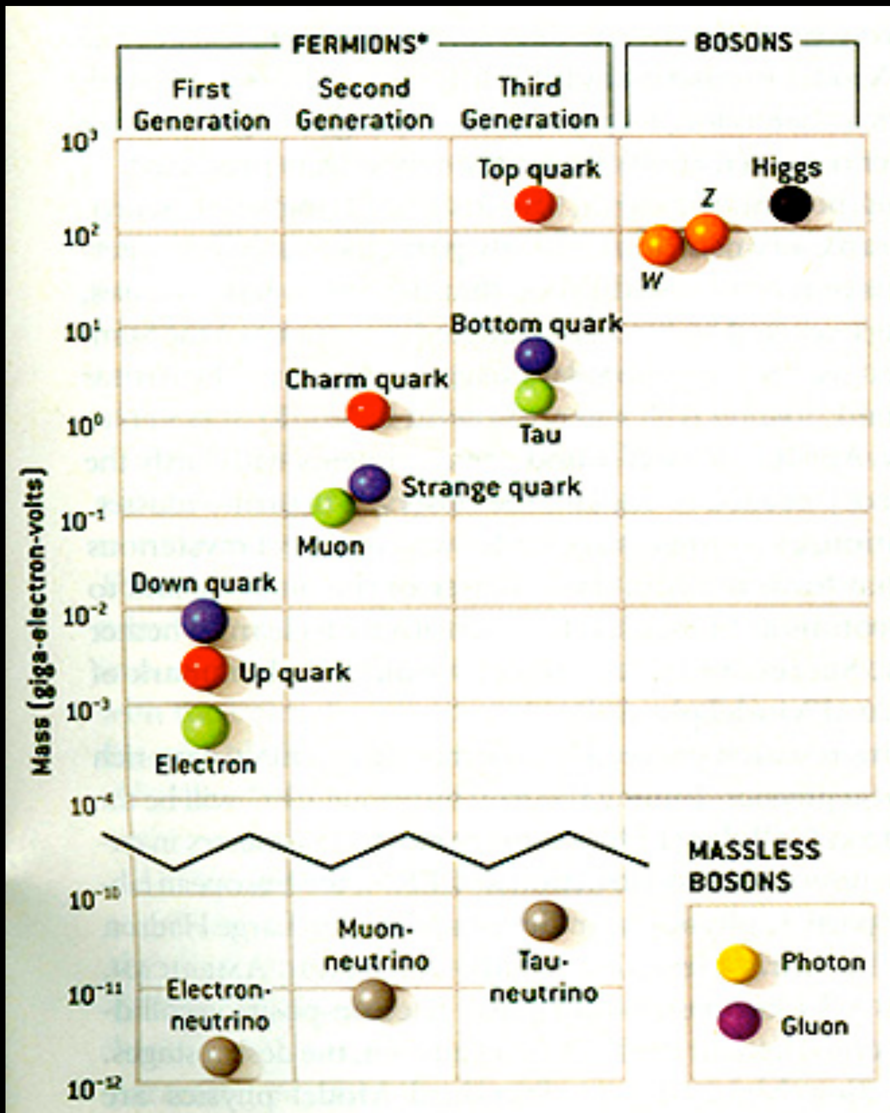
Matter	anti-Matter
1,000,000,001	1,000,000,000

The baryon asymmetry of the Universe

Mystery: What powered cosmic inflation?



Mystery: Why are there so many types of particles?



Why do the particles have such a large range of masses?

Why does the pattern of particles repeat three times?

Why do neutrinos have mass at all (in the Standard Model they are massless)?

Outstanding Questions in Particle Physics *circa* 2011

EWSB
- ❑ Does the Higgs boson exist?

Quarks and leptons:
- ❑ why 3 families ?
- ❑ masses and mixing
- ❑ *CP* violation in the lepton sector
- ❑ matter and antimatter asymmetry
- ❑ baryon and charged lepton number violation

Physics at the highest E-scales:
- ❑ how is gravity connected with the other forces ?
- ❑ do forces unify at high energy ?

Dark matter:
- ❑ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ❑ one type or more ?
- ❑ only gravitational or other interactions ?

Neutrinos:
- ❑ *ν* masses and and their origin
- ❑ what is the role of *H*(125) ?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation
- ❑ additional species → sterile *ν* ?

The two epochs of Universe's accelerated expansion:
- ❑ primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- ❑ today: dark energy (why is Λ so small?) or gravity modification ?

Outstanding Questions in Particle Physics *circa* 2016

… there has never been a better time to be a particle physicist!

Higgs boson and EWSB
- ❑ m_H natural or fine-tuned ?
  → if natural: what new physics/symmetry?
- ❑ does it regularize the divergent V_LV_L cross-section at high $M(V_LV_L)$? Or is there a new dynamics ?
- ❑ elementary or composite Higgs ?
- ❑ is it alone or are there other Higgs bosons ?
- ❑ origin of couplings to fermions
- ❑ coupling to dark matter ?
- ❑ does it violate CP ?
- ❑ cosmological EW phase transition

Quarks and leptons:
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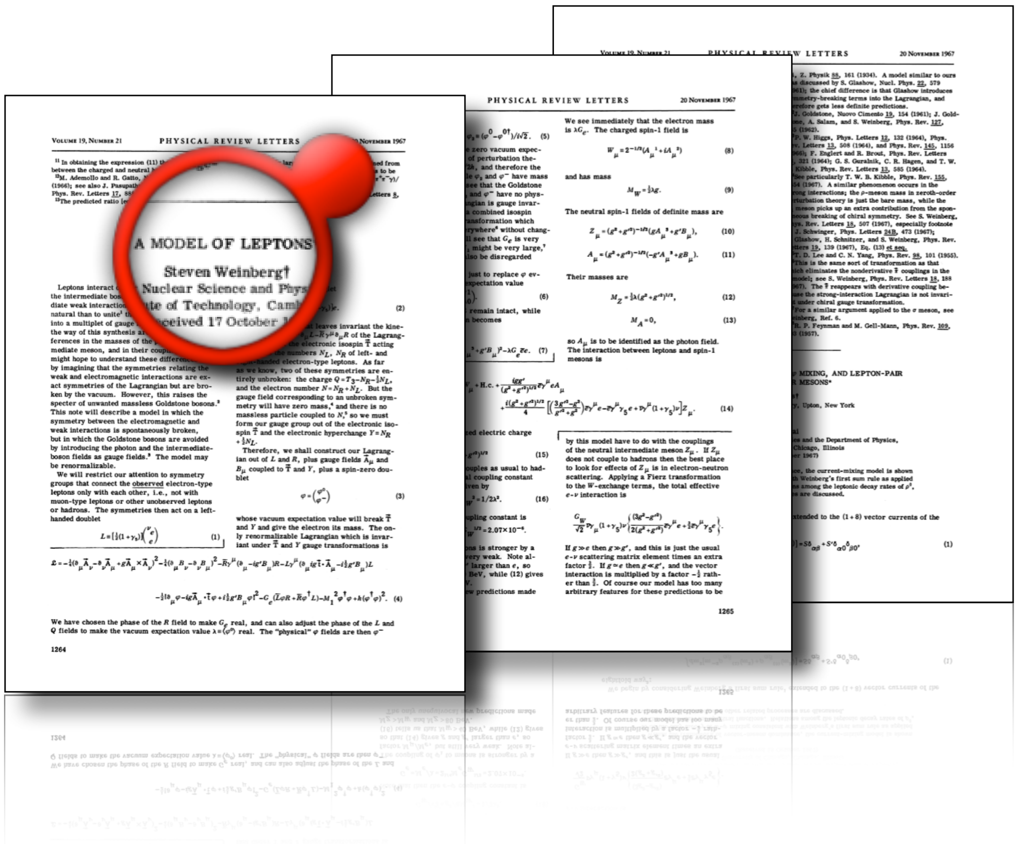
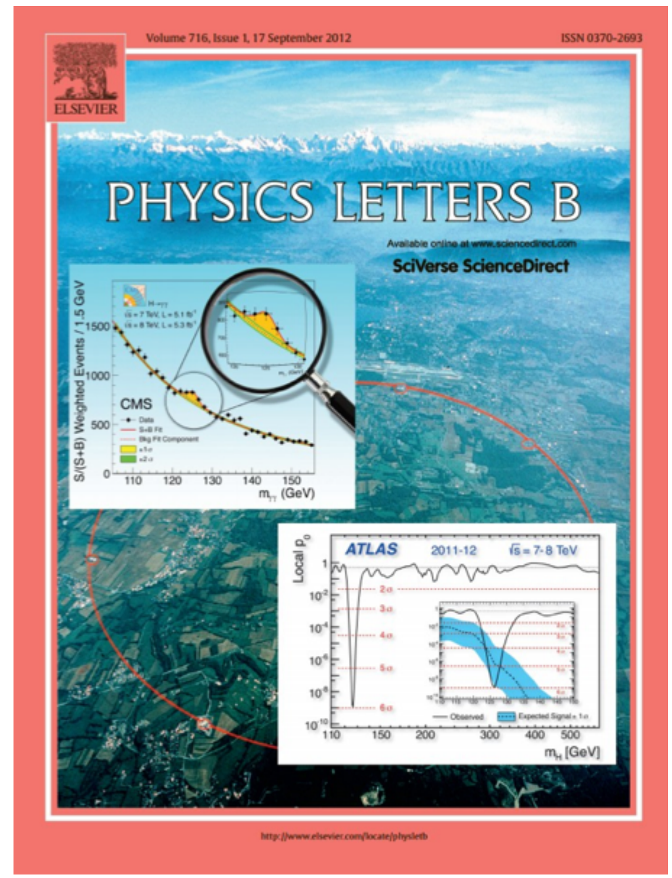
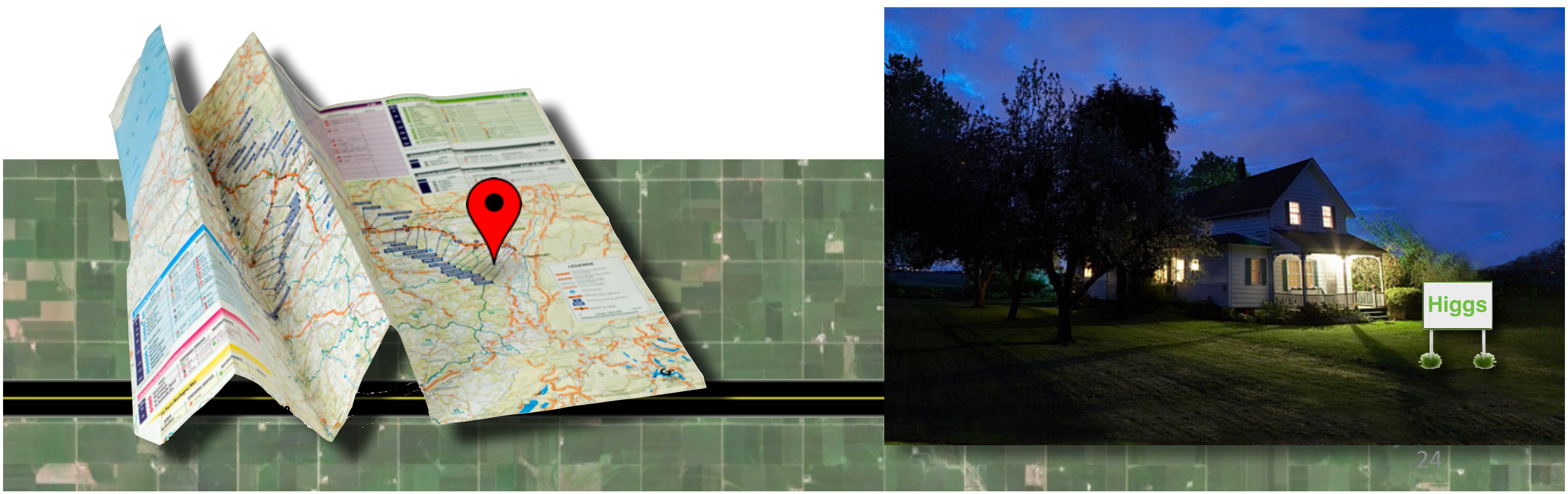
The two epochs of Universe's accelerated expansion:
- ❑ primordial: is inflation correct ?
  which (scalar) fields? role of quantum gravity?
- ❑ today: dark energy (why is Λ so small?) or gravity modification ?

between **1967 - 2012**





The Standard Model Guided Research

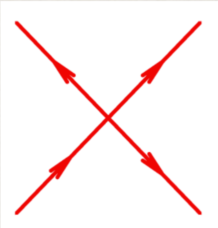


No-lose completion of the Standard Model

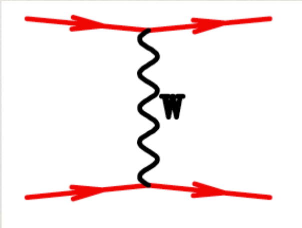
- In our quest to complete the standard model we have been aided by no-lose theorems.

Guaranteed discoveries

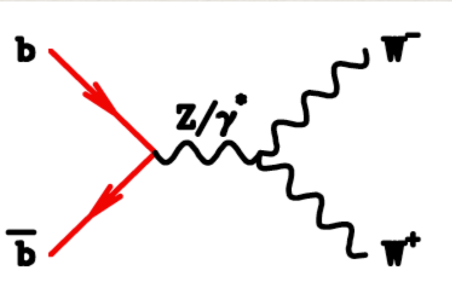
- Motivation for the W



$$\sim \sqrt{2}G_F E^2 = \frac{E^2}{v^2} < 16\pi^2 \Longrightarrow E_c < 4\pi v$$



- Motivation for the top quark



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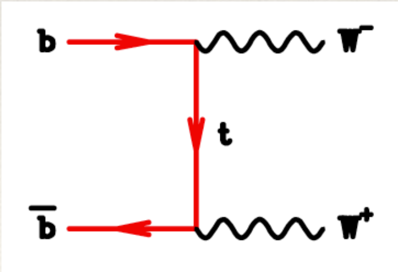
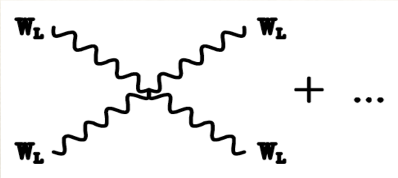


No-lose completion of the Standard Model

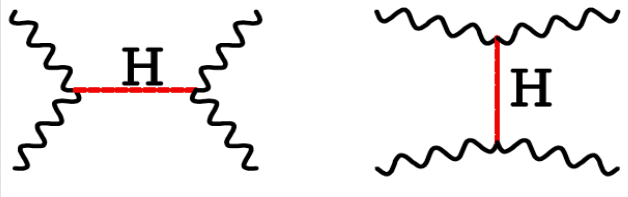
- Shortcomings of theory of WW scattering



$$\sim g_W^2 E^2/m_W^2 < 16\pi^2 \implies E_c < 4\pi v$$

Guaranteed discoveries

- before the critical energy Ec, new physics must enter,
- either a new particle which keeps the theory perturbative



- or, new physics to describe the non-perturbative regime.

Now that the standard model is complete, there are no further no-lose theorems.
In principle, the standard model could be valid to the Planck scale

No guaranteed discoveries

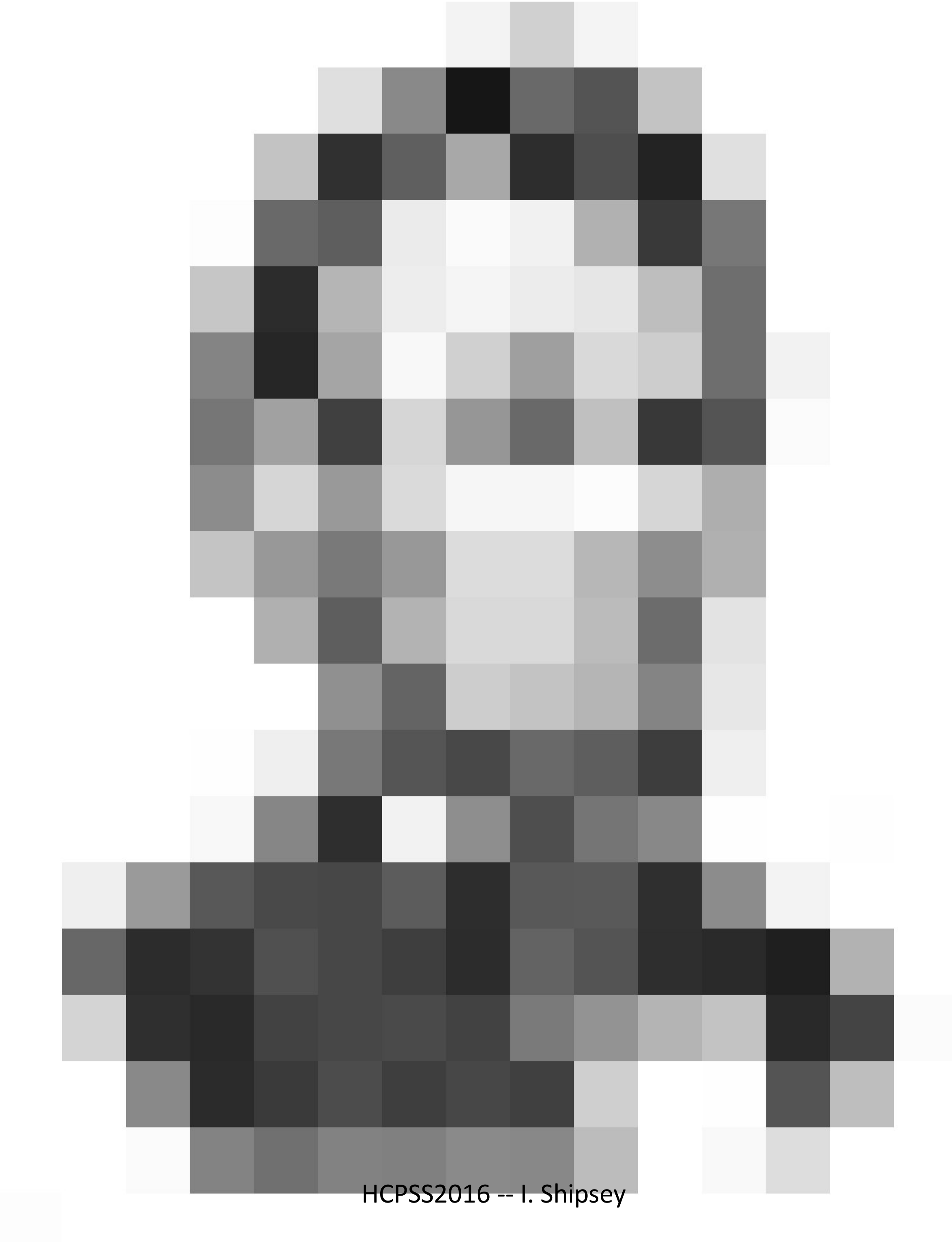
Perception & understanding *with a roadmap*

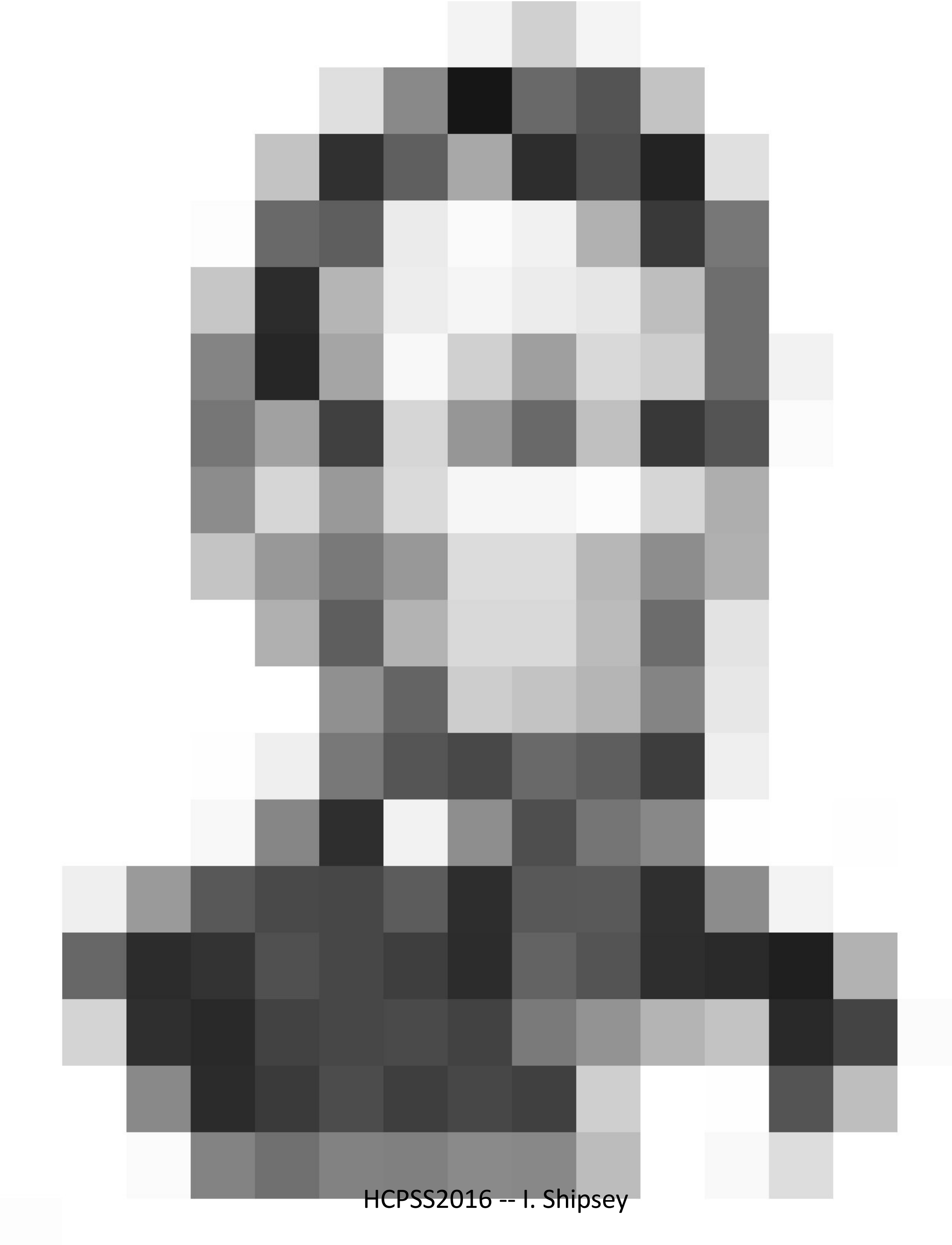
Perception is a dynamic combination of top-down (theory) and bottom-up (data driven) processing

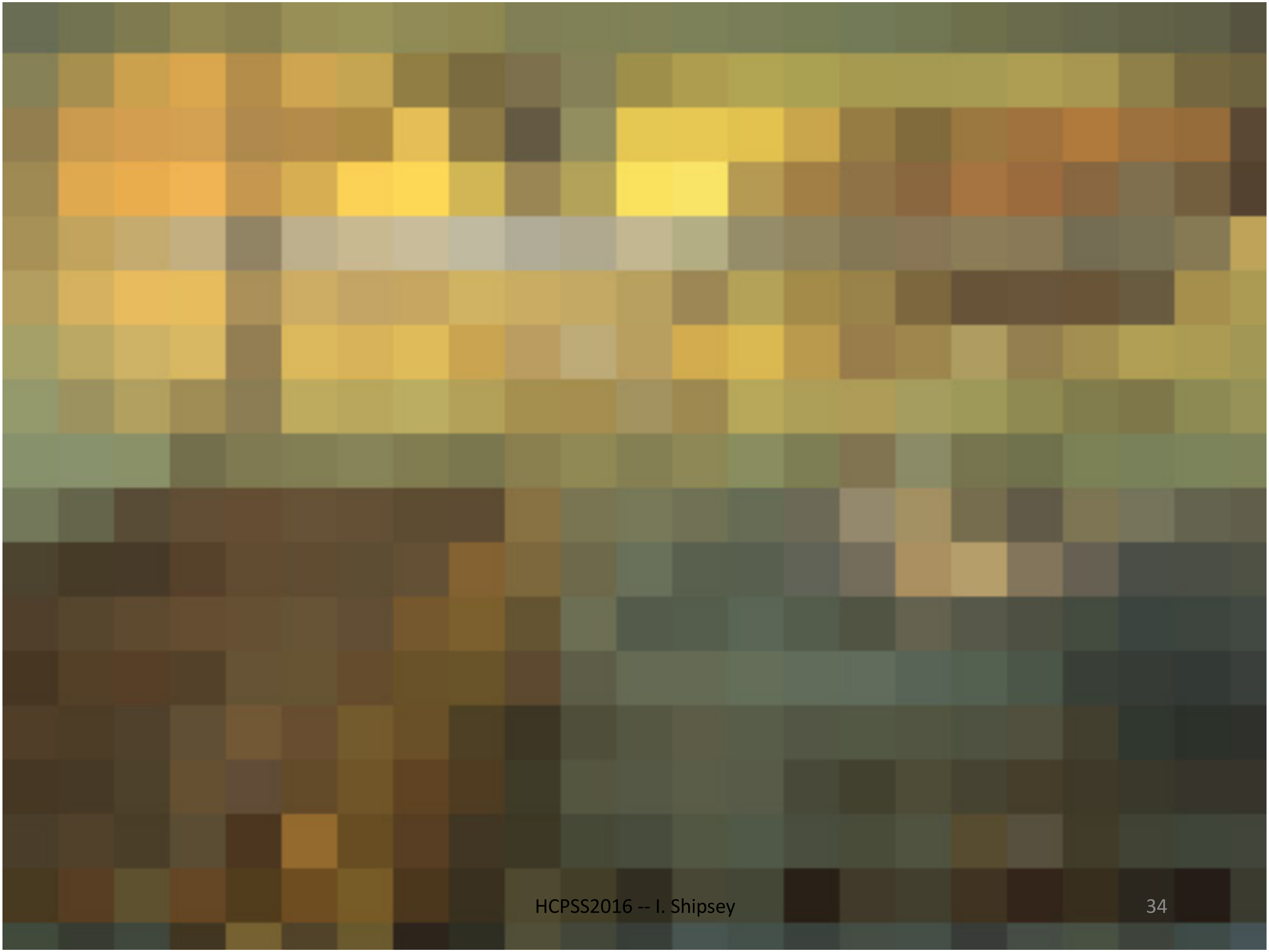
- The need for detail (quality and quantity of the data) depends on the *distinctiveness* of the object and the *level of familiarity*

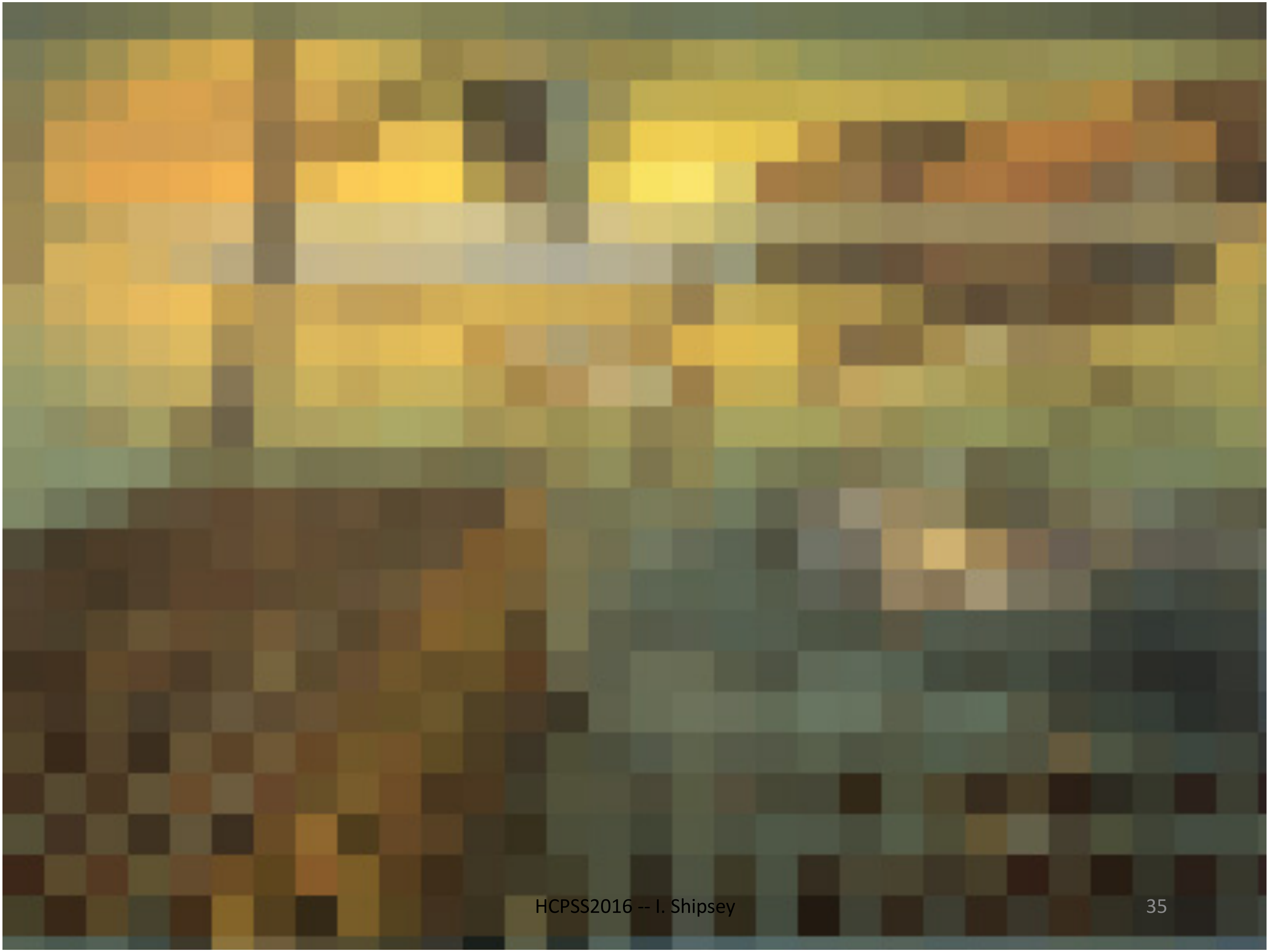
When we know the characteristics and context of what to expect (W,t,H) a little data *goes* a long way (top-down dominates)

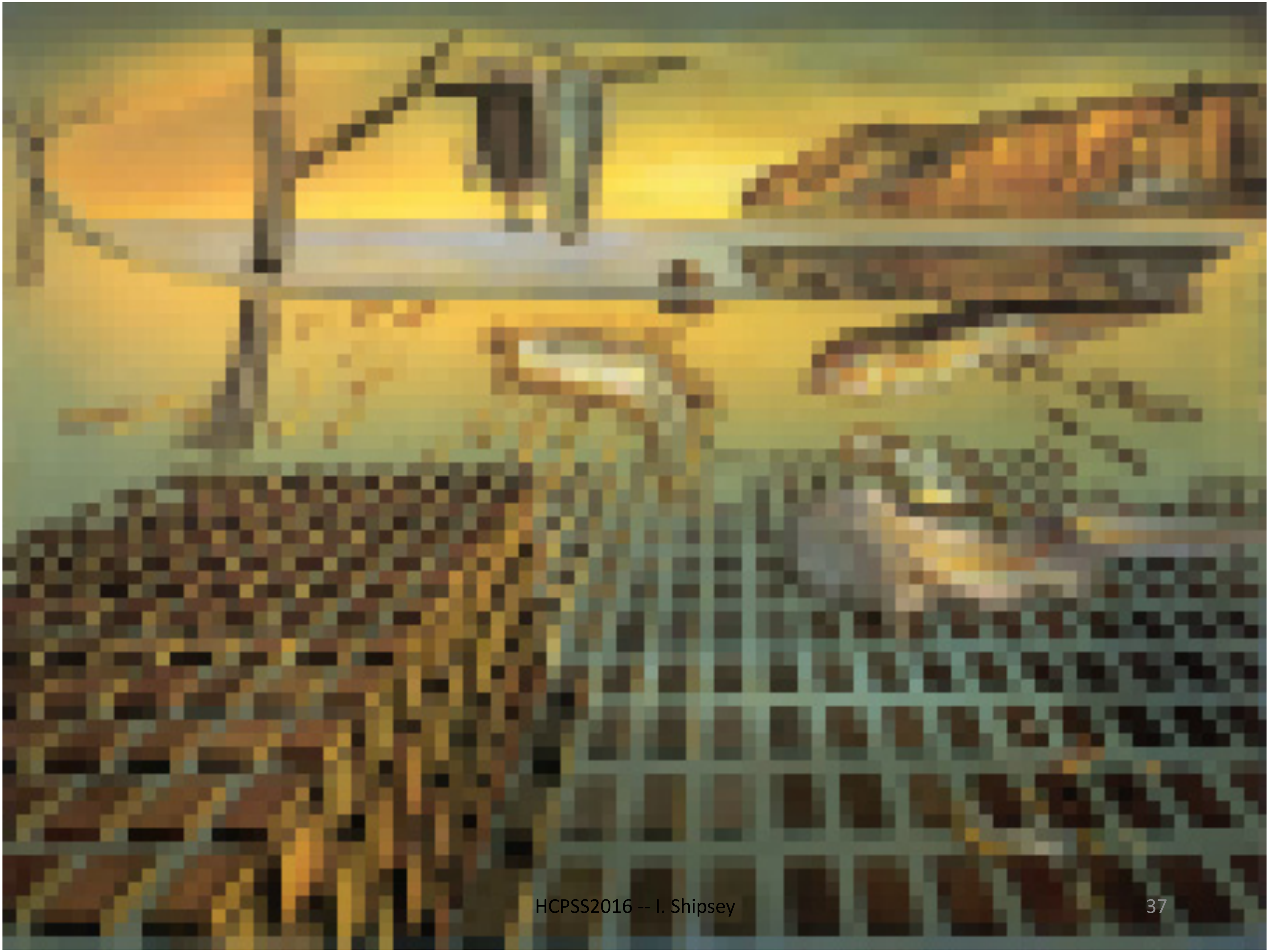
Visual examples…

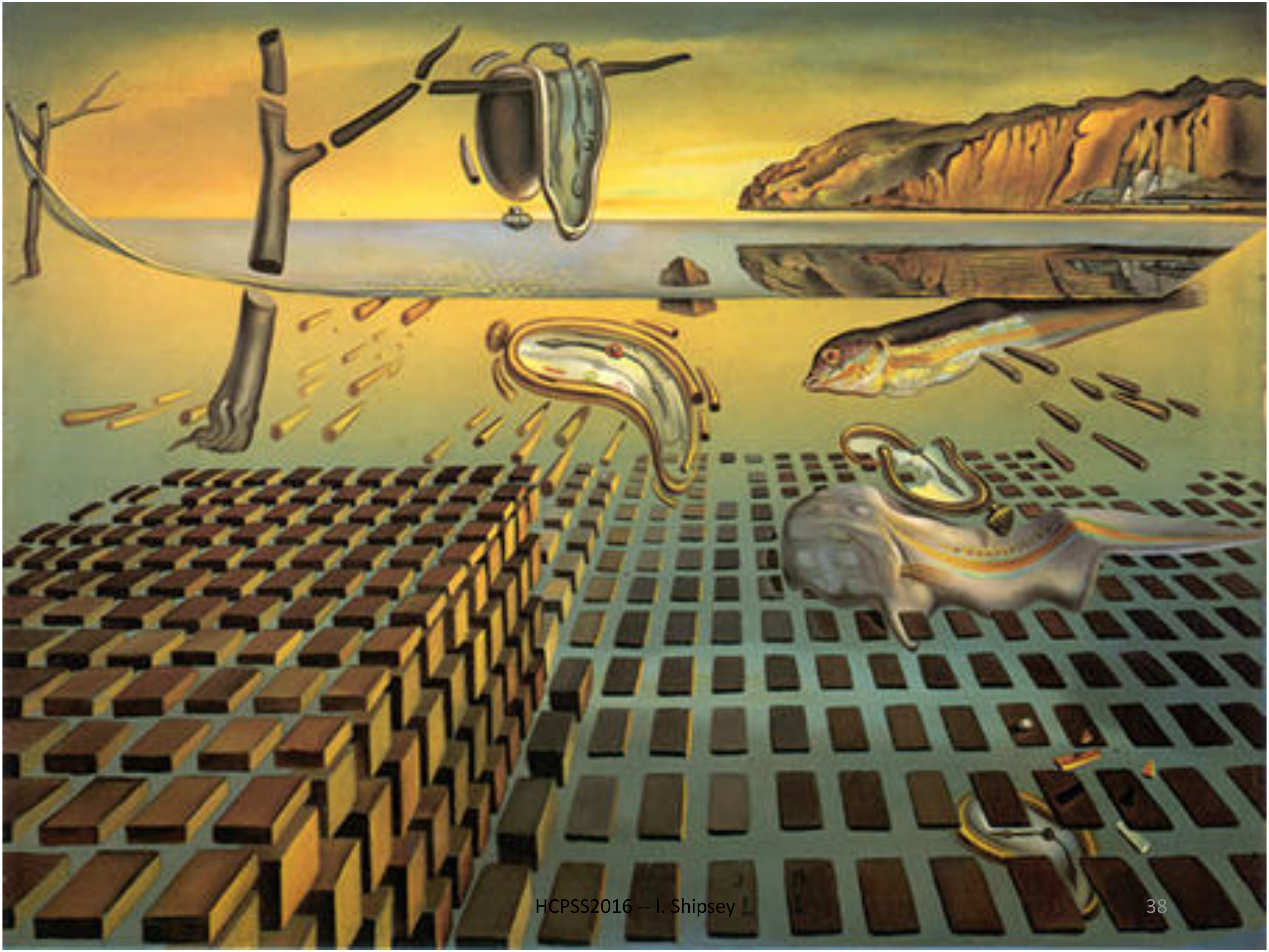




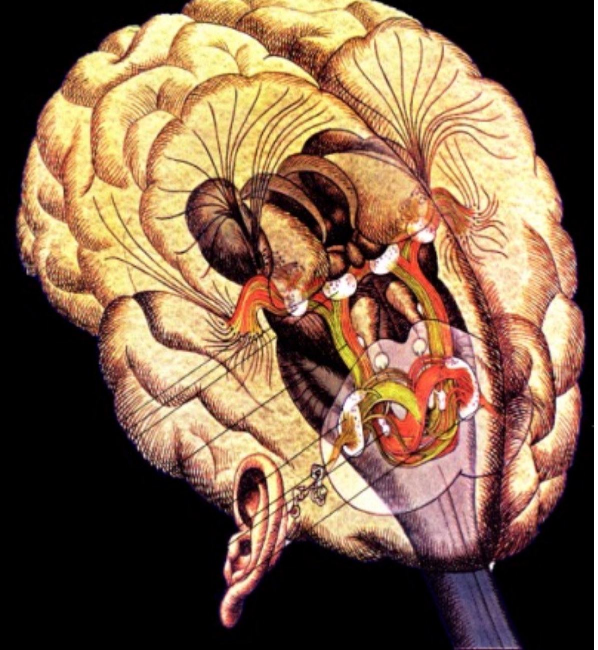




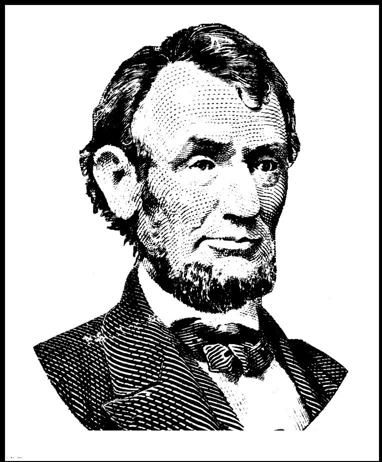




Perception & understanding

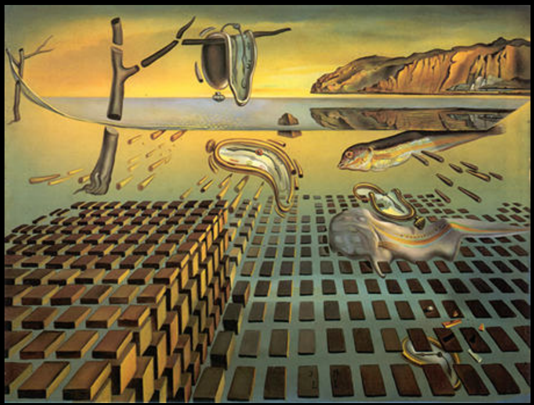


With a roadmap (theory)



(W,t,H) a little data goes a long way (top-down dominates)

w/o a roadmap (data driven)

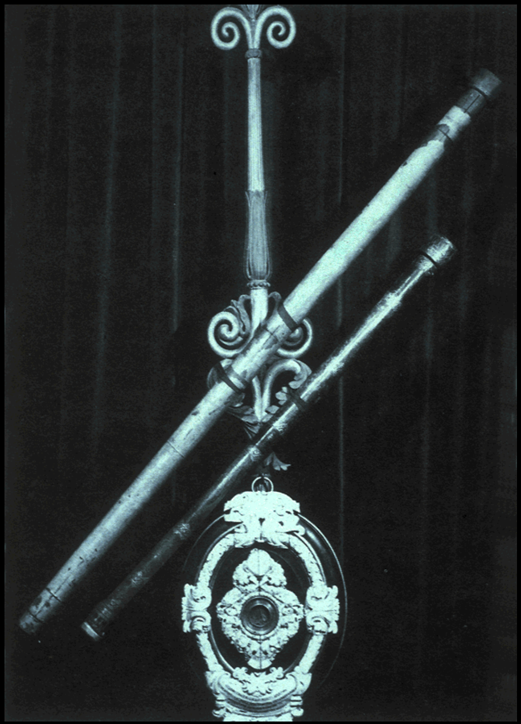


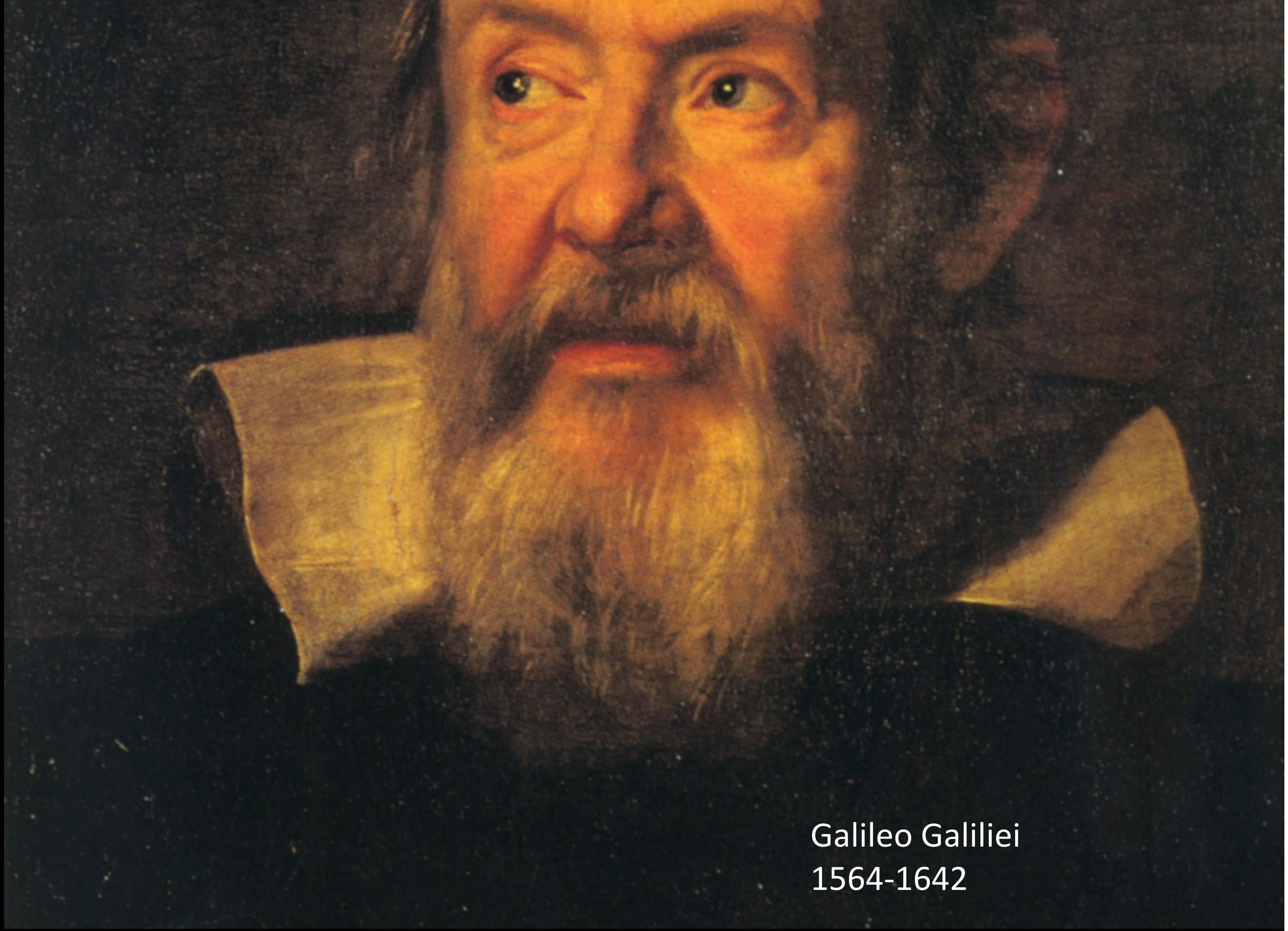
New physics need lots of data (bottom up dominates)

We are in a data driven era

#1 Context

"Measure what is measureable and make measureable what is not so."





Galileo Galiliei
1564-1642

These questions are compelling, difficult and intertwined → require multiple approaches high-E colliders, neutrino experiments (solar, short/long baseline, reactors 0νββ decays), cosmic surveys (CMB, optical/IR spectroscopic and photometric), dark matter direct, indirect and astrophysical detection, precision measurements of rare decays and phenomena, dedicated searches (WIMPS, axions, dark-sector particles), …

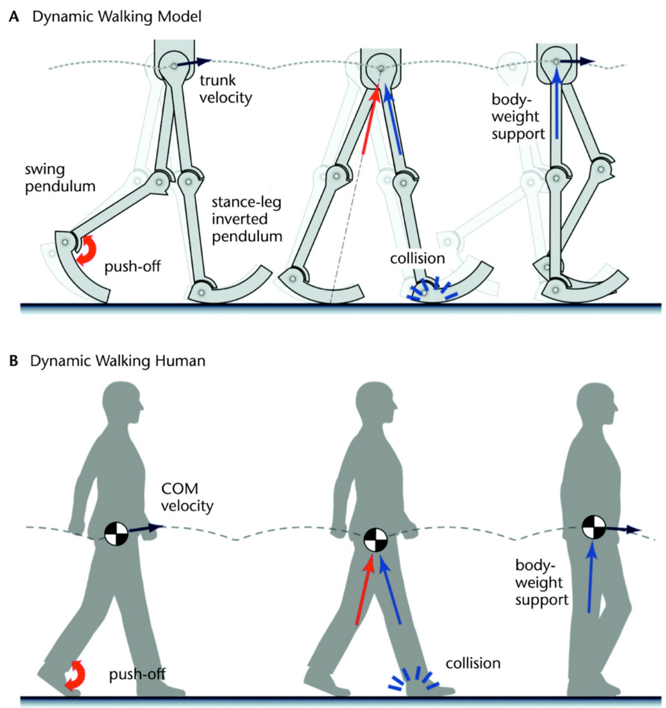
Main questions and main approaches to address them

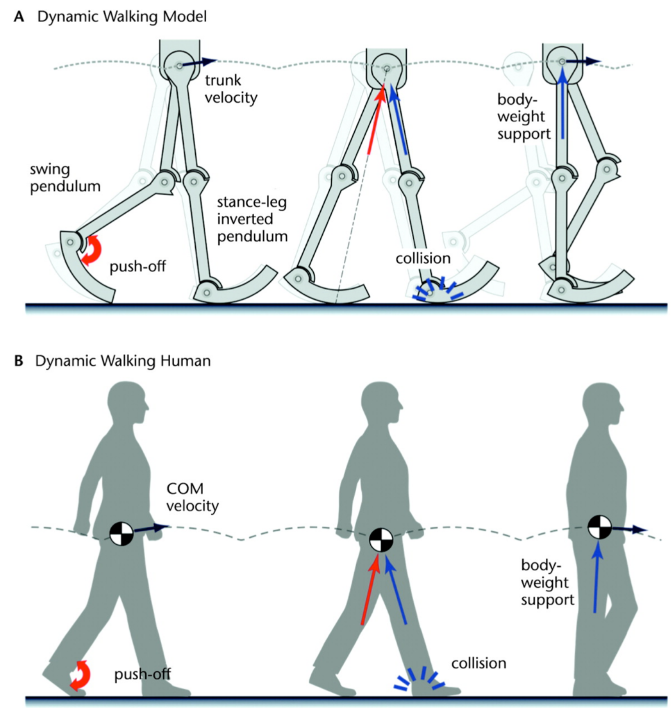
	High-E colliders	High-precision experiments	Neutrino experiments	Dedicated searches	Cosmic surveys
Higgs , EWSB	x				
Neutrinos			x	x	x
Dark Matter	x			x	x
Flavour, CP-violation	x	x	x	x	
New particles and forces	x	x	x	x	
Universe acceleration					x

These complementary approaches are ALL needed: their combination is crucial to explore the largest range of E scales, properly interpret signs of new physics, and build a coherent picture of the underlying theory.

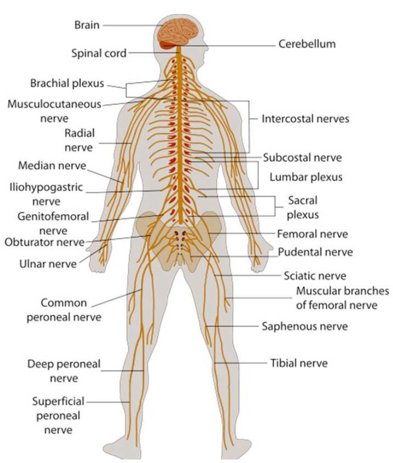
Standard Model is an effective theory

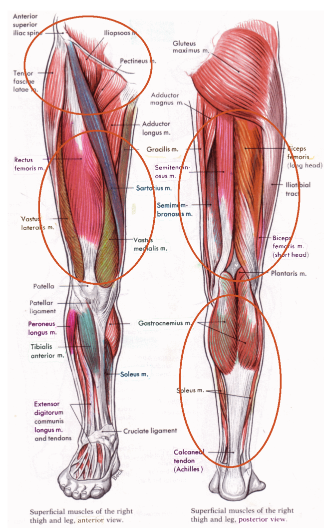
Draw free-body diagrams and make a SM of walking



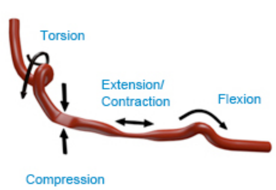


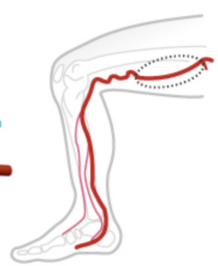
Draw free-body diagrams and make a SM of walking





But it's not the actual physiology of walking!






Credit:Mario Livio
The mass of the Higgs, the amount of dark energy and the values of other observables could be vacuum selection effects (our universe interpreted in terms of the multiverse) but it is premature to think so

Discoveries in particle physics

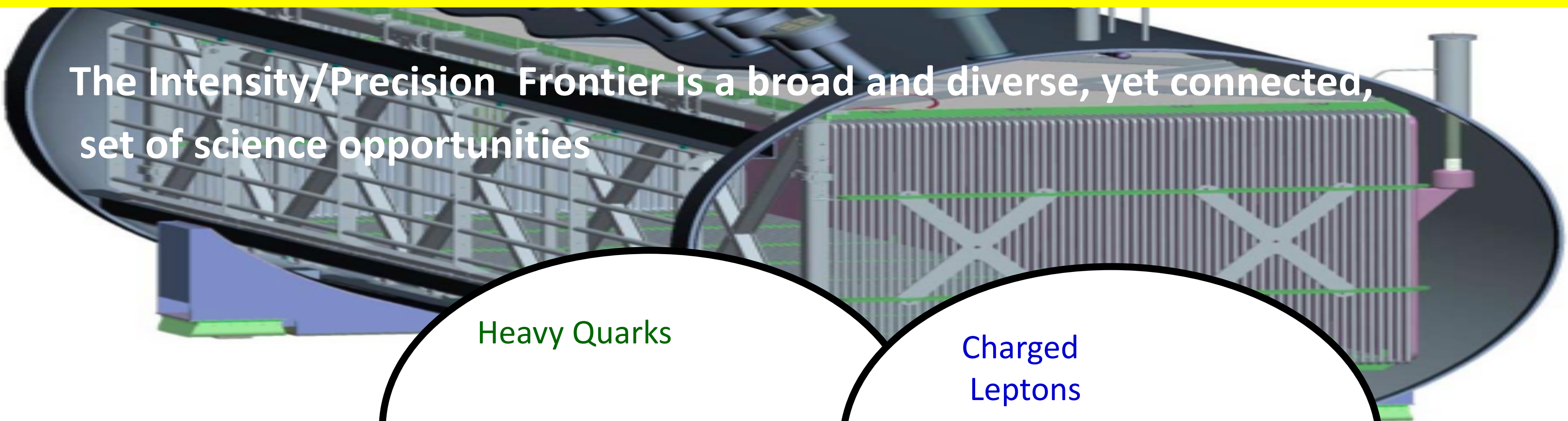
Based on an original slide by S.C.C. Ting

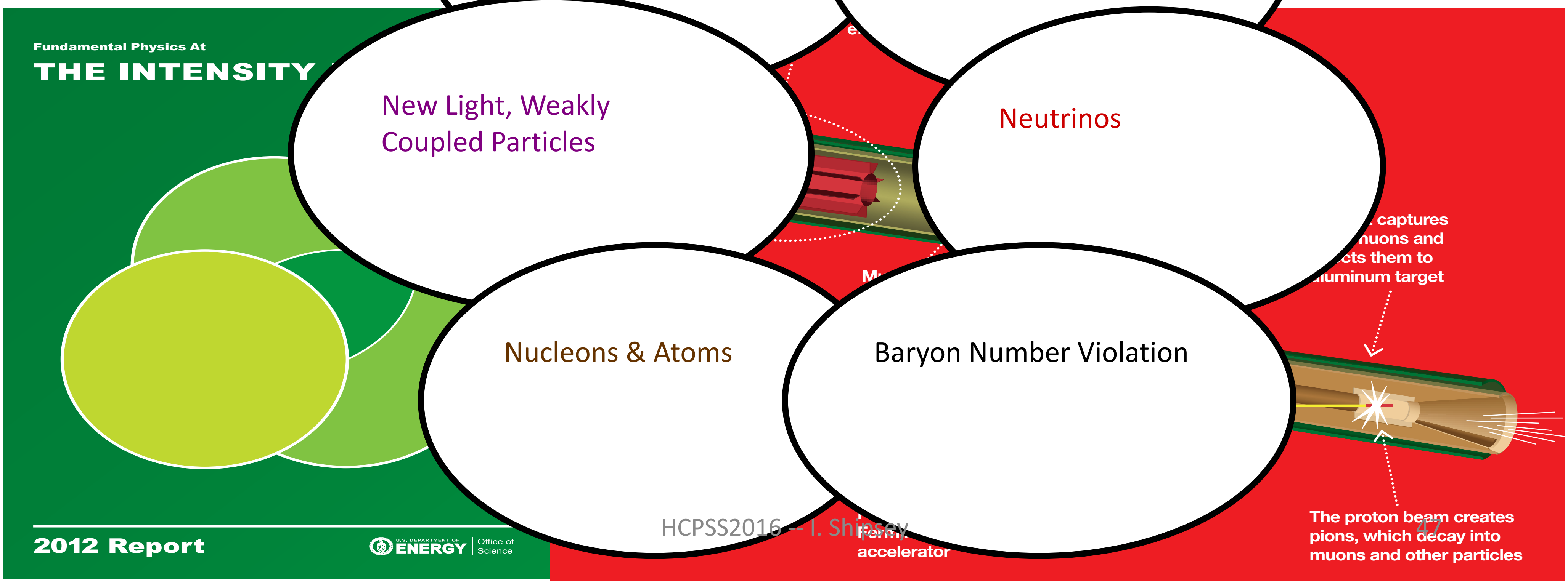
Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	Neutral Currents -> Z,W
AGS BNL (1960)	π N interactions	Two kinds of neutrinos Time reversal non-symmetry charm quark
FNAL Batavia (1970)	Neutrino Physics	bottom quark top quark
SLAC Spear (1970)	ep, QED	Partons, charm quark tau lepton
ISR CERN (1980)	pp	Increasing pp cross section
PETRA DESY (1980)	top quark	Gluon
Super Kamiokande (2000)	Proton Decay	Neutrino oscillations
Telescopes (2000)	SN Cosmology	Curvature of the universe Dark energy

precision instruments are key to discovery when exploring new territory

The Intensity/Precision Frontier

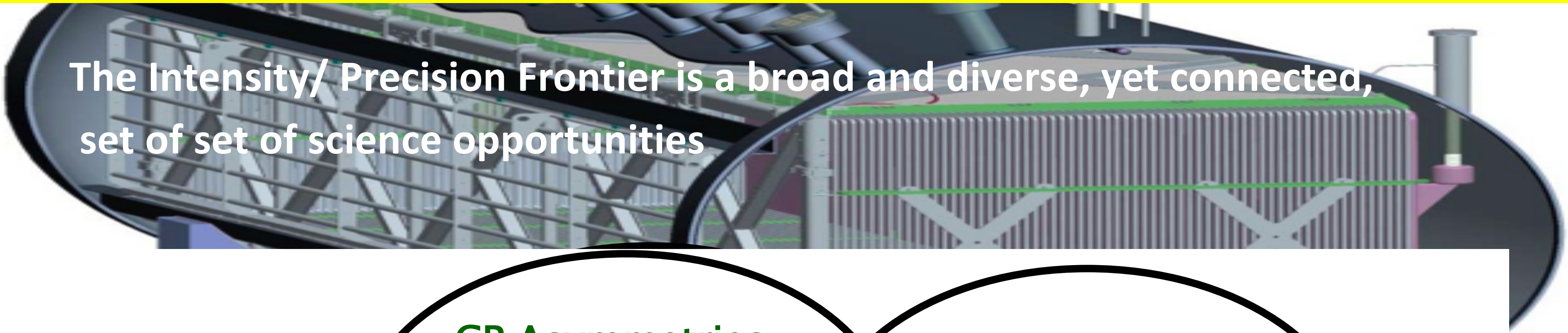
The Intensity/Precision Frontier is a broad and diverse, yet connected, set of science opportunities



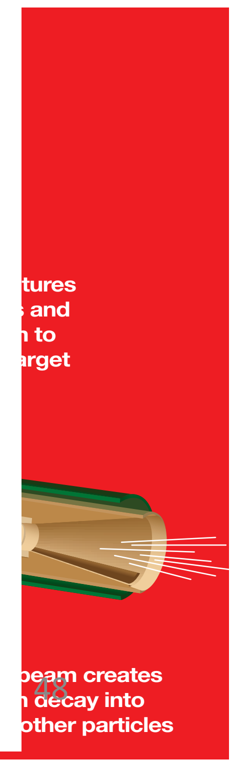


- Heavy Quarks
- Charged Leptons
- New Light, Weakly Coupled Particles
- Neutrinos
- Nucleons & Atoms
- Baryon Number Violation

The Intensity/Precision Frontier



The Intensity/ Precision Frontier is a broad and diverse, yet connected, set of set of science opportunities



Quark Flavor Physics

CP Asymmetries,
Rare decays,
Distributions
K's, Charm, B's

LFV with μ,τ
g−2
EDM

Charged lepton Flavor Physics

New particle searches

LFV with
ν Oscillations
0νββ

EDMs
Parity Violation

Proton Decay
Neutron Oscillation

New physics can show up at the intensity/precision frontier before the energy frontier

The power of quantum loops:

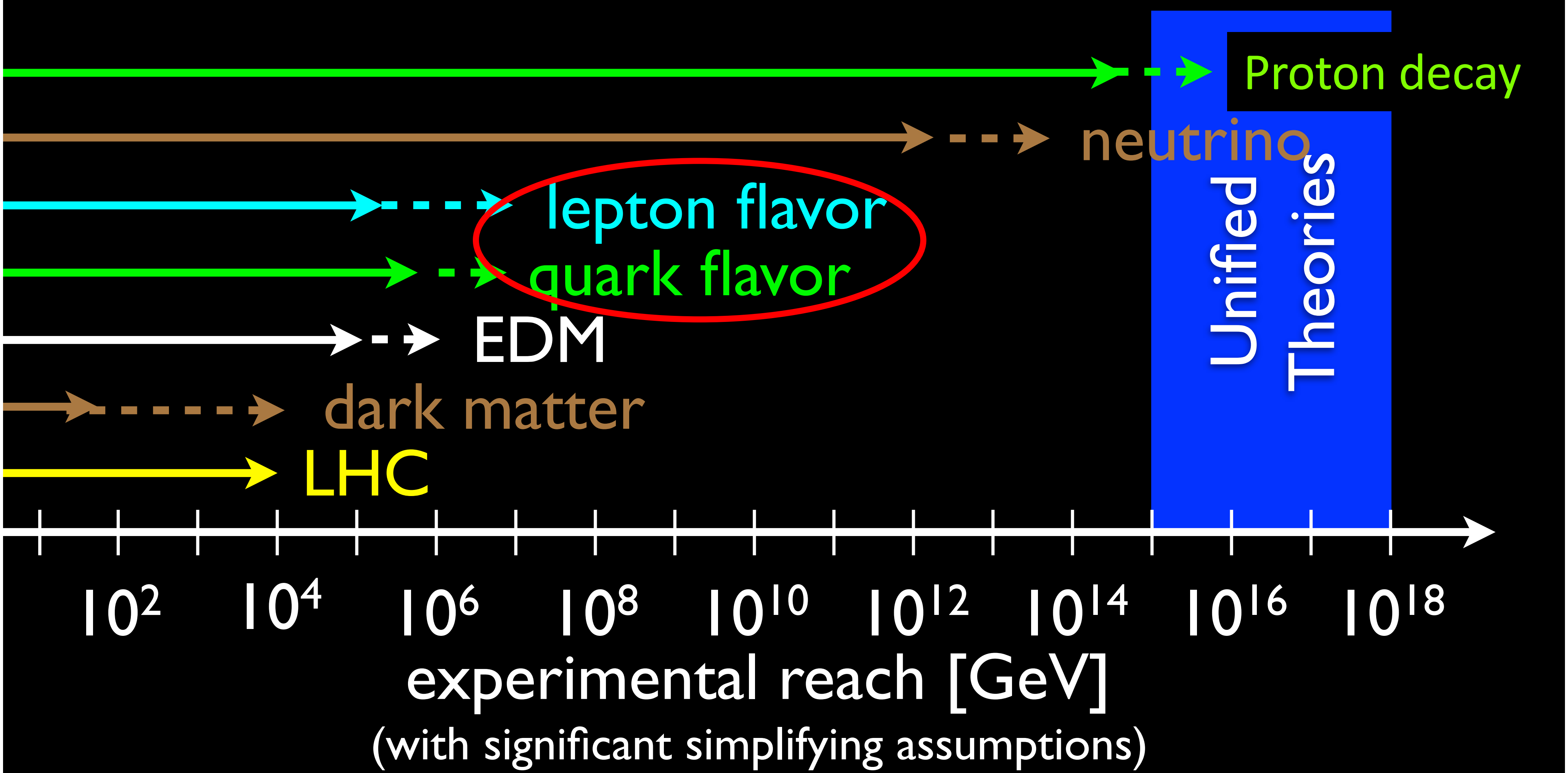
Beta-decay @ MeV energies informs us of a virtual mediator at 80 GeV (W)

GIM mechanism before the discovery of charm

CP violation/ CKM before the discovery of beauty and top

Neutral currents before the discovery of Z

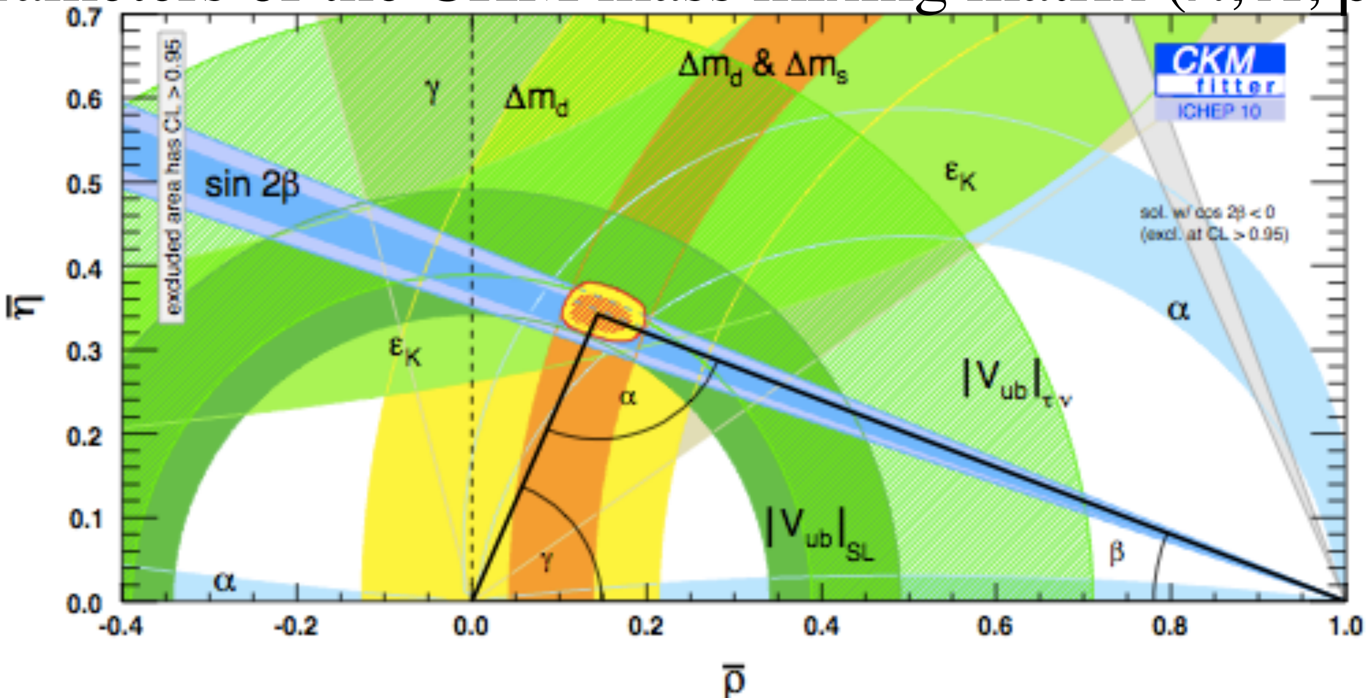
The power of quantum loops



Quark flavor physics

Triumph of the CKM description

- All the flavour changing processes are described by the four parameters of the CKM mass mixing matrix (λ, A, ρ, η)



- From this plot, we know already either new physics energy scale is >> TeV (far beyond LHC) or the flavour structure of new physics is very special.

The need for more precision

Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed"

– A.Soni

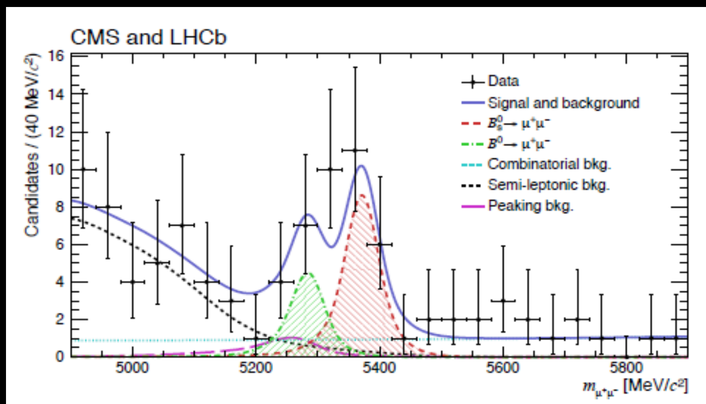
- "A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky."

– L.Okun

(remember: $B(K_L^0 \to \pi^+\pi^-) \sim 2\ 10^{-3}$)

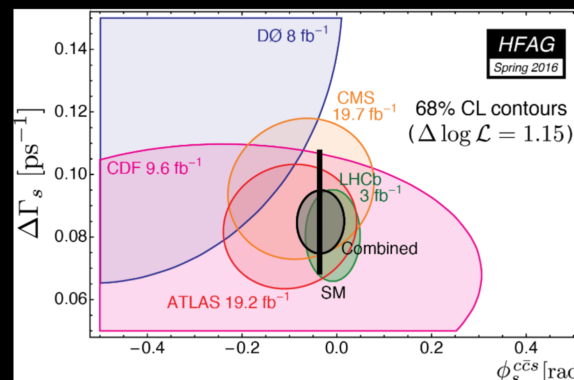
Flavour physics at the LHC a great success, with run-1 delivering in all important topics

Observation of $B_s \to \mu\mu$

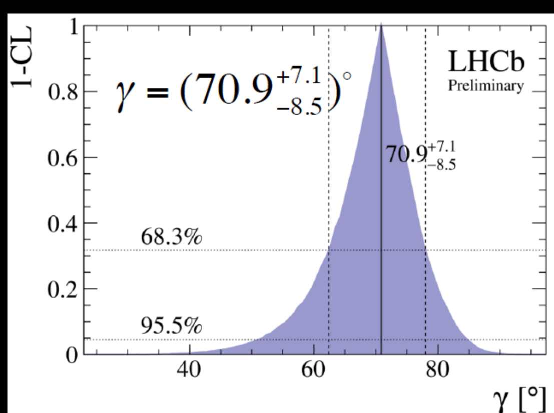


[Nature 522 (2015) 68]

Precise studies of CPV in the B_s system

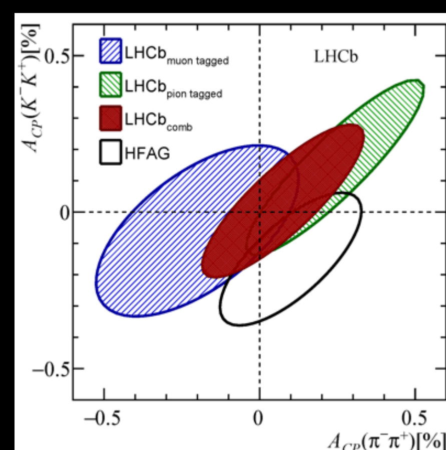


Great steps forward in knowledge of unitarity triangle angle γ (ϕ_3)



[LHCb-PAPER-2016-032]

Probing for CPV in charm with per mille precision

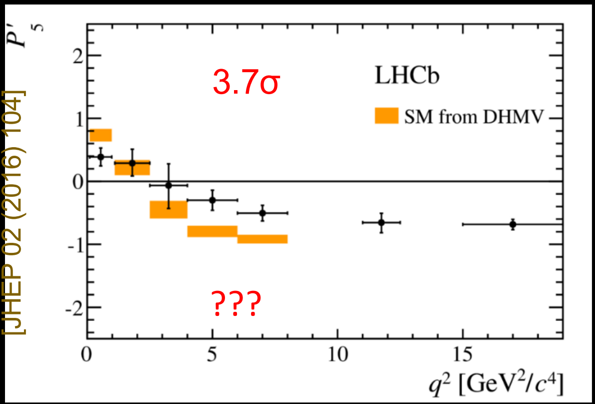


[LHCb-PAPER-2016-035]

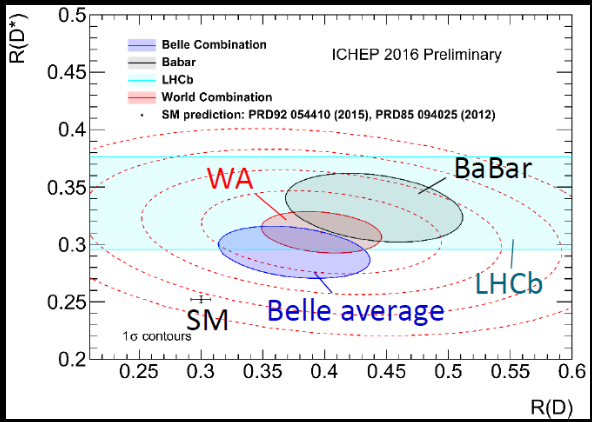
But some intriguing anomalies have emerged from LHC-b and the B-factories

Anomalous behaviour
In $b \to sl^+l^-$ observables

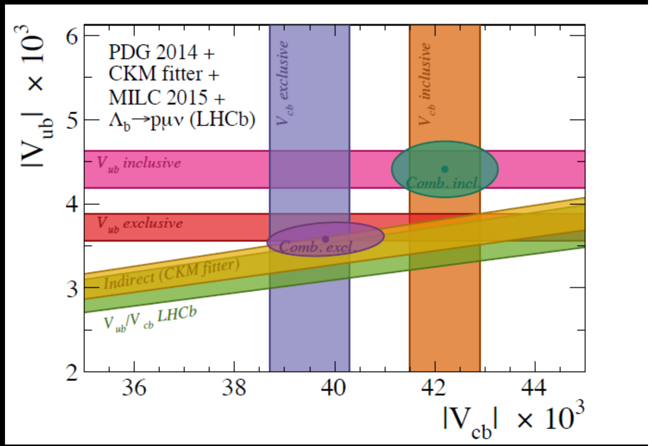
$B^0 \to K^* \mu\mu$ P_5' vs q^2



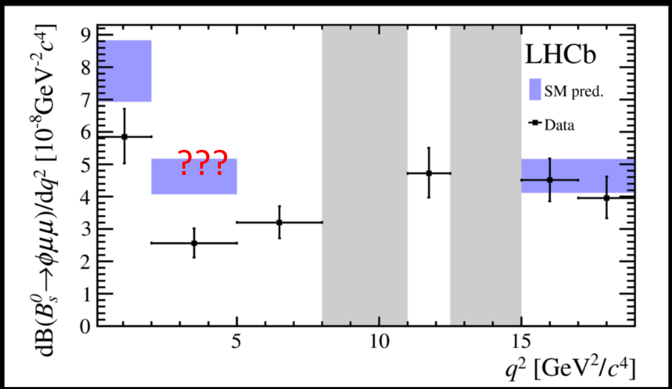
Hints of lepton universality violation in $B \to D^{(*)} l \nu$ …



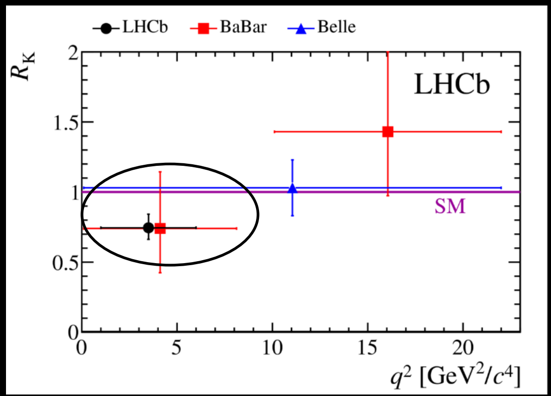
And longstanding inconsistency In exclusive vs inclusive V_{ub} and V_{cb} determinations.



$B_s \to \phi\mu\mu$
differential BR vs q^2

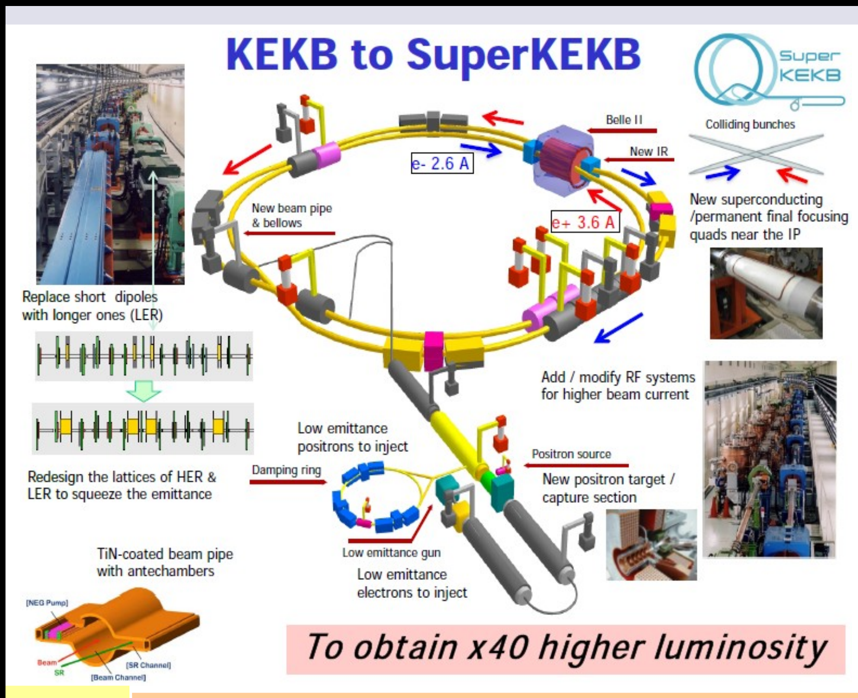


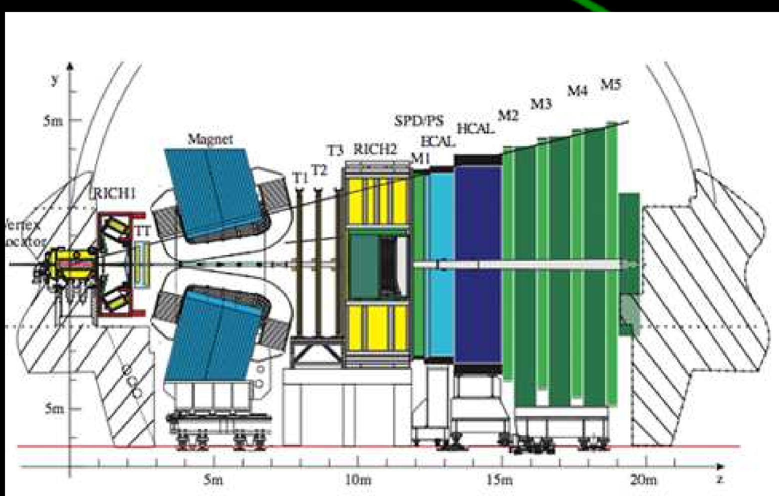
…and in $B \to Kl^+l^-$



The quest for indirect discovery of new physics requires patterns of deviations to exist

Physics Reach Belle II & LHCb upgrade

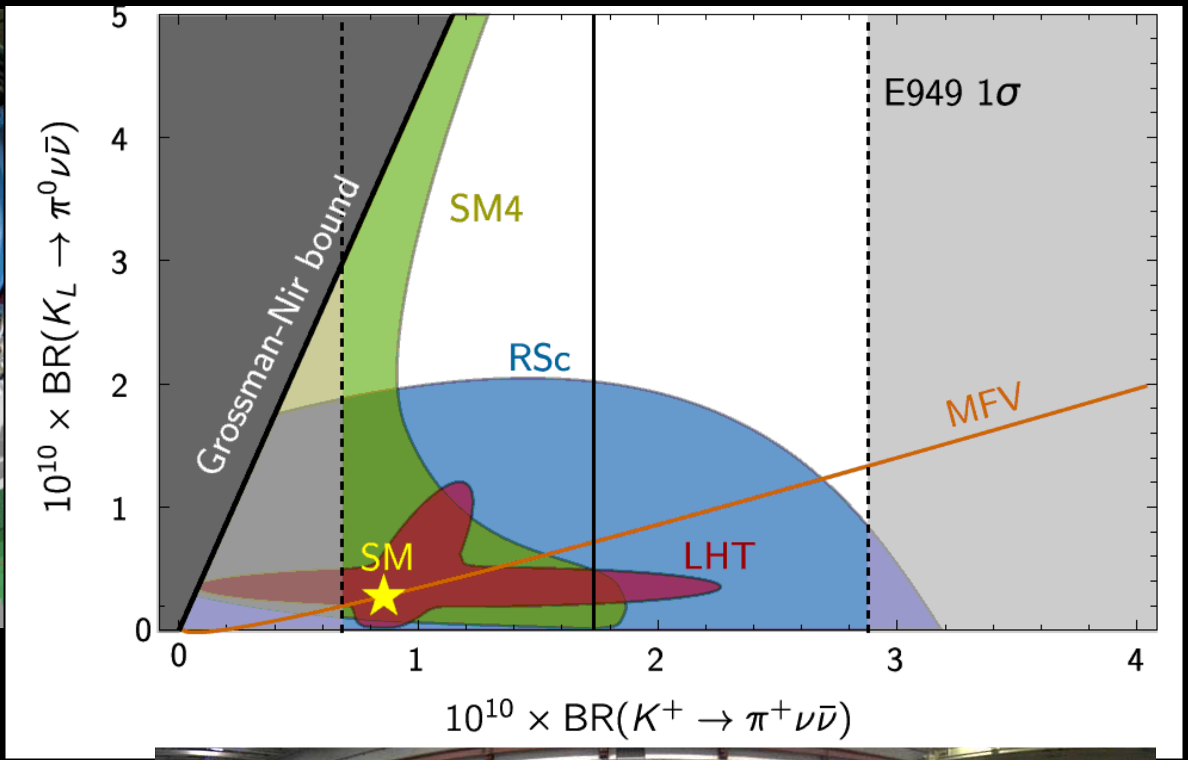




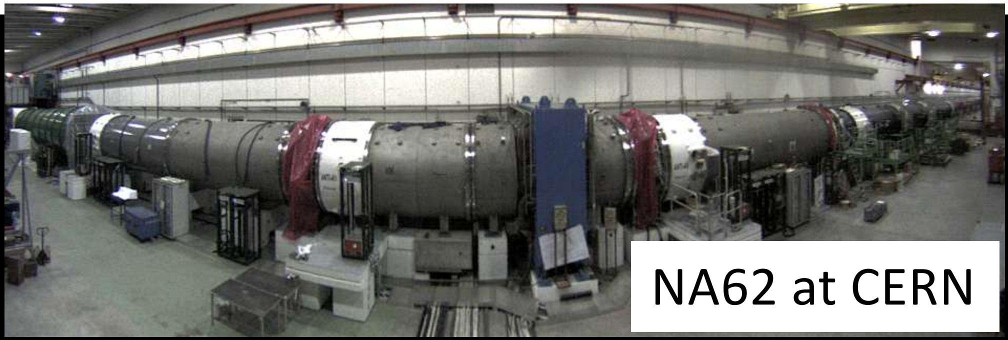
Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\lvert V_{us}\rvert$ $[K \to \pi\ell\nu]$	**	0.1%	K-factory
$\lvert V_{cb}\rvert$ $[B \to X_c\ell\nu]$	**	1%	Belle II
$\lvert V_{ub}\rvert$ $[B_d \to \pi\ell\nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K_S^0]$	***	$8 \cdot 10^{-3}$	Belle II/LHCb
ϕ_2		1.5°	Belle II
ϕ_3	***	3°	LHCb
CPV			
$S(B_s \to \psi\phi)$	**	0.01	LHCb
$S(B_s \to \phi\phi)$	**	0.05	LHCb
$S(B_d \to \phi K)$	***	0.05	Belle II/LHCb
$S(B_d \to \eta' K)$	***	0.02	Belle II
$S(B_d \to K^*(\to K_S^0\pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A_{SL}^d	***	0.001	LHCb
A_{SL}^s	***	0.001	LHCb
$A_{CP}(B_d \to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B \to \tau\nu)$	**	3%	Belle II
$\mathcal{B}(B \to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d \to \mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb
zero of $A_{FB}(B \to K^*\mu\mu)$	**	0.05	LHCb
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B \to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K \to \pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K \to e\pi\nu)/\mathcal{B}(K \to \mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\lvert q/p\rvert_D$	***	0.03	Belle II
$arg(q/p)_D$	***	1.5°	Belle II

New generation of Kaon experiments

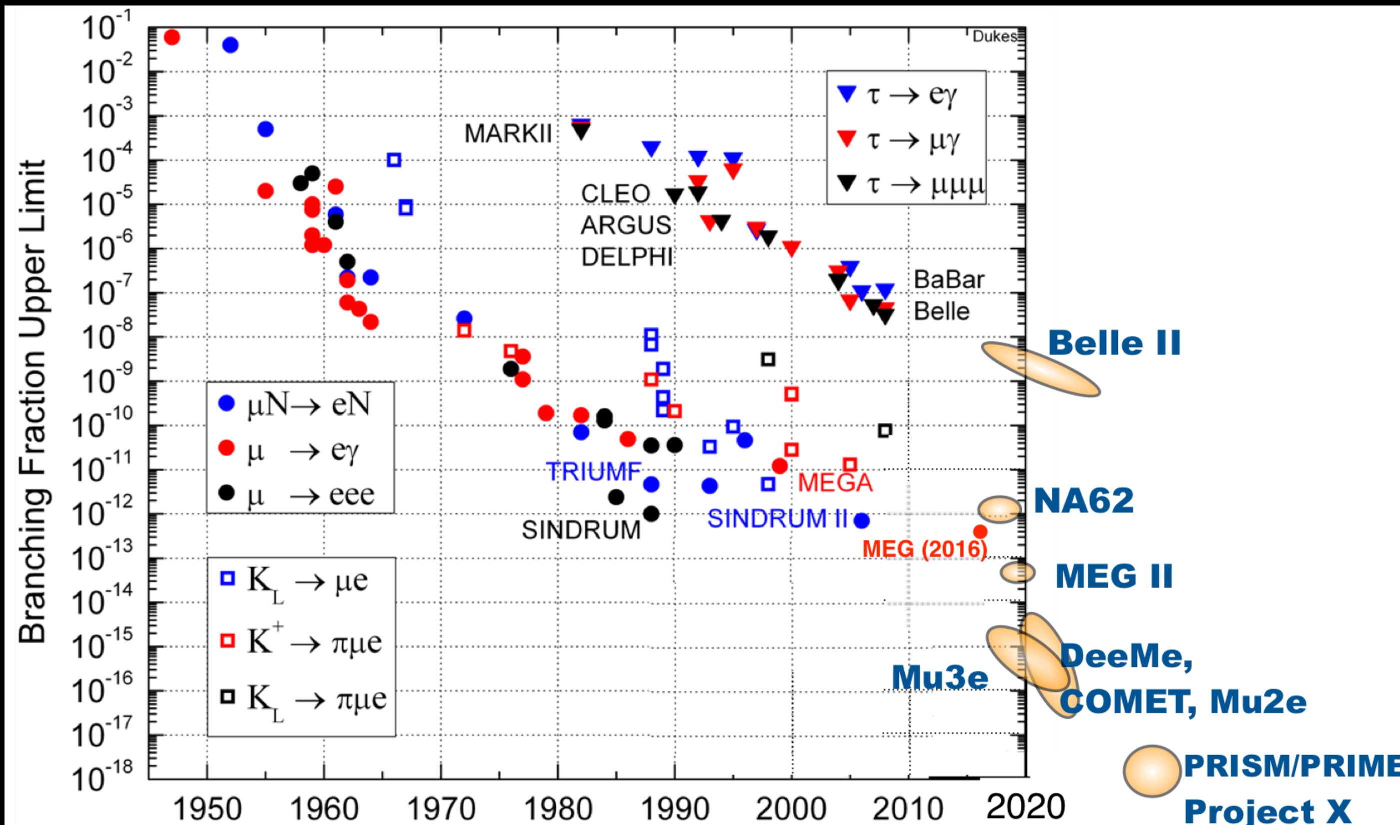
O(1) SM $K_L \rightarrow \pi^0 \nu\nu$ events

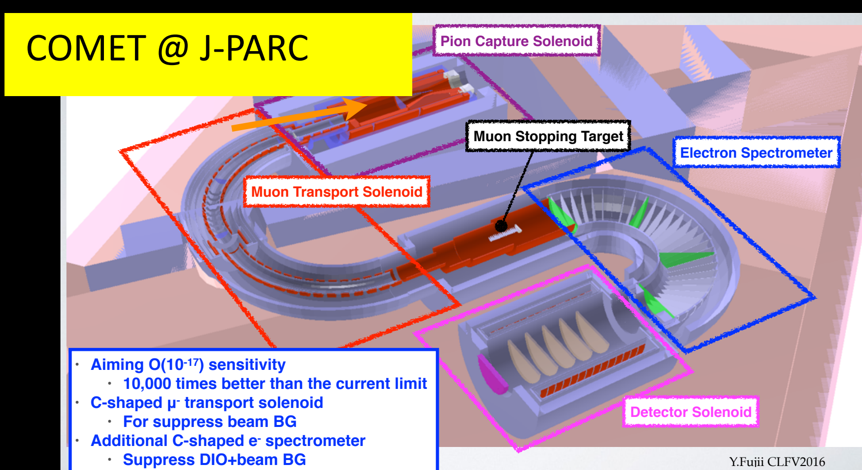


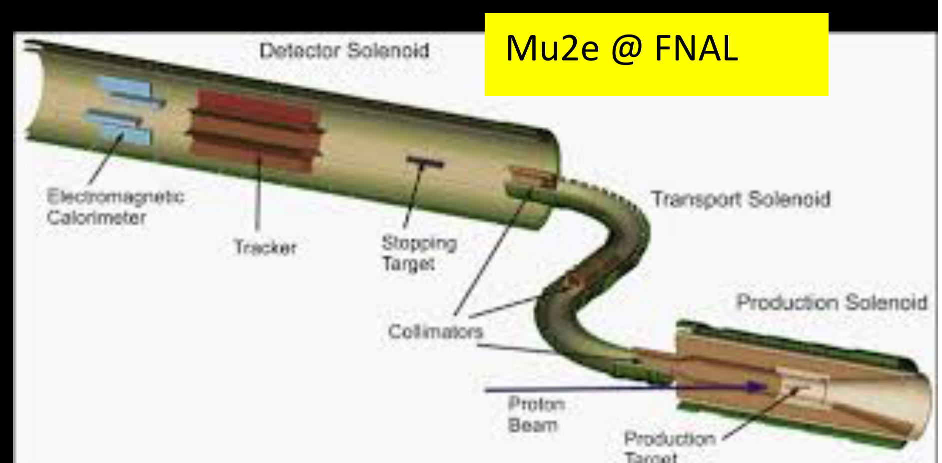
O(100) SM $K^+ \rightarrow \pi^+\nu\nu$ events



New generation of muon experiments (cLFV)



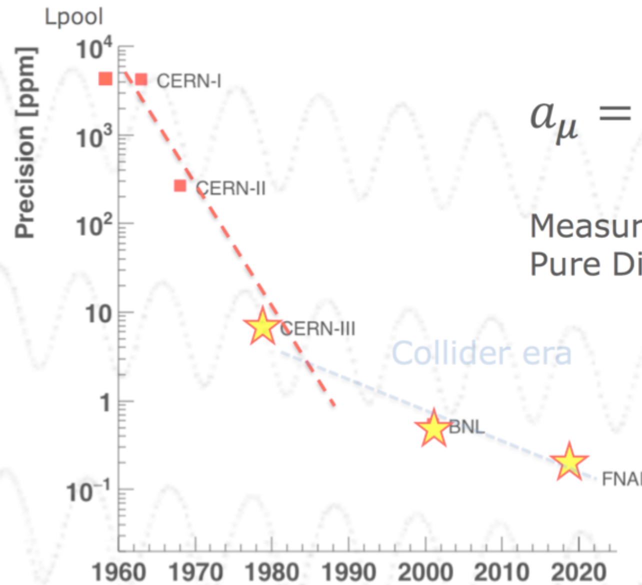




g-2

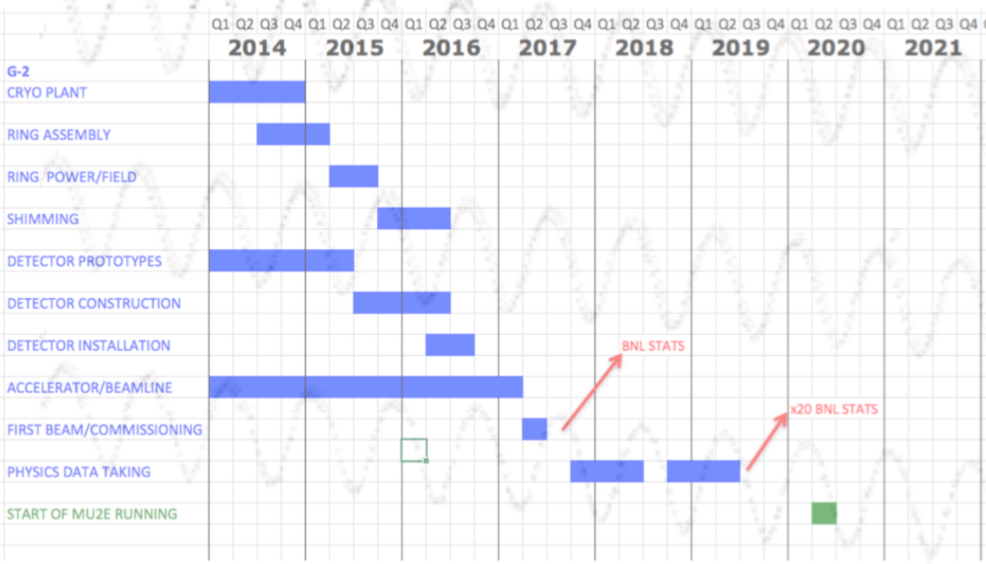
Theory: 12,672 Feynman Diagrams
2.00231930436356 ± 0.0000000000154

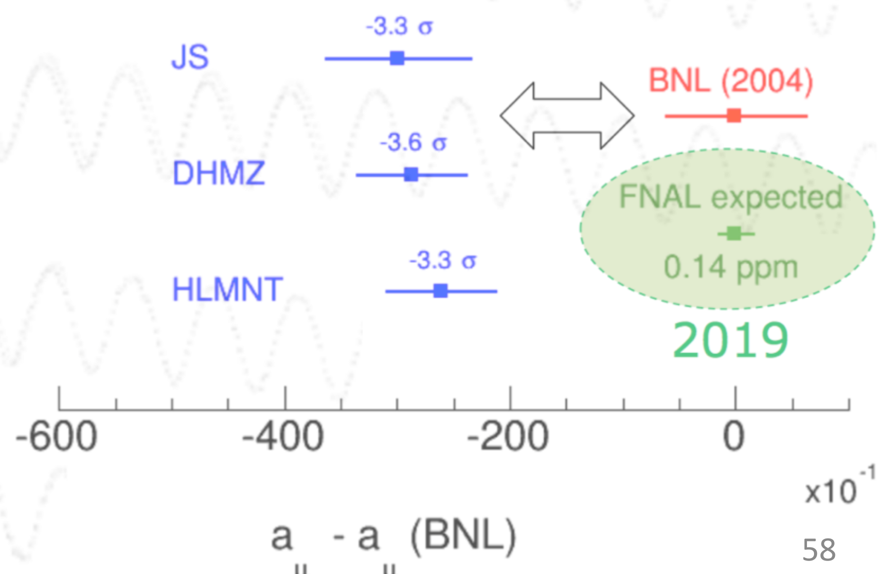
- Experiment construction on schedule and on budget.
- Improved experimental design.
- Improved simulaton.
- Aims to reduce error from 0.2ppm to 0.07ppm.



$$a_\mu = \frac{(g-2)}{2}$$

Measuring deviations from Pure Dirac prediction





What is flavor physics?

Flavour (particle physics)

From Wikipedia, the free encyclopedia

In particle physics, **flavour** or **flavor** is a quantum number of elementary particles. In quantum chromodynamics, flavour is a global symmetry. In the electroweak theory, on the other hand, this symmetry is broken, and flavour-changing processes exist, such as quark decay or neutrino oscillations.

Flavour in particle physics

Flavour quantum numbers:

- Baryon number: B
- Lepton number: L
- Strangeness: S
- Charm: C
- Bottomness: B'
- Topness: T
- Isospin: **I** or I_3
- Weak isospin: **T** or T_3
- Electric charge: Q
- X-charge: X

Combinations:

- Hypercharge: Y
  - $Y = (B + S + C + B' + T)$
  - $Y = 2\,(Q - I_3)$
- Weak hypercharge: Y_W
  - $Y_W = 2\,(Q - T_3)$
  - $X + 2Y_W = 5\,(B - L)$

Flavour mixing

- CKM matrix
- PMNS matrix
- Flavour complementarity

What is in a name?

“The term flavor was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks.”

RMP 81 (2009) 1887

What is in a name?

Isospin

What is the difference between the proton (charge = +1) and the neutron (neutral)?

masses almost identical

coupling to the strong interaction identical

Heisenberg (in 1932 – a big year for flavour physics) proposed (p,n) members of isospin doublet:

p: $(I;I_z) = (½; +½)$ n: $(I,I_z) = (½; –½)$

Later extended to other particles

pions form an isospin triplet $\pi^{+,0,-}$: $(I; I_z) = (1; +1,0,–1)$

Isospin Symmetry

- Strong interaction same for proton & neutron
  - Hamiltonian invariant under global SU(2) rotation
  - pions thought to be Yukawa particles
    - gauge bosons responsible for mediating strong force (related to local SU(2) symmetry ... <u>not</u> correct description of strong interaction)
- Isospin is not an exact symmetry
  - nonetheless proved to be a very useful concept
  - successful because $m_u \sim m_d$ & $m_u, m_d < \Lambda_{QCD}$

The flavor puzzle

Fermions ("matter")	Bosons ("forces")
Quarks: uuu ccc ttt / ddd sss bbb; **Leptons**: e μ τ / ν_e ν_μ ν_τ $\times$ {MATTER, ANTIMATTER}	$gggggggg$, γ, W^+, W^-, Z, H

Why are there so many particles?

Flavor Physics & Parameters of the Standard Model

- 3 gauge couplings
- 2 Higgs parameters
- 6 quark masses
- 3 quark mixing angles + 1 phase
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase)

CKM matrix

PMNS matrix

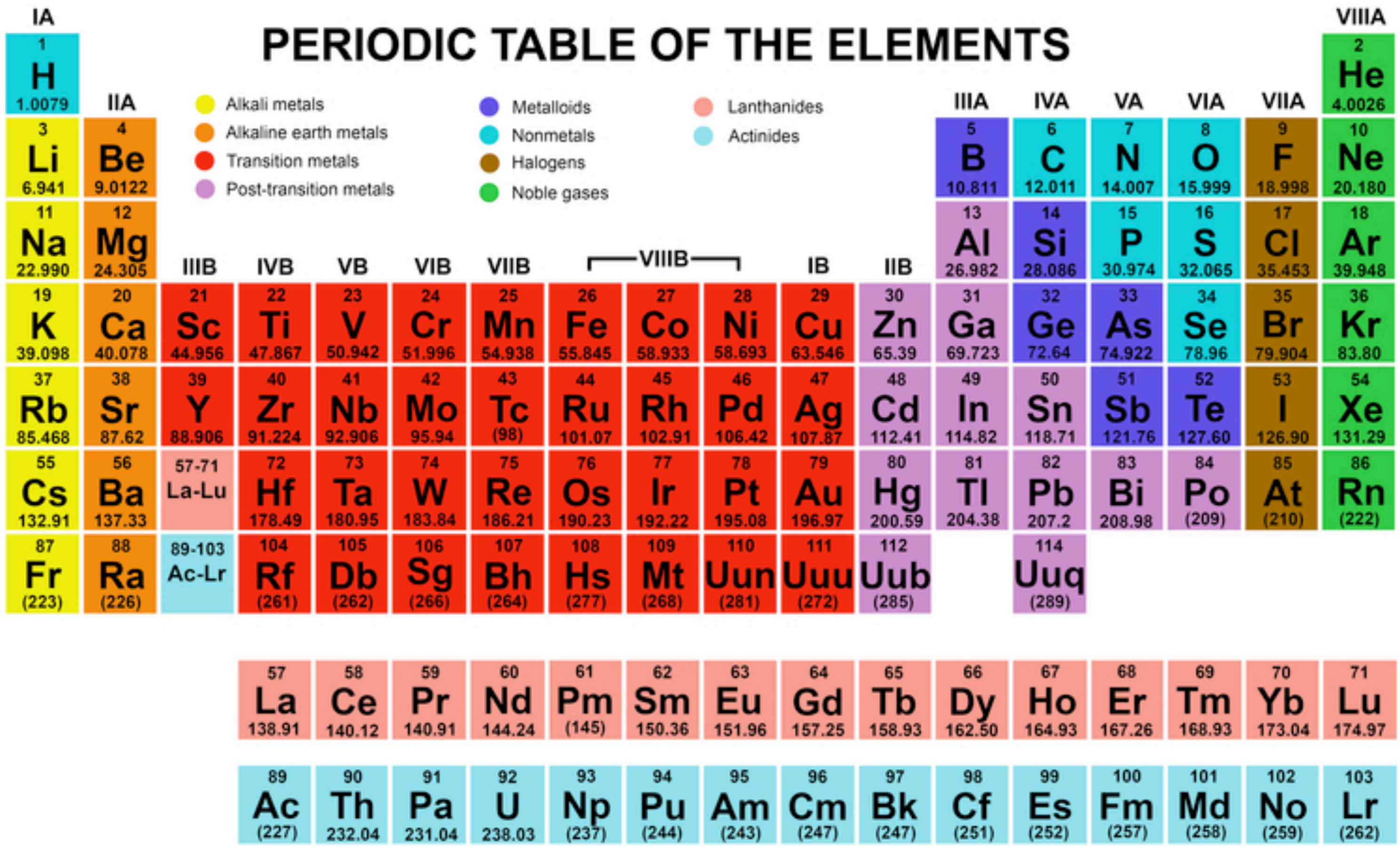
FLAVOUR PARAMETERS

( ) = with Dirac neutrino masses

Flavor (broadly defined) is a big over-arching challenge of particle physics for the first half of this century

- What are the dynamical origins of fermion masses, mixings, and CP violation?
- What are the scales associated with this dynamics?
- What are the symmetries and symmetry breakings?
- What is the complete Higgs sector and how does it work?
- How are quark and lepton flavor related?
- What other flavor sectors are accessible, e.g.
  - superpartners
  - dark sector

What is the underlying dynamics of flavor?



Saying that the Standard Model with the Higgs mechanism is a successful theory of fermion masses is like saying that the Periodic Table is a successful theory of atoms

Reducing the scope

- Flavor physics includes
  - Neutrinos
  - Charged leptons
  - Kaon physics
  - Charm & beauty physics
  - (Some aspects of) top physics

- Focus here will be on beauty
  - will touch on others when appropriate

Heavy quark flavour physics

- Focus on
  - flavour-changing interactions of charm and beauty quarks
- But quarks feel the strong interaction and hence hadronise
  - various different charmed and beauty hadrons
  - many, many possible decays to different final states
- Hadronisation greatly increases the observability of CP violation effects
  - the strong interaction can be seen either as the "unsung hero" or the "villain" in the story of quark flavour physics

I. Bigi, hep-ph/0509153

Where the b-physics program is: the successful CKM-project of the past two decades (a non-lose theorem) has morphed into
the Flavor-New Physics project (where a no-lose theorem does not exist)

In a nutshell

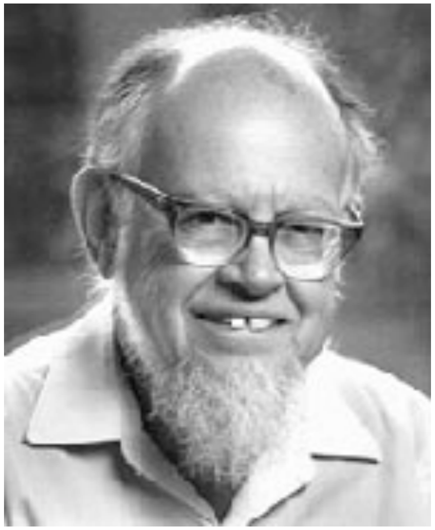
Amplitudes and *Phases* in the Weak Interaction

N. Cabibbo

M.Kobayashi

T.Maskawa

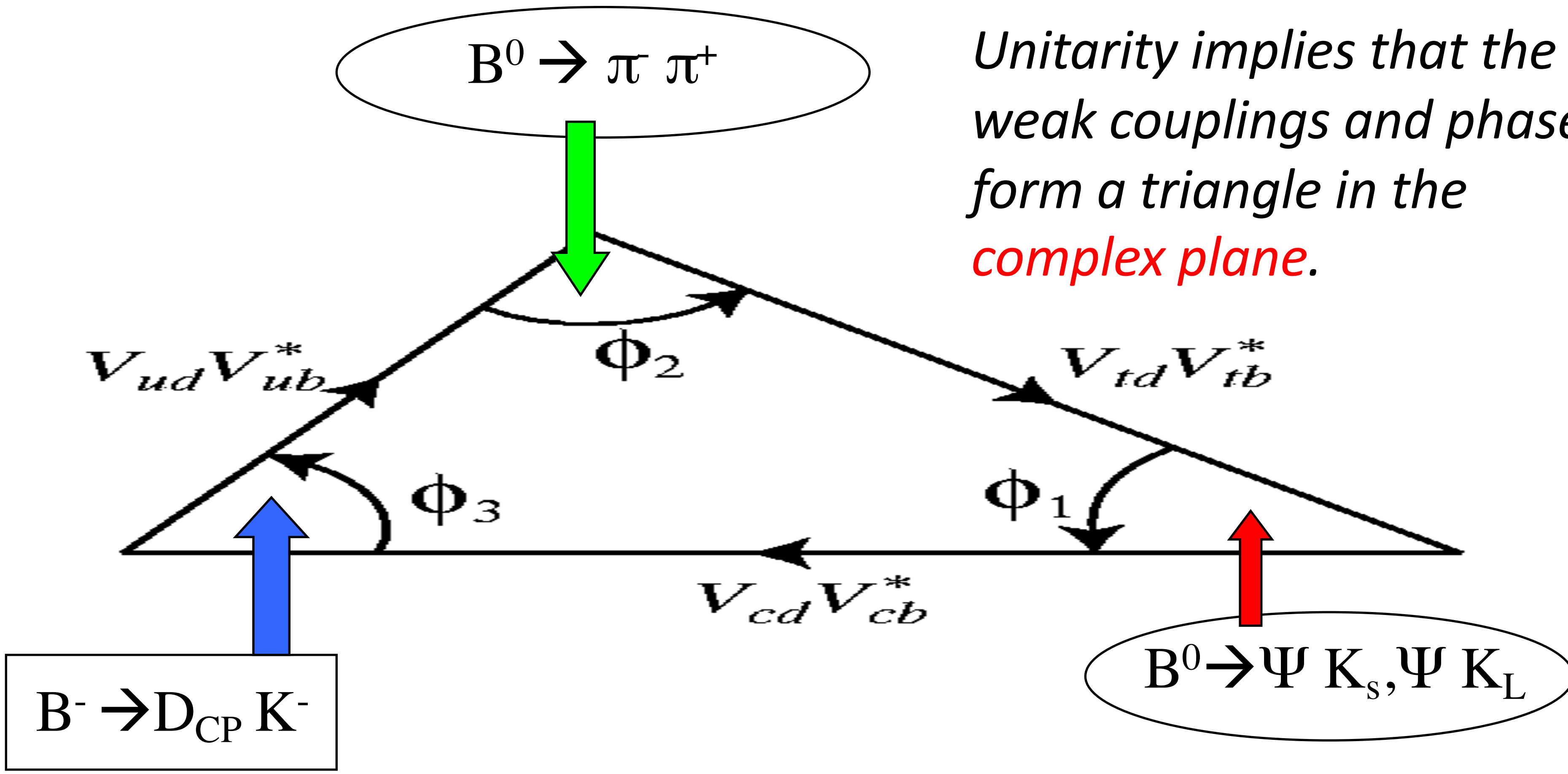
$$V_{\mathrm{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



L. Wolfenstein

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Three Angles: ($\varphi_1,\varphi_2,\varphi_3$) *or* ($\beta$, α, γ)



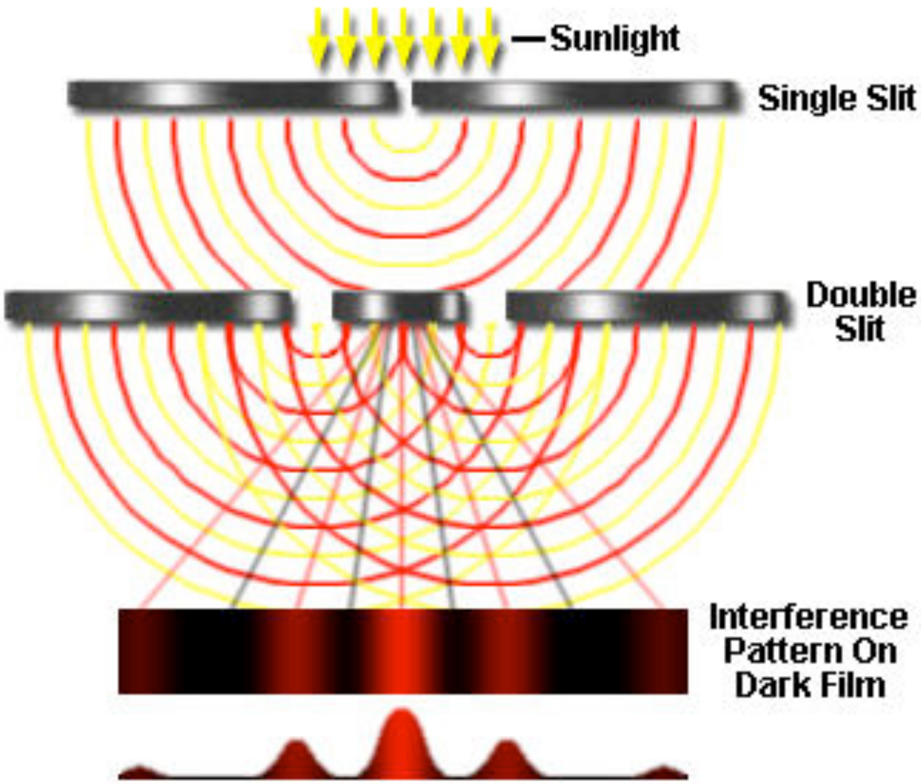
Unitarity implies that the weak couplings and phases form a triangle in the complex plane.

Big Questions: *Are determinations of angles consistent with determinations of the sides of the triangle ? Are angle determinations from loop and tree decays consistent ?*

Time-dependent *CP* violation is

"*A Double-Slit experiment*" with particles and antiparticles

QM interference between two diagrams



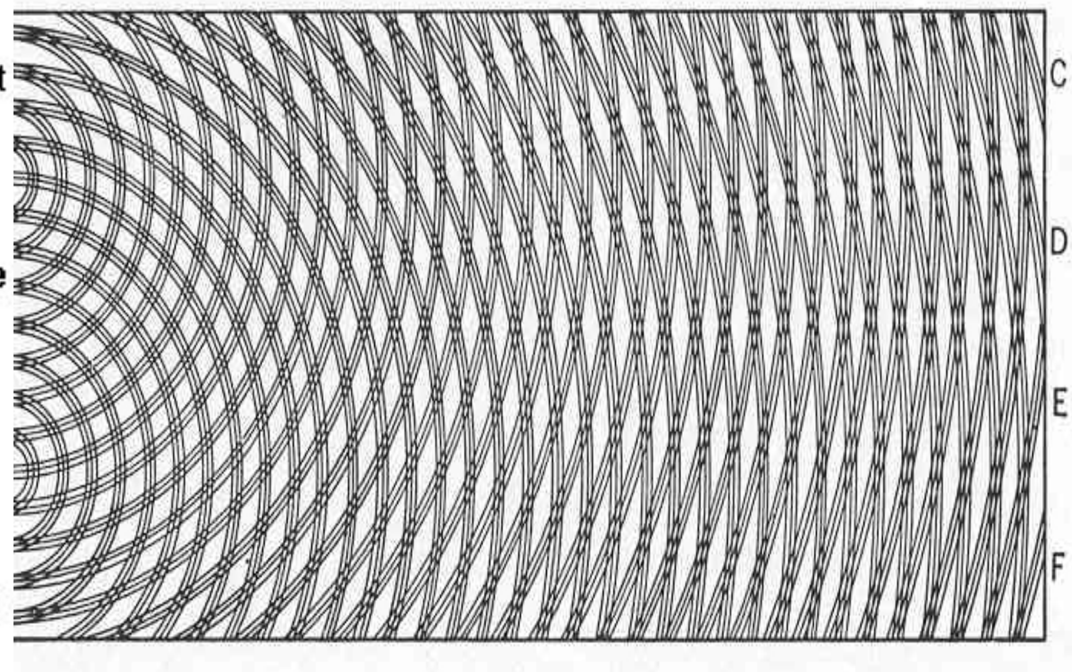


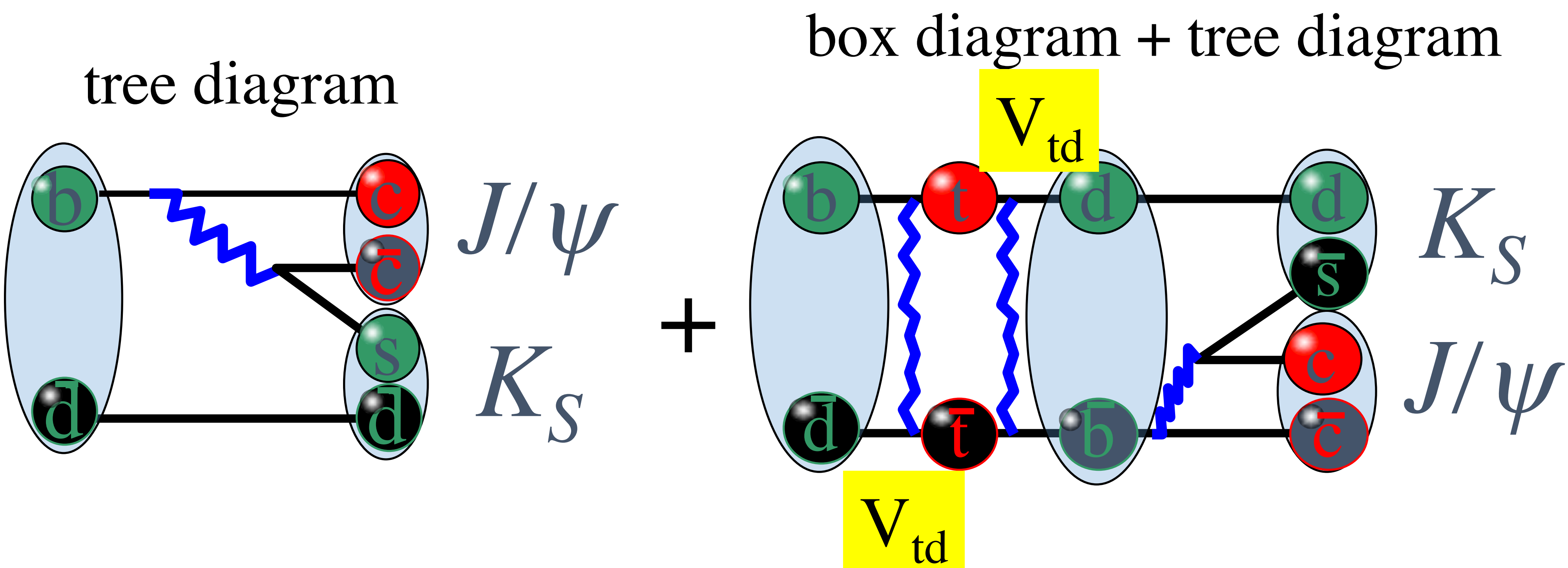
FIG. 1

Measures the phase of V_{td} or equivalently the phase of B_d–anti B_d mixing.

Time-dependent *CP* violation is

"*A Double-Slit experiment*" with particles and antiparticles

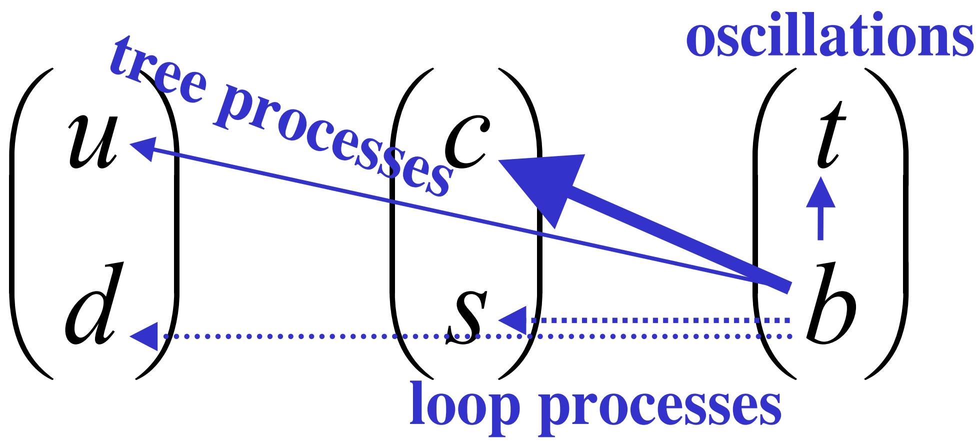
QM interference between two diagrams



Measures the phase of V_{td} or equivalently the phase of B_d–anti B_d mixing.

In more detail

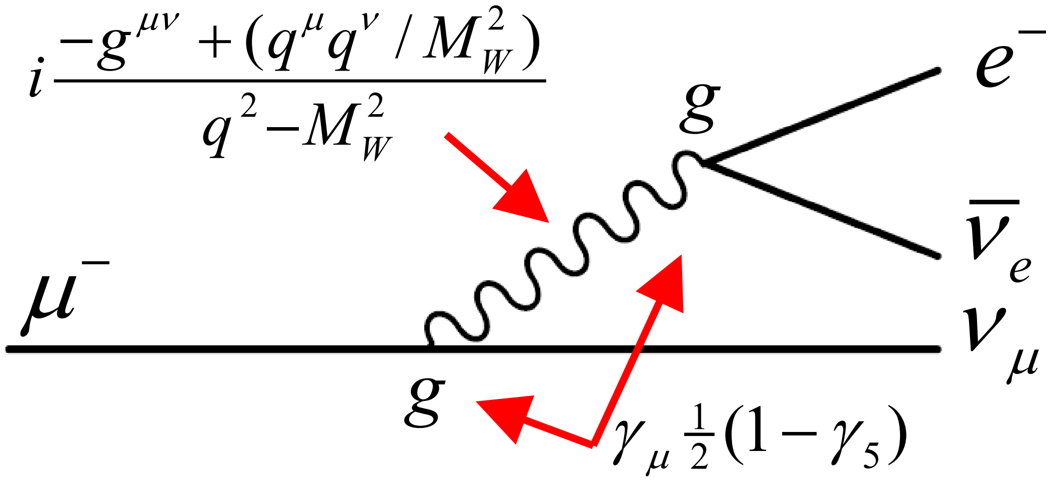
Perspective on the b quark



1. **Mass**: The *b* quark is the heaviest quark that forms hadronic bound states. m_B=5.28 GeV
2. **Lifetime**: It must decay outside of its own quark generation → decay is suppressed → relatively long lifetime (1.6 ps)
3. **Decay modes**: *b*→*c* decay is dominant; large mass→ many accessible final states. Many processes: trees, loops, oscillations.
4. ***CP* violation**: Cabibbo-Kobayashi-Maskawa matrix → very large *CP* asymmetries in some *B* decays.

Muon Decay:

W-mediated *b*-quark transitions have several key features in common with muon decay.



$$q^2 \leq m_\mu^2 = M_W^2$$

Very strong dependence of decay rate on mass!

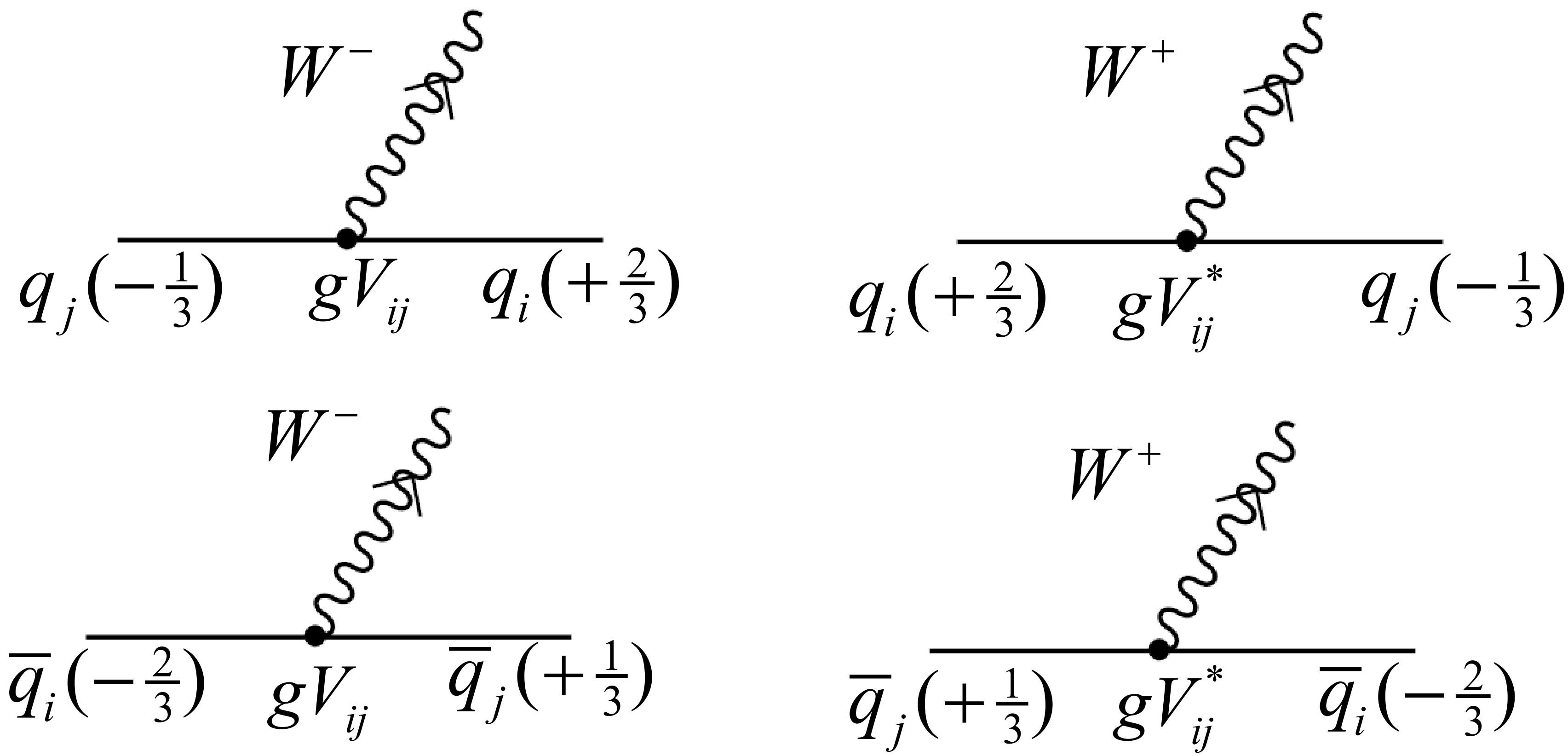
$$\frac{G_F}{\sqrt{2}} \equiv \frac{g^2}{8M_W^2}$$

$$\Gamma = \frac{G_F^2 m_\mu^5}{192\pi^3} \cdot (1 - 8x + 8x^3 - x^4 - 12x^2 \ln x)$$

(ignoring QED radiative corrections)

$$x \equiv \frac{m_e^2}{m_\mu^2}$$

Reminder: vertex factors for W-mediated quark transitions



Universal weak coupling g must be multiplied by element of CKM matrix V_{ij}.

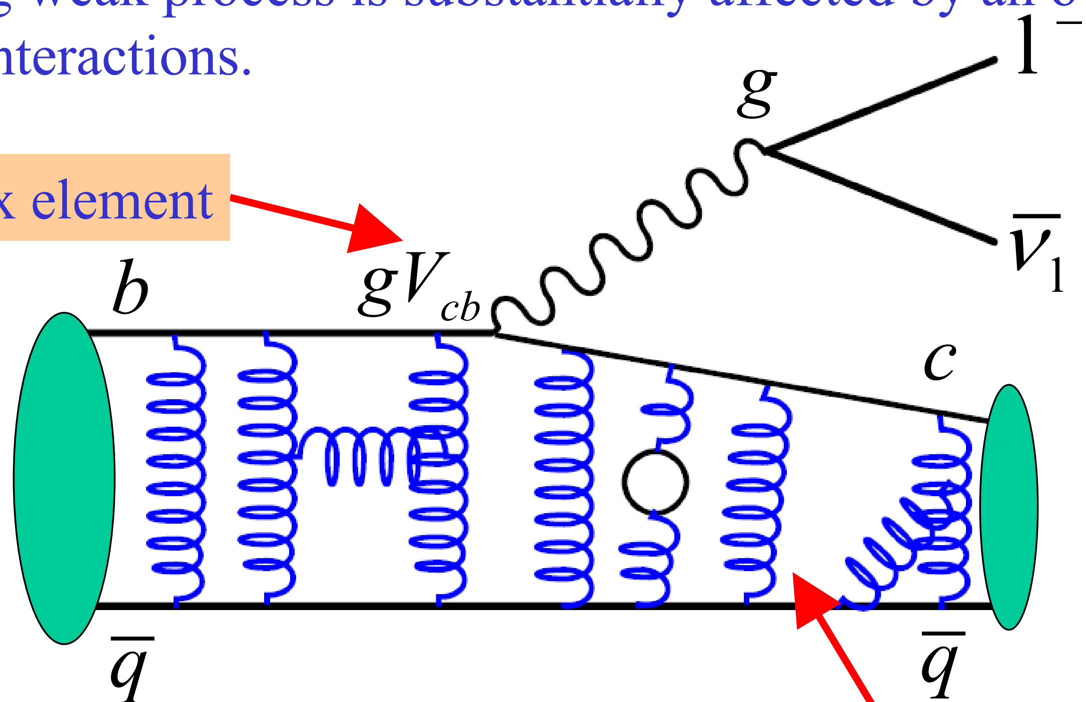
emit W^- or absorb $W^+ \Rightarrow V_{ij}$

emit W^+ or absorb $W^- \Rightarrow V_{ij}^*$

B-quark ideal, B-meson reality

Underlying weak process is substantially affected by an overlay of strong interactions.

CKM matrix element

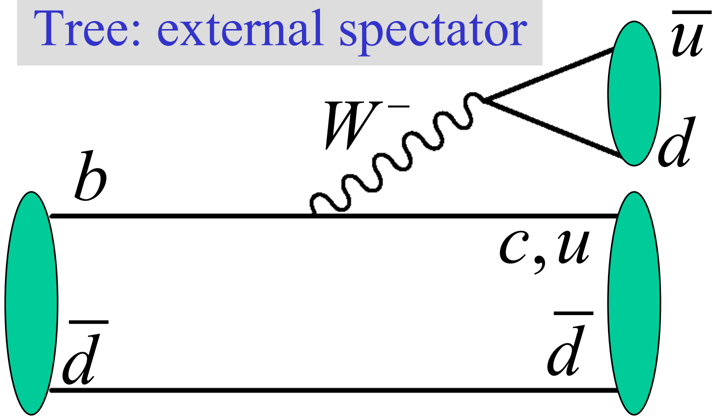


Initial system is bound state: *b*-quark is not at rest in B frame.

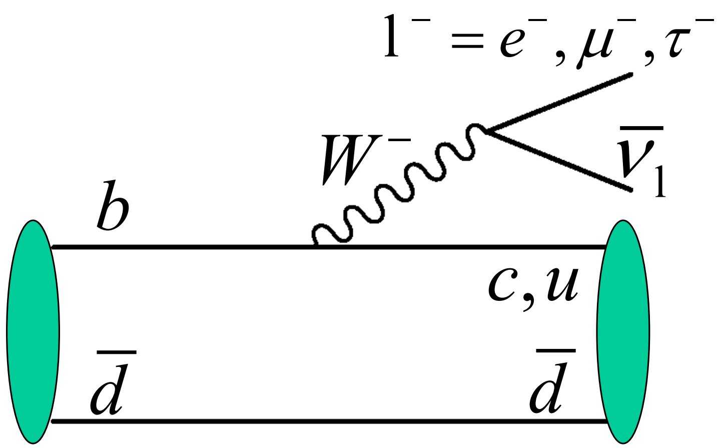
Exchange of gluons is between daughter quark and spectator quark to form the final state meson.

Weak Transitions in B Decay

Tree: external spectator



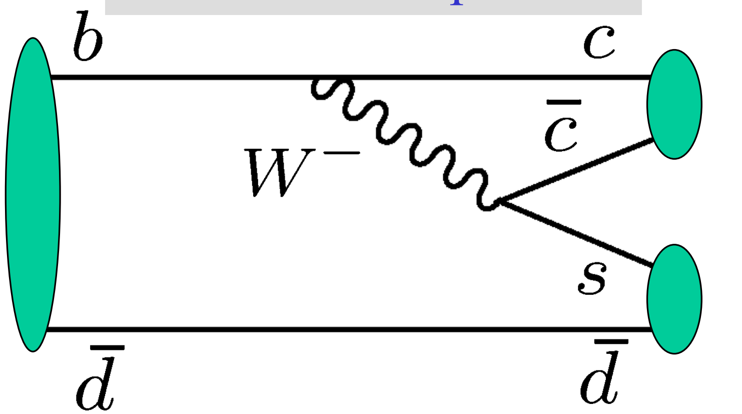
Hadronic decay:
- External spectator diagram
- b→c is dominant
- Upper vertex can also produce $\bar{u}s, \bar{c}s, \bar{c}d$



Semileptonic decay:
- Charge of lepton is correlated w/charge of b (b) quark
- Largest B branching fraction
- Strong interactions do not affect upper vertex particles!

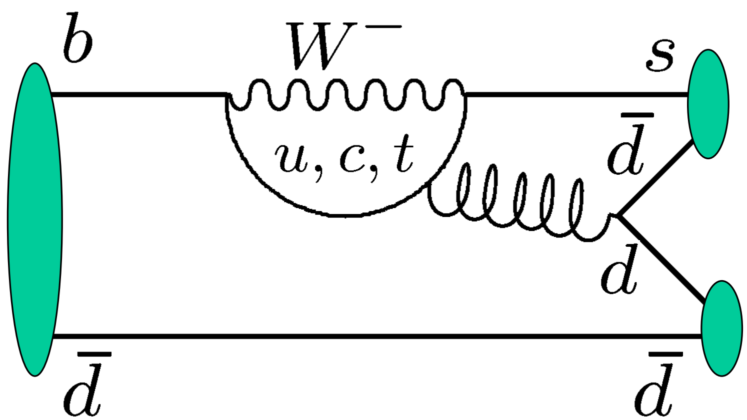
Weak Transitions in B Decay

Tree: internal spectator



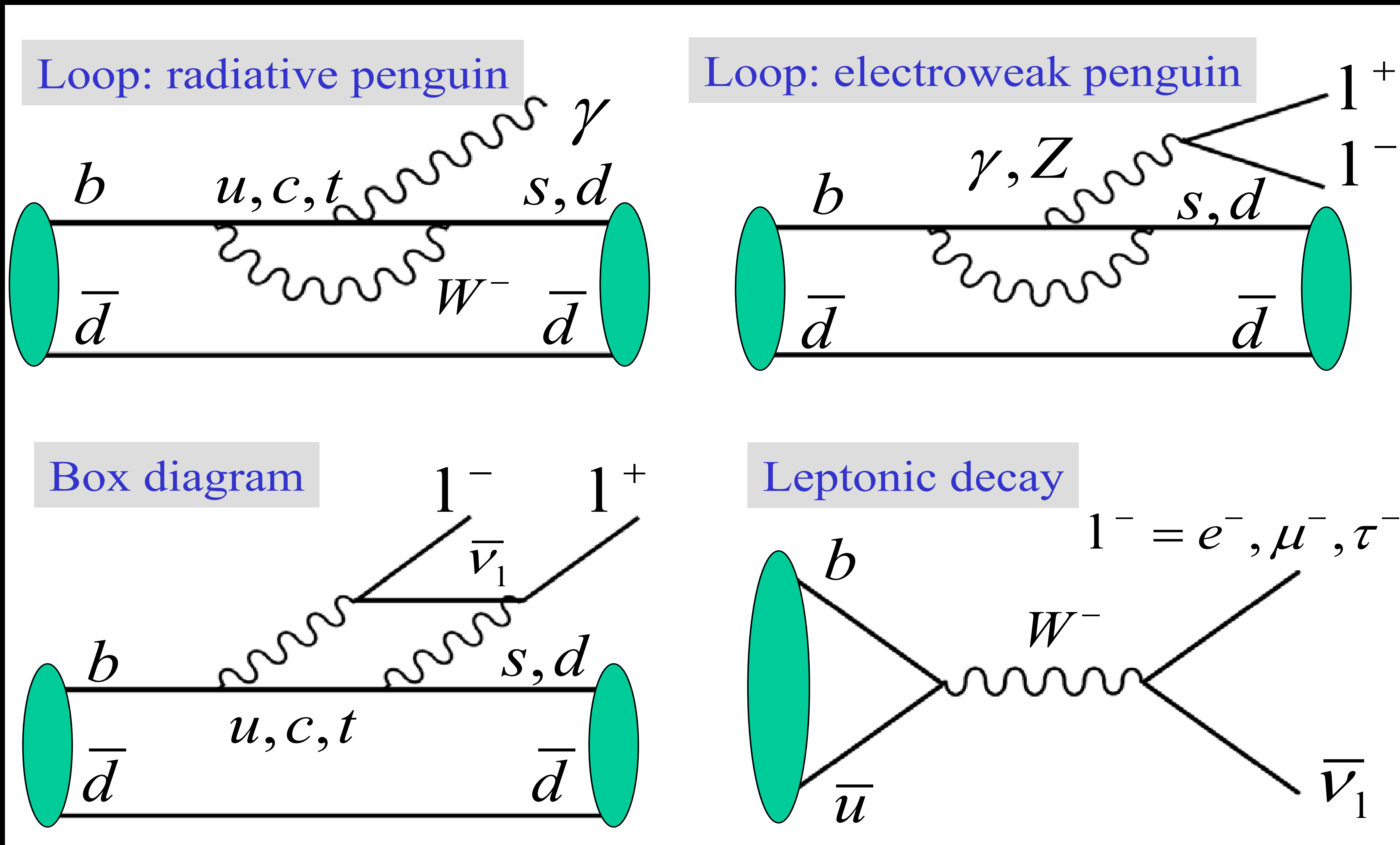
Hadronic decay:
- "Internal" spectator diagram
- Color suppressed
- In B^0 decays, can interfere with ext. spectator diagram.

Loop: gluonic penguin

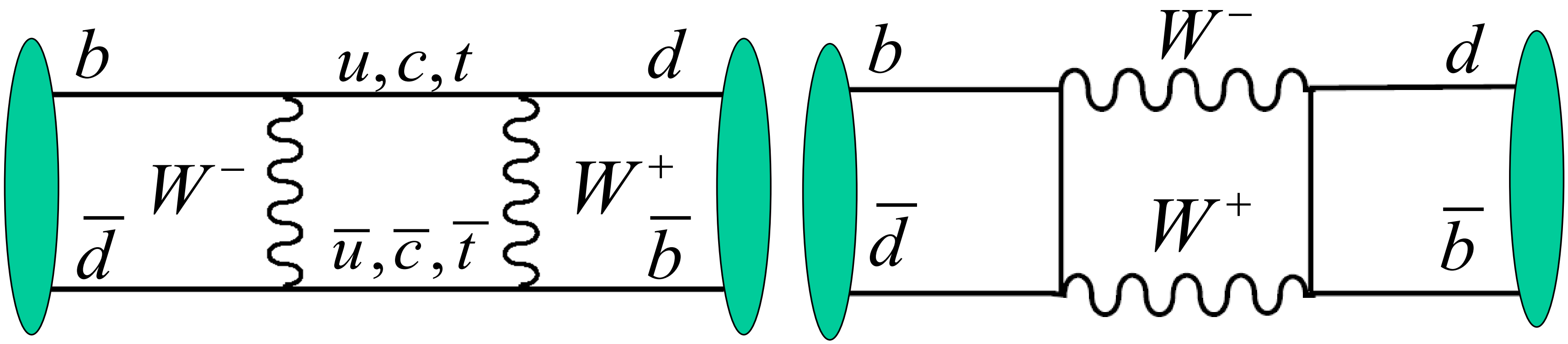


Hadronic decay:
- Gluonic penguin diagram
- Many such modes have now been observed!
- Loop diagrams are suppressed in SM→ good place to search for new physics amplitudes.

Weak Transitions in B Decay

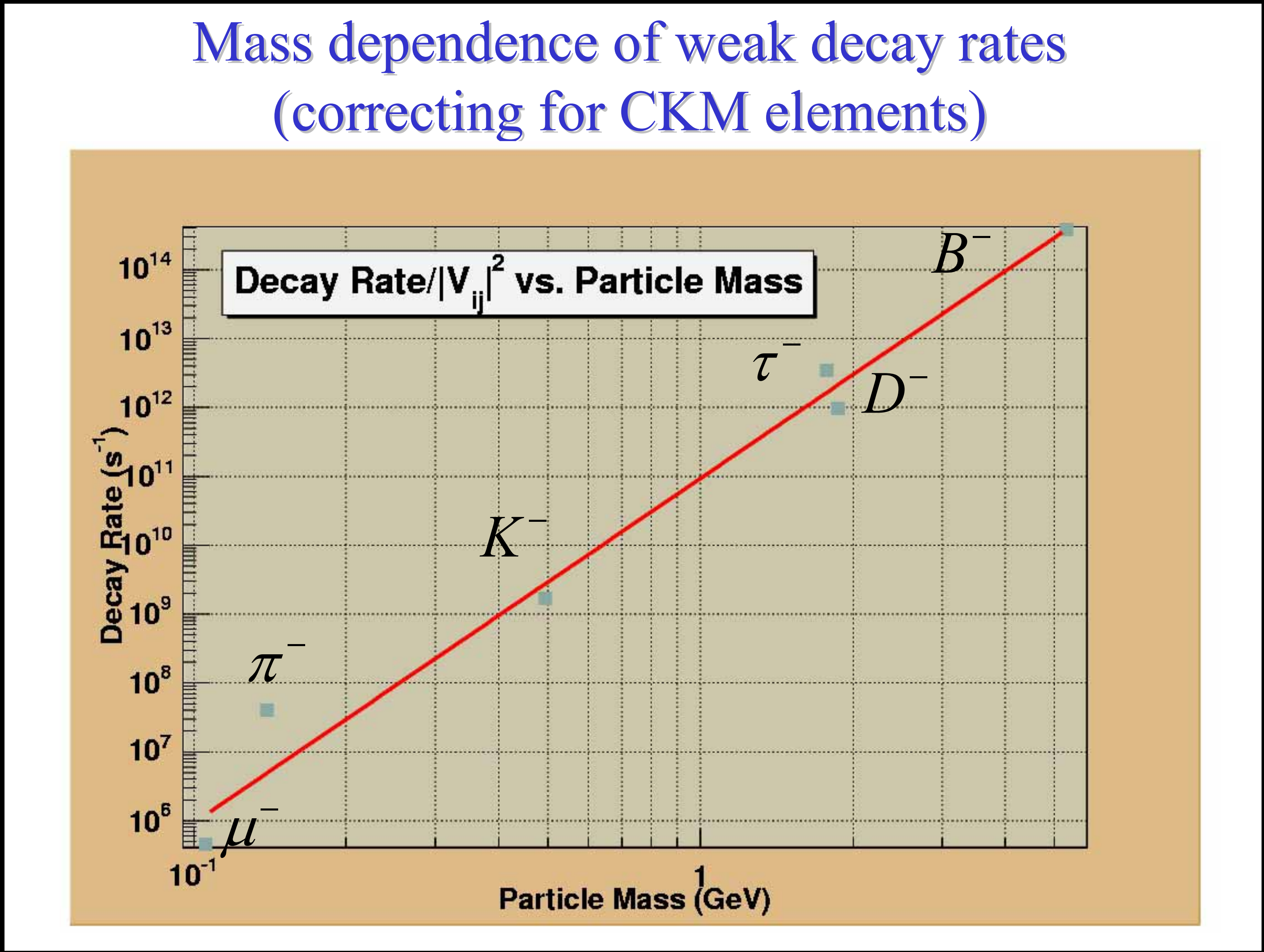


Weak transitions underlying $B^0\,\overline{B}^0$ oscillations



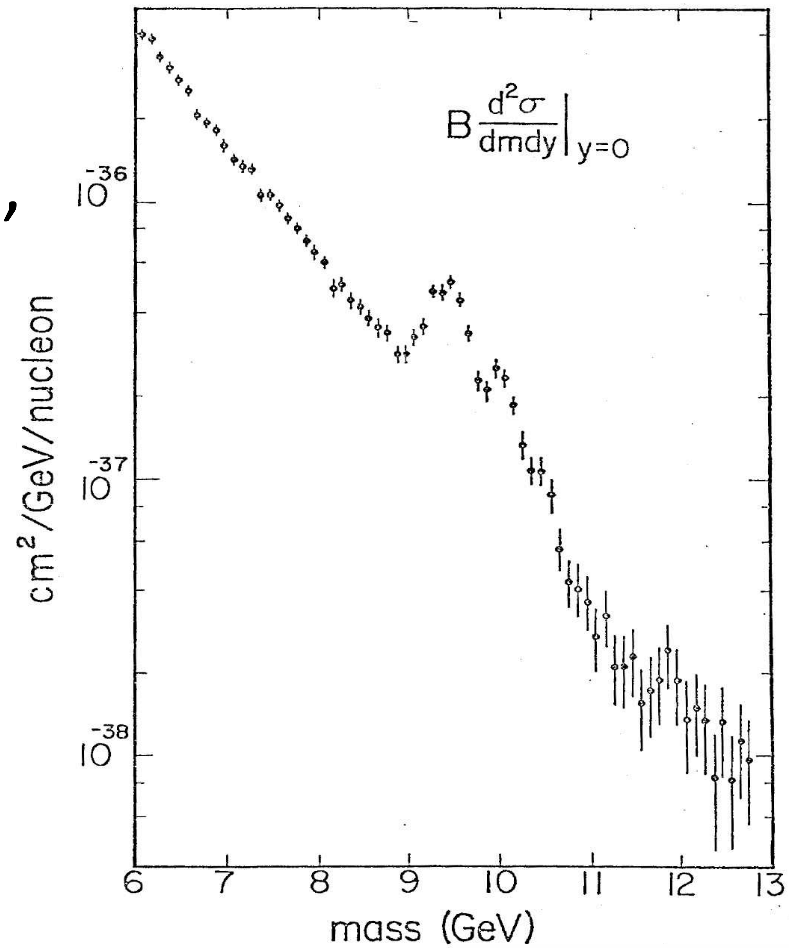
B^0 and $\overline{B}^0$ spontaneously evolve into each other. More precisely, a particle that is initially a B^0 evolves into a superposition of B^0 and $\overline{B}^0$.

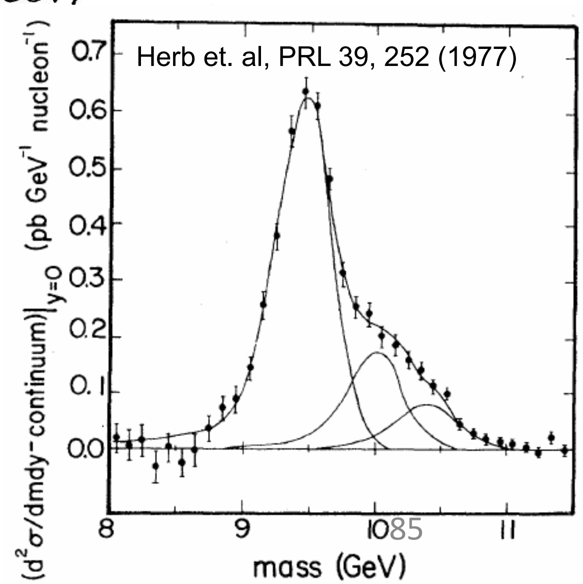
Prior expectation: ~10^{-14}s



From discovery to completion of the CKM project

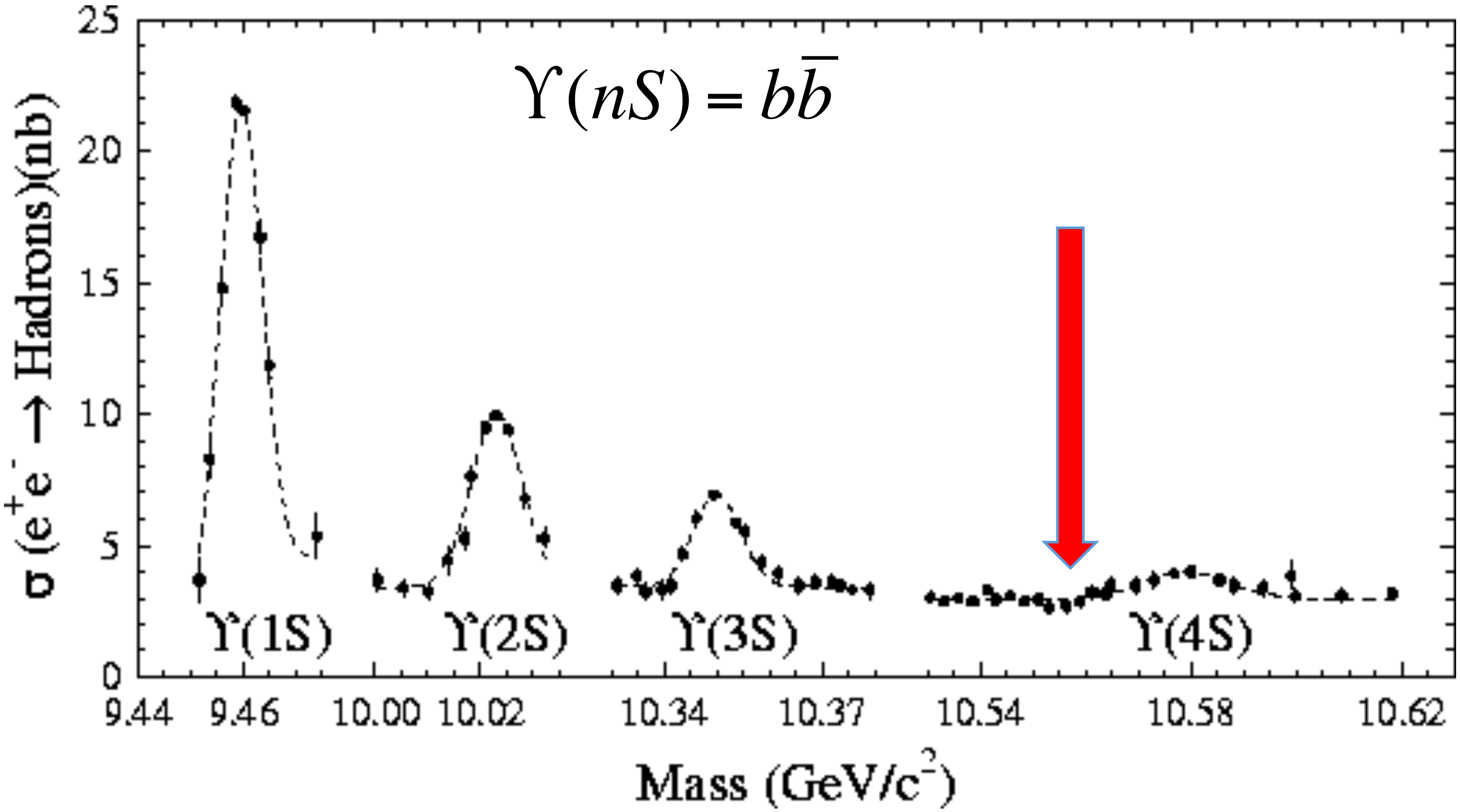
400 GeV proton-nucleus collisions at Fermilab. In 1977, Lederman's team find a resonance at 9.5 GeV decaying to pairs of muons.





HADRONS

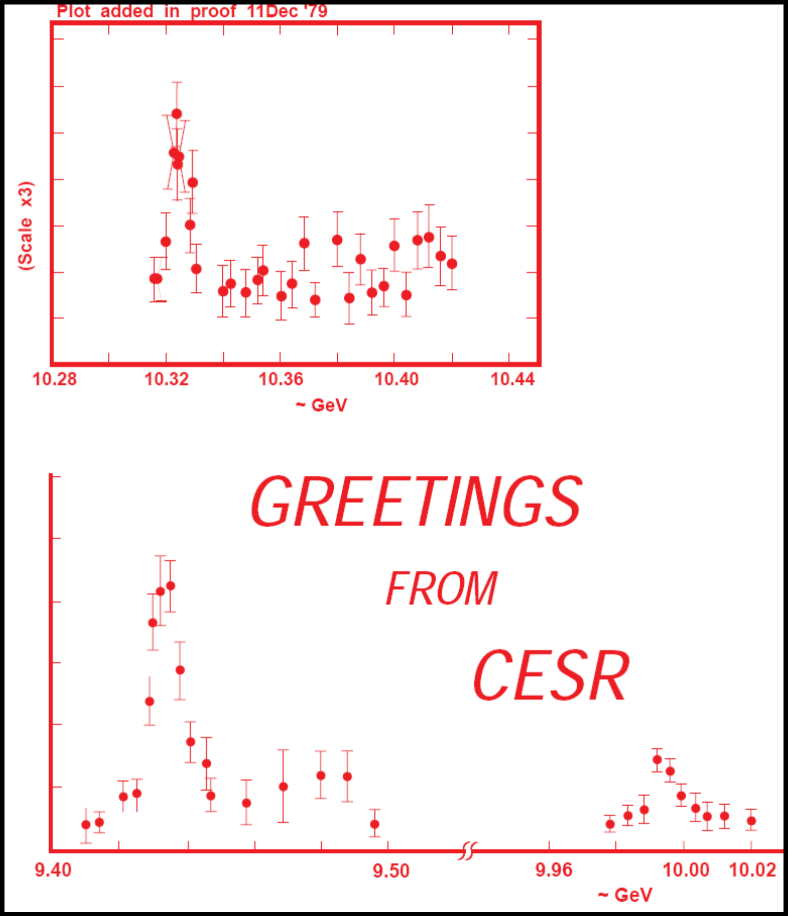
Radial excitations



Electron-positron collisions at DORIS (Germany) and CESR (Cornell) allowed the resolution and discovery of these "*positronium-like*" radial excitations.

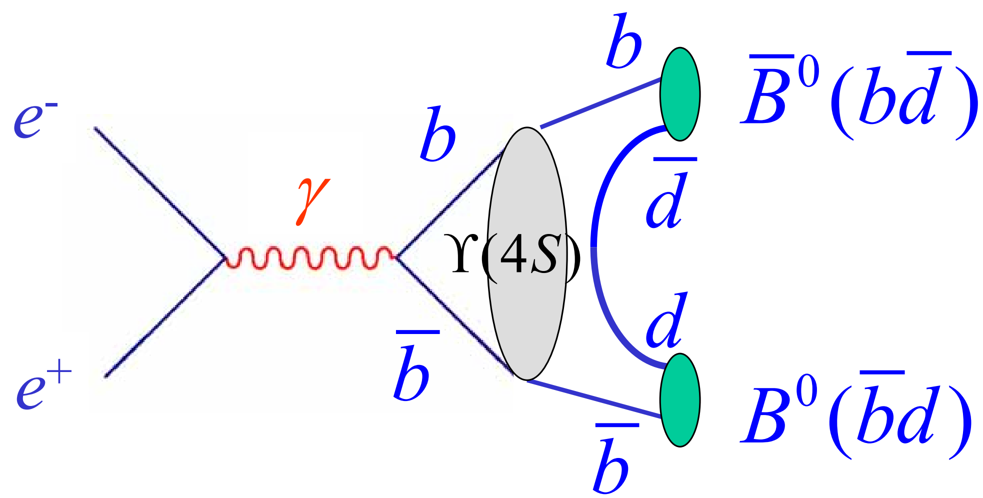
Typical card celebrating the winter holidays

Particle physics holiday card (1979)

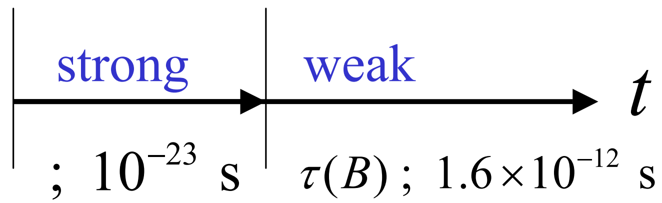


B production at the Υ(4S)

Production of B mesons in e^+e^- collisions



$$m_B = 5.28\ \text{GeV}$$
$$m_b \approx 4.6\ \text{GeV}$$



$$e^+e^- \to \gamma \to b\bar{b} \to \Upsilon(4S) \to B^0(\bar{b}d)\bar{B}^0(b\bar{d}) \qquad B^+(\bar{b}u)B^-(b\bar{u})$$

$$e^+e^- \to \gamma \to u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, b\bar{b}, e^+e^-, \mu^+\mu^-, \tau^+\tau^-$$

The Power of Production at threshold

Rather than using invariant mass, one can use “beam-constrained mass” or “energy-substituted mass” to isolate the signal. The resolution is usually about an order of magnitude better !

$$m_{\rm bc} = \sqrt{E^{\star 2}_{\rm beam} - p^{\star 2}_{B}},$$

Also use the energy difference (given below in the CM frame) to extract the signal

$$\Delta E = E_{rec} - E_{beam}$$

Much of the background can be removed

BaBar’s definition of m_{ES} is slightly different

The Power of Production at threshold

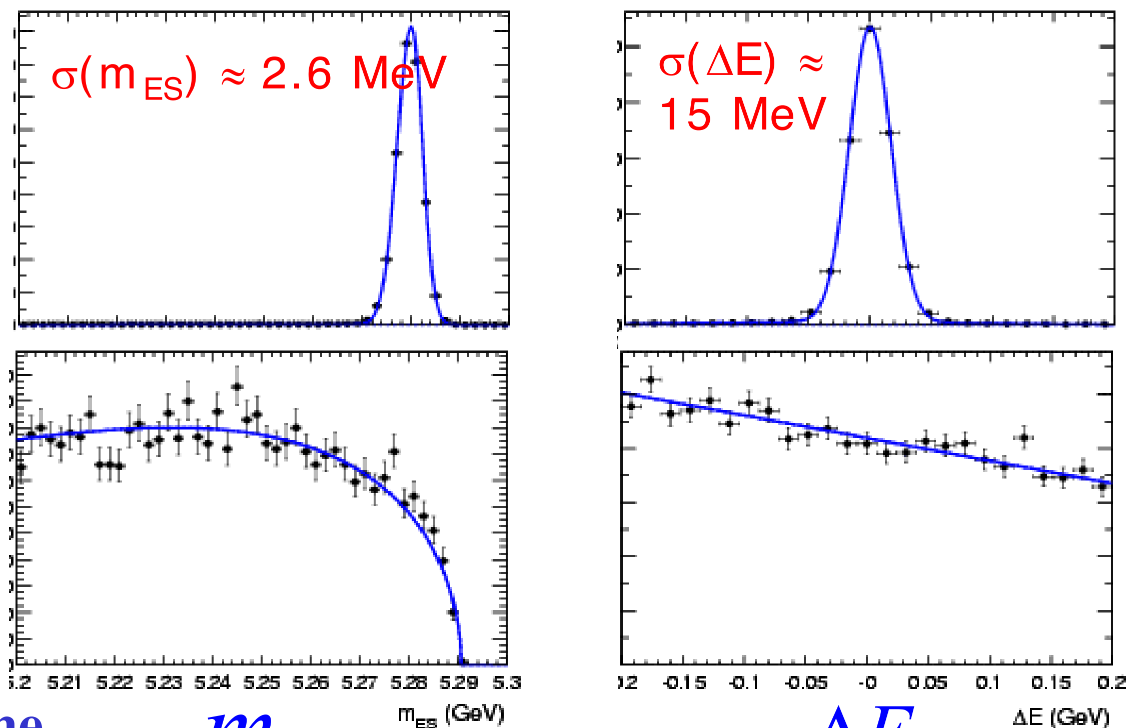
Beam energy-substituted mass | **Energy difference** | **Event shape**

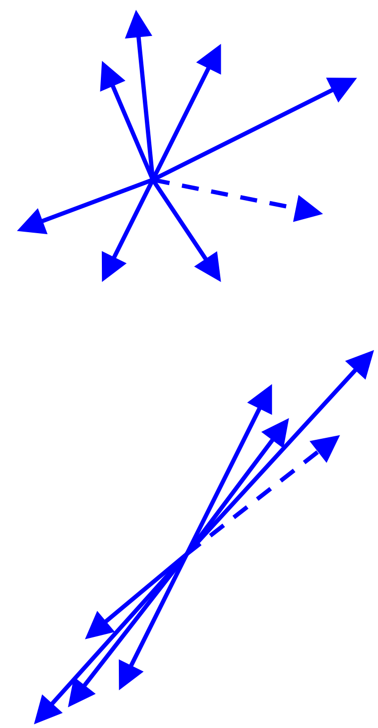
$$m_{ES} = \sqrt{E^{*2}_{beam} - \left|\vec{p}^{\,*}_B\right|^2}$$

$$\Delta E = E^*_B - E^*_{beam}$$

$B\bar{B}$ events

$q\bar{q}$ events ($q=u,d,s,c$)



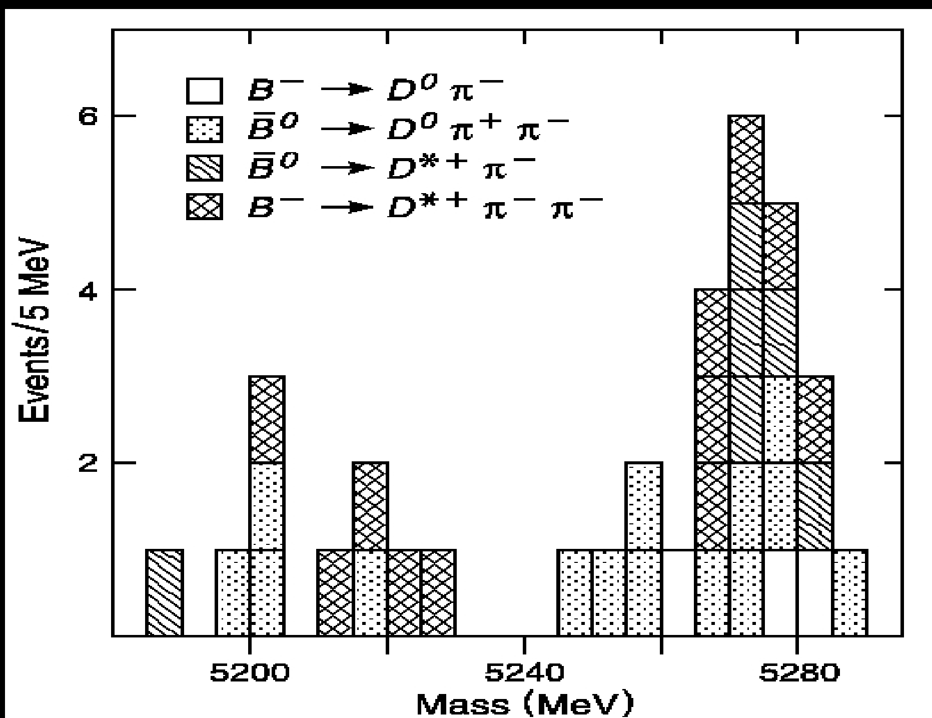


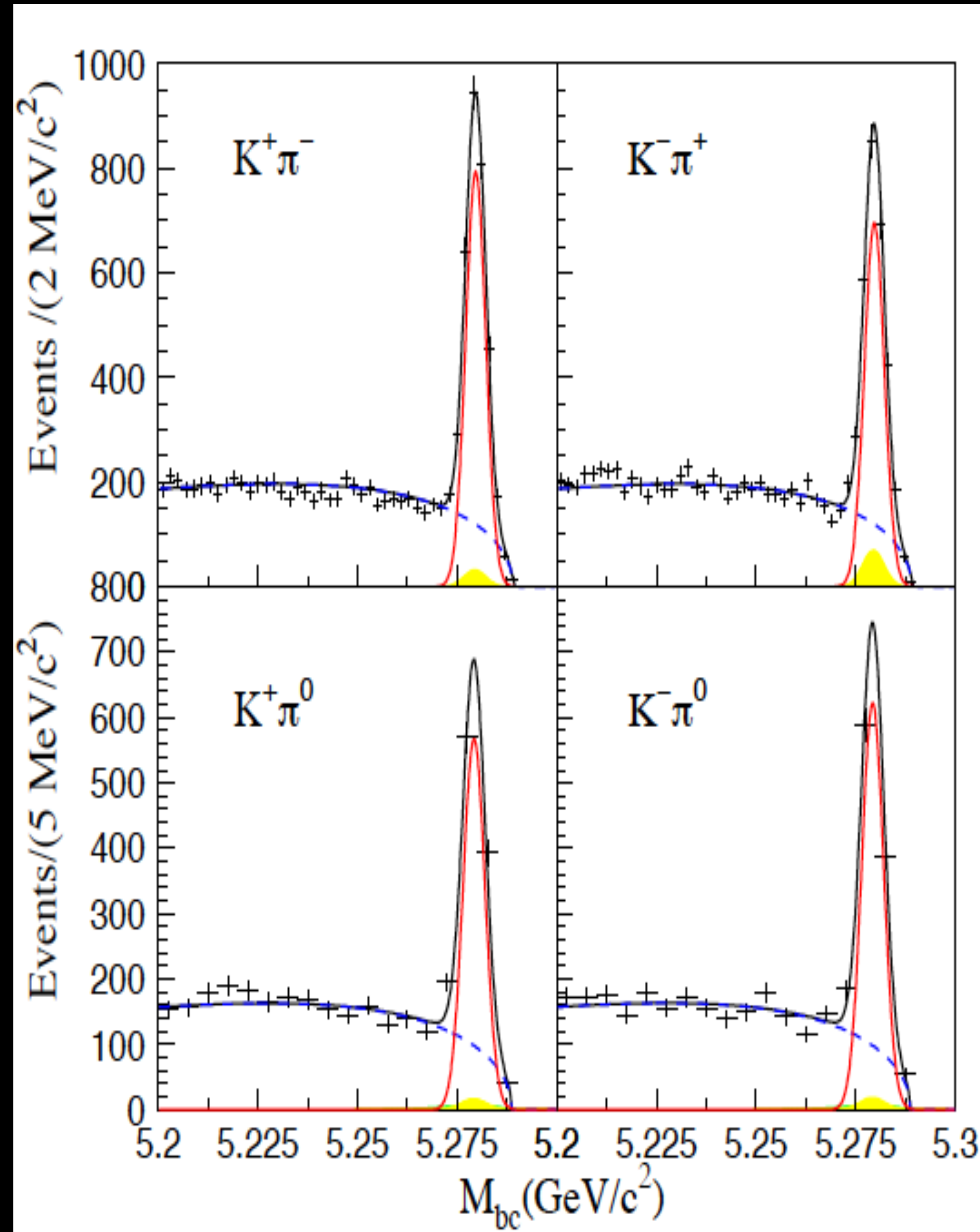
m_{ES} $\quad\quad$ ΔE

* e^+e^- CM frame

Now:

Then:



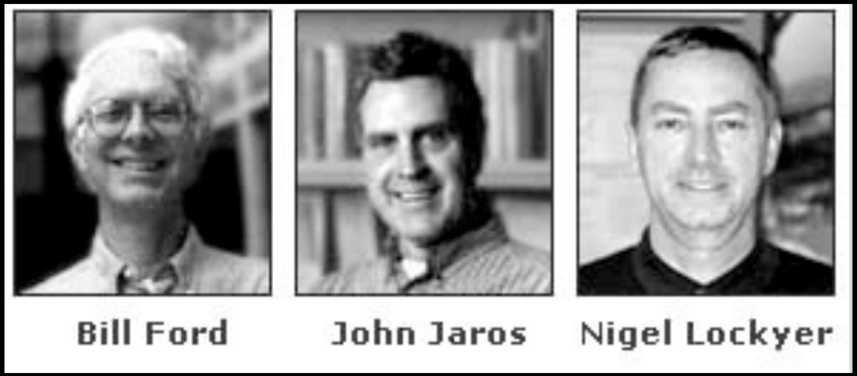


CLEO discovery of B meson

Belle studies of CP violation

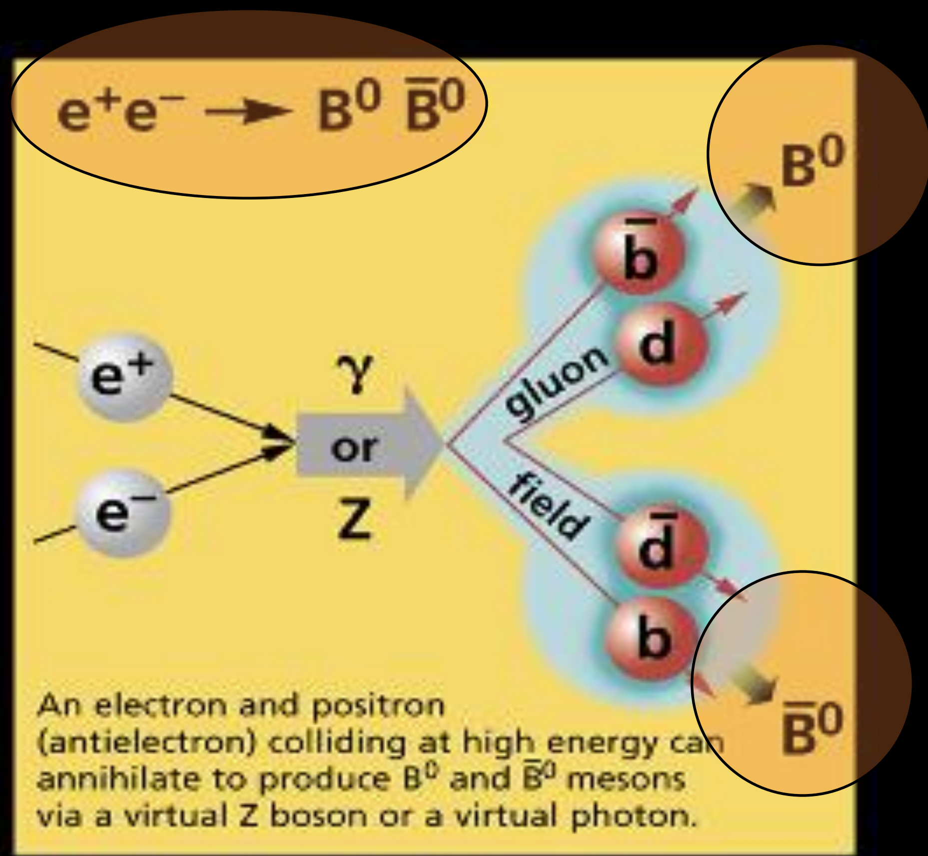
Unexpectedly long B lifetime

- The initial measurements of the B lifetime came from *e+e- collisions* at 29 GeV at PEP, at SLAC.



1.5 ps Surprisingly long !

B Mesons: *"Laboratory Rats of the Weak Interaction"*



Exotic bound state of matter and antimatter (hydrogen-like)
***b* quark mass ~ 5x proton mass**

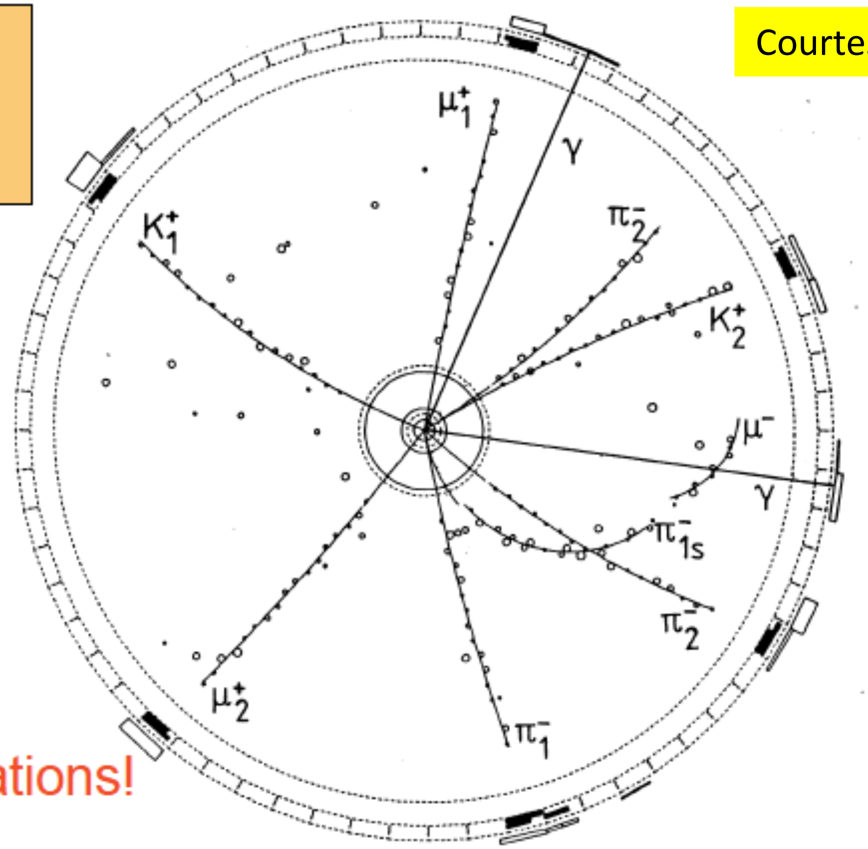
Lifetime ~ 1.5ps

$$\begin{pmatrix} t \\ b \end{pmatrix}$$

1987: ARGUS at Υ(4S) finds that the neutral B meson can transform into its anti-particle, "B-Bbar mixing"

Produce matter-antimatter pairs in ARGUS at DESY

$e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0$



By the time of decay

$B^0\bar{B}^0 \to B_1^0 B_2^0$

Matter-Antimatter oscillations!

Ikaros Bigi and Tony Sanda realized that the long lifetime of the B meson and the possibility of particle-antiparticle mixing could lead to CP non-conservation in the B sector.

Origin and implications of the long *B* lifetime

All *B* decays are CKM suppressed, with $b \rightarrow c$ decays dominant

$$\Gamma \propto G_F^2 \left|V_{cb}\right|^2 m_b^5 \qquad \left|V_{cb}\right| ; \ 0.04 \qquad \left|V_{cb}\right|^2 ; \ 1.6\times 10^{-3}$$

$$c\tau_B = (3\times 10^8 \ \text{ms}^{-1})(1.6\times 10^{-12} \ \text{s}) = 0.48 \ \text{mm}$$

How far will *B* mesons travel before decaying?

- The factor βγ=0.0646 at the Υ(4S)
- Average decay length is only ~29μm

A new idea

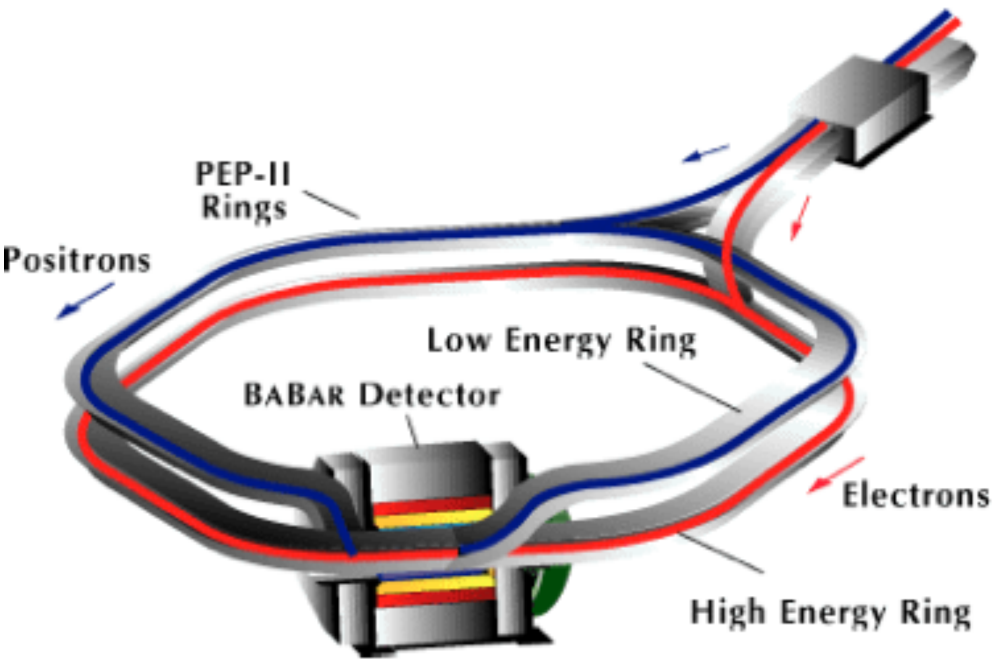
At a Snowmass meeting *in 1988* Pier Oddone (LBL) proposed using asymmetric energy beams.

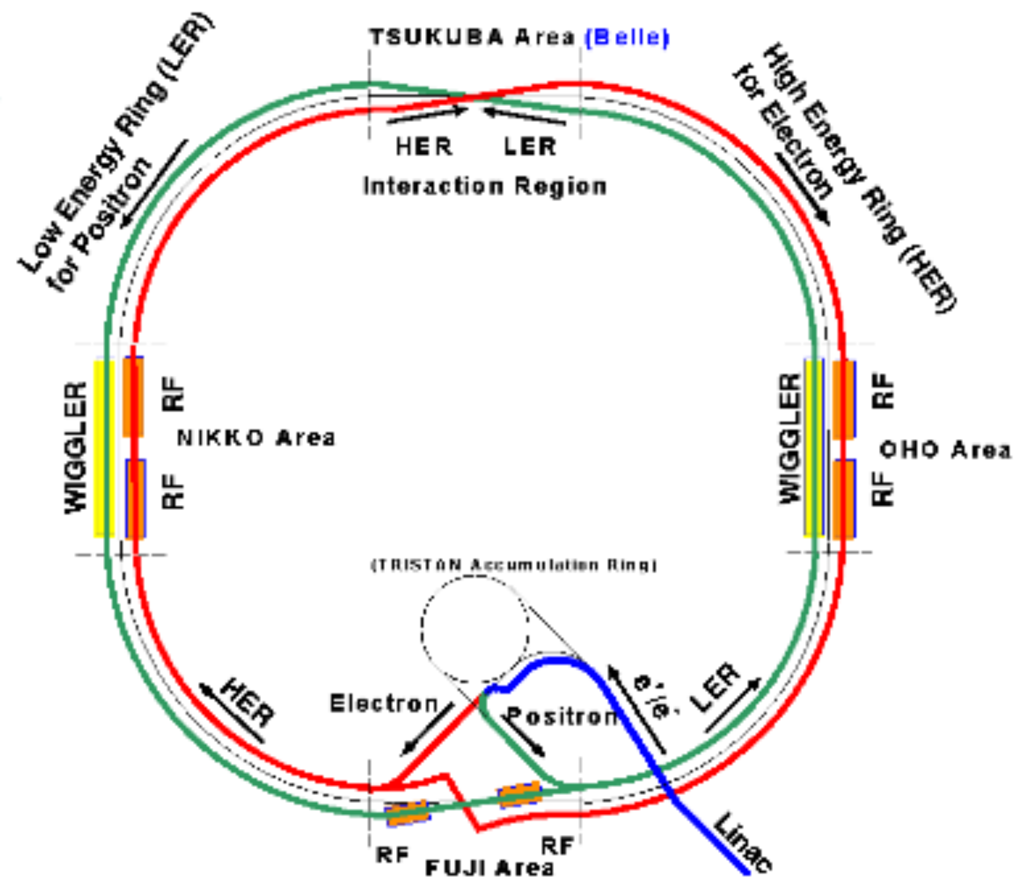
Decay lengths are dilated from ~20 microns to ~200 microns. Time integrated CP asymmetries vanish at the Upsilon(4S) but can be measured in this case.

The 1st Generation Asymmetric B Factories

PEPII at SLAC
9.0 GeV e^- on 3.1 GeV e^+

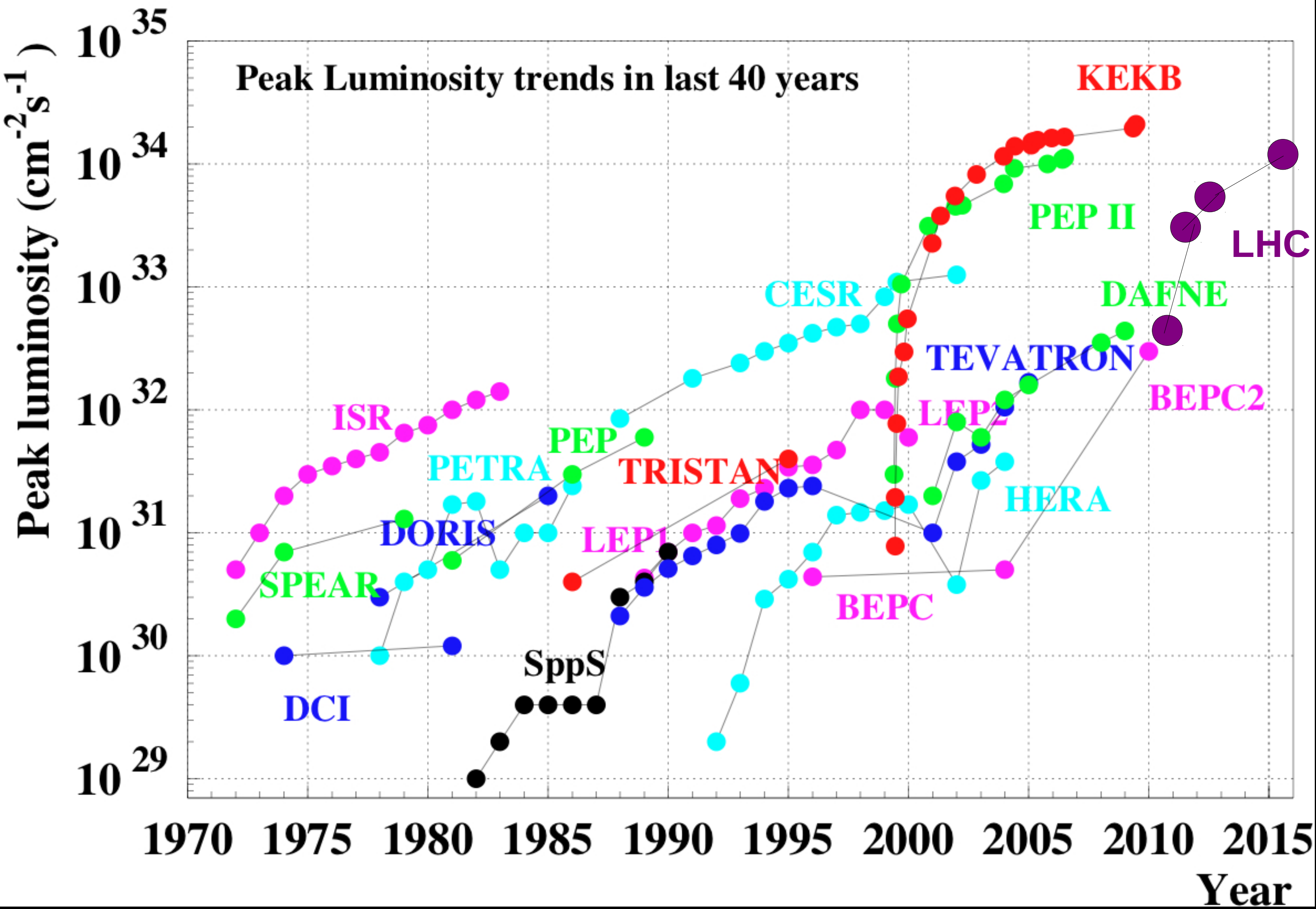
KEKB at KEK
8.0 GeV e^- on 3.5 GeV e^+



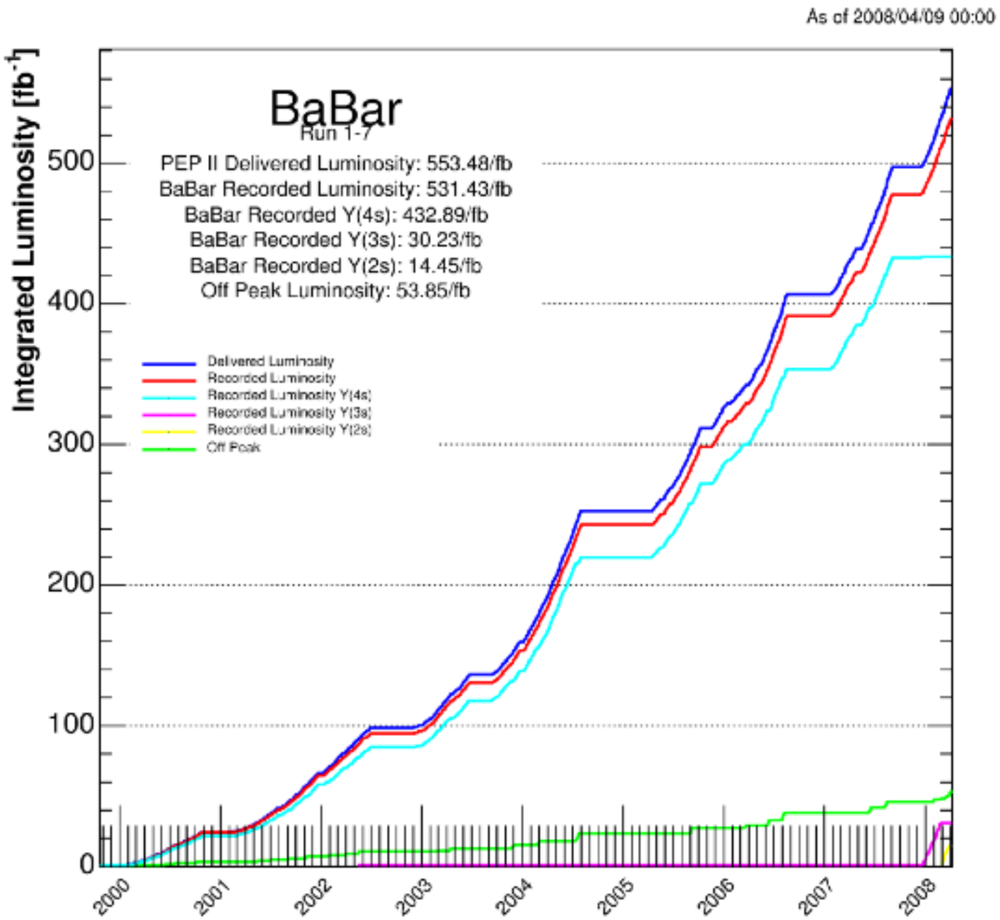


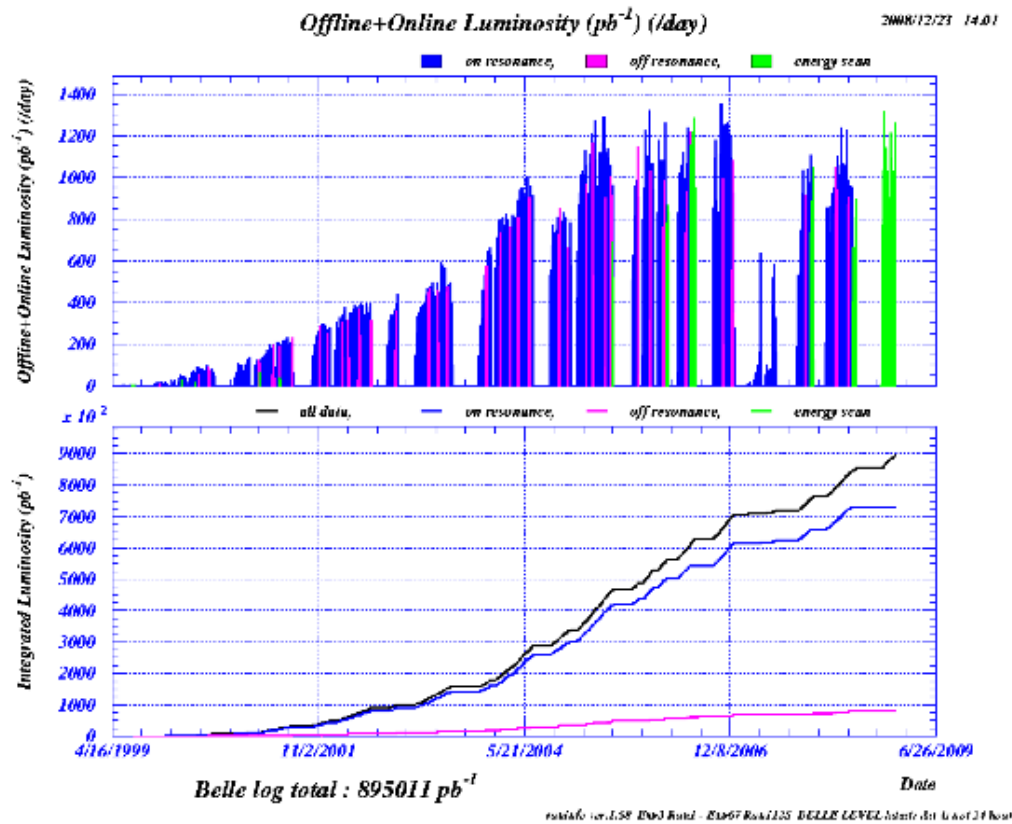
The 1st Generation Asymmetric B Factories

World record luminosities (2)



The 1st Generation Asymmetric B Factories





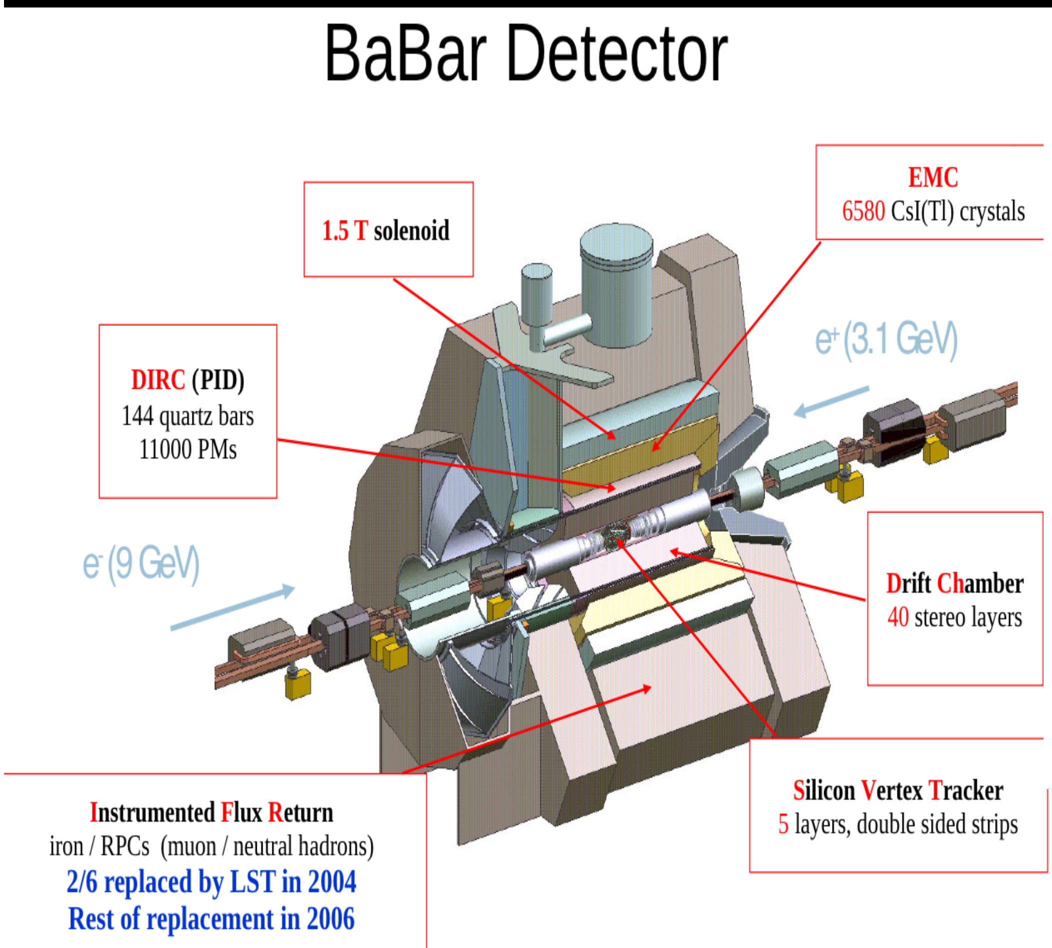
~ 433/fb on Y(4S)

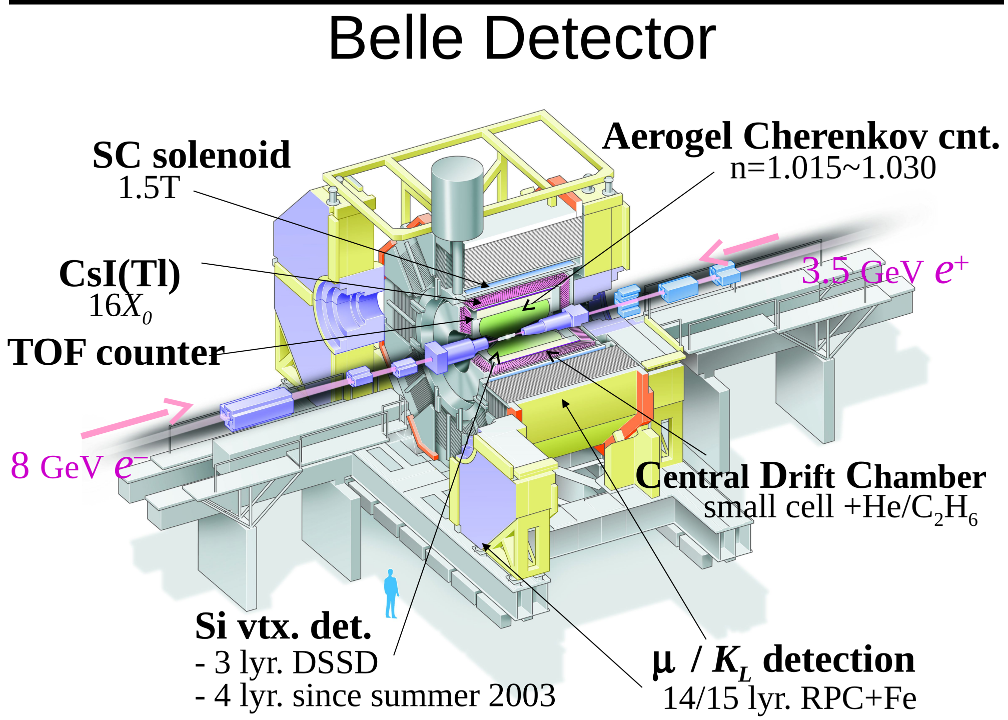
~ 711/fb on Y(4S)

Total over 10^9 $B\bar{B}$ pairs recorded

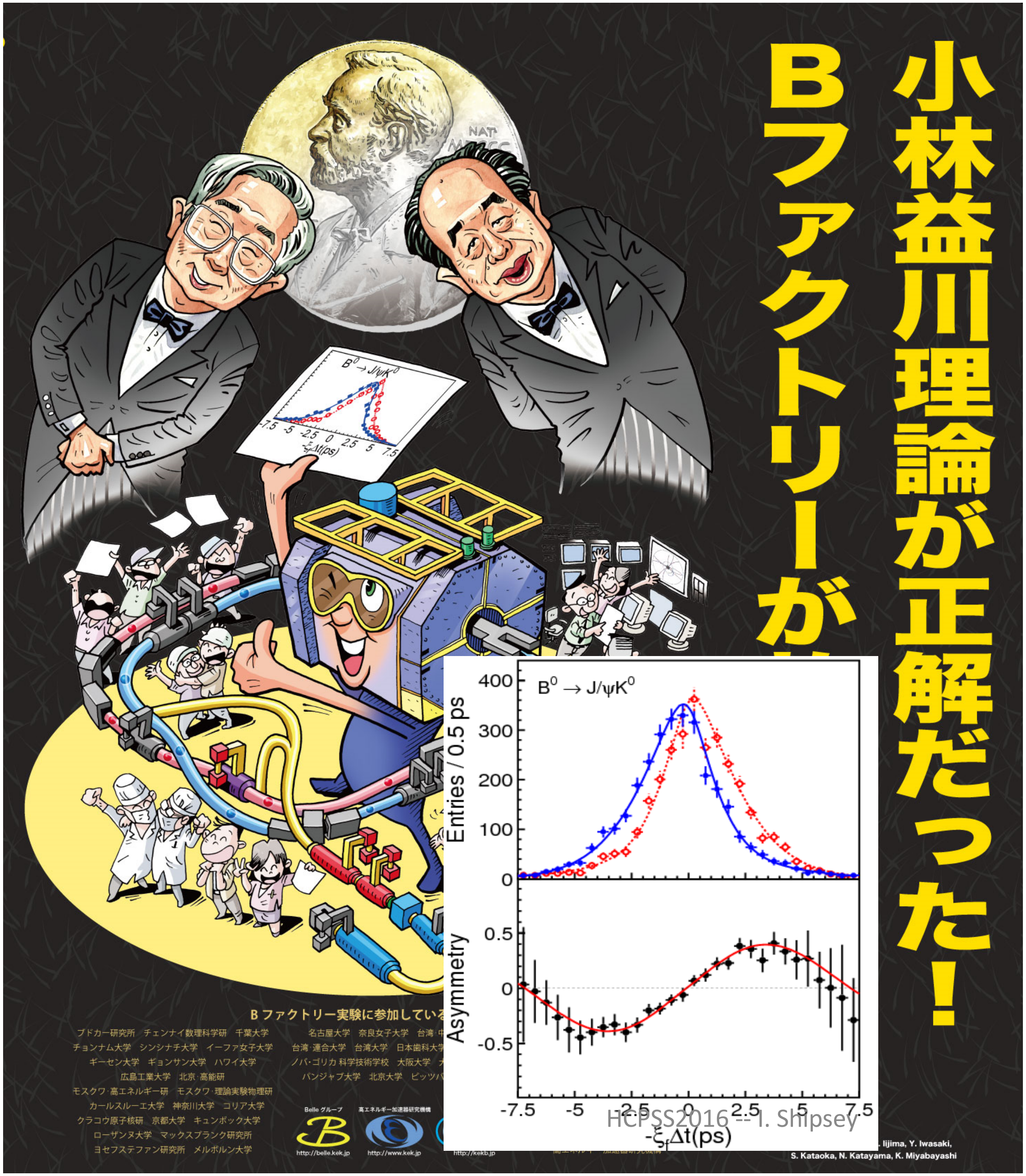
36

The 1st Generation Asymmetric B Factories





LHCb & Super-KEKB/Belle II will be introduced later in the talk



2008:

Critical Role of the B factories in the verification of the KM hypothesis was recognized and cited by the Nobel Foundation

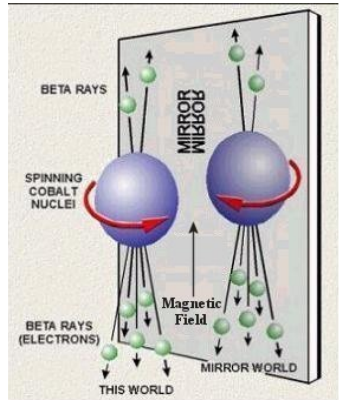
A single irreducible phase in the weak interaction matrix accounts for most of the CPV observed in kaons and B's.

CP violating effects in the B sector are O(1) rather than O(10^{-3}) as in the kaon system.

Nobel Prizes from Surprising Discoveries about
Weak Interactions of Quarks

T.D. Lee

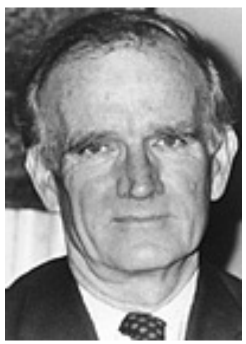
C.N. Yang



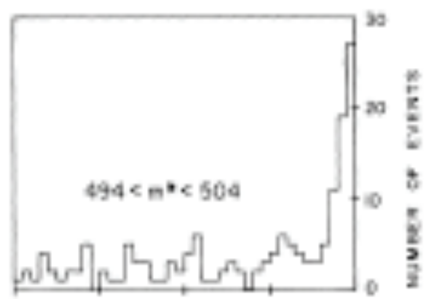
Maximal P violation

1957

J. Cronin



V. Fitch

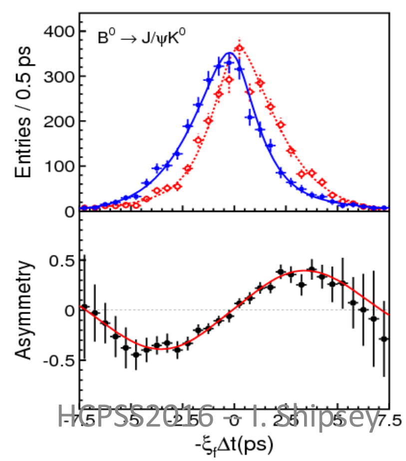


Small CP violation

1980

M. Kobayashi

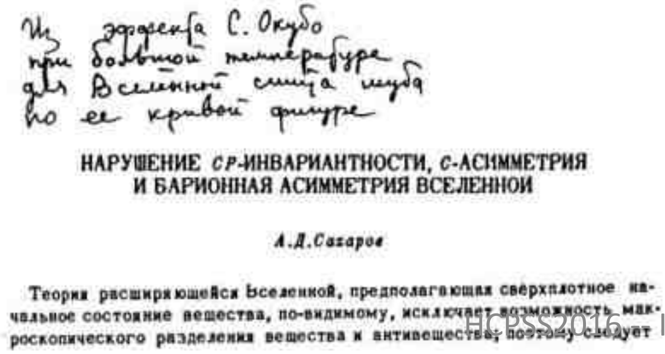
T. Maskawa



O(1) CP violation and 3 generations

2008

Are we done ? (Didn't the B factories accomplish their mission, recognized by the 2008 Nobel Prize in Physics ?)


Из эффекта С. Окубо
При большой температуре
Для Вселенной сшита шуба
По ее кривой фигуре

НАРУШЕНИЕ *CP*-ИНВАРИАНТНОСТИ, *C*-АСИММЕТРИЯ И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сахаров

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует

BAU: KM (Kobayashi-Maskawa) mechanism still short by 10 orders of magnitude !!!

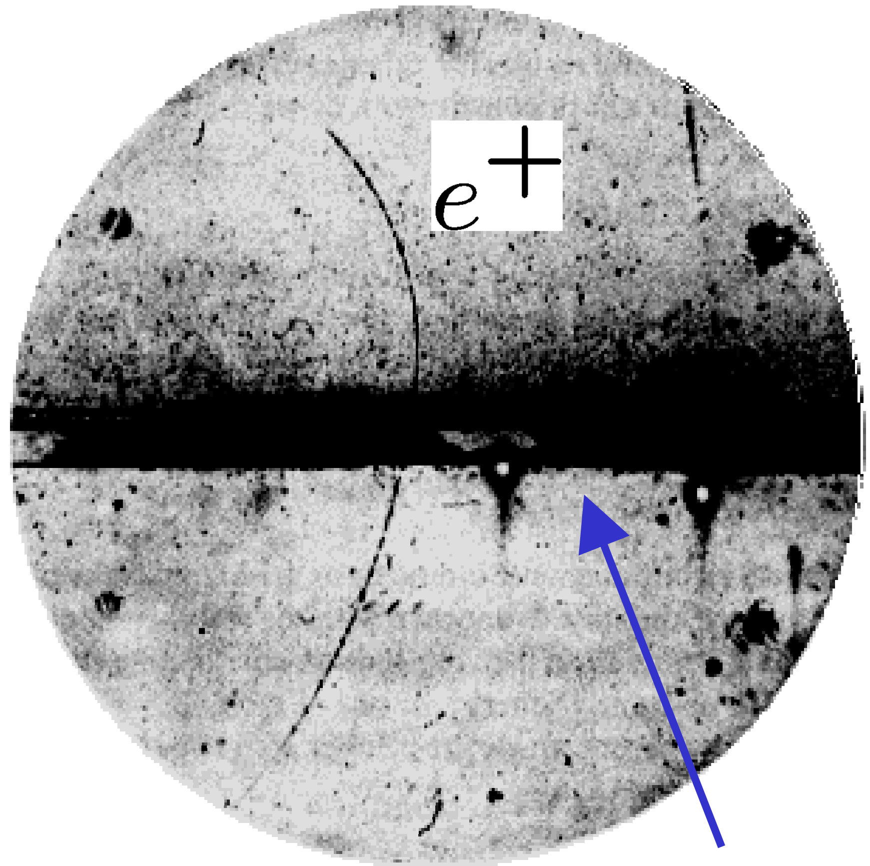
Discovery of antimatter

- **Dirac relativistic wave equation (1928): extra, "negative-energy" solutions. Positron interpretation confirmed by Anderson.**
- **A radical idea: doubling the number of kinds of particles!**

$$e^- \rightarrow e^+$$
$$p(udu) \rightarrow \bar{p}(\bar{u}\bar{d}\bar{u})$$
$$\gamma \rightarrow \gamma$$
$$\nu \rightarrow \bar{\nu} \ (= \nu?)$$

- **Supersymmetry: doubles the number of particles again!**

$$e^- \rightarrow \tilde{e}^-$$



$\otimes \vec{B}$

Pb: 6 mm thick

P.A.M. Dirac, Proc. Roy. Soc. (London), **A117**, 610 (1928); ibid., **A118**, 351 (1928).
C.D. Anderson, Phys. Rev. **43**, 491 (1933).

Parity Violation

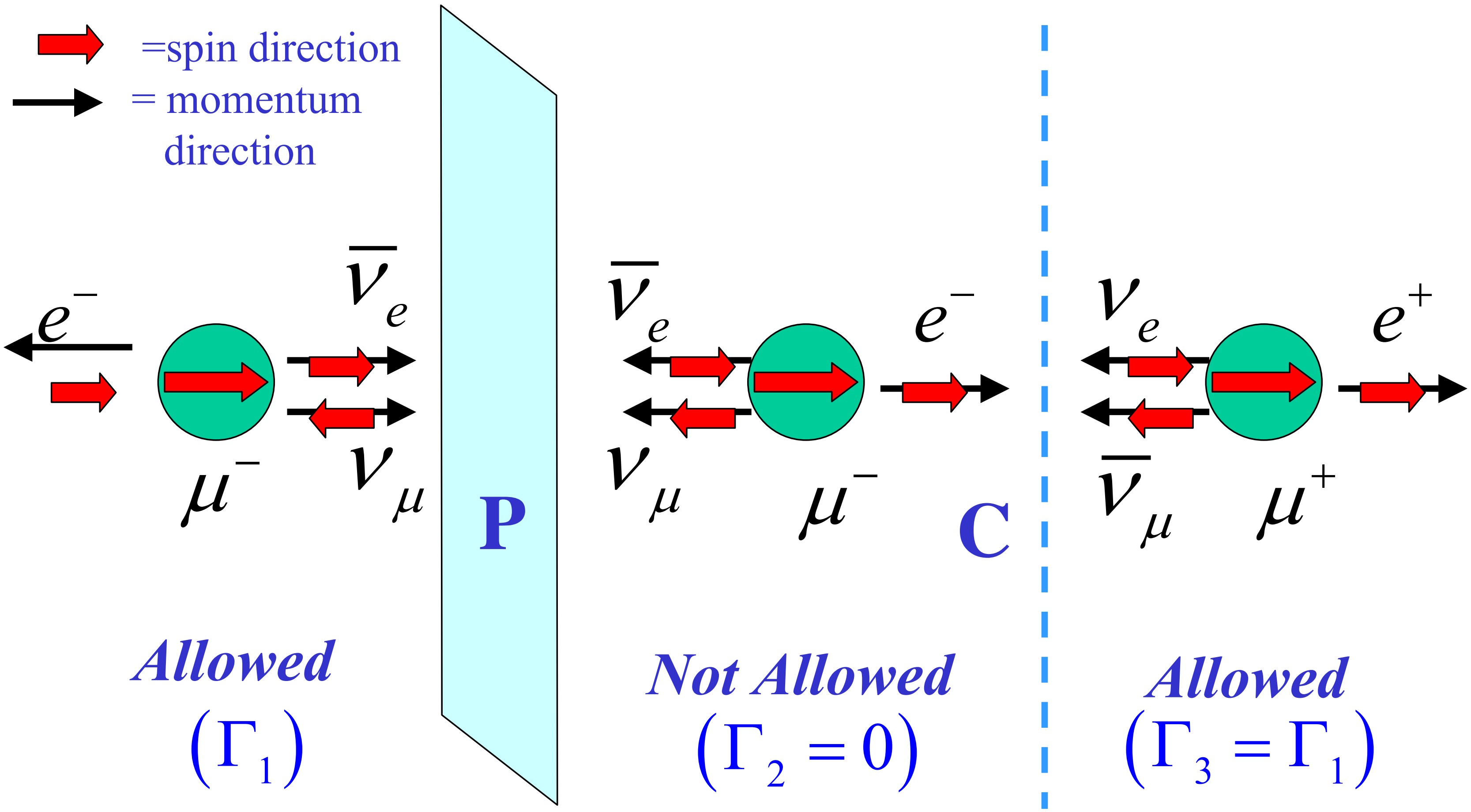
The θ – τ puzzle:

- two strange charged particles discovered
  - the "θ" decaying to $\pi^+\pi^0$
  - the "τ" decaying to $\pi^+\pi^-\pi^+$
- parities of 2π and 3π are opposite, but masses and lifetimes of θ & τ found to be the same

Parity violation discovered 1957 (C.N.Wu et al, then many others, all following T.D.Lee and C.N.Yang)

θ & τ are the same particle: " K^+ "

P and C violation in polarized muon decay



P and C are individually violated <u>maximally</u> in the weak interactions, but combined CP is a good symmetry for most weak processes!

Discovery of CP violation

- CP violation at a tiny level (10^{-3}) was first discovered in 1964 in the decays of neutral kaons (mesons with strange quarks).

$$B(K_L^0 \to \pi^+\pi^-) = (2.0 \pm 0.4) \times 10^{-3} \qquad \eta_{CP}(\pi^+\pi^-, L=0) = +1$$

- Demonstrated that $K_L{}^0$ is not an eigenstate of CP: $[H, CP] \neq 0$

Jim Cronin's Nobel Prize lecture:

"...the effect is telling us that at some tiny level there is a fundamental asymmetry between matter and antimatter, and it is telling us that at some tiny level interactions will show an asymmetry under the reversal of time. We know that improvements in detector technology and quality of accelerators will permit even more sensitive experiments in coming decades. We are hopeful then, that at some epoch, perhaps distant, this cryptic message from nature will be deciphered."

For a fascinating historical perspective on the discovery of CP violation, see J. Cronin @ 50 years of CP violation https://indico.ph.qmul.ac.uk/indico/conferenceDisplay.py?confId=15

Experimental Proposal (1963)

PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXPERIMENT

J. W. Cronin, V. L. Fitch, R. Turlay

(April 10, 1963)

I. INTRODUCTION

The present proposal was largely stimulated by the recent anomalous results of Adair et al., on the coherent regeneration of K^o_1 mesons. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K^o_2 \to \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \to \mu^+ + \mu^-$. In addition, if time permits, the coherent regeneration of K_1's in dense materials can be observed with good accuracy.

II. EXPERIMENTAL APPARATUS

Fortuitously the equipment of this experiment already exists in operating condition. We propose to use the present 30° neutral beam at the A.G.S. along with the di-pion detector and hydrogen target currently being used by Cronin, et al. at the Cosmotron. We further propose that this experiment be done during the forthcoming μ-p scattering experiment on a parasitic basis.

The di-pion apparatus appears ideal for the experiment. The energy resolution is better than 4 Mev in the m^* or the Q value measurement. The origin of the decay can be located to better than 0.1 inches. The 4 Mev resolution is to be compared with the 20 Mev in the Adair bubble chamber. Indeed it is through the greatly improved resolution (coupled with better statistics) that one can expect to get improved limits on the partial decay rates mentioned above.

III. COUNTING RATES

We have made careful Monte Carlo calculations of the counting rates expected. For example, using the 30° beam with the detector 60-ft. from the A.G.S. target we could expect 0.6 decay events per 10^{11} circulating protons if the K_2 went entirely to two pions. This means that one can set a limit of about one in a thousand for the partial rate of $K_2 \to 2\pi$ in one hour of operation. The actual limit is set, of course, by the number of three-body K_2 decays that look like two-body decays. We have not as yet made detailed calculations of this. However, it is certain that the excellent resolution of the apparatus will greatly assist in arriving at a much better limit.

If the experiment of Adair, et al. is correct the rate of coherently regenerated K_1's in hydrogen will be approximately 80/hour. This is to be compared with a total of 20 events in the original experiment. The apparatus has enough angular acceptance to detect incoherently produced K_1's with uniform efficiency to beyond 15°. We emphasize the advantage of being able to remove the regenerating material (e.g., hydrogen) from the neutral beam.

IV. POWER REQUIREMENTS

The power requirements for the experiment are extraordinarily modest. We must power one 18-in. x 36-in. magnet for sweeping the beam of charged particles. The two magnets in the di-pion spectrometer are operated in series and use a total of 20 kw.

⇒ Cronin & Fitch, Nobel Prize, 1980

⇒ 3 generations, Kobayashi & Maskawa, Nobel Prize, 2008

Cosmology: Sakharov's three conditions

A. Sakharov (1967): How to generate an asymmetry between *N*(baryons) and *N*(anti-baryons) in the universe (assuming equal numbers initially)?

1. Baryon-number-violating process
2. Both C and CP violation
3. Departure from thermal equilibrium

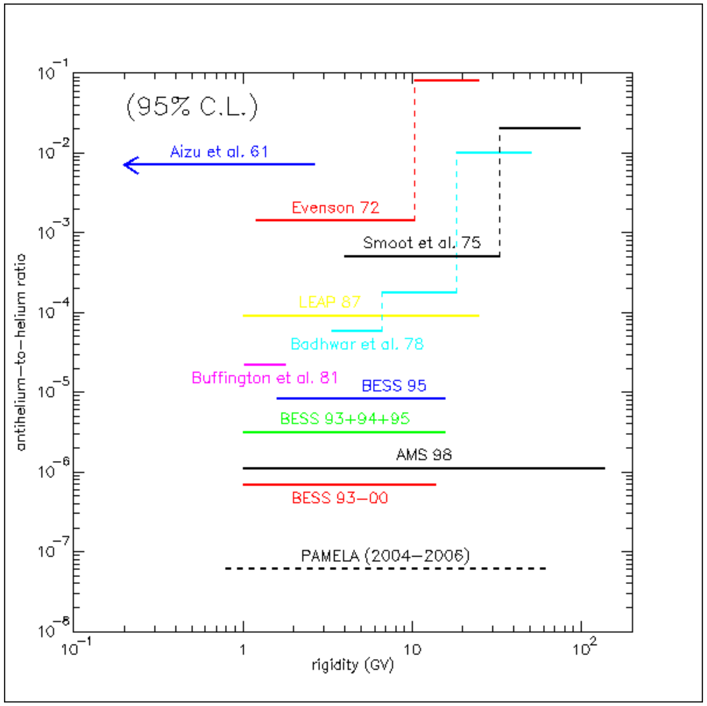
$$\left(N_{\text{bar}} - N_{\text{anti-bar}}\right) \propto \sum_i \left[\Gamma(X \to Y_i) - \Gamma(\bar{X} \to \bar{Y}_i)\right] \cdot \Delta B_i$$

$$\Delta N_B/N_\gamma = (\text{N(baryon)} - \text{N(antibaryon)})/N_\gamma \sim 10^{-10}$$

We appear to owe our existence to some form of CP violation at work in the early universe

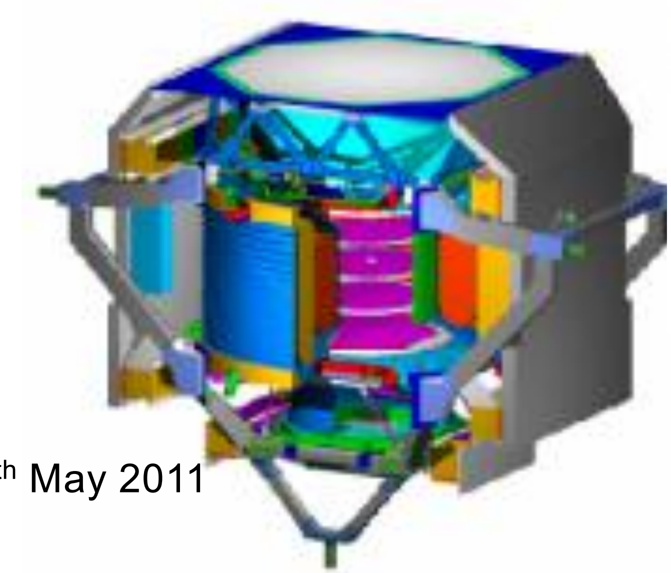
Digression^3: Are there antimatter dominated regions of the Universe?

- Possible signals:
  - Photons produced by matter-antimatter annihilation at domain boundaries – not seen
    - Nearby anti-galaxies ruled out
  - Cosmic rays from anti-stars
    - Best prospect: Anti-^{4}He nuclei
    - Searches ongoing ...



Searches for astrophysical antimatter

Alpha **M**agnetic **S**pectrometer Experiment on board the International Space Station



launched 16th May 2011

Payload for **A**nti**M**atter **E**xploration and **L**ight-nuclei **A**strophysics Experiment on board the Resurs-DK1 satellite

launched 15th June 2006

CKM CP Violation & the BAU

- We can estimate the magnitude of the baryon asymmetry of the Universe caused by KM CP violation

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx \frac{n_B}{n_\gamma} \sim \frac{J \times P_u \times P_d}{M^{12}}$$

N.B. Vanishes for degenerate masses

$$J = \cos(\theta_{12})\cos(\theta_{23})\cos^2(\theta_{13})\sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\sin(\delta)$$
$$P_u = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)$$
$$P_d = (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)$$

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- The Jarlskog parameter J is a parametrization invariant measure of CP violation in the quark sector: J ~ $O(10^{-5})$
- The mass scale M can be taken to be the electroweak scale O(100 GeV)
- This gives an asymmetry $O(10^{-17})$
  - much much below the observed value of $O(10^{-10})$

More CP Violation needed

- Widely accepted that SM CPV insufficient to explain observed baryon asymmetry of the Universe
- To create a larger asymmetry, require
  - new sources of CP violation
  - that occur at high energy scales
- Where might we find it?
  - quark sector: discrepancies with KM predictions
  - lepton sector: CP violation in neutrino oscillations
  - gauge sector, extra dimensions, other new physics: precision measurements of flavour observables are generically sensitive to additions to the Standard Model

CP violation and aliens from outer space

We can use our knowledge of CP violation to determine whether alien civilizations are made of matter or antimatter without having to touch them.

$$A_{CP} = \frac{\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\overline{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)} ; \quad -8\%$$

$b\overline{d}$ $\qquad$ $\overline{b}d$

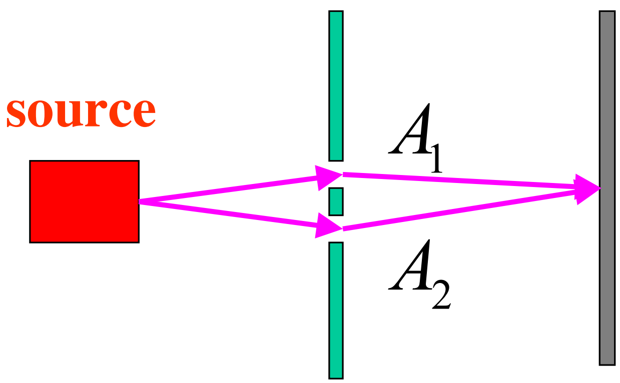
We have these inside of us.

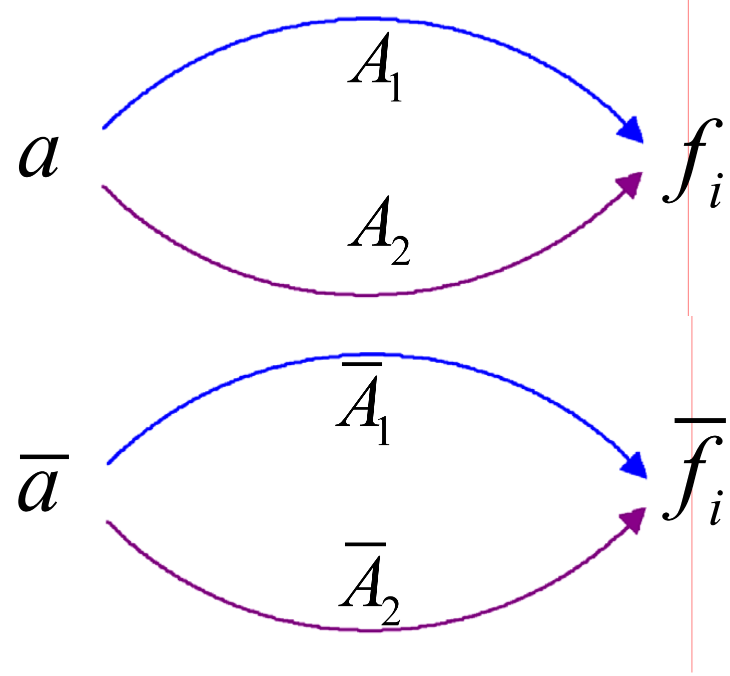
$K^- = \overline{u}s$

$\pi^- = \overline{u}d$

How are CP violating asymmetries produced?

The Standard Model predicts that, if CP violation occurs, it must occur through specific kinds of quantum interference effects..





Double-slit experiment: if the final state does not distinguish between the paths, then the amplitudes A_1 and A_2 interfere!

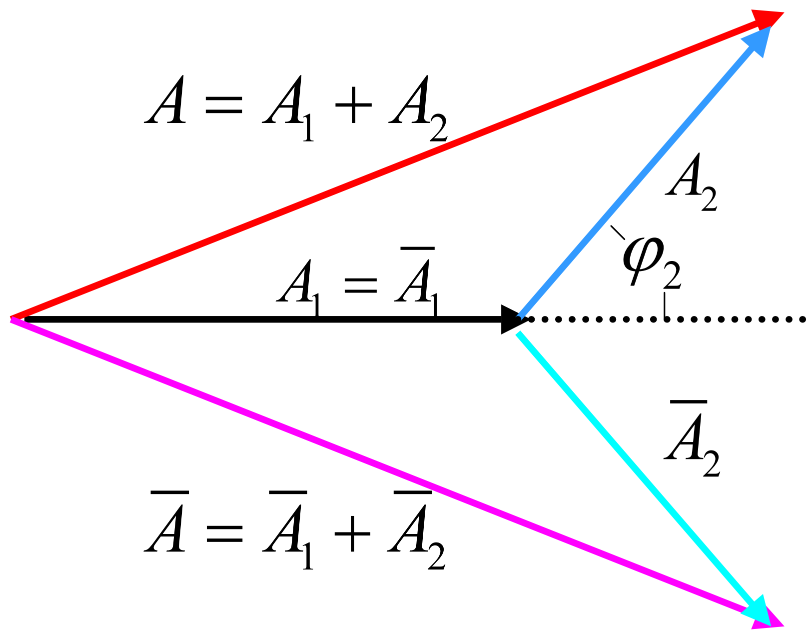
Two amplitudes with a CP-violating relative phase

- Suppose a decay can occur through two processes, with amplitudes A_1 and A_2. Let A_2 have a CP-violating phase ϕ_2.

$$A = A_1 + A_2 e^{i\varphi_2}$$

$$\overline{A} = \overline{A}_1 + \overline{A}_2 e^{-i\varphi_2}$$

No CP asymmetry!



Two amplitudes with CP-conserving & CP-violating phases

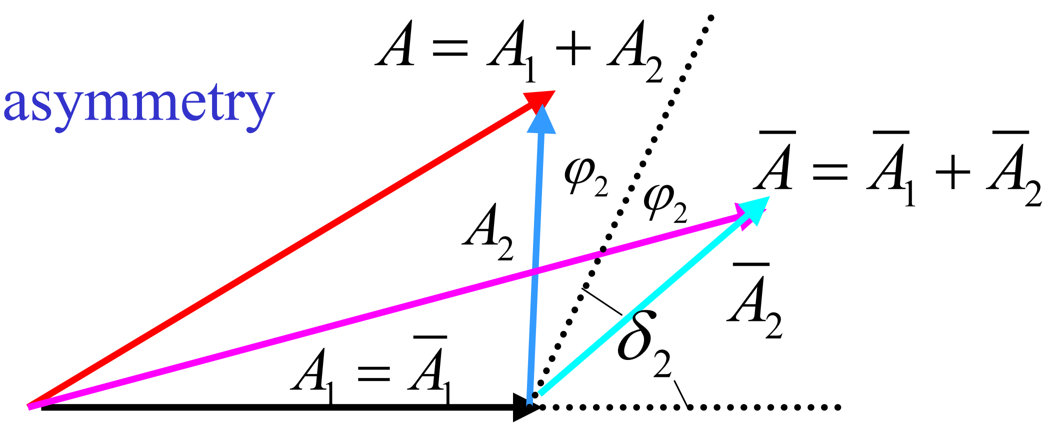
- Next, introduce a *CP-conserving* phase in addition to the *CP-violating* phase.

$$A = A_1 + A_2 e^{i(\varphi_2 + \delta_2)}$$

$$\overline{A} = \overline{A}_1 + \overline{A}_2 e^{i(-\varphi_2 + \delta_2)}$$

- Now have a CP asymmetry

$$|A| \neq |\overline{A}|$$



Three Kinds of *CP* Violation

We have seen that CP violation arises as an interference effect.

- Need at least two interfering amplitudes
- Need relative CP-violating phase
- Need relative CP-conserving phase

A single CP-violating amplitude will not produce observable CP violation!

What breaks the flavor symmetry ?

- In the Standard Model, the vacuum expectation value of the Higgs field breaks the electroweak symmetry
- Fermion masses arise from the Yukawa couplings of the quarks and charged leptons to the Higgs field (taking m_ν=0)
- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks
- Consequently, the only flavour-changing interactions are the charged current weak interactions
  - no flavour-changing neutral currents (GIM mechanism)
  - not generically true in most extensions of the SM
  - flavour-changing processes provide sensitive tests

What causes the difference between matter and anti-matter?

- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks

$$V_{CKM} = U_u U_d^+$$

U matrices from diagonalisation of mass matrices

Quark mixing formalism

- Lagrangian for charged current interactions is

$$L_{cc} = -\frac{g}{\sqrt{2}} J^{\mu}_{cc} W^{\dagger}_{\mu} + h.c.,$$

- where

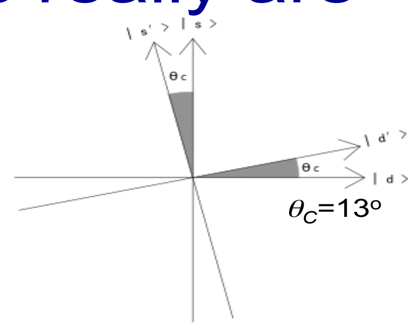
$$J^{\mu}_{cc} = (\bar{\nu}_e,\ \bar{\nu}_\mu,\ \bar{\nu}_\tau)\,\gamma^\mu V_{MNS} \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} + (\bar{u}_L,\ \bar{c}_L,\ \bar{t}_L)\,\gamma^\mu V_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

- Consider the charm quark. It forms a 2nd generation doublet with the strange quark (c,s). Yet it also decays into the d quark which is in the first generation with the u quark (u,d).

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$$

- We say this happens because the s & d quarks are "mixed" i.e. their wave functions really are described by a rotation matrix

$$\begin{bmatrix} d' \\ s' \end{bmatrix} = \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix}$$



θ_C=13°

where the s´ couples to c

What causes the difference between matter and anti-matter?

- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks

$$V_{CKM} = U_u U_d^{+}$$

U matrices from diagonalisation of mass matrices

- It is a 3x3 complex unitary matrix
  - described by 9 (real) parameters
  - 5 can be absorbed as phase differences between the quark fields
  - 3 can be expressed as (Euler) mixing angles
  - the fourth makes the CKM matrix complex (i.e. gives it a phase)
    - weak interaction couplings differ for quarks and antiquarks
    - CP violation

CKM Matrix

The CKM matrix and its mysterious pattern

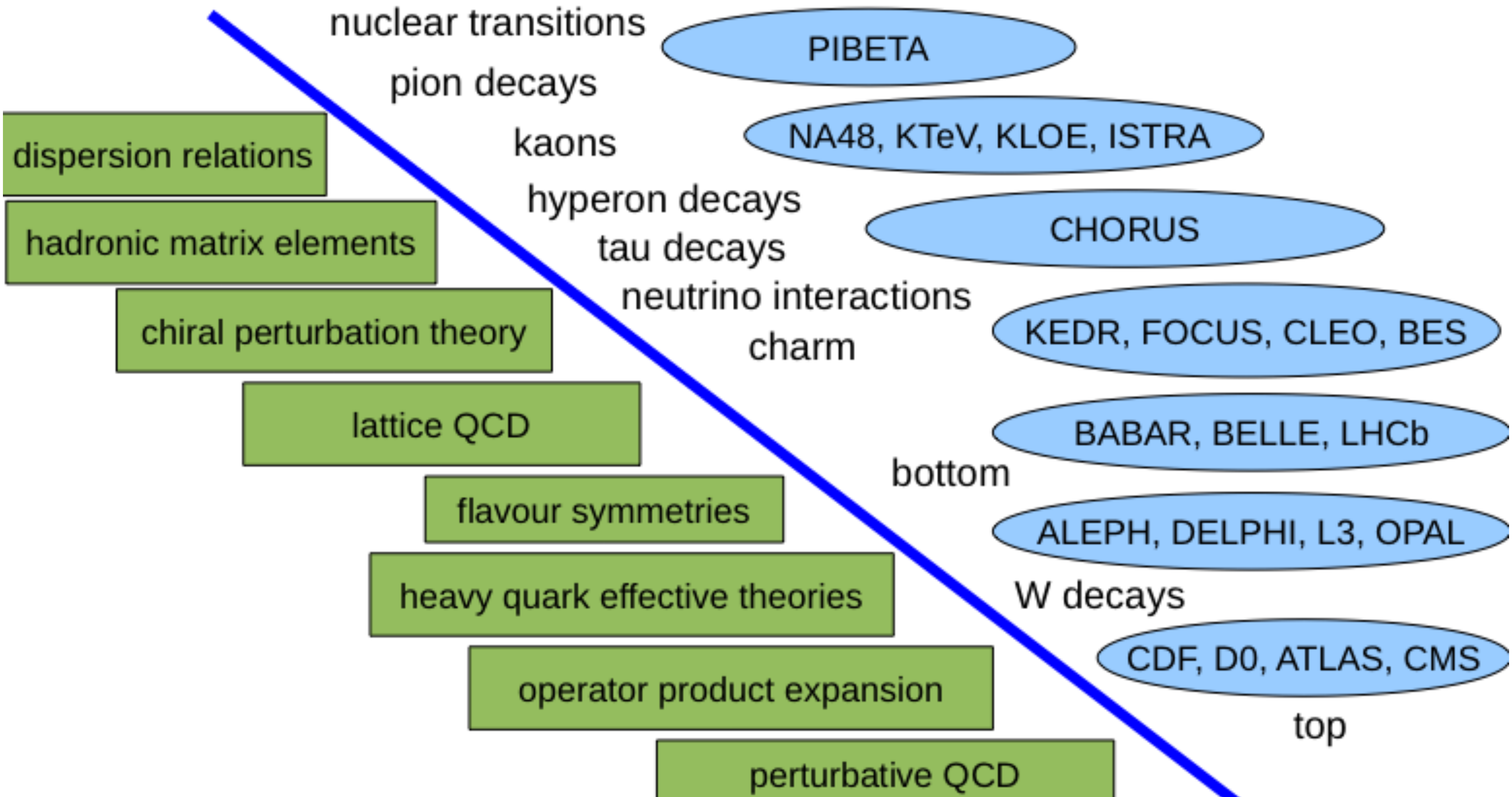
(Wolfenstein parametrization)

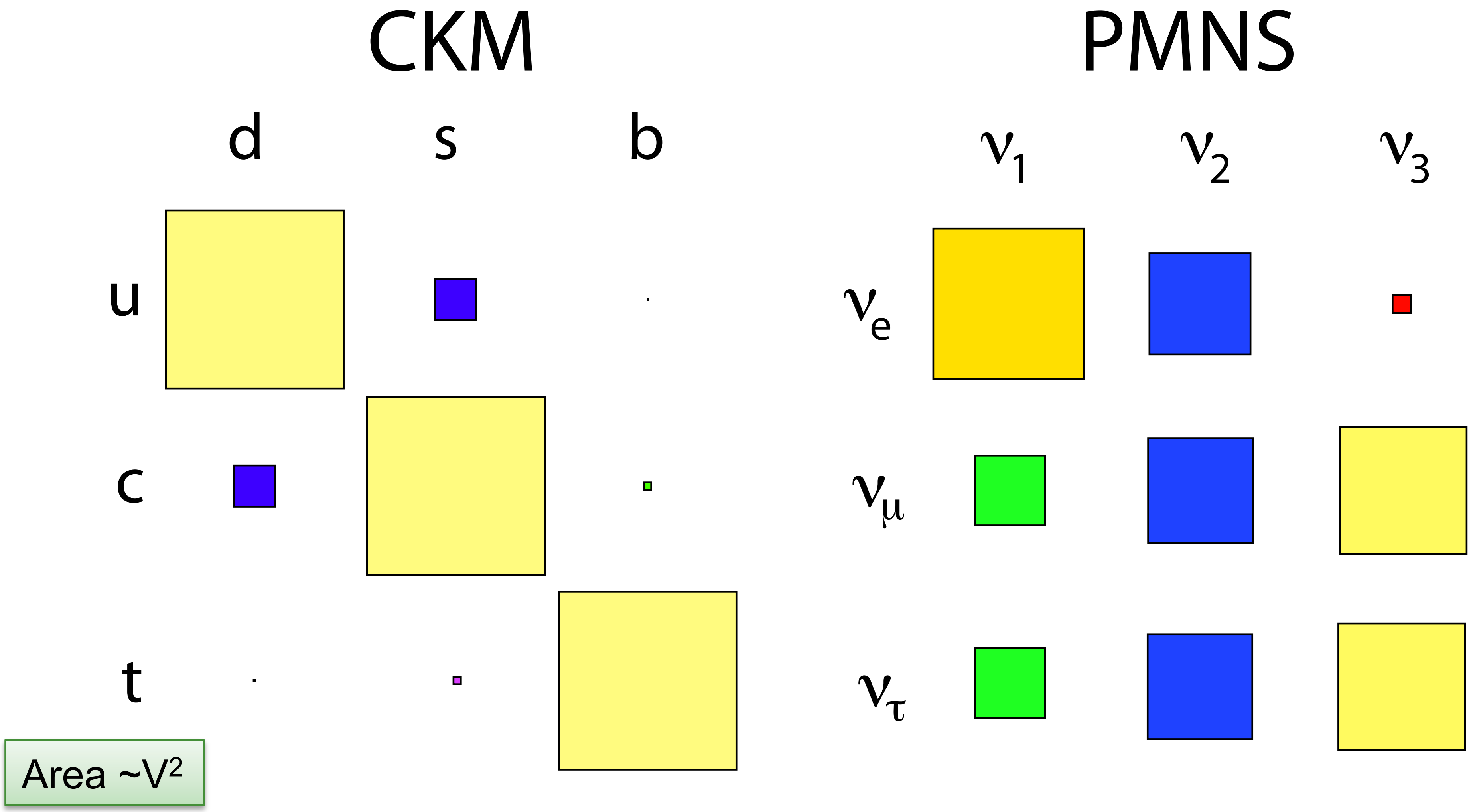
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$$; \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ -0.23 & 0.97 & 0.04 \\ 0.004 & -0.04 & 1 \end{pmatrix} \quad \text{(magnitudes only)}$$

- The SM offers no explanation for this numerical pattern.
- But SM framework is highly predictive:
  - ❑ Unitarity triangle: (Col 1)(Col 3)* =0 etc.
  - ❑ Only 4 independent parameters: A, λ, ρ, η
  - ❑ One independent *CP*-violating phase parameter

Range of CKM Phenomena

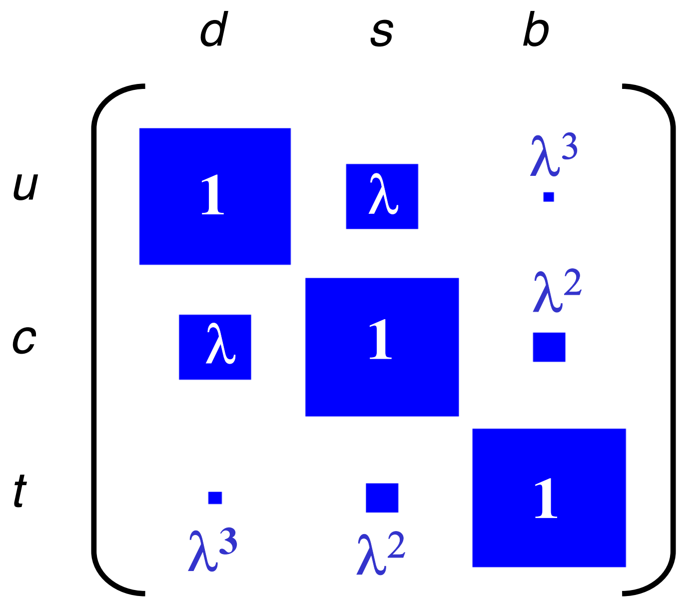




Why these values? Are the two related? Are they related to masses?

CKM Matrix: Simplified picture

Magnitudes of CKM elements



Largest phases in the Wolfenstein parametrization

$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$

Note: all terms in the inner product between columns 1 and 3 are of order λ^3. This produces a unitarity triangle of roughly equal sides.

Unitarity Triangles

Unitarity

[Column i][Column j]*=0

[Row i][Row j]*=0

$$V_{ud}V_{us}^{*}+V_{cd}V_{cs}^{*}+V_{td}V_{ts}^{*}=0$$

$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0$$

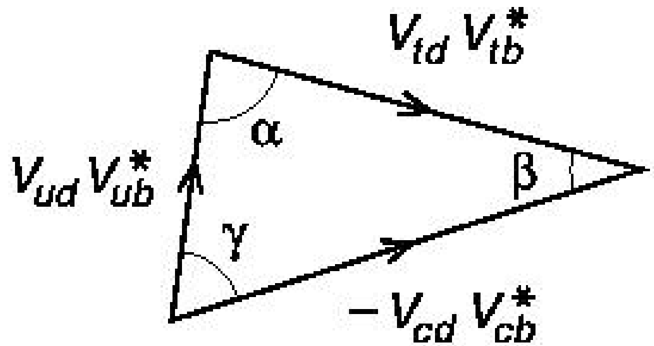
$$V_{us}V_{ub}^{*}+V_{cs}V_{cb}^{*}+V_{ts}V_{tb}^{*}=0$$

$$O(\lambda)+O(\lambda)+O(\lambda^{5})=0$$

$$O(\lambda^{3})+O(\lambda^{3})+O(\lambda^{3})=0$$

$$O(\lambda^{4})+O(\lambda^{2})+O(\lambda^{2})=0$$

(Col 1)(Col 3)* =0



Overall orientation of the triangle has no physical significance.

Fat unitarity triangle
➔large angles
➔large CP asymmetry
But only certain decays have interfering amps!

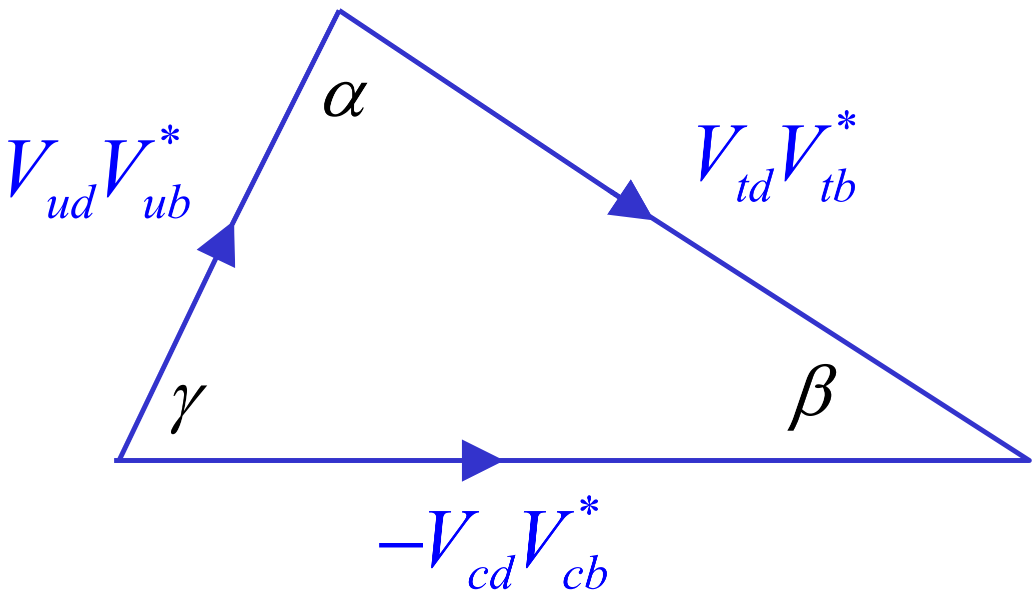
Consider two complex numbers z_1 and z_2.

$$z_1 = |z_1| e^{i\theta_1} \qquad z_2 = |z_2| e^{i\theta_2} \quad \Rightarrow \quad \frac{z_2/|z_2|}{z_1/|z_1|} = e^{i(\theta_2-\theta_1)} \qquad \arg\left(\frac{z_2}{z_1}\right) = \theta_2 - \theta_1$$

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

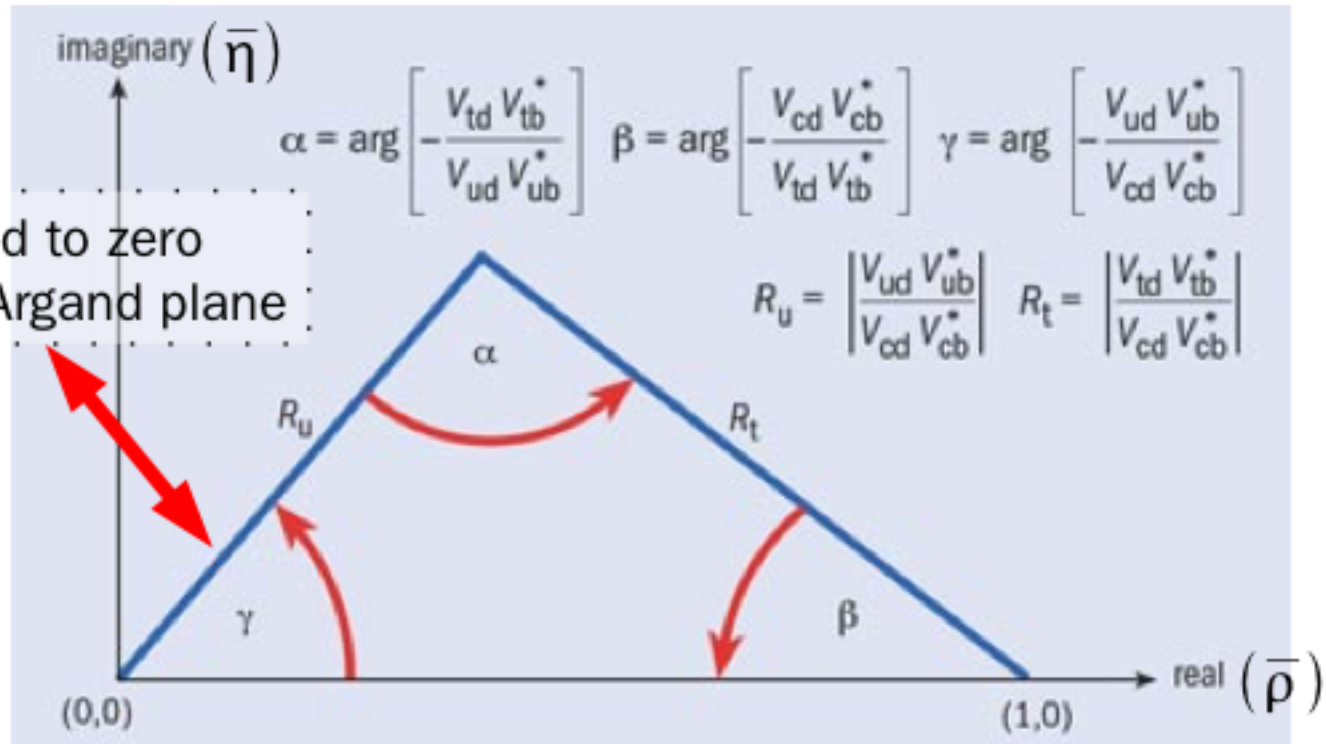
$$\gamma = \arg\left(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



The Unitarity Triangle

$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0$$

Three complex numbers add to zero
⇒ triangle in Argand plane

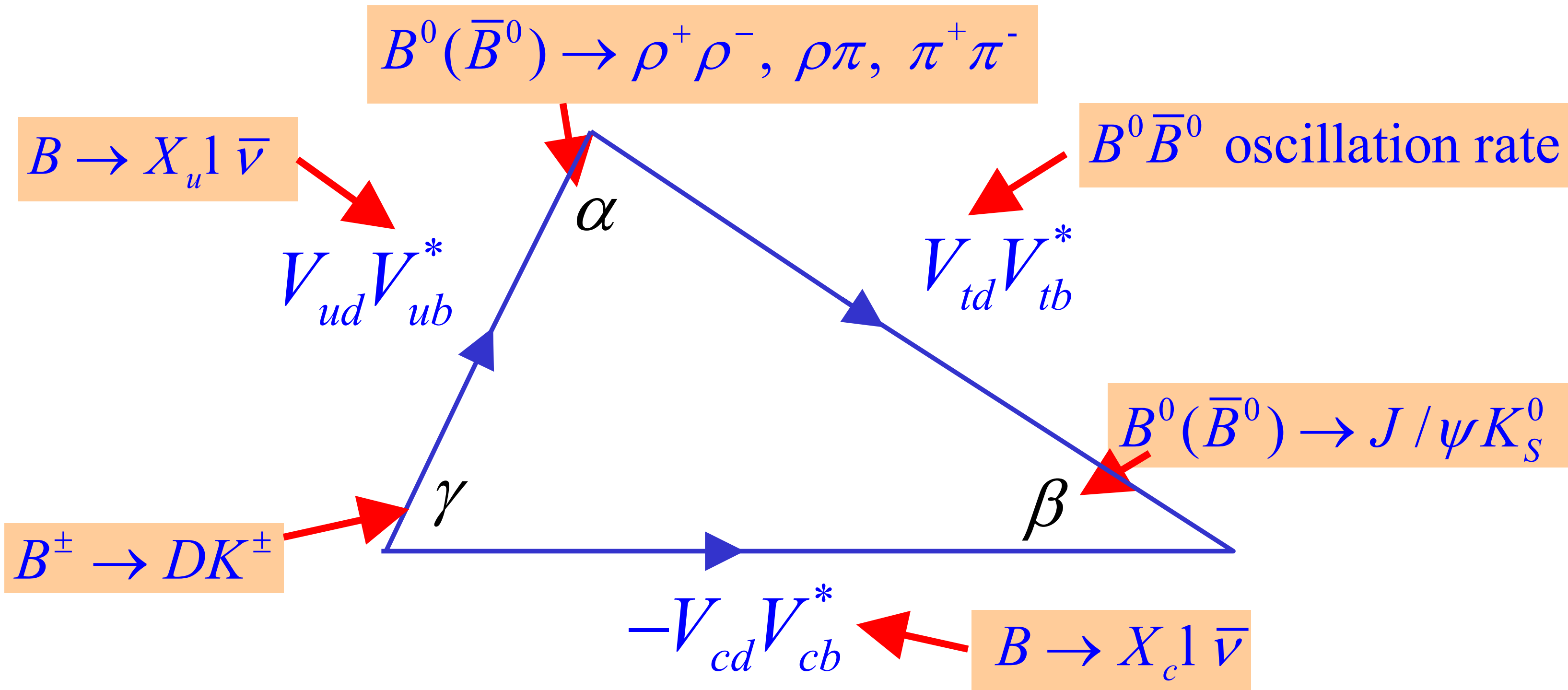


Axes are $\overline{\rho}$ and $\overline{\eta}$ where

$$\overline{\rho}+i\overline{\eta} \equiv -\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}$$

$$\rho+i\eta = \frac{\sqrt{1-A^2\lambda^4}(\overline{\rho}+i\overline{\eta})}{\sqrt{1-\lambda^2}\left[1-A^2\lambda^4(\overline{\rho}+i\overline{\eta})\right]}$$

Standard Model predicts that ALL measurements of *W*-mediated quark processes must be consistent with the CKM framework.



- **Angles** of triangle: measure from CP **asymmetries** in *B* decay
- **Sides** of triangle: measure **rates** for b→ulν, $B^0\overline{B}^0$ mixing
- **Other constraints** in ρ,η plane from CP violation in *K* decay

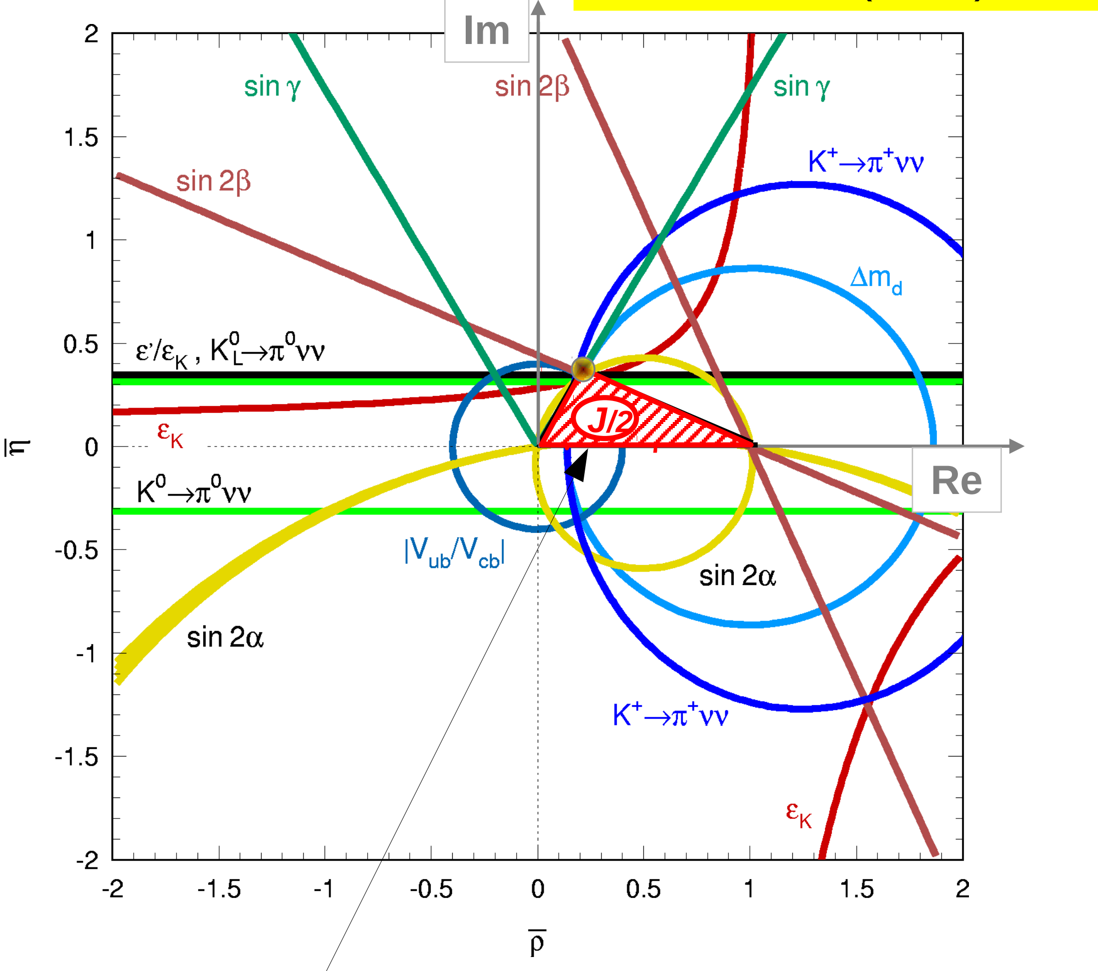
CKM constraints on unitarity plane

In the Standard Model the KM phase is the sole origin of CP violation

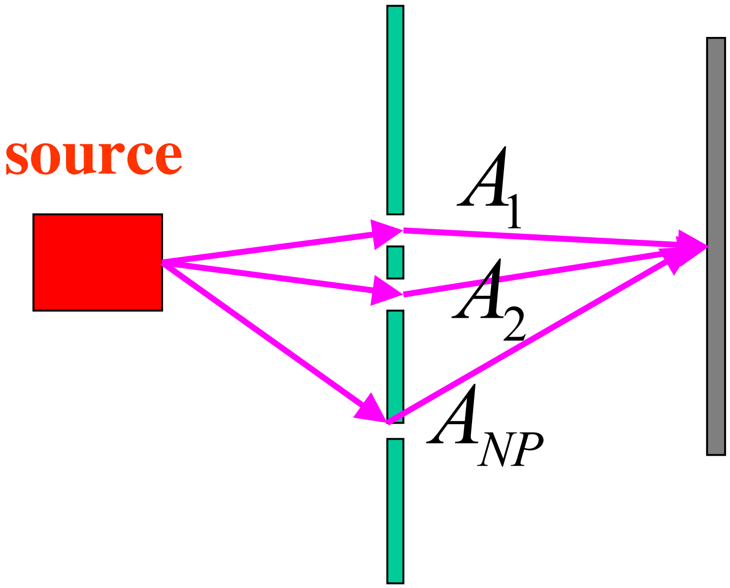
Hence:

all measurements must agree on the position of the apex of the Unitarity Triangle

(Illustration shown assumes no experimental or theoretical uncertainties)



Area of (all of) the Unitarity Triangle(s) is given by the Jarlskog invariant



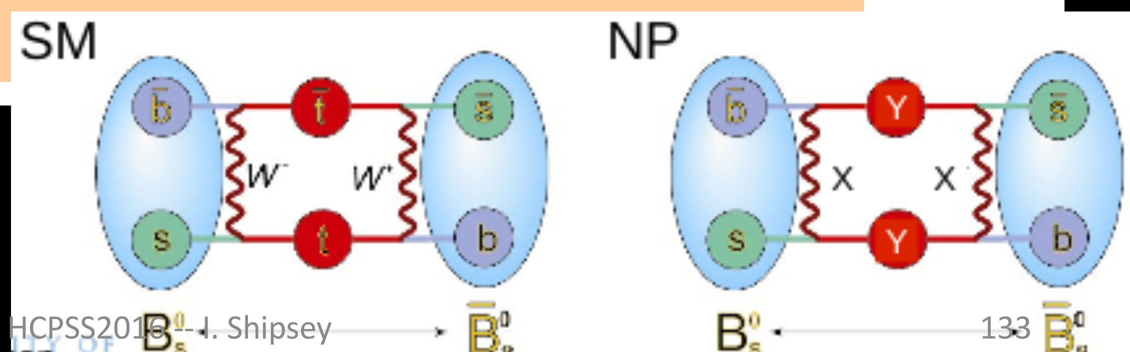
Study processes in which there can be <u>extra amplitudes</u> arising from new physics (NP).

Must be sure that all SM amplitudes are fully understood.

A_{NP} from physics at high mass scales is small

$\Rightarrow$ want to use processes in which $A_{1,2}$ are small

Hope to find a departure from the expected (SM) pattern of CP-violating asymmetries!



If history is our guide

New physics can show up at the intensity/precision frontier before the energy frontier

The power of quantum loops:

Beta-decay @ MeV energies informs us of a virtual mediator at 80 GeV (W)

GIM mechanism before the discovery of charm

CP violation/ CKM before the discovery of beauty and top

Neutral currents before the discovery of Z

The GIM Mechanism

$K^+ \rightarrow \mu^+\nu_\mu$ & $\pi^0\mu^+\nu_\mu$ so why not $K^0 \rightarrow \mu^+\mu^-$ & $\pi^0\mu^+\mu^-$?

- GIM (Glashow, Iliopoulos, Maiani) mechanism (1970)

  no tree level flavour changing neutral currents

  suppression of FCNC via loops

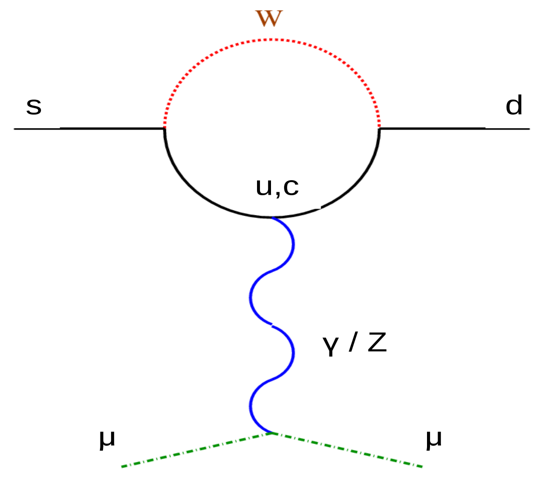
- Requires that quarks come in pairs (predicting charm)

$$A = V_{us}V_{ud}^* f(m_u/m_W) + V_{cs}V_{cd}^* f(m_c/m_W)$$

2x2 unitarity: $V_{us}V_{ud}^* + V_{cs}V_{cd}^* = 0$

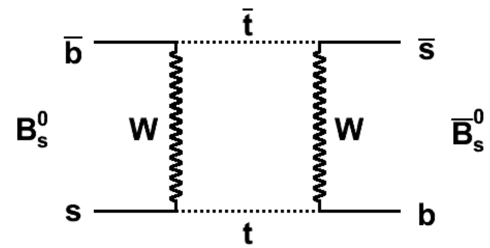
$m_u, m_c < m_W \therefore f(m_u/m_W) \sim f(m_c/m_W) \therefore A \sim 0$

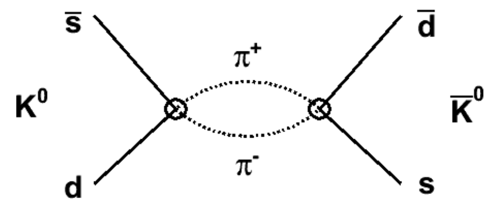
kaon mixing $\Rightarrow$ predict m_c



Neutral meson oscillations

- We have flavour eigenstates M^0 and $\bar{M}^0$
  - M^0 can be K^0 ($\bar{s}d$), D^0 ($c\bar{u}$), B_d^0 ($\bar{b}d$) or B_s^0 ($\bar{b}s$)
- These can mix into each other
  - via short-distance or long-distance processes





- Time-dependent Schrödinger eqn.

$$i\frac{\partial}{\partial t}\begin{pmatrix} M^0 \\ \bar{M}^0 \end{pmatrix} = H\begin{pmatrix} M^0 \\ \bar{M}^0 \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} M^0 \\ \bar{M}^0 \end{pmatrix}$$

  - H is Hamiltonian; M and Γ are 2x2 Hermitian matrices
- CPT theorem: $M_{11} = M_{22}$ & $\Gamma_{11} = \Gamma_{22}$

particle and antiparticle have equal masses and lifetimes

Solving the Schrödinger equation

- Physical states: eigenstates of effective Hamiltonian

$$M_{S,L} = p\, M^0 \pm q\, \bar{M}^0$$

p & q complex coefficients that satisfy $|p|^2 + |q|^2 = 1$

label as either S,L (short-, long-lived) or L,H (light, heavy) depending on values of Δm & ΔΓ (labels 1,2 usually reserved for CP eigenstates)

  - CP conserved if physical states = CP eigenstates ($|q/p| = 1$)

- Eigenvalues

$$\lambda_{S,L} = m_{S,L} - \tfrac{1}{2}i\Gamma_{S,L} = (M_{11} - \tfrac{1}{2}i\Gamma_{11}) \pm (q/p)(M_{12} - \tfrac{1}{2}i\Gamma_{12})$$

$$\Delta m = m_L - m_S \qquad \Delta\Gamma = \Gamma_S - \Gamma_L$$

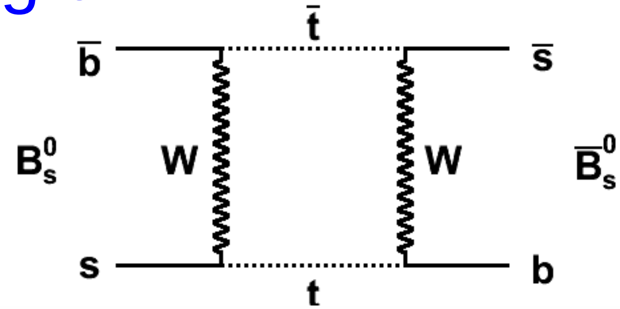
$$(\Delta m)^2 - \tfrac{1}{4}(\Delta\Gamma)^2 = 4(|M_{12}|^2 + \tfrac{1}{4}|\Gamma_{12}|^2)$$

$$\Delta m \Delta\Gamma = 4\mathrm{Re}(M_{12}\Gamma_{12}^*)$$

$$(q/p)^2 = (M_{12}^* - \tfrac{1}{2}i\Gamma_{12}^*)/(M_{12} - \tfrac{1}{2}i\Gamma_{12})$$

Simple picture of mixing parameters

- Δm: value depends on rate of mixing diagram



  - together with various other constants ...

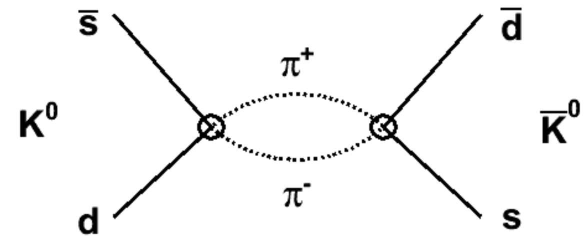
$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{tb}|^2 |V_{td}|^2$$

  - that can be made to cancel in ratios

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

remaining factors can be obtained from lattice QCD calculations

- ΔΓ: value depends on widths of decays into common final states (CP-eigenstates)



  - large for K^0, small for D^0 & B_d^0

- $q/p \approx 1$ if $\arg(\Gamma_{12}/M_{12}) \approx 0$ ($|q/p| \approx 1$ if $M_{12} << \Gamma_{12}$ or $M_{12} >> \Gamma_{12}$)

  - CP violation in mixing when $|q/p| \neq 1$

$$\left(\epsilon = \frac{p-q}{p+q} \neq 0\right)$$

Simple picture of mixing parameters

	Δm $(x = \Delta m/\Gamma)$	$\Delta\Gamma$ $(y = \Delta\Gamma/(2\Gamma)))$	$\lvert q/p \rvert$ $(a_{sl} \approx 1 - \lvert q/p \rvert^2)$
K^0	large ~ 500	$\sim$ maximal ~ 1	small $(3.32 \pm 0.06) \times 10^{-3}$
D^0	small $(0.63 \pm 0.19)\%$	small $(0.75 \pm 0.12)\%$	small $0.52^{+0.19}_{-0.24}$
B^0	medium 0.770 ± 0.008	small 0.008 ± 0.009	small -0.0003 ± 0.0021
B_s^0	large 26.49 ± 0.29	medium 0.075 ± 0.010	small -0.0109 ± 0.0040

well-measured only recently (see later)

More precise measurements needed (SM prediction well known)

Constraints on NP from mixing

- All measurements of Δm & $\Delta\Gamma$ consistent with SM
  - K^0, D^0, $B_d^{\ 0}$ and $B_s^{\ 0}$
- This means $|A_{NP}| < |A_{SM}|$ where $\mathcal{A}_{\rm SM}^{\Delta F=2} \approx \frac{G_F^2 m_t^2}{16\pi^2} (V_{ti}^* V_{tj})^2 \times \langle \overline{M} | (\overline{Q}_{Li}\gamma^\mu Q_{Lj})^2 | M \rangle \times F\left(\frac{M_W^2}{m_t^2}\right)$
- Express NP as perturbation to the SM Lagrangian
  - couplings c_i and scale $\Lambda > m_W$ $\quad \mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields})$
- For example, SM like (left-handed) operators $\Delta\mathcal{L}^{\Delta F=2} = \sum_{i\neq j} \frac{c_{ij}}{\Lambda^2} (\overline{Q}_{Li}\gamma^\mu Q_{Lj})^2$

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Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Bounds on Λ in TeV ($c_{ij}=1$) Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Bounds on c_{ij} ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

Constraints on NP from mixing

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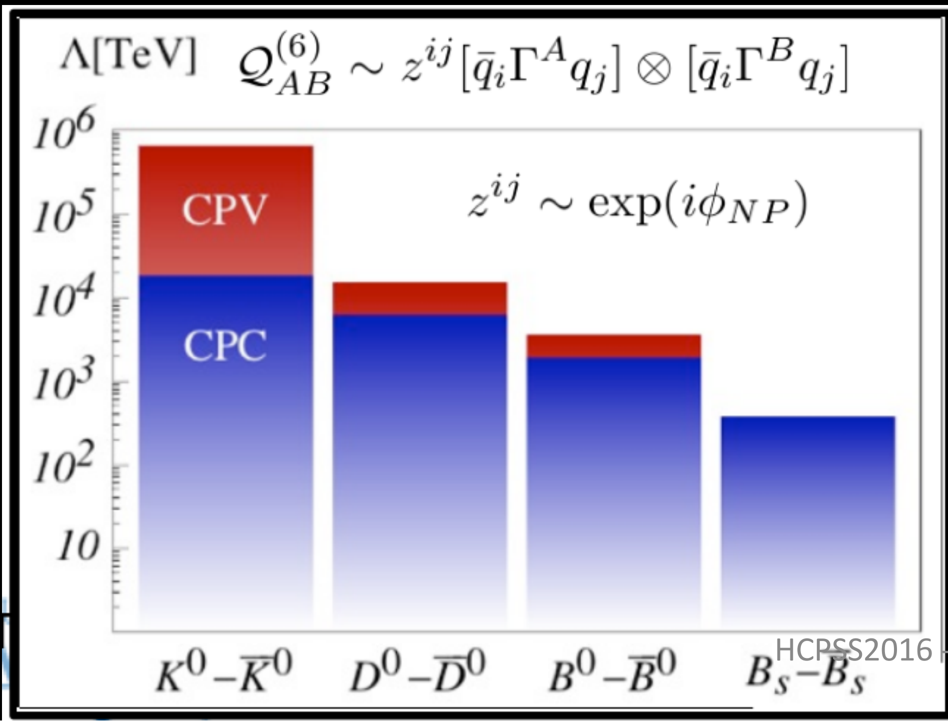
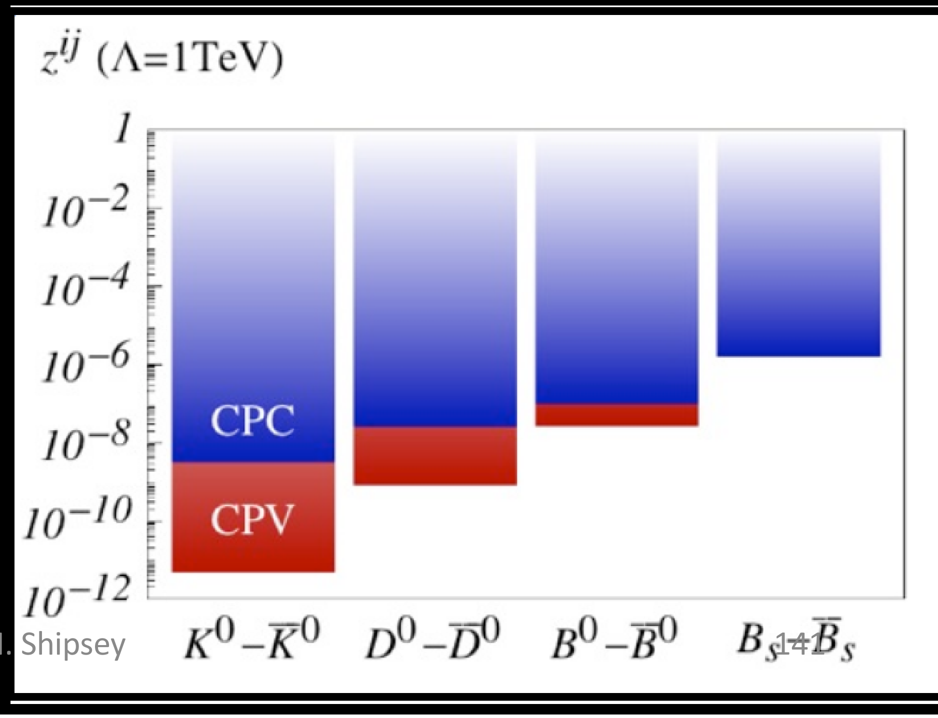
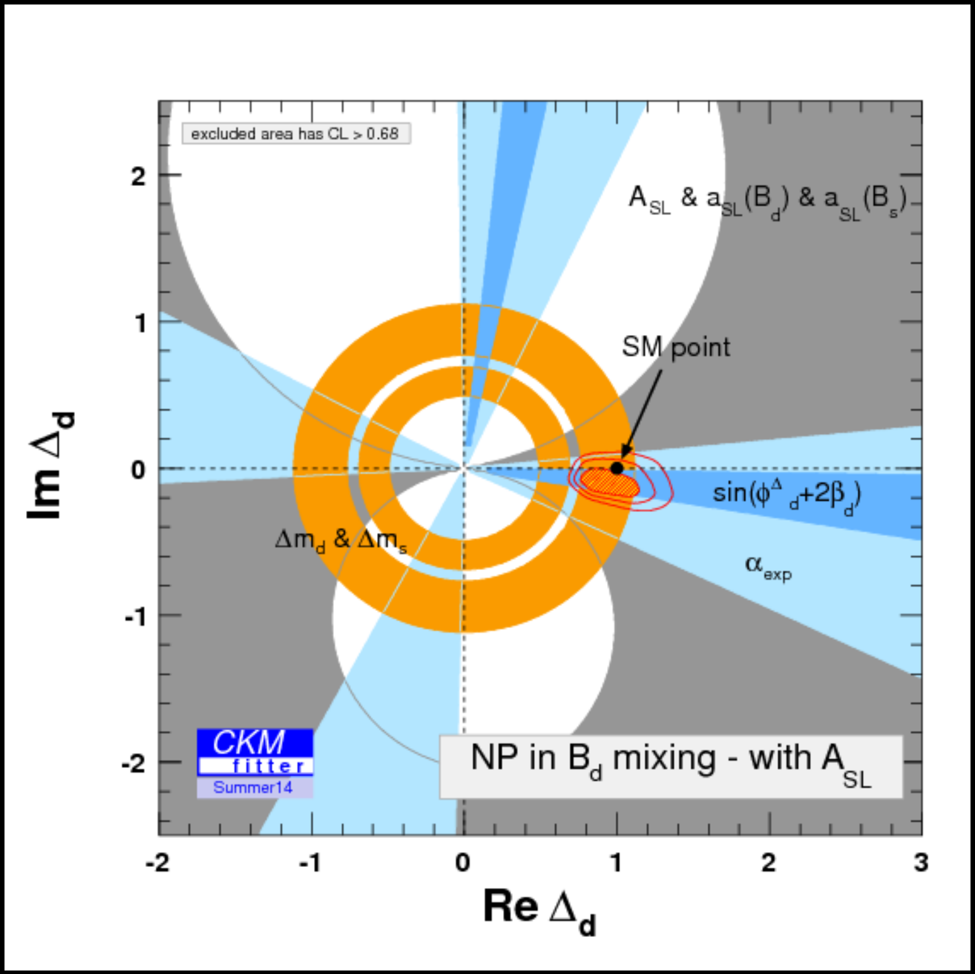
Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Bounds on Λ in TeV ($c_{ij}=1$) Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Bounds on c_{ij} ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\,d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\,u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\,d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\,s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

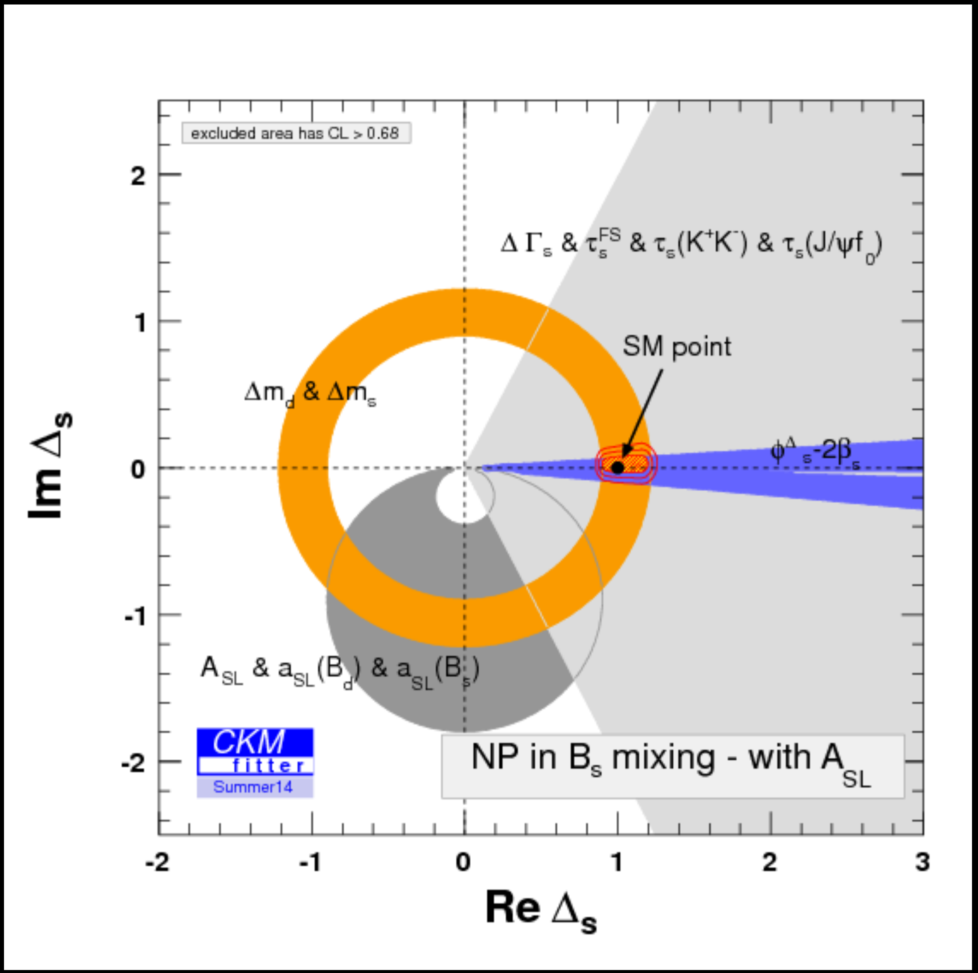




Similar story in pictures

including more inputs (& more up-to-date)





arXiv:1501.05013

Phys.Rev. D91 (2015) 073007

New Physics Flavour Problem

- Limits on NP scale at least 100 TeV for generic couplings
  - model-independent argument, also for rare decays
- But we need NP at the TeV scale to solve the hierarchy problem (and to provide DM candidate, etc.)
- So we need NP flavour-changing couplings to be small
- Why?
  - minimal flavour violation?
    - perfect alignment of flavour violation in NP and SM
  - some other approximate symmetry?
  - flavour structure tells us about physics at very high scales
- There are still important observables that are not yet well-tested

NPB 645 (2002) 155

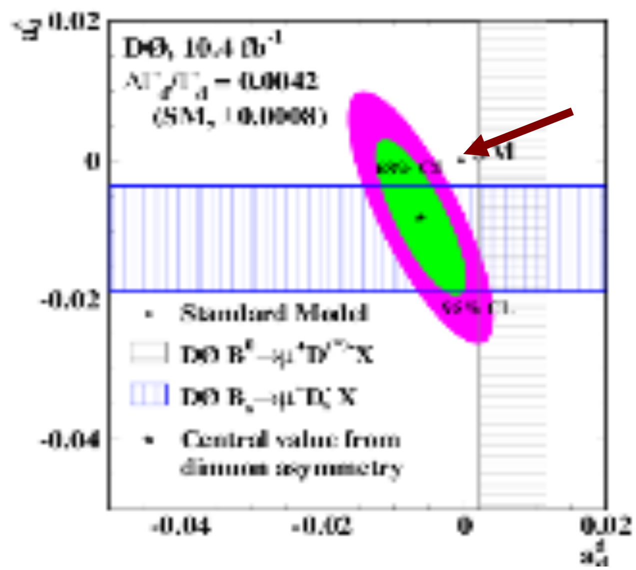
Like-sign dimuon asymmetry

- Semileptonic decays are flavour-specific
- B mesons are produced in $B\bar{B}$ pairs
- Like-sign leptons arise if one of $B\bar{B}$ pair mixes before decaying
- If no CP violation in mixing N(++) = N(– –)

- Inclusive measurement ↔ contributions from both B_d^0 and B_s^0
  - relative contributions from production rates, mixing probabilities & SL decay rates

PRD 89 (2014) 012002

$$A_{SL} = (1 - |q/p|^4)/(1+|q/p|^4)$$

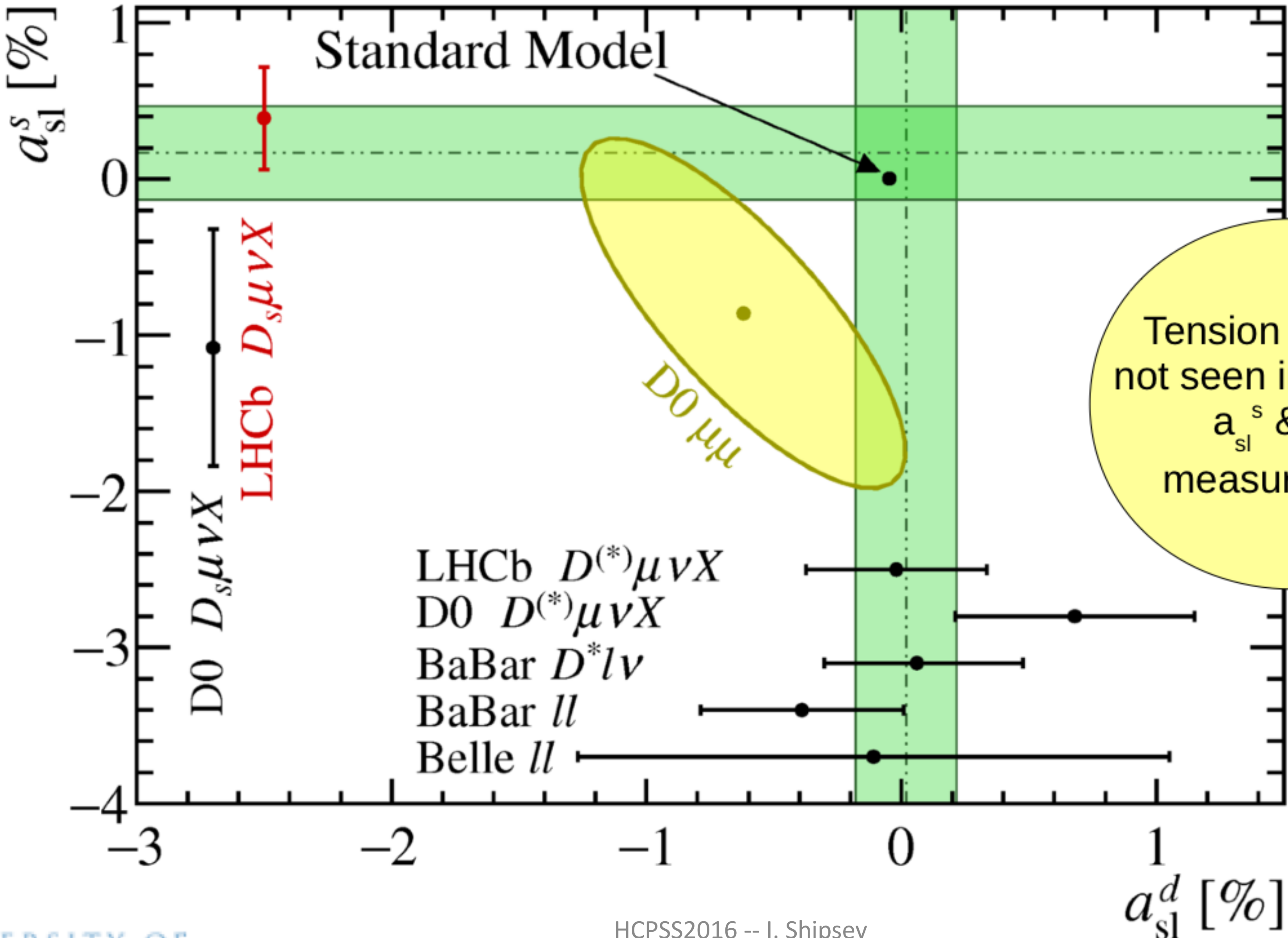


SM predictions

48

Global $a_{sl}^{s} - a_{sl}^{d}$ plot

arXiv:1605.09768

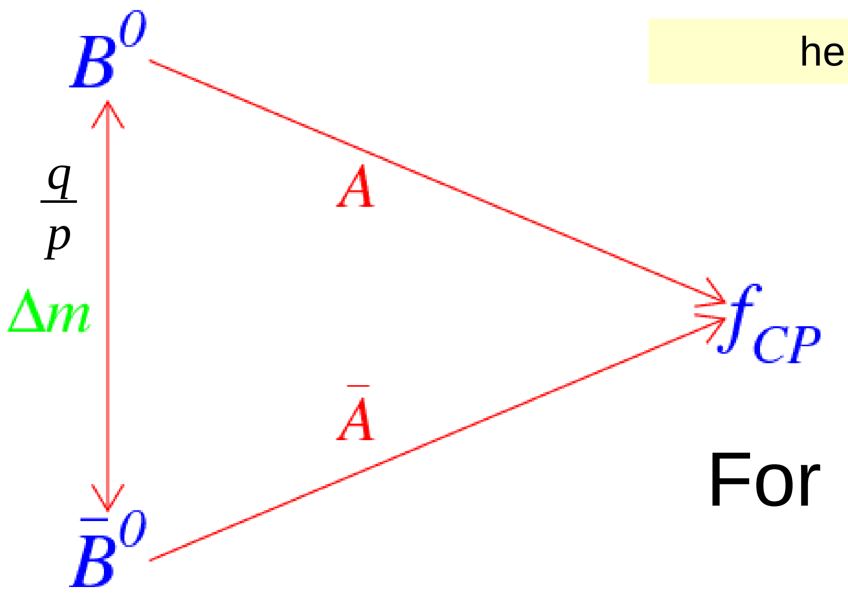


Tension with SM not seen in separate a_{sl}^{s} & a_{sl}^{d} measurements

Time-Dependent CP Violation in the B^0–$\overline{B}^0$ System

- For a B meson known to be 1) B^0 or 2) $\overline{B}^0$ at time t=0, then at later time t:

$$\Gamma\left(B^0_{phys}\to f_{CP}(t)\right) \propto e^{-\Gamma t}\left(1-\left(S\sin(\Delta m\, t)-C\cos(\Delta m\, t)\right)\right)$$
$$\Gamma\left(\overline{B}^0_{phys}\to f_{CP}(t)\right) \propto e^{-\Gamma t}\left(1+\left(S\sin(\Delta m\, t)-C\cos(\Delta m\, t)\right)\right)$$



here assume ΔΓ negligible – will see full expressions later

$$S=\frac{2\,\Im(\lambda_{CP})}{1+|\lambda_{CP}^2|}\qquad C=\frac{1-|\lambda_{CP}^2|}{1+|\lambda_{CP}^2|}\qquad \lambda_{CP}=\frac{q}{p}\frac{\bar{A}}{A}$$

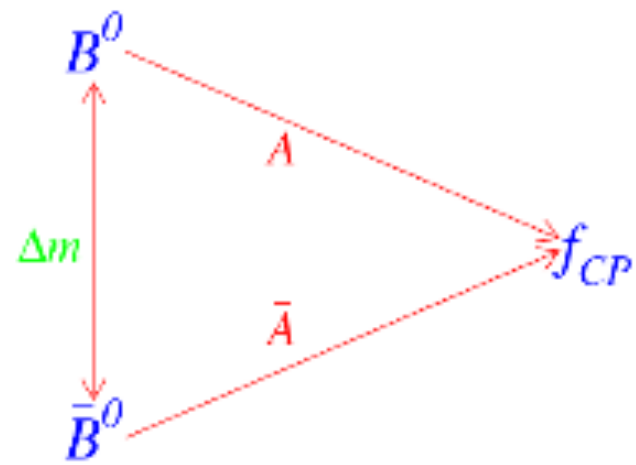
For $B^0 \to J/\psi\, K_S$, $S=\sin(2\beta)$, $C=0$

NPB 193 (1981) 85

Types of CP violation

- Consider decay of neutral particle to a CP eigenstate

$$\lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$



$$\left|\frac{q}{p}\right| \neq 1$$ CP violation in mixing

$$\left|\frac{\overline{A}}{A}\right| \neq 1$$ CP violation in decay

$$\Im\left(\frac{q}{p}\frac{\overline{A}}{A}\right) \neq 0$$ CP violation in interference between mixing and decay

Principle of measurement at Asymmetric B Factory

To measure t require B meson to be moving

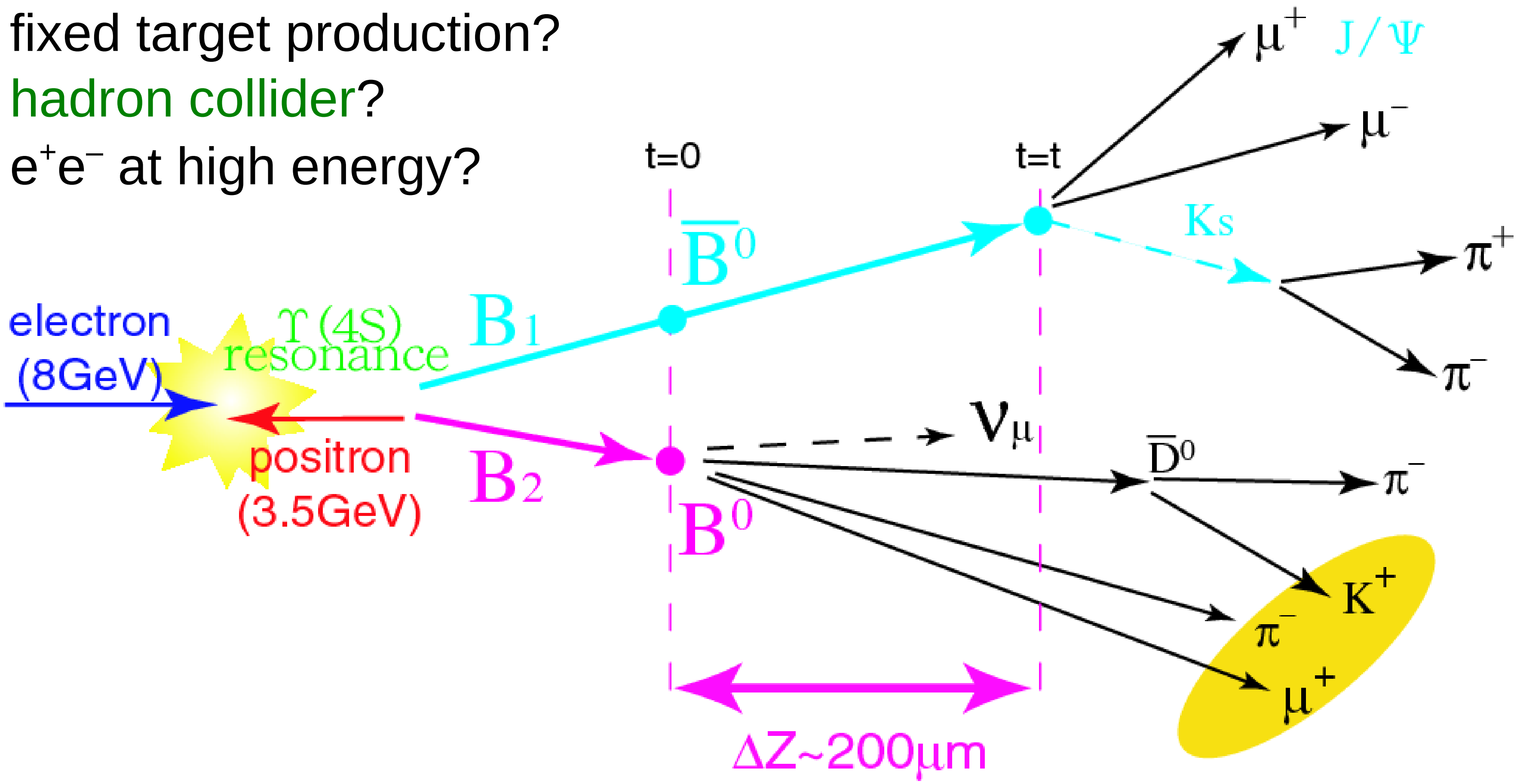
→ e^+e^- at threshold with asymmetric collisions (Oddone)

Other possibilities considered

→ fixed target production?

→ hadron collider?

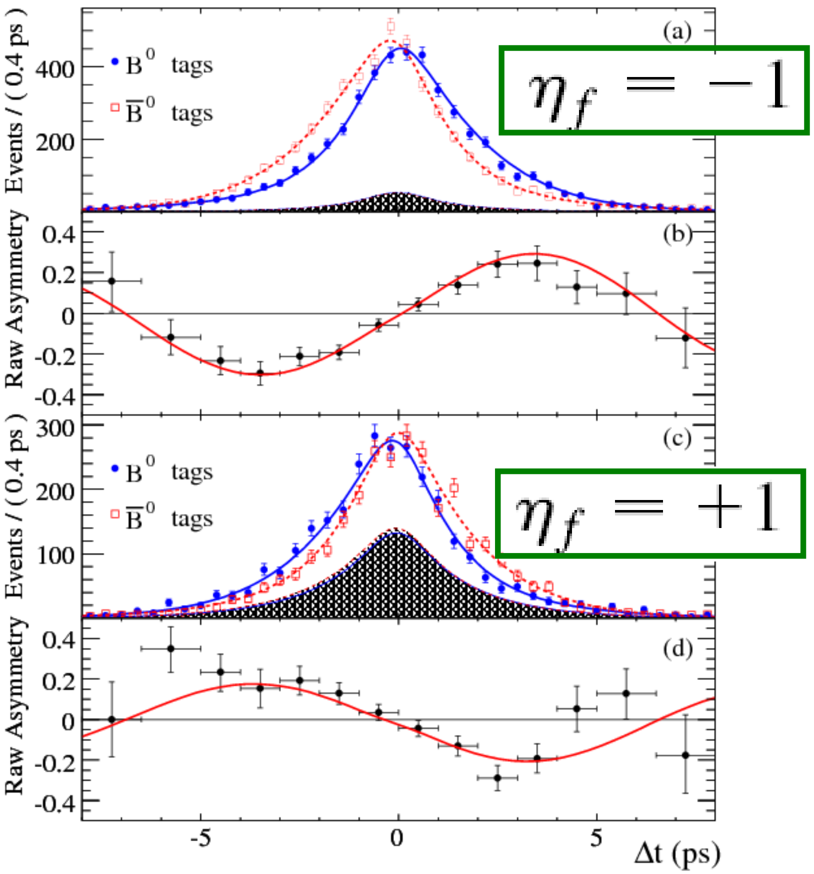
→ e^+e^- at high energy?



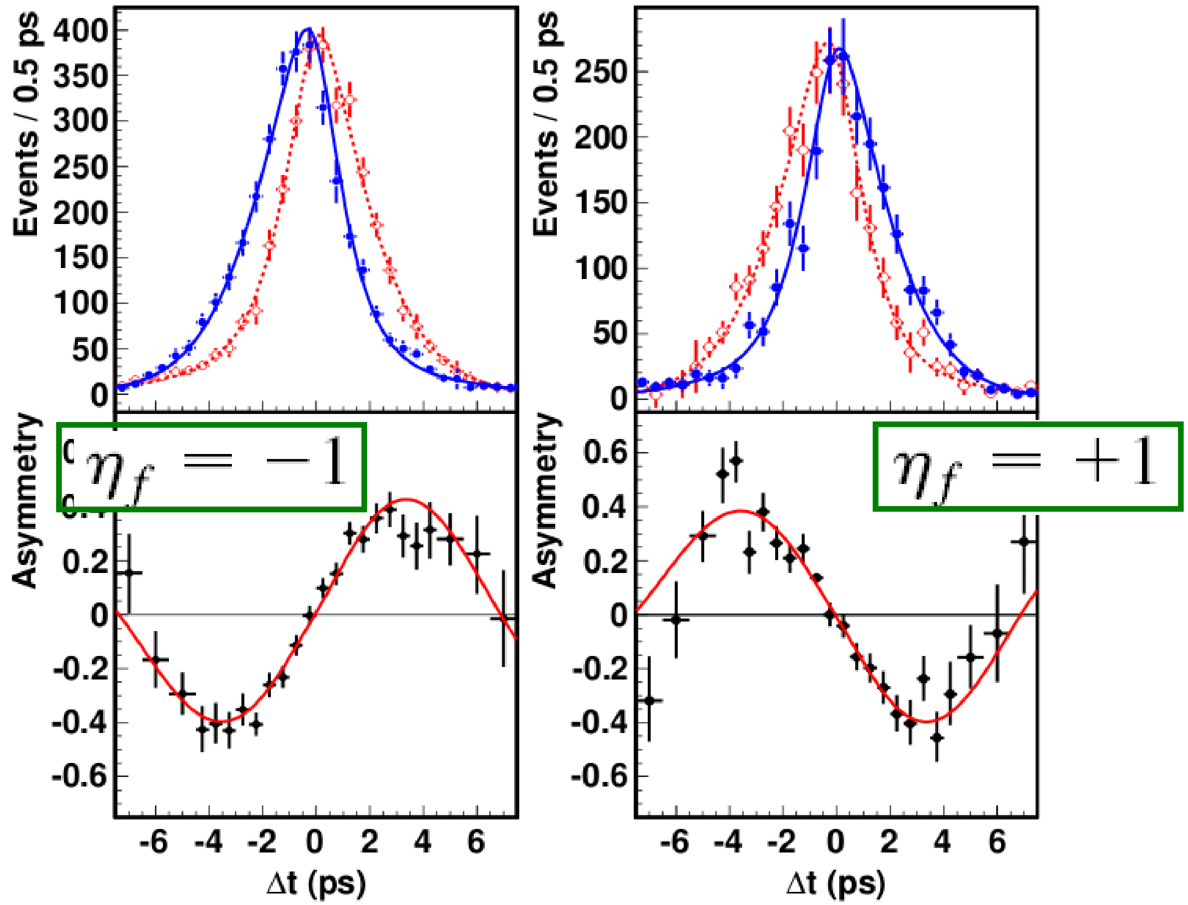
Results for the golden mode

$$B^0 \to J/\psi K^0$$

BABAR **BELLE**



PRD 79 (2009) 072009



PRL 108 (2012) 171802

Compilation

Results on previous slide

Note LHCb also highly competitive