The Next 20 Years in Experimental Particle Physics.

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Over the last two years the Particle Physics community has developed a roadmap for the experimental program within the US, based on the open questions in particle physics. This was necessary as new experiments take a very long time to realize and require large amounts of funding. In this talk I will describe this program from the point of view of an experimentalist and how it tries to address the current and future open questions in particle physics.

Intro 1

Background & why this talk

History:

Worked on ν physics for many years

Joined MSU = joining Dzero(DØ) exp. (1983) $p \rightarrow \; \leftarrow \bar{p}$ @ Tevatron

Founding member of this enterprise
Design , hardware construction, commission, +++
Lots of physics (123 publications)
Started new Theory-Exp collaboration for results (CTEQ)
Co-Spokesman for 6 years + project manager (end 2002)

During this time DØ collab grew from
12 institutions & 73 members in 1983 to:

Some of my DØ colleagues.....

Original DØ (1983): 12 institutions (11US, 1 F): 73 members

Now: 77 institutions & ~750 members (50% non US)

Approximately: 10 fold increase

Already had two DØ speakers and another one next week.

Not another talk on DØ

Intro 2

Just like any experimentalist, prime desire: Solve problems & measure things

Current activities DØ:
- Working on top cross section & mass
- Building/upgrading calorimeter trigger at first level (a la ATLAS at LHC)

Last year spent time considering future of exp. particle physics (accelerator based)

Motivated by future Linear Collider

- On HEPAP for 3 years
- Very difficult decisions at Tevatron in last few months

Need to look ahead to future (a bright one!)
Any breakthrough in HEP has to come from experiment

This talk: Where exp. HEP is going, what plans are, difficulties, etc (accelerator based)

Next lay foundation →

My opinion & views; right or wrong

Status of Particle Physics (1)

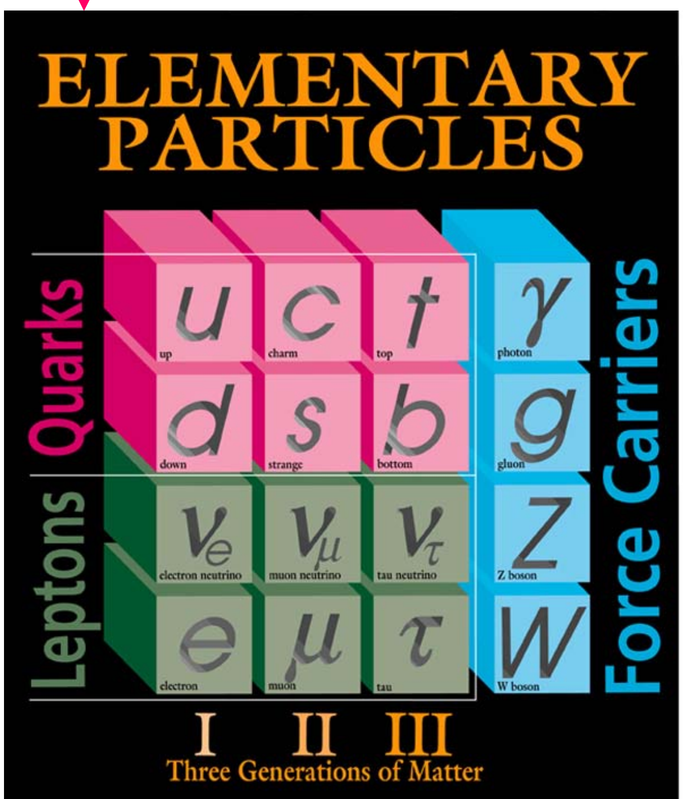
Described by Standard Model

Formulated, refined & tested over last 30 years.

"best tested model/theory in physics"

Normally described by theorist-with extra predictions

Exp. view: clear separation between exp. verified & what is prediction



All matter made up of fermions (quarks & leptons)

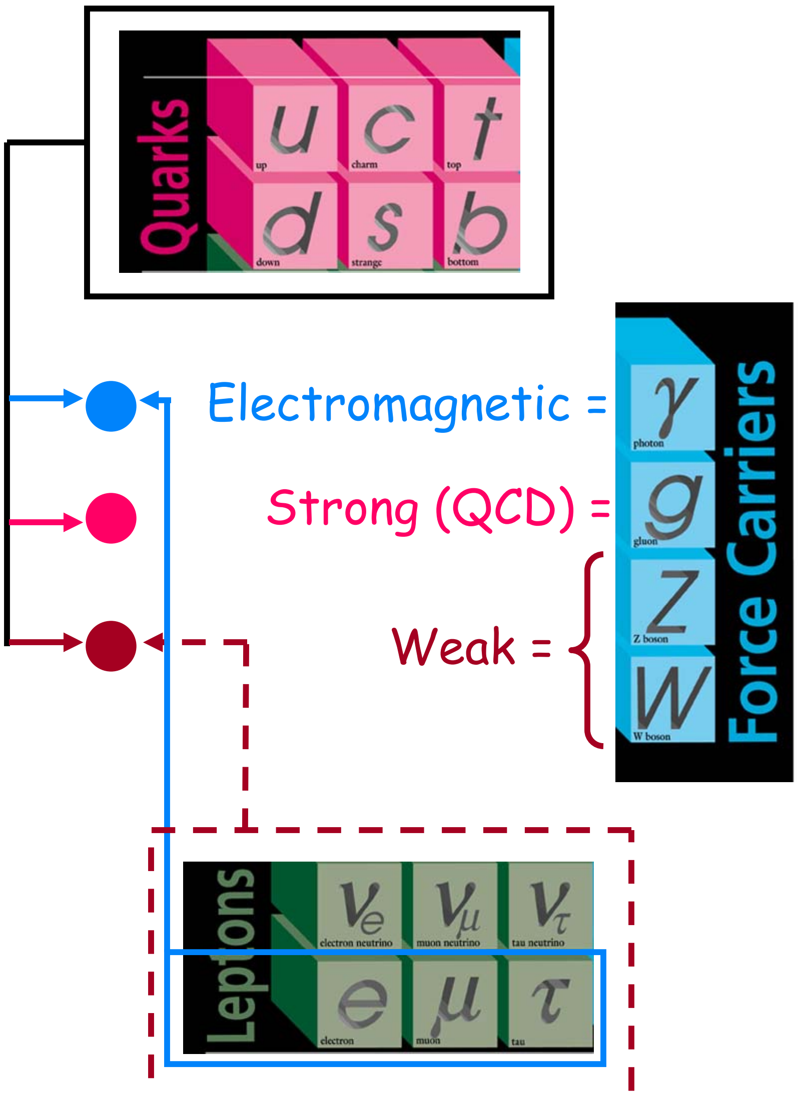
Interactions/forces between them mediated by bosons

Understood at such a level that ALL interactions/cross sections can be well calculated and simulated

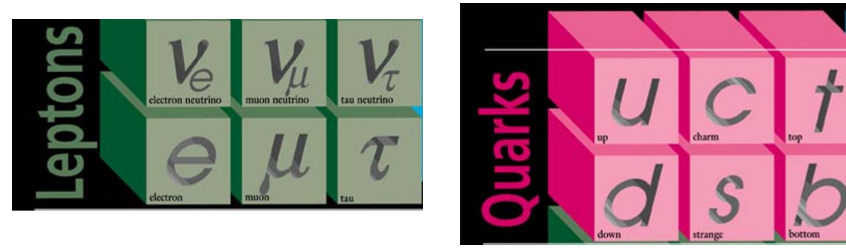
Very good predictive power (verified by experiment)

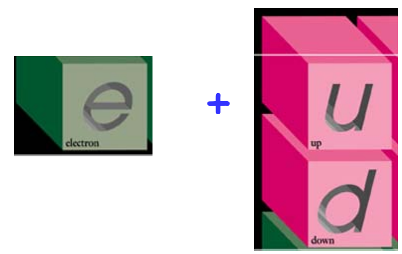
Status of Particle Physics (2)

Interactions/Forces (more detail)



Fermions make up all known matter



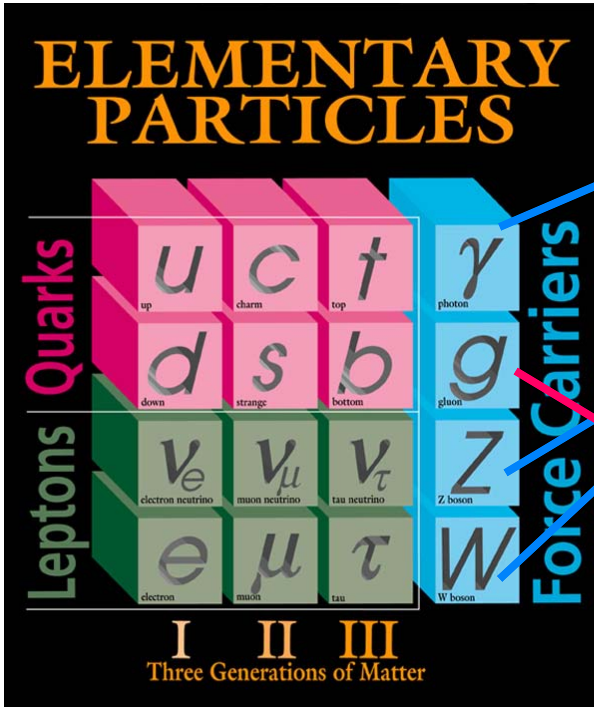


= All of "day to day" matter

Nuclear reactors

= neutrino industry; rapidly evolving field

Status of Particle Physics (3) beyond SM



Electro Magnetic

Weak

Strong (QCD)

Electro Weak (EW)

Higgs ?

Unified

New symmetries

≈200 GeV

Energy

Very well verified by exp.;
very good predictive power

Anticipated, predicted;
expected unification
(basis for SM)

Not clear yet how gravity will fit in.

Exp. verification of SM

Took about last 30 years to establish, verify, augment and put SM on current solid footing (theory & experiment)

Many different experiments at different accelerators
Diversity and breadth of past program needed to accomplish this

Examples:

- Electron beams
- Neutrino beams
- Electron-Positron colliders
- Hadron- Hadron colliders
- Electron- Hadron collider
- Asymmetric electron-positron colliders (B factories)

+

Non-accelerator experiments (later)

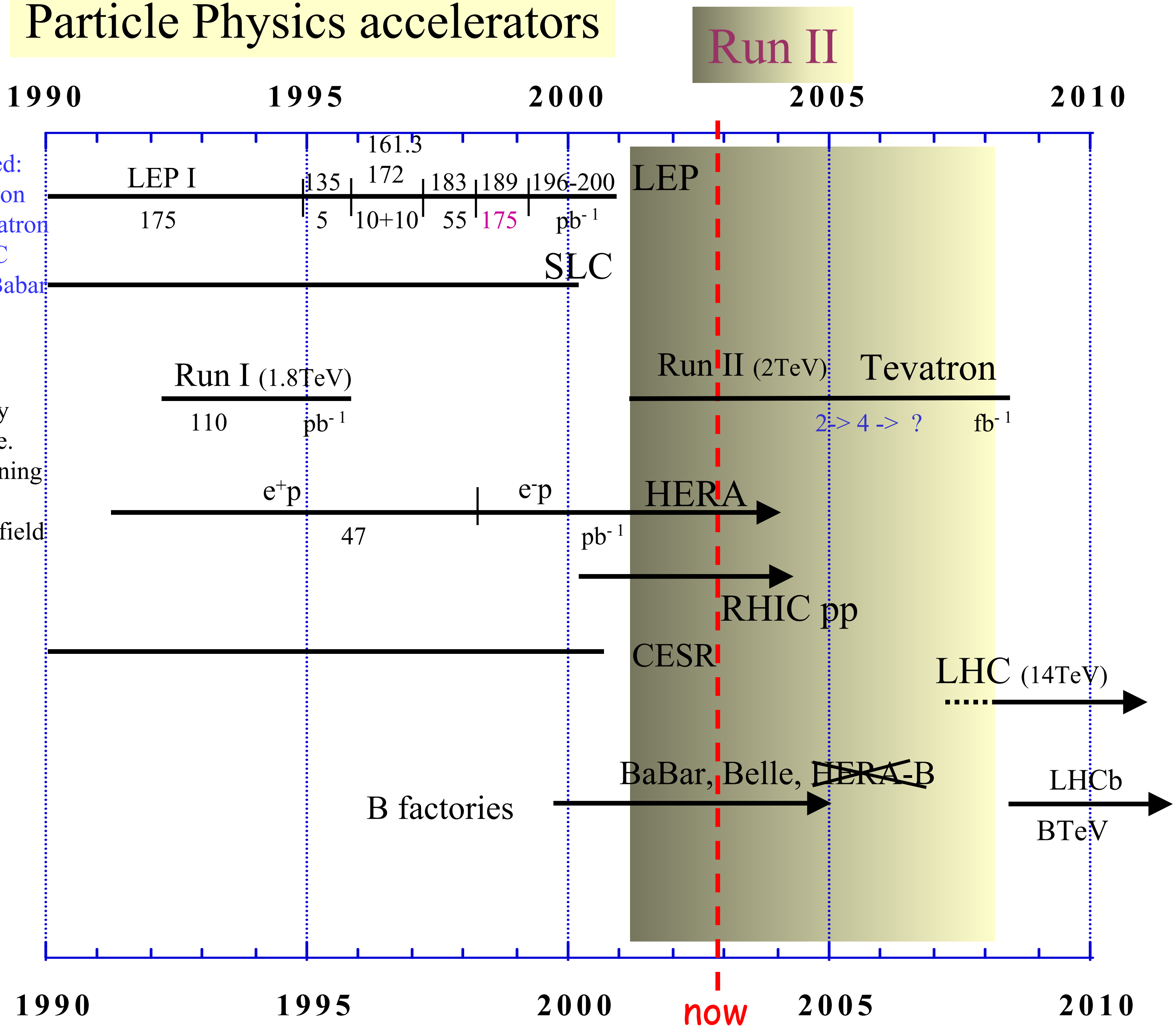
interplay needed

Personal: Worked in this area during this time, starting with ν experiments that established EW part of Standard Model (non abelian gauge theories), on to QCD and all the way to discovery of top quark at Tevatron

Particle Physics accelerators

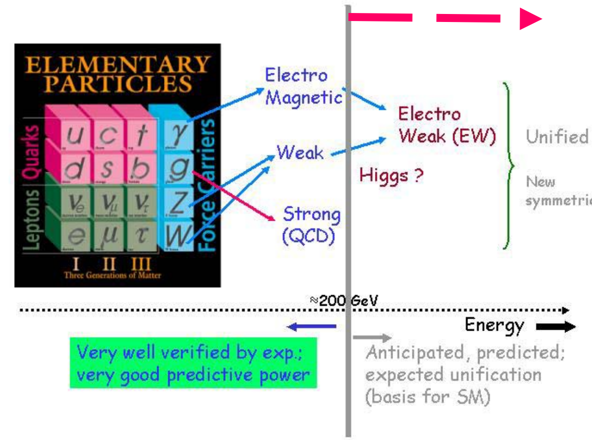
Interplay needed:
LEP<-> Tevatron
HERA<-> Tevatron
HERA<-> LHC
Tevatron <-> Babar

Program already into next decade.
Long term planning necessary & integral part of field



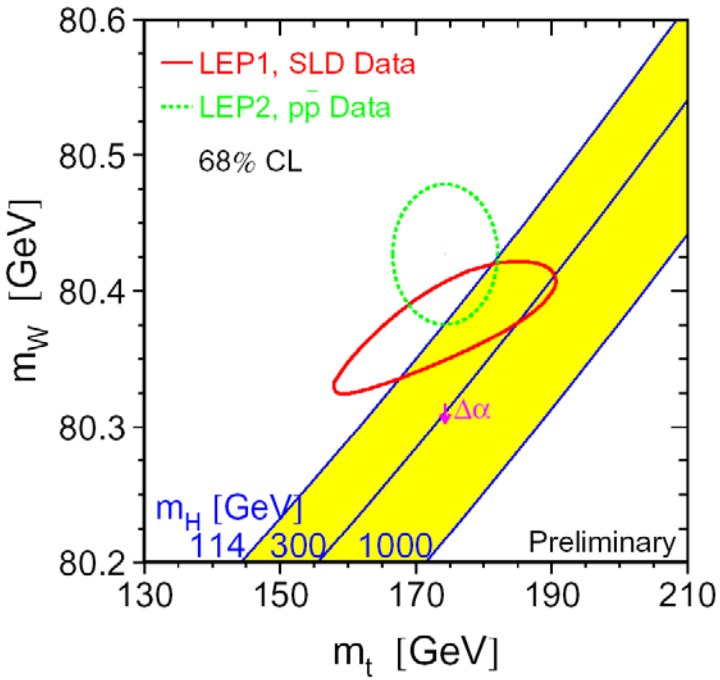
Examples of exp. input

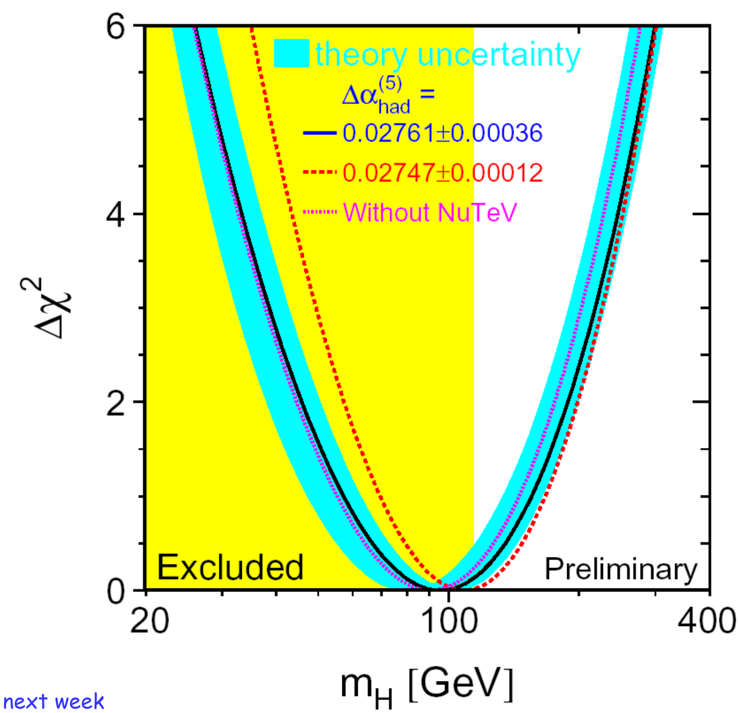
"Energy frontier"



Mainly driven by results from highest energies:

Precision measurements of W, Z ,top mass
Searches for Higgs
Searches for new physics (SUSY, etc.)
Mass scales probed: LEP ≈ 110GeV & Tevatron ≈ 250 GeV





ALL expt's

More last week & next week

Difference in “energy frontier” experiments (ee)

Two main kind of machines:

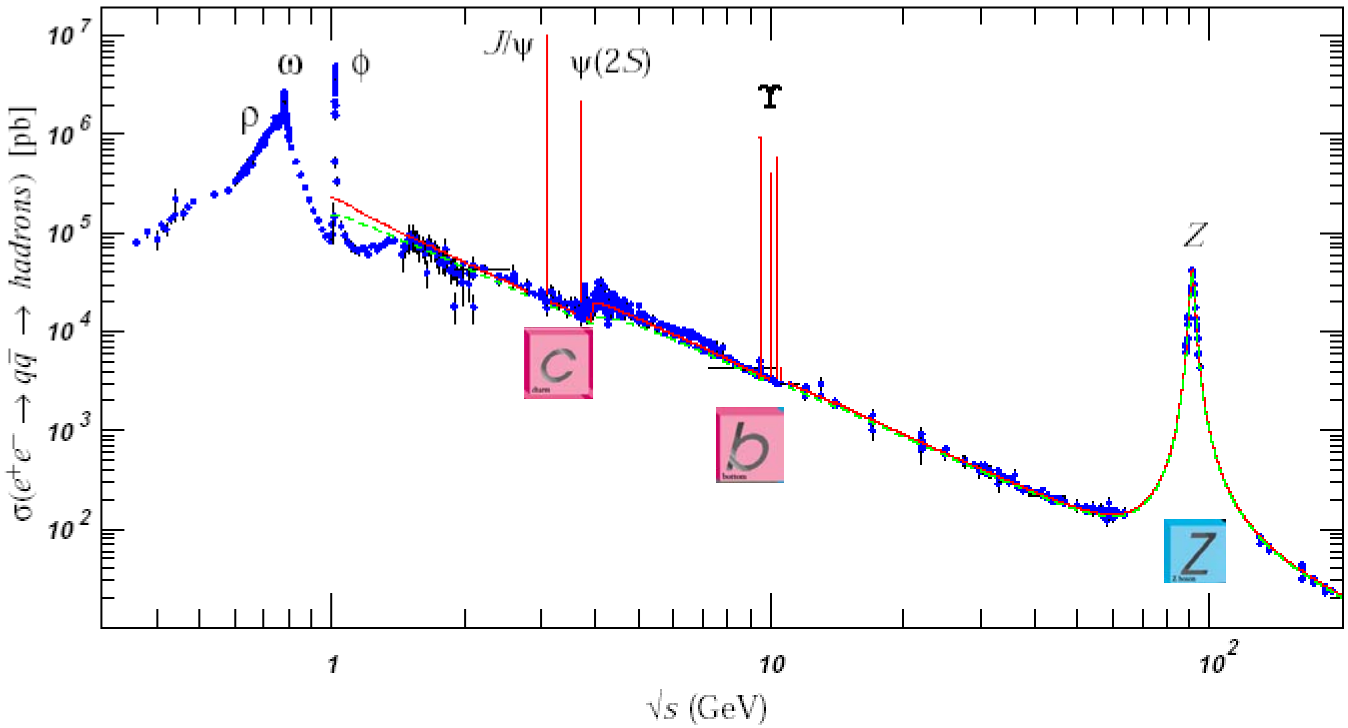
1) electron –positron (e^+e^- annihilation) colliders

2) proton-(anti)proton collider (Tevatron, future LHC)

e^+e^- annihilation: Total energy of e^+ and e^- available as E_{cms} or $\sqrt{s}$

Scan over resonances

Maximum achieved for E_{cms} =192 GeV

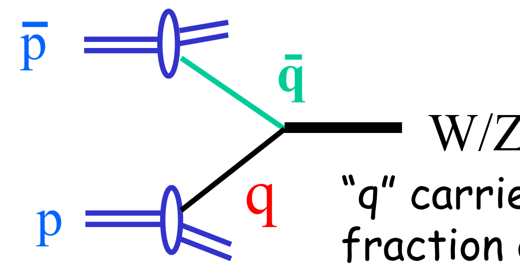


Energy range covered by e^+e^- colliders

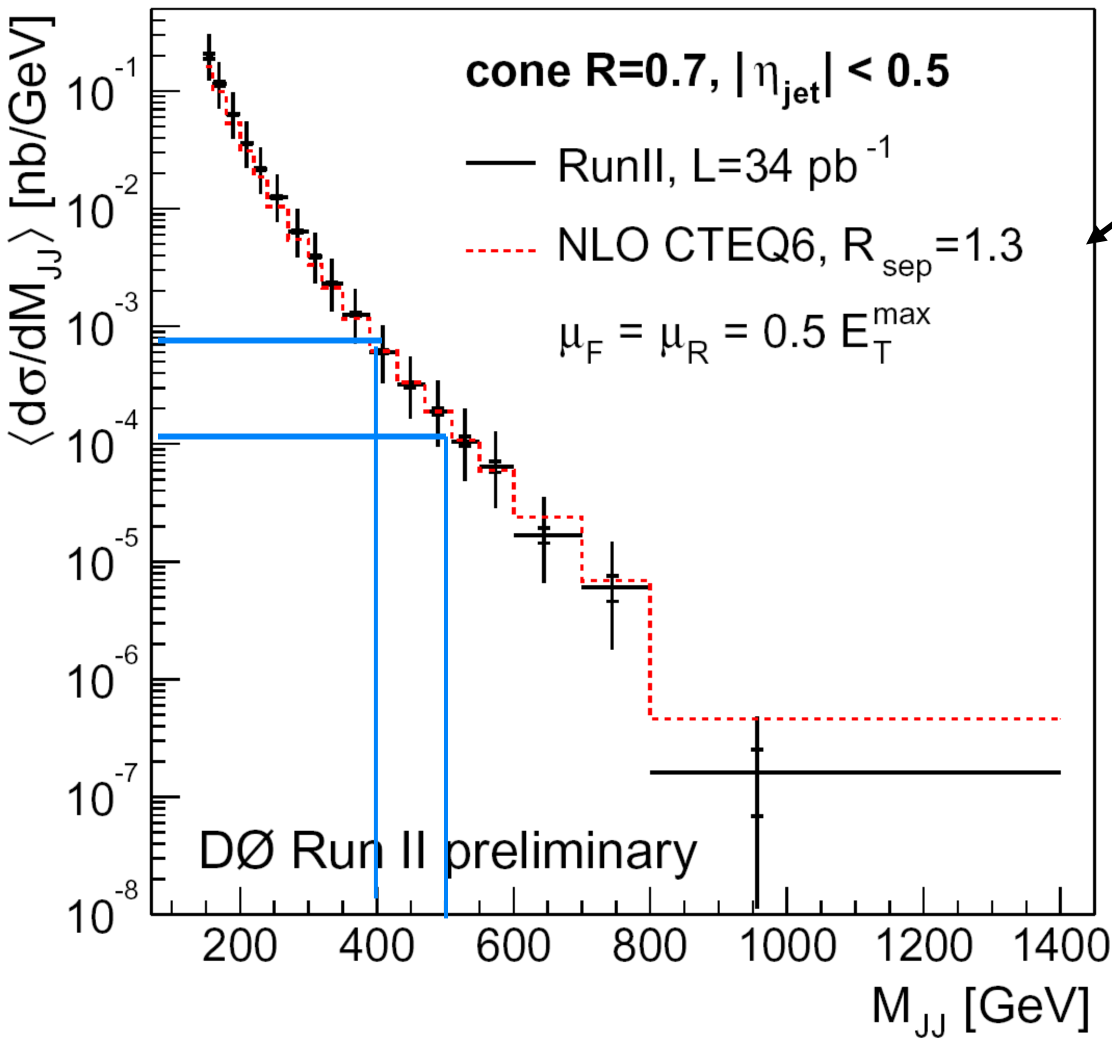
Very clean environment; precision physics

Difference in "frontier" machines (pp)

$p\bar{p}$ or pp fundamentally different from e^+e^-
Only a fraction of total hadron energies is available for scatter



"q" carries fraction of energy of "p"



Example: E_{cms} available at Tevatron (2 TeV) for 2 jet production

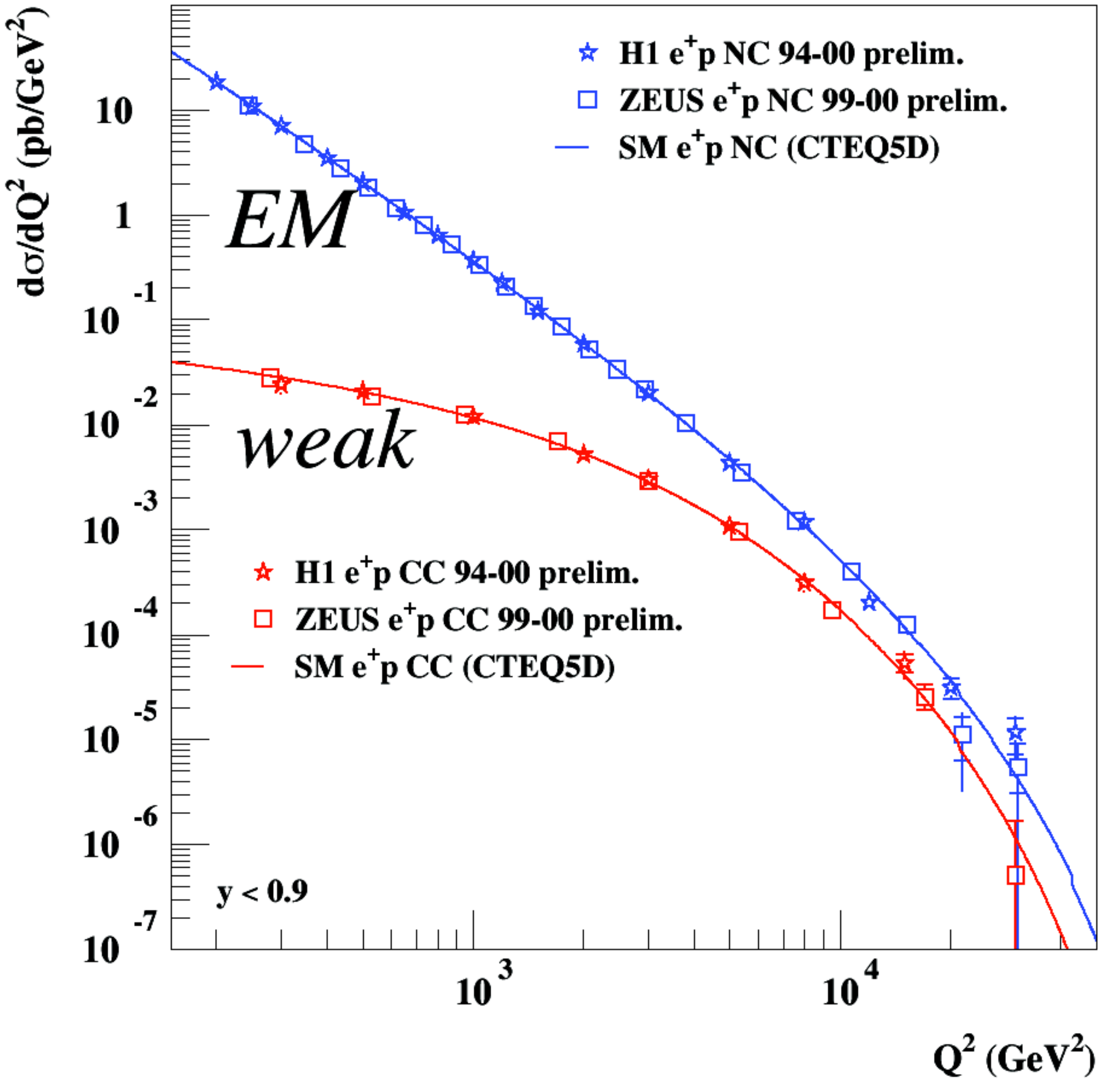
- Cross sections drops rapidly
- For pair production can produce particle with roughly $M_{jj}/2$
- Cross section smaller than jets
- Efficiency for final state less
- Best limits for SUSY ≈250 GeV

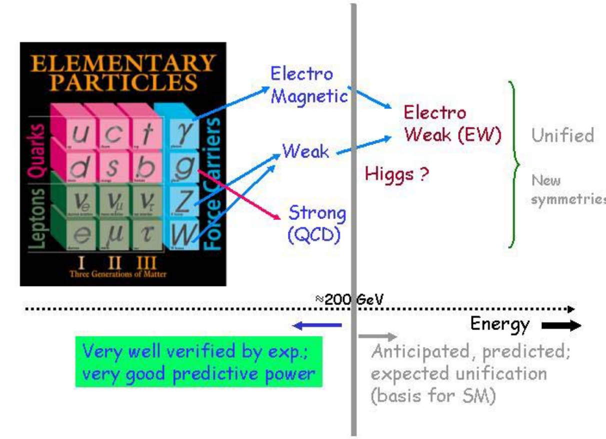
≈ 2TeV/8

Also note: to increase mass range from 400 to 500 GeV need 10x luminosity. Main reason for large lum needs

Unification of EW forces

Total cross section e^+p @HERA vs. momentum transfer (Q^2)

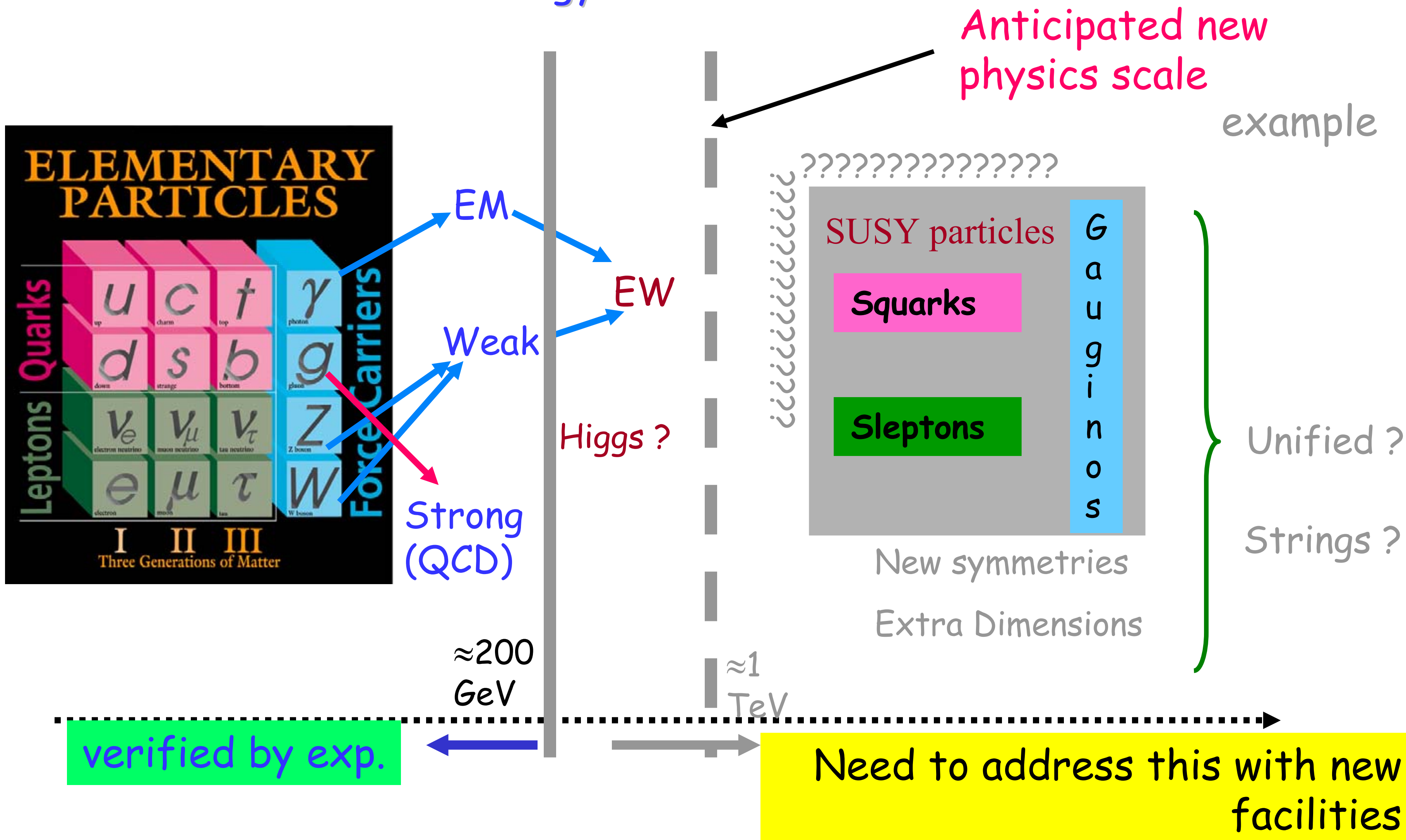




As "energy" increases strength of EM and Weak force become similar. Needed for unification.

Indication of EW unification

Energy frontier



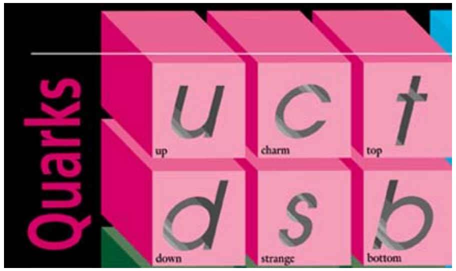
Scale: smaller ⟵ Energy ⟶ larger

larger ⟵ Distance ⟶ smaller

(Historically not correct)

CP violation/mixing/oscillations

quark sector



Under weak interaction quarks can change flavor, as long as charge changes by 1.

Possible transitions described by Cabbibo-Kobayashi-Maskawa (CKM) matrix.

$$\begin{array}{c} \quad d \qquad\quad s \qquad\quad b \\ \left| \begin{array}{ccc} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{array} \right| \begin{array}{c} u \\ c \\ t \end{array} \end{array}$$

(CKM matrix)

Each element (V_{ij}) is complex and needs to be measured. SM (unitary) predicts relationships

➔ CP violation & oscillations

CP violation first observed in Kaon("s") system (very small). Difficult to understand in that system.

Study B ("b") meson final states (higher mass, better understood)

See accelerators

Resulted in building of B factories all over the world.

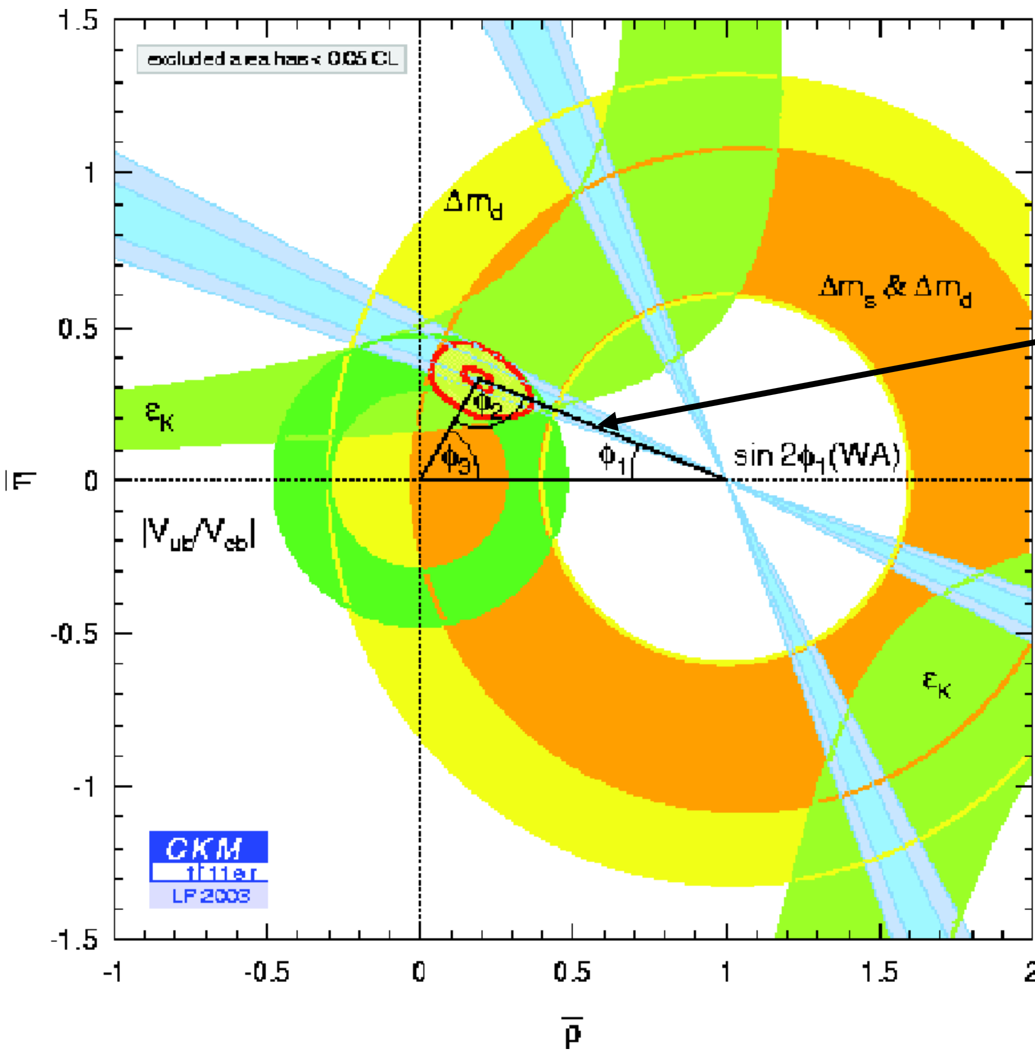
Desire to better measure CKM elements & understand CP violation

First observation though by CDF at Tevatron

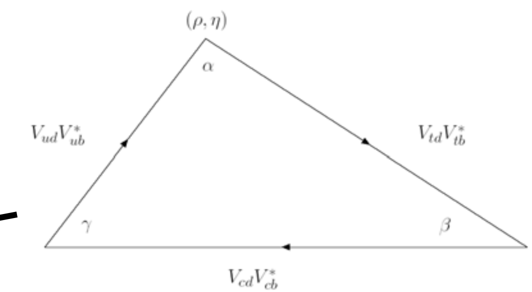
CP violation important to explain matter dominated universe ?

CP violation/mixing/oscillations cont'd

Very precise results from B factories. No surprises except for a new meson state



Triangle should close in SM (unitarity)



Many measurements contribute

Excellent agreement between exp. results and confirmation of unitarity

Oscillations in neutrino sector

If oscillate, then has mass

Many decades suspected that neutrinos might mix/oscillate, because flavor eigenstates are combinations of mass eigenstates. So pure beam of ν_i will contain ν_j after some time.

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \sin^2 1.27 \frac{\Delta m^2}{E} L,$$

Δm^2 in eV^2
E in GeV
L in km

many

Experiments done at reactors/neutrino beams over decades; no indication; wrong parameter space (L/E small)

First indication from Super Kamiokande (1998):

Deficit of cosmic ray ν_μ and ν_e from the sun

Appearance !

This initial result followed by several others: SNO, KamLand (all solar/atmospheric or reactor experiments; all unique)

Have established a clear picture of neutrino oscillations and spawned a whole area in our field

In very short amount of time

Verify with controlled beam

Observations from universe

Questions about universe:

Where is anti matter ?

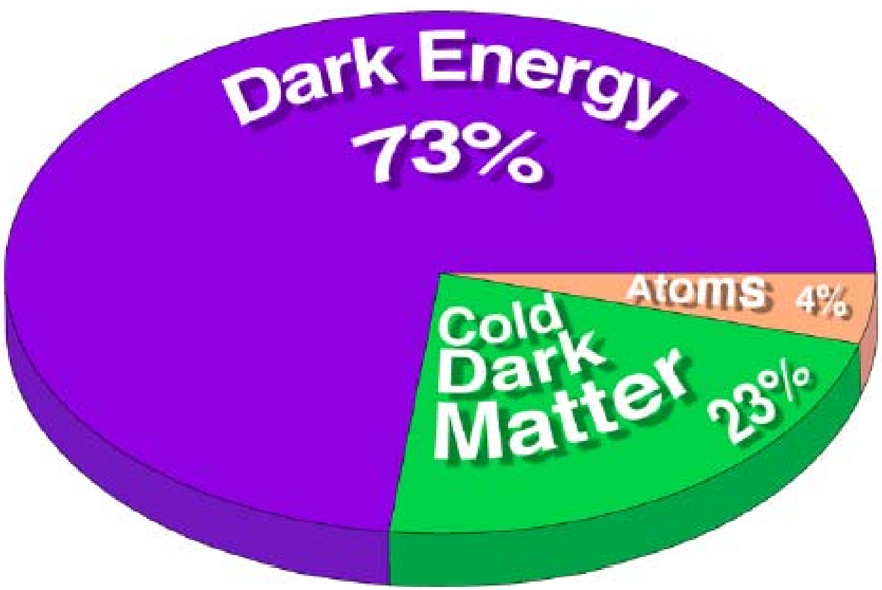
Most mass in universe not in SM particles

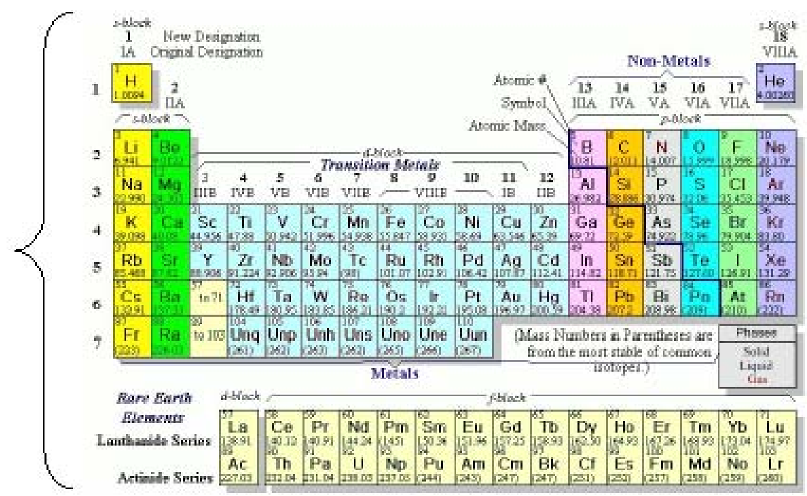
Dark matter; new particle needs to be found

Dark energy ?? ← Excellent astrophysics/astronomy experiments (CMB, supernovae)

Supernovae Cosmology project
High-Z Supernovae Search team

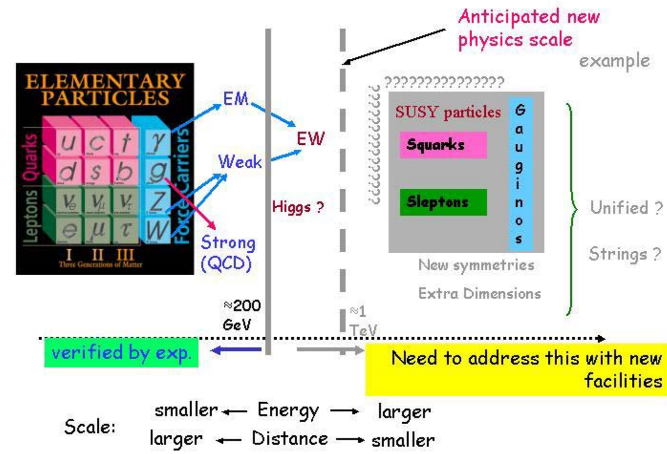
High Energy cosmic rays ?



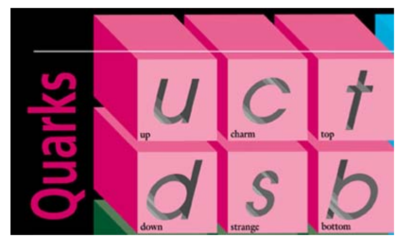


Particle Physics Areas broadly

Energy Frontier



Flavor Physics
Leptons & Quarks



Cosmology/Astrophysics

Particle Physics Roadmap

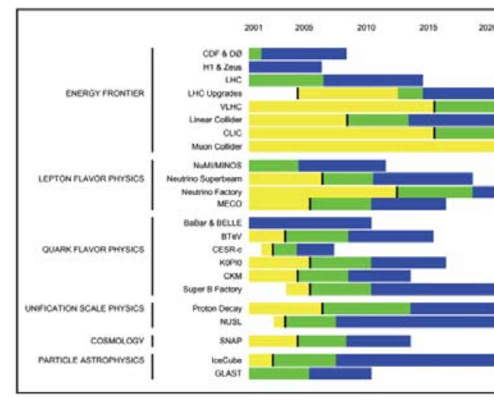
This program formed basis for Roadmap for US Particle Physics developed in 2001/2002 (HEPAP subpanel)

Factors that made necessary to develop roadmap:

- Facilities take a lot of $$, especially a new collider
- Very large efforts needed (people)
- Annula budget for HEP in US frozen since years (~$800M)
- Needs international collaboration/cooperation/prioritization

Establish P5= Particle Physics Project Prioritization Panel

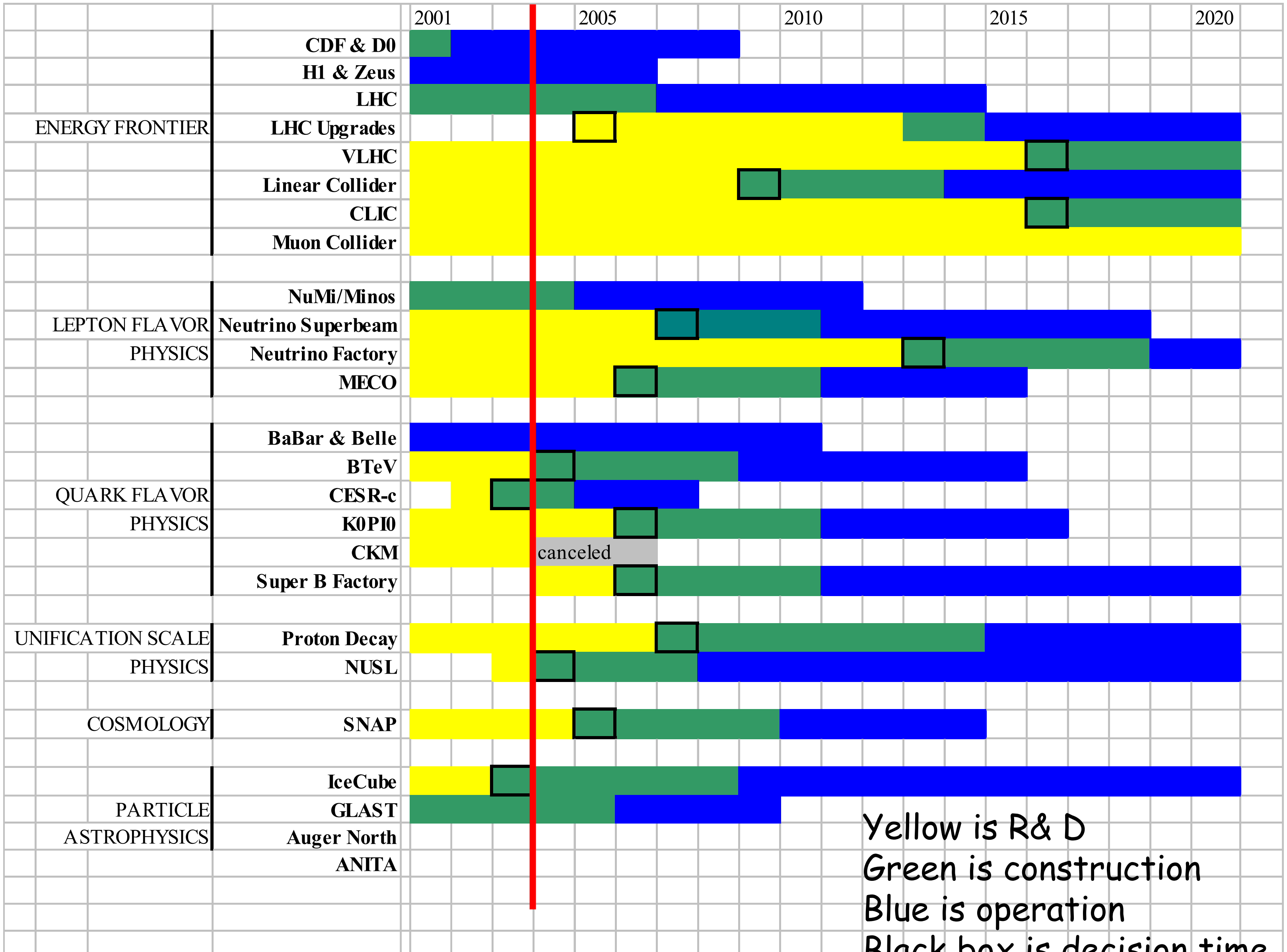
Guardian for Roadmap and set national priorities for mid-size projects ($50-600M)



New for US

Provide guidance and national priorities

Road map I



2001
2005
2010
2015
2020
ENERGY FRONTIER
CDF & D0
H1 & Zeus
LHC
LHC Upgrades
VLHC
Linear Collider
CLIC
Muon Collider
LEPTON FLAVOR PHYSICS
NuMi/Minos
Neutrino Superbeam
Neutrino Factory
MECO
QUARK FLAVOR PHYSICS
BaBar & Belle
BTeV
CESR-c
K0PI0
CKM
canceled
Super B Factory
UNIFICATION SCALE PHYSICS
Proton Decay
NUSL
COSMOLOGY
SNAP
PARTICLE ASTROPHYSICS
IceCube
GLAST
Auger North
ANITA
Yellow is R& D
Green is construction
Blue is operation
Black box is decision time

After roadmap made public

Roadmap outlines very broad program and very carefully written

However one of major recommendations of subpanel report:

Build a Linear e^+e^- Collider(LC) with energy range 0.5 to 1.5TeV

Worldwide consensus in community, that this should be next large facility to be built (first time in HEP)

Cost & complexity of LC seem to dominate future plan

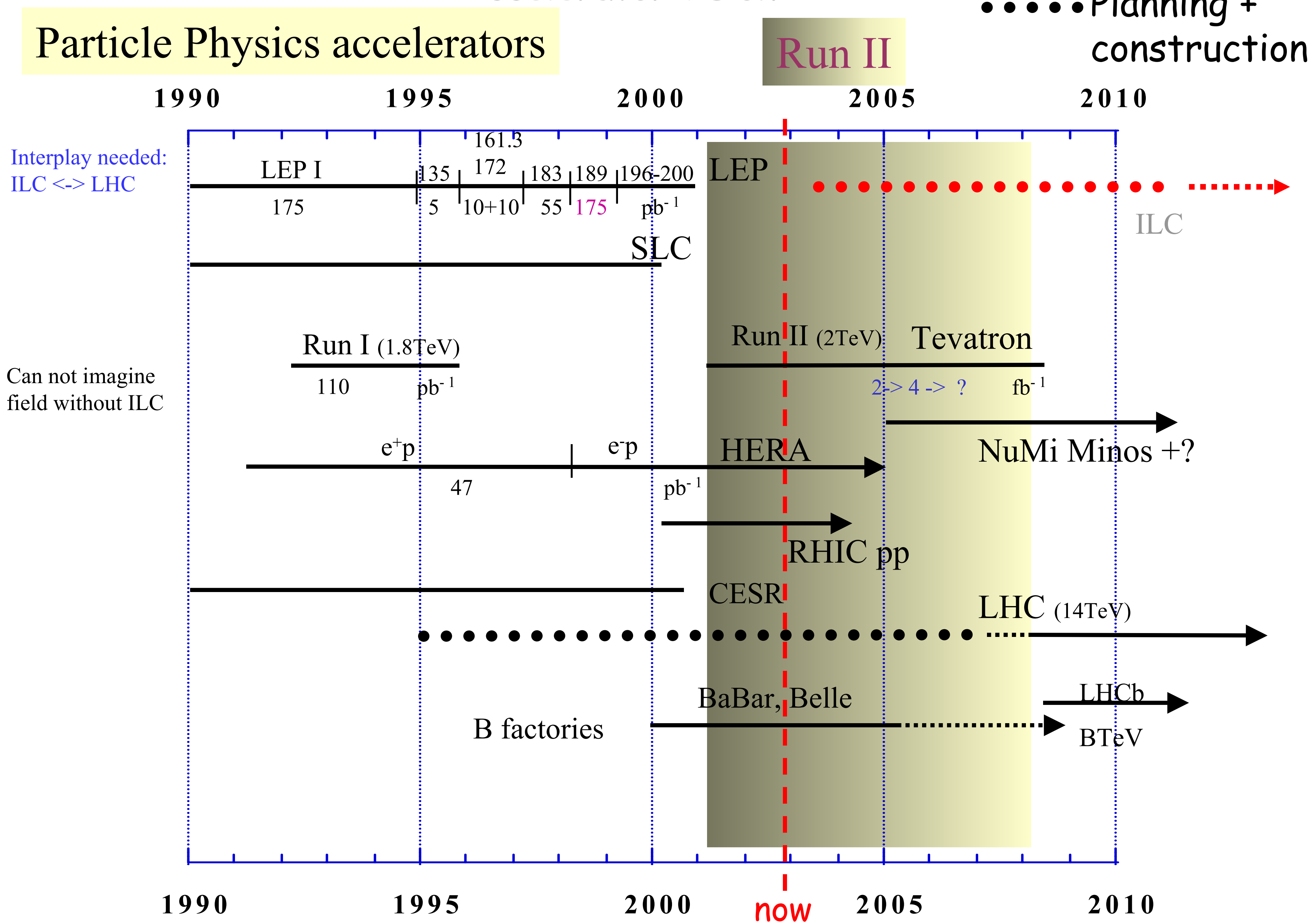
This concerns many in field to the point where the field is not coherent anymore Not good

Need to continue working on future plan which includes a LC somewhere in world

(me: should be in US)

Vision to address "energy frontier" →

Accelerator vision



Process continues

In meantime US funding agencies progress on facilities for DoE Office of Science

March 2002 HEP submits list of recommended facilities to be considered for Office of Science "20 year facility plan"

Other fields do the same

Criticism on procedure

HEP facilities request (2)

Facility request to DoE

HEP Facilities Summary Table

Project	Type	Physics	Cost	Scientific Potential	Proposed Facility	State of Readiness	Possible Time Scale
Linear Collider	Facility	Energy Frontier	$5B – $7B	Absolutely Central	Absolutely Central	R&D	2015 Operation
LHC Luminosity Upgrade	Facility	Energy Frontier	$150M (US Part)	Absolutely Central	Absolutely Central	R&D	2014 Operation
LHC Energy Upgrade	Facility	Energy Frontier	Unknown	Don't Know Enough Yet	Don't Know Enough Yet	R&D	Decision in Next Decade
SNAP	Experiment	Cosmology	$400M – $600M	Absolutely Central	Absolutely Central	R&D	2009 Launch
BTEV	Experiment	Quark Physics	$120M	Important	Important	Ready for Decision on Construction	2008 Operation
CKM	Experiment	Quark Physics	$100M	Important	Important	Ready for Decision on Construction	2008 Operation
Super-B Factory	Facility	Quark Physics	Unknown	Don't Know Enough Yet	Don't Know Enough Yet	R&D	Decision Later This Decade

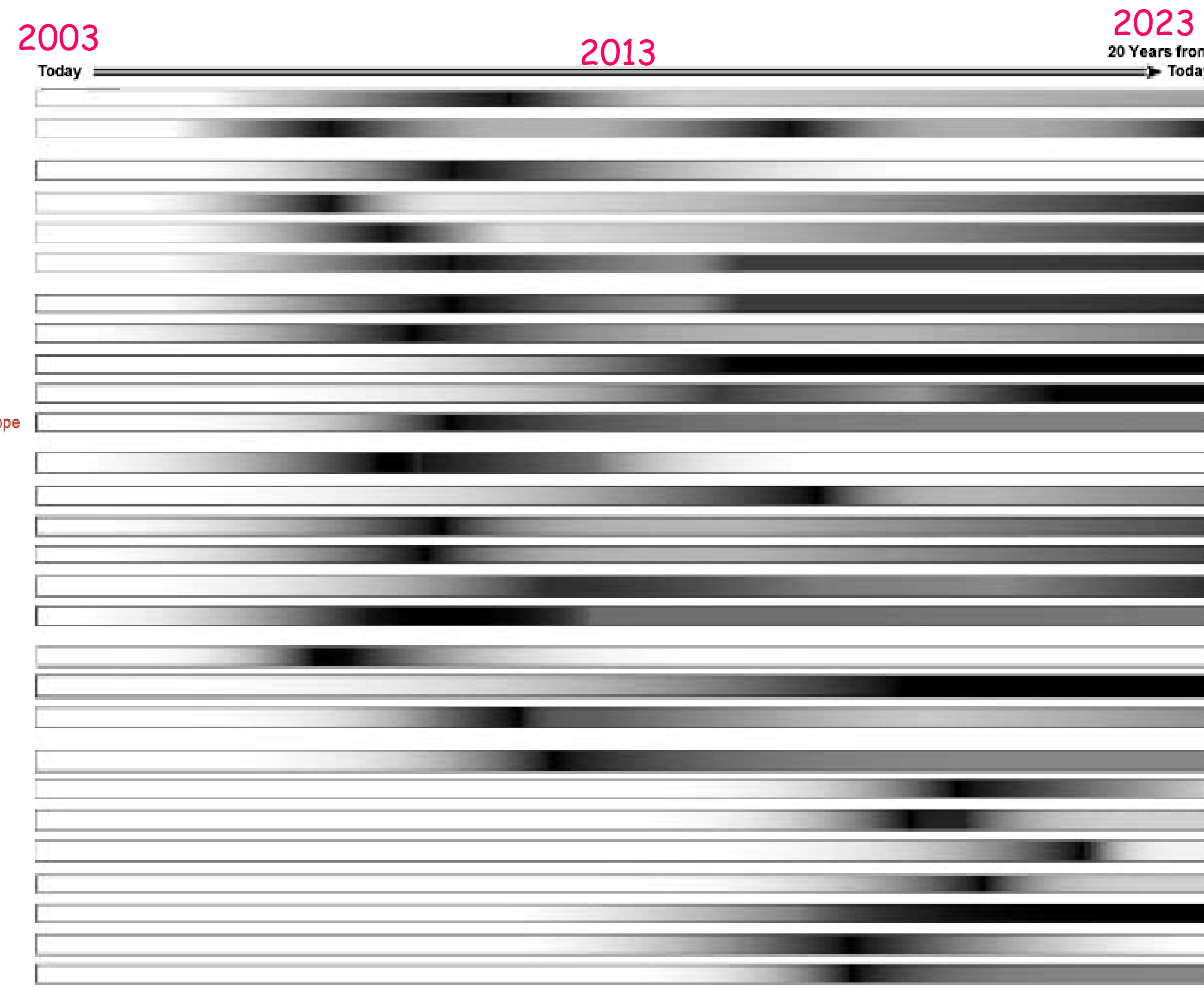
HEP facilities request (2)

Double-Beta Decay	Experiment	Neutrino Physics	$100M	Absolutely Central	Don't Know Enough Yet	R&D	2005 Prototype
Off-Axis Neutrino Detector new	Experiment	Neutrino Physics	$120M	Important	Important	Project Engineering and Design	2010 Operation
Neutrino Super Beam	Facility	Neutrino Physics	$250M – $500M (Accelerator and Beam Only)	Absolutely Central	Don't Know Enough Yet	Project Engineering and Design	Decision Later This Decade
Underground Detector	Facility	Neutrino Physics and Proton Decay	$500M	Absolutely Central	Don't Know Enough Yet	R&D	Decision Later This Decade
Neutrino Factory	Facility	Neutrino Physics	Unknown	Don't Know Enough Yet	Don't Know Enough Yet	R&D	Decision in Next Decade

Not listed: VLHC

Next step Nov 11, 2003 release of "20 year facility plan" for DoE Office of Science

DoE 20 year facility plan



Term	Priority	Program	Facility
Near-Term	1	FES	ITER
Near-Term	2	ASCR	UltraScale Scientific Computing Capability
Near-Term	Tie for 3	HEP	Joint Dark Energy Mission
Near-Term	Tie for 3	BES	Linac Coherent Light Source
Near-Term	Tie for 3	BER	Protein Production and Tags
Near-Term	Tie for 3	NP	Rare Isotope Accelerator
Near-Term	Tie for 7	BER	Characterization and Imaging
Near-Term	Tie for 7	NP	CEBAF Upgrade
Near-Term	Tie for 7	ASCR	Esnet Upgrade
Near-Term	Tie for 7	ASCR	NERSC Upgrade
Near-Term	Tie for 7	BES	Transmission Electron Achromatic Microscope
Mid-Term	12	HEP	BTeV
Mid-Term	13	HEP	Linear Collider
Mid-Term	Tie for 14	BER	Analysis and Modeling of Cellular Systems
Mid-Term	Tie for 14	BES	SNS 2-4 MW Upgrade
Mid-Term	Tie for 14	BES	SNS Second Target Station
Mid-Term	Tie for 14	BER	Whole Proteome Analysis
Mid-Term	Tie for 18	NP	Double Beta Decay Underground Detector
Mid-Term	Tie for 18	FES	Next Step Spherical Tokamak
Mid-Term	Tie for 18	NP	RHIC II
Far-Term	Tie for 21	BES	National Synchrotron Light Source Upgrade
Far-Term	Tie for 21	HEP	Super Neutrino Beam
Far-Term	Tie for 23	BES	Advanced Light Source Upgrade
Far-Term	Tie for 23	BES	Advanced Photon Source Upgrade
Far-Term	Tie for 23	NP	eRHIC
Far-Term	Tie for 23	FES	Fusion Energy Contingency
Far-Term	Tie for 23	BES	HFIR Second Cold Source and Guide Hall
Far-Term	Tie for 23	FES	Integrated Beam Experiment

Peak Cost ■ Near-term ■ Mid-term ■ Far-term ■

Programs:

- ASCR = Advanced Scientific Computing Research
- BES = Basic Energy Sciences
- BER = Biological and Environmental Research
- FES = Fusion Energy Sciences
- HEP = High Energy Physics
- NP = Nuclear Physics

Summary of facilities plan

Finite number of HEP projects:

- JDEM (SNAP)
- BTeV
- Linear Collider
- Super Neutrino Beam (proton driven)
- Neutrinoless Double Beta Decay (NP)

SLAC is not an obvious HEP accelerator lab anymore
build free electron laser

NSF is not directly part of this; may/should complement program
For example interested in Underground Lab

US HEP program ??

Clear program to be executed/operated for next 5 to 10 years.

However there is no long term coherent plan for US HEP program, which is part of an international plan

Need such a plan to be able to have a credible program in US around 2010 to 2015. Need to formulate plan now to achieve this.

It will require setting priorities

Currently we seem to be drifting with several potential directions (which may happen) but no plan:

Linear Collider …… should come to US
Underground lab proton decay, ν experiment, etc
Active neutrino program which may have surprises
Non-accelerator based HEP is interesting & active,
but need controlled environment to verify

→ Example: find particle "dark matter"

active= surprises

Summary

Next breakthrough has come from experiment (LHC …)

World short term HEP program excellent to address open questions:

- Tevatron & B factories now
- Neutrino program now and near future — US, Japan beams
- LHC physics into next decade
- Astrophysics exciting & new probes

For long term need a better plan incorporating roadmap laid out

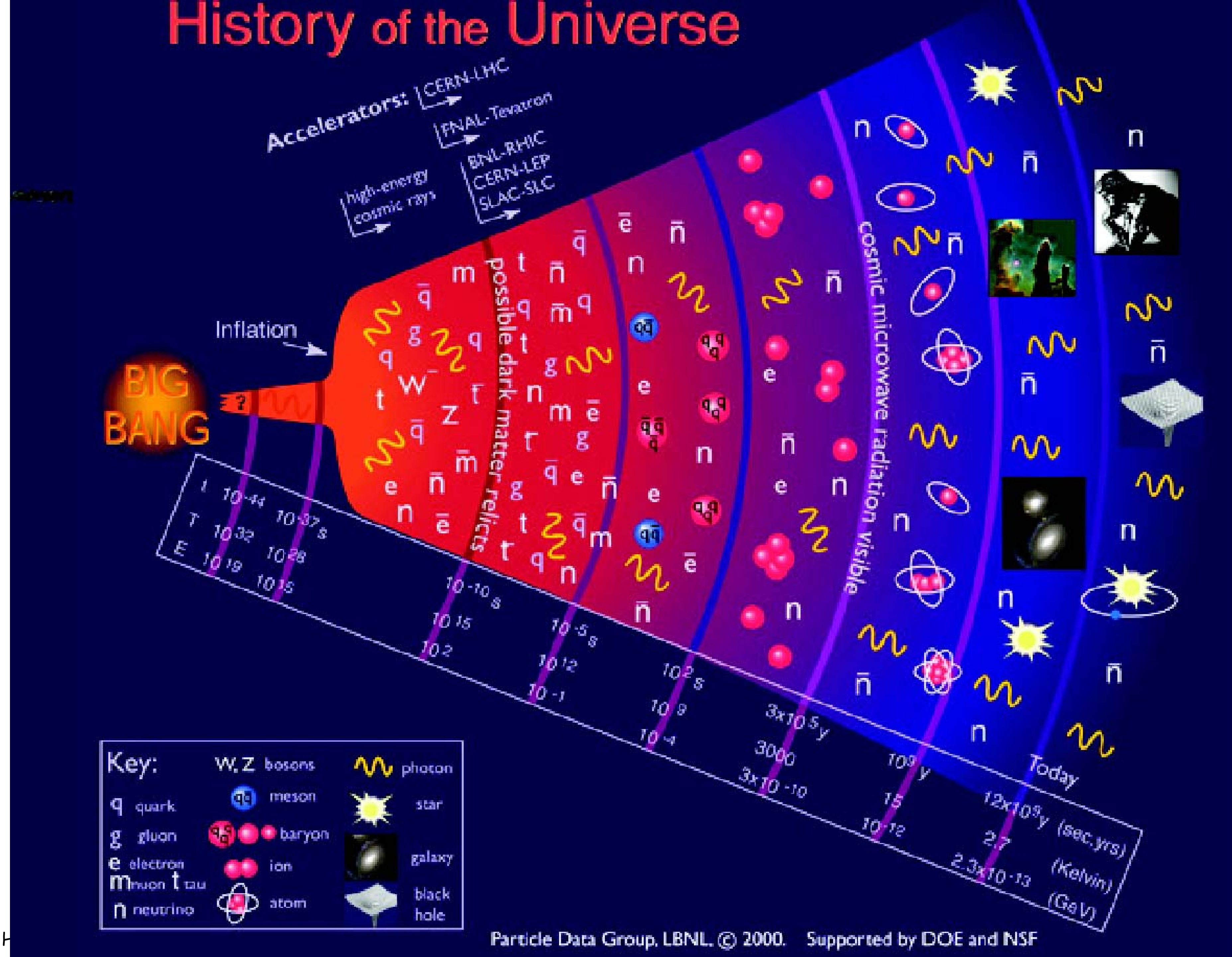
- Plan needs to be coherent & defensible to get funds necessary
- Part of an international plan

Funding will not come first, because of increased scrutiny from funding agencies

Bright future and lots of physics ahead. Have to find a way to explore it ALL

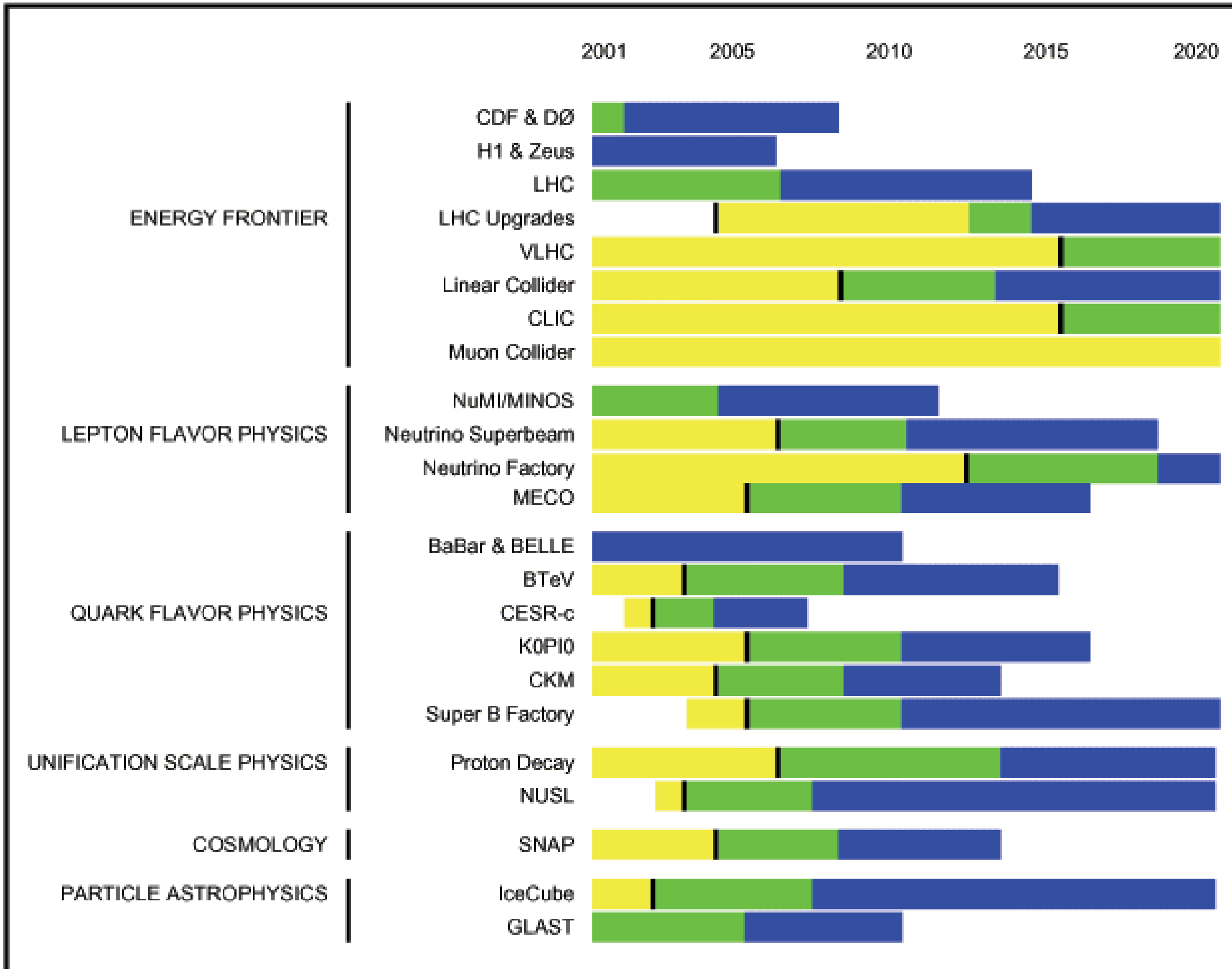
Backup slides

Additional slides start here

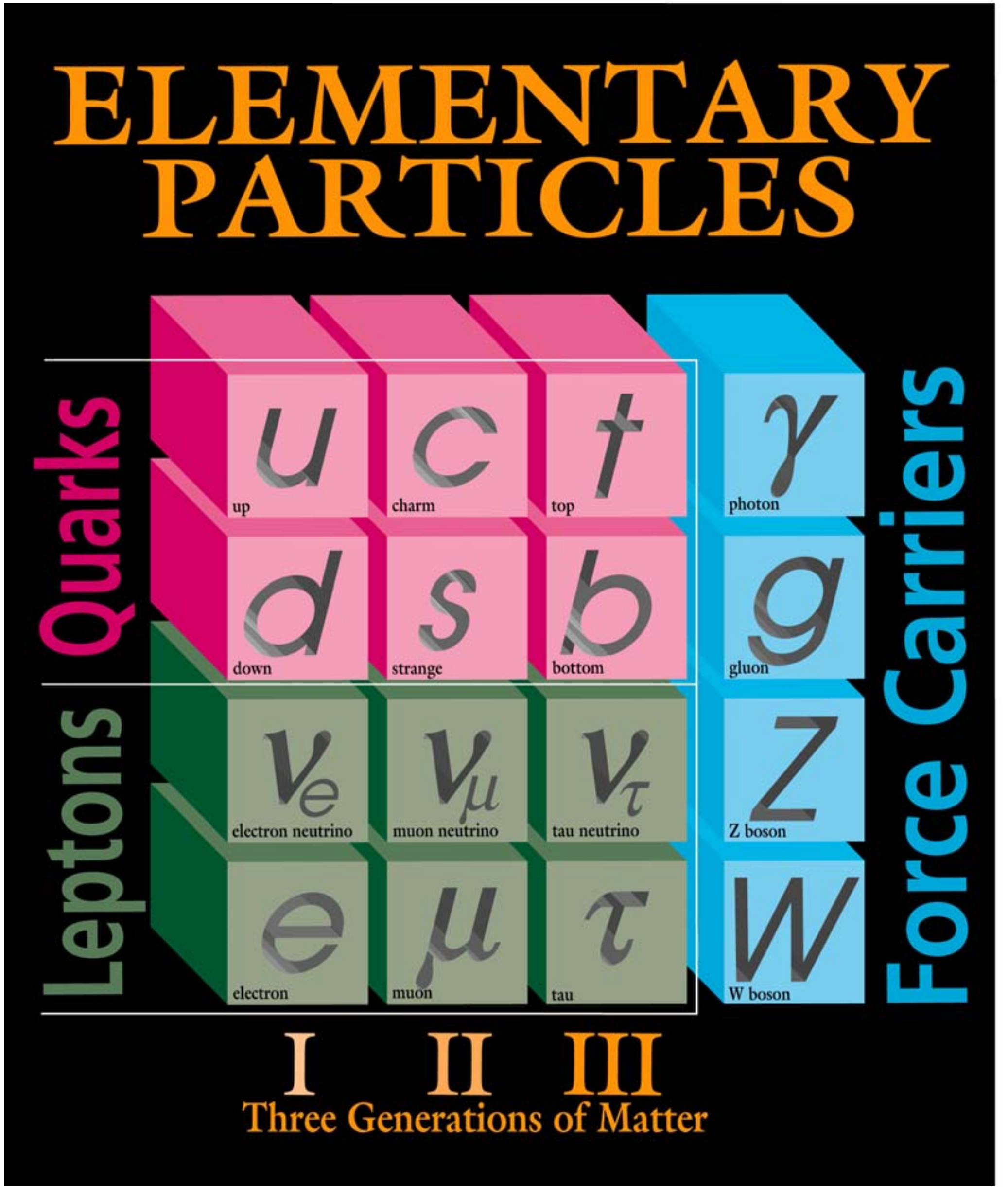


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
(sec.yrs)
(Kelvin)
(GeV)
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
e electron
ion
galaxy
m muon t tau
n neutrino
atom
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

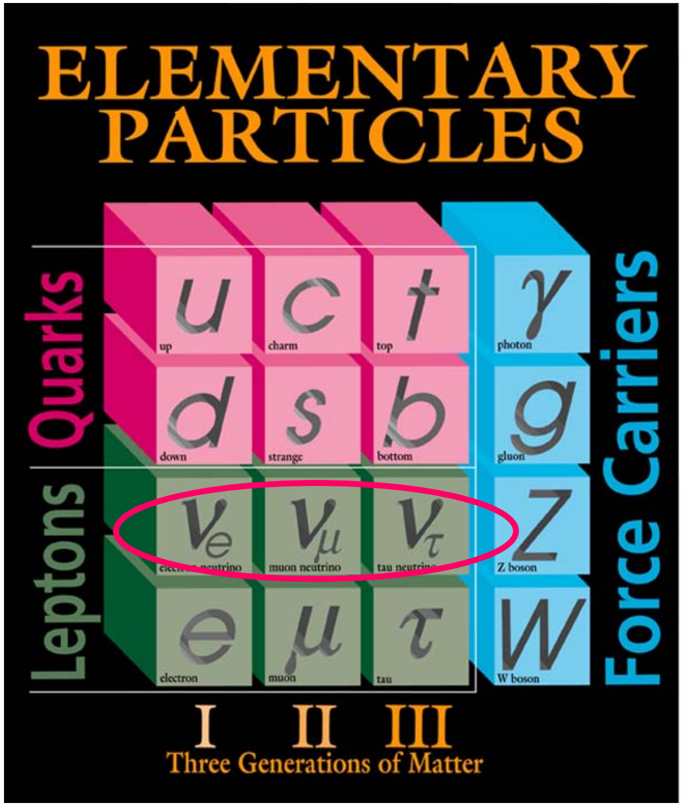
original roadmap

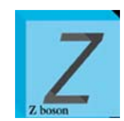


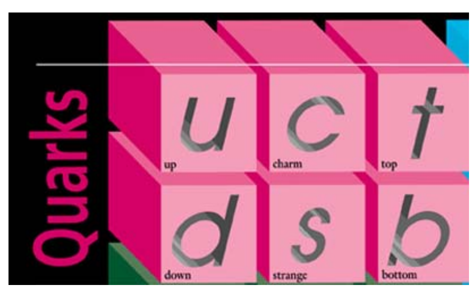
High Res Sm overview



ν oscillations





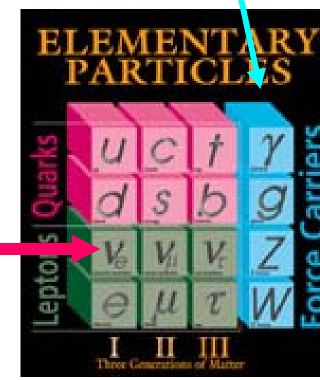


BIG open questions in particle physics

SUSY particles

Squarks ?
Sleptons
All the “ino’s”

Need direction from experiment



- EW symmetry breaking
- Beyond SM , new symmetries what are they ? SUSY, Higgs
- Generation of mass
- Composition of universe (dark mater, “dark energy”)
- Neutrino masses & oscillations (CP violation ?): just another oscillation
- CP violation I.e. why only matter where is antimatter ?

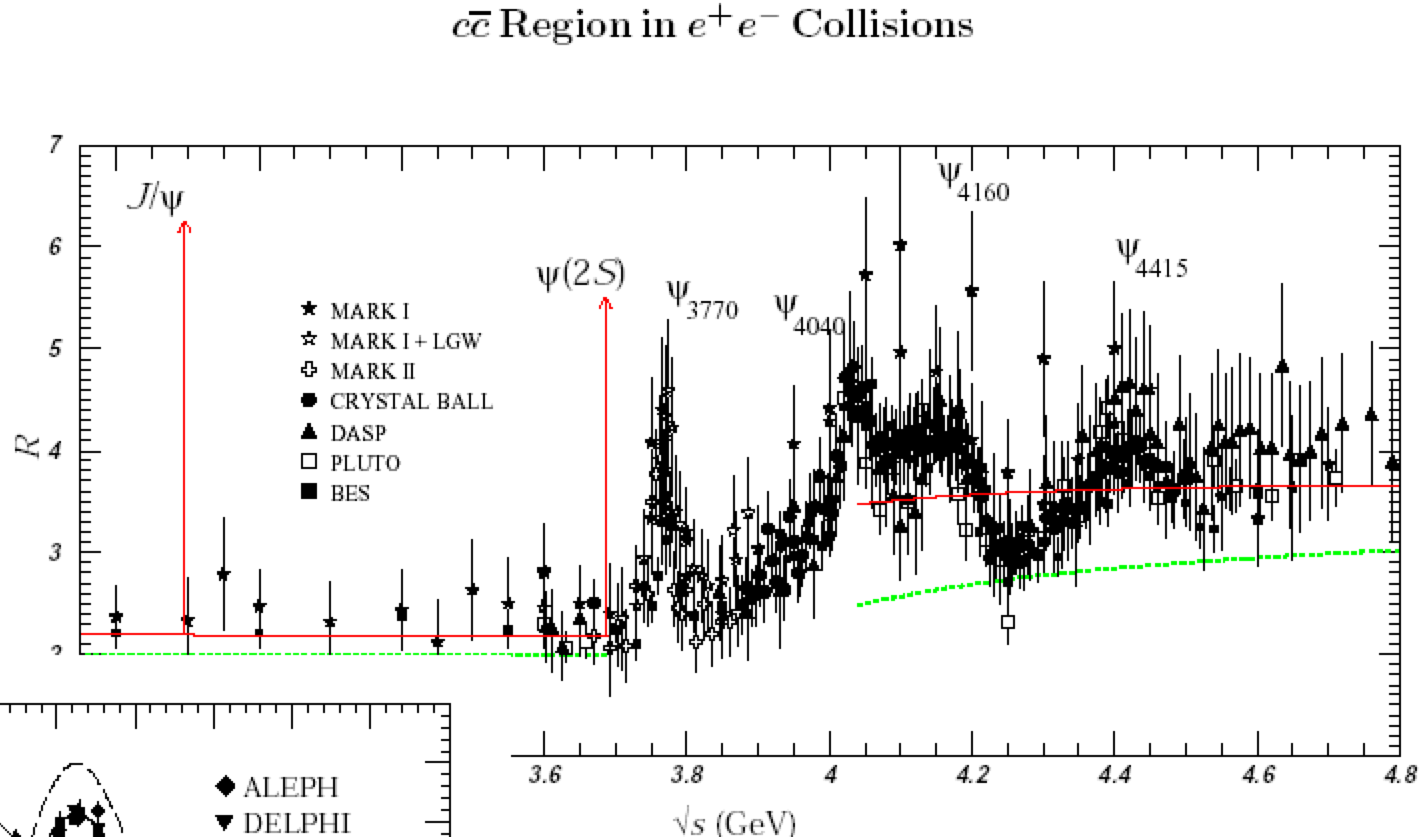
What for sure do we have in place and will run (gets us to ~2012-13)

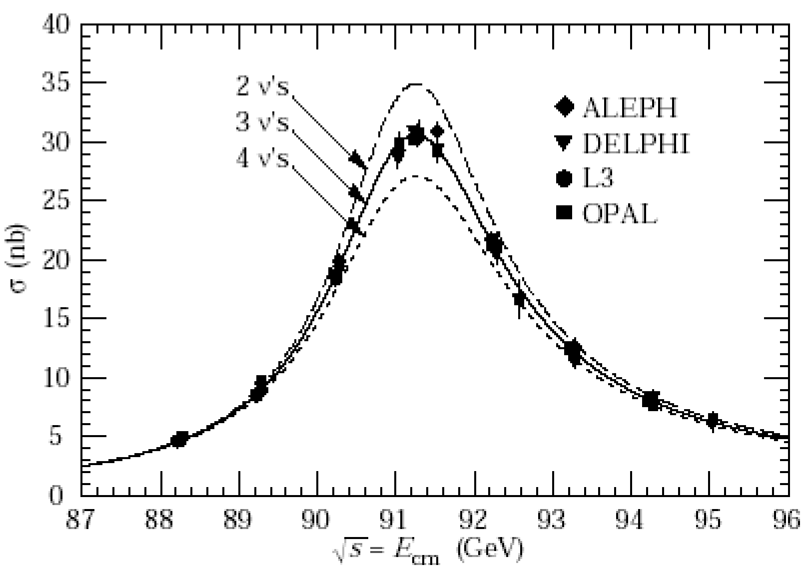
Relatively well defined program and long term program

What are our plans beyond yet

What are the plans of funding sources for us ?

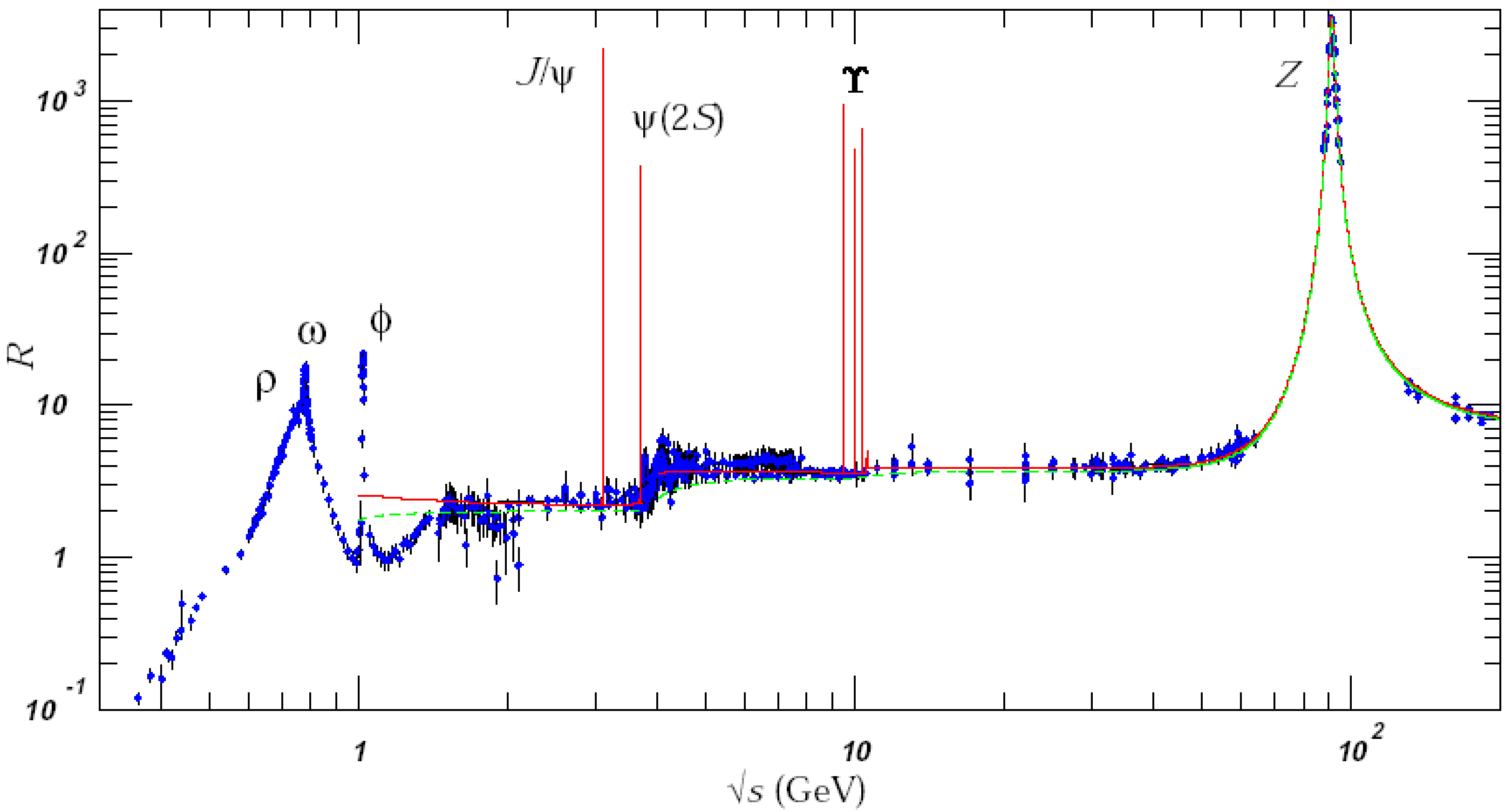
Difference in "energy frontier" expt's





H.

Backup e+e-



gure 39.6, Figure 39.7: World data on the total cross section of $e^+e^- \to hadrons$ and the ratio $R = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu$
CD simple pole). The curves are an educative guide. The solid curves are the 3-loop pQCD predictions for $\sigma(e^+e^- \to hadrons)$ and
ratio, respectively [see our Review on Quantum chromodynamics, Eq. (9.12)] or, for more details, K.G. Chetyrkin *et al.*, Nucl. Ph
586, 56 (2000), Eqs. (1)–(3)). Breit-Wigner parameterizations of J/ψ, $\psi(2S)$, and $\Upsilon(nS), n = 1..4$ are also shown. **Note:** The experim