WHY LHC?

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Contents

- Basic Constituents of Matter and their Interactions : Matter Fermions and Gauge Bosons (Std Model)
- High Energy Colliders
- Discovery of Std Model Particles at Colliders
- Higgs Mechanism : Higgs Search at LHC
- Supersymmetry : SUSY Search at LHC

(Natural units: $\hbar$ & $c = 1 \Rightarrow m = mc^2$, $m_p \approx 1$ GeV)

Basic Constituents of Matter

Mass (GeV)

Fermions (Spin = 1/2 ħ) e

Leptons ν_e ν_μ ν_τ 0

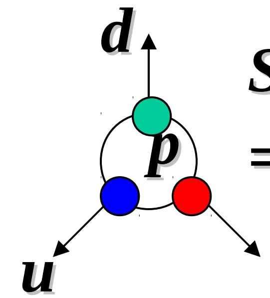
e .0005 μ 0.1 τ 1.8 -1

Quarks u 0.3 c 1.5t 175 2/3 d 0.3 s 0.5 b 5 -1/3

For each Pair : Δe = 1 => Weak Int

Quarks also carry Colour Charge (C)=>Strong Int

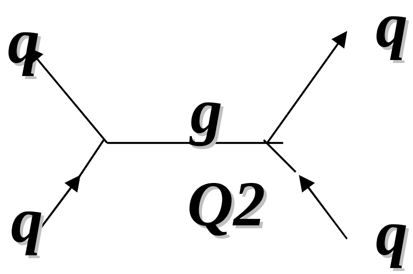
Basic Ints (Gauge Bosons & Groups)



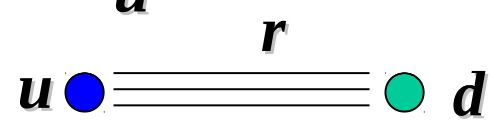
$SU(3) \Rightarrow C_g \Rightarrow ggg$ ***Int***

=> Confinement

1. Strong Int (QCD) :SU(3)

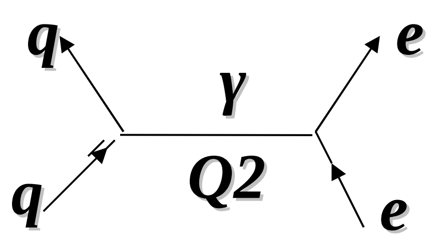


$C_q{}^2 \alpha_s / Q^2$

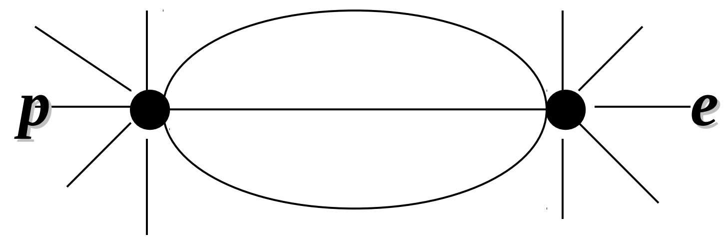


$F = \text{Constant} \Rightarrow V \rightarrow r$

2. E.M. Int (QED) :U(1)

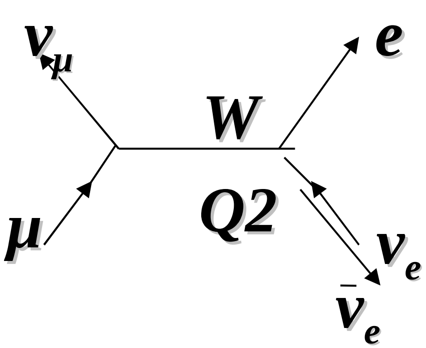


$e_q e_e\, \alpha / Q^2$



$F = \alpha/r^2 \Rightarrow V = \alpha/r$

3. Weak Int : SU(2)



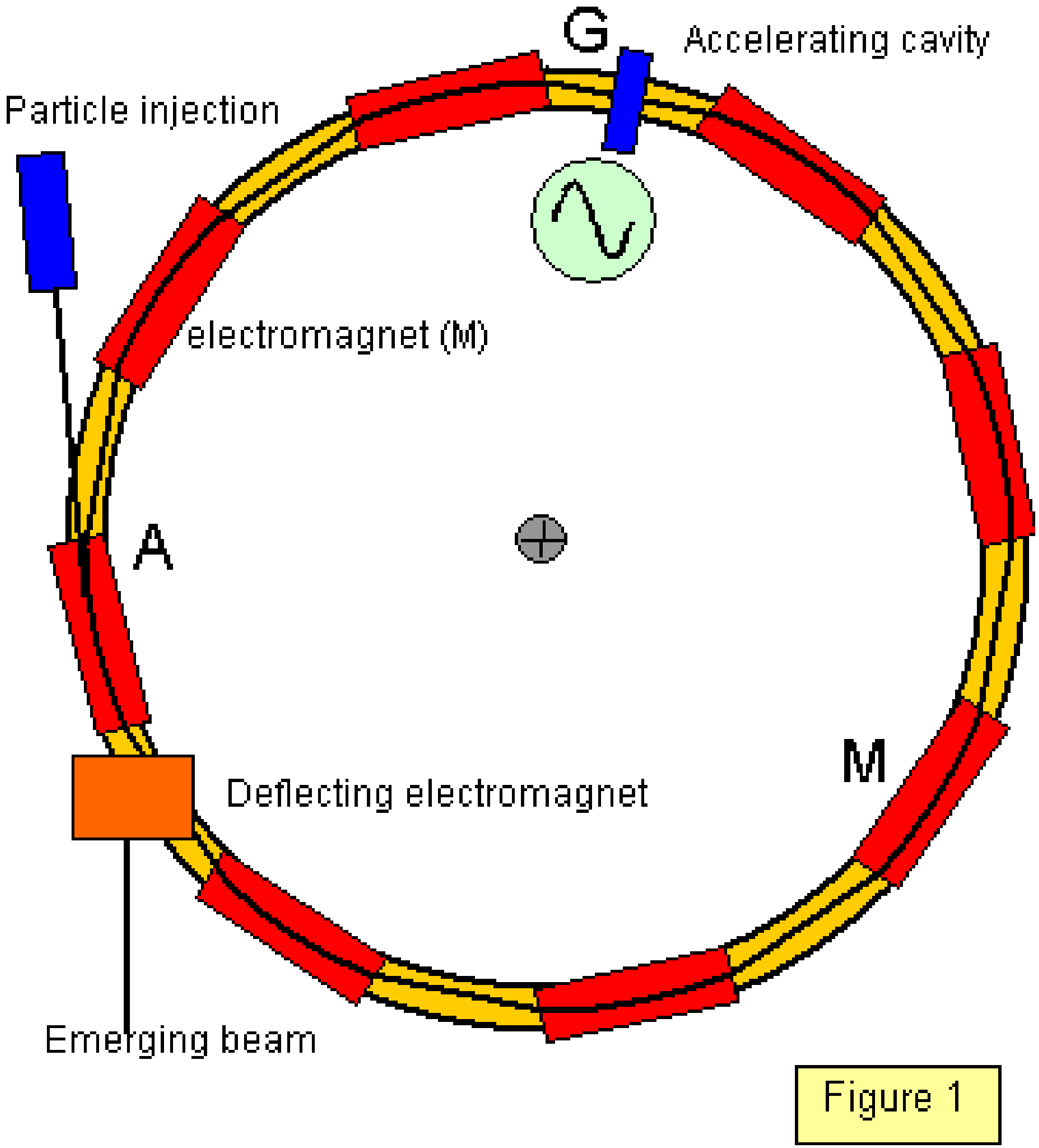
$\alpha_W / Q^2 - M_W{}^2 \quad \Rightarrow \quad V = (\alpha/r) \,.\, \text{Exp}\,(-r\, M_W)$

$\mu \longrightarrow e \nu_\mu \bar{\nu}_e \;:\; Q2 \ll M_W{}^2 \Rightarrow DA_\mu = \alpha_W / M_W{}^2$

SU(2)xU(1) EW Th (GSW) => $\alpha_W = \alpha/\sin^2\theta_W \approx 4\alpha$

=> DAμ ≈ $4\alpha/M_W^2$ => M_W=80 GeV, M_Z=91GeV

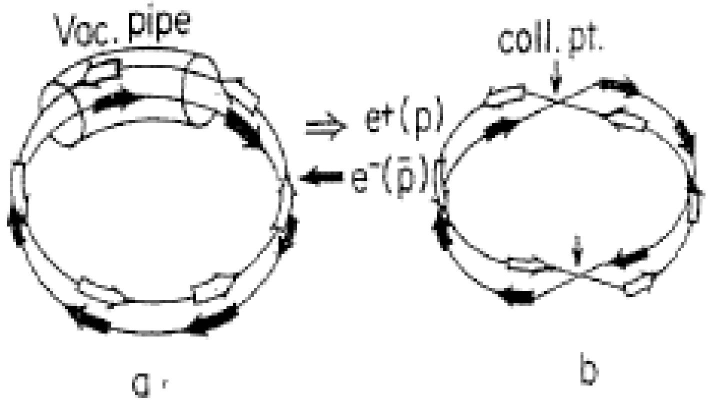
- p (uud), n (udd), e => All the Visible Matter
- Heavier Leptons & Quarks Decay by Weak Int
- They can be Observed in Accelerator or Cosmic ray
- Cosmic ray Observation of μ and k ($s\bar{u}$) in 1947
- νs are stable but very hard to Observe <= Weak Int
- ν_e Observed in Atomic Reactor Expt in 1956
- ν_μ in BNL PS in 1962 (KGF Cosmic ray in 1965)
- e^+e^- Collider : c (1974), τ (1975), b (1977), g (1979)
- p^-p Collider : W & Z (1983), t (1995), ν_τ (2000) FT



$$eBv = mv^2/R$$
$$eB = mv/R$$

e^+e^- ($\bar{p}p$) Collider

Accleration Mode



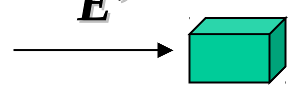
Collision Mode

Advantage of Collider over Fixed Target Accelerator

E ***E***

$$\sqrt{s} = 2E$$

E'



$$\sqrt{s} = \sqrt{2mE'}$$

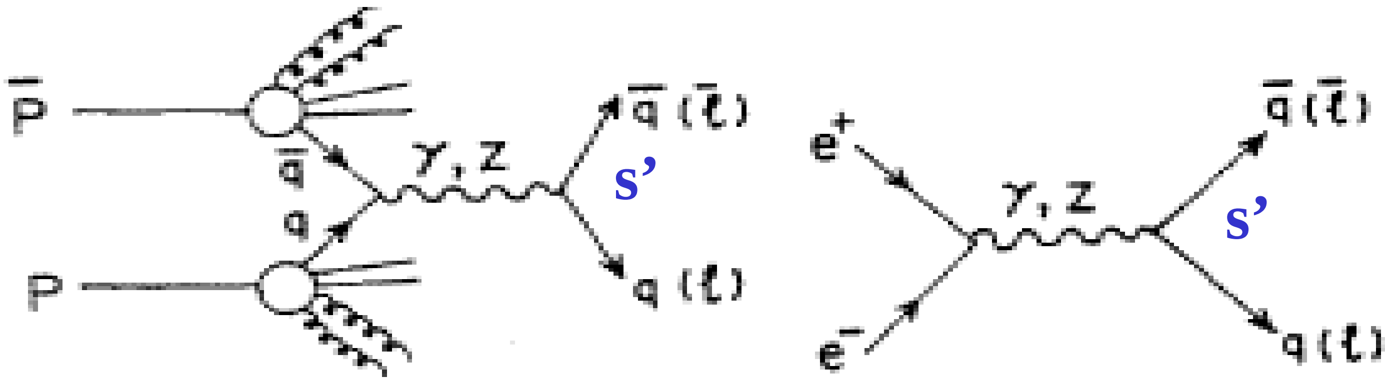
Tevatron $\bar{p}p$ Collider

$$\sqrt{s} = 2\times1000GeV$$

$1TeV$

$$E'_{Equiv} = \frac{s}{2m_p} = \frac{(2000GeV)^2}{2\times1GeV} = 2000{,}000GeV$$

p^-p Collider vs e^+e^- Collider



$s' \sim \langle x_q \rangle^2 s_{p^-p}$ $\quad$ $s' = s_{e\,e+}$

1/6

$$Same\sqrt{s'} \Rightarrow \sqrt{s_{\bar{p}p}} \approx 6\sqrt{s_{ee^+}} : \Delta E_{Sync} \approx \frac{4\pi.e^2 E^4}{3m_e{}^4\rho}$$

$$\sqrt{s'} \approx M_Z \approx 100GeV : \sqrt{s_{\bar{p}p}} \approx 600GeV, \sqrt{s_{ee^+}} \approx 100GeV$$

CERN: p^-p Coll. (ρ = 1 km), LEP-I (ρ = 5 km)

COST: (200 + 100) million\$, 1 billion\$

Precission:Tune e^-e^+ Energy = M_Z => Higher Rate & Better Mass Res

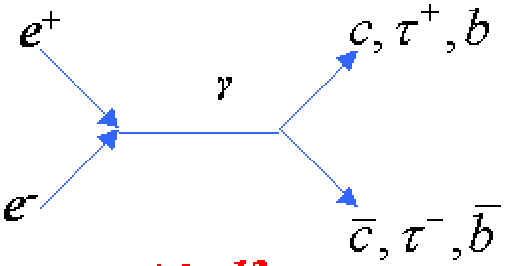
Z events/yr : LEP-I ~ 10^6, CERN p^-p Coll. ~ $10^{1\text{-}2}$

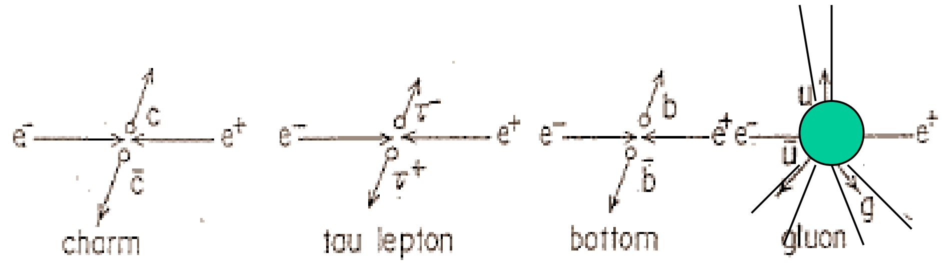
Signal : Clean , Dirty (Debris from Spectator q & g)

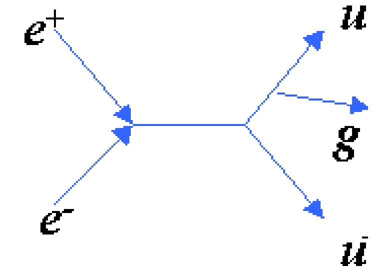
Past, Present & Proposed Colliders

Period	Machine	Location	Beam	Energy(GeV)	Radius	Highlight
70's	SPEAR	Stanford	e^+e^-	3 + 3		charm , τ
	DORIS	Hamburg		5 + 5		bottom
	CESR	Cornell		8 + 8	125 m	bottom
	PEP	Stanford		18+18		
	PETRA	Hamburg		22+22	300 m	gluon
80's	TRISTAN	Japan	e^+e^-	30+30		
	S$\bar{P}$PS	CERN	$\bar{p}\,p$	300+300	1 km	W,Z boson
90's	Tevatron	Fermilab	$\bar{p}\,p$	1000+1000		Top
	SLC	Stanford	e^+e^-	50+50		Z
	LEP-I	CERN		50+50	5 km	Z
	(LEP-II)			100+100		W
	HERA	Hamburg		30+800		
			e p			
2009	LHC	CERN	p p	7000+7000	5 km	Higgs,SUSY
2???	ILC	???	e^+e^-	500+500		

$\Leftrightarrow k_T \sim \hbar/1fm \sim 0.2$ GeV



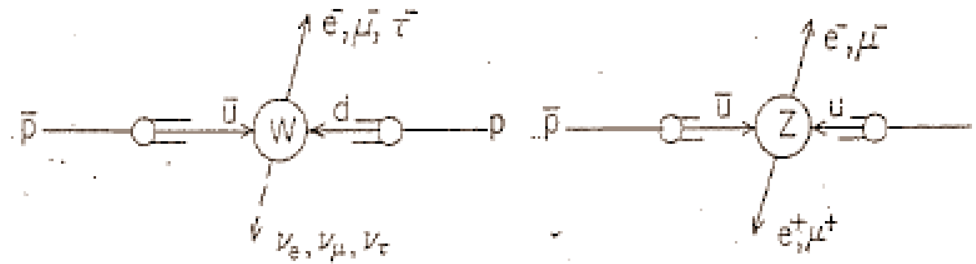




$\tau \sim 10^{-12}$s

$c\tau \sim 300\ \mu m$

3-jets

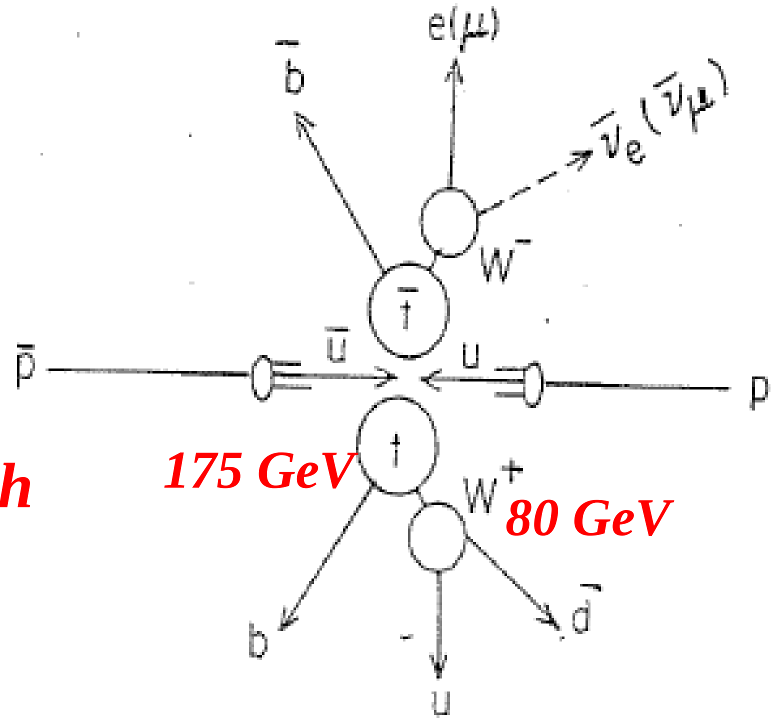


80 GeV   W & Z bosons   91 GeV

Hard e / μ ($p_T \sim 40$ GeV) with apparent p_T imbalance (missing - p_T)

Hard back-to-back e^+e^- / $\mu^+\mu^-$ ($p_T \sim 45$ GeV)

Hard Isolated e / μ with
3 - 4 Hard jets



Top pair production

Godbole, Pakvasa & Roy, Phys. Rev. Lett. 50, 1539 (1983)
Gupta & Roy, Z. Phys. C39, 417 (1988)

Mass Problem : Higgs Mechanism

How to give mass to the SU(2) Gauge Bosons w/o breaking Gauge Sym of the L ? For simplicity look at the U(1) Gauge Th (EM Int).

$$L_{EM} = (\partial_\mu - ieA_\mu)\overbrace{\phi^*}^{v+h}(\partial_\mu + ieA_\mu)\overbrace{\phi}^{v+h} - [\mu^2\phi^*\phi + \lambda(\phi^*\phi)^2] - \frac{1}{4}F_{\mu\nu}F_{\mu\nu}$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \Leftrightarrow E_{1..3}, B_{1..3}$$

$-M^2 A_\mu A_\mu$ (struck through)

$$GaugeTr: \phi \to e^{i\alpha(x)}\phi, A_\mu \to A_\mu + \frac{1}{e}\partial_\mu \alpha(x)$$

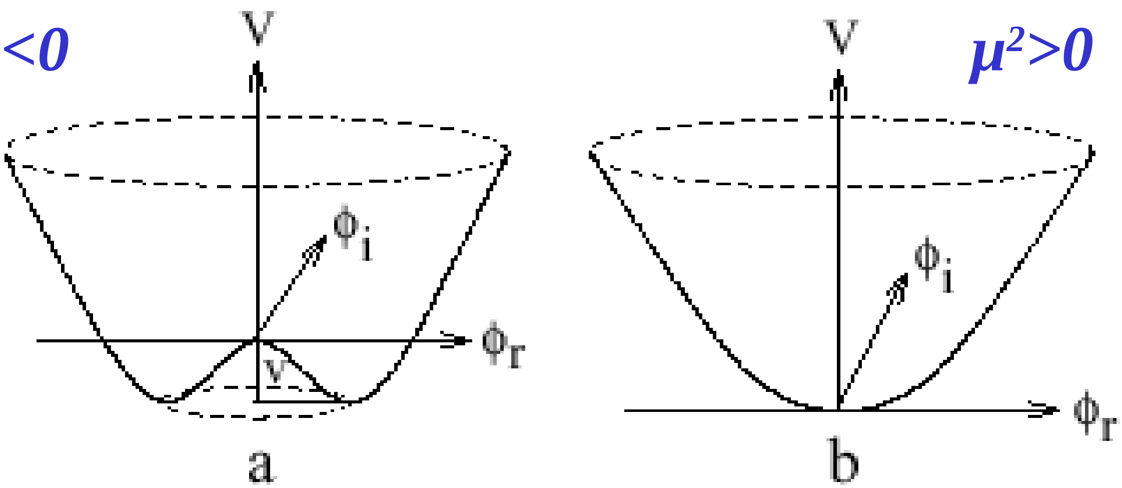
$$V = \mu^2\phi^*\phi + \lambda(\phi^*\phi)^2$$

$\mu^2<0$ ***$\mu^2>0$***

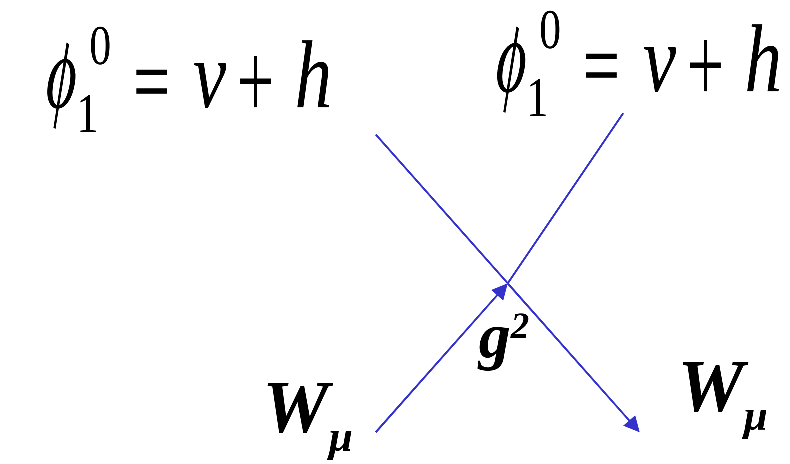
$$v = \sqrt{-\mu^2/\lambda}$$ **vev**

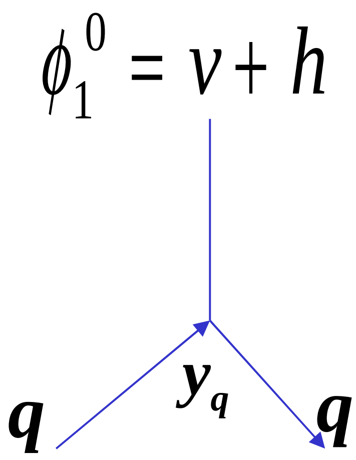
$$\Rightarrow \phi_r = v + h(x)$$

$$\Rightarrow M = ev$$ $\boldsymbol{m_q = y_q v}$



$$\Rightarrow m_h = \sqrt{-\mu^2} = \sqrt{\lambda}v = \sqrt{\lambda}/e \times M$$ ***~ 10^2 GeV***





$$\underbrace{g^2 v^2}_{M_W^2} W_\mu W_\mu + \underbrace{g^2 v}_{g M_W} h W_\mu W_\mu \qquad \underbrace{y_q v}_{m_q} \bar{q} q + \underbrace{y_q}_{m_q / v} h \bar{q} q$$

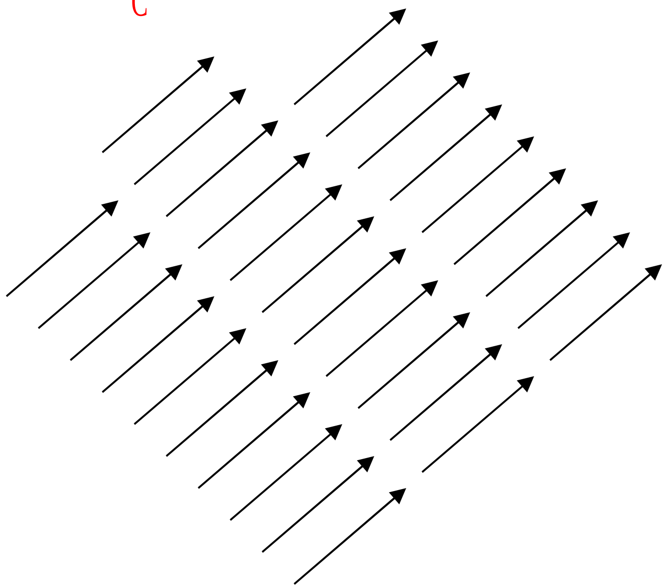
Higgs couplings to Particles is Proportional to their Mass =>Most Important Channels for Higgs Search are the Heavy Pairs: h (WW, ZZ, tt, bb, ττ) & $H^\pm$ (tb, τν)

τ Polarization Effect <= Roy, Phys.Lett.B459, 607 (1999)

Ferromagnetism

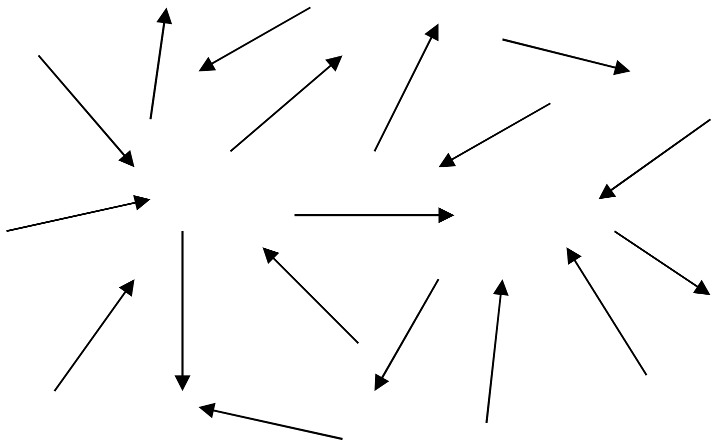
(Spontaneous Symmetry Breaking)

$T < T_C$

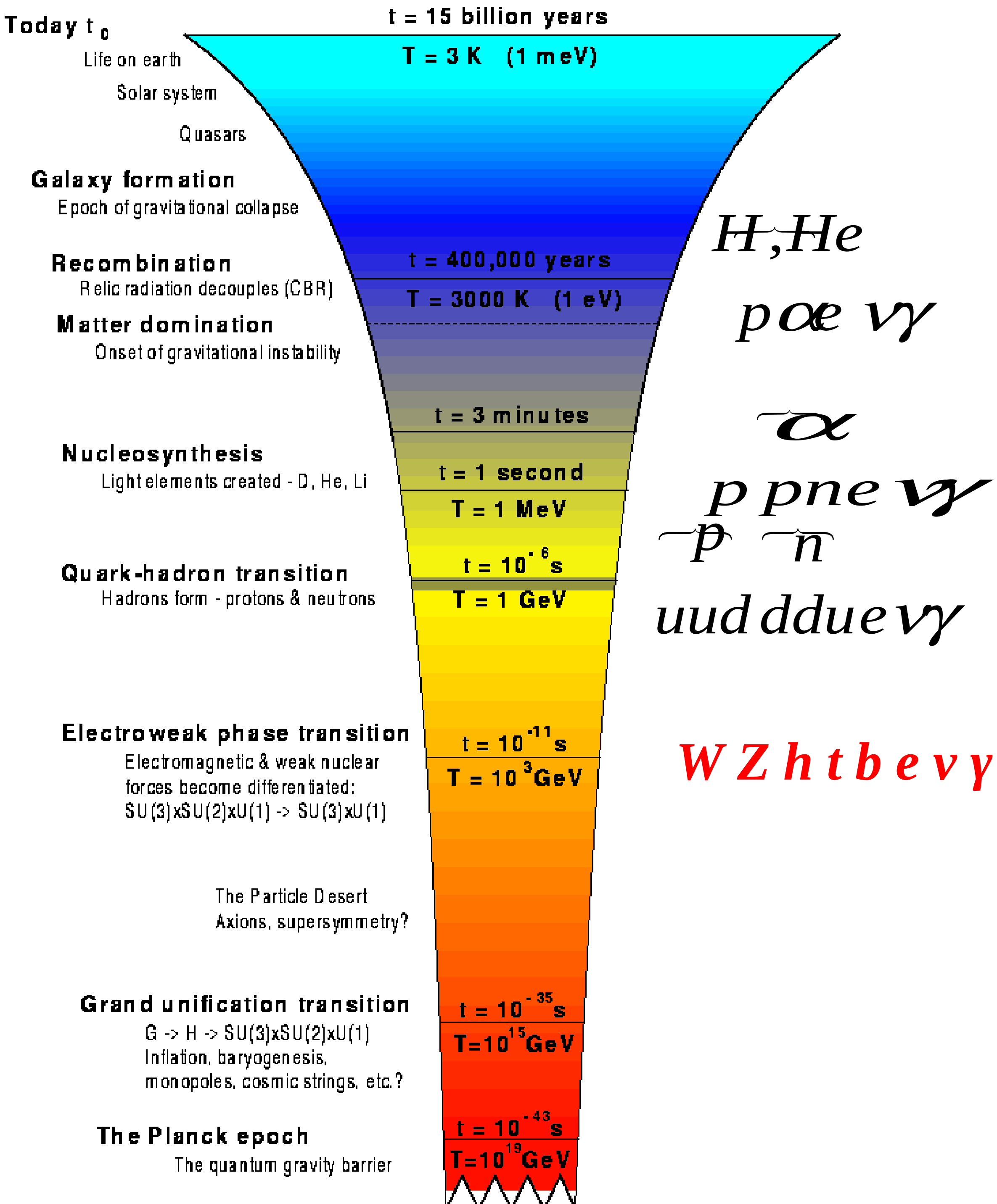


Rotational Symmetry Broken

$T > T_C$



Rotational Symmetry

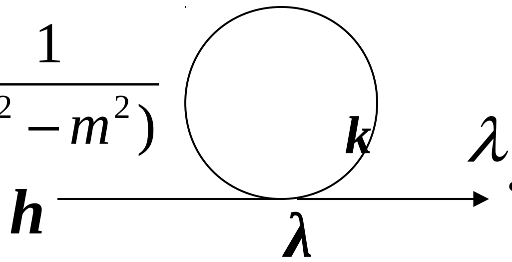


Today t_0
Life on earth
Solar system
Quasars
Galaxy formation
Epoch of gravitational collapse
Recombination
Relic radiation decouples (CBR)
Matter domination
Onset of gravitational instability
Nucleosynthesis
Light elements created - D, He, Li
Quark-hadron transition
Hadrons form - protons & neutrons
Electroweak phase transition
Electromagnetic & weak nuclear forces become differentiated:
SU(3)xSU(2)xU(1) -> SU(3)xU(1)
The Particle Desert
Axions, supersymmetry?
Grand unification transition
G -> H -> SU(3)xSU(2)xU(1)
Inflation, baryogenesis, monopoles, cosmic strings, etc.?
The Planck epoch
The quantum gravity barrier
t = 15 billion years
T = 3 K (1 meV)
t = 400,000 years
T = 3000 K (1 eV)
t = 3 minutes
t = 1 second
T = 1 MeV
$t = 10^{-6}$ s
T = 1 GeV
$t = 10^{-11}$ s
$T = 10^{3}$ GeV
$t = 10^{-35}$ s
$T=10^{15}$ GeV
$t = 10^{-43}$ s
$T=10^{19}$ GeV
H, He
$p\ \alpha\ e\ \nu\ \gamma$
$\bar{\alpha}$
$p\ p\ n\ e\ \nu\ \gamma$
$\bar{p}\ \bar{n}$
$u\ u\ d\ d\ d\ u\ e\ \nu\ \gamma$
$W\ Z\ h\ t\ b\ e\ \nu\ \gamma$

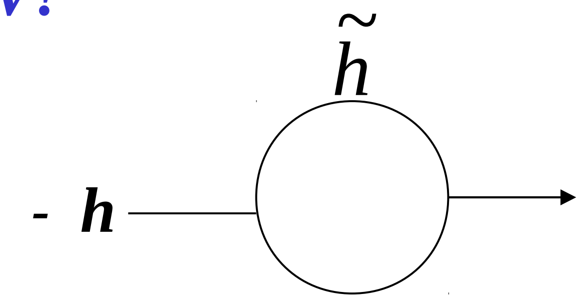
Hierarchy Problem: Supersymmetry (SUSY) Solution

How to control Higgs Mass $m_h \sim M_W \sim 10^2$ GeV?

$$\frac{1}{(k^2-m^2)}$$



$$\lambda\int\frac{k^3dk}{(k^2-m^2)}\propto k^2 \triangleright \infty$$



Without a protecting symmetry scalar mass gets quad. div. quantum corr. $\Rightarrow m_h \to \infty(M_{GUT}; M_{Plank})$

10^{16} 10^{19} ***GeV***

SUSY:
fermions<=>bosons

$$R=(-1)^{3B+L-2s}$$

	s		s		s	R
q,l	1/2	γ,g,W,Z	1	$h_{1,2}$	0	$+1$
$\tilde{q},\tilde{l}$	0	$\tilde{\gamma},\tilde{g},\tilde{W},\tilde{Z}$	1/2	$\tilde{h}_{1,2}$	1/2	-1

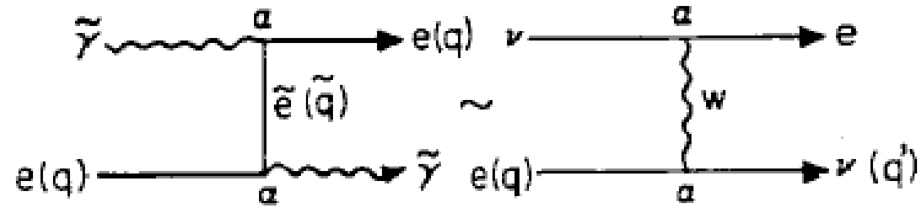
=> Superparticles mass ~ 10^2 GeV

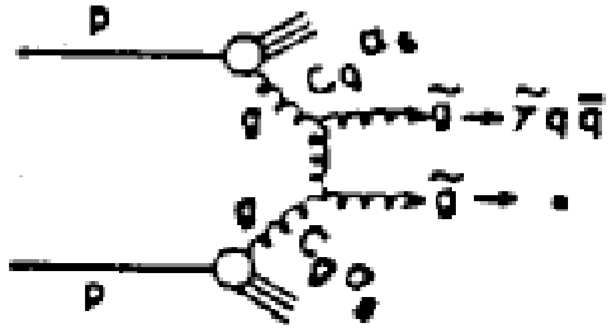
R Cons.=> Pair-prod of SP & Stable LSP (Cold dark matter)

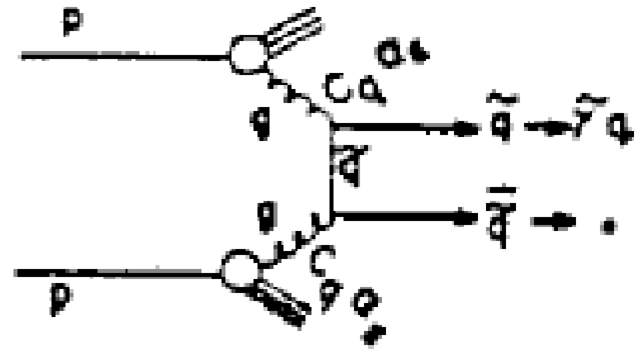
LSP $\tilde{\gamma}$ Weakly Int Massive Particle (WIMP)

$$M_{\tilde{e},\tilde{q}} \approx M_W$$

=> LSP escapes detection like ν
=> Apparent imbalance of P_T
(Missing-P_T Signature)







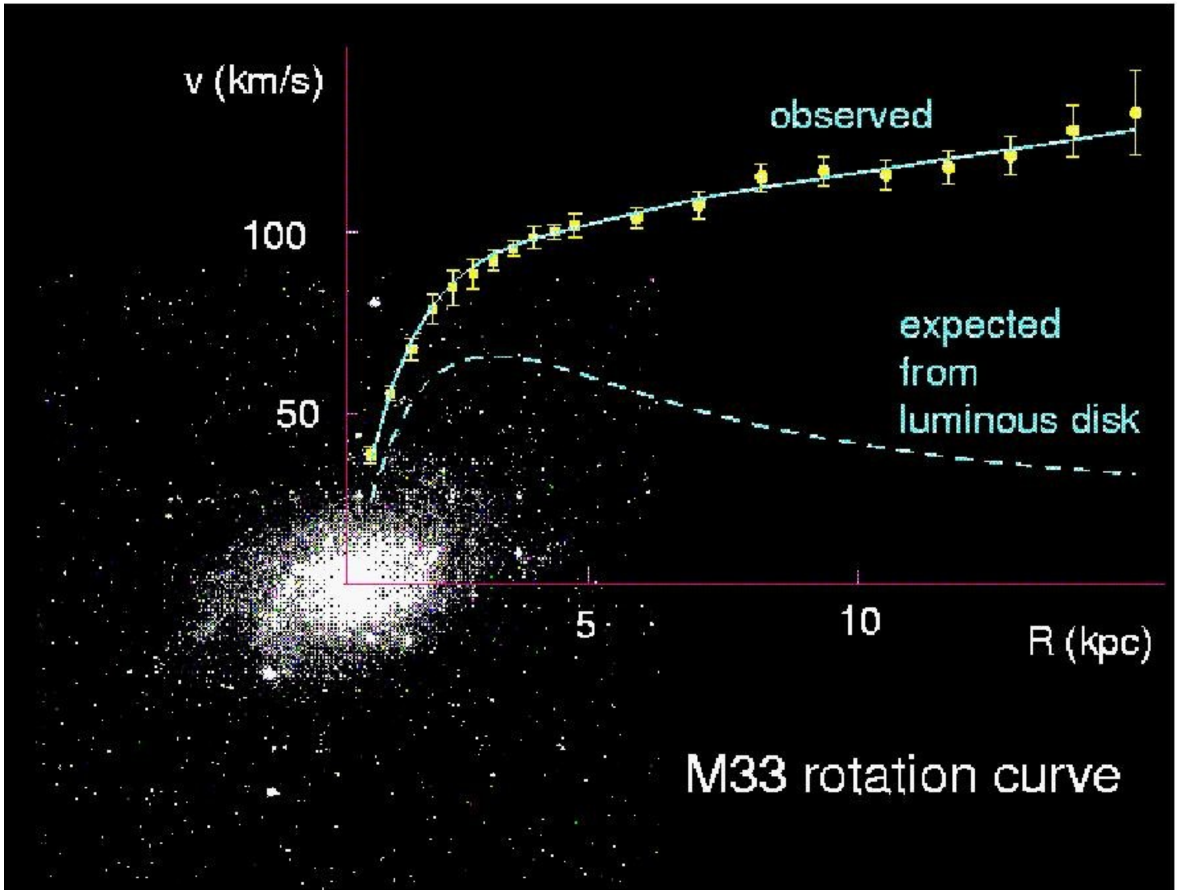
Pair production of Gluinos and Squarks at LHC
=> Multi-jet plus Missing-P_T Signature for SUSY

Reya & Roy, Phys. Lett. 141B, 442 (1984); Phys. Rev. Lett. 53, 881 (1984)

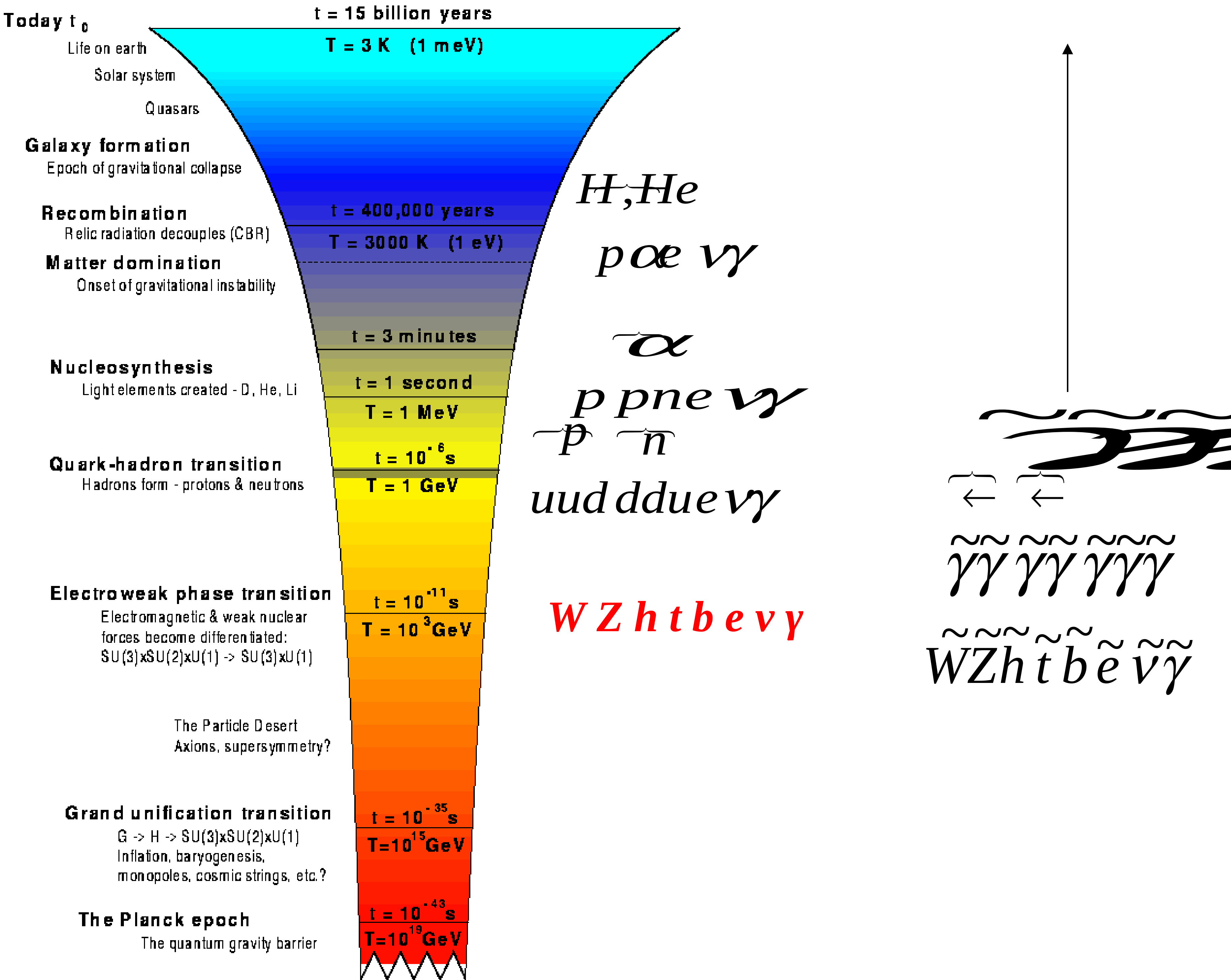
Conclusion

- Higgs & Superparticles are the minimal set of missing pieces reqd. complete the picture of particle physics (MSSM).
- LHC offers comprehensive Higgs and Superparticle search up to $M_{H,SUSY}$= 1000GeV.
- It will either complete the picture a la MSSM or provide valuable clue for an alternative picture : Little Higgs, Extra Dim, ETC...↓
- LSP is leading candidate for the cosmic dark matter ~ 10 times the baryonic matter of the Universe.

Rotation curve of nearby dwarf spiral galaxy M33, superimposed on its optical image



$$\frac{v^2}{R} = G\frac{M(R)}{R^2} \Rightarrow v \propto \sqrt{\frac{M(R)}{R}}$$



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