

PARTICLE PHYSICS FROM A WARPED EXTRA DIMENSION

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Outline

- ❖ My introduction
- ❖ Review of SM
- ❖ “Problems” of SM: Planck-weak and flavor hierarchies
- ❖ basics of **general extra** dimension: -
 - tower of new (Kaluza-Klein) particles / modes from 4D viewpoint
- ❖ **warped** / curved extra dimension:
 - solution to hierarchy problem
 - solution to flavor puzzle
- ❖ LHC **signals**: multi-TeV KK resonances decaying into **boosted** top quarks / W / Z / Higgs

My trajectory

- B. Tech in Electrical **Engineering** from IIT Bombay
- Ph.D. in **Physics** from UC, Berkeley
- **Postdocs** at U. of Oregon, Johns Hopkins U., IAS (Princeton)
- Assistant **professor** at Syracuse U.
- Assistant → Full professor @ UMD

I am a theorist...

...but don't we know theory already:
Standard Model (**SM**) of Particle Physics?!

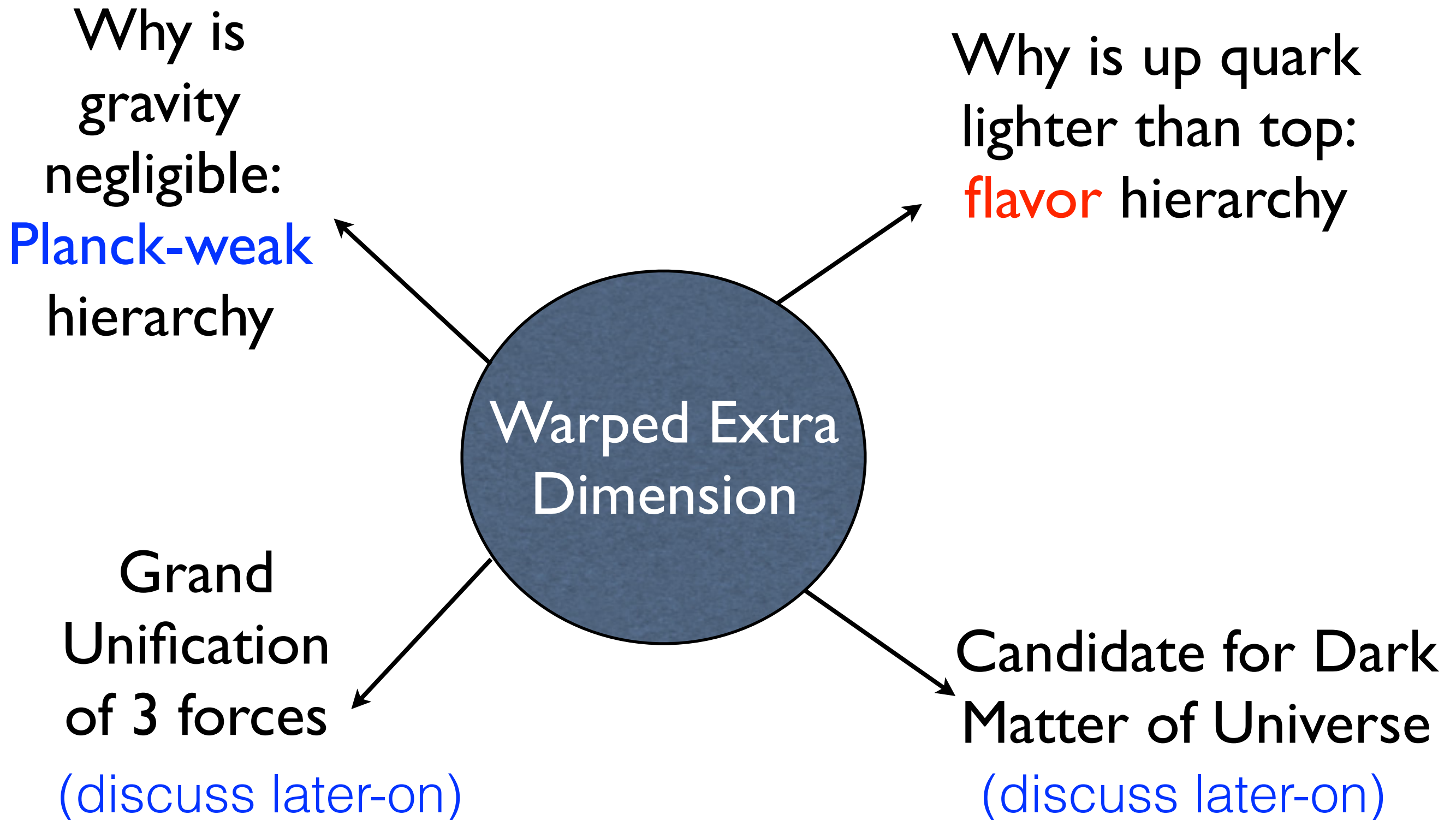
BSM theorist (I)

- SM highly successful in accounting for observations
- However, SM has “problems”: Planck-weak and flavor hierarchies → go **beyond**/extend SM...but how?!

BSM theorist (II)

- SM tested **directly** only up to $\sim$ **TeV** (=1000 GeV, 1 GeV = mass of proton $\times c^2$) energies
- At $E > \text{TeV}$ (distances shorter than 10^{-19} m), replace it by new theory, **reducing** to SM (effective theory) **below** TeV
- like special theory of relativity reduces to Galilean for speeds $\ll c$ or quantum mechanics to classical at distances smaller than atomic
- one such BSM here: **warped extra** dimension!

Open questions of Standard Model of Particle Physics...addressed by warped extra dimension

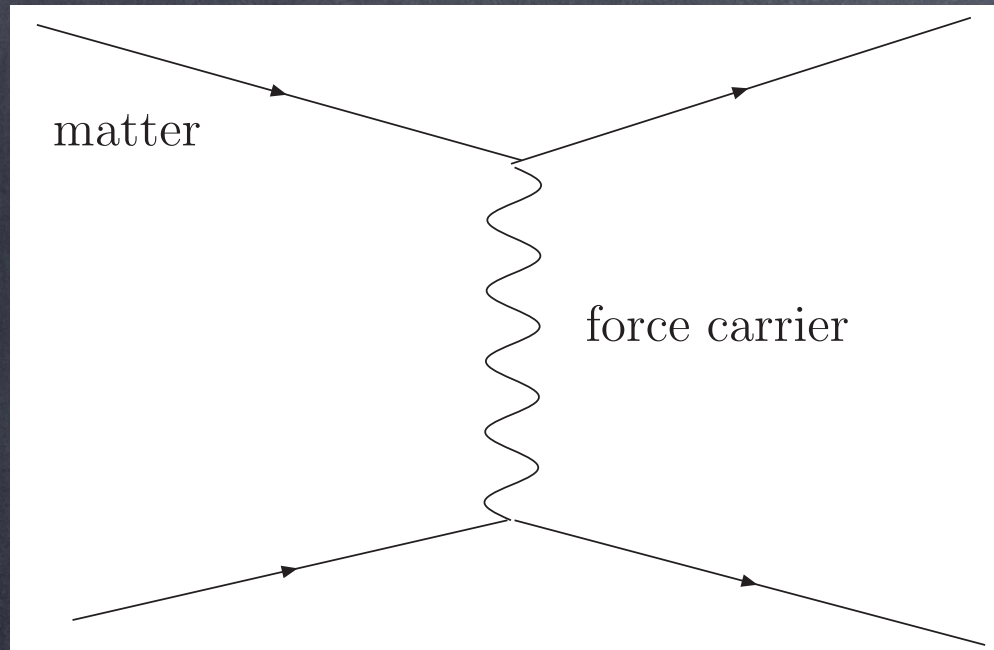


Range of experiments will test...

Review of Standard Model (SM)

Theory of interactions of elementary particles

- Forces due to exchange of spin-1 gauge bosons



(Feynman diagram)

strong	EM	weak
gluon	photon	W, Z

- Fermionic (spin-1/2) matter

Quarks (strong interactions)

“flavors”

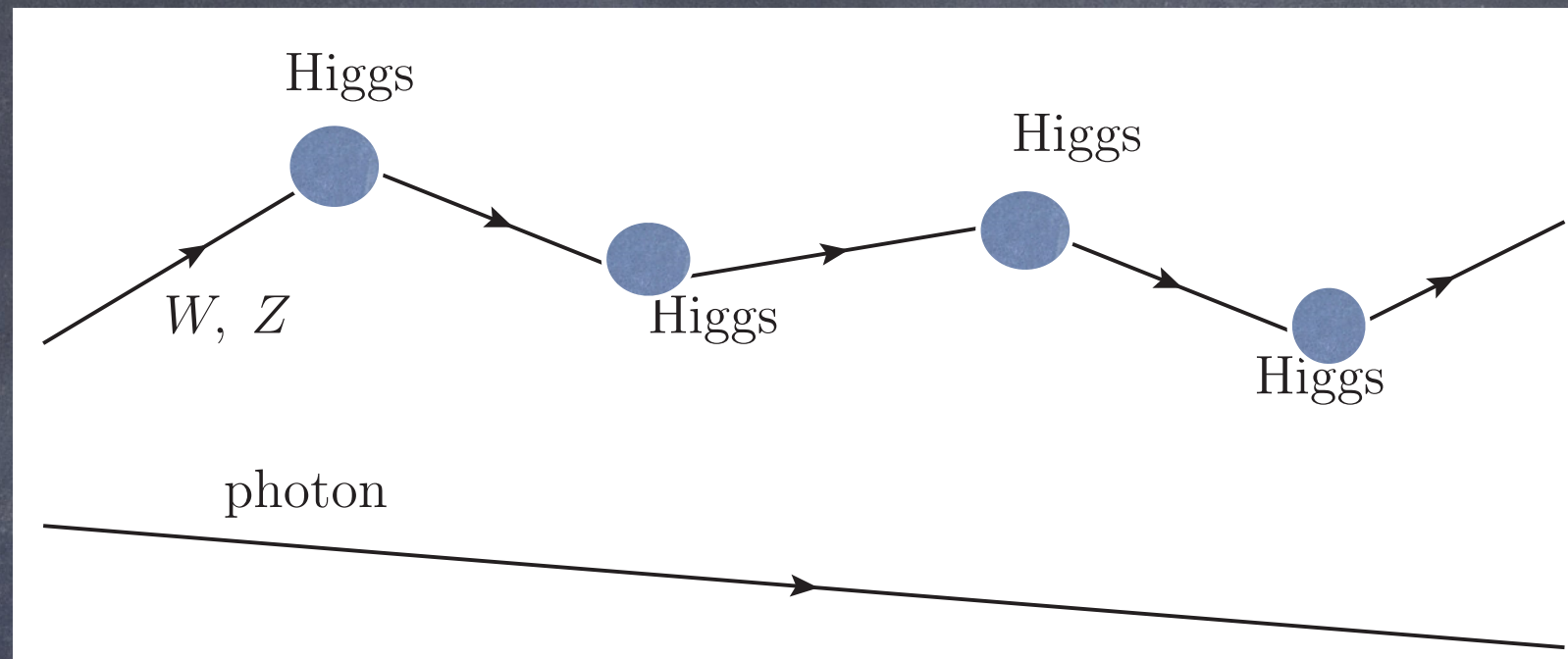
$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$$

leptons (no strong force)

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Higgs boson (origin of masses...)

- EM and Weak unified into **ElectroWeak** force



- **W, Z** massive (**short** range for weak force) via coupling to Higgs (spin-0) **condensate** (in vacuum)
- **photon** mass**less** (Higgs condensate is **neutral**)

(a la **superconductor**: massive **photon** via coupling to condensate of Cooper pairs)

Size of Higgs condensate

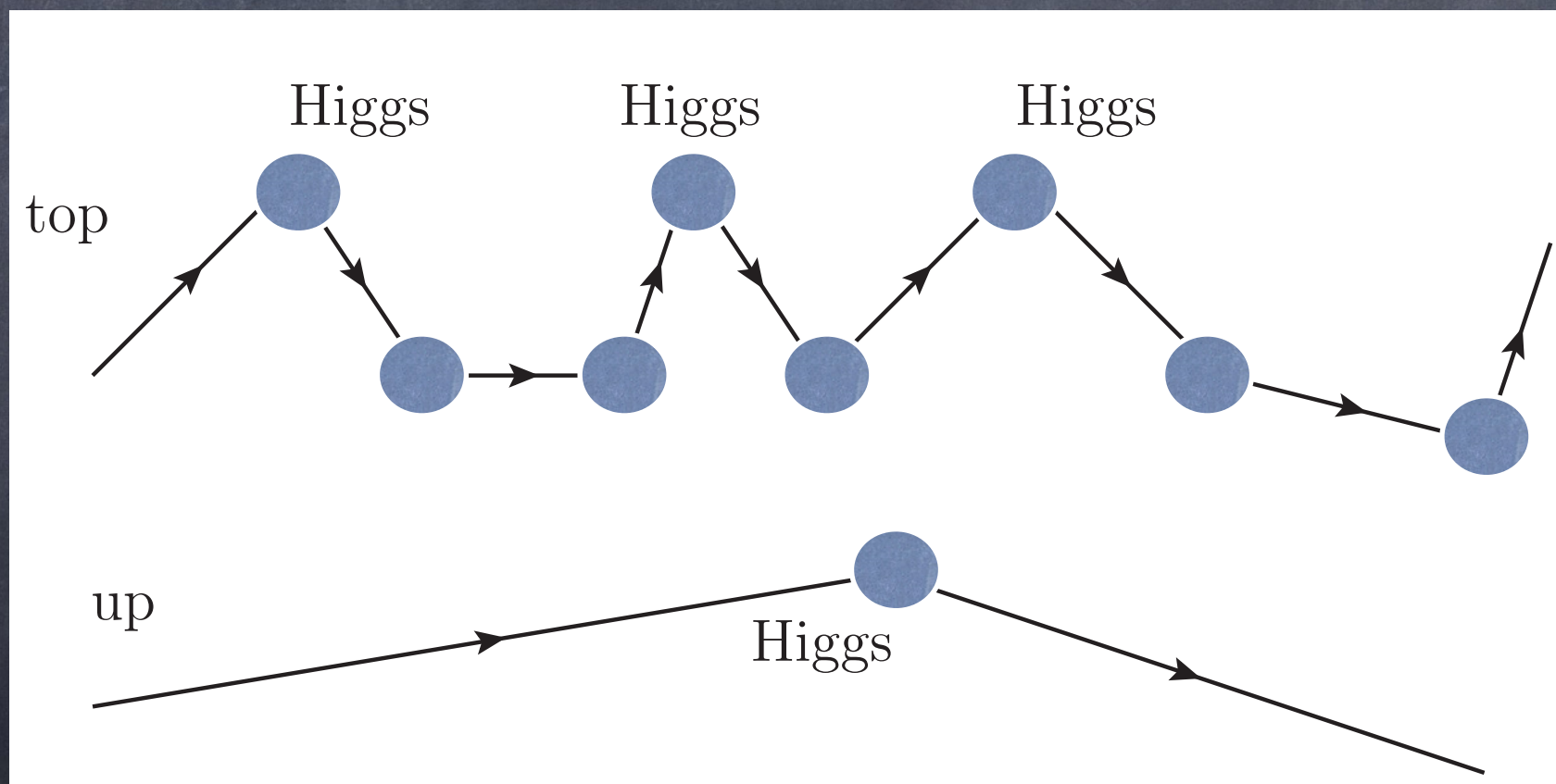
• Mass $\sim$ condensate $\times$ coupling



dimensionless
($\hbar = 2\pi$, $c = 1$)

Condensate $M_{weak} \sim 100$ GeV from W,Z masses and couplings

• Fermions: Top (up quark) is heavy (light) due to large (small) coupling to Higgs condensate



• $M_{weak} \sim$ mass scale of heaviest SM particles

• reach of current colliders (LHC) $\sim$ several TeV

(1 TeV =
1000 GeV)

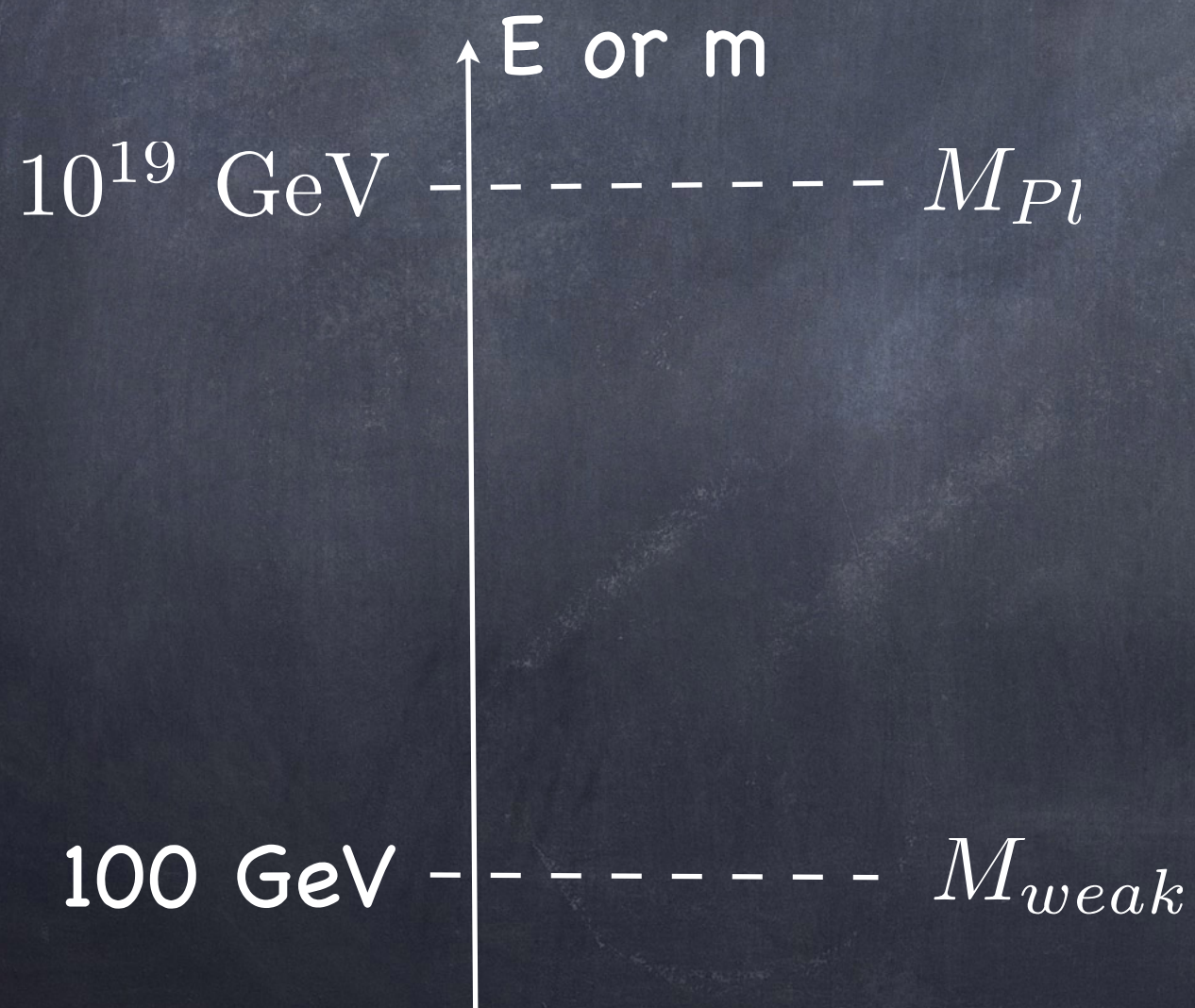
Planck-weak hierarchy
Problem

Hint for (much) **higher** mass scales

• Quantum **gravity** $\longrightarrow$ **new** physics at

$$M_{Pl} \sim \sqrt{\hbar c^5 G_N^{-1}} \sim 10^{19} \text{ GeV}$$

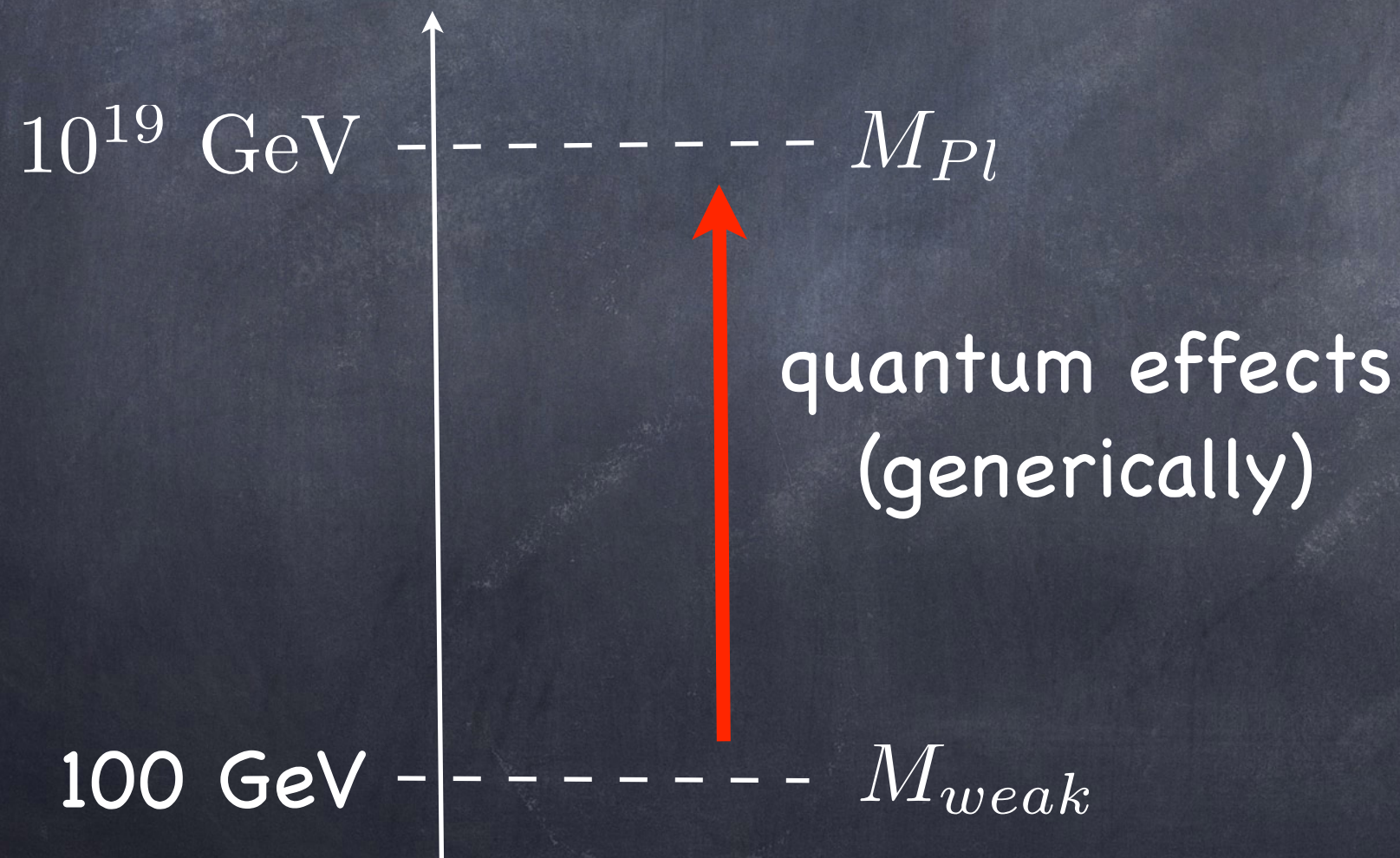
(Gravity is **super**-weak at low energies)



Higgs condensate $\longrightarrow$ higher scale

- Quantum corrections (spin-0) $\longrightarrow$

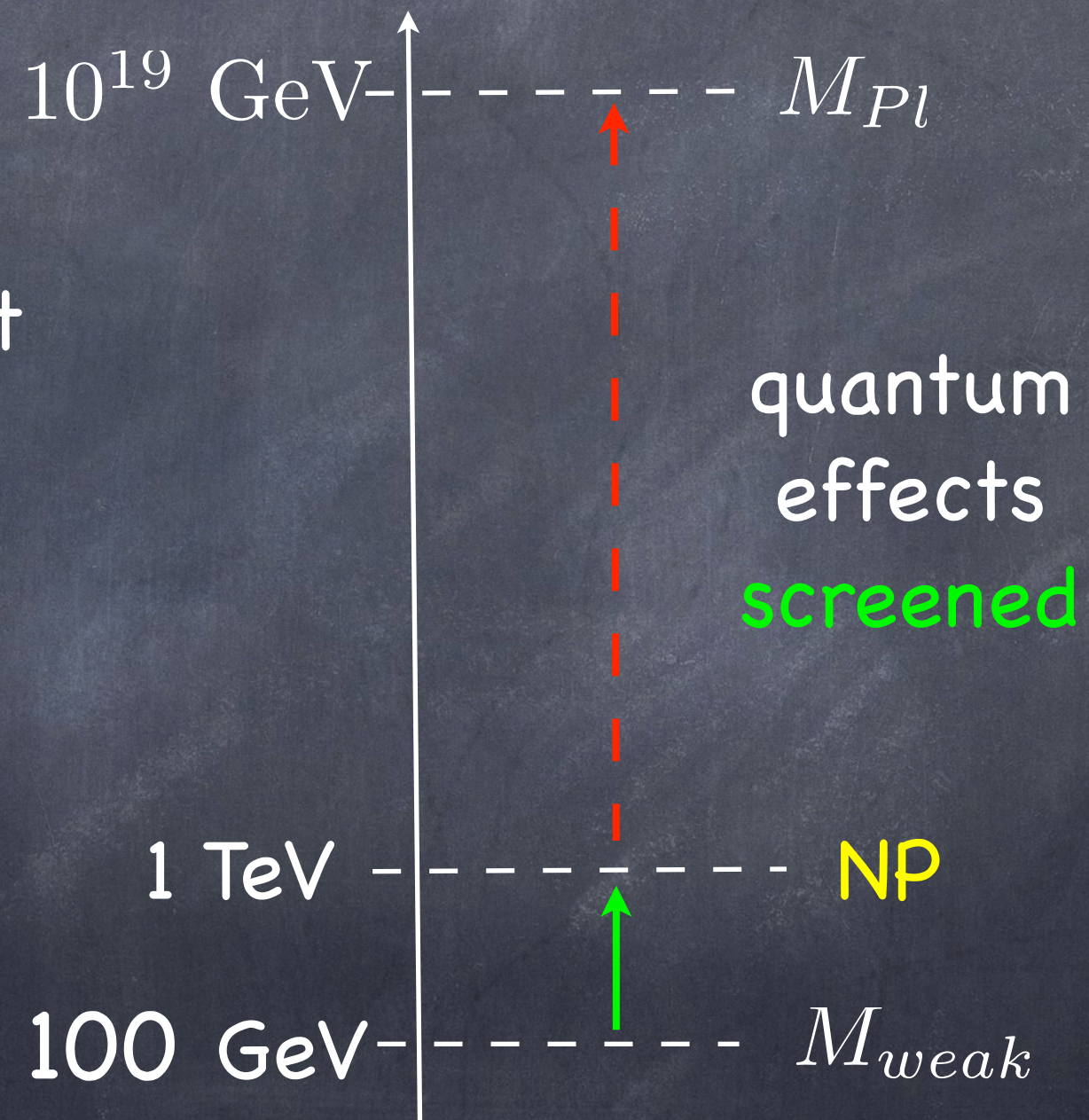
$M_{weak} \sim 100 \text{ GeV} \ll M_{Pl} \sim 10^{19} \text{ GeV}$ is unstable



- Biggest mystery for past several decades!

Solution to hierarchy problem

- New physics (NP) at **TeV** scale



Flavor Puzzle

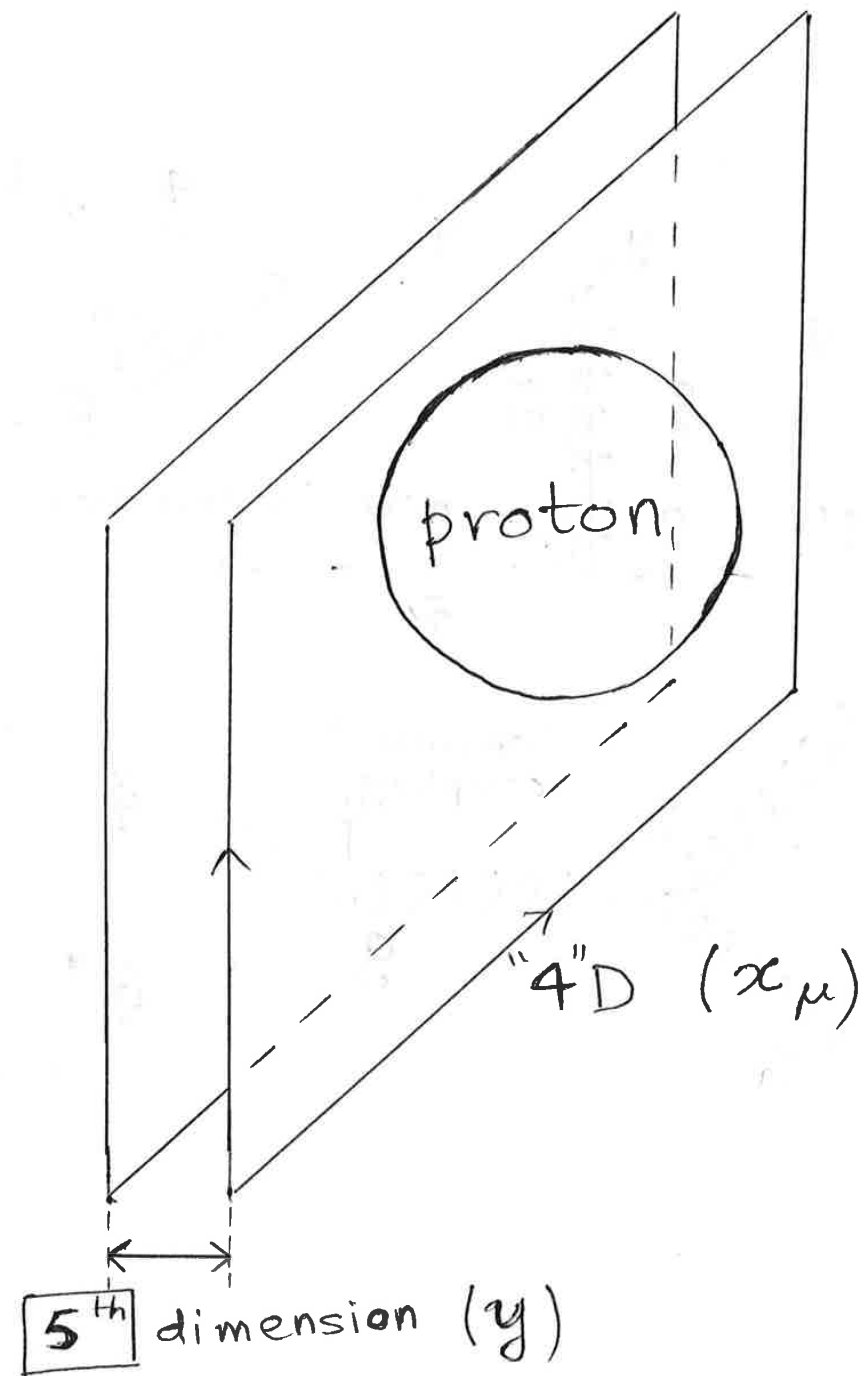
Hierarchical masses (coupling to Higgs) for 3 generations

- **same** strong, EM and weak forces
- masses (coupling to Higgs) hierarchical:
 $m_u \ll m_c \ll m_t$ (up-type, charge $+2/3$, quarks)
 $m_d \ll m_s \ll m_b$ (down-type, charge $-1/3$, quarks)
 $m_e \ll m_\mu \ll m_\tau$ (charge -1 leptons)

(General) extra
dimensión

Why haven't we "seen" it (yet)?

👁 It's small!



Why should it be compact/``small''?

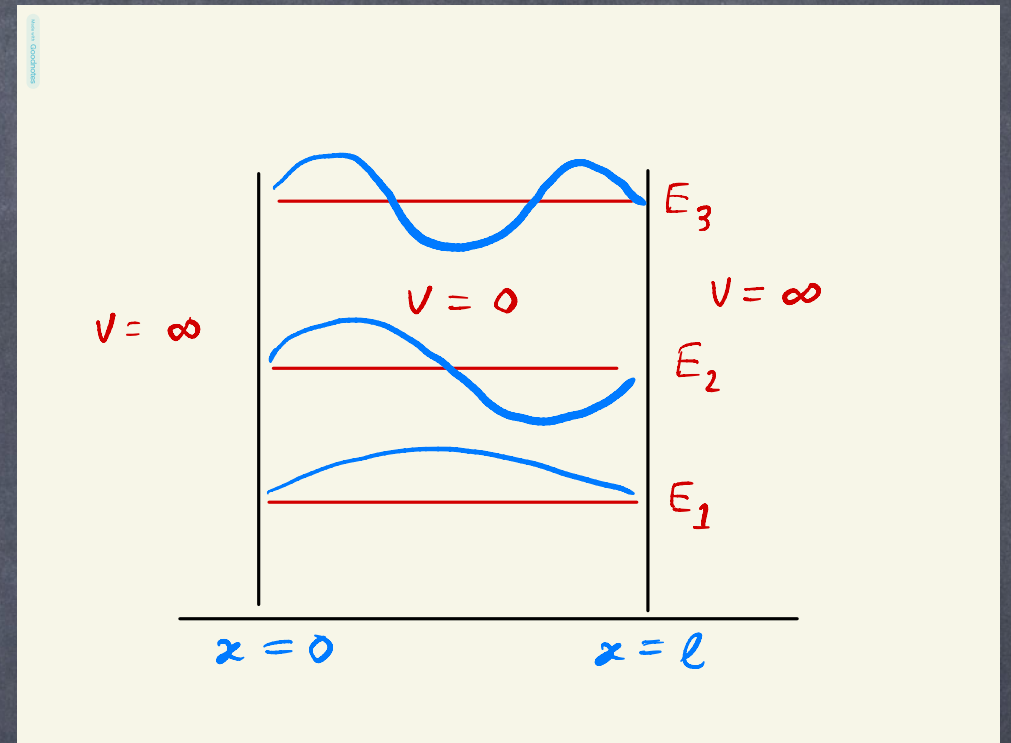
- If 5th dimension was infinite, **Newton's law** $\propto 1/r^3$
(Gauss' law)
- we have **measured** it to be $\propto 1/r^2$ down to $100 \mu\text{ m}$

What can we see in future (I)?

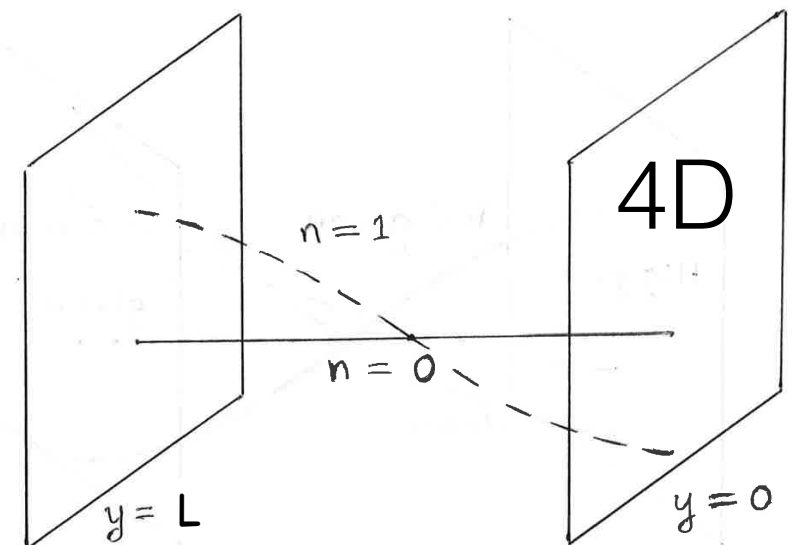
- **SM** field (x_μ, y) : Fourier expand (compact) y
- From 4D viewpoint, dynamics in y similar to **quantum mechanics** of particle in 1D infinite potential well

$$\psi_n(x) \propto \sin\left(\frac{n\pi x}{l}\right);$$
$$p_{x,n} \propto \frac{n\pi}{l}; E_n \propto \frac{n^2 \pi^2}{l^2}$$

- **Kaluza-Klein (KK)** modes (still function of x) with **profile in y** and **quantized** $p_5 \sim n/L$



flat...



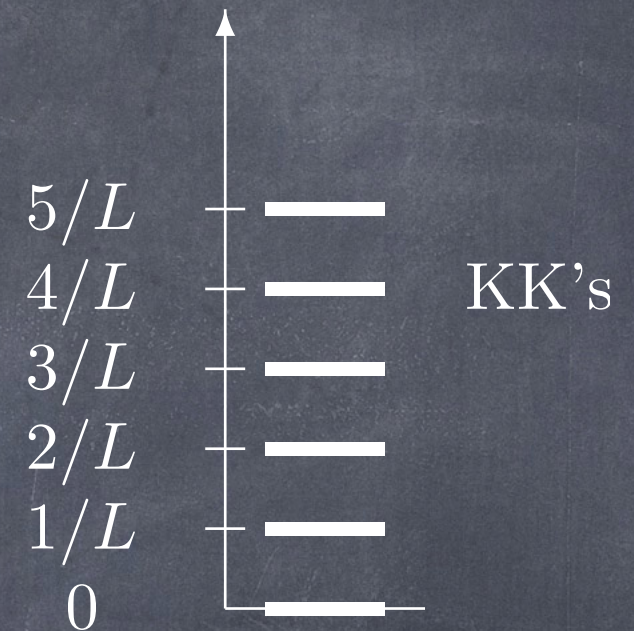
What can we see in future (II)? m_{4D}

$$E^2 = |\vec{p}|^2 + m_{4D}^2 \text{ becomes } \xrightarrow{\text{set to 0}}$$

$$E^2 = |\vec{p}|^2 + p_5^2 + M_{5D}^2 \Rightarrow$$

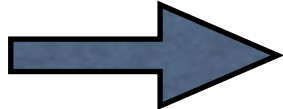
$$\vec{p} = 0 \text{ mode (at rest in 3D): } E \sim n/L \Rightarrow$$

$$(\text{rest}) \text{ mass, } m_{4D} \sim n/L$$



- Each **KK** mode like **massive** field (particle upon quantization) from **4D** viewpoint:
- p_5 "converted" to 4D mass
- lightest mode ($n = 0$) identified with **observed/SM**
- heavier (KK) modes ($n \neq 0$):
new particles (signals + solve problems)
- KK mass scale** $\gtrsim$ TeV, haven't seen it yet!

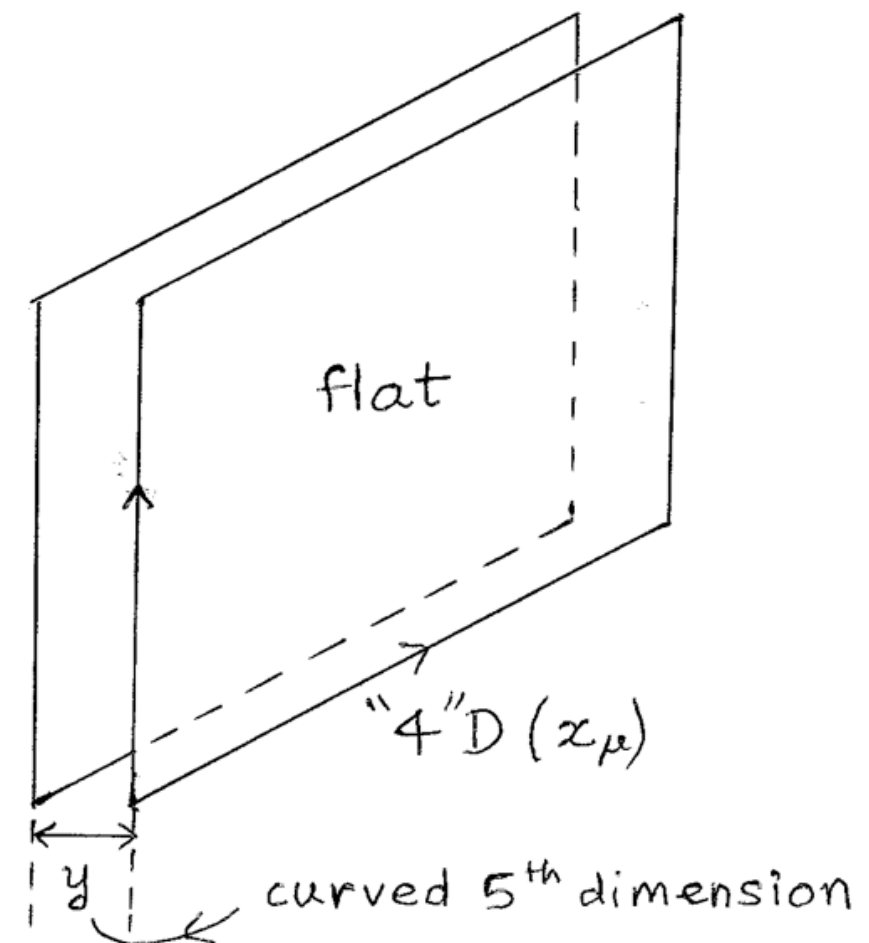
Summary

- 5D field  tower of (massive) KK modes
(from 4D viewpoint)
- profiles from (generalized) wave equation in 5D
space-time

Warped Extra Dimensión
(general)

Where's the curvature?

- Einstein: gravity is curvature of space-time: usual curvature extremely small, gravity very weak
- Warped space highly curved: curvature in extra dimension hidden if tiny in size or KK scale $> \text{TeV}$



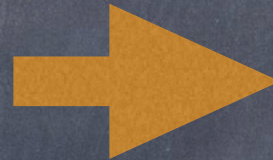
Warped extra dimension intuitively

- Analogy with expanding universe:

(flat) 3D space expands with time
("exponentially" for inflation: e^{N_e}
with $N_e \sim 60$)

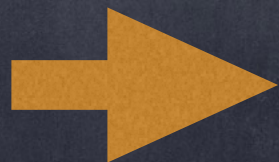
Nobel, '11 for
acceleration
now!

(4D space-time is curved!)

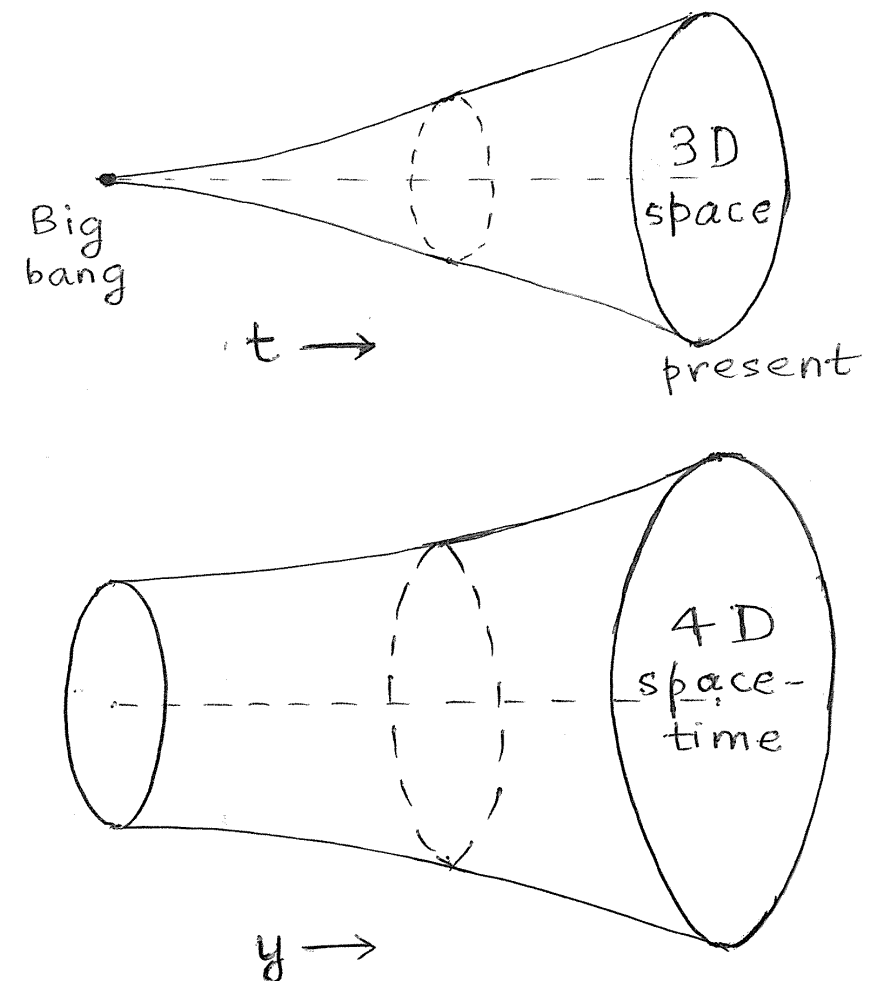


Wavelength of light emitted from
galaxies (in past) red-shifted (now)

- (flat) 4D space-time "expands"
exponentially with moving along 5th
dimension (5D space-time is warped!)



gravitational red-shift generates
hierarchies in mass scales between
different positions in 5th dimension



Warped Extra Dimension:
gravity and Higgs:
Planck-weak hierarchy
problem

Solution to (Planck-weak) hierarchy problem (Randall-Sundrum model)

- specifically, gravitational red-shift of Planck scale to weak: e^{N_e} (with $N_e \sim 30$) $\sim \frac{M_{\text{Pl}}}{M_{\text{weak}}}$
- equivalently (more technically), solve Einstein equation for metric:

flat 4D (neglect matter, radiation):

$$(ds)^2 = dx^i dx_i + (dt)^2, \quad i = 1, 2, 3$$

curved (back-reaction of matter, radiation) 4D (flat 3D):

$$(ds)^2 = a(t) dx^i dx_i + (dt)^2$$

← scale-factor → galaxy red-shifts

flat 5D (neglect 5D vacuum energy):

$$(ds)^2 = dx^\mu dx_\mu + (dy)^2 \quad \mu = 0, 1, 2, 3$$

warped (back-reaction of 5D vacuum energy) 5D (flat 4D):

$$(ds)^2 = e^{-2ky} dx^\mu dx_\mu + (dy)^2$$

← warp-factor (analogous to scale-factor)

Solution to (Planck-weak) hierarchy problem

(continued)

- master equation: $M_{4D}^{\text{eff}}(y) \sim e^{-ky} M_{5D}^{\text{fund}}$ (analogous to galaxy redshift due to scale-factor)
warp-factor $\nearrow$
- 4D (zero-mode) **graviton** profile $\sim e^{-ky}$ (near $y = 0$)

$$y \sim 0 \Rightarrow M_{4D}^{\text{eff}} \sim M_{5D}^{\text{fund}} \\ \Rightarrow \text{choose } M_{5D}^{\text{fund}} \sim M_{\text{Pl}}$$

Planck brane $\nwarrow$

(no warping at $y = 0$)

- **Higgs** (near other end, $y = L$) mass/weak scale:

TeV brane $\nwarrow$

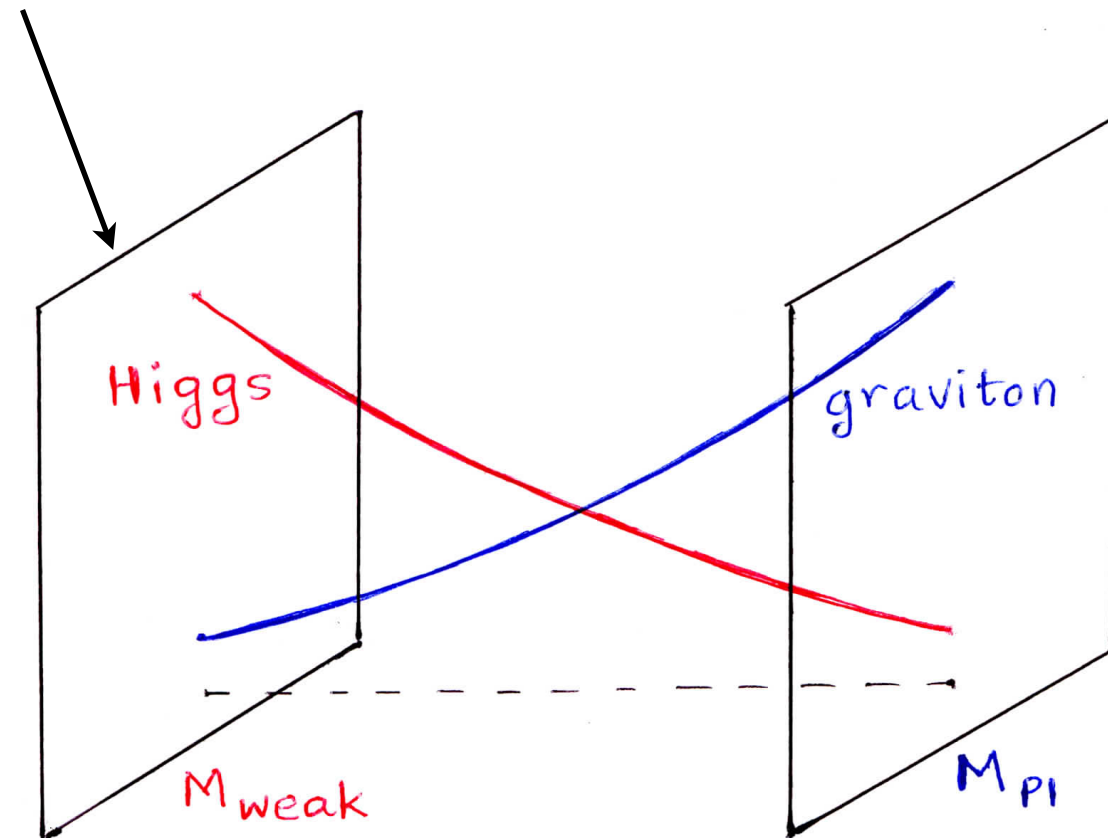
$$y \sim L \Rightarrow M_{4D}^{\text{eff}} \sim e^{-kL} M_{5D}^{\text{fund}} \\ \Rightarrow \text{choose } kL \sim 30 \text{ for } M_{\text{weak}} \sim 100 \text{ GeV}$$

(significant warping at $y = L$)

Solution to (Planck-weak) hierarchy problem (Randall-Sundrum model) (using overlap of profiles)

- small overlap of Higgs with gravitational field
 $\sim e^{-kL}$ $\rightarrow$
- small (TeV) Higgs mass/condensate $\ll M_{Pl}$
- ...provided $L \sim 30/k$
- ...stabilized (naturally) by adding 5D scalar (Goldberger, Wise mechanism)

Contino, Nomura, Pomarol;
KA, Contino, Pomarol



Mantra: coupling of
modes $\propto$ overlap of
profiles

Warped Extra Dimension:

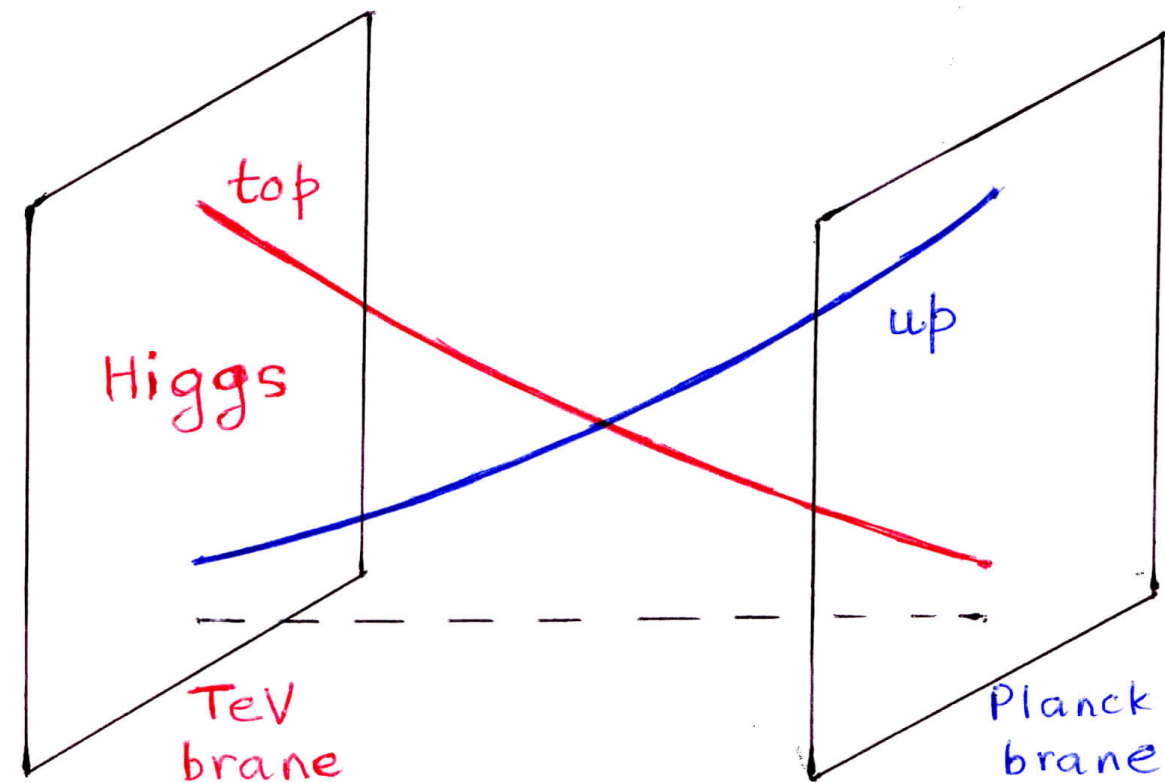
Fermions and Gauge

Bosons:

flavor puzzle

Fermion mass hierarchy

- 5D Dirac equation: lightest profile sensitive to M_{5D} and boundary conditions (Grossman, Neubert; Gherghetta, Pomarol; Huber, Shafi)
- small up quark vs. large top mass from overlap with Higgs

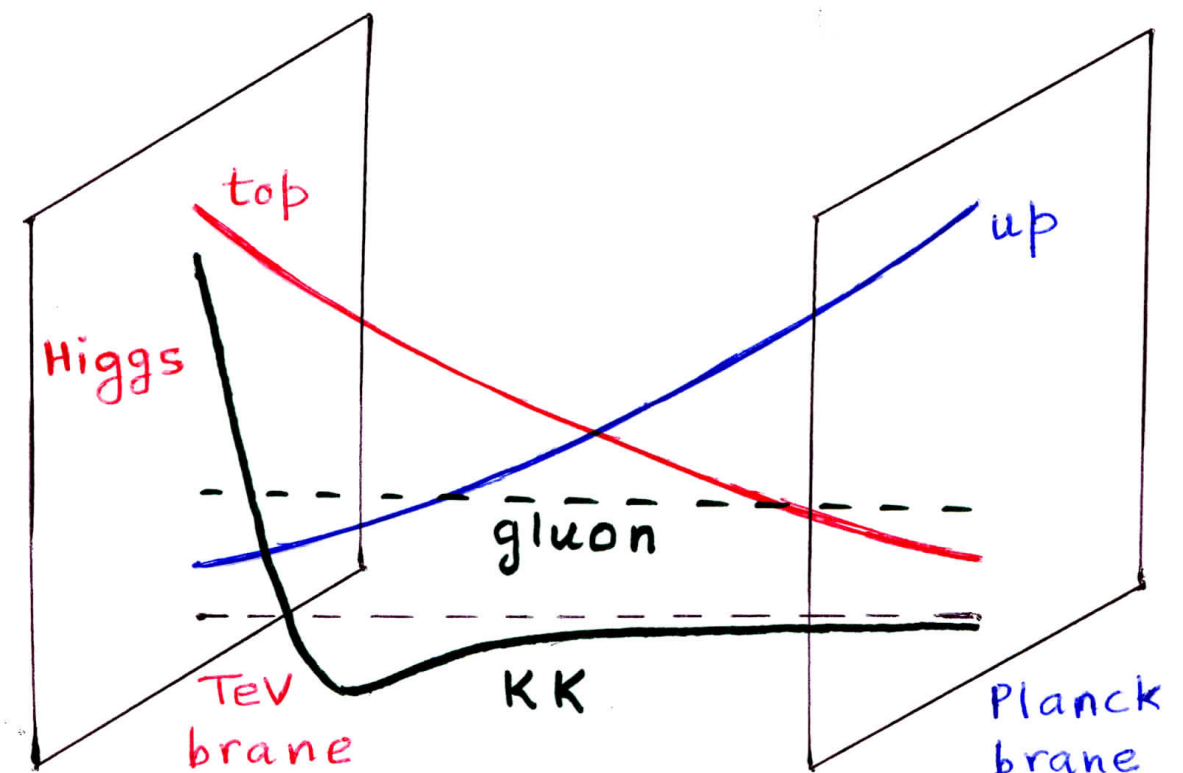


Bulk Gauge Bosons

(Davoudiasl, Hewett, Rizzo;
Chang, Hisano, Nakano, Okada, Yamaguchi; Pomarol)

- KK's localized near **TeV** brane with mass $\sim$ **TeV** (from **5D Maxwell** equations)
- gauge KK "like" **Higgs**: **large** (**small**) coupling to top (**up**) quark

gauge KK's couple
 $\propto$ **fermion mass**



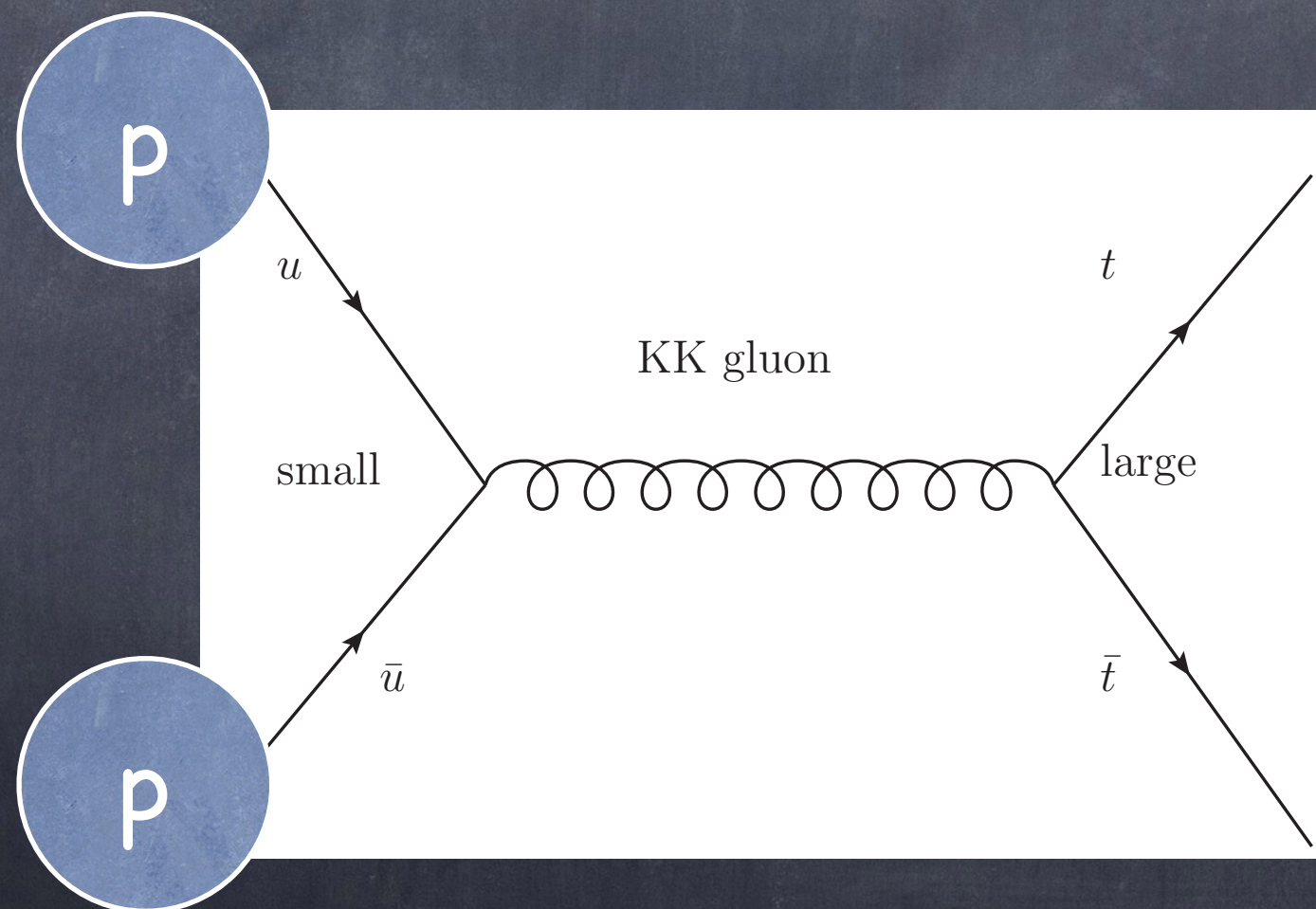
...Onto Signals!

DIRECT KK PRODUCTION
@LHC/FUTURE HIGH-
ENERGY COLLIDERS

$$E \gtrsim \text{TeV}$$

(1). KK gluon decays to tops

[KA, Belyaev, Krupovnickas, Perez, Virzi (2006)]

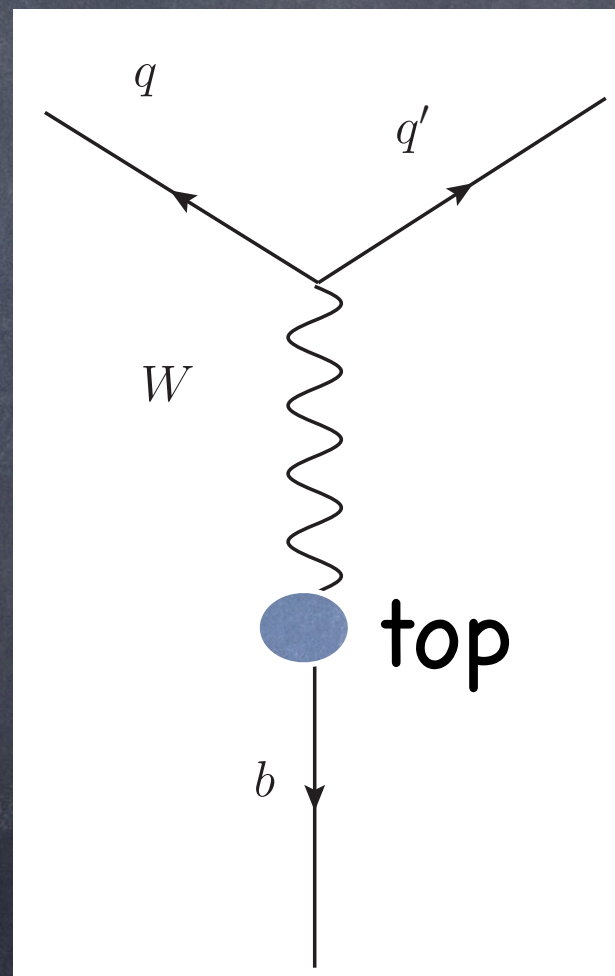


(due to top being near TeV brane)

• Coupling to up (top) quark small (large)

Top identification **before** LHC

- top $\sim$ **at rest** (in lab frame)



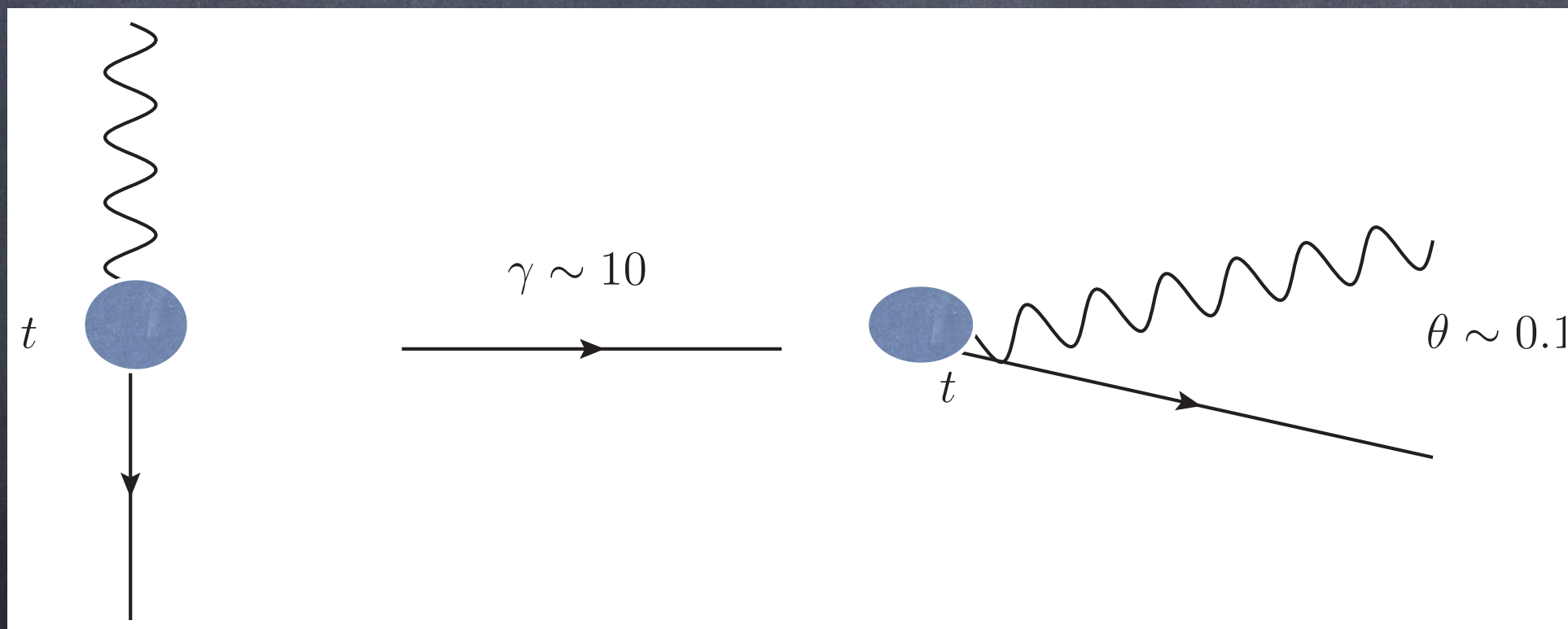
- b and W decay products **well-separated**

Problem: tops from KK gluon **boosted**

[KA, Belyaev, Krupovnickas, Perez, Virzi (2006)]

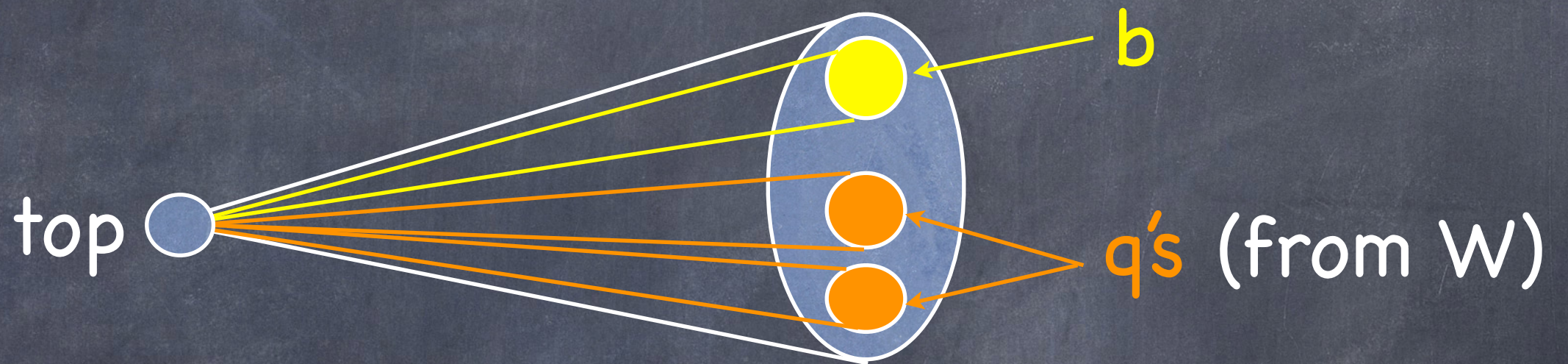
$$\gamma_{top} \sim E_{top}/m_{top} \sim (3 \text{ TeV}/2)/170 \text{ GeV} \sim 10 \Rightarrow$$

opening angle between b and W $\sim 1/\gamma_{top} \sim 0.1$



• b and W decay products **merge**

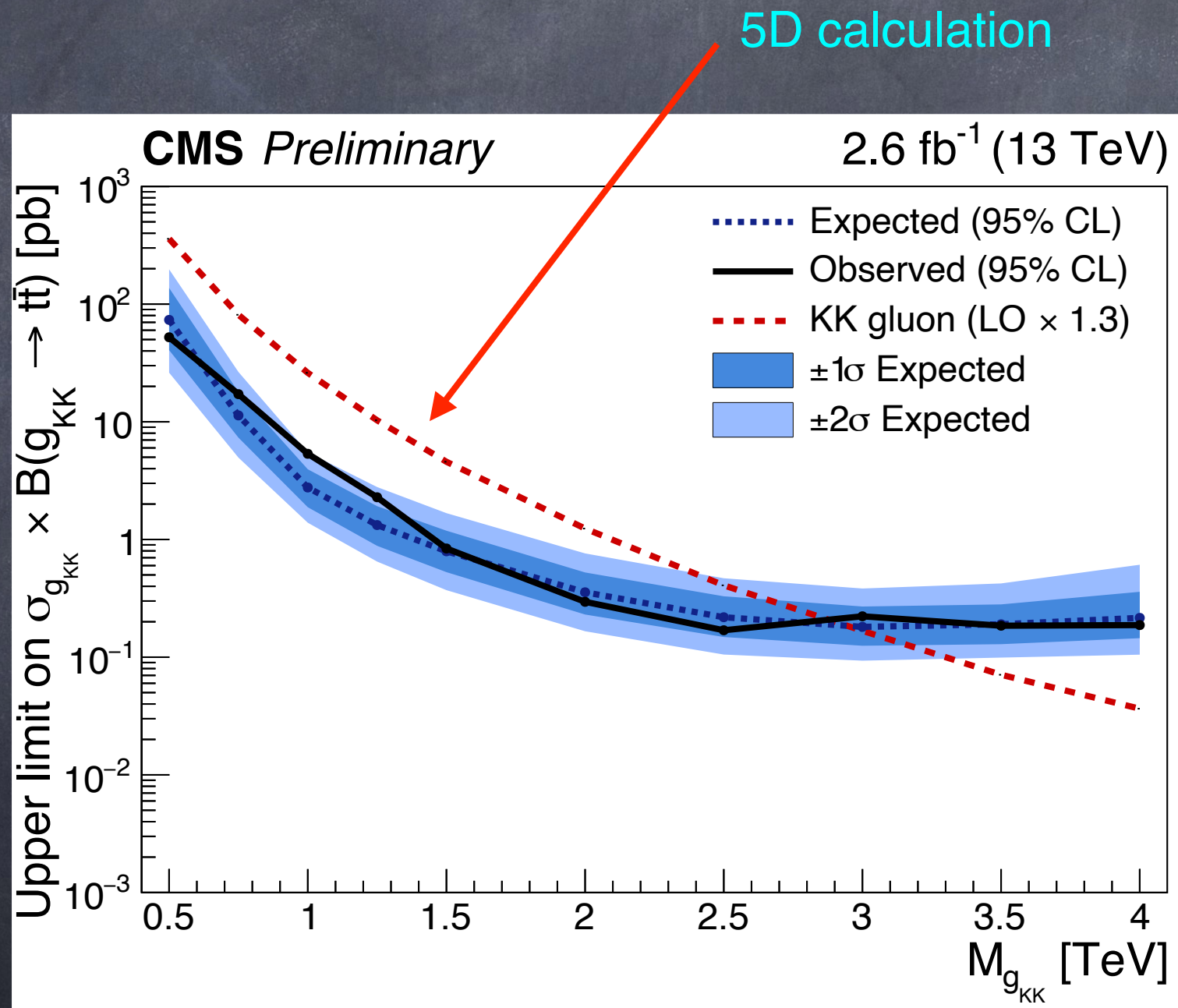
Solution: **special** identification strategy



- quarks manifest in detectors as spray of hadrons (jets):
top-jet (coarse-grained)
- use jet **substructure** (**joint** effort: theorists/
phenomenologists and experimentalists)

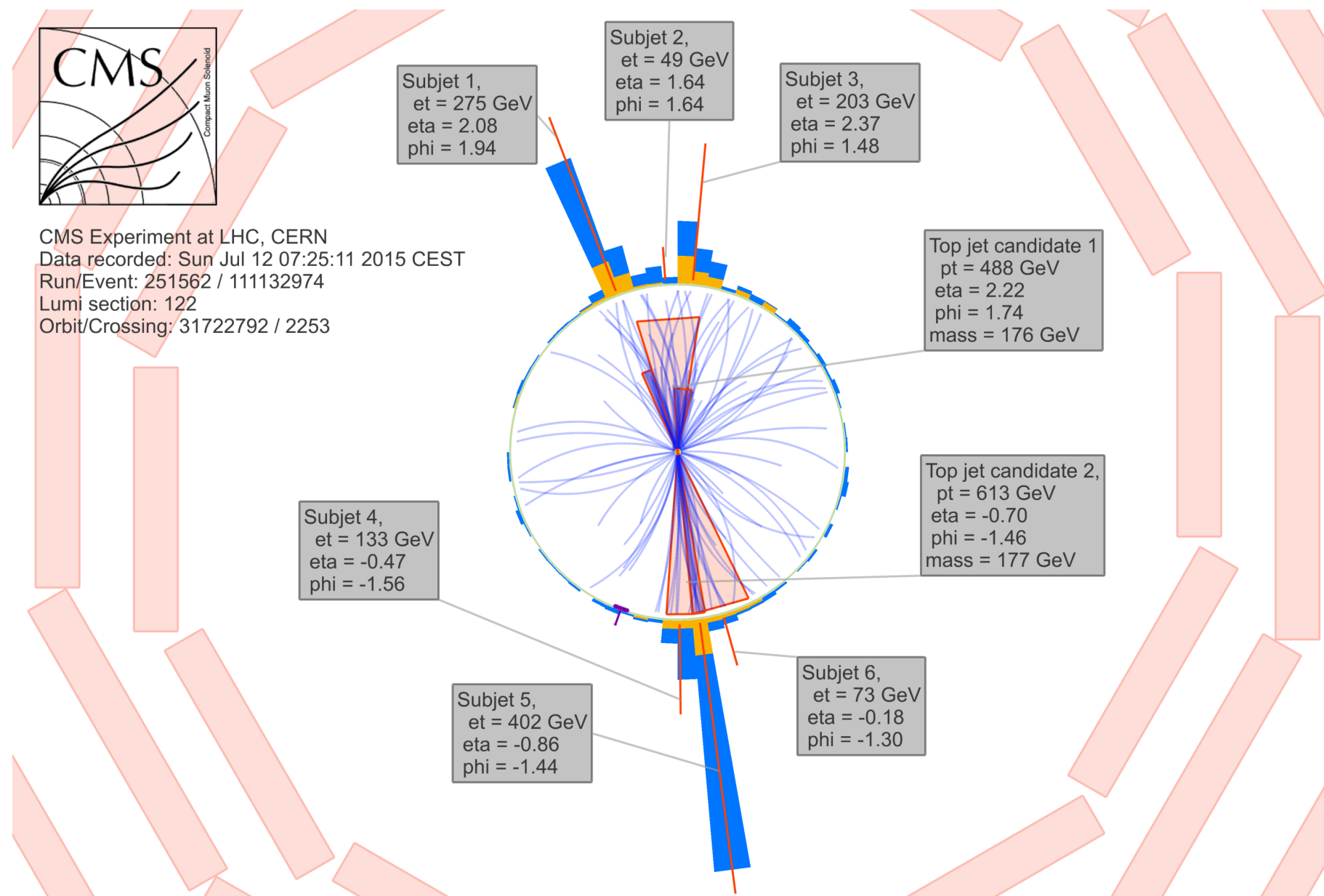
LHC search results

- ...already in boosted top regime
(bound on KK gluon mass $\sim$ a few TeV)



(CMS PAS
B2G-15-002)

Real boosted top event!

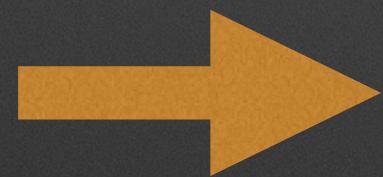


• **Two** top-jets: each with 3-sub-jets (b and 2 jets from W merged)

• Invariant mass: 2491 GeV

Research boosted...

(2) Boosted **W/Z/Higgs** from (colorless)
KK **W/Z/graviton** [KA, Davoudiasl, Perez, Soni (2006);
KA, Davoudiasl, Gopalakrishna, Han, Huang, Perez, Si,
Soni (2007); KA, Gopalakrishna, Han, Huang, Soni (2008)]



“Boost” **conference**: meet annually (from
2009) to deal with boosted objects (top, W, Z,
Higgs...) in general (arising from decay of any
heavy particle, not just KK's)

Testable solutions to puzzles of nature

Why is gravity weak

KK at LHC:
boosted
top/W/Z/H

Why is up quark lighter than top

KK decay to top quark; LHCb
(discuss offline!)

Warped Extra Dimension

Grand Unification of 3 forces

(Top) GUT (discuss partners at LHC offline!)

Candidate for Dark Matter of Universe

LZ (Carter Hall's talk)
(discuss offline!)