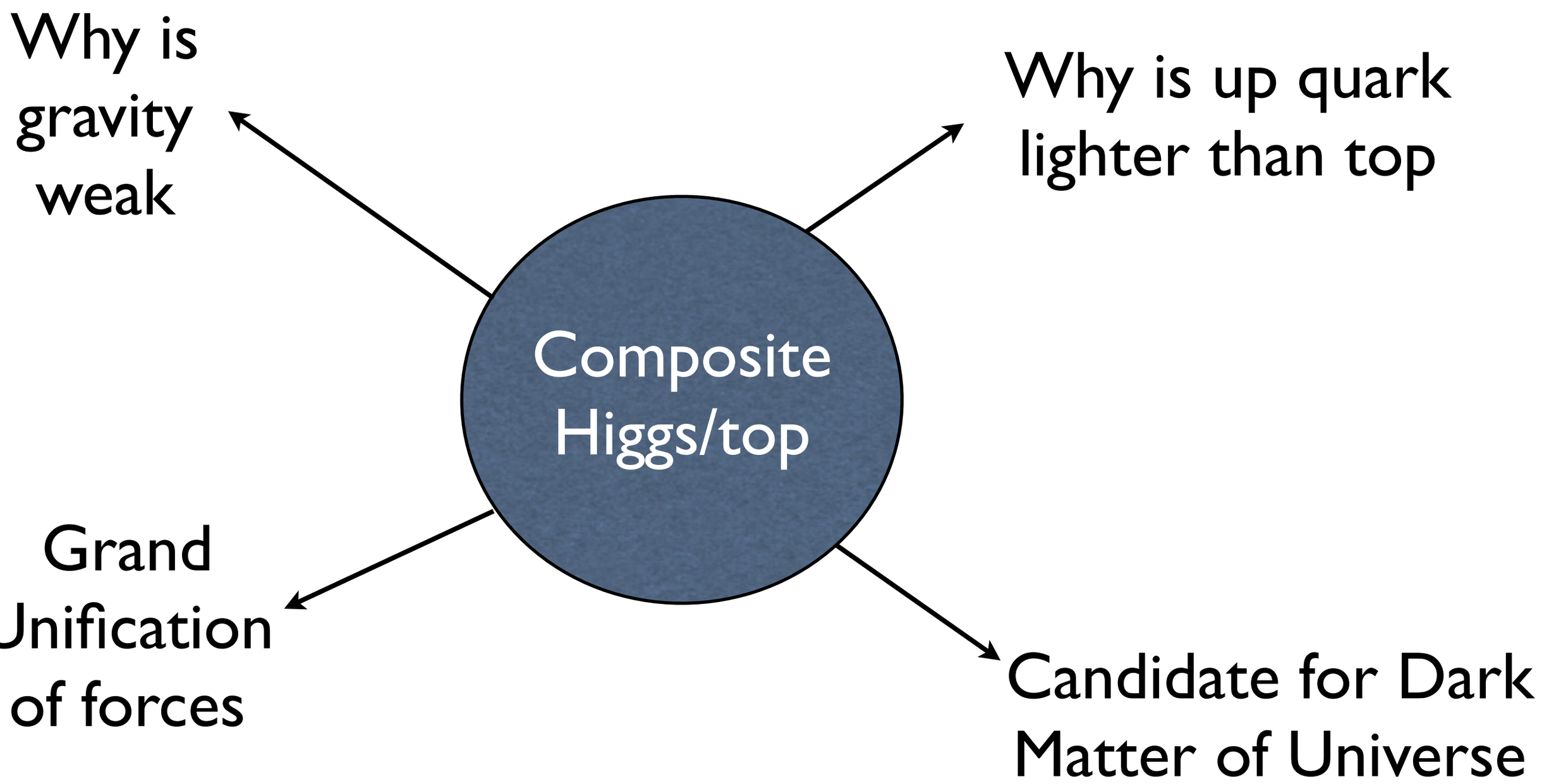
IS THE HIGGS BOSON COMPOSITE?

Kaustubh Agashe (University of Maryland)

Open questions of Standard Model of Particle Physics...addressed by Composite Higgs/top

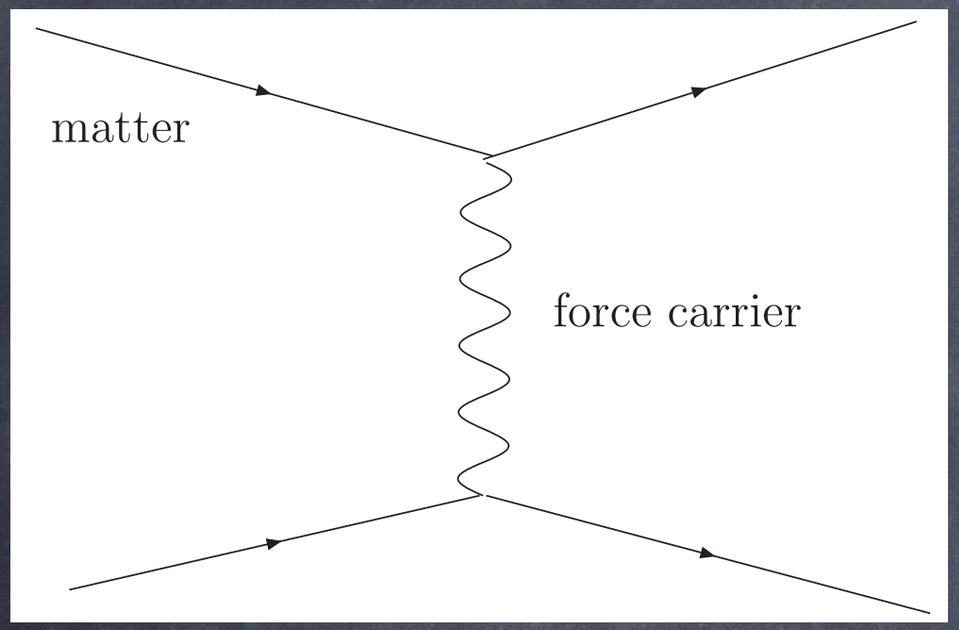


Range of experiments will test...

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"

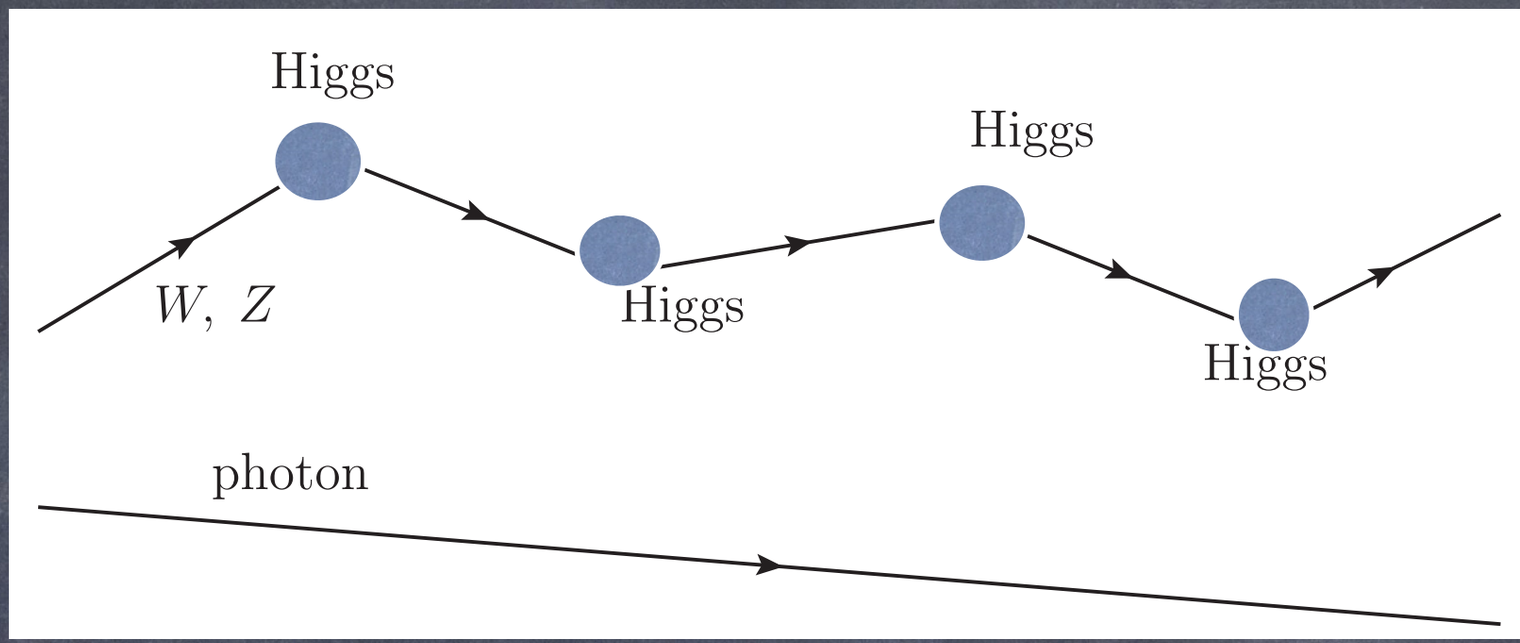
$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$$

leptons (no strong...)

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

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 massless (Higgs condensate is neutral)

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

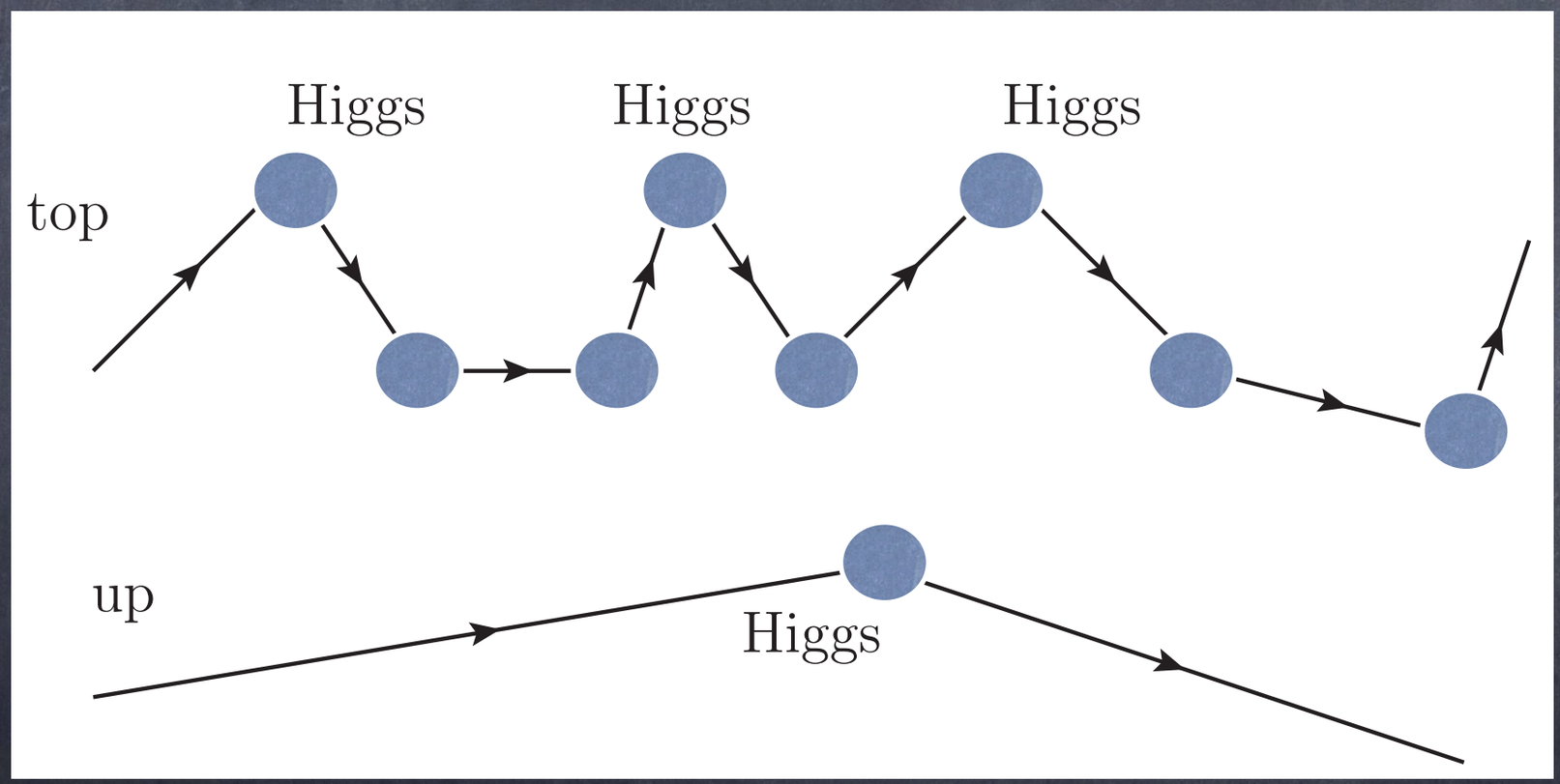
Size of Higgs condensate

- Mass $\sim$ condensate x coupling

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

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)

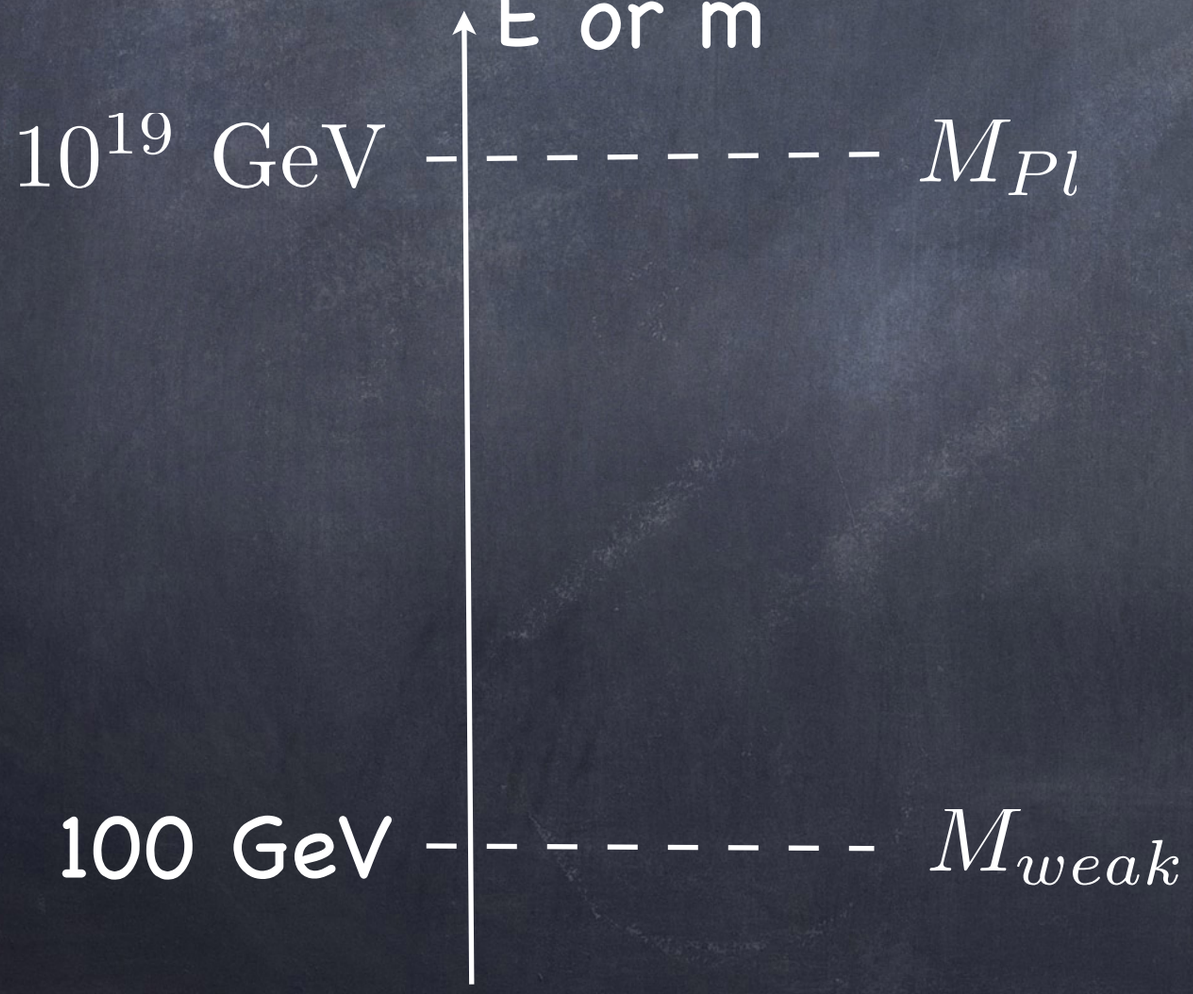
Hierarchy Problem

Hint for (much) higher mass scales

- Quantum gravity ⟹ new physics at

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

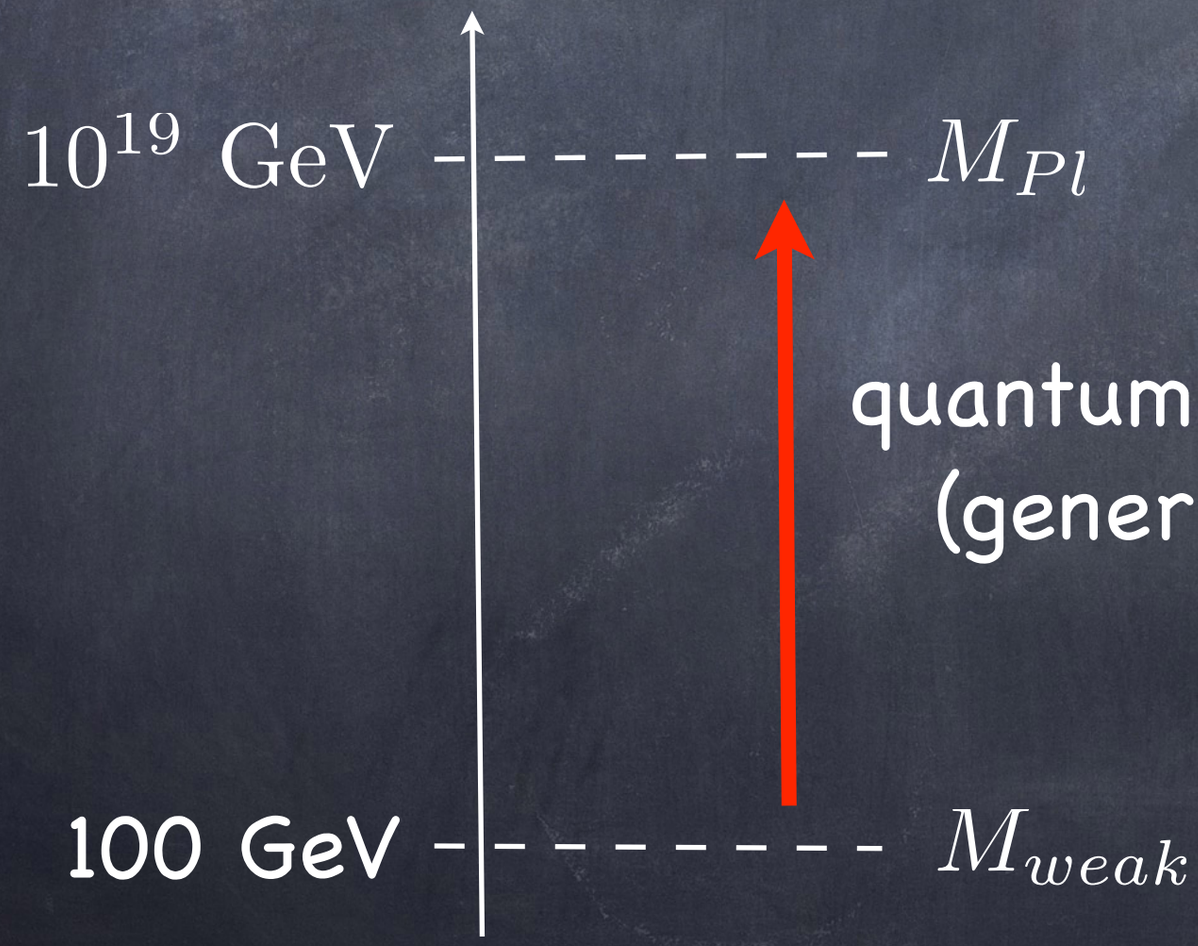
(Gravity is super-weak at low energies)



Higgs condensate ⟶ higher scale

- Quantum corections (spin-0) ⟹

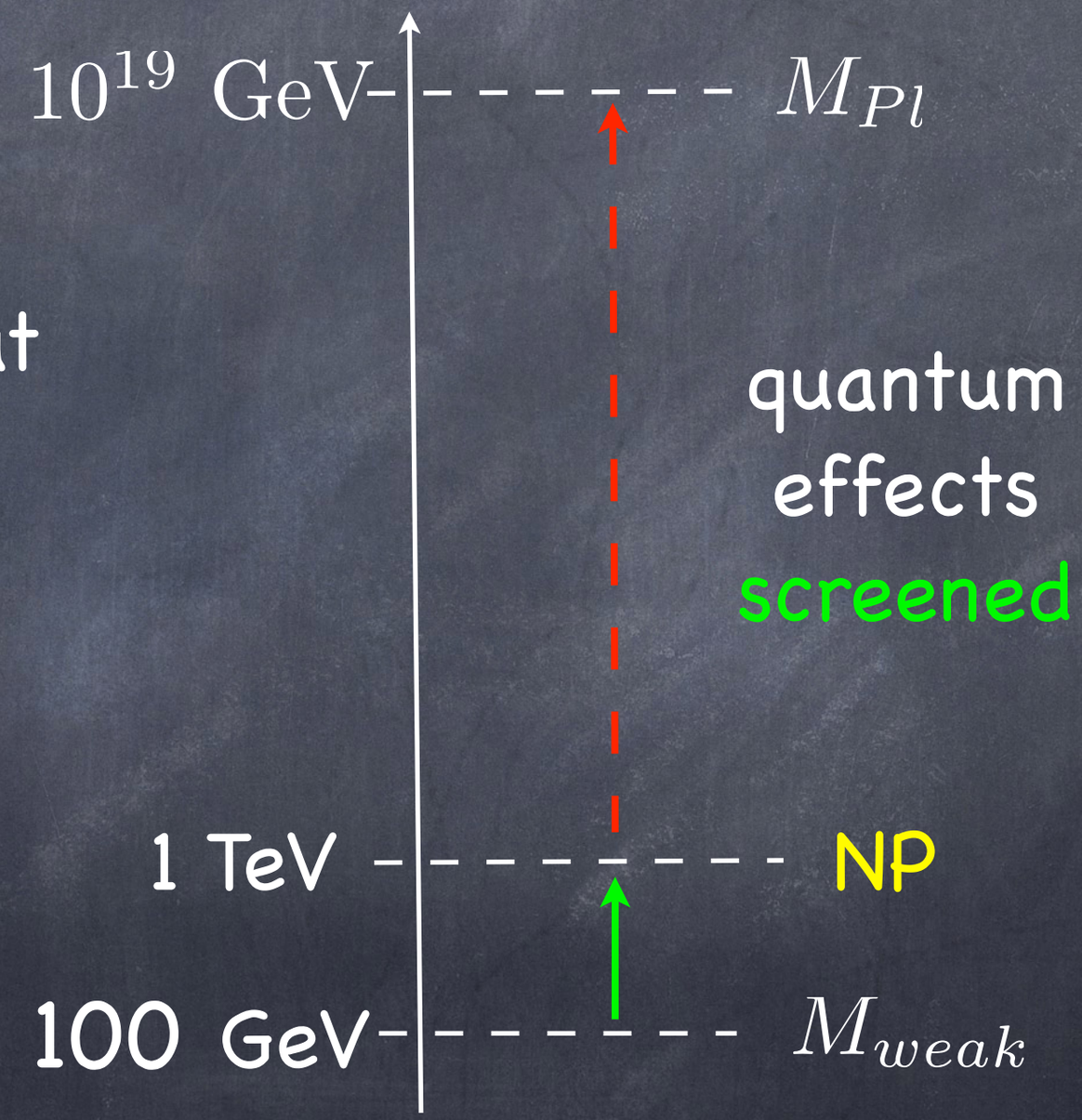
$M_{weak} \sim 100$ GeV $<< M_{Pl} \sim 10^{19}$ GeV is unstable



- Biggest mystery for past several decades!

Solution to hierarchy problem

- New physics (NP) at TeV scale



Outline

- Higgs being composite "protects" weak from Planck scale

- Requires composite top quark

- Modeling by (warped) extra dimension

→ Signals (various types) of heavy composites

- Direct production

- Indirect effects

- Grand Unification of 3 forces

→ Dark Matter → Various types of detection

★ techniques developed here for composite Higgs/top signals have general applicability

COMPOSITE HIGGS

Basic idea

- Higgs boson (discovery in 2012, Nobel prize in 2013) has (new) constituents

- a la quarks bound inside spin-0 pion (or spin-1/2 proton)

- compositeness scale/structure above $\sim$TeV: size $\sim 10^{-19}$ m ($\sim 10^{-4}$ of pion)

- M_{weak} not dragged up to Planck scale (like pion mass isn't); Higgs is not point-like above $\sim$ TeV

... → COMPOSITE TOP QUARK

Top quark [2nd last to be discovered (1995)] is heaviest particle of SM

- largest coupling to (composite) Higgs boson

- likely to be composite also: otherwise coupling too small, like electron-pion

- central to theory/phenomenology

Top quark

Other SM fermions (mostly) elementary

- smaller coupling to Higgs via (small) composite admixture ($\sin\theta$):

$$|\mathrm{SM}\rangle = \cos\theta\,|\mathrm{elementary}\rangle + \sin\theta\,|\mathrm{composite}\rangle$$

(elementary-composite mixing like γ-ρ in usual strong sector)

- accounts for SM fermion mass hierarchy

Modeling of composite Higgs/top

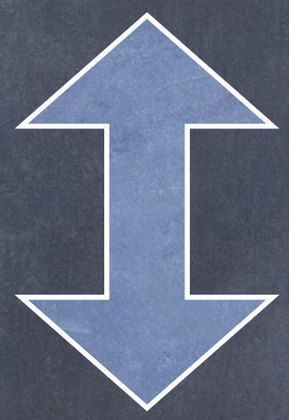
- idea old [Georgi, Kaplan (1984)]: difficult to calculate (just like usual strong nuclear force): constituents of Higgs boson strongly-coupled

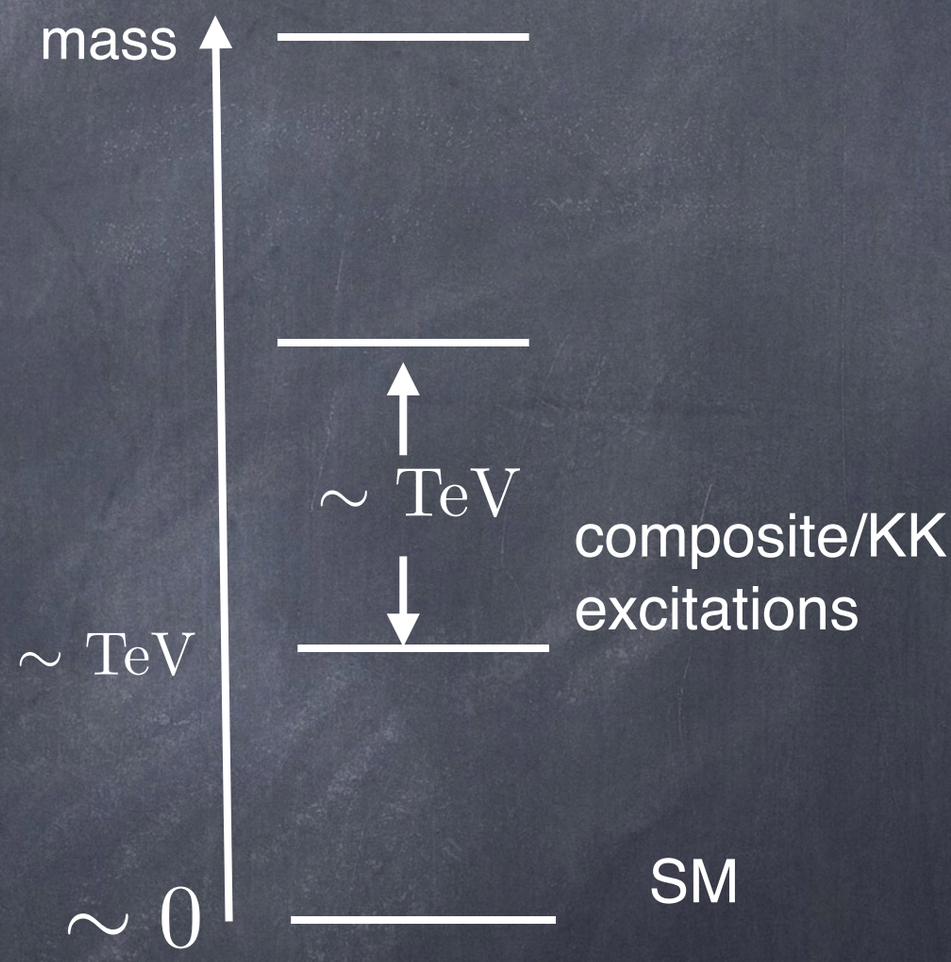
- AdS/CFT [Maldacena (1997); Witten (1998); Gubser, Klebanov, Polyakov (1998)]: weakly-coupled (calculable) dual description in highly curved (warped) extra dimension [Randall, Sundrum (1999)] 
concrete, realistic model [KA, Contino, Pomarol (2004)]

Dual extra dimensional description

Intuition behind duality

- Tower of bound states ($\sim$ excitations of pion, rho-meson...) in 4D (= 3 space + time) picture with strong dynamics

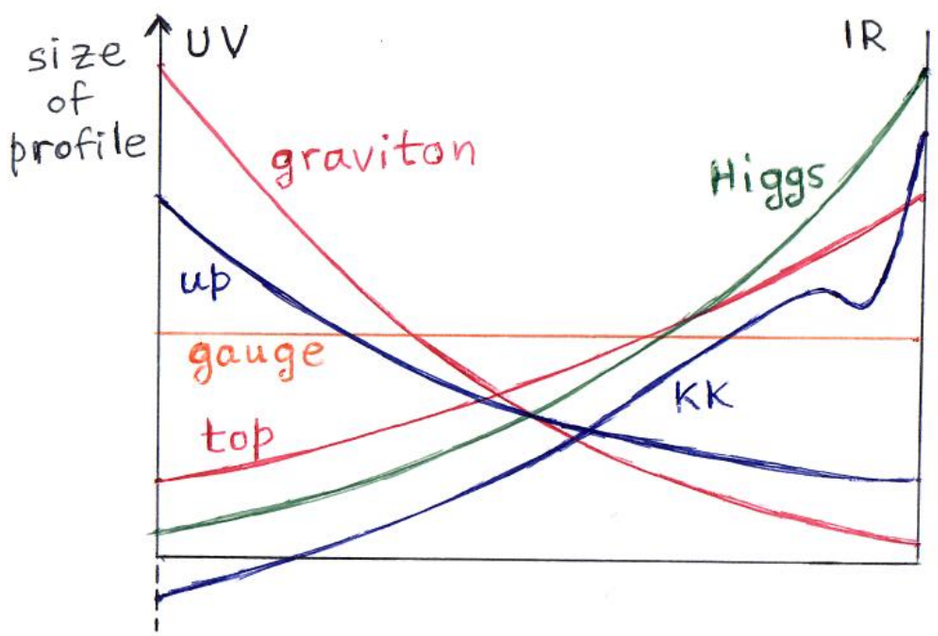




- Kaluza-Klein (KK) tower from motion in a compact extra (5th) dimension: $\sim$modes of particle in 1 D box (with profiles)

Warped snapshot

- geometrize degree of compositeness
- overlap of profiles dictates all hierarchies (Planck-weak and flavor)
- explicit calculations in 5D framework vs. qualitative summary for signals here (using 4D picture)



SIGNALS OF COMPOSITE HIGGS BOSON/TOP QUARK

Originate from new,

heavy (~TeV) composites

Need to know their

identity and ordering of

couplings

Identity of (heavy) composites...like real hadrons

- Higgs (EW charge) and top (color and EW charge) are composites

Pion (made of quarks) has electric charge

- constituents also carry EW/color charges: elementary/SM gauge bosons (W/Z/gluon/photon) couple to them

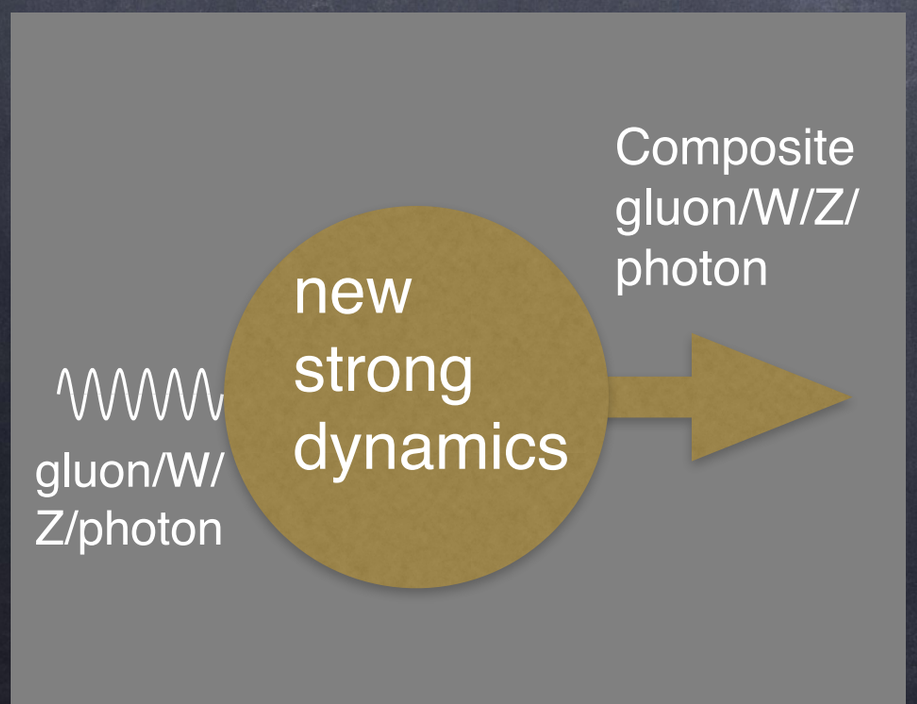
Quark current coupled to photon

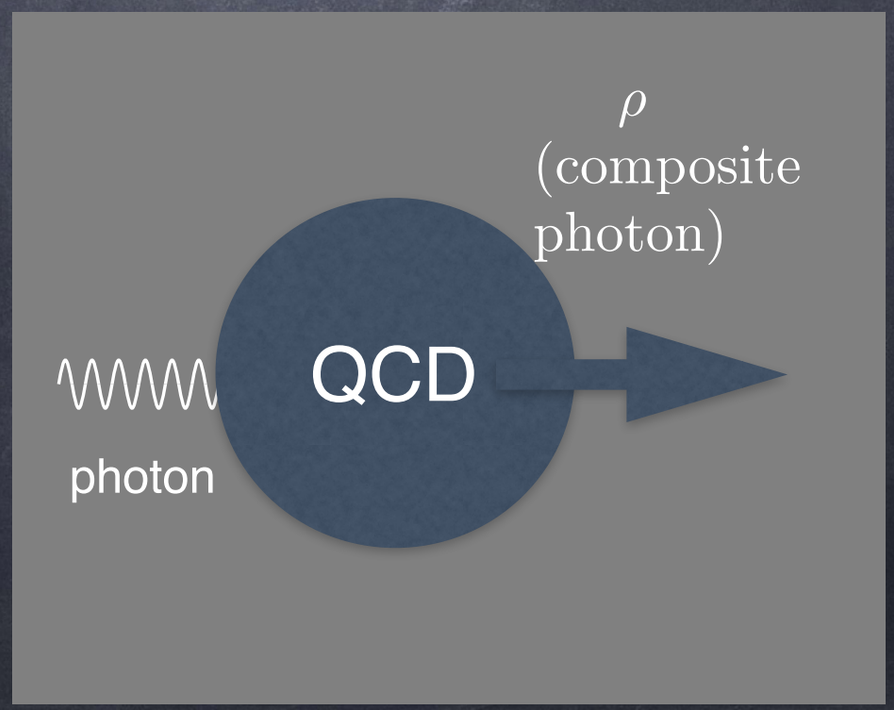
made of constituents

- $J_\mu|\text{vacuum}\rangle \sim$ composite gauge boson

quark current interpolates rho-meson (composite/heavy photon)

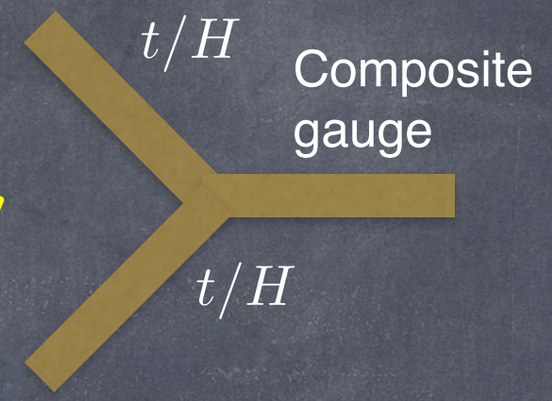
[heavy W/Z/gluon/photon (spin-1)]



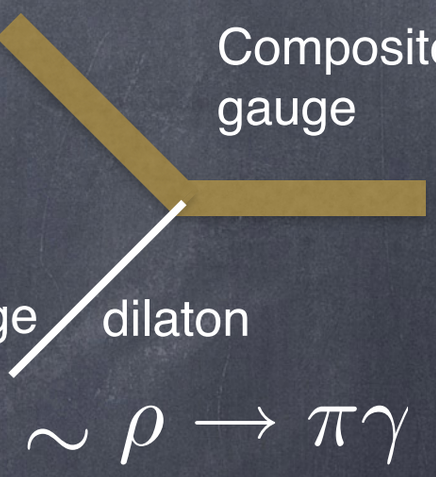


Couplings of (heavy) composites...like real hadrons

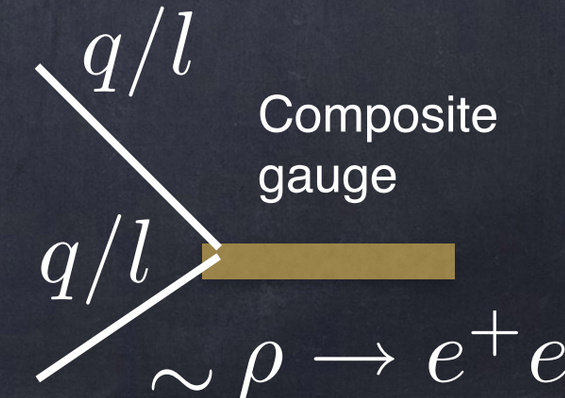
- coupling among **all** composites maximum (dominates **decay**): heavy composite with **top**/**Higgs** (including W/Z longitudinal)



- **2** composite, **1** elementary: neither here nor there? Not quite in simple **extensions** of minimal model [KA, Du, Hong, Sundrum (2016) and KA, Collins, Du, Hong, Kim, Mishra (2016-18)]: heavy composite gauge boson to SM gauge boson and dilaton (spin-0 composite)



- **1** composite, **2** elementary (relevant for **production** in proton/electron collision): heavy composite to **light quarks/leptons**

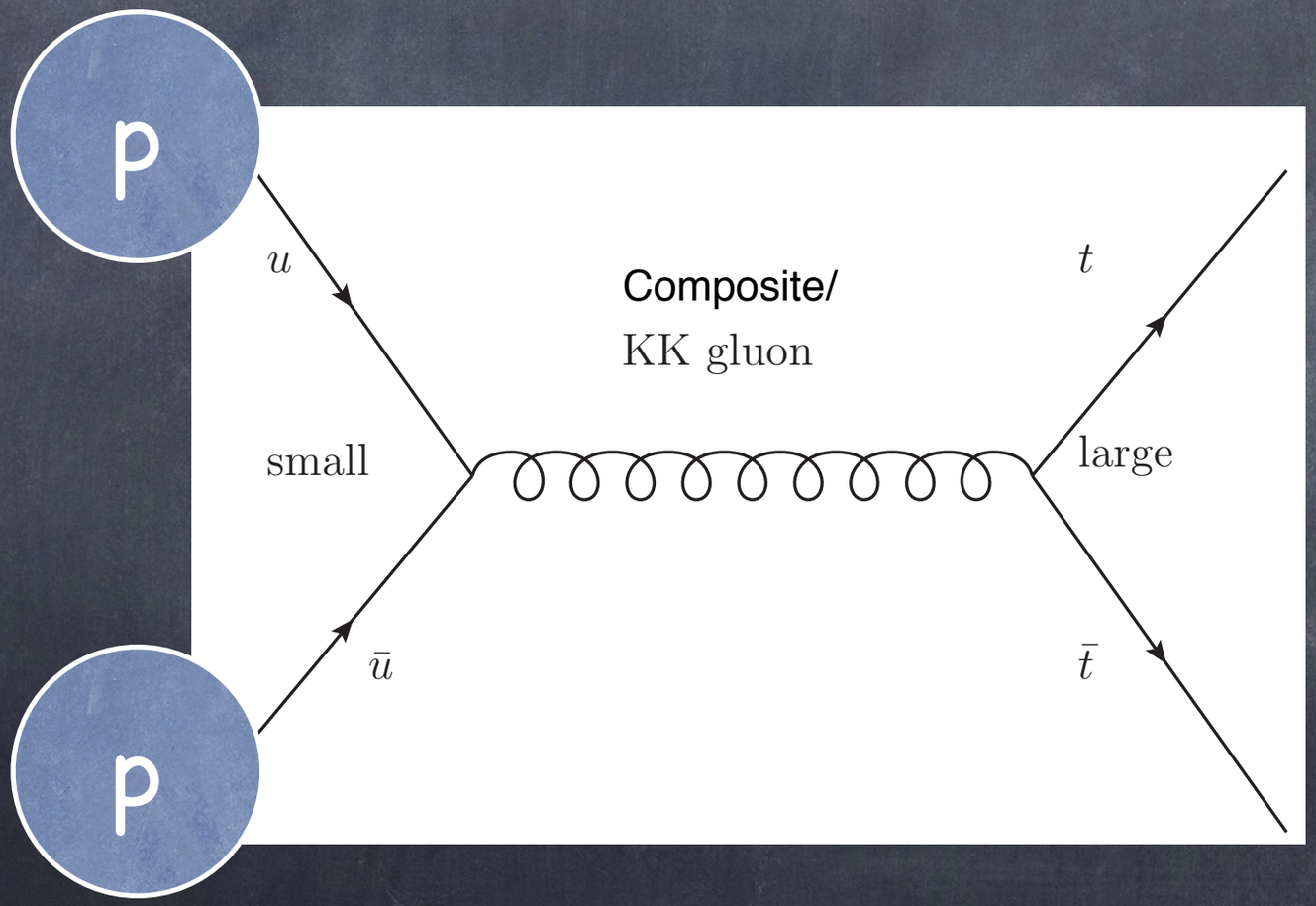


DIRECT HEAVY COMPOSITE PRODUCTION @LHC/FUTURE HIGH-ENERGY COLLIDERS

$E \gtrsim \mathrm{TeV}$

(1). Heavy/Composite gluon decays to tops

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

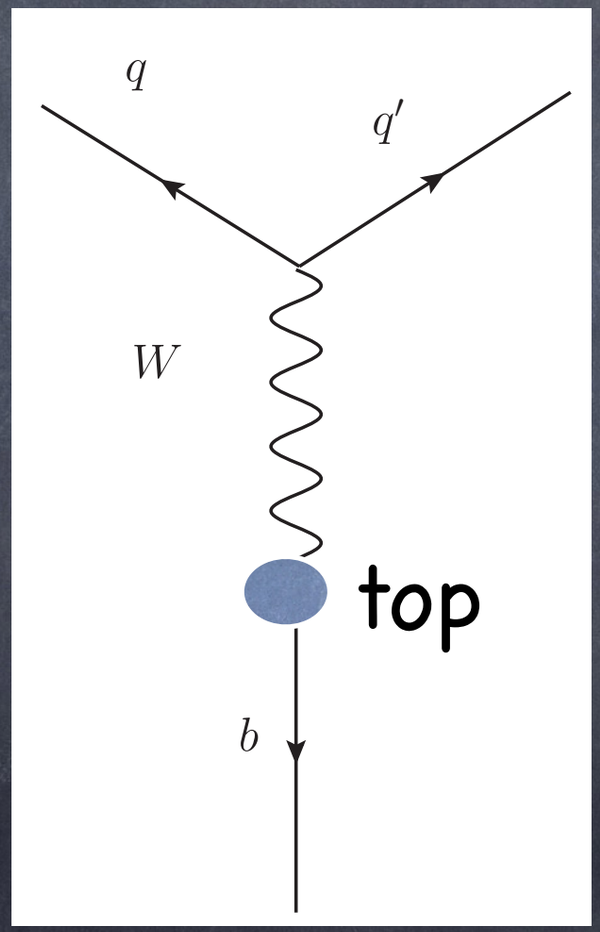


(due to top being composite)

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

Top identification before LHC

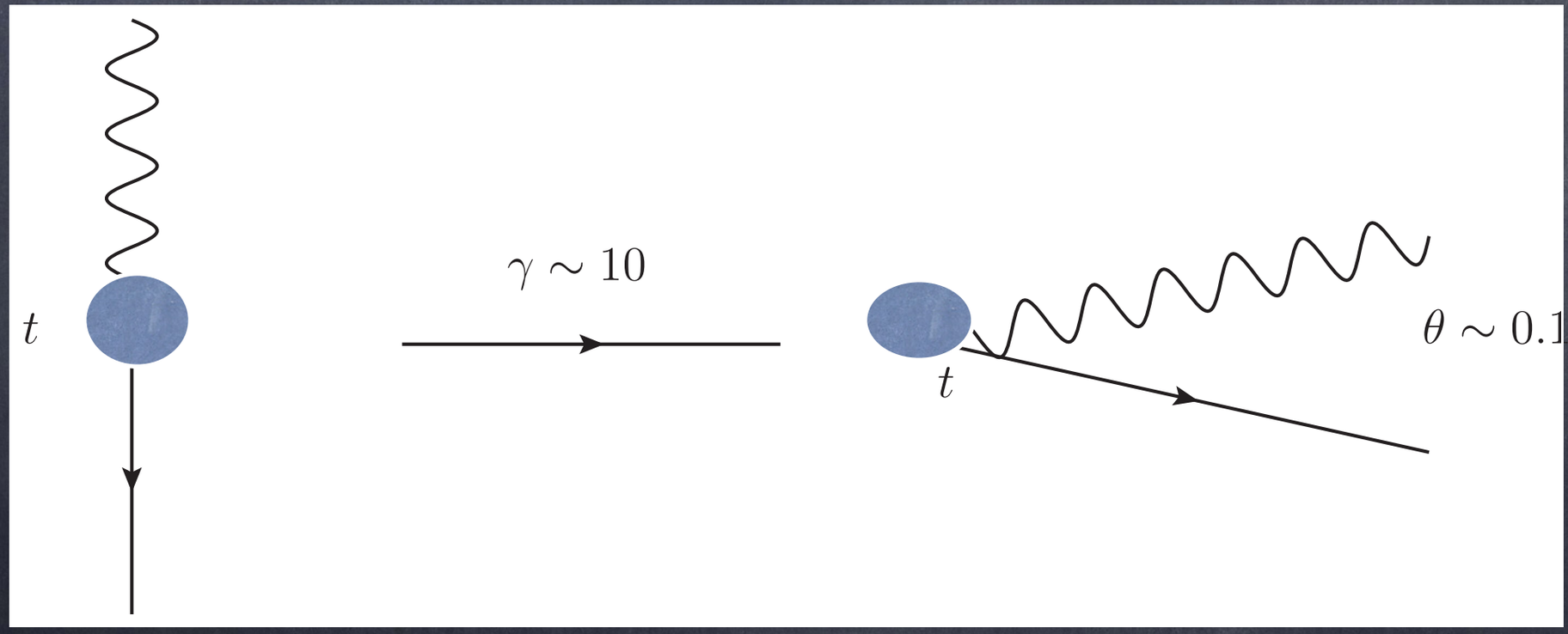
- top $\sim$ at rest (in lab frame)



- b and W decay products well-separated

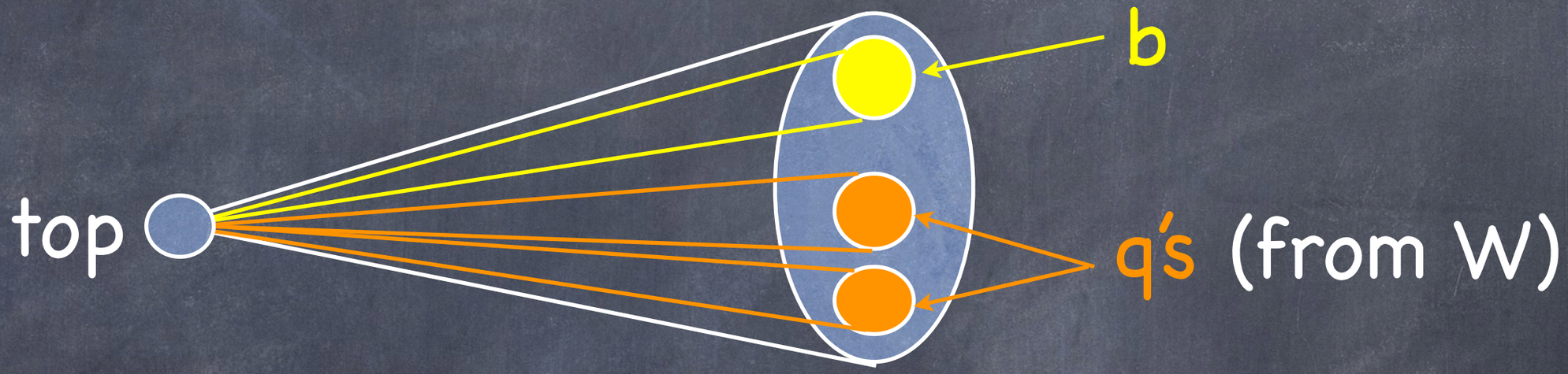
Problem: tops from composite/KK gluon boosted [KA, Belyaev, Krupovnickas, Perez, Virzi (2006)]

$\gamma_{top} \sim E_{top}/m_{top} \sim (3\ \mathrm{TeV}/2)/170\ \mathrm{GeV} \sim 10$ ⇒
opening angle between b and W $\sim 1/\gamma_{top} \sim 0.1$



- b and W decay products merge

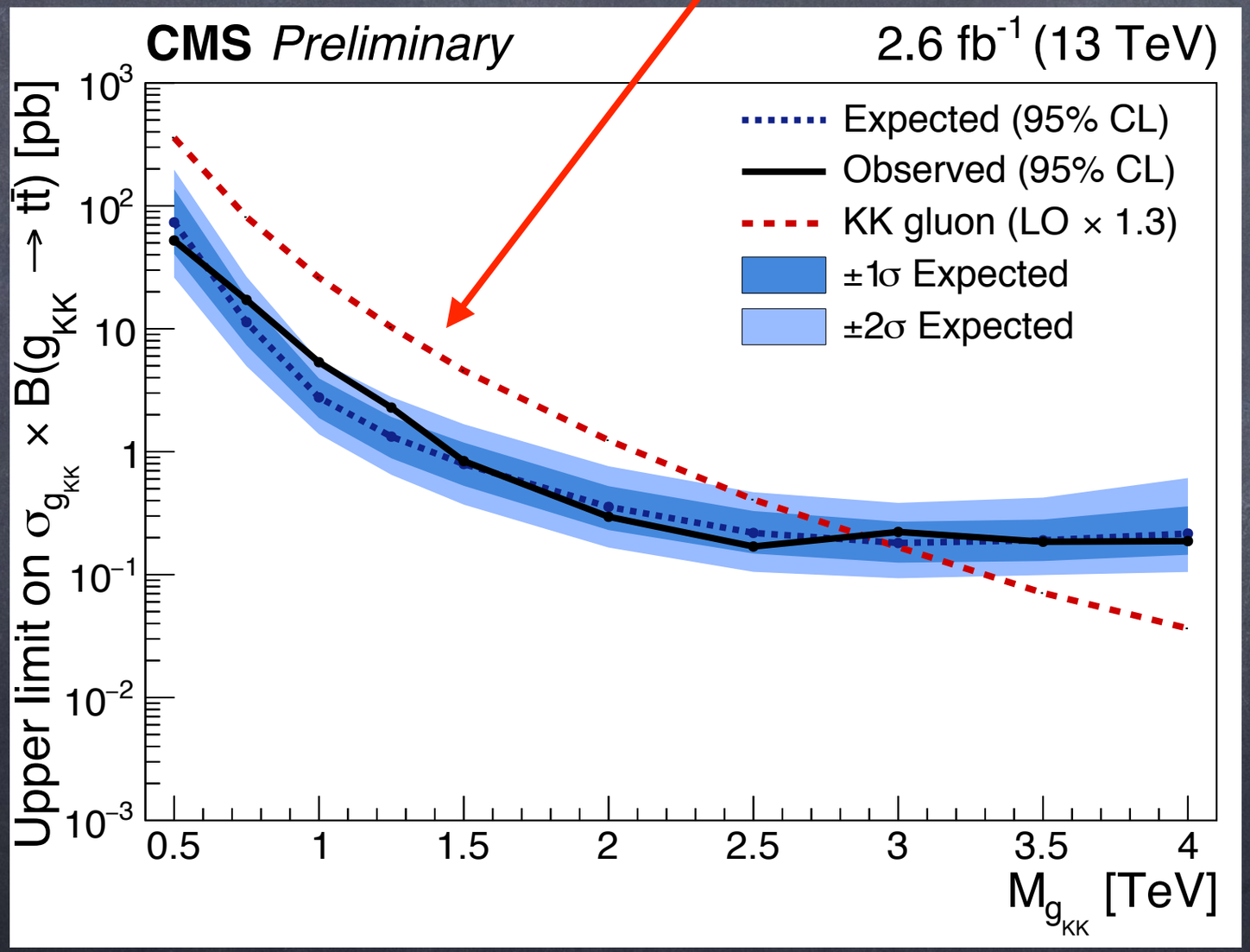
Solution: special identification strategy



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

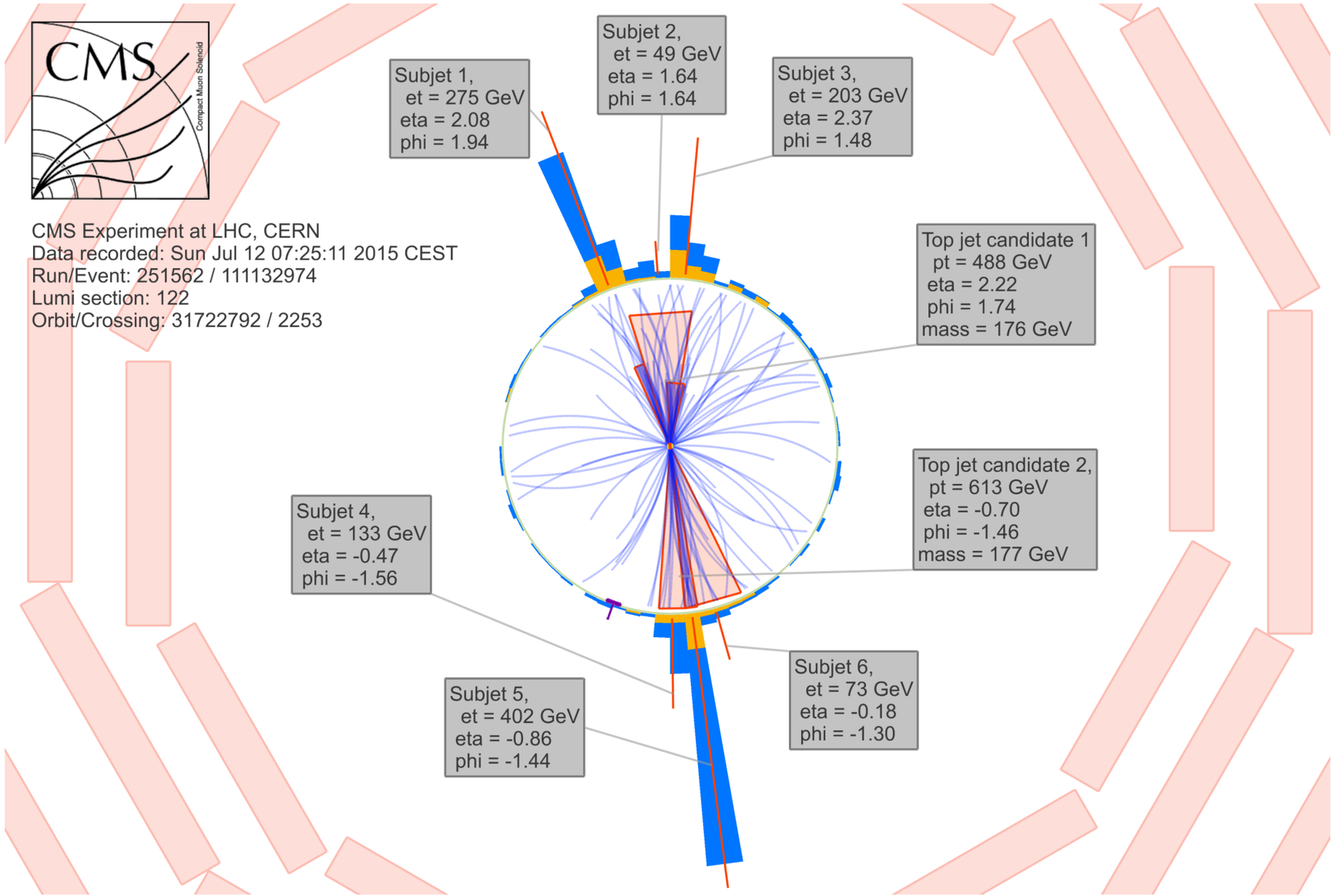
LHC search results

- ...already in boosted top regime
  (bound on composite/KK gluon mass ~ 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...

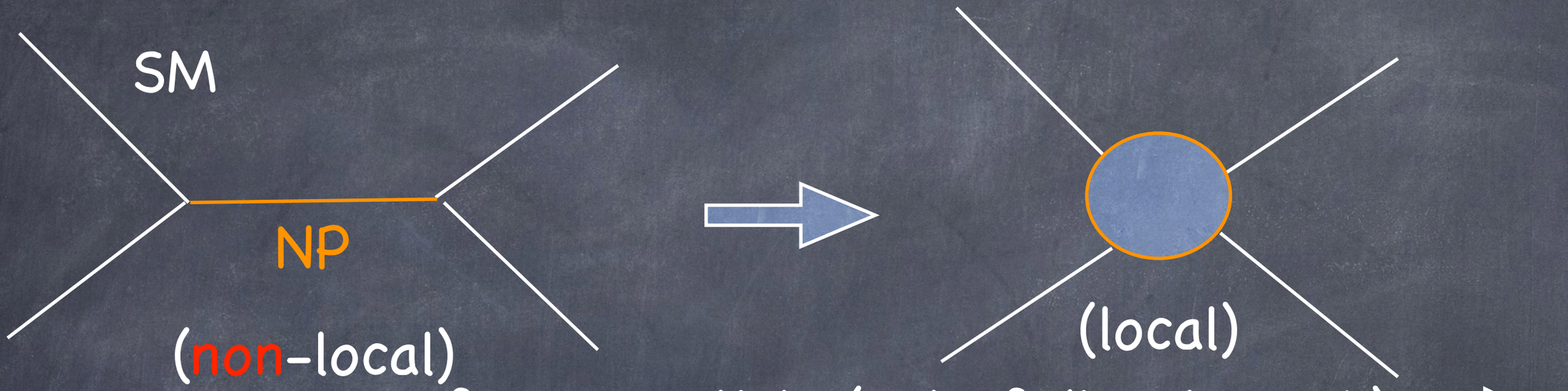
(2) Boosted W/Z/Higgs from (colorless) composite W/Z/graviton

[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 composites)

INDIRECT/VIRTUAL EFFECTS

Basic idea (any heavy, new physics)

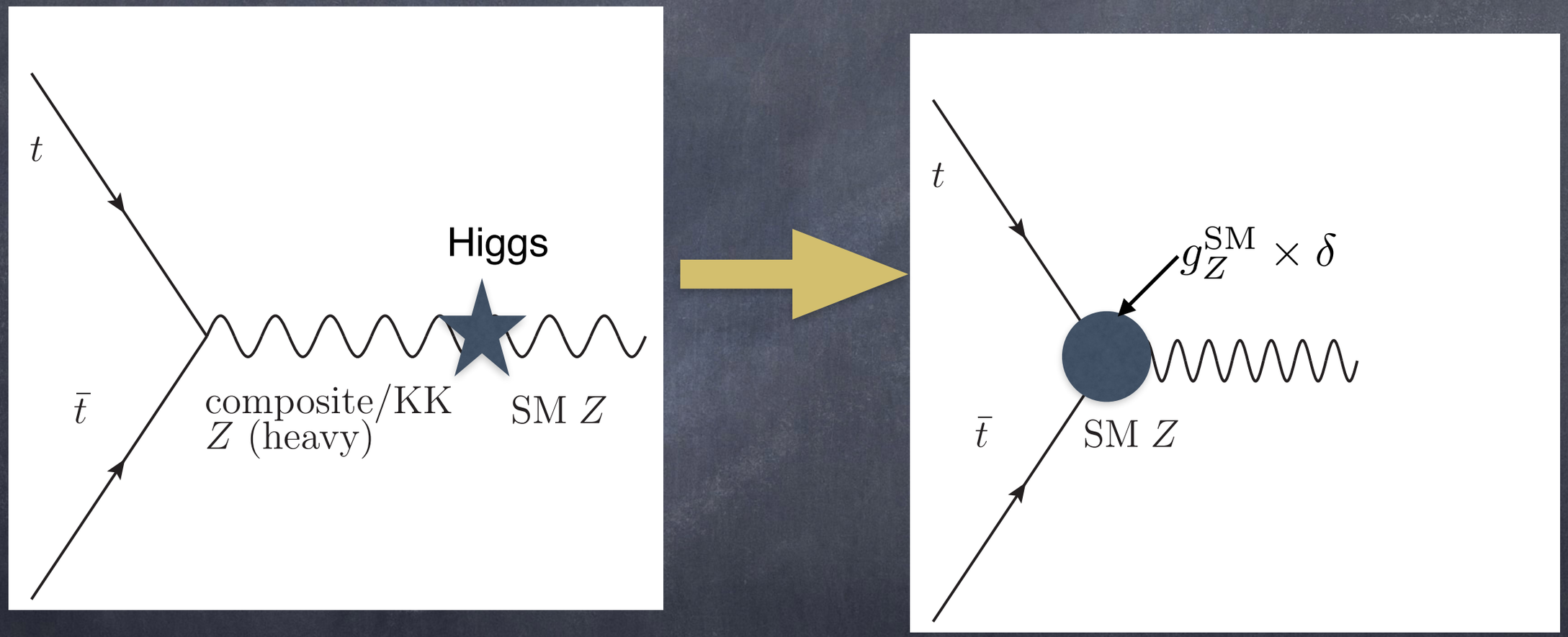


- Energy << mass of new particle (out of direct reach)
  short range/suppressed force
  (like low-energy weak nuclear force from W exchange)
- modify properties of SM particles (Higgs and top, couple strongly to heavy composites)
- Sensitivity to new physics by precision analysis of SM particles produced abundantly at lower energy $(E \ll \mathrm{TeV})$
- complementary to direct probes

Various types...

Shift existing couplings

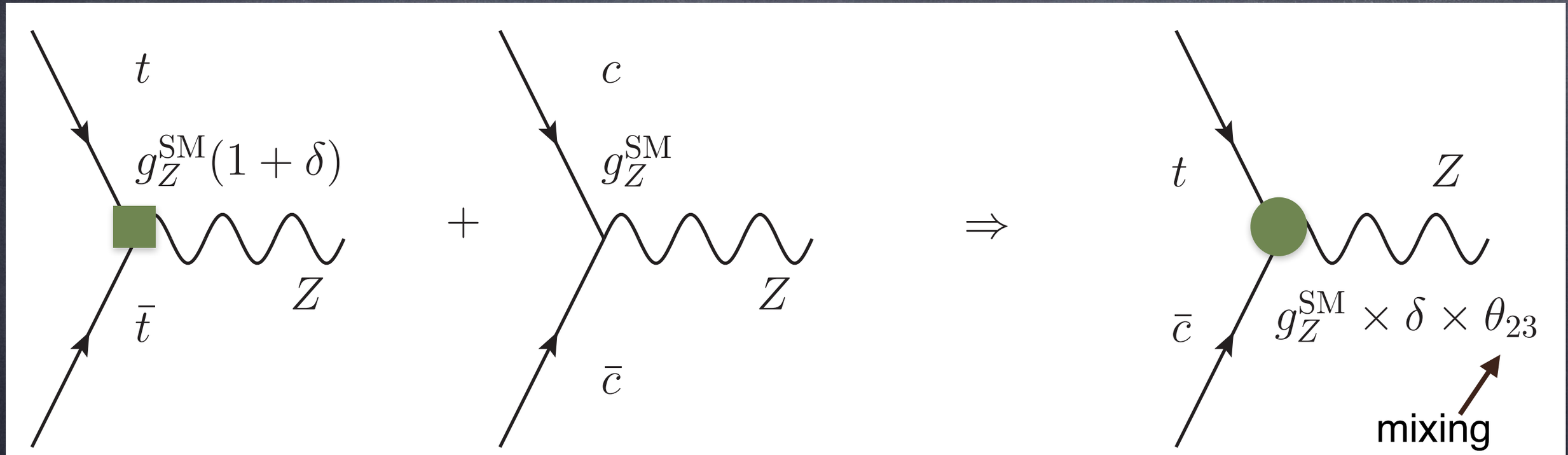
- top to Z/h ($\sim$ form factor from compositeness)



- Higgs to W, Z, top

New couplings

- (composite) top coupling shifted; charm not composite → flavor-mixing generates top-charm-Z (unitary rotation on non-identity matrix) [KA, Perez, Soni (2006)]

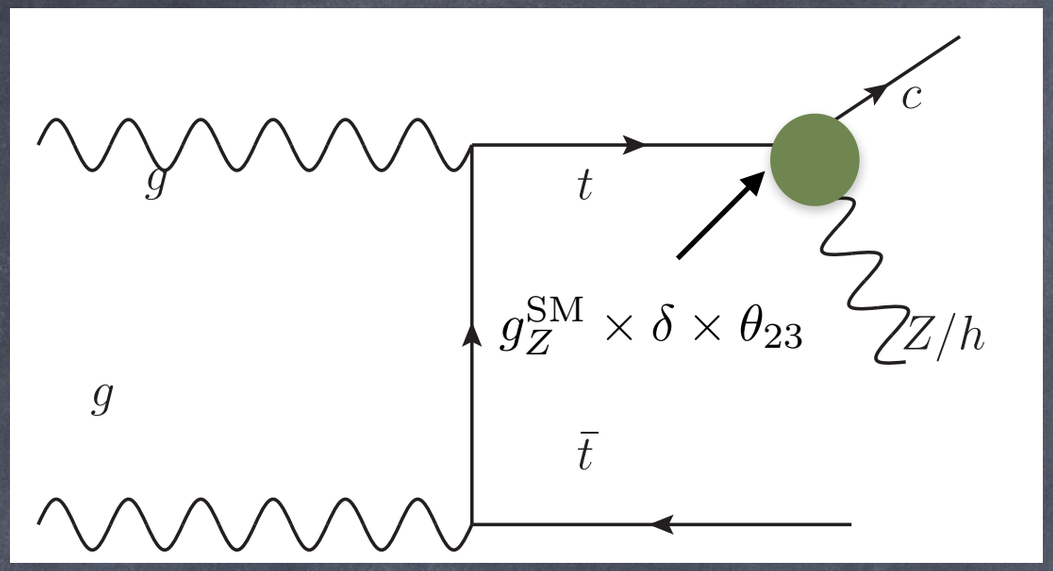


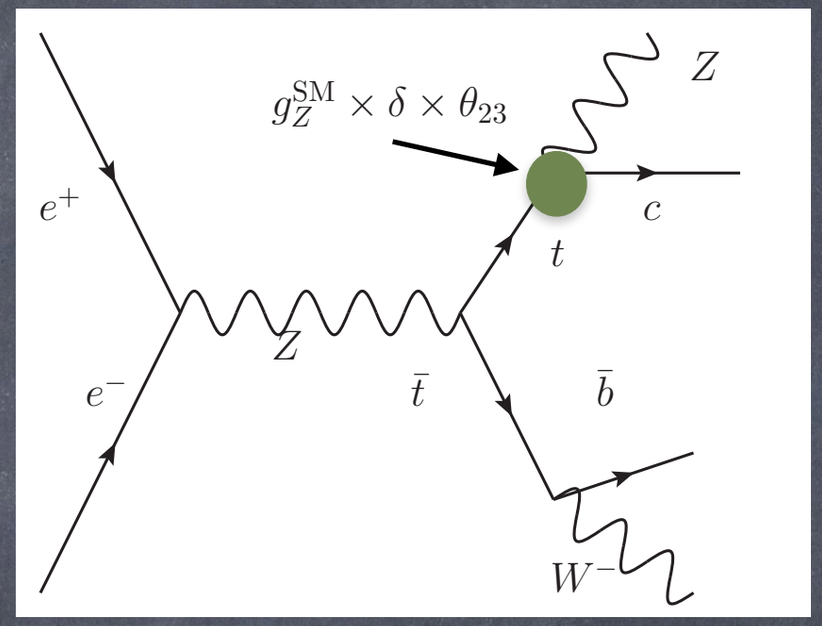
- similarly, top-charm-Higgs [KA, Contino (2009)]

(negligible in SM: coupling matrix identity, up to tiny loop effects)

Testing at LHC and e^+e^- (future) collider

- LHC

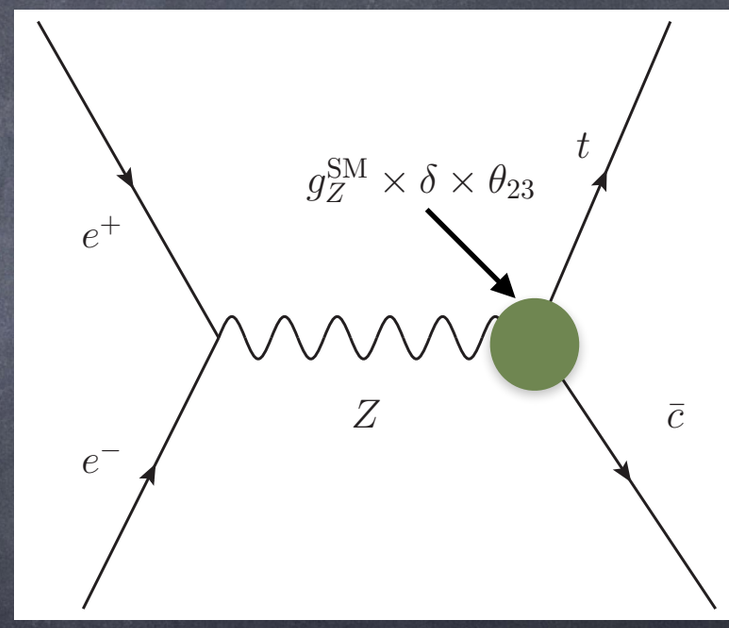




- e^+e^- ($E \gtrsim 350$ GeV): via decay

linear (Japan)

circular (CERN/China)



- e^+e^-[$E \gtrsim 250$ GeV ($\sim$ Higgs factory)]: (single top) production (not for h)

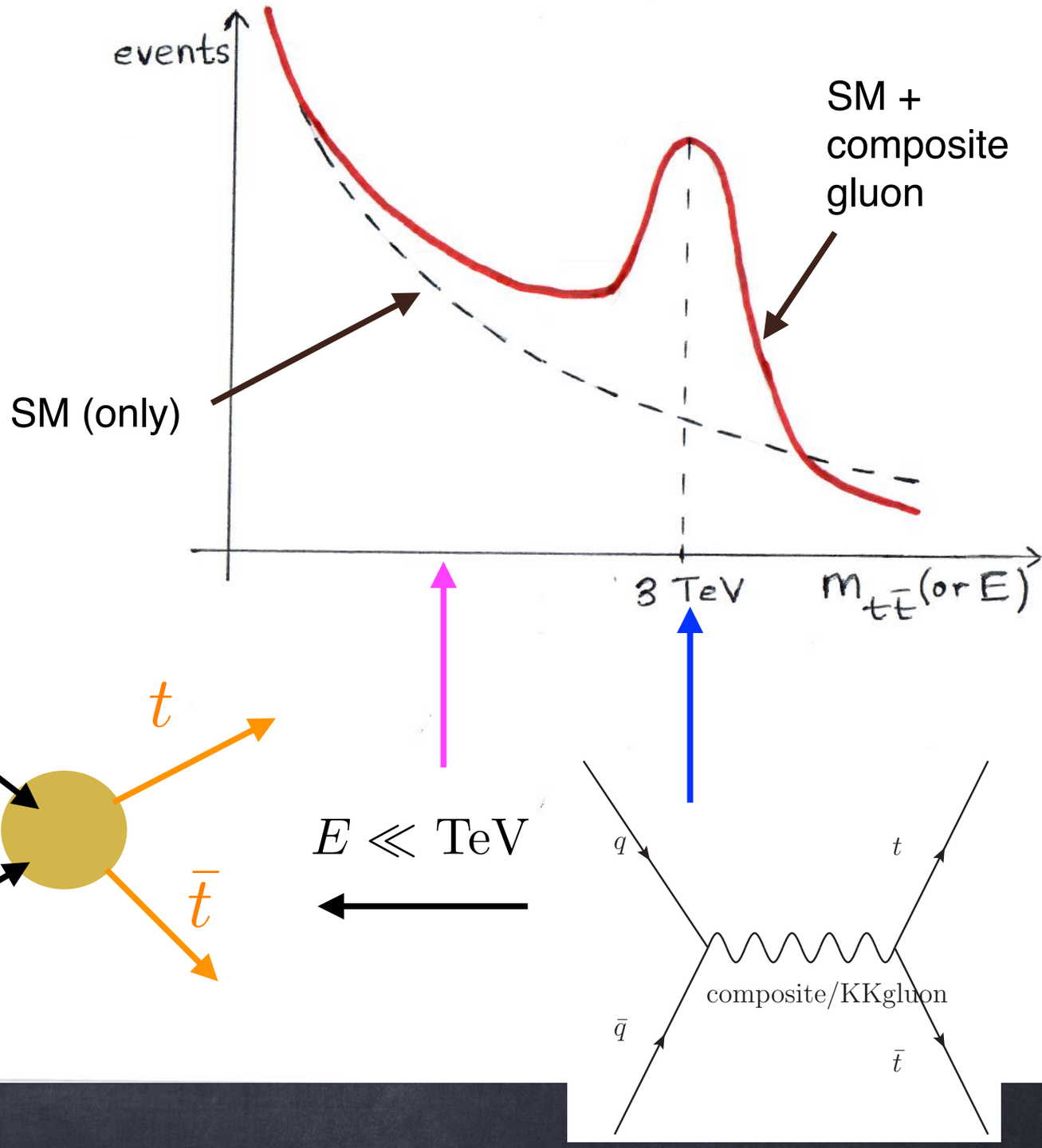
Prediction: BR $(t \to cZ) \sim O\left(10^{-5}\right)$ for compositeness scale ~ 3 TeV
Sensitivity: $\sim 10^{-4}$ at LHC; $\sim 10^{-3}$ (decay), 10^{-4} (single top) at e^+e^-

Prediction: BR $(t \to ch) \sim O\left(10^{-4}\right)$
Sensitivity: $\sim$ a few $\times\, 10^{-4}$ at LHC

New contribution to top-pair production at LHC

- same diagram as before (direct effect), but low energies (heavy, composite gluon is virtual)

(LHC can probe both: total E = 13 TeV, but E of constituents varies)



...IMPLICATION FOR MEASUREMENT OF TOP MASS?!

Haven't we done that already?!

- counter-intuitive at first
- (most) existing methods assume (in one way or another) top(s) produced by SM processes, e.g., compute distribution of decay product as function of m_t, find best fit to data

$$\text{Prediction } (m_t; \text{ theory }) = \text{data},$$
$$\text{with theory} = \text{SM}$$

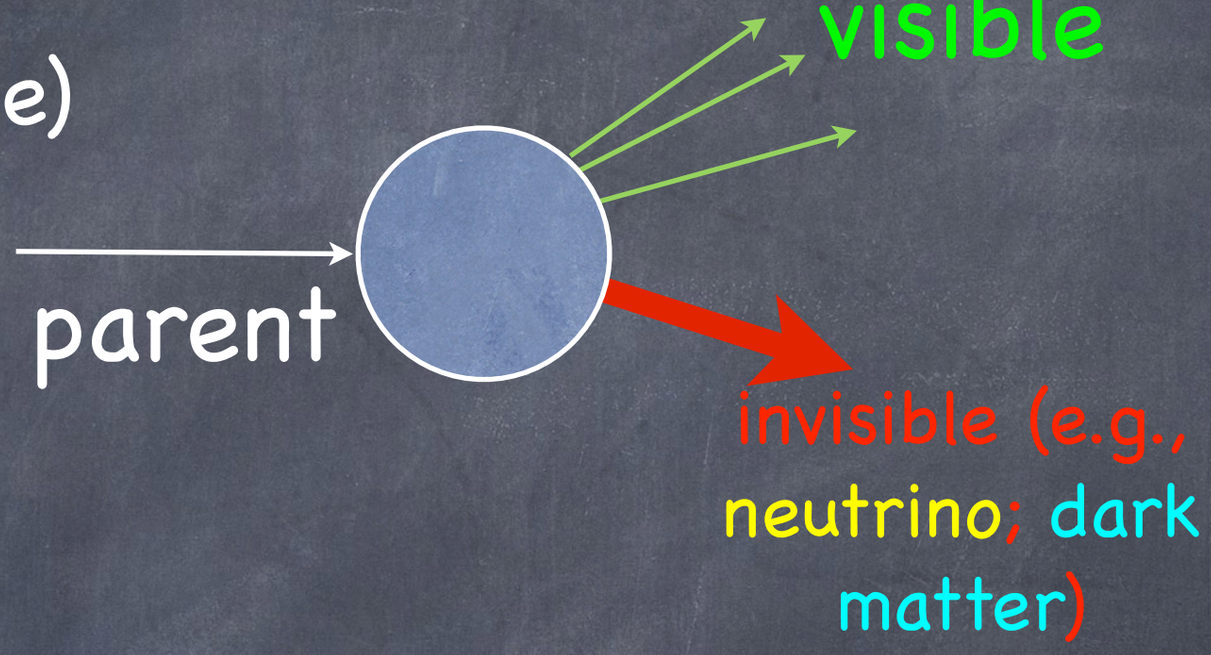
- new (unknown) contribution → above not quite accurate
- need method independent of production mechanism

USING ENERGY-PEAKS FOR MEASURING (OLD AND NEW) PARTICLE MASSES

[KA, Franceschini, Kim (2012); KA, Franceschini, Kim (2013); KA, Franceschini, Kim, Wardlow (2015); KA, Franceschini, Hong, Kim (2015); KA, Franceschini, Kim, Schulze (2016)]

Basic goal (simple!)

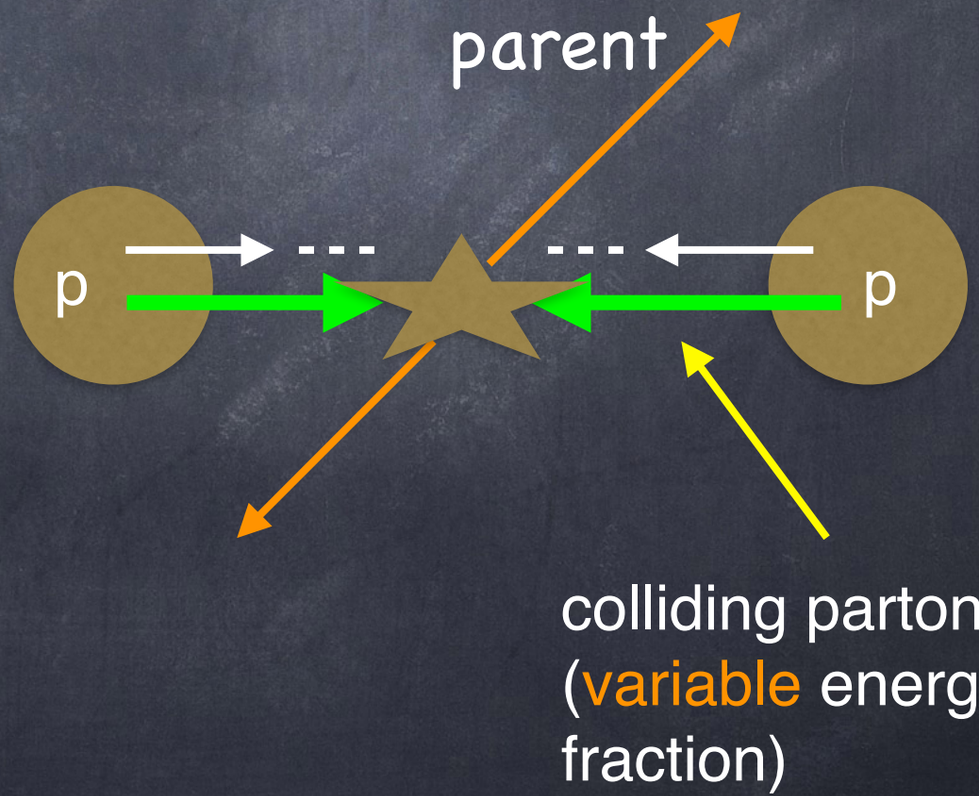
- determine mass of parent particle by measuring (visible) decay products (child particles)



- challenges for decay kinematics (only)-based method (independent of production mechanism):

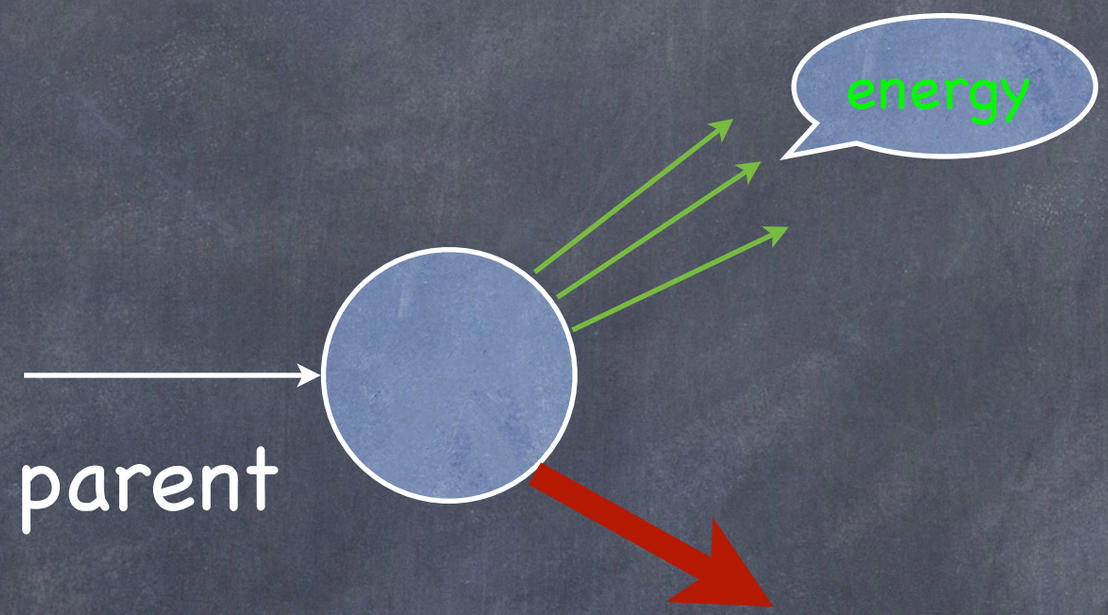
  Missing particles (cannot fully reconstruct decay)

  Unknown velocity (boost) of parent in lab frame (depends on production details)



Simple, yet Subtle idea

- use (only) energy of decay product: not invariant under parent boost ⇒ (Lorentz-invariant) mass??!!



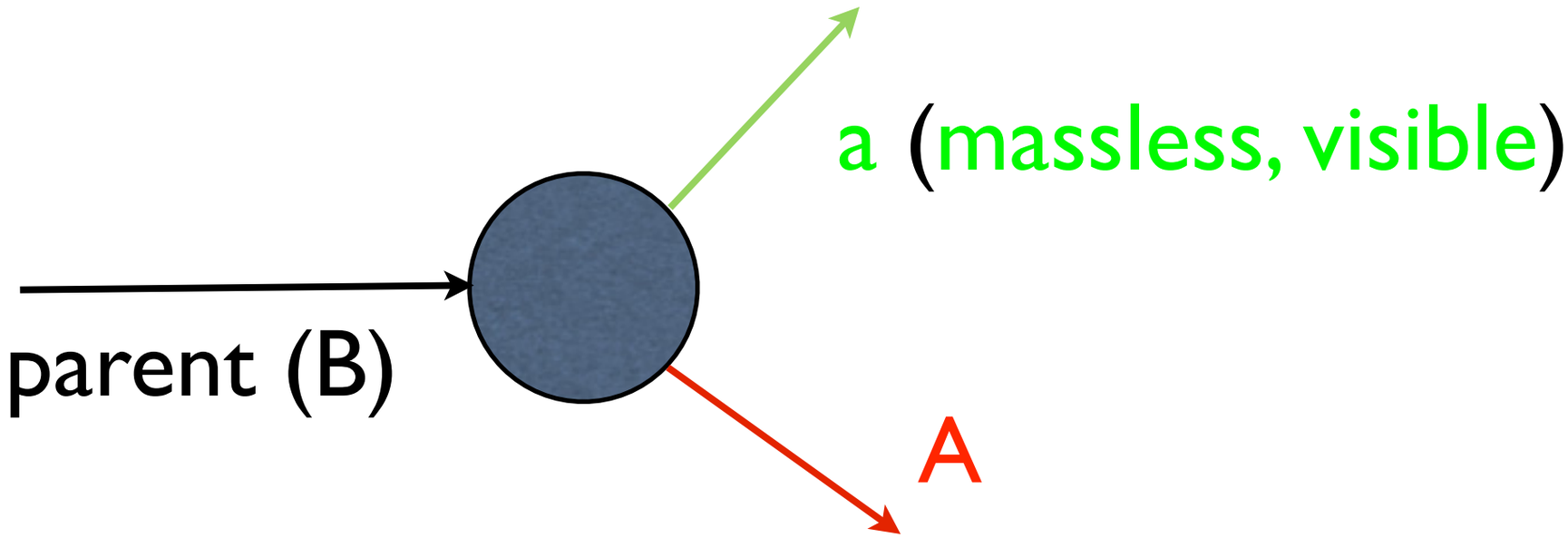
- Location of peak of energy (distribution) is invariant under boosts of parent particle (even if rest of shape is not)!

- CMS @ LHC measured top quark mass using this ``energy-peak"

SUMMARY OF NEW OBSERVATION/"INVARIANCE" OF TWO-BODY DECAY KINEMATICS

Basic set-up/assumptions

- 2-body decay: one child particle visible, massless:



- ...other (A) don't care (except for its mass)!
- unpolarized parent (all spin orientations equal)

Energy of child particle

- mono-chromatic and simple function of masses in rest frame of parent:

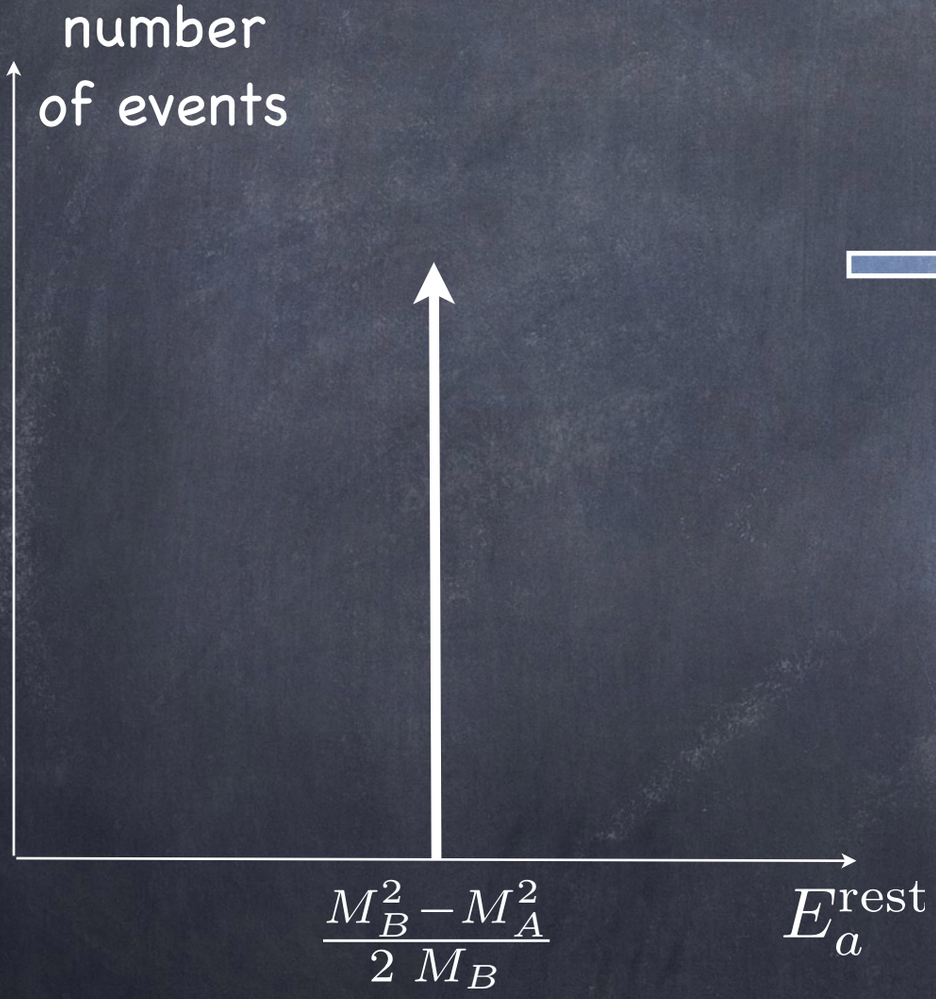
$$E_a^{\rm rest} = \frac{M_B^2 - M_A^2}{2M_B}$$

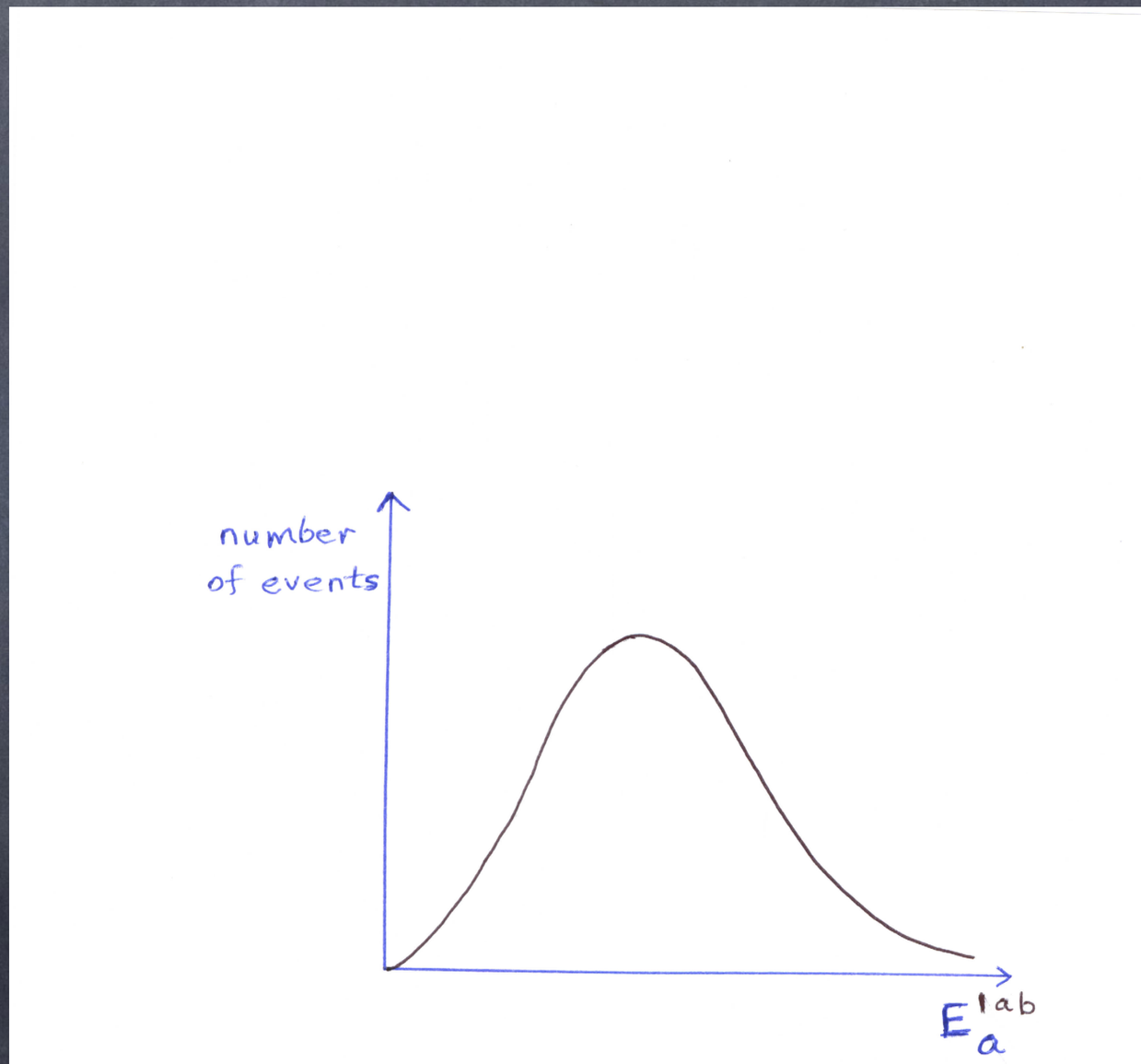
- determine M_B if M_A known and $E_a^{\rm rest}$ measured

...but not Lorentz (parent boost)-invariant

...too simple to be practical/useful?!

- hadron collider: parent has unknown boost; varies event to event ⇒ distribution in $E_a^{\rm lab}$





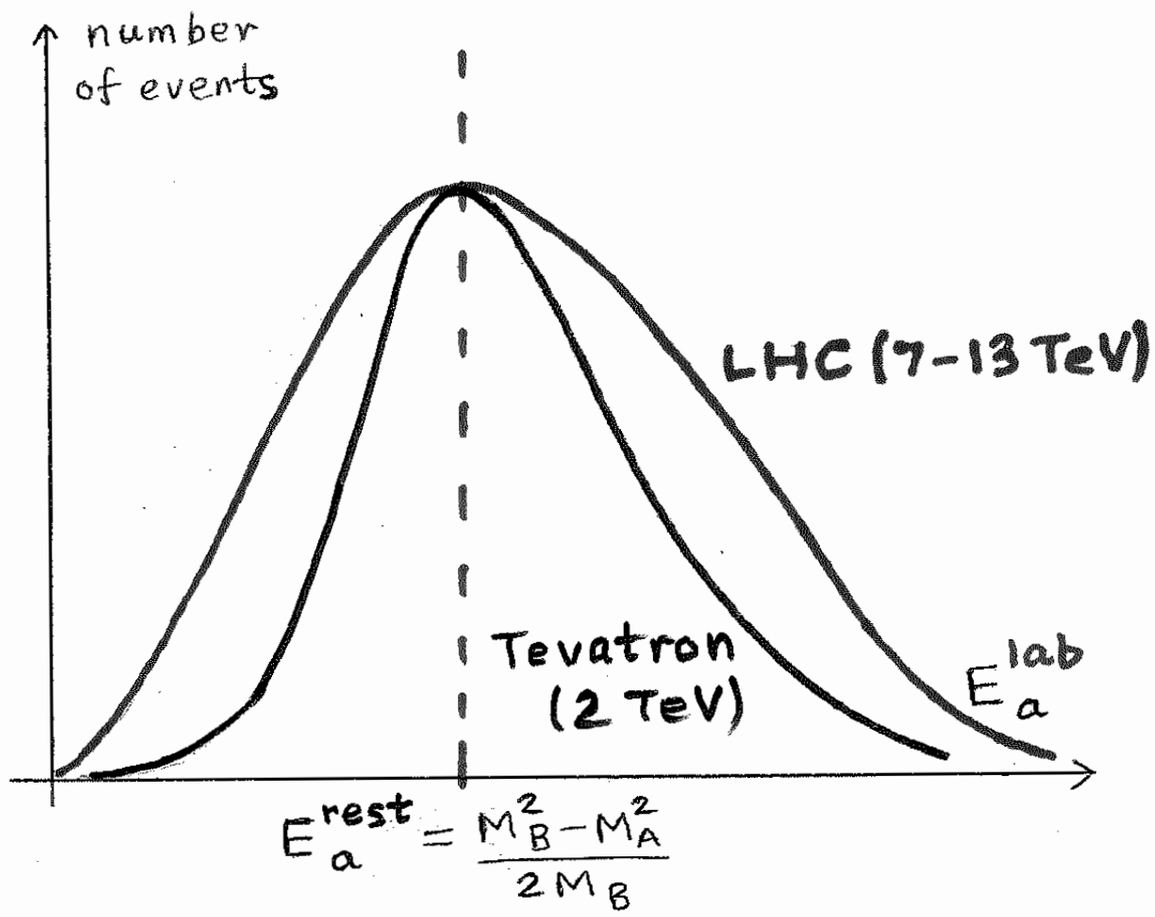
- lose rest-frame information??!!

Conservation of invariance!

- Show analytically (in next 2 slides!): peak (of lab. distribution) still retains this information... simply, precisely, robustly!

independent of boosts of parent

- Distribution of log of energy is symmetric about peak (back-up slides)



DERIVATION OF INVARIANCE

Rectangle (covering $E_a^{\rm rest}$) for fixed, but arbitrary boost

In general:

$\theta_{aB} = 0 \Rightarrow$ (max) $E_a^{\rm lab} > E_a^{\rm rest}$

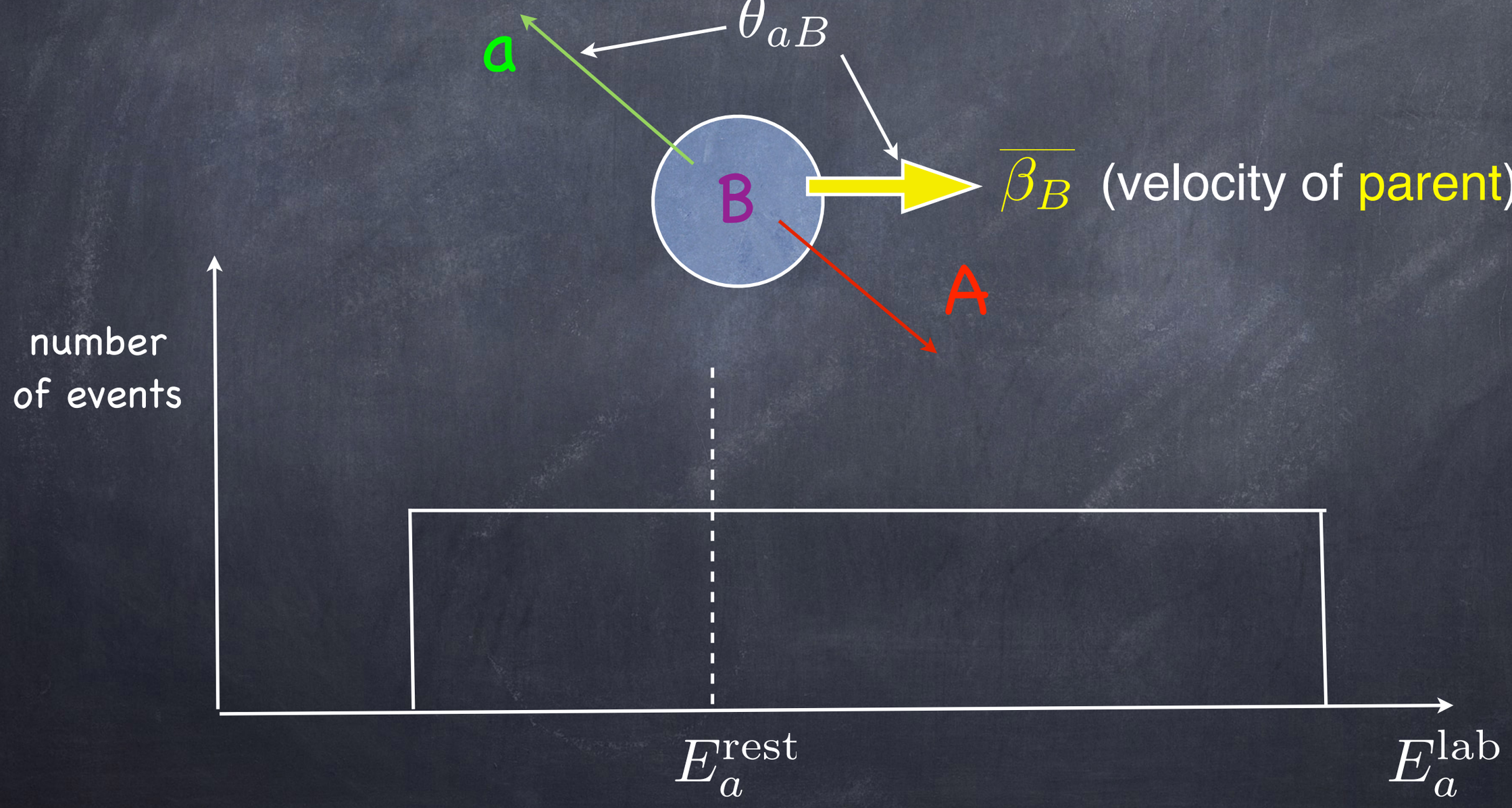
$\theta_{aB} = \pi \Rightarrow$ (min) $E_a^{\rm lab} < E_a^{\rm rest}$

$\Rightarrow$ intermediate θ_{aB} gives $E_a^{\rm lab} = E_a^{\rm rest}$

+

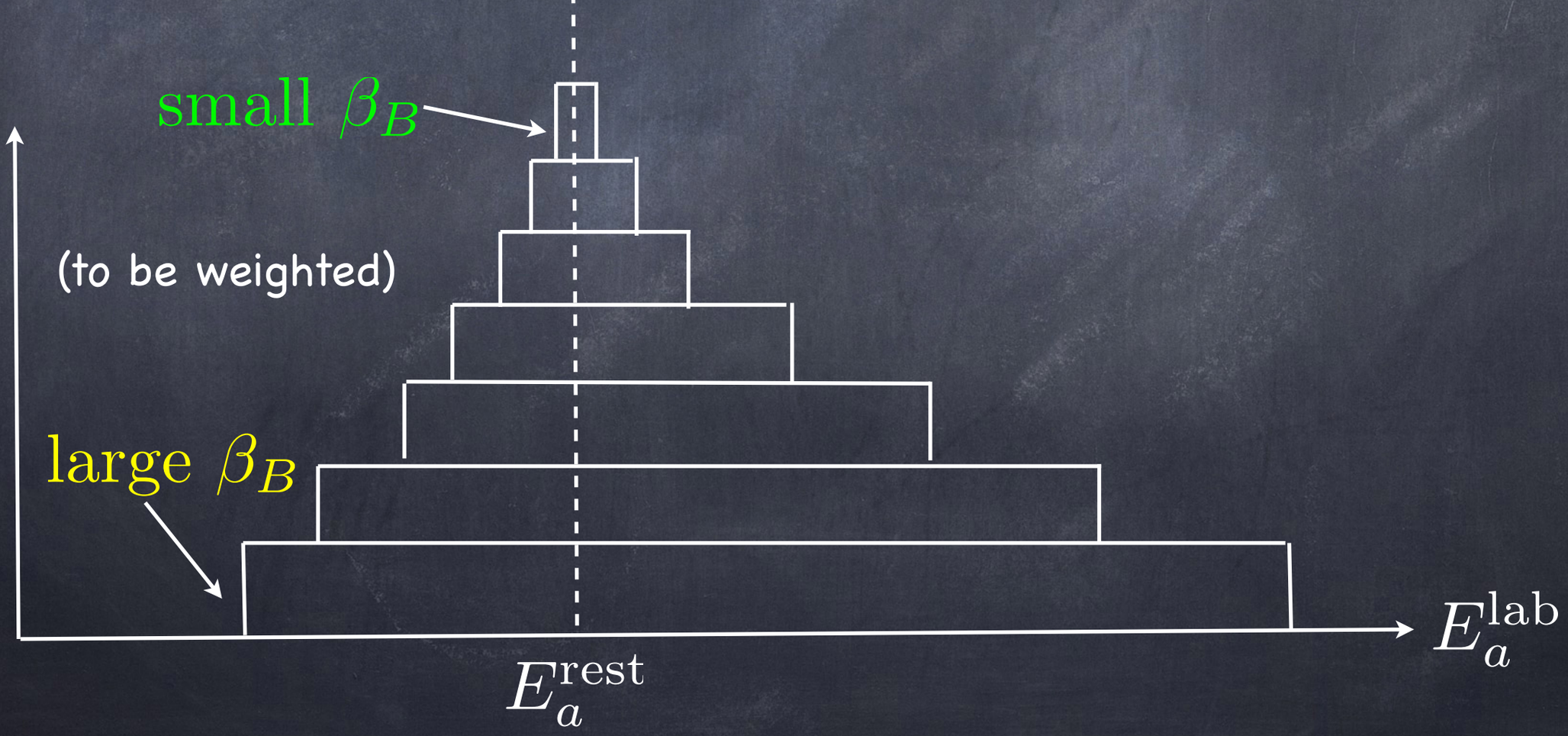
Assume unpolarized parent:

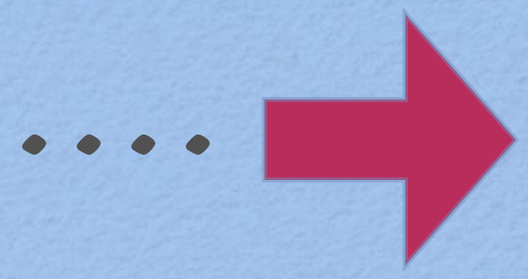
$\Rightarrow \cos\theta_{aB}$ is flat (rectangle)



(Generic) Boost distribution: "stacking" up rectangles [KA, Franceschini, Kim (2012)]

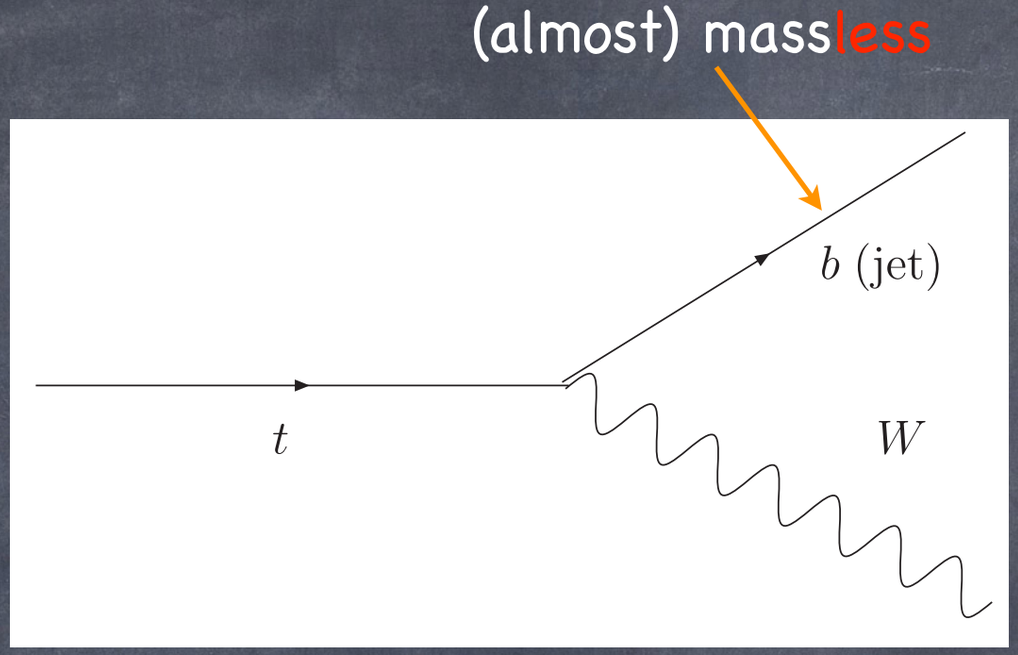
- distribution of $E_a^{\rm lab}$ has peak at $E_a^{\rm rest}$ (see also Stecker: "Cosmic gamma rays")
- ....no matter what is the (parent) boost distribution!
- boost distribution depends on production mechanism, parent mass, PDF's...





TECHNIQUE/APPLICATION

Top quark mass

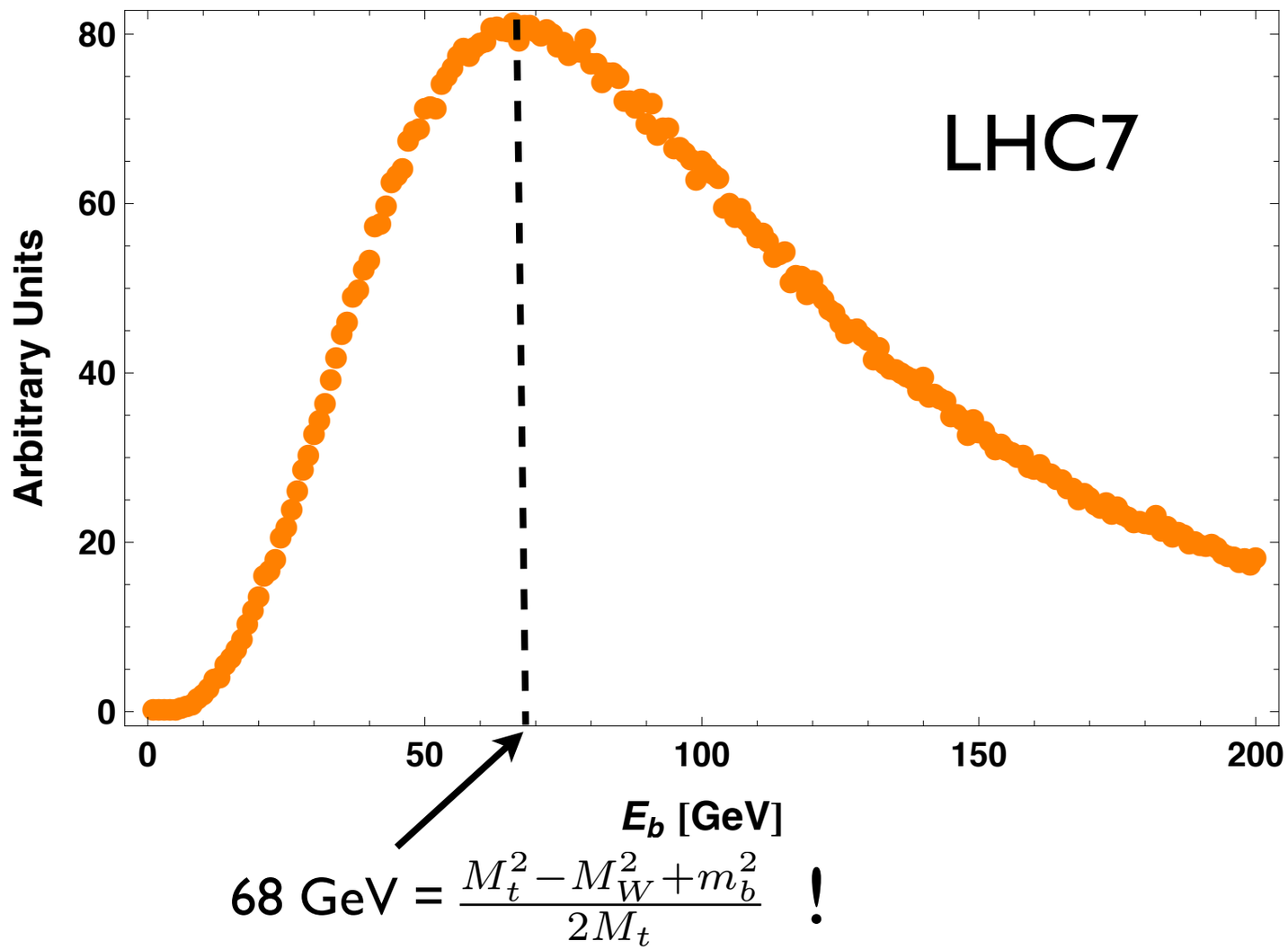


- Peak in measured b-jet energy distribution $\approx \frac{M_t^2 - M_W^2}{2M_t}$
- Assuming M_W (but no need to reconstruct it!), get M_t

Analytical result → robust, but anyway, numerical simulation (colliders messy)…

- bottom from top quark decay as example:

bottom mass negligible → peak is not expected to shift from $E_b^{\text{rest}} = \frac{M_t^2 - M_W^2 + m_b^2}{2M_t}$ modified



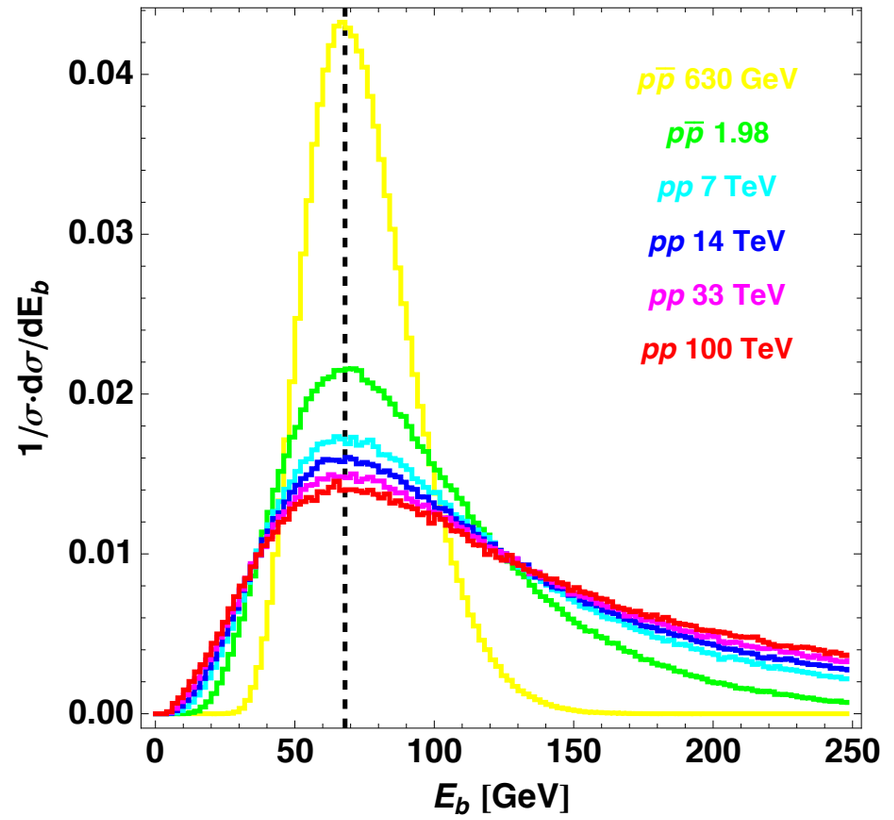
- …can it be an "accident" (e.g., this collider only)?!

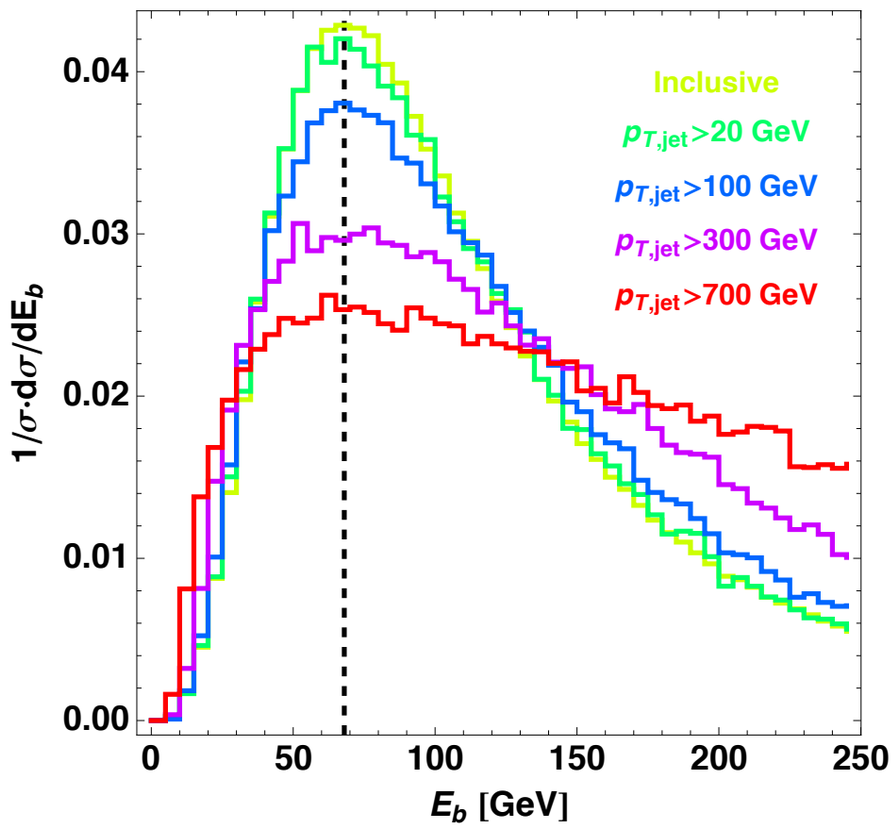
``Invariant" (under boost distributions) feature in non-invariant (energy)distribution: subtle!

- vary collider energy

- vary initial state (from partons) radiation

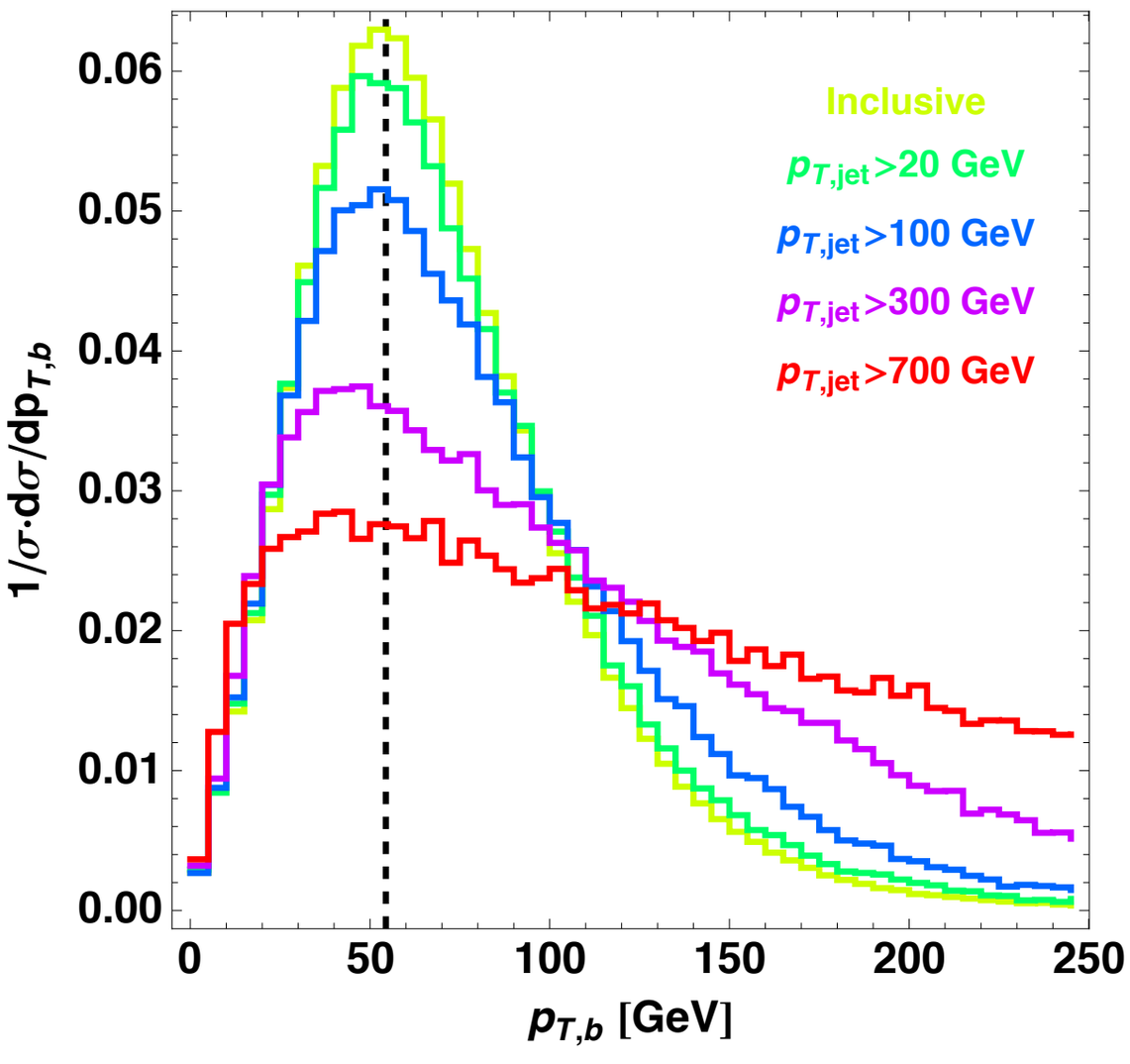
- ...but, peak stays put, even though shape changes (broadens for more boosted top)

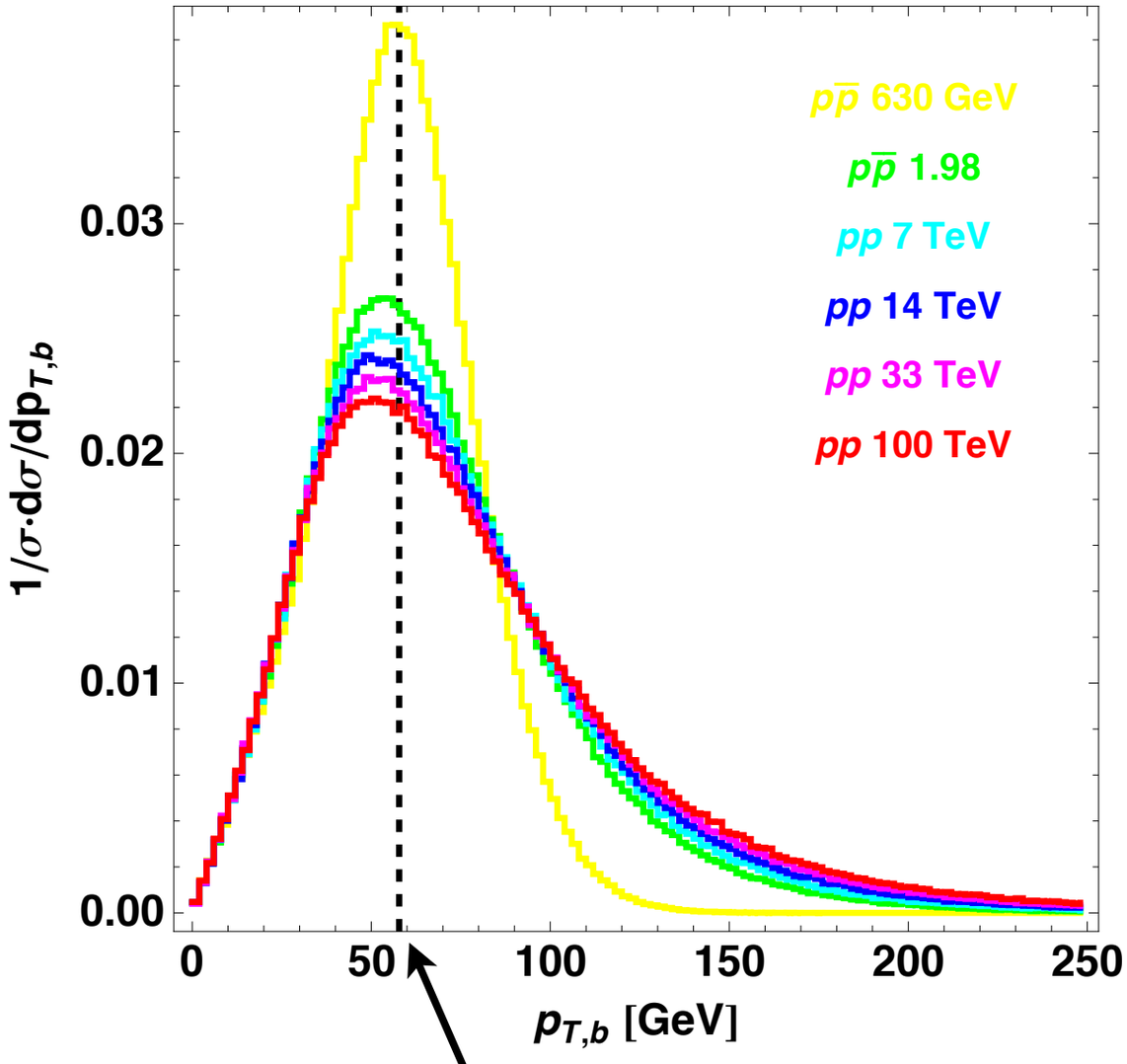




...accidents don't happen: no such invariance for transverse momentum (p_T) !

analytic guidance crucial





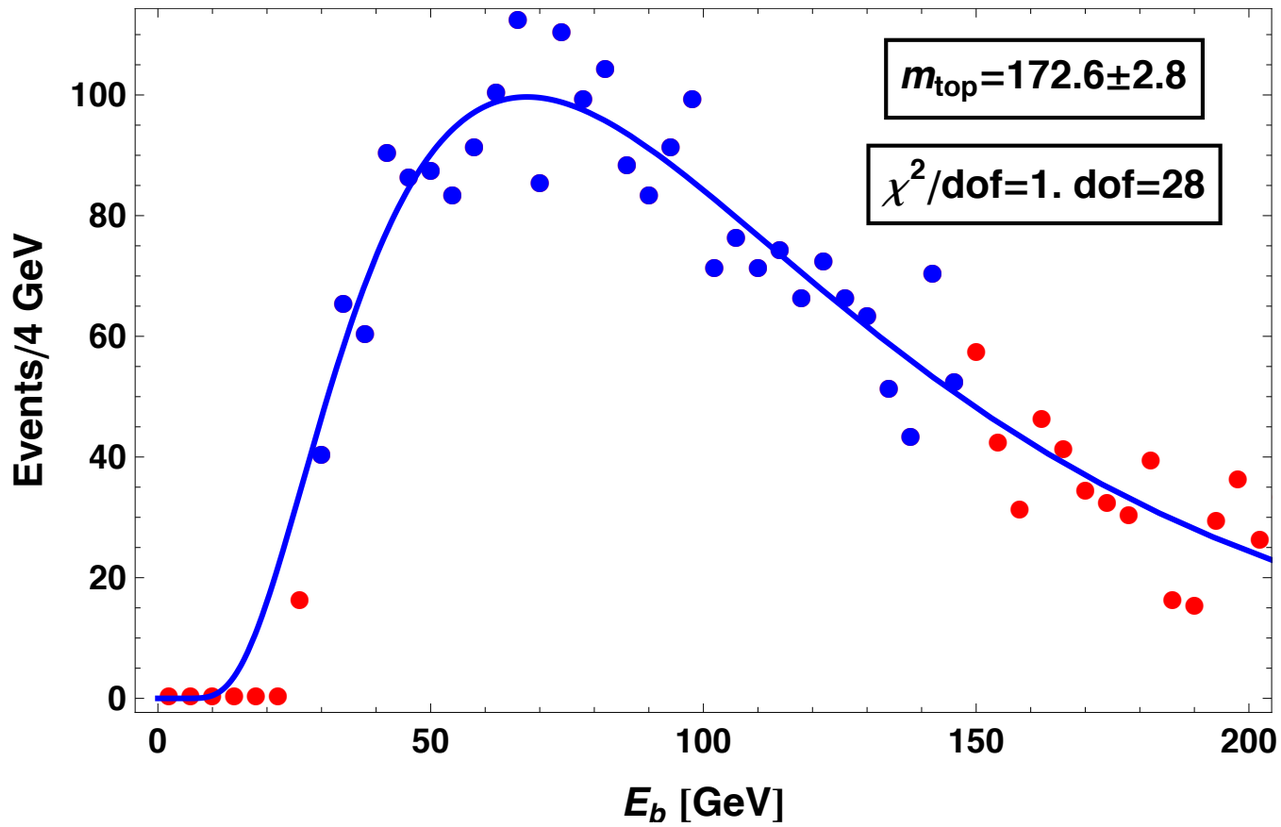
not 68 GeV

- peak (and shape) change...

Result for top mass (phenomenological)

(1 pseudo-experiment shown)

5/fb @ LHC7
in $e\mu bb$
channel



(use only
blue dots)

- consistent with input value
- fitting not spoiled by event selection and detector effects (colliders even more messy!)

...cut to CMS (real data!)

- implementation on run 1 data in CMS PAS TOP-15-002:

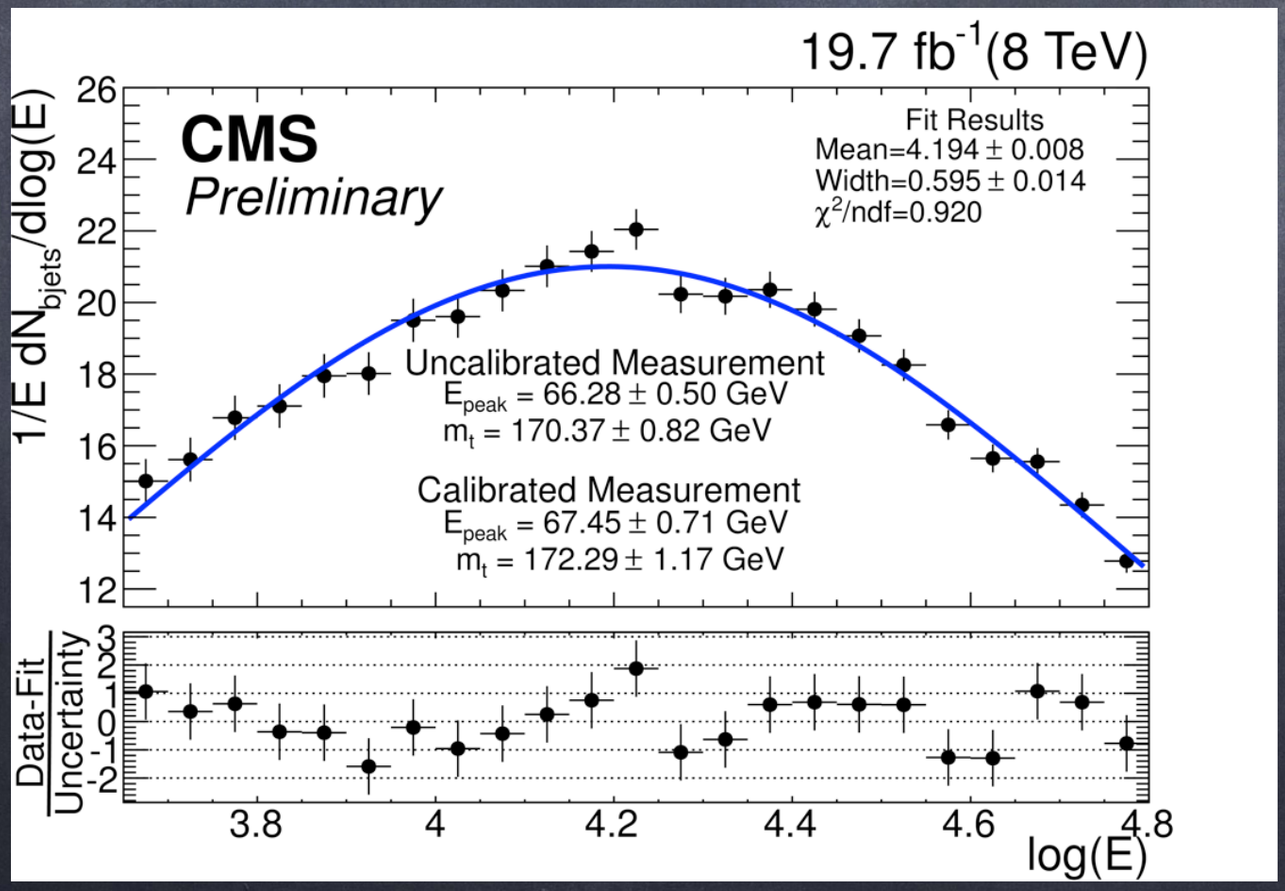
$$m_t = 172.29 \pm 1.17\,(\text{stat.}) \pm 2.66\,(\text{syst.})\ \text{GeV}$$

- Complementary to other methods (error $\sim$ 1 GeV)

- Sources of error: jet-energy scale; modeling of top p_T

use B-decay length?

higher-order (theory) calculation [KA, Franceschini, Kim, Schulze (2016)]



- ATLAS might not be far behind!

note!

General applicability

- Top quark: other (not just composite top) new contributions to production

- other particles…

Composite Higgs/Top:

GUT

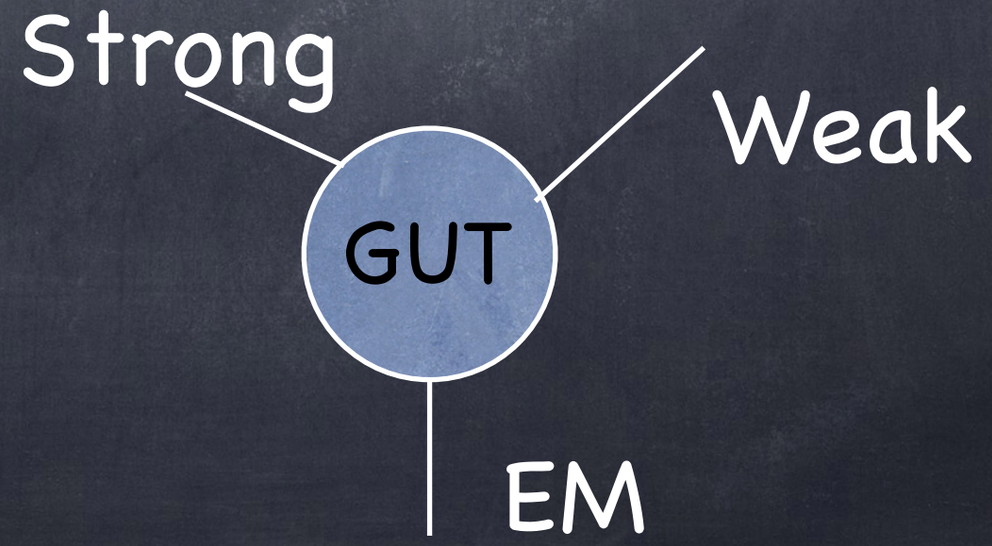
Strength of forces not constant!

- 3 strengths different at observed distance scales (energies)
- Strengths evolve with energy due to quantum effects:

$$1/r^2 \to 1/r^2 \ \log r$$

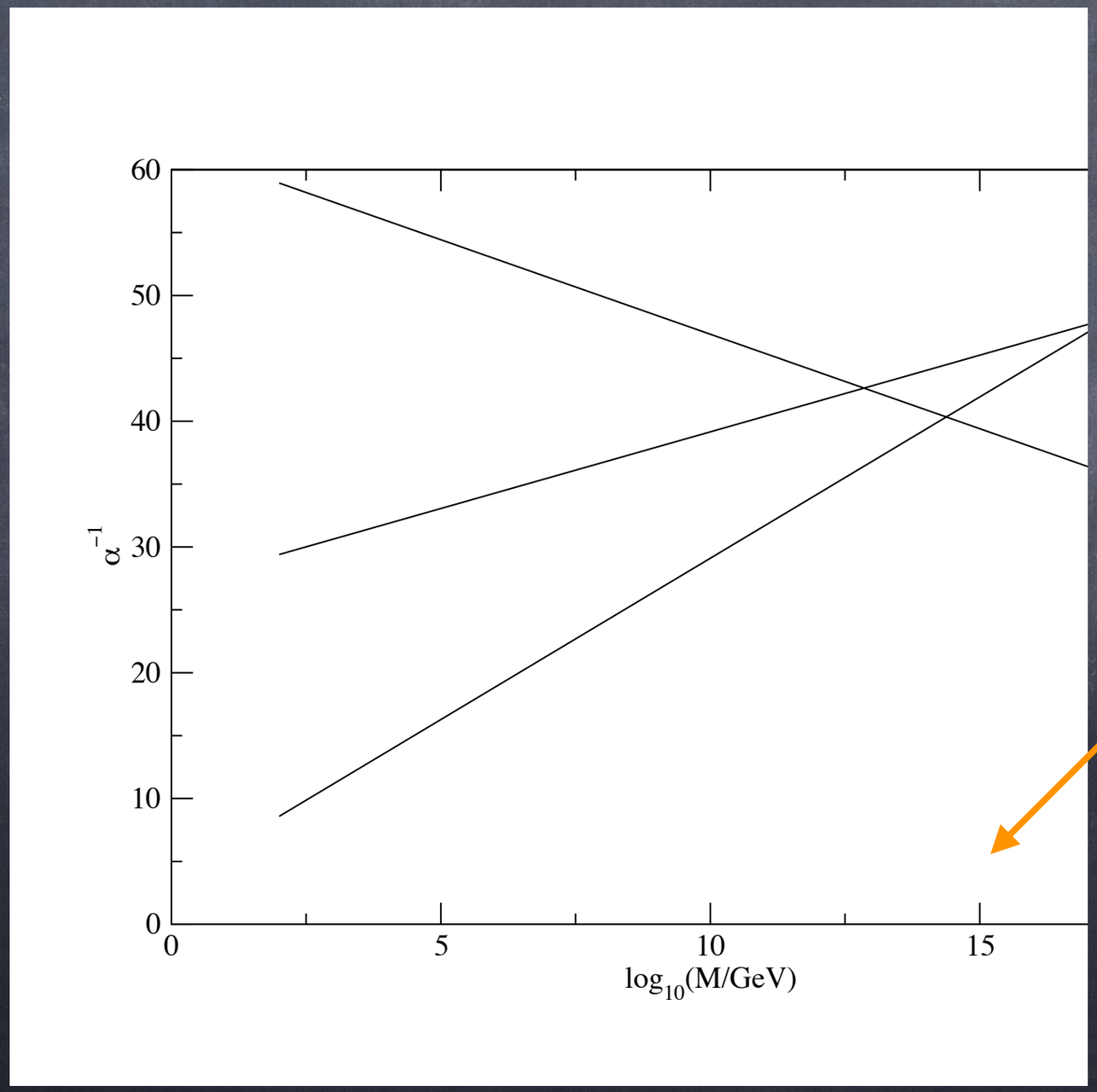
- ...differently for 3 forces of SM ⇒ couplings meet?

3 forces unified into Grand Unified Theory (GUT)?



GUT in SM

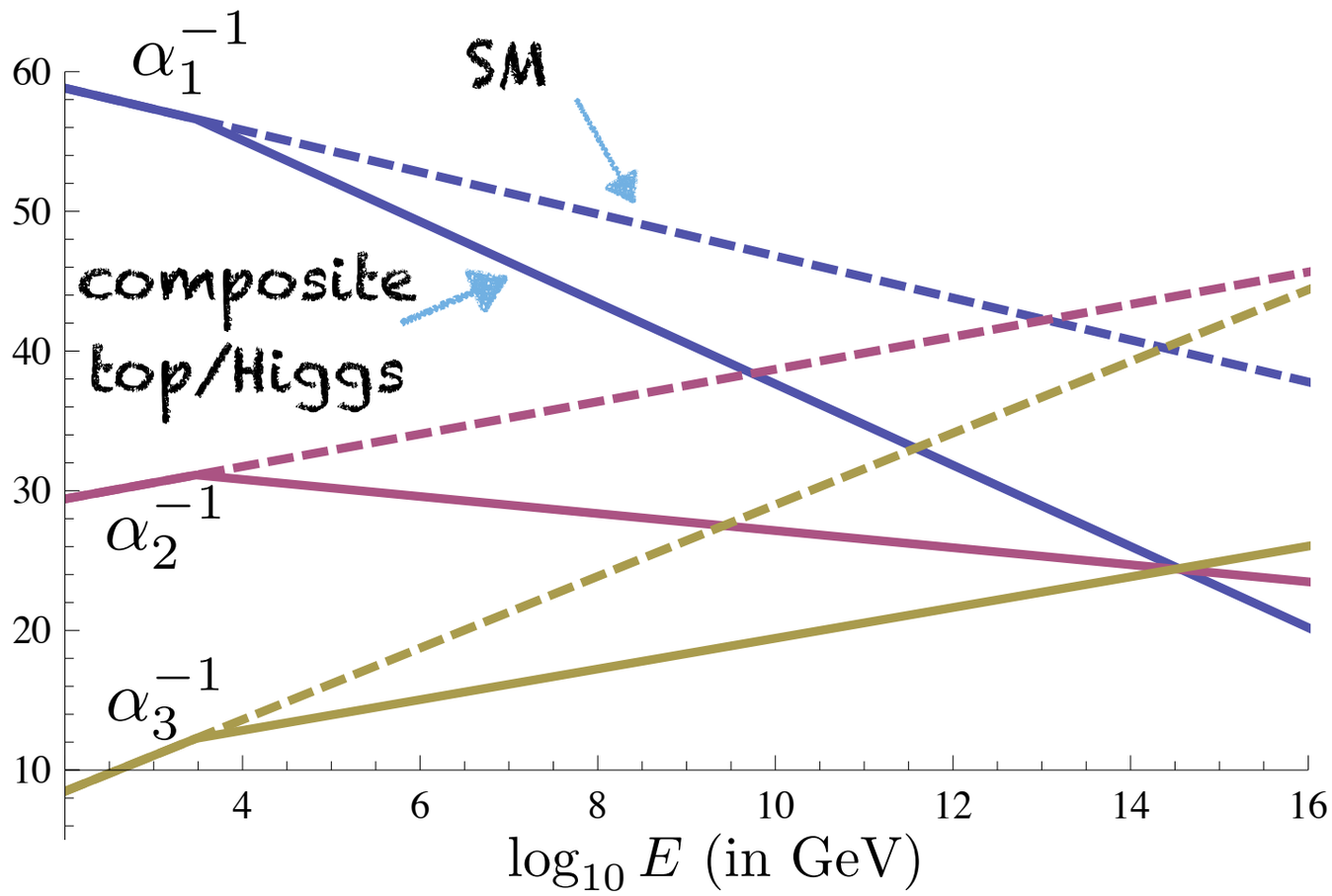
- ...good...but not so good given precision on couplings..



not far from/close to
Planck/gravity scale

Composite GUT [KA, Contino, Sundrum (2005)]

- Top/Higgs compositeness ⇒ evolution of couplings modified from TeV: replace top/Higgs by (strongly coupled) constituents
- Assume unified multiplets in strong dynamics ⇒ "kinks" are correlated ⇒ Precise meeting

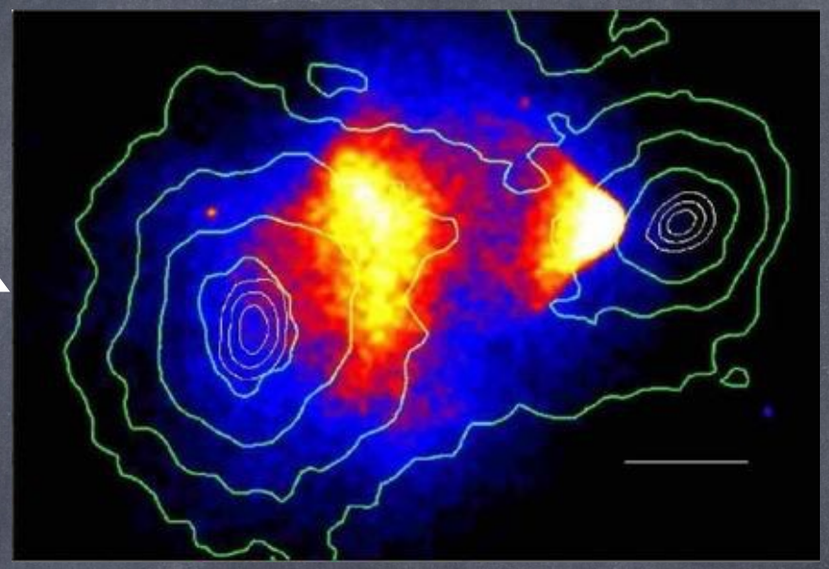


Composite Higgs/Top:

GUT → DM

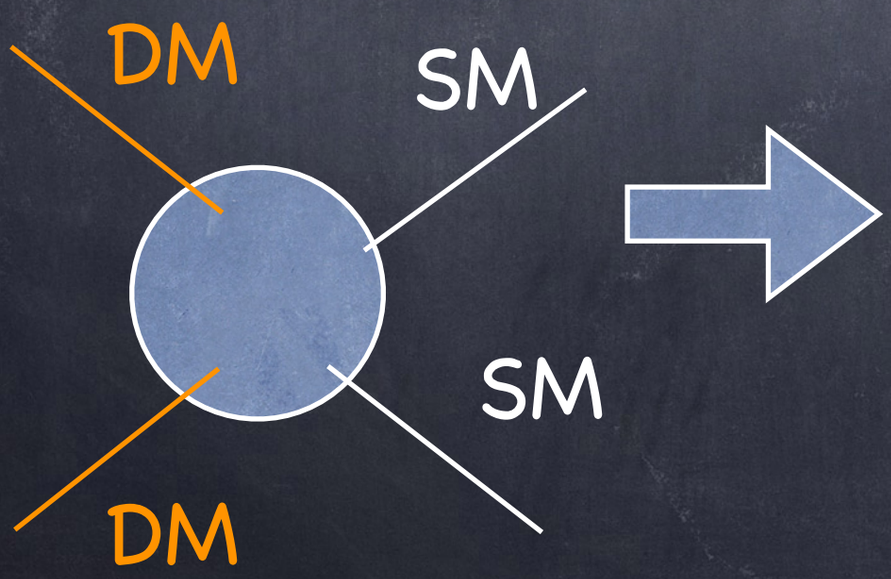
"Need" stable WIMP

- Evidence for Dark Matter: galaxy rotation curves, CMB, lensing, bullet cluster…



- Stable (new) particle
- Weakly Interacting Massive Particle (WIMP):

Mass ~ 100 GeV + Annihilation rate of weak strength

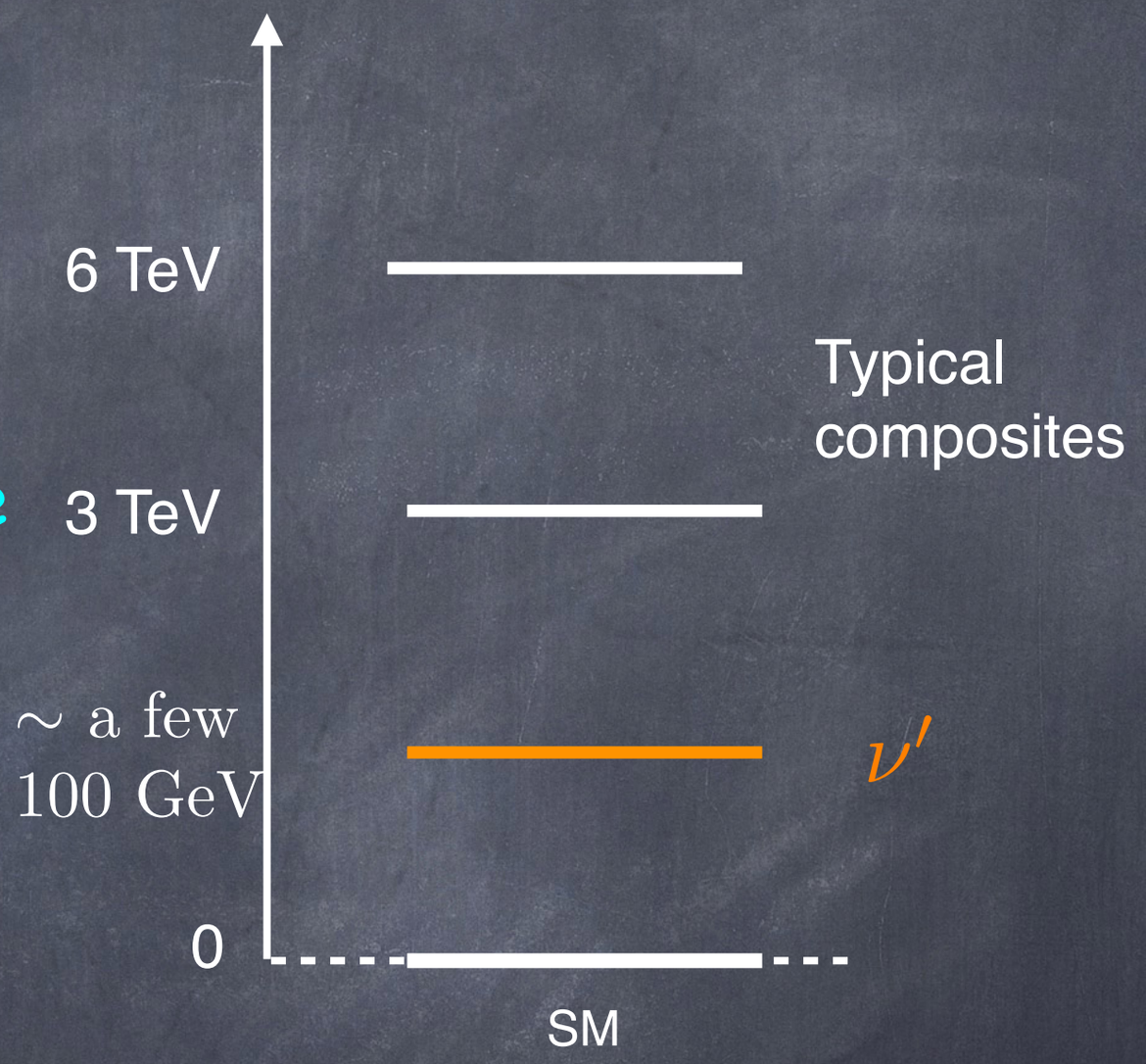


abundance in right ballpark
(annihilate in early universe:
thermal equilibrium, but then
can't find each other as
universe expands: freeze out)

Candidate in Composite GUT

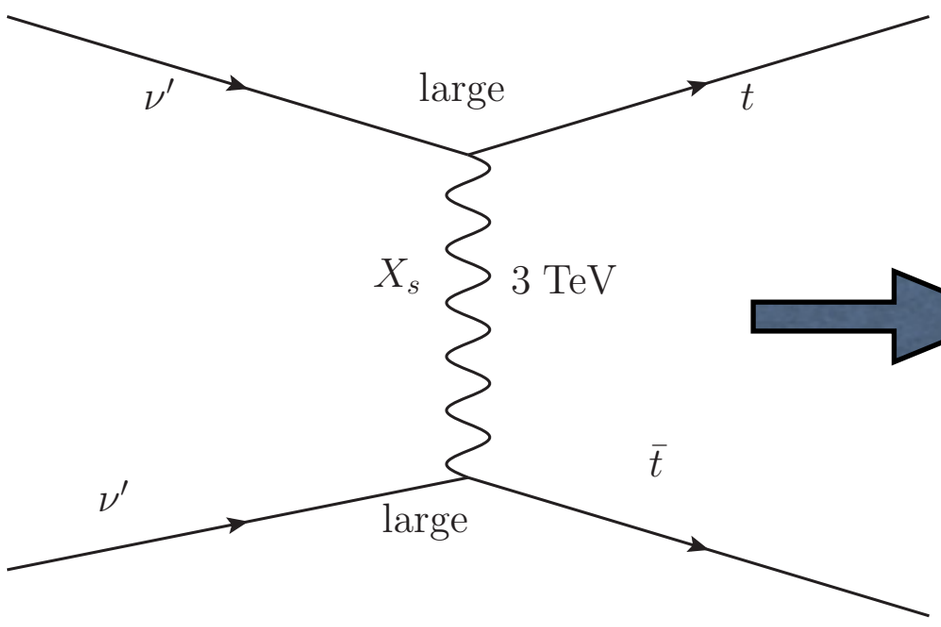
[KA, Servant(2004)]

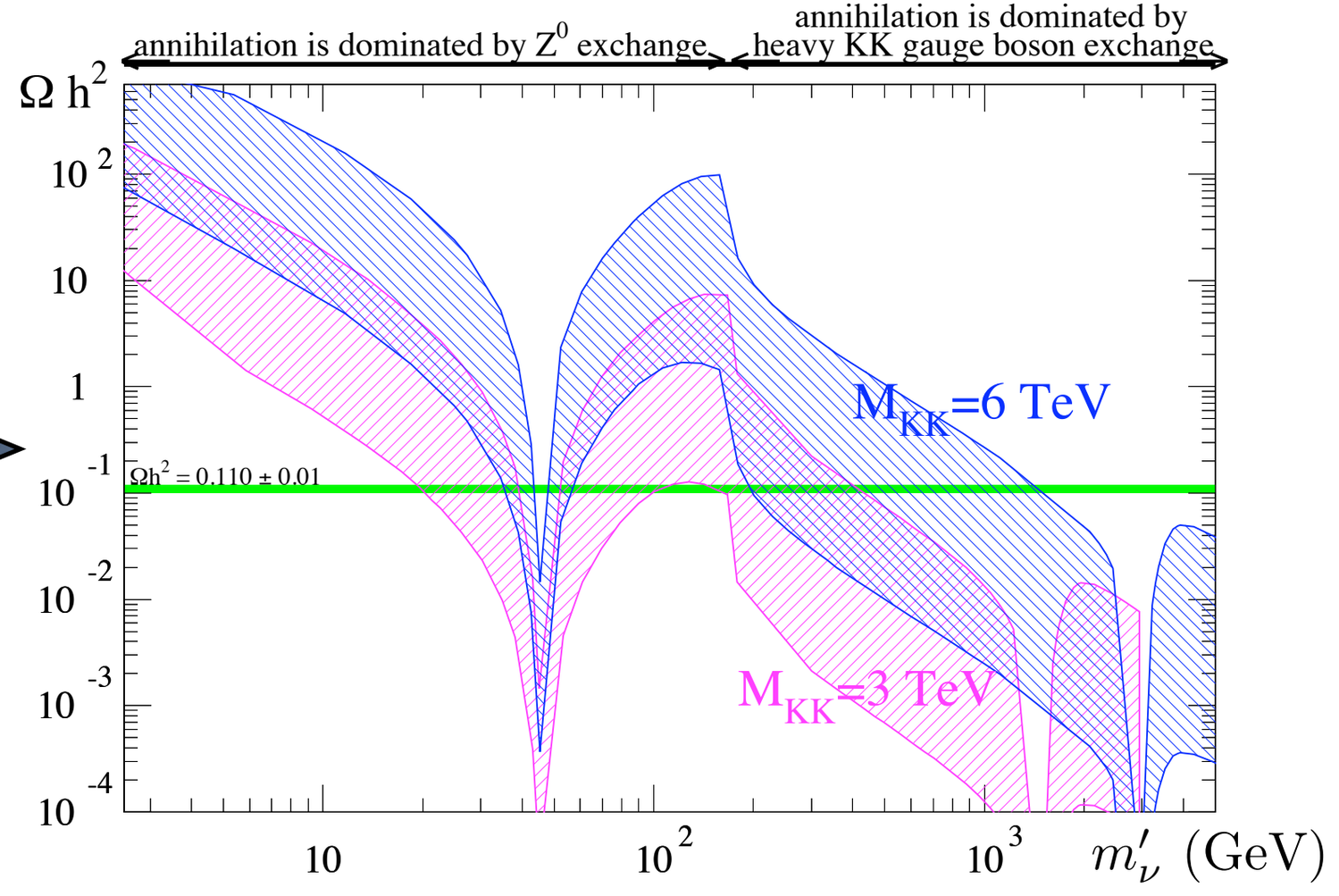
- symmetry imposed to suppress proton decay → stable particle
- "Exotic" neutrino (ν'): GUT partner of top (others are colored...)
- Mass $\sim$ a few 100 GeV < typical composite scale of 3 TeV naturally (related to top compositeness)



(Stable) WIMP in Composite GUT

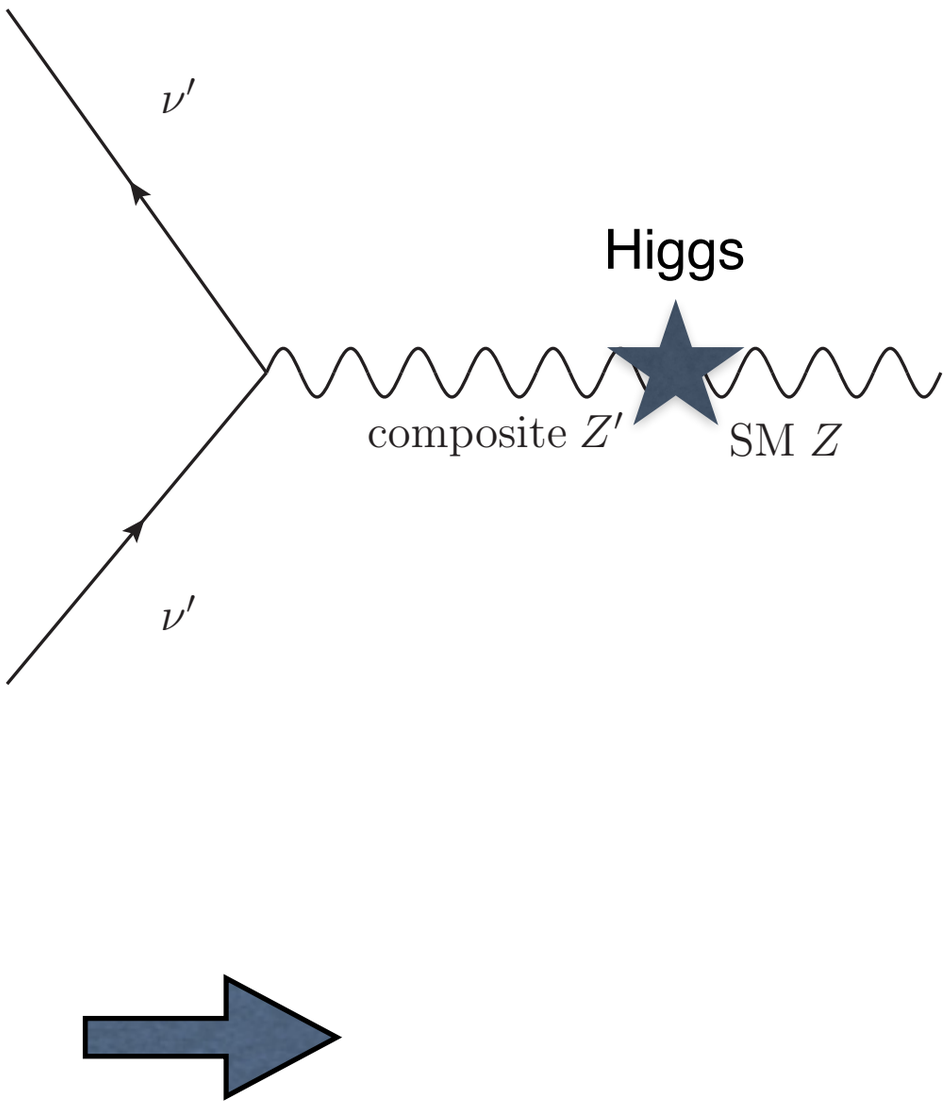
- Annihilation via exchange of 3 TeV (``>>" weak scale) composite, but strong coupling
- (Stable) ``neutrino" is a WIMP ⟹ Dark Matter

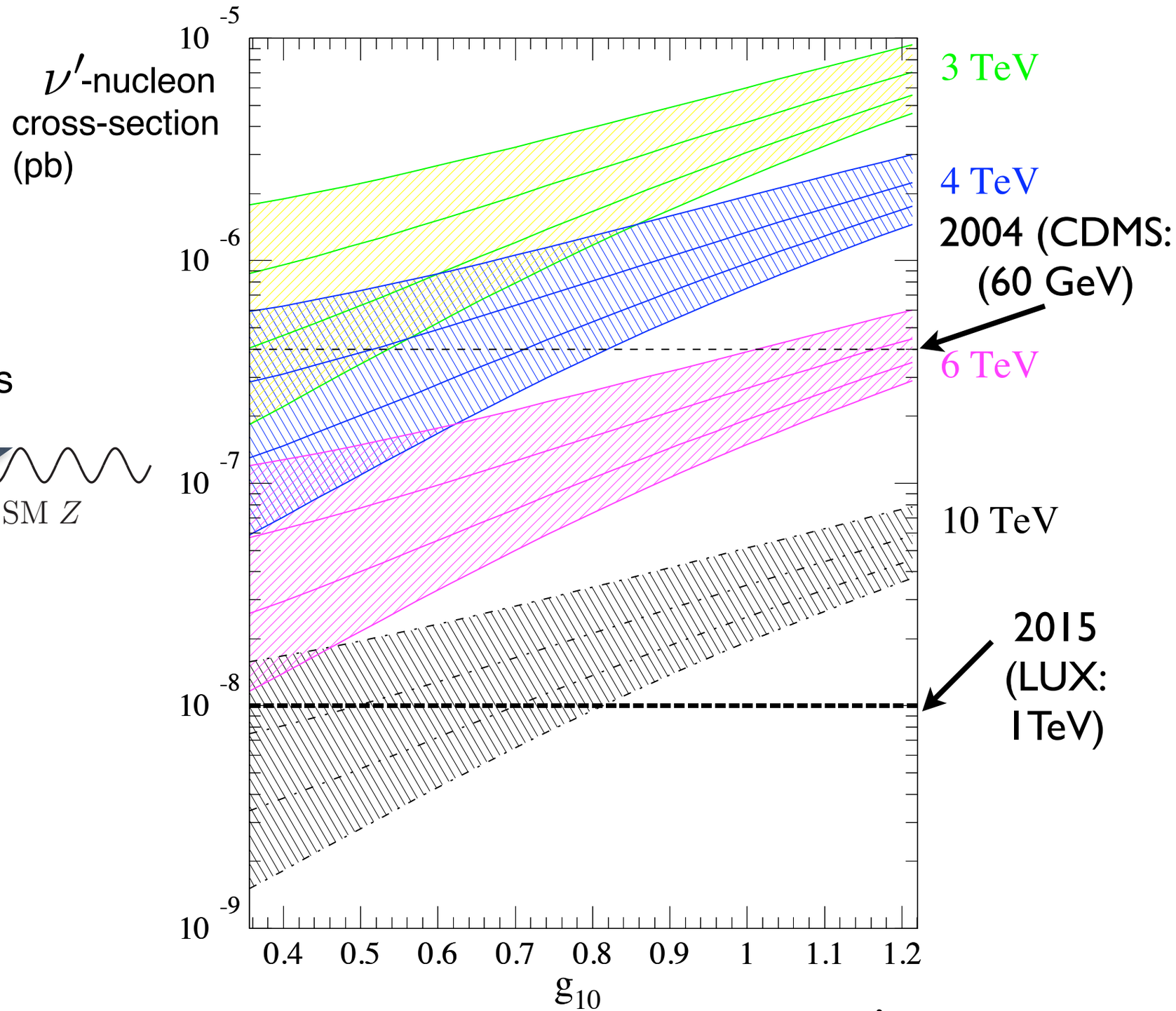




DM SIGNALS

(Standard) direct detection

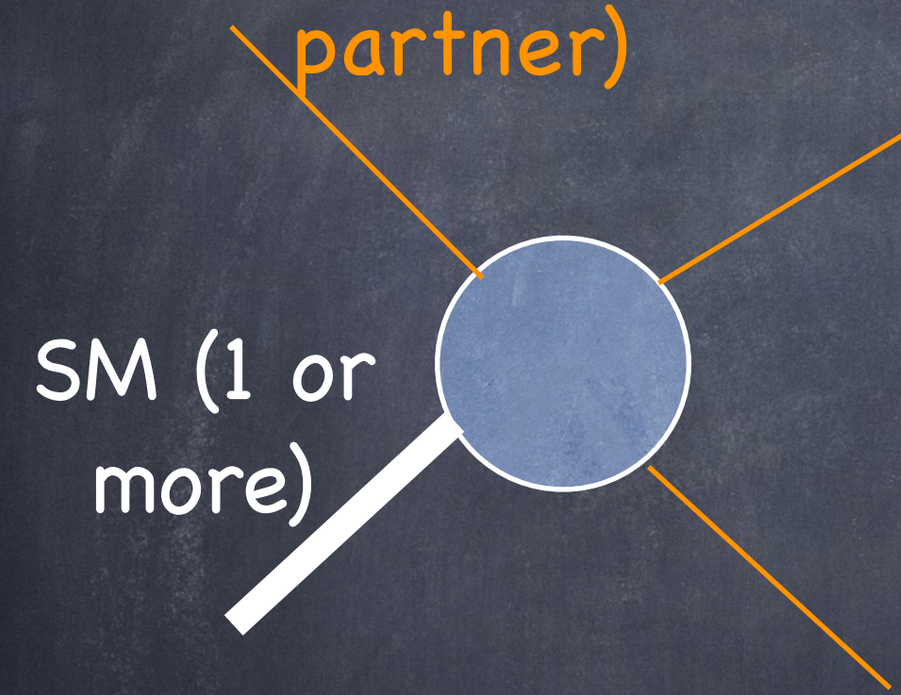




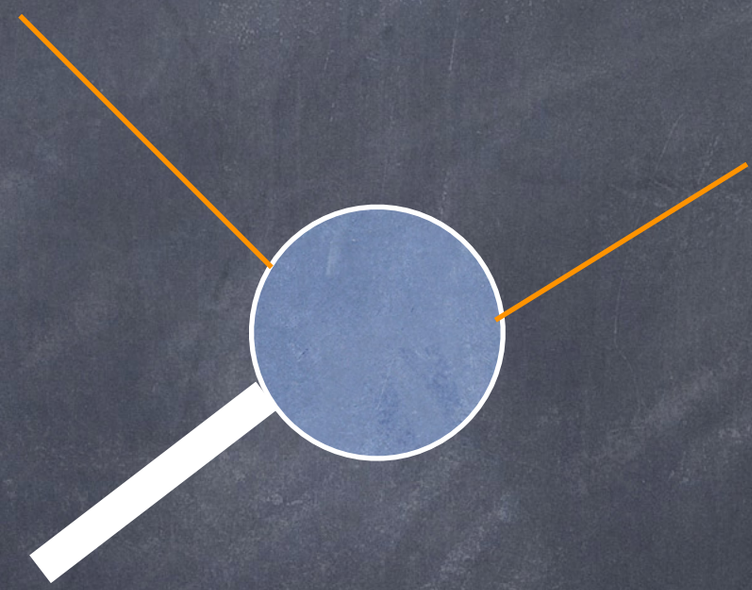
- ...tension for model example (evade by decoupling ν' from Z')

Non-standard effects

- Take-home : Z_3 symmetry (composite GUT) vs. Z_2



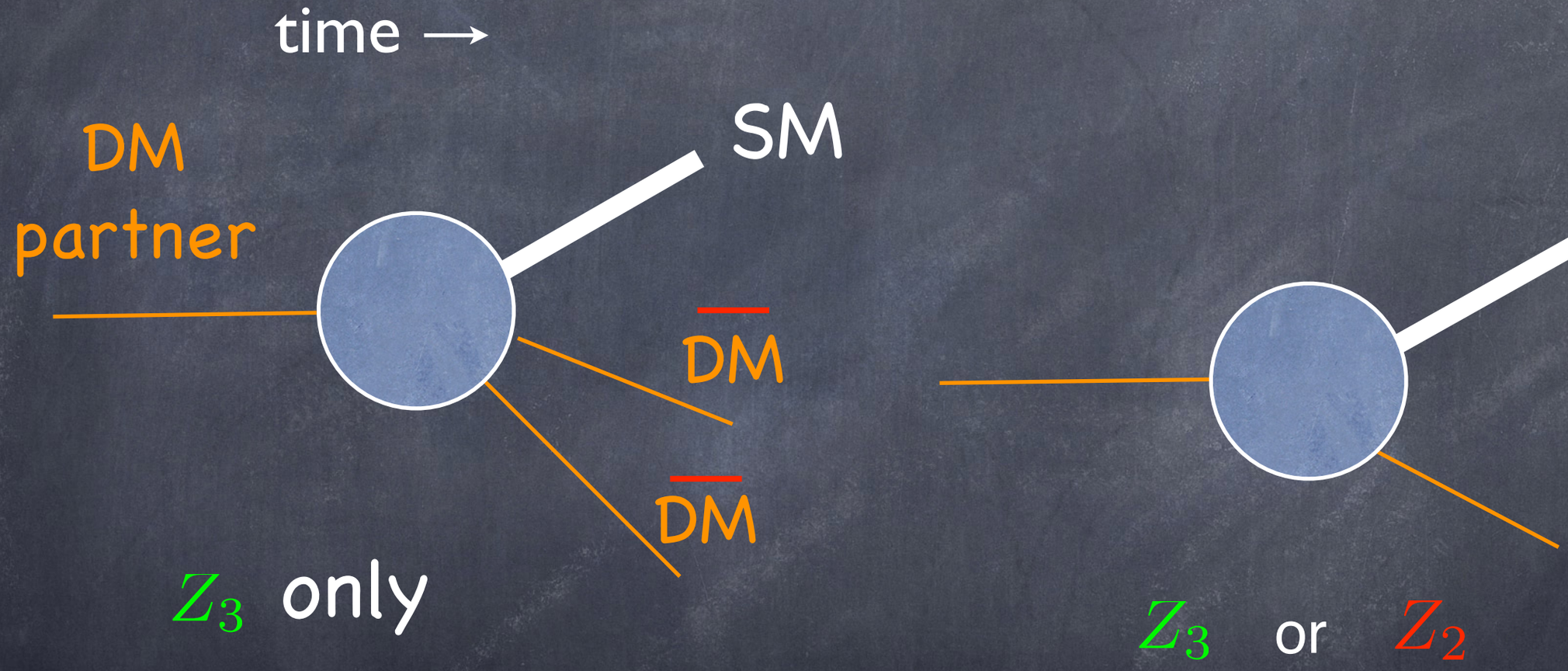
Z_3 only



Z_3 or Z_2

(I) At colliders (Dark Matter invisible)

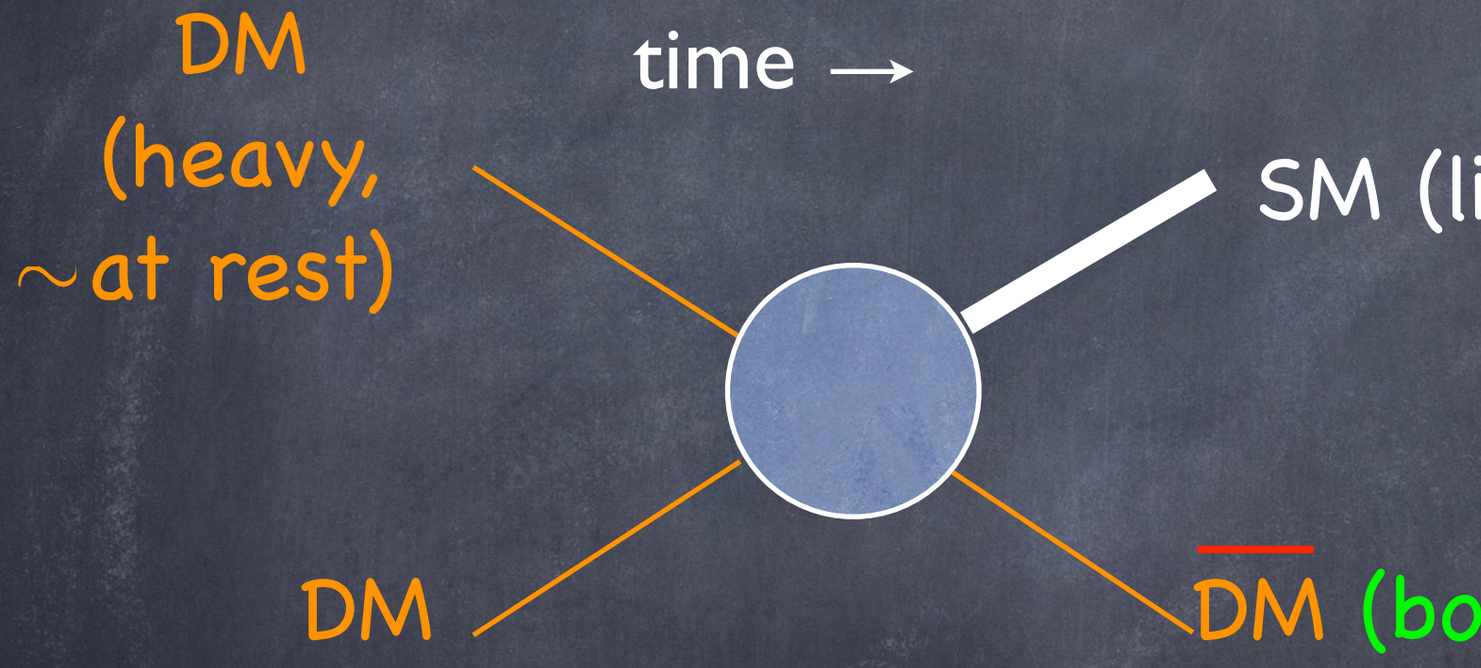
[KA, Kim, Toharia, Walker (2010); KA, Kim, Walker, Zhu (2010); KA, Franceschini, Kim, Wardlow (2012)]



- New decay chain for DM partner in Z_3 vs. Z_2

(II) Dark Matter Detection:
Boosted Dark Matter

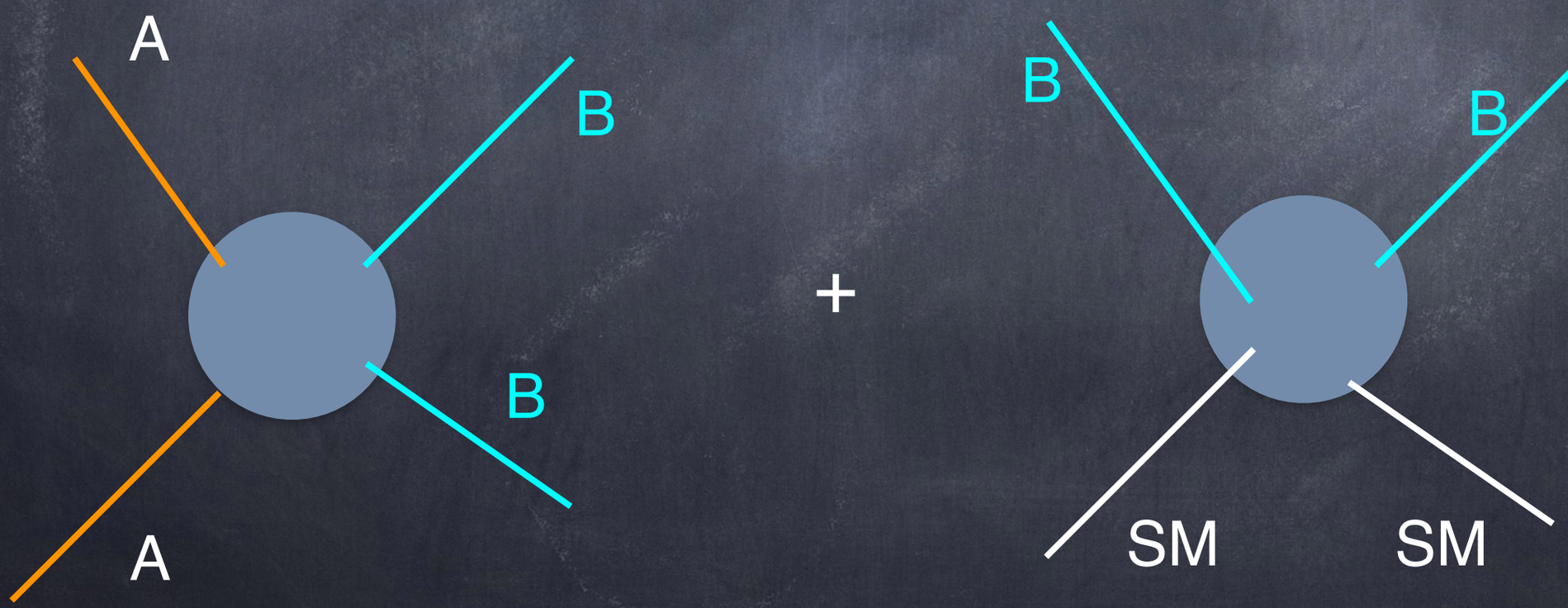
- only in Z_3: (semi) annihilation (in Galactic Center/Sun)



- vs. (usual) ~ at rest Dark Matter

Boosted Dark Matter model

- simple model [KA, Cui, Necib, Thaler (2014)]
- Dominant component of dark matter A (decoupled from SM) annihilates into (lighter, thus boosted) sub-dominant B (weakly interacting with SM)

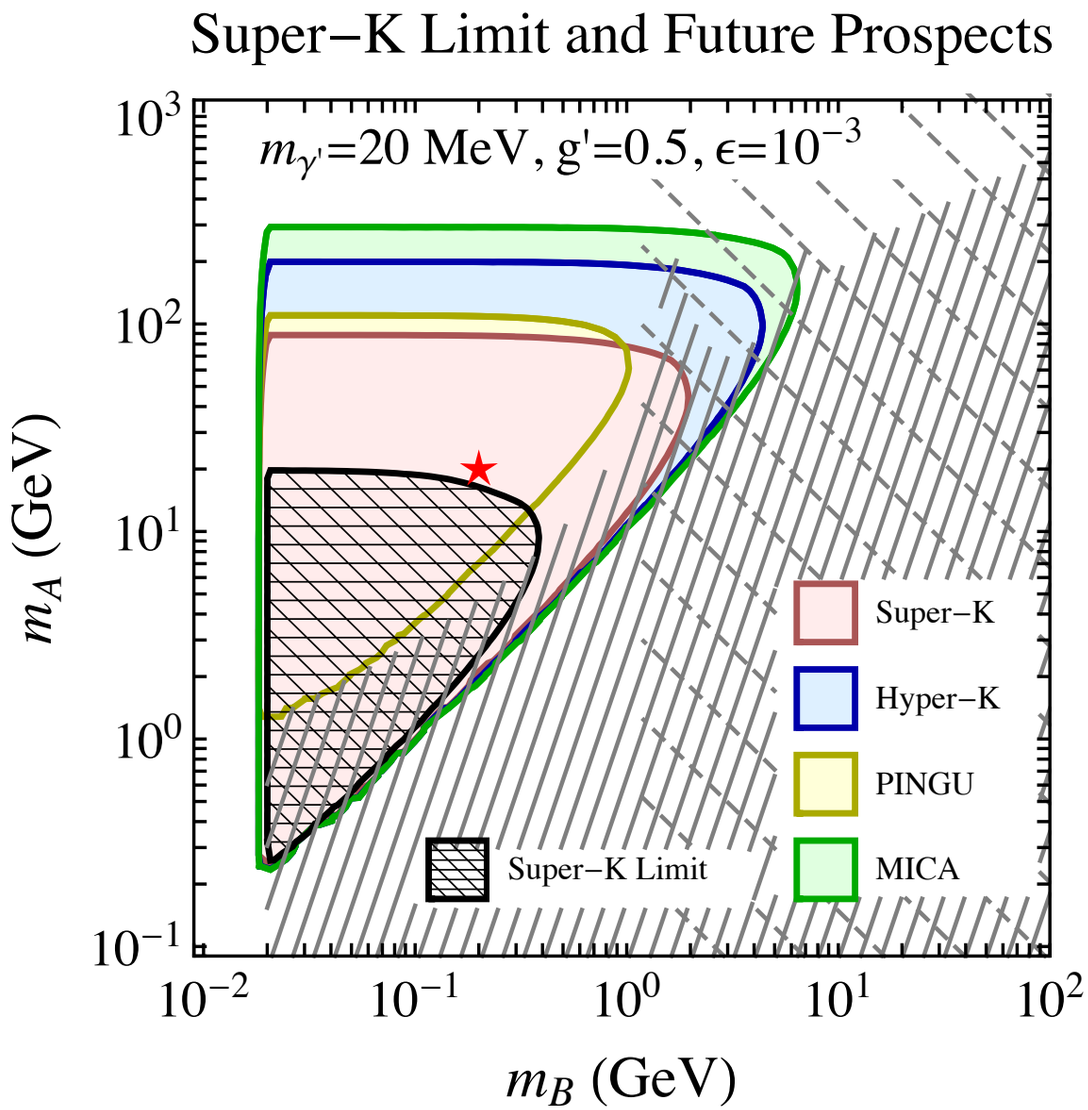


Boosted Dark Matter Signals

- usually these are indirect dark matter detectors (of SM particles from dark matter annihilation), cf. directly detect (boosted) dark matter (still from dark matter annihilation) here

- scattering off of electron (not nucleus): detected by Cherenkov radiation

- basic idea/technique applicable to other boosted dark matter models



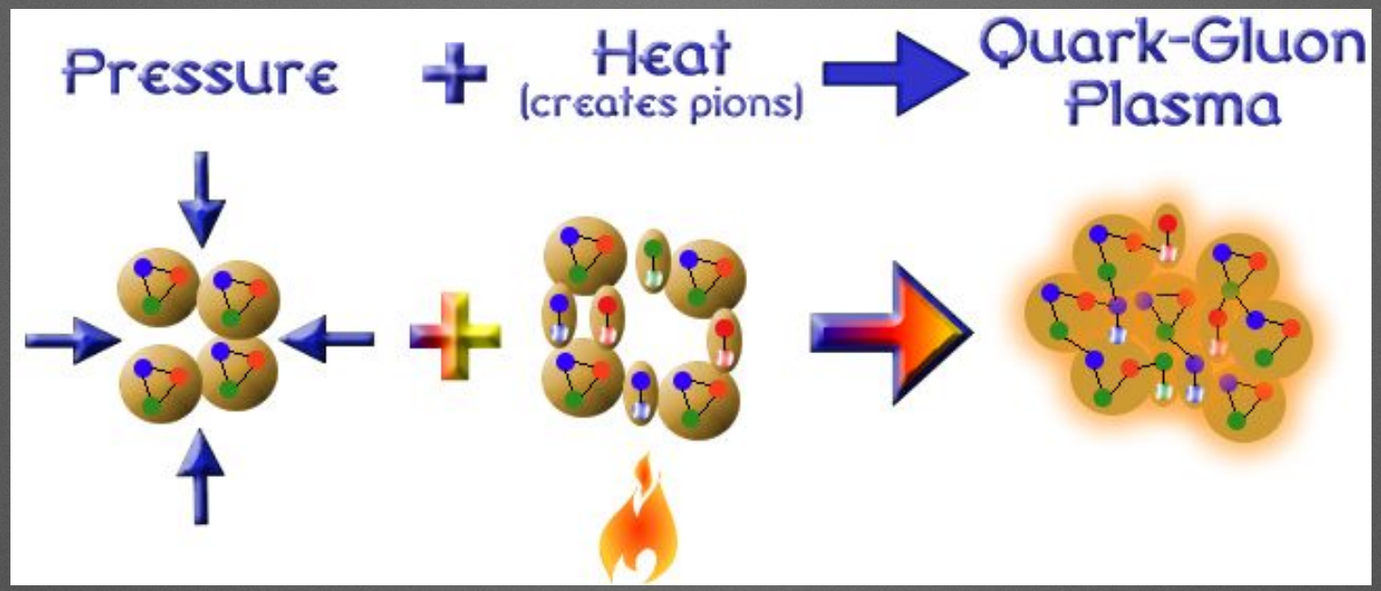
2σ reach with 10 years data

(Super/Hyper-K in Japan; PINGU/MICA at South pole)

Cosmological (de-)confinement phase transition (PT)

(executive summary: for details, see talk (slides/video of) by Majid Ekhterachian at Fermilab on October 15, 2020: https://theory.fnal.gov/events/event/tbd-96/)

4D picture of composite Higgs PT



- temperature, $T = 0$: constituents bound ($\sim$hadron phase of QCD)

- $T \gg \mathrm{TeV}$: deconfined phase (quark-gluon plasma)

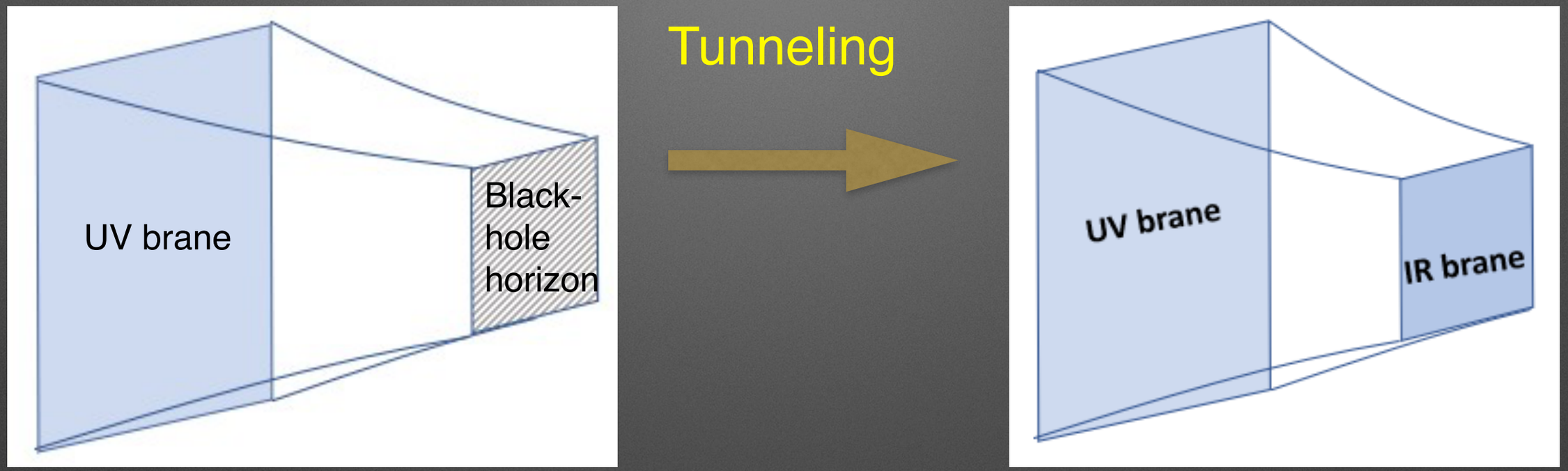
- Confinement transition as T lowered in early universe

- Motivation: consider genesis (lepto-, baryo-, DM), inflation…
  at $T \gg \mathrm{TeV}$; stochastic gravitational wave (GW) signals from PT

- …but strongly-coupled: difficult to picture/calculate…

...on to 5D for calculability/weakly-coupled picture (I)

$T \gg \mathrm{TeV}$ $T = 0$

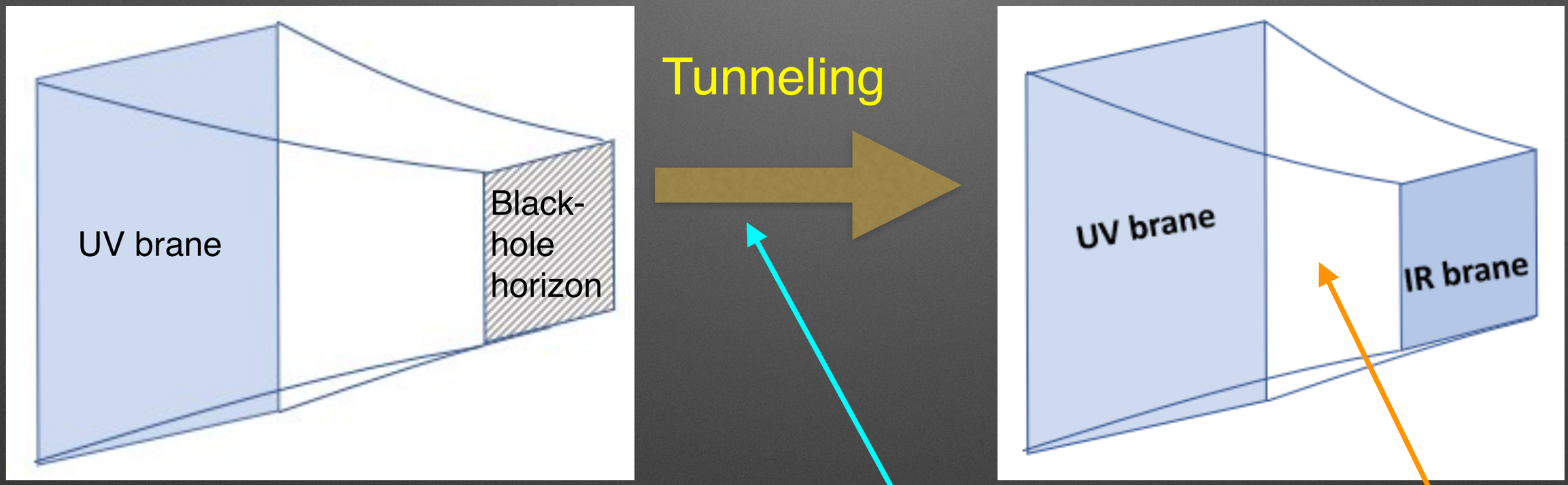


- $T = 0$: usual RS1 phase/warped model, with TeV brane
- $T \gg \mathrm{TeV}$: black hole (BH) covers TeV brane
- PT: TeV brane emerges out of BH, non-perturbatively (!), still semi-classical treatment...

5D: calculable/weakly-coupled picture (II)

- studied earlier: Creminelli, Nicolis, Rattazzi (2001); Randall, Servant (2006); Nardini, Quiros, Wulzer (2007); Konstandin, Servant (2011); Baratella, Pomarol, Rompineve (2018); Megia, Nardini, Quiros (2020)…

KA, Du, Ekhterachian, Kumar, Sundrum (2020):



- more controlled/within 5D EFT “bounce” configuration

- supercooling (dilute primordial abundances) in minimal model vs. (simple) modification to make it faster, preserve abundances (GW and collider signal/ radion mass also affected)

(potential for stabilizing scalar vs. only mass term)

CONCLUSIONS

Testable solutions to puzzles of nature

Why is gravity weak

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

Why is up quark lighter than top

LHCb; $\mu \to e$…

Charge 5/3 top/bottom partner

Neutrino mass/ experinments

Composite Higgs/top

Grand Unification of forces

(Top) GUT partners at LHC

Candidate for Dark Matter of Universe

Xenon…; LZ; boosted

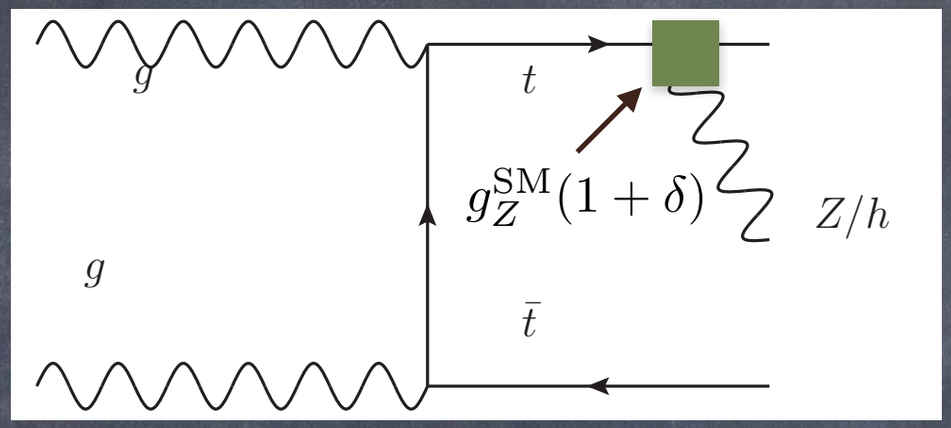
BACK-UPs

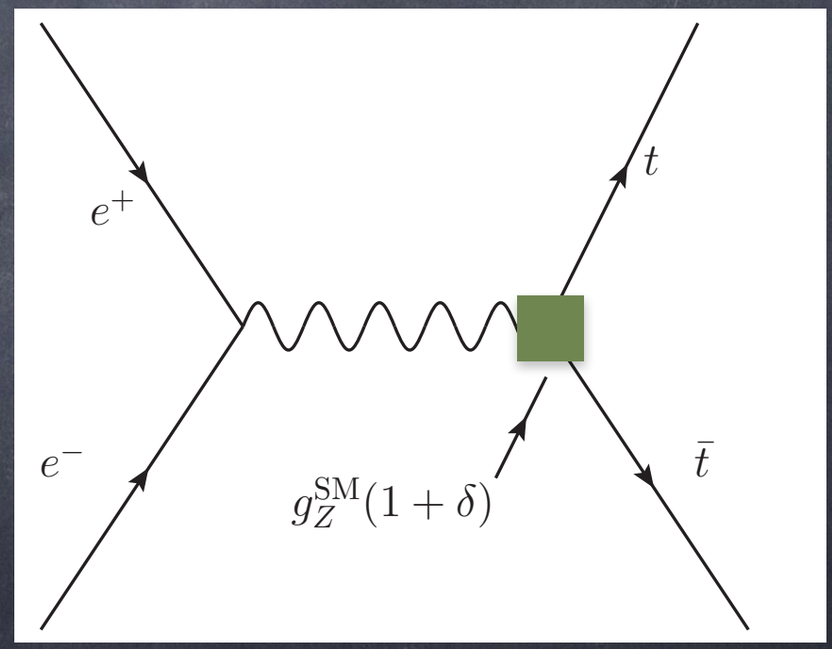
Alternative to SUSY

- Add superpartners of SM: supersymmetry (SUSY) relates fermions (spin-1/2...) to bosons (spin-0...)
- Quantum corrections to Higgs mass/ condensate (Bose-Fermi) cancel: Higgs elementary till Planck scale
- Composite Higgs: dynamical suppression of quantum corrections (also understood as cancellation with other bound states)

Testing at LHC and e^+e^- collider (future) [KA, (2005)]

- LHC





linear (Japan)

- e^+e^- **(need** $E \gtrsim 2\, m_t \sim 350$ GeV**)**

Prediction: $\sim O(10\%)$ for compositeness scale ~ 3 TeV
Sensitivity: $\sim O(10\%)$ at LHC, $\sim O(1\%)$ at e^+e^-

Resonant (no missing energy) vs. pair production (with missing energy)

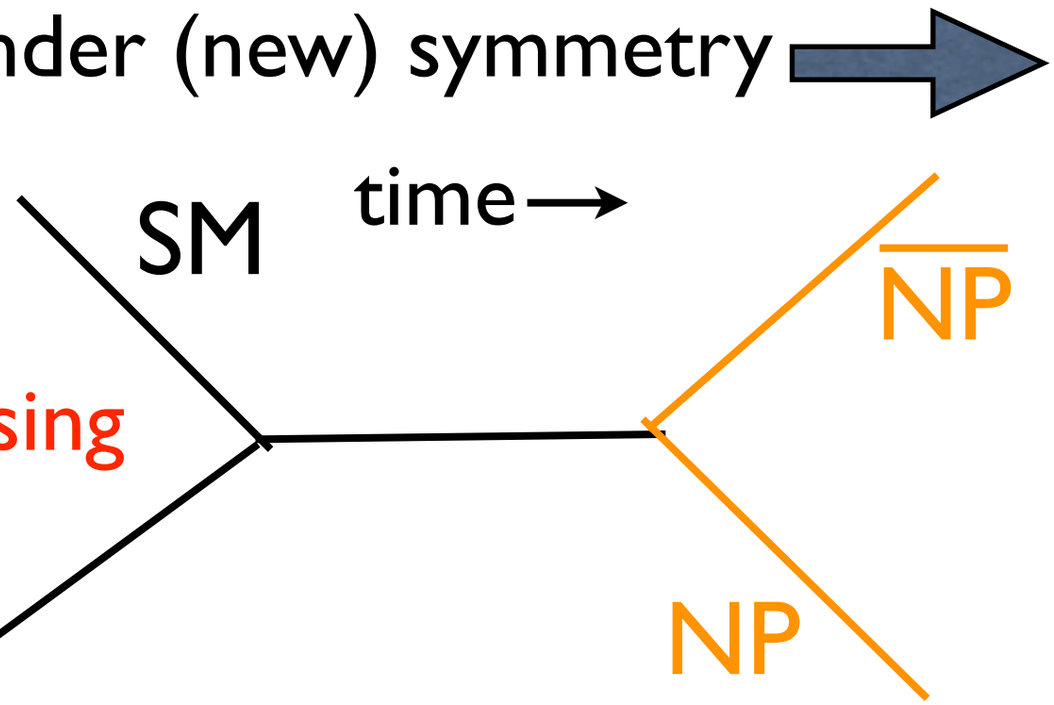
- New particles (NP) are charged under (new) symmetry

lightest stable (dark matter?)

pair produce other particles

``parent" decays into dark matter (missing energy) + SM (standard model)

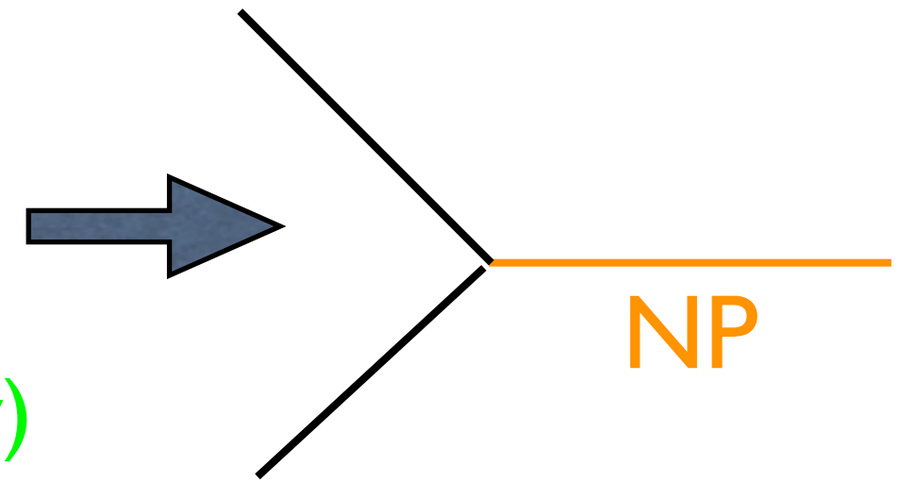
SUSY (superpartner of SM with spin differing by 1/2) with R-parity is prototype



- ....vs. no symmetry for new particles

resonant/single production

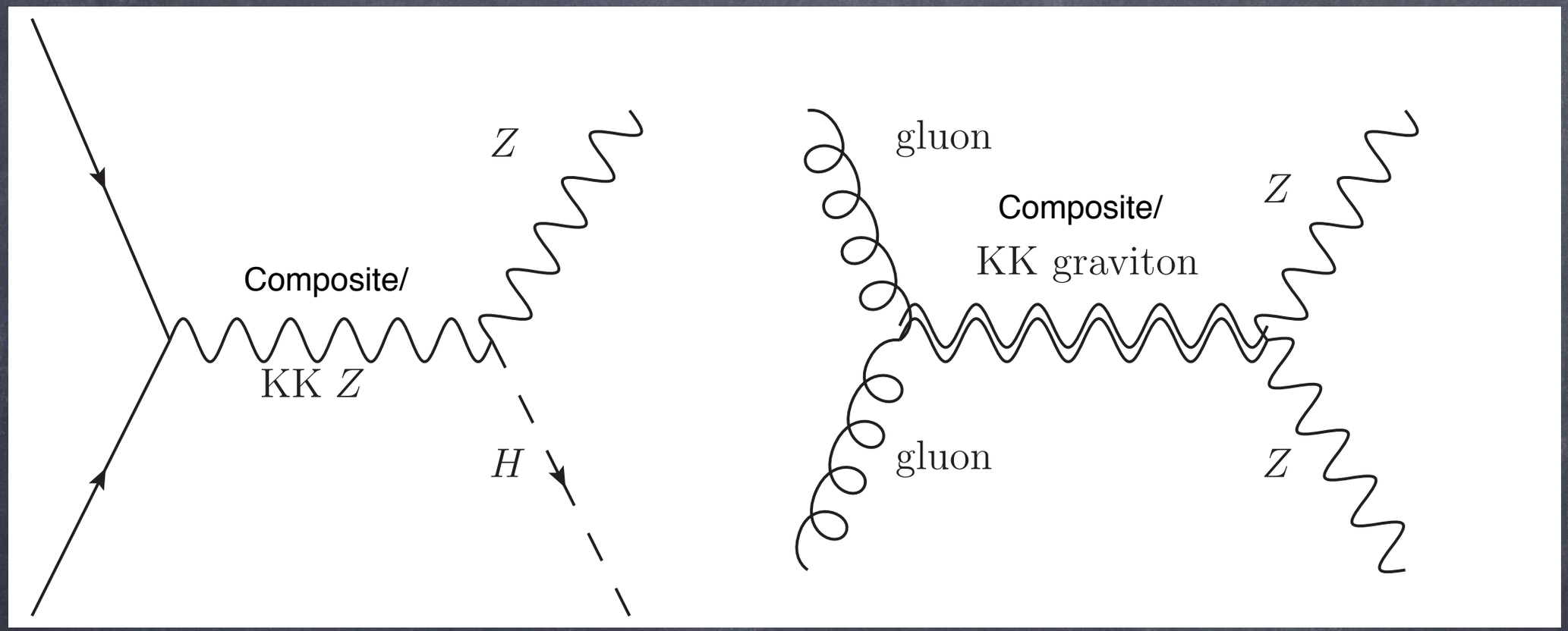
decay to only SM (no missing energy)



e.g., composite Higgs

(Onto composite Higgs: heavy, composite particles)

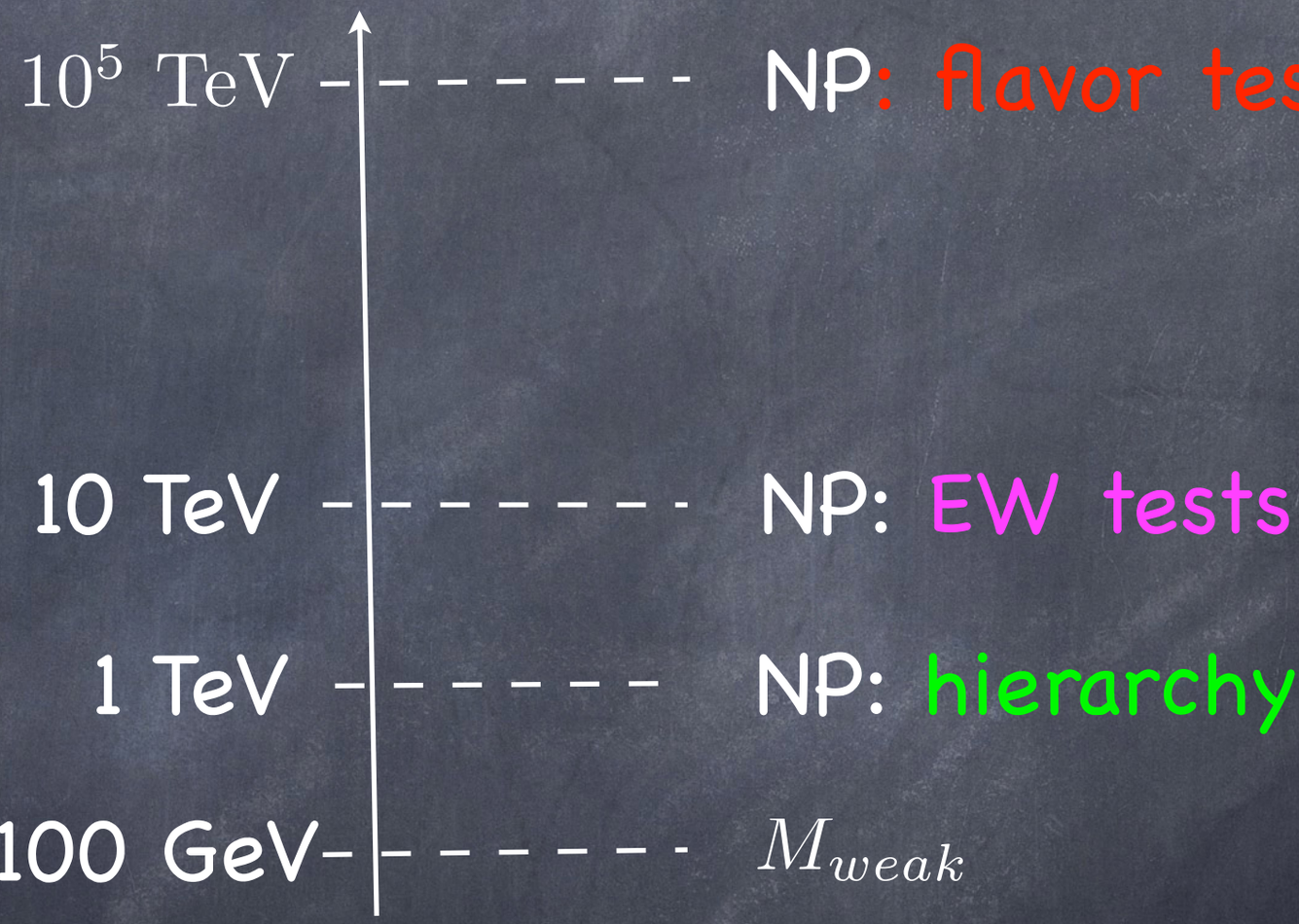
(2) Boosted W/Z/Higgs from (colorless) composite W/Z/graviton [KA, Davoudiasl, Perez, Soni (2006); KA, Davoudiasl, Gopalakrishna, Han, Huang, Perez, Si, Soni (2007); KA, Gopalakrishna, Han, Huang, Soni (2008)]



- ElectroWeak composite/KK decay to W, Z, H(iggs) (and top)...but not to ZZ, HH
- composite/KK graviton decays to ZZ, HH
- ...with $W,\ Z \to \bar{q}q'$...which merge...

No hierarchy, but tension with precision tests

- New physics contributes to precision tests
- ElectroWeak tests (gauge bosons) sensitive to 10 TeV
- Flavor tests (quarks and leptons) 100,000 TeV
- New physics has to be special!

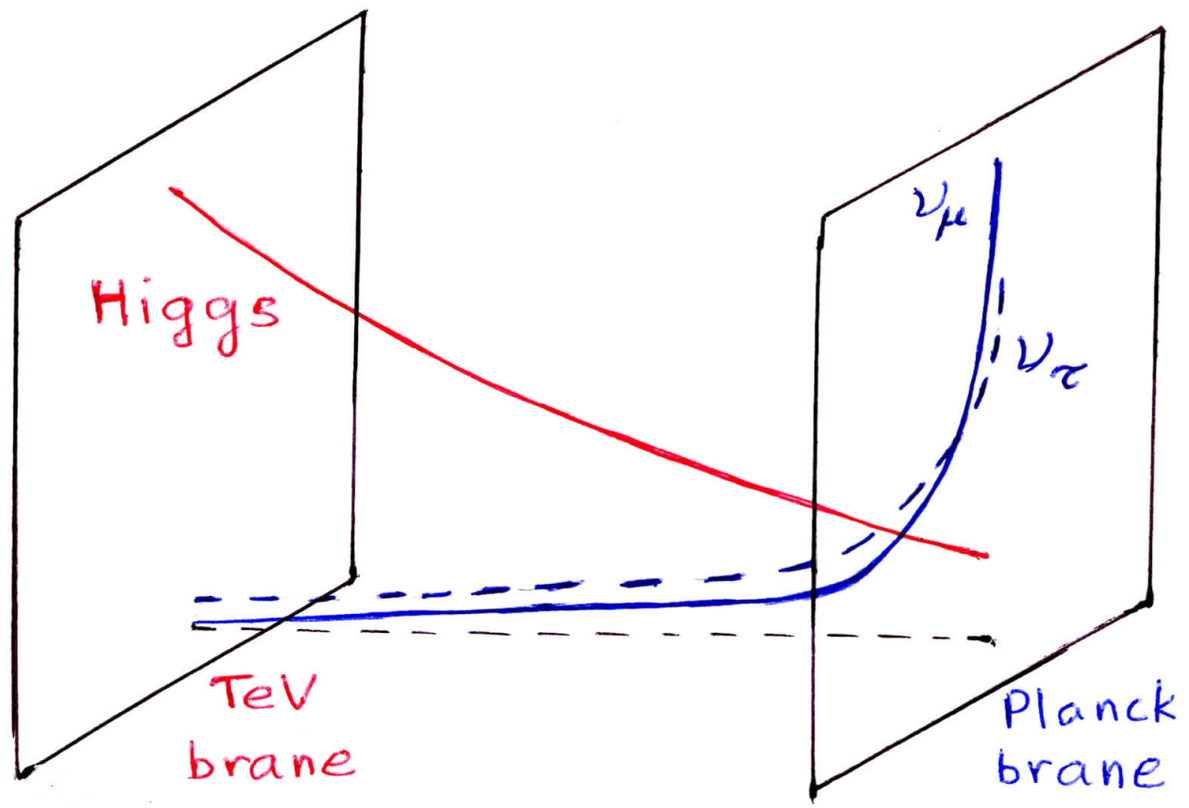


Generalize protective mechanisms of SM

- Severe mention with flavor tests avoided:
  - (Flavor-violating) Couplings of SM fermions to heavy composites $\sim$...to (composite) Higgs
  - Flavor conversion $\propto$ quark mass (a la GIM mechanism of SM)
- Electroweak tests (I): precisely measured/predicted mass ratio of W,Z intact by extending extra $SU(2)$ of SM Higgs (custodial isospin) to strong dynamics

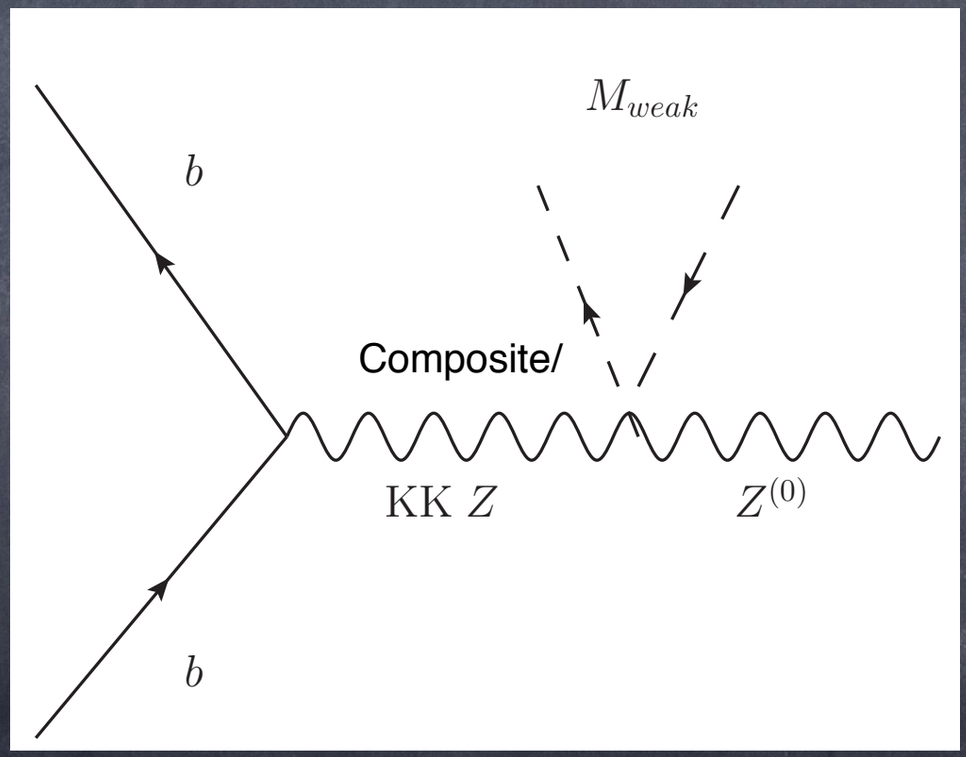
Neutrino anarchy [KA, Okui, Sundrum (2008)]

- Fermion profile very ⇒ close to Planck... overlap "switches" to dominated near Planck brane ⇒
- very small coupling to Higgs/mass (Higgs tail)
- non-hierarchical coupling/mass (profiles similar size)
- "Signal": works only for Dirac ν ⇒ no $0\nu\beta\beta$ decay!



ElectroWeak Precision Tests (II)

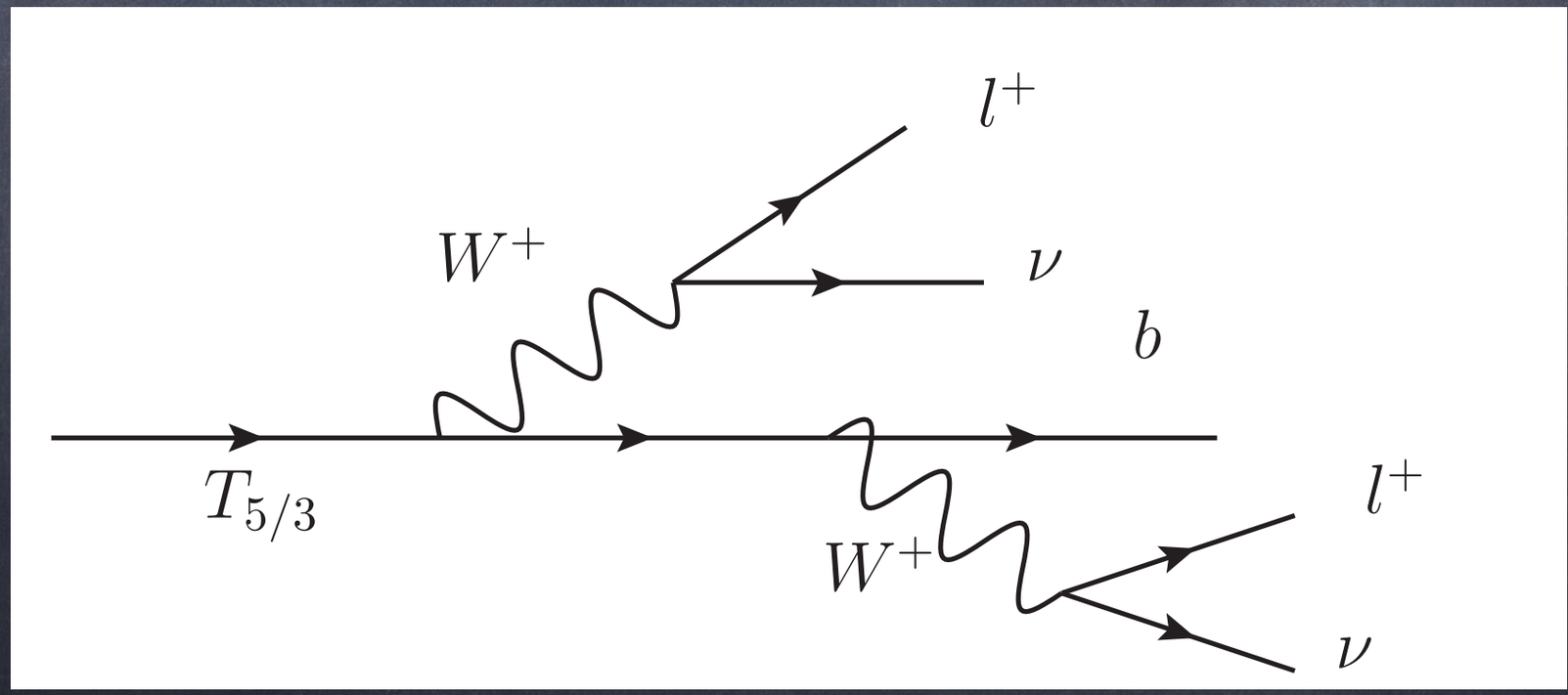
- Another problem: $Zb\bar{b}$ coupling
  due to isospin partner of b (top) being heavy
  (composite)



- extend isospin symmetry [KA, Contino, DaRold, Pomarol (2006)]

(3). Exotic charged particles

- predicts charge 5/3 fermionic partner of top/bottom quark
- decays to same sign W's/dilepton
  [Contino, Servant (2008); Mrazek, Wulzer (2009)]



Dark Matter?!

- no new symmetry in (minimal) warped model ⇒
  no dark matter (unlike SUSY)

- ...but, Dark Matter (naturally) in extension to GUT

Grand unified global symmetry (G) of strong dynamics (I) ⟹ ``prediction'' of $\sin^2\theta_W$

- Another bonus of (partially) composite top quark: running of SM gauge couplings modified above TeV...

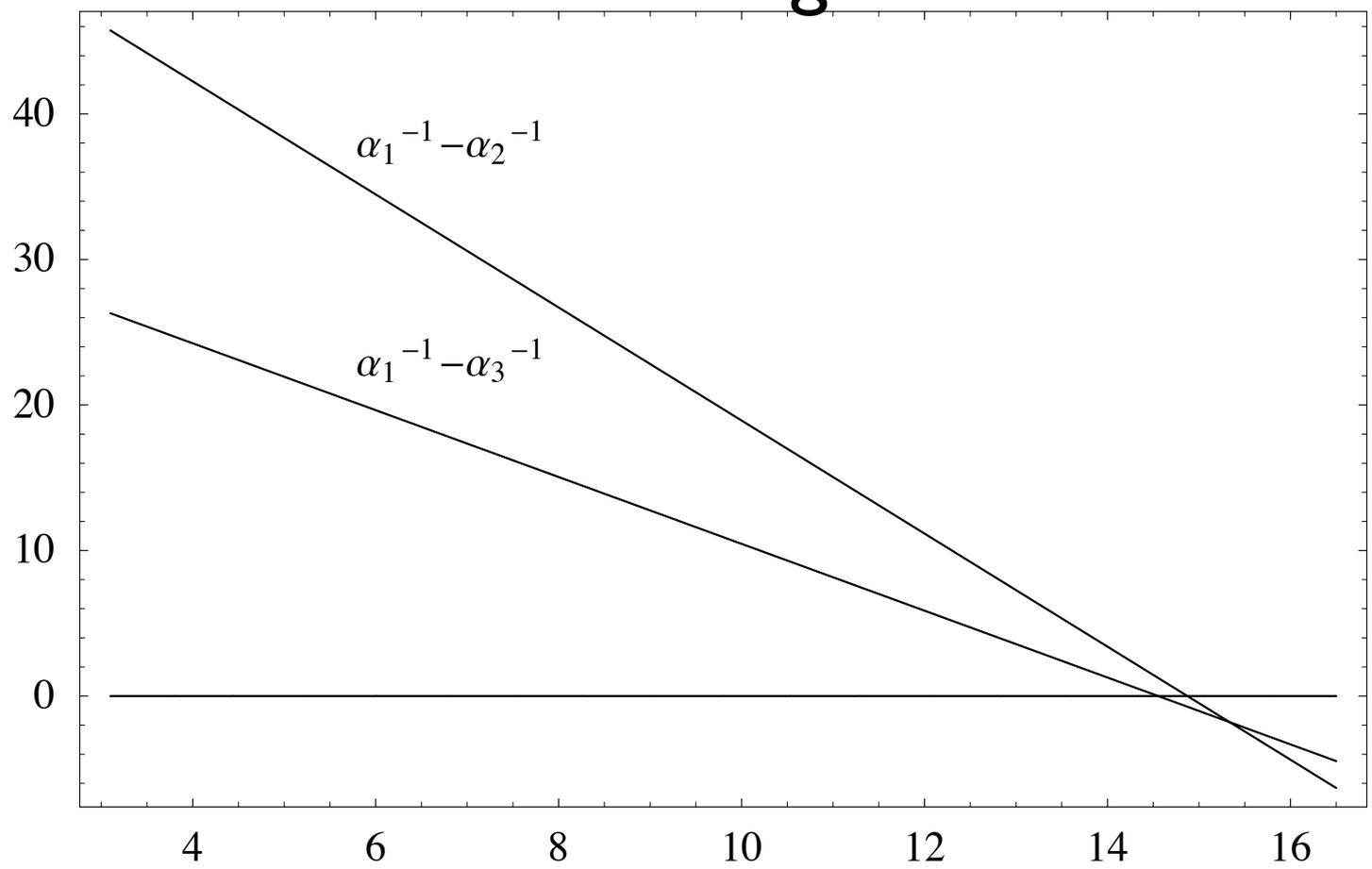
- ...such that they unify (with precision similar to SUSY) close to (usual) GUT scale!

Composite GUT [KA, Contino, Sundrum (2005)]

- Evolution of couplings modified due to different SM particles' compositeness

- Higgs/top quark composite ⇒ starting at TeV, replace by constituents: assume unified multiplets, do not modify relative evolution ⇒ effectively ``subtract'' top/Higgs (usual) contribution

- Top quark effect ``correct'' sign/size



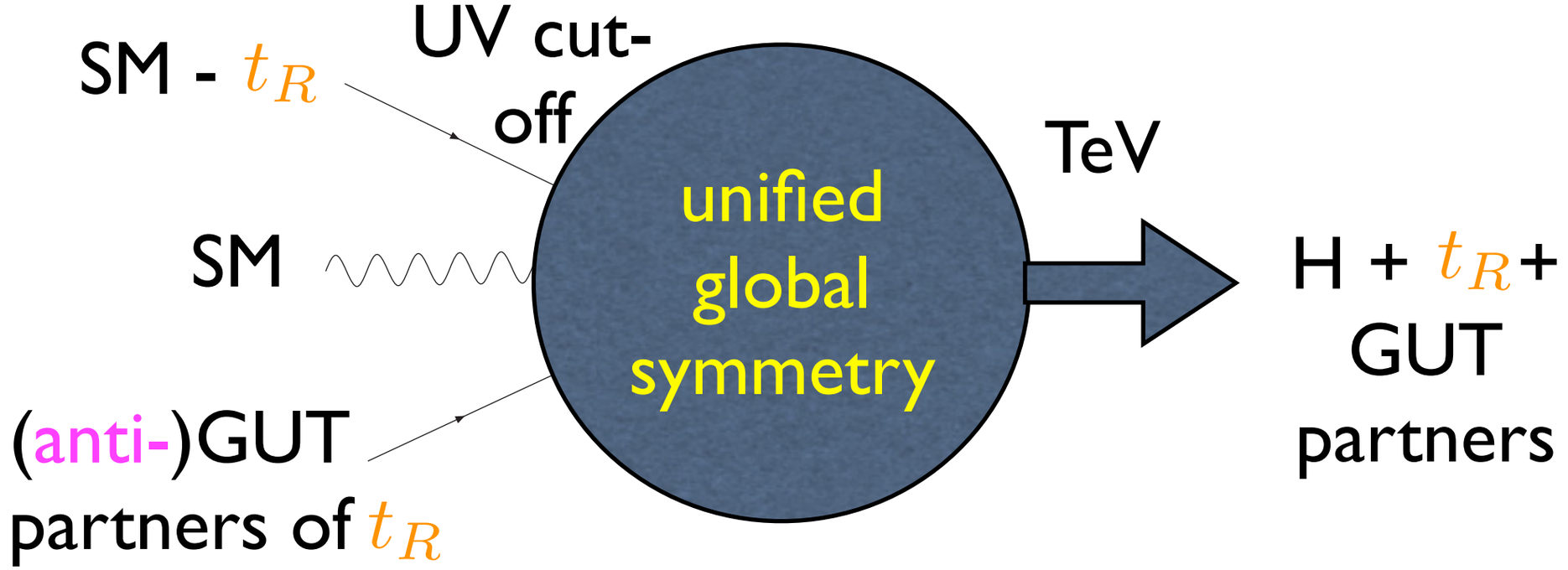
Precise meeting (comparable to SUSY)

Unification in strong dynamics picture: details

- Composite t_R and H ⇨ above TeV, replace running due to t_R and H by strong dynamics

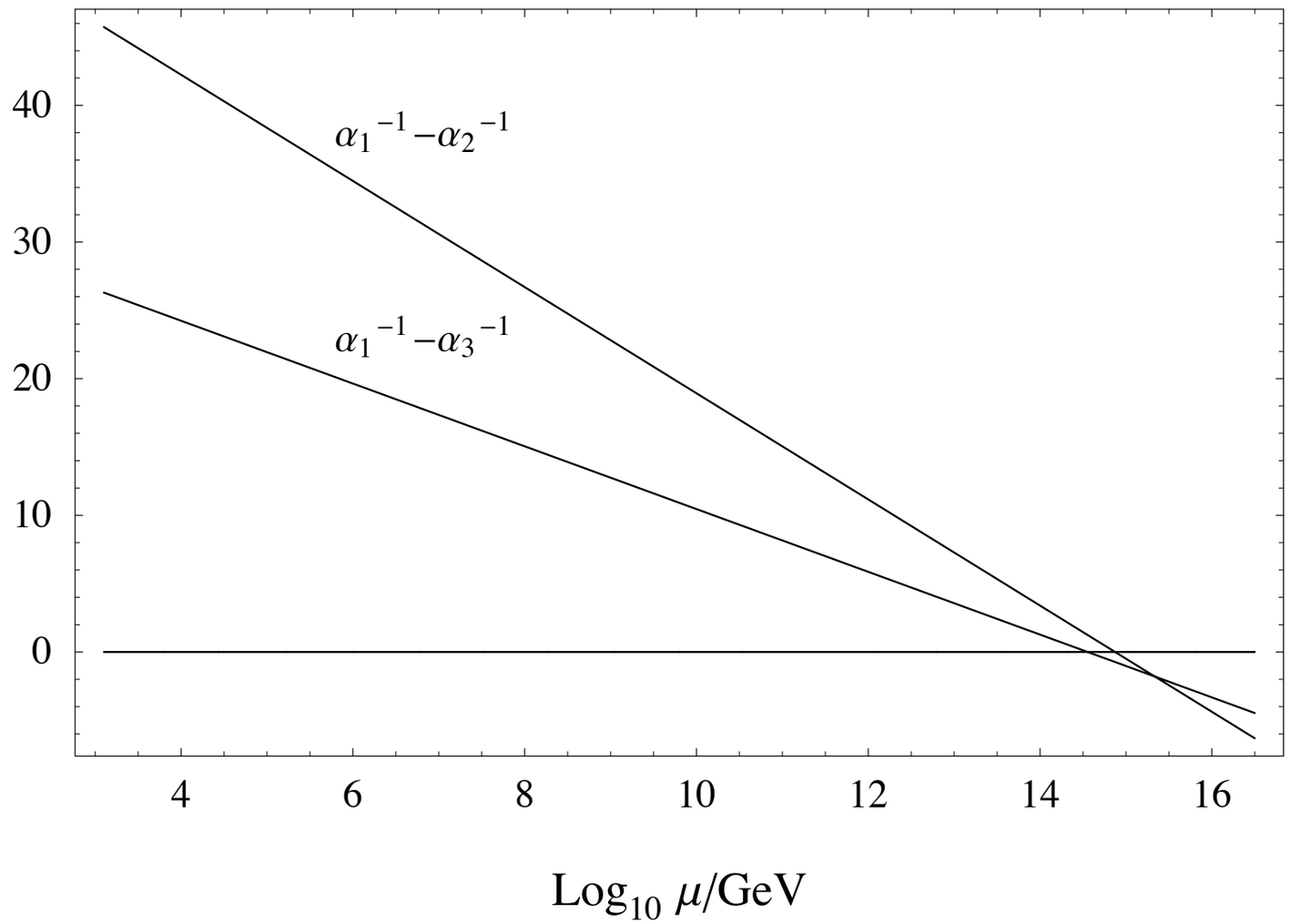
- Global unified symmetry for strong dynamics ⇨ LO running of SM gauge couplings from loops universal ⇨ "subtract" t_R contribution

- Add external fermions to make composite GUT partners of t_R heavy: running =(universal $-t_R$)



LO: (magical!) prediction due to β-function: $\mathrm{SM} - 2t_R - H$

(KA, Contino, Sundrum)



Grand unified G (II) ⇒ Dark Matter from proton stability!

- SM singlet GUT-partner of top quark with 1/3 baryon-number (exotic RH neutrino!) can be stable...
- ...and WIMP!

GUT partners of t_R light

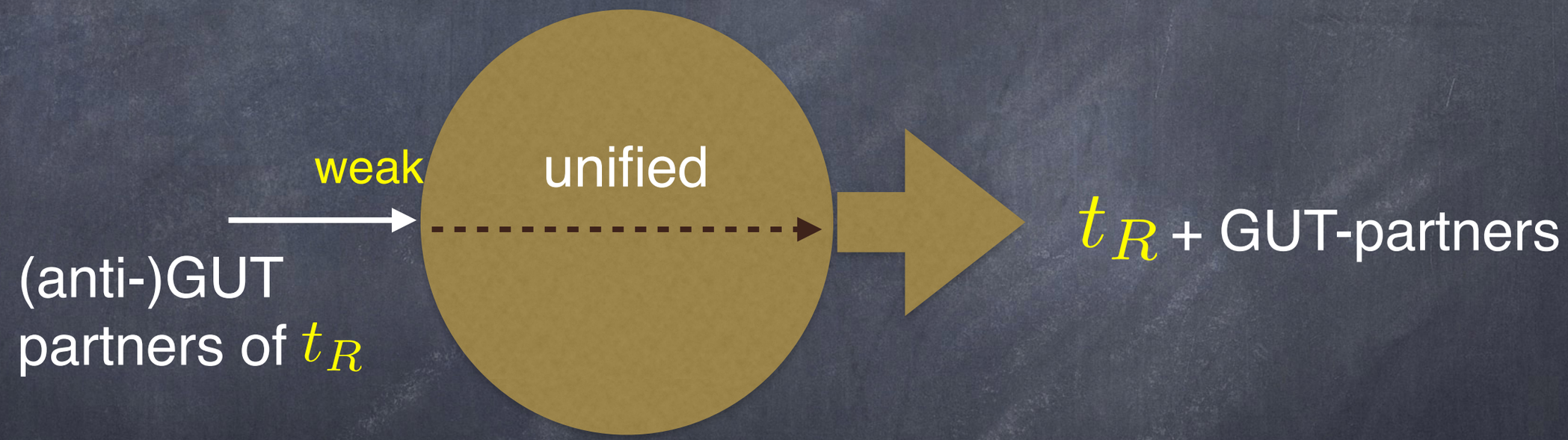
- heavy top + constraint from shift in $Zb\bar{b}$ + flavor violation

- t_R(not t_L: partner of b_L)composite

- GUT partners (massive) of t_R(naturally) light ($\lesssim$1 TeV) vs. composite gauge and other GUT partners ($\sim$ 3 TeV)
- produce at LHC (even if other composite/KK's beyond reach)

why GUT-partner of t_R is light

- elementary (external to strong dynamics)
  (anti-) GUT-partner marries composite



- small mass if above coupling not strong

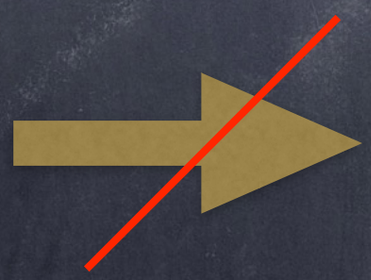
Stability of (colorless) GUT-partner of t_R

- have B = 1/3 (same as top: for suppressing proton decay)
- no color (strong nuclear force charge)
- cannot decay into (purely) SM state, which has integer B if colorless, e.g., made of proton(s), pion(s), leptons...so lightest (can be ν') stable!

ν'

colorless

$B = 1/3$



SM only

colorless

$B = 0, 1, 2...$

e.g. π, n (made of quarks, each with B = 1/3); e

DM-stabilization symmetry

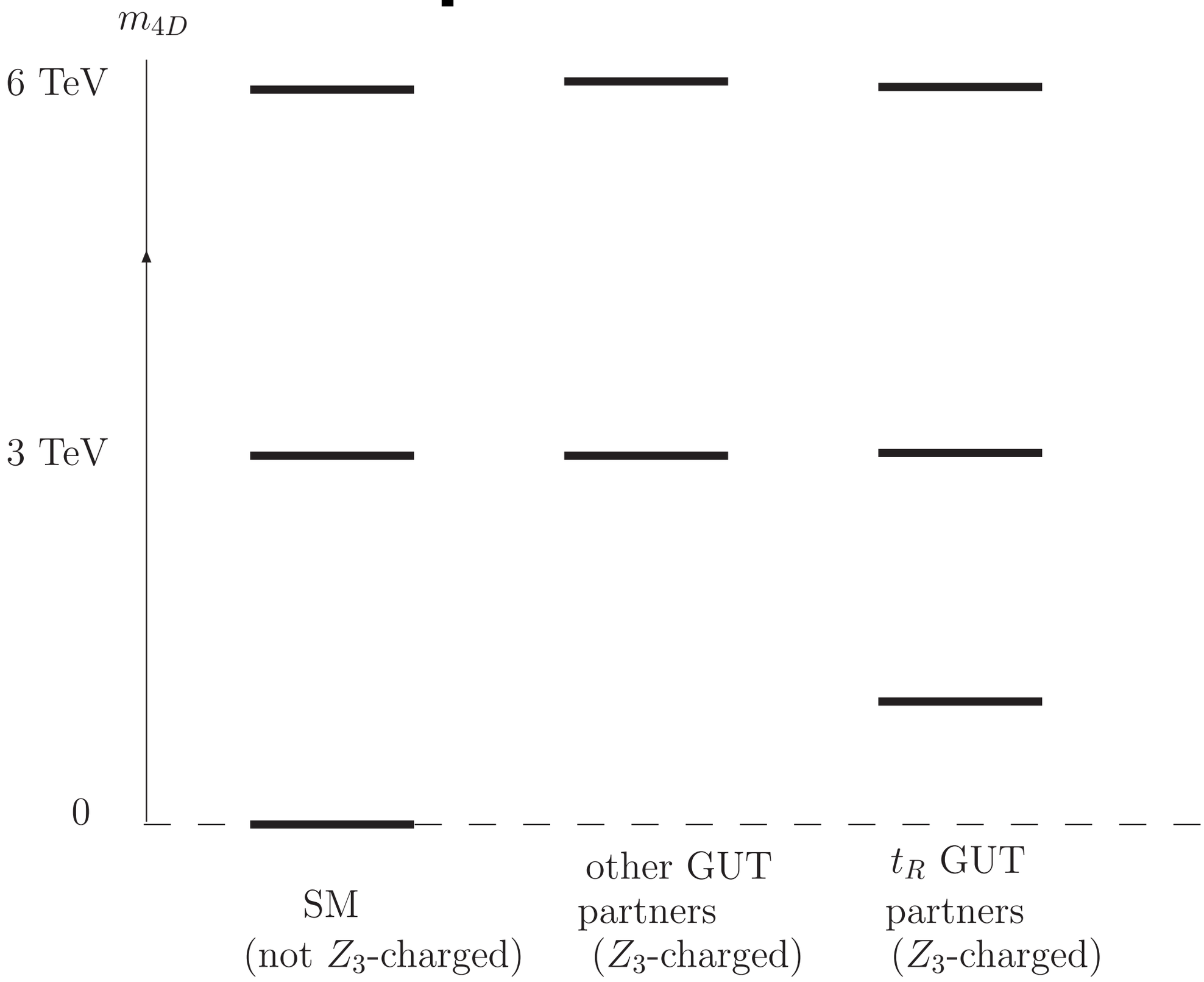
Z_3 symmetry: $\Phi \to \exp \frac{2\pi i q}{3} \Phi$,
with $q = (\alpha - \bar{\alpha} - 3\ B)$

[α ($\bar{\alpha}$) is number of color (anti-color) indices and B is baryon-number]

SM (and excitations): $q = 0$	GUT-partners of SM: $q = \pm 1$
u, d $(1, 0, 1/3)$	e', ν' $(0, 0, 1/3)$
e, ν $(0, 0, 0)$	u', d' $(1, 0, 0)$
γ, W, Z $(0, 0, 0)$ g $(1, 1, 0)$	X/Y $(1, 0, 0)$ and $(0, 1, 0)$

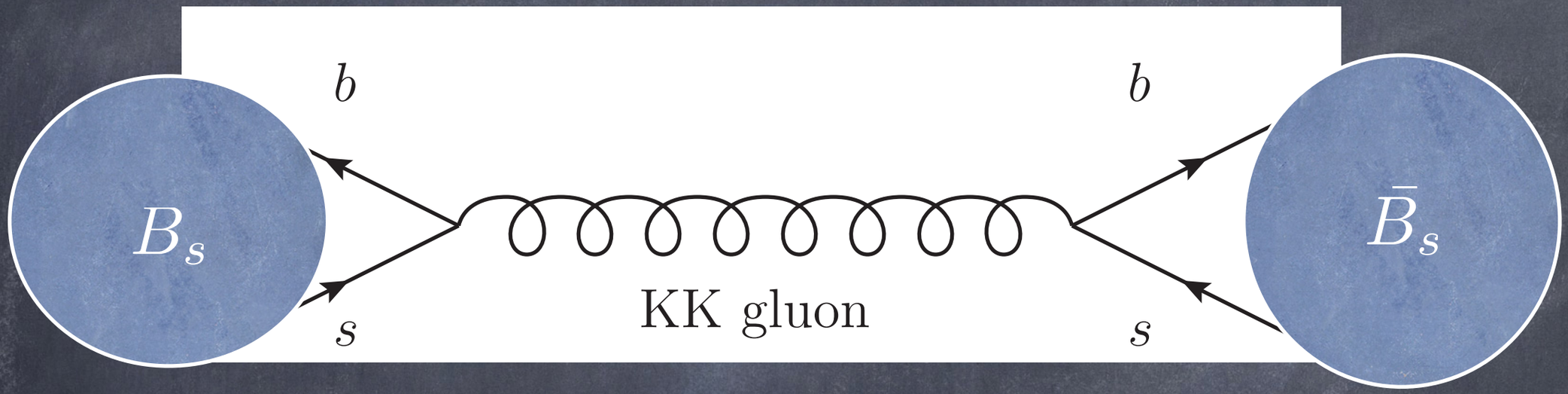
charges $\to (\alpha, \bar{\alpha}, B)$

Spectrum


m_{4D}
6 TeV
3 TeV
0
SM
(not Z_3-charged)
other GUT
partners
(Z_3-charged)
t_R GUT
partners
(Z_3-charged)

Other-than-top flavor signals (lower energy)

- LHCb: $B_s \leftrightarrow \bar{B}_s$ [Burdman (2003); KA, Perez, Soni (2004)]



- future:$\mu \to e$...project X [Huber (2003); KA, Blechman, Petriello, (2006)]

Motivation for experimental proposal

- LOI by Mu2e collaboration (FERMILAB-TM-2396-AD-E-TD)
- sensitive to KK mass ~ 20 TeV (beyond LHC reach)

FERMILAB-TM-2396-AD-E-TD

Letter of Intent

A Muon to Electron Conversion Experiment at Fermilab

The Mu2e Collaboration

28 September 2007

•••

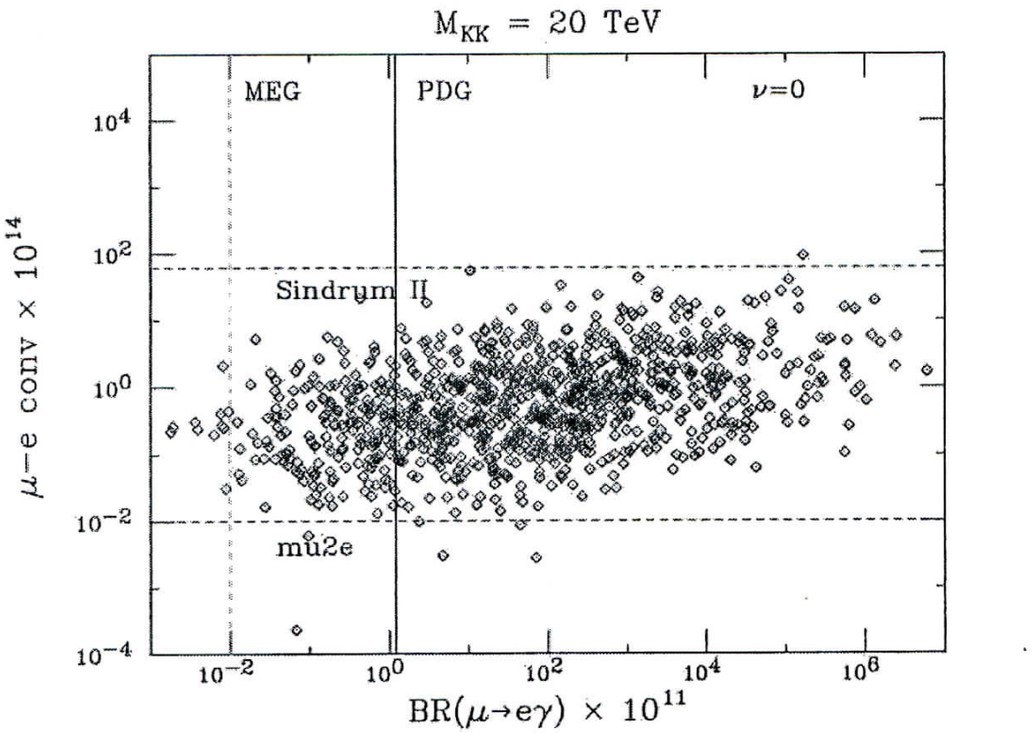


Figure 1.4: $\mu^+{}^{48}\mathrm{Ti} \to e^+{}^{48}\mathrm{Ti}$ rate as a function of Br($\mu \to e+\gamma$) for the Randall-Sundrum model with one warped, compact extra dimension, in the scenario where the Higgs boson is allowed to propagate in the bulk.

Dimensional transmutation

- conformal strong dynamics: couplings do not evolve
- perturbation to strong dynamics evolves slowly/logarithmically → $\mathrm{TeV} \ll M_{\mathrm{Pl}}$
- (roughly) similar to QCD: $\mathrm{GeV} \ll M_{\mathrm{Pl}}$ and $\Lambda_{\mathrm{SUSY}} \ll M_{\mathrm{Pl}}$

SEVERAL MASS MEASUREMENT TECHNIQUES SO FAR (MANY CASES)

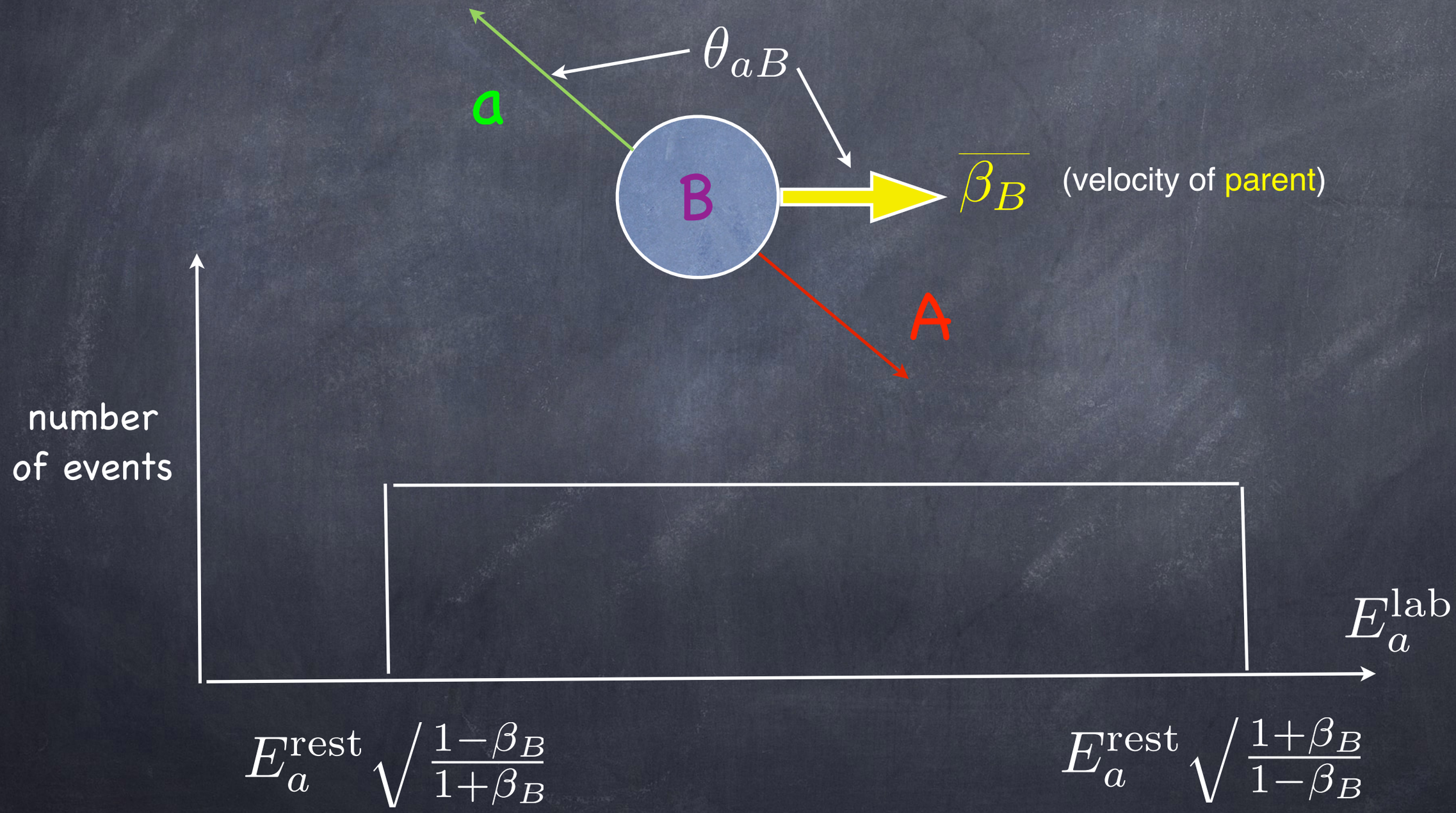
Bottomline: (in my opinion)

no slam dunk!

- useful to have more techniques, especially simpler; complementary (different systematics, e.g., avoid MET or combinatorics or assumptions about boosts)

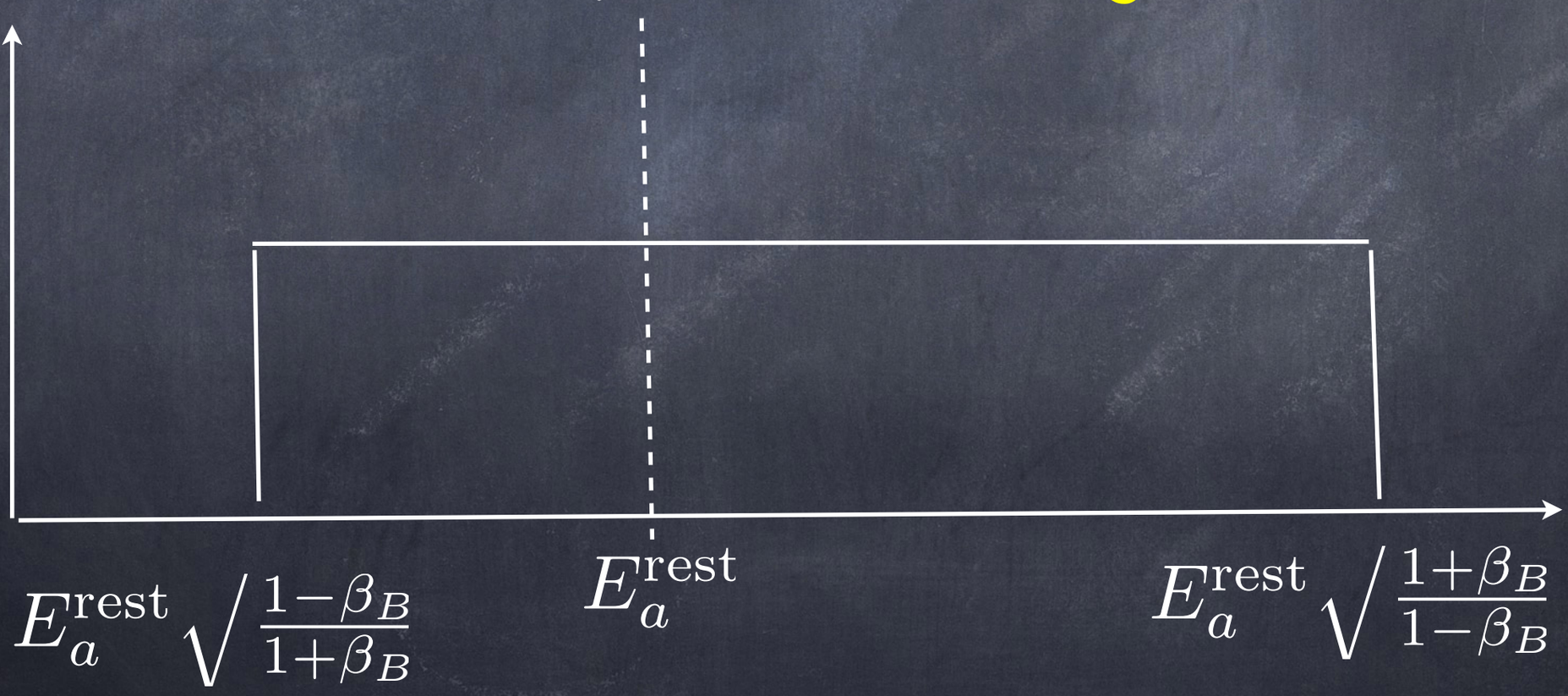
Rectangle for fixed, but arbitrary boost

- In general: $E_a^{\rm lab} = E_a^{\rm rest}\gamma_B\left(1+\beta_B\cos\theta_{aB}\right)$
- Assume unpolarized parent: $\cos\theta_{aB}$ is flat



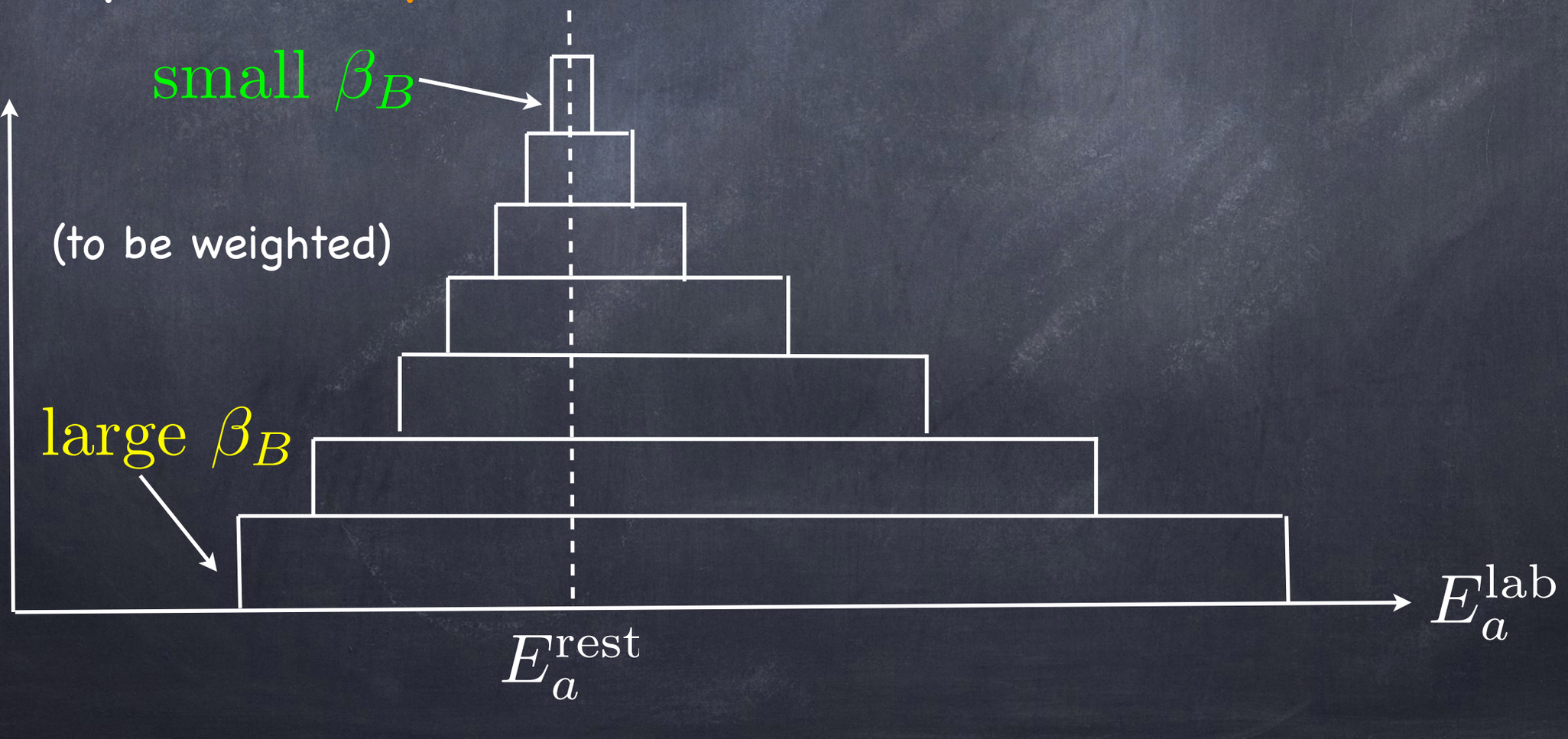
Rectangle vs. rest energy

- contains $E_a^{\rm rest}$ (for any boost)
- no other $E_a^{\rm lab}$ gets larger contribution from given boost than does $E_a^{\rm rest}$
- no other $E_a^{\rm lab}$ is contained in every rectangle (e.g., $\beta_B \to 0$)
- asymmetric on linear (symmetric on log...)



(Generic) Boost distribution: ``stacking" up rectangles [KA, Franceschini, Kim (2012)]

- distribution of $E_a^{\rm lab}$ has peak at $E_a^{\rm rest}$ (see also Stecker: "Cosmic gamma rays")
- symmetric on log-scale about $E_a^{\rm rest}$
- ....no matter what is the boost distribution!
- boosts depends on production mechanism, mass, PDF's...



Formal proof

- Single Rectangle ($x \in \frac{E_a^{\rm lab}}{E_a^{\rm rest}}$) :

$$\frac{1}{\Gamma}\frac{d\Gamma}{dx}\Big|_{\text{fixed } \gamma_B} = \frac{\Theta\left(x-\gamma_B+\sqrt{\gamma_B^2-1}\right)\Theta\left(-x+\gamma_B+\sqrt{\gamma_B^2-1}\right)}{2\sqrt{\gamma_B^2-1}}$$

- Stacking up rectangles:

$$f(x) \equiv \frac{1}{\Gamma}\frac{d\Gamma}{dx} = \int_{\frac{1}{2}\left(x+\frac{1}{x}\right)}^{\infty} d\gamma_B \frac{g(\gamma_B)}{2\sqrt{\gamma_B^2-1}}$$

- Slope:

$$f'(x) = \frac{\text{sgn}(1-x)}{2x} g\left(\frac{1}{2}\left(x+\frac{1}{x}\right)\right)$$

- Behavior at x = 1:

$f'(x=1) \propto g(1) = 0 \Rightarrow$ extremum or
$f'(x)$ flips its sign at $x = 1 \Rightarrow$ a cusp
$f(x)$ is positive and vanishes for both $x \to 0$ and $x \to \infty$
$\Rightarrow$ peak at $E_a^{\rm rest}$

Why another method for top quark mass??!!

(Other than as test/practice for new)

- existing analyses: assume SM matrix element, compute entire distribution ⇨ M_t valid only in SM!

- Our method is (largely) independent of production mechanism

- New physics in production, e.g., composite Higgs/ top

Effects of polarization

- SM is dominantly unpolarized (strong interactions)

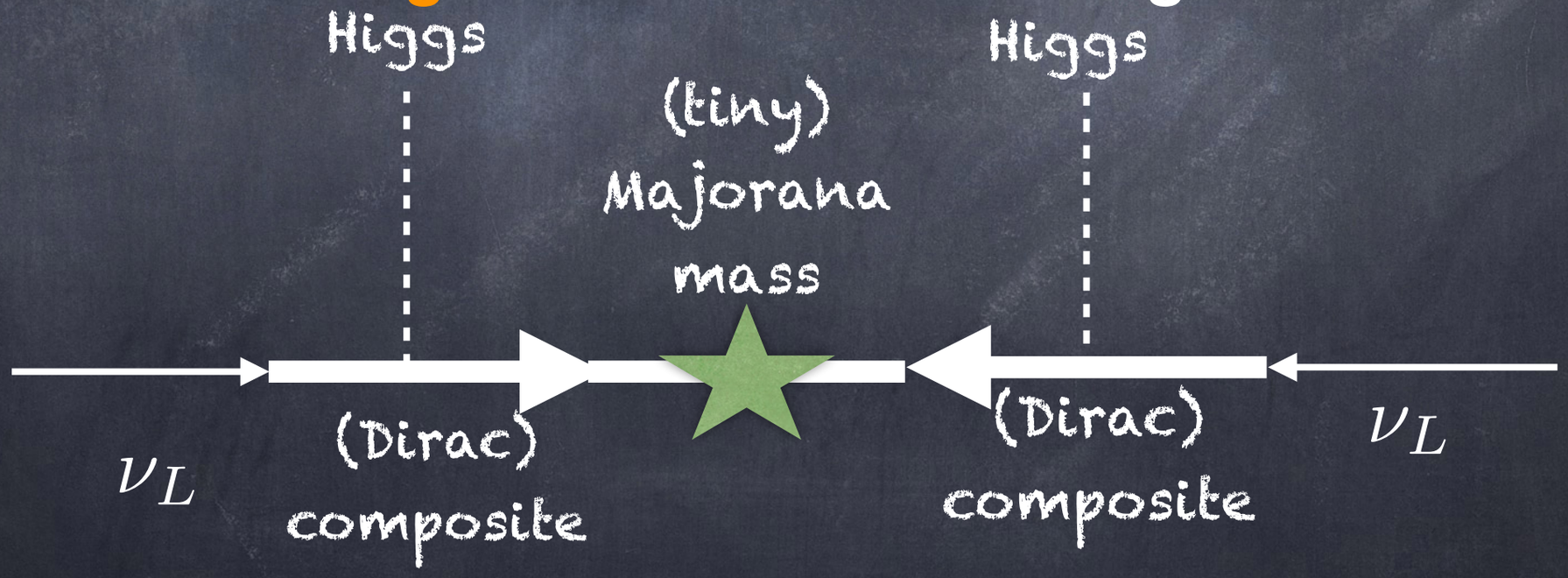
- polarized new contribution will shift peak

- compare to other measurements for diagnosis

Seesaw & Leptogenesis [KA, Hong, Vecchi (2015); KA, Du, Ekhterachian, Fong, Hong, Vecchi (2017, 2018)]...

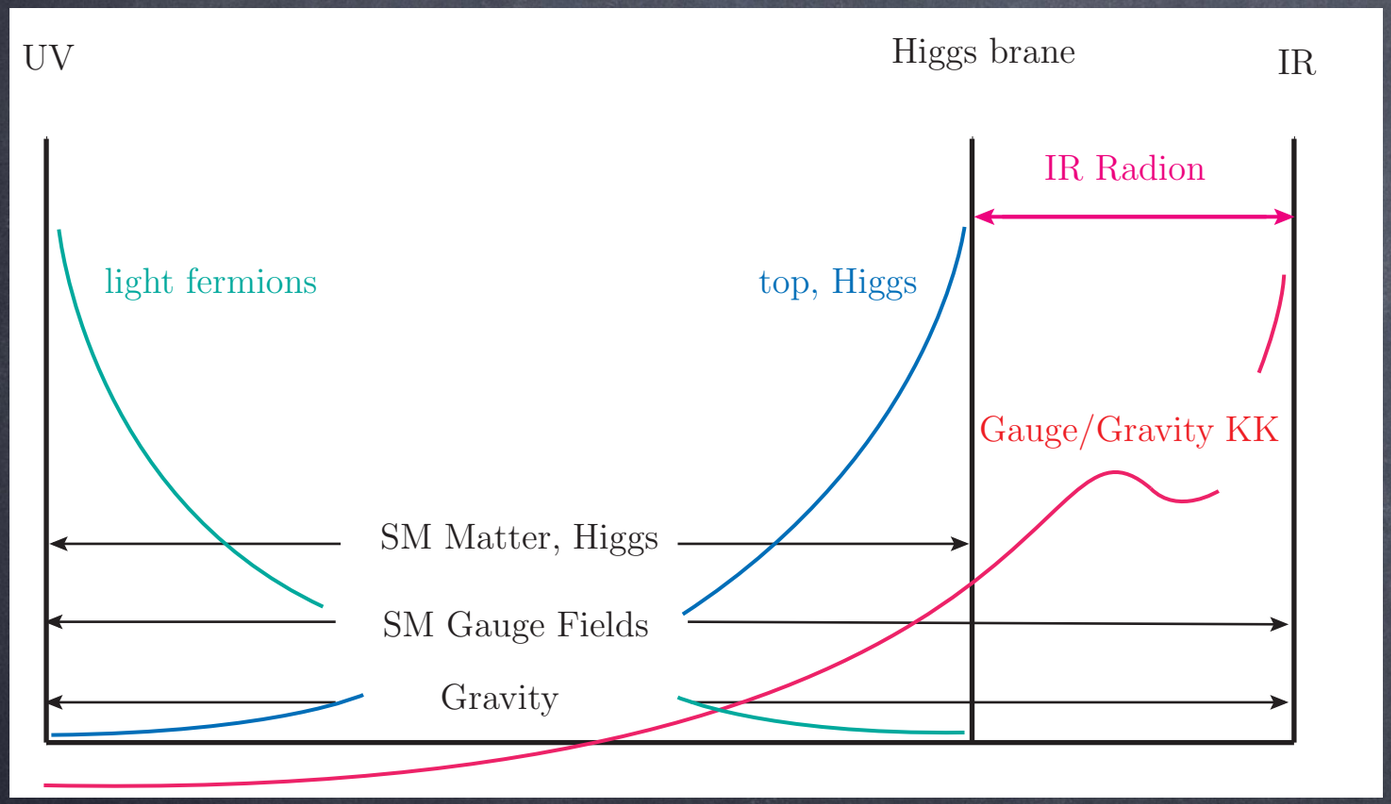
- Warped/(partially) composite seesaw for neutrino mass is ``hybrid'': bottomline SM neutrino mass from exchange of TeV (mostly) Dirac SM singlet neutrinos (called inverse seesaw), whose tiny Majorana mass comes from usual (type I), high-scale seesaw

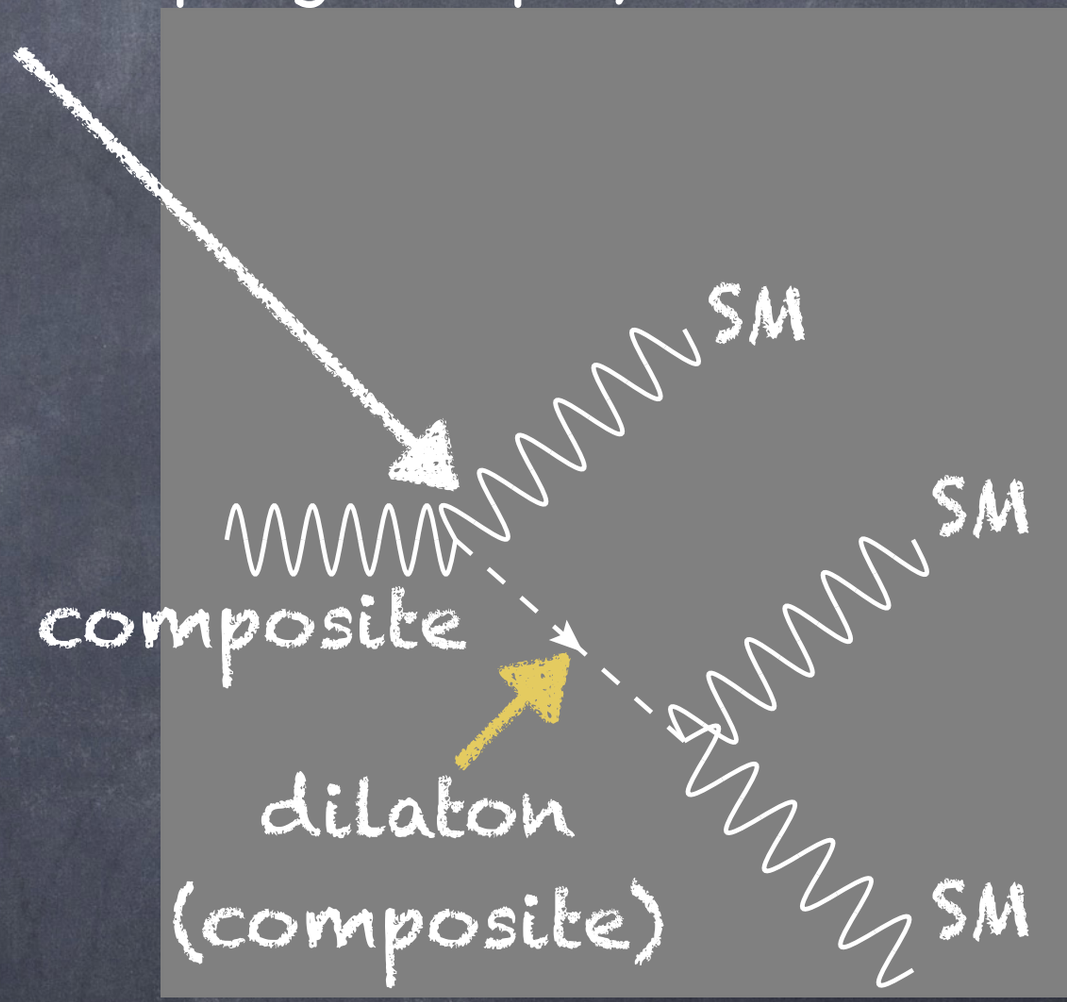
(most) natural model + signals of neutrino mass generation at TeV



Novel collider signals [KA, Collins, Du, Hong Kim, Mishra (2016-2018)]...

- New (cascade) decay channel for composite/KK gauge boson in extended model: "intermediate"-strength coupling into play





- take-home: look for double (3 and 2-particle) resonance structure!