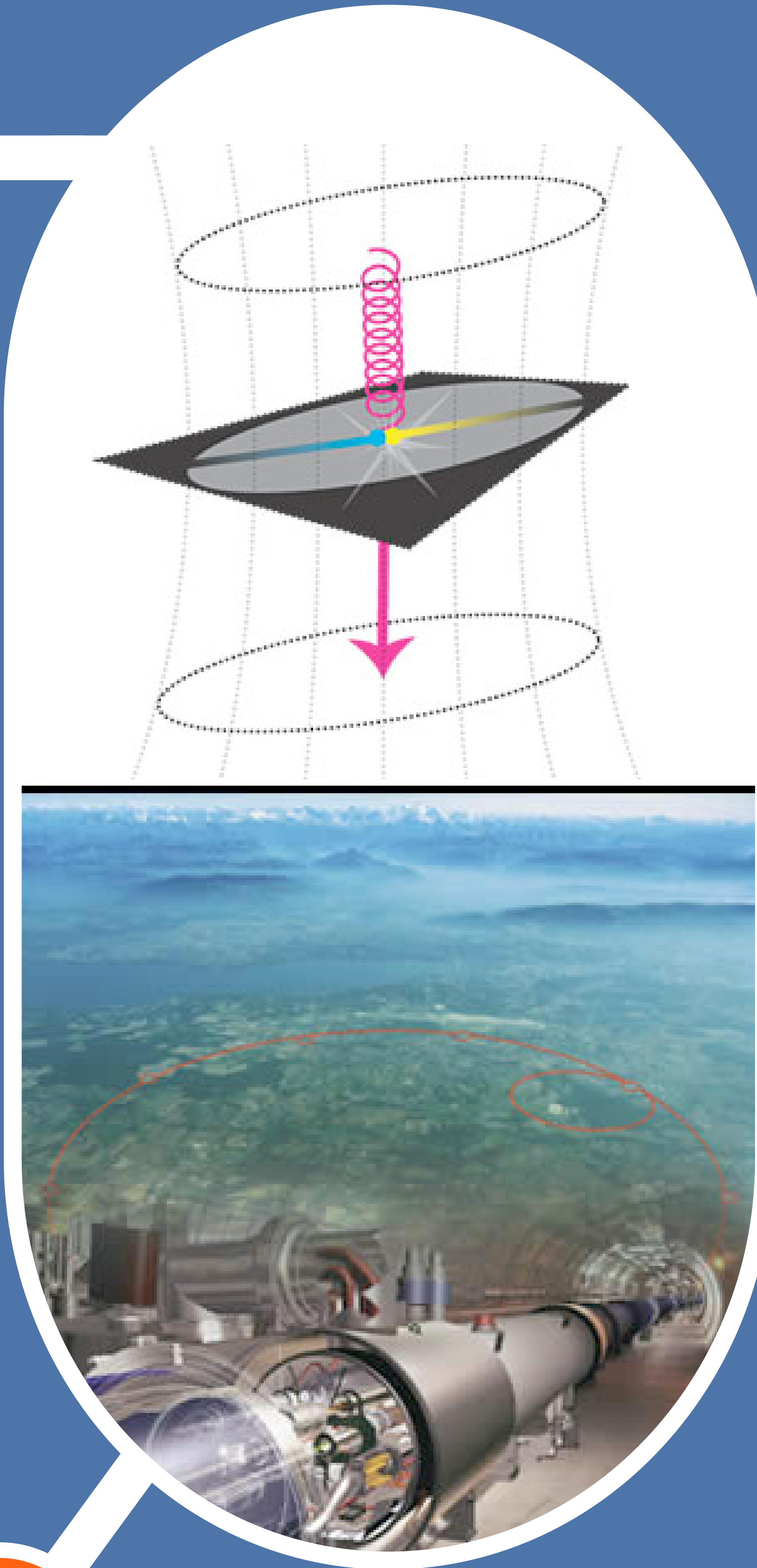
Extra Dimensions

Ben Lillie
Argonne National Laboratory and The University of Chicago

SUSY 07

Plan

- Lessons for colliders from extra dimensions
- Spins (UED)
- Tops (RS)



UED and SUSY

a tale of two spins

Universal Extra Dimensions

Appelquist, Cheng, Dobrescu hep-ph/0012100

- Exactly what it sounds like

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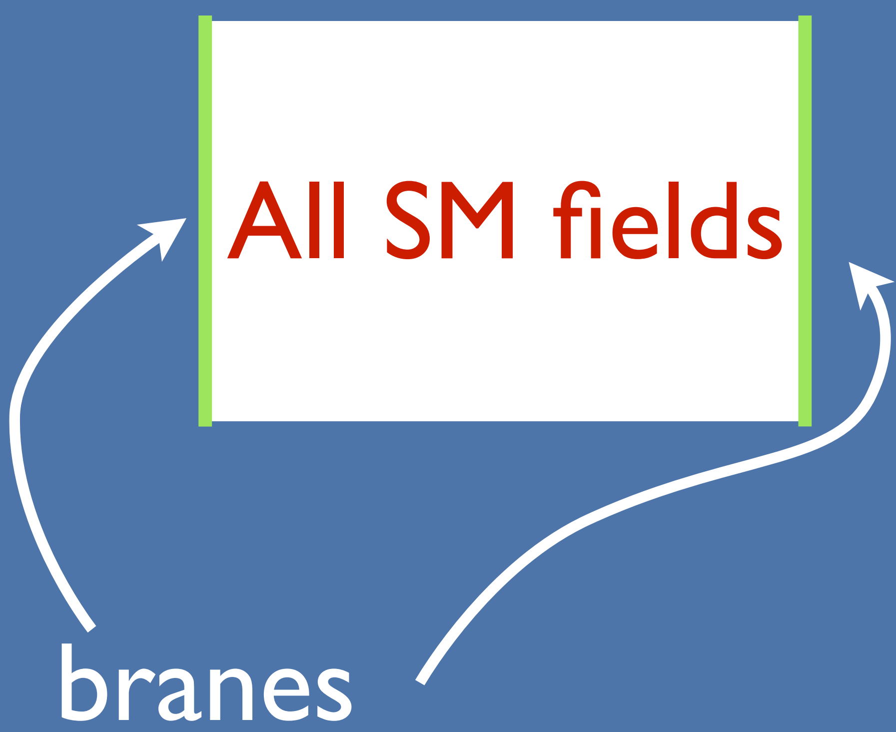

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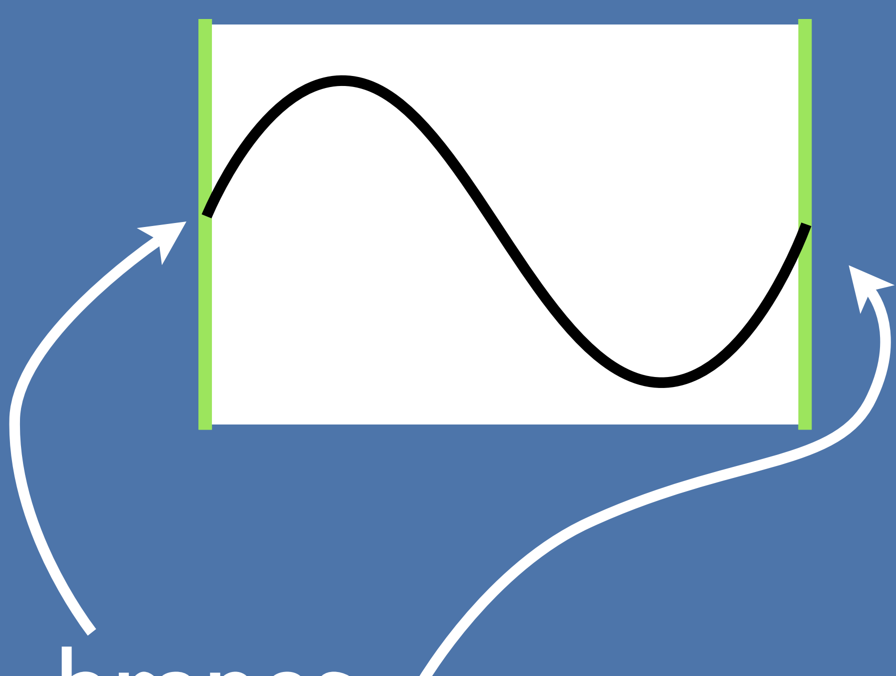

Kaluza-Klein modes:

$$m^{(n)2} = n^2/R^2 + m_0^2$$

(SM mass)

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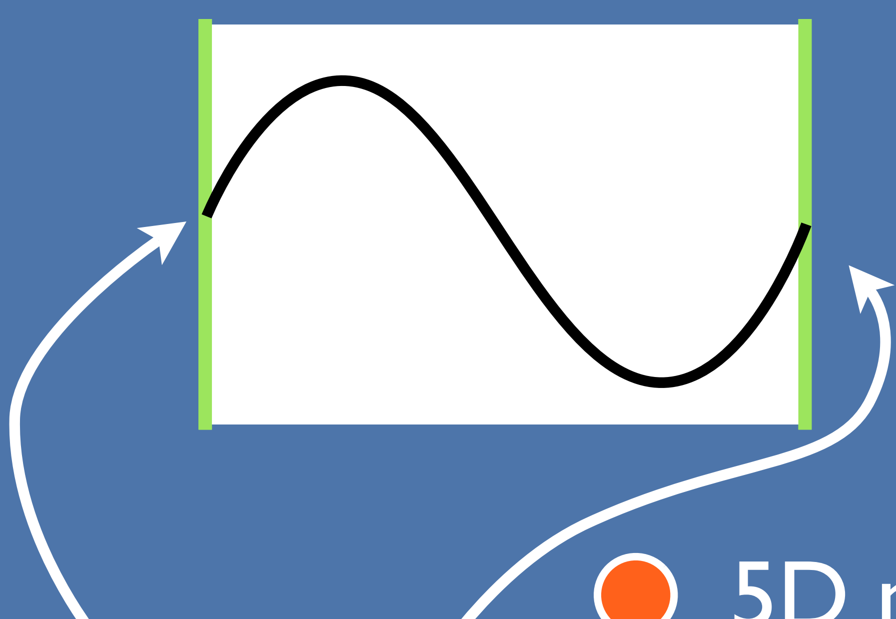

branes

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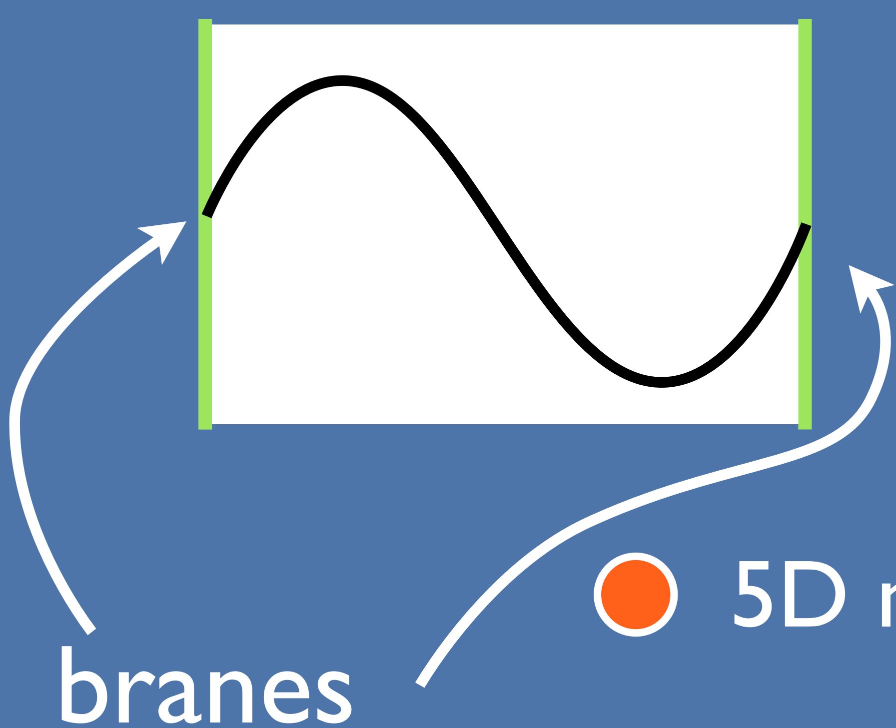

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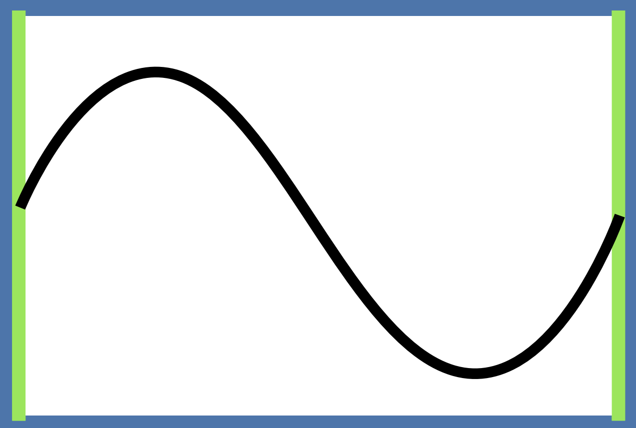

branes

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$$m^{(n)2} = n^2/R^2 + m_0^2$$

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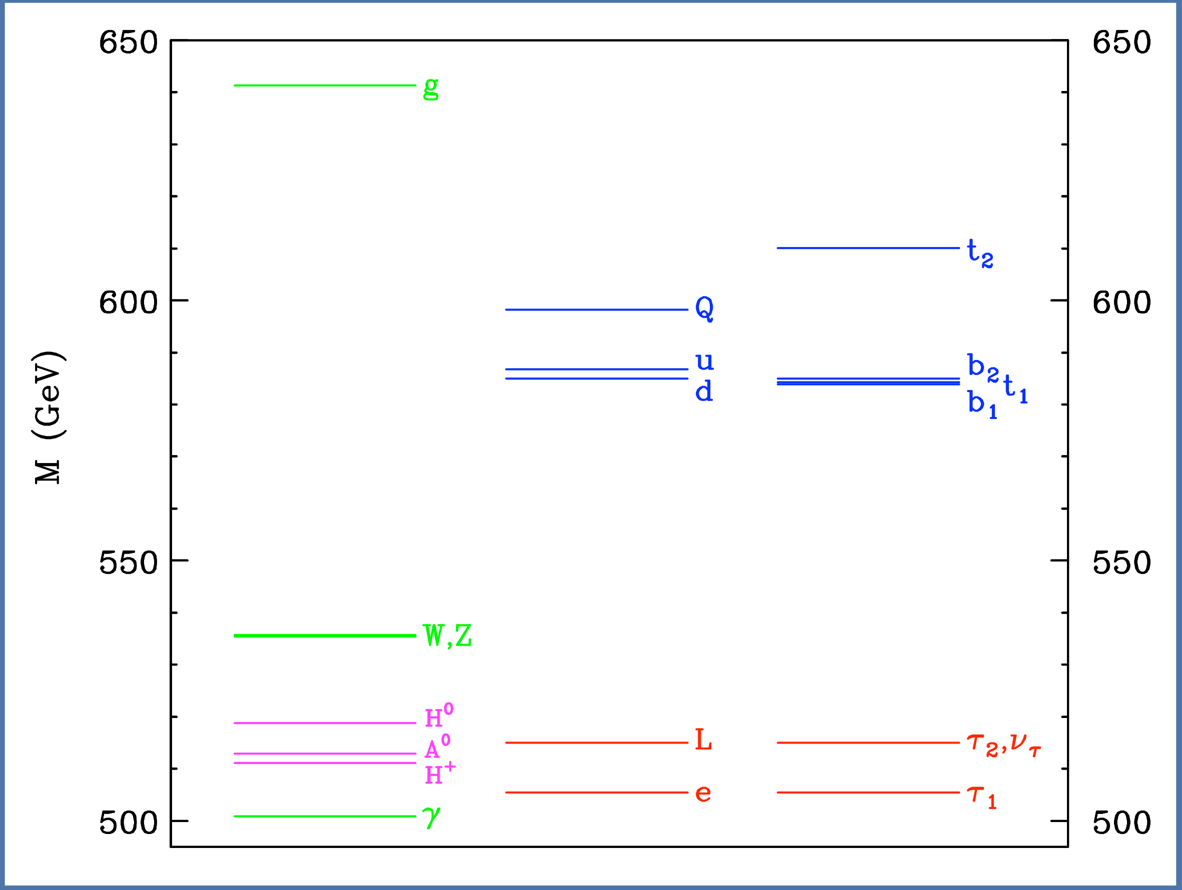
- 5D momentum ⇒ KK number conservation
- Walls break momentum conservation
- KK parity left conserved

Spectrum - KK level 1

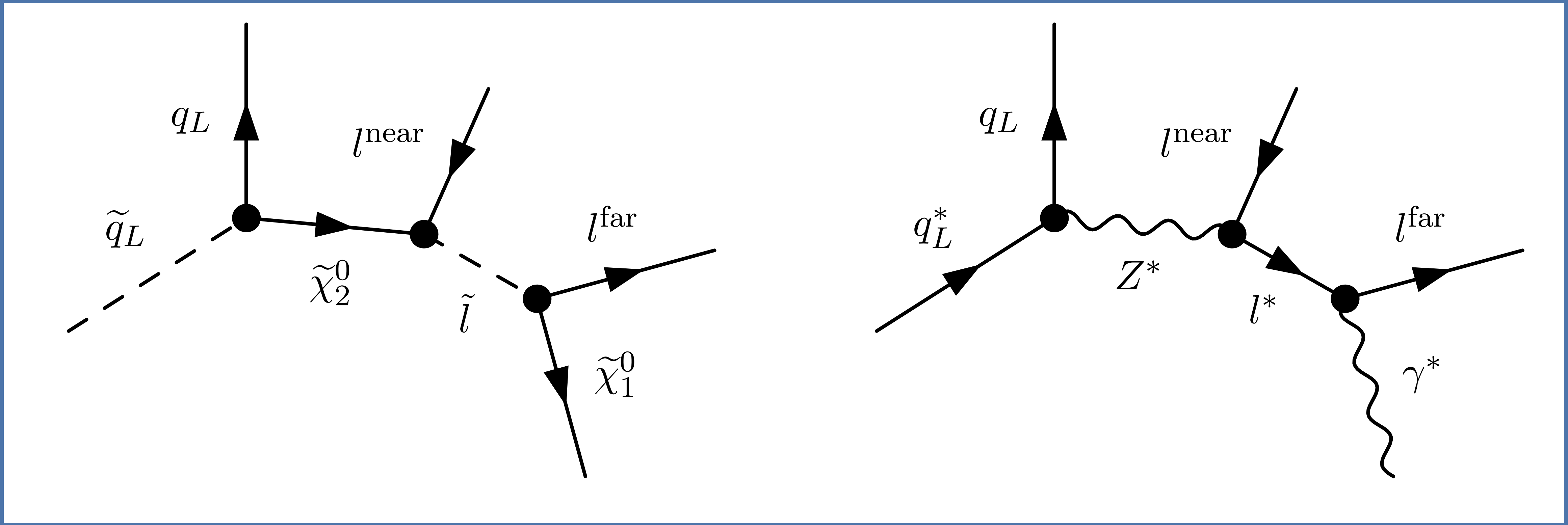
Cheng, Matchev, Schmaltz hep-ph/0204342 0205314

- Lightest state is stable
- 1-loop corrections are calculable
- Spectrum certainly possible in the MSSM



Is there a difference?

Smillie, Webber, hep-ph/0507170
(Barr, hep-ph/0405052)



$$\hat{m} = m_{ql}^{\text{near}} / (m_{ql}^{\text{near}})_{\max} = \sin(\theta^*/2)$$

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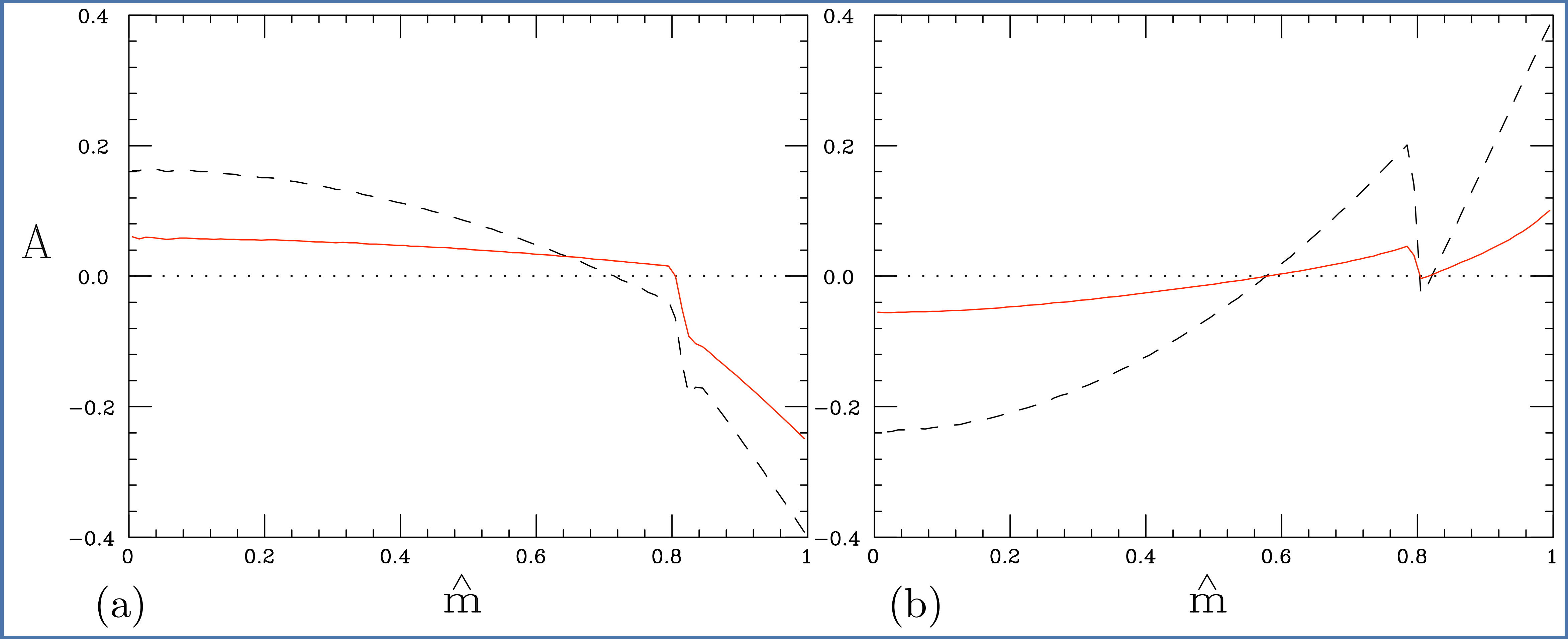
Charge asymmetry



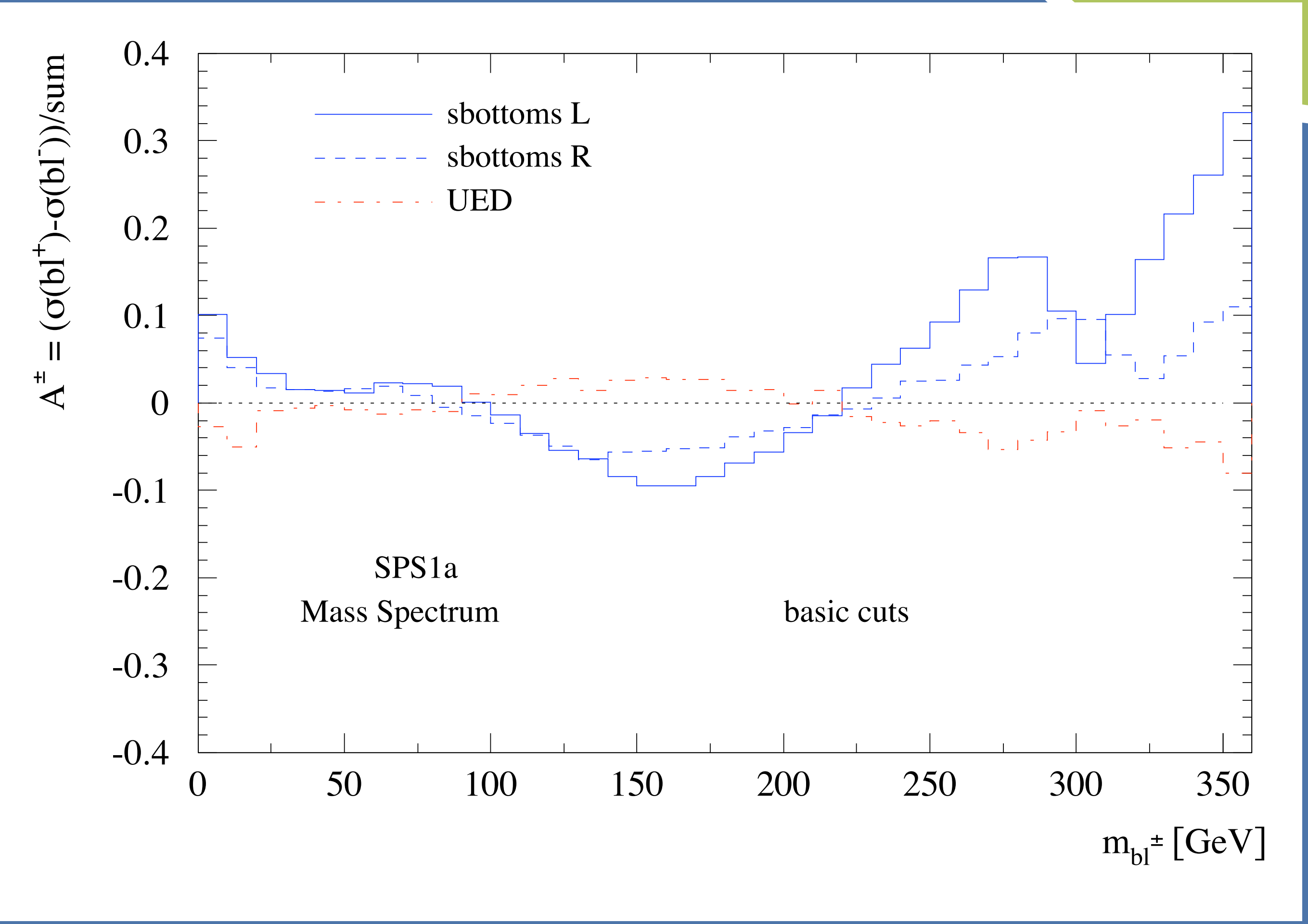
UED-like

mSUGRA-like

$$\hat{m} = m_{ql}^{\text{near}} / (m_{ql}^{\text{near}})_{\max} = \sin(\theta^*/2)$$

Is it a gluino?

Alves, Éboli, Plehn hep-ph/0605067



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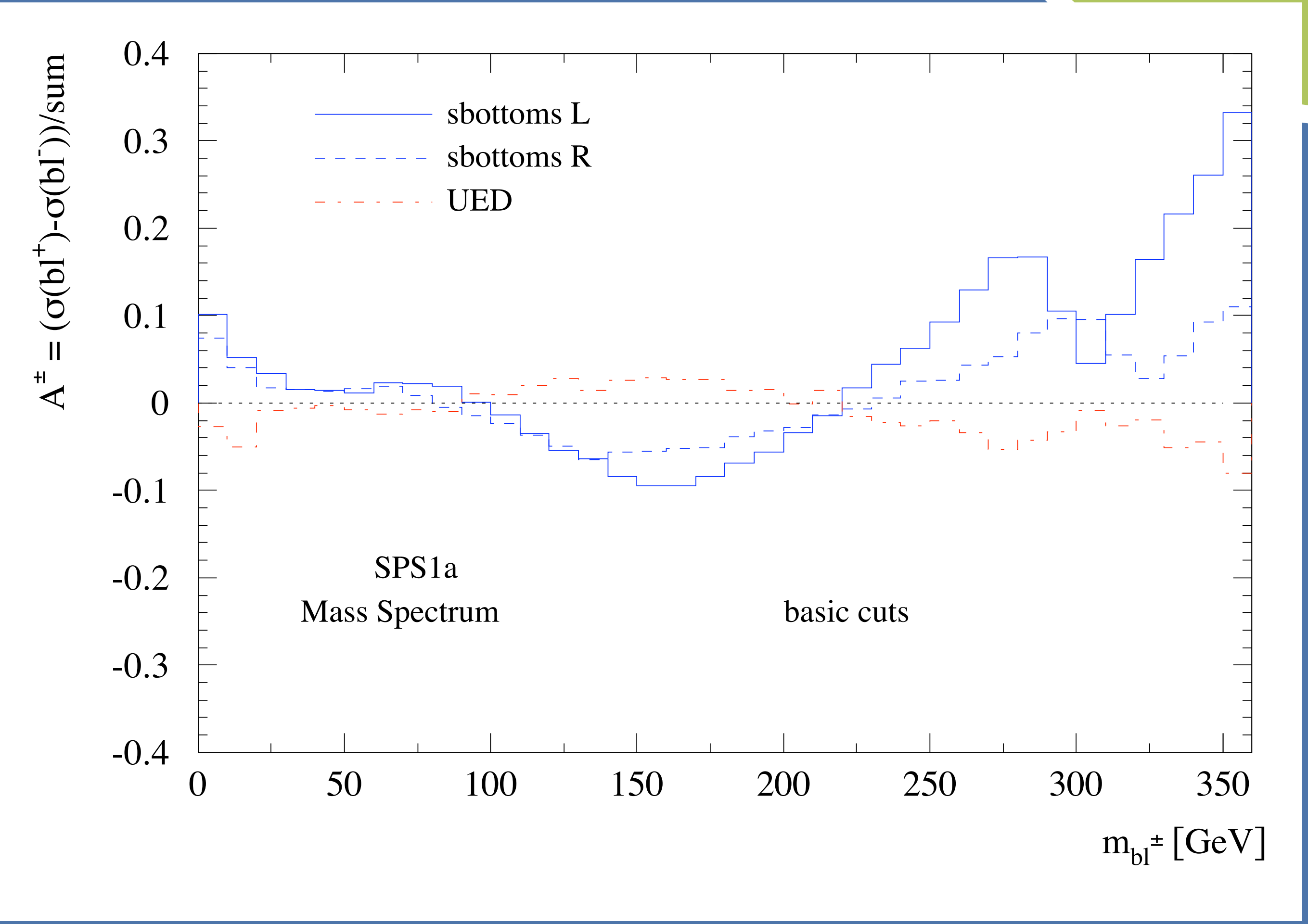
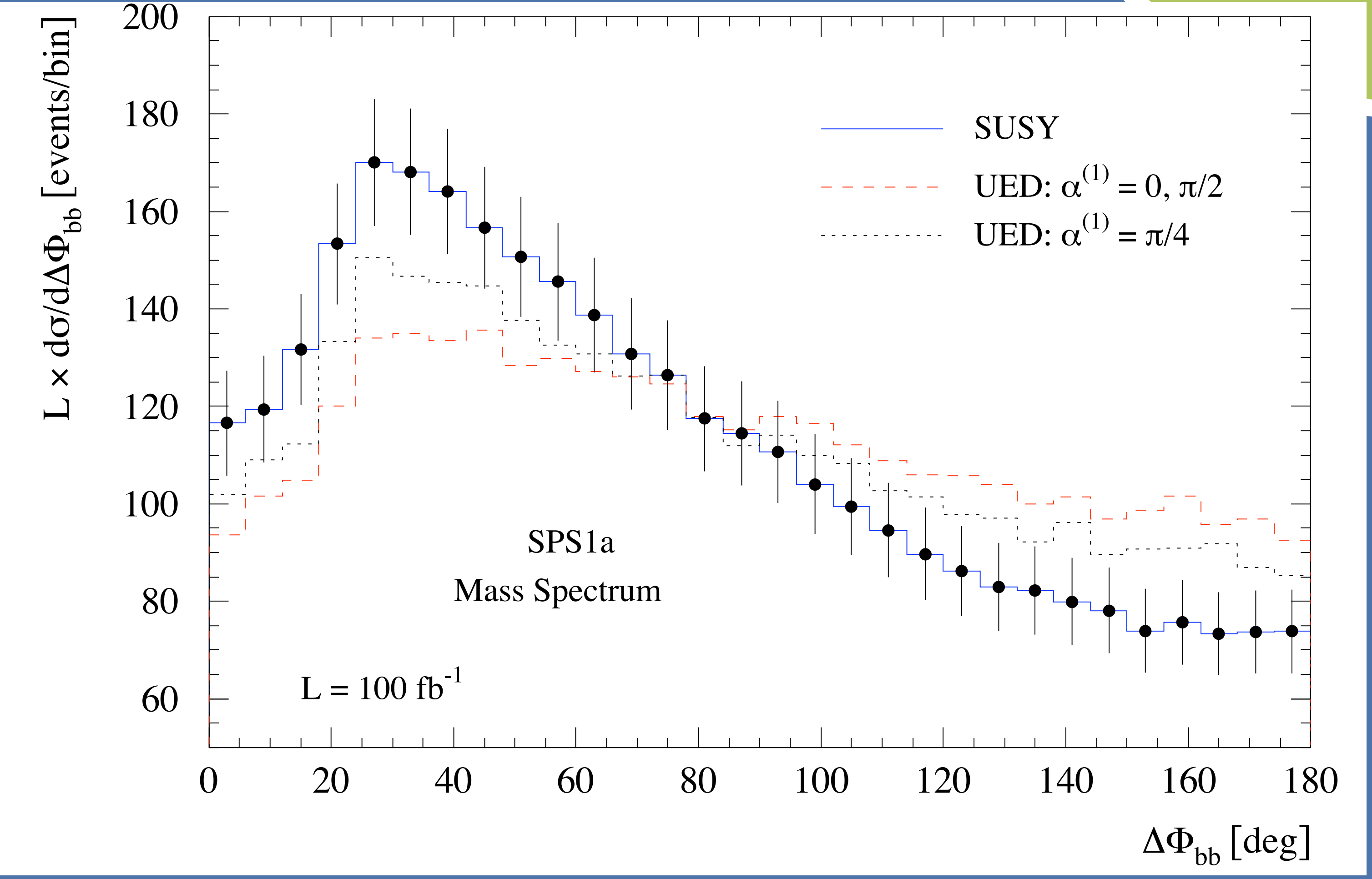
- Can also use decays through a sbottom (b').



Is it a gluino?

Alves, Éboli, Plehn hep-ph/0605067

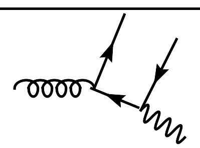
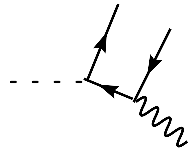
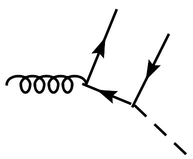
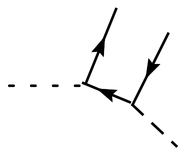
- Can also use decays through a sbottom (b').
- Purely hadronic observables available
  - e.g. azimuthal angle between b-jets



For every spin, turn, turn, turn

Wang, Yavin, hep-ph/0605296
Kilic, Wang, Yavin, hep-ph/0703085

$$\frac{d\Gamma}{dt_{f\bar{f}}} \propto \alpha + \beta t_{f\bar{f}}$$

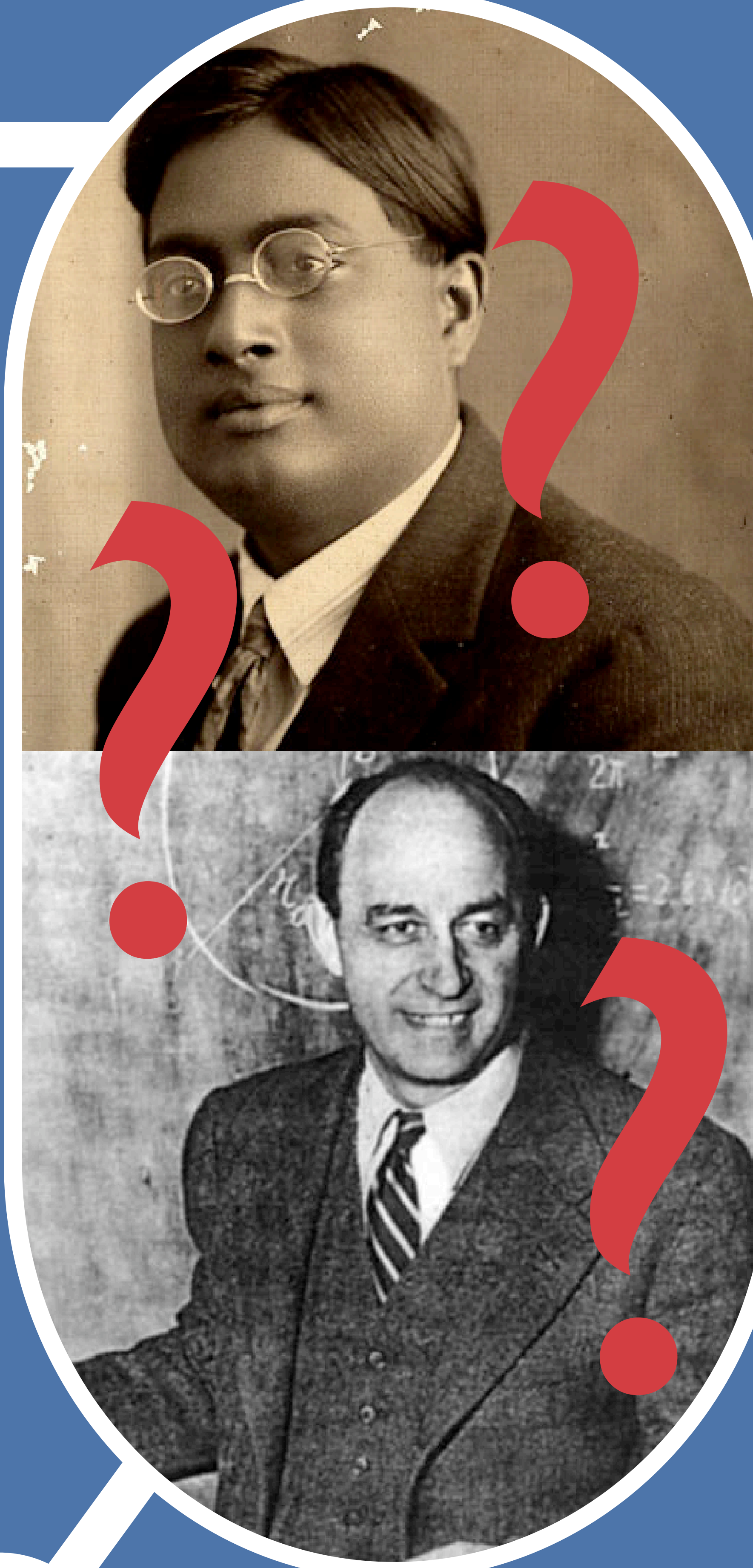
Scenario	Slope β	Intercept α
	$\left(2M_{g'}^2 - M_Q^2\right)\left(M_Q^2 - 2M_{\gamma'}^2\right)$	$(M_Q^4 + 4M_{\gamma'}^2 M_{g'}^2)\ t_{f\bar{f}}^{(edge)}$
	$-\left(M_Q^2 - 2M_{\gamma'}^2\right)$	$M_Q^2\ t_{f\bar{f}}^{(edge)}$
	$\left(2M_{g'}^2 - M_Q^2\right)$	$M_Q^2\ t_{f\bar{f}}^{(edge)}$
	-1	$t_{f\bar{f}}^{(edge)}$

- Observation of non-zero slope:
  - Matter partner is fermionic
  - Possible to extract spin information about other particles in the chain (requires luck)

Lesson 1

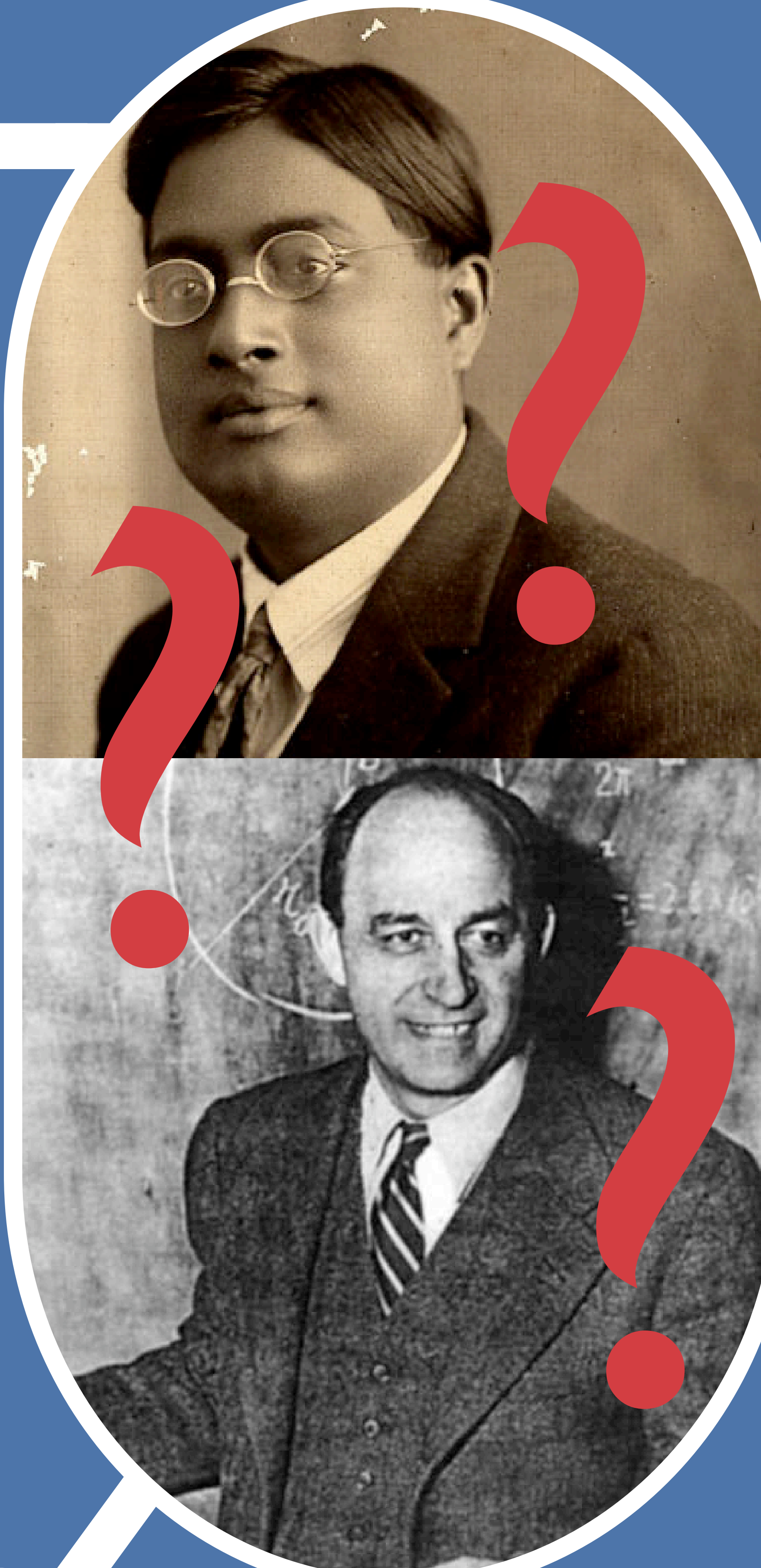
Lesson 1

- We need spin measurements at the LHC



Lesson 1

- We need spin measurements at the LHC
  - Even (especially?) in processes with MET



Lesson 1

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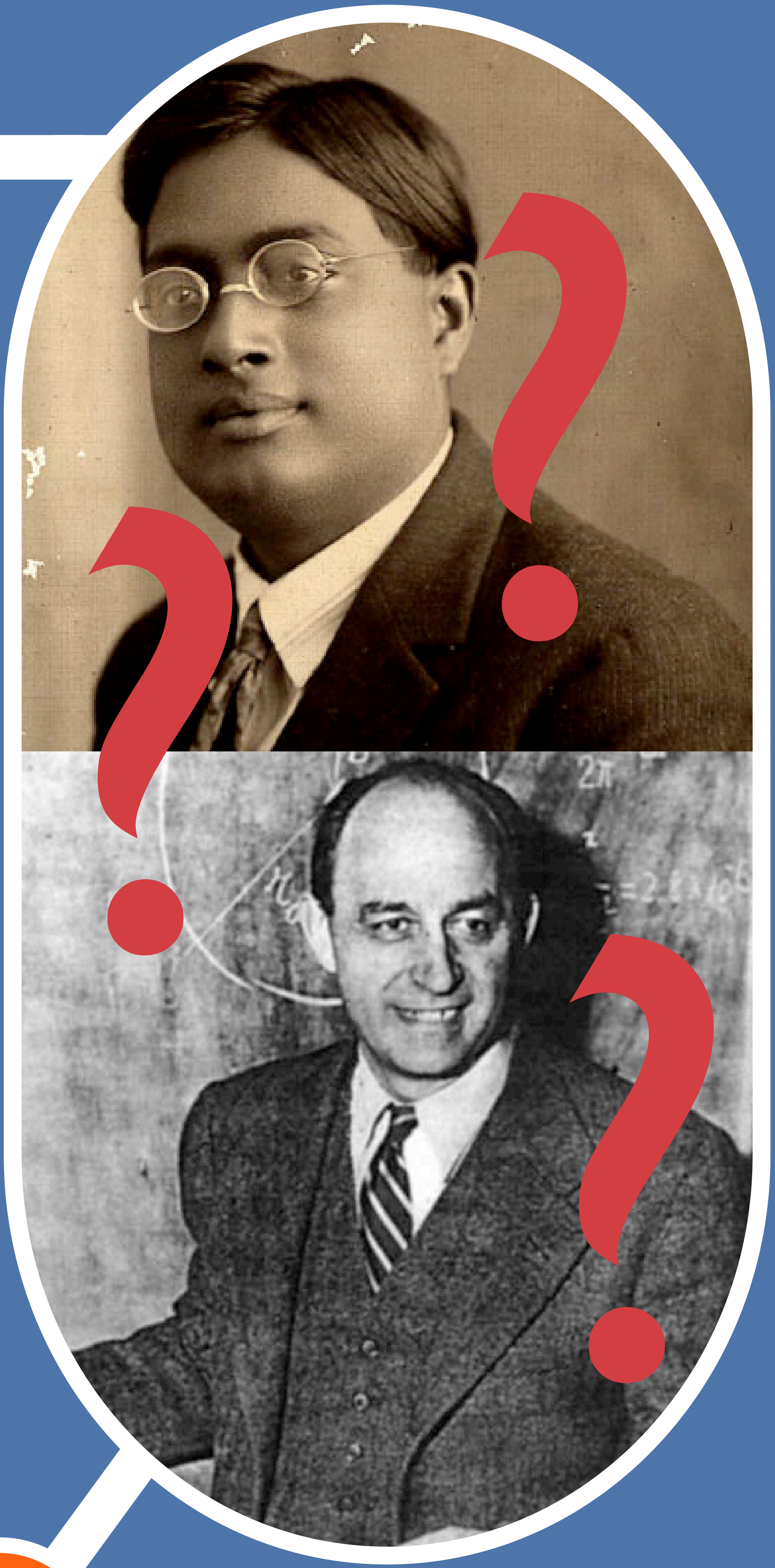
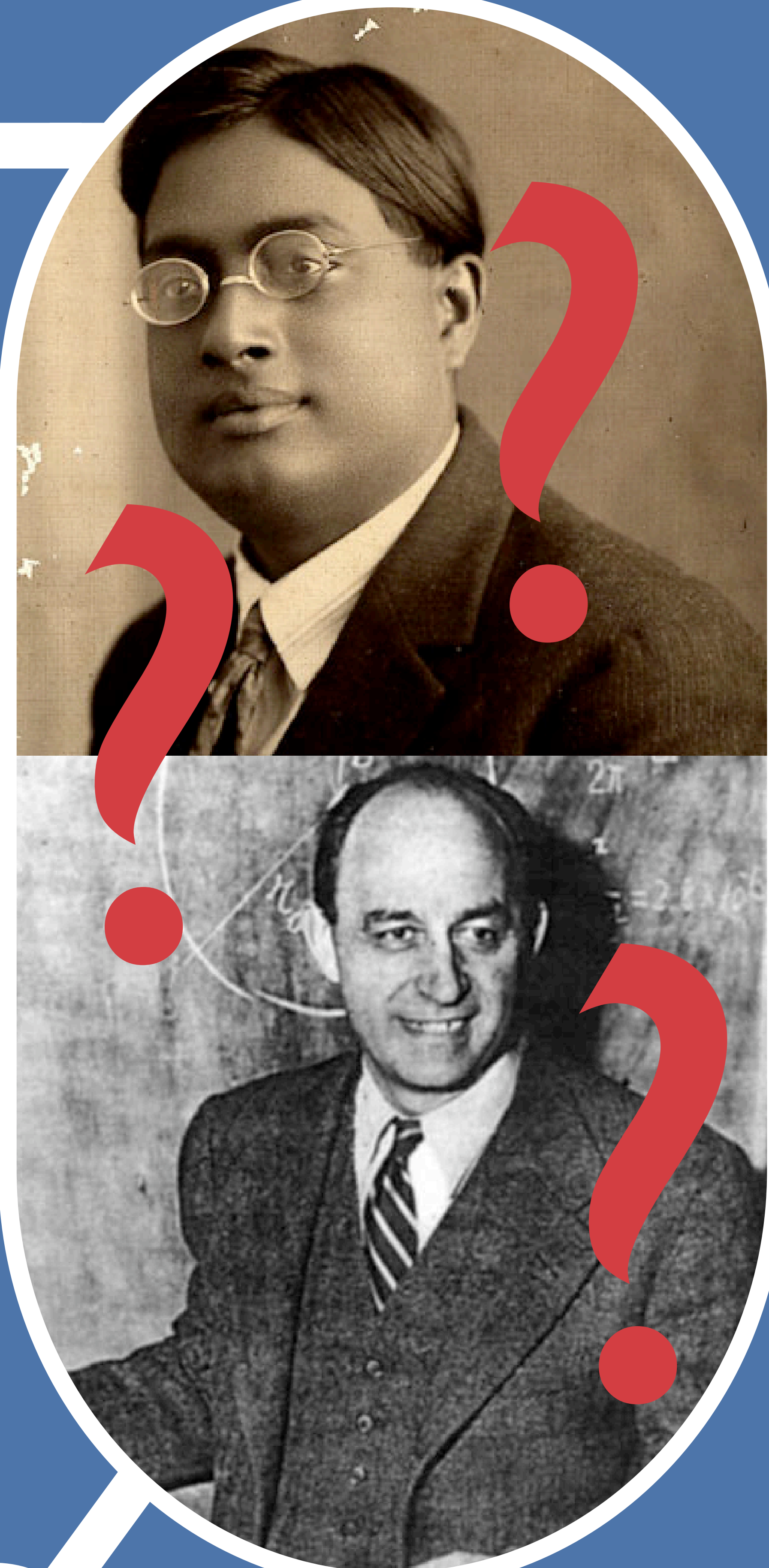


Lesson 1

- We need spin measurements at the LHC
  - Even (especially?) in processes with MET
- It's possible
- Needs realistic experimental study



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- Easy (easier) at the ILC

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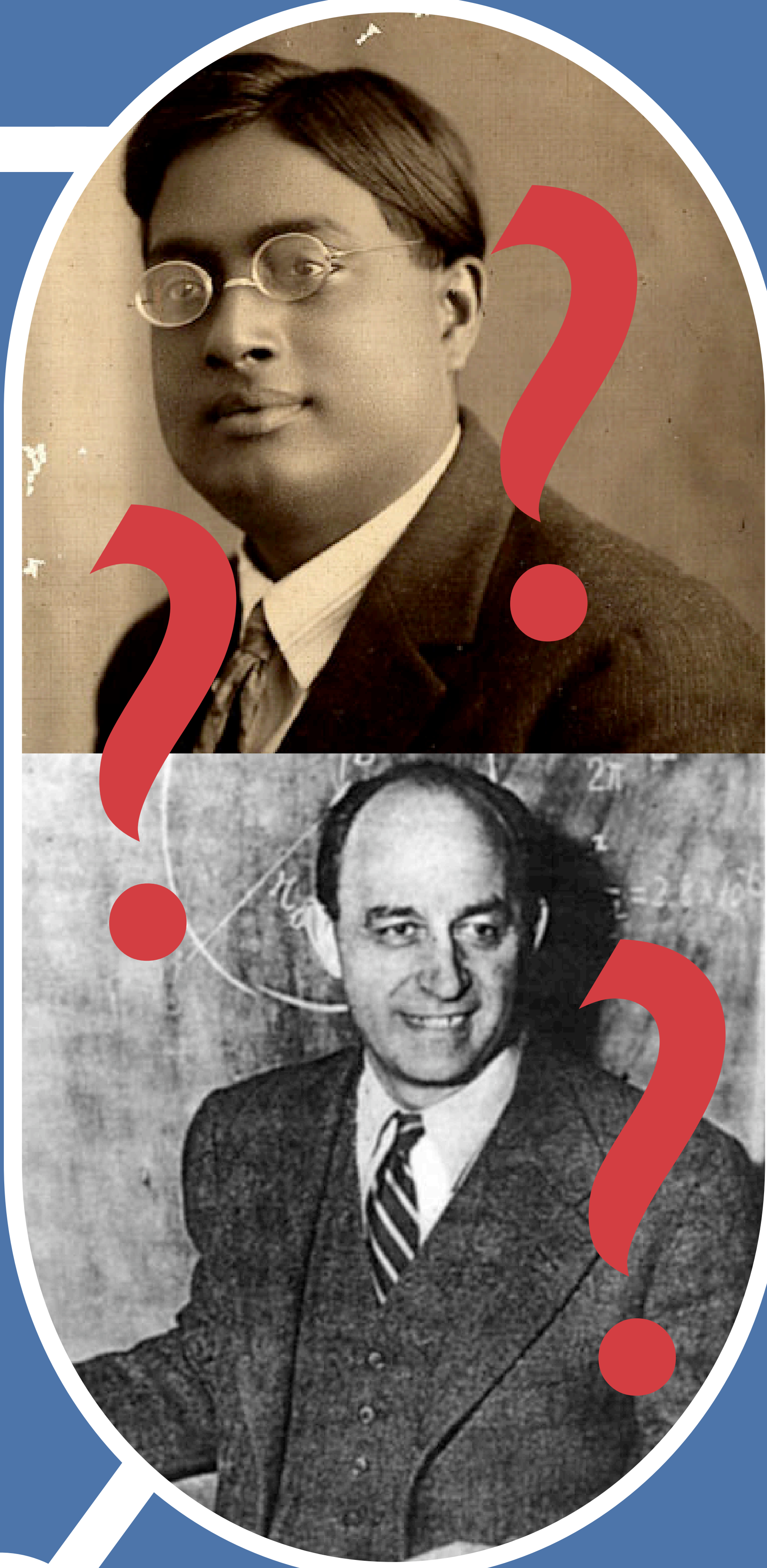
- We need spin measurements at the LHC
  - Even (especially?) in processes with MET
- It's possible
- Needs realistic experimental study
- Easy (easier) at the ILC
  - Take as a challenge!



Is that all?

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- The gluon partner is either a vector (spin 1) or a spinor (spin 1/2), right?

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- The gluon partner is either a vector (spin 1) or a spinor (spin 1/2), right?
    - Wrong

If 5D, why not 6D?

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5D

$$(A_\mu, A_5)$$

$$\downarrow$$

$$A_\mu$$

2+1=3

If 5D, why not 6D?

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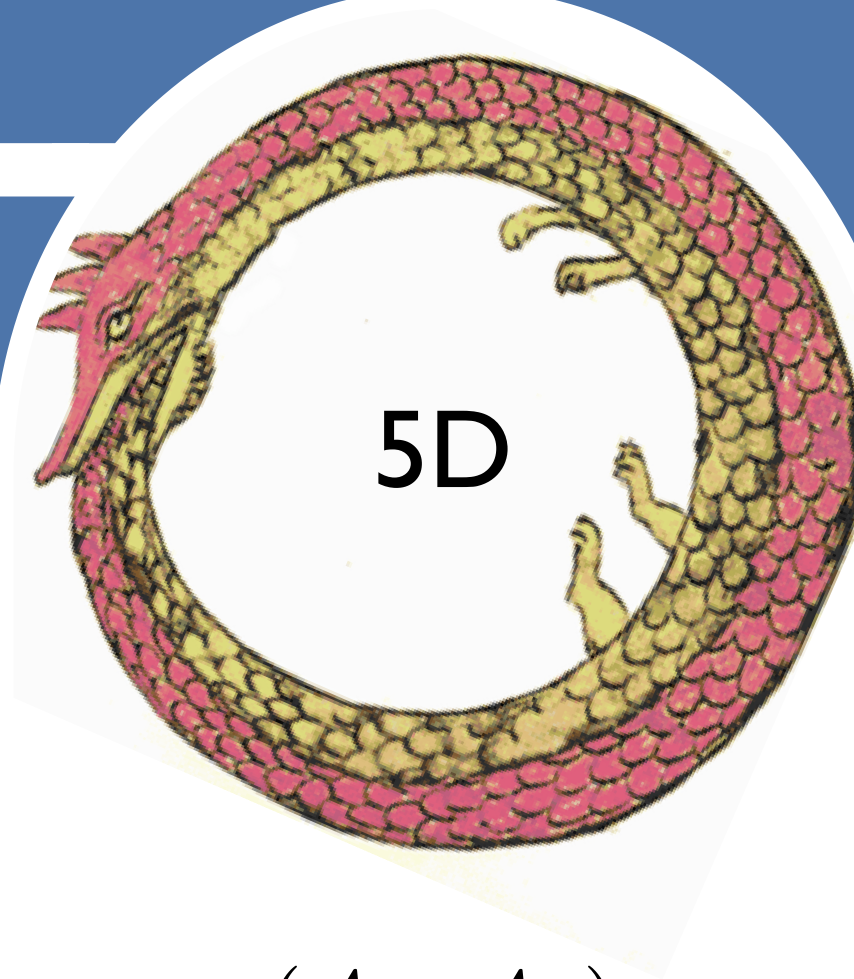


$$(A_\mu, A_5)$$

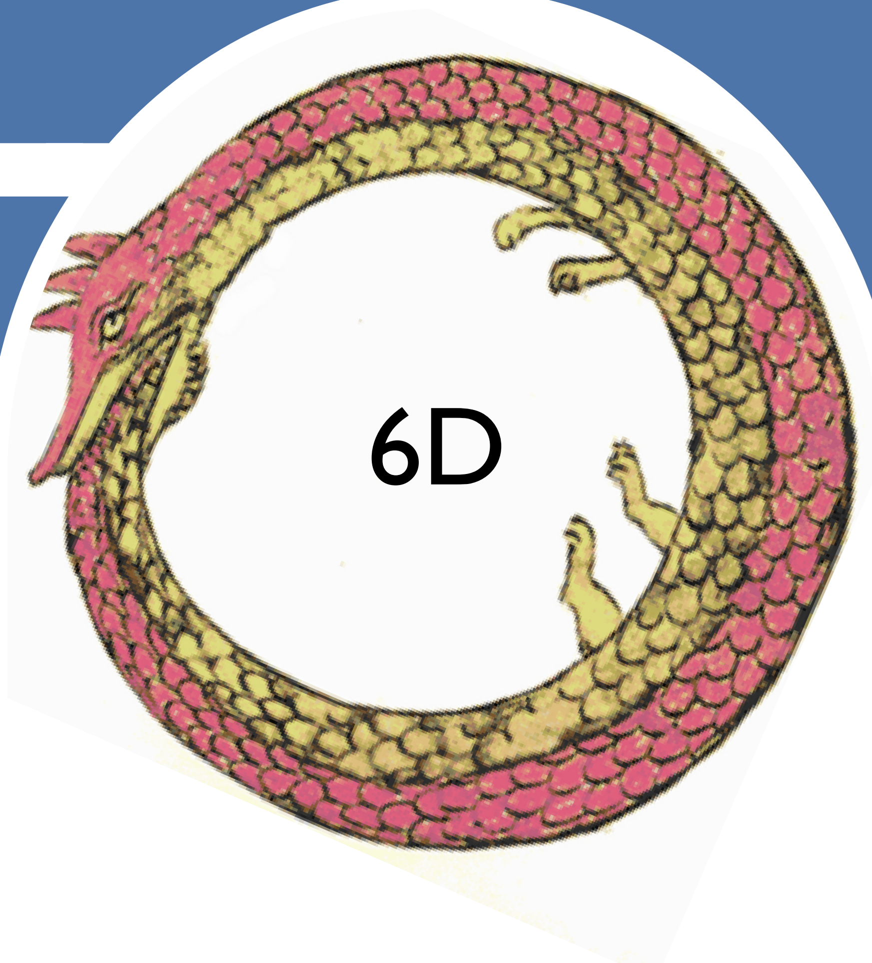
$$\downarrow$$

$$A_\mu$$

2+1=3

If 5D, why not 6D?

- A vector needs to eat another degree of freedom to be massive
  - The KK modes eat their own A_5
- In 6D there is an extra degree of freedom



$$(A_\mu, A_5, A_6)$$

$$\downarrow$$

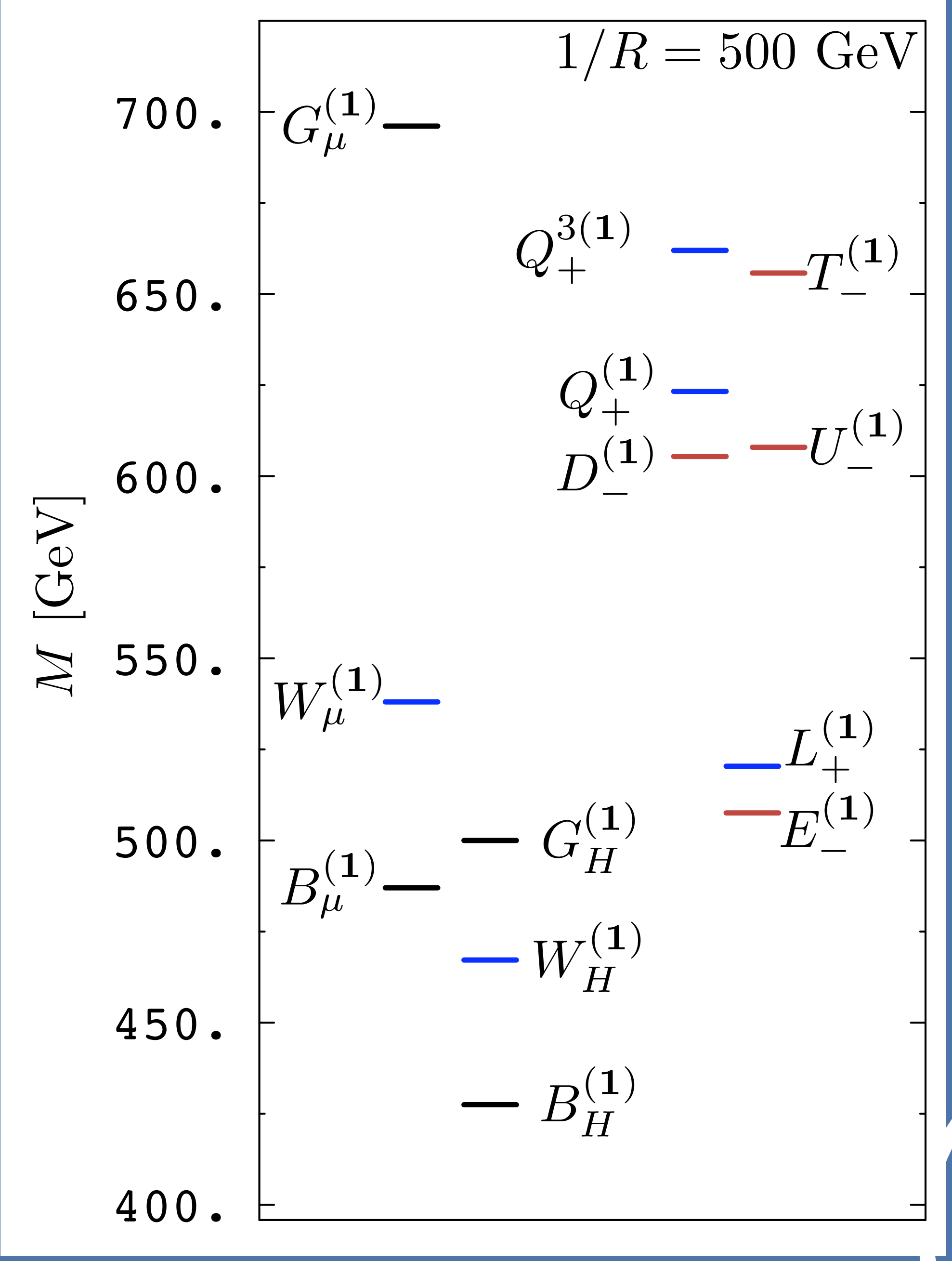
$$(A_\mu, \phi)$$

2+2=3+1

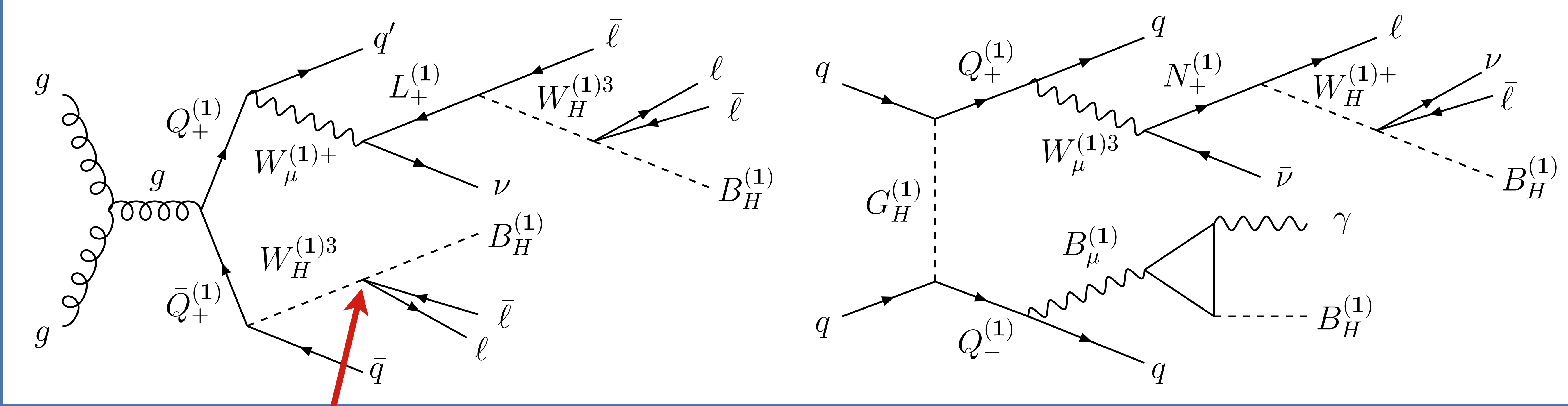
6D spectrum

Dobrescu, Kong, Mahbubani hep-ph/0703231
Dobrescu, Hooper, Kong, Mahbubani arxiv: 0706.3409

- Scalars are lightest states!
  - ⇒Scalar DM
- Lightest colored state also scalar



Lepton-Photon

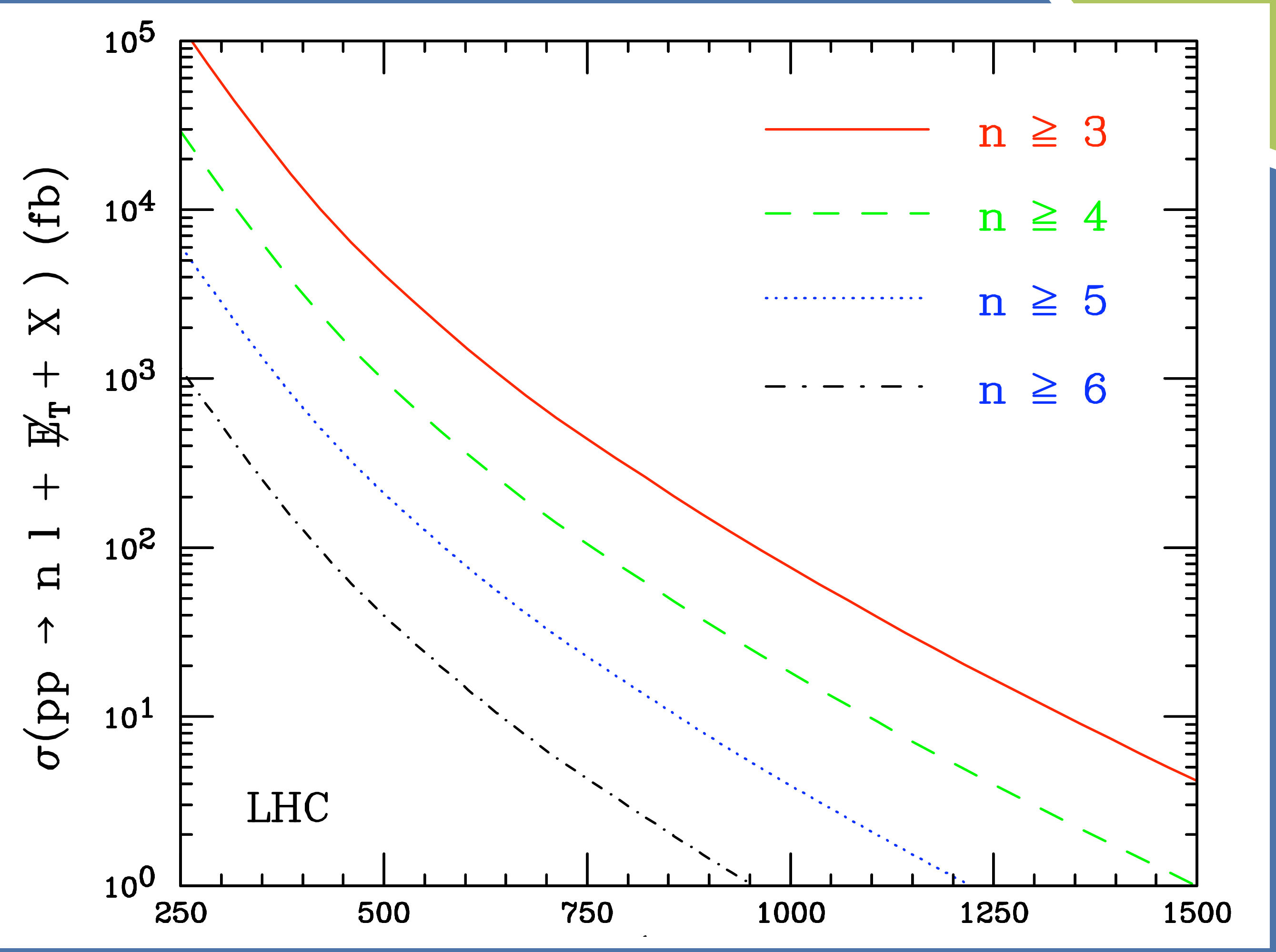


goes through KK fermion

⇒ lepton modes dominate

Lepton-Photon

n leptons



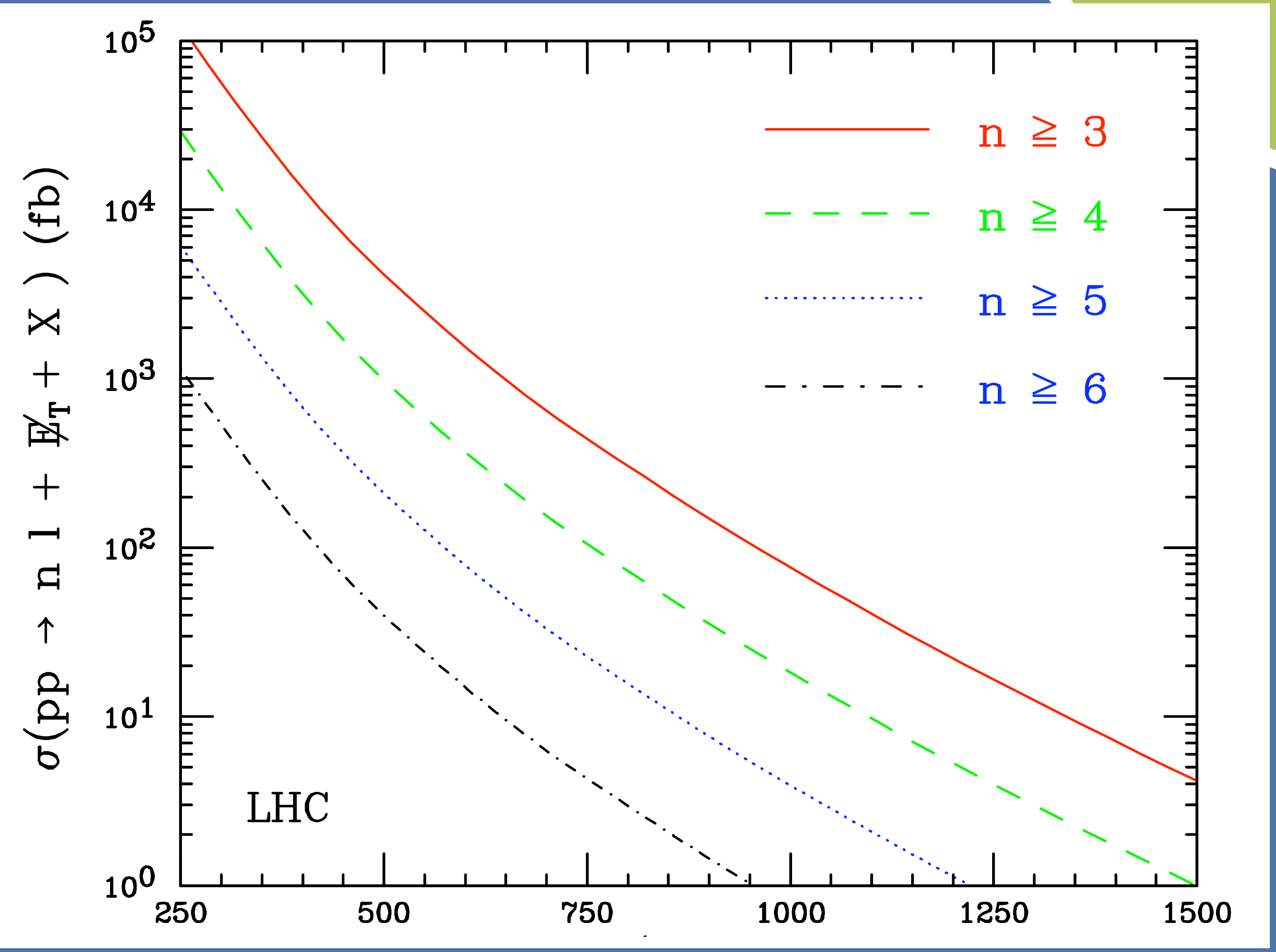
$1/R\ (GeV)$

(compactification radius)

Lepton-Photon

n leptons

- Small mass splittings so leptons and photons are soft



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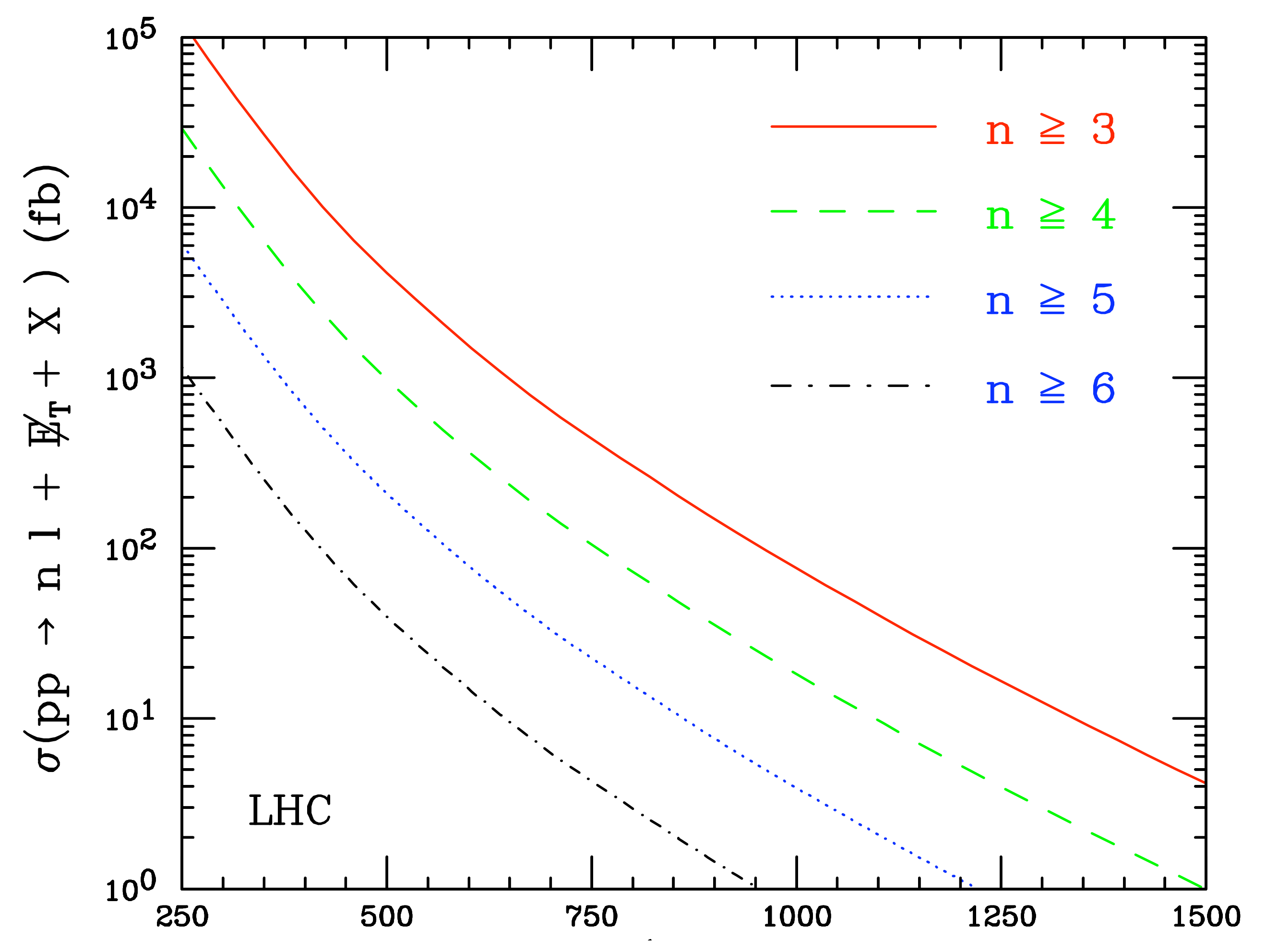


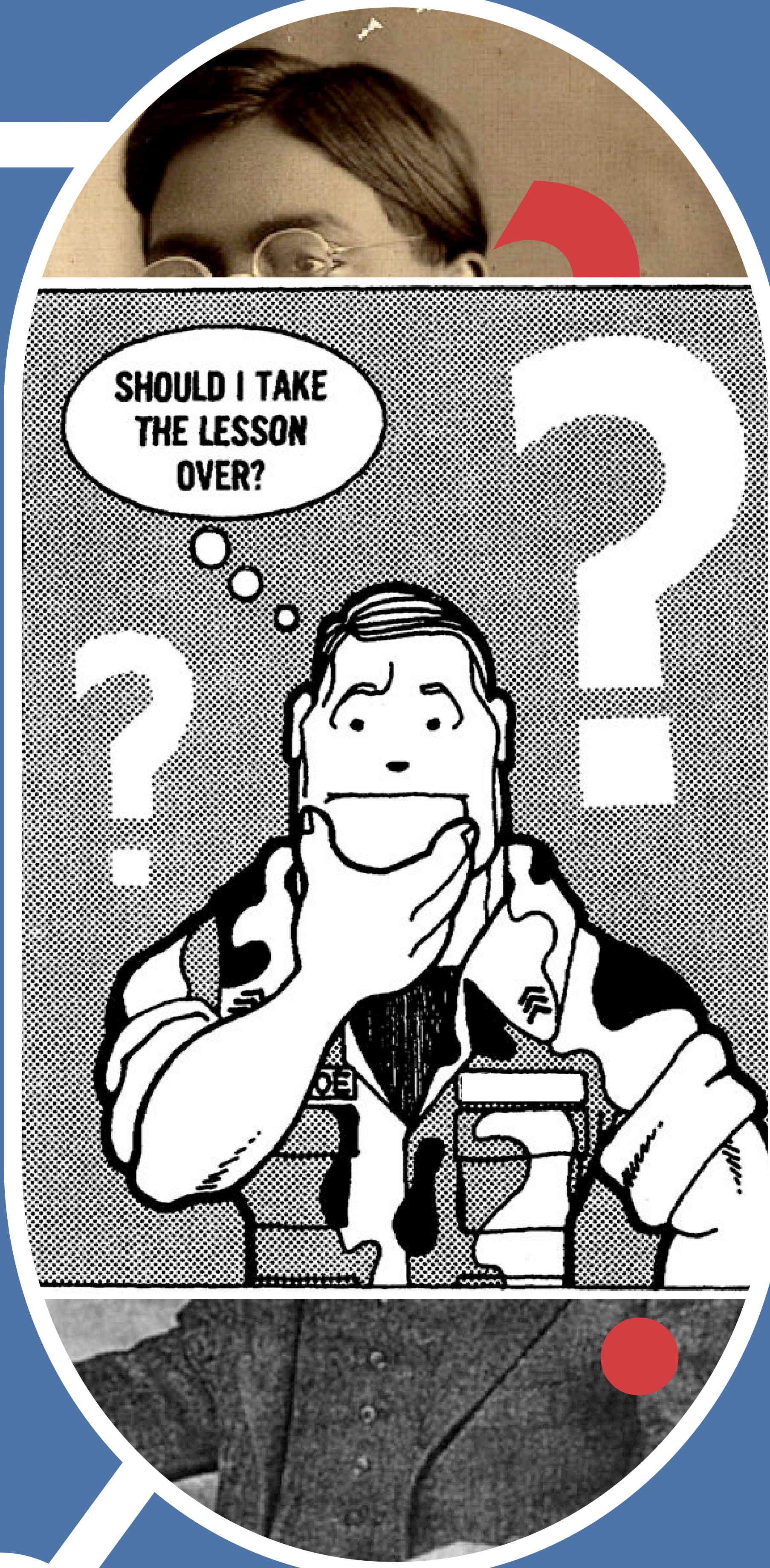
$1/R\ (GeV)$

- Small mass splittings so leptons and photons are soft
- Scalar DM: measuring spin gives a important prediction/check

(compactification radius)

Lesson 2

- Don't forget lesson 1



Warped dimensions

or

why thinner isn't better

The Randall-Sundrum model

L. Randall, R. Sundrum hep-ph/9905221

$$ds^2 = dx^2 - dy^2$$

The Randall-Sundrum model

L. Randall, R. Sundrum hep-ph/9905221

- UEDs →Flat metric

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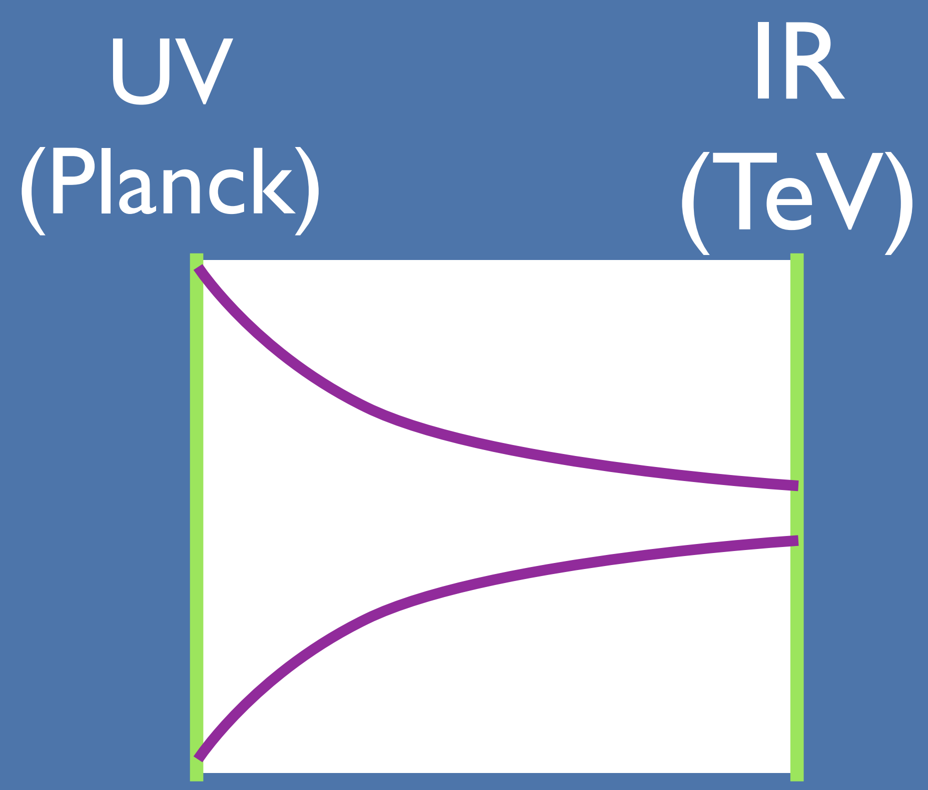

$$ds^2 = e^{-2ky} dx^2 - dy^2$$

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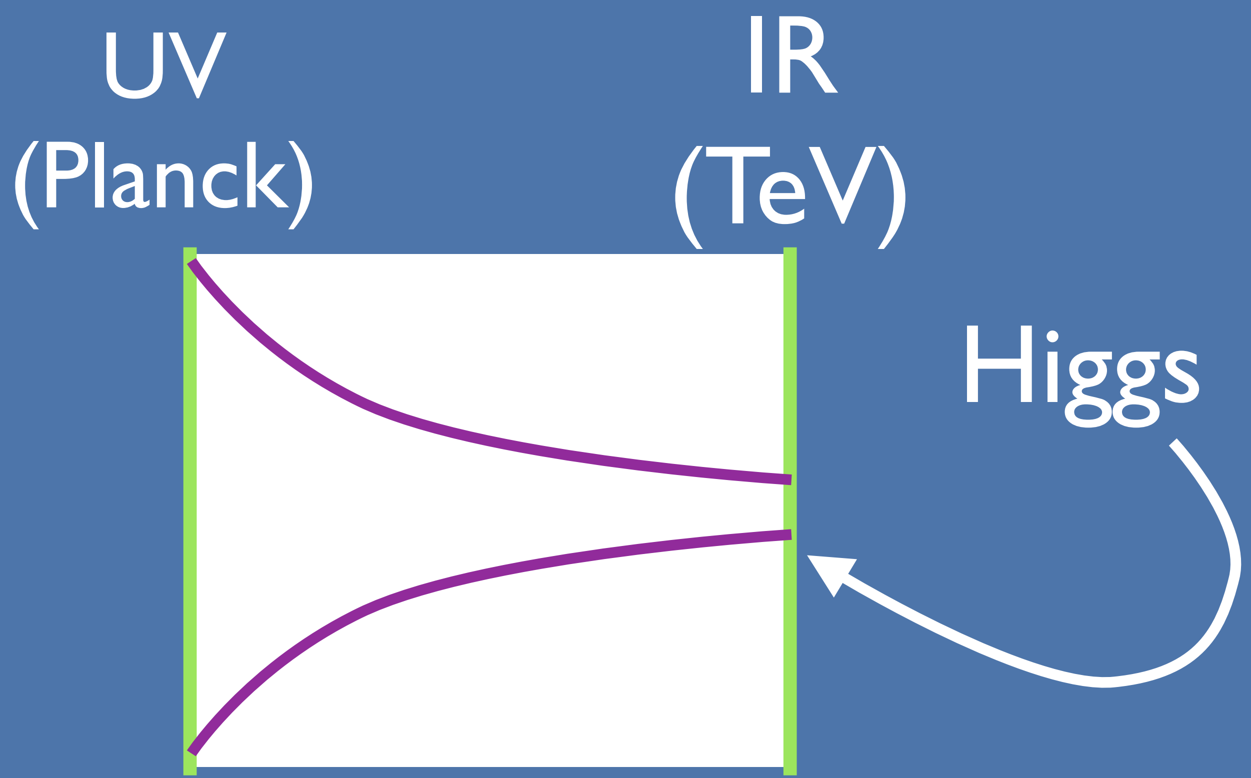


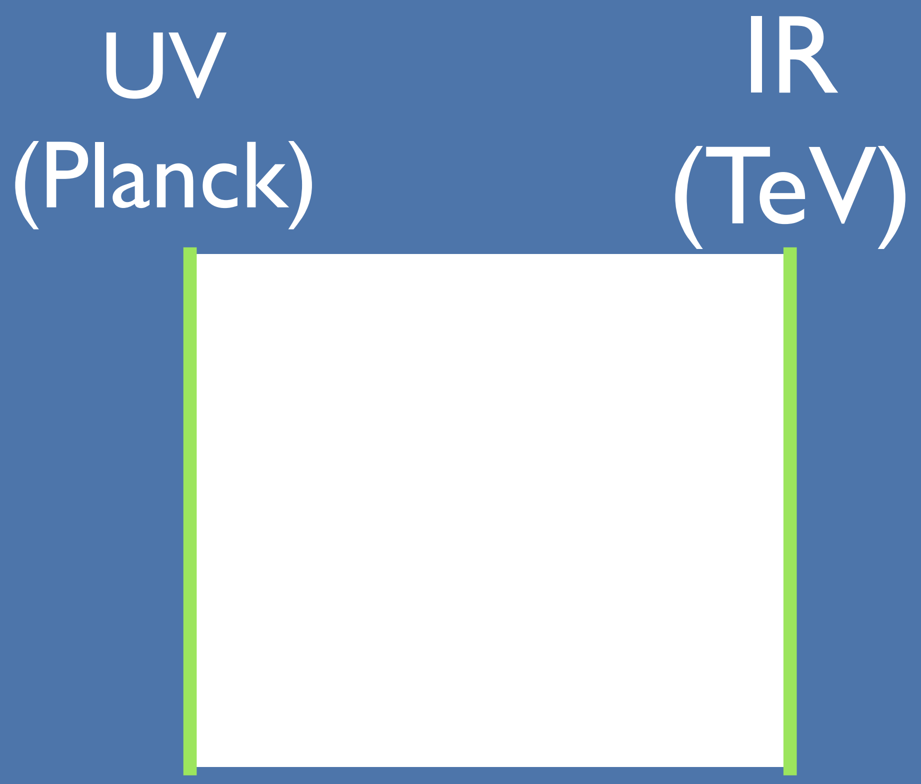
$$ds^2 = e^{-2ky} dx^2 - dy^2$$

$$M \to e^{-\pi k L} M \quad (L \simeq 30/k)$$

- UEDs → Flat metric
- RS uses the AdS, or "warped" metric
- Geometrically solves the Hierarchy problem

Where to put the SM?

Davoudiasl, Hewett, Rizzo, hep-ph/9911262
Pomarol, hep-ph/9911294



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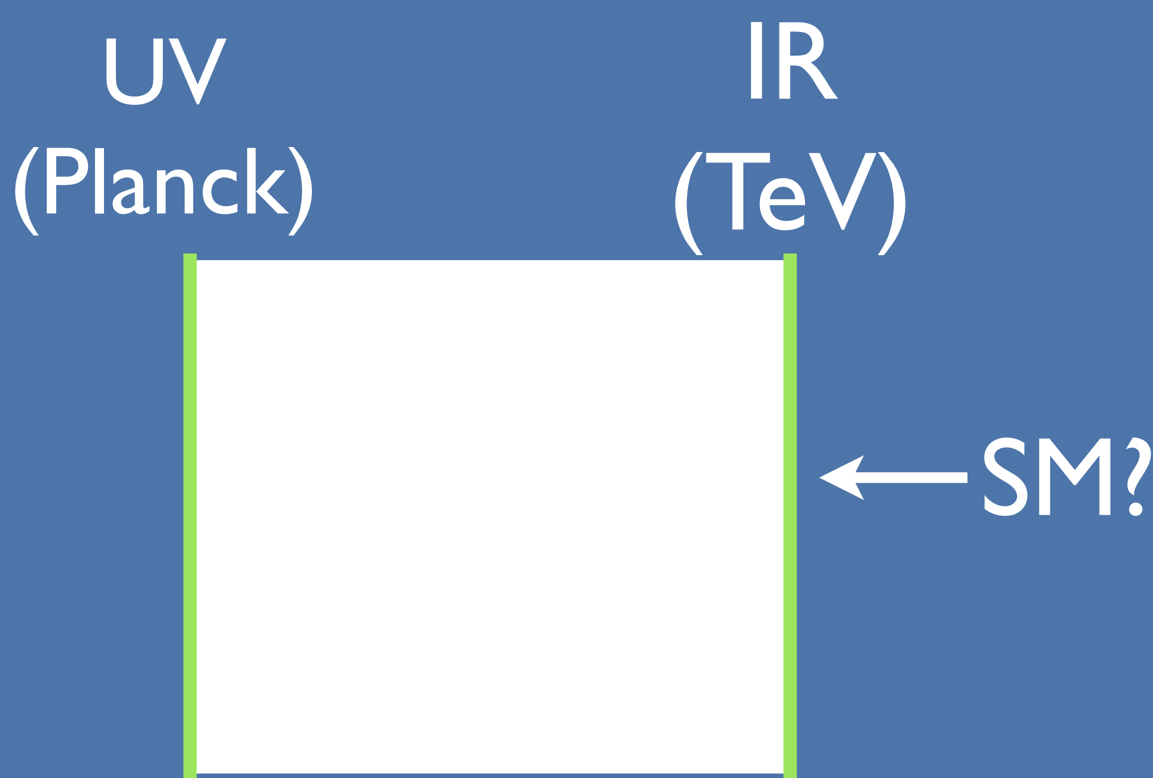

- Could localize the entire SM to the IR brane

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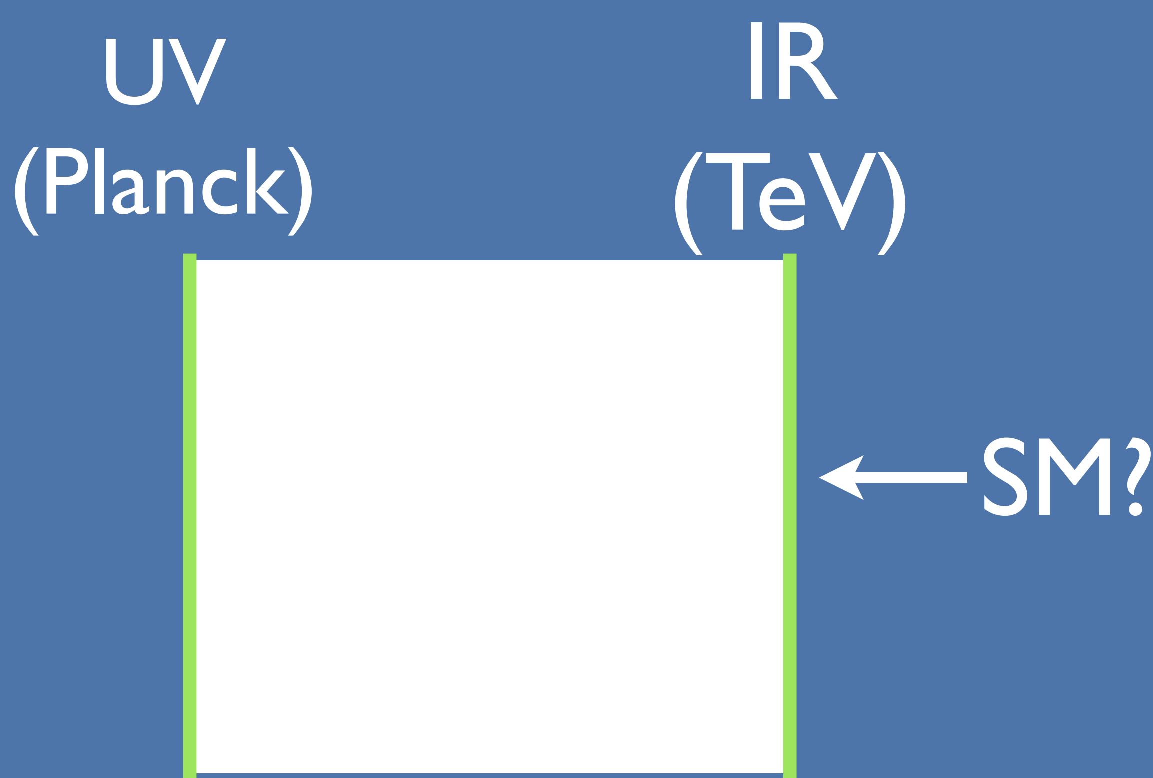

$\frac{\bar{\psi}\psi\bar{\psi}\psi}{\Lambda^2} \longleftarrow$ FCNC, $\cancel{CP}$

- Could localize the entire SM to the IR brane
- Cutoff is lowered by the same geometry to ~ 10 TeV

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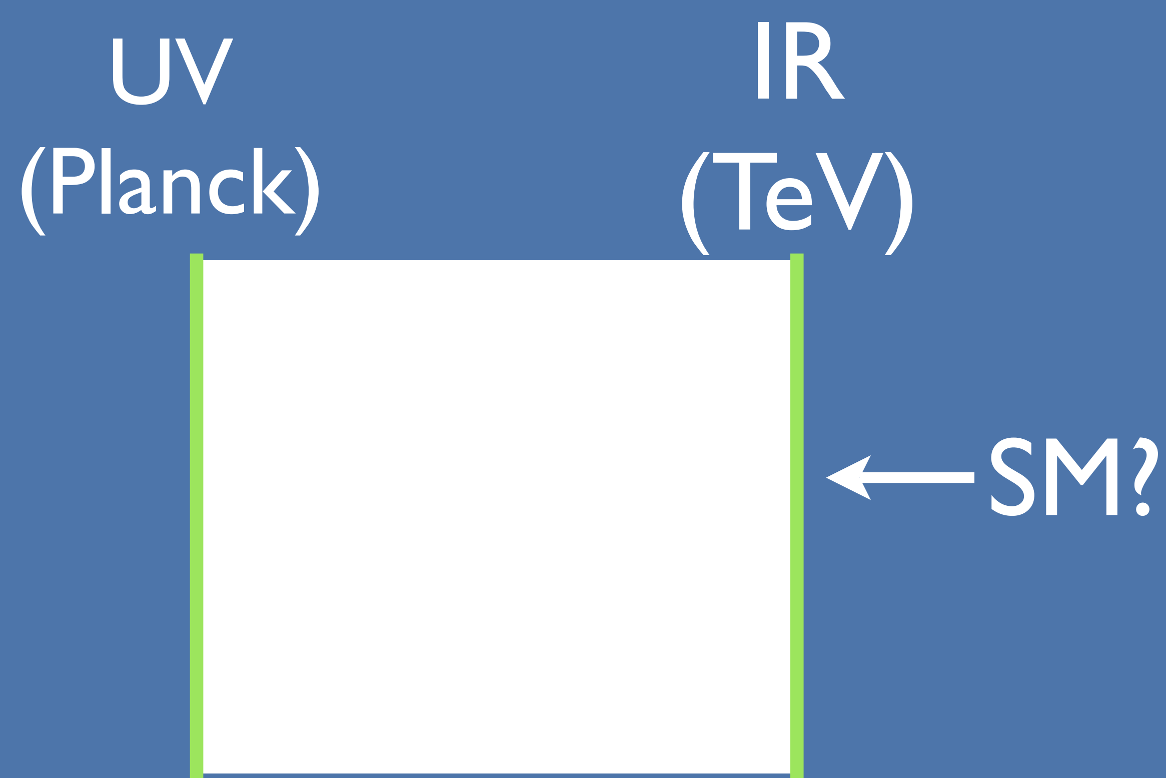

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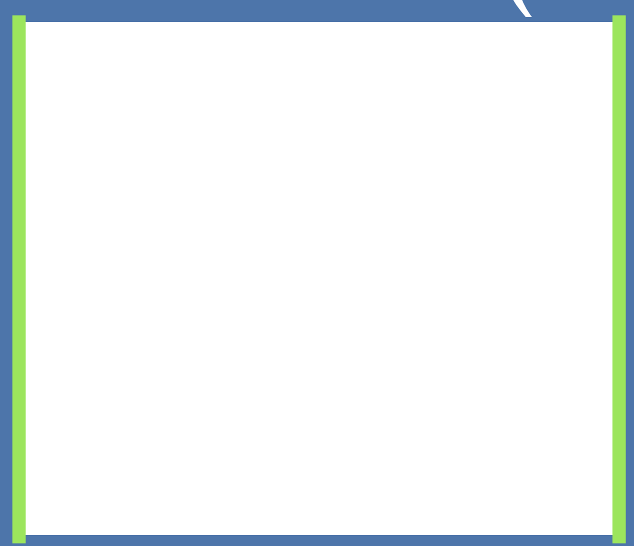
UV (Planck)

IR (TeV)



← SM?

$$\frac{\bar{\psi}\psi\bar{\psi}\psi}{\Lambda^2}$$ ← FCNC, $\cancel{CP}$

Λ ← TeV

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  - Bad

Where to put the SM?

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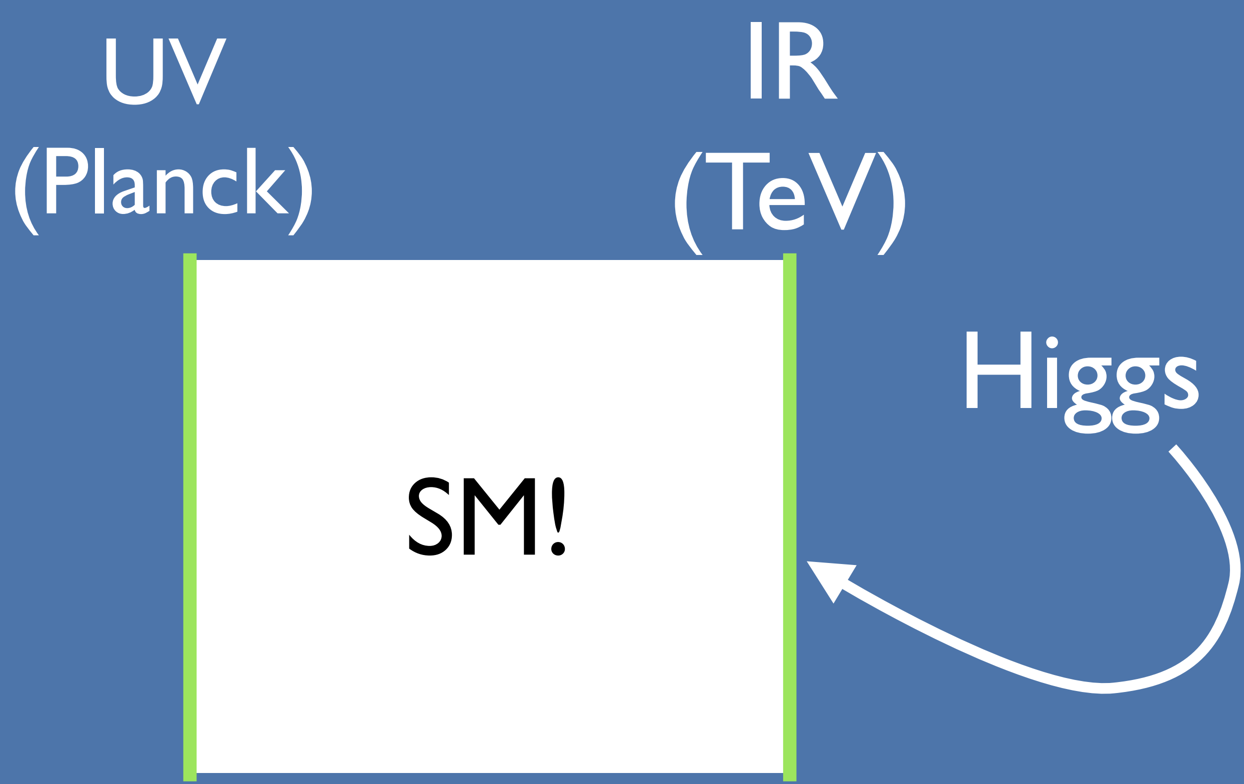
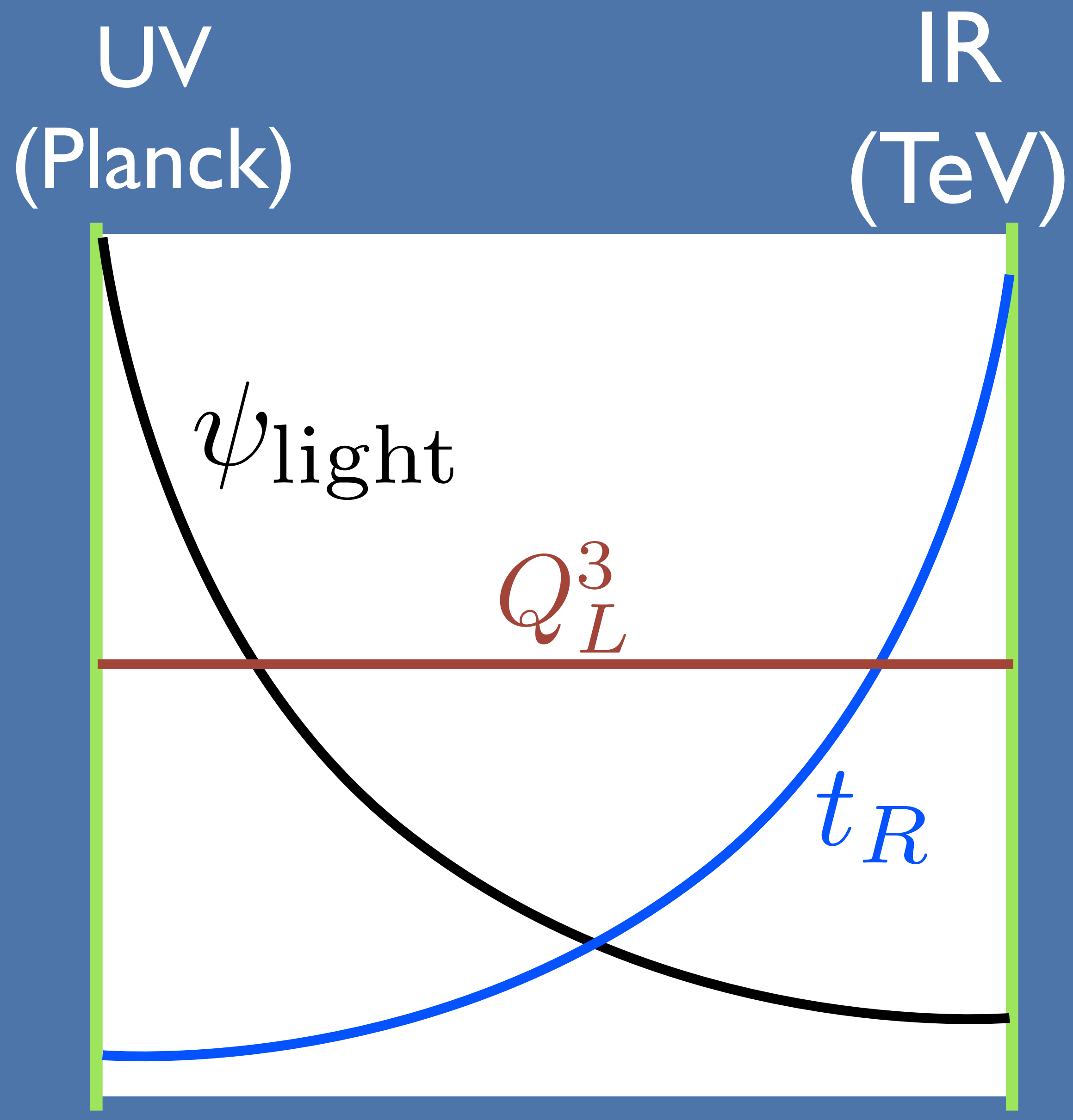


$$\frac{\bar{\psi}\psi\bar{\psi}\psi}{\Lambda^2} \longleftarrow \text{FCNC, } \cancel{CP}$$

Plank

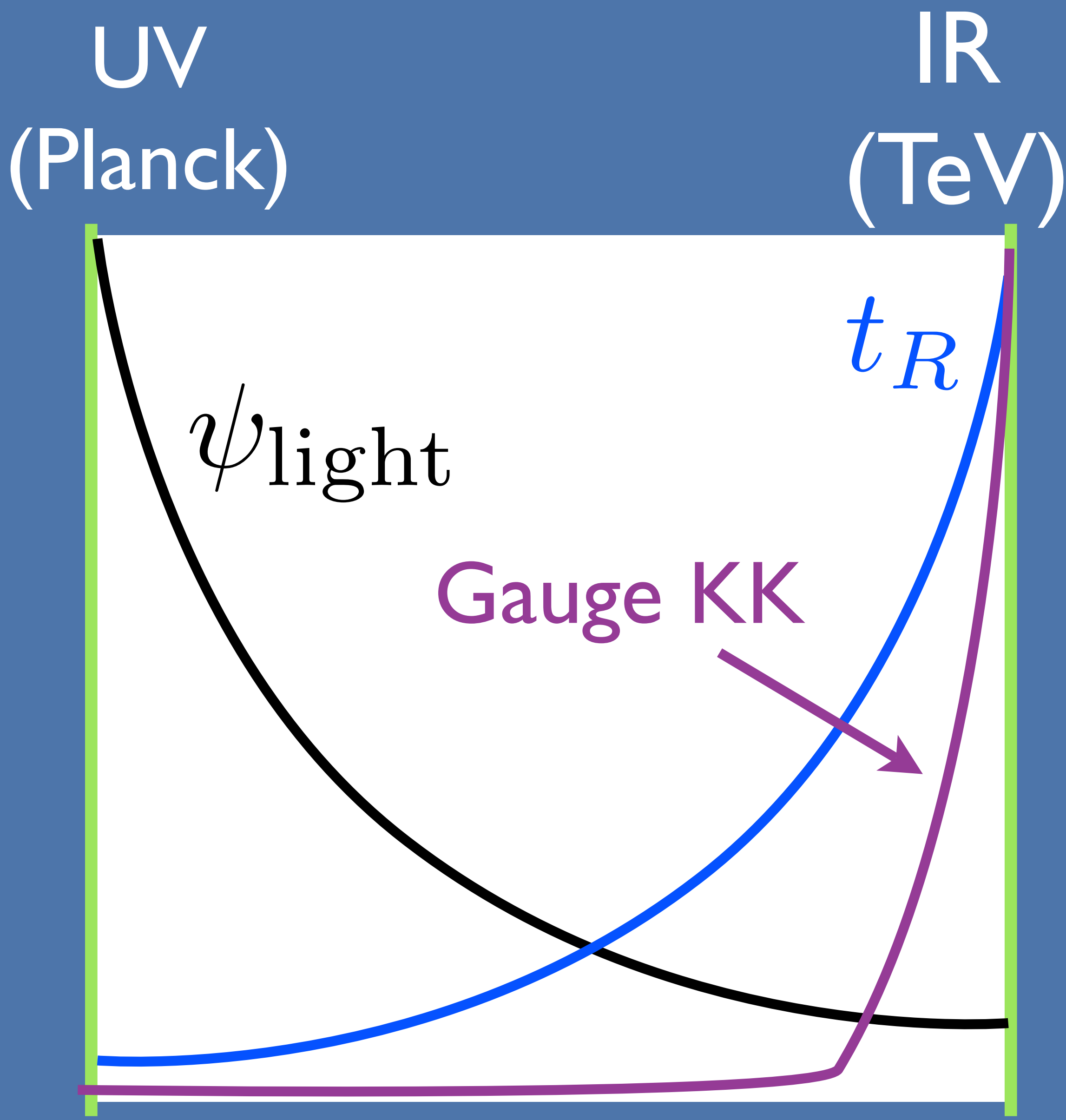
- Could localize the entire SM to the IR brane
- Cutoff is lowered by the same geometry to ~ 10 TeV
  - Bad
- SM (except Higgs vev) in bulk solves this problem

The good...



- Generates fermion mass hierarchy
  - Overlap on IR brane is exponentially supressed
- Model variations can change arrangement of chiralities
  - Always strong IR localization for one top chirality

...the bad...



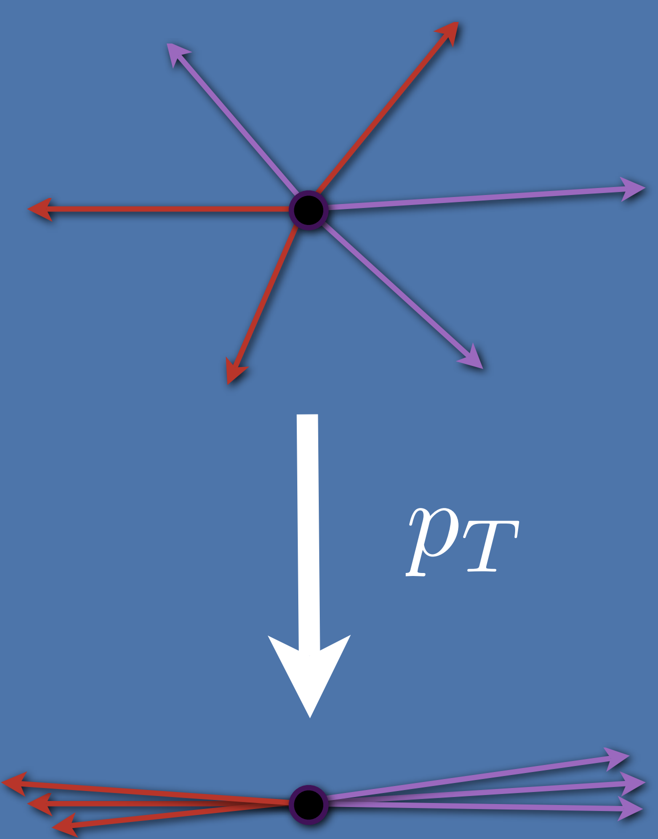
- Strong coupling to top (and maybe bottom)
- Weak(er) coupling to light fermions

$$g_{ttA} \simeq 4 g_{\text{SM}}$$
$$g_{ffA} \simeq -\frac{1}{5} g_{\text{SM}}$$

- **ALL** gauge KKs decay primarily into $t\bar{t}$

… the ugly

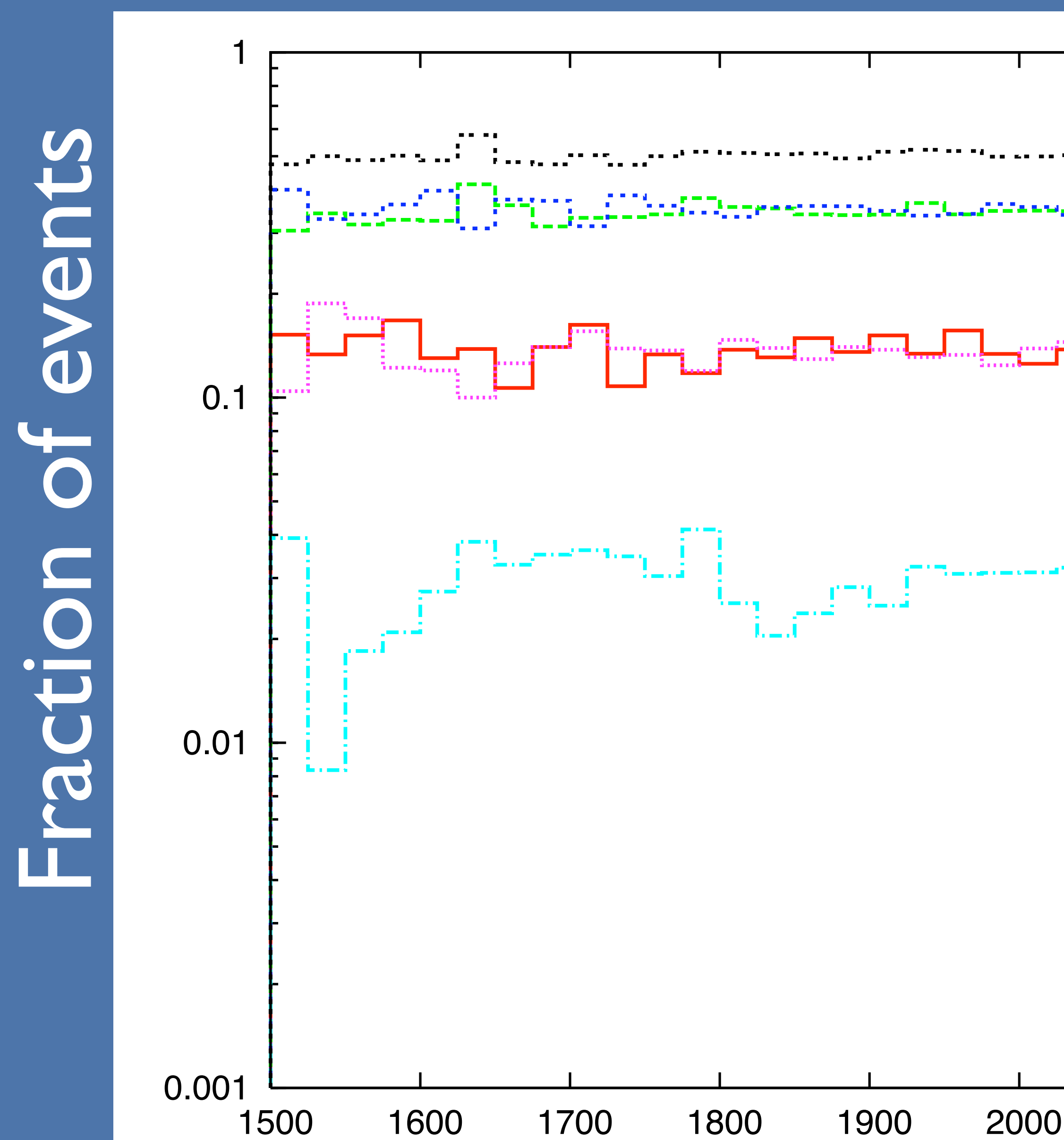
- Resonance masses are generally > 2-3 TeV
- Produce highly collimated "top-jets"
  - Traditional top searches will fail

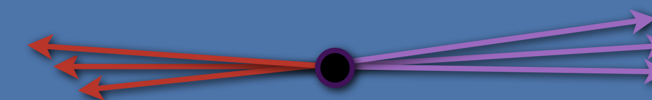


6 degrees of collimation

Lillie, Randall, Wang, hep-ph/0701166

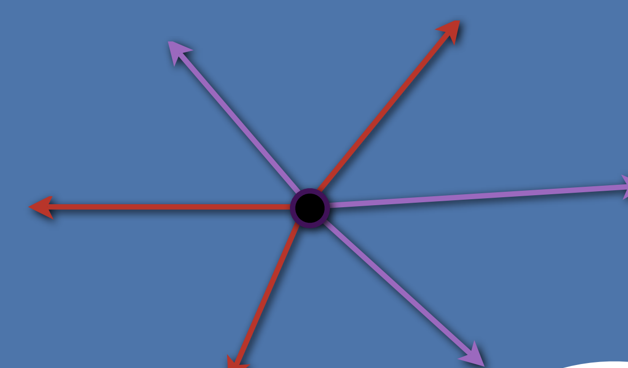
2 TeV resonance





1 top completely collimated: 50%

Both fully separated: 5%

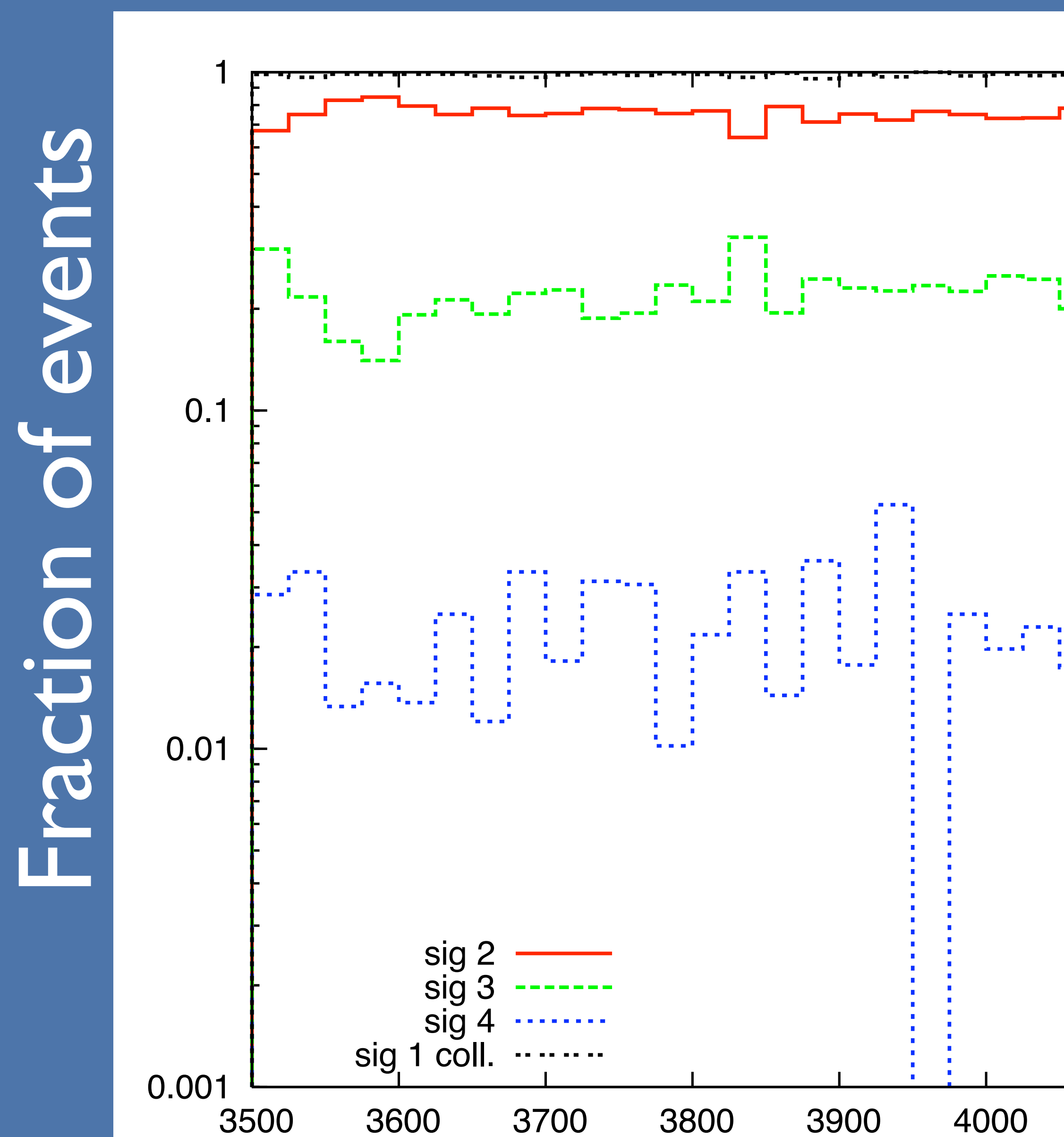


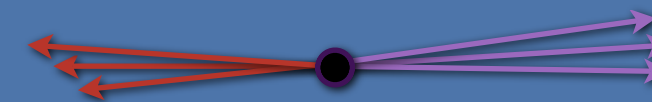
"Separated": $\Delta R > 0.4$

6 degrees of collimation

Lillie, Randall, Wang, hep-ph/0701166

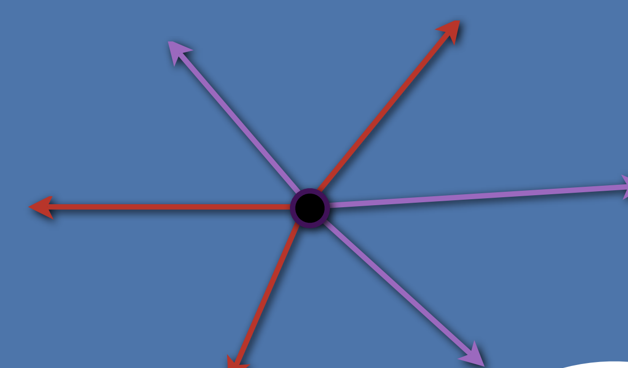
4 TeV resonance





1 top completely collimated: ~99%

Both fully separated: ~0%



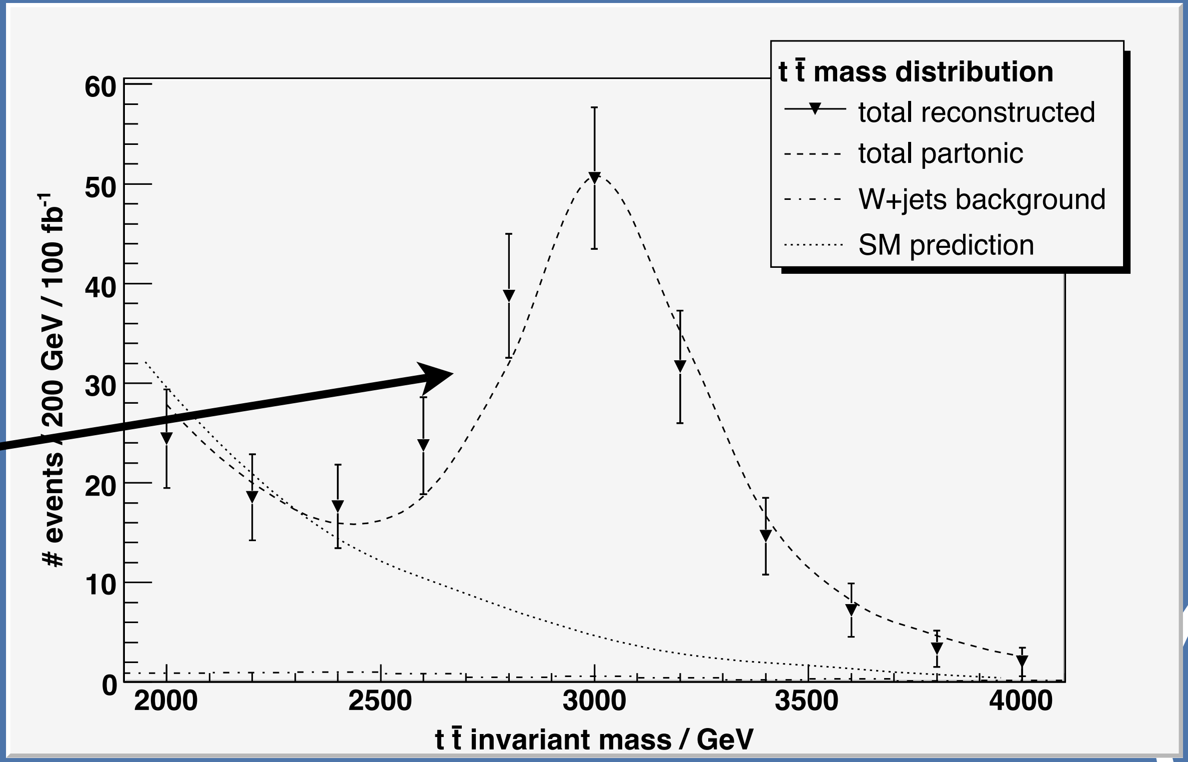
"Separated": $\Delta R > 0.4$

Finding energetic tops

Agashe, Belyaev, Krupovnickas, Perez, Virzi hep-ph/0612015

- Tag events with lepton + missing
  - modified lepton isolation criterion: lepton can be inside b-jet if $m_{\ell b} > 40\ \mathrm{GeV}$

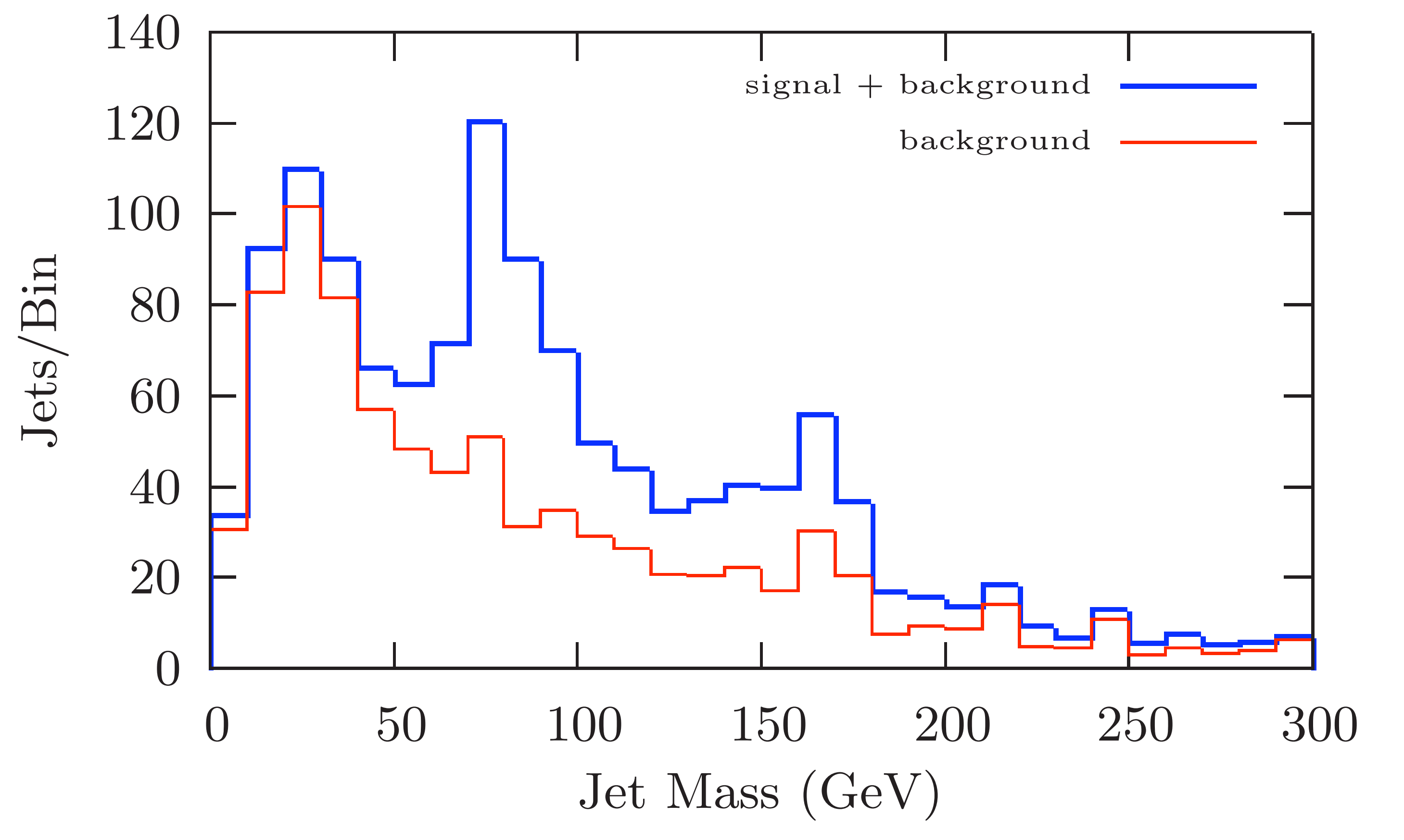
Gluon KK resonance



Finding energetic tops

Skiba, Tucker-Smith, hep-ph/0701247

- Search for b'
- Focus on jet mass as discriminant
  - How robust is the jet mass?

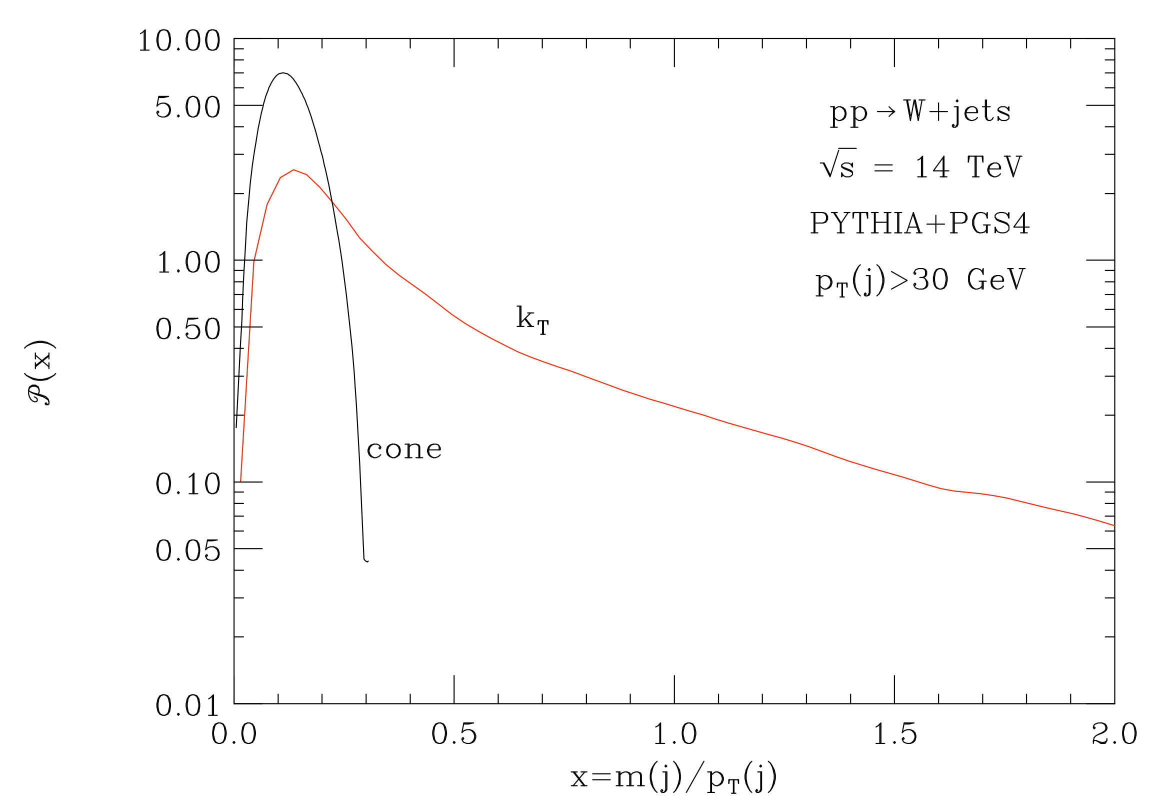


k_T algorithm $D = 0.5$

Finding energetic tops

Baur, Orr, arxiv:0707.2066

- Found strong jet algorithm dependence
  - k_T algorithm slurps up a lot of the underlying event
    - Can be fixed by underlying event subtraction?



$$R = D = 0.5$$

cone k_T

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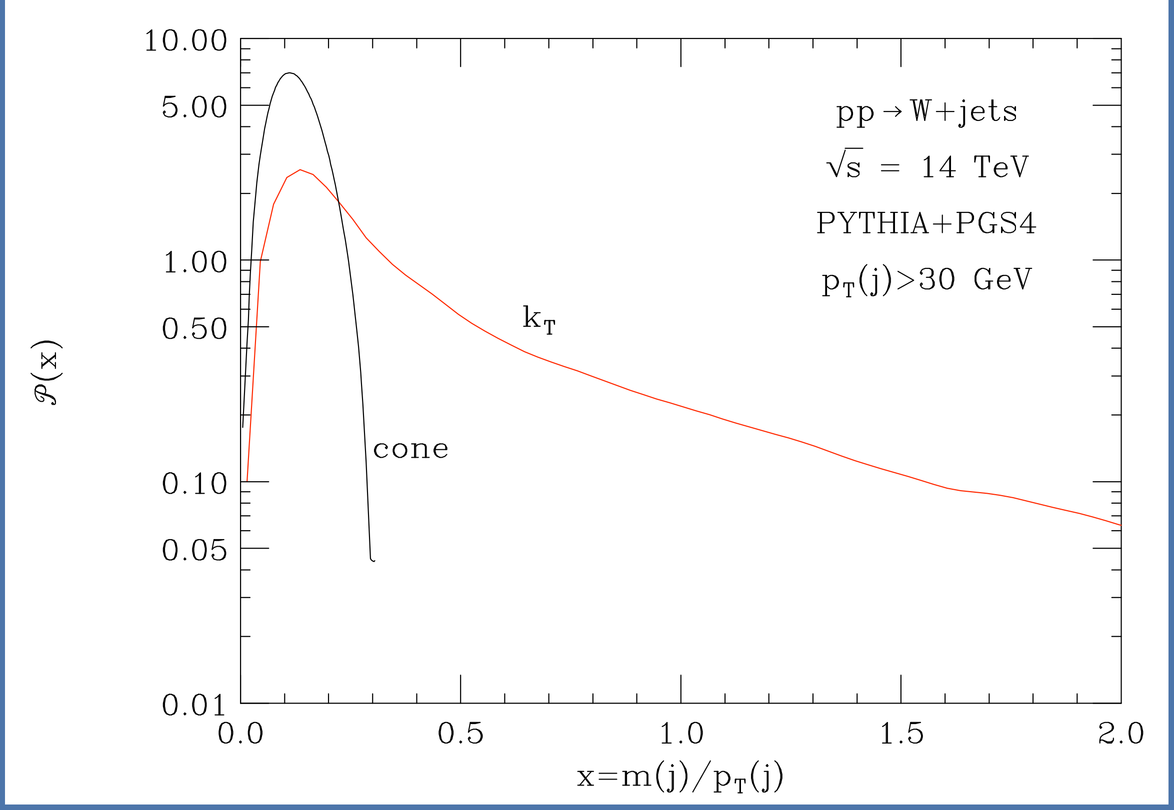


$$R = D = 0.5$$

cone k_T

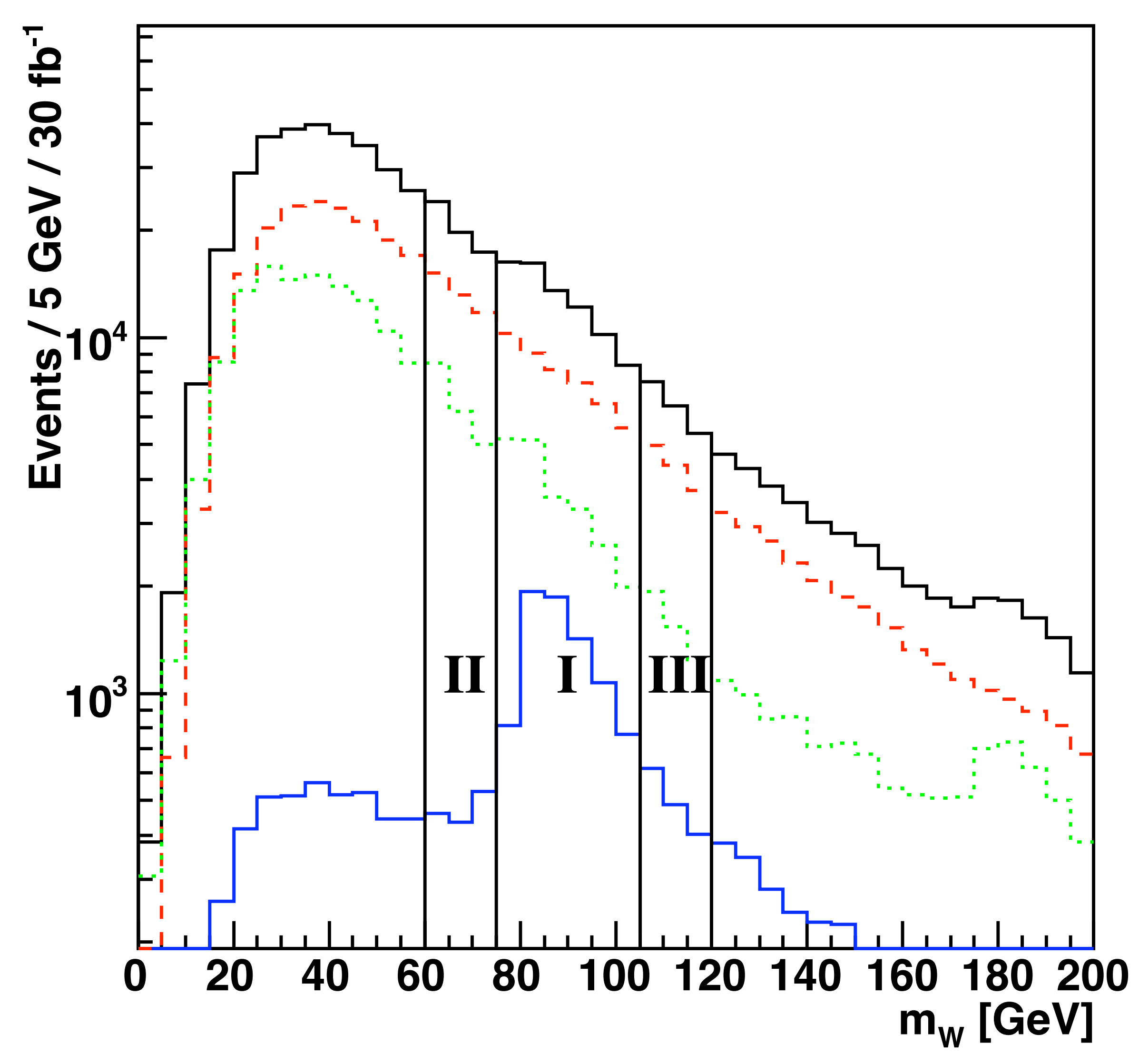
Fundamental QCD limit?

$$\langle m(j)\rangle \propto \sqrt{\alpha_s} p_T(j)$$

Finding energetic other-than-tops

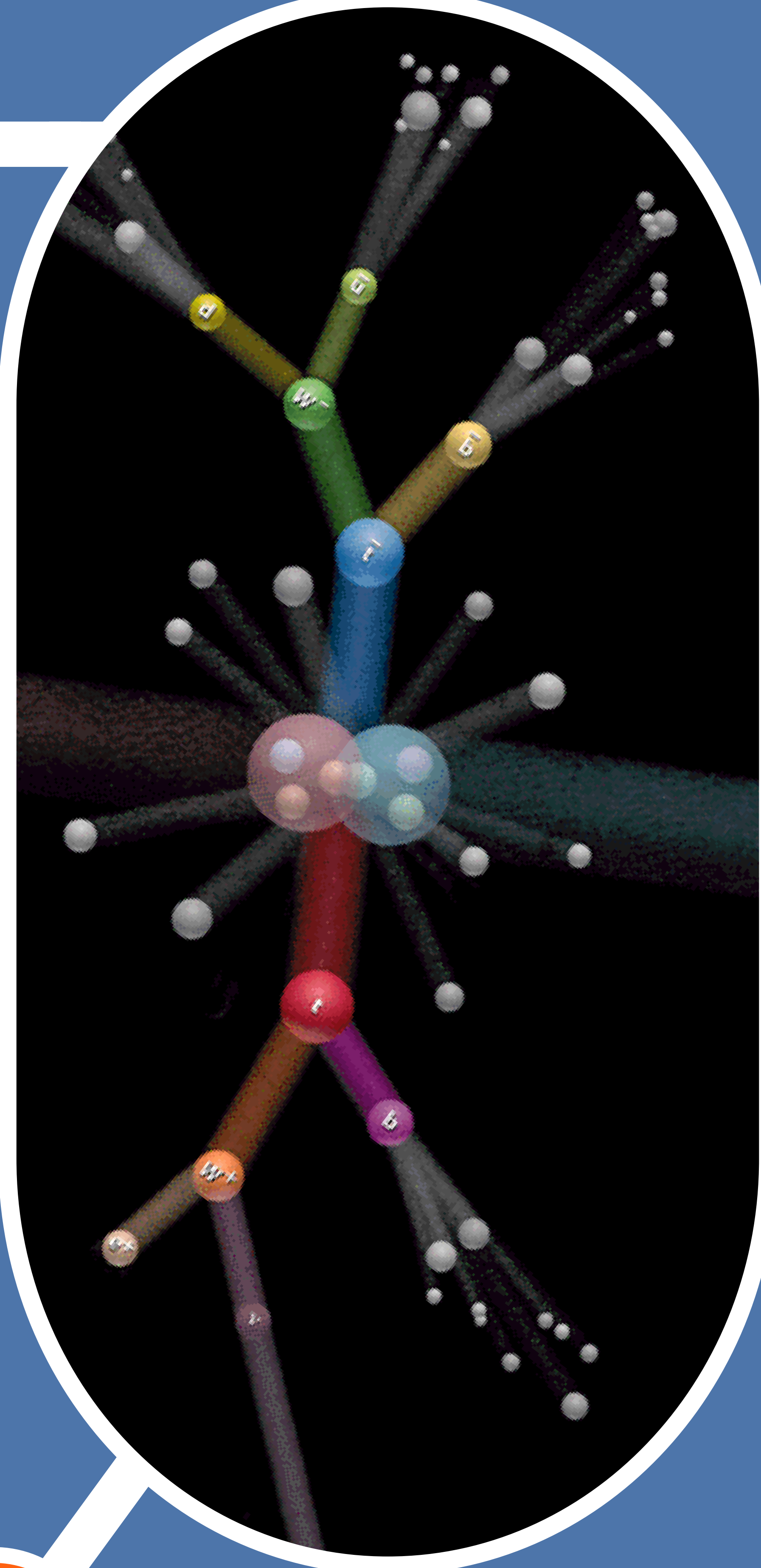
Butterworth, Ellis, Raklev, hep-ph/0702150

- Use jet-mass to identify gauge and higgs bosons in SUSY events
  - Would also be useful in, e.g., longitudinal W-scattering



Lesson 3

- High energy top channels are crucial
- A robust algorithm for tagging "top-jets" is needed
- Many unresolved issues
  - b-tagging efficiency?
  - Reliability of jet mass?
  - All-hadronic channels?
- Full study needed



Conclusions

- Extra dimensions point to important and difficult channels and analyses
  - It's possible we *can* measure spins in long decay chains at the LHC
  - It's certain that we should try
  - Still unique challenges in high mass resonance production
- They also might just turn out to exist....