Beyond the SM theory: Probing TeV New Physics

DPF 2009

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Outline

- Brief Introduction
- TeV new physics and Electroweak symmetry breaking.
- TeV new physics and Cold Dark Matter.
- Other TeV new physics with unique signals
- Conclusion.

Exciting era: many experimental probe of TeV New Physics.

- High energy colliders, direct probes of the energy frontier.
    - Tevatron, Large Hadron Collider.
- Weakscale dark matter searches.
    - Direct and Indirect Searches.
- Precision frontier.
    - Flavor, CP...

Many possible NP have been proposed

H. Murayama

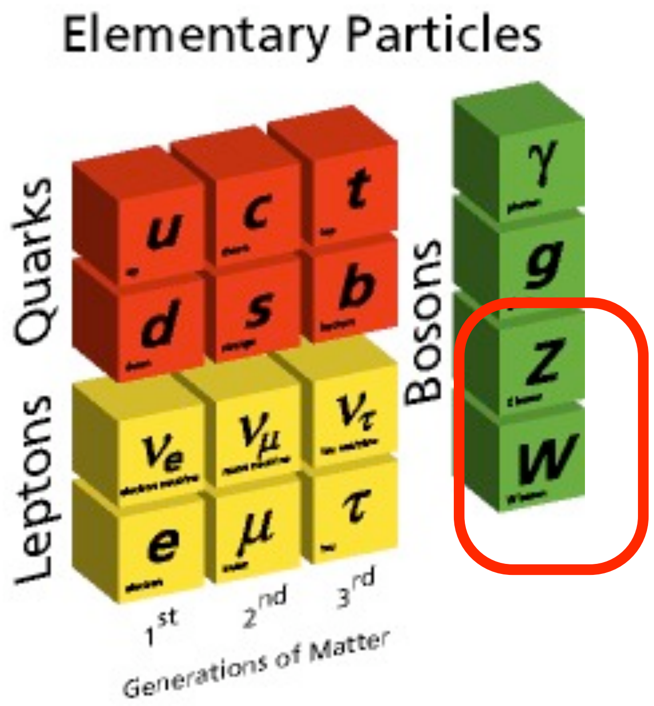
- Last 30+ years, many directions, variations, combinations.
- Impossible to have a comprehensive overview here.

My talk:

- I will only scratch the surface by
  - giving very broad brushed perspective of classes of ideas, and scenarios.
  - listing generic signals, highlight distinct features.
  - providing leads and clues for further study.
- Major omissions:
  - Low energy searches: flavor, CP. (Talks by Browder, Grinstein, Hitlin, Roberts, ...)
  - Direct and Indirect detection of Dark Matter. (Talks by: Golwala, Pierce, ...)

Electroweak symmetry breaking.

- Weak interaction mediated by spin-one massive gauge boson



$$m_{W,Z} \simeq 10^2 \ \mathrm{GeV}$$

- Unitarity of quantum theory requires new physics must be set in at

$$\Lambda < \frac{4\pi m_{W,Z}}{g_{\mathrm{w}}} \simeq \ \mathrm{TeV}$$

The simplest new physics:

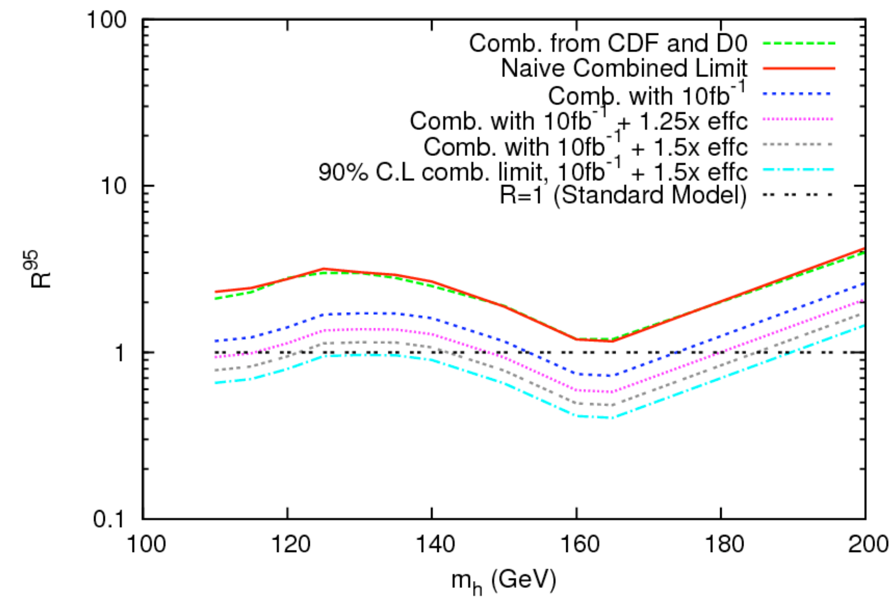
- A spin-0 scalar with weak scale mass.
  - *The Higgs boson.*
- Higgs search. (Talk by M. Kruse)
- However, extended Higgs sector can significantly change Higgs decay.

e.g.

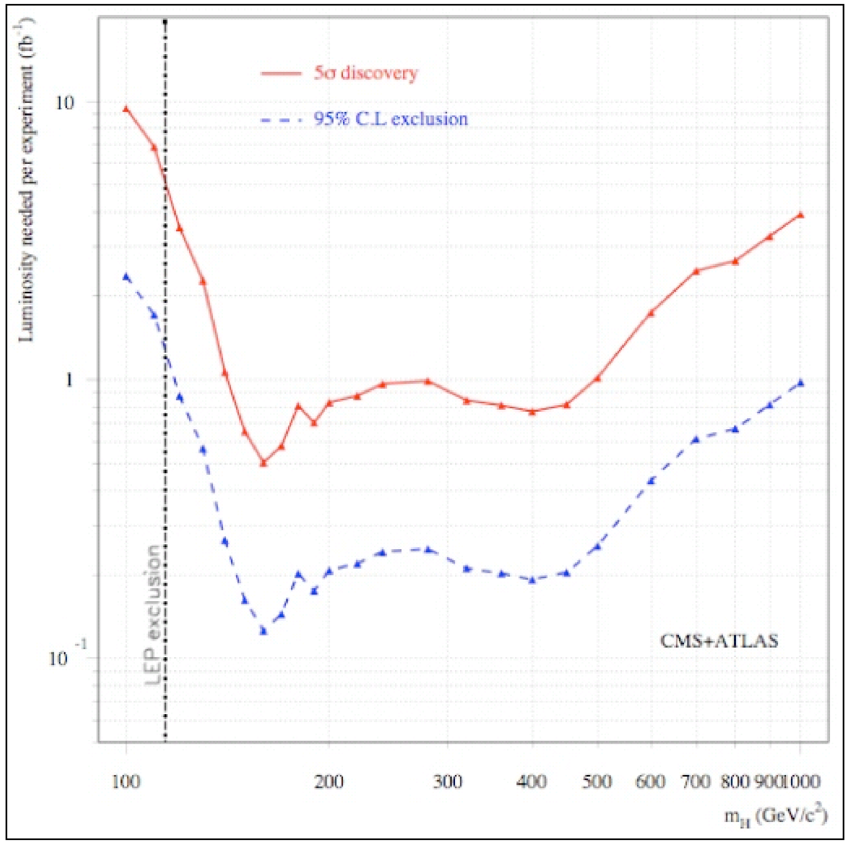
$$h \rightarrow aa$$

$$a \rightarrow b\bar{b},\ \tau\bar{\tau},\ \gamma\gamma,\ gg,\ \mu^+\mu^-$$

Dermisek and Gunion hep-ph/0502105
Chang, Fox and Weiner hep-ph/0511250
Graham, Pierce and Wacker hep-ph/0605162
Review: Chang, Dermisek, Gunion, and Weiner, arXiv:0801.4554
Abazov et al. [D0 Collaboration], arXiv:0905.3381.
Bellazzini, Csaki, Falkowski and Weiler, arXiv:0906.3026



Tevatron: Draper et. al. 2009



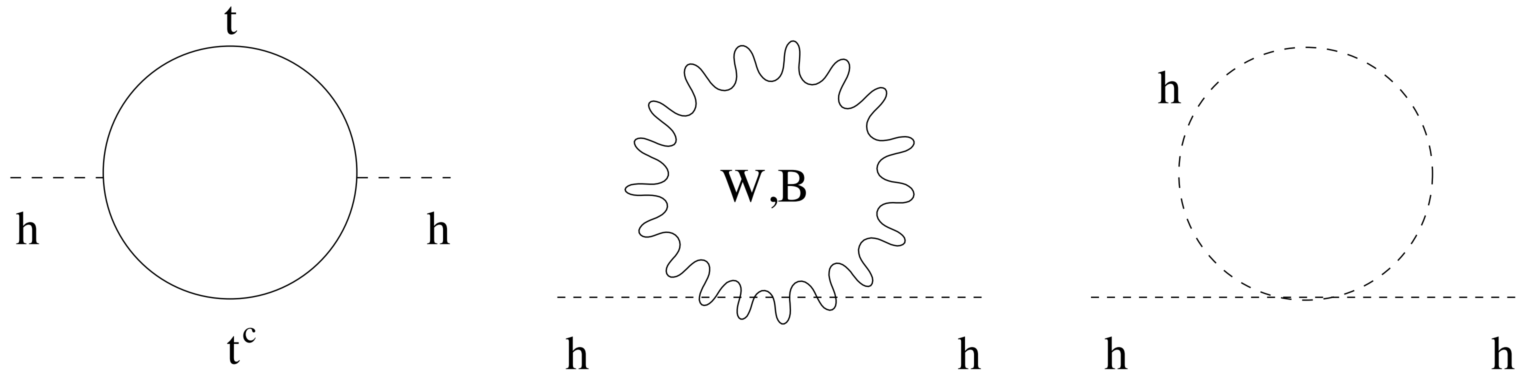
LHC: Blaising, et al, 2006

Hierarchy problem.

- Naturalness. Electroweak scale very different from Planck scale.

$$m_{W,Z} \simeq 10^2 \text{ GeV}, \quad M_{\text{Planck}} \simeq 10^{19} \text{ GeV}$$

- Technical naturalness.



$$m_{\text{EW}}^2 = m_0^2 + c\Lambda^2, \ \Lambda = \text{ cut-off scale}$$

$$\text{typically: } m_0 \sim \Lambda \gg m_{\text{EW}} \simeq 100 \text{ GeV}$$

$$\text{if: } \Lambda \sim M_{\text{Planck}}, \ 10^{-32} \text{ tuning.}$$

$$\text{Technical naturalness} \rightarrow \Lambda \sim \text{ TeV}$$

TeV new physics!

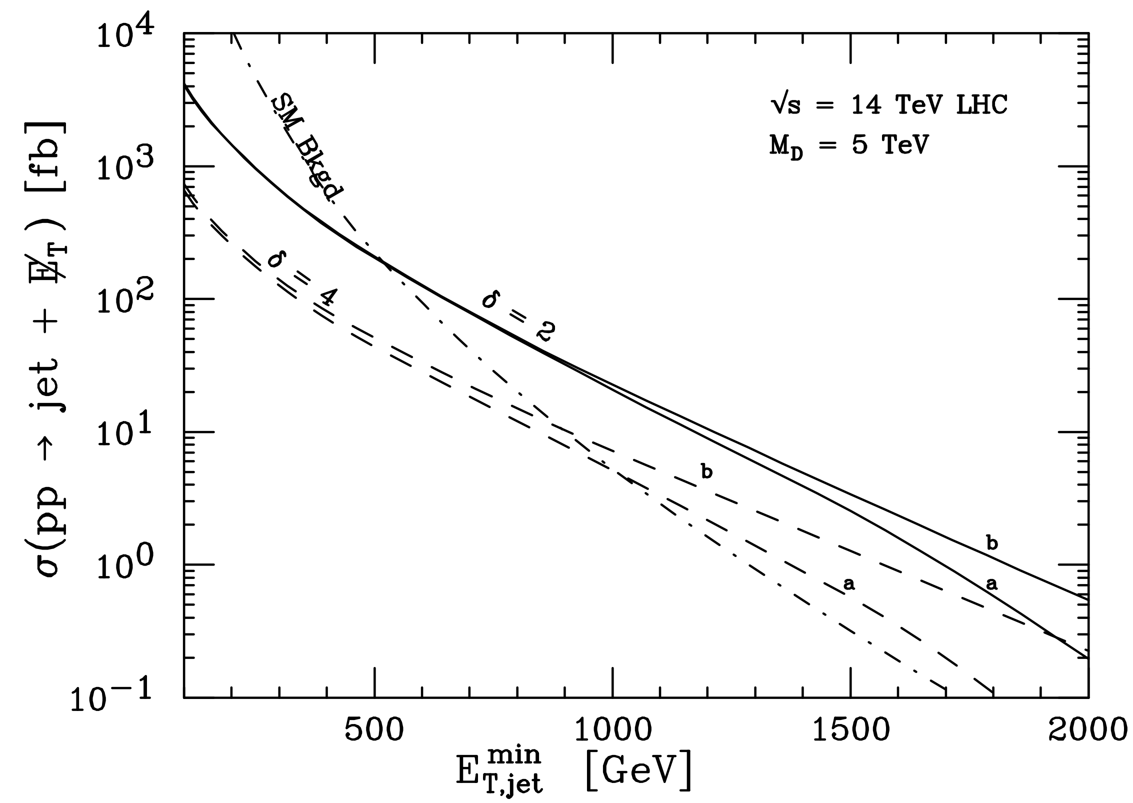
Approach 1: low cut-off

- Quantum gravity scale is low:
  Large extra-dimensions. Arkani-Hamed, Dimopoulos and Dvali, 1998

$$D = 4 + n, \; M^2_{\rm Planck} \simeq M_*^{2+n} R^n, \; M_* \sim \; {\rm TeV}$$
$$n = 2 \rightarrow R \sim 10^{-4}{\rm m}, \; \rightarrow {\rm Large\ extra\ dim.}$$

- A distinct possibility with distinct phenomenology. Giudice, Rattazzi, and Wells, 1998
  Han, Lykken and Zhang, 1998

  - KK-tower of gravitons.
    - Missing energy.
    - Non-resonant modification 2 to 2.....
  - Blackholes!



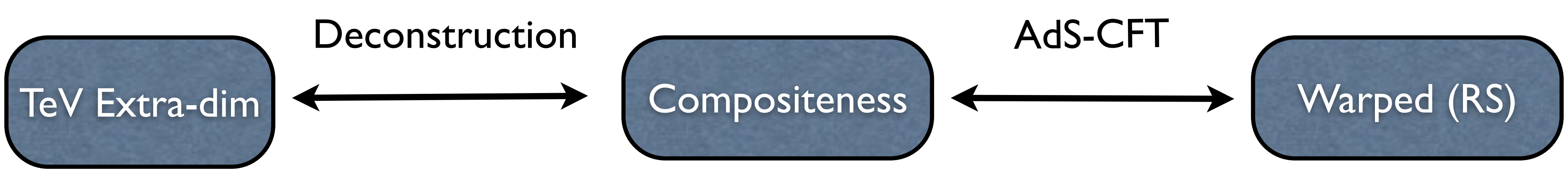
Question now is why quantum gravity scale is low.

Low cut-off: compositeness

- Known to work.
    - QCD. Logarithmic running generates a exponential scale separation.
    - Physics completely different above or below the QCD scale. mesons $\longrightarrow$ quark, gluons.
        - A "cut-off" for low energy physics.
- A "scaled-up" version of QCD can generate electroweak symmetry breaking, and solve naturalness problem. Weinberg1979; Susskind, 1979 Georgi and Kaplan, 1984
- A "conservative" approach. Maybe nature will repeat itself?

Signal of compositeness

- QCD: composite resonances.
- TeV compositeness: TeV composite resonances.
- Equivalences in model space (low energy)



Appelquist, Cheng and Dobrescu, 2000

Weinberg1979; Susskind, 1979
Georgi and Kaplan, 1984

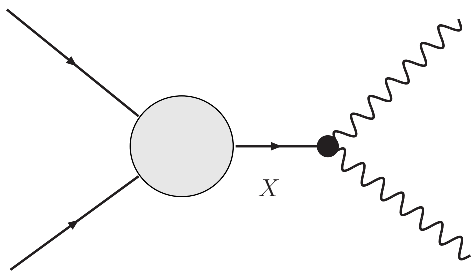
Randall and Sundrum, 1999

$$\begin{aligned} \text{TC/compositeness:} \quad & \pi_T(\sigma_T), \rho_T \ldots \\ \text{extra-dim.:} \quad & A_5, W_{\rm KK}, Z_{\rm KK} \ldots \\ \text{Mooses (Little Higgs, Higgsless):} \quad & h, W', Z' \ldots \end{aligned}$$

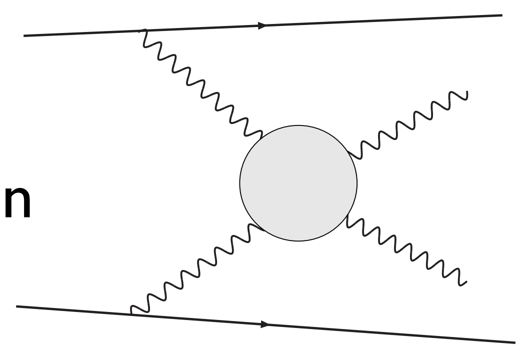
Signals of compositeness

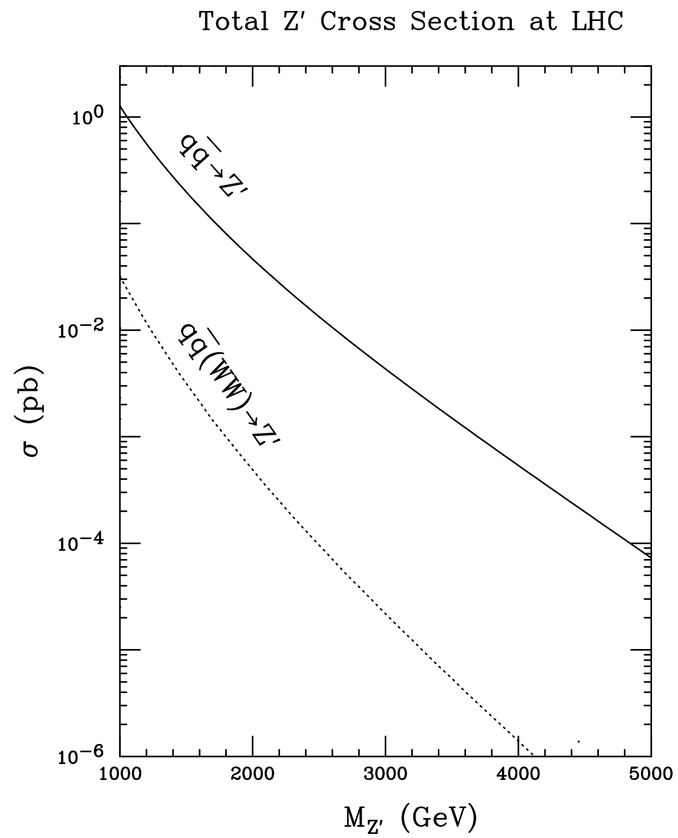
- Composite resonances couples strongly to other composite modes, in particular Z_L and W_L

2 to 1 resonance

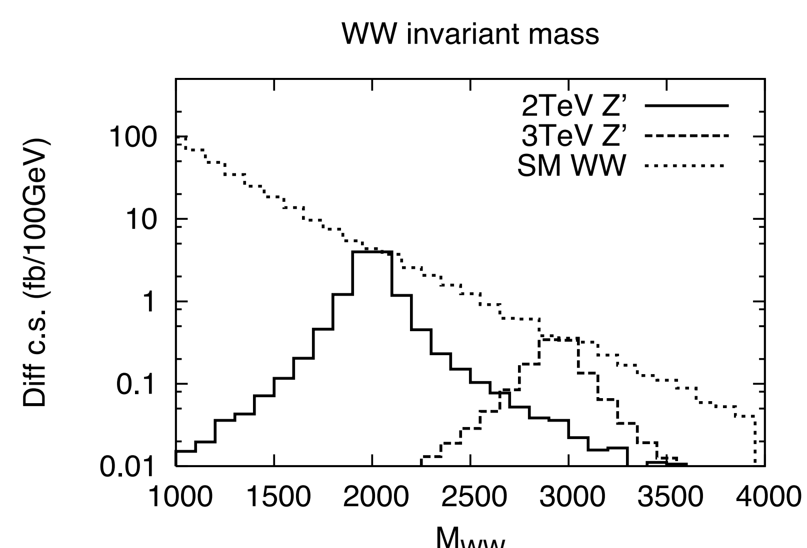


Weak Boson Fusion





Significant BR to WW, ZZ...



Agashe et. al., arXiv:0709.0007

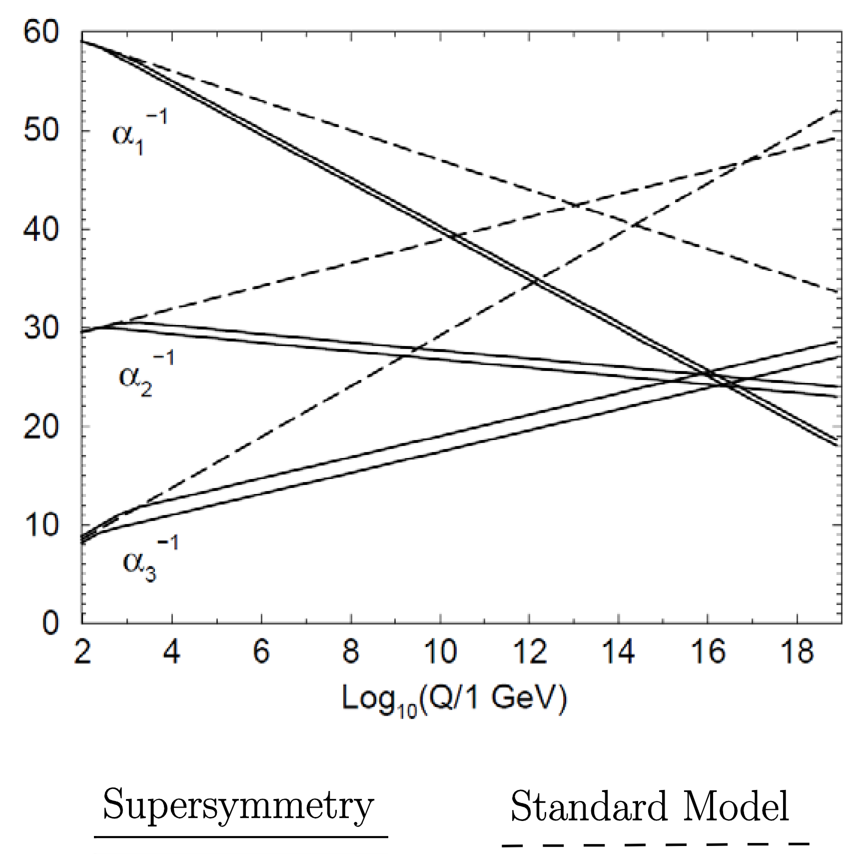
Approach II: divergence cancelation

- Supersymmetry. boson ⟷ fermion
  - Quadratic divergences cancel to all orders in perturbation theory.

- A theorist's dream theory.

Supersymmetry predicts the *unification* of gauge interactions.

Very compelling internal beauty and consistency.



"Little" Hierarchy Problem:

- Tension between the sizes of precisely measured higher dim. operators and the size of radiative correction to EW scale.

  after LEP, B-factories, EDM...

$$\text{Naturalness of the weak scale} \;:\; \Lambda_{\rm NP}^2 \sim 16\pi^2 \Lambda_{\rm EW}^2$$

$$\frac{\mathcal{O}^{(5)}}{\Lambda_{\rm NP}}, \; \frac{\mathcal{O}^{(6)}}{\Lambda_{\rm NP}^2} \to \text{EWPT, flavor, EDM...} \;:\; \Lambda_{\rm NP}^2 \sim (16\pi^2)^2 \Lambda_{\rm EW}^2$$

- A O(1%) tuning. Inspiration of many many model building efforts.

- More symmetries:

  - e.g., SUSY: AMSB, GMSB, ...

Raising the cut-off in composite models

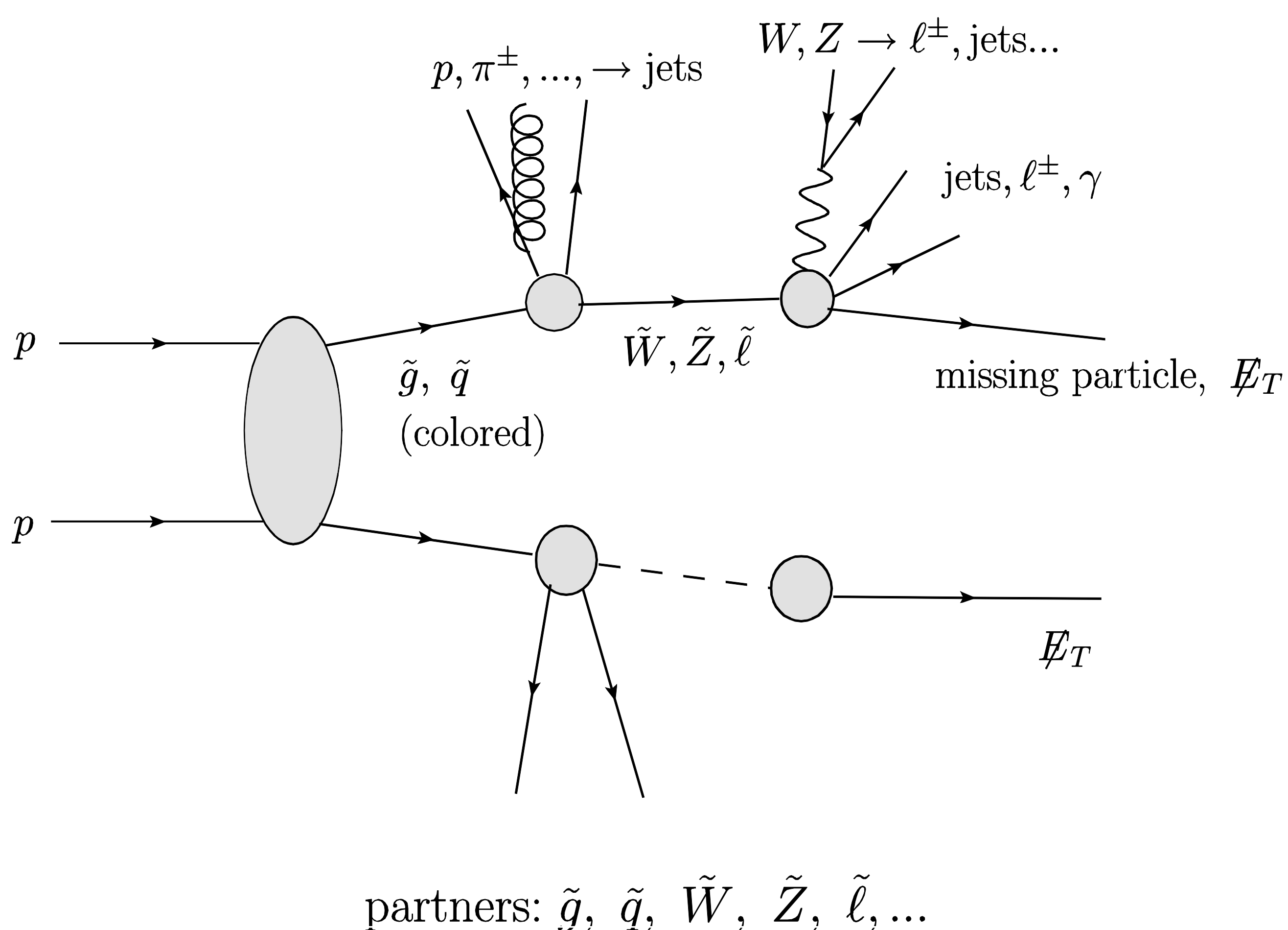
- Partial cancelation (at one-loop) of divergences.
  - Introducing partners: $W', \; Z', \; T', \; \ldots$
  - Little Higgs   twin Higgs   ...

    Arkani-Hamed et. al. 2001   Chacko et. al. 2005
- Introducing discrete symmetry to suppress corrections to precision variables by one loop.
  - KK-parity,   Appelquist, Cheng and Dobrescu, hep-ph/0012100
  - T-parity ....   Cheng and Low, 2003
  - Stable (LKP, LTP, ...). $\rightarrow \not{E}_T$

Signal of "partners": SUSY, LH...

- Could be early discovery, hard to completely understand.

Arkani-Hamed, Kane, Thaler and LTW, hep-ph/0512190

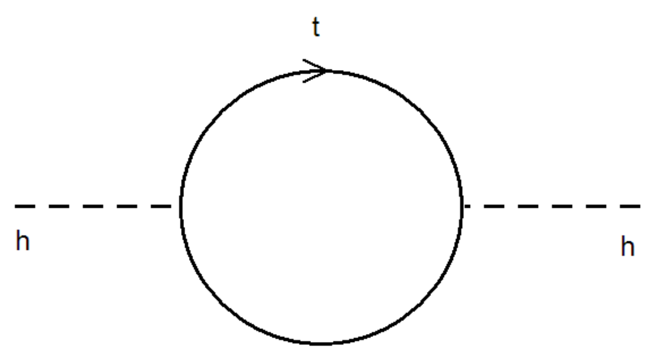


$$\#\ \text{jets}\ + \#\ \text{leptons} + \not{E}_T$$

Another angle: “best” motivated search channels

Example: connection with top sector

- Naturalness. Top quark has large coupling to Higgs, responsible for the largest contribution to EWSB.



$$\delta m_h^2 = -\frac{3}{8\pi^2} y_t^2 \Lambda^2$$

- Need top partners: $\tilde{t}$, or T', or ...
- Signal: top-partner production.
  - Combining with a stable particle:

$$p\ p(\bar{p}) \to T'\bar{T}' \to t\bar{t} + \not{E}_T$$

Challenging since SM $t\bar{t}$ can also have large $\not{E}_T$

Meade and Reece hep-ph/0601142
Belyaev, Chen, Tobe and Yuan, hep-ph/0609179
Carena, Hubisz, Perelstein, and Verdier. hep-ph/0610156
Matsumoto, Nojiri and Nomura, hep-ph/0612249
Han, Mahbubani, Walker and LTW, arXiv:0803.3820

Connection with top sector.

- Top quark is much heavier.

$$m_t \gg m_b,\ m_c,\ m_s,\ \ldots$$

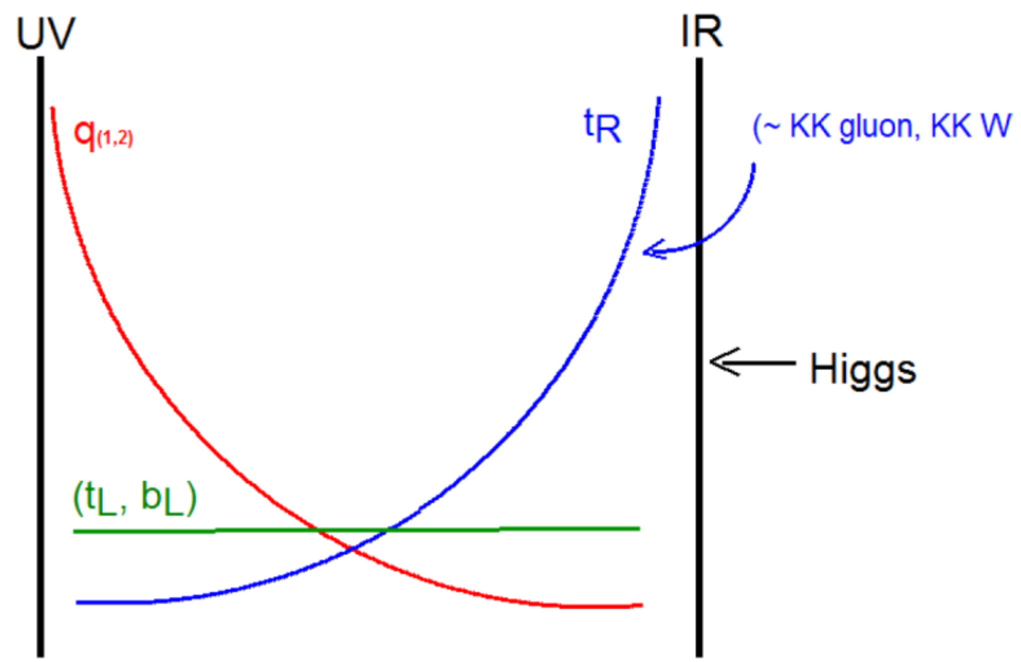
Something unique (only "known" to top quark)?

- Example:
  - Top is composite (new strong interaction).
  - New strong interaction has other resonances.
  - Composite resonance decays into top quarks with large branching ratio.

A model in RS.

- Randall-Sundrum matter in the bulk.

Agahse, Delgado, May, and Sundrum, hep-ph/0308036

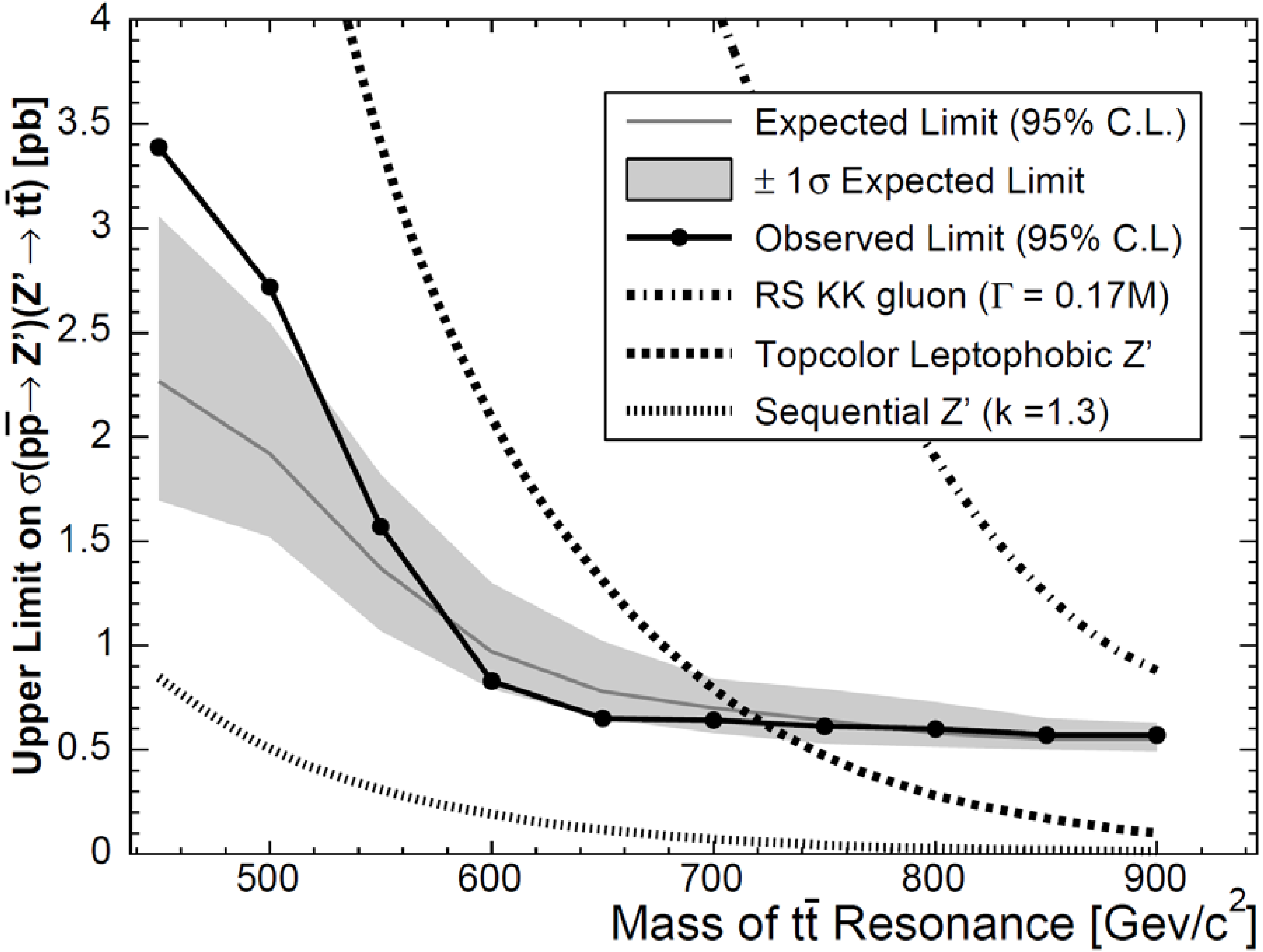


top is composite $\longrightarrow$ top is heavy

Other composite states (KK gluon, KK W) dominantly decay into $t\bar{t}$.

Bump searching.

A bound from CDF.



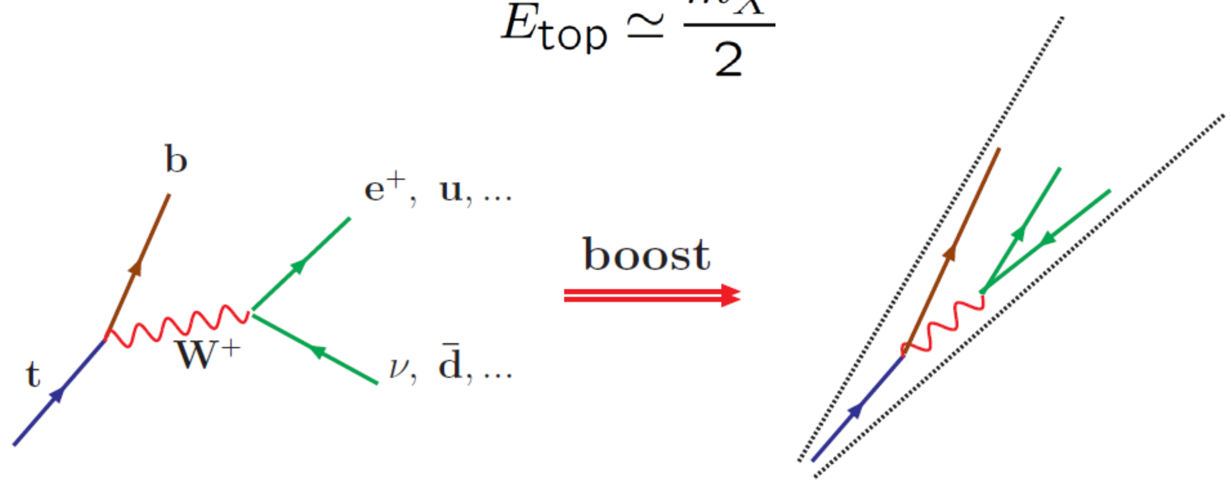
Aaltonen, et. al., [CDF collaboration], arXiv:0710.5335

Challenge of identifying boosted tops

- Composite resonance is likely to be heavy ~ 2-3 TeV.

$$p\ p(\bar{p}) \longrightarrow X \longrightarrow t\bar{t}$$

$$E_{\text{top}} \simeq \frac{m_X}{2}$$

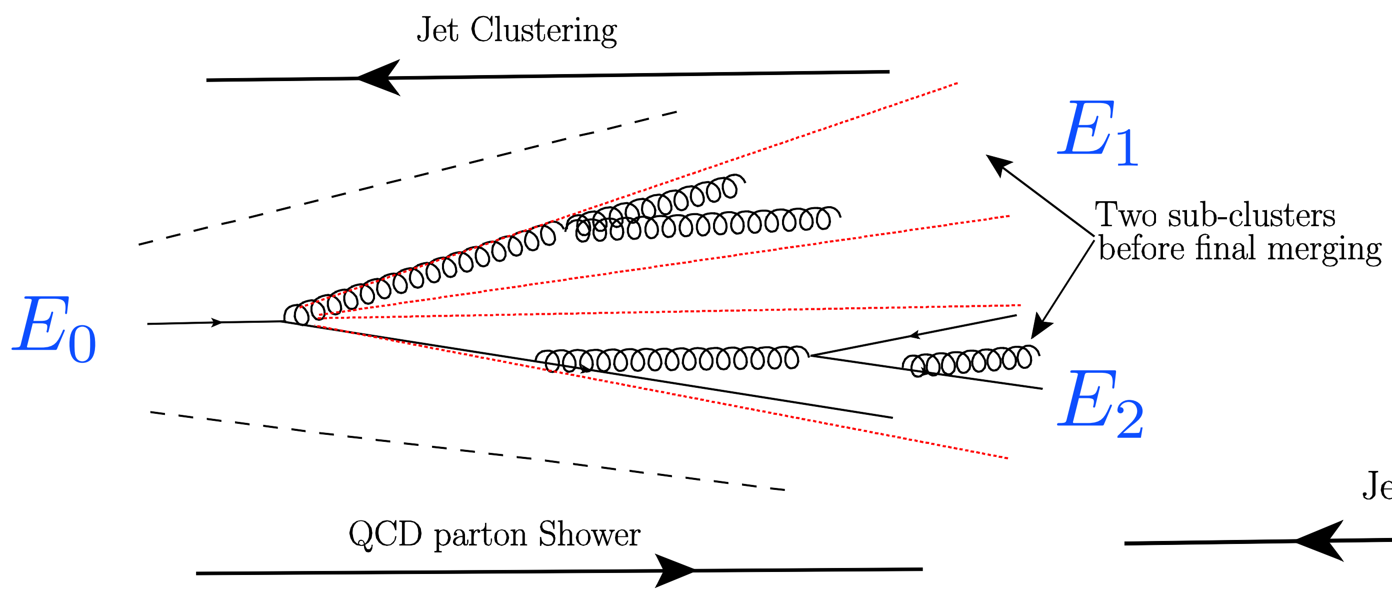


- Obvious strategy, looking for substructures.

G. Brooijmans, et. al., arXiv:0802.3715
J. Thaler and LW, arXiv:0806.0023
L. Almeida, S. Lee, G. Perez, G. Sterman, I.Sung, J. Virzi. arXiv:0807.0234
L. lmeida, S. Lee, G. Perez, I. Sung and J. Virzi, arXiv:0810.0934
D. Kaplan, K. Rehermann, M. Schwartz, and B. Tweedie, arXiv:08060848
P. Maksimovic and Rappoccio, CMS AN-2008/069

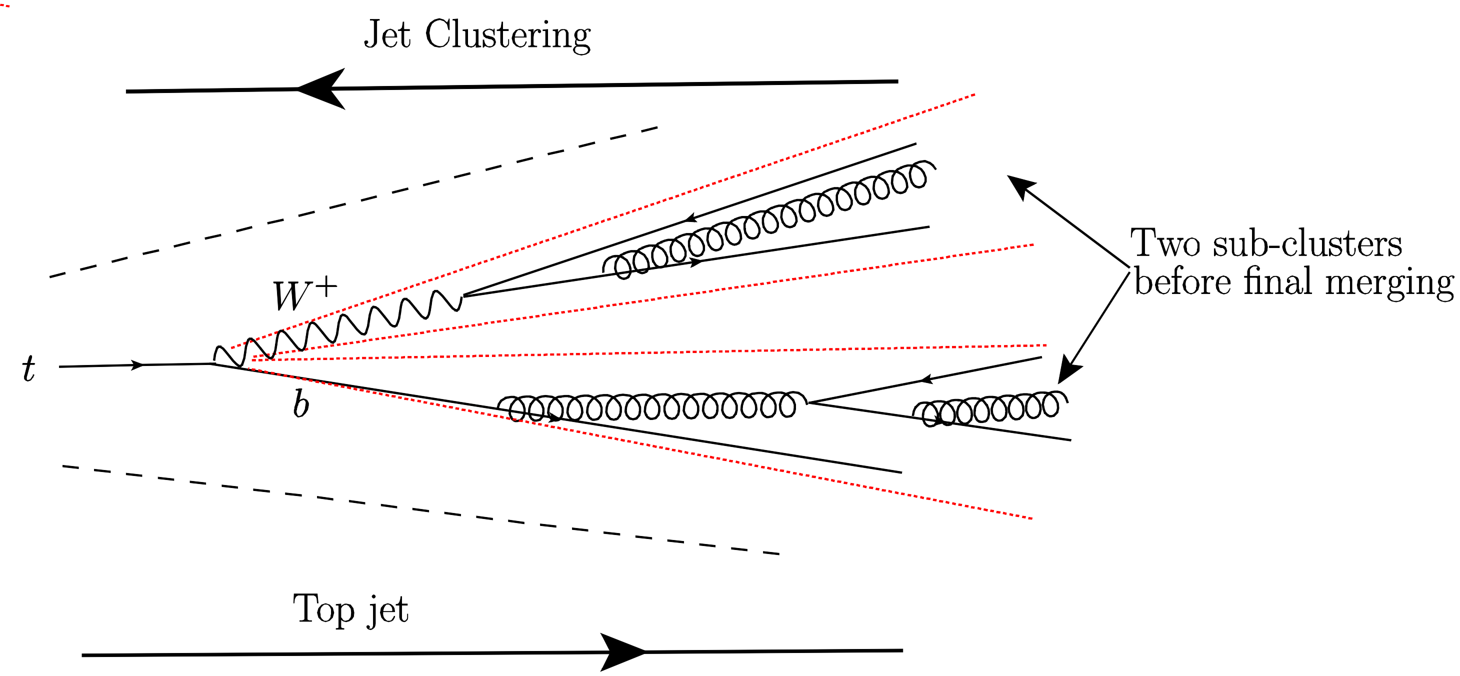
"Following" the jet formation:

- "Inverse" of the jet clustering history.

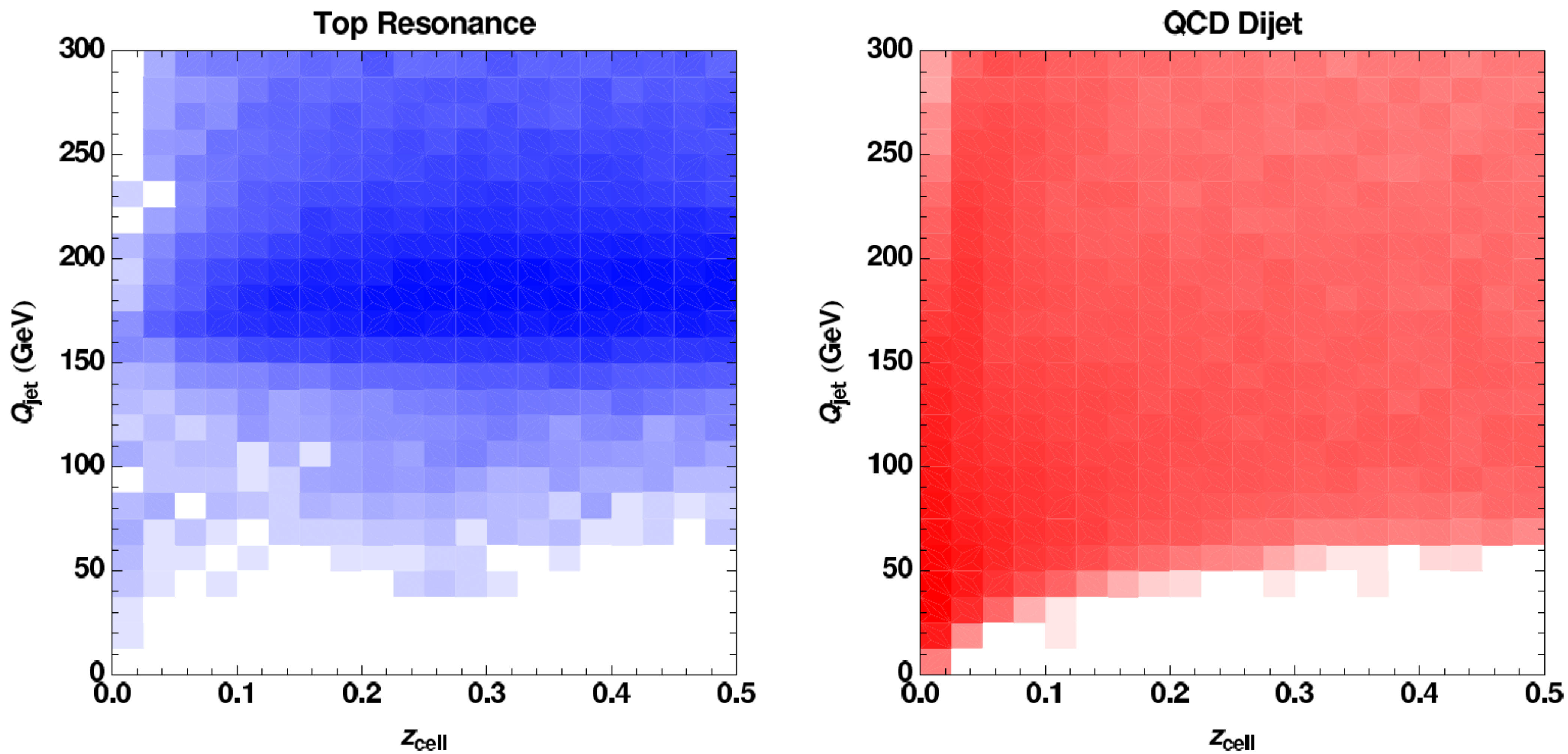


$$z = \frac{\min(E_1, E_2)}{E_0}$$

$$Q : \text{ jet mass}$$



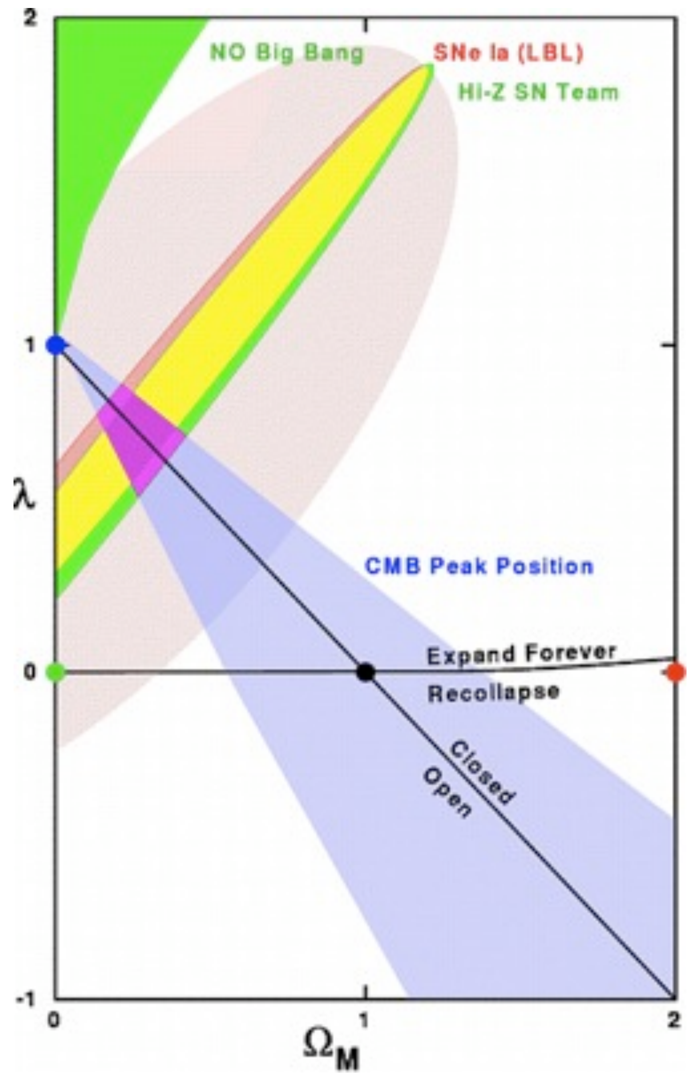
Use of jet mass and z.

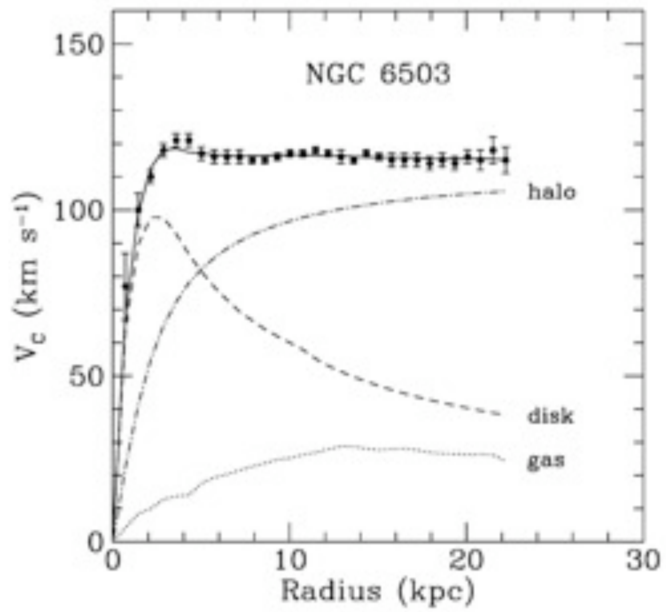


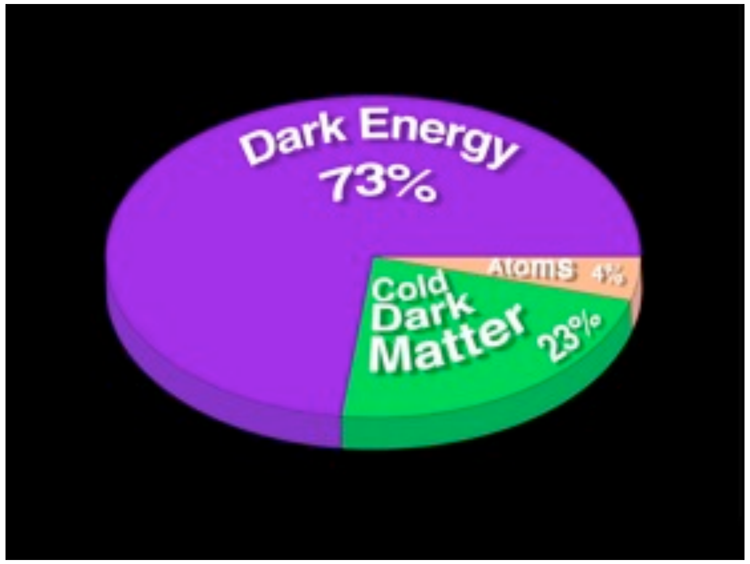
Thaler and LTW, arXiv:0806.0023

Cold Dark Matter in the Universe

- They exist, they gravitate, and they are dark.







Many many models. Talk by Pierce.

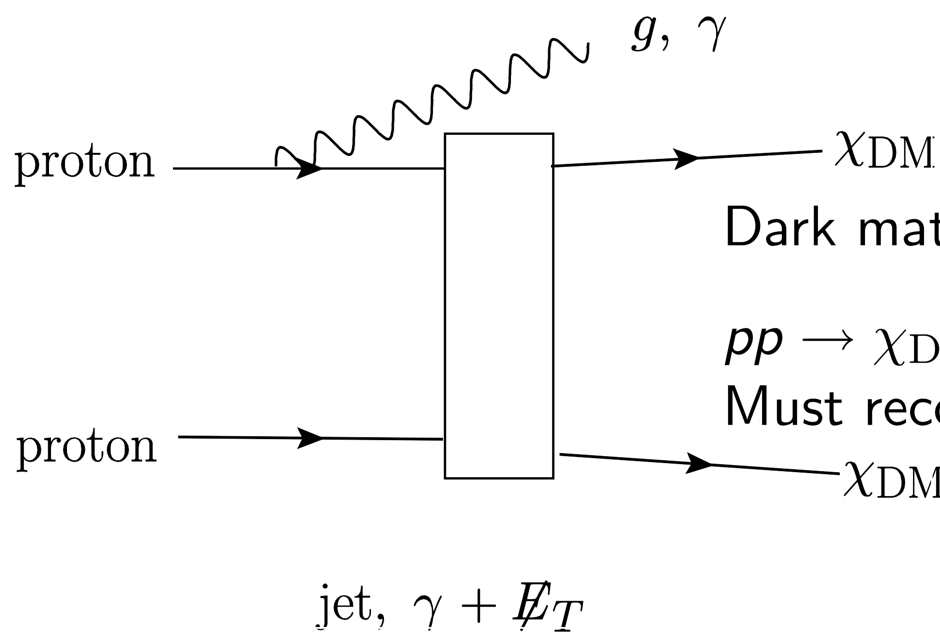
- Neutral. Related to weak scale.
  - Partners of the Standard Model neutral particles.
    - Supersymmetry: neutralino, well established.

      H. Goldberg, 1983

      J. Ellis, J. Hagelin, D. Nanopoulos, K. Olive, and M. Srednicki, 1984
    - Compositeness: γ', Z'
- Stable
  - Partners are odd under some discrete symmetry.
  - Lightest partner stable.
    - Supersymmetry: R-partity, LSP.
    - Compositeness: T-parity, LTP.
    - Others: KK-parity, LKP...

Generic features of LHC signal of CDM.

- The most model independent channel.



Dark matter: stable, neutral, $\rightarrow \not{E}_T$.

$pp \rightarrow \chi_{\rm DM}\chi_{DM} + X$.
Must recoil against something observable: $X = \gamma$, jet

- Large SM background, 10 times the signal.
- A discovery in “mono-jet”…
- Very challenging.

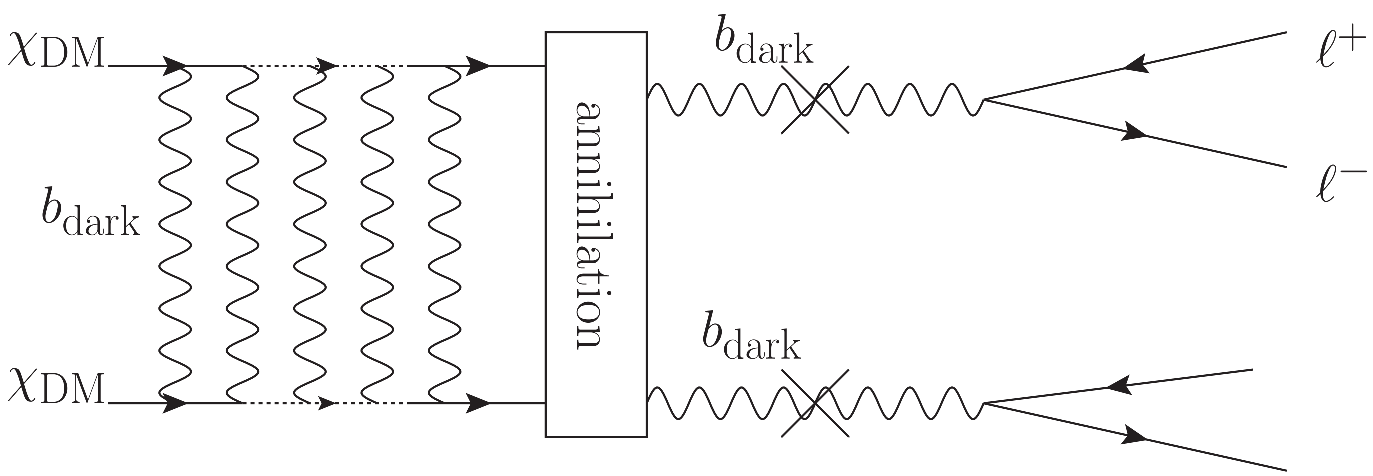
Recent evidences, and "tension". Talk by Pierce.

- Excesses in electron and positron fluxes.

  PAMELA: O. Adriani, et al., arXiv:0810.4995   Fermi-LAT: Abdo, et. al. arXiv:0905.0025

- Some tension if we assume the source is DM annihilation.

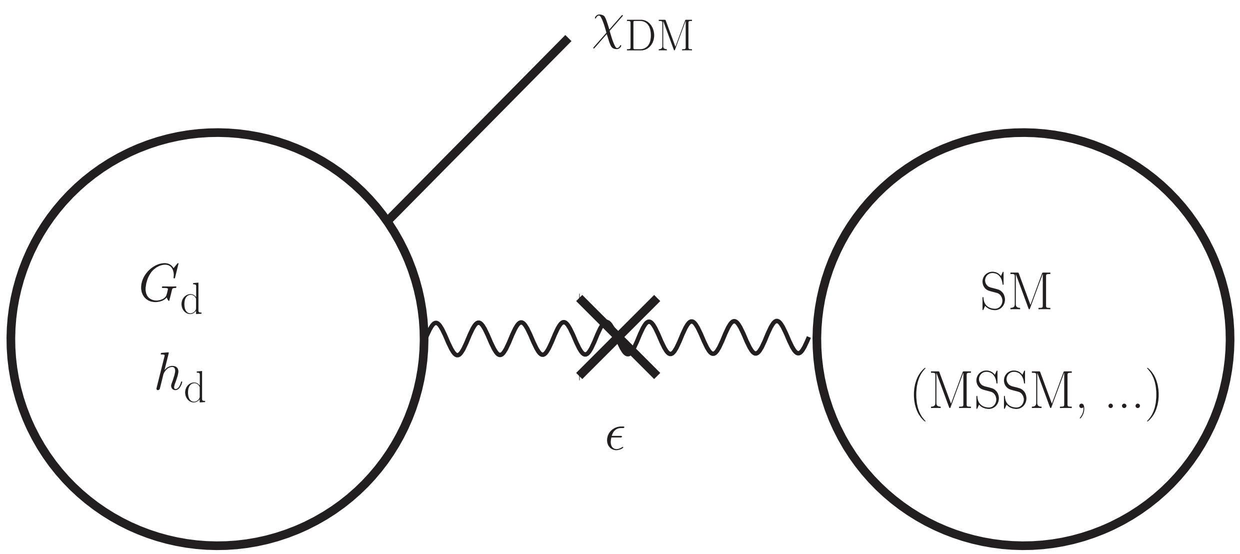
- Sommerfeld enhancement is a possible solution.



  - DM has long range mediated by GeV force carrier.

  - GeV "dark sector" couples to SM with small couplings.

Basic dark sector model ingredients:



- Model choices:

M. Pospelov, A. Ritz and M. Voloshin, arXiv:0711.4866
N. Arkani-Hamed, D. Finkbeiner, T. Slatyer and N. Weiner, arXiv0810.0713

  - Dark matter identity.
  - Self-interaction $G_{\rm d}$: gauge interaction...
  - GeV scale, dark Higgs $h_{\rm d} : v_d = \langle h_d \rangle \sim {\rm GeV}$
  - Supersymmetric scenarios: natural generation of the GeV Scale.

Various constructions:

- Earlier proposals:

  M. Pospelov, A. Ritz and M. Voloshin, arXiv:0711.4866
  N. Arkani-Hamed, D. Finkbeiner, T. Slatyer and N. Weiner, arXiv:0810.0713

- U(1) models:

  E. J. Chun and J. C. Park, arXiv:0812.0308
  C. Cheung, LTW, J. Ruderman, and I. Yavin, arXiv:0902.3246
  A. Katz and R. Sundrum, arXiv:0902.3271
  D. E. Morrissey, D. Poland and K. M. Zurek, arXiv:0904.2567

- Non-abelian model, SUSY:

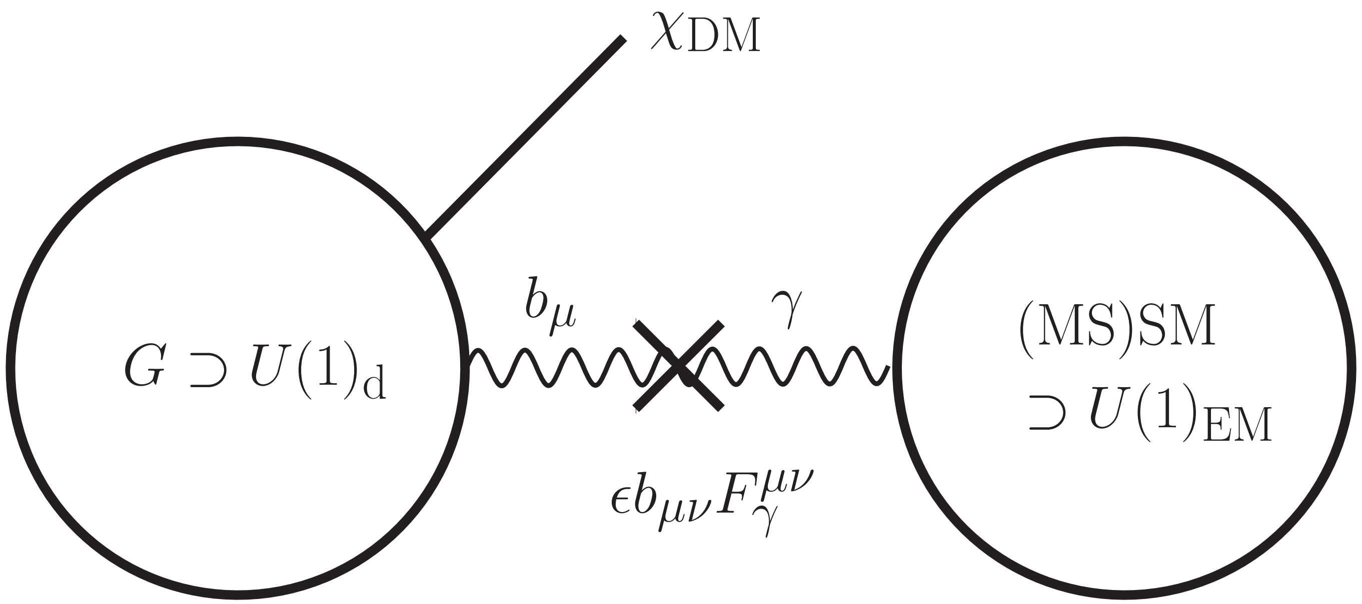
  M. Baumgart, C. Cheung, LTW, J.~Ruderman, I. Yavin, arXiv:0901.0283

- Scalar Portal:

  Y. Nomura and J. Thaler, arXiv:0810.5397

- More...

Simplest choice: abelian dark sector



- Simplest self-interaction: $G_{\rm d} = U(1)_{\rm d}$

- Natural connection to the SM: kinetic mixing

$$\mathcal{L}_{\rm kin.mix} = -\frac{\epsilon}{2} b_{\mu\nu} F_\gamma^{\mu\nu}$$

- Supersymmetry can be an elegant way of generating the GeV scale.

For a very simple and predictive construction:
C. Cheung, LTW, J. Ruderman, and I. Yavin, arXiv:0902.3246

"Seeing" GeV dark interactions.

$$V \supset \epsilon \cos\theta_W b_\mu J^\mu_{\rm EM} - \epsilon \sin\theta_W Z_\mu J^\mu_{\rm dark}$$

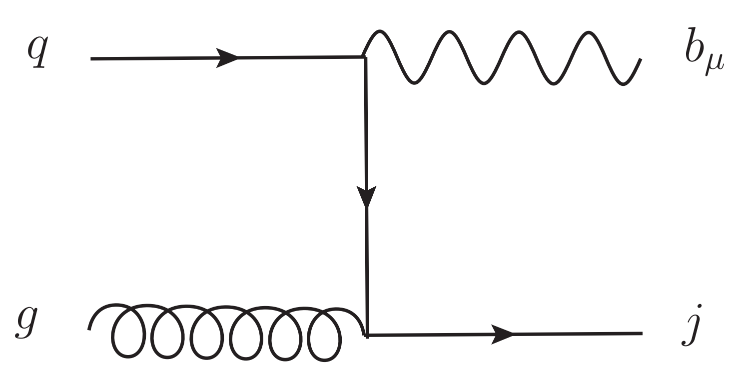
Direct b_μ (γ') prod.

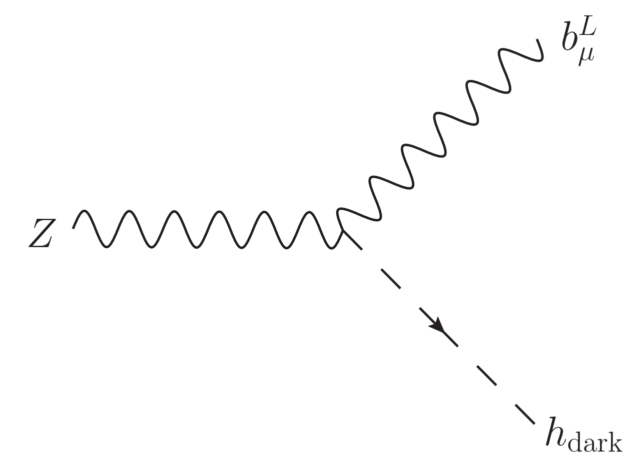
prompt "dark" photon

$$\epsilon b_\mu J^\mu_{\rm EM}$$

rare Z decay

$$\epsilon Z_\mu J^\mu_{\rm dark}$$

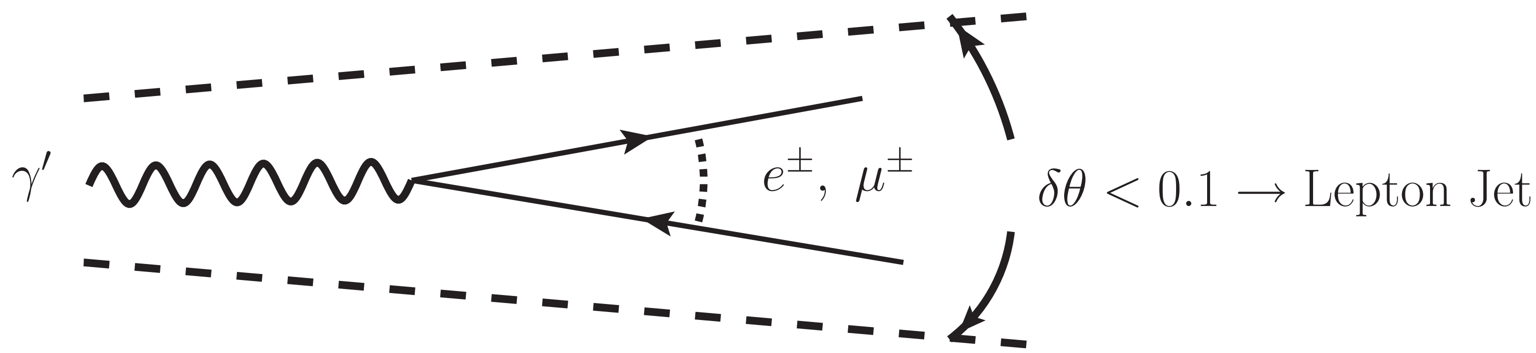




Collider signal: lepton jets.

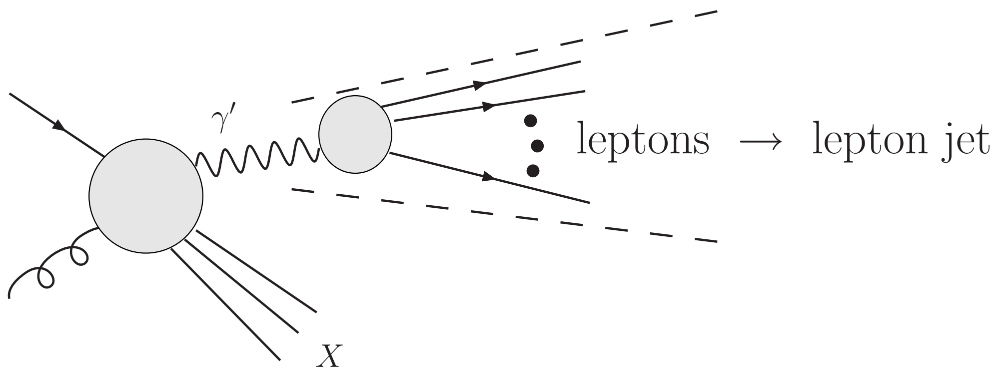
Decay of dark photon leads to highly collimated lepton pair.

"Lepton jet."



$$\begin{matrix} \text{Typical } E_{\gamma'} > 10 \text{ GeV} \\ m_{\gamma'} \sim \text{ GeV} \end{matrix} \rightarrow \delta\theta \sim m_{\gamma'}/E_{\gamma'} < 0.1$$

Unique objects.



More different signals.

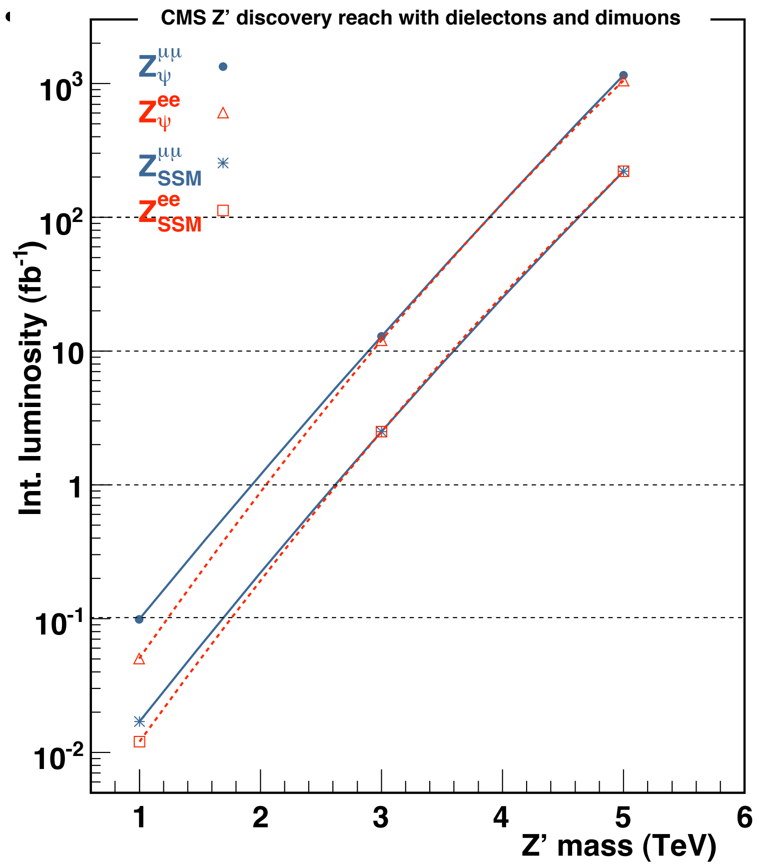
- Something SM cannot do.
  - Sometimes easy, sometimes not.
- Introducing new interactions (new symmetries).
- More often than not, introducing new particles as well.

Simplest possibility: extra U(1)

- Quite common in GUT and string constructions.

- Distinct signal, high mass resonance.

$$p\, p(\bar{p}) \to Z' \to \ell^+ \ell^-$$



- Can decay into other exotic states as well.

$$\text{e.g. } p\, p(\bar{p}) \to Z' \to \tilde{\ell}\tilde{\ell}^* \to \ell^+ \ell^- + \not{E}_T$$

Baumgart, Hartman, Kilic and LTW, hep-ph/0608172

Additional gauge theory.

- For example: $SU(N)$ with N_F flavors (Q_i).
- Heavy flavor, low confinement scale, "quirk".

  Kang and Luty, arXiv:0805.4642

  - Macroscopic correlations, exotic resonances.
- Light flavor, suppressed coupling to SM. "hidden valley".

  Strassler and Zurek: hep-ph/0604261

  - QCD like. New resonances decay to heavy SM quarks, displaced vertices.
  - Conformal. "Un-particle." Georgi, hep-ph/0703260
  - Higher multiplicity, more spherical events.

    Strassler, arXiv:0801.0629

Conclusions.

- LHC and Tevatron provide great opportunities of probing TeV new physics.
- Many possible scenarios.
- Many possible signals.
  - Can be either generic or very special.
  - Important to anticipate possible forms of NP signal as much as possible.