(What We Can Learn from)

Top at Future Colliders

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Outline

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3. EWSB and Top Beyond the SM
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Introduction: Top in the SM

- Top is 10 years old!!

  (pause to reflect on passage of time, mortality, etc…)

- Is it Standard Model top?

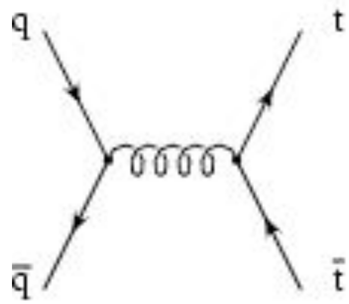
  $q = +2/3\ e$ — **spin = 1/2**
  isospin = 1/2 — **$I_3 = -1/2$**
  color triplet — **$V_{tb} \cong 1$**
  SM gauge couplings to γ, Z, W, g — **CKM mixing**

- …we hope not entirely!
- Huge mass = 175 GeV

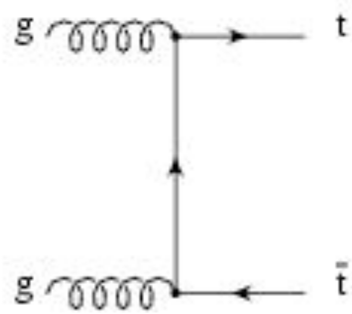
  Life as a quark: decays before hadronizing
  Yukawa coupling $\lambda_t \sim 1$: Coincidence ?!

$t\bar{t}$ Production

- Hadron colliders: strong production



Dominates at Tevatron

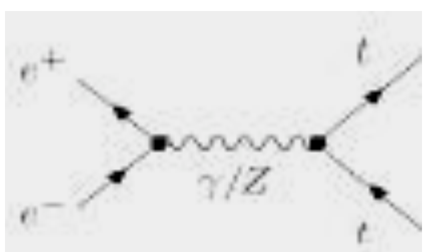


Dominates at LHC

sensitive to

tg coupling

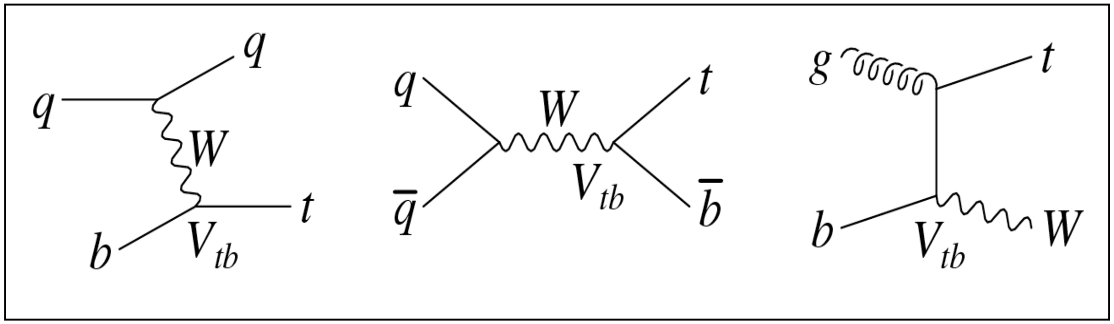
- Lepton colliders (ILC): electroweak production



$t\gamma$, tZ couplings

Single Top Production

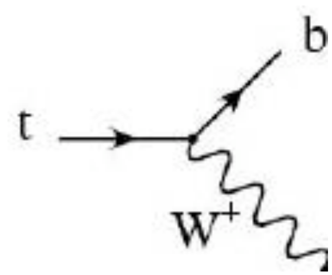
- Hadron colliders: electroweak production
  - Three modes:
    - T-channel: q b $\rightarrow$ q' t
    - S-channel: q q' $\rightarrow$ t $\bar{b}$
    - Associated: g b $\rightarrow$ t W^-



Sensitive to tWb coupling ($|V_{tb}|$)

Top Decay

- SM: BR into W^+b ~ 100%



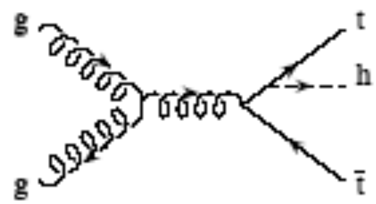
sensitive to coupling to Wb

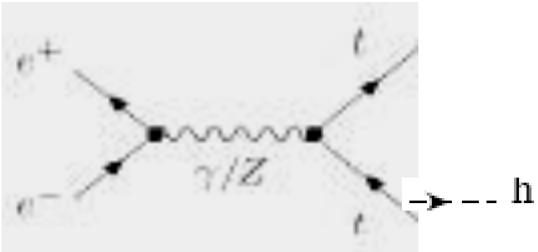
- Γ_t = 1.4 GeV >> Λ_{QCD}. So top decays before hadronizing and spin info gets passed to decay products.
- Total width << exp'tal resolution; hard to measure (but see e+e- threshold)

  ➔ can't measure magnitude of Wtb coupling
- Decay measures structure of Wtb coupling (V-A)
- Top kinematic reconstruction measures m_t
- Other decays CKM or loop suppressed

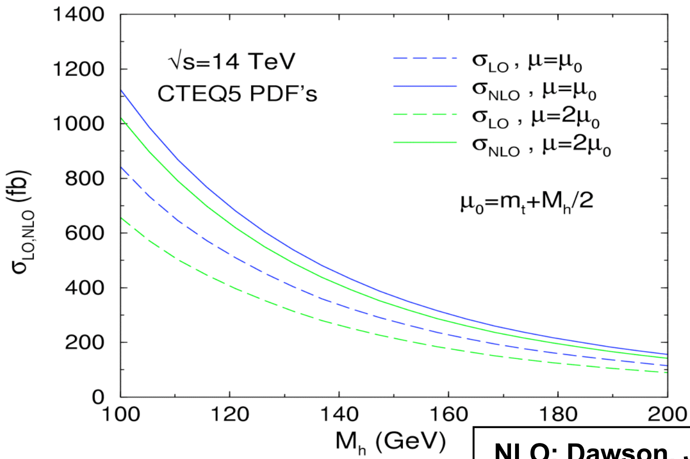
Other SM top Processes

- $t\bar{t}H$ production (LHC, ILC)





sensitive to
λ_t=tth coupling



NLO: Dawson, Jackson, Orr, Reina, Wackeroth, PRD 68, 034022 (2003)

- $t\bar{t}\gamma$, $t\bar{t}Z$ production (LHC)

sensitive to

ttγ, ttZ couplings

Electroweak Symmetry Breaking in the SM

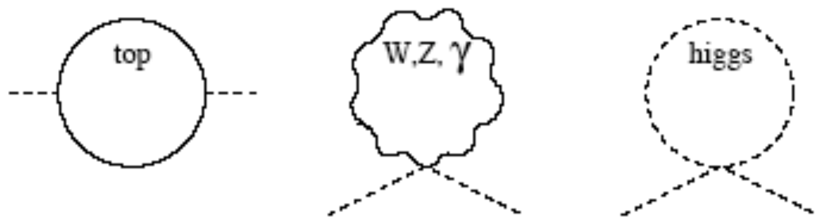
- Higgs mechanism breaks EW symmetry and gives mass to fermions via Yukawa interaction.

And why do we think top is special?

- Higgs couples to fermions according to (v = Higgs vev = 246 GeV)

  $\lambda_f = m_f \sqrt{2} / v \quad \rightarrow \quad \lambda_t \sim 1$

- Hierarchy problem: Higgs mass gets quadratically divergent corrections:



$\Delta m_h^2 \sim \Lambda^2$ (top dominates)

- Λ is momentum cutoff in loop integral; in SM, cutoff is where gravity becomes strong: $\Lambda \sim M_{Pl} \sim 10^{19}$ GeV. But we expect $m_h \sim$ weak scale $\sim 10^2$ GeV.

This hierarchy in scales leads to fine tuning over 17 orders of magnitude in energy. Unnatural!

Solutions to the Hierarchy Problem

Good news: many candidate solutions. They come in roughly 3 classes:

1. **Weakly coupled:** introduce new particles to cancel SM divergences
   - Cancellation requires new particles to be related to SM particles via symmetries (hence "partners")
   - If we require ≤ 10% fine tuning, must have scale for top partners < ~2 TeV
   - All other SM particles allow higher scales
     ➔ **first TeV-scale new physics likely associated with top!**
   - Examples: SUSY, Little Higgs

2. **Strongly coupled:** new strong dynamics enters at TeV scale
   - New dynamics gives physical TeV-scale cutoff
   - Higgs is composite; not fundamental degree of freedom above Λ
   - Top typically enters uniquely due to its large mass
   - Examples: Technicolor and its descendents

Solutions to the Hierarchy Problem, cont.

3. **Modified spacetime:** introduce extra spacetime dimensions to lower Λ
   - Extra space dimensions lower effective M_{Pl} :

     Λ is still M_{grav}, but M_{grav} ~ TeV
   - No fine tuning after all!
   - Examples: ADD, RS, UED, Higgsless

… and of course, you may mix and match solutions!

Each of these solutions:

- typically gives rise to new TeV-scale physical degrees of freedom which can potentially be produced at the LHC and/or ILC
- affects top phenomenology
- Has to contend with the astounding success of the SM, especially in precision electroweak measurements

Supersymmetry

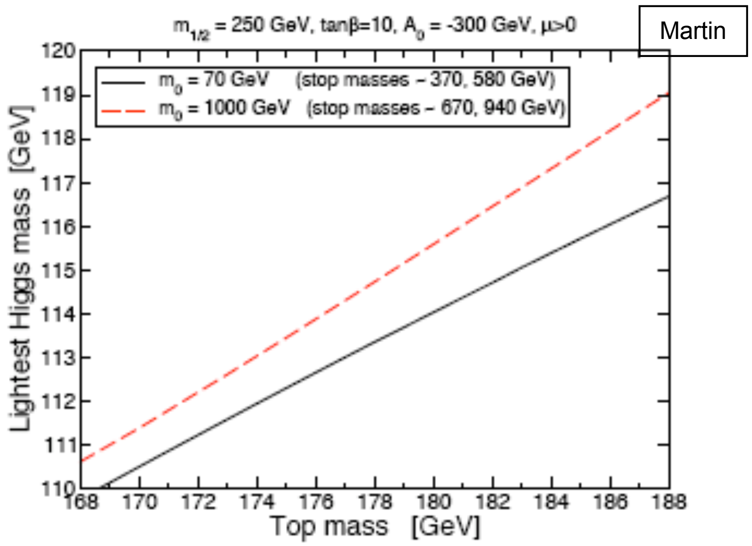
Features:

- Two Higgs doublets (5 physical Higgses: h^0, H^0, H^{+-}, A^0)
- Each SM particle gets a partner with opposite spin-statistics (squarks, sleptons, gauginos, higgsinos): no fine-tuning
- Heavy top gives EWSB automatically
- Gauge coupling unification possible
- String theory wants (high energy) SUSY
- Stop is typically lightest squark
- Discrete symmetry R-parity in some models (including MSSM)
  – SUSY partners must be pair produced
  – Lightest partner (LSP) is stable and therefore dark matter candidate
- Many parameters (~100) but predictive
- m_t < 160 GeV rules out MSSM

Supersymmetry, cont.

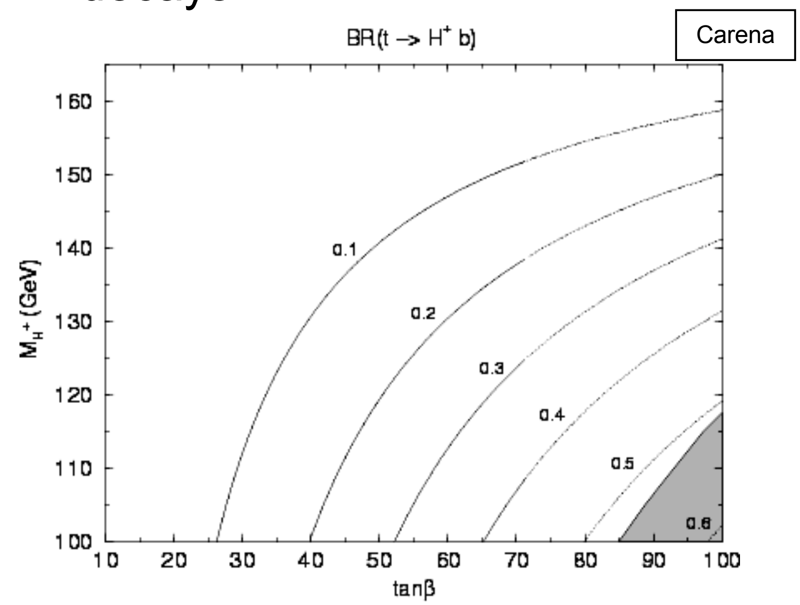
Impact on top phenomenology:

- M_h increases with m_t



- Modification (suppression) of Top Yukawa coupling; measure in ttH at LHC, ILC
- Also: Look for top in decays of heavy partners

- Coupling to H^+b: look for $t \rightarrow H^+b$ decays



- Curves of constant BR; shaded area excluded at TeVatron

Little Higgs Models

Features:

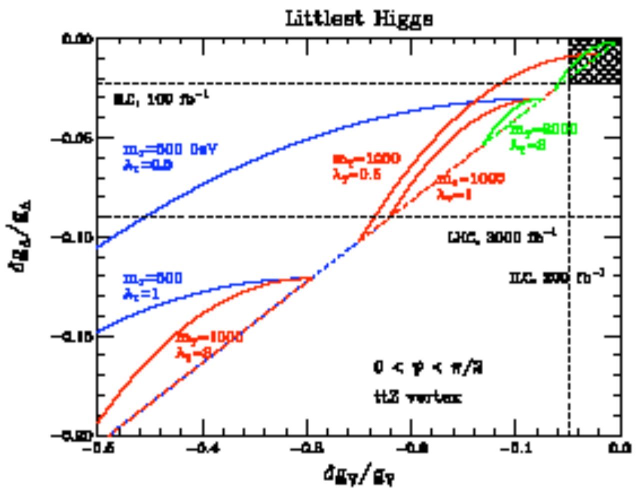
- Higgs field is Nambu-Goldstone boson resulting from breaking of continuous global symmetry
- Special symmetry breaking structure ensures cancellation of quadratic divergences in m_H without SUSY
- Higgs divergences cancelled by particles with same spin-statistics as in SM
- Littlest Higgs: simplest version; new TeV-scale particles:
  - Vector-like top partner T, 1-2 TeV
  - EW Gauge boson partners
  - Weak triplet scalar field
- Model-dependent: Symmetry group, exact new particle content
- Discrete symmetry T-parity introduced in some models to solve ``little hierarchy'' (1-2 TeV scale for new physics vs. > 5-7 TeV from precision EW)
  - New particles must be pair produced (no tree-level exchange)
  - Lightest partner (LTP) is stable and therefore dark matter candidate
- T, W', Z' (and other new particles, if they exist) should be produced at LHC, ILC (pairs only if T-parity conserved)

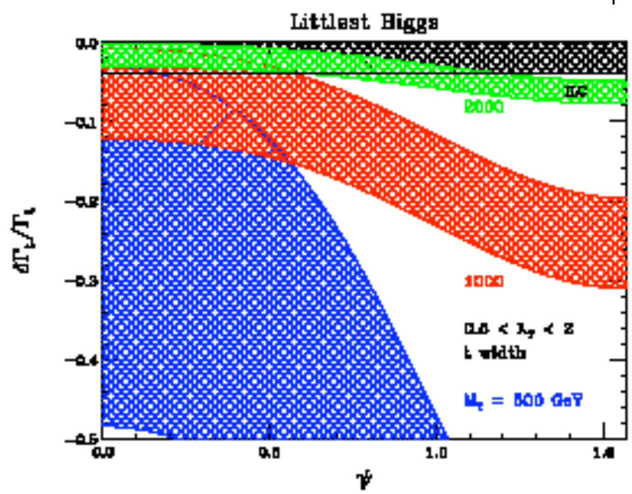
Little Higgs, cont.

Impact on top phenomenology:

- Vector-like T mixes with t_L, modifying couplings to W, Z (magnitude, structure)
- New gauge bosons also mix (but not in T-parity conserving models), also modify t couplings to W, Z

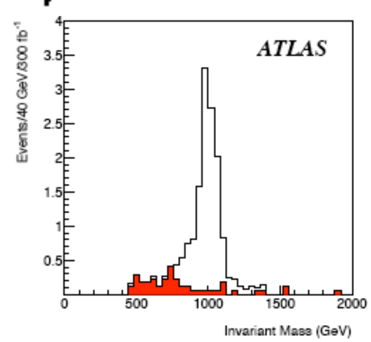
Berger, Perelstein, Petriello





- Heavy T pheno: decays to th, tZ, bW; LHC reach to about 3 TeV

- Models predict relation between masses, couplings, symmetry breaking scale

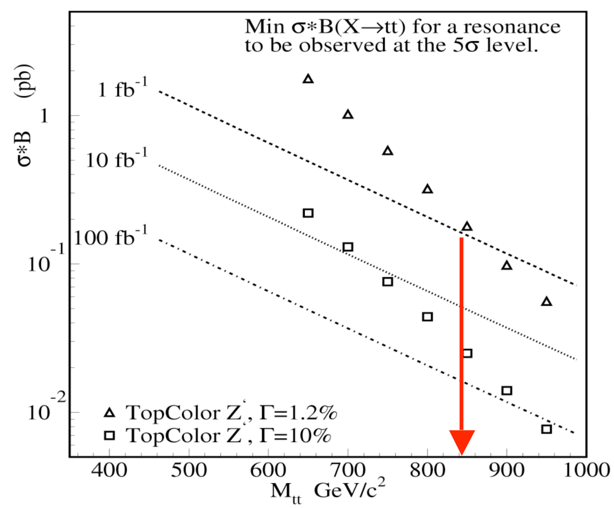


Invariant mass of the Zt pair, reconstructed from the $\ell^+\ell^-\ell^\pm\nu b$

Technicolor and its descendents, cont.

Impact on top phenomenology:

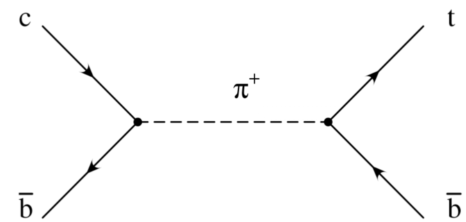
- Resonant top-antitop production via new gauge bosons: look at tt



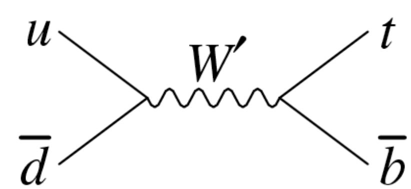
Future EW Physics at the Tevatron, TeV-2000 Study Group

- LHC reach ~4-5 TeV

- Toppions in single top production



- Topflavor W’ in single top production



Modified Spacetime

Features:

- Large extra space dimension(s) reduce effective gravity scale to ~TeV
  - Large means compared to M_{Pl}^{-1}
- String theory wants extra dimensions
- Models characterized by:
  - extra dimensions warped or flat
  - where SM particles live
- Common feature: Fourier modes of bosonic fields ➔Kaluza-Klein excitations of gravitons (and sometimes gauge bosons)
- Phenomenology model dependent
  - **ADD**: Flat extra dim's; SM particles confined to usual 3+1 D ("brane"); gravitons propagate in all dimensions ("bulk"), making gravity look weak (effective M_{Pl} reduced to order TeV). Details depend on size and number of extra dimensions. Gravitons escaping into bulk give missing energy signal
  - **RS**: Warped extra dim's;

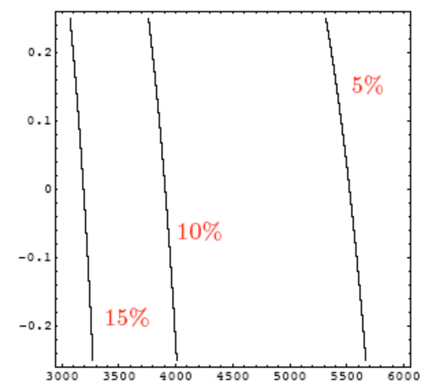
Modified Spacetime, cont.

- **ADD**: $D = 4 + \delta$ δ extra space dimensions
  - SM particles confined to usual 3+1 D ("brane")
  - Gravitons propagate in extra dimensions ("bulk"), making gravity look weak:
    - $M^2_{grav} = M_{Pl}/(2\pi R)^{\delta}$
    - R = compactification radius (size of extra dimension)
    - E.g. for M_{grav} = 1 TeV and $\delta = 4$, R^{-1} = 20 keV
  - Gravitons escaping into bulk give missing energy signal
- **RS**: Warped extra dimensions
  - Hierarchy explained in analogy with gravitational redshift in curved space
  - 2 branes connected by 1 extra dimension
  - SM particles on one brane, graviton wave function peaked on the other; small overlap with SM brane makes gravity look weak
- **UED**: All SM particles propagate uniformly in the bulk (flat ED)
  - Momentum conservation in extra dimensions
  - Discrete symmetry: KK parity
    - KK particles produced only in pairs
    - Lightest KK stable → dark matter candidate
    - Gauge unification
- **Others**: SM fields in warped ED, Higgsless, SUSY in ED, …

Modified Spacetime, cont.

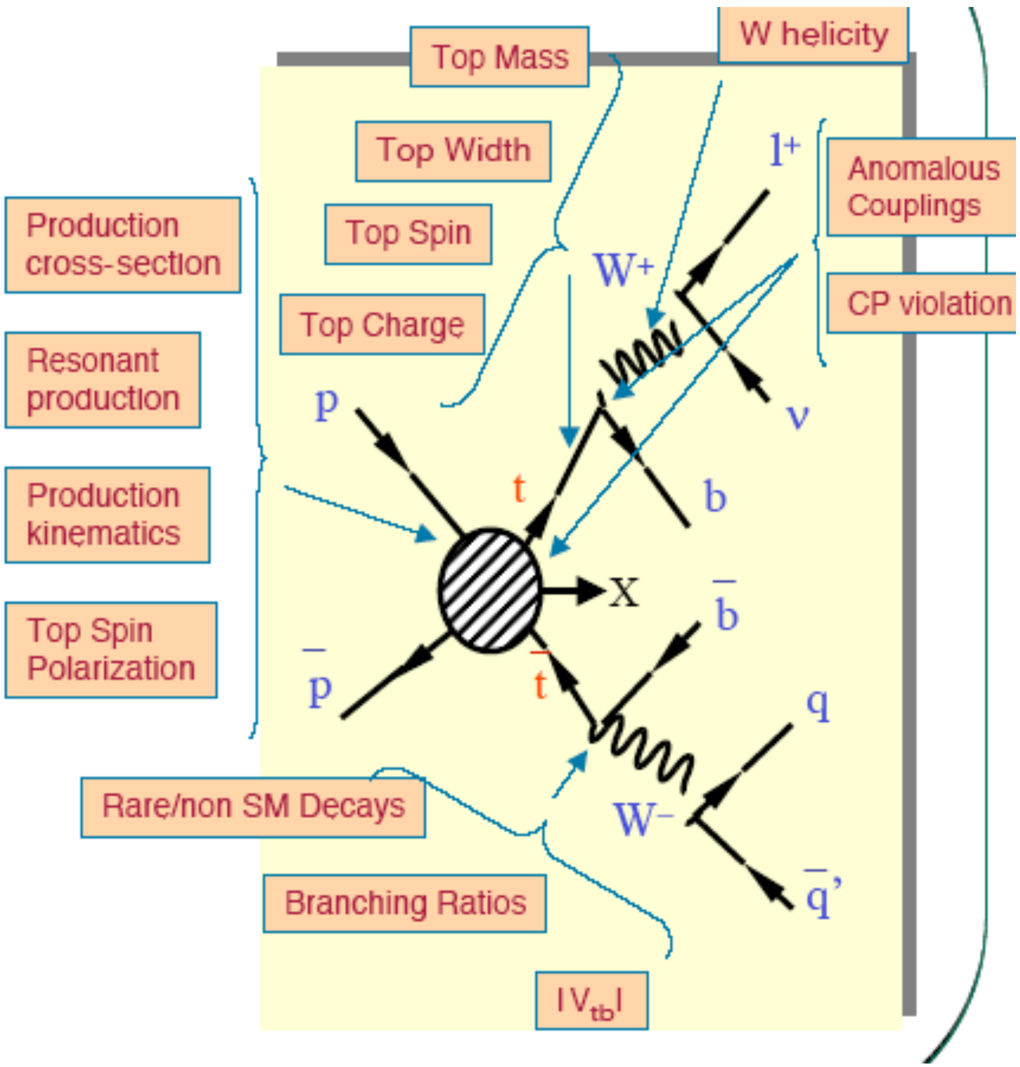
Impact on top phenomenology:

- Top is not so special here
- Top pheno: pair production via s-channel KK production
- Other collider signatures:
  - (ADD):
    - pp → γ E_{miss}, jet E_{miss}
    - e+e- → γ E_{miss}, Z E_{miss}
    - "graviscalars" mix with Higgs, modify SM invisible decay width
  - (RS):
    - Resonant KK production: peaks in dilepton, diphoton inv. mass spectra
    - Effective contact interactions
    - Other details very model dependent
    - Probe up to 1.5 GeV at LHC
  - (UED): pair production of KK modes; probe up to ~500 GeV



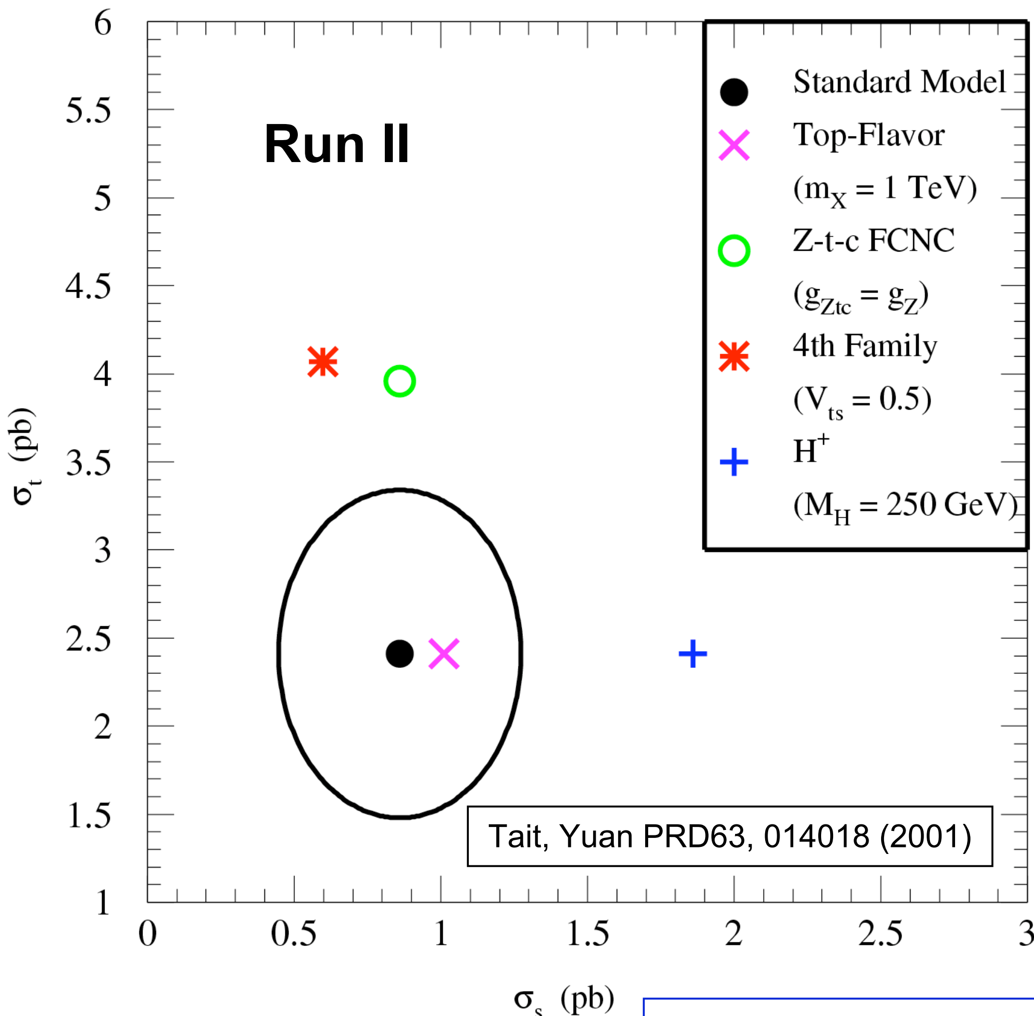
- RS matter in bulk ⇒ mostly t_R shift

Top at LHC: Summary

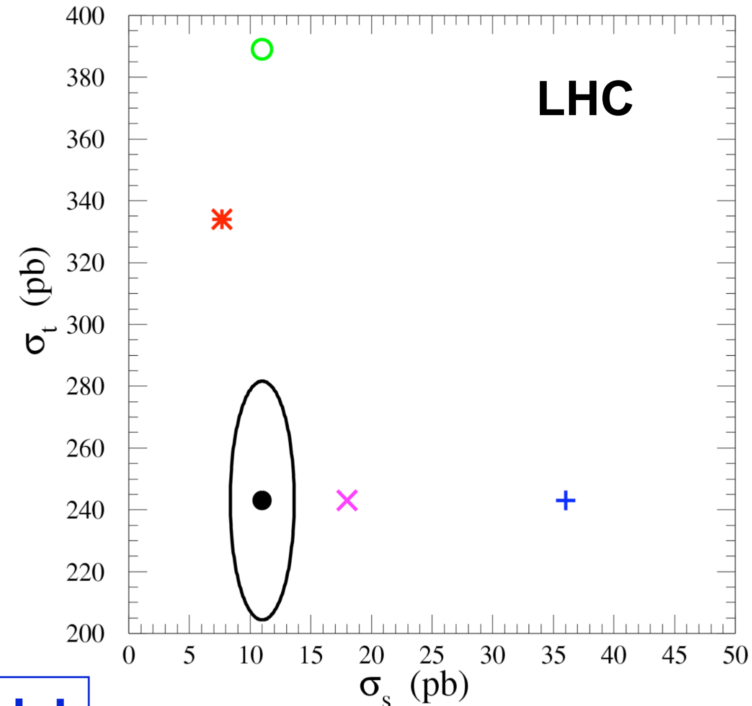


Plus:
Single top
Associated production

σ_s-σ_t Plane

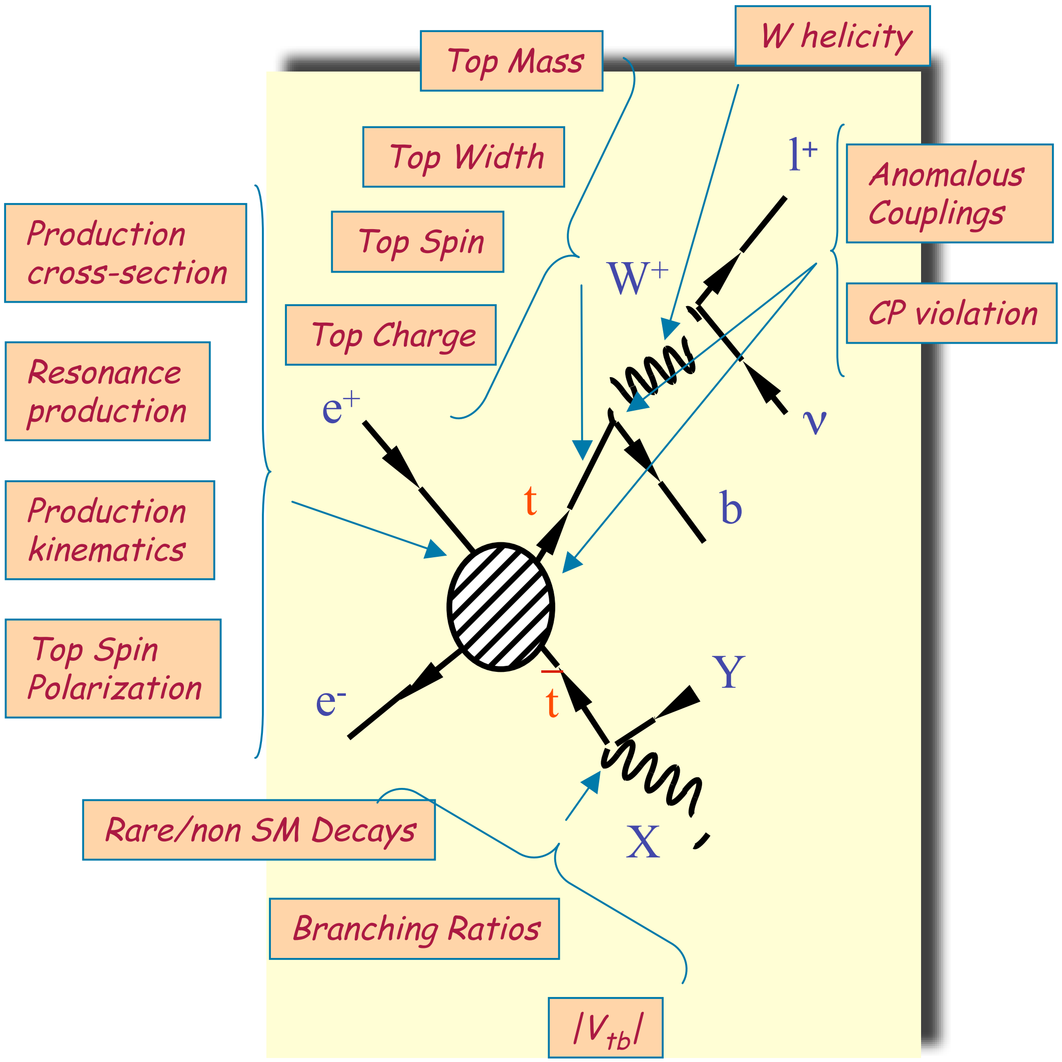


Since they are sensitive to different physics and have different, final states, σ_s and σ_t should be measured independently!



Theory errors only!

Top at ILC: Summary



Plus:
Single top
Associated production

ttV Production: Comparison to e^+e^-

coupling	LHC, 300 fb^{-1}	e^+e^- [19]
$\Delta\widetilde{F}_{1V}^{\gamma}$	$^{+0.043}_{-0.041}$	$^{+0.047}_{-0.047}$, 200 fb^{-1}
$\Delta\widetilde{F}_{1A}^{\gamma}$	$^{+0.051}_{-0.048}$	$^{+0.011}_{-0.011}$, 100 fb^{-1}
$\Delta\widetilde{F}_{2V}^{\gamma}$	$^{+0.038}_{-0.035}$	$^{+0.038}_{-0.038}$, 200 fb^{-1}
$\Delta\widetilde{F}_{2A}^{\gamma}$	$^{+0.16}_{-0.17}$	$^{+0.014}_{-0.014}$, 100 fb^{-1}
$\Delta\widetilde{F}_{1V}^{Z}$	$^{+0.43}_{-0.83}$	$^{+0.012}_{-0.012}$, 200 fb^{-1}
$\Delta\widetilde{F}_{1A}^{Z}$	$^{+0.14}_{-0.14}$	$^{+0.013}_{-0.013}$, 100 fb^{-1}
$\Delta\widetilde{F}_{2V}^{Z}$	$^{+0.38}_{-0.50}$	$^{+0.009}_{-0.009}$, 200 fb^{-1}
$\Delta\widetilde{F}_{2A}^{Z}$	$^{+0.50}_{-0.51}$	$^{+0.052}_{-0.052}$, 100 fb^{-1}

Conclusions

- Top is unique as a laboratory for EWSB and fermion masses.
- Its huge mass may be a clue that it is special, and it plays an important role in the SM and beyond.
- We have many candidates for new physics signals at the LHC and ILC, and many things to study
- But we also need to keep our eyes open for the unexpected, which may be more interesting still!