Beyond the Standard Model

Lecture #1: Overview of BSM

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outline of these lectures

- **Lecture 1: Overview of BSM**
  - **The vastness of theory space.**
  - **Major Beyond the Standard Model (BSM) frameworks.**
  - **Constraints on BSM models from current precision data.**
  - **BSM models can be phenomenological “look-alikes”.**
  - **BSM models as templates for LHC analyses.**

- **Lecture 2: Supersymmetry**
  - Why SUSY is the dominant BSM framework.
  - SUSY as a space-time symmetry.
  - Softly-broken SUSY and the Higgs naturalness problem.
  - The MSSM.
  - Radiative electroweak symmetry breaking.
  - R-parity conservation and dark matter.
  - SUSY production at LHC.

- **Lecture 3: Missing Energy Look-alikes**
  - **Realistic SUSY models and their "mediators".**
  - **mSUGRA and LHC "benchmarks".**
  - **What is the LSP?**
  - **Universal Extra Dimensions, KK-parity, and the LKP.**
  - **Little Higgs, T-parity, and the LTP.**
  - **Look-alikes at the LHC.**

- **Lecture 4: Exotica**
  - **Warped extra dimensions.**
  - **The AdS/CFT correspondence.**
  - **Higgsless models.**
  - **Unparticles.**
  - **Quirks.**
  - **Black Holes and the end of everything.**

theorists are trouble

BSM = Beyond the Standard Model

- Not all BSM phenomena are observable (with human technology and/or funding).
- The full BSM “Theory Space” of possible SM extensions has NOT been mapped out.
- “Theory Space” has high dimensionality (maybe space-time does too), and contains an infinite number of possibilities.
- But given experimental resolutions/limitations, there are in practice a finite number of possibilities to sort out.
- And many, many, many are already ruled out.

experimental evidence for BSM physics

- dark matter and dark energy:
  - see lectures by K. Olive
- neutrinos:
  - see lectures by M. Lindner
- persistent discrepancies in precision measurements:
  - g-2 of the muon, etc.
  - see lectures by Y. Grossman, M. Beneke
- hints from cosmic radiation:
  - see lectures by M. Teshima

theoretical arguments for BSM physics

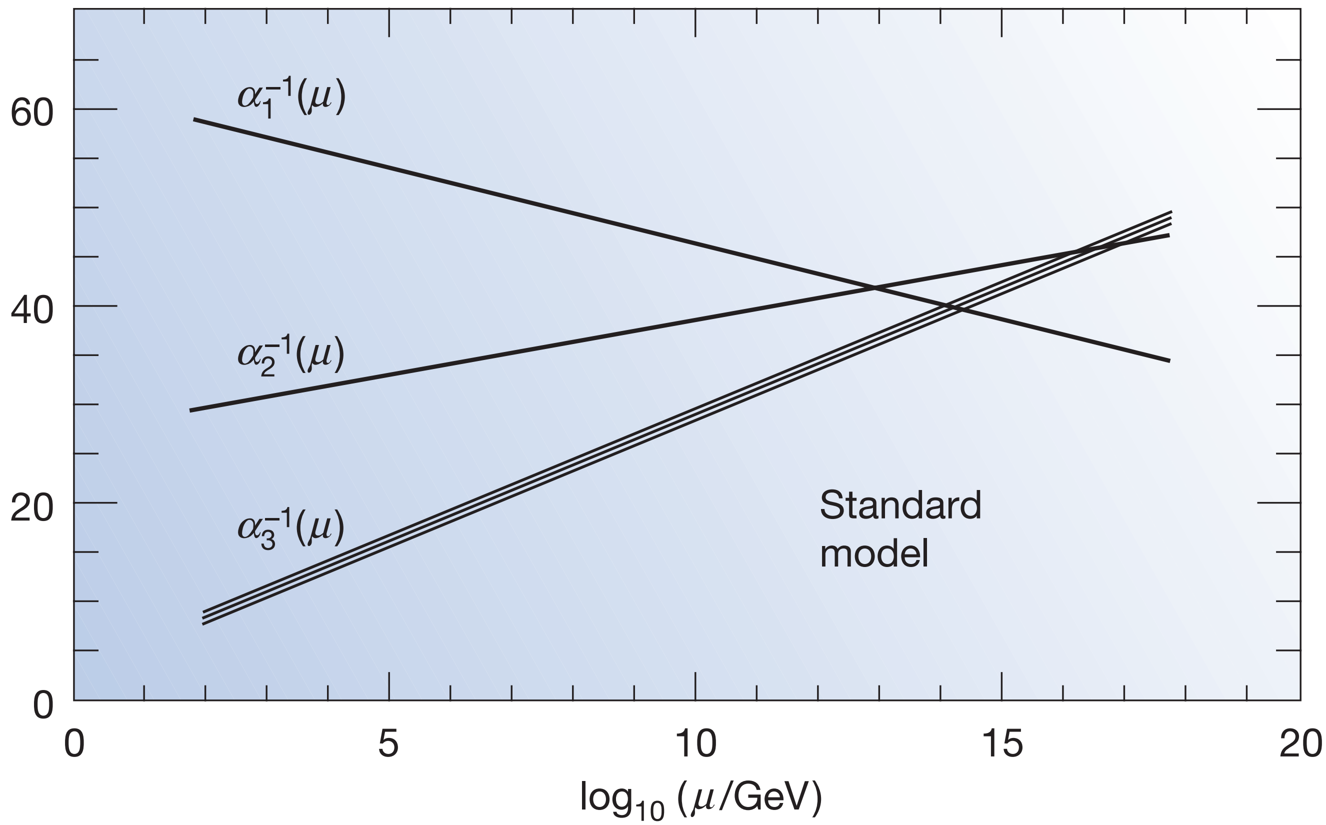
- Problem of Higgs naturalness
- Problem of relating gravity to the gauge forces
- Problem of flavor hierarchies in fermion masses and mixings
- Problem of baryogenesis and CP violation

Problem of Higgs naturalness

- The Standard Model is renormalizable, meaning that although there are ultraviolet (UV) divergences in the quantum corrections, I can remove any explicit dependence on the UV cutoff

- However the couplings of the SM “run”, i.e. they have different values at different energies.

- We can ask what do the SM couplings look like at very, very high energies:



- **The SM gauge couplings don't unify, but they do come together around $10^{13} - 10^{16}$ GeV.**

- **At even higher energies, hypercharge becomes strongly interacting, and the SM breaks down.**

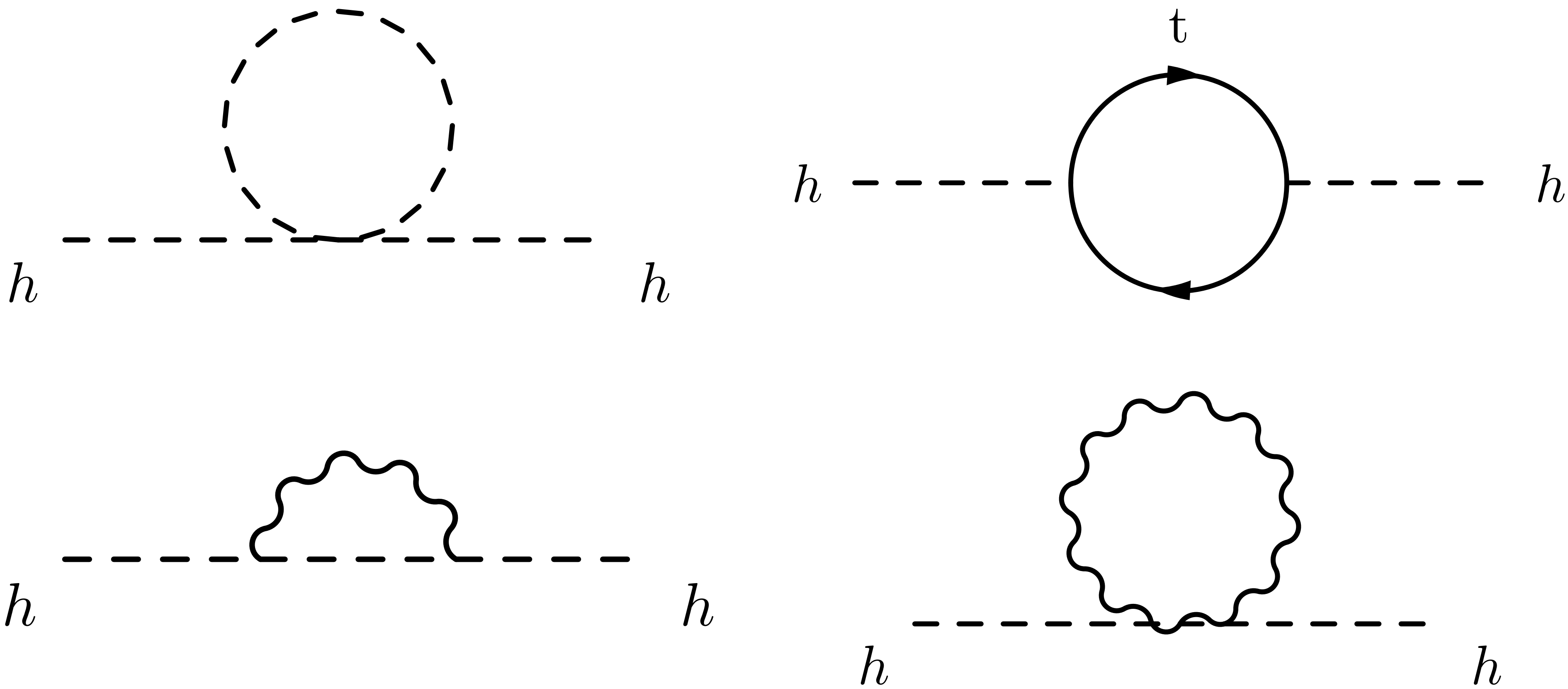
Problem of Higgs naturalness

- So there is some maximum energy scale Λ beyond which I shouldn't be running the SM couplings. Denote the SM couplings evaluated at this scale by
  $\mathbf{g_1}(\boldsymbol{\Lambda}),\ \mathbf{g_2}(\boldsymbol{\Lambda}),\ \mathbf{g_3}(\boldsymbol{\Lambda}),\ \mathbf{m_H}(\boldsymbol{\Lambda}),\ \lambda(\boldsymbol{\Lambda}),\ldots$

- Now it would also be reasonable to integrate out the effects of some of the very high energy SM physics, say all of the effects due to SM momenta between $\Lambda/2$ and Λ

- This gives me the SM couplings at energy scale $\Lambda/2$ as functions of the SM couplings at the original maximum UV scale Λ.

- For the gauge couplings the difference is just a logarithmic rescaling...



- **But** $\mathbf{m_h^2(\Lambda/2) = m_h^2(\Lambda) + \sim \frac{1}{16\pi^2}\Lambda^2}$
- **So the only way to get** $\mathbf{m_h^2}(1\ \mathrm{TeV}) << \mathbf{m_h(\Lambda)}$ **is if** $\mathbf{m_h(\Lambda)}$ **were magically "fine-tuned".**

Problem of Higgs naturalness

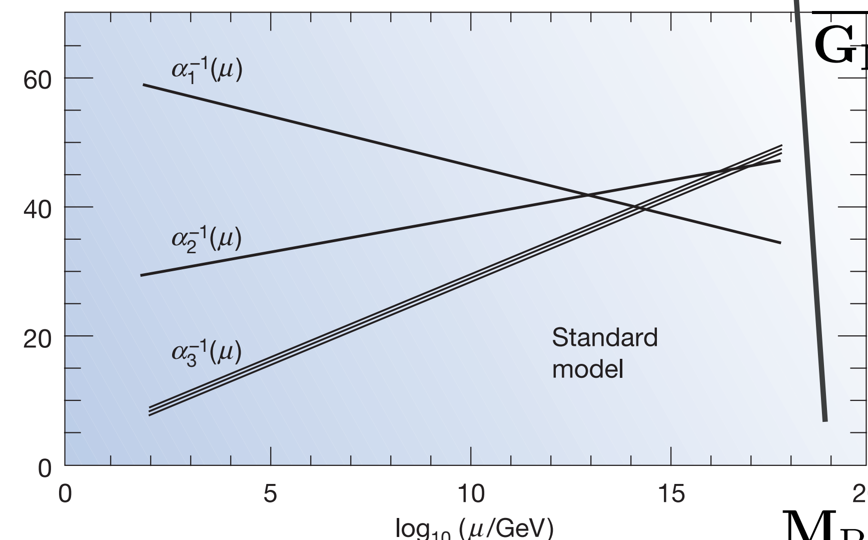
- There are three ways around this problem:

1. We live in a fine-tuned universe, otherwise “intelligent life” wouldn’t exist (anthropic principle).

2. The maximum UV scale Λ is only a few hundred GeV (but this is ruled out already by experiment).

3. The limit $m_h \to 0$ has enhanced symmetry, so the statement that $m_h << \Lambda$ is just telling us that some (NEW!) symmetry is not-too-badly broken.

Problem of relating gravity to the gauge forces



$$\frac{\mathbf{1}}{\mathbf{G_N}\mu^{\mathbf{2}}}$$

$$\mathrm{M_{Planck}} = \mathbf{10^{19}}\ \mathrm{GeV} = \mathbf{G_N^{-1/2}}$$

- **Gravity is very very weak at low energies.**
- **Naively at around 10^{18} GeV it should compete with the gauge forces.**
- **We don't know if the forces unify. GUTs? Strings? We don't even really know if gravity is a quantum force.**
- **We understand why $\Lambda_{\mathbf{QCD}} << \mathrm{M_{Planck}}$ but not why $\mathbf{m_h}, \mathbf{m_Z} << \mathrm{M_{Planck}}$**

Problem of flavor hierarchies in fermion masses and mixings

- We have just seen that the Higgs naturalness problem is also a hierarchy problem.
- The SM has additional hierarchies in fermion mass scales.
- These are not naturalness problems because chiral symmetry protects the masses of fermions.
- But it is still very bothersome that we have no explanation for

$$\frac{\mathbf{m_t}}{\mathbf{m_u}} \sim \mathbf{30,000} \qquad \frac{\mathbf{m}_\tau}{\mathbf{m_e}} \sim \mathbf{3,500} \qquad \frac{\mathbf{m_t}}{\mathbf{m_b}} \sim \mathbf{40} \qquad \frac{\mathbf{m_c}}{\mathbf{m_s}} \sim \mathbf{14} \quad \ldots$$

Problem of baryogenesis and CP violation

- The universe (within a radius of ~1000 megaparsecs) has a net excess of baryons over antibaryons.

- The SM has CP violation from Yukawa couplings (CKM), and it has nonperturbative processes that should violate baryon number conservation at very high temperatures.

- This would have produced some baryon excess in the early universe, during the electroweak-breaking phase transition.

- But the net SM baryon excess is many orders of magnitude less than what we see.

- There is an additional source of Standard Model CP violation from QCD, but these “strong CP” effects are not seen in experiment.

ingredients of BSM models

- **New particles:**
  - These may be heavier "partners" of SM particles, or not.
  - They may have SM charges, or not.
  - They may couple directly to SM matter, or not.
  - They may be fundamental, composite (i.e. bound states), or perhaps they are not even particles.

ingredients of BSM models

- New symmetries:
    - Broken symmetries: e.g.
        - spontaneously broken supersymmetry,
        - approximate conformal symmetry,
        - global symmetries that are explicitly broken or partially gauged.
    - Unbroken symmetries: e.g.
        - R-parity,
        - KK parity.

New unbroken symmetries often imply new stable particles.

ingredients of BSM models

- **New gauge or Yukawa interactions:**
  - **These new forces may be weak or strong at the relevant energy scales.**
  - **They may be partially or fully unified with SM forces at some higher energy scales.**

- **New degrees of freedom:**
  - **e.g. extra dimensions, new charges, “stringy” excitations.**
  - **SM particles may or may not access these degrees of freedom.**

frameworks, models, scenarios

- Supersymmetry is $\boxed{\text{NOT}}$ a BSM model; it is a BSM framework containing an infinite number of models.

- BSM models usually attempt to solve one or more problems not addressed by the Standard Model. If explicitly embedded into a well-understood theoretical framework, they can claim to be "complete" in the same sense as the Standard Model.

- A complete BSM model means you can (in principle) predict its consequences for any observable, from cosmology to B physics to precision electroweak to LHC.

frameworks, models, scenarios

- Incomplete BSM models, which focus more narrowly on one phenomenon (e.g. getting a light Higgs, a large extra dimension, or a particular new source of CP violation) are sometimes more correctly called “scenarios”.

- Complete BSM models are nowadays highly constrained by experimental data.

- BSM “scenarios” are harder to evaluate, but often make dramatic testable predictions.

major BSM frameworks

- **Weak scale supersymmetry (SUSY):**
  - **Basic idea: Space-time symmetry relating particles of different spins, so every SM particle has a "superpartner".**
  - **SUSY is spontaneously broken, and SUSY breaking is connected to electroweak symmetry breaking. The superpartners get SUSY-breaking contributions to their masses of order ~100 to 1000 GeV.**
  - **Maximum energy scale considered: ~ 10^{19} GeV.**

major BSM frameworks

- Little Higgs, Twin Higgs:
  - Basic idea: The Higgs is light because it is a pseudo-Goldstone boson of some weakly broken global symmetry.
  - In other words, the Higgs is light compared to some multi-TeV new physics scale, for the same reason that the pion is light compared to the mass of the proton.
  - Maximum energy scale considered: ~ 10 TeV.

dual BSM frameworks (AdS/CFT)

- New strong dynamics (Technicolor etc):
  - Basic idea: New strong gauge forces create fermion condensates that break electroweak symmetry and give masses to SM fermions; they also create new composite particles.
  - Maximum energy considered: ~ 1000 TeV.
- Randall-Sundrum (“RS1”) warped extra dimensions:
  - Basic idea: There is a 5th dimension of finite extent with strongly warped geometry, such that 10^{19} GeV at one end rescales to ~1 TeV at the other end. SM particles are localized in different places in the 5th dimension.
  - Maximum energy considered: ~ 10^{19} GeV

major BSM frameworks

- Universal Extra Dimensions (UED):
  - Basic idea: There is one or more flat extra dimensions with finite extent ~1/TeV.
  - SM particles are zero modes; each SM particle has a whole tower of heavier Kaluza-Klein partners.
  - Maximum energy scale considered: ~ 10 TeV.

major BSM frameworks

- Hidden Valleys (also “unparticles”, some dark matter models,…):
  - Basic idea: The is a whole other “sector” of sub-TeV particles that couple only weakly to the SM particles.
  - This hidden sector has its own forces and symmetries.
  - Maximum energy scale considered: ~ 10 TeV.

BSM models vs ElectroWeak Precision Tests

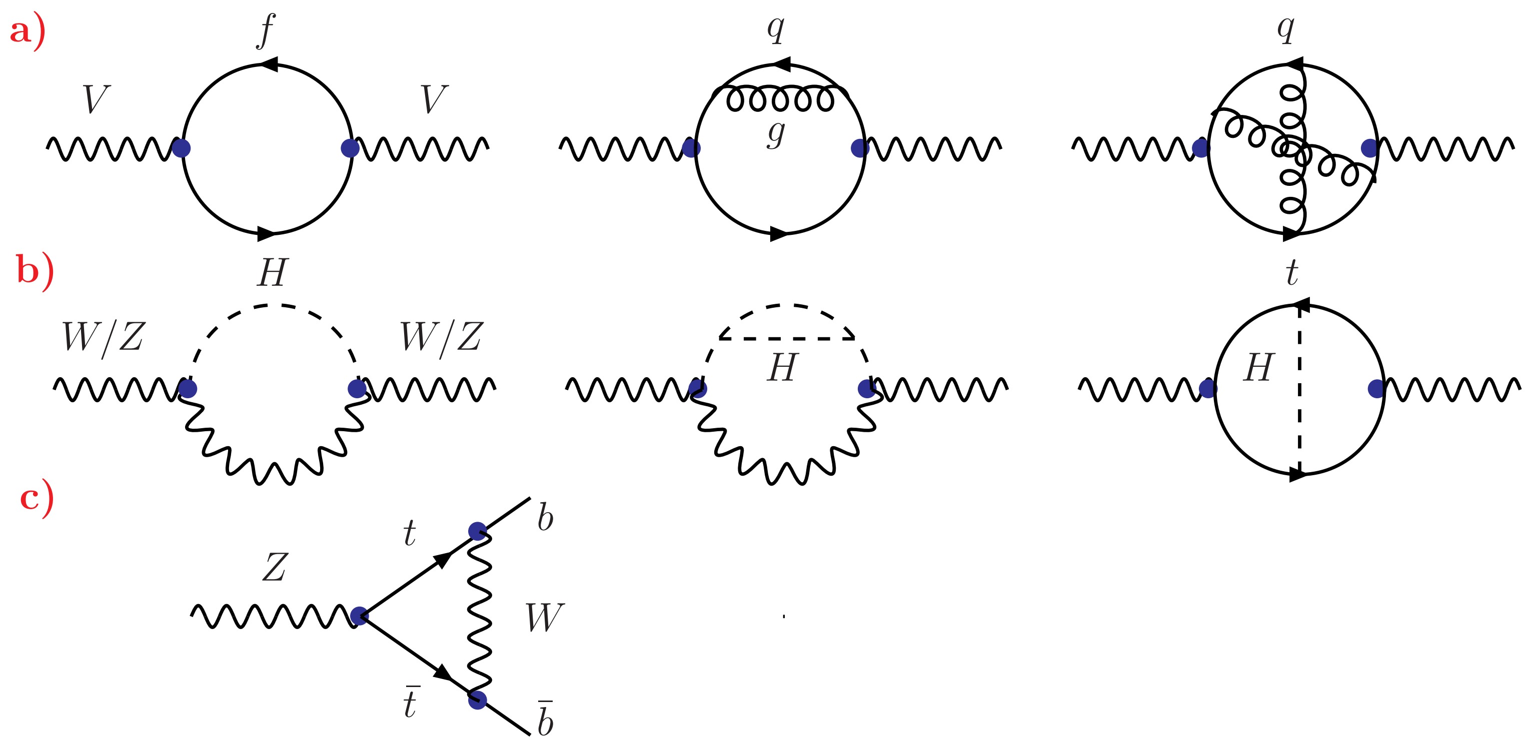
- Experiments at LEP and elsewhere have measured a large number of electroweak observables with part-per-thousand accuracy.

- Taken together, these EWPT are sensitive to quantum effects of BSM physics above the TeV energy scale.

- Most SM extensions that you would write down, involving new particles and new tree-level interactions at scales of a few hundred GeV to a couple TeV, are ALREADY RULED OUT by existing data.

- New flavor-violating or CP violating interactions are even more constrained by data, up to ~1000 TeV in some cases (and even more for proton decay).

Most relevant electroweak quantum corrections:



a) SM “oblique” corrections to W,Z self-energies, from fermion loops.

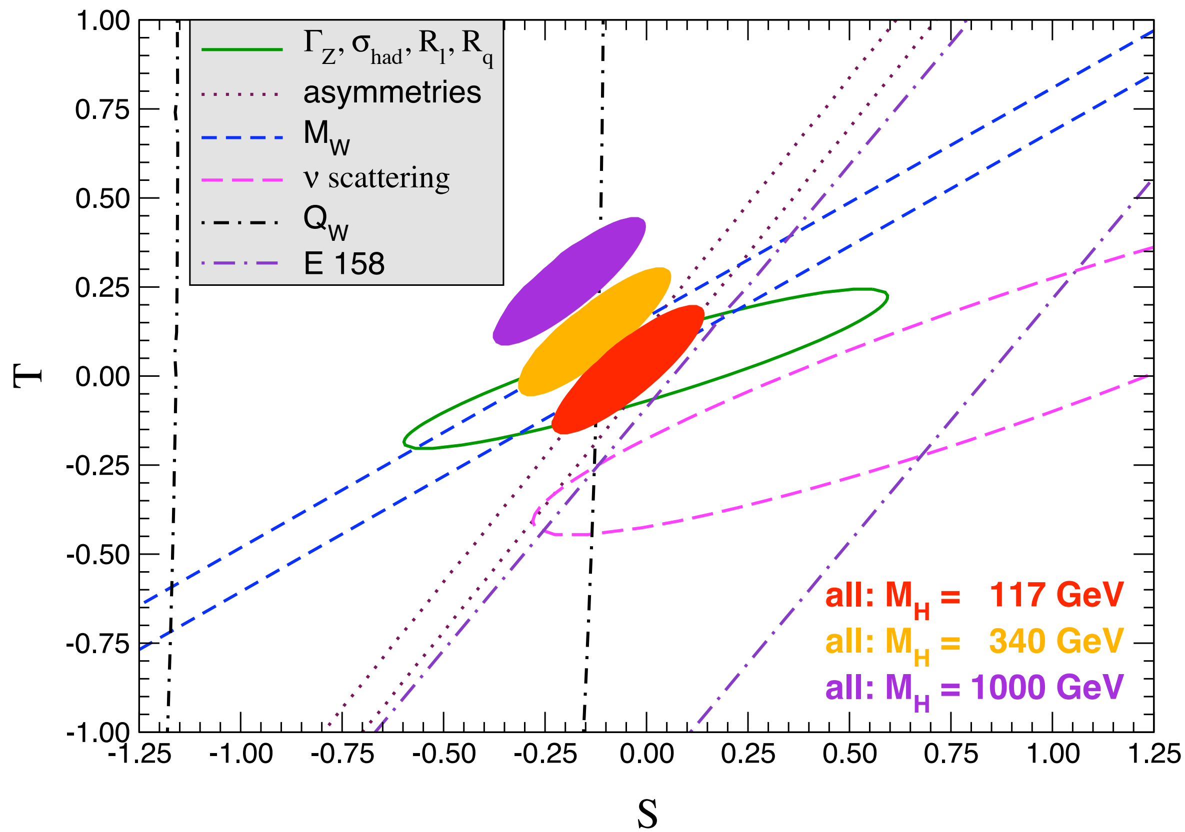
b) SM “oblique” corrections from Higgs and from Higgs+top.

c) Loop corrections to the Zbb vertex.

BSM models vs ElectroWeak Precision Tests

- **Many (but not all) new physics effects on electroweak observables can be parameterized in terms of the Peskin-Takeuchi variables S and T, which measure deviations in the W and Z self-energies.**
- **S and T are defined to be zero in the SM for some reference value of the Higgs mass, but can get O(1) contributions from new physics.**
- **Basically, S counts particles that get mass from EW symmetry-breaking...**
- **... and T is sensitive to mass splittings within a weak doublet, and other SU(2)-breaking effects.**

BSM models vs ElectroWeak Precision Tests



$$S = -0.10 \pm 0.10 \; (-0.08)$$

$$T = -0.08 \pm 0.11 \; (+0.09)$$

Very restrictive!
But a little room to cancel Higgs against new physics.

BSM models vs ElectroWeak Precision Tests

- **BSM models that are not already ruled out can be divided into three categories, according to how they manage to satisfy the (very tough!) EW precision constraints:**

  - **Models where symmetries forbid new tree-level effects and have cancellations between "partners" to suppress loop effects. Example: supersymmetry.**

  - **Models where the new particles are all very heavy (> 2,3,5,10 TeV) to suppress their EW effects. Examples: generic Randall-Sundrum, generic Little Higgs.**

  - **Models where some "accidental" cancellation is needed to improve the tension with EW data. Example: topcolor-assisted technicolor.**

BSM models can be look-alikes

- Because there are a limited number of mechanisms to “hide” new physics from the constraints of current data, BSM models that have very different theoretical starting points can end up looking quite similar phenomenologically.

- This is accentuated by the desire among BSM model-builders to include a good dark matter candidate, usually leading to “missing energy” signatures as a dominant phenomenological prediction.

- It will be a great challenge to deduce a unique underlying theory from the discovery of a few new particles.

BSM physics at the LHC

- In these lectures I will concentrate on the possibility that pp collisions at the LHC will “break through” a threshold of new physics and produce new particles.

- the $\mathrm{Sp\bar{p}S}$ did this at $\sqrt{\mathrm{s}} = 600$ GeV for the W and Z.

- the Tevatron did this at $\sqrt{\mathrm{s}} = 1.8$ TeV for the top quark.

BSM physics at the LHC

- What this means in practice is that new particles will be produced "on-shell".

$$\mathbf{p^2 \equiv p_\mu p^\mu \simeq m^2}$$

- LHC experiments may also detect virtual effects of new heavy particles beyond the reach of on-shell production, but I will discuss this only in passing.

- It is also possible to produce objects at the LHC that are not particles (in the usual sense), as I will discuss briefly.

how to make new particles at the LHC

1. s-channel resonance, with decay to a pair of SM particles, or to a pair of exotic particles, or to one of each.

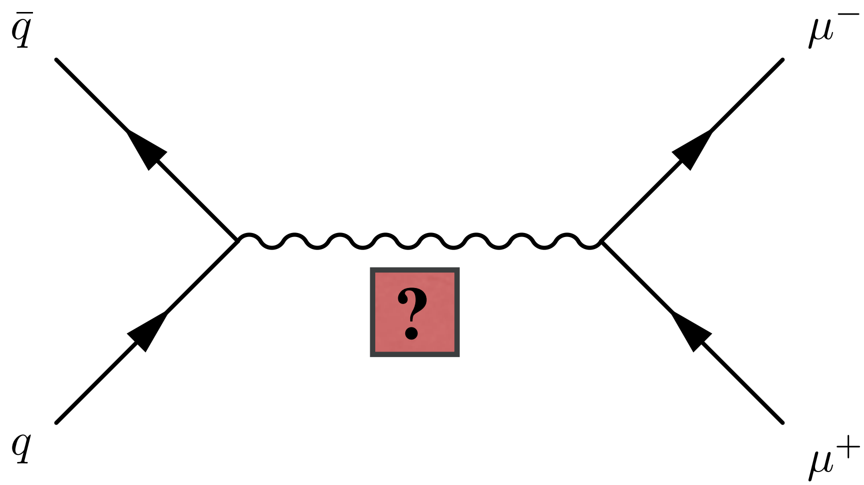
2. associated production with a SM particle.

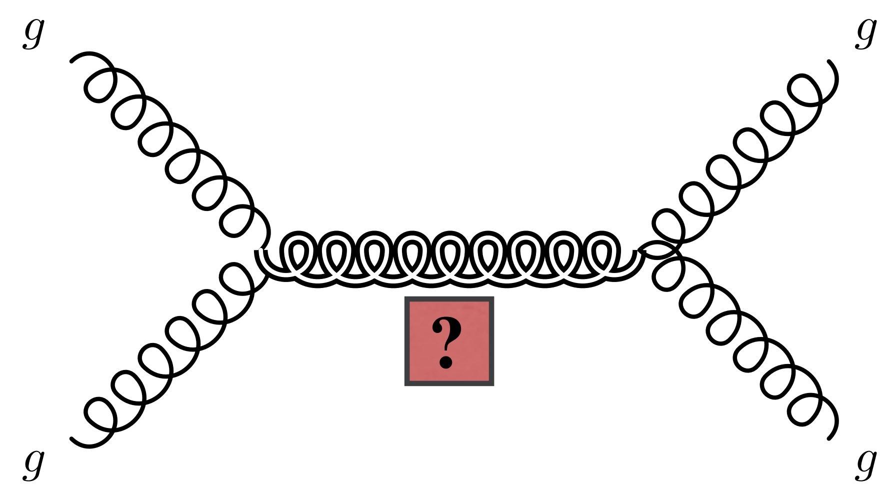
3. BSMsstrahlung.

4. pair production, with decay to SM particles, exotic particles, or a mixture of both.

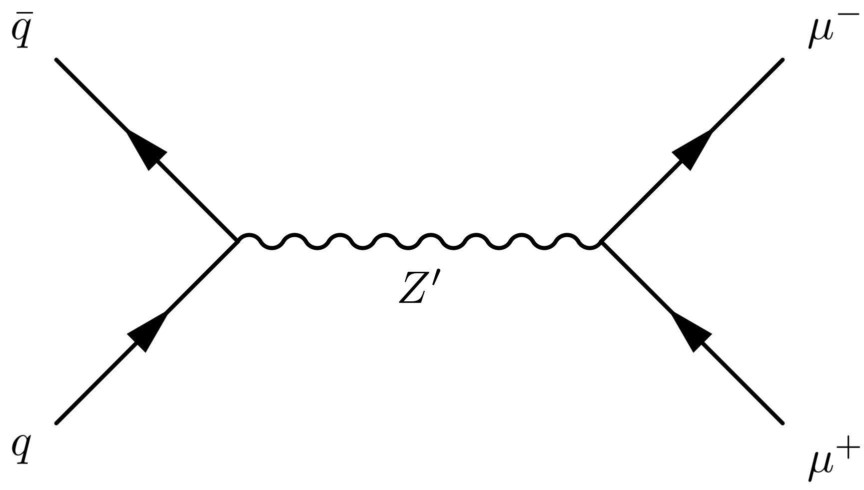
5. produced in decays of heavy SM particles: top, Higgs.

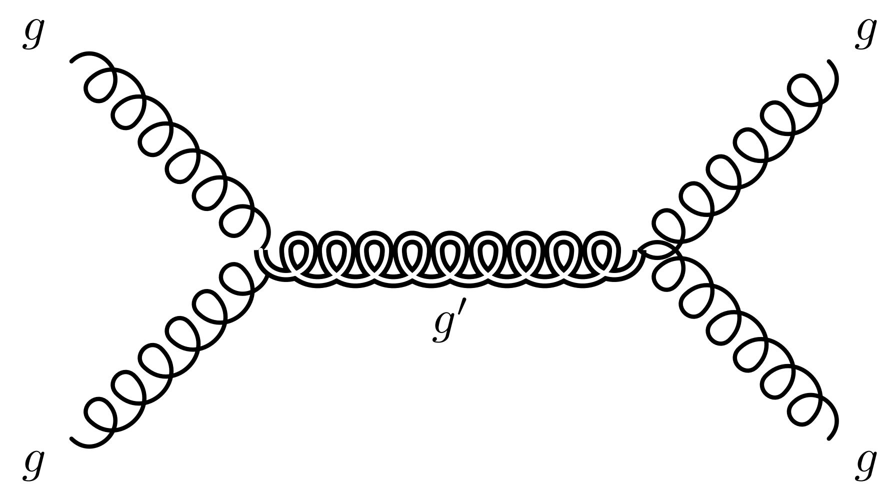
s-channel resonances



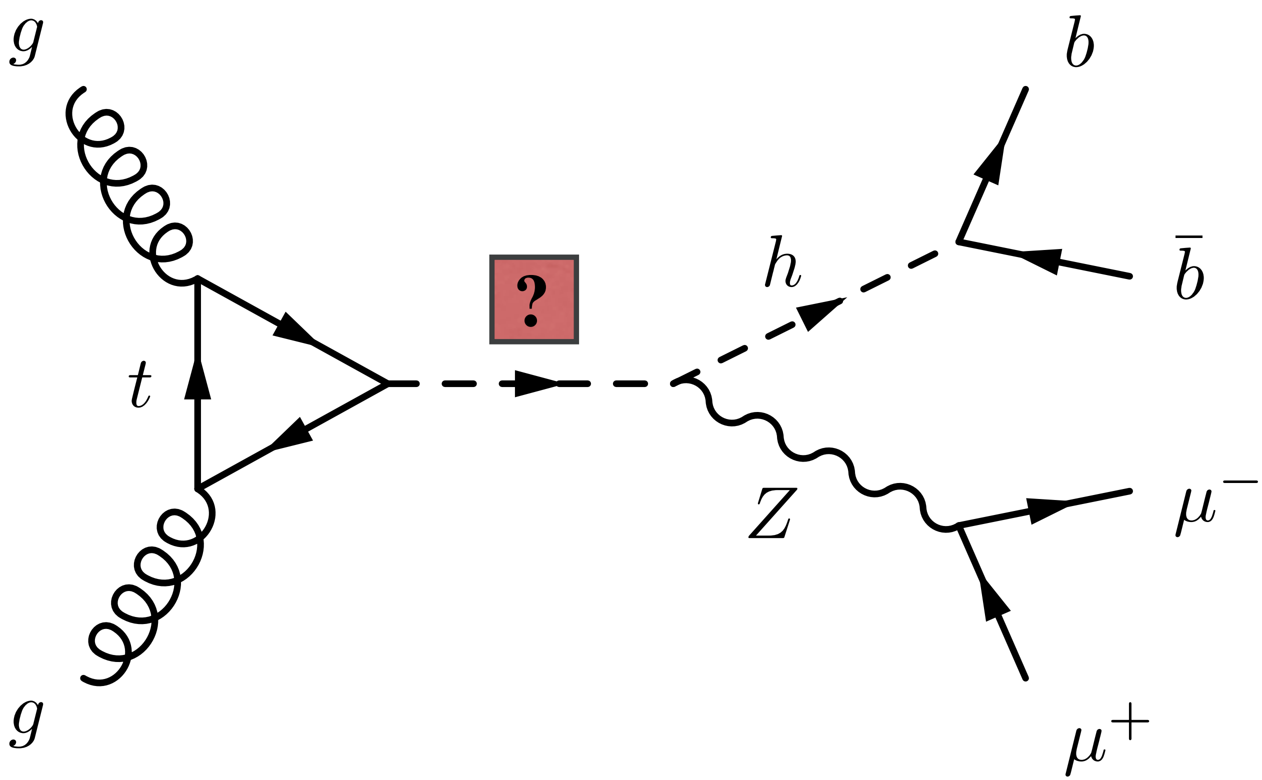


s-channel resonances

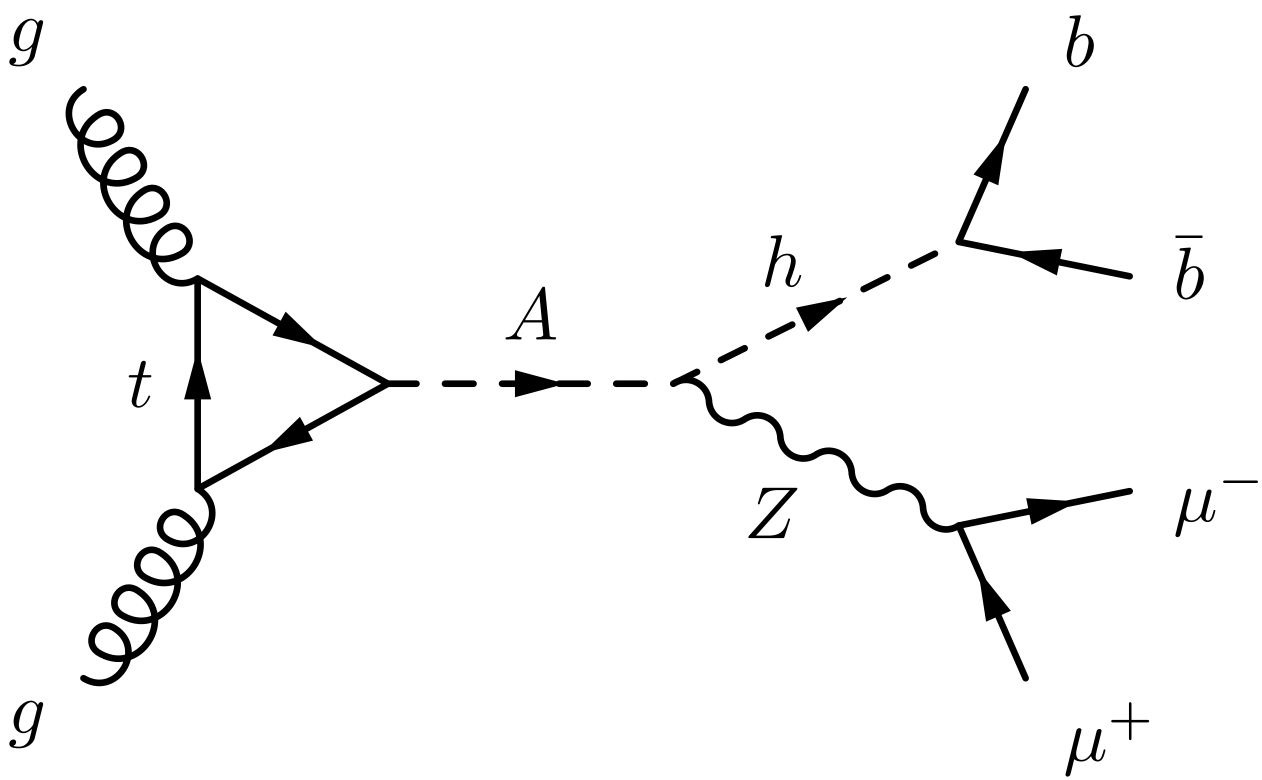




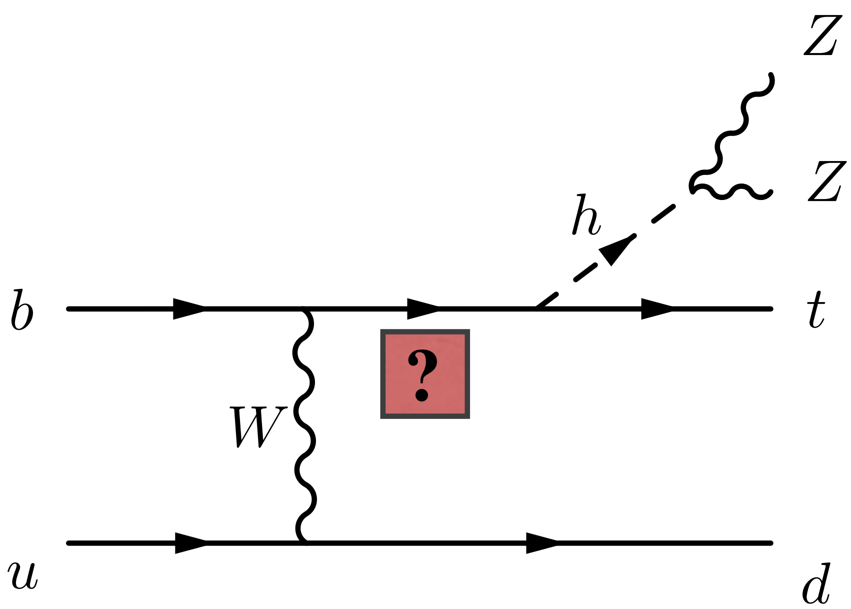
s-channel resonances

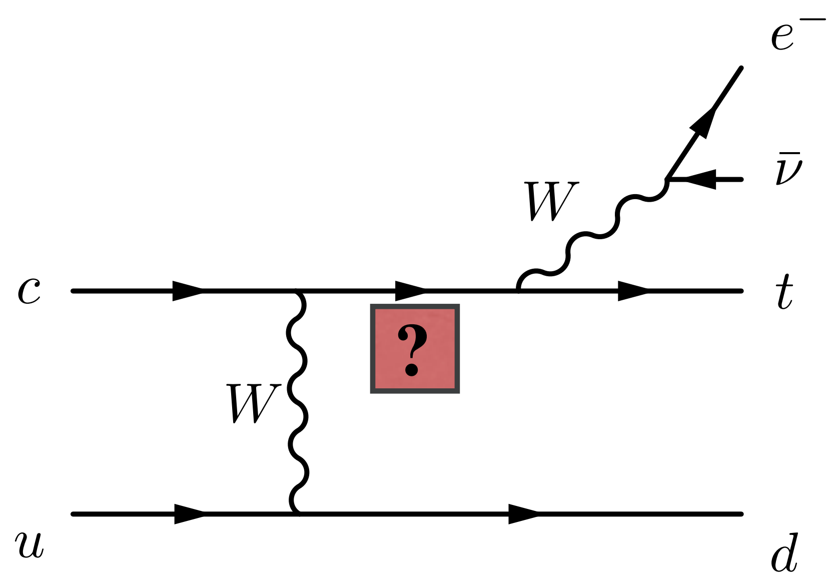


s-channel resonances



associated production with a SM particle





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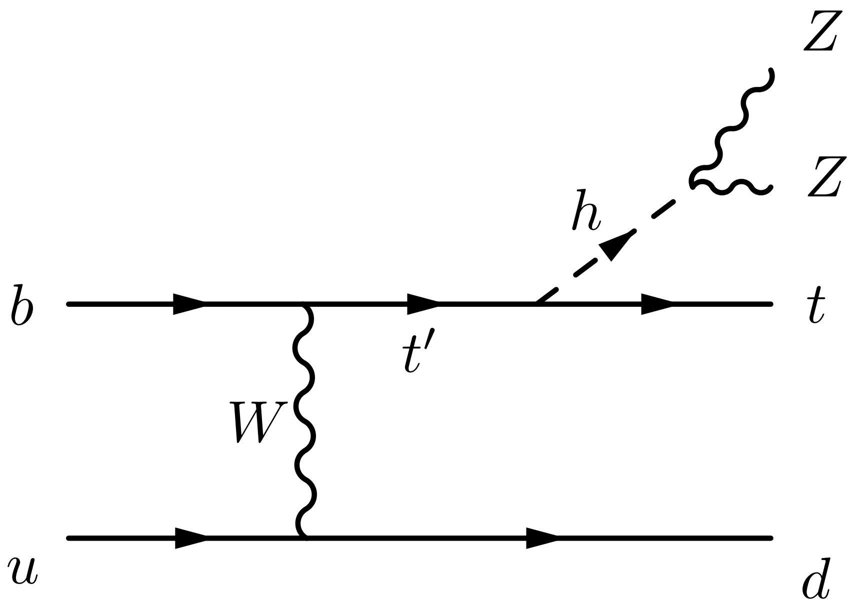

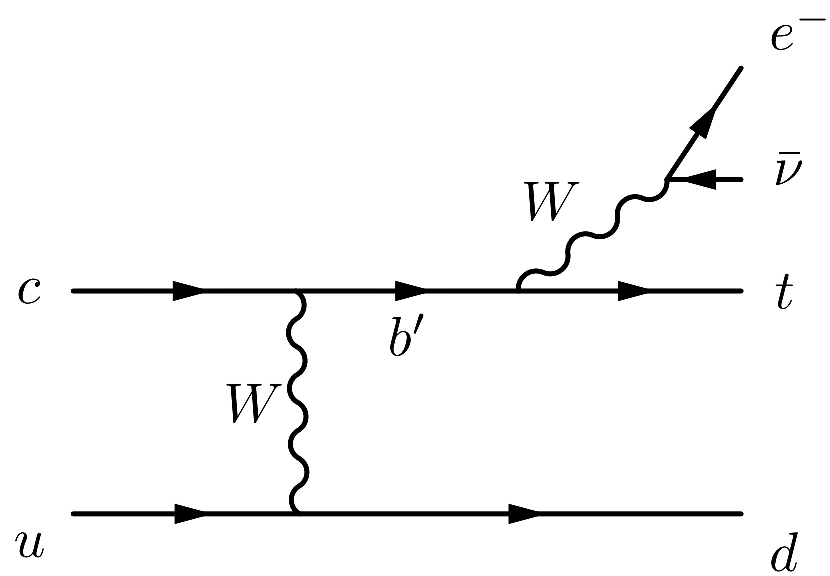

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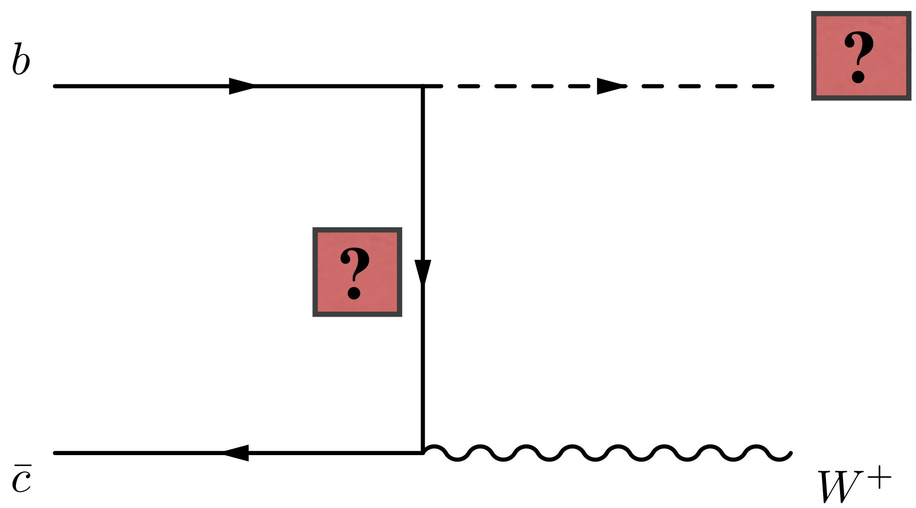
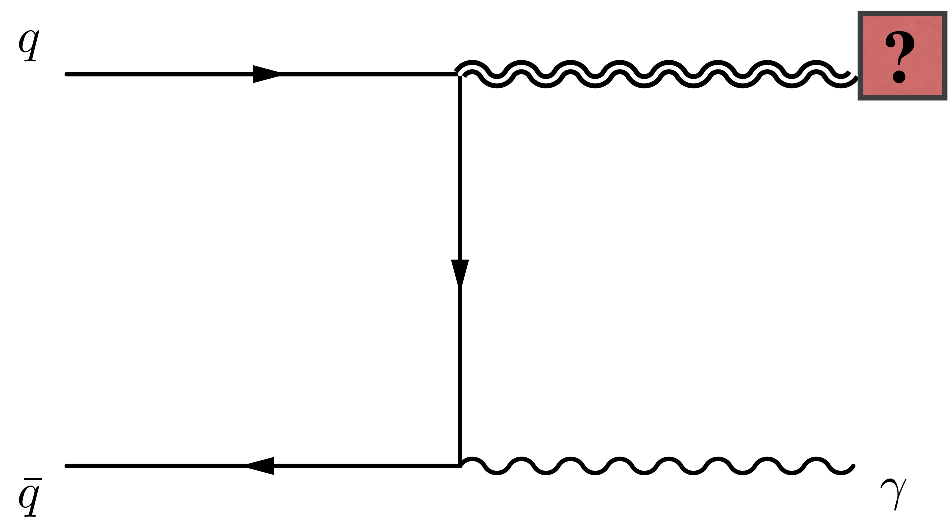
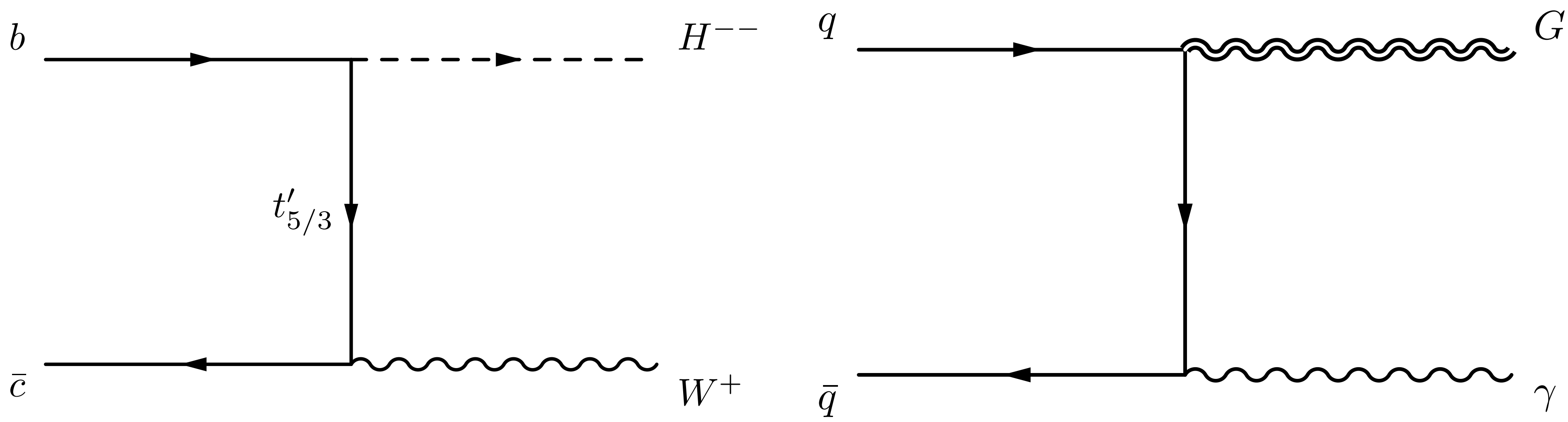
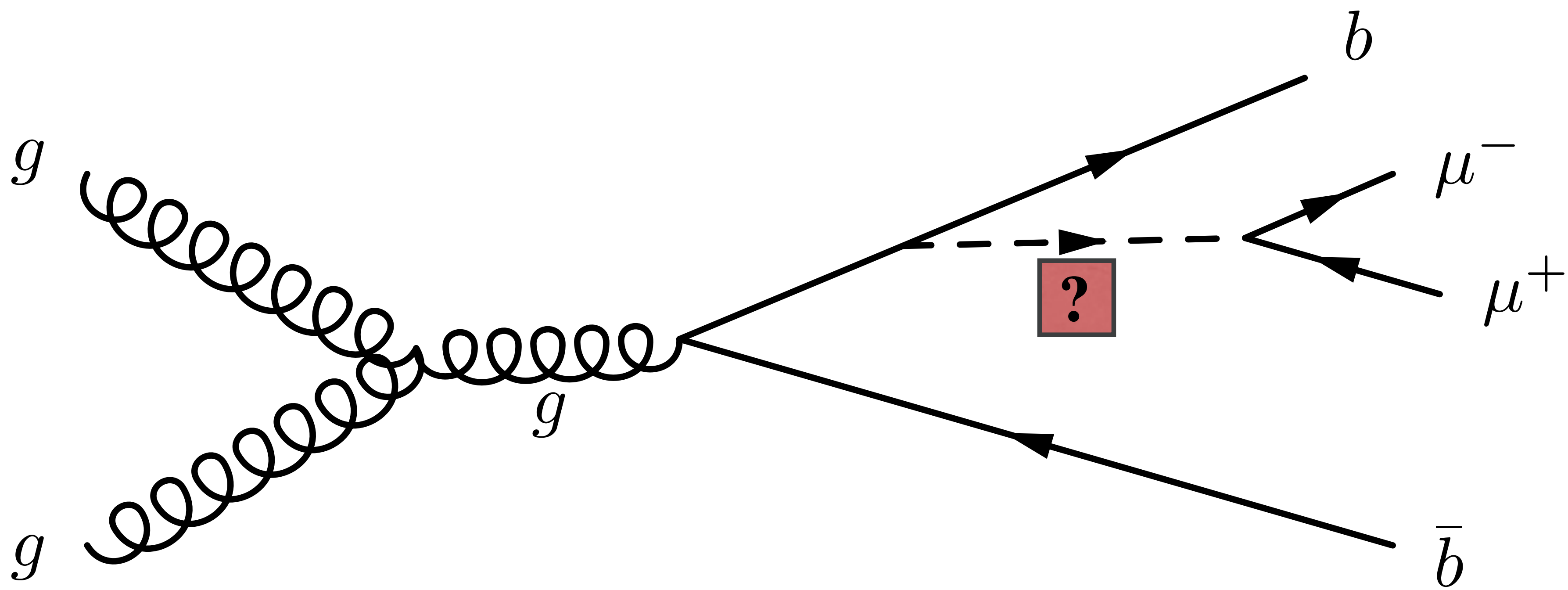




associated production with a SM particle



BSMsstrahlung



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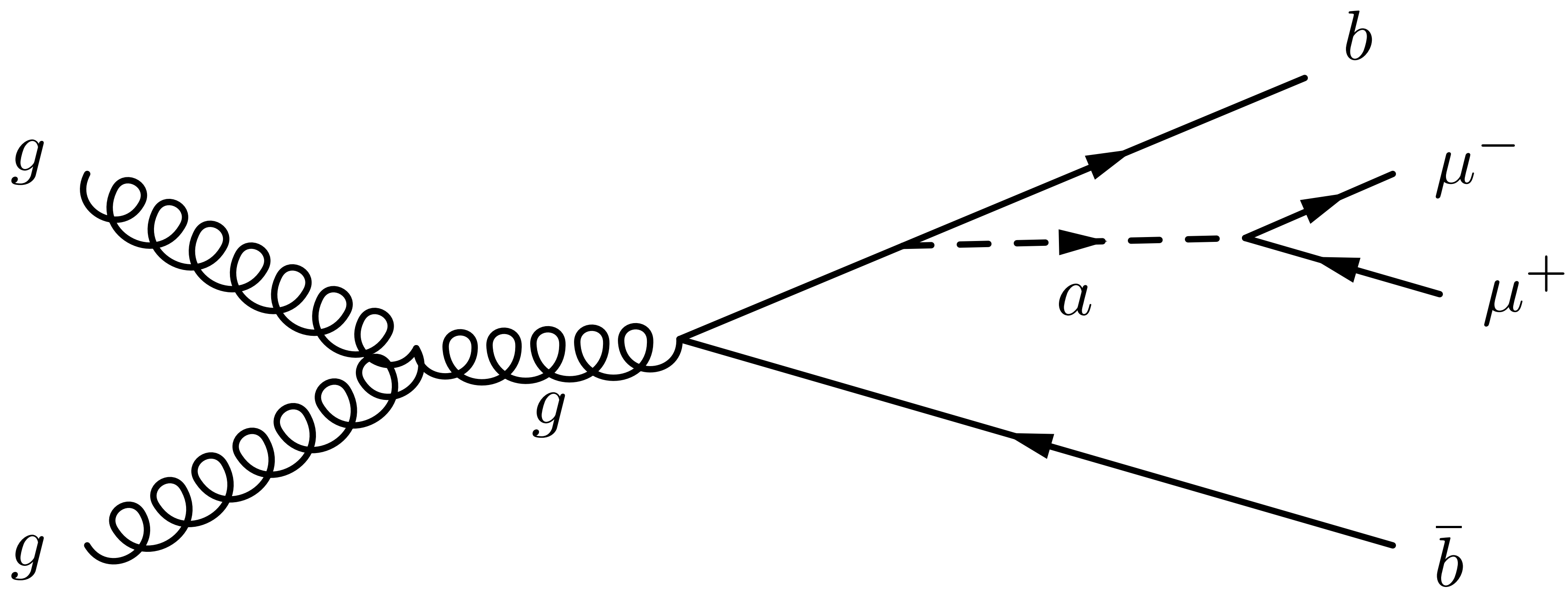
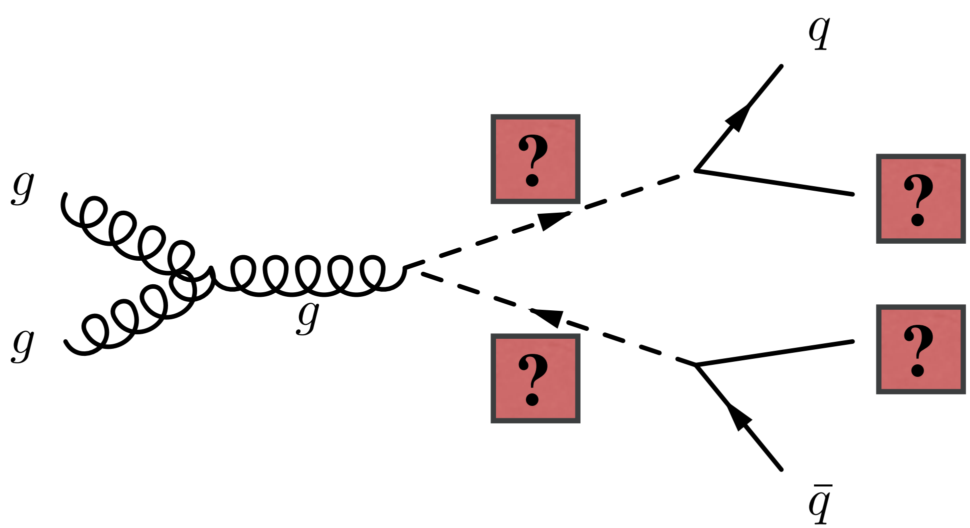
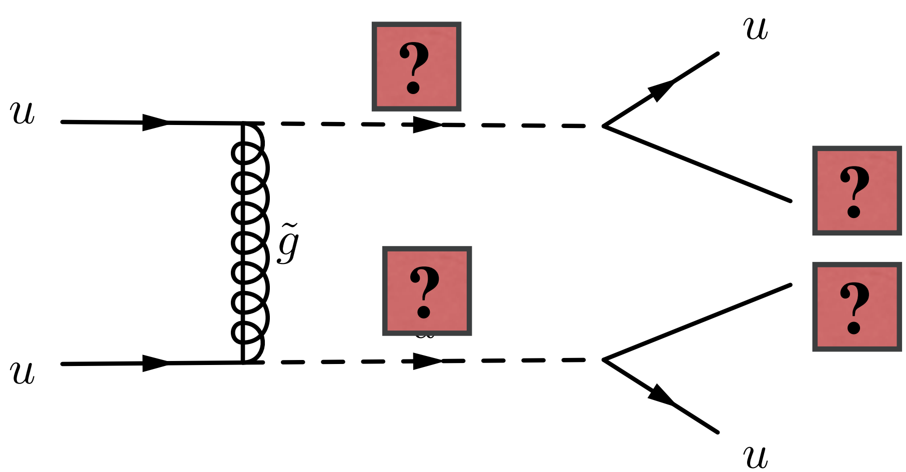


pair production, with decays to both SM particles and exotics





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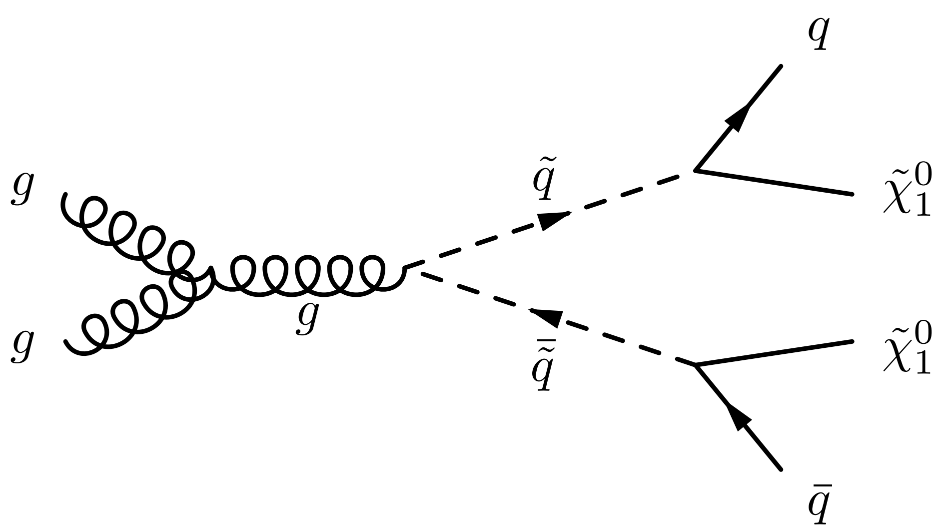
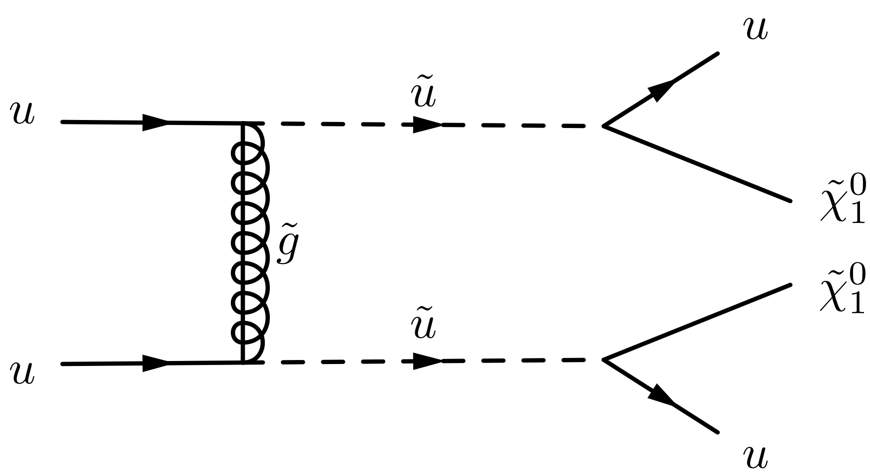
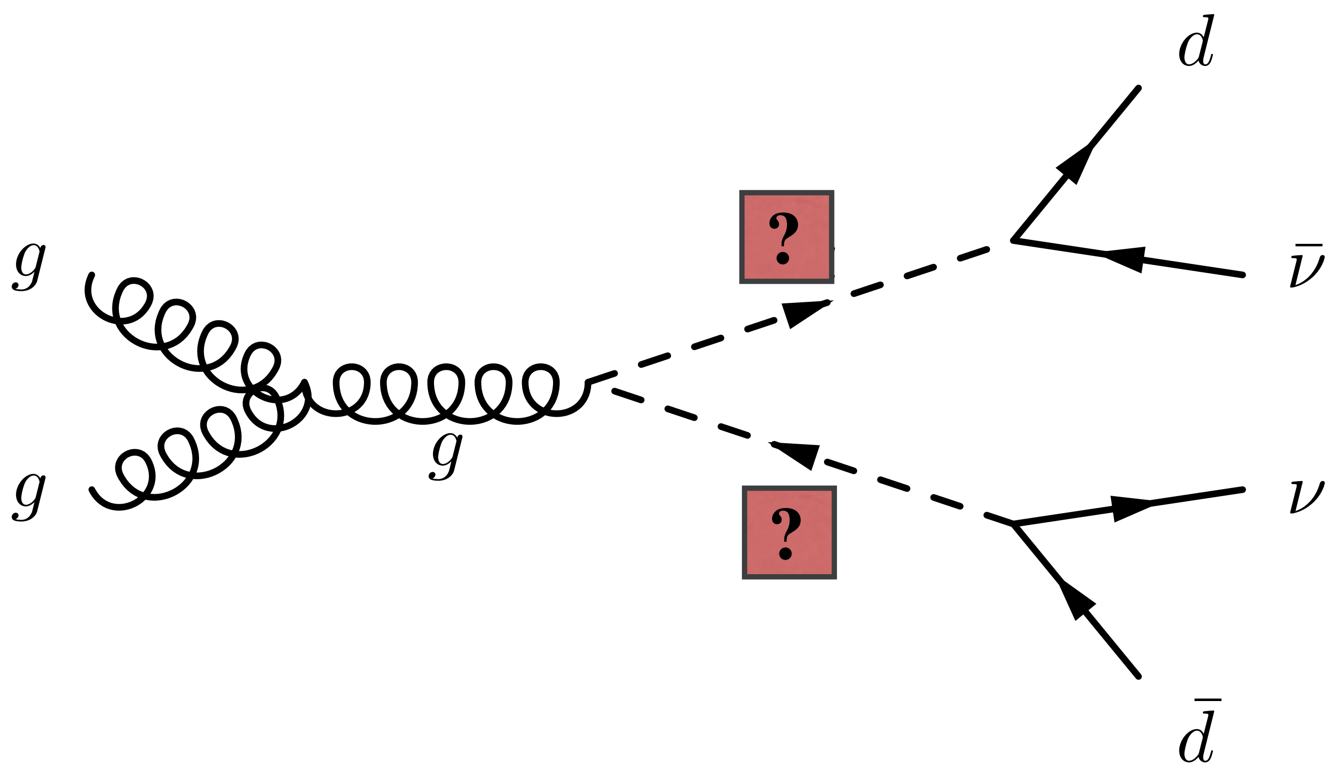




pair production, with decays to SM particles



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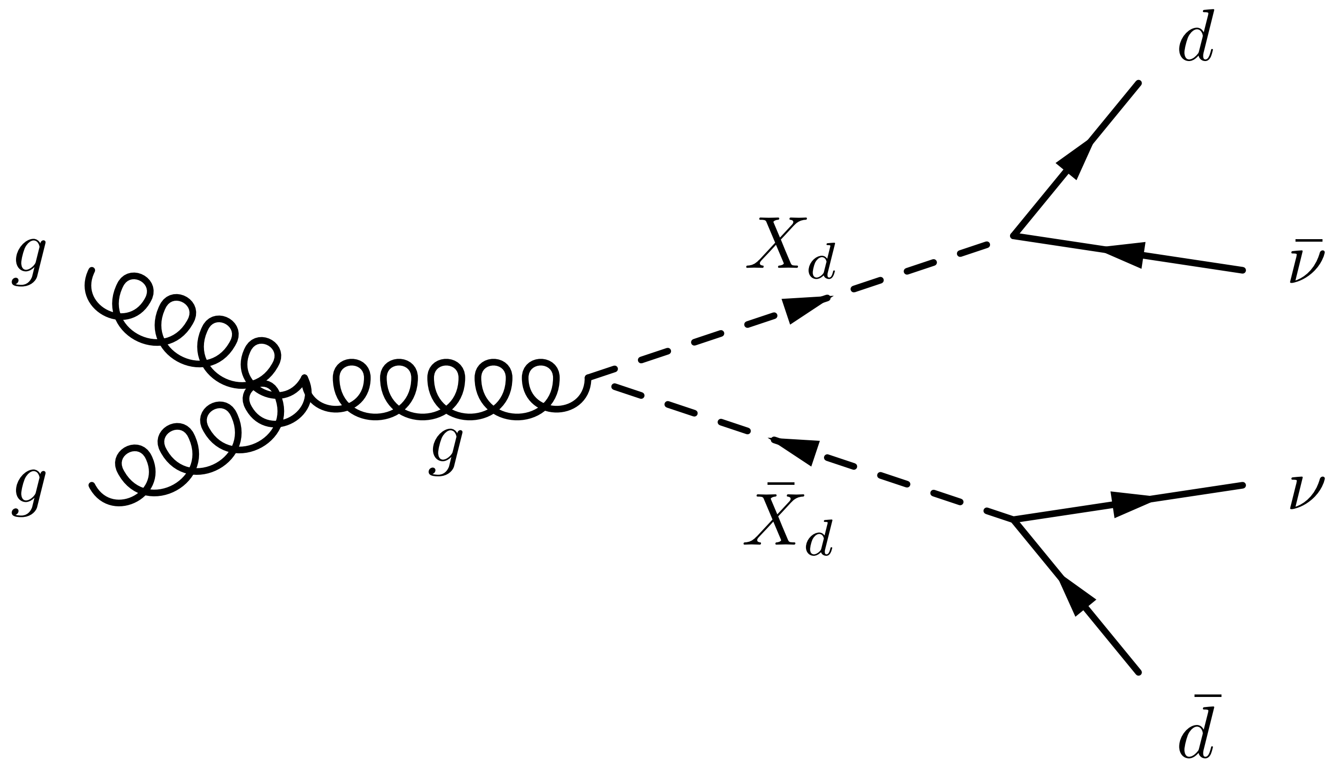
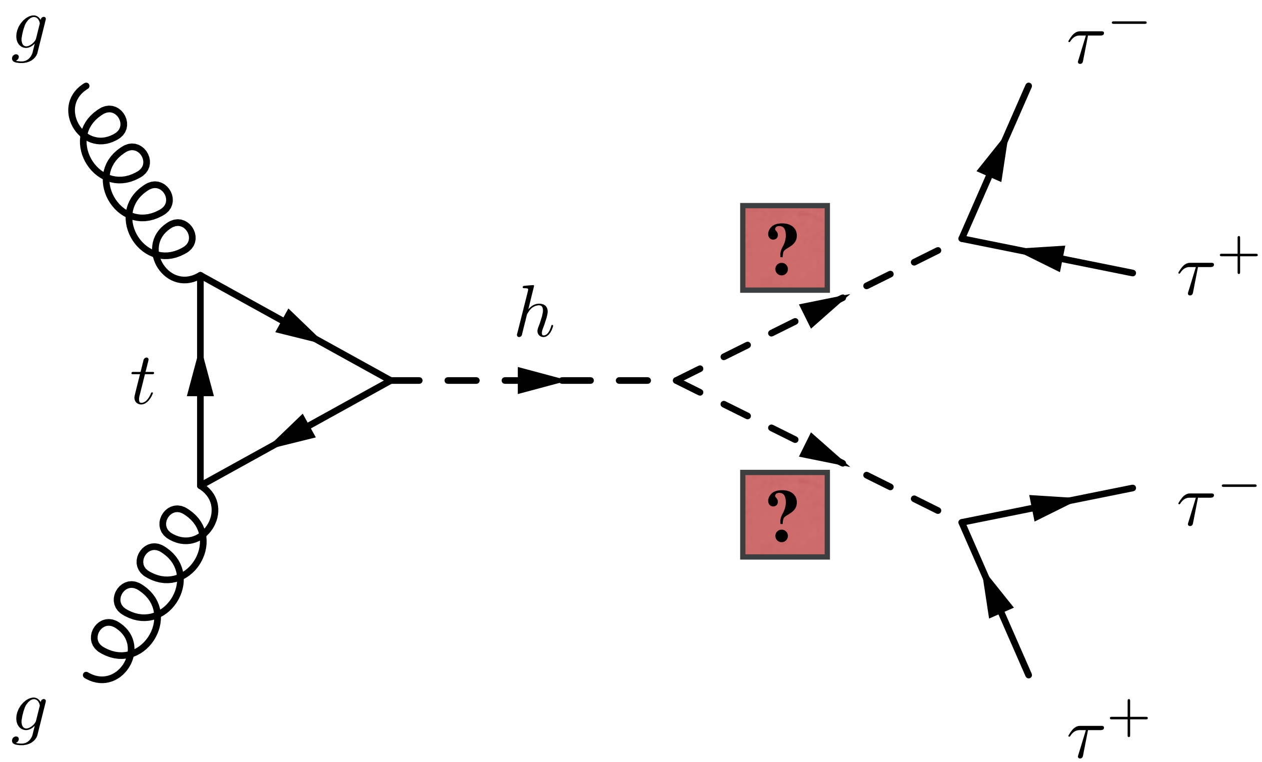


decay of SM particle into exotics



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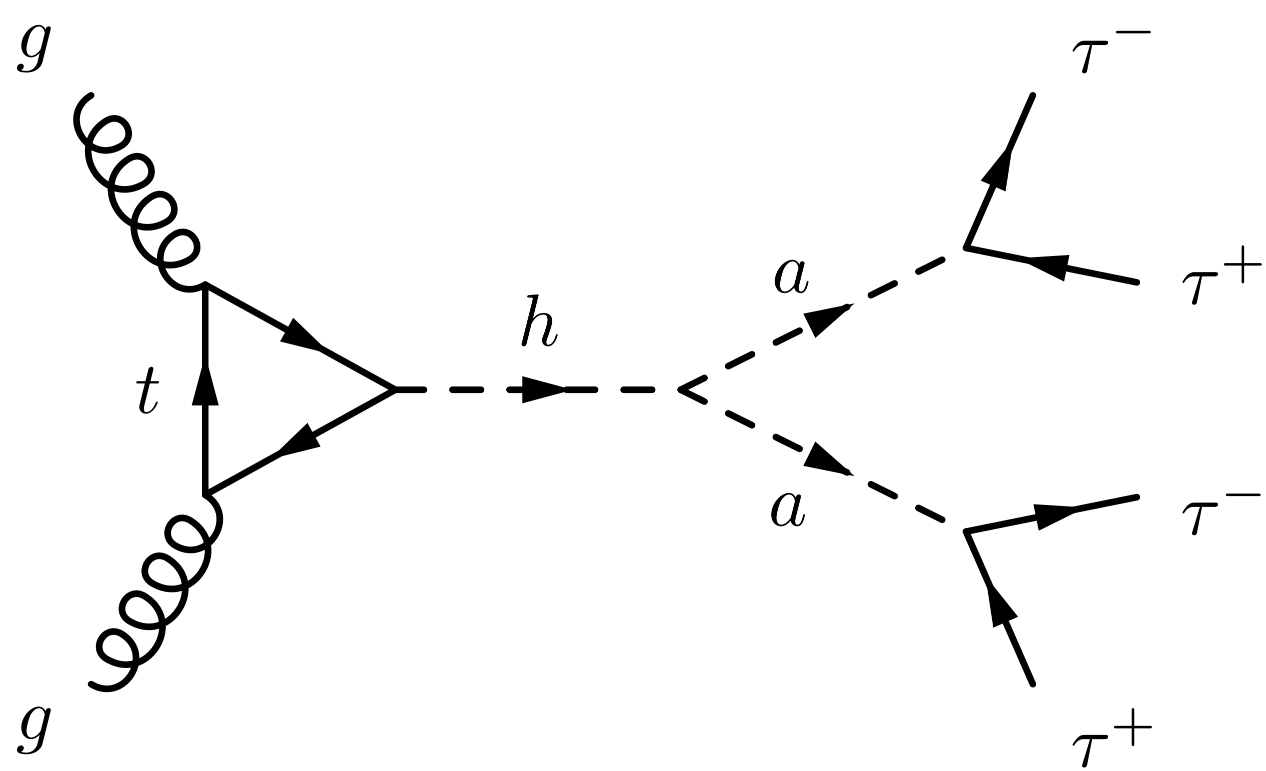


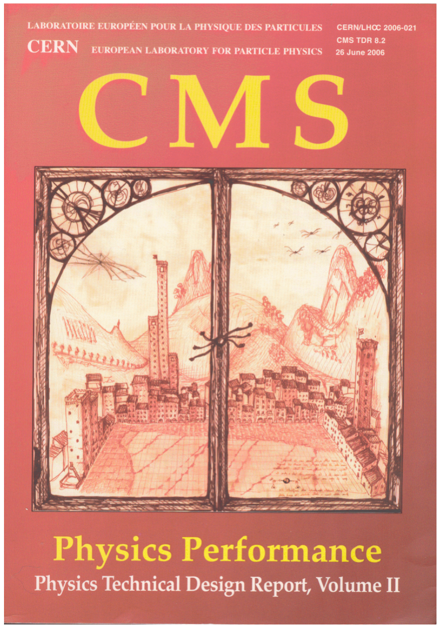
An example of looking for new physics at LHC:

dijets

why dijets?

- relatively simple (mostly bump hunting)

- well studied; e.g. full public analysis in CMS Physics Technical Design Report



what are dijets?

what kind of events belong to the dijet topology?

- events should have at least two jets!

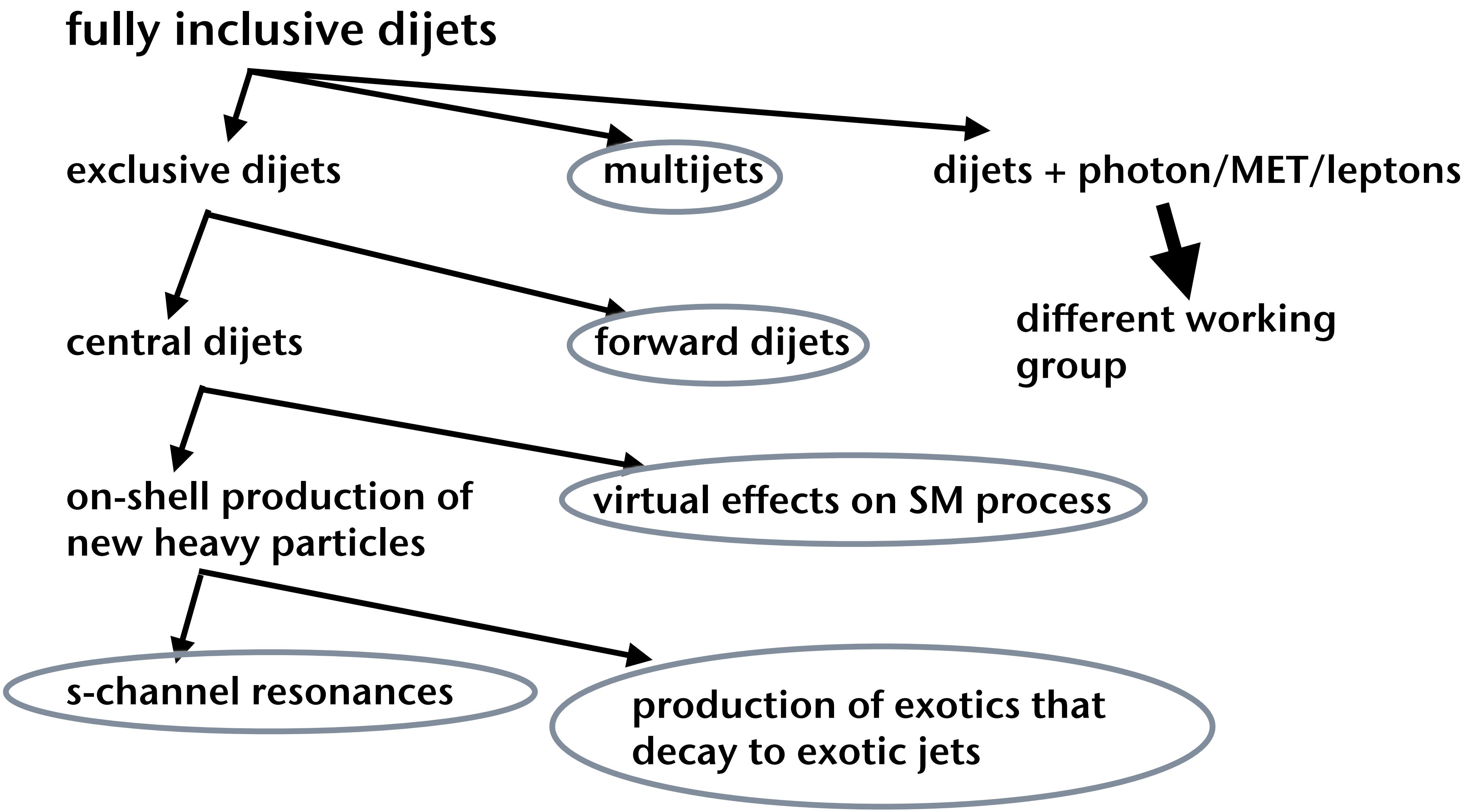
- dijets with photons and/or missing transverse energy (MET) and/or 2 or more leptons belong to other topologies.

- dijet + single lepton + no MET violates lepton number, so is (presumably) a detector background.

- multijets are part of "inclusive" dijets.

- forward jets are a special case of dijets.

what are dijets?

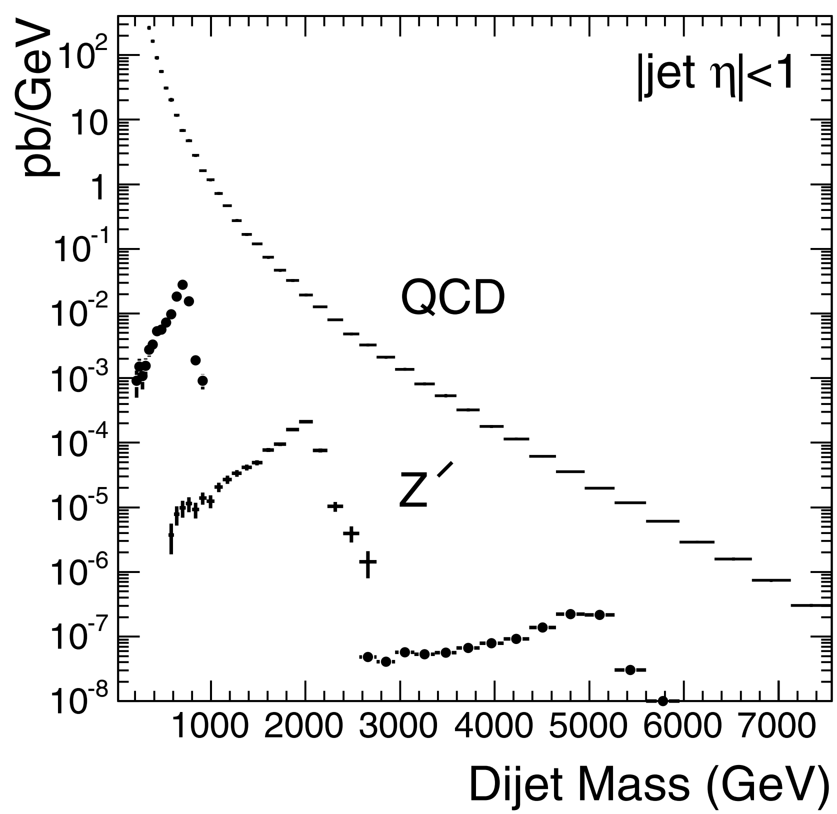


dijet resonances

- appear as a bump in the dijet invariant mass plot

- could also appear as a rise or dip in the tail, but I will ignore this

- what are the observables?



dijet resonance observables

- cross section times branching fraction: $\sigma \times \Gamma_{\mathbf{jj}}$

- mass
  - requires $\mathbf{E_T},\ \eta,\ \phi$ and “jet mass” to make a jet 4-vector and thus to make a dijet invariant mass.
  - need jet corrections if you want extracted mass = physical mass.

- width
  - for very broad resonances, hard to measure.
  - for narrow resonances, masked by dijet mass resolution:

$$\frac{\sigma}{\mathbf{M}} \sim \mathbf{1.3}\sqrt{\frac{1\ \mathrm{GeV}}{\mathbf{M}}}$$

model-independent analysis of dijets?

- given these observables, why can’t I just do a completely bottom-up model-independent analysis of any observed dijet resonance signal?

- then extract the mass and width of the resonance from a fit to the data.

- such an analysis would begin by writing down the (nearly) model-independent general formula for resonance production at a hadron collider:

near the resonant peak, ignoring interference effects, we can write:

$$\mathbf{M^2\frac{d\sigma}{dM^2} = \int dx_1 dx_2 \frac{\kappa^2 \hat{s}}{(\hat{s} - M_0)^2 + \Gamma^2 M_0^2}}$$

$$\times \sum_{\mathbf{i,j}} \mathbf{Q_{i,j}^2 f_i(x_1) f_j(x_2) \left[\delta(\frac{M^2}{s} - x_1 x_2) + D_{ij}\left(\frac{M^2}{\hat{s}}, \alpha_s\right)\right]}$$

$\mathrm{M} =$ dijet invariant mass

$\mathrm{x_1,\ x_2} =$ momentum fractions of the initial state partons

$\mathrm{f_i(x_1),\ f_j(x_2)} =$ parton distribution functions

$\hat{\mathrm{s}} =$ partonic subprocess center of mass energy squared = $\mathrm{x_1 x_2 s}$

$\mathrm{M_0,\ \Gamma} =$ mass and width of the resonance

$\kappa =$ overall coupling strength to the initial state quarks/gluons

$\mathrm{Q_{i,j}} =$ couplings of the resonance to initial state partons

$\mathrm{D_{i,j}} =$ higher order QCD corrections

unknown inputs

$$\mathbf{M^2 \frac{d\sigma}{dM^2} = \int dx_1 dx_2 \frac{\kappa^2 \hat{s}}{(\hat{s} - M_0)^2 + \Gamma^2 M_0^2}}$$

$$\mathbf{\times \sum_{i,j} Q_{i,j}^2 f_i(x_1) f_j(x_2) \left[\delta(\frac{M^2}{s} - x_1 x_2) + D_{ij}\left(\frac{M^2}{\hat{s}}, \alpha_s\right)\right]}$$

- what are the possible parton initial states?
- what are possible color, weak and electric charges?
- what is the spin of the resonance?

table of possible initial parton states, spins and charges for a dijet resonance

initial partons	spin	electric charge	color charge	weak charge
qq	0, 1, 2, ...	4/3, 1/3, -2/3	3, 6	0, 1
qg	1/2, 3/2, ...	2/3, -1/3	3, 6, 15	1/2
gg	0, 1, 2, 3, ...	0	1, 8, 10, 27	0
$q\bar{q}$	0, 1, 2, ...	0, 1	1, 8	0, 1
bq, bg, $b\bar{q}$				

~ 100 possibilities!

failure of bottom-up analysis@LHC

- Ignorance of parton initial state implies orders of magnitude uncertainty from parton distributions.

- This uncertainty is entangled with orders of magnitude uncertainty about couplings (strong, weak, em, other) and charges (note $\sigma \times \Gamma_{jj} \propto Q^4$).

- It helps if you can measure the width separately, since $\Gamma \propto \kappa M_0$, but in most cases width is too narrow to measure.

BSM models as templates for searches

- A wisely chosen spread of BSM theory models makes this problem managable.

- ~10 models can do the work of 100's or 1000's or ∞

- Don't need to believe in any of them, though well-motivated examples are to be preferred.

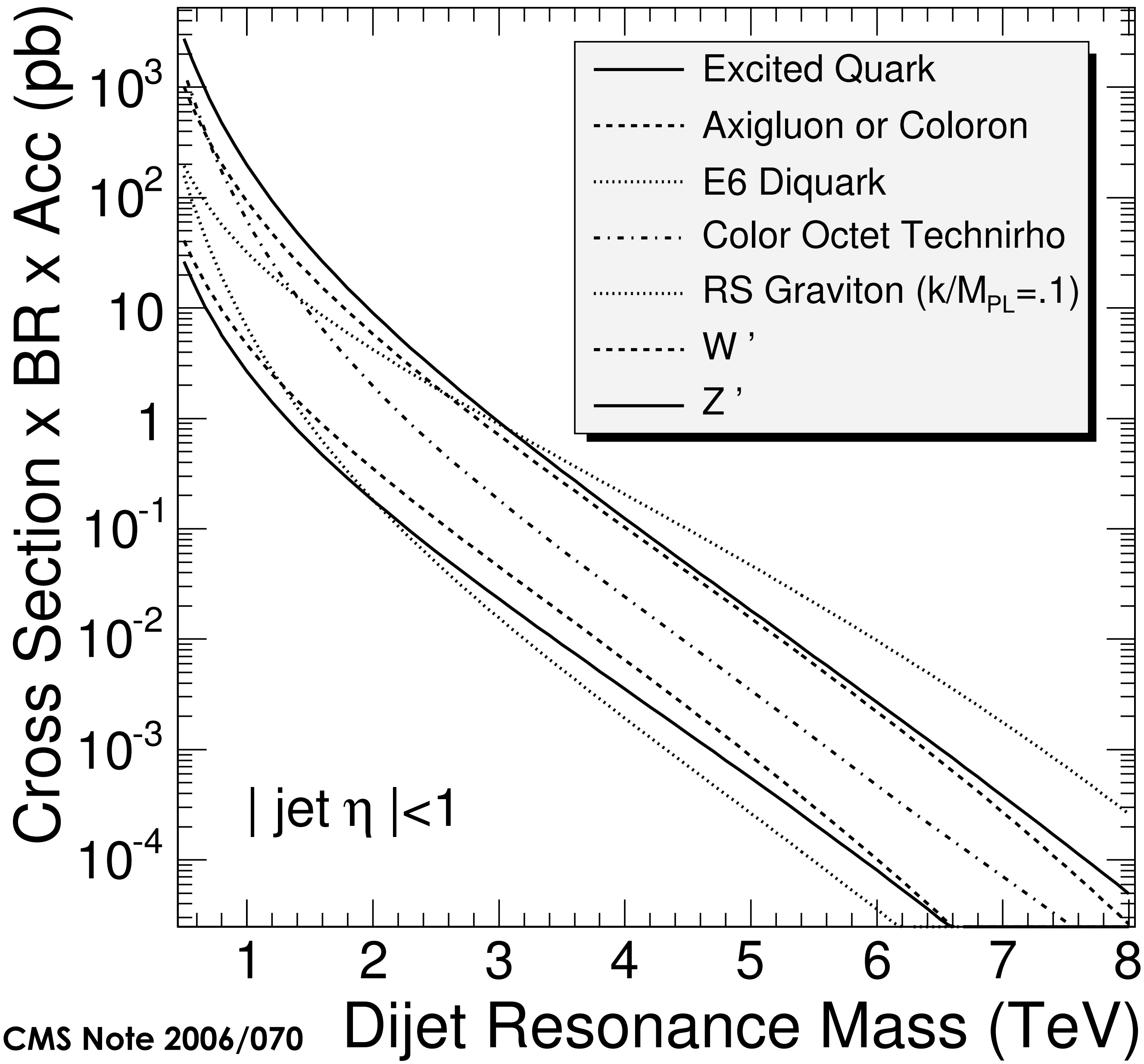
BSM models as templates for searches

- Choice of template models should be dictated by the observables and kinematics of the search channel…

- …not by your local theorist's biases, the latest fad, etc.

- A well-chosen set of template models applied to inclusive searches is probably as close as you can get to a model-independent discovery strategy

model templates for dijet searches



CMS Note 2006/070

- excited quark
- axigluon or coloron
- E6 diquark
- techinrho
- RS graviton
- W'_{SSM}
- Z'_{SSM}

initial partons	spin	electric charge	color charge	weak charge
qq	0, 1, 2, ...	4/3, 1/3, -2/3	3, 6	0, 1
qg	1/2, 3/2, ...	2/3, -1/3	3, 6, 15	1/2
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$q\bar{q}$	0, 1, 2, ...	0, 1	1, 8	0, 1
bq, bg, $b\bar{q}$				

looks pretty good

model templates for discriminating signals

- We need to study not only our sensitivity to signals but also our ability to discriminate between different possible origins of the same signal.

- This means developing model templates that intentionally resemble in each other in a given channel.

- It means developing robust discriminating observables.

- Model templates allow us to study the correlations between signals in different channels: e.g. dijets versus dileptons and diphotons.

Summary of first lecture - I

- **BSM "theory space" is vast, not well-mapped.**
- **Both experimental hints and deep theoretical problems point to new physics at high energies.**
- **BSM physics generally involves new particles, new symmetries, new forces, perhaps other new degrees of freedom.**
- **Major BSM frameworks:**
    - **Weak scale supersymmetry (SUSY)**
    - **Little Higgs**
    - **Universal extra dimensions (UED)**
    - **Randall-Sundrum warped models <=> Technicolor**
    - **Hidden Exotica**

Summary of first lecture - II

- **BSM models are very constrained by electroweak precision data (EWPT); can characterize models by how they escape these constraints.**
- **BSM models can be phenomenological look-alikes, even when their theoretical starting points are vastly different.**
- **Many, many different processes at LHC could produce new particles.**
- **Even “simple” LHC signatures, e.g. dijet resonances, are too complicated to analyze in a model-independent way.**
- **Need BSM models as “templates” for LHC experiments.**
- **Many interesting LHC signatures not yet studied sufficiently or at all.**