Targets for early discoveries at the LHC

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LHC first data. Ann Arbor, Michigan.

Early.

- 7 TeV, $\sim 1 \text{ fb}^{-1}$
- Estimates at 8 TeV.
  - Enhancement in mass reach $\sim 8/7$
  - Fixed mass, rate enhanced by $\mathcal{O}\ 50\% - 100\%$
- Higher luminosity, enhanced by $\sim \sqrt{\frac{\mathcal{L}}{\text{fb}^{-1}}}$

Early targets.

- Discoverable. Many possibilities.
    - Brief review of some simple criteria.
- Likely? More theory motivations.
    - Our “favorite” scenarios lead to discoverable signals.

Will be subjective, cannot be complete.
Try to emphasize less “well-known” or less “well-mentioned” but not “strange” channels.

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In the next year or so, LHC will venture significantly into the territories of many interesting new physics scenarios.
Exciting opportunities to make discoveries!

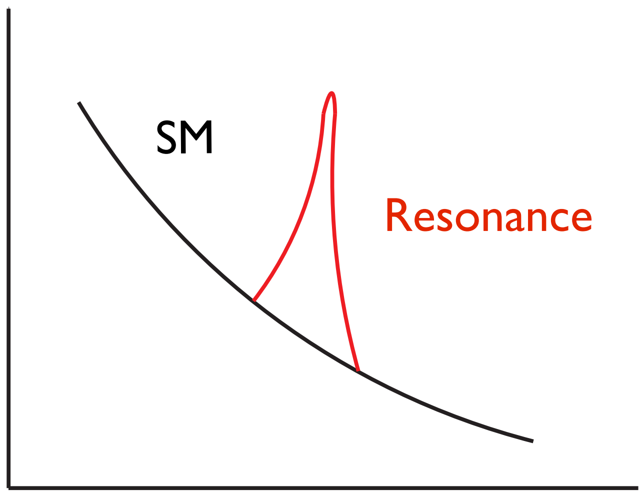
Two possible ways of early discovery:

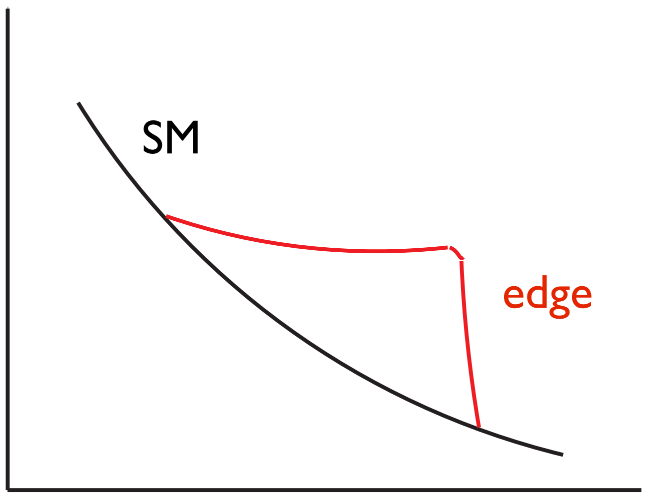
- Large rate, necessary condition.

- Final states with more energetic (hard) objects, for example:

$$(\geq 3 \text{ jets}) + \not{E}_T \quad (\geq 2 \text{ jets}) + (\geq 1\ell) + \not{E}_T$$

- Special kinematical features:





Rates: phase space

- General phase space factor:

$$d\Pi_n = \Pi_f \left(\int \frac{d^3 p_f}{(2\pi)^3} \frac{1}{2E_f} \right) (2\pi)^4 \delta^{(4)}(p_a + p_b - \sum p_f)$$

- One additional particle in production

$$\sim \text{an additional factor of } \frac{1}{16\pi^2}$$

- For example

... variables $\subset \{0,1\}$

$$d\Pi_2 = \frac{1}{4\pi}\frac{1}{2}\lambda^{1/2}(1, m_1^2/\hat{s}, m_2^2/\hat{s})d...$$

$$d\Pi_3 = \frac{1}{(4\pi)^3}\lambda^{1/2}(1, m_1^2/m_{23}^2, m_2^2/m_{23}^2)2|\vec{p}_1|dE_1 d...$$

Production rate also depends on

- Initial state parton density.
- Coupling constants
  - More final state particles, higher power of coupling constants.
  - QCD process dominates over weak processes.
- Singularities (enhancements) of matrix elements
  - Resonances.
  - Collinear and soft regime...

Winning by rate and topology.

- Either pair production (colored) or single production of weakly coupled states.

- Initial states.
    - Mostly dominated by gluon.
    - Valence quark can also be significant.
    - $\bar{q}$

- Final states.
    - Long, complicated decays. More hard objects, preferably leptons.

Interesting exercise: best discoverable channels based just on these rules.
Answers: "supermodels", Bauer et. al., arXiv:0909.5213

Nature may not go out of its way to be kind to us.

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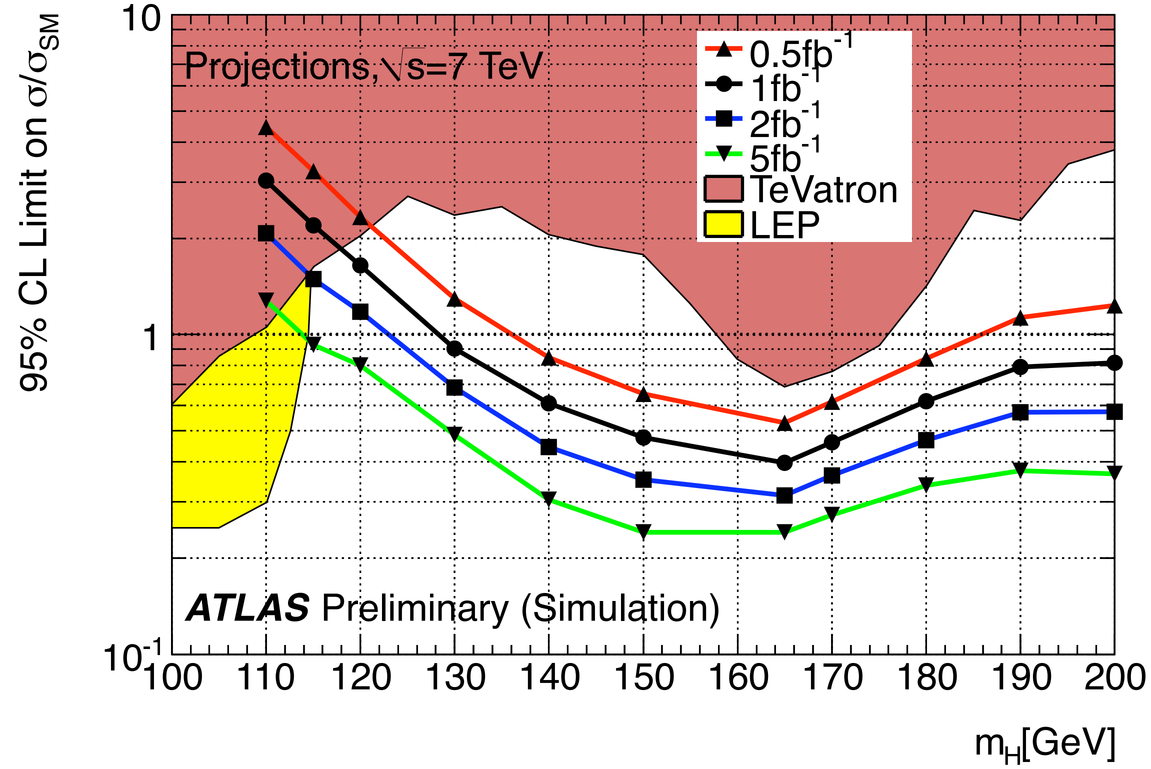
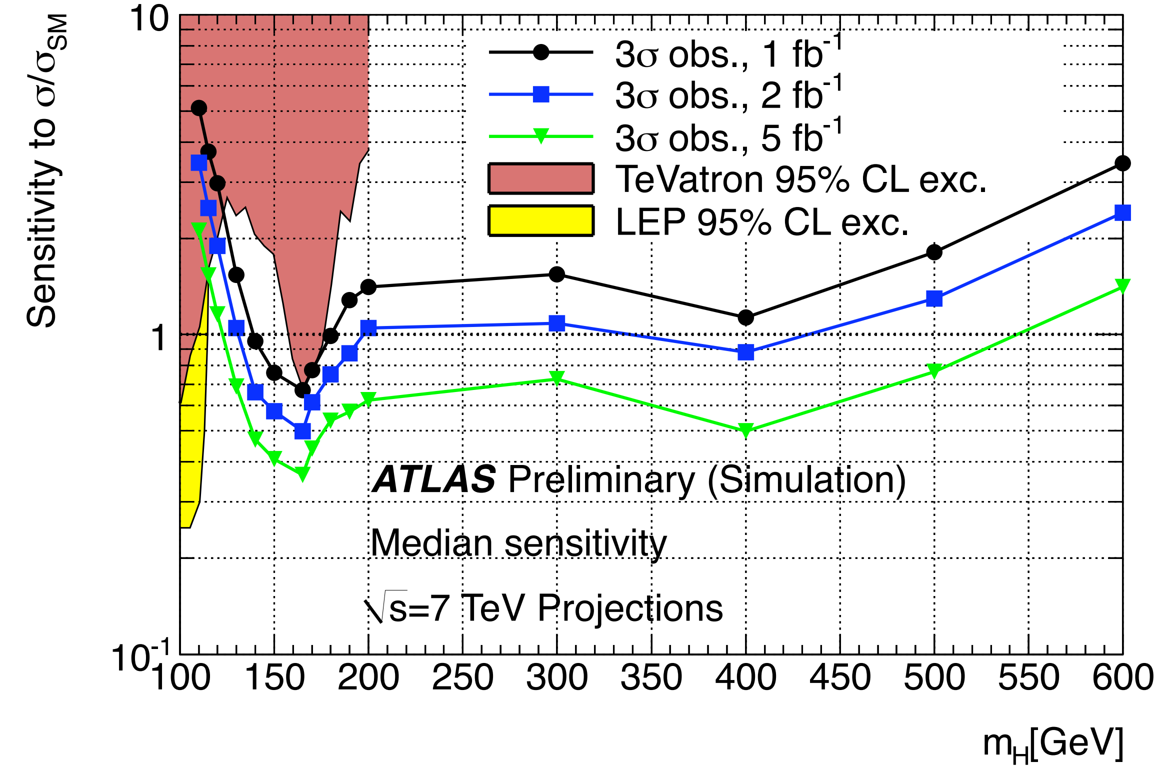
What's more likely?

Obviously, the Higgs.





Covered later at this conferece.

Partners

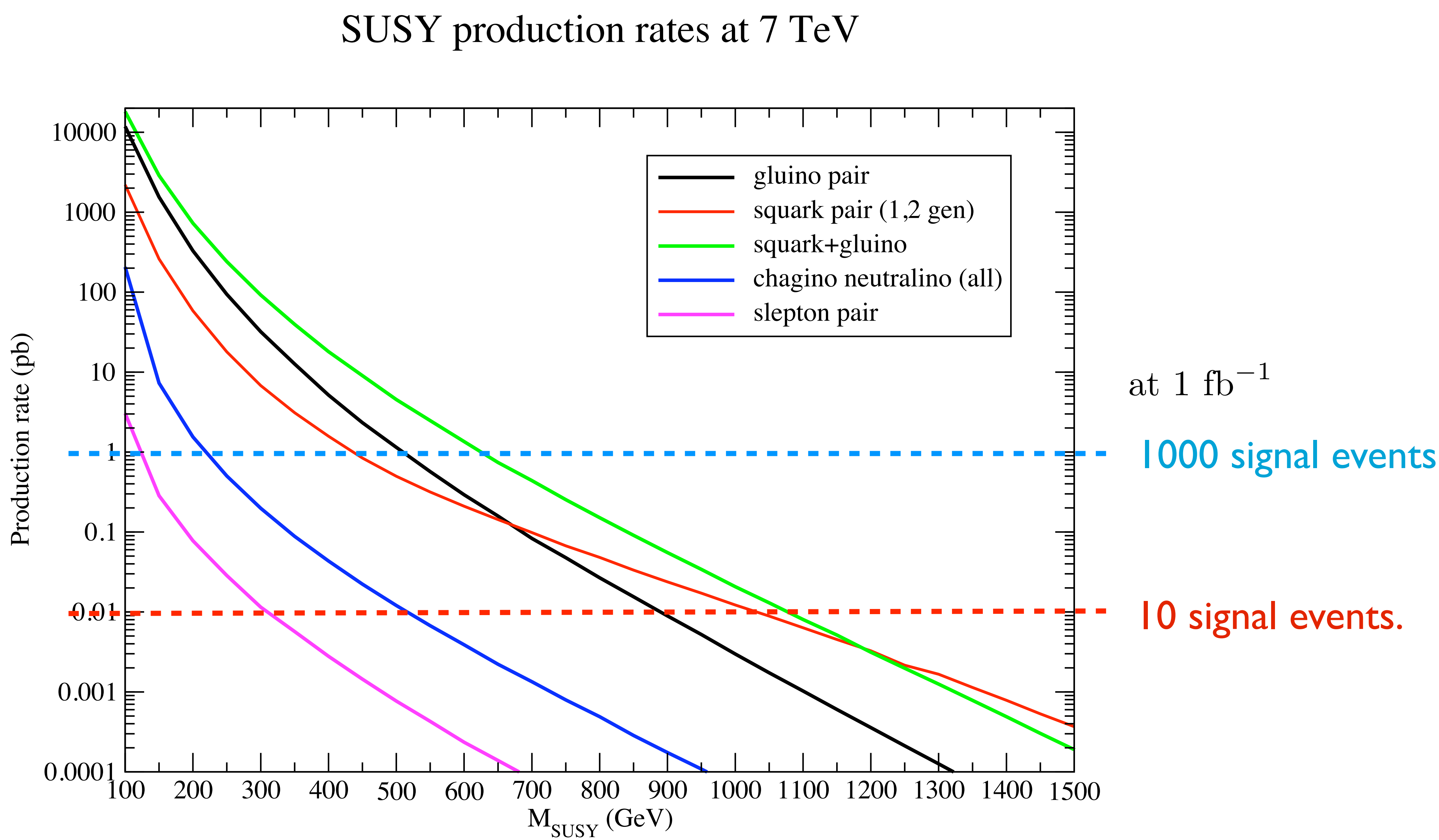
New particles with similar gauge quantum numbers as SM particles.
Motivated by solving hierarchy problem.

Superpartners: $\tilde{g},\ \tilde{q},\ \tilde{W}, \tilde{Z},\ \tilde{\ell}...$

KK partners: $g^{\rm KK},\ q^{\rm KK},\ W^{\rm KK}, Z^{\rm KK},\ \ell^{\rm KK}...$

....

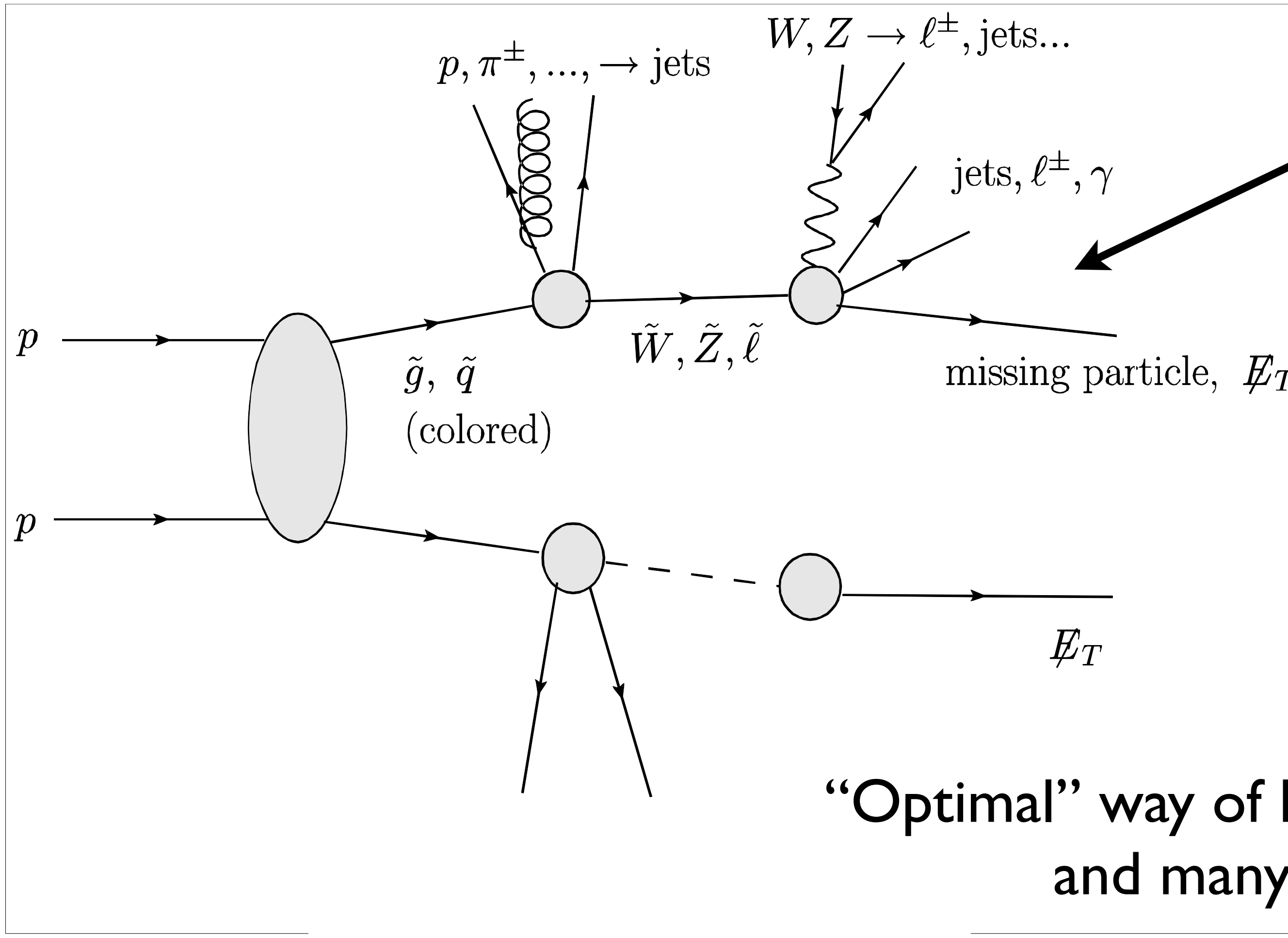
Production.



Dominated by the production of colored states.

Similar pattern for other scenarios. Overall rates scaled by spin factors.

Signature of partners



Decay chain

"Optimal" way of having both large production rate and many hard final state objects.

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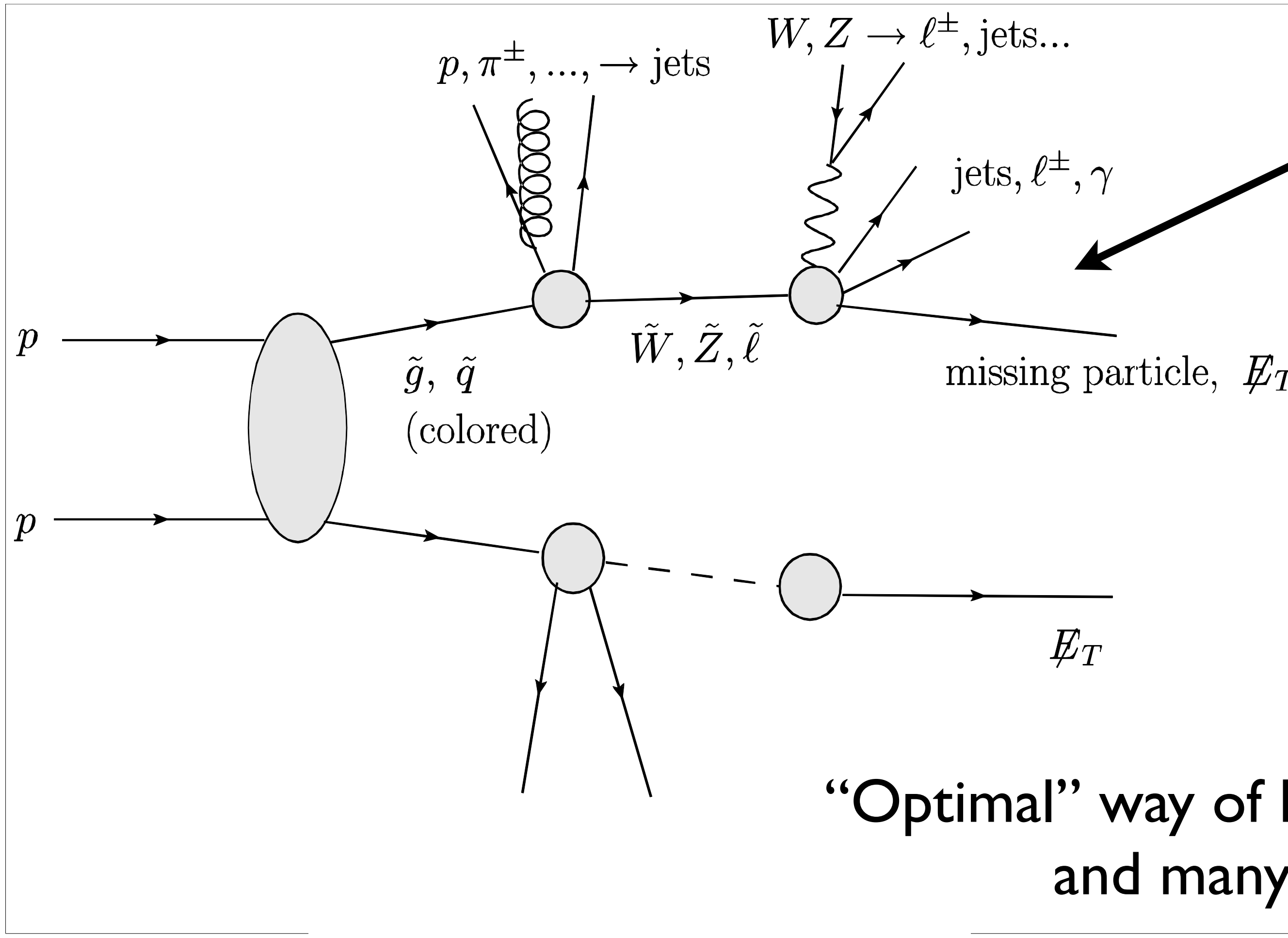


Decay chain

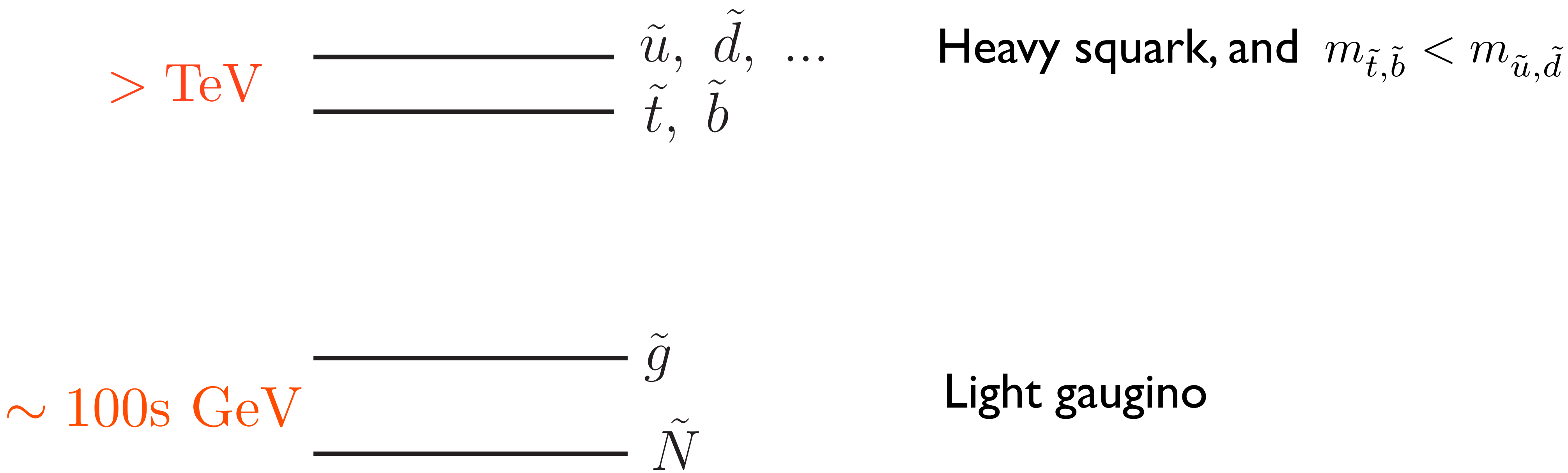
"Optimal" way of having both large production rate and many hard final state objects.

- "Well known", many studies in the past 2 decades.
- If we are reasonably lucky and partners are not too heavy, this can lead to early discovery.

$$\text{At 7 TeV and 1 fb}^{-1} : \sim 10^3 \ \tilde{q} \text{ and } \tilde{g} \ (\sim 500 \text{ GeV})$$

Talks by ATLAS and CMS at this conference.

A promising, and complicated, scenario.



- Better consistency with constraints:
  - flavor, CP, Higgs mass
- A generic feature of large classes of models.
  - Scalar heavier than inos.
  - 3rd generation scalar somewhat lighter. (mixing, RGE)

Many recent models: Acharya, et al. 07; Everett, et. al. 08; Langacker et. al. 07; Heckman et al. 08; Sundrum 09; Barbieri et. al., 10.....

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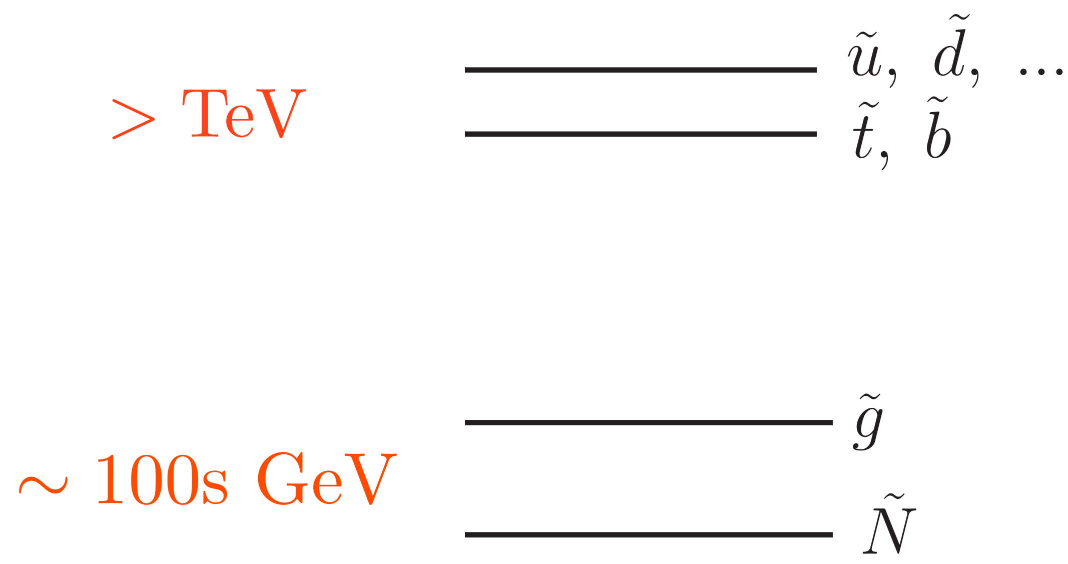
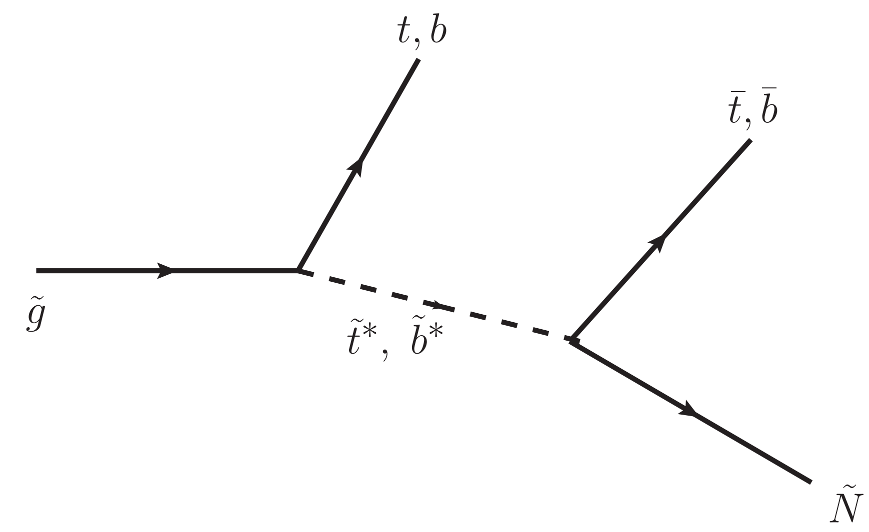




The Dominant channel

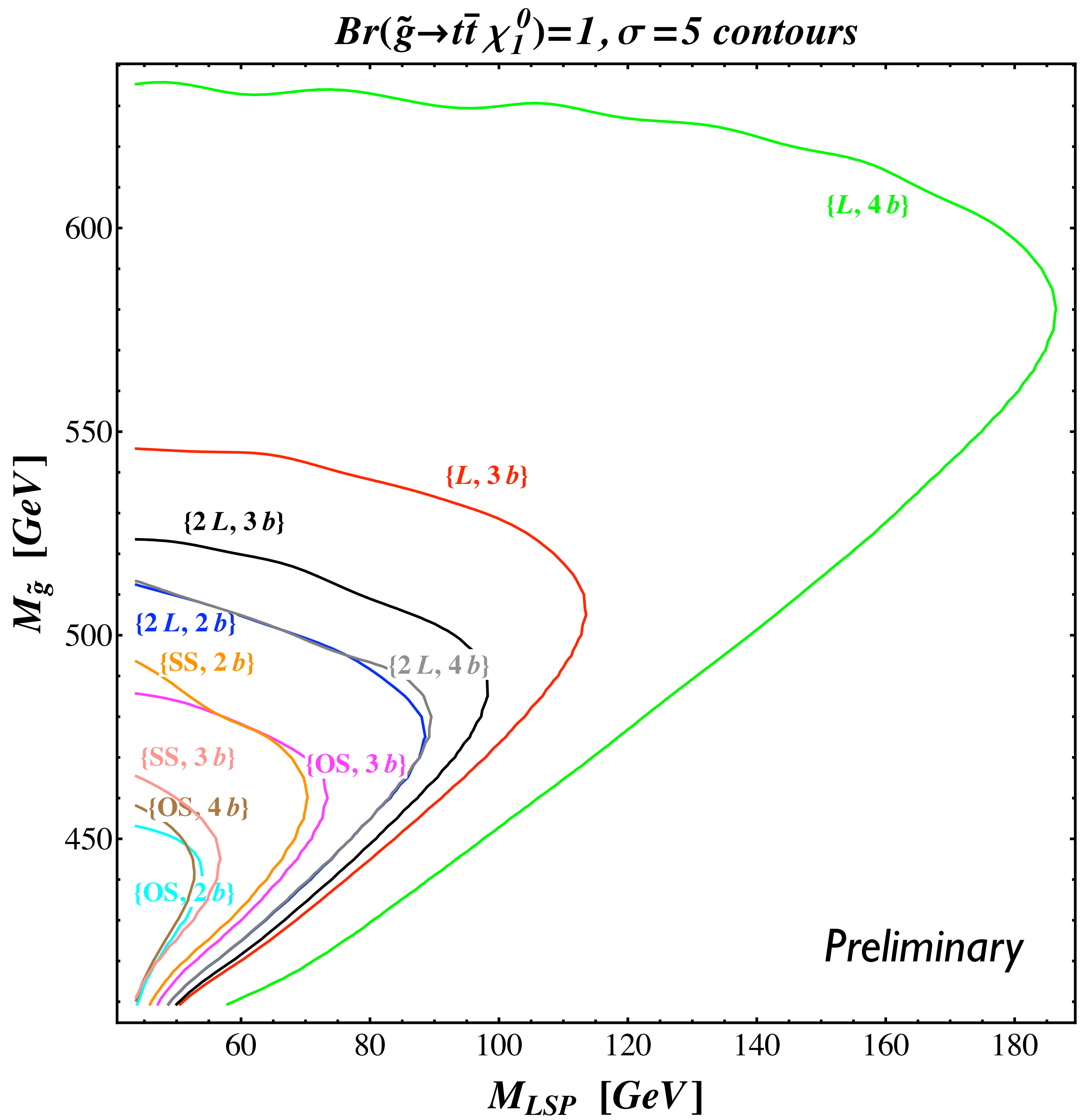
$$p\ p \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t}(\text{or } t\bar{t}b\bar{b},\ t\bar{t}t\bar{b}\ \ldots)$$

$$\tilde{g} \to t\bar{t}(b\bar{b}) + \tilde{N},\ \text{or}\ \ t\bar{b} + \tilde{C}^- \quad t \to b\ell^+\nu$$

- Multiple b, multiple lepton final state.
  - Good early discovery potential.
  - Challenging to interpret: top reconstruction difficult.

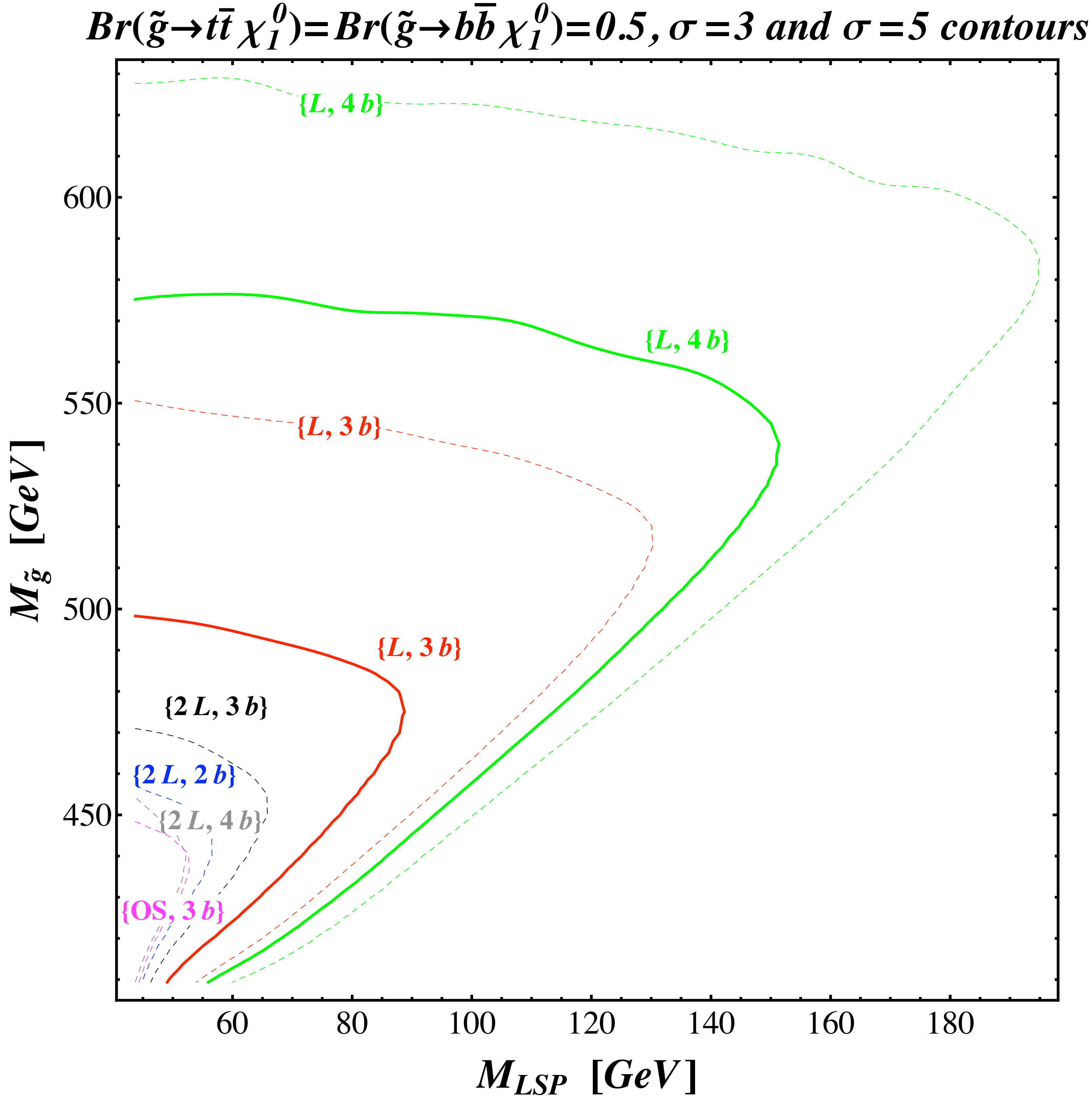
Acharya, Grajek, Kane, Kuflik, Suruliz, Wang, arXiv:0901.3367
Kane, Kuflik, Lu, Wang, to appear.

Reach at 7 TeV and one inverse fb.



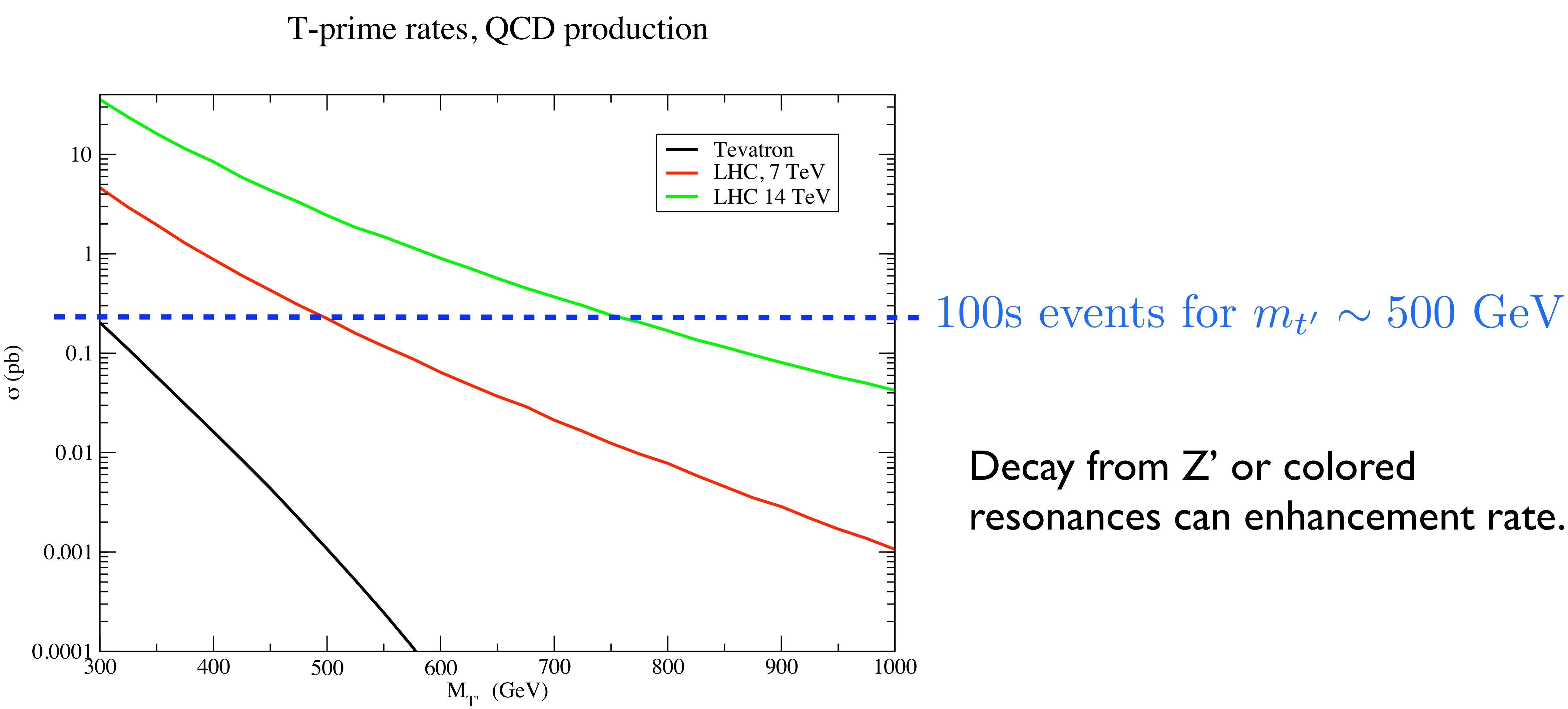
Kane, Kuflik, Lu and Wang, to appear

Reach:


Br(g̃→tt̄ χ₁⁰)=Br(g̃→bb̄ χ₁⁰)=0.5, σ=3 and σ=5 contours
{L, 4 b}
{L, 4 b}
{L, 3 b}
{L, 3 b}
{2 L, 3 b}
{2 L, 2 b}
{2 L, 4 b}
{OS, 3 b}
600
550
500
450
60
80
100
120
140
160
180
M_g̃ [GeV]
M_LSP [GeV]

More top-like signal

- top partner, top like heavier quarks.



Decay from Z' or colored resonances can enhancement rate.

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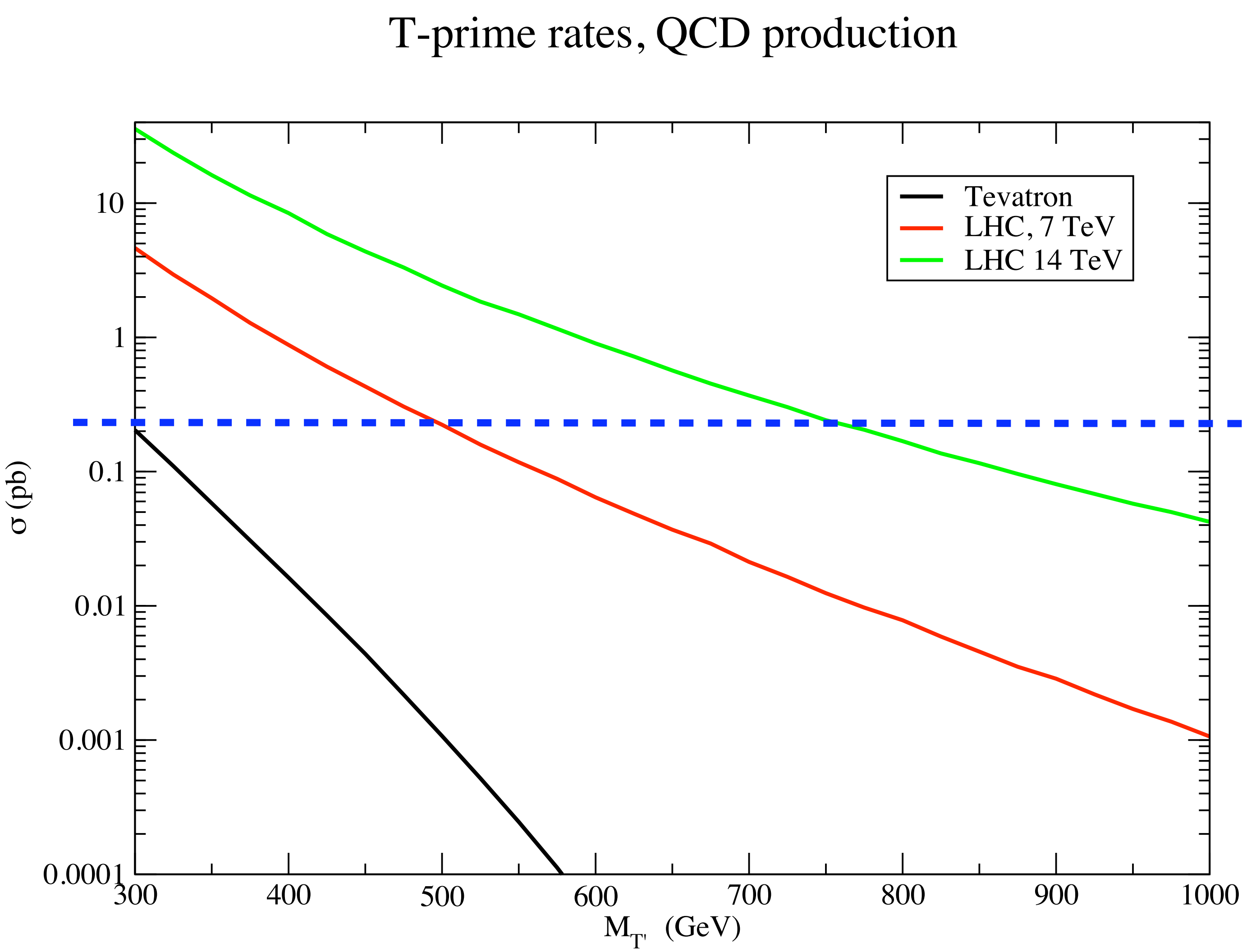

100s events for $m_{t'} \sim 500$ GeV

Decay from Z' or colored resonances can enhancement rate.

$$t' \rightarrow W + b,\ \ t + h(Z),\ \ t + \text{invisible}$$

Decays signal similar to top, will appear in the ttbar sample. Different reconstructed mass.

For example, Han, Mahbubani, Walker, Wang, arXiv:0803.3820

Long lived.

NP with light (very) weakly coupled particles

- Charged tracks, decays in outer detectors (HCAL, muon)...
- Very unique signal, rates may not need to be as large.

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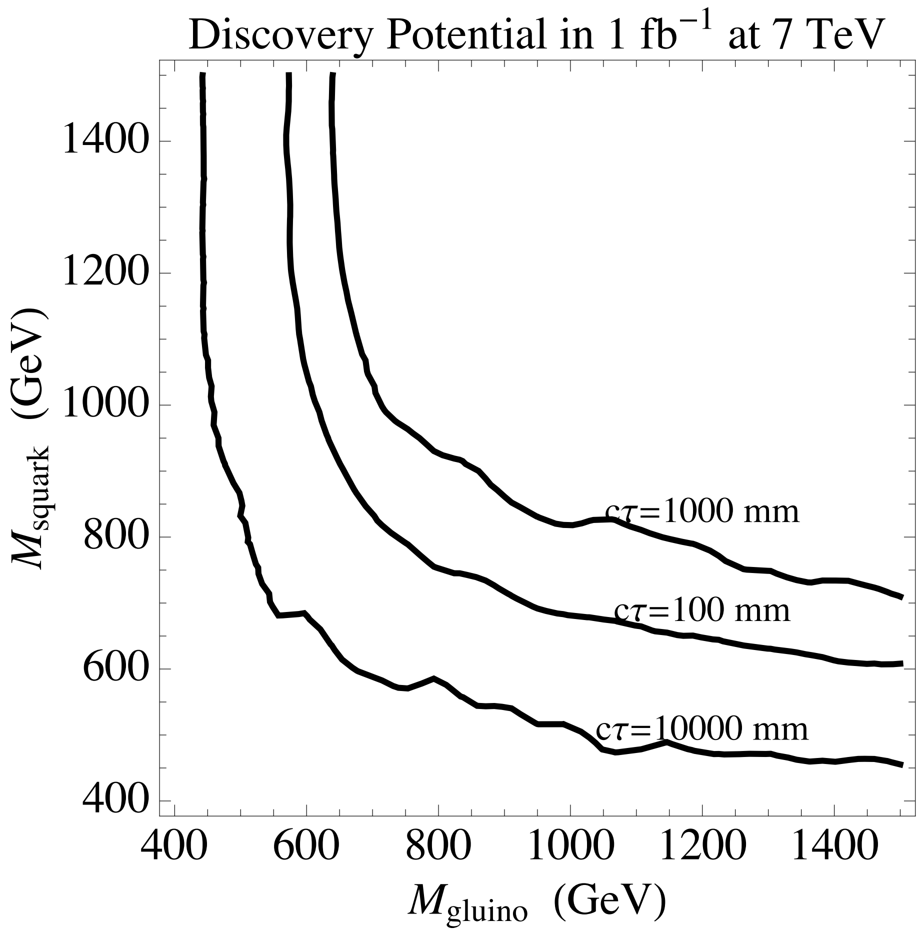
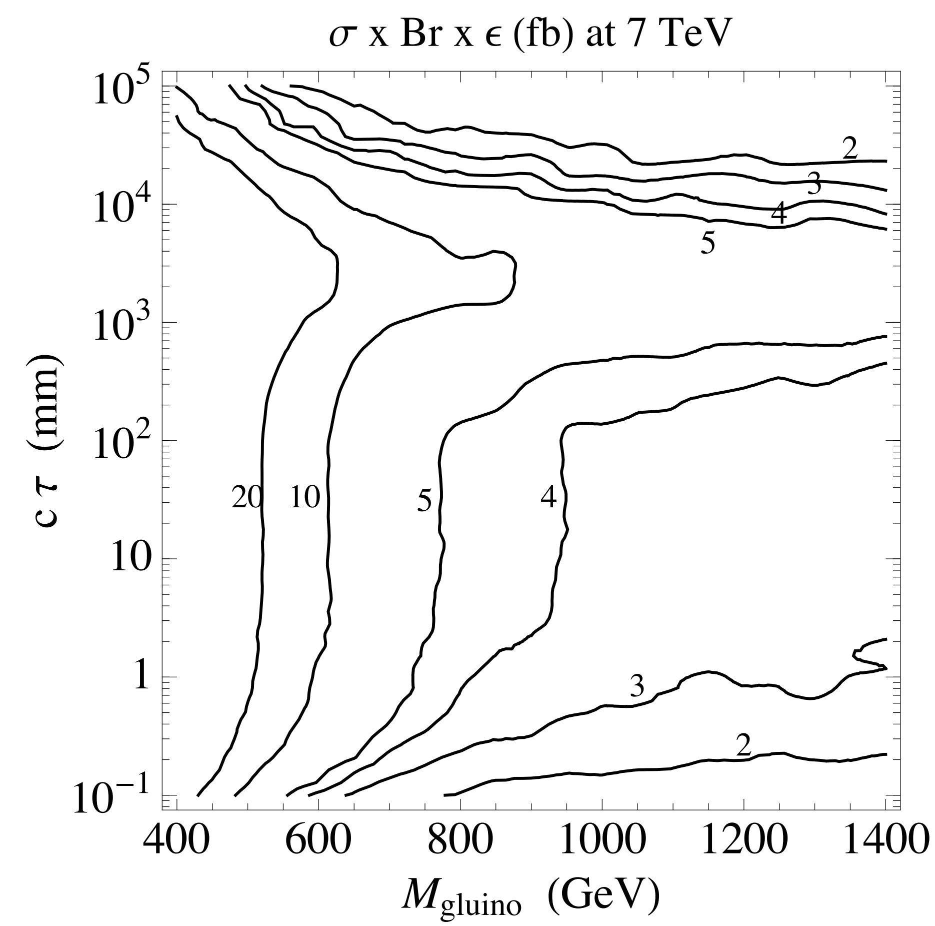
GMSB

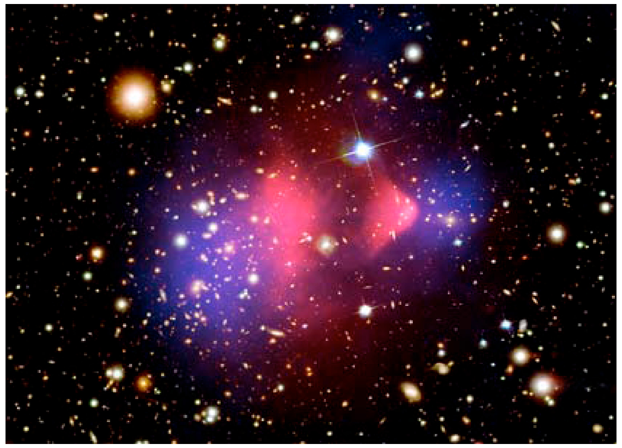




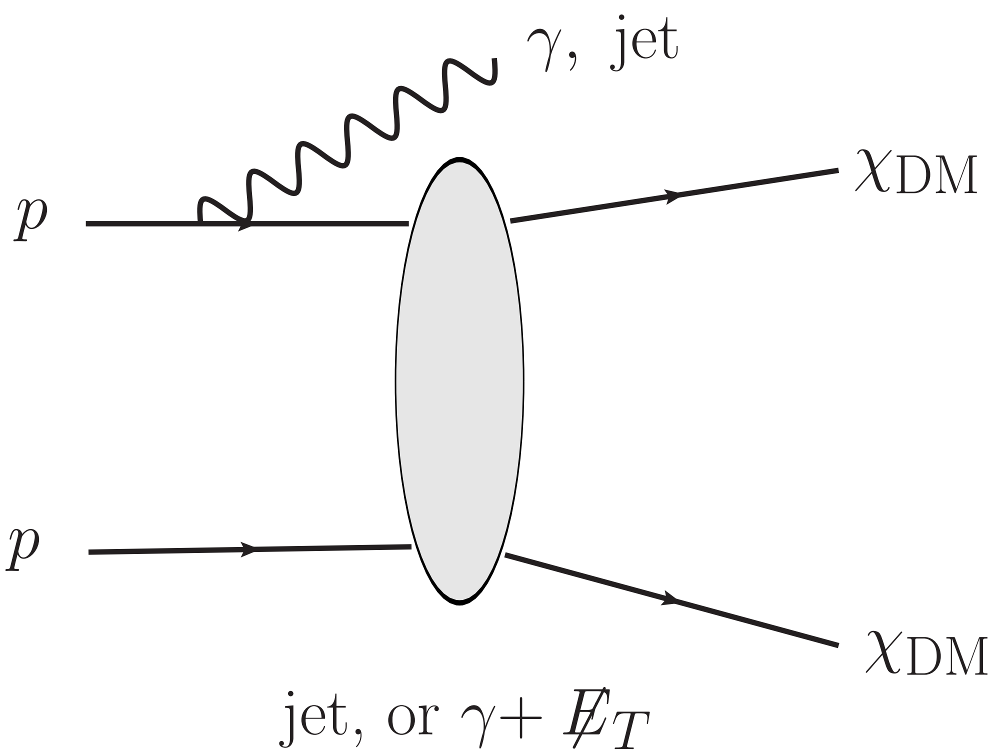
Higgsino NLSP $m_{\tilde{h}} = 250$ GeV $\tilde{h} \rightarrow Z(h) + \text{gravitino}$

Gauge mediation: P. Meade, D. Shih, M. Reece, arXiv:1006.4575

Collider Signals of dark matter.



- Basic channel

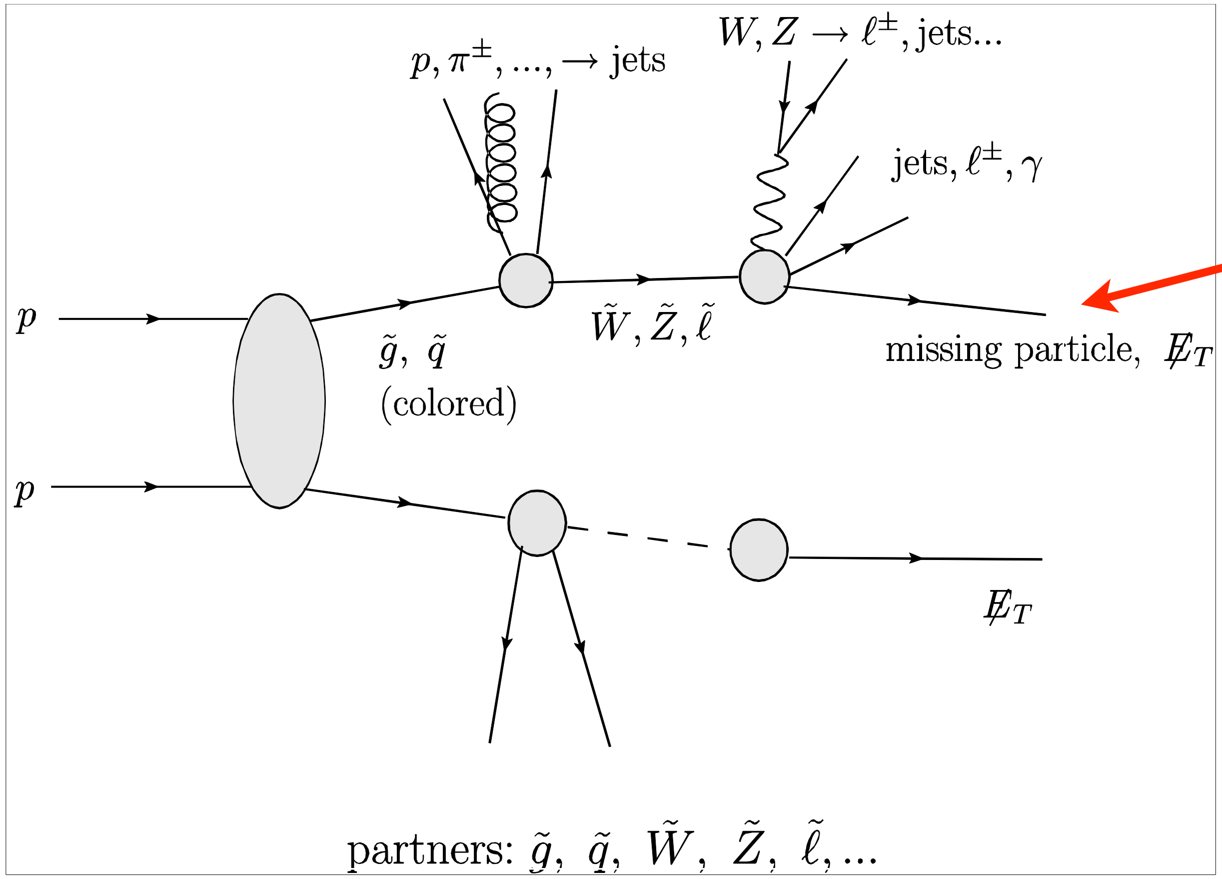


- Large Standard Model background, about 10 times the signal.

- Challenging.

A luckier scenario:

- DM candidate embedded in an extended TeV new physics scenario



DM candidate

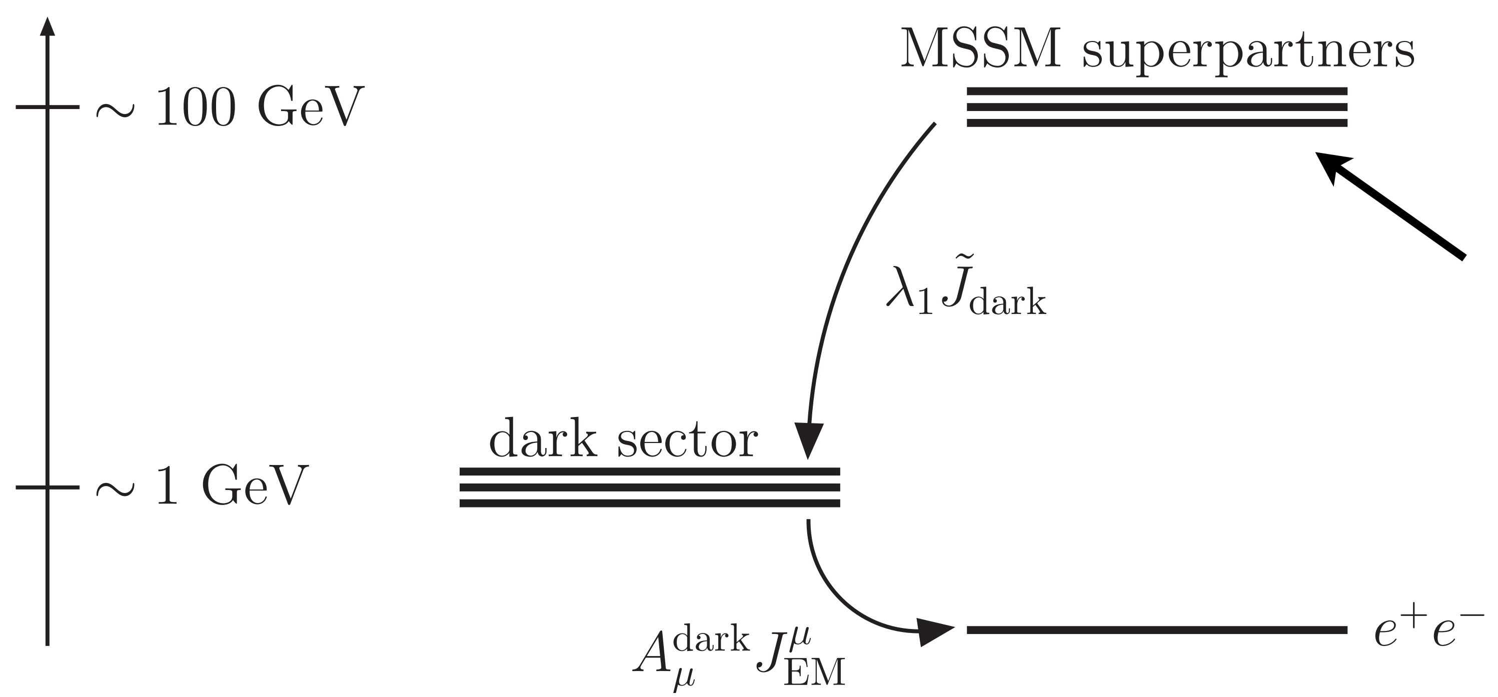
Example: SUSY
Lightest superpartner (LSP)
Neutral and stable.

- Could be early discovery.

New class of signal: dark Force

- Dark matter self-interaction, mediated by

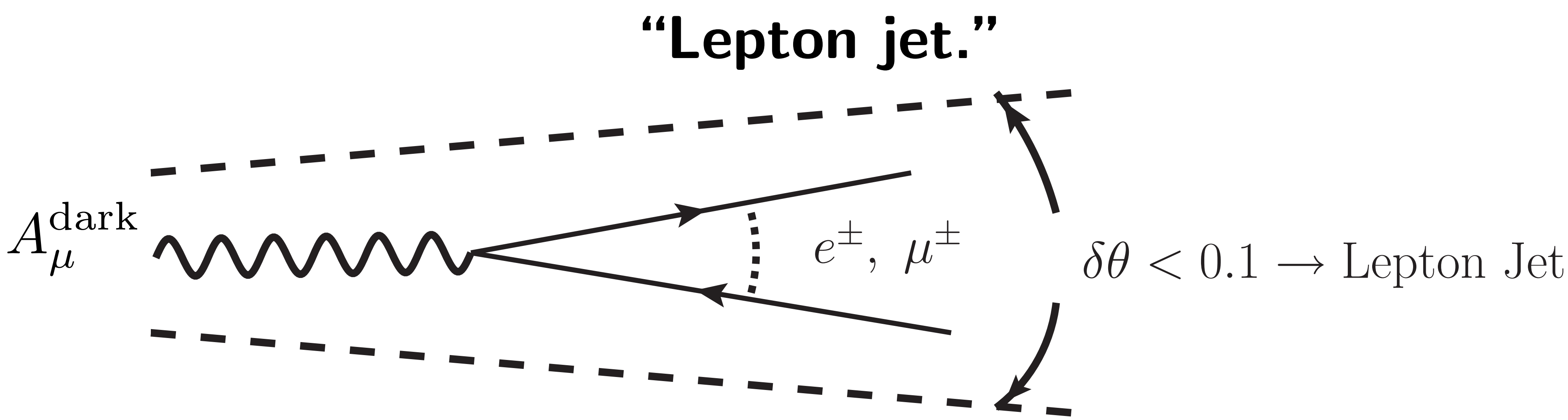
$$A_\mu^{\text{dark}}, \quad m_{A^{\text{dark}}} \sim \text{ (100s MeV - GeV)}$$



Arkani-Hamed, Finkbeiner, Slatyer, Weiner 0810.0713
Arkani-Hamed, Weiner 0810.0714
also see Pospelov, Ritz, Voloshin 0711.4866

Lepton Jets

- Decay of the dark photon arising from a heavier particle (Z boson, MSSM LSP) leads to a highly collimated lepton pair.

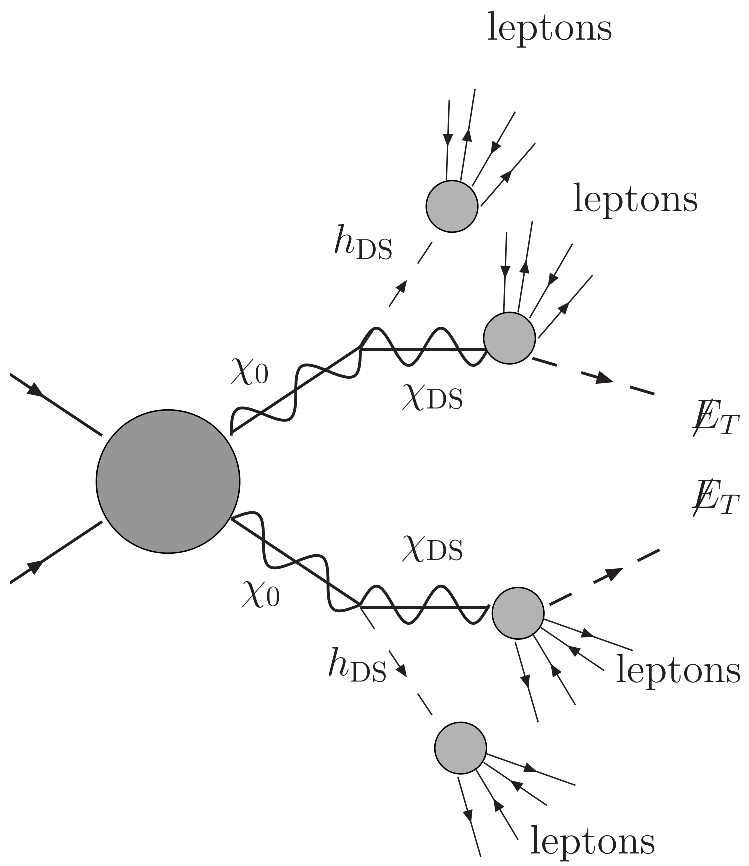


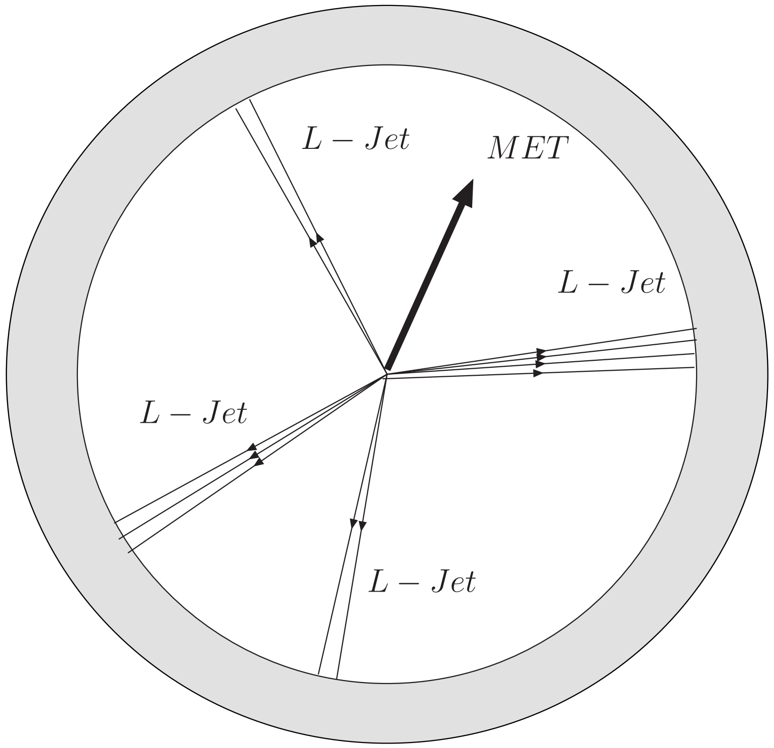
Typical $E_{\gamma'} > 10$ GeV
$m_{\gamma'} \sim$ GeV
$\to\ \delta\theta \sim m_{\gamma'}/E_{\gamma'} < 0.1$

- Arkani-Hamed, Weiner 0810.0714; Baumgart, Cheung, Ruderman, LTW, Yavin 0901.0283; Cheung, Ruderman, LTW Yavin 0909.0290

Supersymmetric dark force

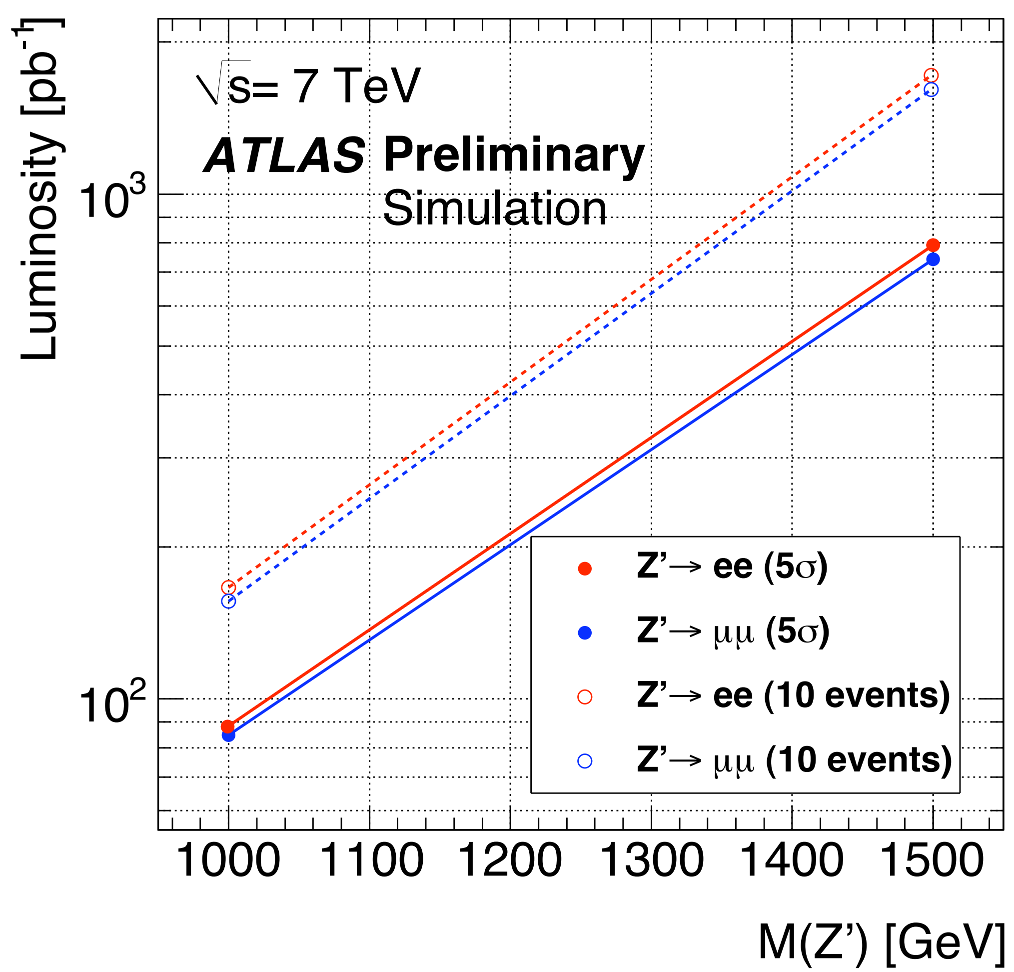
- Most natural way of generating the GeV scale.
- Spectacular signal.
- Early discovery.

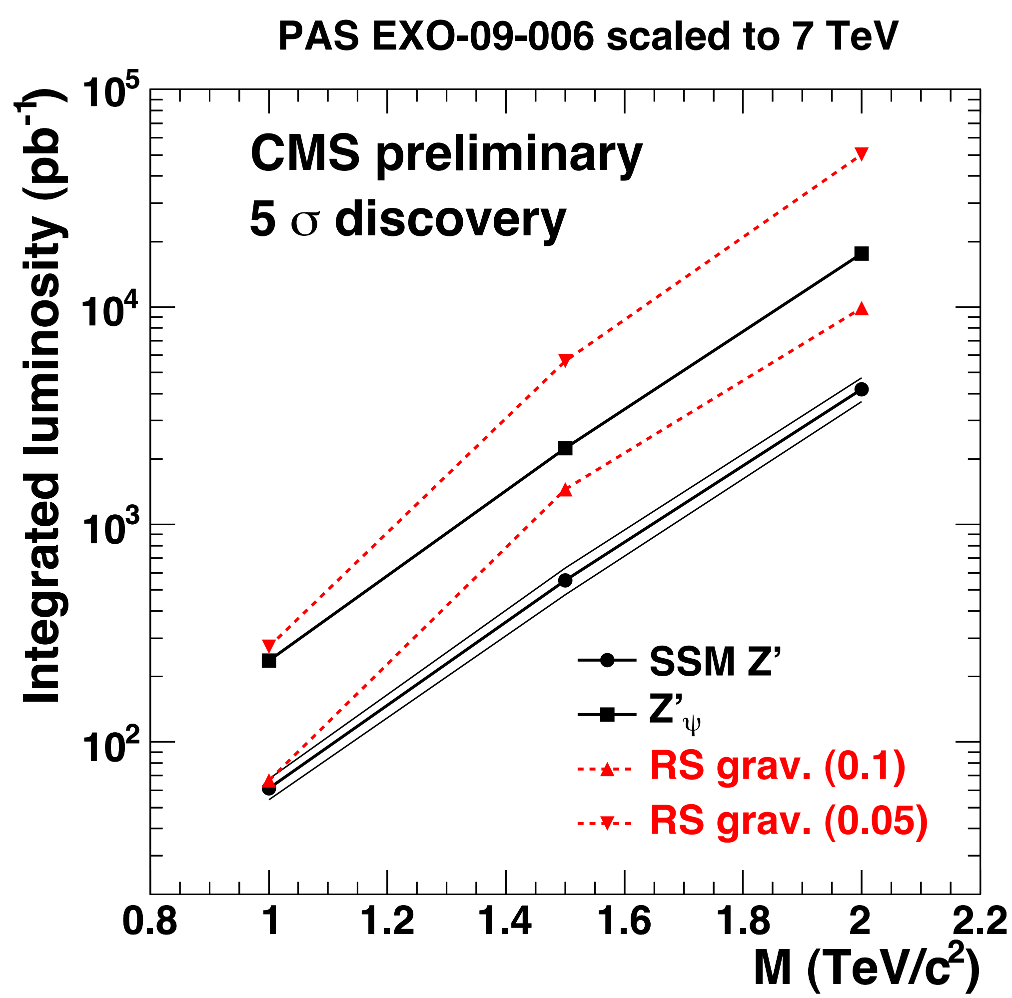




Resonances: $Z' \to \ell^+\ell^-$

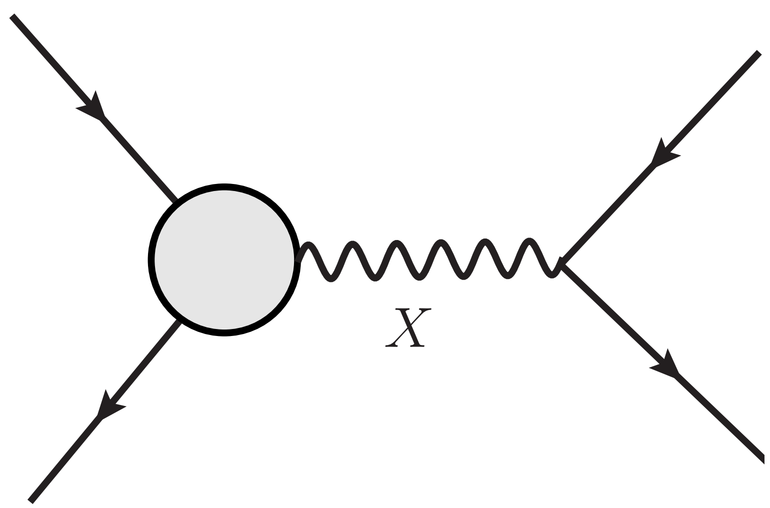
- Good sensitivity at early LHC.





More interesting zprime-like resonances

- Not just an extension of the SM gauge symmetry, but also part of the dynamics of electroweak symmetry breaking.
  - Strongly couples to $t\bar{t},\ W^+W^-,\ W^\pm Z, \ldots$



$t,\ W^+,\ Z,\ h\ldots$

$\bar{t},\ W^-,\ Z,\ h\ldots$

$$E_{t,W,Z,h} \sim \frac{m_X}{2}$$

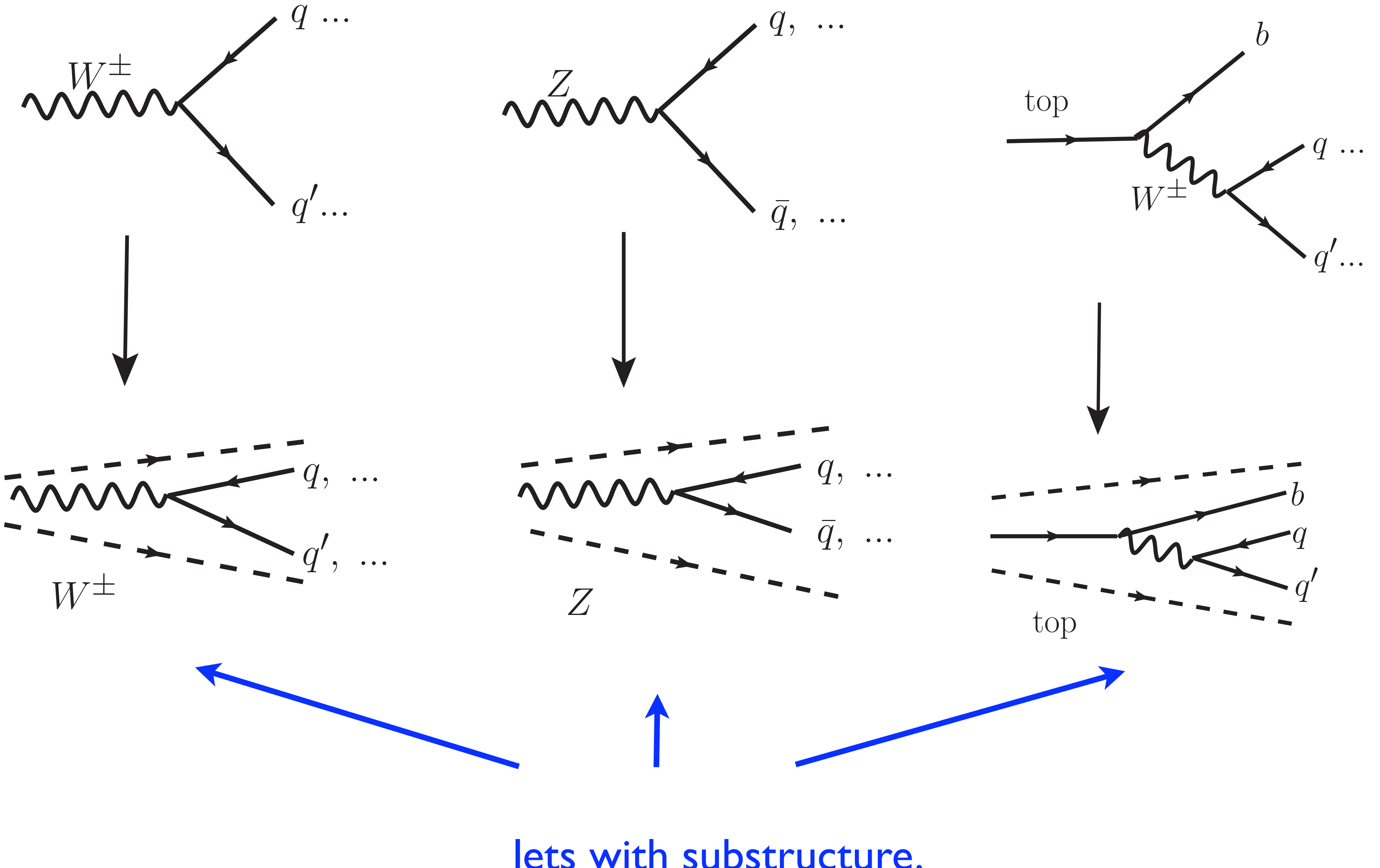
highly boosted if $m_X \sim$ TeV

- X can also be Randall-Sundrum KK-gluon, axi-gluon, ect., strongly couples to tops.

Jet substructure.

- When produced at TeV-scale energies, they have a large boost.

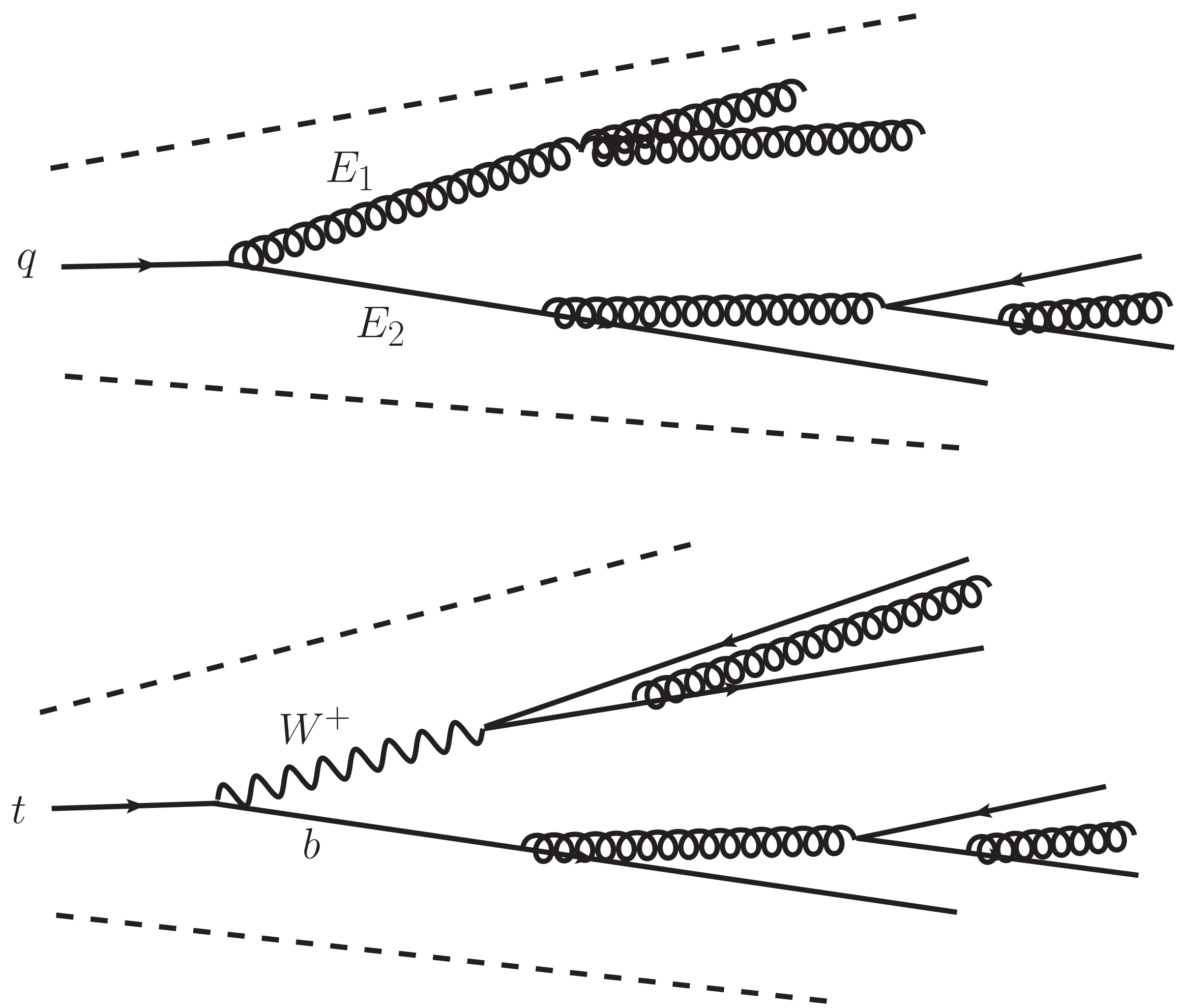
boost



Challenge: distinguishing them from QCD jets (q and g).

Example: boosted top tagging at the LHC

- Fully collimated tops look like QCD jets.



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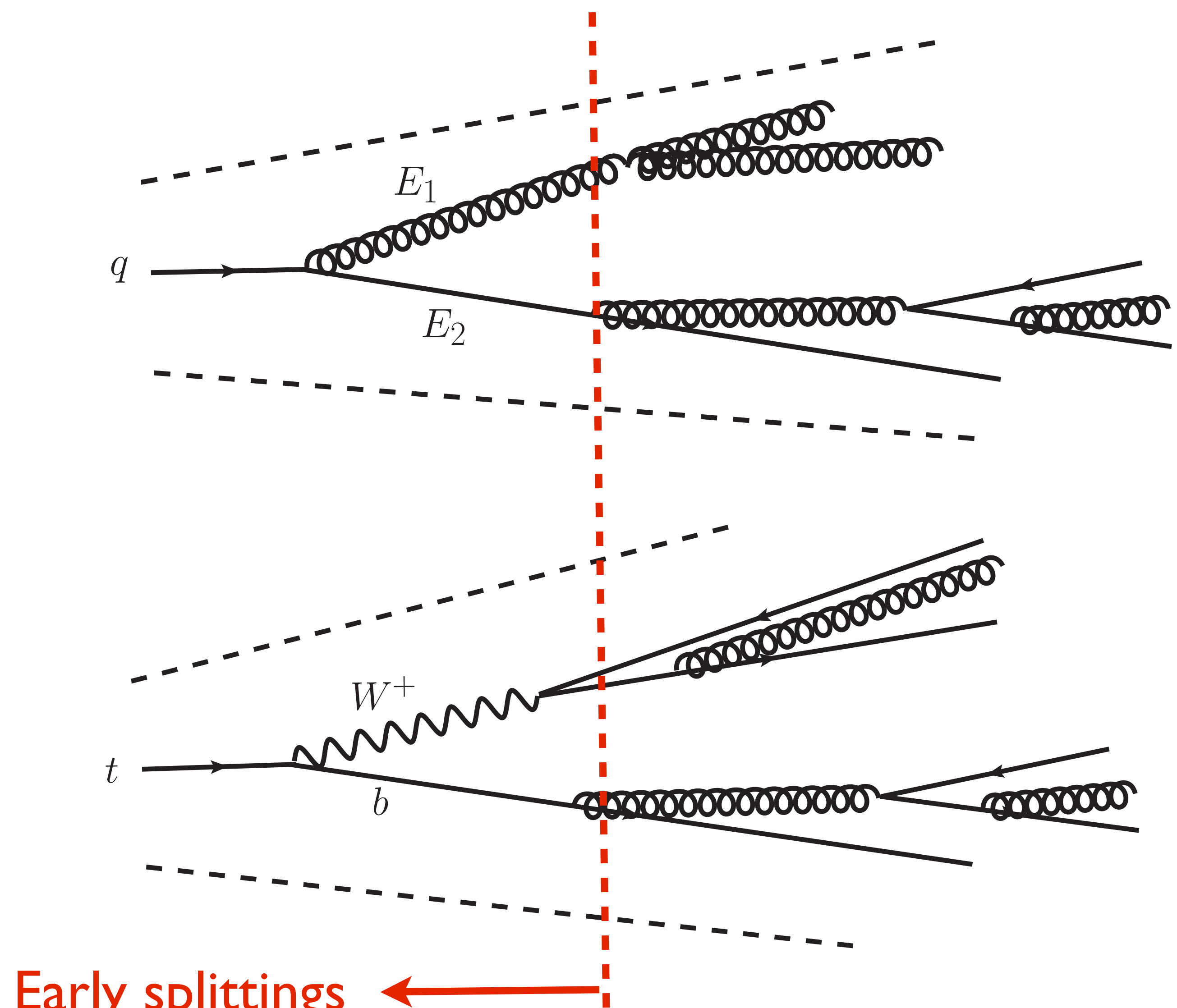
Basic distinction:
- QCD: radiation.
- Top decay: $t \to bW(\to qq')$ 3 hard objects.



Zooming in near the first splitting

QCD. Soft radiation: $z = \frac{\mathrm{Min}(E_1, E_2)}{E_1 + E_2} \to 0$

Top. Decay: $z = \frac{\mathrm{Min}(E_\mathrm{W}, E_b)}{E_\mathrm{W} + E_b} \to \text{finite}$

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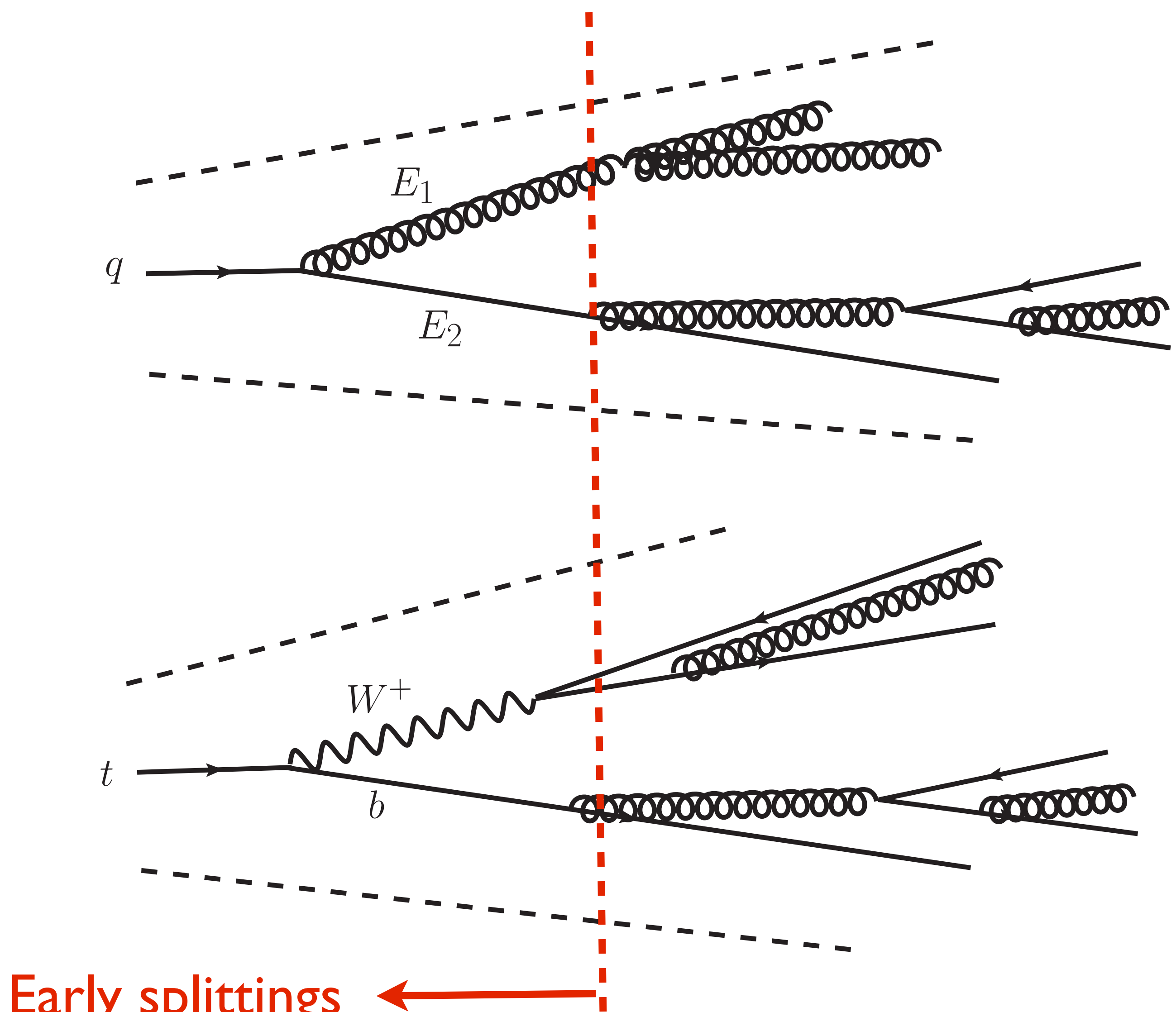

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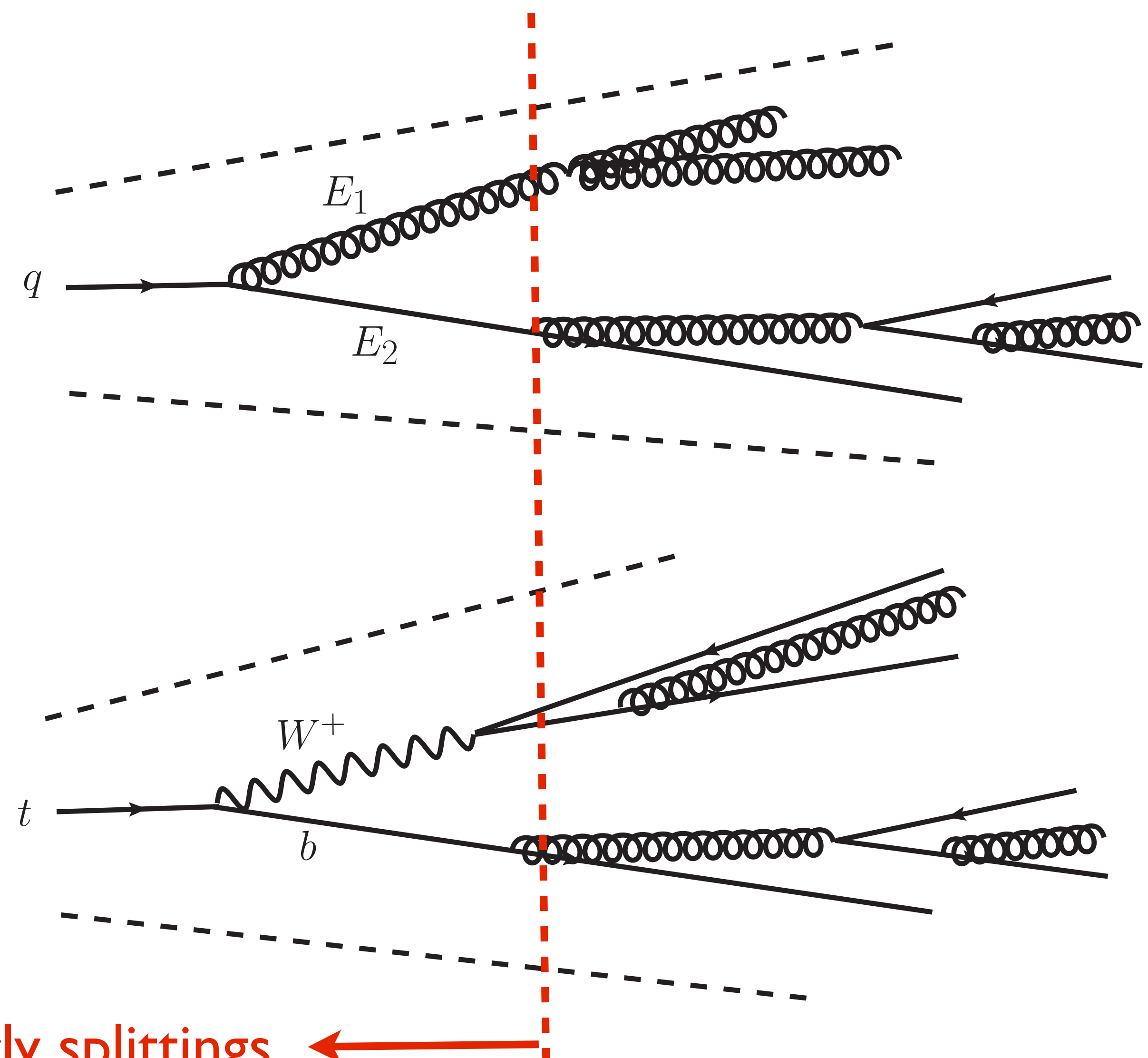

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Early splittings

microscope: jet substructure variables

Many recent activities on jet substructures (jet shape).

- Similar variables have been designed and studied for boosted top, W, Z and h, and have been found to be effective.

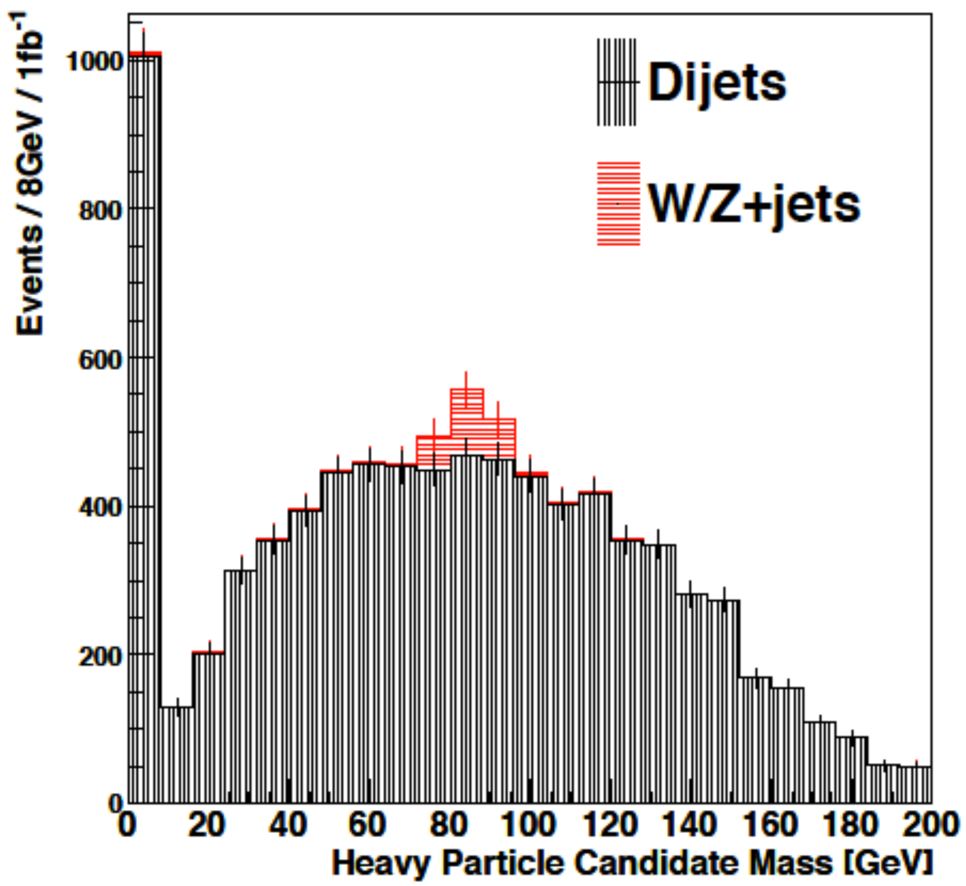
- New jet algorithms have also been proposed.
  - Filtering, trimming, pruning.
  - Cleaning out contaminations from additional radiation in the event, preserving jet shape..

For recent developments
Boost 2010: http://indico.cern.ch/conferenceTimeTable.py?confId=74604#20100622

Jets with structures at early LHC.

- At least some of them can be studied early on.
  - ~ TeV Z' or colored resonance decay.
  - Part of SUSY decay chain.
- SM background provides large sample of QCD jets.
  - Measure the substructure of QCD jets well.
  - Study SM W/Z and tops with moderate boost.

Boost W at early LHC

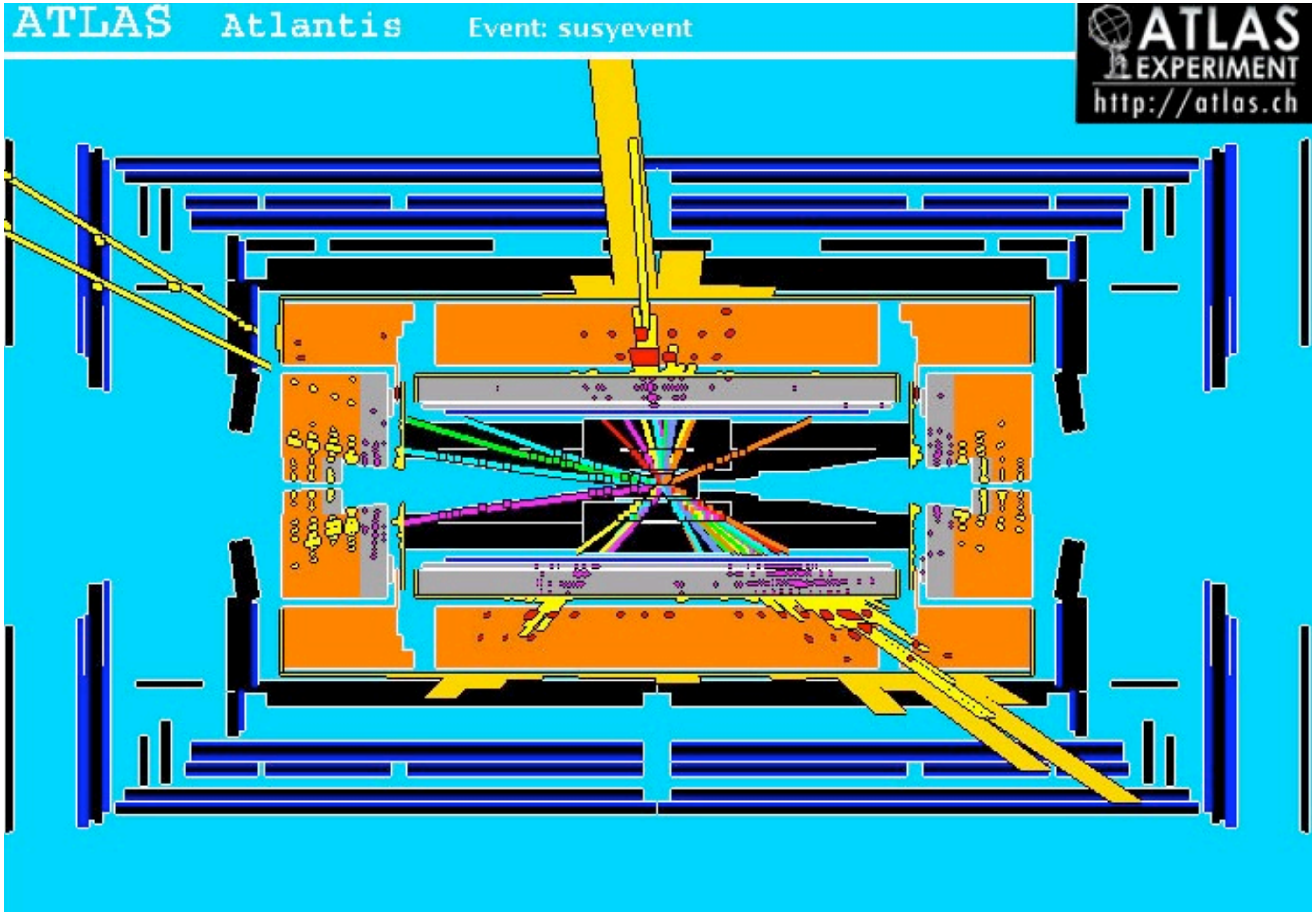


$$p_T^j > 400 \text{ GeV}$$

$$\sim 5\sigma \text{ at } 1 \text{ fb}^{-1}$$

Adam Davison, talk at Boost 10

In the next year or so, there are many exciting opportunities for making new physics discoveries at the LHC.



SM Rates at 7 TeV:

- QCD di-jet: $p_T^j > 100 \text{ GeV}, \ 300 \text{ nb}$
- Heavy flavor: $b\bar{b}, \ p_T^b > 100 \text{ GeV}, 1 \text{ nb}$
- W+... : $W^\pm \to \ell\nu, \ 14 \text{ nb}$

$$W^\pm(\to \ell\nu) + 1 \text{ jet}, \ p_T^j > 100 \text{ GeV}, \ 70 \text{ pb}$$

one lepton + jets + MET

$$W^\pm(\to \ell\nu) + 2 \text{ jet}, \ p_T^j > 100 \text{ GeV}, \ 2 \text{ pb}$$

$$W^\pm(\to \ell\nu) + 1 \text{ jet}, \ p_T^j > 200 \text{ GeV}, \ 5 \text{ pb}$$

- Z + ... : $Z(\to \ell^+\ell^-), \ 1.4 \text{ nb}$

di-lepton + jets

$$Z(\to \ell^+\ell^-) + 1 \text{ jet}, \ p_T^j > 100 \text{ GeV} \ , 10 \text{ pb}$$

New Physics: ~ pb

SM rates at 7 TeV

- di-boson: $W^+W^- : 30 \text{ pb}$ di-lepton + MET, ~ 1.2 pb

  $W^+W^- + \ 1 \text{ jet}, \ p_T^j > 100 \text{ GeV}, \ 2 \text{ pb}$

  di-lepton+jet+MET ~ 0.1 pb

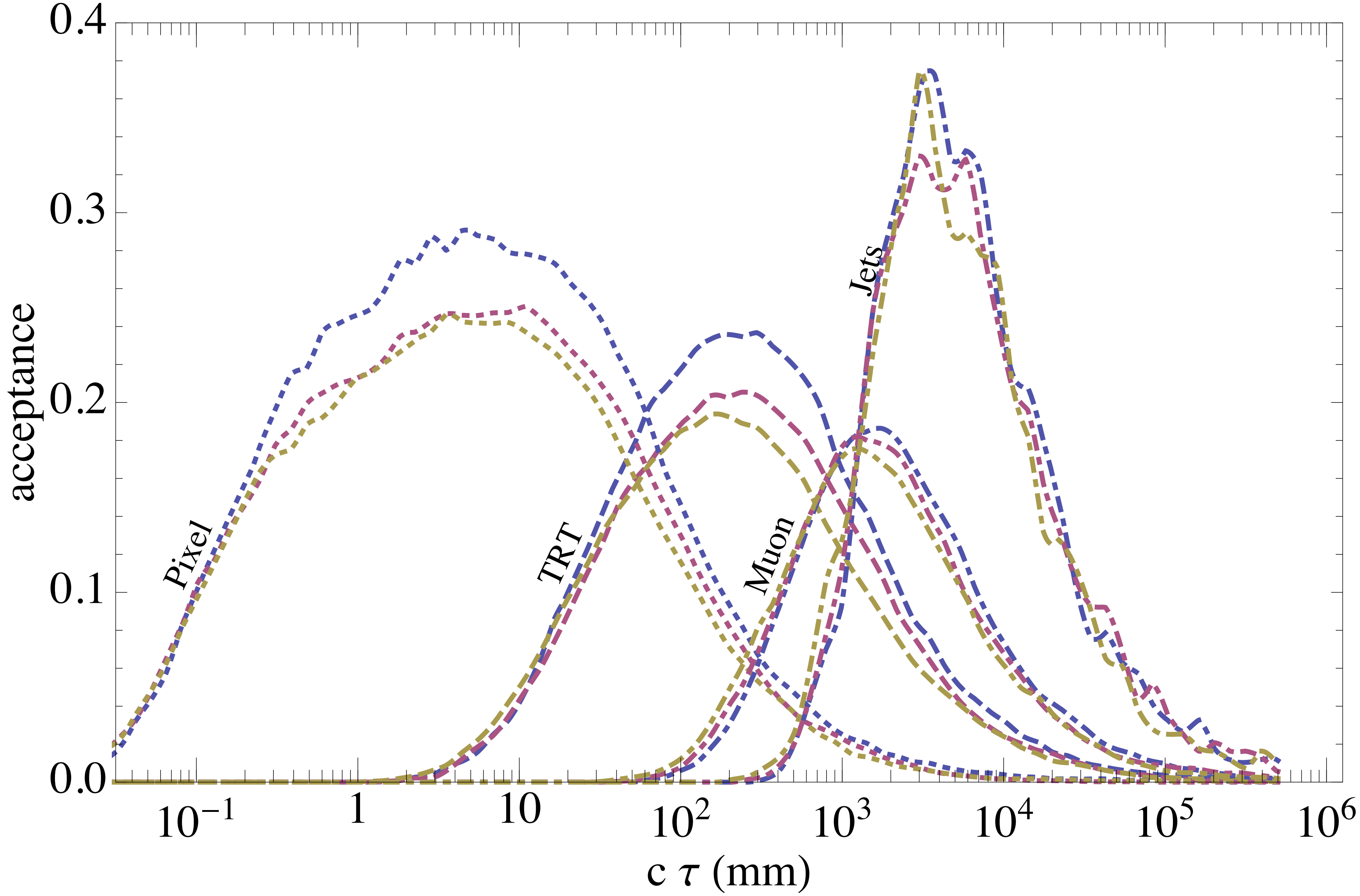
  $W^+Z : \ 7 \text{ pb}, \ W^-Z : \ 3.7 \text{ pb}$

  tri-lepton + MET ~ 0.1 pb

- top pair: 160 pb! Always has 6 objects.

  $t\bar{t} \rightarrow bbW^+W^- \rightarrow \ bbjj\ell\nu, \ bb\ell\nu\ell\nu, bbjjjj$

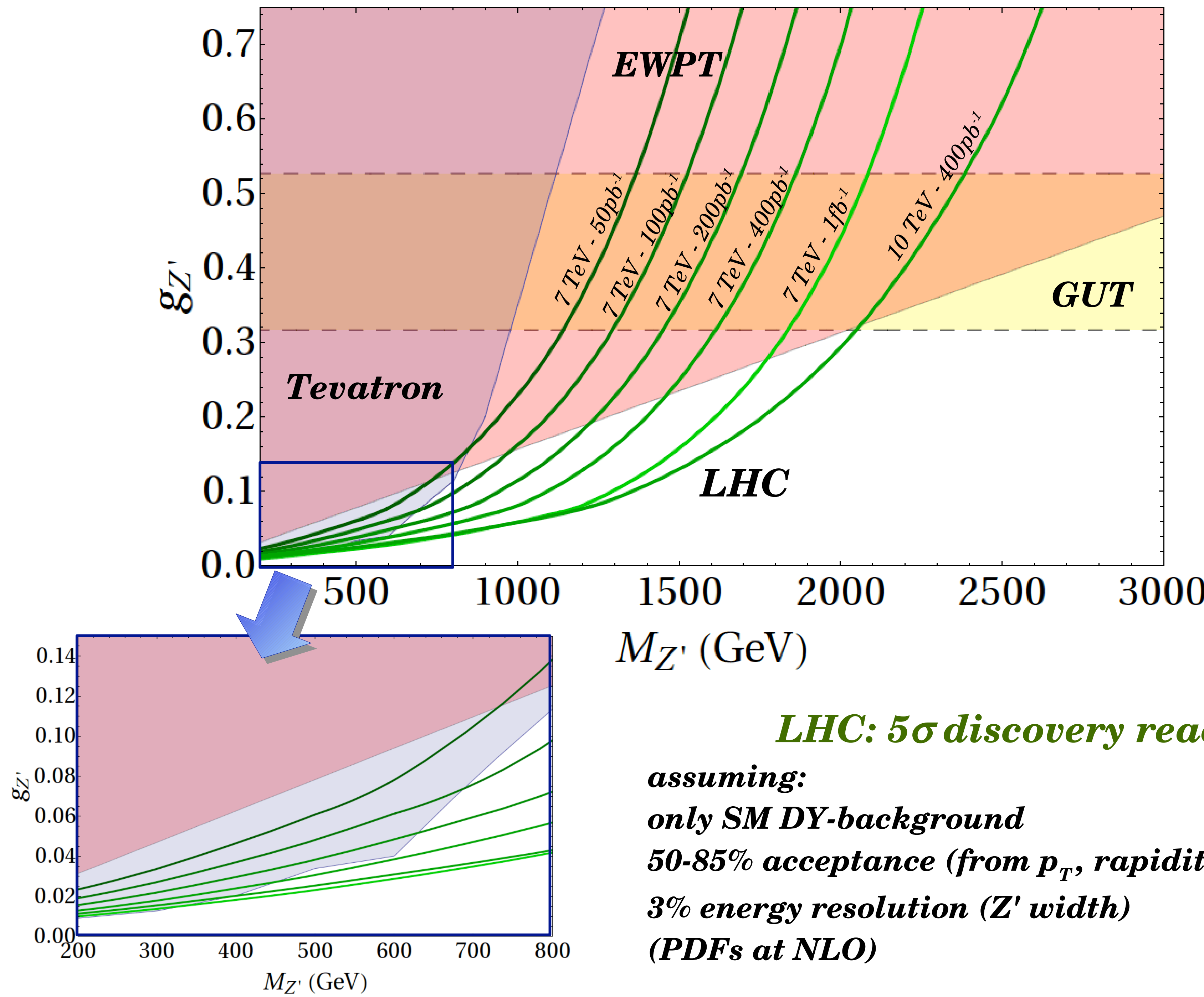
  - (MET+lepton+Jet 40%, Heavy flavor...)
  - Looks like new physics, pair production of a massive particle followed by a decay cascade.



0.4
0.3
0.2
0.1
0.0
acceptance
Pixel
TRT
Muon
Jets
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
c τ (mm)

Resonances: $Z' \to \ell^+ \ell^-$

EWPT vs Tevatron vs LHC



LHC: 5σ discovery reach

assuming:
only SM DY-background
50-85% acceptance (from p_T, rapidity cuts, etc.)
3% energy resolution (Z' width)
(PDFs at NLO)

Villadoro, Moriond 2010