# Targets for early discoveries at the LHC

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# 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!

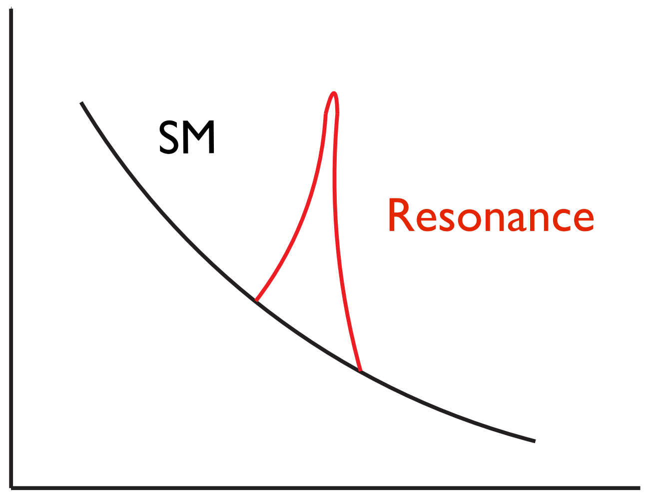
# Two possible ways of early discovery:

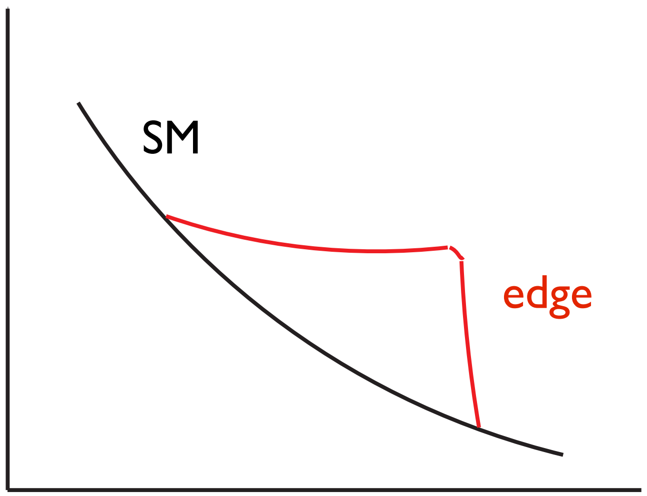
- Large rate, necessary condition.

- 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:



# 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

# 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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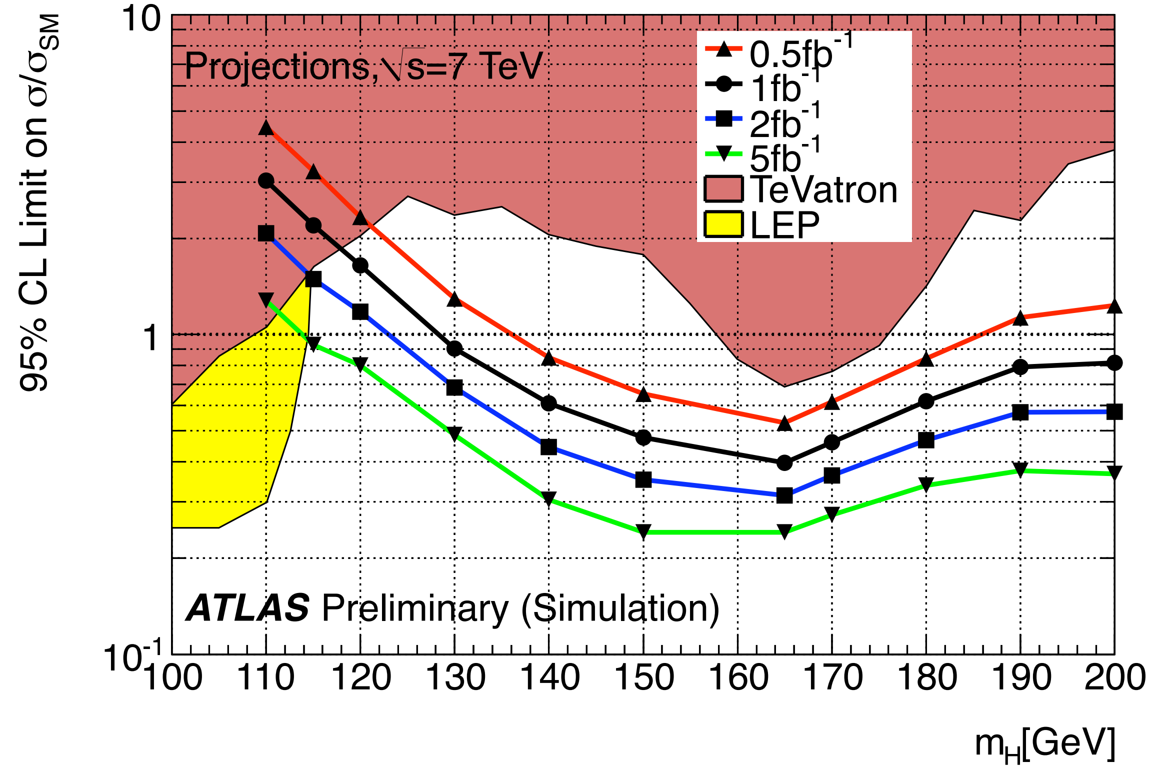
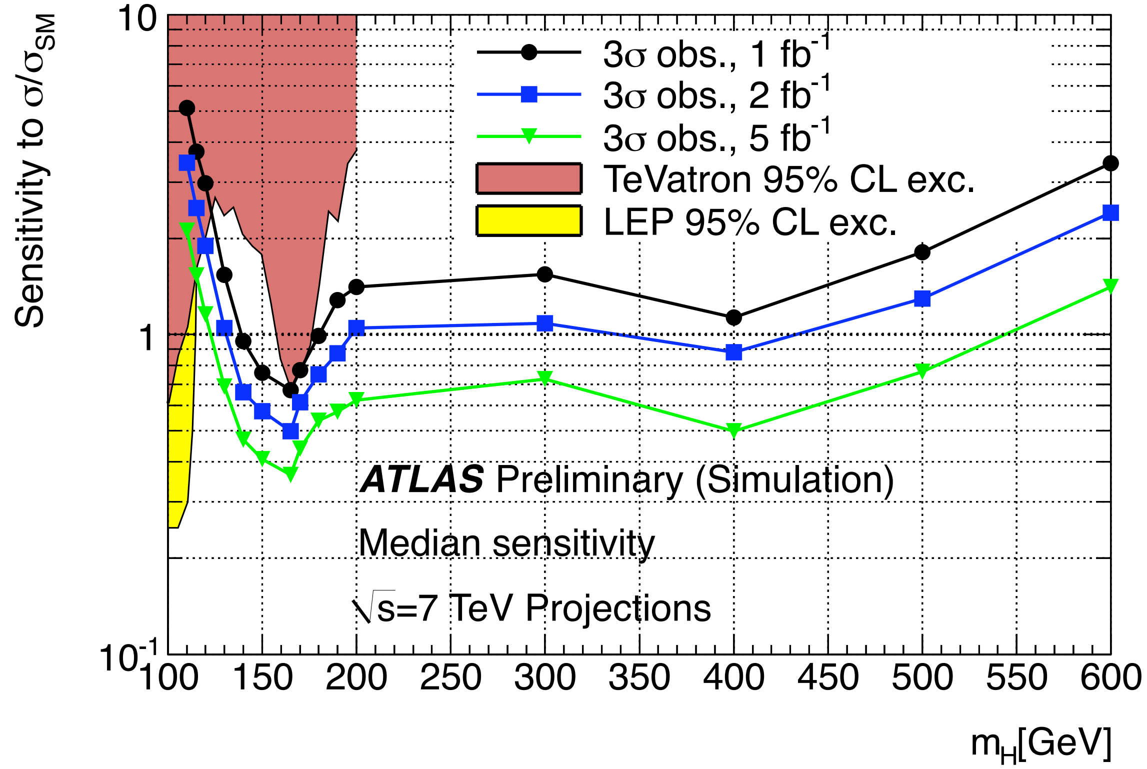
# What's more likely?

# Obviously, the Higgs.




Well studied.

# Partners

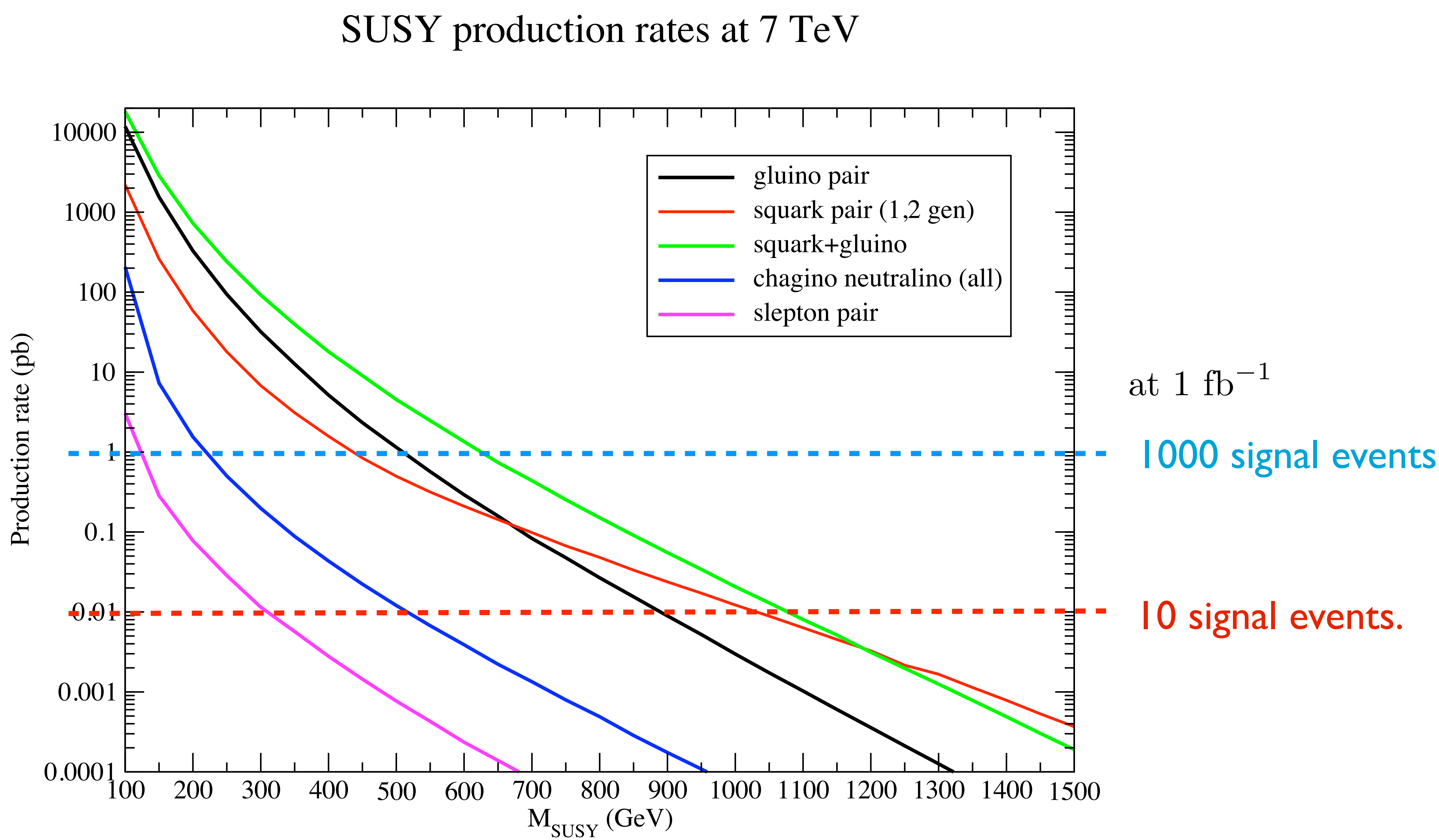
New particles with similar gauge quantum numbers as SM particles.
Motivated by solving hierarchy problem.

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

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

...

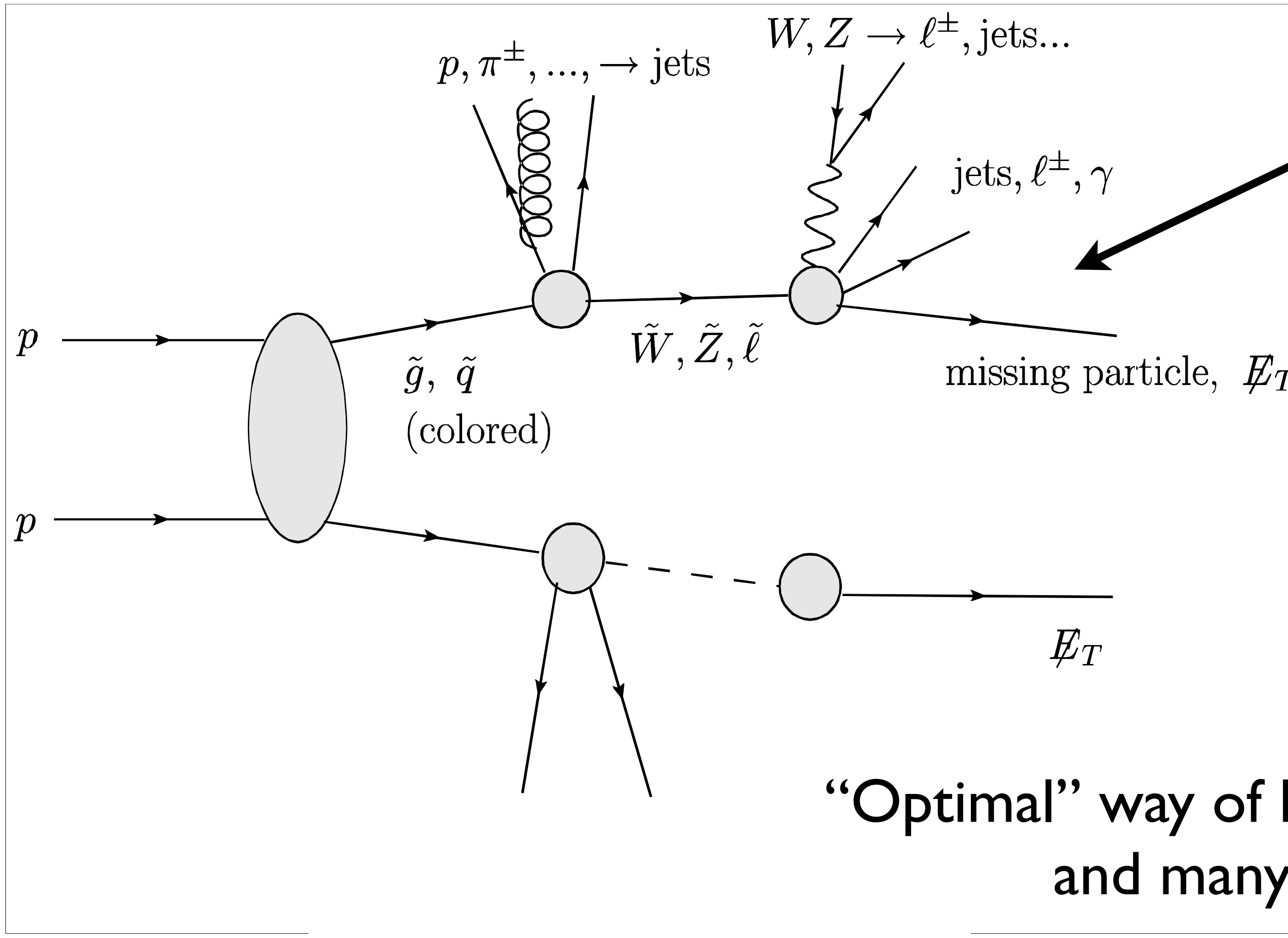
# Production.




## Dominated by the production of colored states.

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

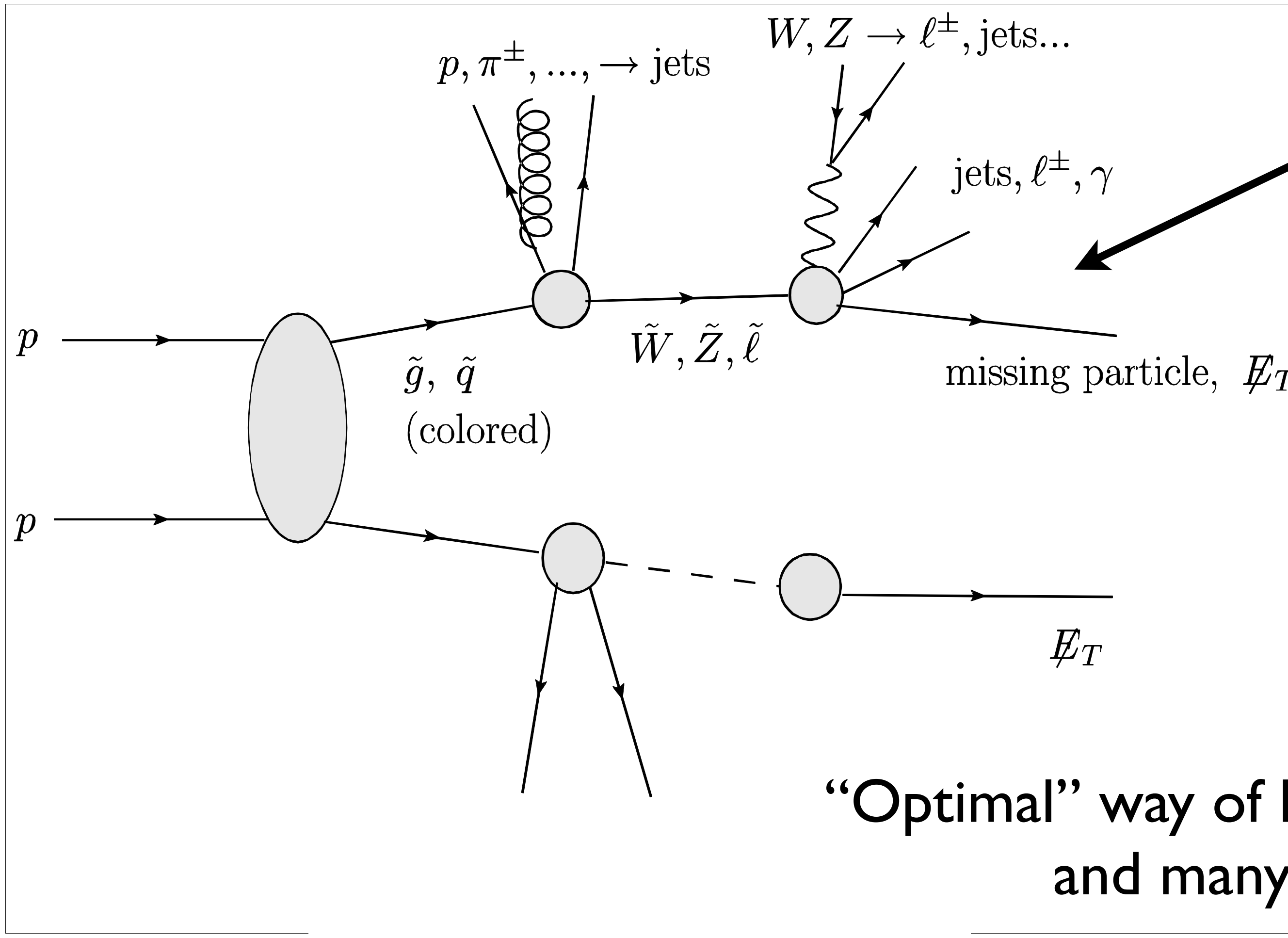
# Signature of partners




Decay chain

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

# Signature of partners



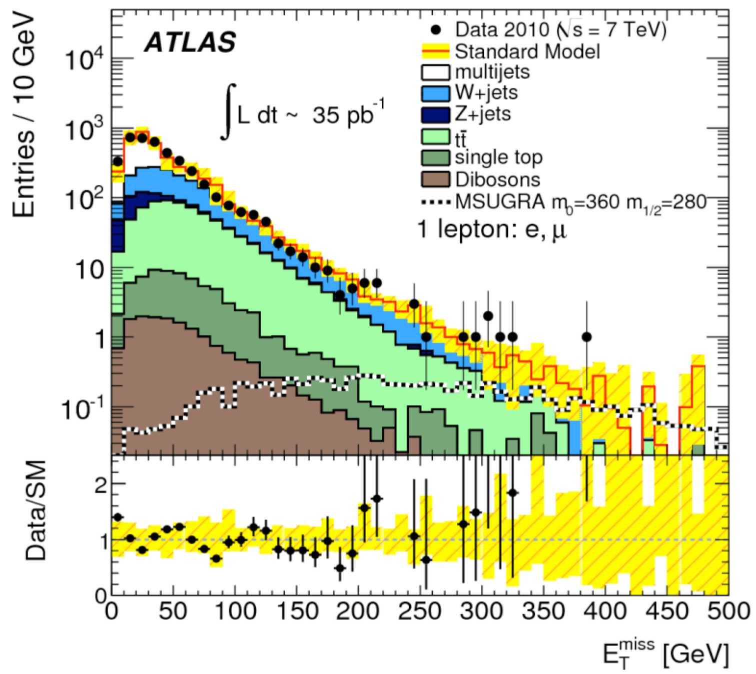

Decay chain

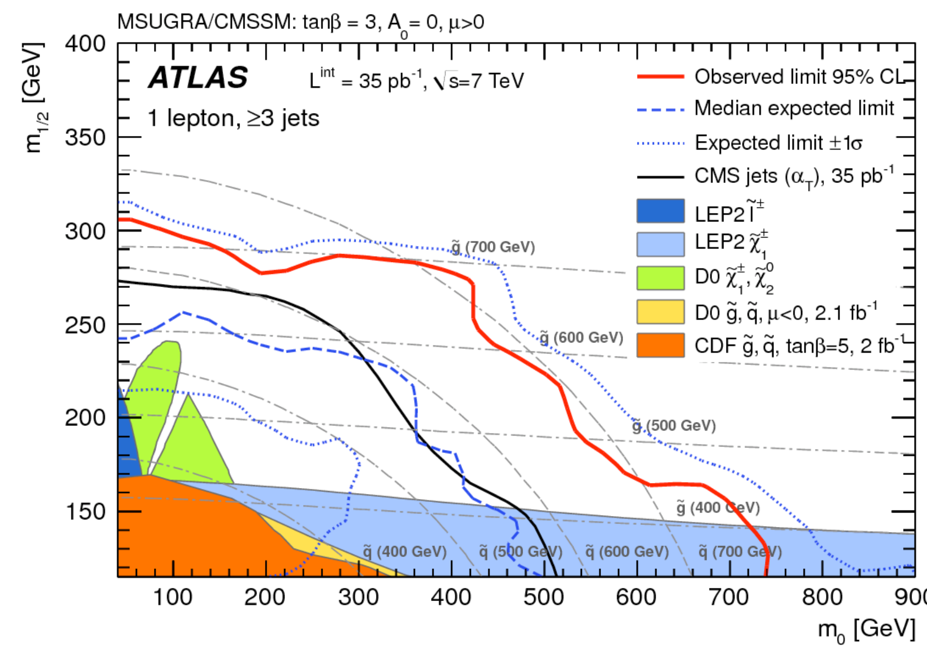
"Optimal" way of having both large production rate and many hard final state objects.

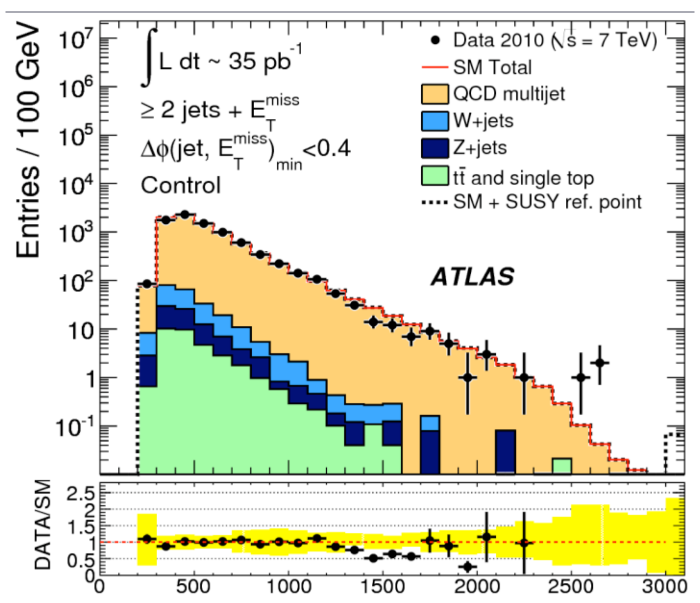
- "Well known", many studies in the past 2 decades.
- If we are reasonably lucky and partners are not too heavy, this can lead to early discovery.

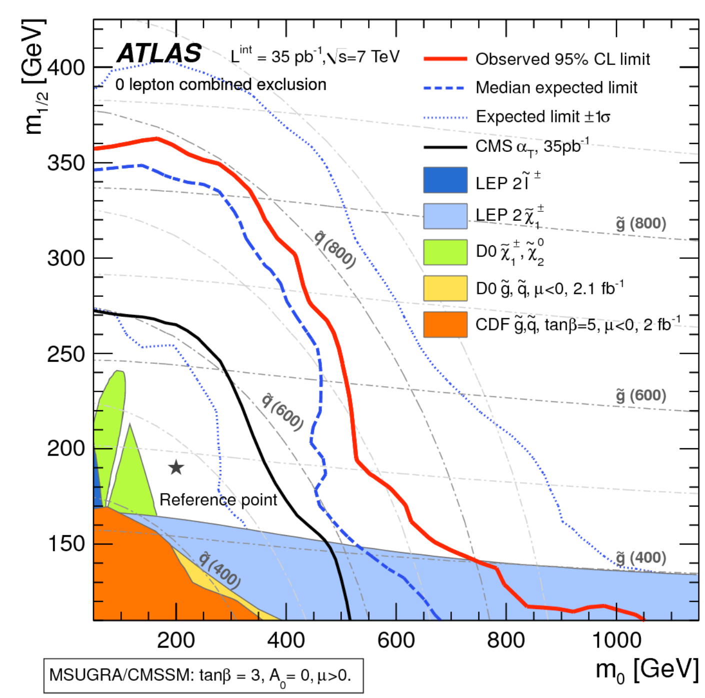
$$\text{At 7 TeV and 1 fb}^{-1} : \sim 10^3 \; \tilde{q} \text{ and } \tilde{g} \; (\sim 500 \text{ GeV})$$

# Recent progresses



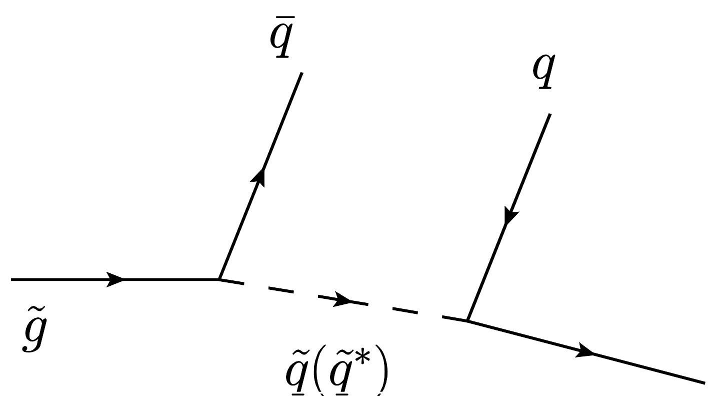
# Relevant parameters for early LHC

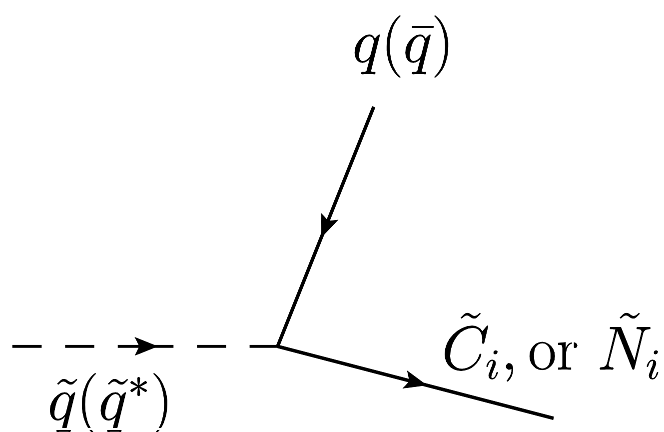
- Masses of color particles. Controlling rates.

$$m_{\tilde{q}},\ M_{\tilde{g}}$$

- Electroweak-ino: neutralinos and charginos

$$M_1,\ M_2,\ \mu$$

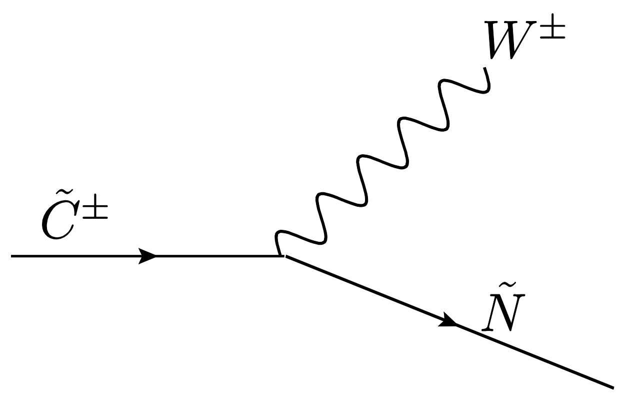


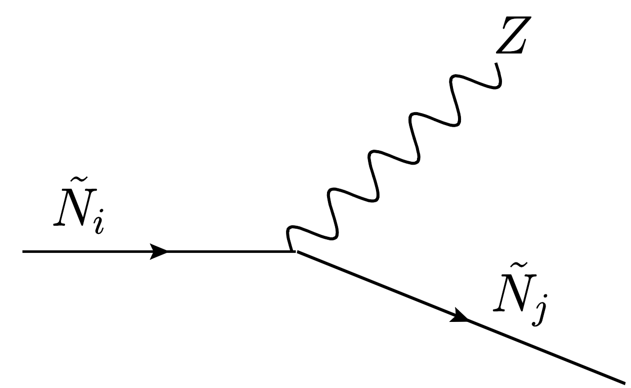




$$(m_{\tilde{q}},\ M_{\tilde{g}}) - (m_{\tilde{N}_i},\ m_{\tilde{C}_i}) \sim p_T^{\text{jets}}$$

# Relevant parameters

- Ino mass also controls the later stages of decay chain, W, Z, leptons.

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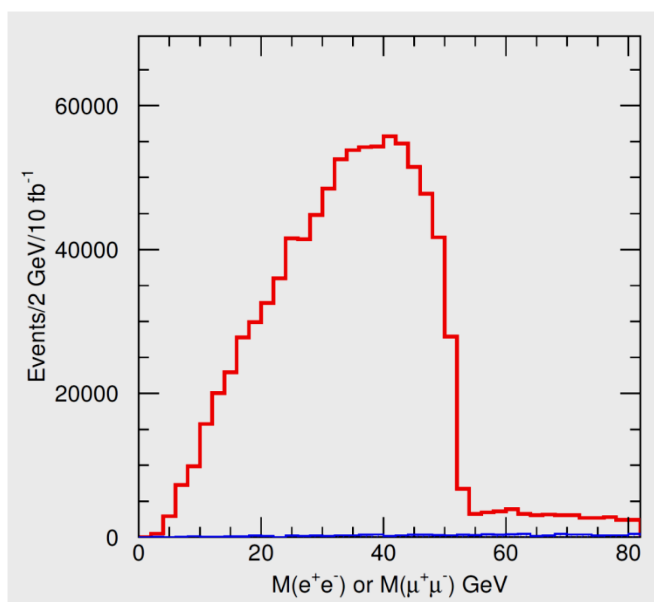
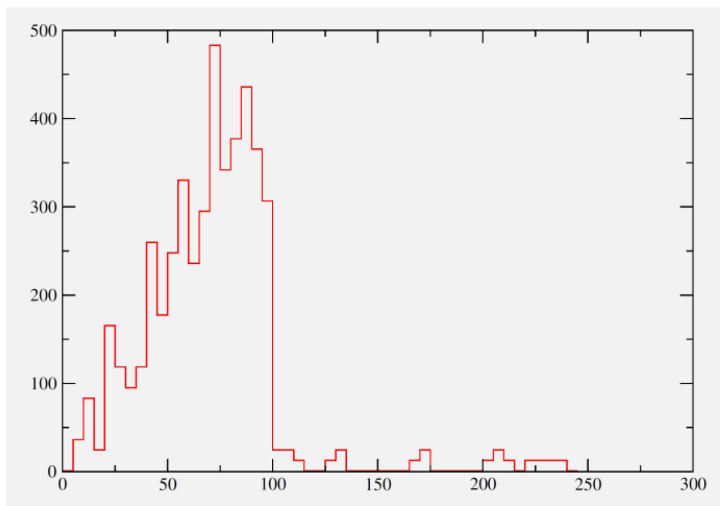
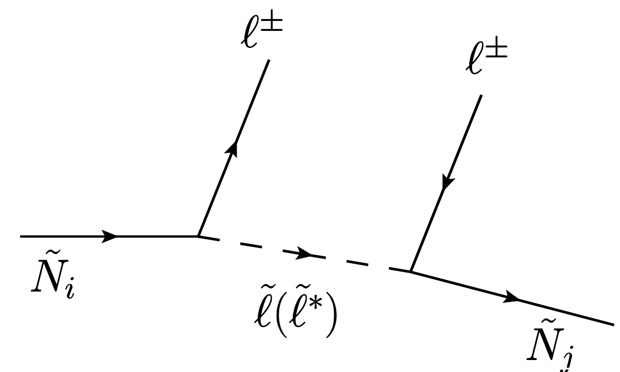



$$M_{\tilde{N}_2} - M_{\tilde{N}_1} < m_Z \longrightarrow \tilde{N}_2 \rightarrow \tilde{N}_1 + \ell^+ + \ell^- \text{ Only 3-body}$$
$$m_{\ell\ell} = \sqrt{(p^2_{\ell+} + p^2_{\ell-})} \longrightarrow \text{end-point at } M_{\tilde{N}_2} - M_{\tilde{N}_1}$$

# Relevant parameters

- Sleptons.  Whether it is "in" the decay chain. Many leptons.
  - Edge in di-lepton invariant mass.




$$m_{\tilde{\ell}} < M_{\tilde{N}_2} \quad \longrightarrow \tilde{N}_2 \rightarrow \tilde{N}_1 + [\tilde{\ell}] \rightarrow \tilde{N}_1 + \ell^+ + \ell^-$$

$$M_{\ell\ell}^{\max} \quad = M_{\tilde{N}_1}\sqrt{1-\frac{m_{\tilde{\ell}}^2}{M_{\tilde{N}_2}^2}}\sqrt{1-\frac{M_{\tilde{N}_1}^2}{m_{\tilde{\ell}}^2}}$$

- 3rd generation.
  - "top-ness" and "bottom-ness" of the events.

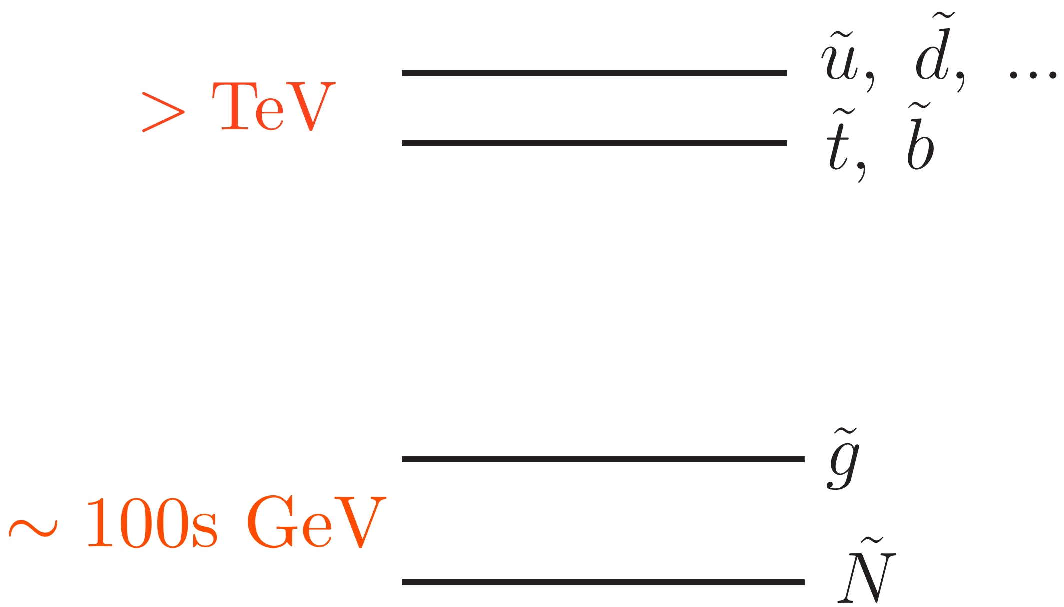
$$m_{\tilde{t}},\ m_{\tilde{b}}$$

# Summary

- Colored. $m_{\tilde{q}},\ M_{\tilde{g}}$
- Inos. $M_1,\ M_2,\ \mu$
- Slepton. $m_{\tilde{\ell}}$
- 3rd generation. $m_{\tilde{t}},\ m_{\tilde{b}}$
- Some others in specific searches
    - tau $m_{\tilde{\tau}}$
    - Higgs $m_h,\ m_A,\ m_H,\ \tan\beta$

# Any special channels?

# A promising, and complicated, scenario.




Heavy squark, and $m_{\tilde{t},\tilde{b}} < m_{\tilde{u},\tilde{d}}$

Light gaugino

- 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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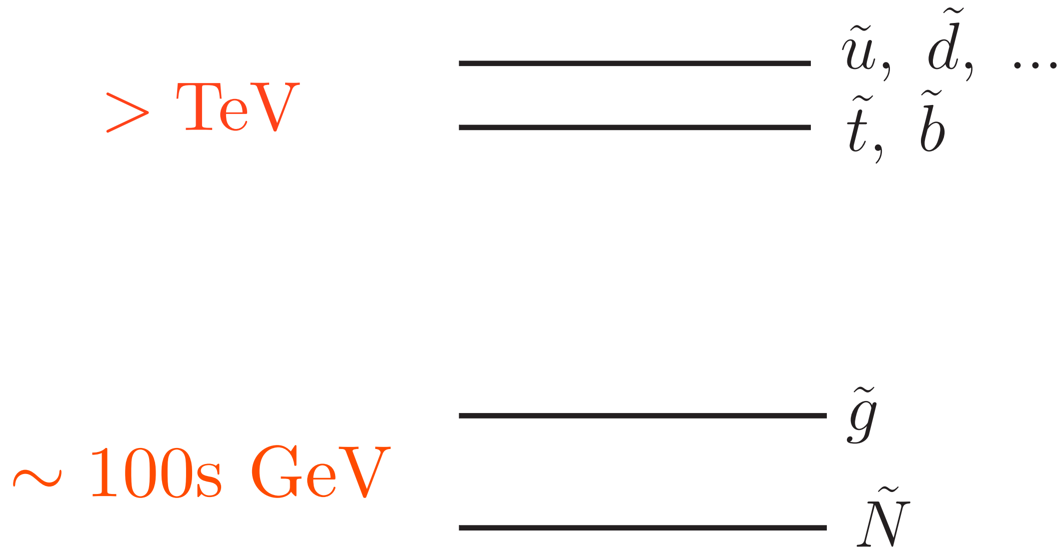
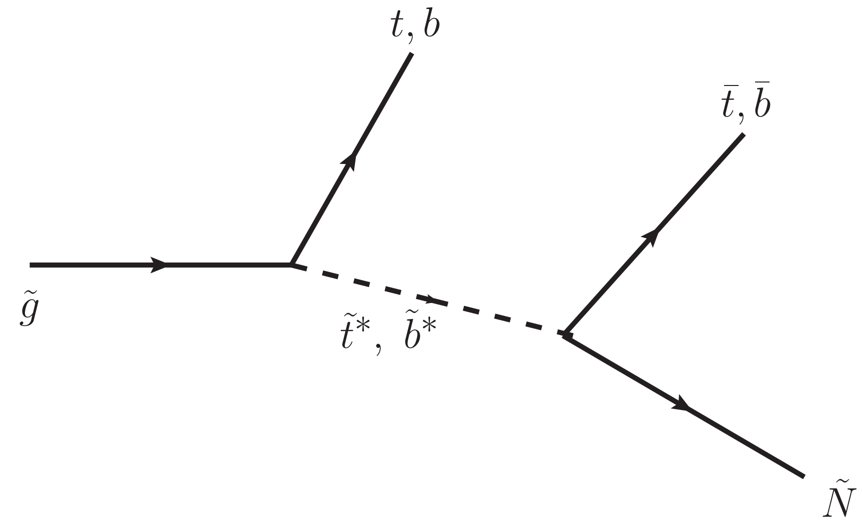



The Dominant channel

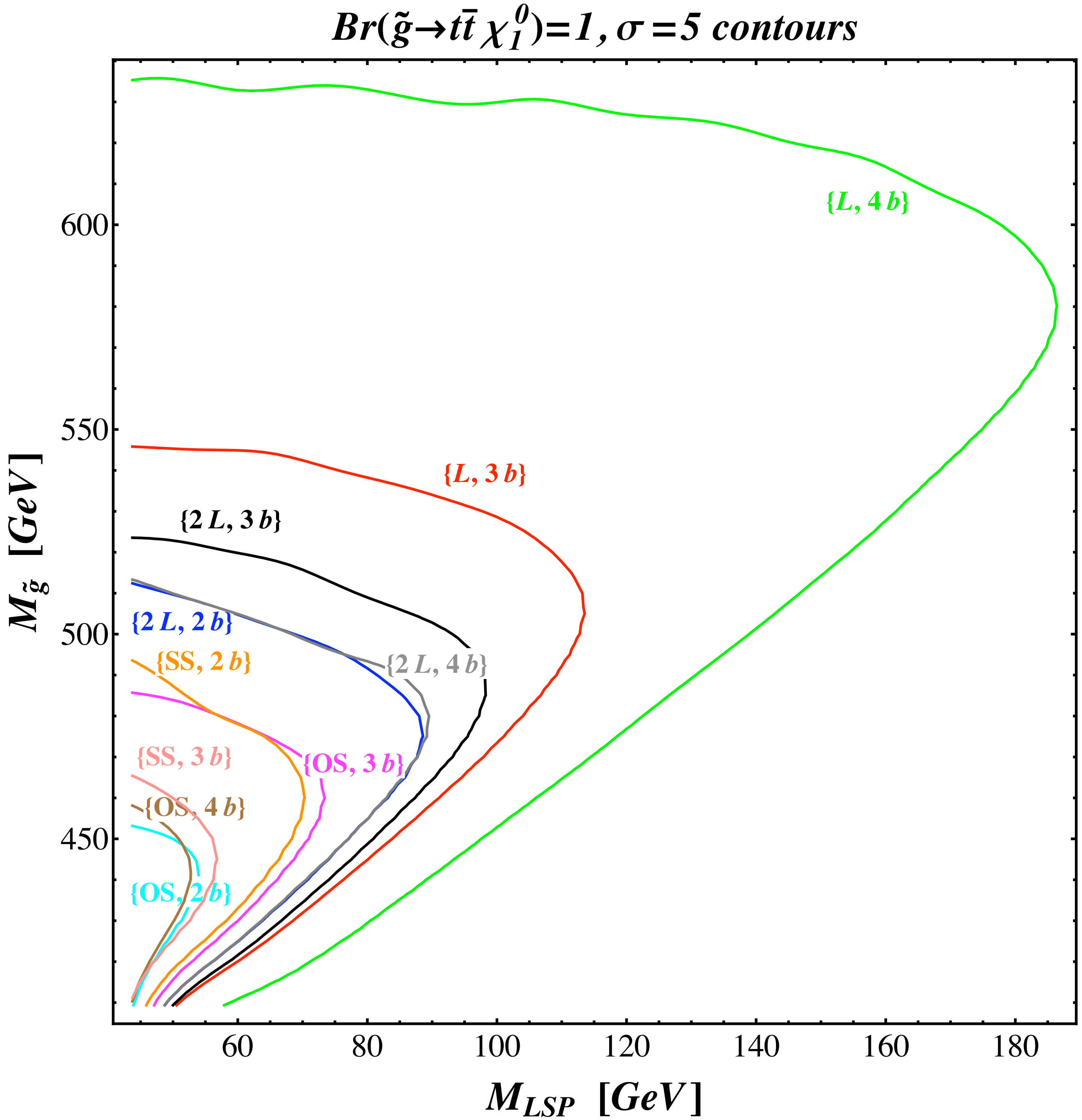
$$p\ p \rightarrow \tilde{g}\tilde{g} \rightarrow t\bar{t}t\bar{t}(\mathrm{or}\ t\bar{t}b\bar{b},\ t\bar{t}t\bar{b}\ \ldots)$$

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

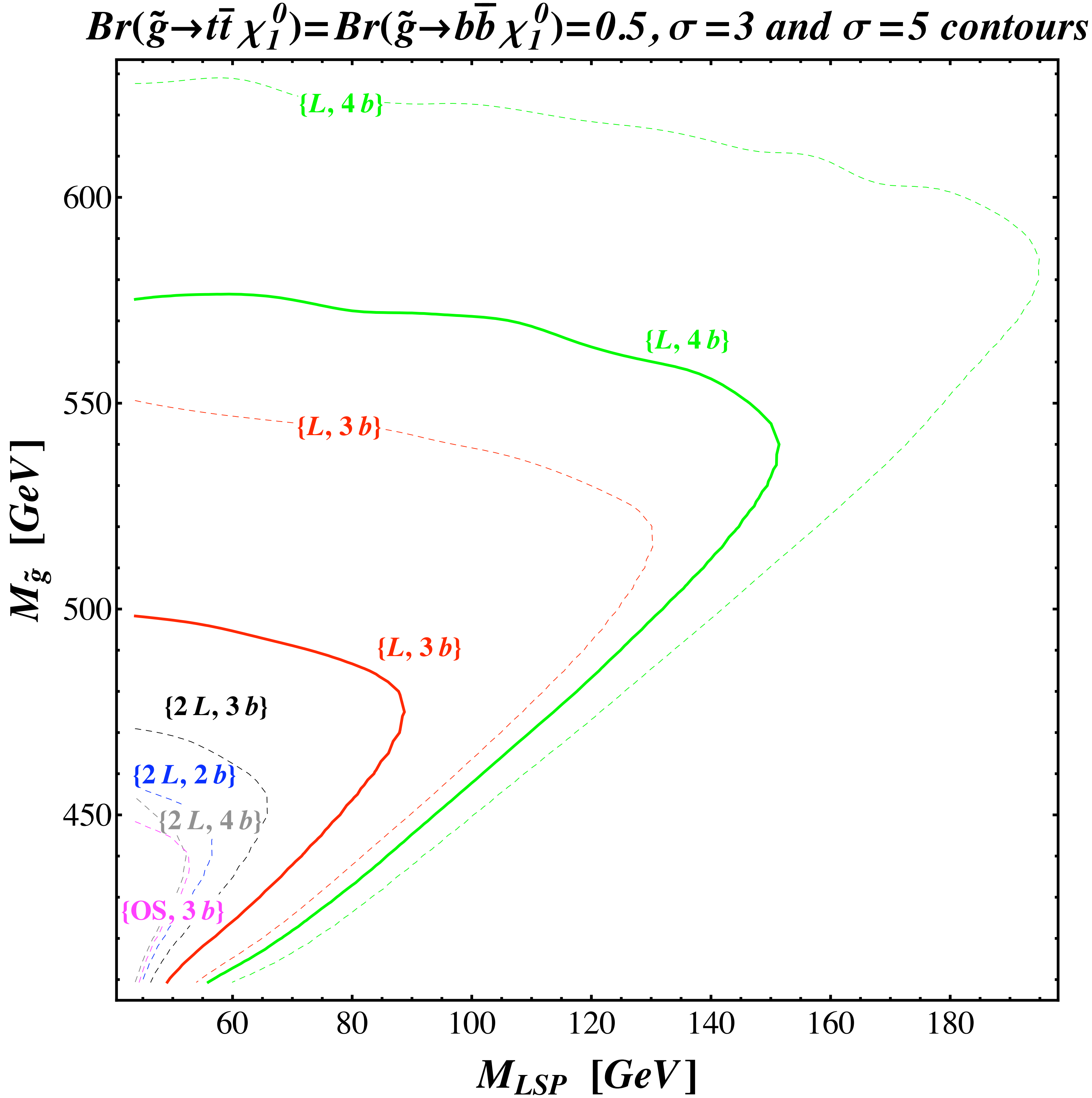
- Multiple b, multiple lepton final state.
  - Good early discovery potential.
  - Challenging to interpret: top reconstruction difficult.

Acharya, Grajek, Kane, Kuflik, Suruliz, Wang, arXiv:0901.3367
Kane, Kuflik, Lu, Wang, 1101.1963.

# Reach at 7 TeV and one inverse fb.



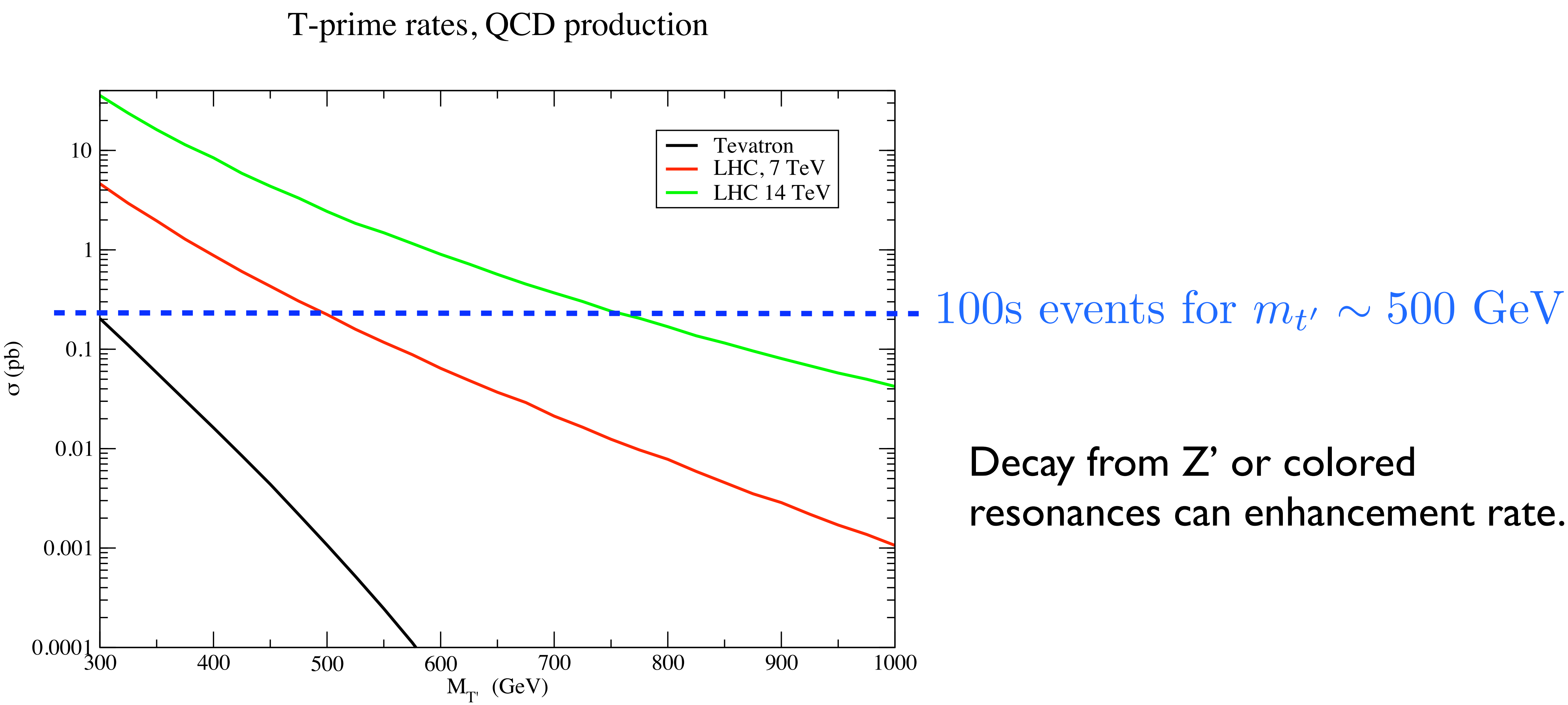
# Reach:



$Br(\tilde{g}\to t\bar{t}\,\chi_1^0)=Br(\tilde{g}\to b\bar{b}\,\chi_1^0)=0.5$, $\sigma=3$ and $\sigma=5$ 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
$M_{\tilde{g}}$ [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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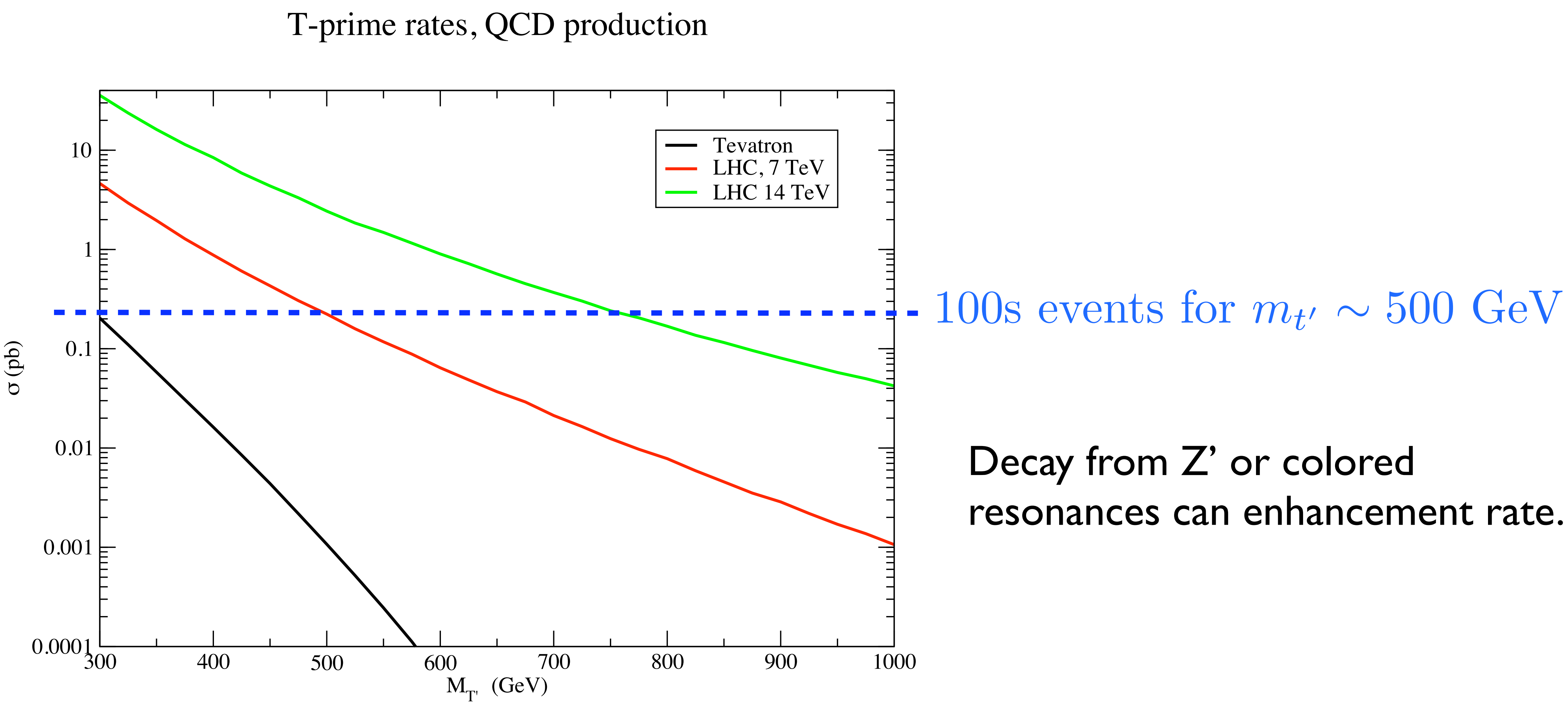


Decay from Z' or colored resonances can enhancement rate.

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

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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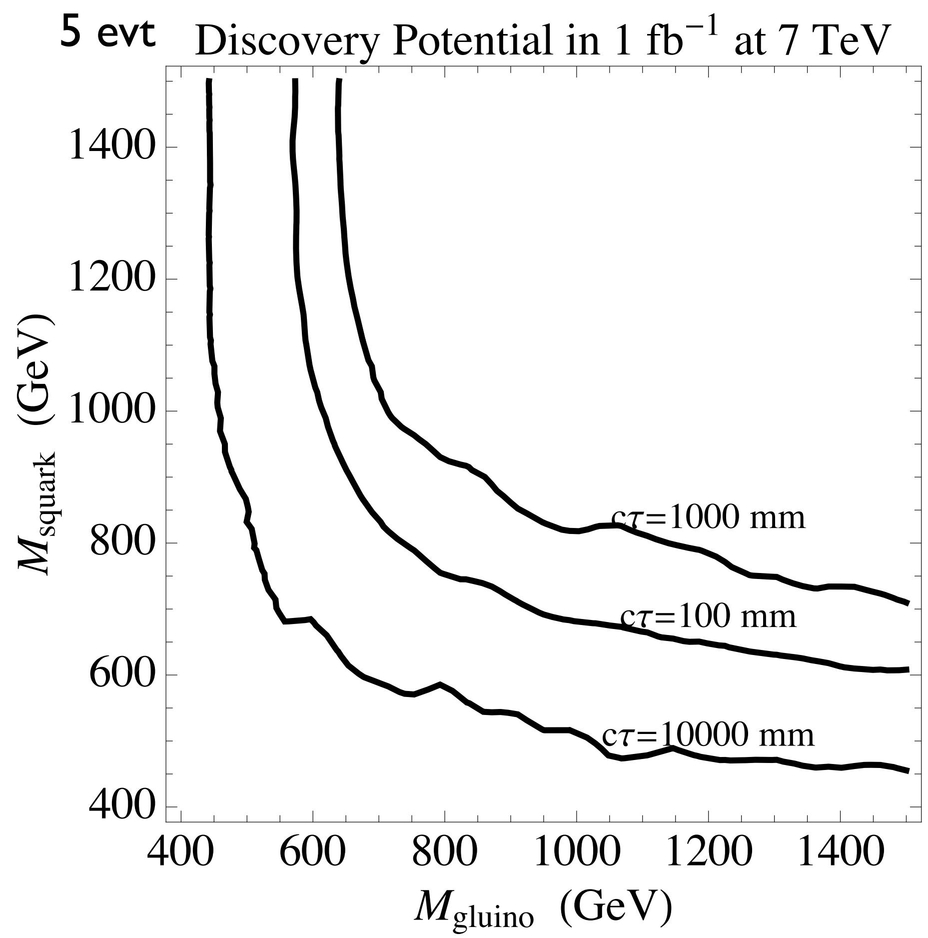
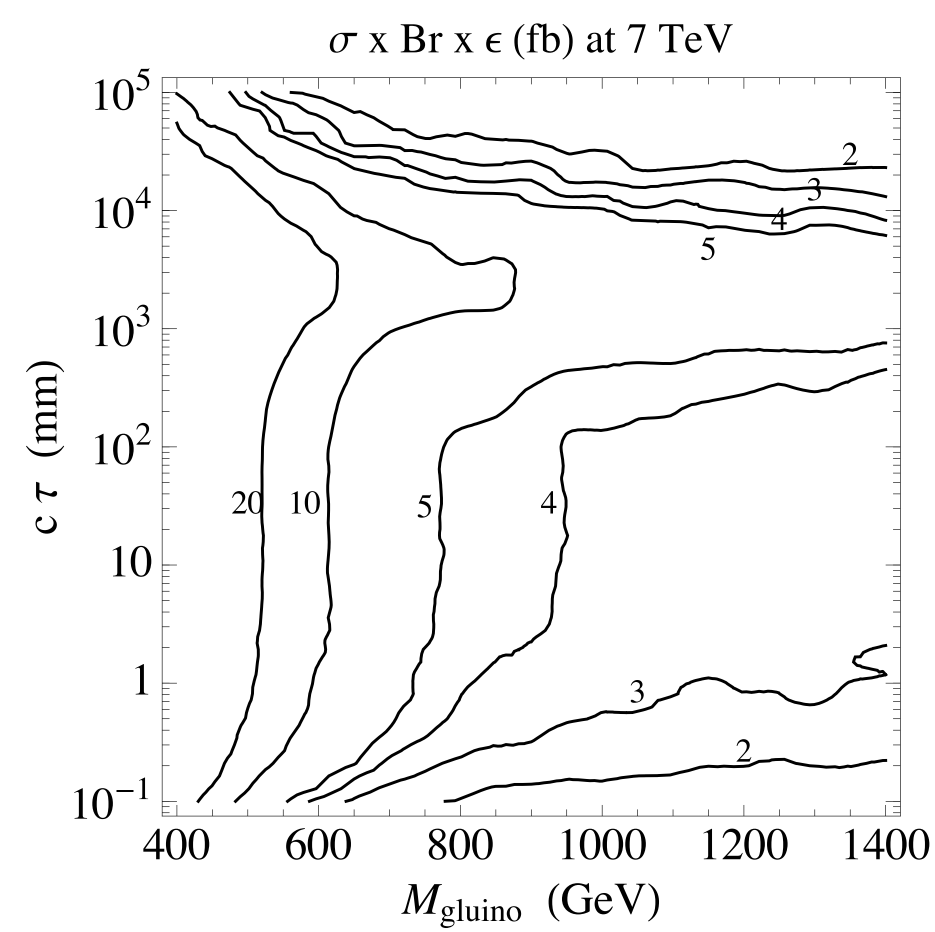
GMSB

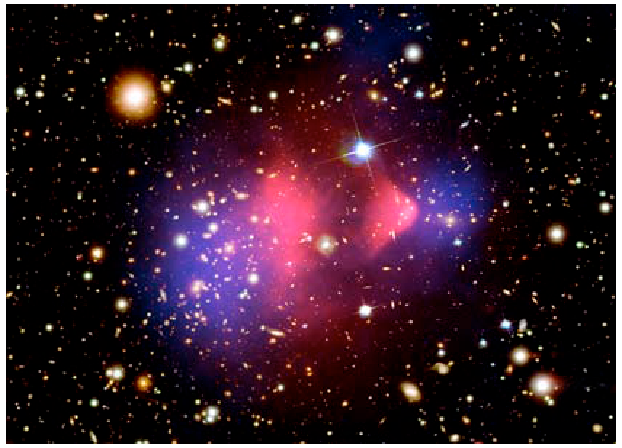


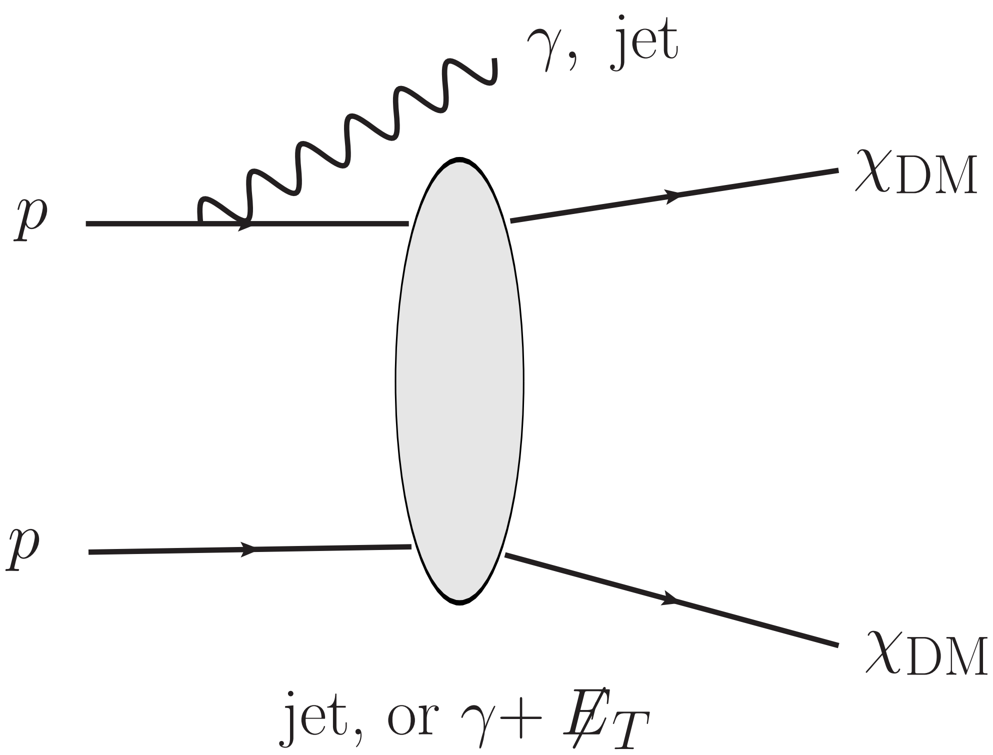

Higgsino NLSP $m_{\tilde{h}} = 250$ GeV $\tilde{h} \to Z(h) + \text{gravitino}$

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

# Collider Signals of dark matter.



- Basic channel

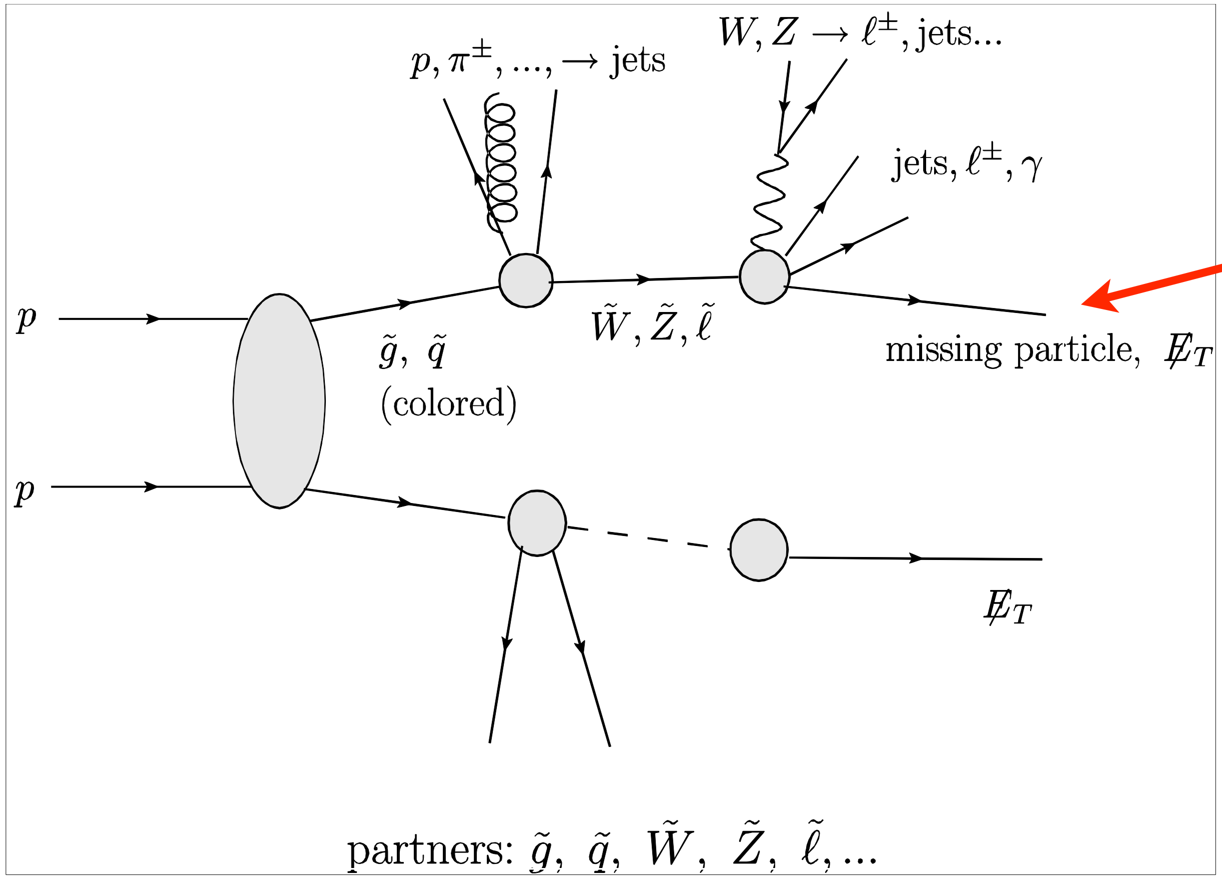



- Large Standard Model background, about 10 times the signal.

- Challenging.

# A luckier scenario:

- DM candidate embedded in an extended TeV new physics scenario




DM candidate

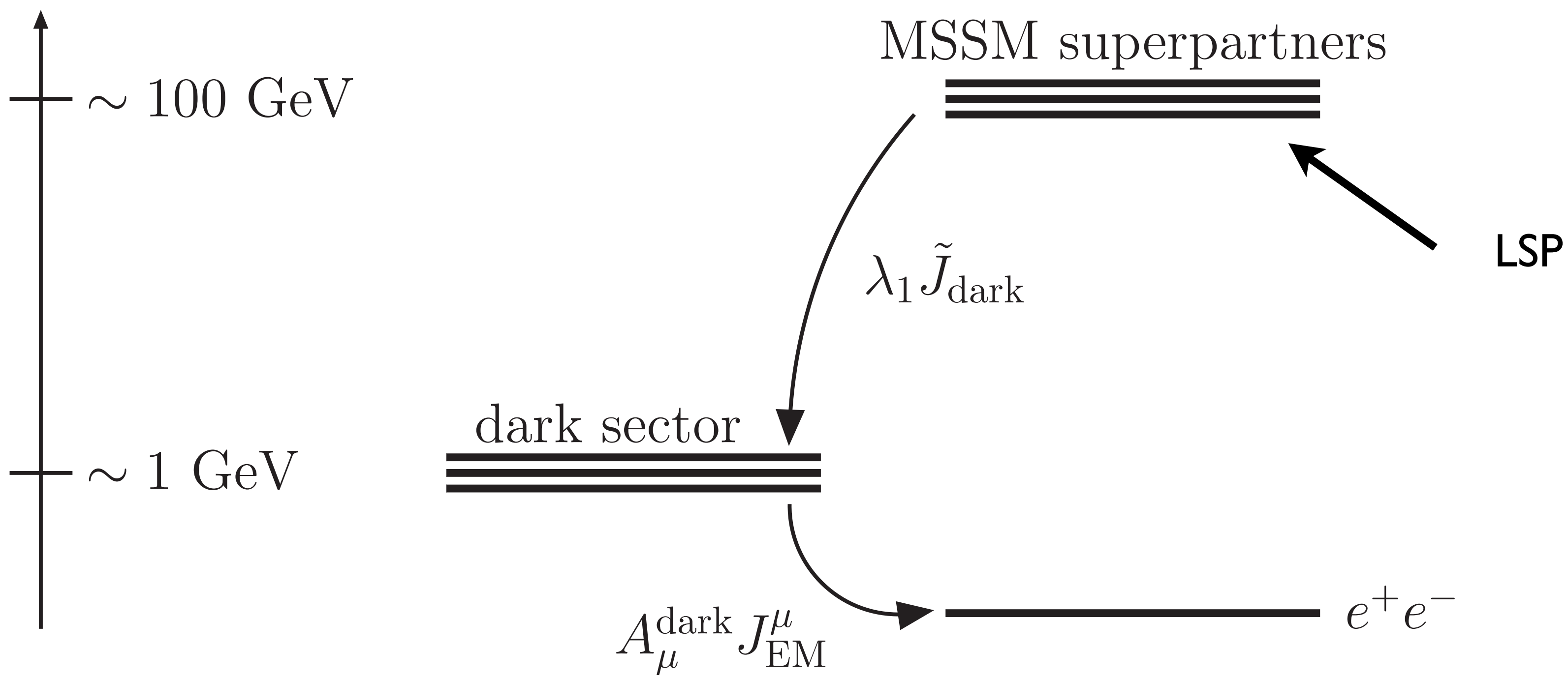
Example: SUSY
Lightest superpartner (LSP)
Neutral and stable.

- Could be early discovery.

# New class of signal: dark Force

- Dark matter self-interaction, mediated by

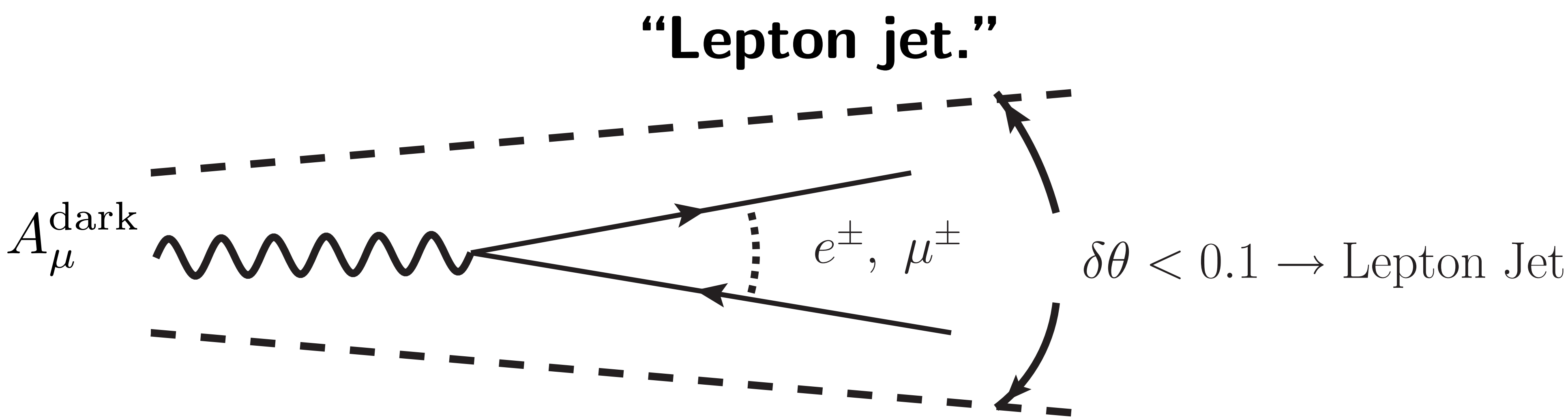
$$A_\mu^{\rm dark}, \quad m_{A^{\rm dark}} \sim \ (100{\rm s\ MeV\ -\ GeV})$$




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.

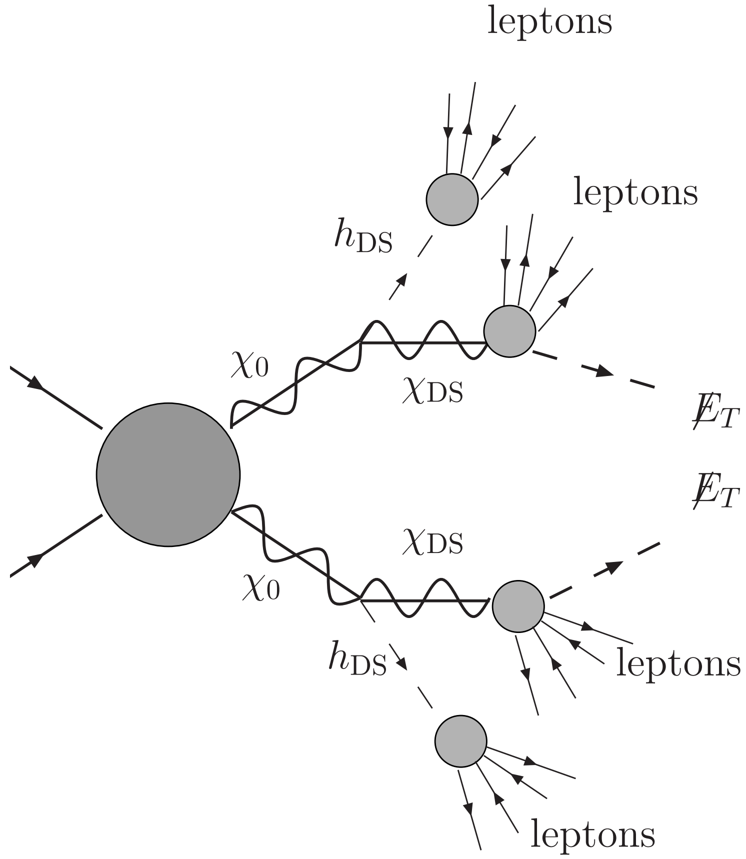


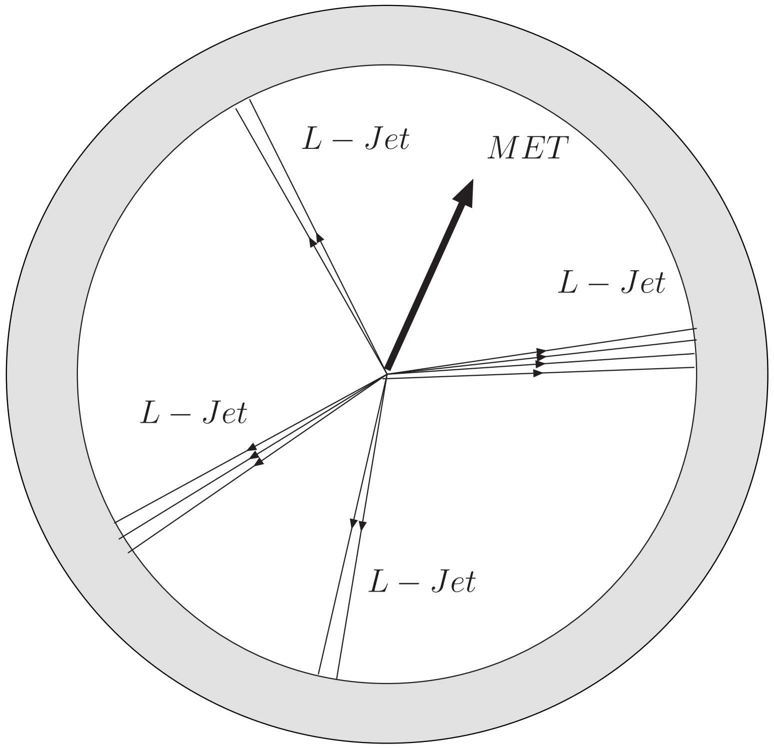

$$\left.\begin{array}{c}\text{Typical } E_{\gamma'} > 10 \text{ GeV} \\ m_{\gamma'} \sim \text{ GeV}\end{array}\right. \to \ \delta\theta \sim m_{\gamma'}/E_{\gamma'} < 0.1$$

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

# Supersymmetric dark force

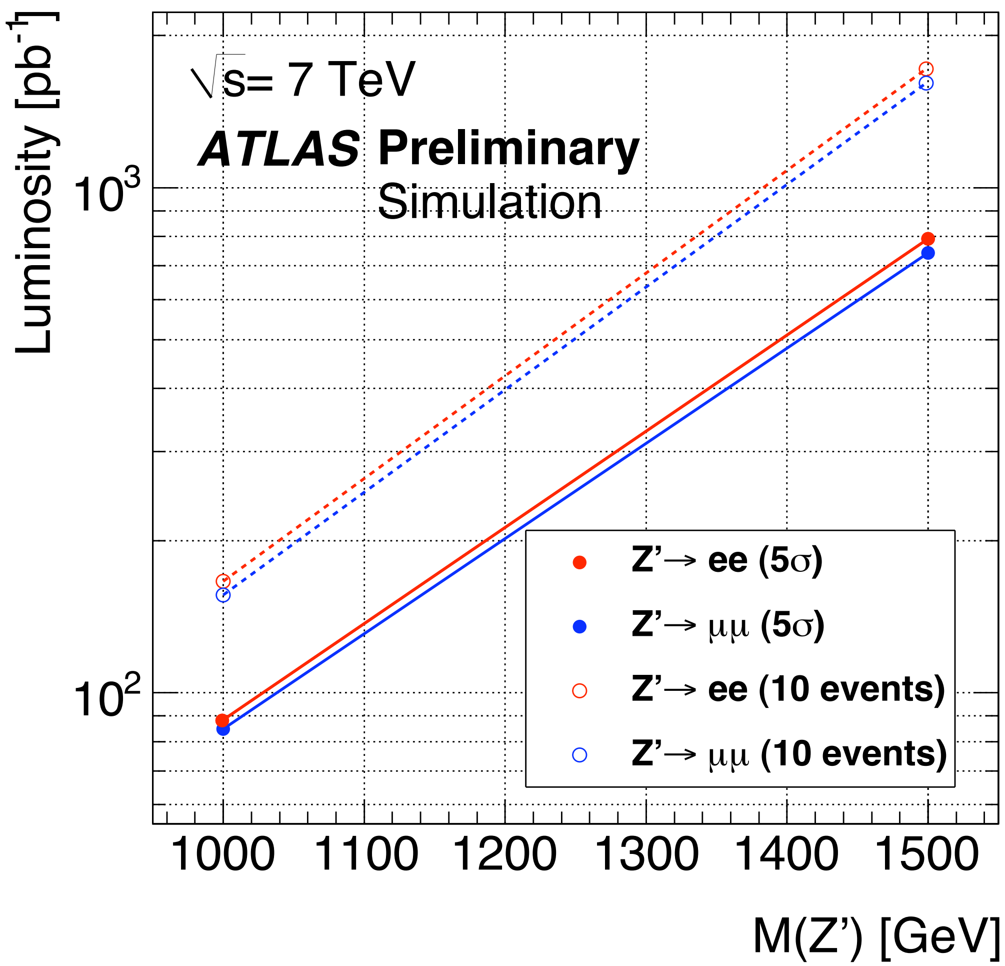
- Most natural way of generating the GeV scale.
- Spectacular signal.
- Early discovery.

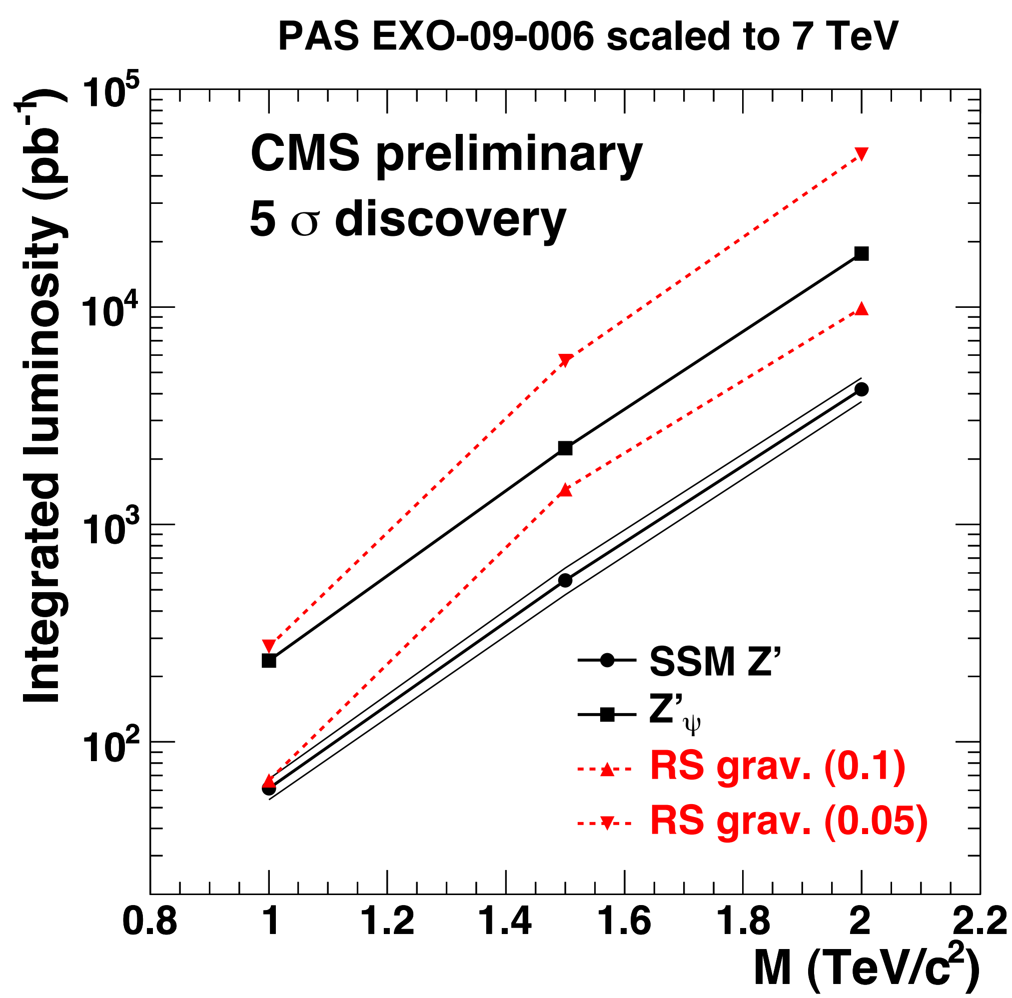


# Resonances: $Z' \to \ell^+ \ell^-$

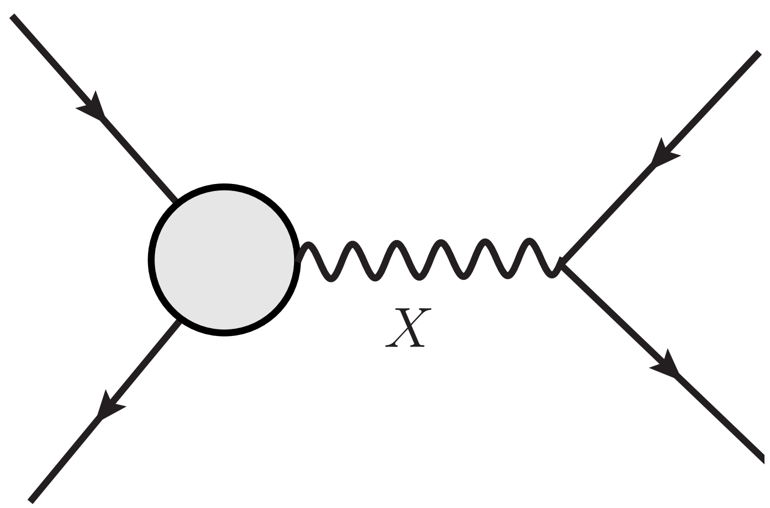
- Good sensitivity at early LHC.



# 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 $t\bar{t},\ W^+W^-,\ W^\pm Z, \ldots$




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

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

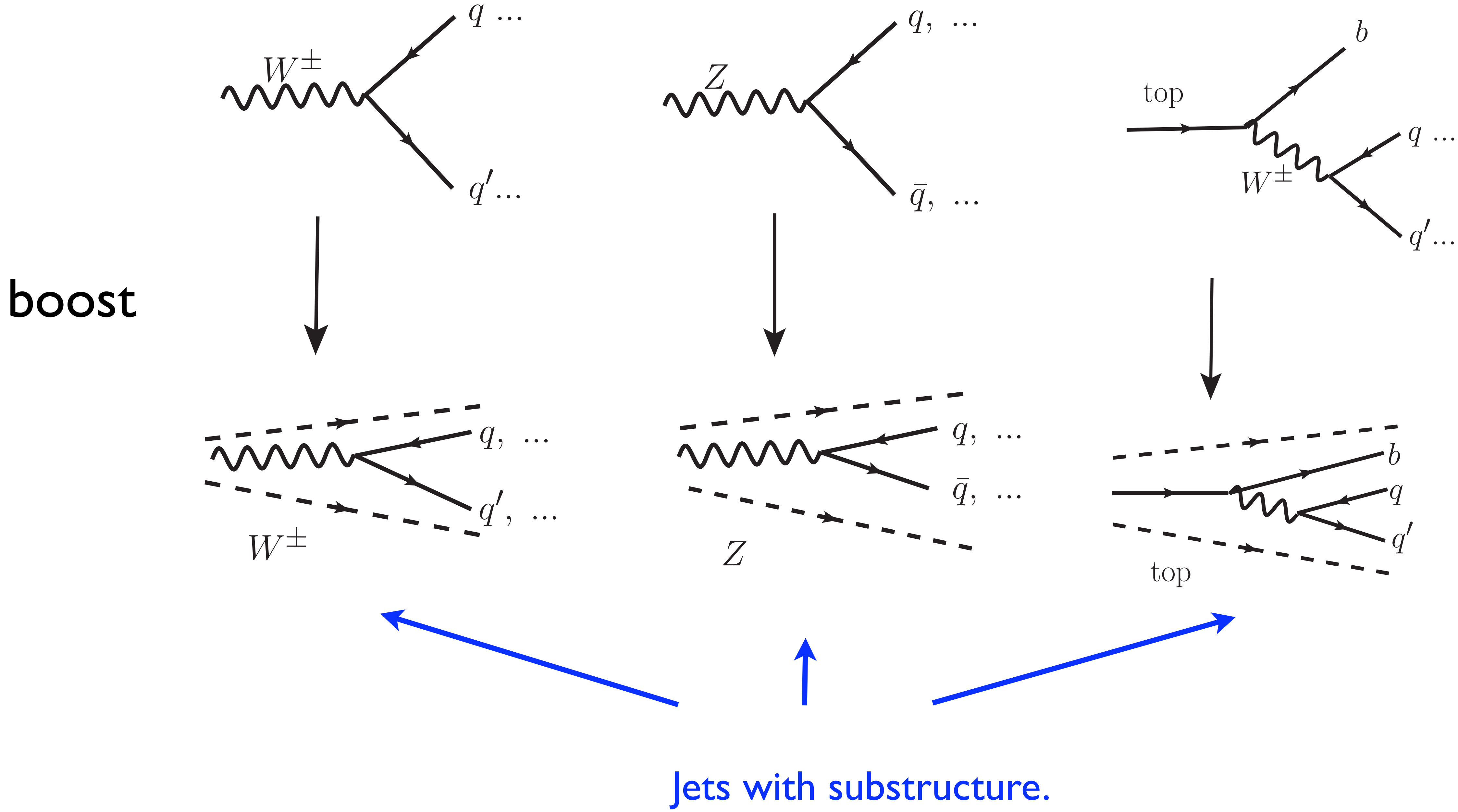
$$E_{t,W,Z,h} \sim \frac{m_X}{2}$$

highly boosted if $m_X \sim$ TeV

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

# Jet substructure.

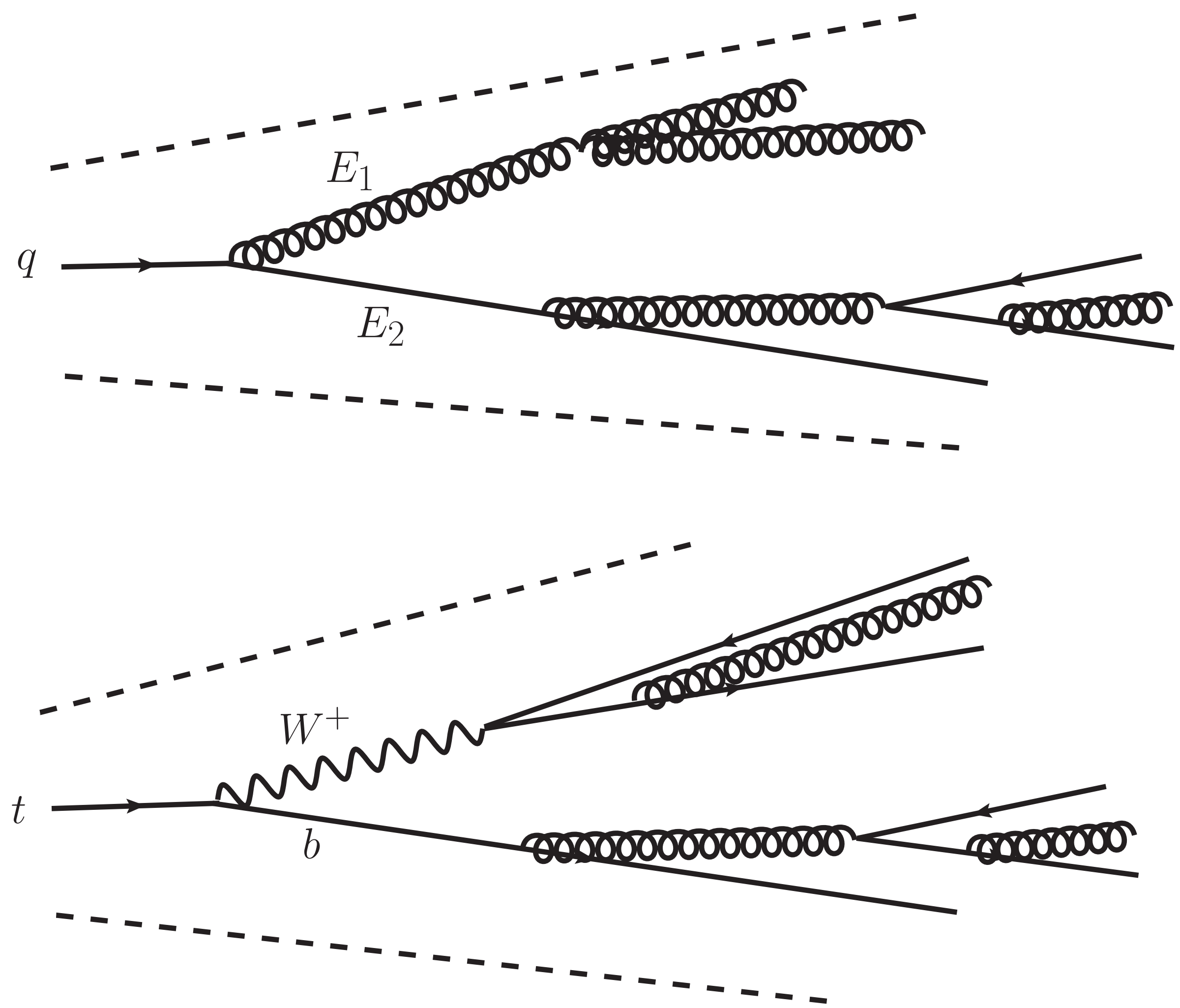
- When produced at TeV-scale energies, they have a large boost.




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

# Example: boosted top tagging at the LHC

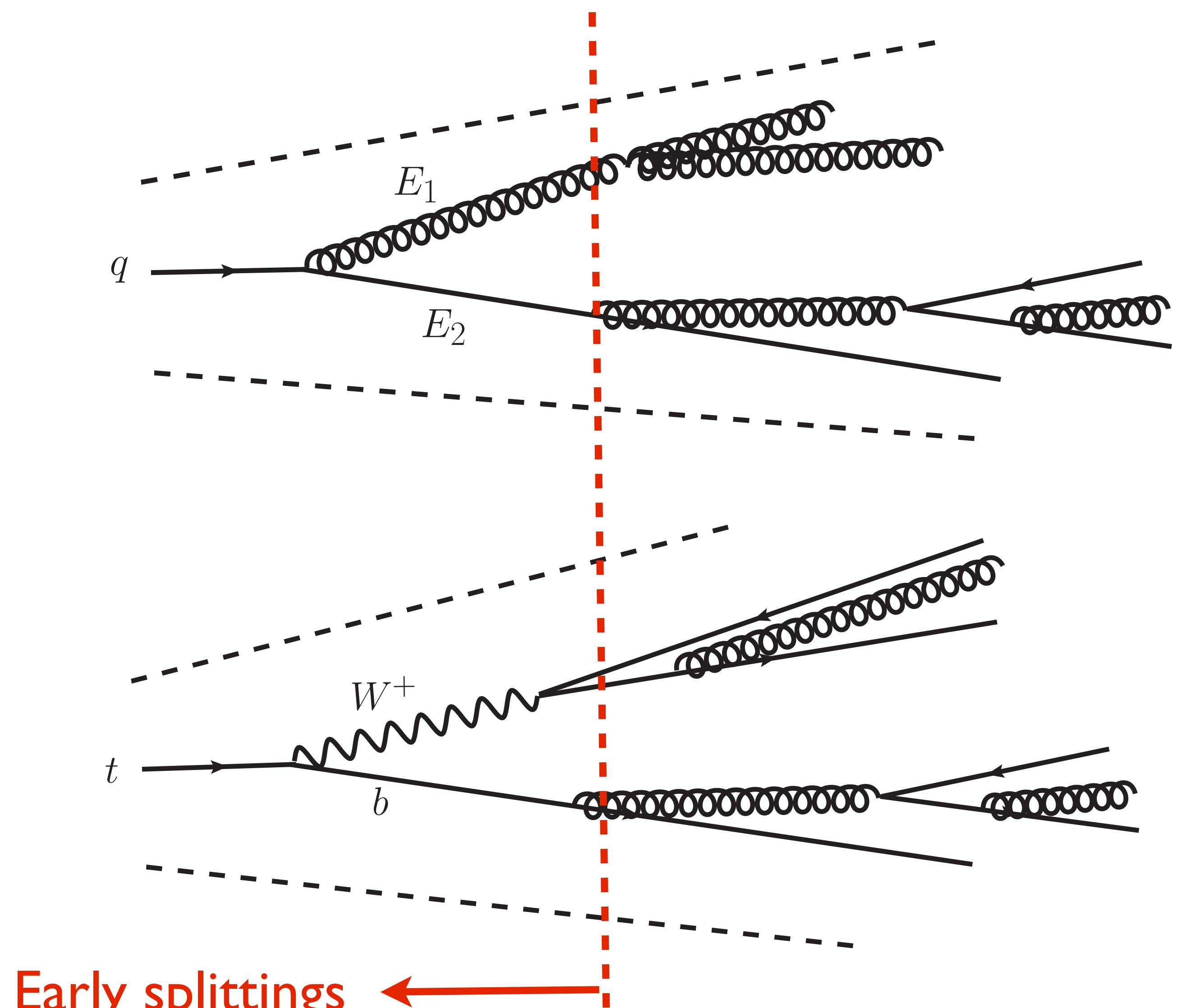
- Fully collimated tops look like QCD jets.



# Example: boosted top tagging at the LHC

- Fully collimated tops look like QCD jets.

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

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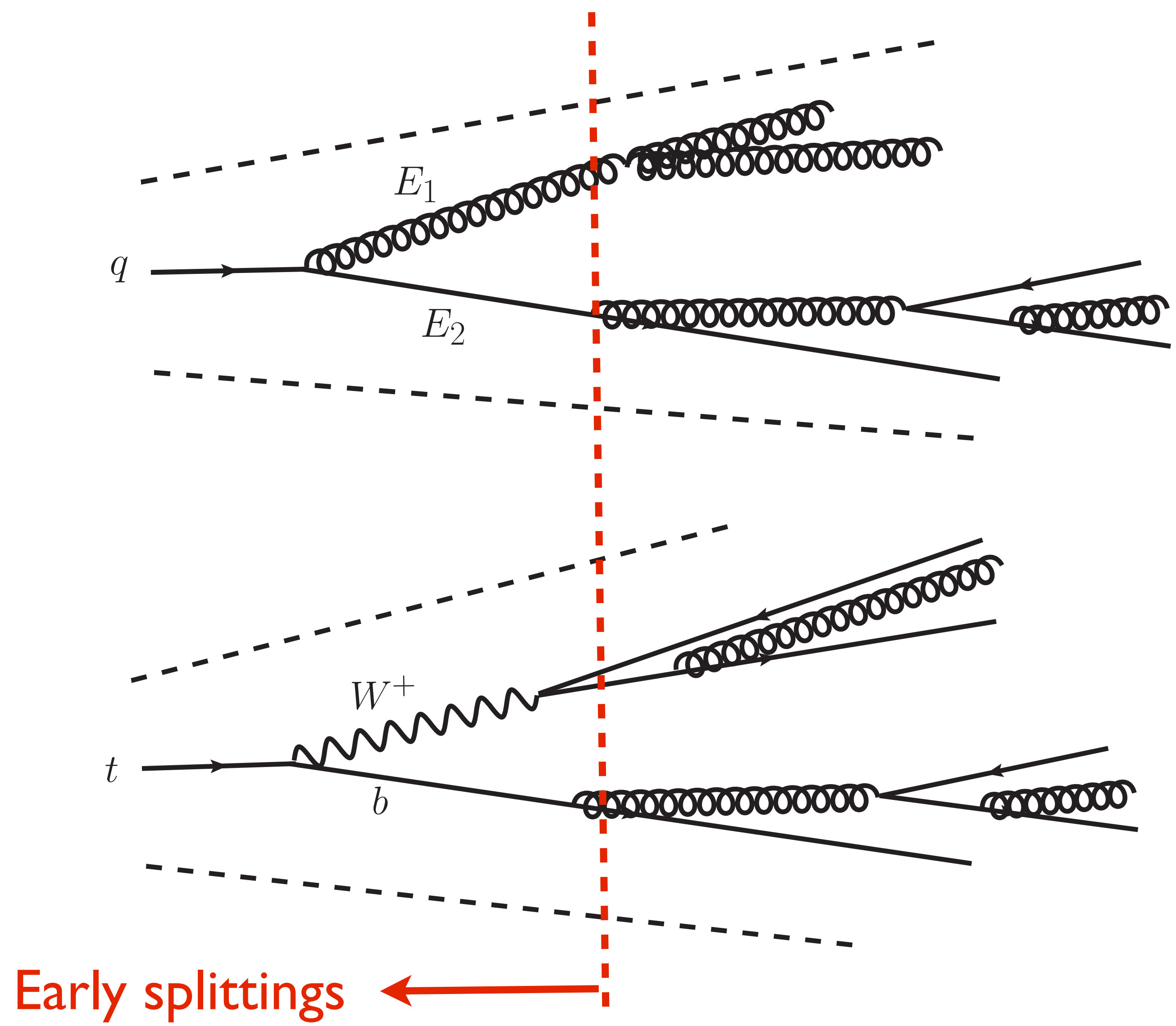



Zooming in near the first splitting

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

Jet mass: $d\sigma \propto \frac{1}{m_{\mathrm{jet}}^2}$

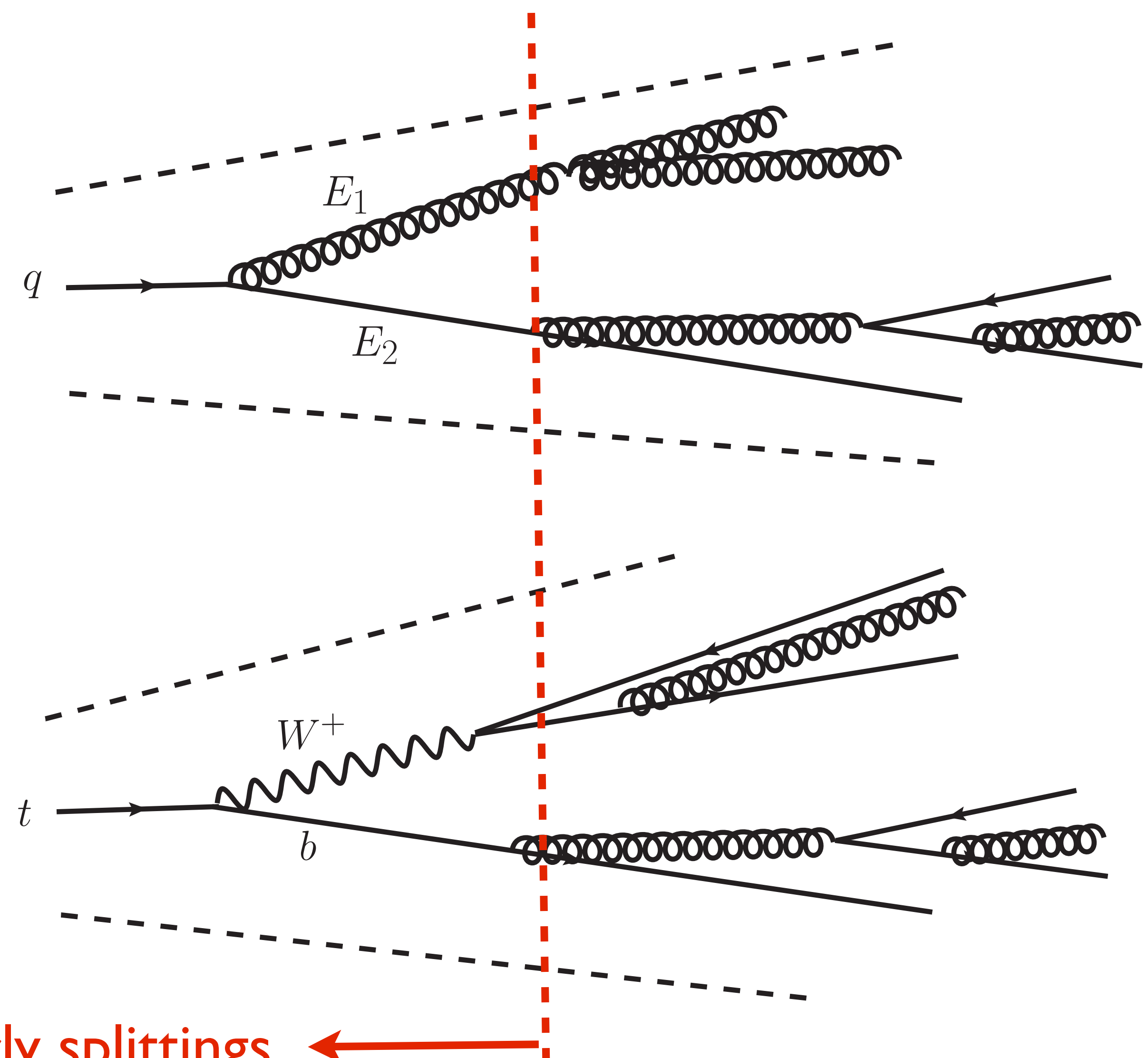
Top. Decay: $z = \frac{\mathrm{Min}(E_{\mathrm{W}}, E_b)}{E_{\mathrm{W}} + E_b} \to \text{finite}$

Jet mass: $m_{\mathrm{jet}} \simeq m_{\mathrm{top}}$

# Example: boosted top tagging at the LHC

- Fully collimated tops look like QCD jets.

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




Zooming in near the first splitting

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

Jet mass: $d\sigma \propto \frac{1}{m_{\mathrm{jet}}^2}$

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

Jet mass: $m_{\mathrm{jet}} \simeq m_{\mathrm{top}}$

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.

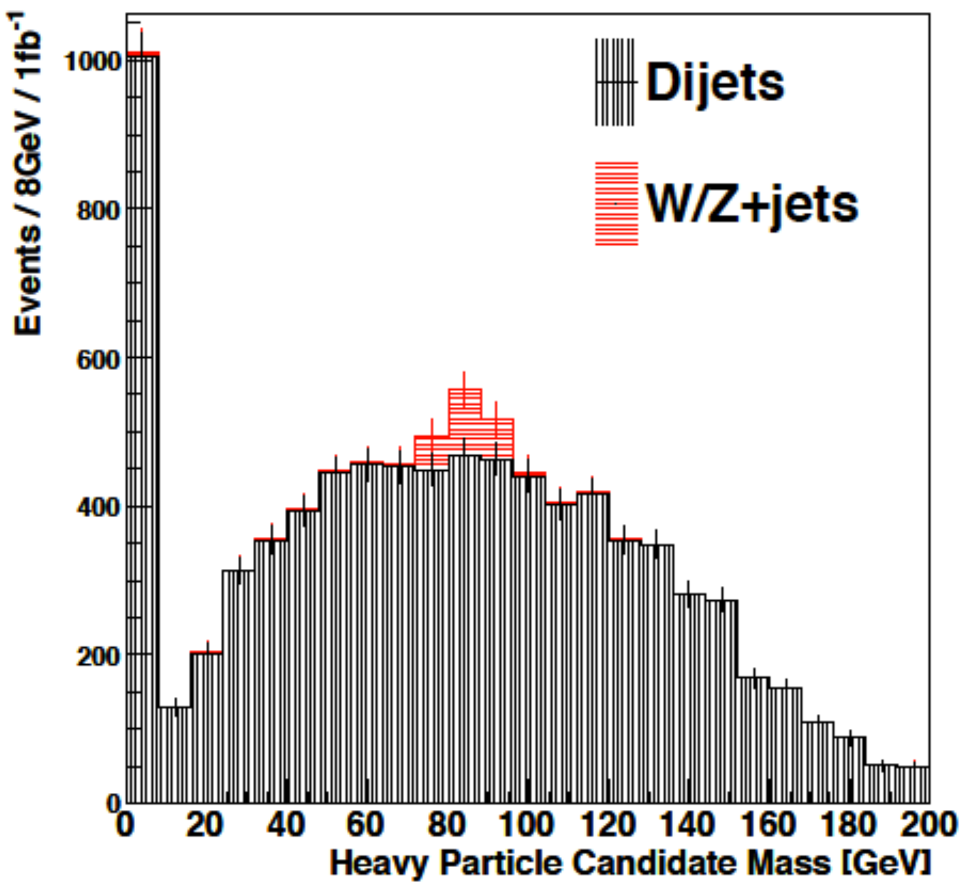
- New jet algorithms have also been proposed.
  - Filtering, trimming, pruning.
  - Cleaning out contaminations from additional radiation in the event, preserving jet shape..

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

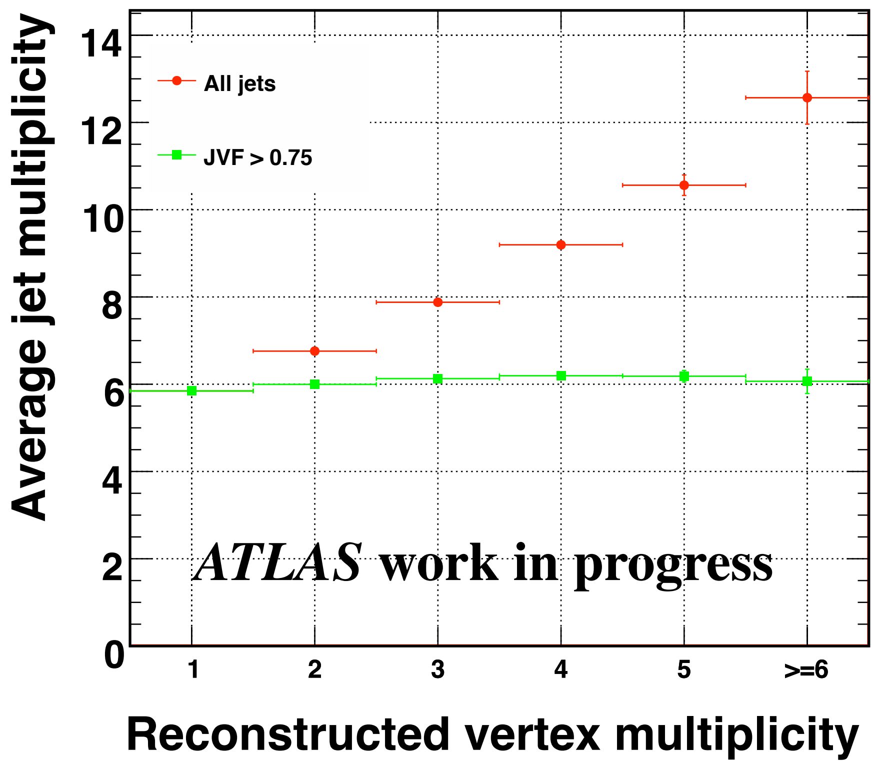



$$p_T^j > 400 \text{ GeV}$$

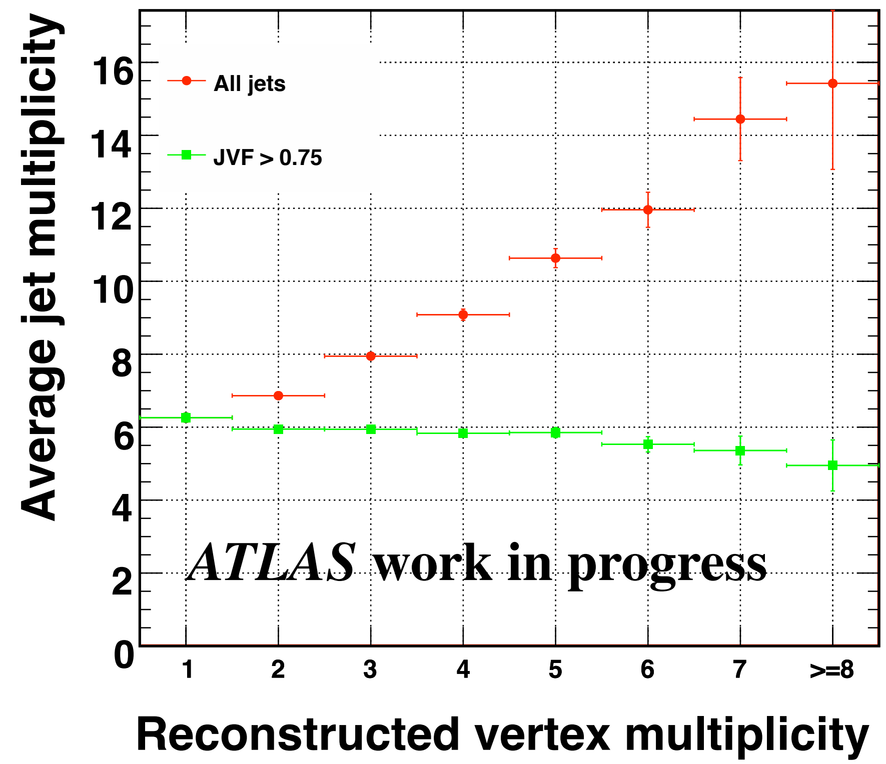
$$\sim 5\sigma \text{ at } 1 \text{ fb}^{-1}$$

Adam Davison, talk at Boost 10

# New method of “cleaning” the event




$\mathcal{L} = 10^{33}$ cm$^{-2}$ s$^{-1}$, $\langle N_{MB} \rangle$=2.3 ($t\bar{t}$)



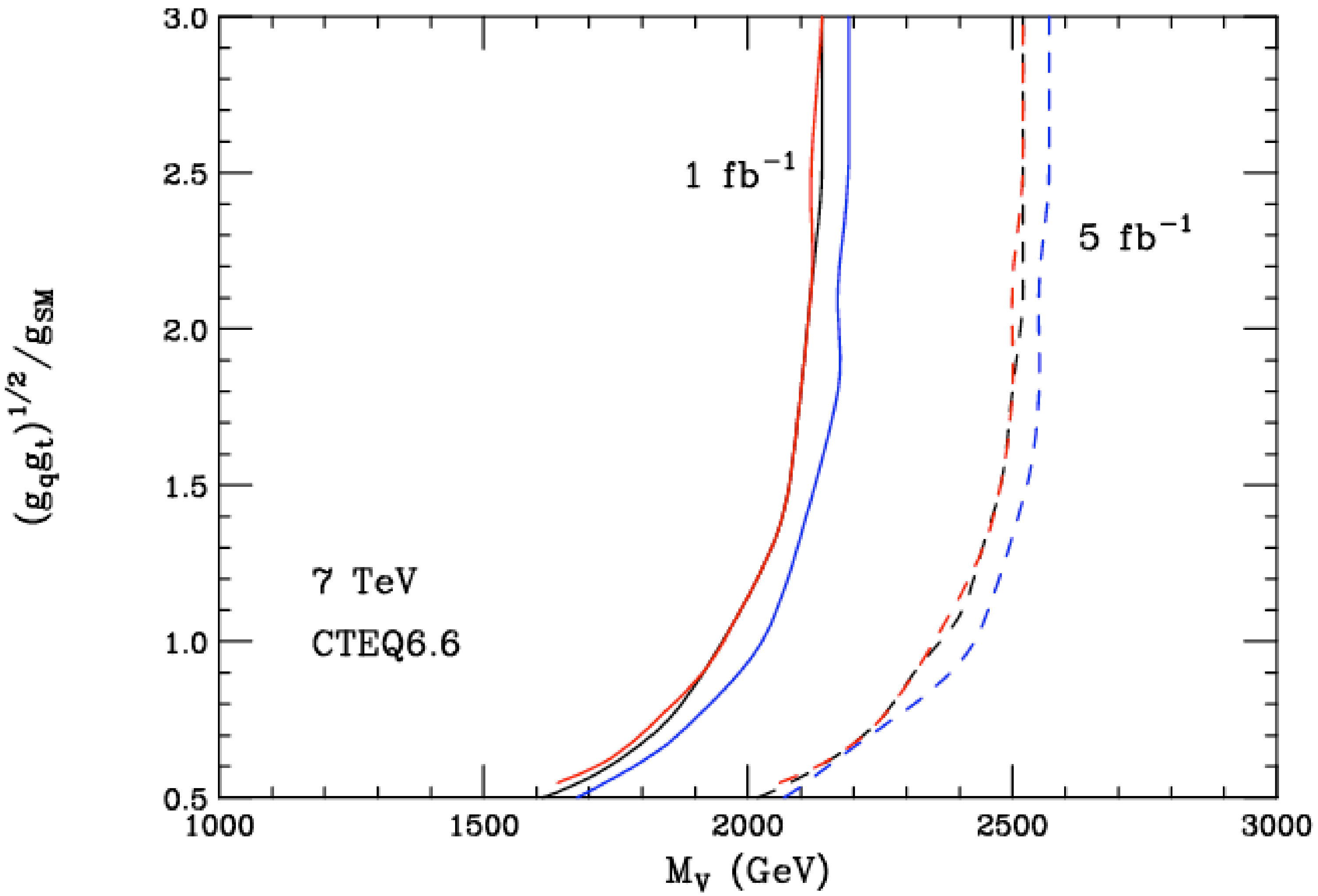

$\mathcal{L} = 2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$, $\langle N_{MB} \rangle$=4.6 ($t\bar{t}$)

http://www.physics.uoregon.edu/~soper/Jets2011/Miller.pdf

# What about “known” new physics

# Axi-gluon

Cao, Mckeen, Rosner, Shaughnessy, Wagner, 1103.3461
Bai, Hewett, Kaplan, Rizzo, 1101.5203




J. Hewett, J. Shelton, M. Spannowsky, T. Tait, M. Takeuchi, 1103.4618

# Axi-gluon

Cao, Mckeen, Rosner, Shaughnessy, Wagner, 1103.3461
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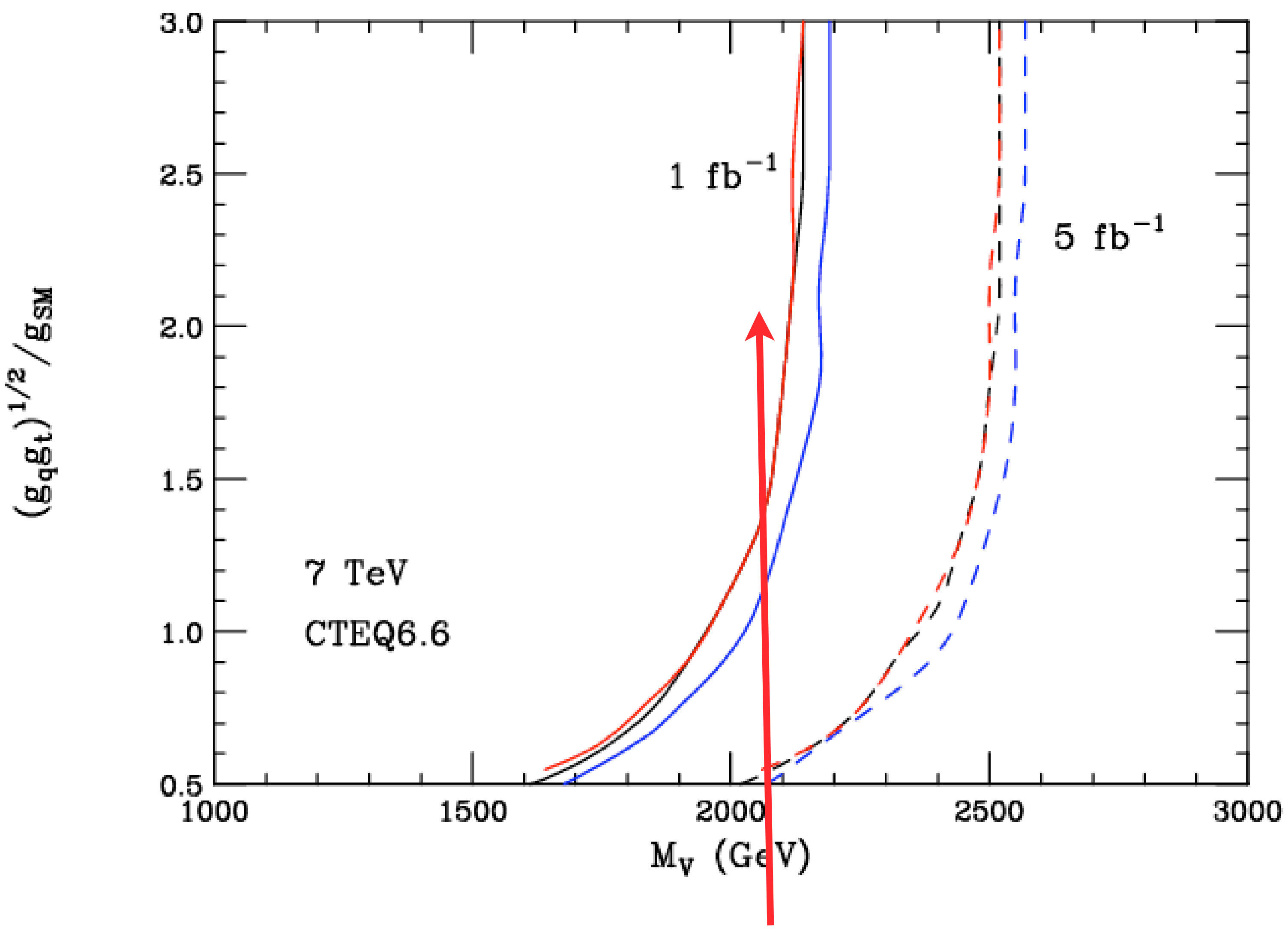
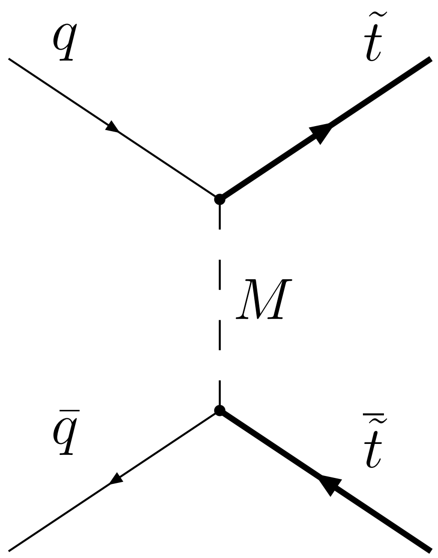



"preferred value": $M_{G'} = 2$ TeV, $g_A^q = 2.2$, $g_A^t = -3.2$ and $g_V = 0$.

J. Hewett, J. Shelton, M. Spannowsky, T. Tait, M. Takeuchi, 1103.4618

# Or more excitingly




(a) $t\bar{t}$ production

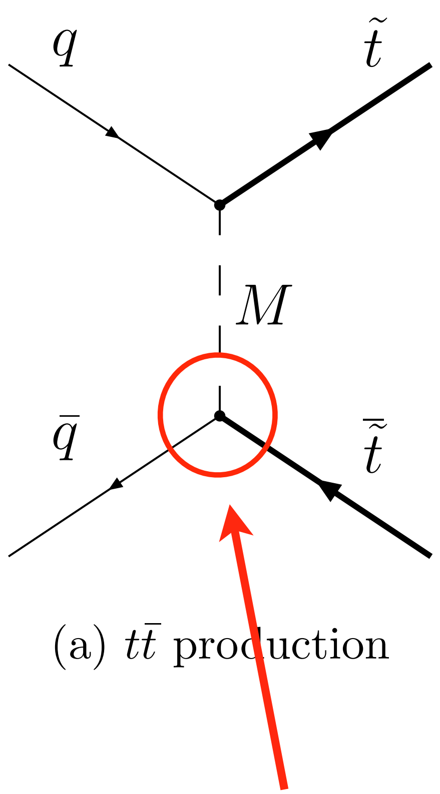
$$M: \; W', \; Z' \text{ (color singlet)}$$

$$\bar{\mathbf{3}}, \; \mathbf{6}$$

Z': same sign di-top.

Now, CDF limit at 6.5 fb-1. Lighter < 200 GeV borderline allowed.
Should be able to see it at LHC very quickly, even at ~ 35 pb-1.

# Or more excitingly



(a) $t\bar{t}$ production

maximal flavor violating

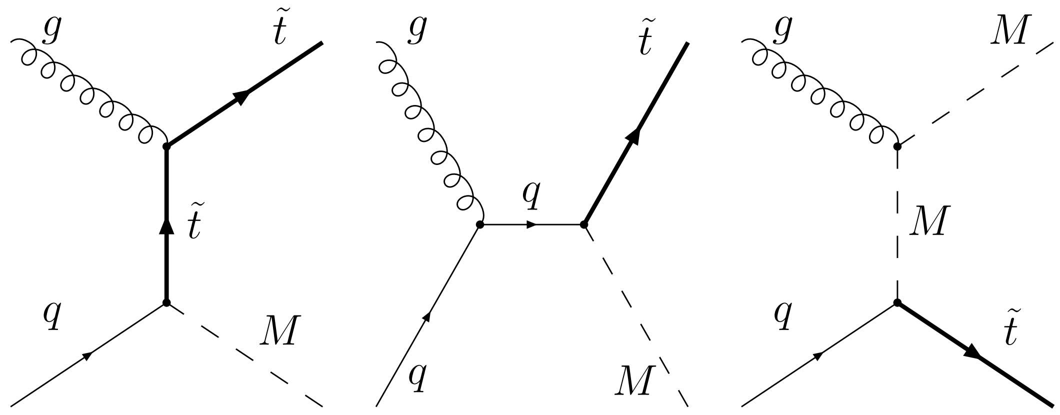
$$M:\ W',\ Z'\ \text{(color singlet)}$$

$$\bar{\mathbf{3}},\ \mathbf{6}$$

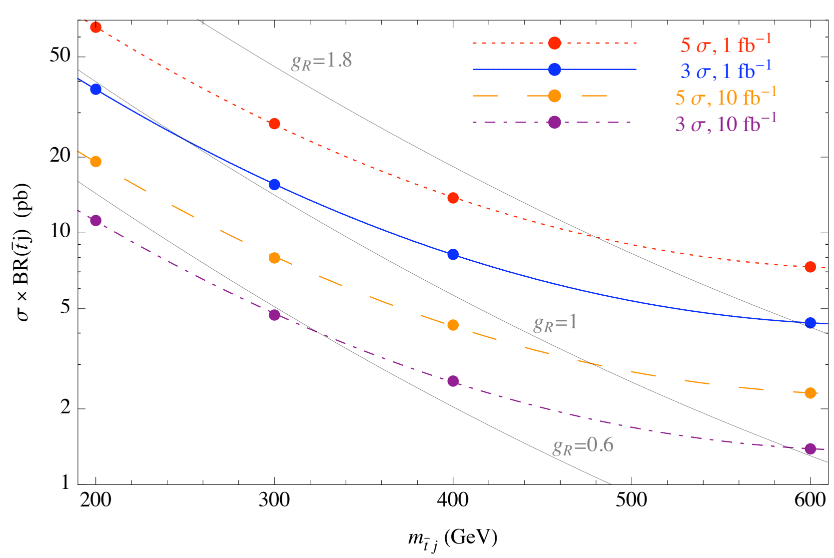
Z': same sign di-top.

Now, CDF limit at 6.5 fb-1. Lighter < 200 GeV borderline allowed.
Should be able to see it at LHC very quickly, even at ~ 35 pb-1.

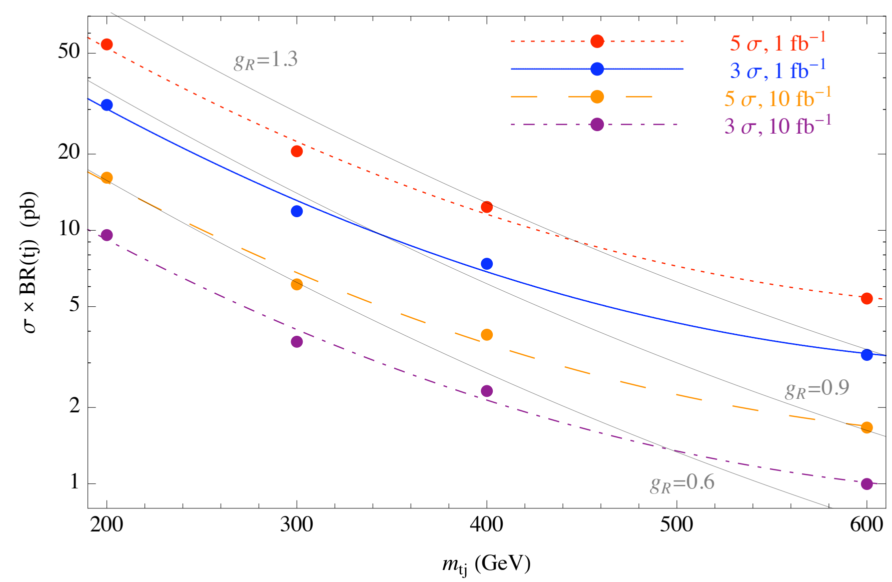
# Searches at the LHC




(b) t-channel (c) s-channel (d) u-channel



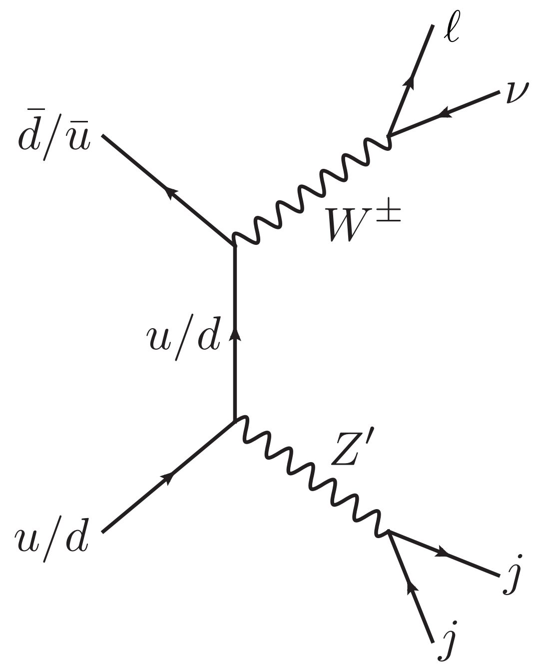

(a) $W'$

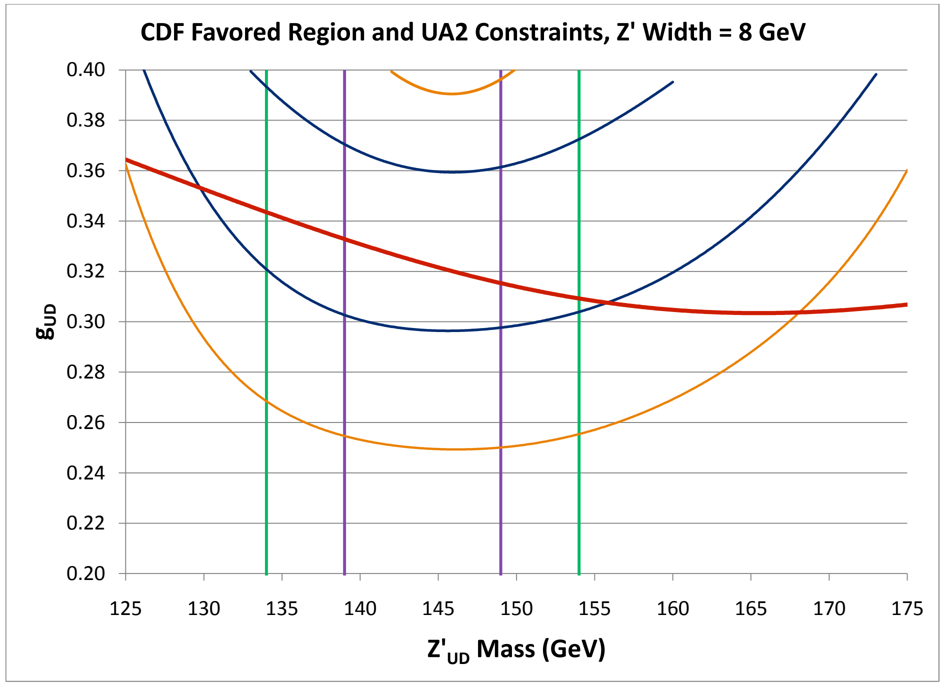



(c) Triplet

Gresham, Kim, Zurek, 1102.0018

# More zprime




F. Yu, 1104.0243

- Lepto-phobic.
- $m_{Z'} \sim 150 \text{ GeV}$
- Should have bounds from Tevatron in $Z + Z', \; \gamma + Z'$
- LHC. Signal rate x 10, background is up at least as much.

# Not mentioned

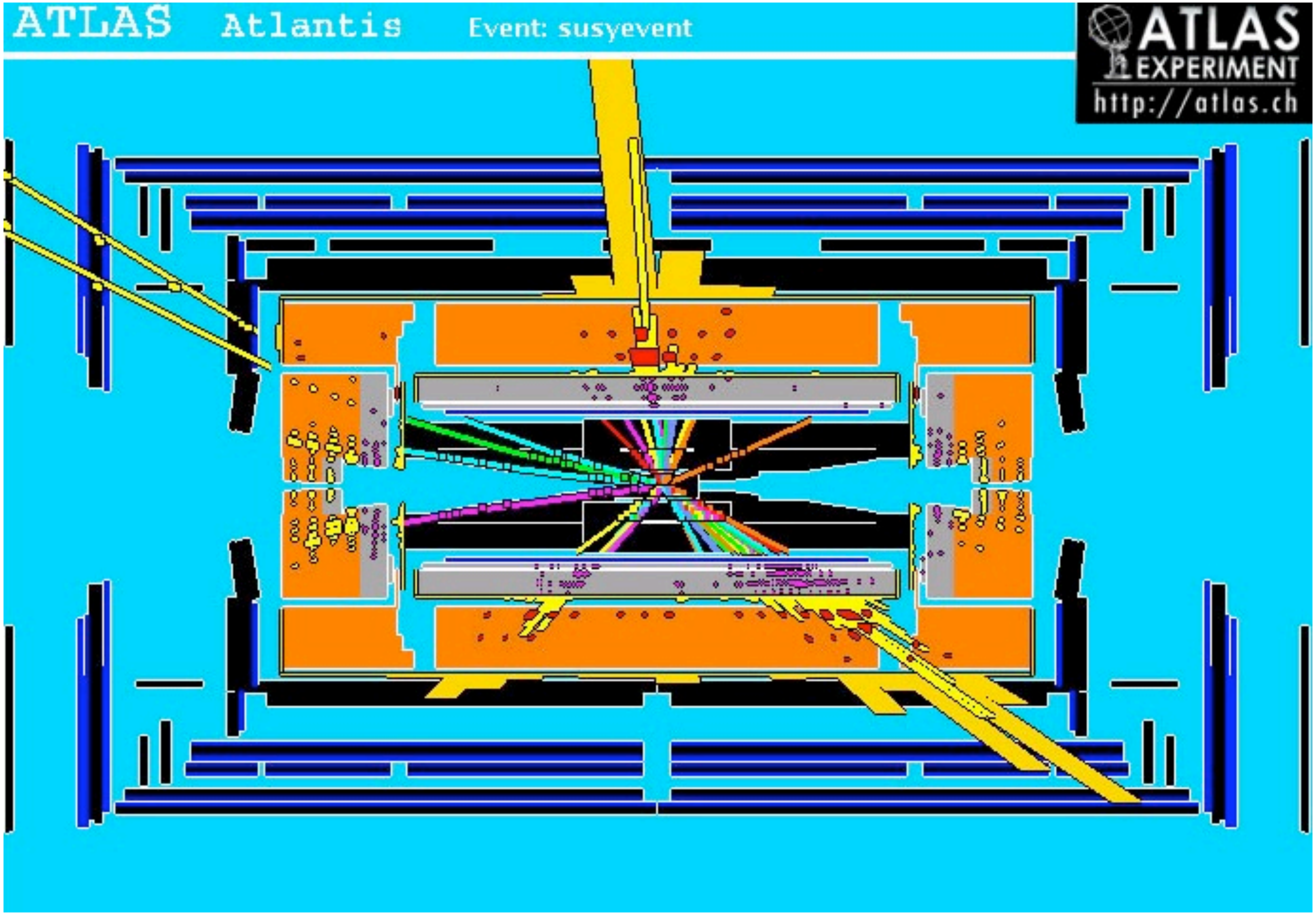
New flavor physics!

# Not mentioned

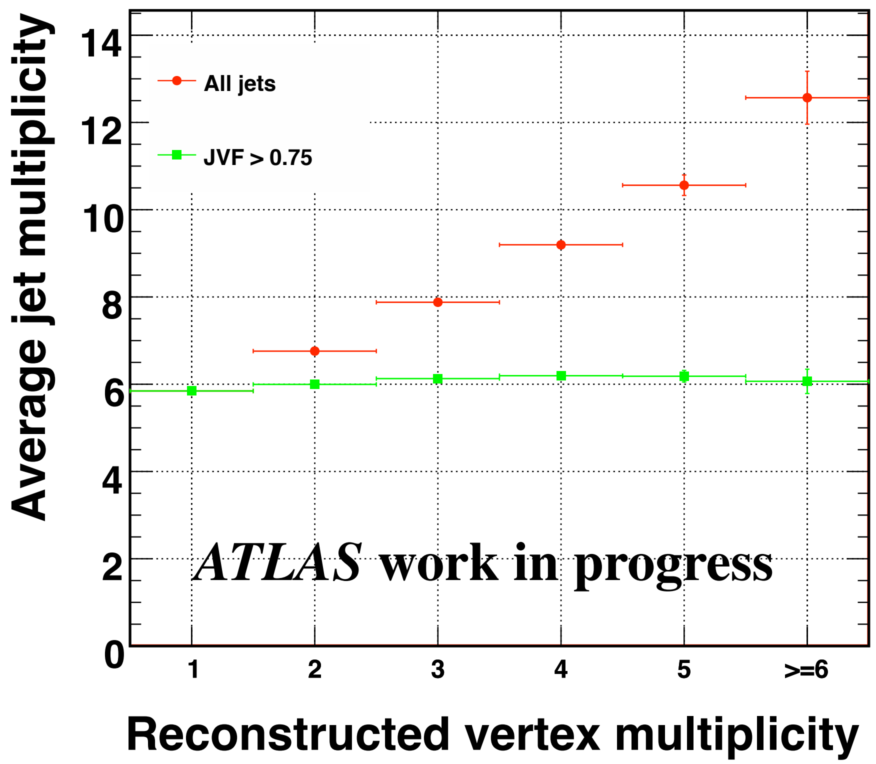
## New flavor physics!

- R-parity violation.
- Hidden valley.
- Blackhole.
- Unparticle.
- Classicalization.
- ....

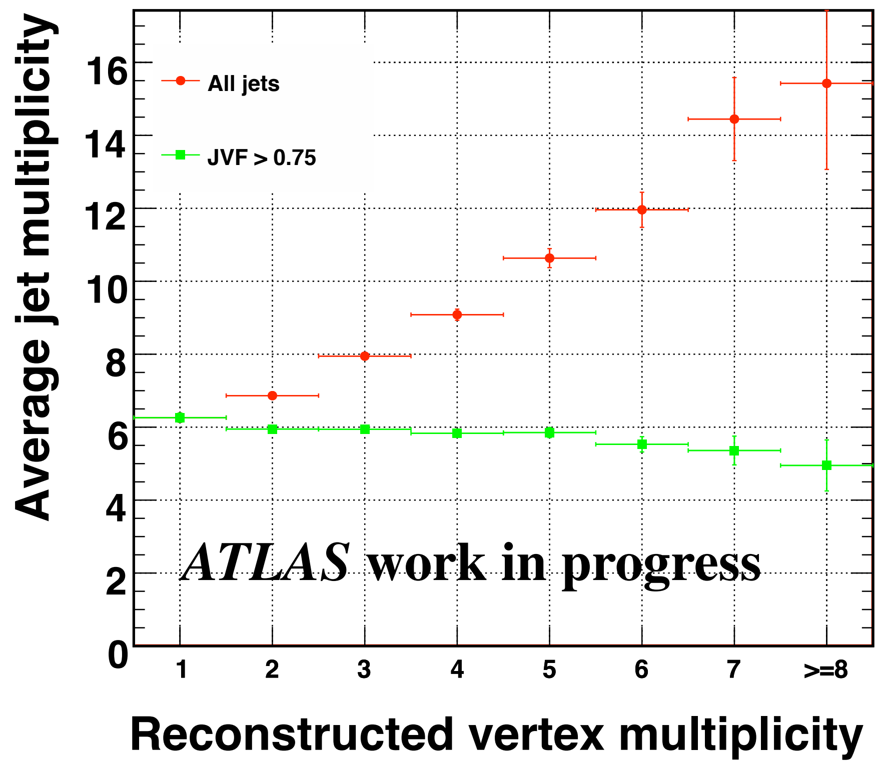
In the next year or so, there are many exciting opportunities for making new physics discoveries at the LHC.



# New method of “cleaning” the event




$\mathcal{L} = 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, $\langle N_{MB}\rangle$=2.3 ($t\bar{t}$)




$\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, $\langle N_{MB}\rangle$=4.6 ($t\bar{t}$)

http://www.physics.uoregon.edu/~soper/Jets2011/Miller.pdf

# 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

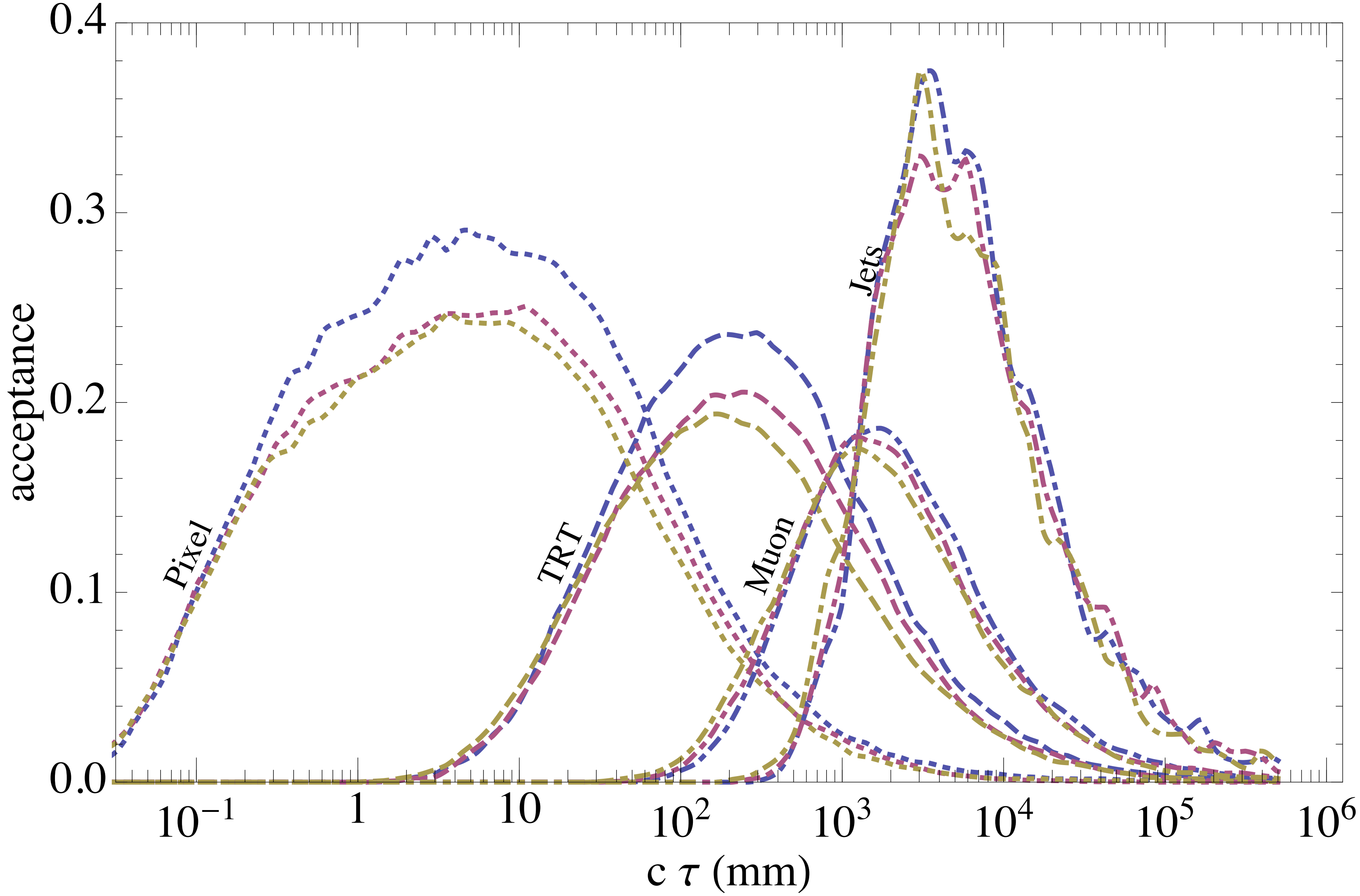
  $W^+Z : \ 7 \text{ pb}, \ W^-Z : \ 3.7 \text{ pb}$

  tri-lepton + MET ~ 0.1 pb

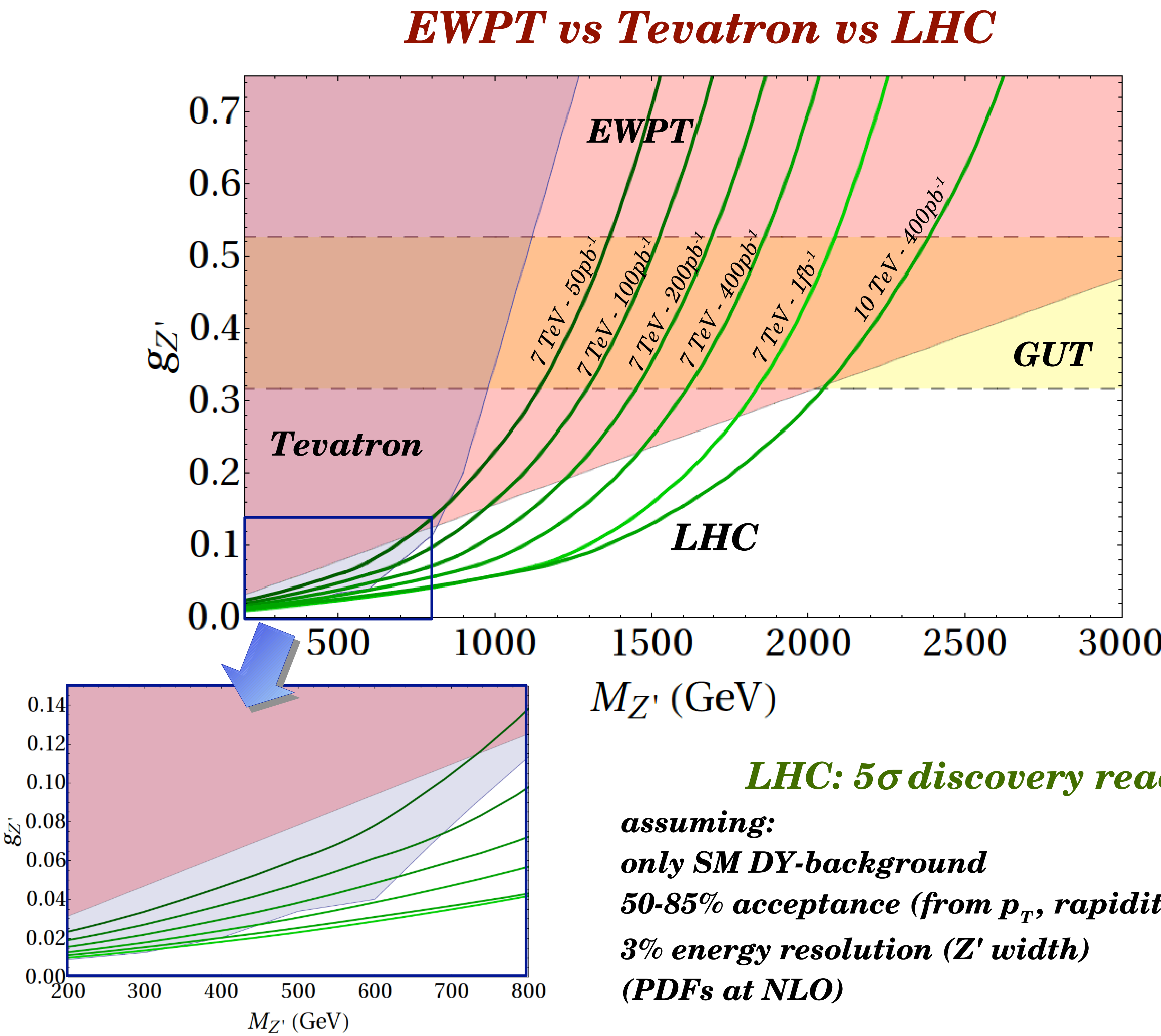
- top pair: 160 pb! Always has 6 objects.

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

  - (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 $\tau$ (mm)

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




***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