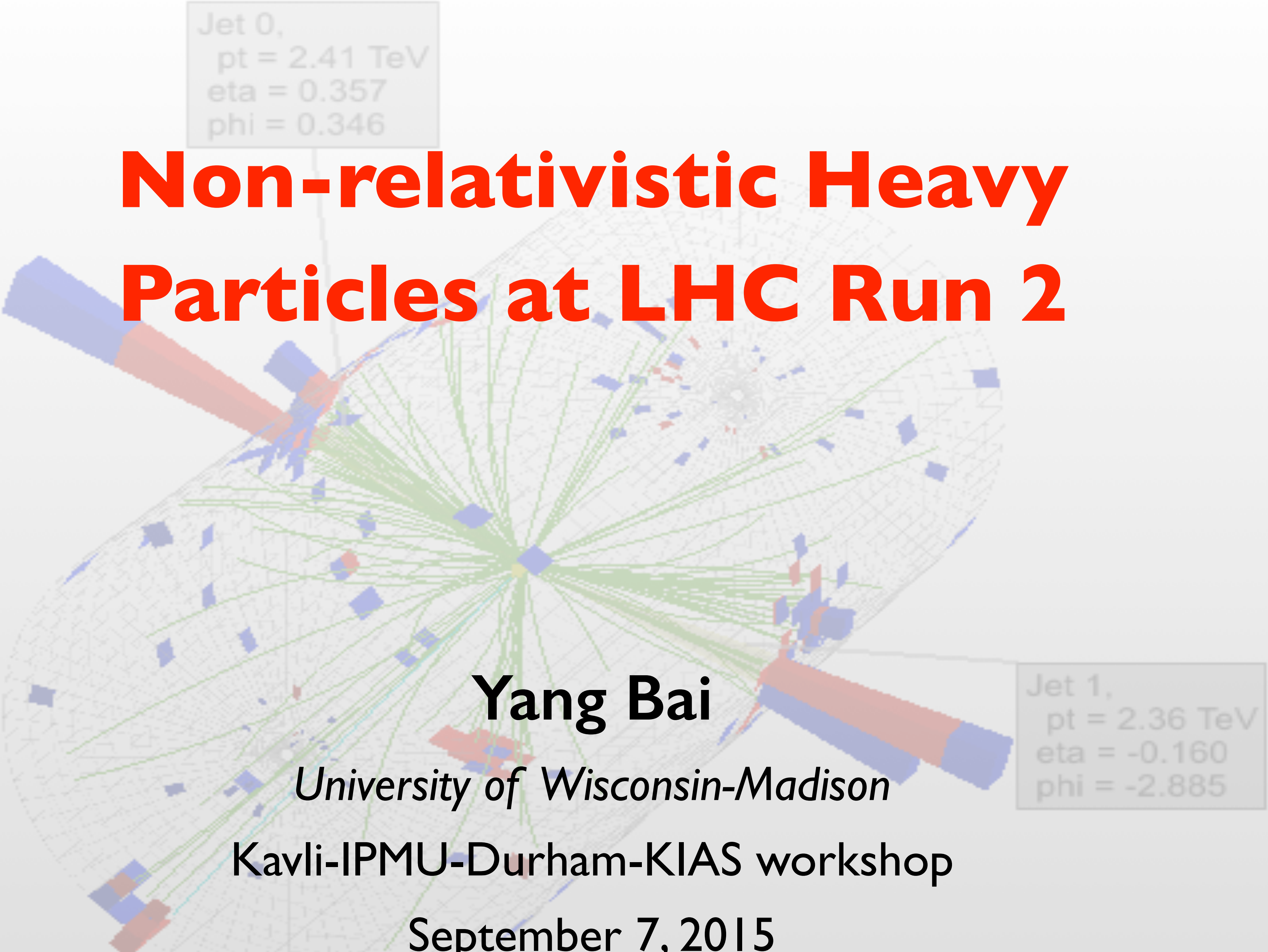


Non-relativistic Heavy Particles at LHC Run 2

Yang Bai

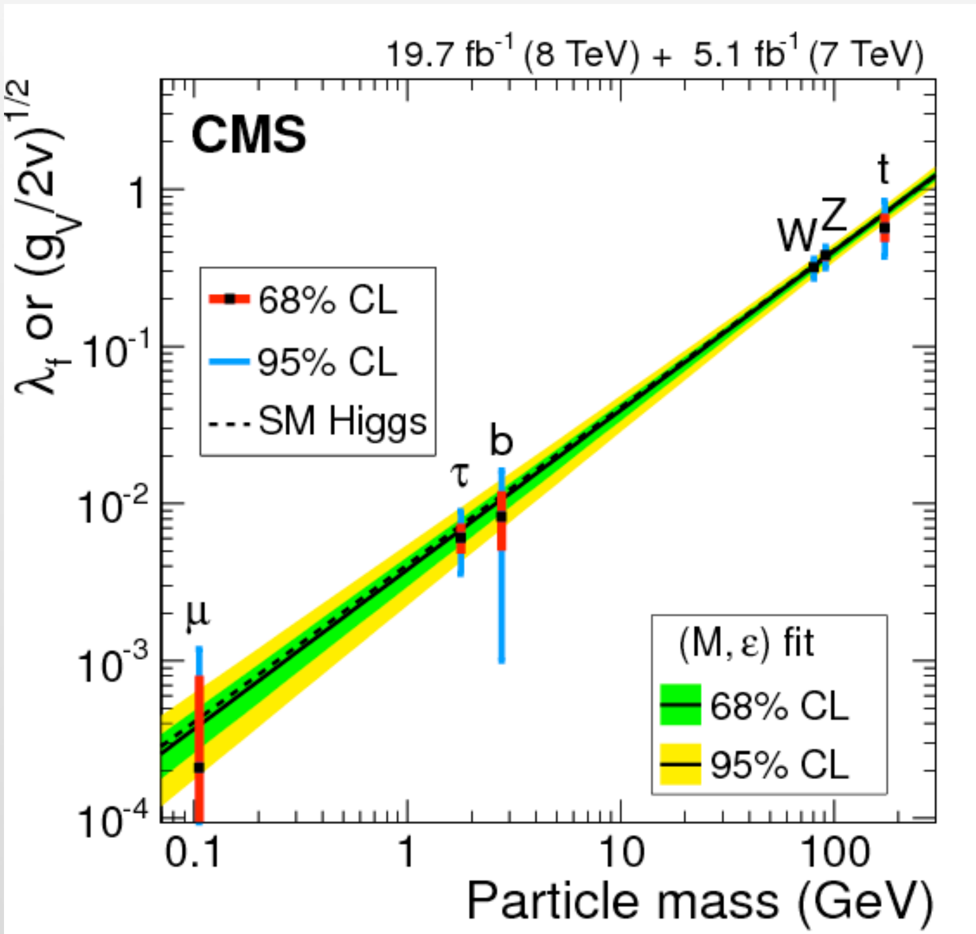
University of Wisconsin-Madison

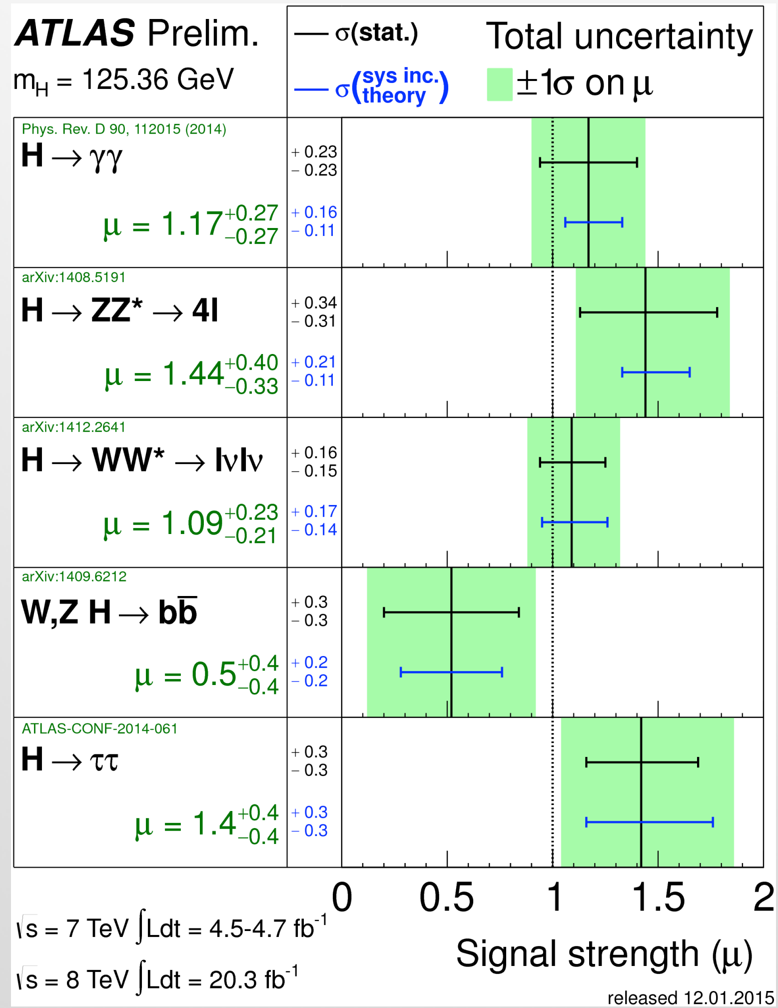
Kavli-IPMU-Durham-KIAS workshop

September 7, 2015

Short Summary of Run I

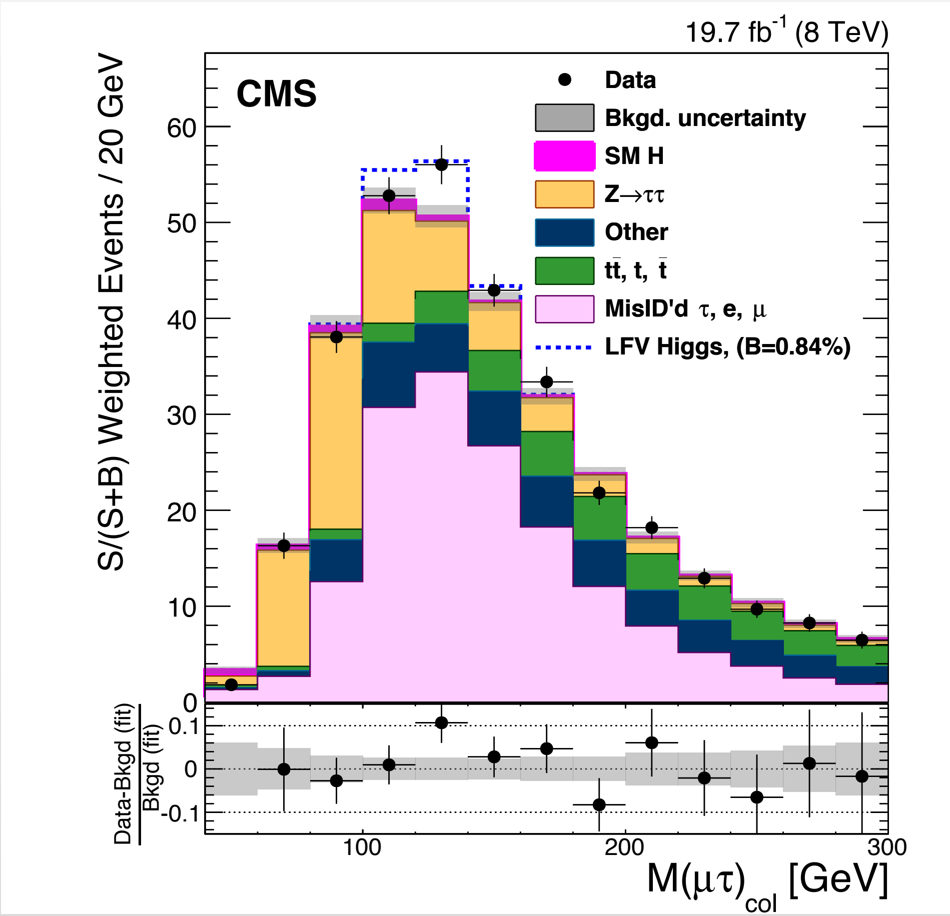
- Discovered the Higgs boson with SM properties

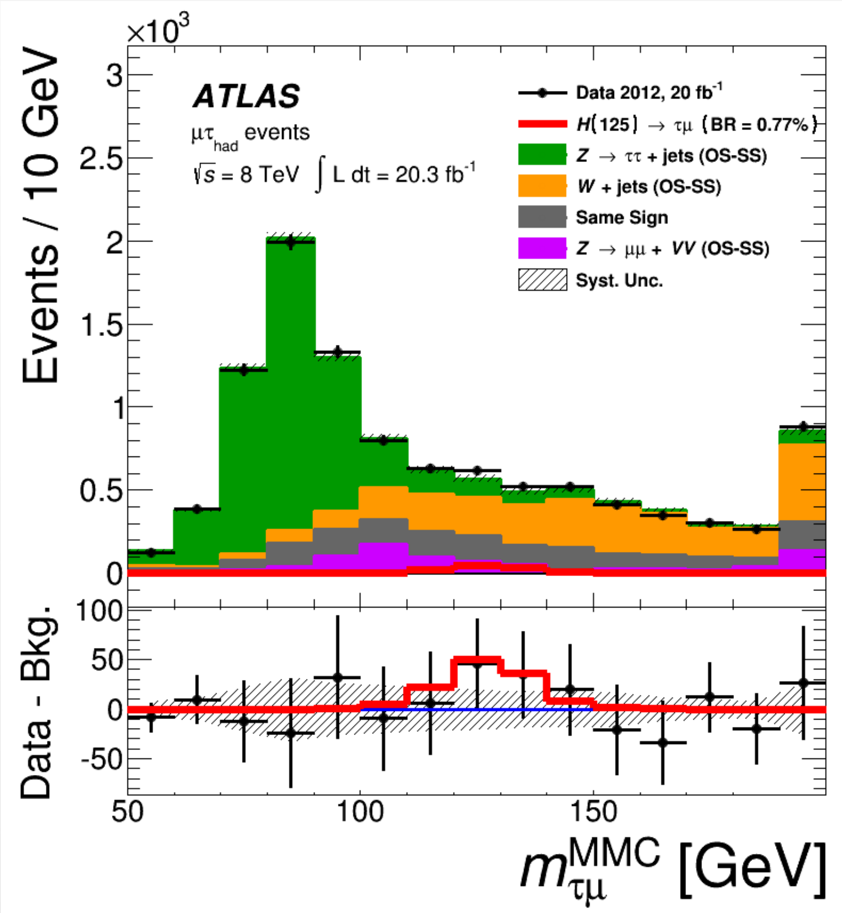




Short Summary of Run I

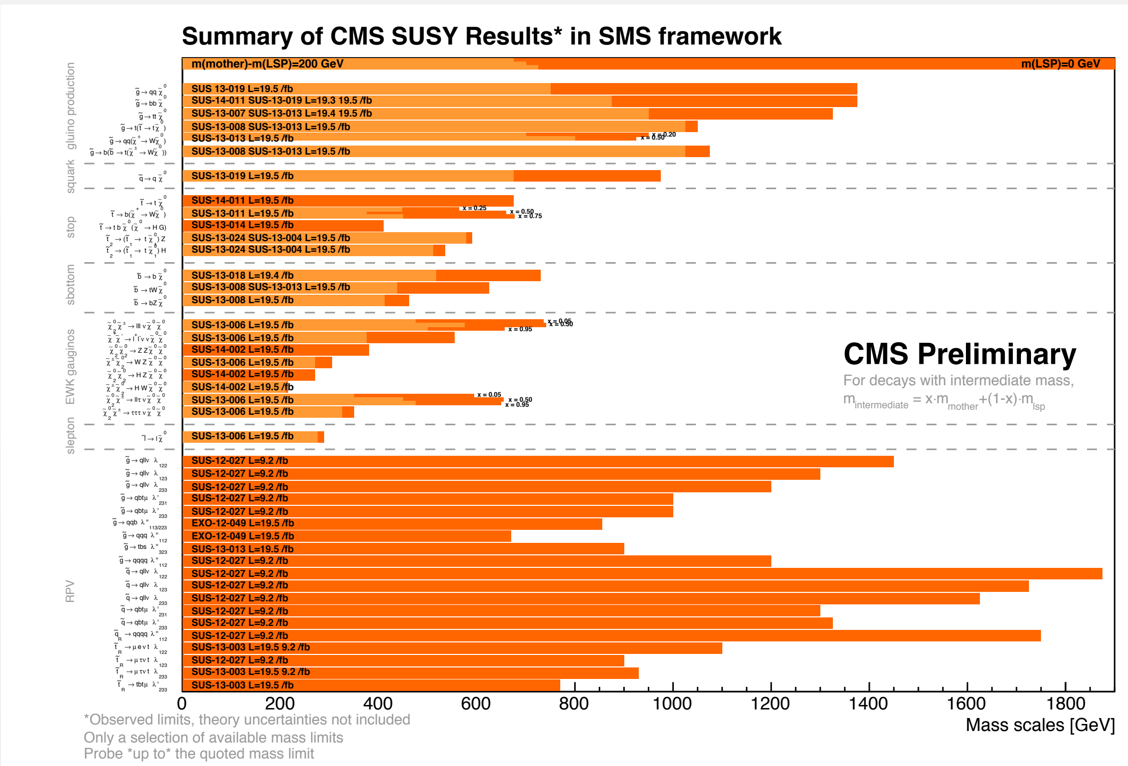
- Flavor-changing decay?

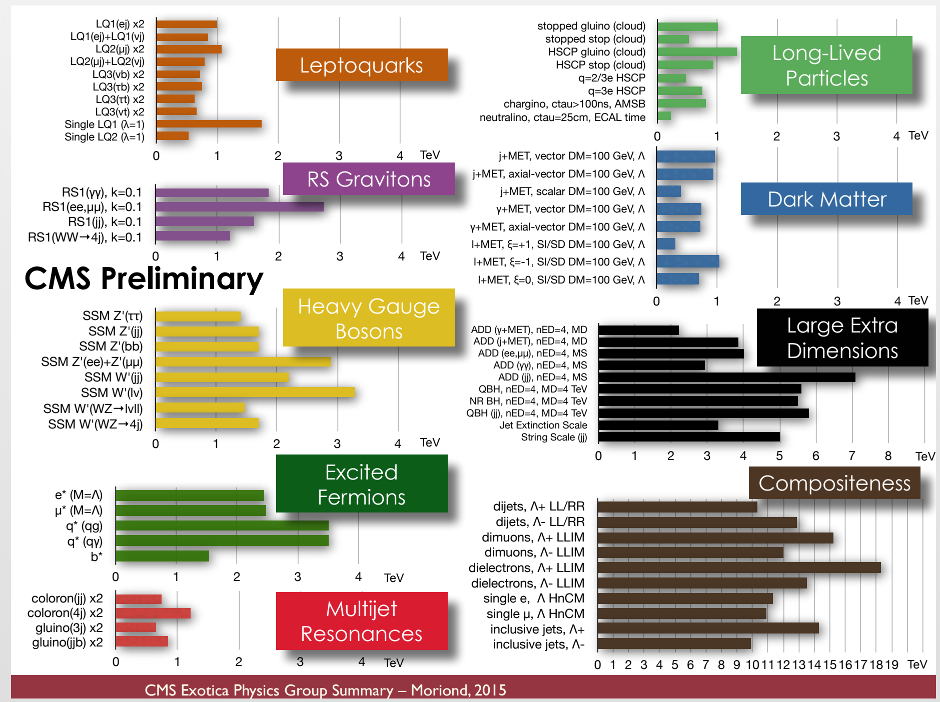




Short Summary of Run I

- No strong sign of BSM physics





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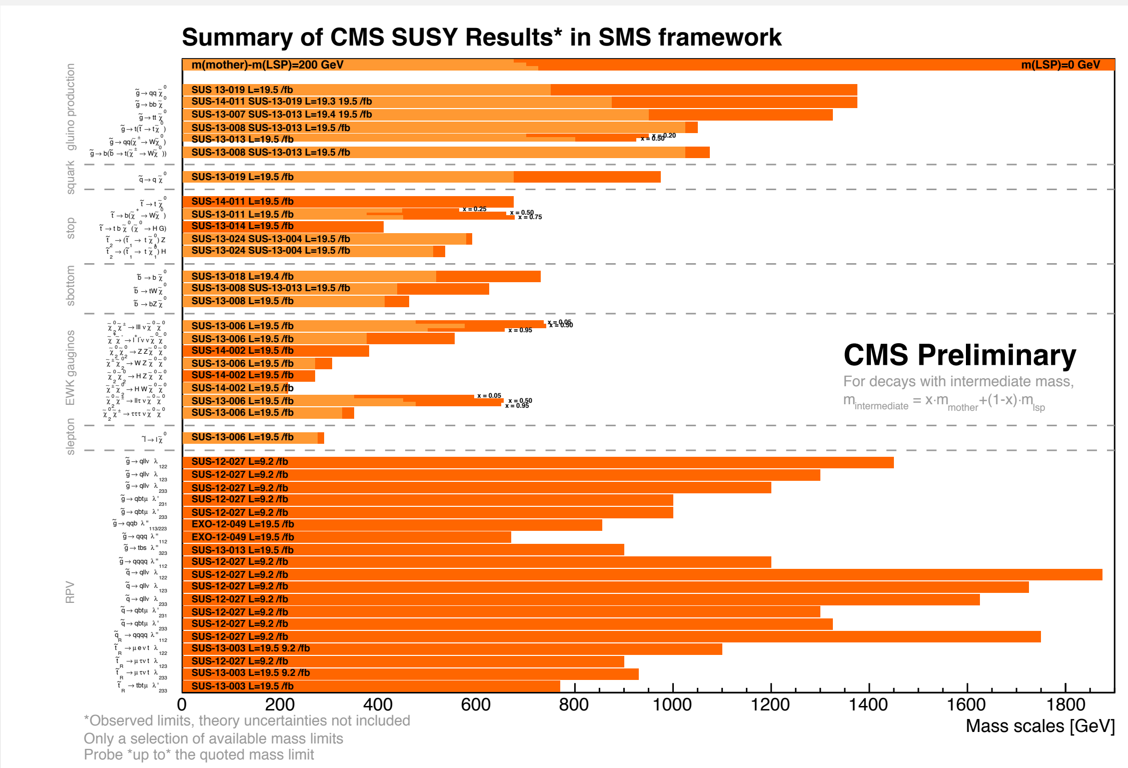
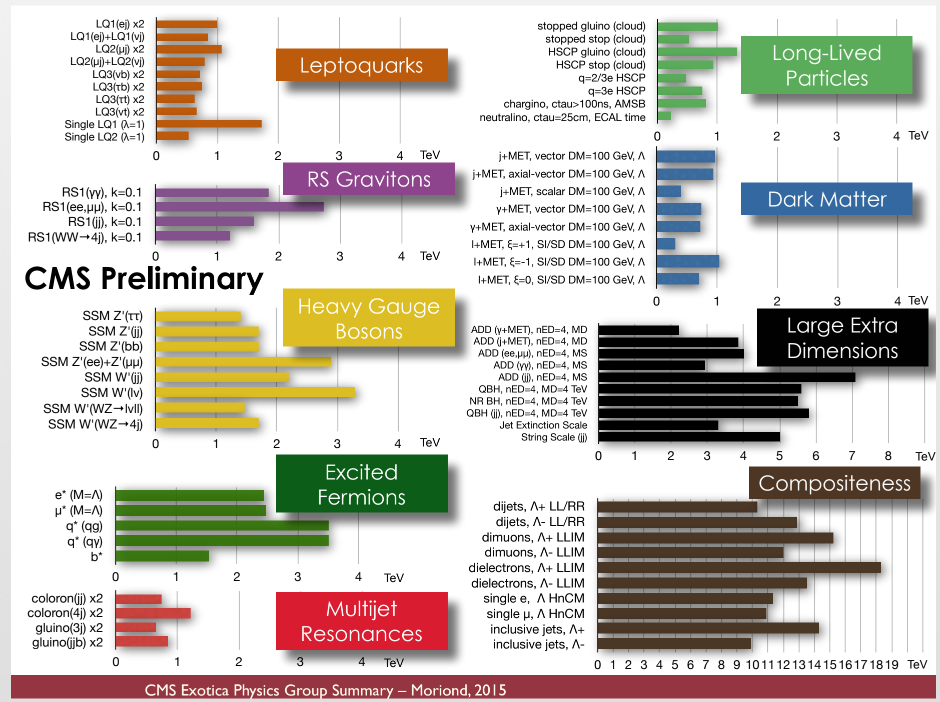
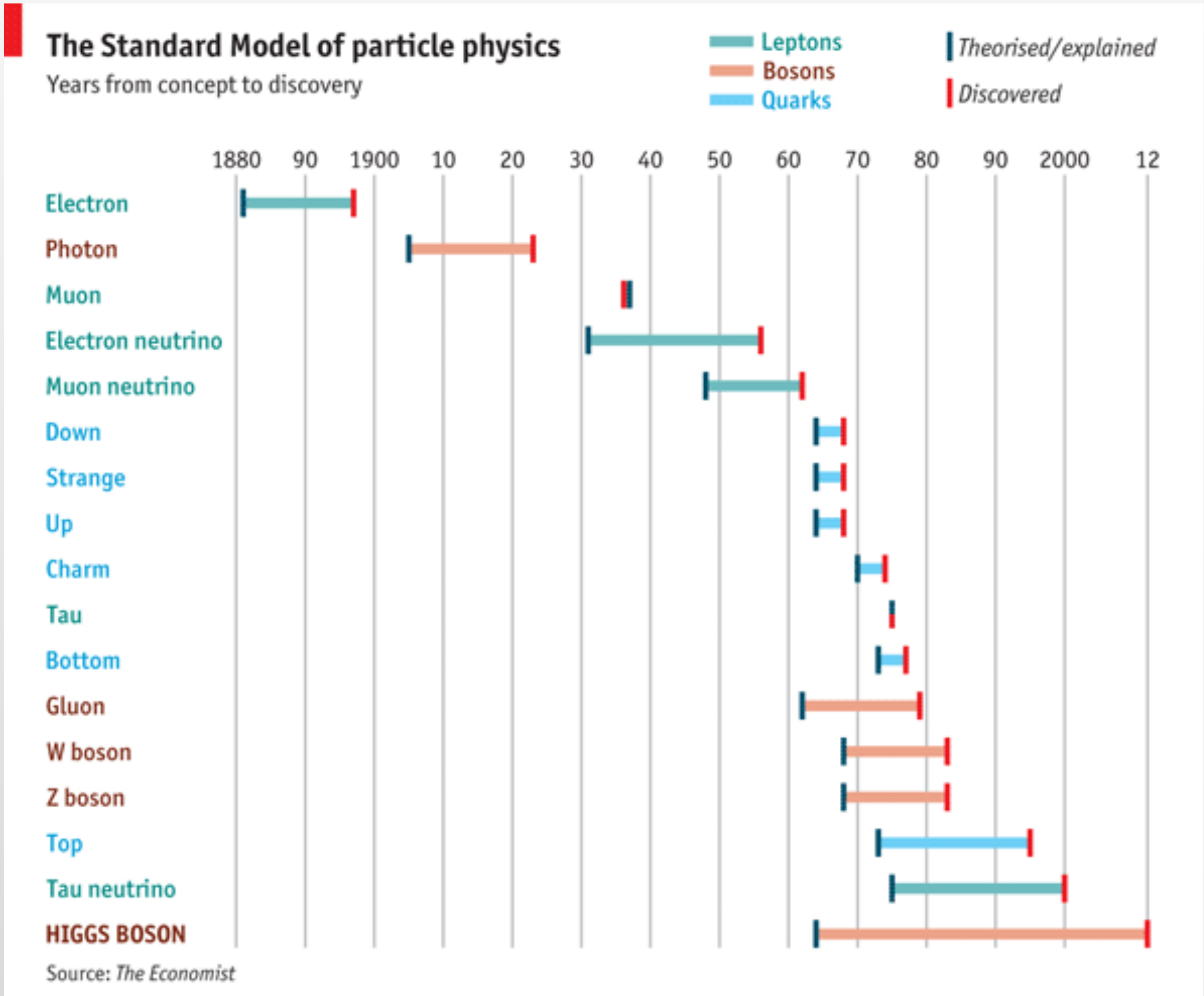




- Is this normal?

Next Particle from Colliders

- Longer time interval between theory and experiment



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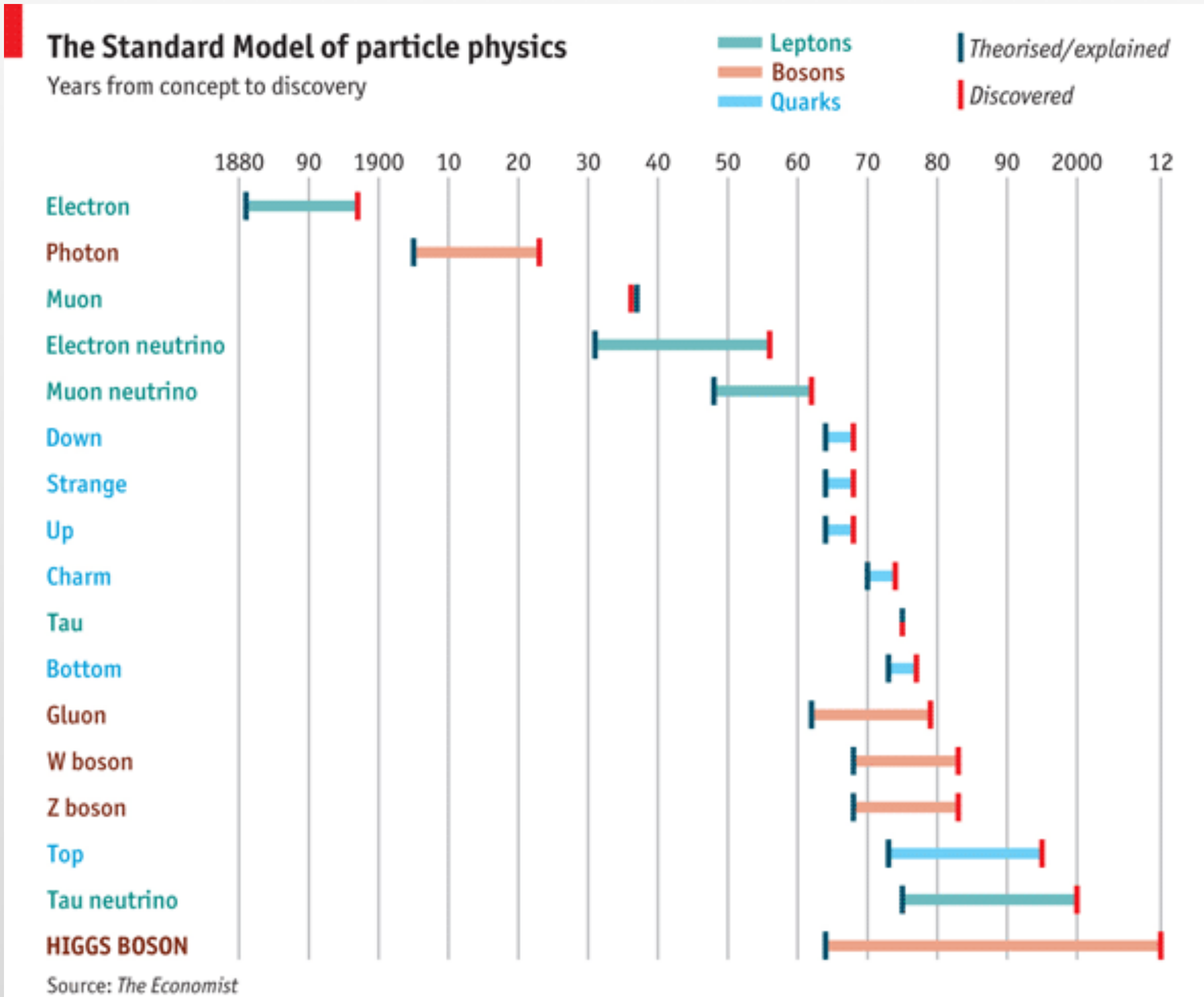
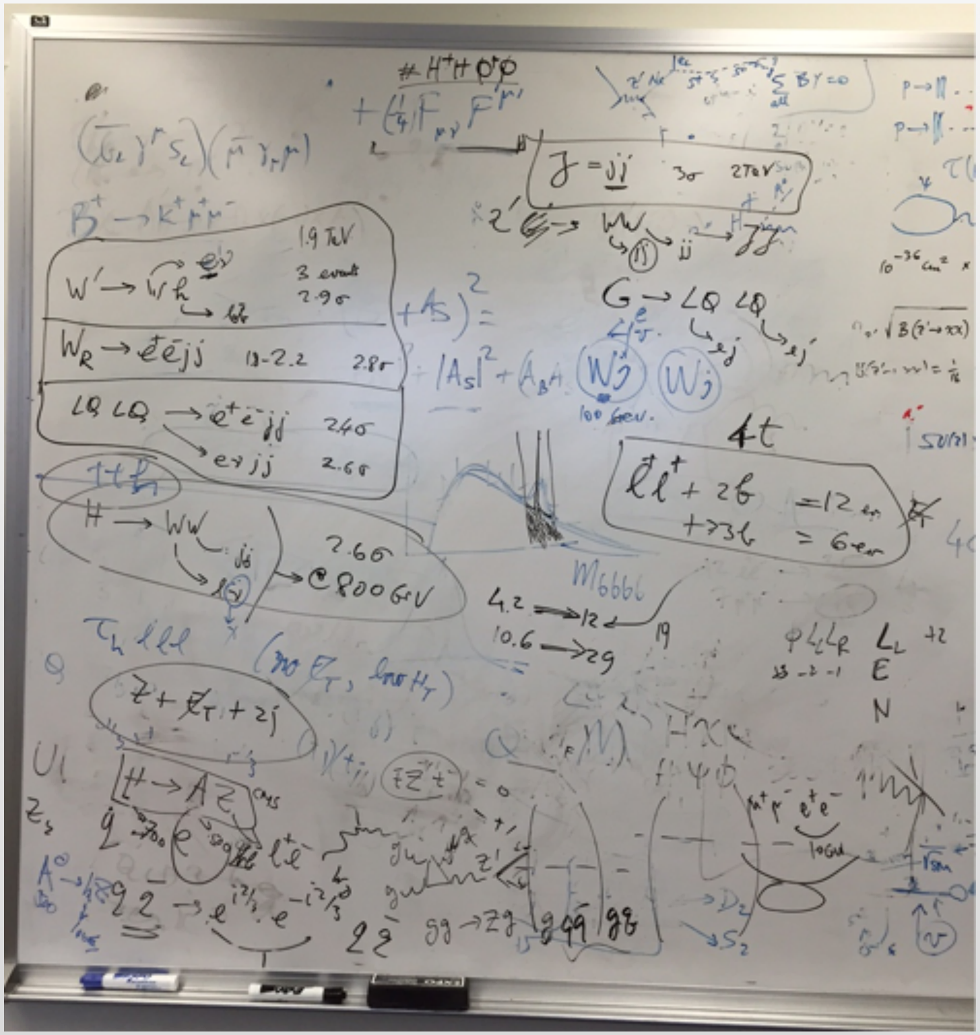


MSSM

> 2029 ?

Short Summary of Run I

- A few tentative hints



from discussion with B. Dobrescu@Fermilab in May 2015

✦ no cross confirmation from CMS and ATLAS

✦ lepton flavor dependent

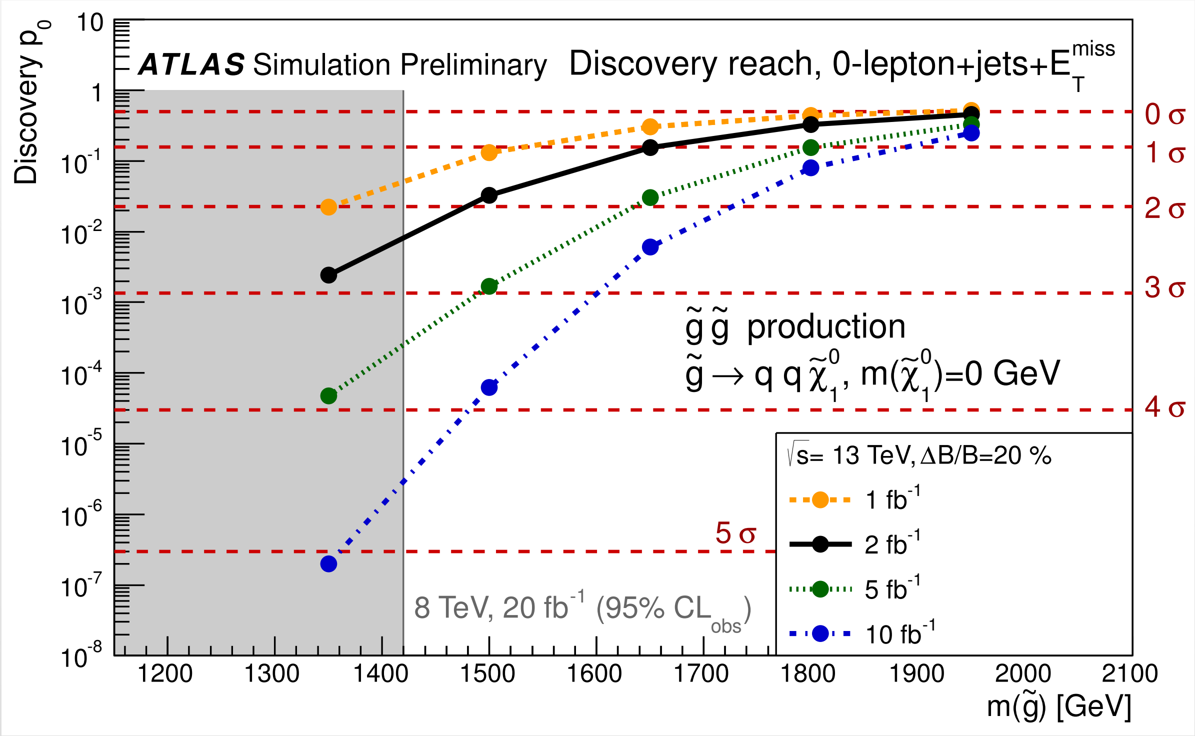
✦ understand more of the boosted objects

see more talks about them here

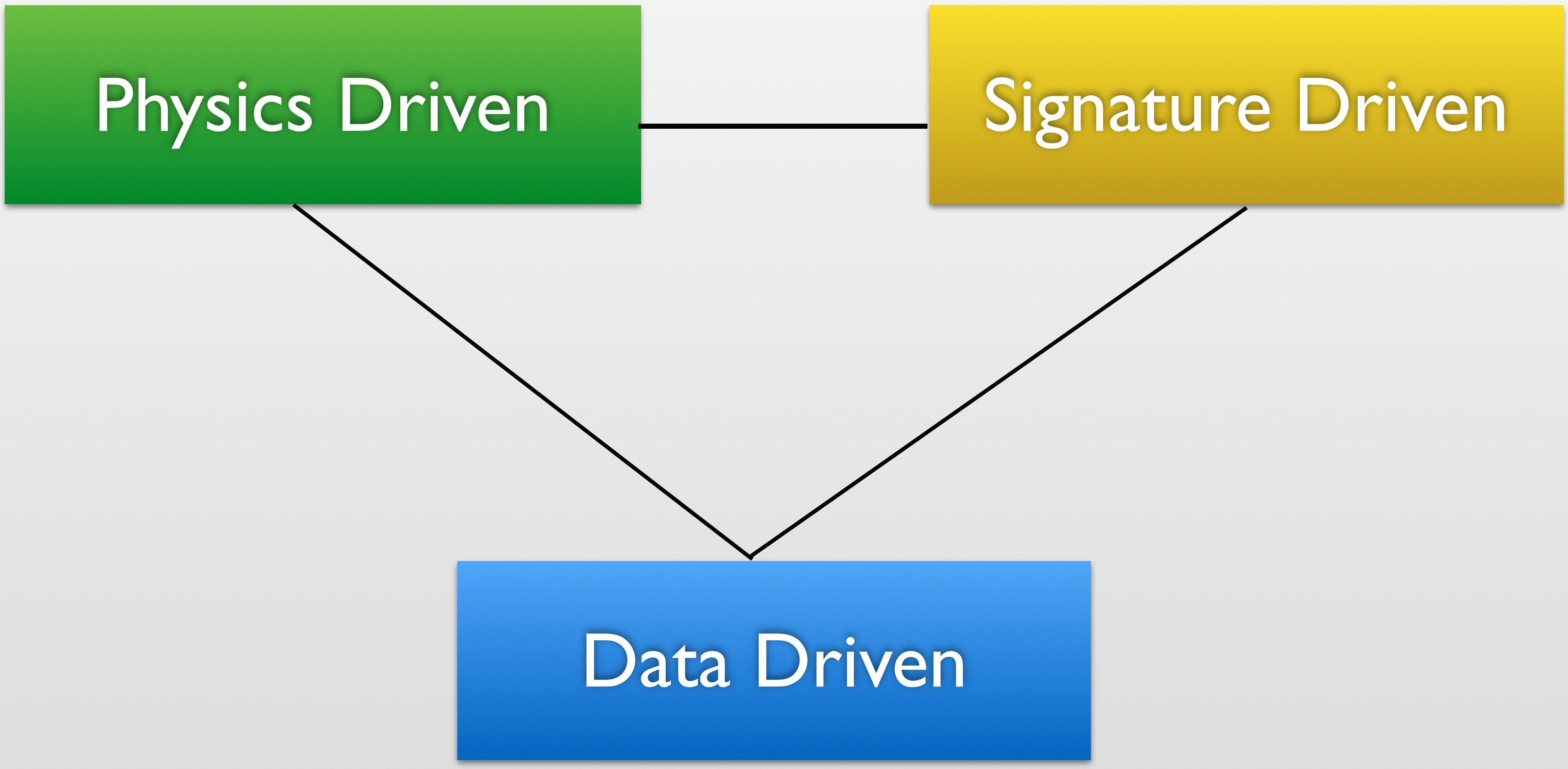
What to Anticipate for LHC Run II?

- Increase the reach for well-motivated new particle masses by a factor of few

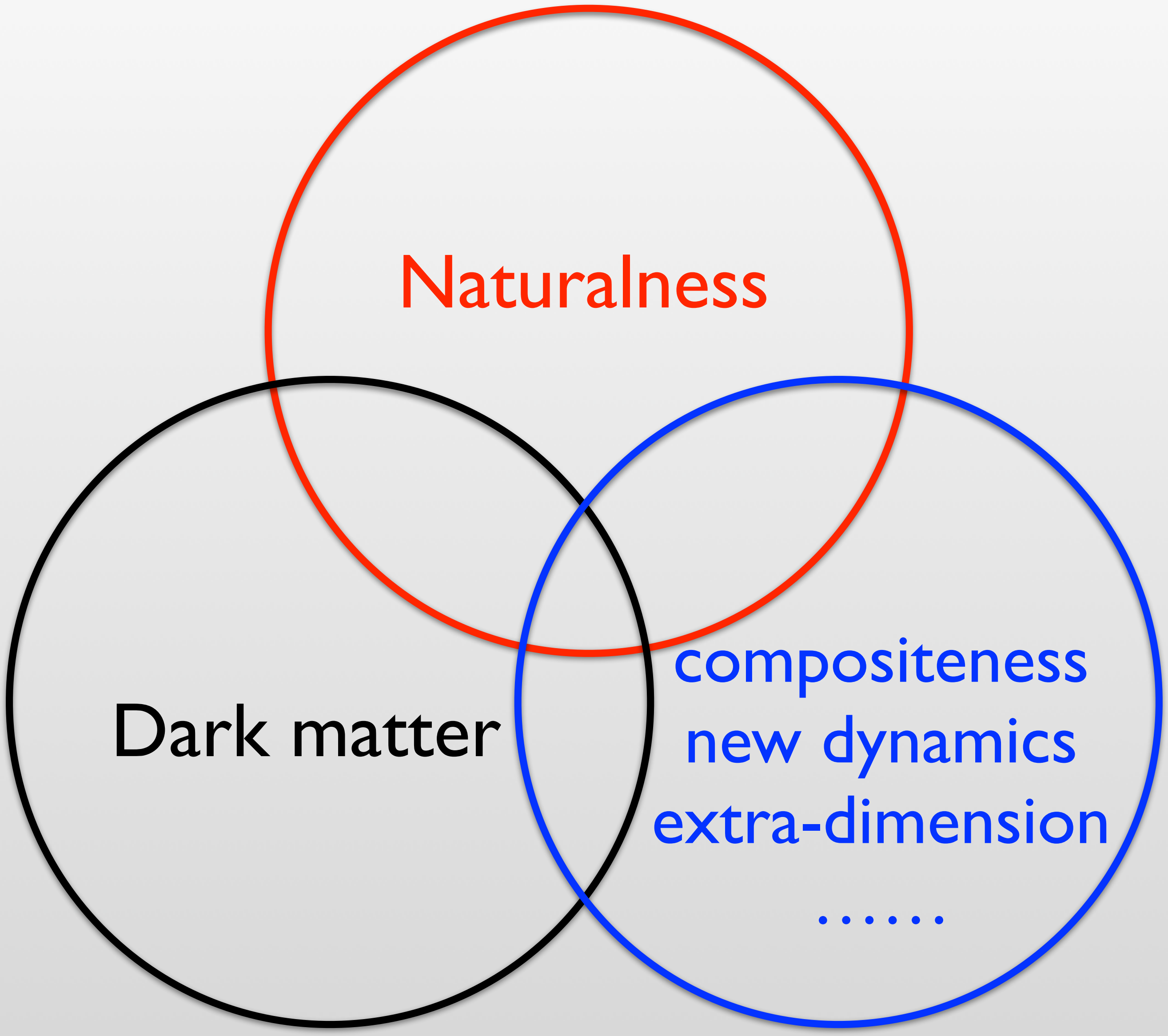
ATLAS-PHYS-PUB-2015-005



- search for brand new (less-motivated) signatures
- no story change yet; but the focus of searches will be shifted


Physics Driven
Signature Driven
Data Driven

Physics Driven



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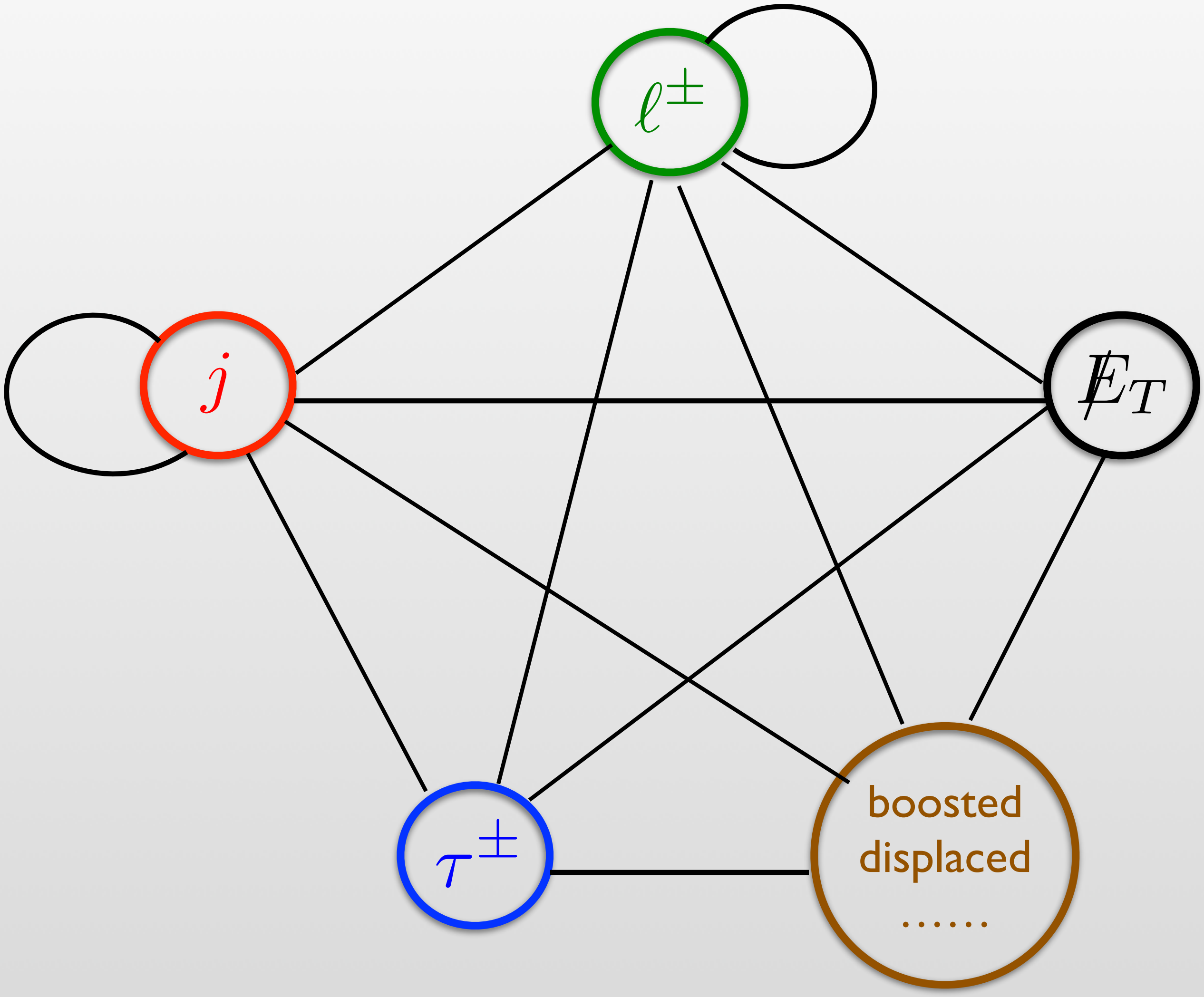

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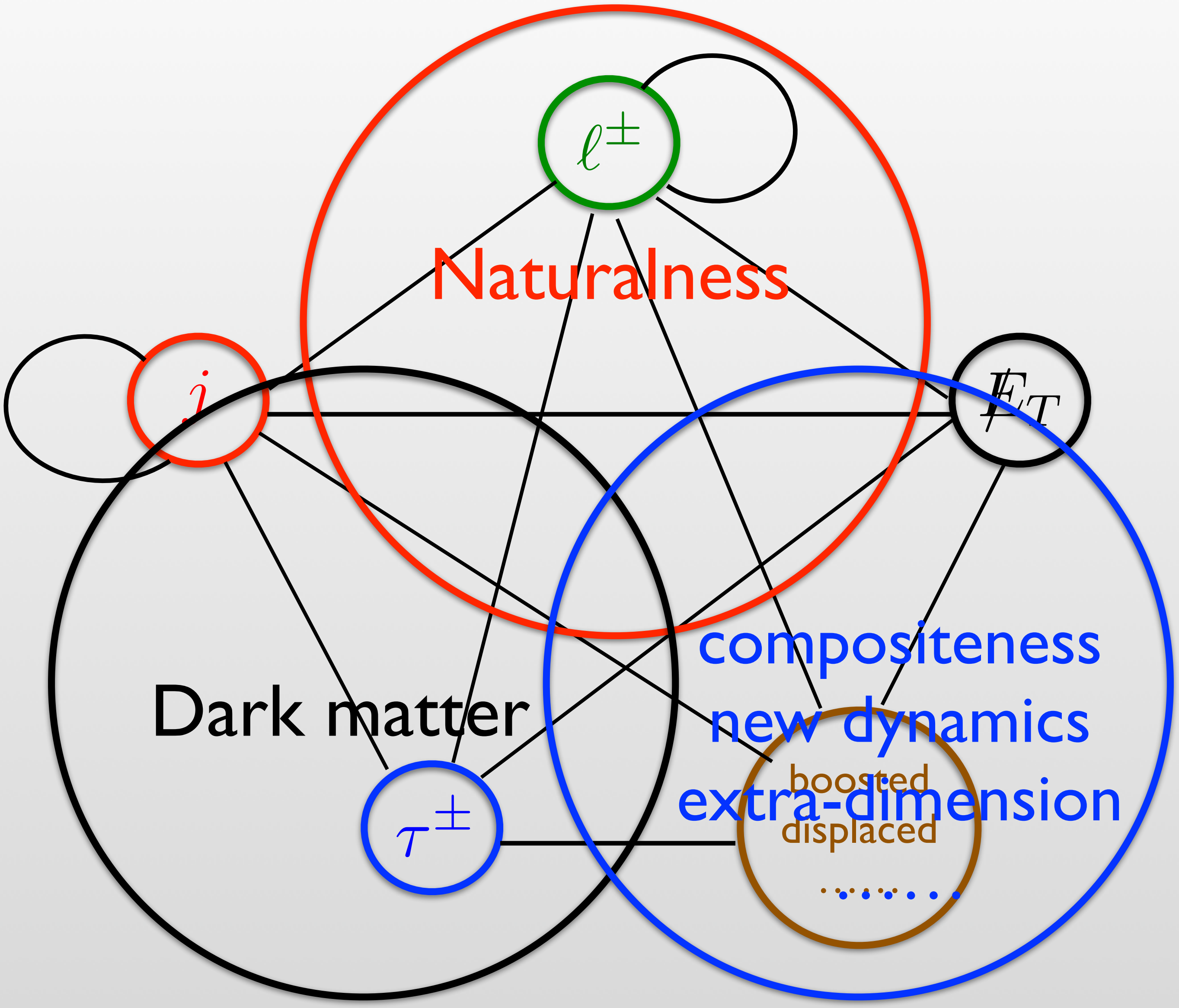

Naturalness

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- Hope Nature will not have a meta tuning such that the LHC is just below the threshold

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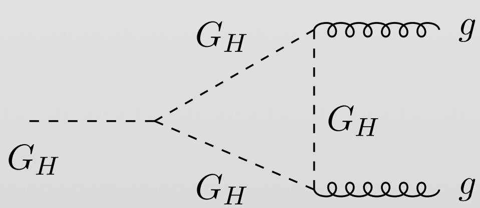

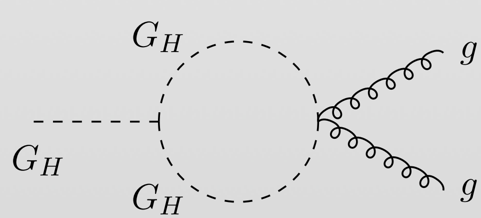

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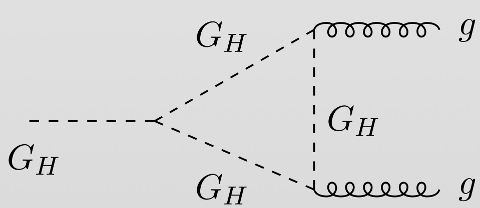

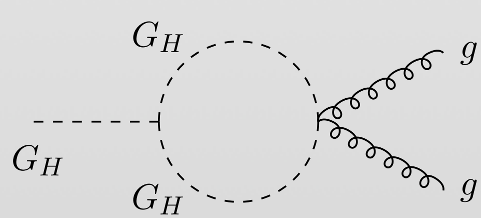

$$\Gamma_0(G_H \to gg) = \frac{15\, \alpha_s^2\, \mu_G^2}{128\, \pi^3\, M_{G_H}} \left(\frac{\pi^2}{9} - 1\right)^2$$

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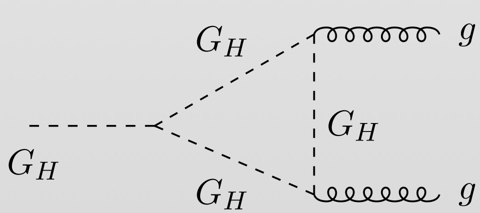

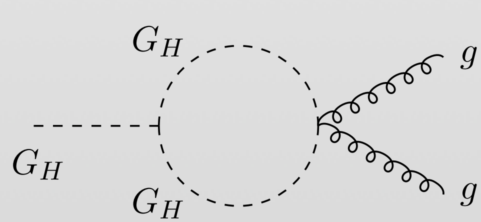

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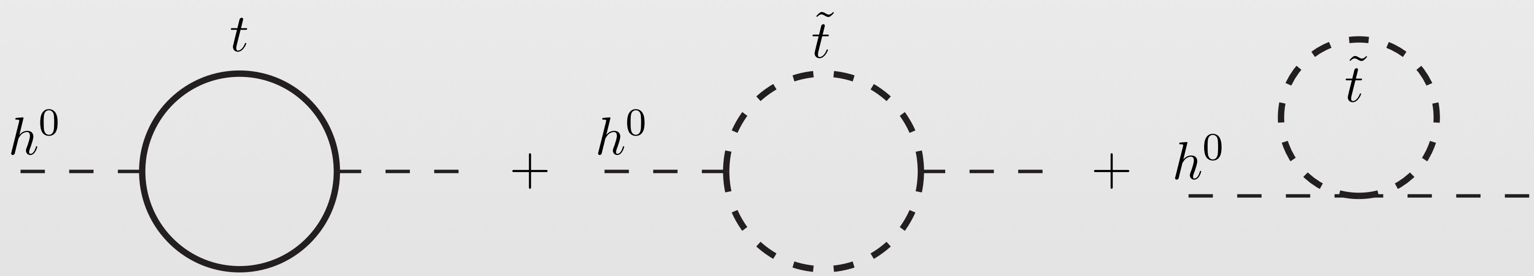
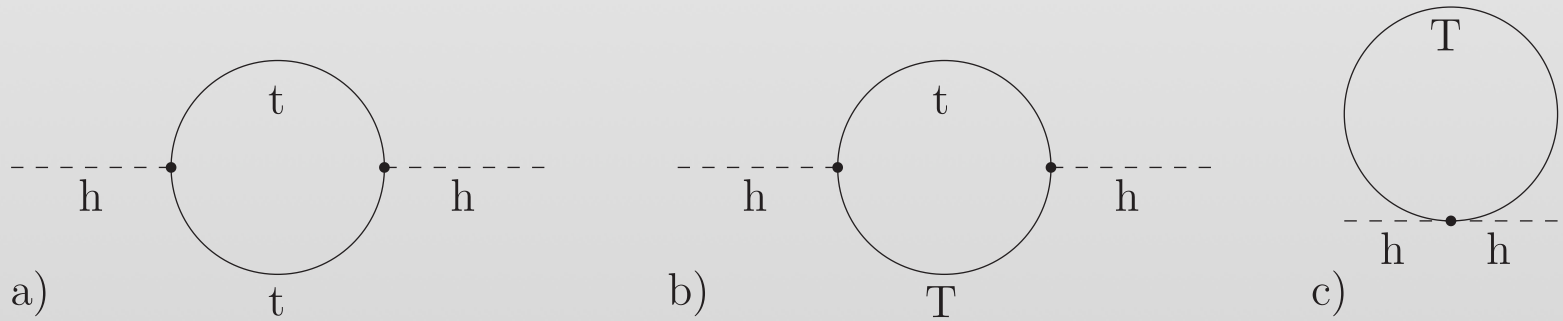
1% tuning

Naturalness: top partner

- The leading model is supersymmetry. The Higgs field could also be a composite particle.
- To cancel the top-quark induced divergence, we can have bosonic or fermionic top partners





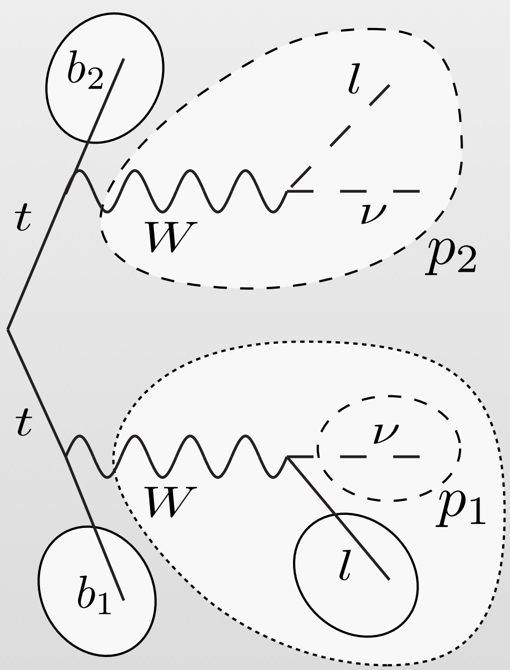
Top Partners at Run I

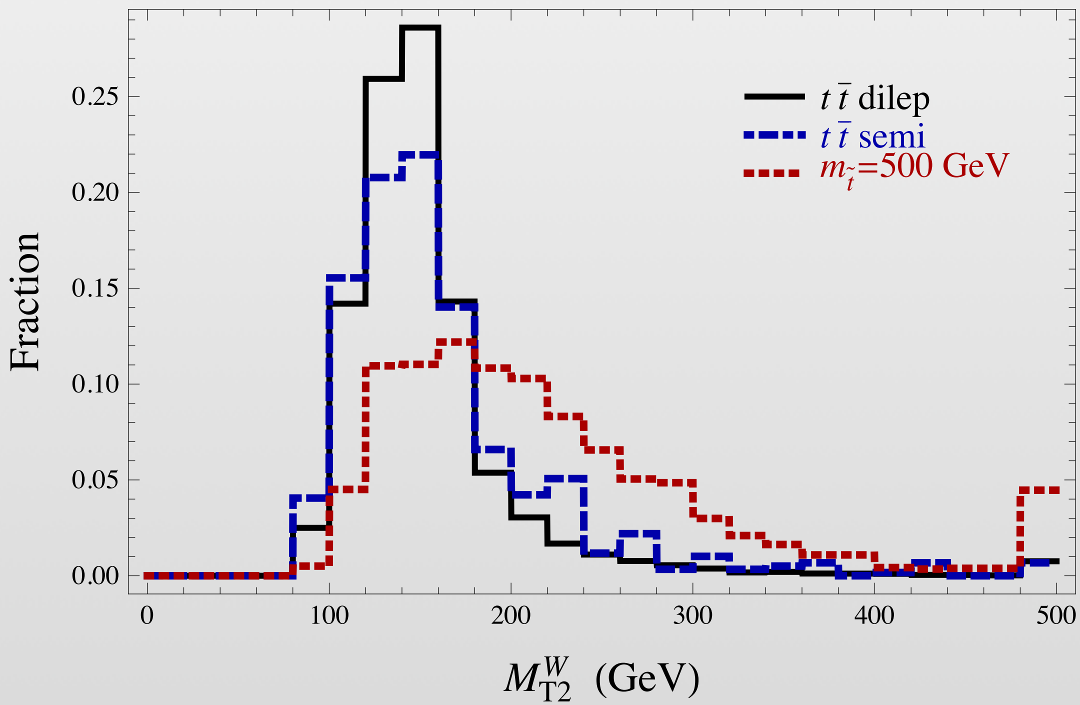
$\tilde{t}_1 \to t + \tilde{\chi}_1^0$ the signal is ttbar+MET

Early work:	Meade and Reece, hep-ph/0601124
	Kong and Park, hep-ph/0703057
	Han, Mahbubani, Walker, Wang, 0803.3820
	……
Endpoints:	YB, Cheng, Gallichio, Gu, 1203.4813
	Cao, Han, Wu, Yang, Zhang, 1206.3865
	Killic and Tweedie, 1211.6106
Spin-correlations:	Han, Katz, Krohn, Reece, 1205.5808
Top-tagging:	Plehn, Spannowsky, Takeuchi, 1205.2696
	Kaplan, Rehermann, Stolarski, 1205.5816
	Dutta, Kamon, Kolev, Sinha, Wang, 1207.1893
Shapes of missing Et:	Alves, Buckley, Fox, Lykken, Yu, 1205.5805
Topness:	Graesser and Shelton, 1212.4495
	……

Kinematical Variables for ttbar+MET

- Noticing the main background is dileptonic ttbar, one can construct the asymmetric MT2 variable. The background is bounded by the top quark mass.





YB, Cheng, Gallichio, Gu, 1203.4813

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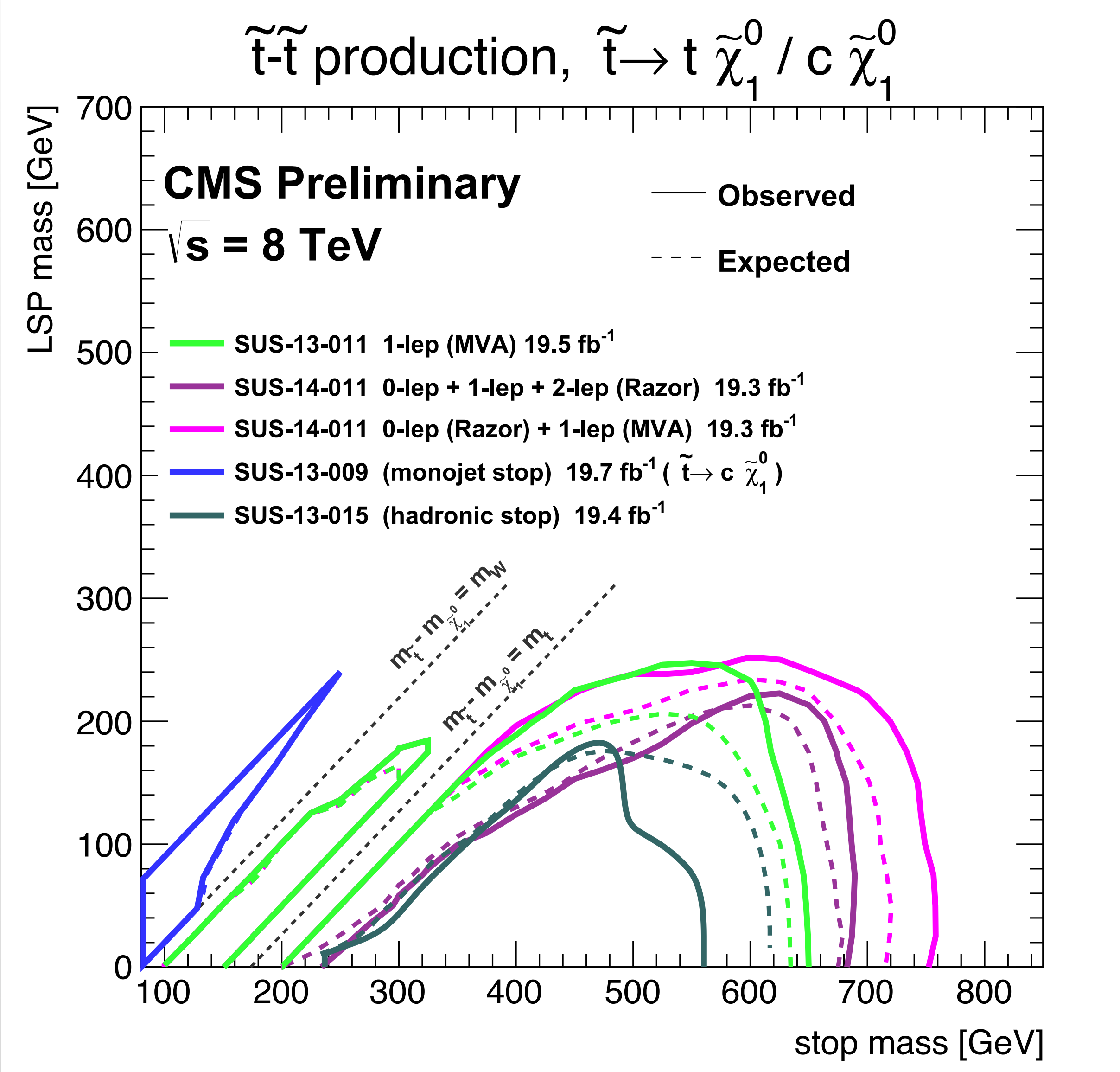
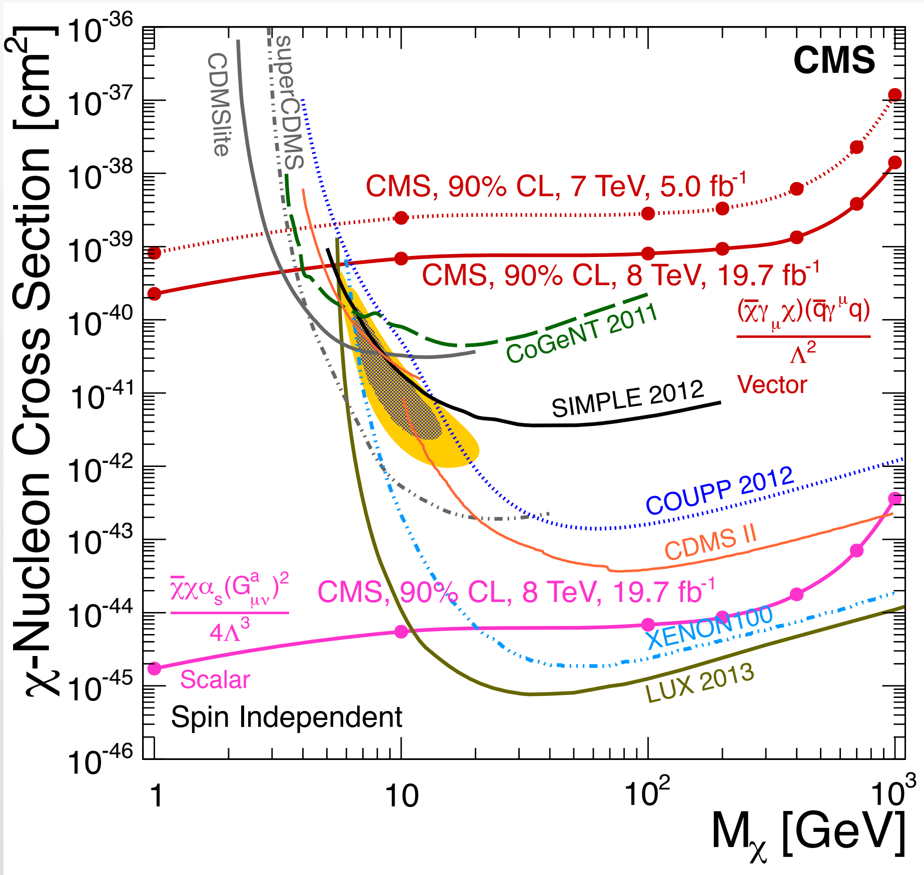
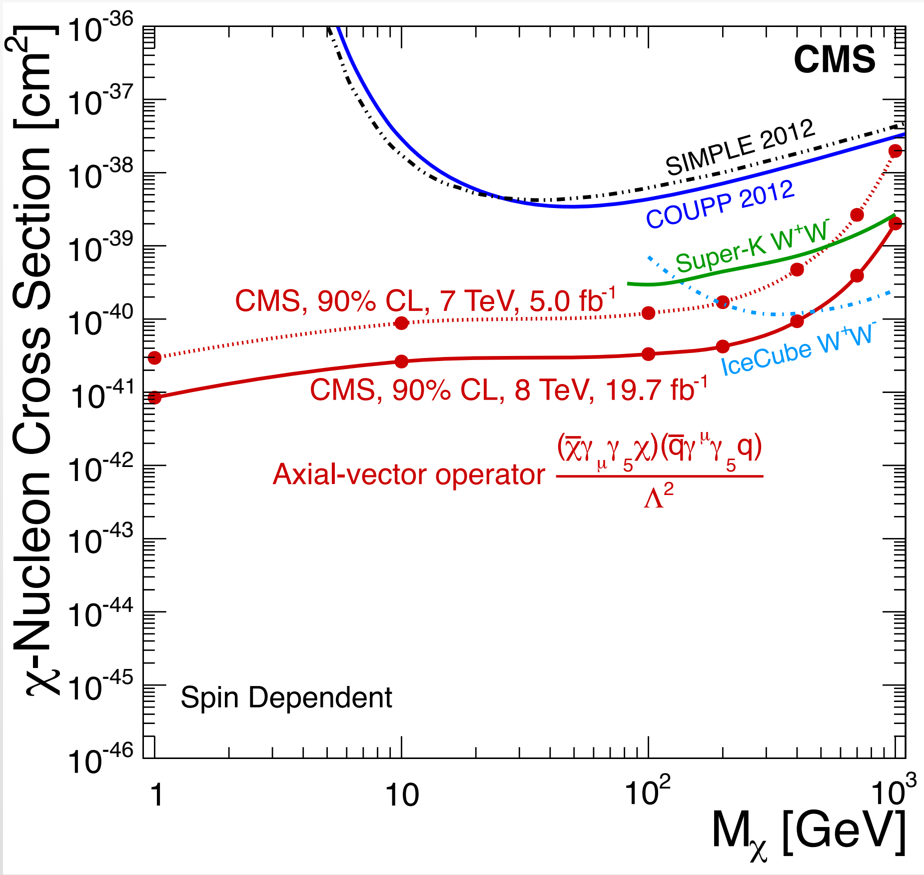


- WIMP dark matter has a scale ~ TeV and may show up at LHC
- Only subset of asymmetric dark matter may has a TeV scale
- the generic EFT-based mono-X signatures have been searched for at the LHC Run 1
- LHC Run 2 will concentrate more on simplified dark matter models
- there could be more exotic dark matter signatures

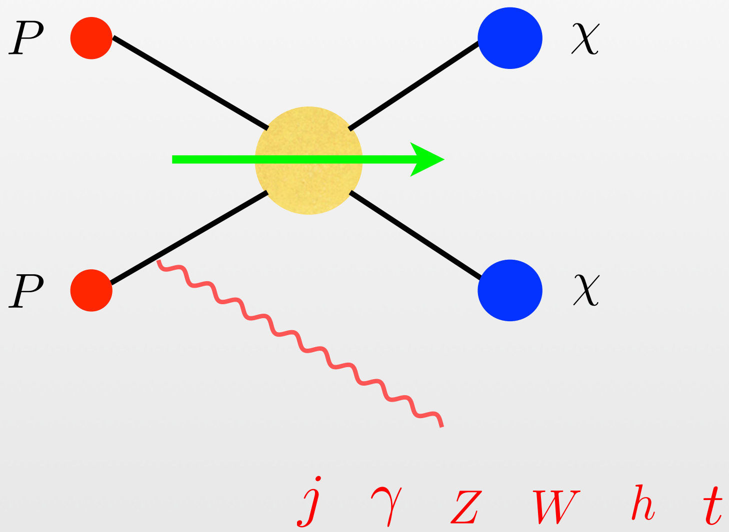
Dark Matter@LHC Run I

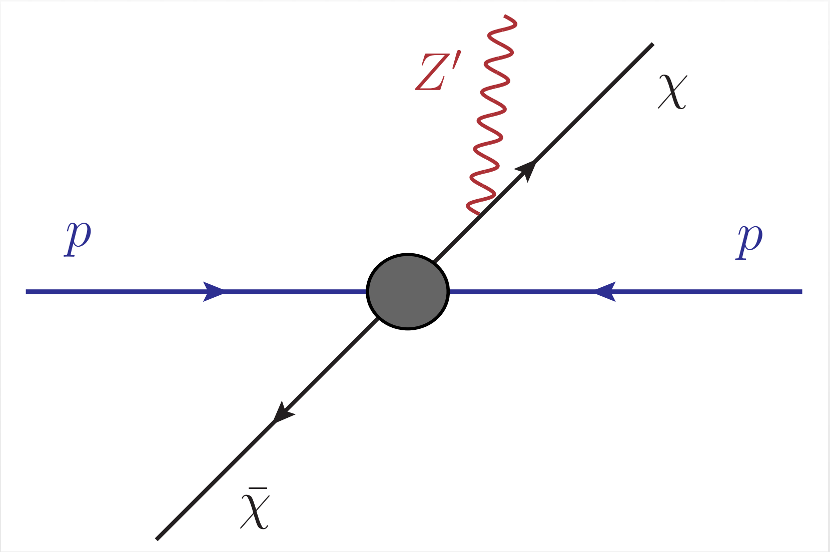




based on dark matter effective operators

Dark Matter FSR Signature





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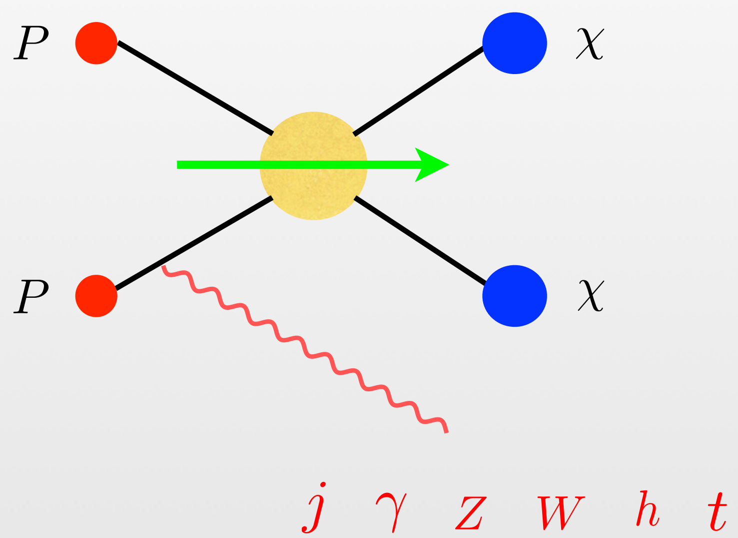
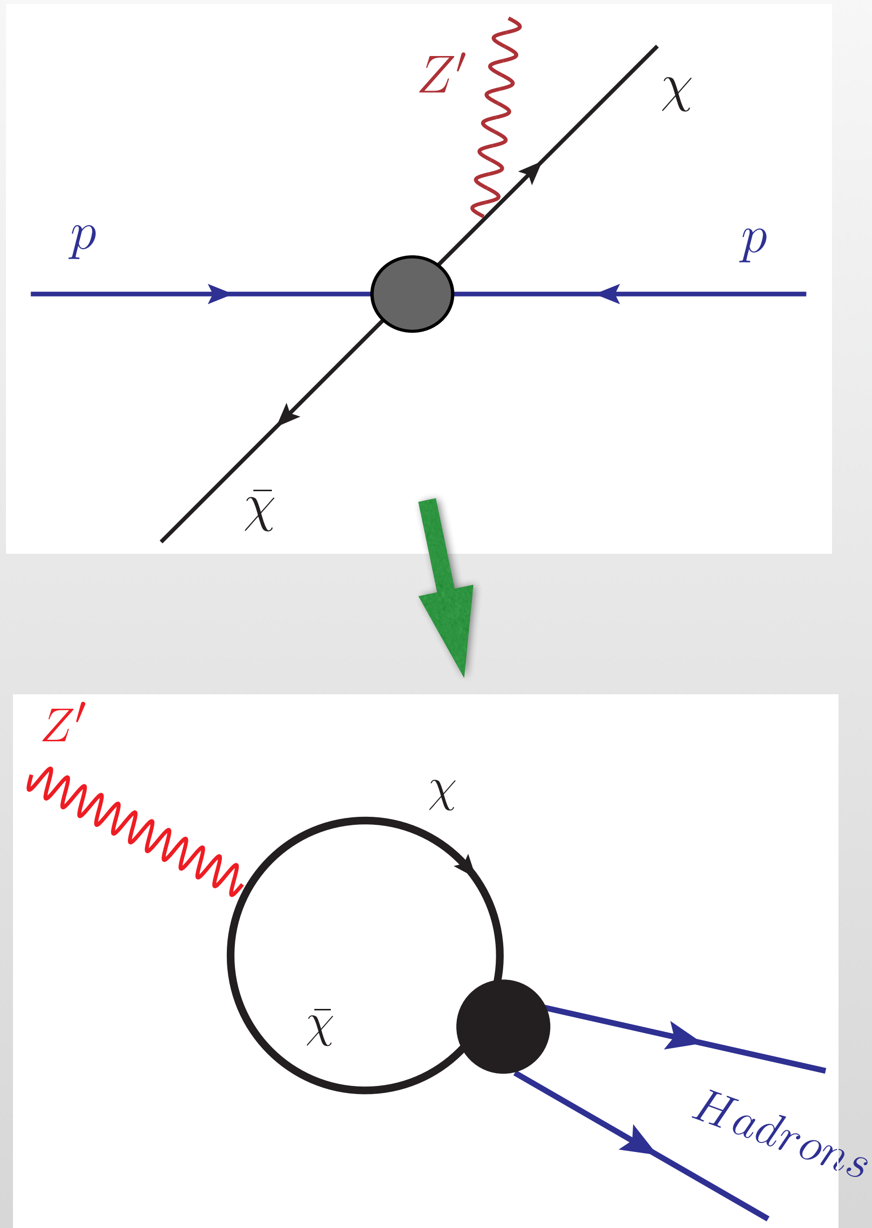
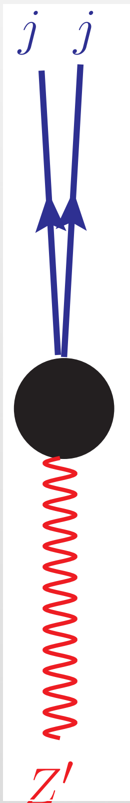


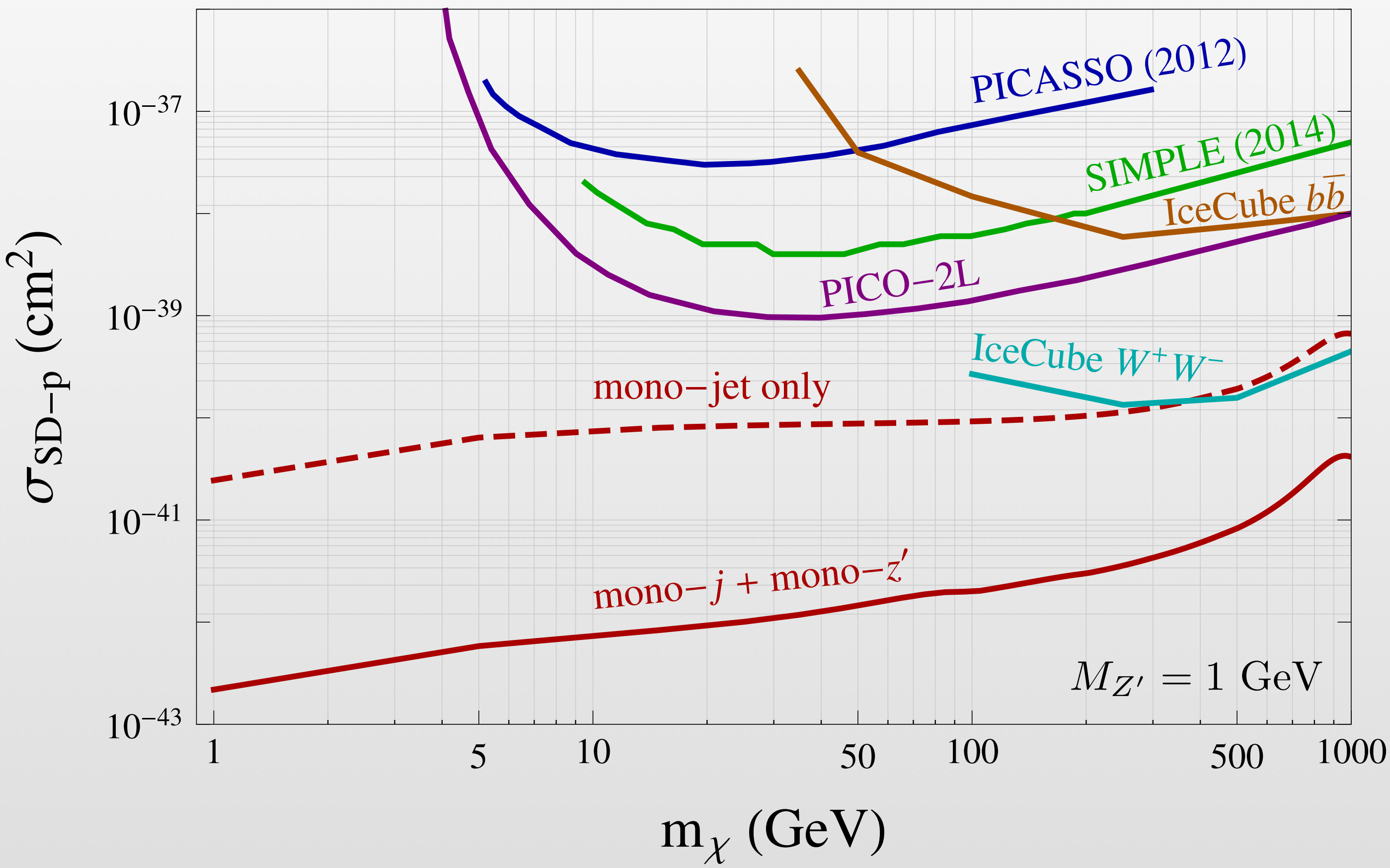


Given the fact that dark matter can be produced at the LHC and couple to Z'; Z' must decay into hadrons

Mono-Z' Jet

$p_T(Z') \gg M_{Z'}$





YB, James Bourbeau, Tongyan Lin
1504.01395

Simplified Dark Matter Models

- Better description, but more models. One may have several hundred models to work with.

- One should use LHC signatures to organize different models. Finding signatures beyond the MSSM could be useful.

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Chromo-Rayleigh Interactions

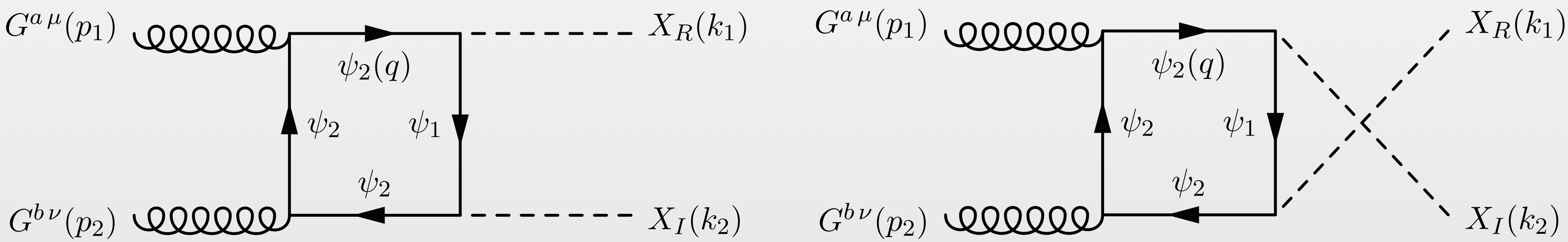
$$\frac{\alpha_s}{4\pi\Lambda_1^2} X^\dagger X G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$\frac{i\,\alpha_s}{4\pi\Lambda_2^2} (XX - X^\dagger X^\dagger) G^a_{\mu\nu} \widetilde{G}^{a\,\mu\nu}$$

“UV”-Completed Simplified Models

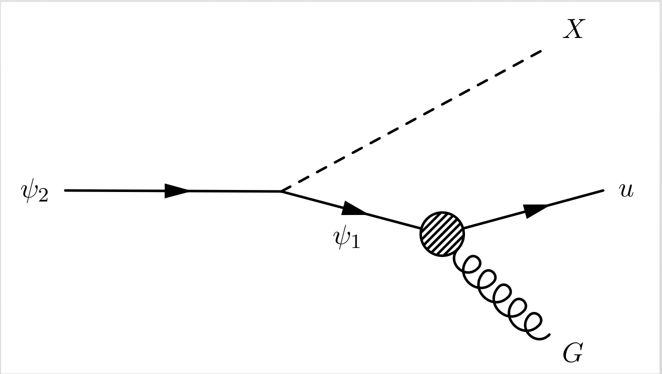
$$\mathcal{L} \supset -y_1 \left(X + X^\dagger\right) (\overline{\psi}_1 \psi_2 + \overline{\psi}_2 \psi_1) - \left(X - X^\dagger\right) (y_2\, \overline{\psi}_1 \gamma_5 \psi_2 + y_2\, \overline{\psi}_2 \gamma_5 \psi_1)$$

- two representative one-loop diagrams (totally 6)



$$\frac{i\,\alpha_s}{4\,\pi\,\Lambda_2^2}(XX - X^\dagger X^\dagger) G^a_{\mu\nu} \widetilde{G}^{a\,\mu\nu}$$

- LHC signature: a pair of dijet-resonance plus MET



$$pp \to \psi_2 \overline{\psi}_2 \to (u\, g\, X)(\bar{u}\, g\, X^\dagger) \to 4j + E_T^{\rm miss}$$

YB, Osborne, 1506.07110

Asymmetric Dark Baryon Model

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm Baryon}} = \frac{m_{\rm DM} n_{\rm DM}}{m_{\rm p} n_p} \approx 5 \sim 6$$

Two conditions: (1): $n_{\rm DM} \sim n_p$ (2): $m_{\rm DM} \sim m_p$

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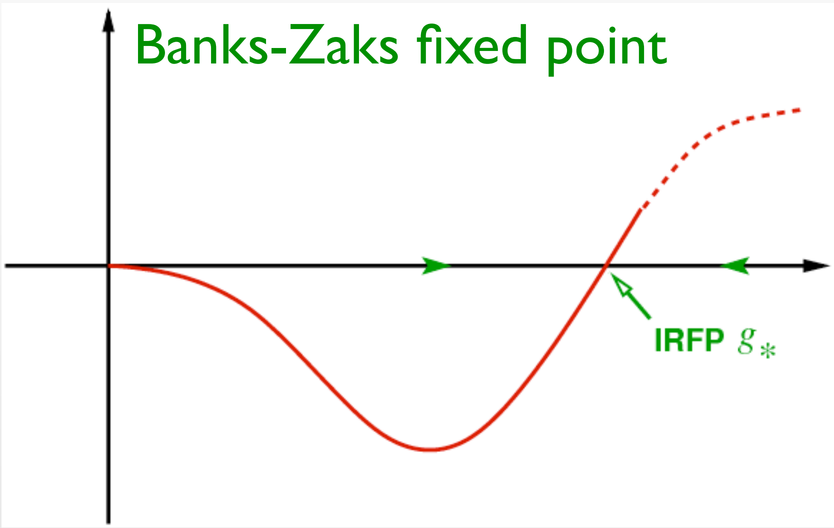
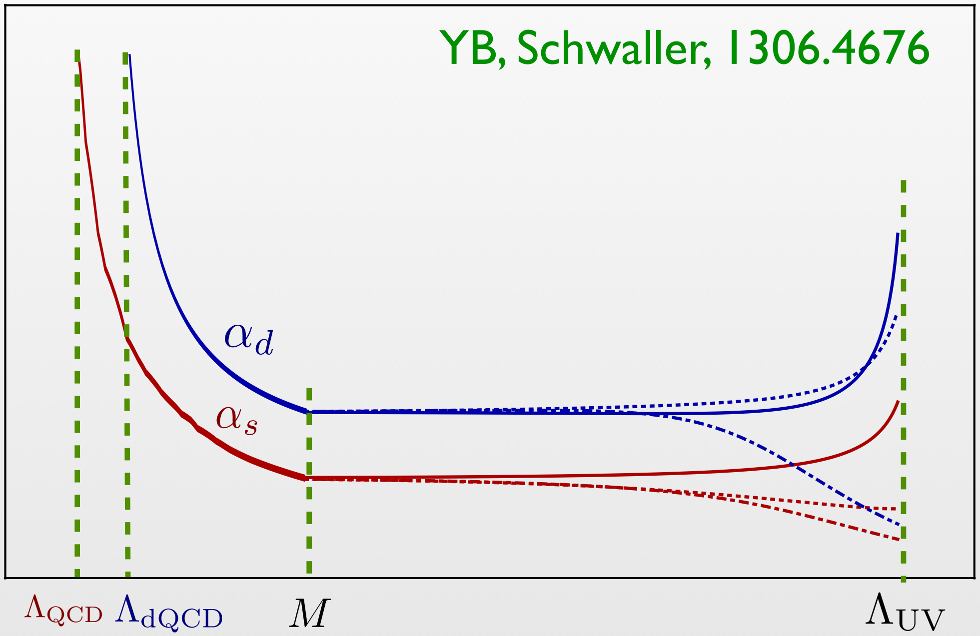
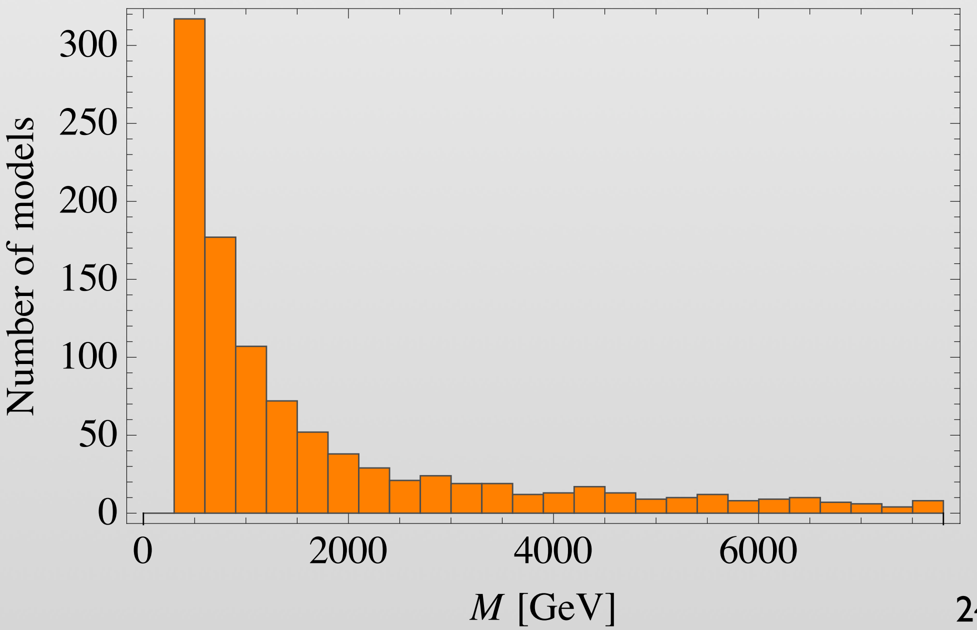
$$\Lambda_{\rm dQCD} \sim \Lambda_{\rm QCD} \quad ?$$

- Need to have QCD and dQCD gauge couplings related to each other

IRFP to Relate QCD and dQCD Scales





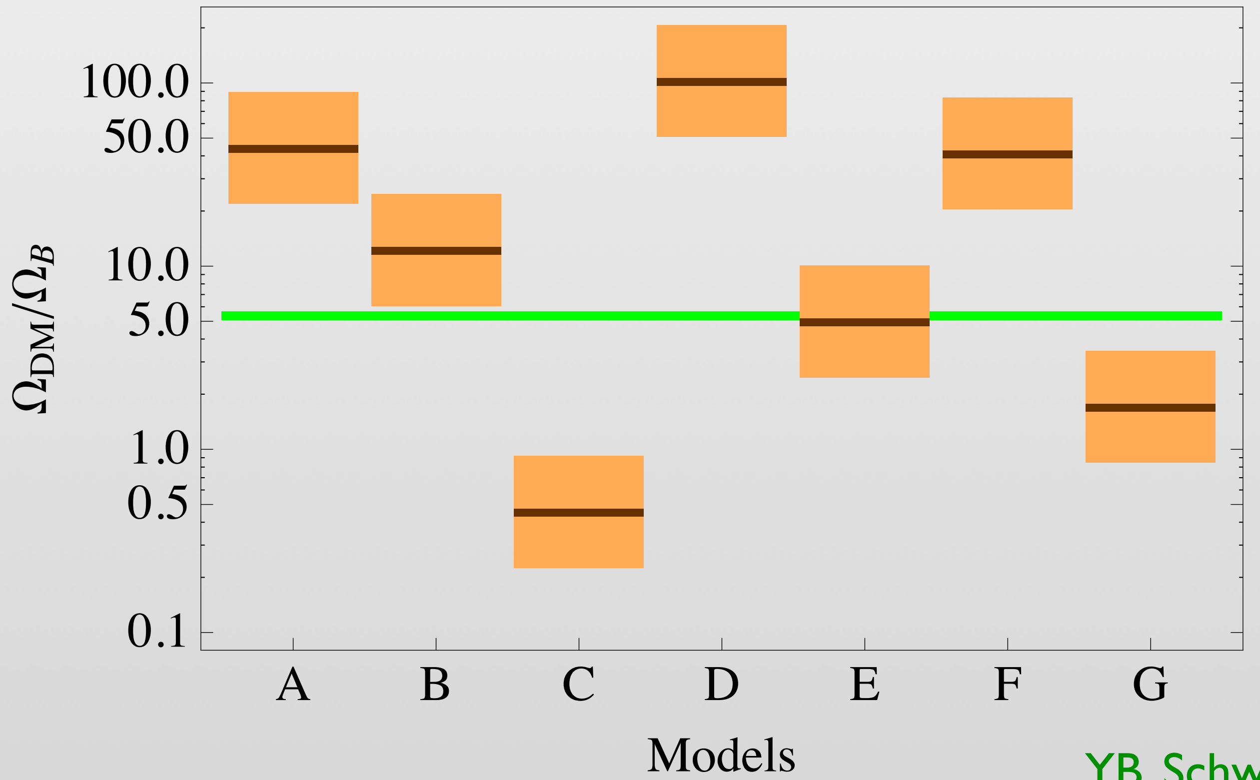


The bi-fundamental of QCD and dark QCD prefers to have masses below 2 TeV

Ratios of Energy Densities

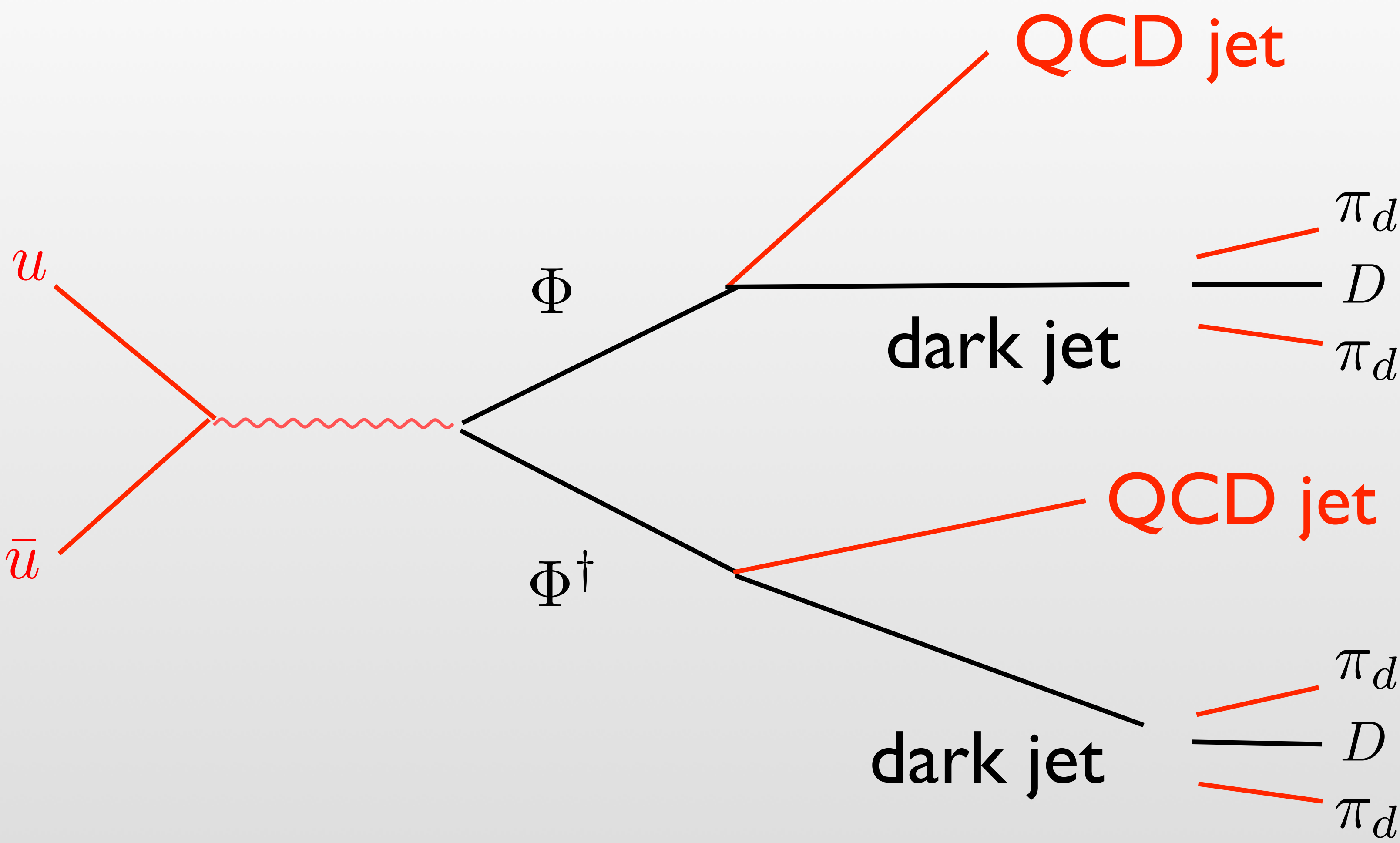
- the bi-fundamental particles can also be used to share the baryon and the dark baryon asymmetries

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm Baryon}} = \frac{n_D m_D}{n_B m_p} \approx \frac{79}{56}\frac{m_D}{m_p}$$



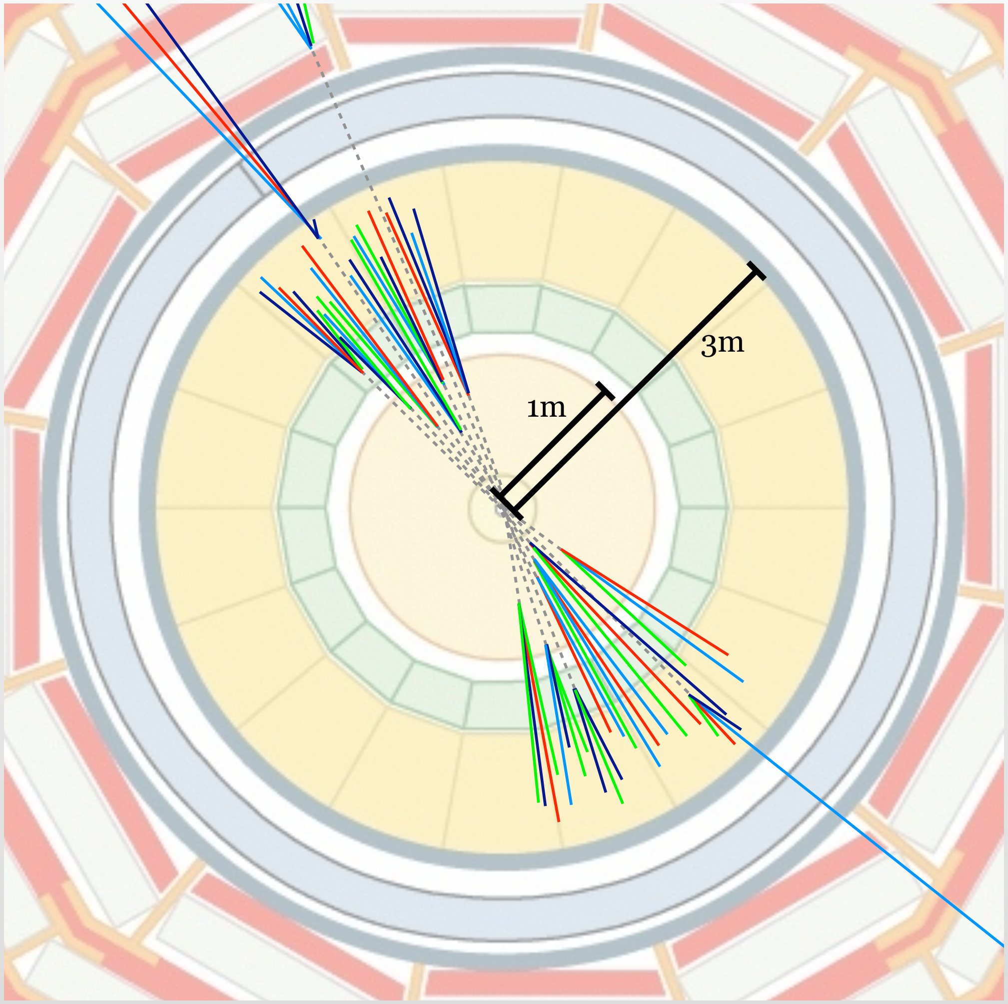
YB, Schwaller, 1306.4676

Signatures at the LHC



- dark pions can decay back to SM particles and are generically long-lived

Emerging Dark Jets



Schwaller, Stolarski, Weiler, 1502.05409

compositeness
new dynamics
extra-dimension
……

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- fully utilize the LHC capability

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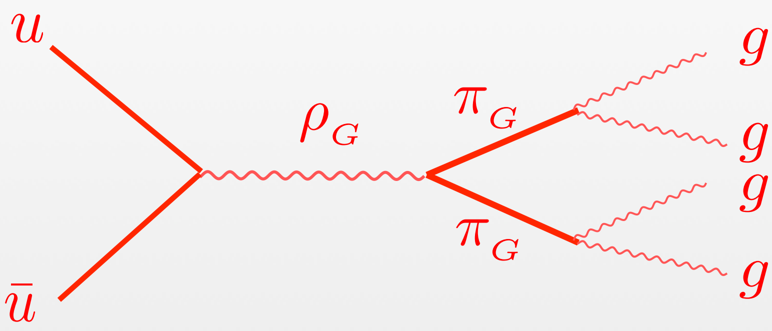
	$SU(N)_G$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
$\psi_{L,R}$	N	3	1	0

for another QCD-like dynamics, we anticipate both rho mesons and pions

Kilic, Okui, Sundrum, 0906.0577
YB, Shelton, 1107.3563

Di-fat-jet Resonance



$$\frac{m_{\pi_G}}{m_{\rho_G}} \sim 0.1$$

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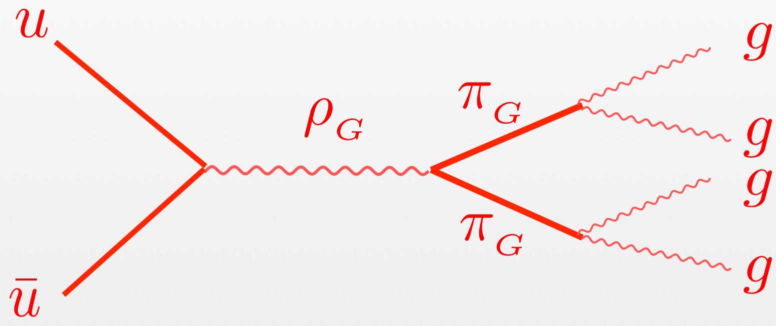

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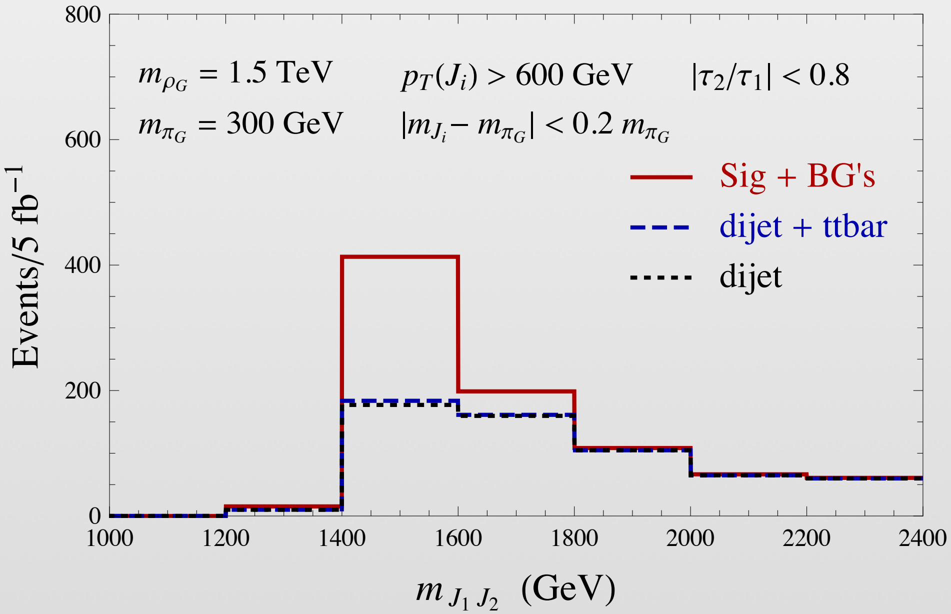
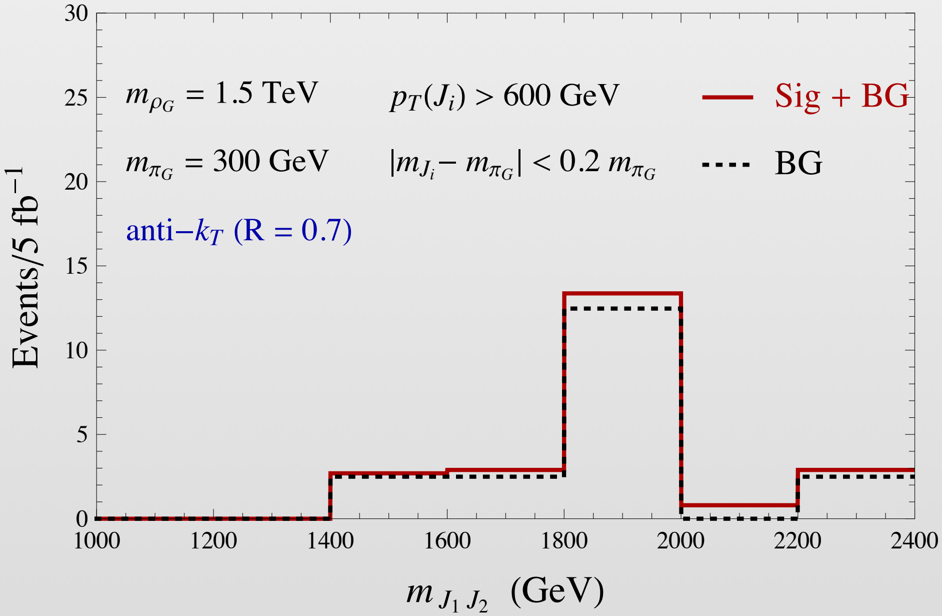
YB, Shelton, 1107.3563





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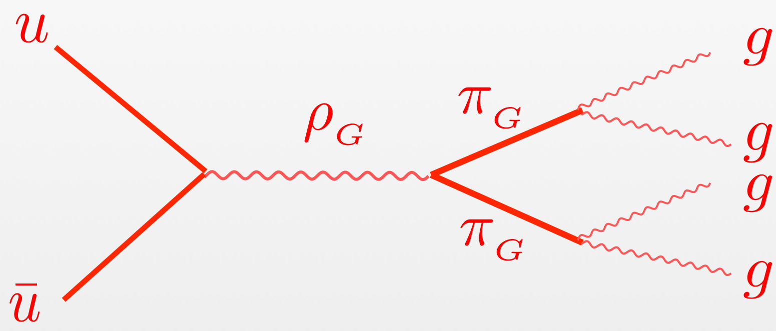

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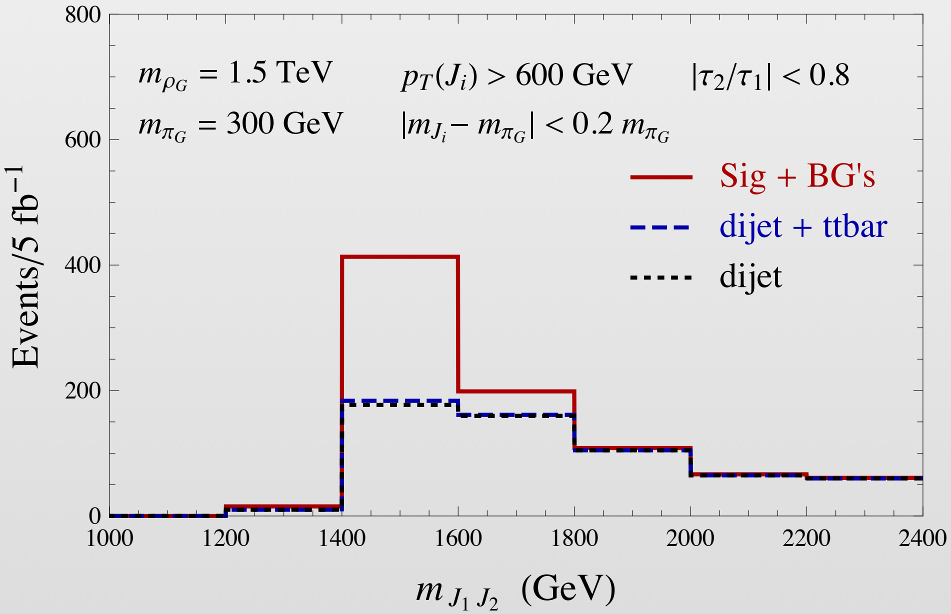
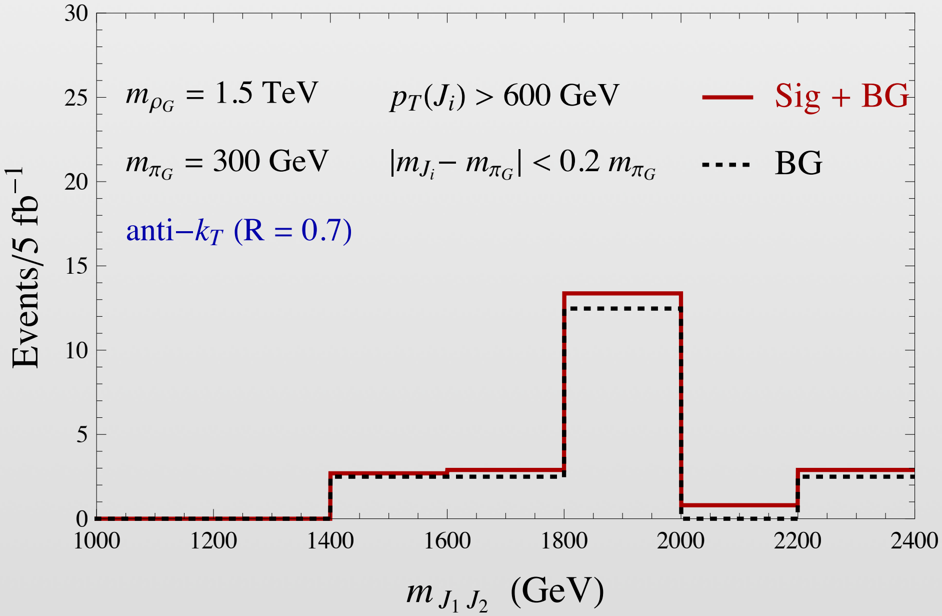
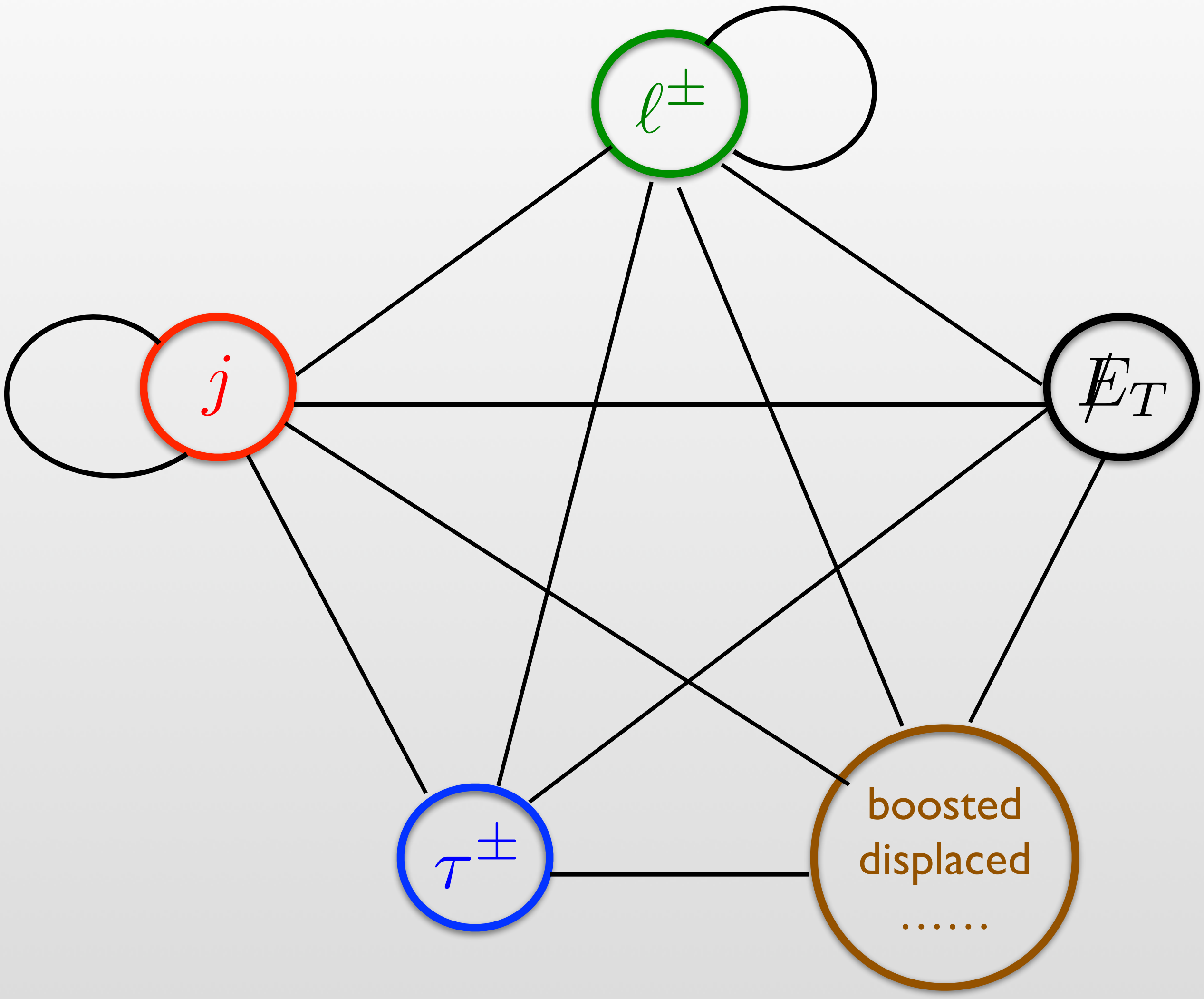
YB, Shelton, 1107.3563



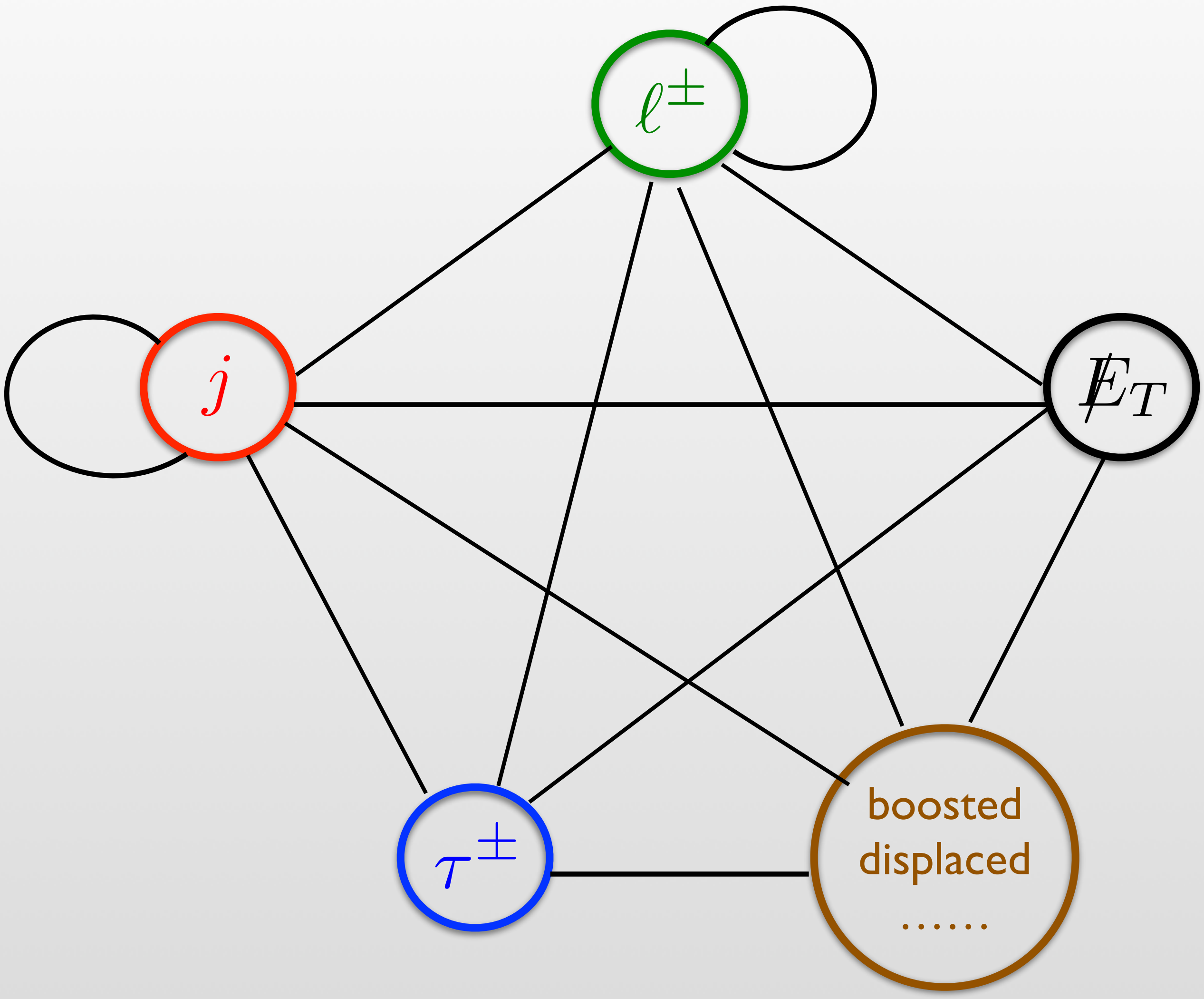


can provide an explanation why the recent di-boson ~ 2 TeV resonance does not show up in leptonic channels

Signature Driven



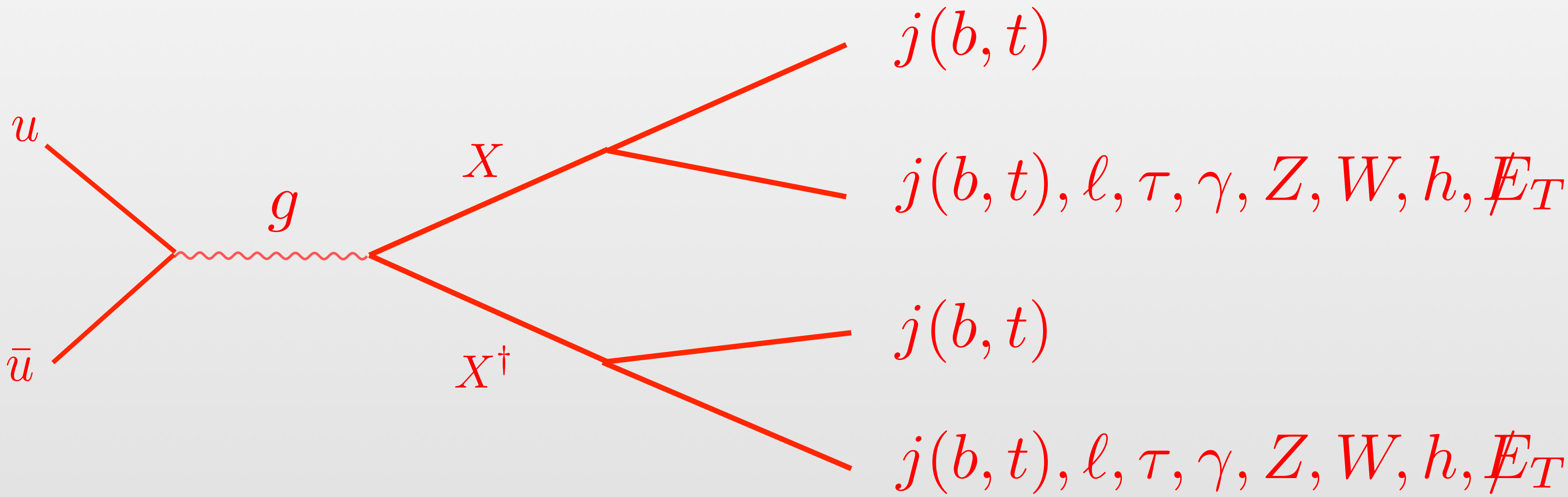
Signature Driven



While there are too many combinations, let us focus QCD charged new particles

QCD Pair-produced Particles

Focusing on two-body decays, at least two QCD charged particles in the final state



QCD Pair-produced Particles

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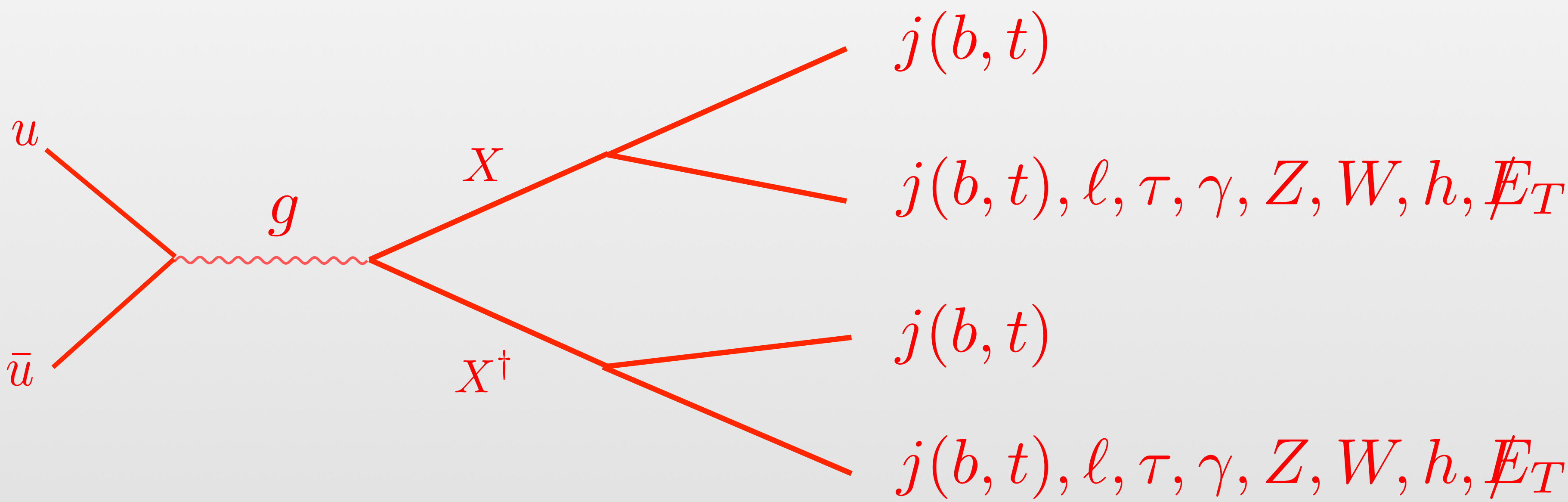
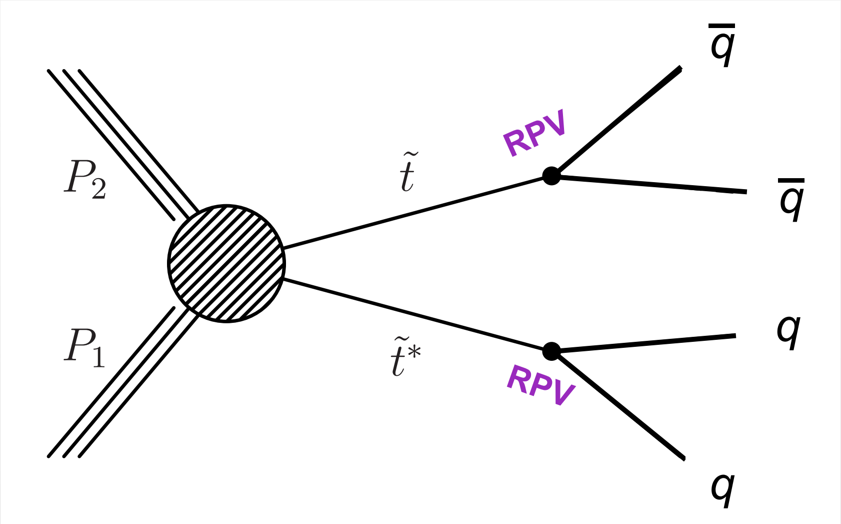


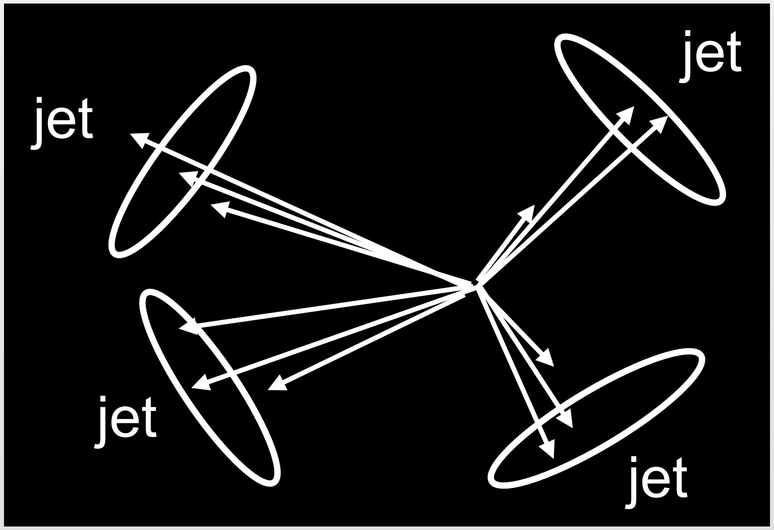
The most challenging one is the four-jet final state. The smallest production cross section is a scalar color-triplet X.

Right-handed Stop Decay

from the following R-parity violating operator

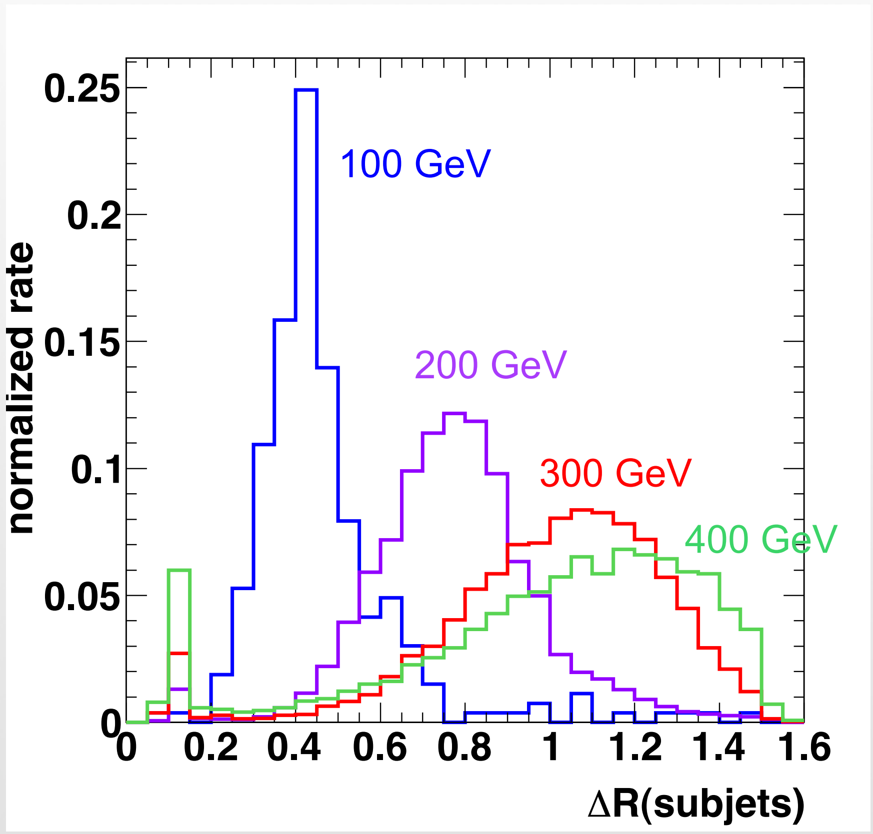
$$\lambda_{3ij}\, \tilde{t}_R\, d^i_R\, d^j_R \qquad (i \neq j)$$





Serve as a benchmark for purely jetty pair-production searches (minimal color and spin)

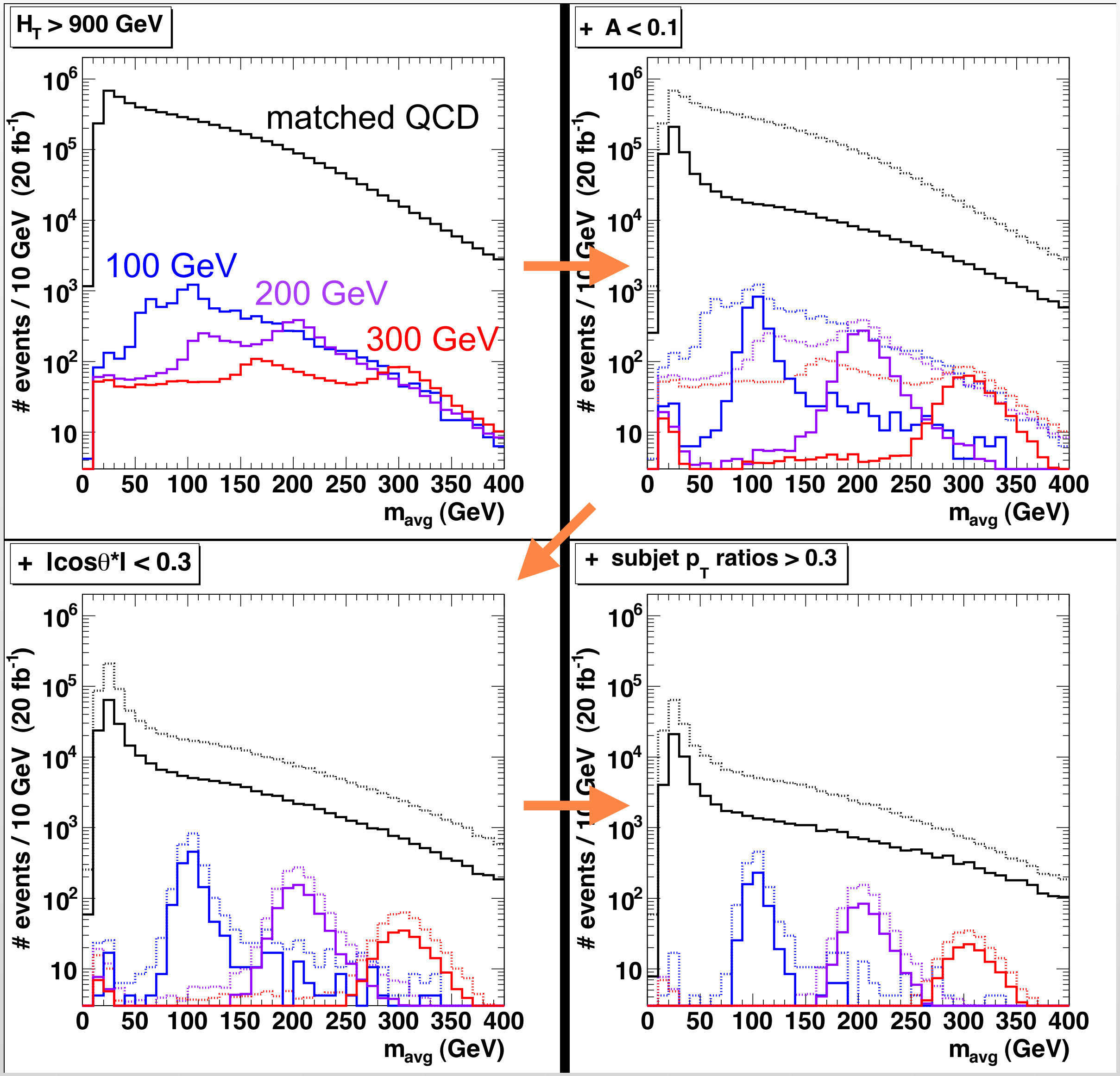
Delta R Distribution



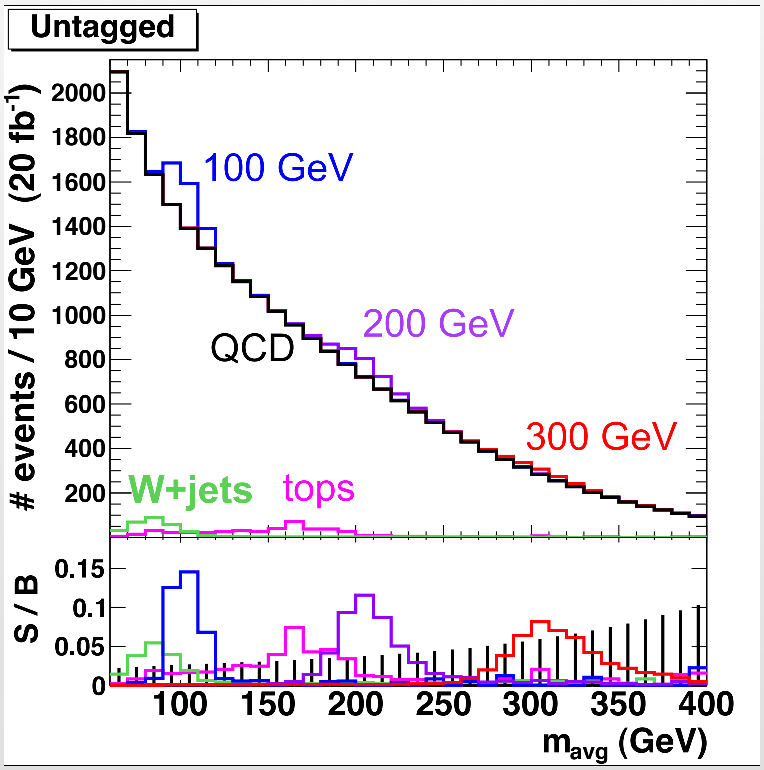
- Jet-Ht trigger: offline Ht > 900 GeV
- Capture stop decays in R = 1.5 C/A jets

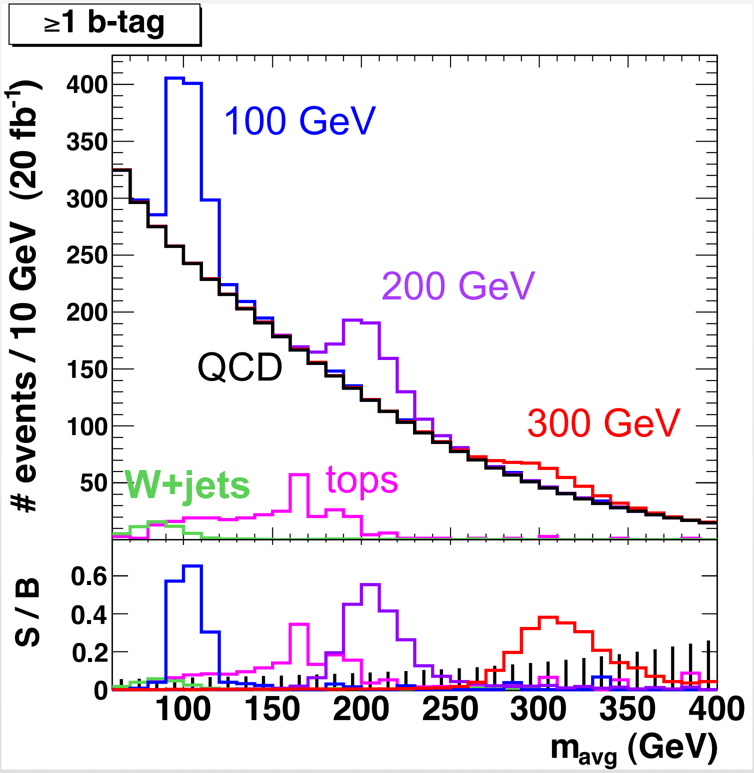
Jet-substructure Cut Flow

8 TeV

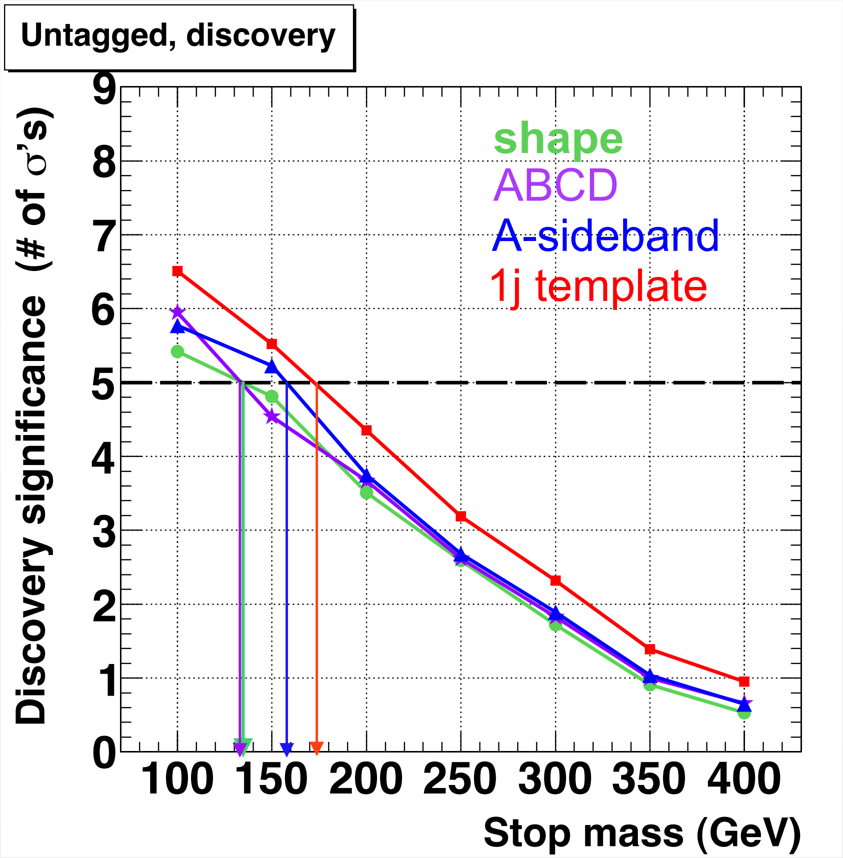


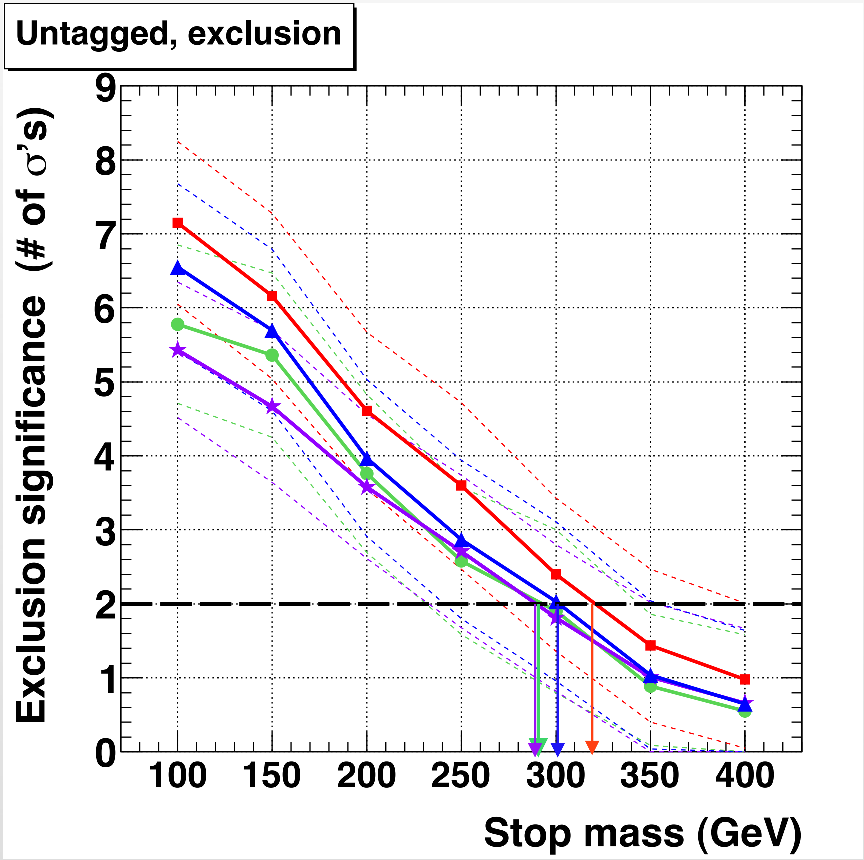
Averaged Mass Peaks





Sensitivities, untagged



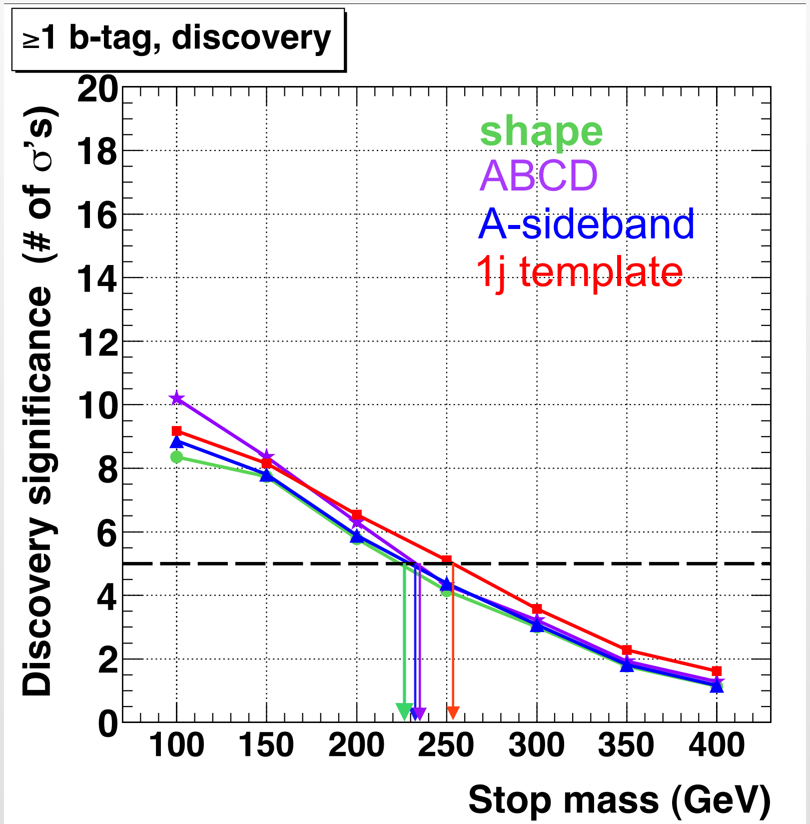


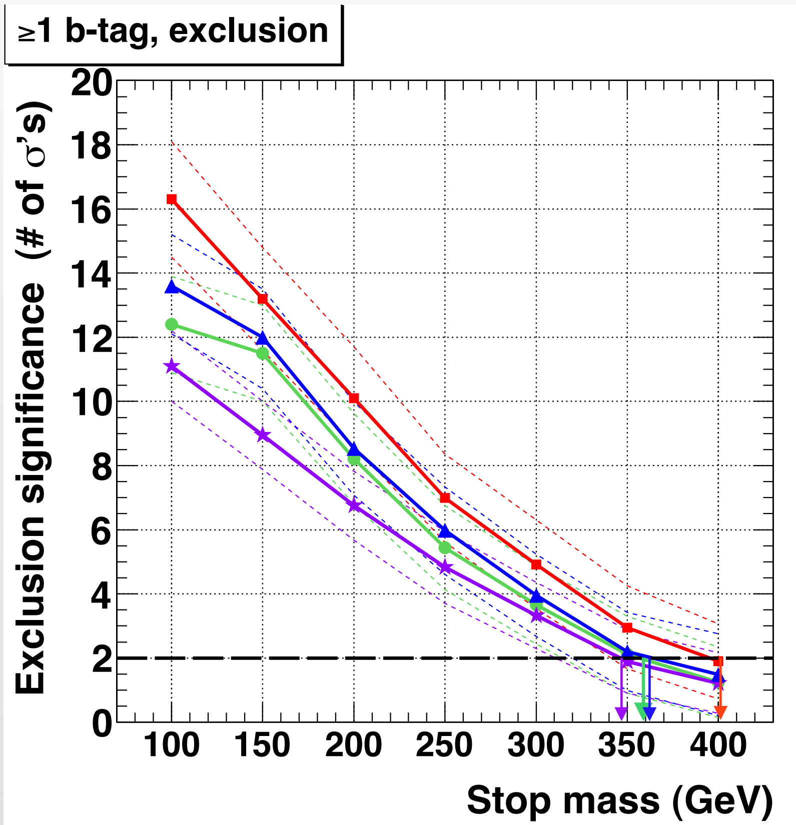
discovery ~150 GeV

exclusion ~300 GeV

YB, Katz, Tweedie, 1309.6631

Sensitivities, b-tagged



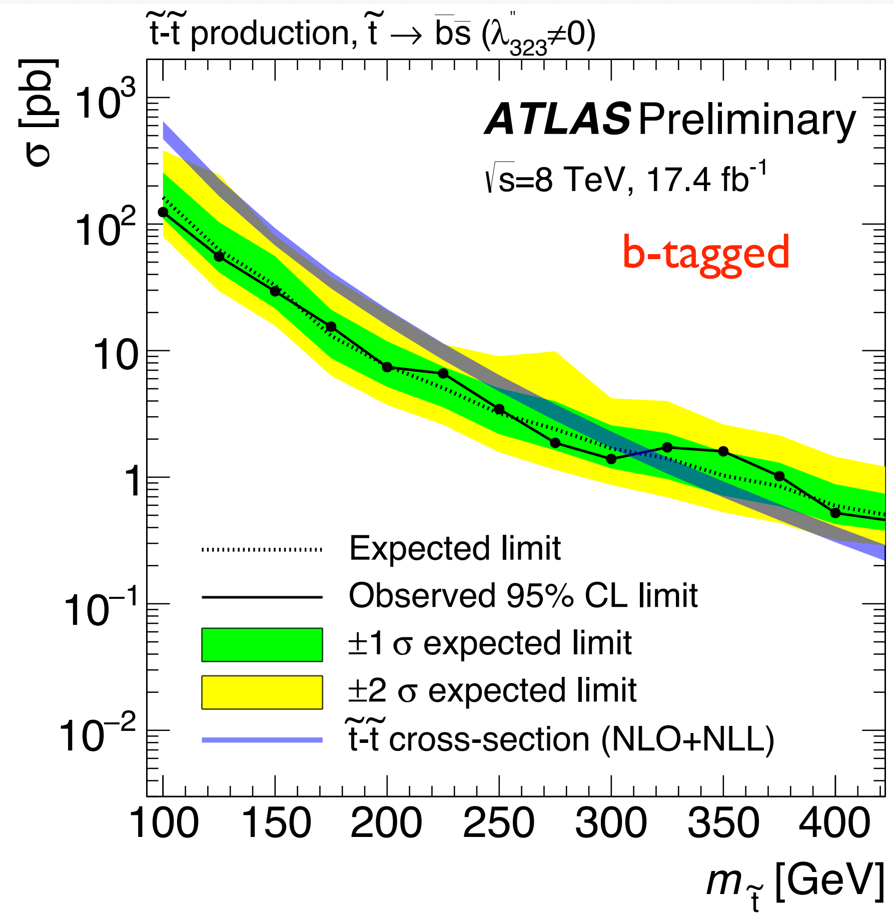


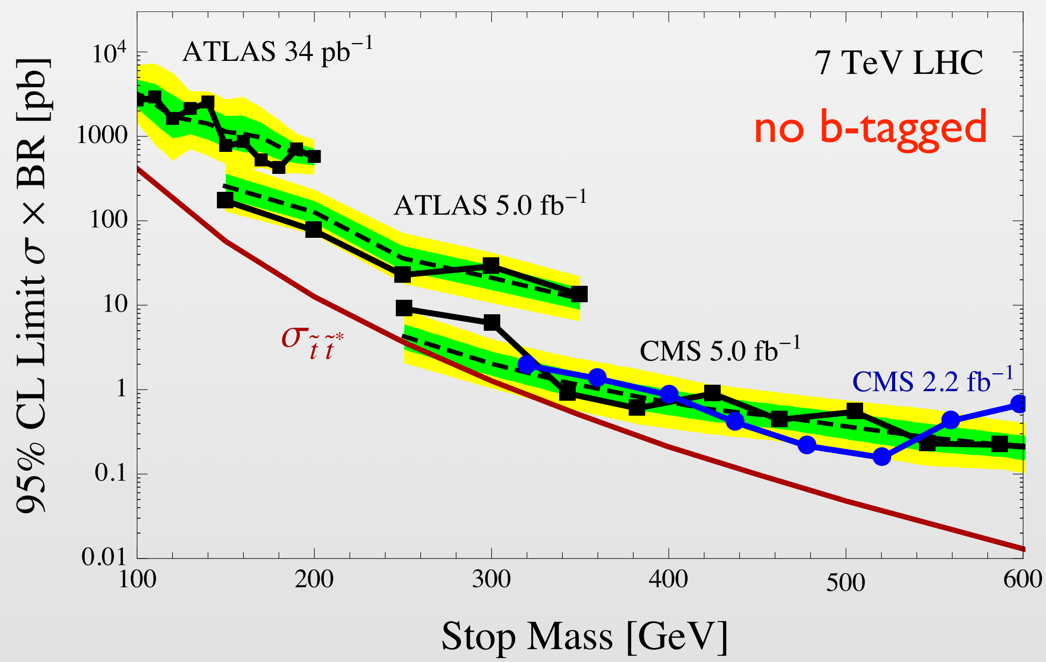
discovery ~250 GeV

exclusion ~350-400 GeV

YB, Katz, Tweedie, 1309.6631

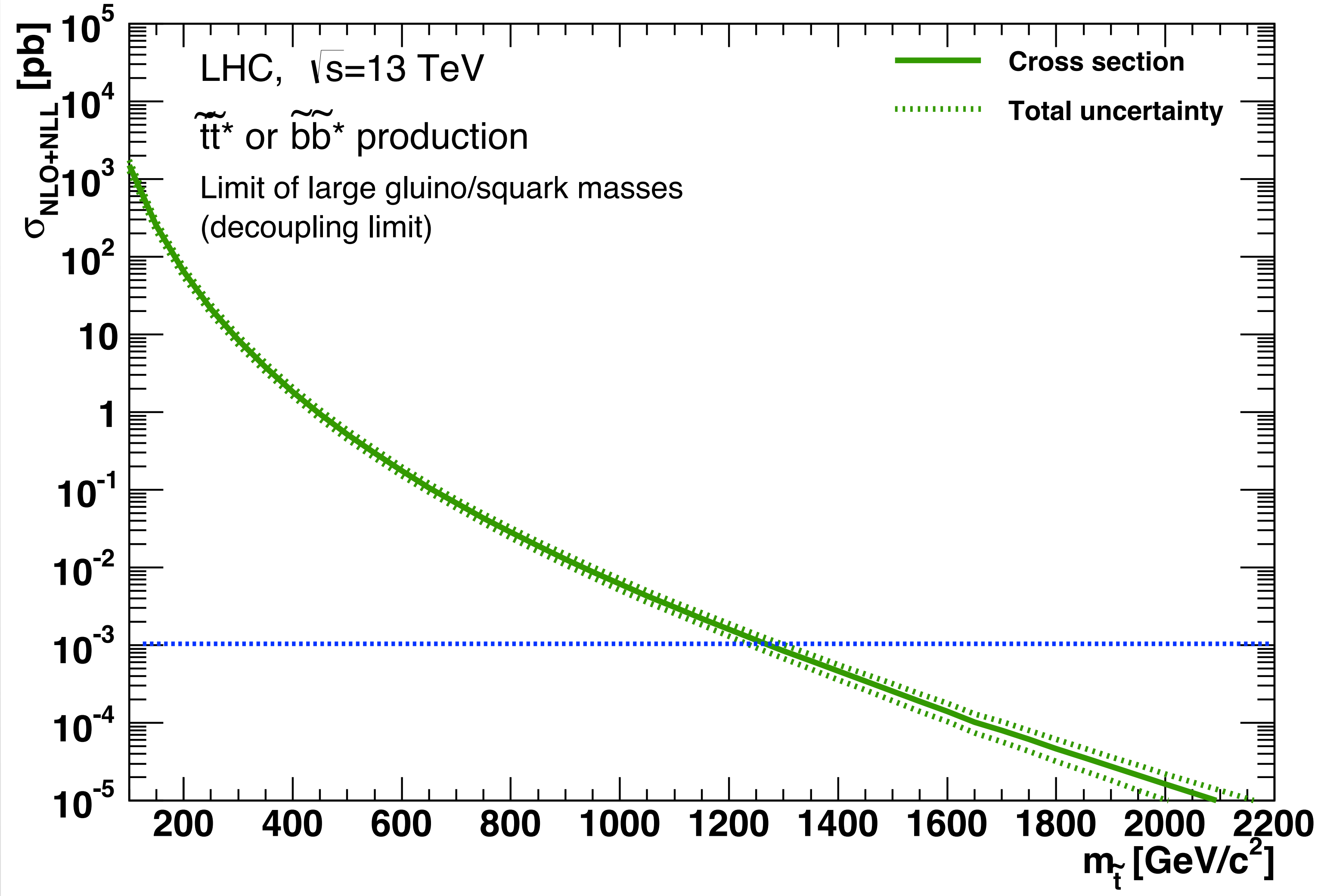
Results from LHC Run I





the non-b-tagging case should be searched for at the LHC Run II

ttbar+MET at LHC Run II



the potential limits on the t' mass are higher

Non-Relativistic Limits of Heavy Particles

$$\hat{\sigma}(q\bar{q} \to t'\bar{t}') = \frac{4\pi\alpha_s^2\beta}{27\,\hat{s}}\left(3-\beta^2\right) \approx \frac{4\pi\alpha_s^2\beta}{9\,\hat{s}},$$

$$\hat{\sigma}(gg \to t'\bar{t}') = \frac{\pi\alpha_s^2}{48\,\hat{s}}\left[(33-18\beta^2+\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right) - \beta(59-31\beta^2)\right] \approx \frac{7\pi\alpha_s^2\beta}{48\,\hat{s}}$$

$$\hat{\sigma}(q\bar{q} \to \tilde{t}\tilde{t}^*) = \frac{2\pi\alpha_s^2\beta^3}{27\,\hat{s}},$$

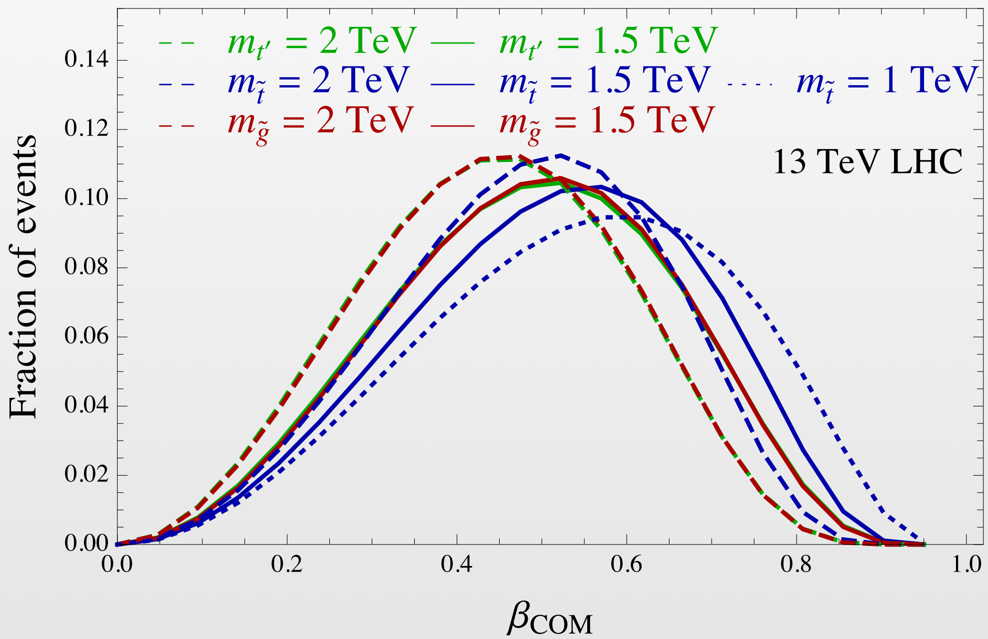
$$\hat{\sigma}(gg \to \tilde{t}\tilde{t}^*) = \frac{\pi\alpha_s^2}{96\,\hat{s}}\left[\beta(41-31\beta^2) - (17-18\beta^2+\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right] \approx \frac{7\pi\alpha_s^2\beta}{96\,\hat{s}}$$

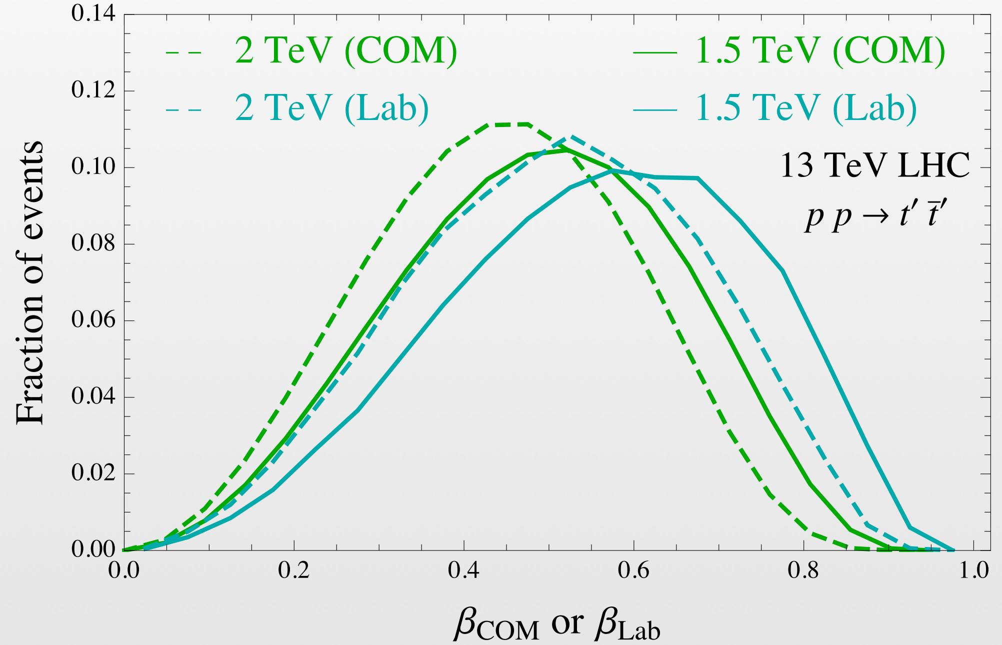
$$\hat{\sigma}(q\bar{q} \to \tilde{g}\tilde{g}) = \frac{4\pi\alpha_s^2\beta}{9\,\hat{s}}\left(3-\beta^2\right) \approx \frac{4\pi\alpha_s^2\beta}{3\,\hat{s}},$$

$$\hat{\sigma}(gg \to \tilde{g}\tilde{g}) = \frac{3\pi\alpha_s^2}{16\,\hat{s}}\left[3(7-2\beta^2-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right) - \beta(33-17\beta^2)\right] \approx \frac{27\pi\alpha_s^2\beta}{16\,\hat{s}}$$

one can understand those β-dependence from s-wave or p-wave production cross sections

Velocity Distributions



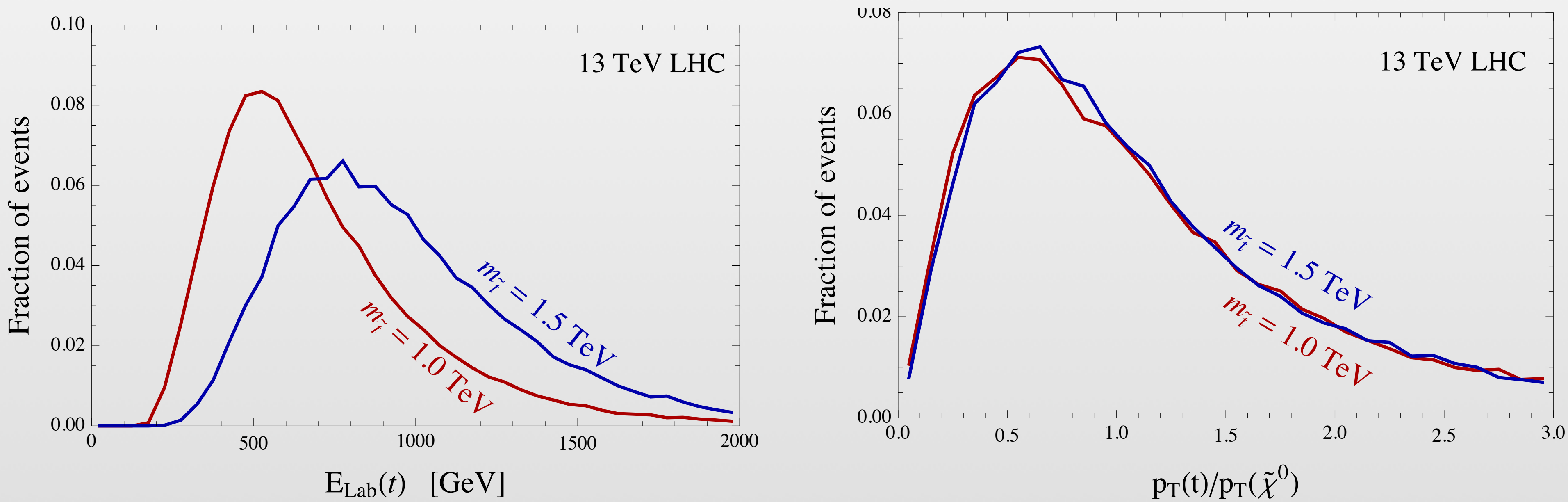


There is no sharp peak for the velocity distributions, but it may help us to understand kinematics

Now, the question is how to use this understanding to improve our searches for heavy particles

Simple Kinematics

Consider one-step decay: $\tilde{t} \to t + \tilde{\chi}^0$

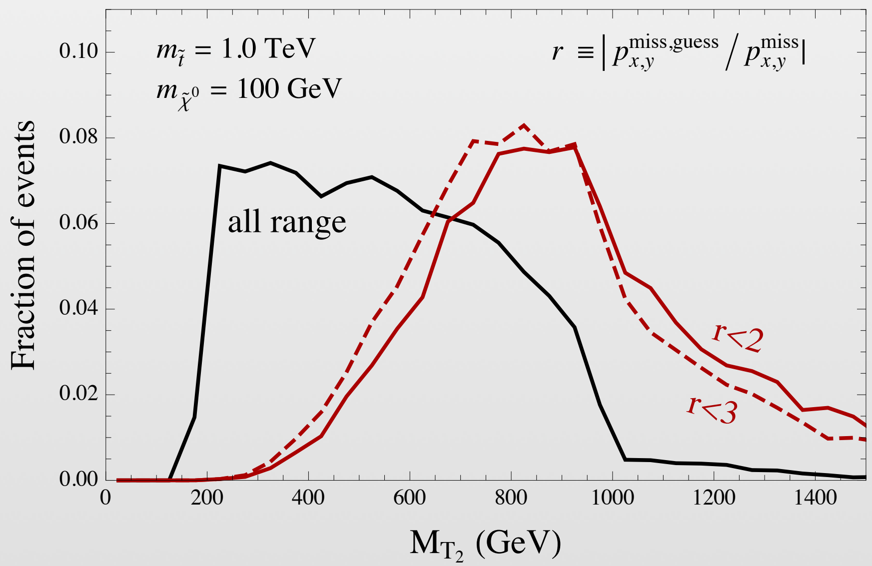


so, the missing neutralino particles have similar pt's compared to the top/anti-top pt's

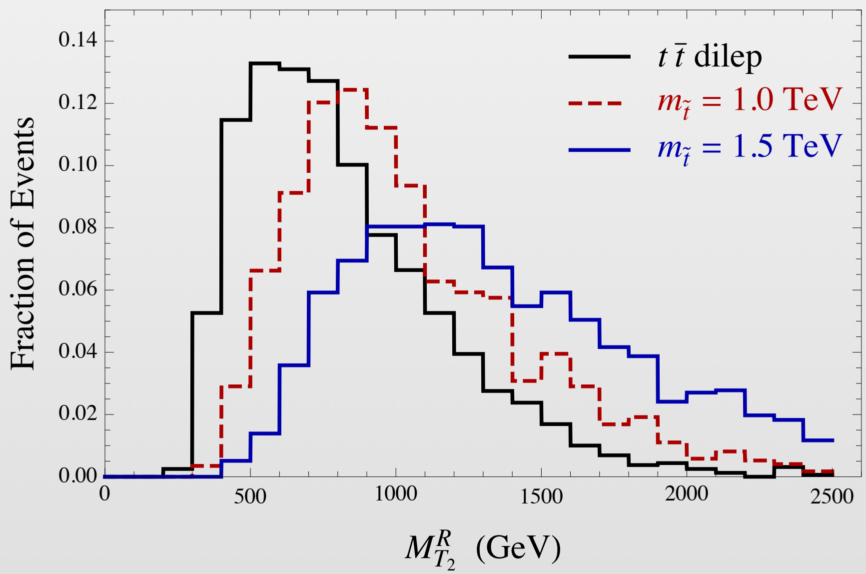
$M_{T_2}^R$ Distribution

When one separates the total $\not{E}_T$, one can restrict the guessed neutralino momenta within a range of $\not{E}_T$

parton-level:



PGS simulation: $\not{E}_T > 200$ GeV

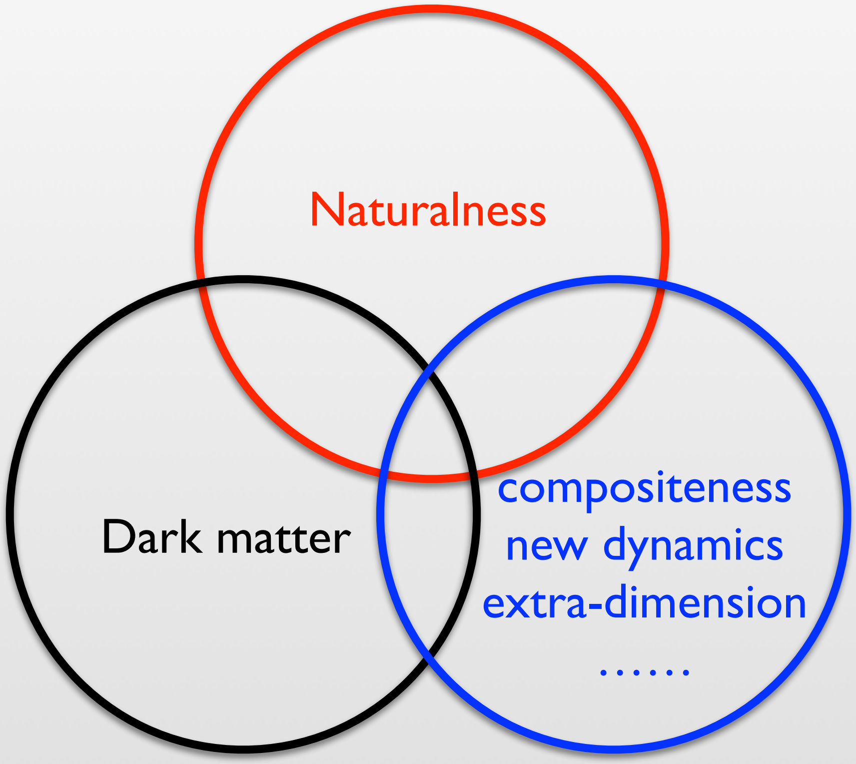


YB, Osborne, Stefanek, work in progress

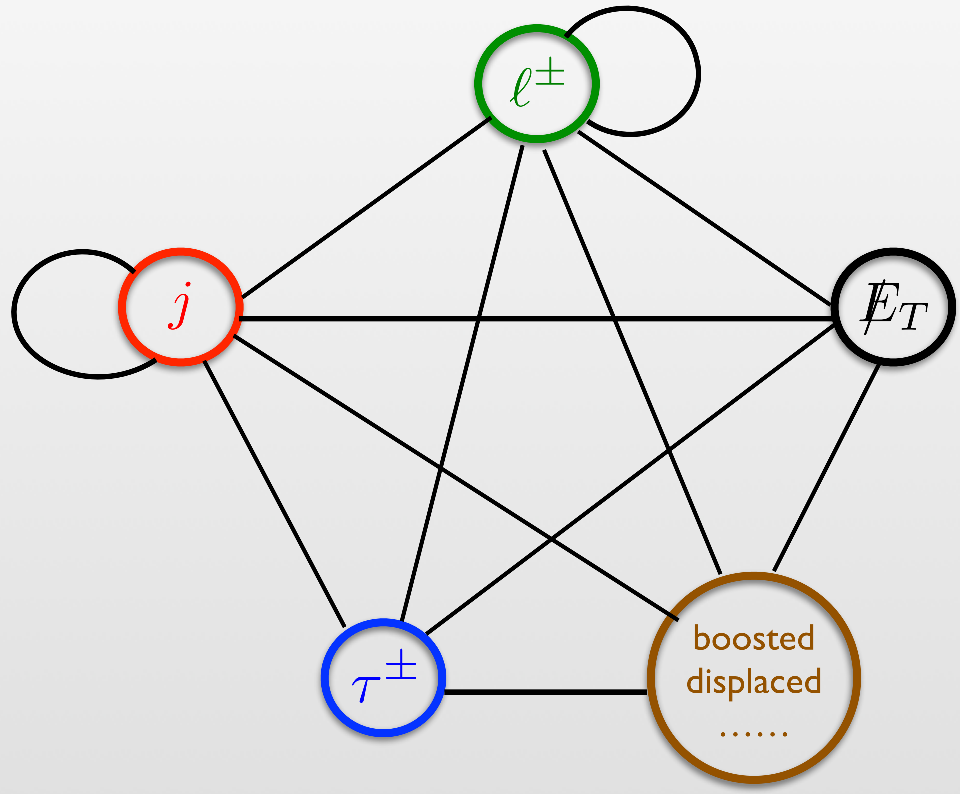
the ttbar+jets background has a tail in $M_{T_2}^R$ without a peak structure; the S/B could be improved.

Conclusions

Physics Driven



Signature Driven



lots of opportunities at the LHC Run 2

Data Driven

Thanks