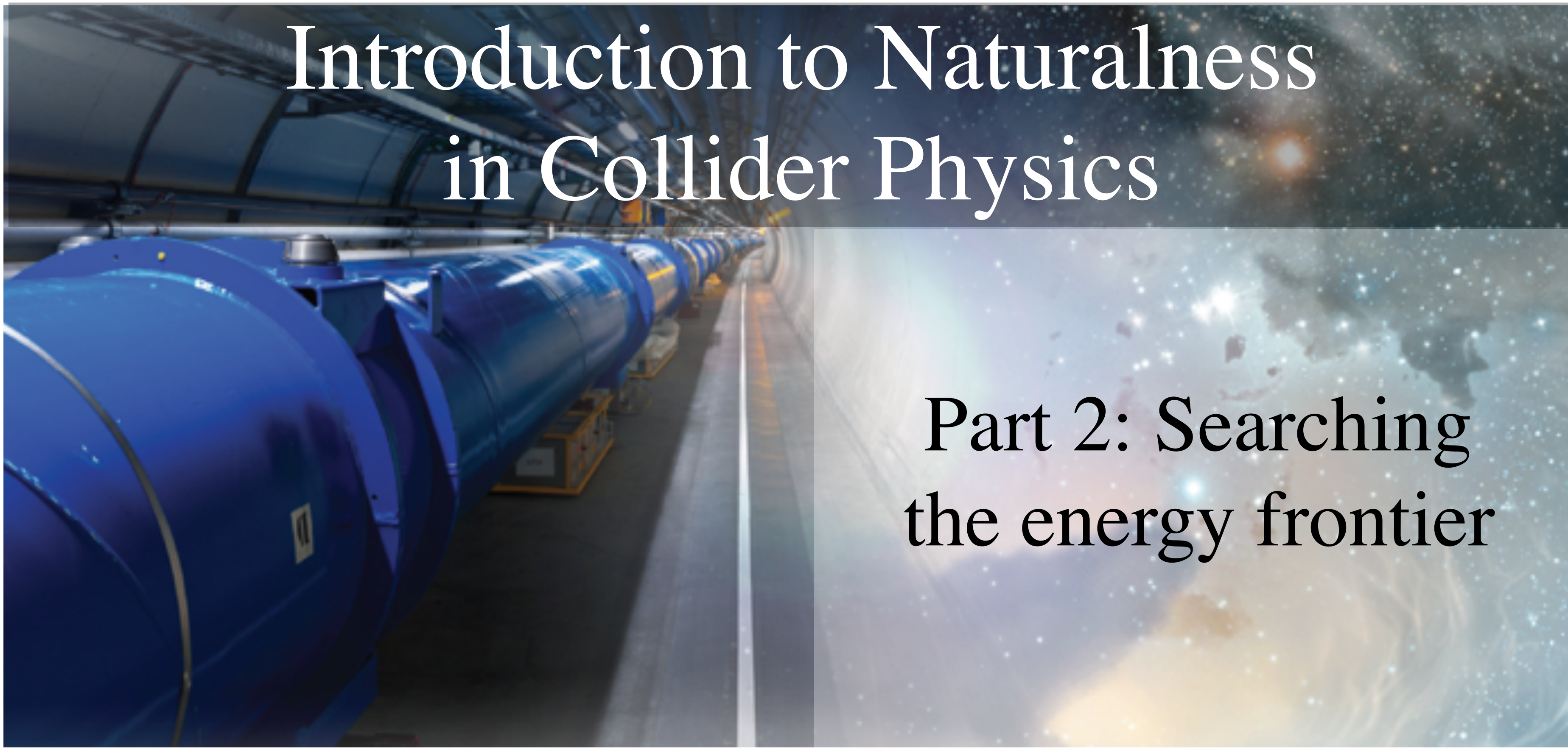
Introduction to Naturalness in Collider Physics



Part 2: Searching the energy frontier

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HARVARD UNIVERSITY

UNC Chapel Hill

CoSMS workshop on naturalness

October 21, 2016

Entering the next phase of our **fantastic journey**…

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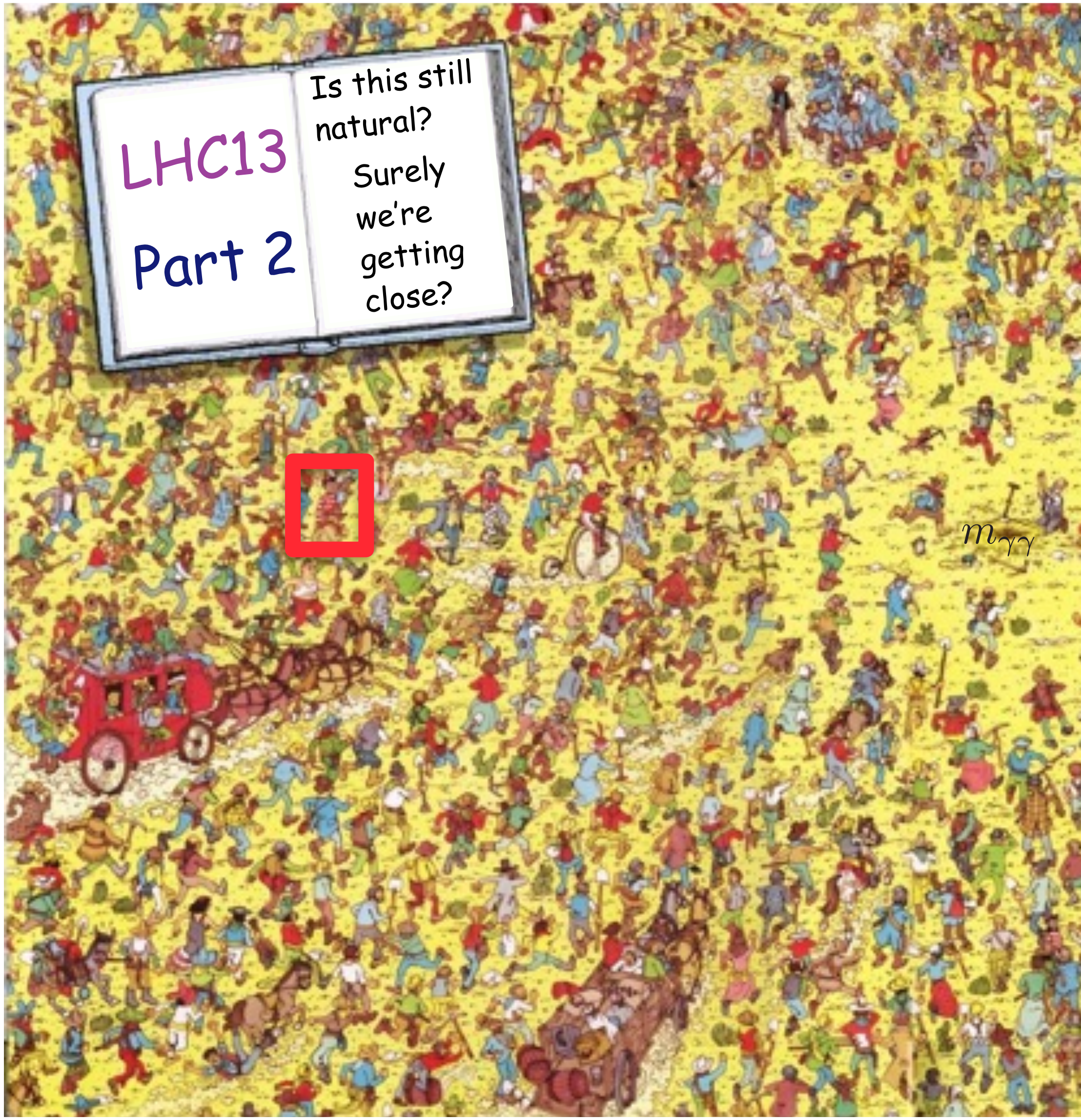
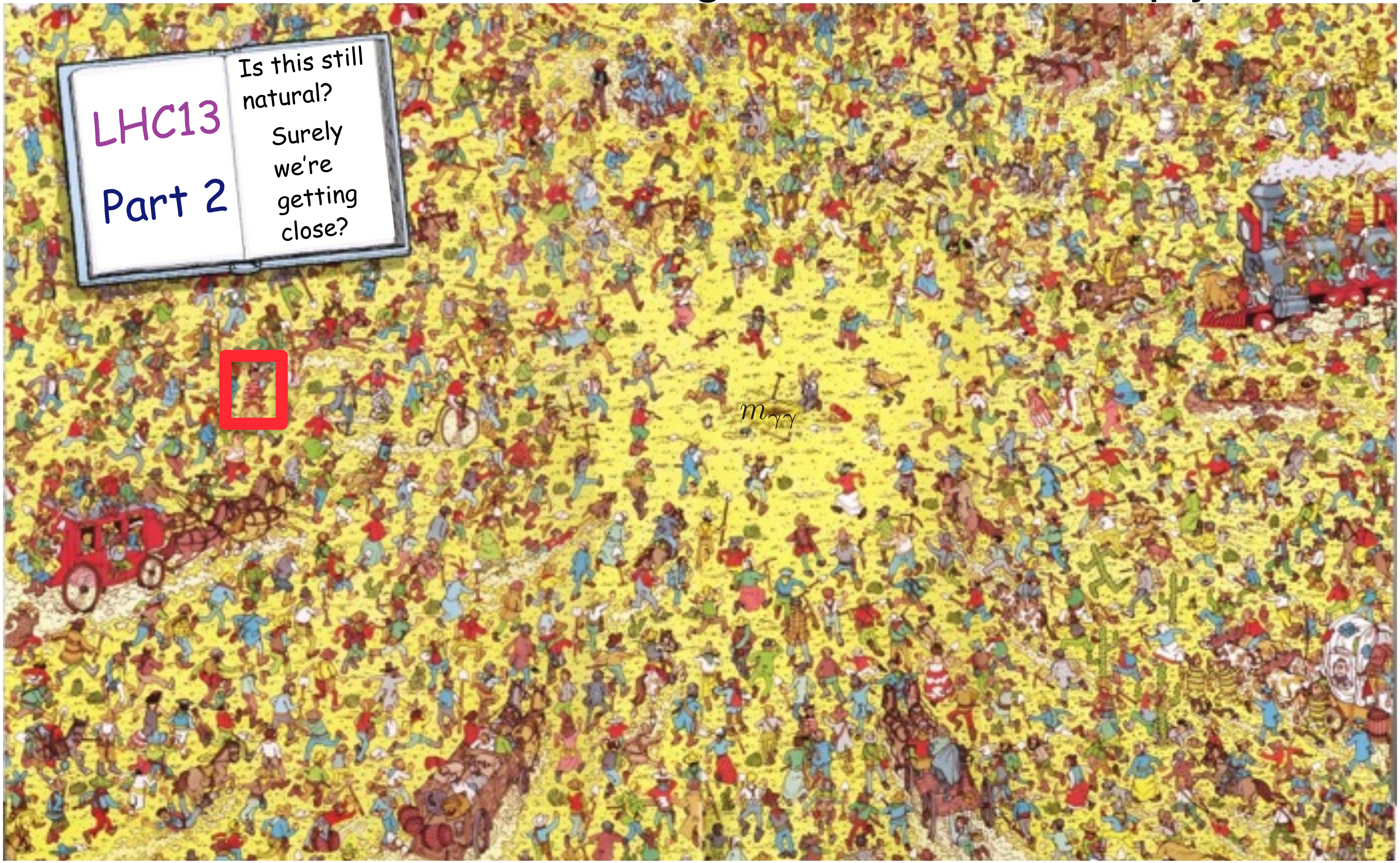
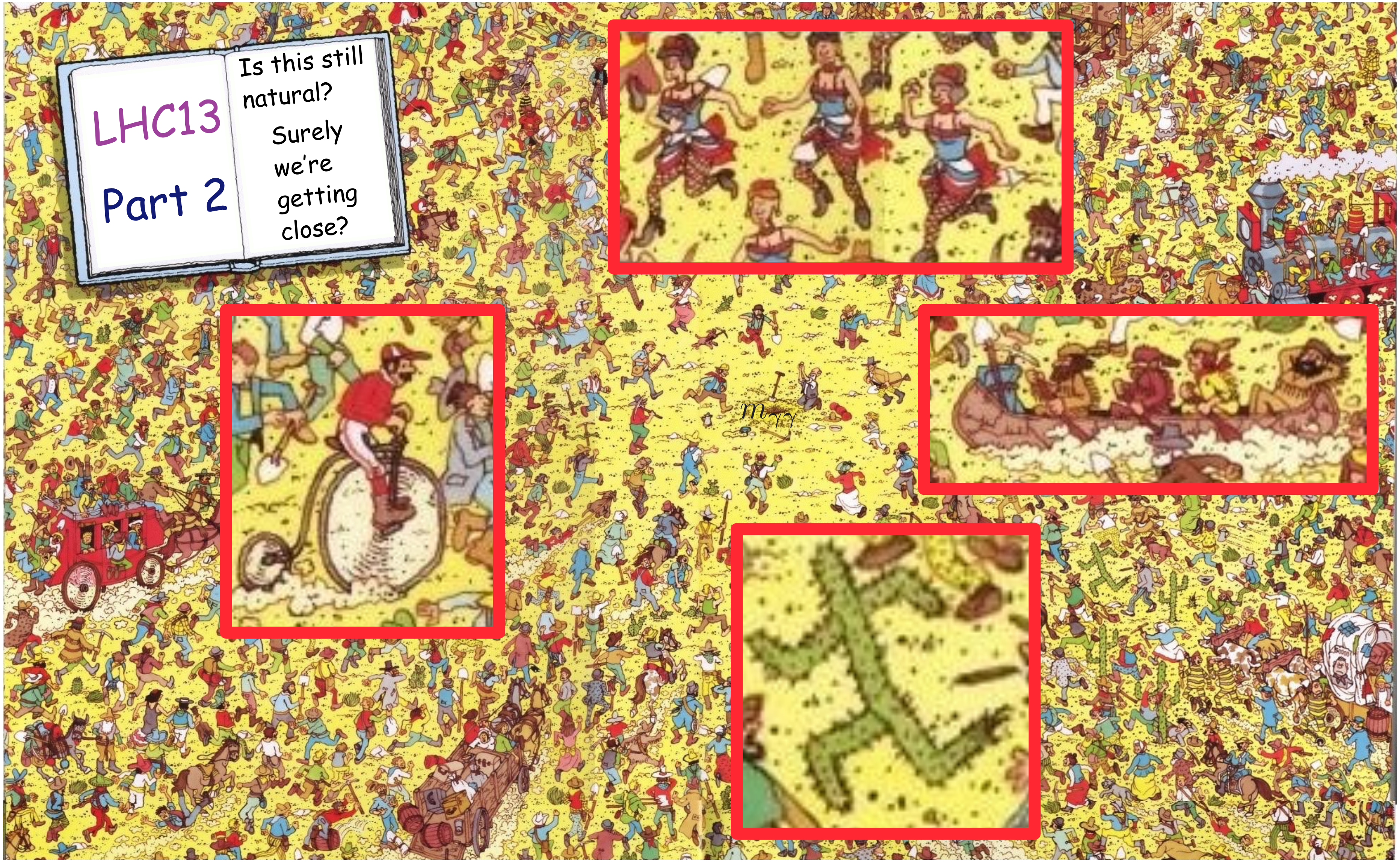


Not quite the right analogy…

…"SUSY" or BSM isn't one signature that we simply look for



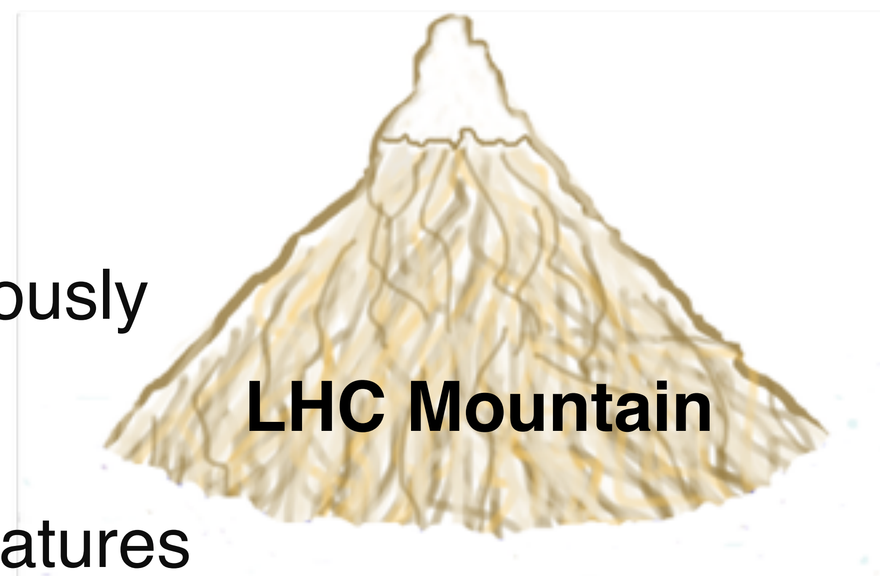
Rather: Is this what LHC13 is supposed to look like?…
…Are our observations consistent with the SM?



Searching Collider Phase Space for **BSM**

Less like searching for a single person

More like exploring a previously unvisited landscape, searching for new flora/fauna/geographical features



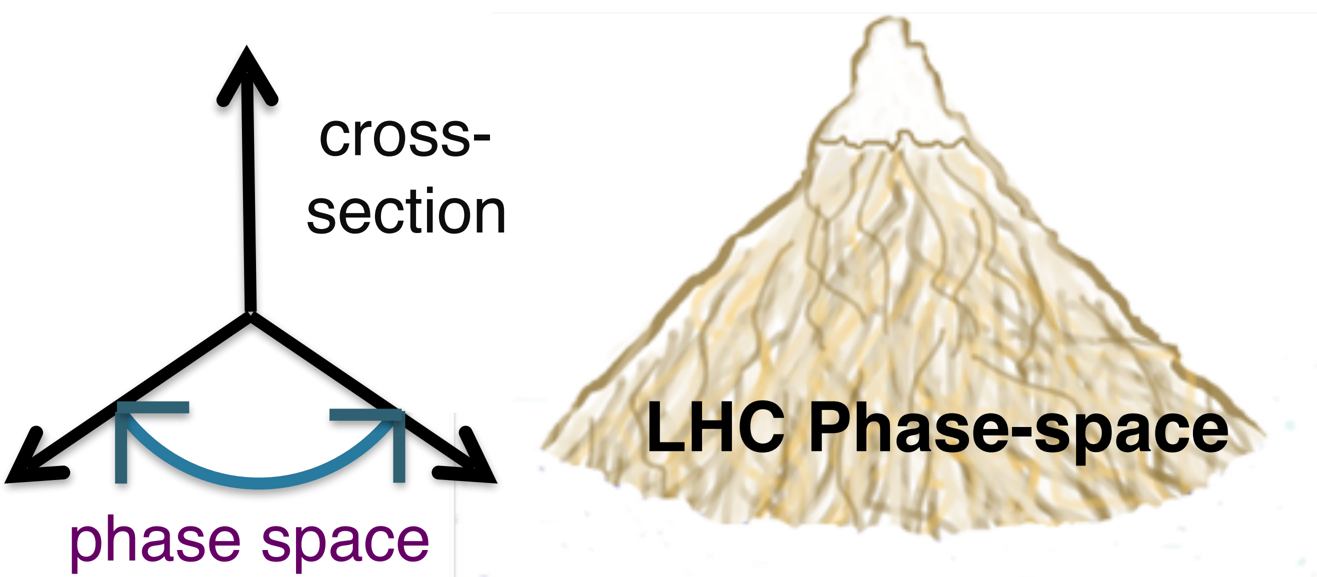
Searching Collider Phase Space for **BSM**

- From the peak to the valley
  - Strategies for searching LHC phase-space for NP
- Where are we now?
  - Partitioning LHC phase-space and current SUSY constraints
- Signals big and small for SUSY:
  - Extending sensitivity to larger sparticle masses and splittings
  - “compressed” sparticle mass-spectra

Searching Collider Phase Space for **BSM**

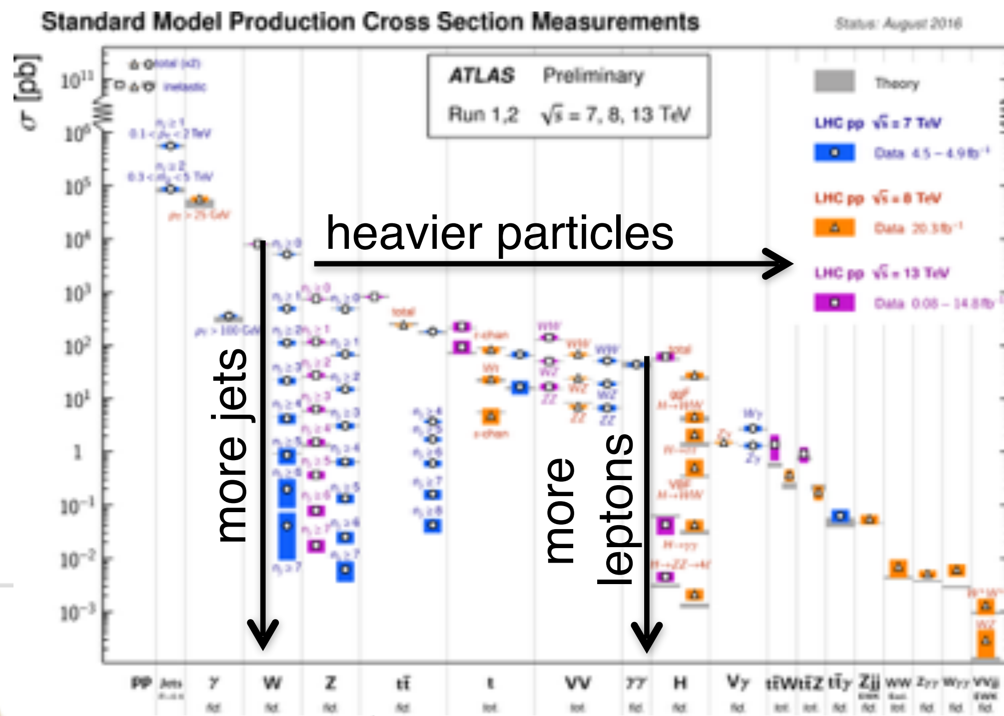
The elevation represents the rate of production of different types of collision events

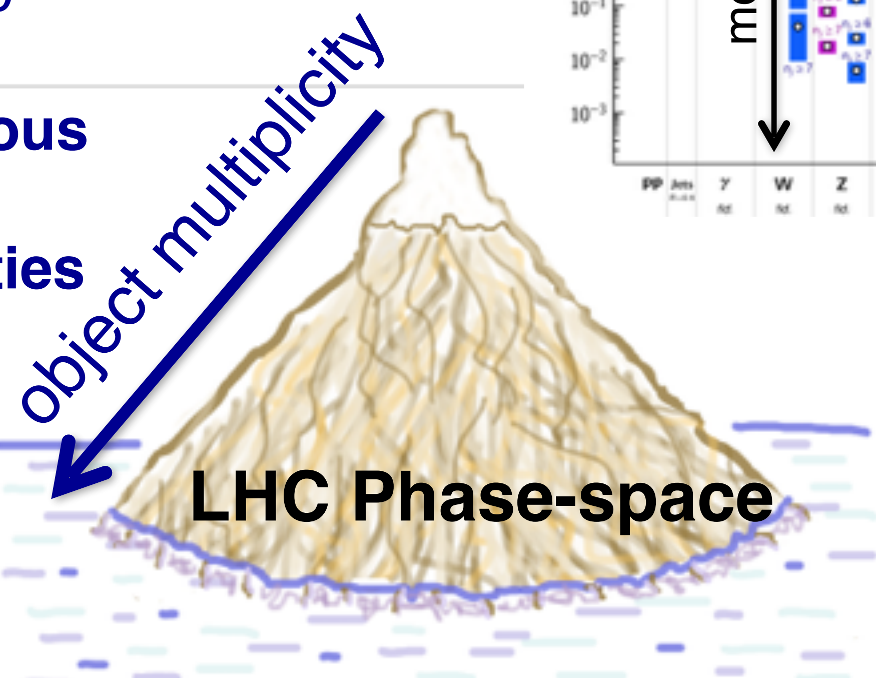
The lateral distance from the center of the mountain represents what’s in those collision events, i.e. how rare they are



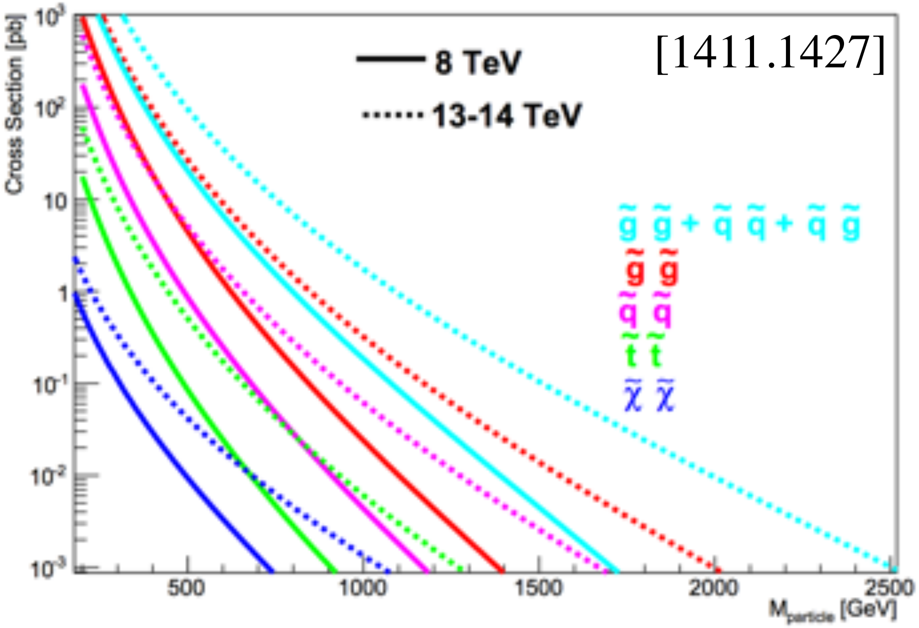
Searching Collider Phase Space for **BSM**

- Particles decaying to **W/Z/γ/leptons/ top quarks/b-jets**
- Cascading decays through SM spectrum (BSM?) can lead to **high/ conspicuous object multiplicities**





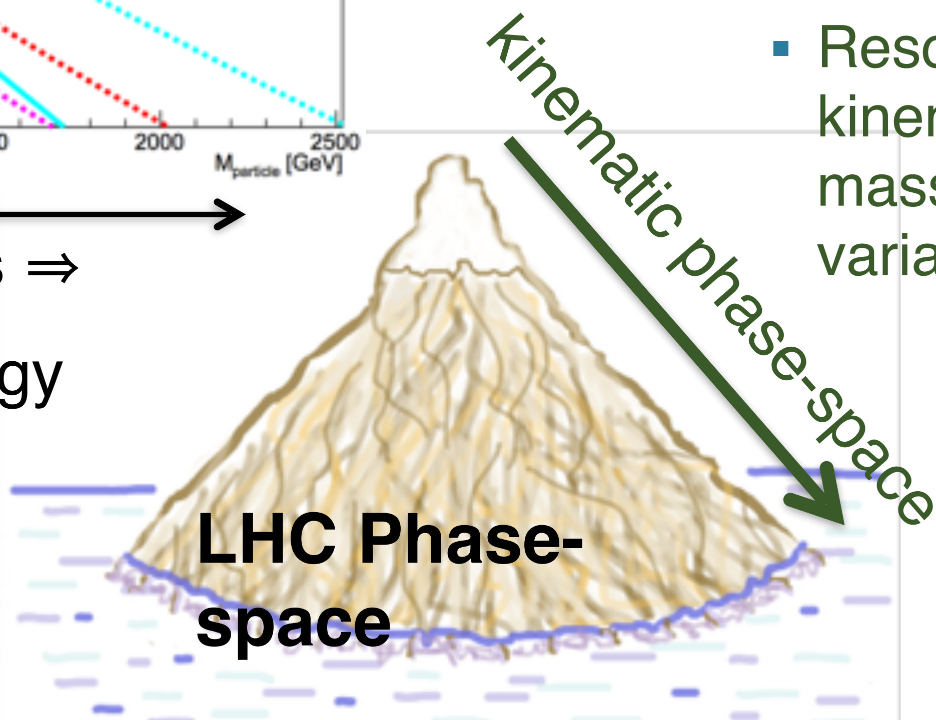
Searching Collider Phase Space for **BSM**



more mass ⇒

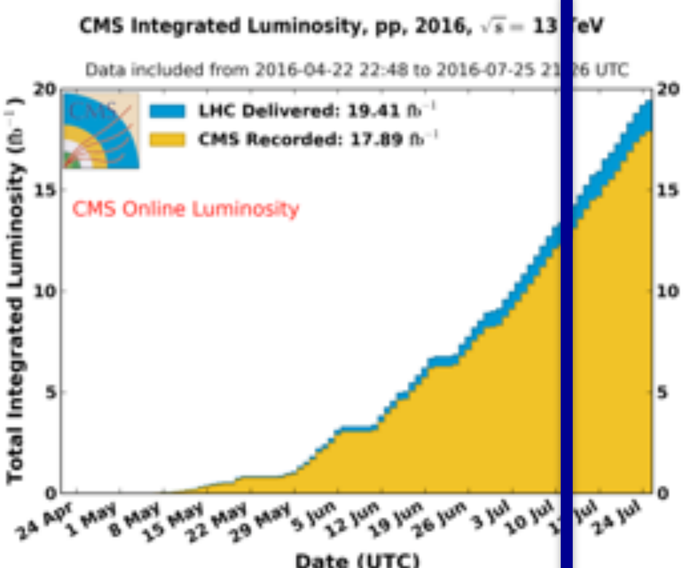
more energy

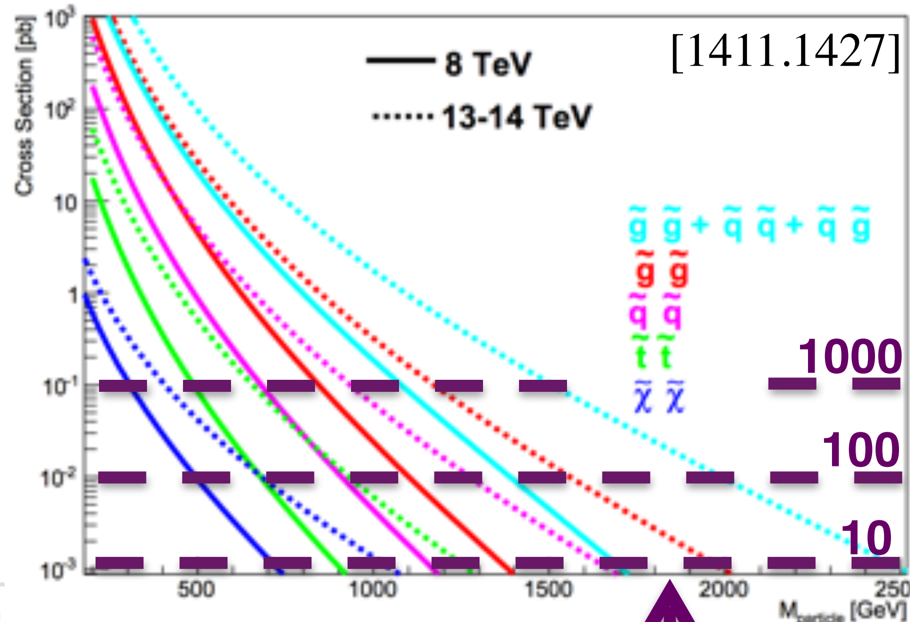
- Heavy BSM particles decaying to SM particles
  ➔ **large visible momenta**
- New symmetry conservation
  ➔ **large missing momenta**
- Resonances, kinematic edges, mass sensitive variables…

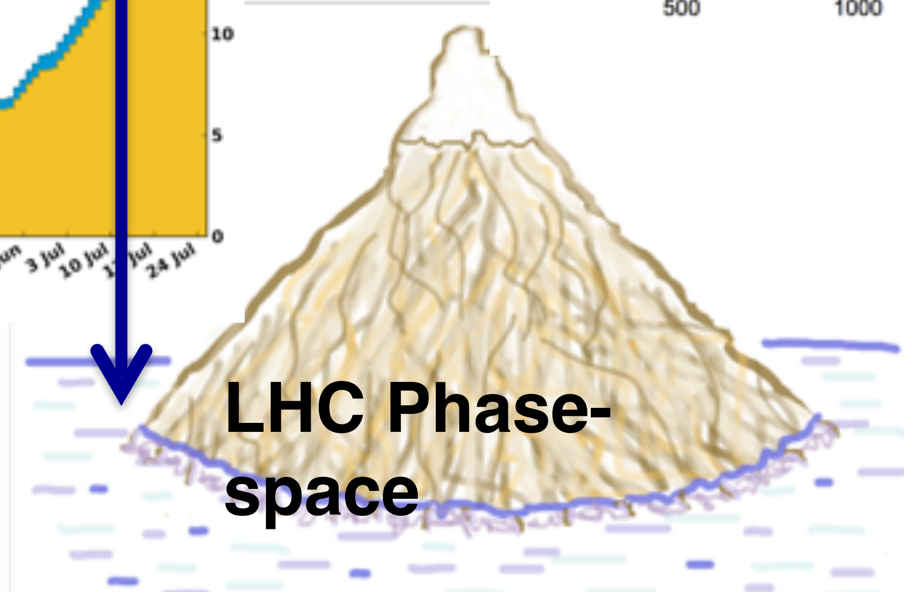


Searching Collider Phase Space for **BSM**

more integrated luminosity (more data) reveals more of the phase-space

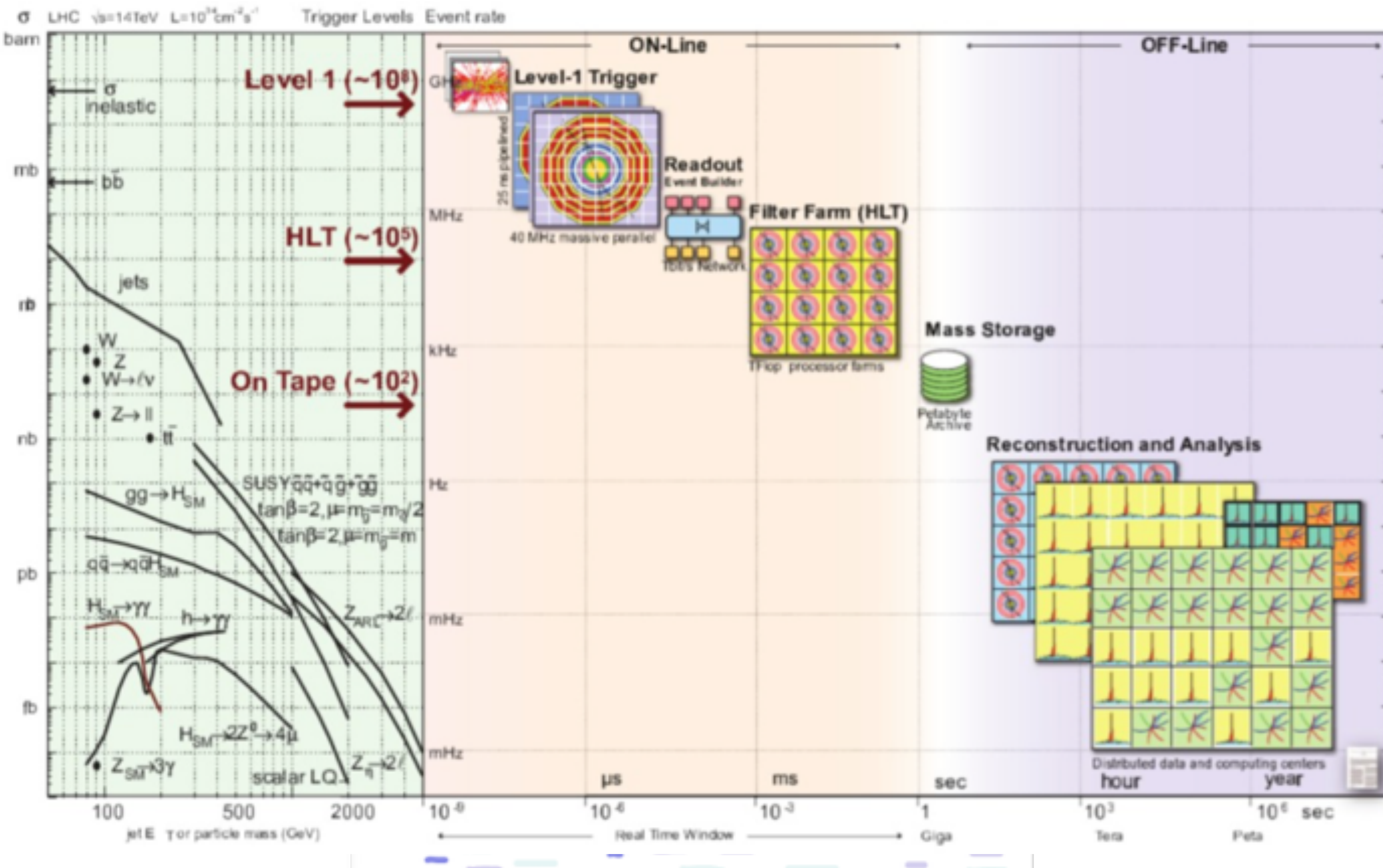






10 events produced / 10 fb^{-1}

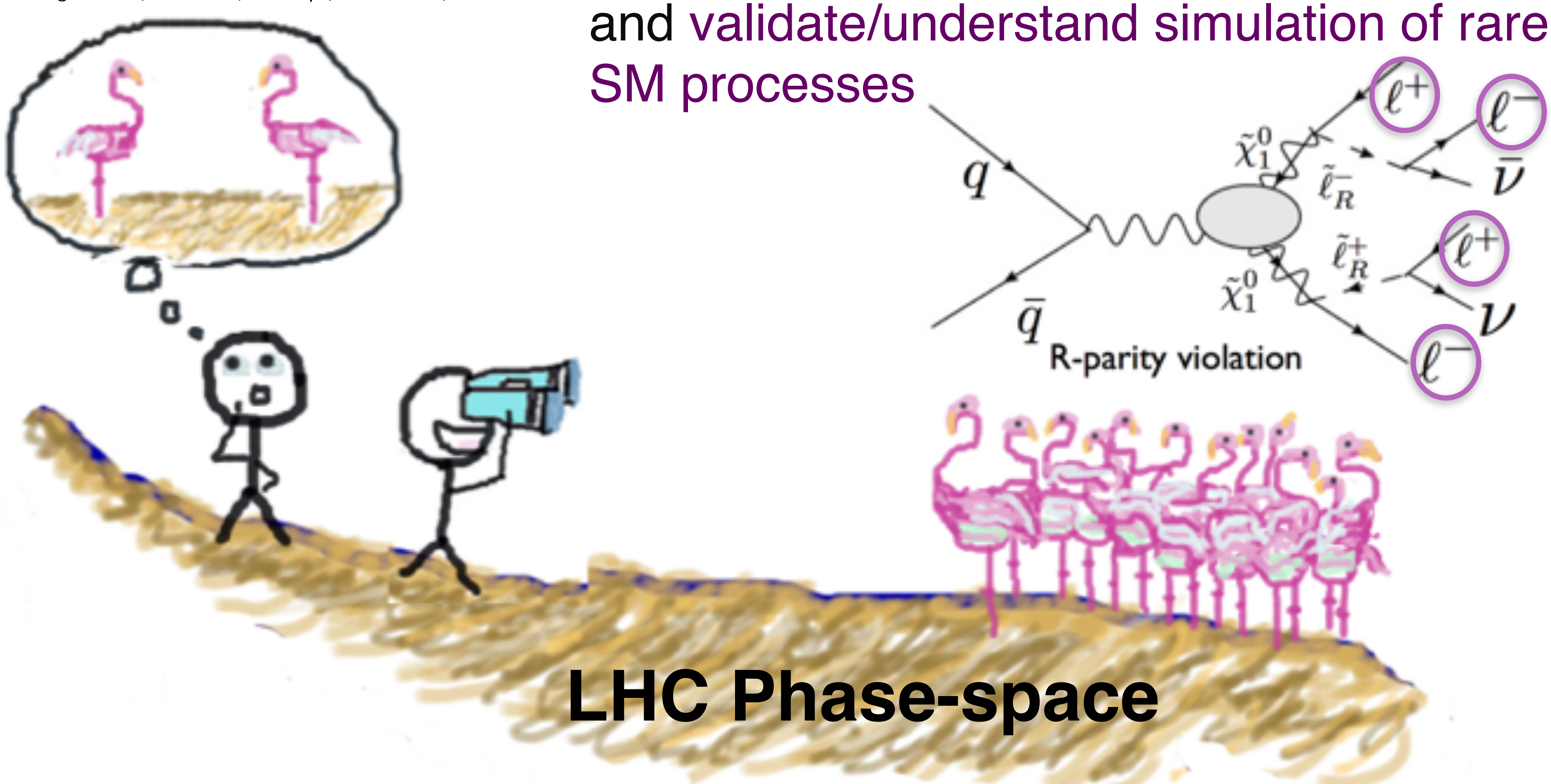
Trigger Challenge



Searching for rare events

- BSM physics can potentially produce event topologies rarely seen in the SM
- Must control/measure object fake-rates and validate/understand simulation of rare SM processes

$Z + \text{jets}, ZZ, Z\gamma, WZ, \cdots$



Searching for kinematic features

- New physics can produce kinematic features that are not expected in the SM – bumps, edges…
- Understanding/measuring/improving physics object reconstruction **essential** **being able to resolve these features**

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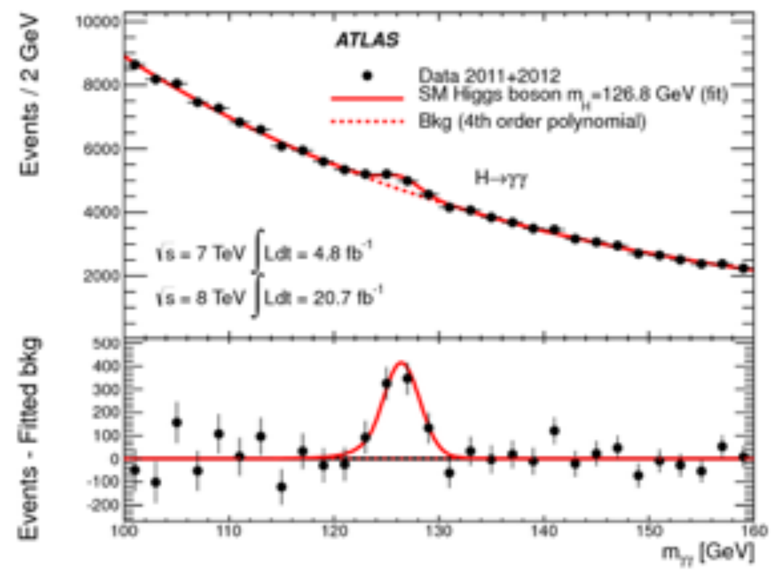
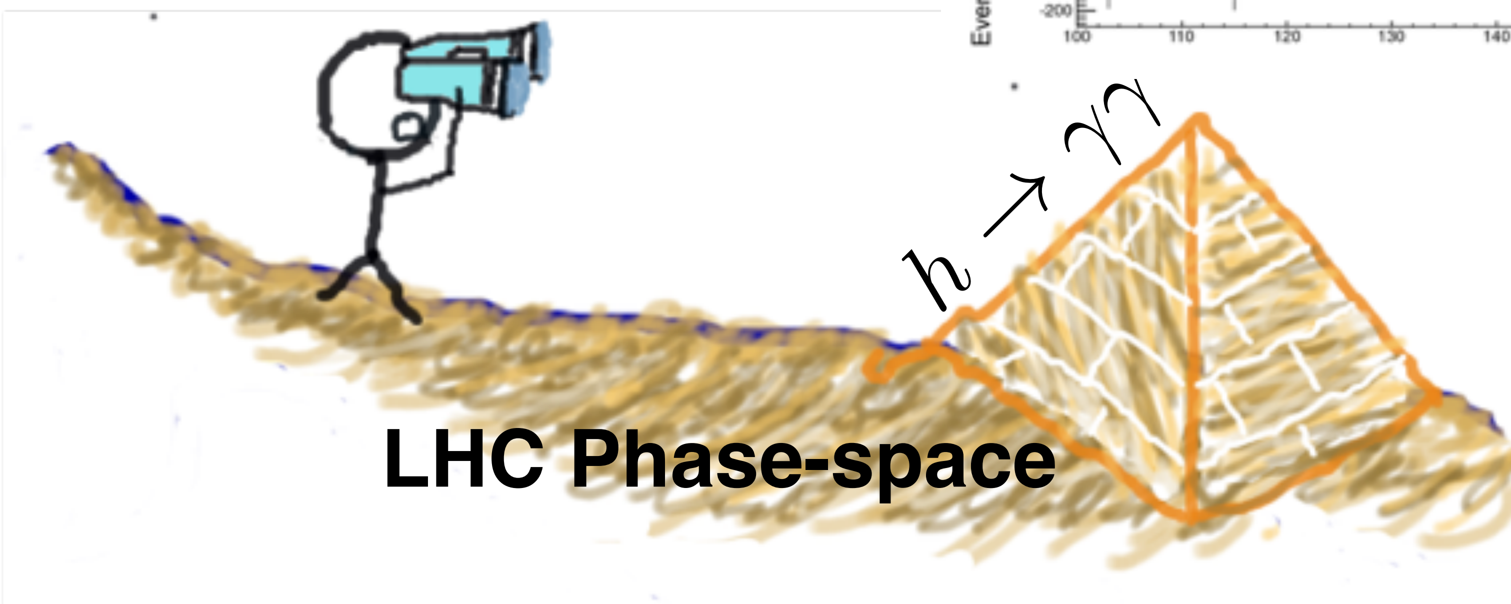
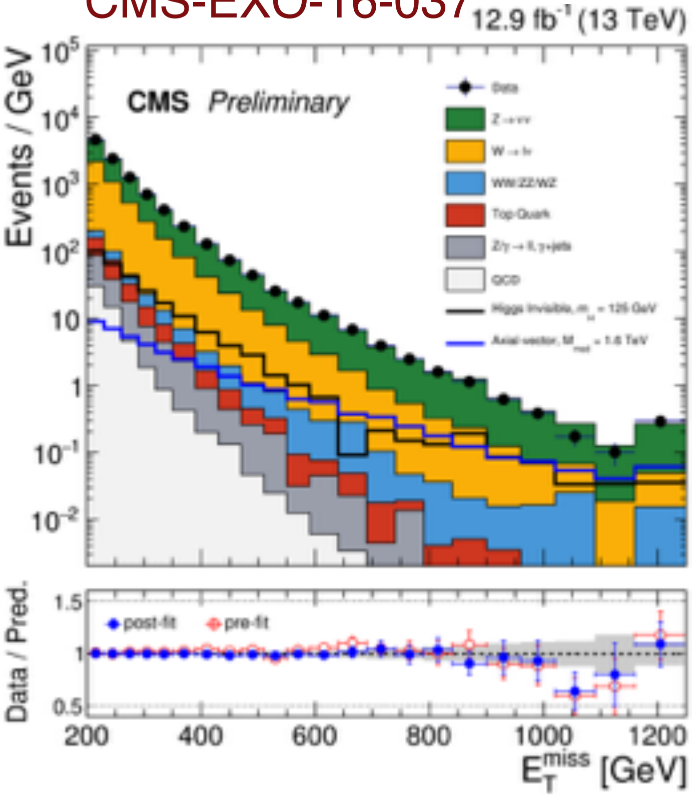




Searching for general excesses

- BSM can produce an excess of events with interesting kinematic features (large missing transverse energy, momentum, mass)
- Final states with weakly interacting particles can lead to 'broad' excesses in the tails of these kinematic distributions

CMS-EXO-16-037



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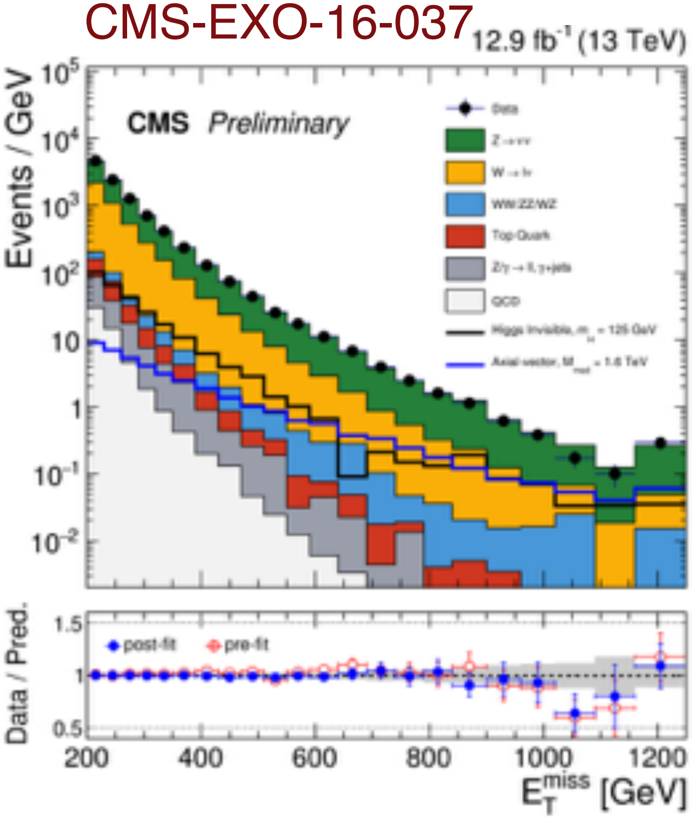
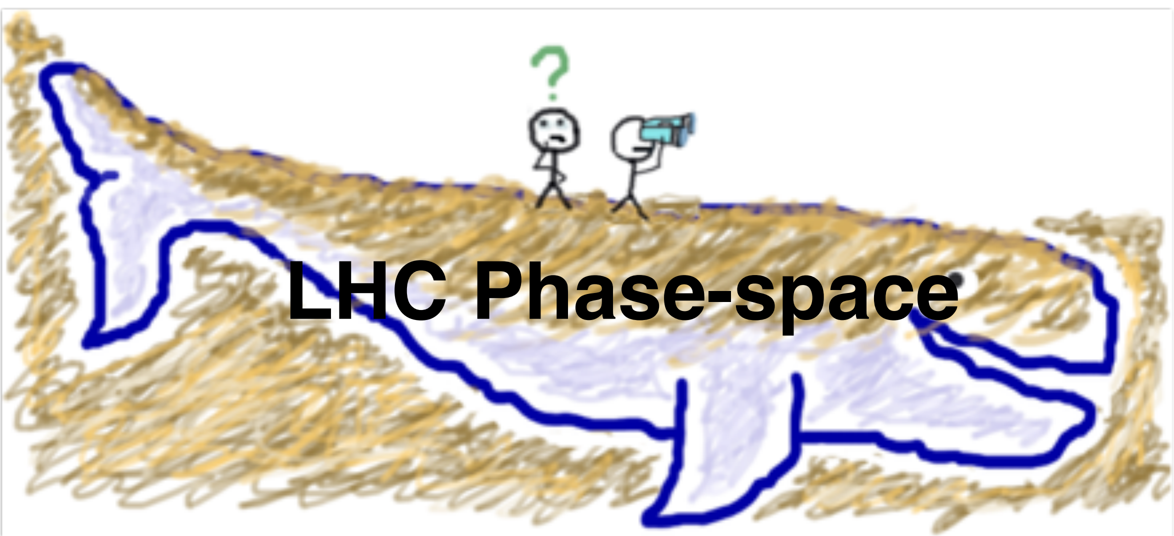
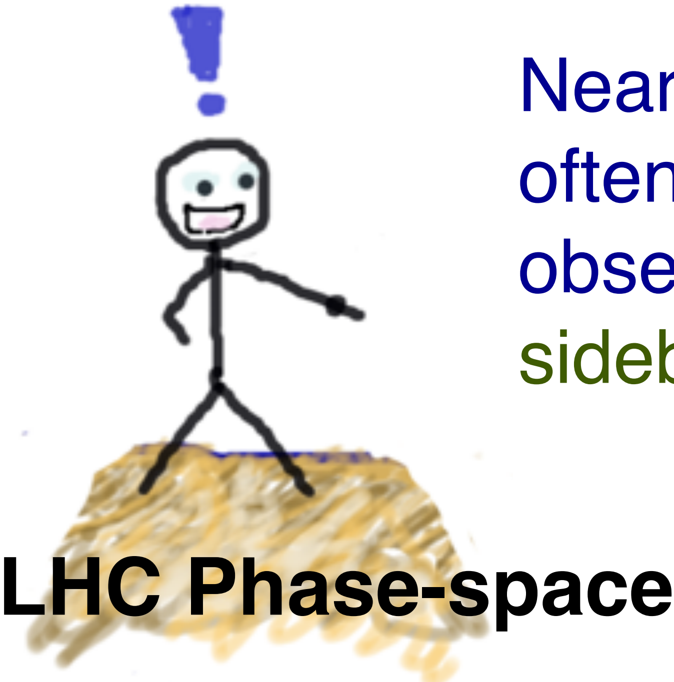


- Must have an accurate reference expectation for the SM to see subtle features!

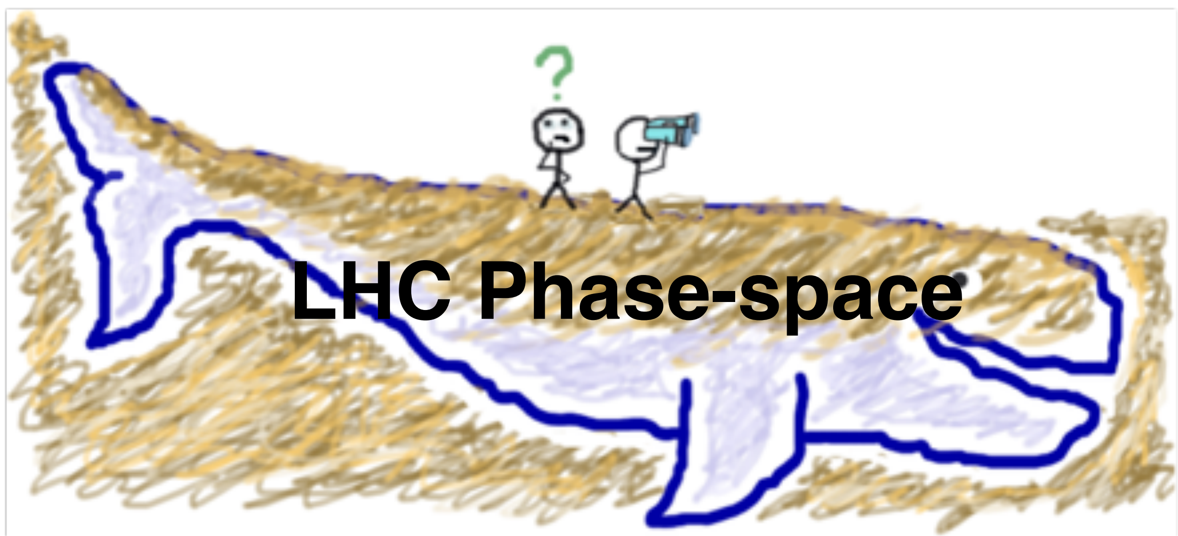


Searching for general excesses



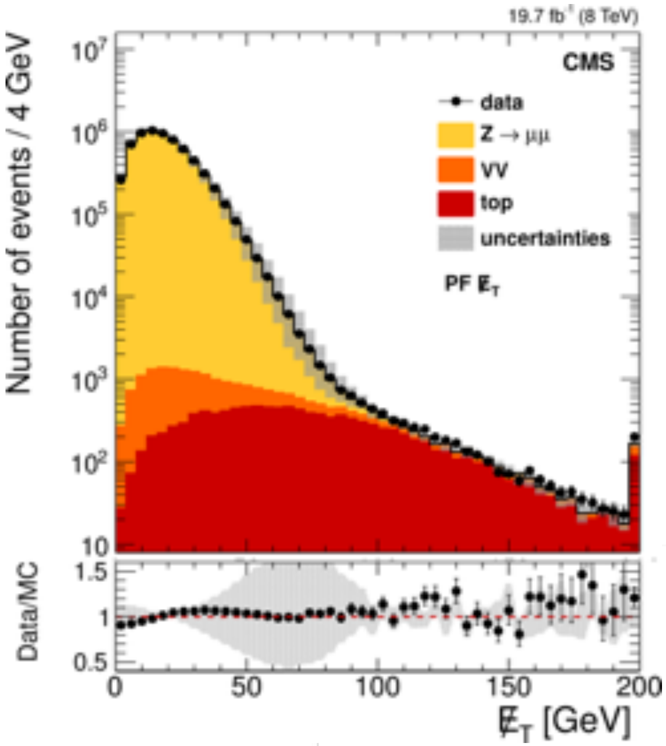
Nearby regions of phase space are often necessary to contextualize our observations in signal sensitive regions

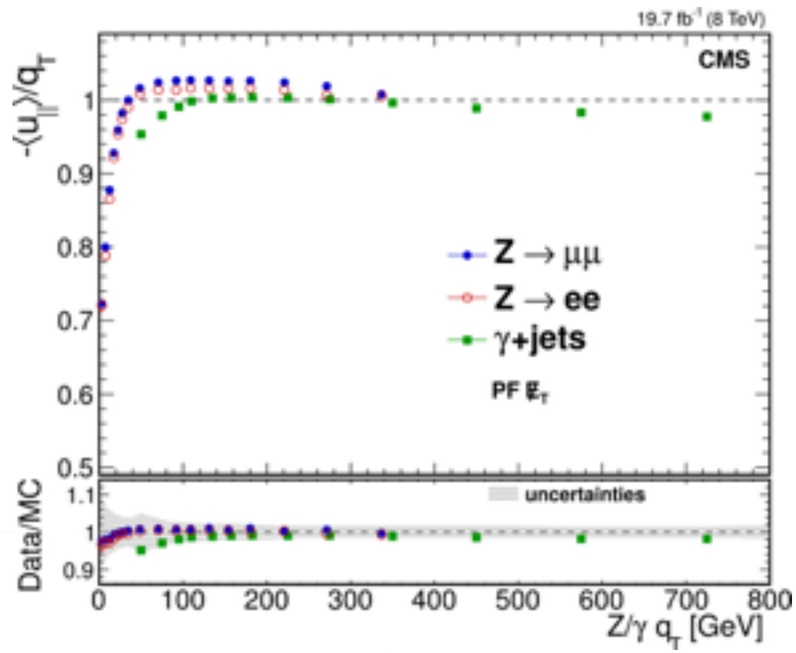
sidebands, control regions, …



The view from the pole(s)

- SUSY searches begin at **‘the pole’**: W/Z bosons, tops, quarkonia cand
- Used to: select control samples of leptons, photons, b-jets, …
  calibrate/measure object reconstruction performance, fake-rates, energy scales
  validate our understanding of the SM in new phase-spa





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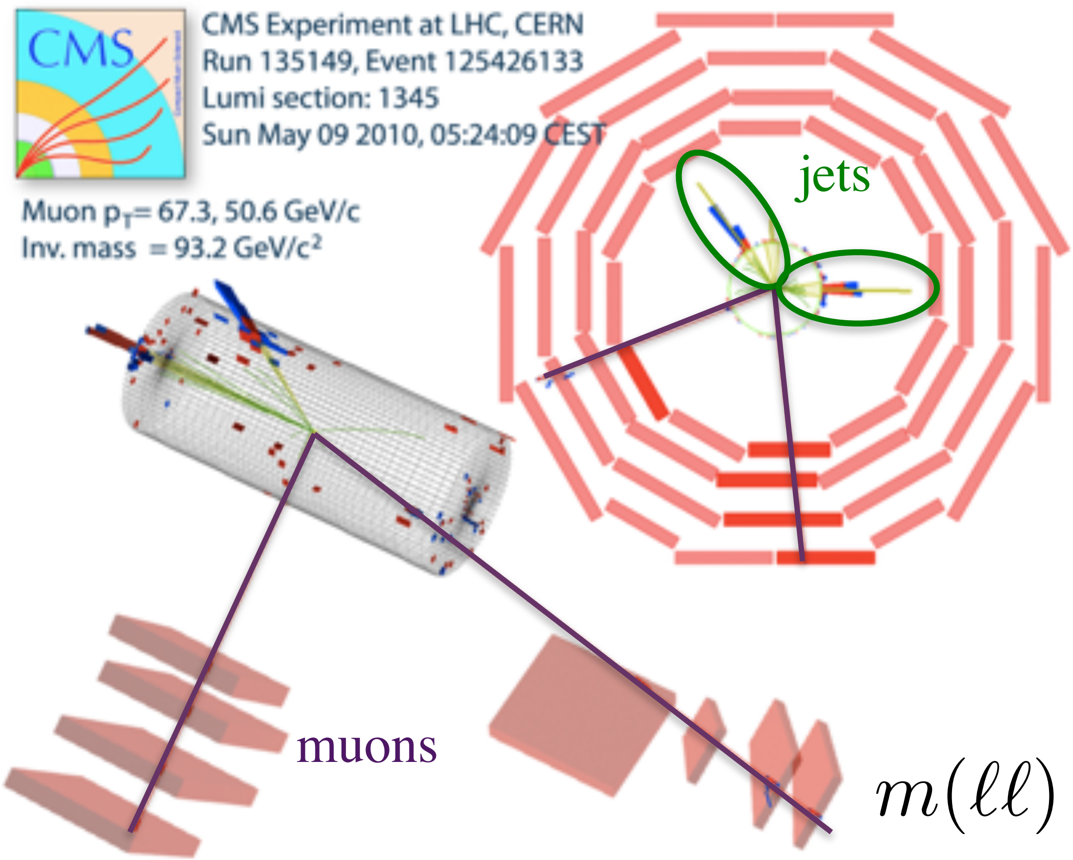
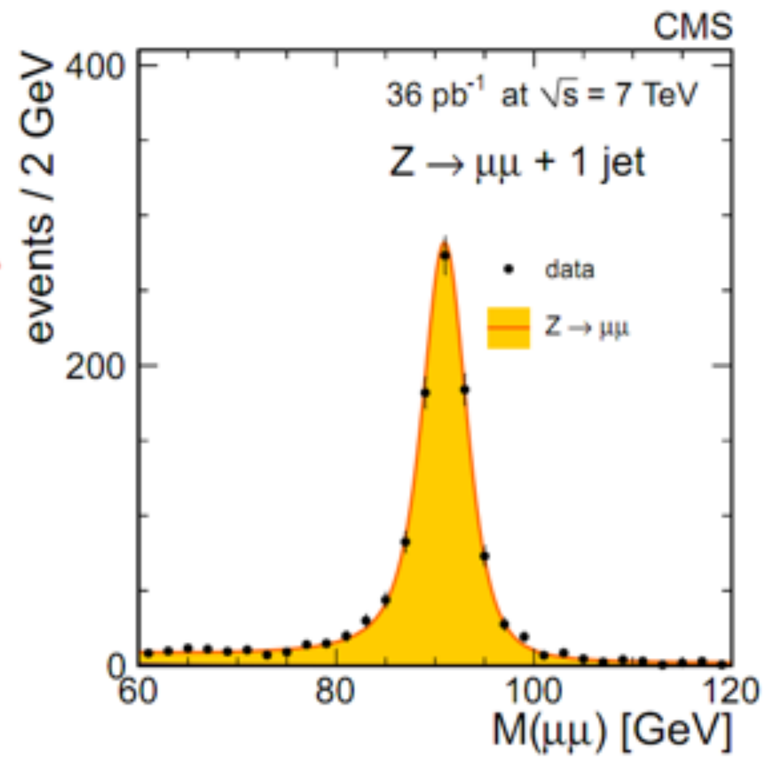
Using Particle Mass

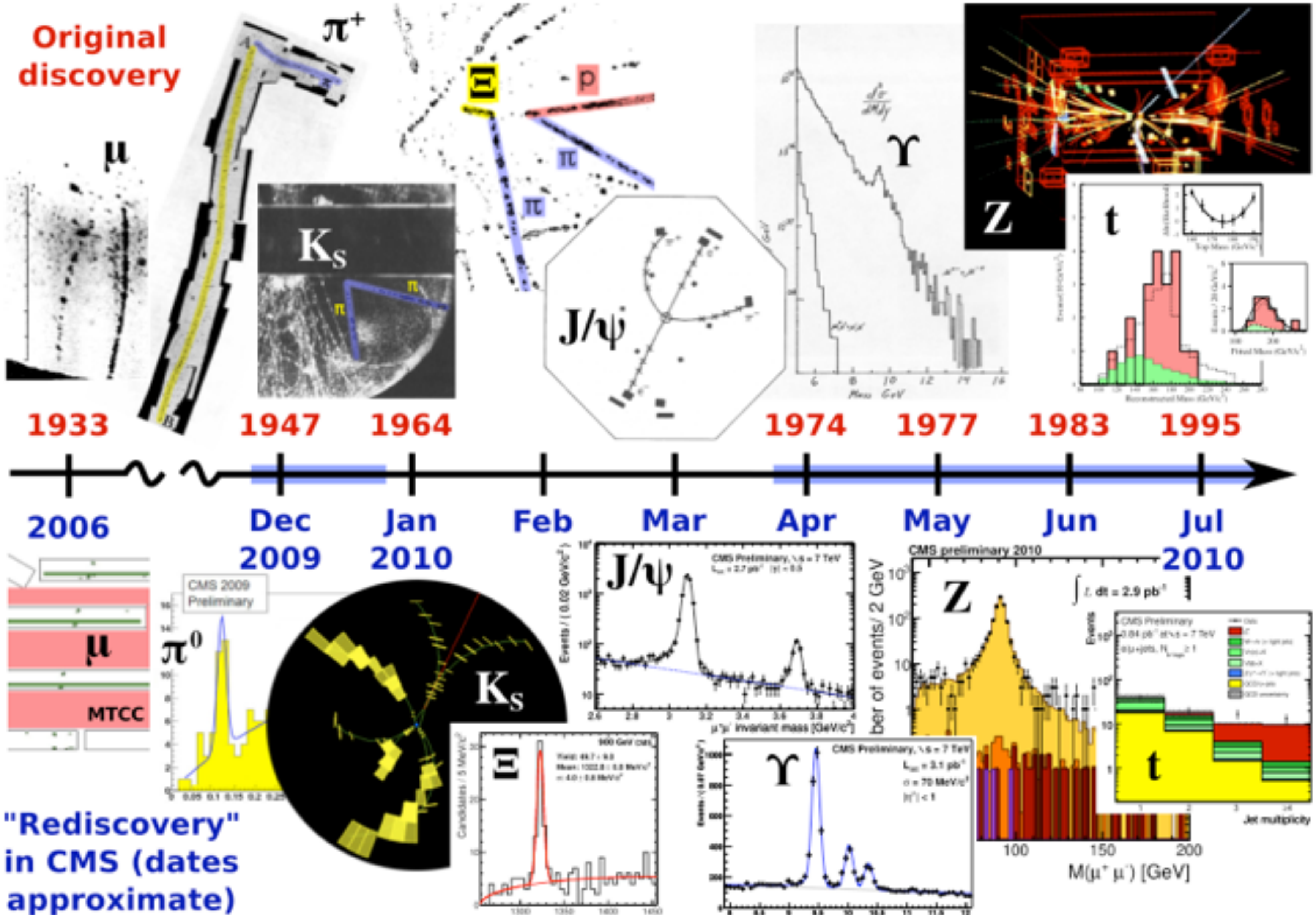




$m(\ell\ell)$ *peaks* at $m_Z \sim 91$ GeV

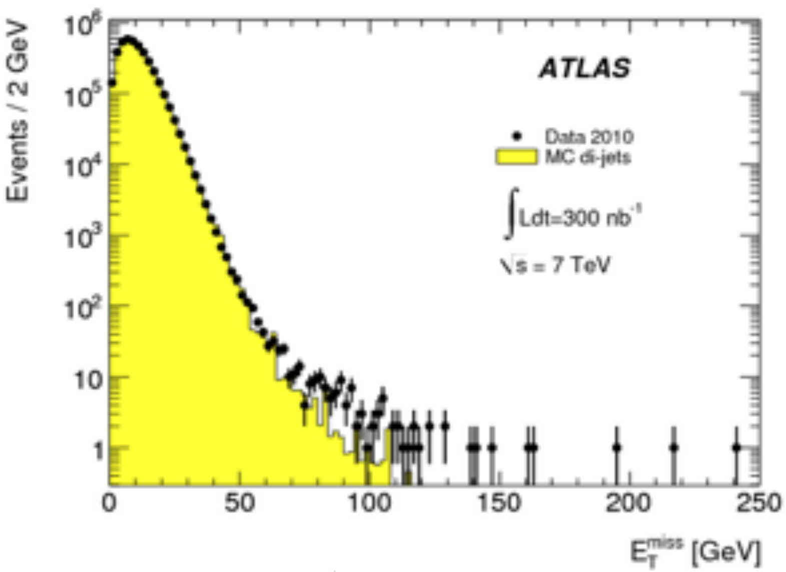
invariant mass of two leptons is
used to identify on-shell Z bosons

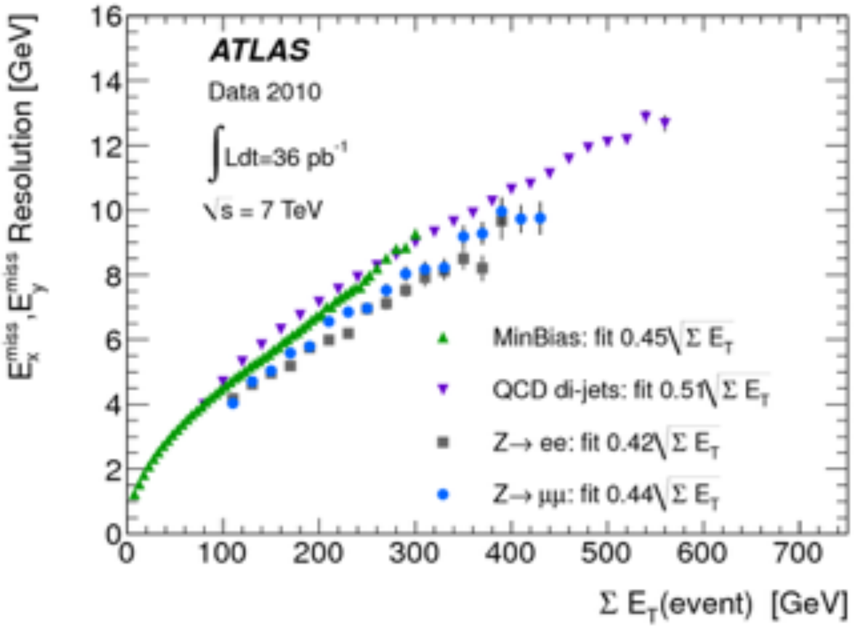
"Re"-discovering the Universe

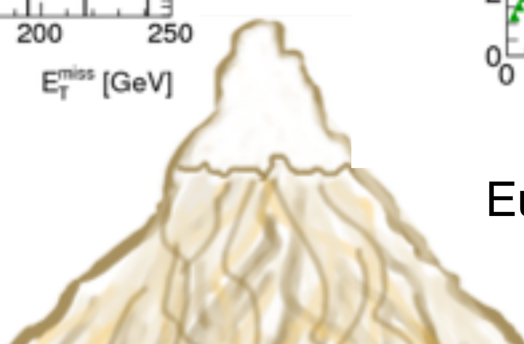


The view from the peak

- BSM searches begin at **'the rate peak': QCD mult-ijets**
- Used to:
  select control samples of leptons, photons, b-jets, …
  calibrate/measure object reconstruction performance, fake-rates, energy scales
  validate our understanding of the SM in new phase-spac

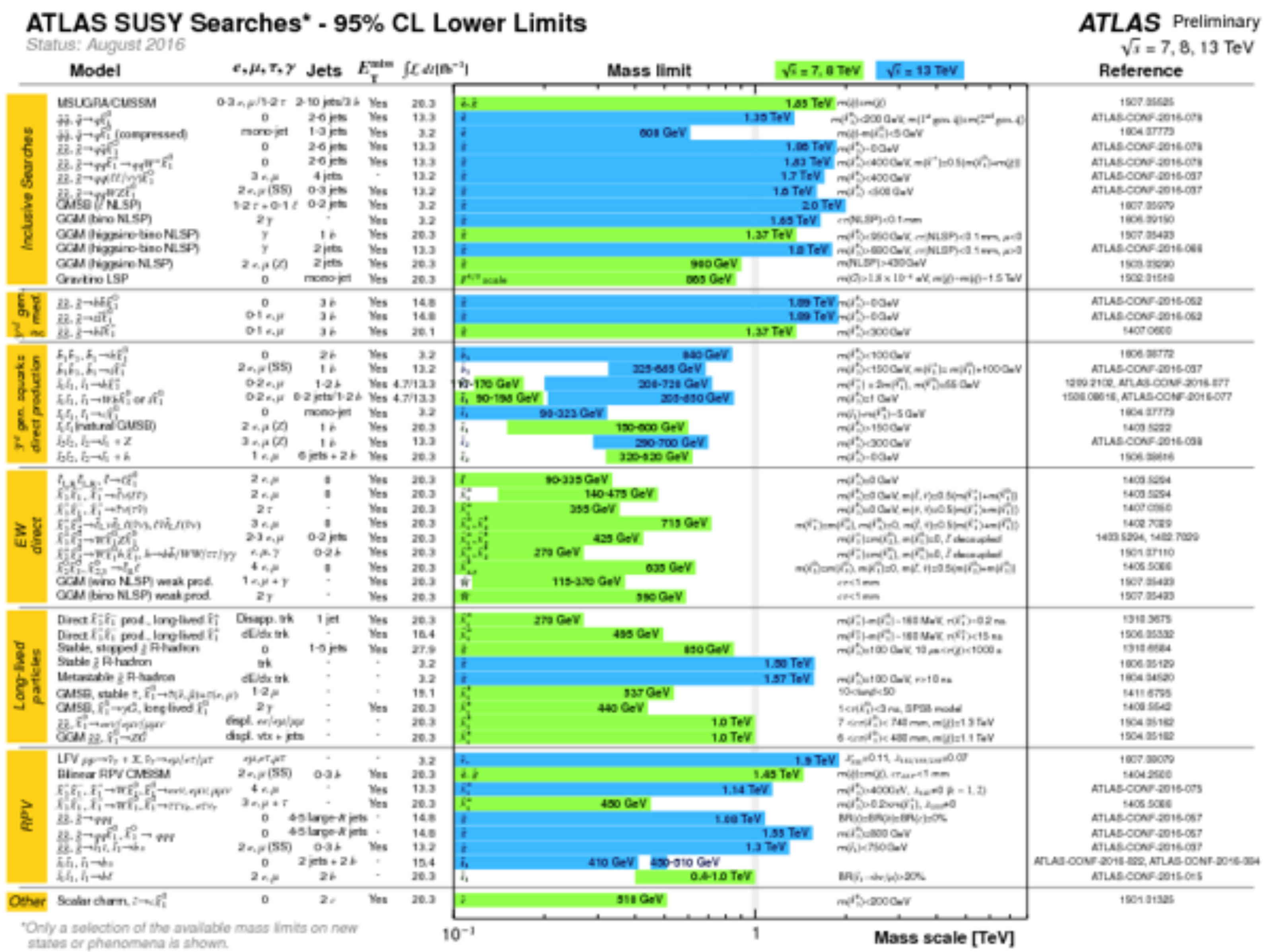






Eur.Phys.J. C72 (2012) 1844

Where are we now?



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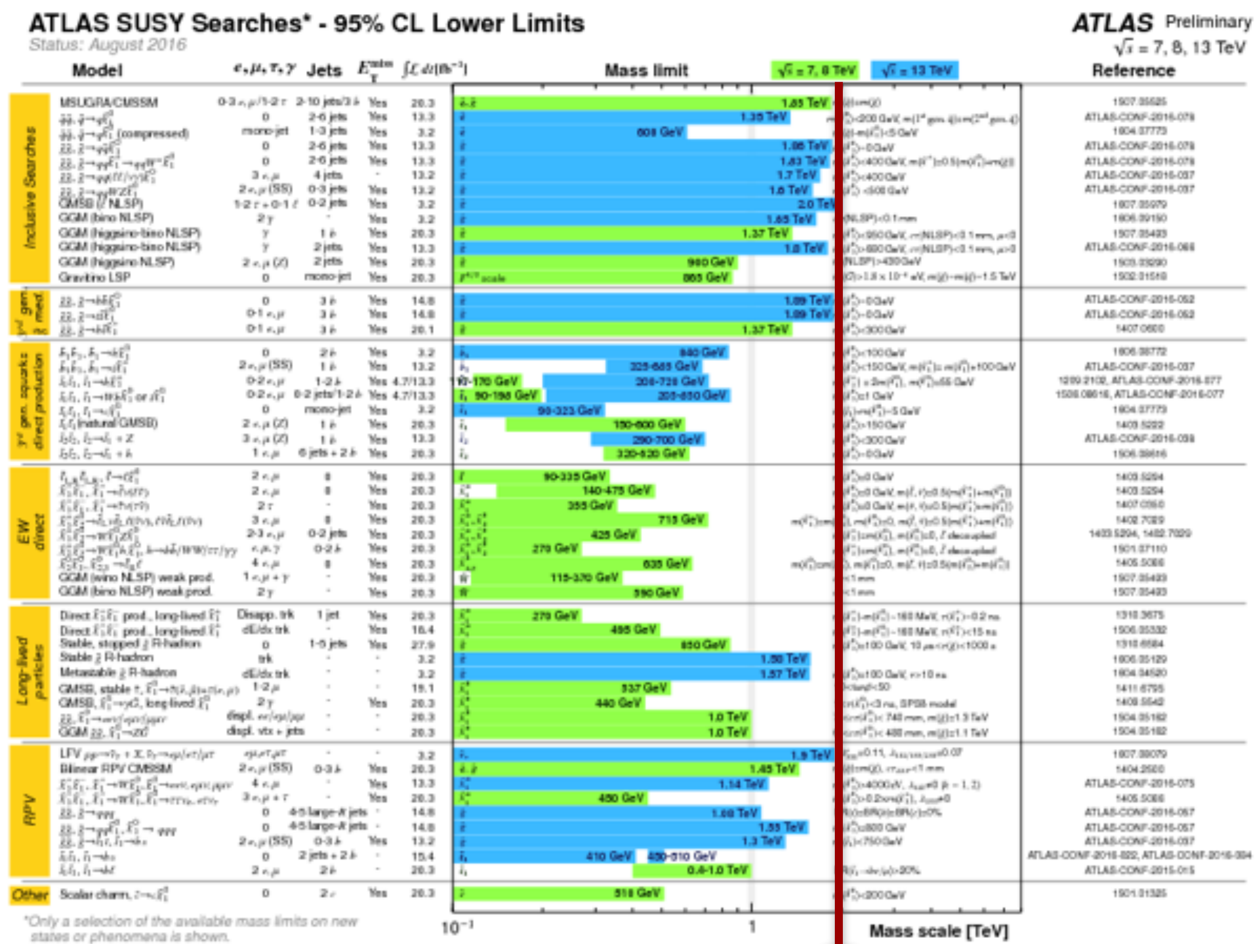
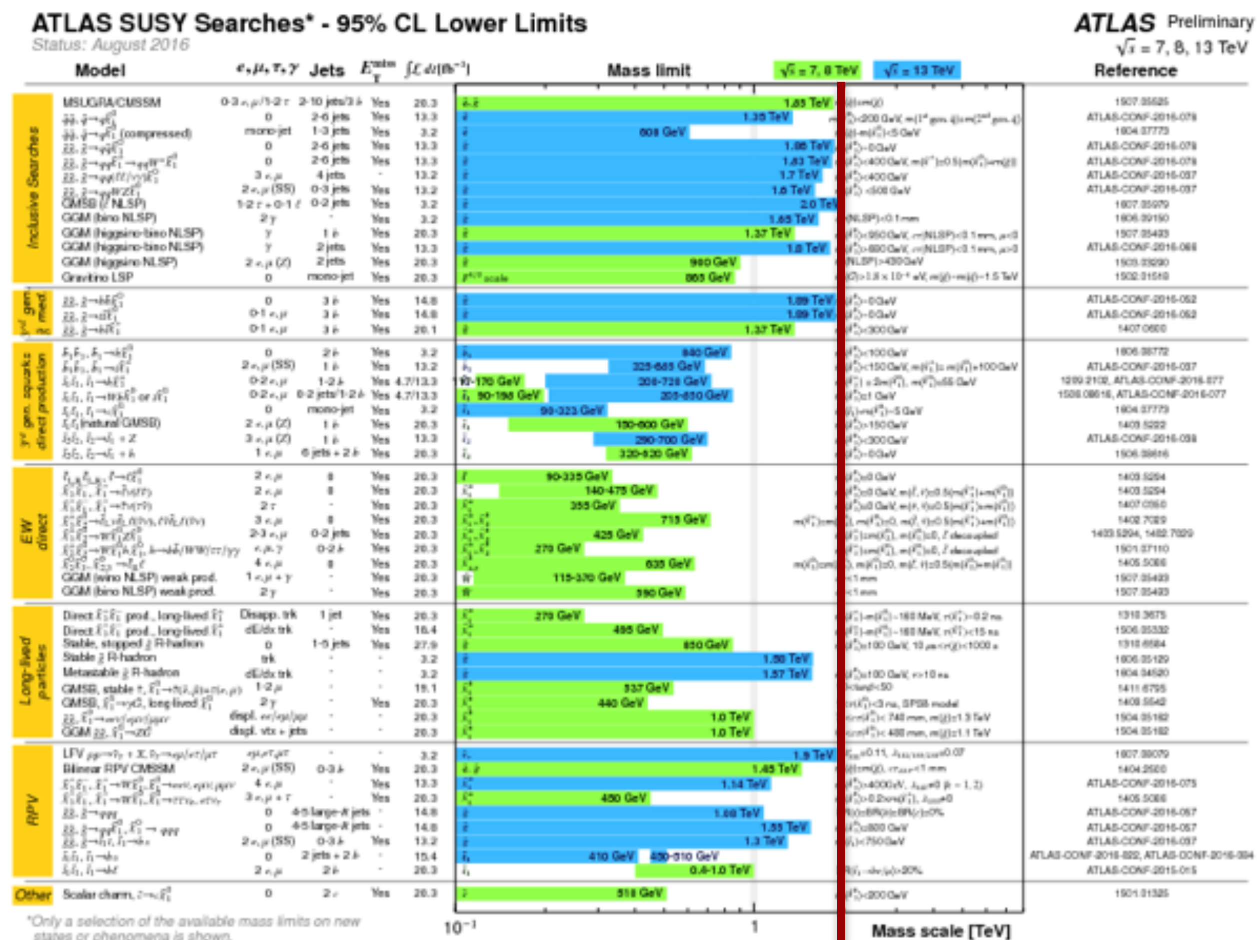


Constraints on sparticle masses in RPC scenarios up to ~2 TeV

Does this mean we've explored the entire LHC13 phase-space to this mass scale? … **NO!**

Where are we now?



In RPC scenarios, sparticle mass does not map 1-to-1 to phase-space, rather:

As escaping LSP’s can be massive, **mass-splittings** between produced sparticles and LSP’s are relevant quantity

Where's the BSM?

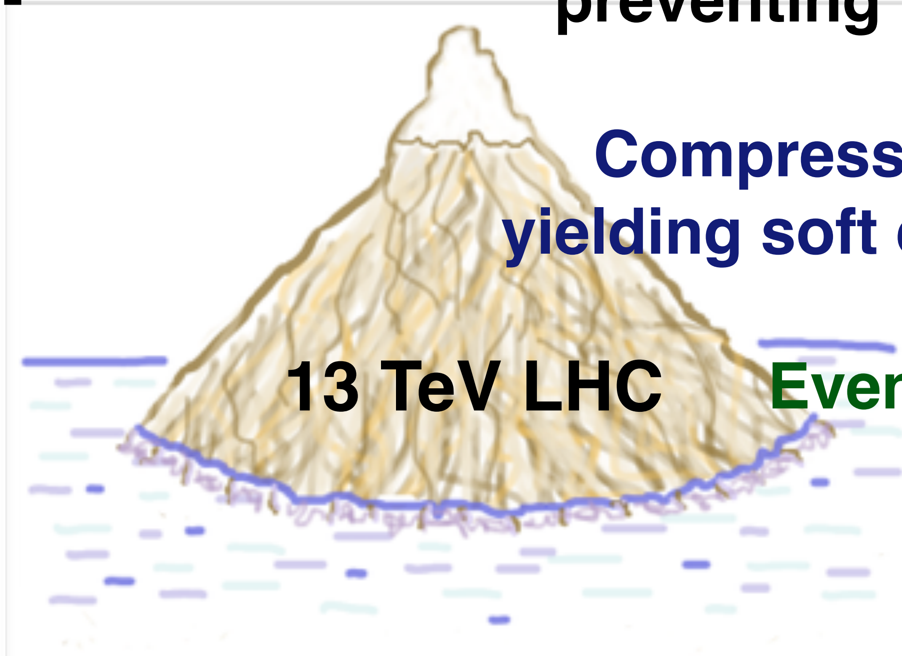
Suppressed BSM cross-sections?

Mixed decays diluting event yields in dedicated searches?

Discrete parity violation (ex. R-parity)
preventing missing energy?

Compressed mass spectra yielding soft decay products?

Even larger masses?



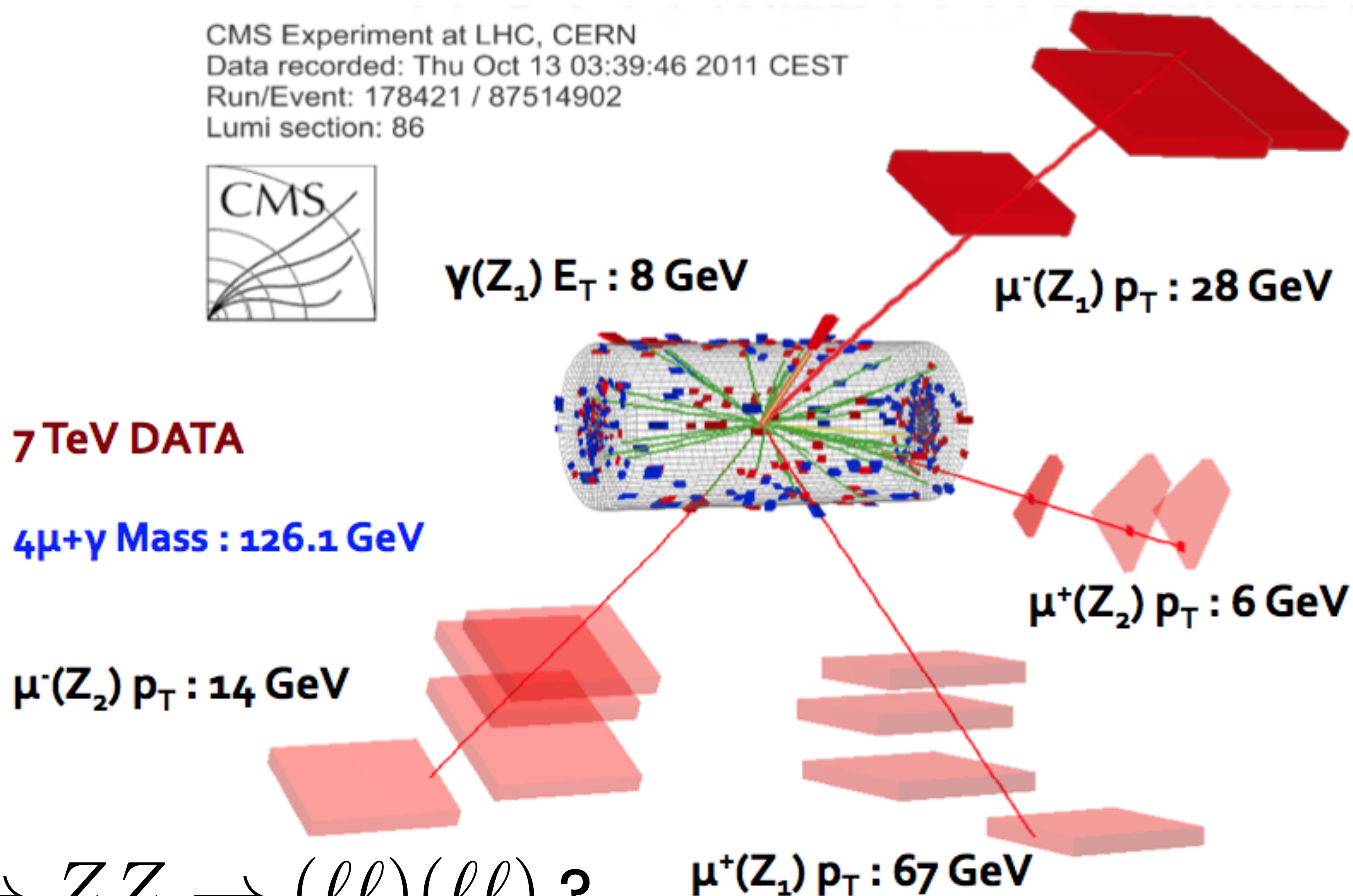
HOW DO WE DISCOVER NEW PARTICLES AT THE FRONTIER OF ENERGY AND SIZE?

The Higgs boson

WANTED: the elusive Higgs

Reward: Noble prize

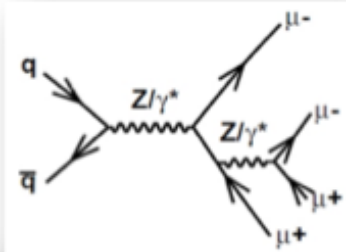
Searching for the Higgs

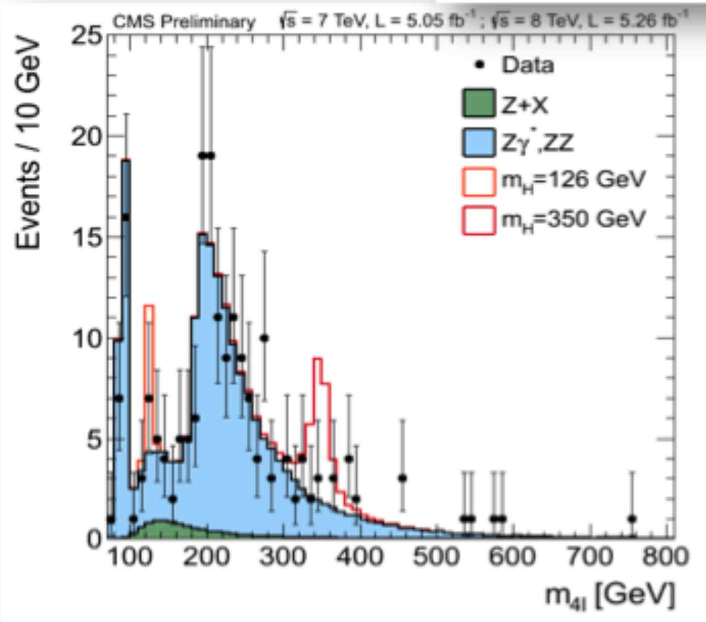


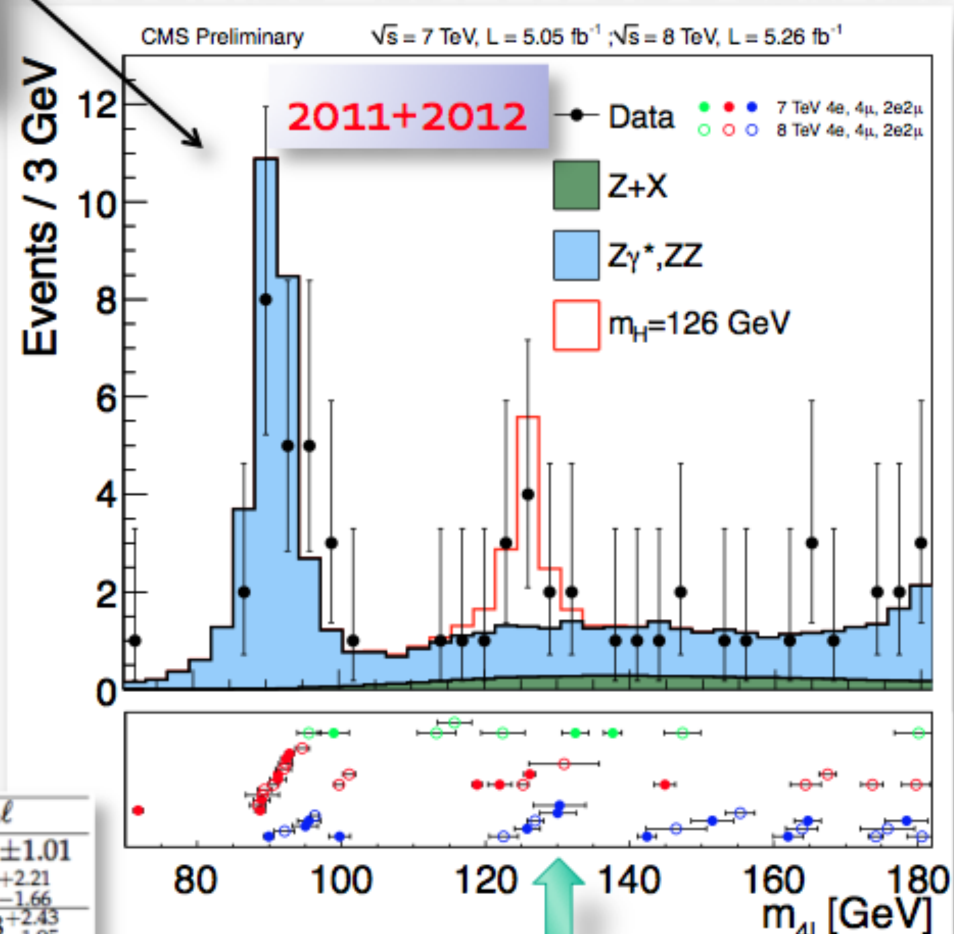
$H \to ZZ \to (\ell\ell)(\ell\ell)$?

Searching for the Higgs

Results: m(4l) spectrum







Yields for m(4l)=110..160 GeV

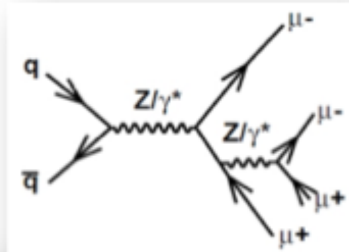
Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	2.65 ± 0.31	5.65 ± 0.59	7.17 ± 0.76	15.48 ± 1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
$m_H = 126$ GeV	1.51 ± 0.48	2.99 ± 0.60	3.81 ± 0.89	8.31 ± 1.18

164 events expected in [100, 800 GeV]

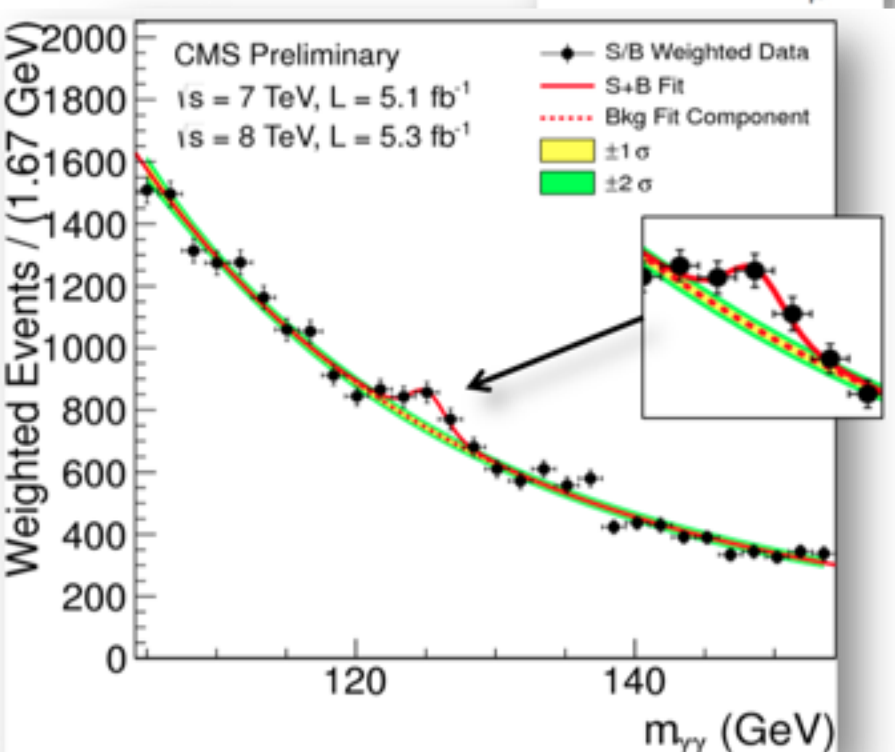
172 events observed in [100, 800 GeV]

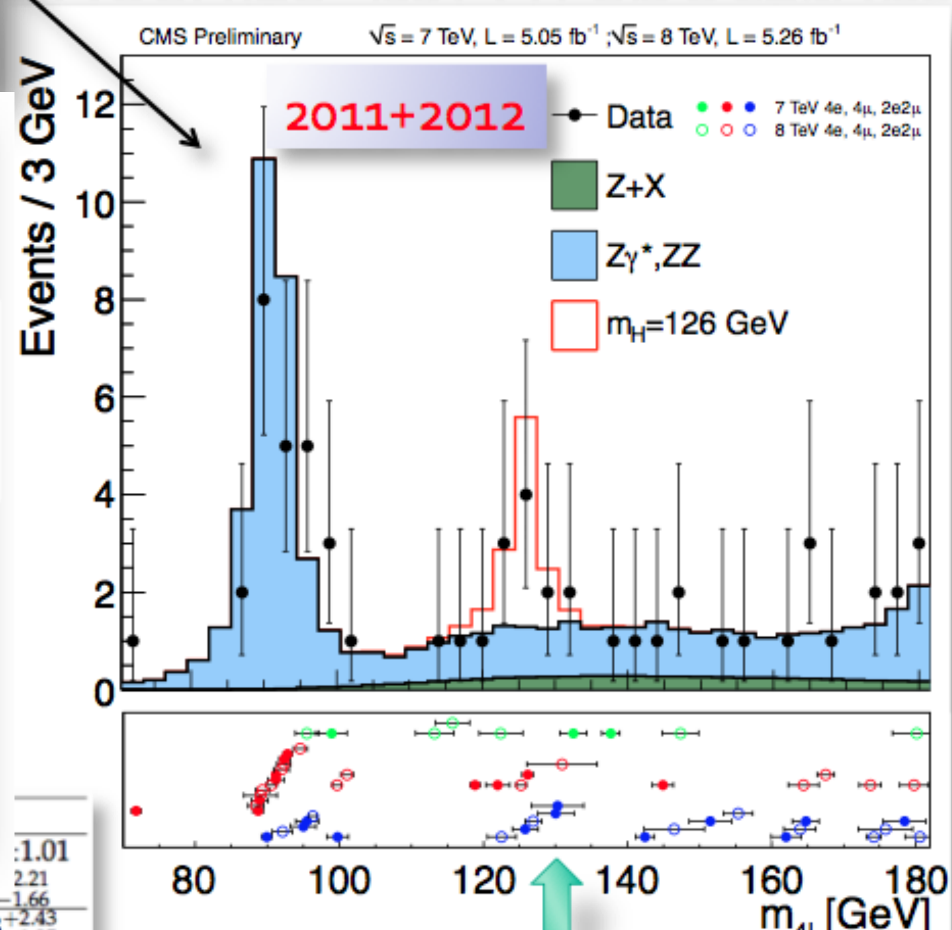
Event-by-event errors

Searching for the Higgs



Results: m(4l) spectrum





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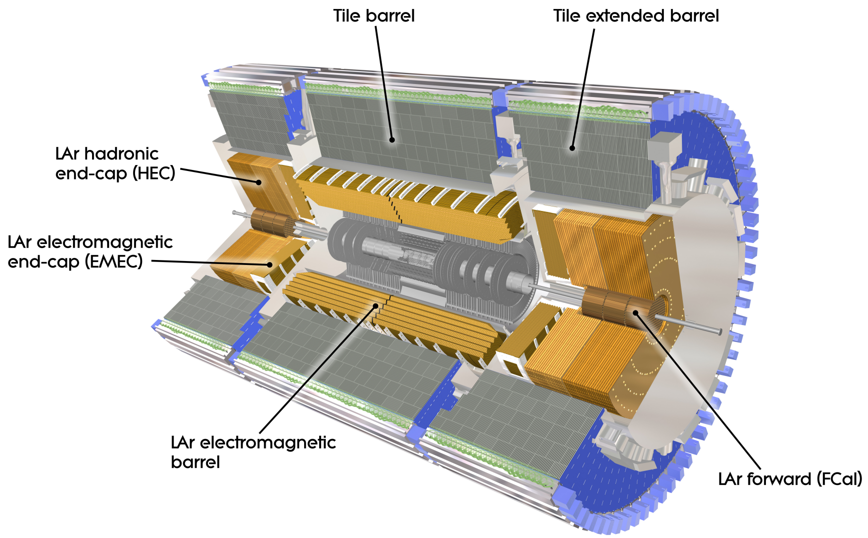
164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]

Event-by-event errors

Weakly interacting particles @ LHC

- **How do we study them?**
  - Can infer their presence through ***missing transverse energy***
  - Hermetic design of LHC experiments allows us to infer ***'what's missing'***

- full azimuthal coverage, up to |η| of ~5
- stopping power of ~12-20 interaction lengths
- ECAL+HCAL components with segmentation comparable to lateral shower sizes

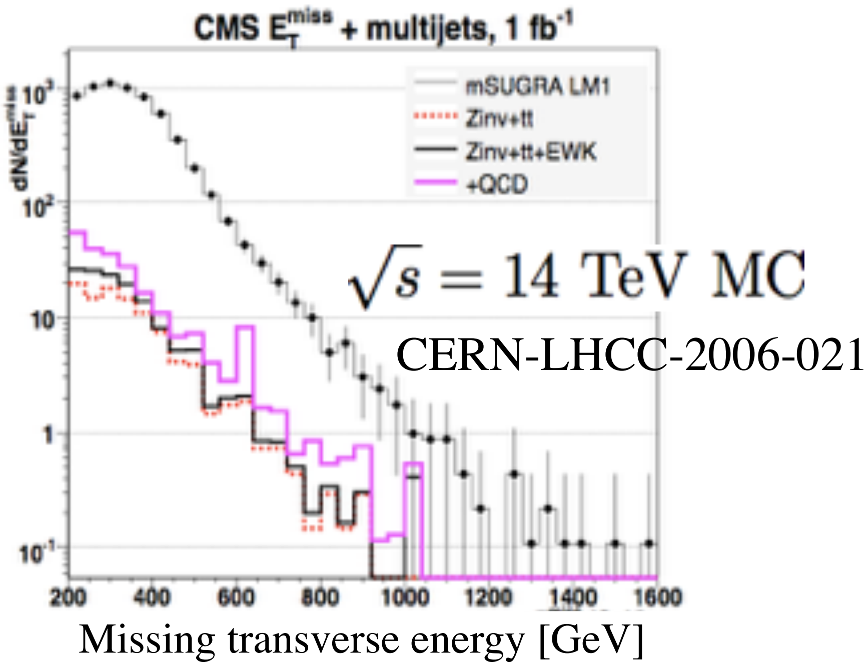


ATLAS Calorimeters

$$\vec{E}_T^{miss} = -\sum_i^{cells} \vec{E}_T$$

Missing transverse energy

Two plots from my SUSY10 conference talk…

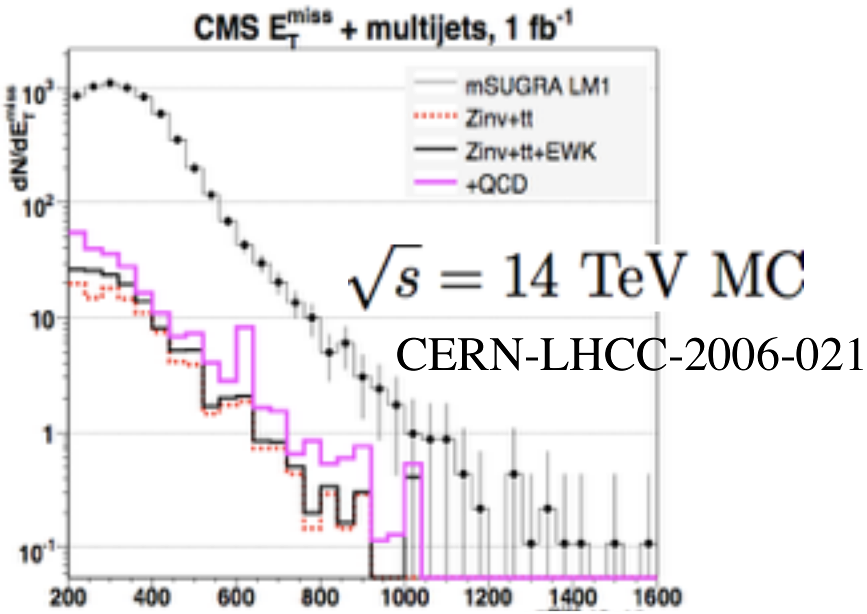


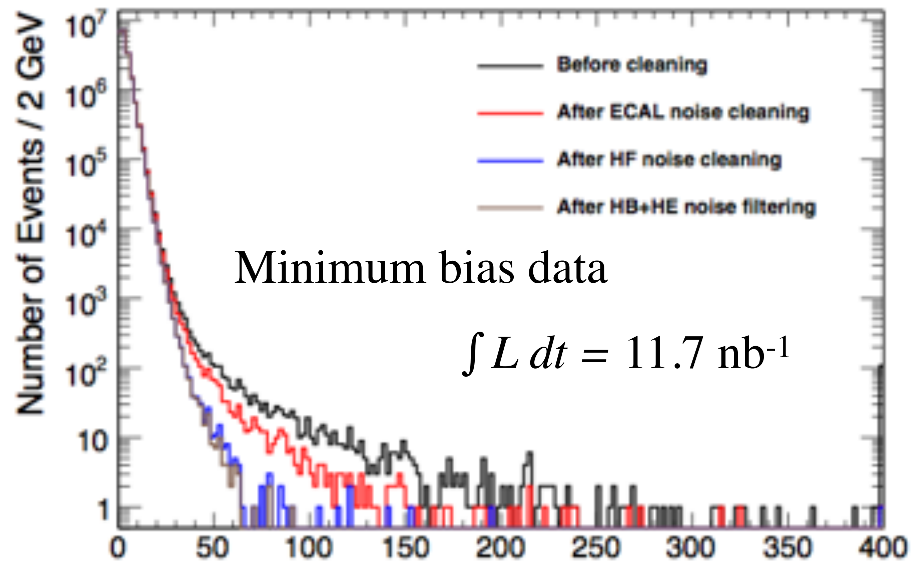
we turned the LHC on in 2010 hoping to see this…

$$\vec{E}_T^{miss} = -\sum_i^{cells} \vec{E}_T$$

Missing transverse energy

Two plots from my SUSY10 conference talk…



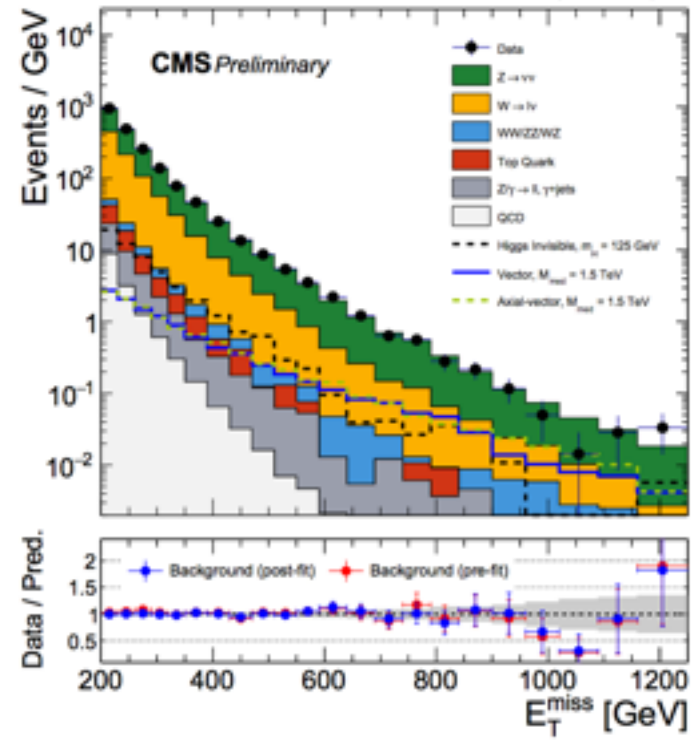


...and we got this

$$\vec{E}_T^{miss} = -\sum_i^{cells} \vec{E}_T$$

Missing transverse energy

CMS-PAS-EXO-16-03 2.3 fb^{-1} (13 TeV)

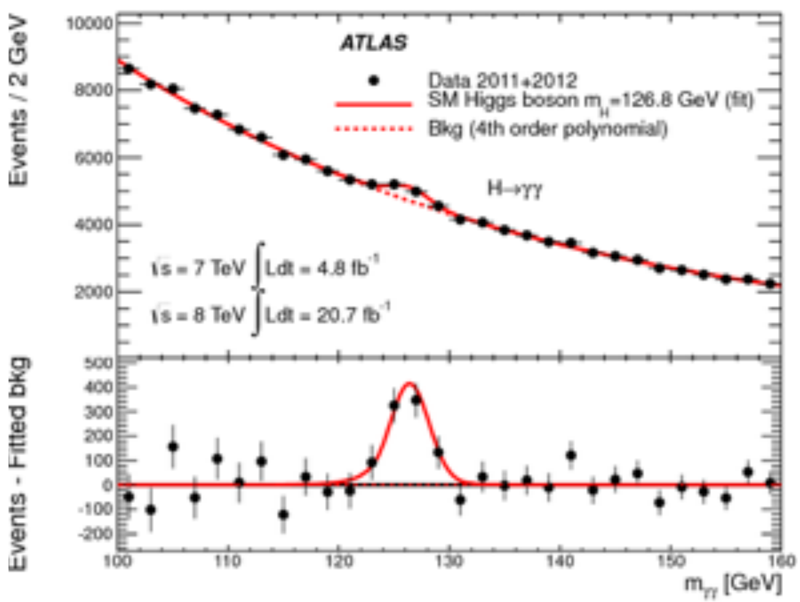


Missing transverse energy is a powerful observable for inferring the presence of weakly interacting particles in events…

…but, it only tells us about their transverse momenta

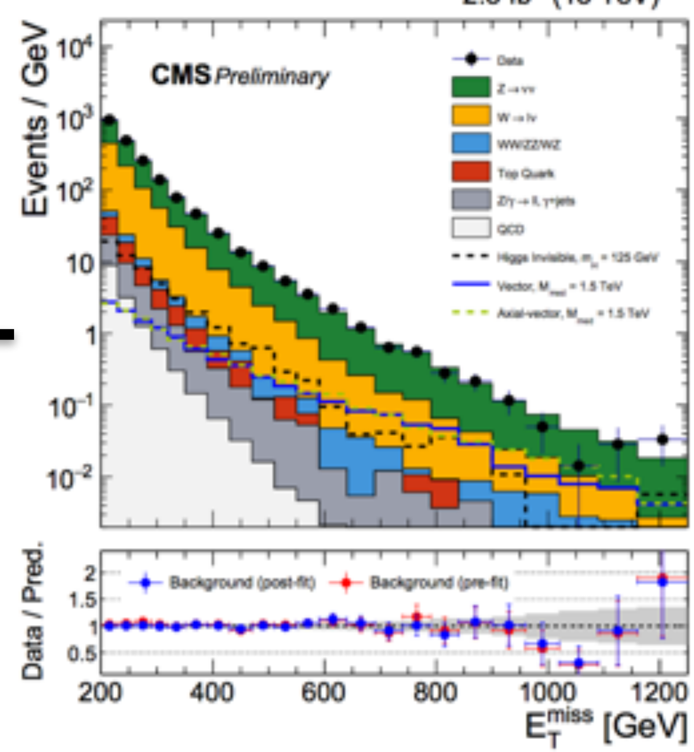
Missing transverse energy

Phys. Lett. B 726 (2013), pp. 88-119



?

CMS-PAS-EXO-16-03

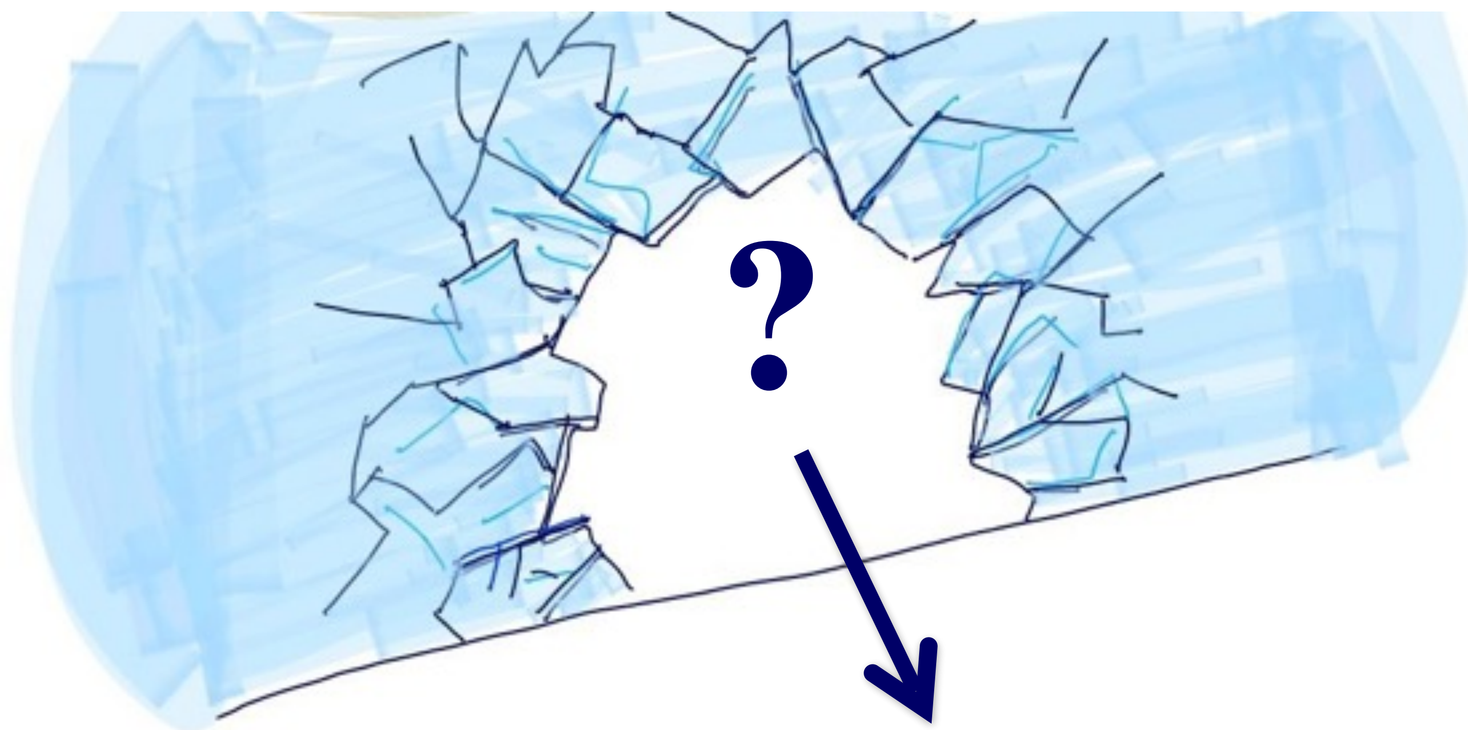


Missing transverse energy is a powerful observable for inferring the presence of weakly interacting particles in events…

…but, it only tells us about their transverse momenta

We would like to better resolve the event kinematics

Missing Transverse Energy



$\vec{E}_T^{miss}$

Missing transverse energy only tells us about the momentum of weakly interacting particles in an event…

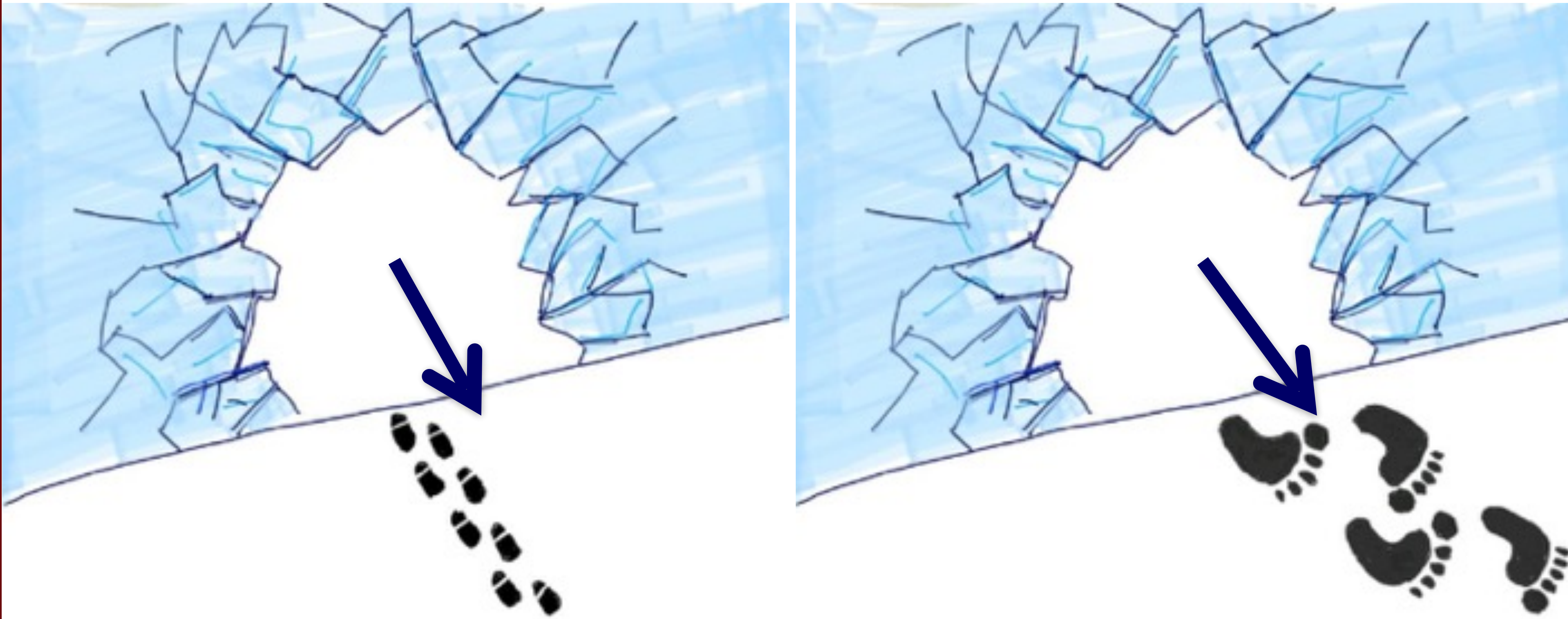
Missing Transverse Energy

…not about the identity or mass of weakly interacting particles, or about the particle(s) they may decay from…

Missing Transverse Energy

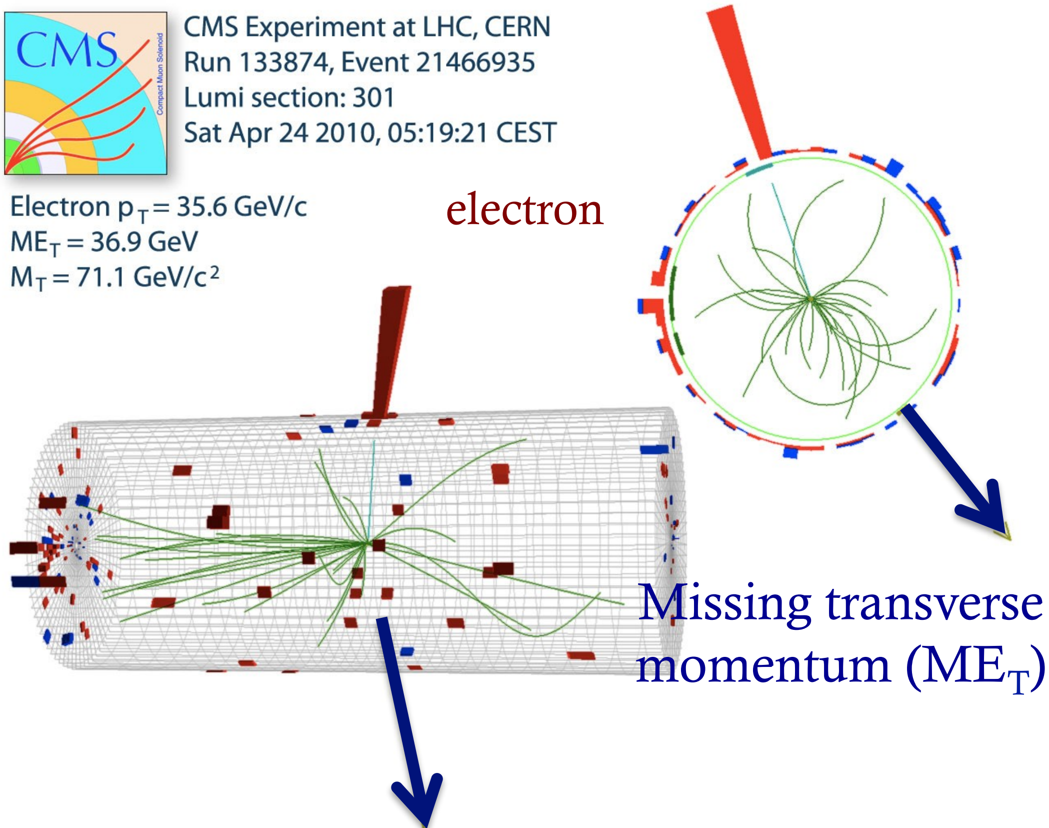
…not about the identity or mass of weakly interacting particles, or about the particle(s) they may decay from…

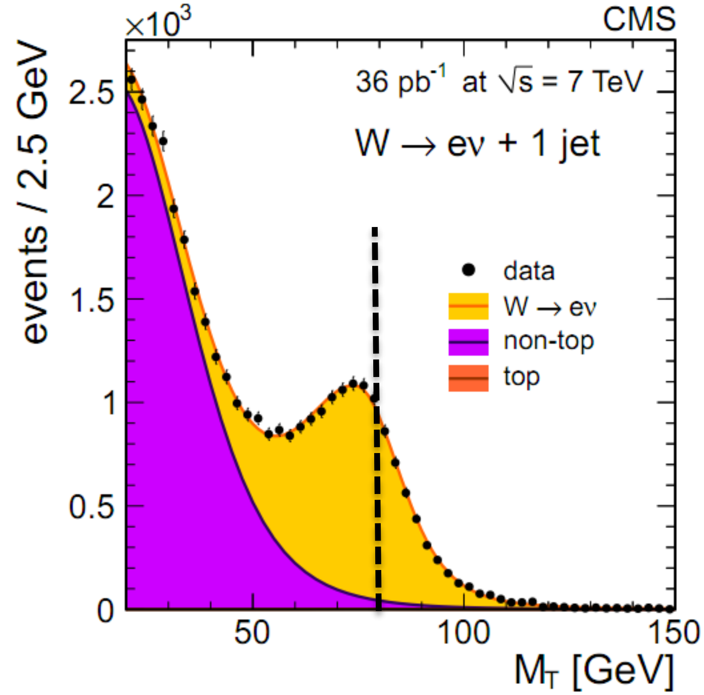
Missing Transverse Energy



We can learn more by using other information in an event to **contextualize the missing transverse energy** and **resolve additional information**

Resolving the invisible $W(e\nu)$



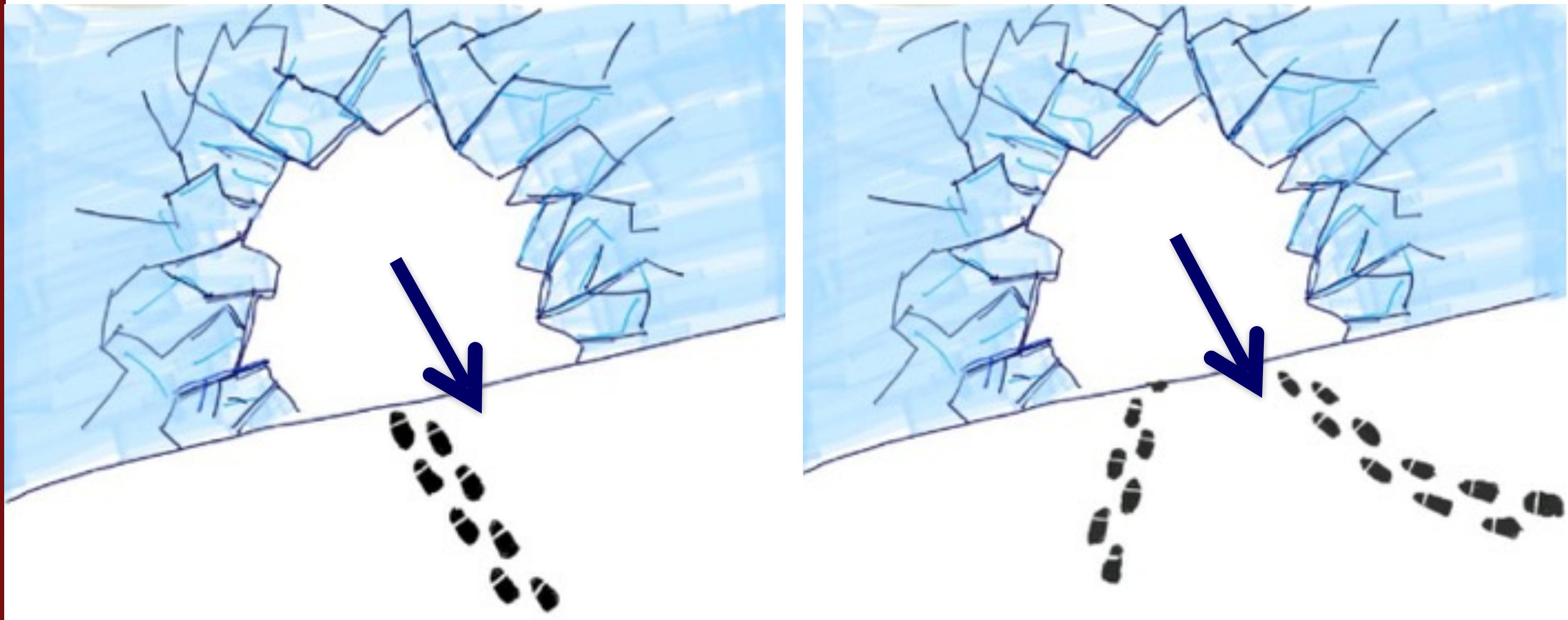


$$m_T = \sqrt{2p_T^e p_T^\nu(1-\cos\phi)}$$

$m_T(\ell\nu)$ has kinematic *edge* at $m_W \sim 80$ GeV

Can use visible particles in events to contextualize missing transverse energy and better resolve mass scales

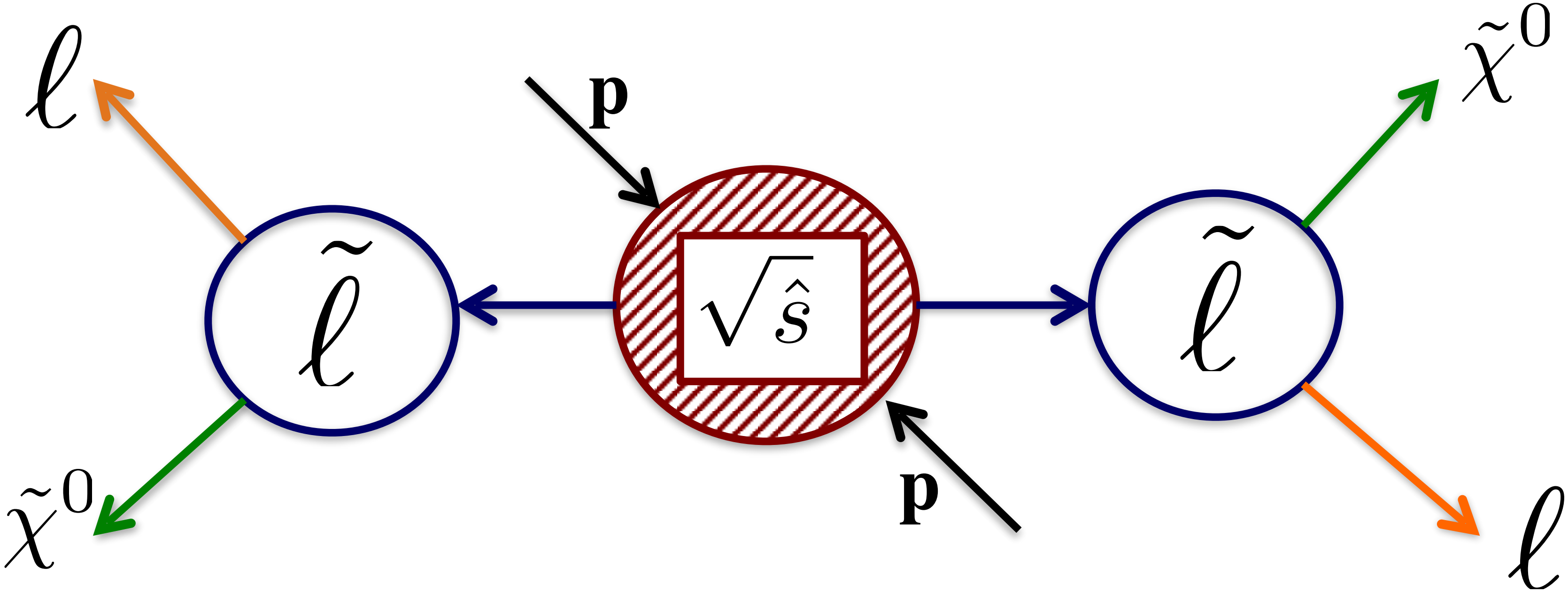
Missing Transverse Energy



We can learn more by using other information in an event to contextualize the missing transverse energy ⇒

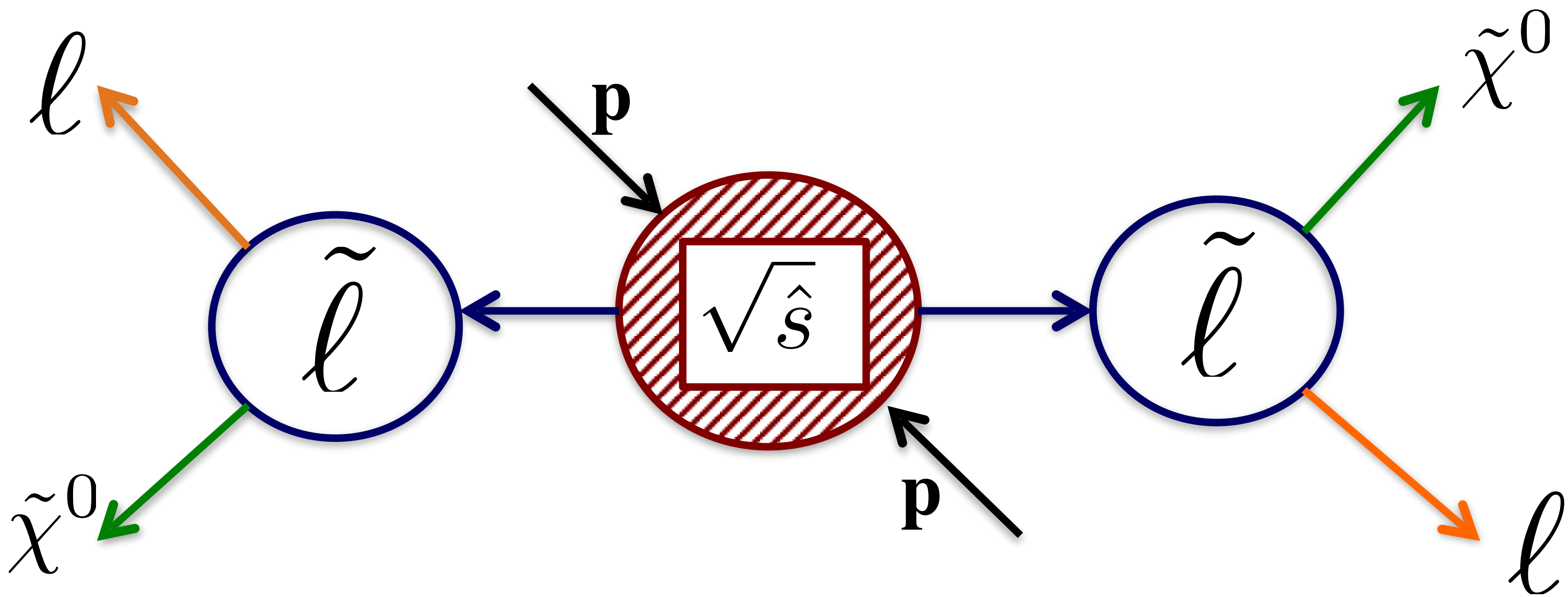
what about multiple weakly interacting particles scenarios?

Example: slepton pair-production



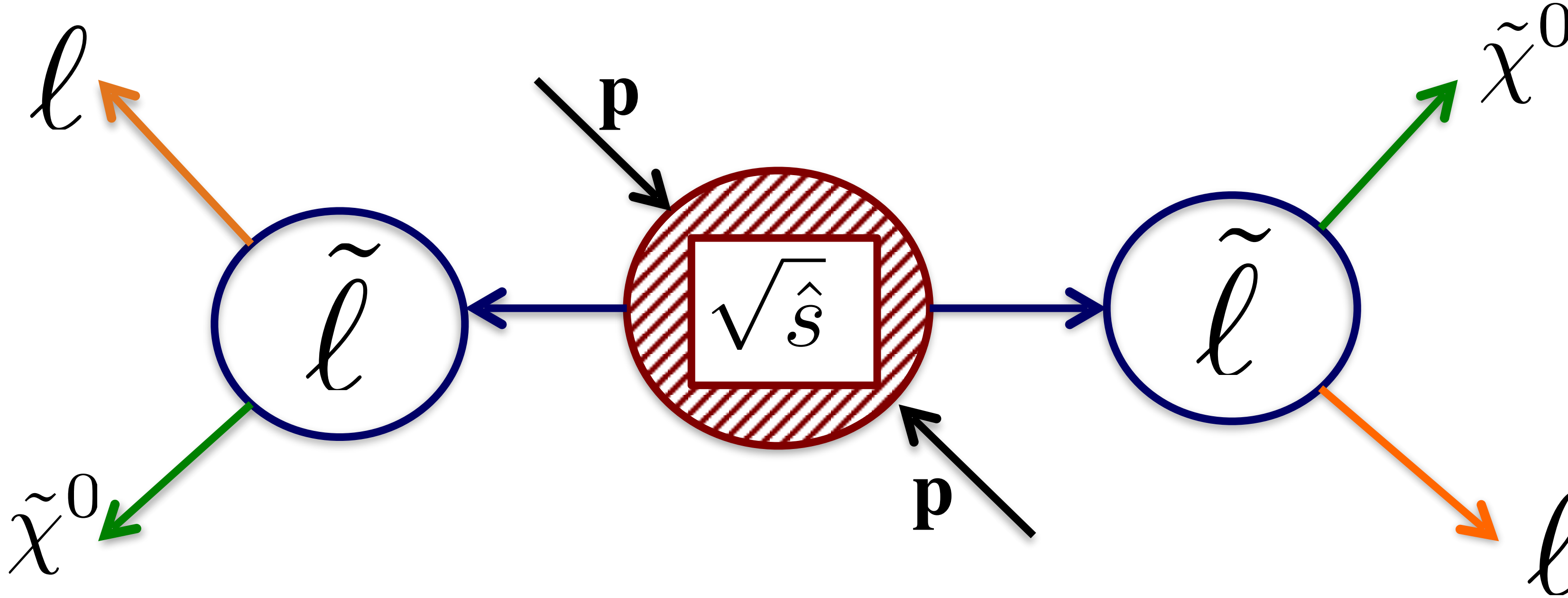
Kinematic topology characteristic of
R-parity conserving SUSY:
sparticle pair-production, each sparticle decaying to
a system of reconstructable SM particles and
one or more weakly-interacting ones

Example: slepton pair-production

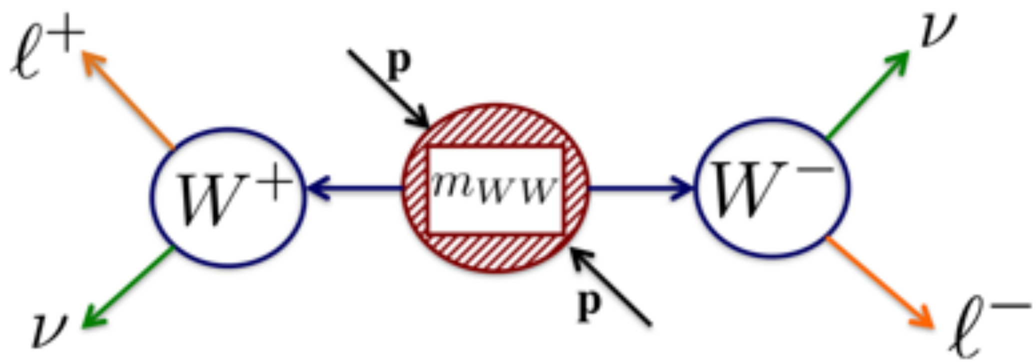


Experimental signature: di-lepton final states with missing transverse momentum

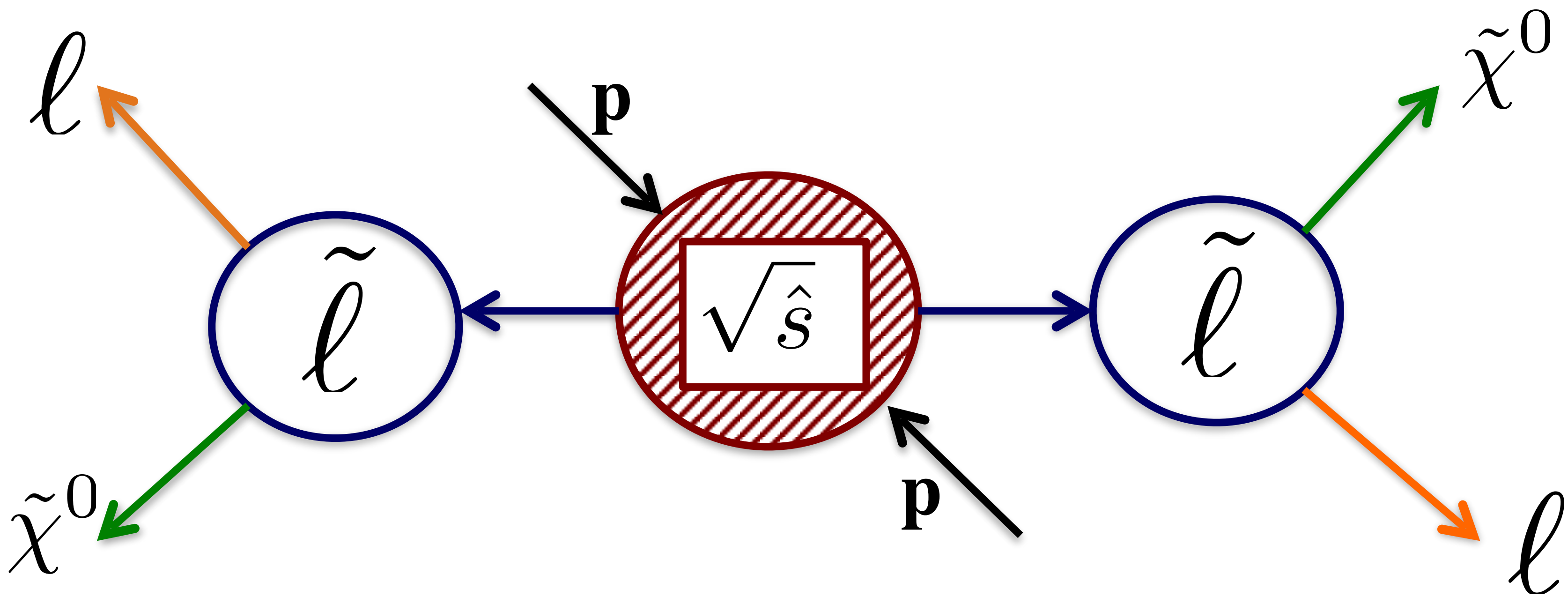
Example: slepton pair-production



Main background:



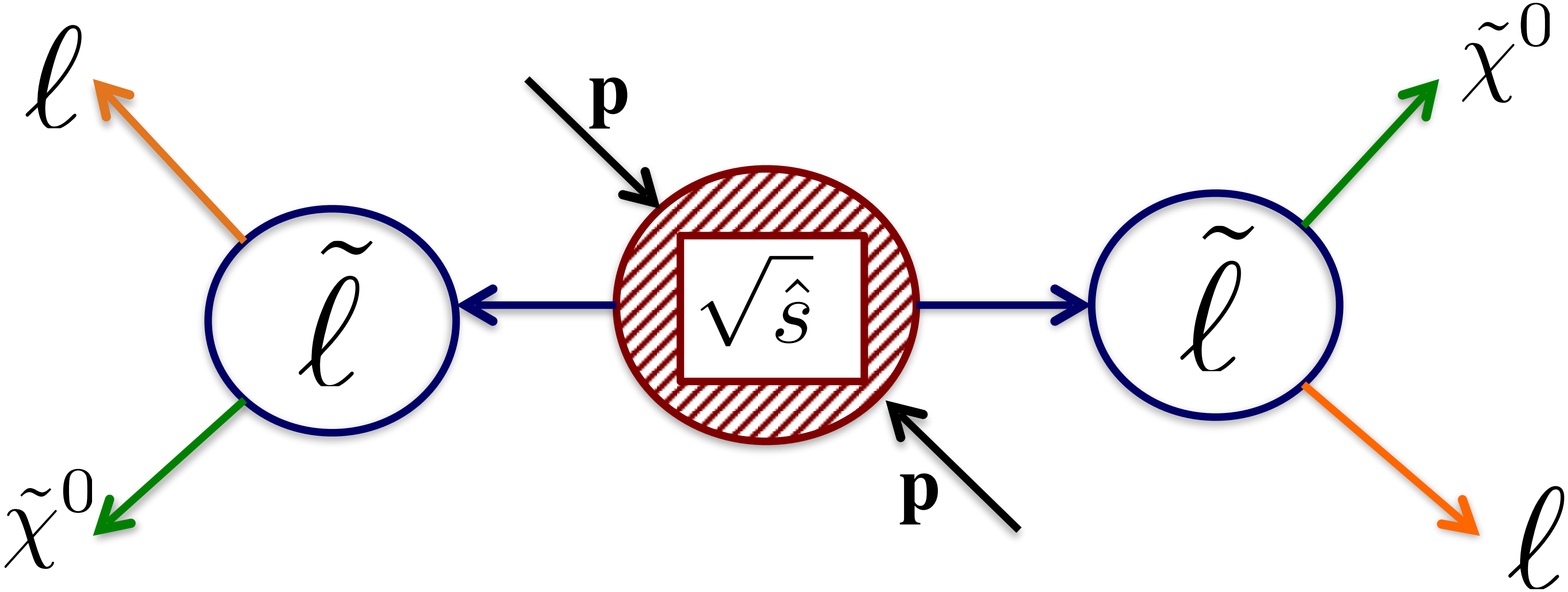
Example: slepton pair-production



What quantities, if we could calculate them, could help us distinguish between signal and background events?

$$\sqrt{\hat{s}} = 2\gamma^{decay} m_{\tilde{\ell}} \qquad M_{\Delta} \equiv \frac{m_{\tilde{l}}^2 - m_{\tilde{\chi}^0}^2}{m_{\tilde{l}}}$$

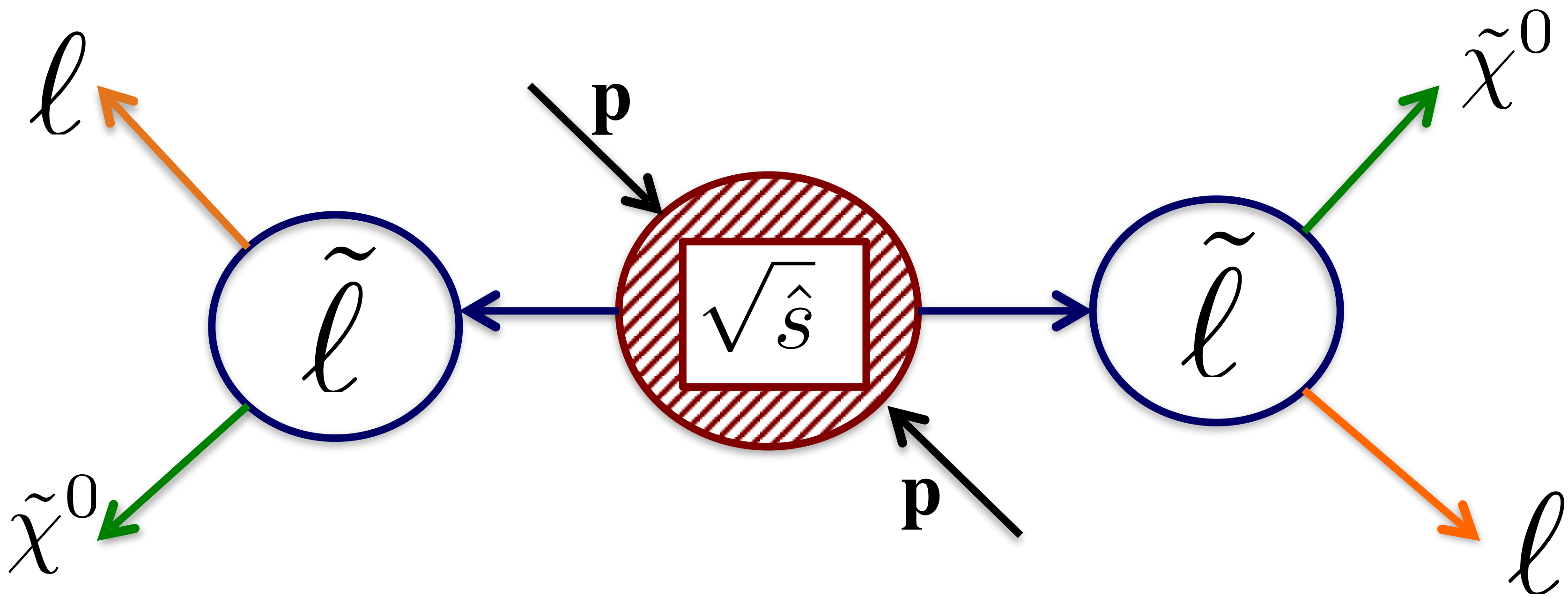
Example: slepton pair-production



What information are we missing?

We don’t observe the weakly interacting particles in the event. We can’t measure their momentum or masses.

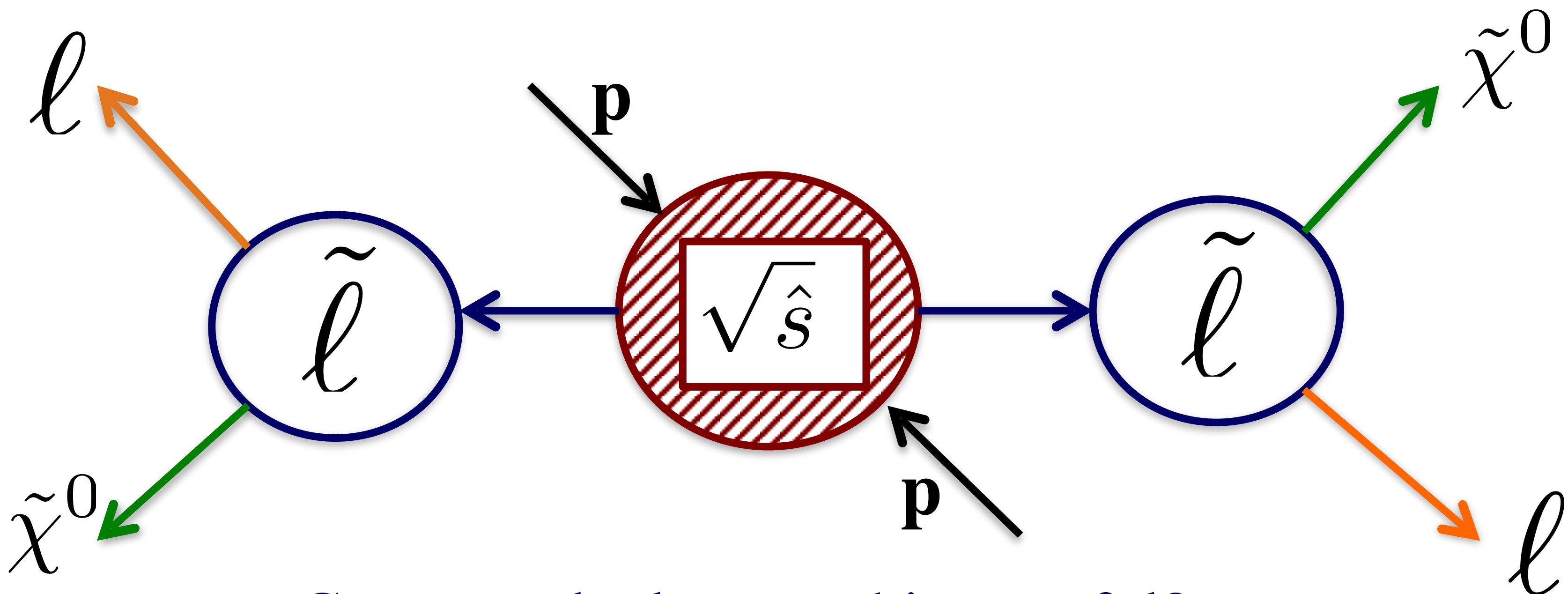
Example: slepton pair-production



What do we know?

We can reconstruct the 4-vectors of the two leptons and the transverse momentum in the event

Example: slepton pair-production



Can we calculate anything useful?

With a number of simplifying assumptions…

$$\vec{E}_T^{miss} = \sum \vec{p}_T^{\,\tilde{\chi}^0} \qquad m_{\tilde{\chi}^0} = 0$$

…we are still 4 d.o.f. short of reconstructing any masses of interest

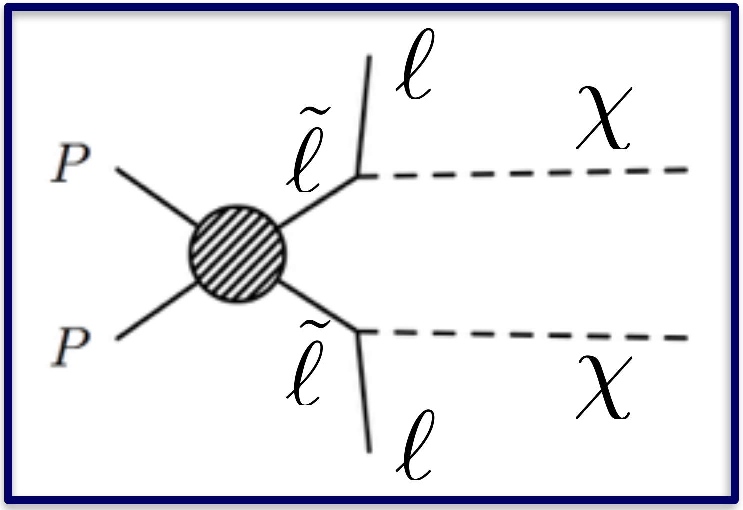
‘Singularity’ Mass Variables

- Popular approach for LHC Run I/II was to use **singularity variables** as observables in searches

- Derive observables that **bound a mass or mass-splitting of interest** by
  - Assuming knowledge of event decay topology
  - “Extremizing” over under-constrained kinematic degrees of freedom associated with weakly interacting particles

Singularity Variable Example: M_{T2}

Generalization of transverse mass to two weakly interacting particle events



$$M_{T2}^2(m_\chi) = \min_{\vec{p}_T^{\,\chi_1} + \vec{p}_T^{\,\chi_2} = \vec{E}_T^{miss}} \max\left[m_T^2(\vec{p}_T^{\,\ell_1}, \vec{p}_T^{\,\chi_1}, m_\chi), m_T^2(\vec{p}_T^{\,\ell_2}, \vec{p}_T^{\,\chi_2}, m_\chi)\right]$$

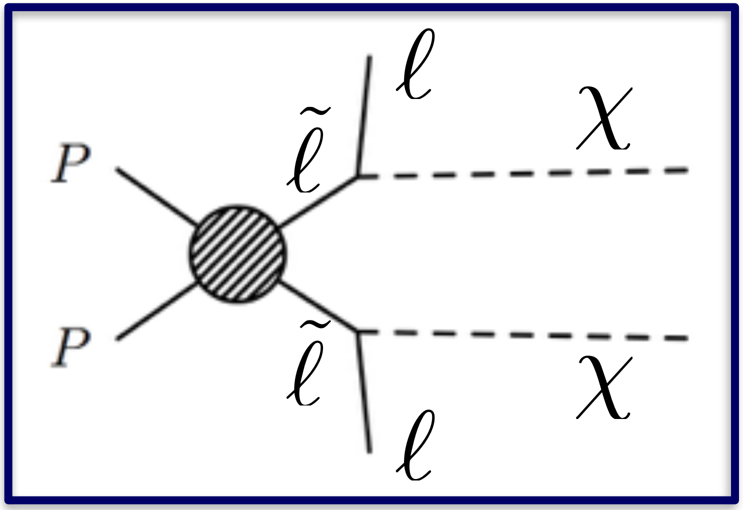
with: $$m_T^2(\vec{p}_T^{\,\ell_i}, \vec{p}_T^{\,\chi_i}, m_\chi) = m_\chi^2 + 2\left(E_T^{\ell_i} E_T^{\chi_i} - \vec{p}_T^{\,\ell_i} \cdot \vec{p}_T^{\,\chi_i}\right)$$

From:

C.G. Lester and D.J. Summers. Measuring masses of semiinvisibly decaying particles pair produced at hadron colliders. *Phys.Lett.*, B463:99–103, 1999.

Singularity Variable Example: M_{T2}

Generalization of transverse mass to two weakly interacting particle events



Extremization over under-constrained d.o.f.

LSP 'test mass'

$$M_{T2}^2(m_\chi) = \min_{\vec{p}_T^{\,\chi_1} + \vec{p}_T^{\,\chi_2} = \vec{E}_T^{miss}} \max\left[m_T^2(\vec{p}_T^{\,\ell_1}, \vec{p}_T^{\,\chi_1}, m_\chi), m_T^2(\vec{p}_T^{\,\ell_2}, \vec{p}_T^{\,\chi_2}, m_\chi)\right]$$

Subject to constraints

with: $m_T^2(\vec{p}_T^{\,\ell_i}, \vec{p}_T^{\,\chi_i}, m_\chi) = m_\chi^2 + 2\left(E_T^{\ell_i} E_T^{\chi_i} - \vec{p}_T^{\,\ell_i} \cdot \vec{p}_T^{\,\chi_i}\right)$

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Singularity Variable Example: M_{T2}

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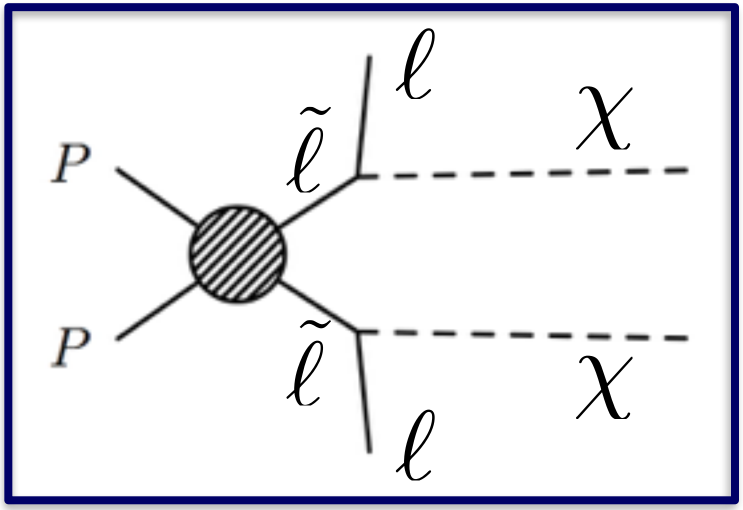

Extremization over under-constrained d.o.f.

LSP 'test mass'

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Subject to constraints

with: $m_T^2(\vec{p}_T^{\,\ell_i},\vec{p}_T^{\,\chi_i},m_\chi) = m_\chi^2 + 2\left(E_T^{\ell_i}E_T^{\chi_i} - \vec{p}_T^{\,\ell_i}\cdot\vec{p}_T^{\,\chi_i}\right)$

Constructed to have a kinematic endpoint (with the right test mass) at: $M_{T2}^{\max}(m_\chi) = m_{\tilde{\ell}}$ $\quad M_{T2}^{\max}(0) = M_\Delta \equiv \dfrac{m_{\tilde{\ell}}^2 - m_{\tilde{\chi}}^2}{m_{\tilde{\ell}}}$

From:

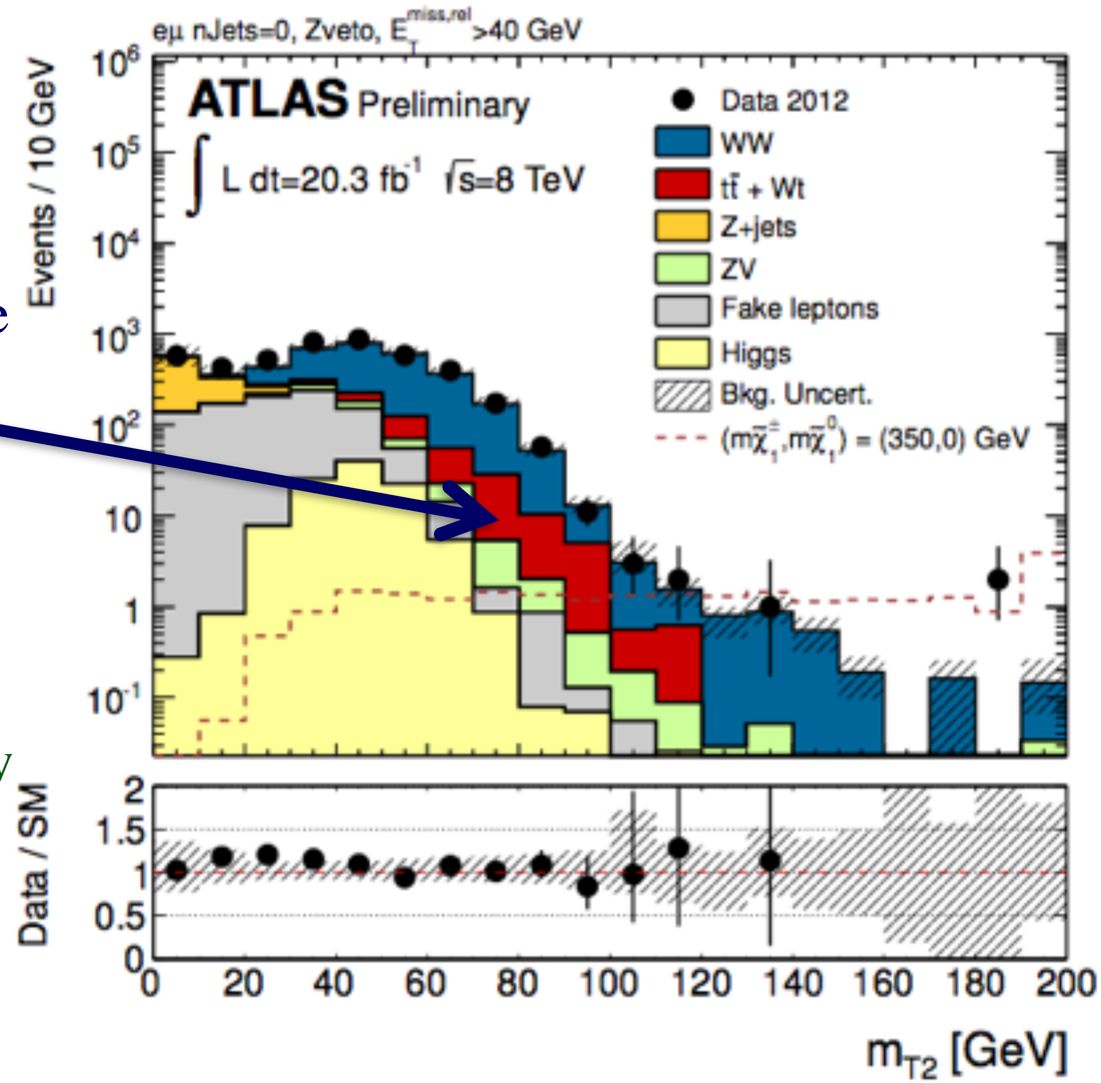
C.G. Lester and D.J. Summers. Measuring masses of semiinvisibly decaying particles pair produced at hadron colliders. *Phys.Lett.*, B463:99–103, 1999.

M_{T2} in practice

From:

ATLAS-CONF-2013-049

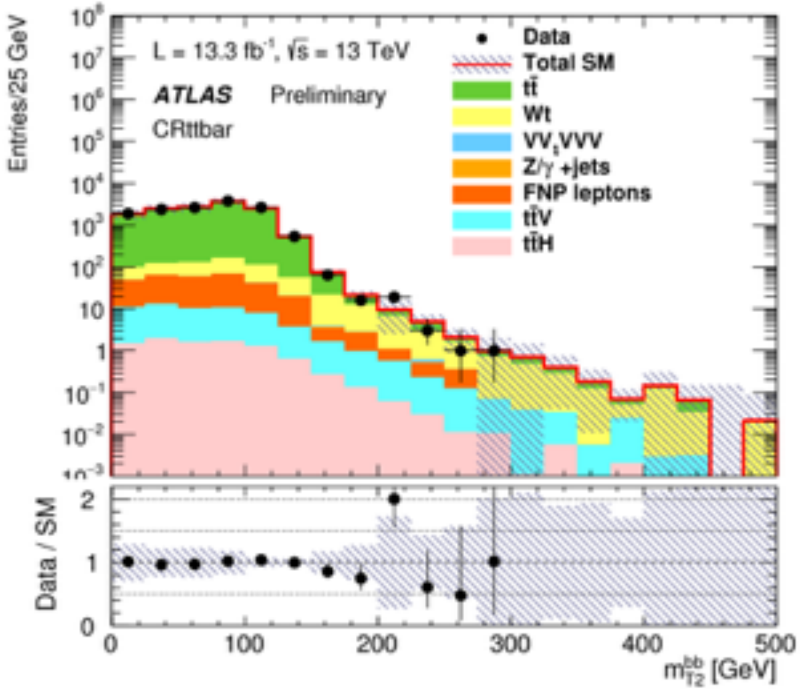
Backgrounds with
di-leptonic W's fall steeply once
M_{T2} exceeds the
W mass Jacobian edge



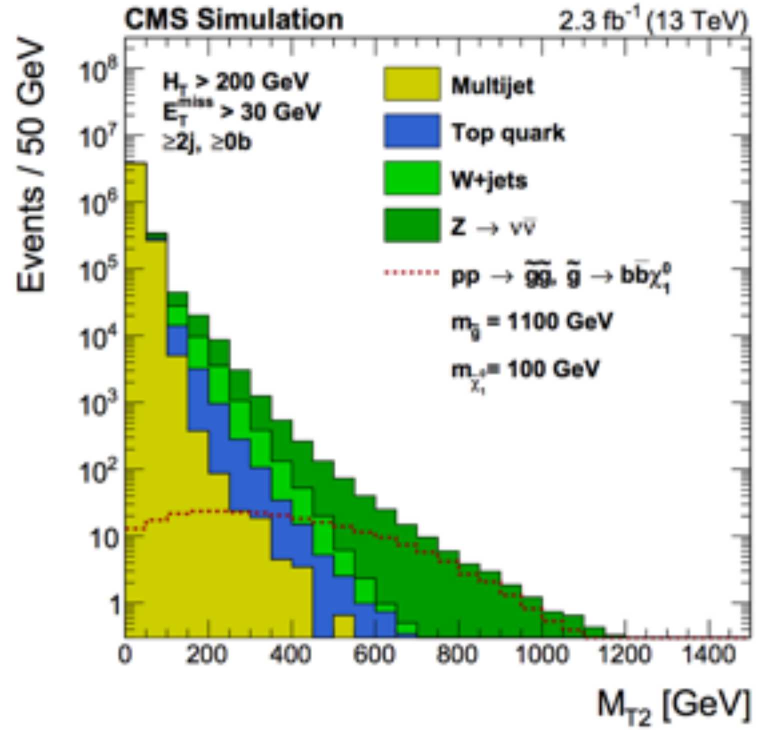
Searches based on singularity
variables have sensitivity to new
physics signatures with mass
splittings larger than the
analogous SM ones

M_{T2} in practice

ATLAS-CONF-2016-076 $M_{T2}(b, b)$



arXiv:1603.04053 $M_{T2}(\text{jet}, \text{jet})$

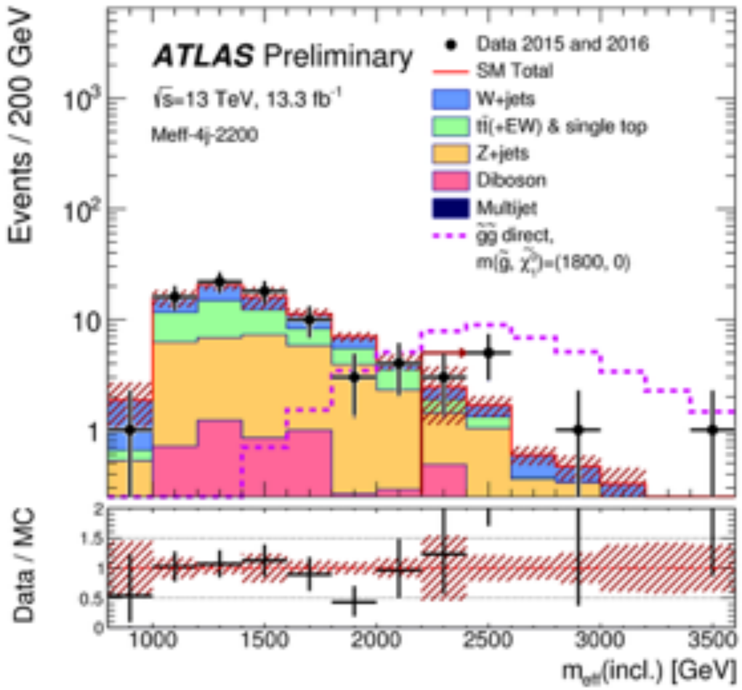


Steeply falling backgrounds with ttbar exhibiting endpoint related to top/W mass difference

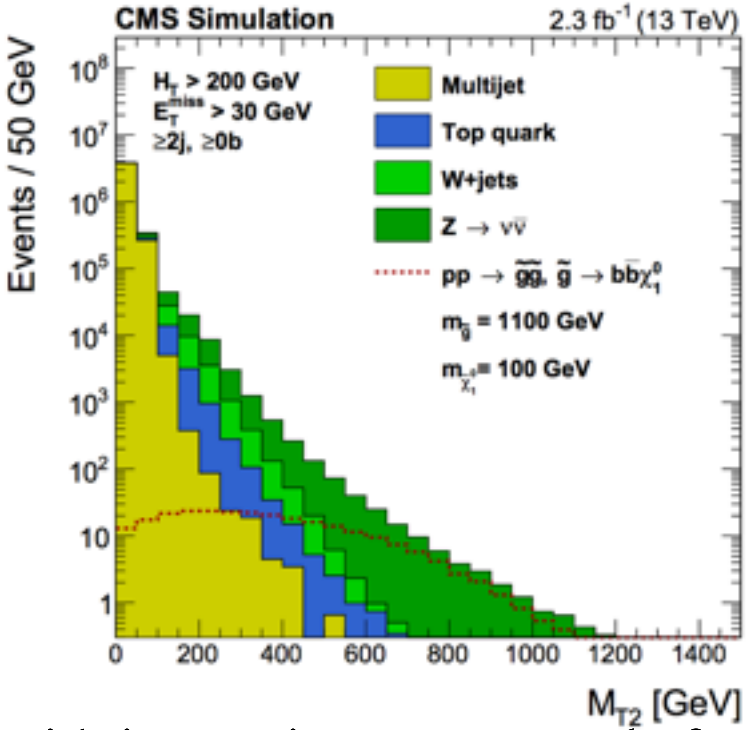
Steeply falling backgrounds with no Jacobian edge ⇒ nonetheless, steeply falling backgrounds from M_{T2} minimization, large mass-splitting signals at larger values

Jets + MET searches

ATLAS-CONF-2016-078 M_{eff}



arXiv:1603.04053 $M_{T2}(\mathrm{jet}, \mathrm{jet})$



Of course, SM background yields decrease with increasing energy scale for most kinematic observables:

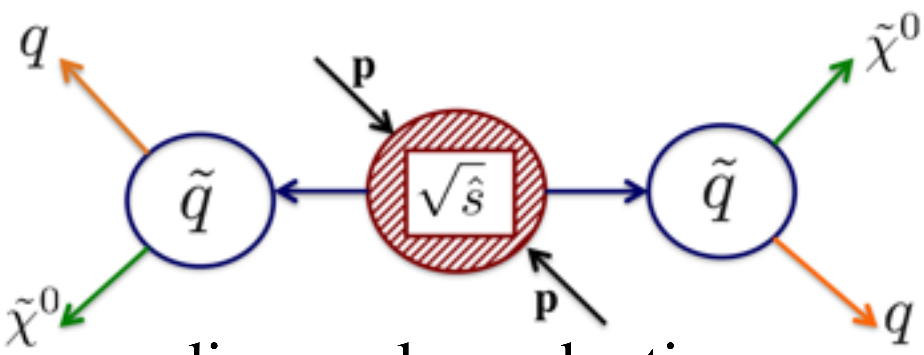
$\Rightarrow$ the more steeply falling the background, the better

$\Rightarrow$ the better resolved the signal energy-scale, the better

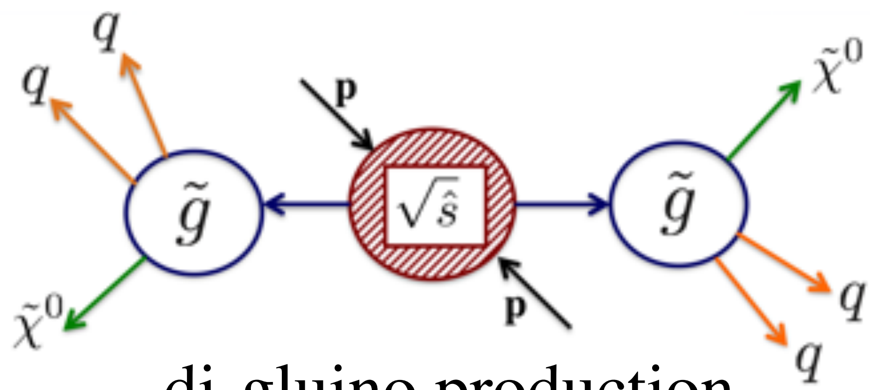
$\Rightarrow$ accurate predictions of SM backgrounds in tails essential

Example: Jets + MET search

Signals:



di-squark production



di-gluino production

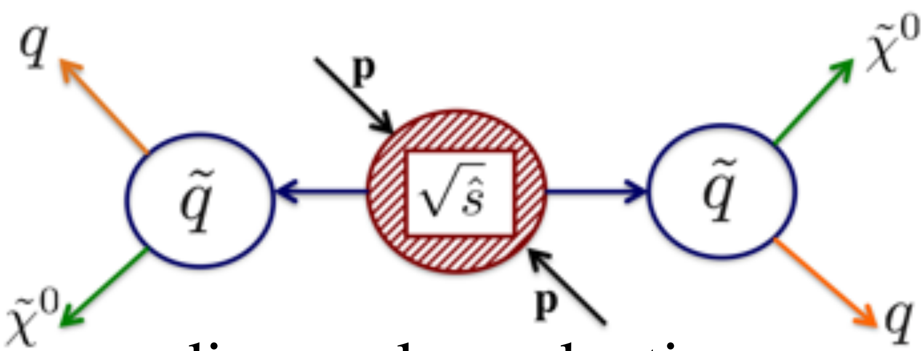
Signals characteristic of new $\mathbb{Z}_2$ symmetry
(ex. R-parity conservation in SUSY)

characteristic energy scale of sparticle decay products:

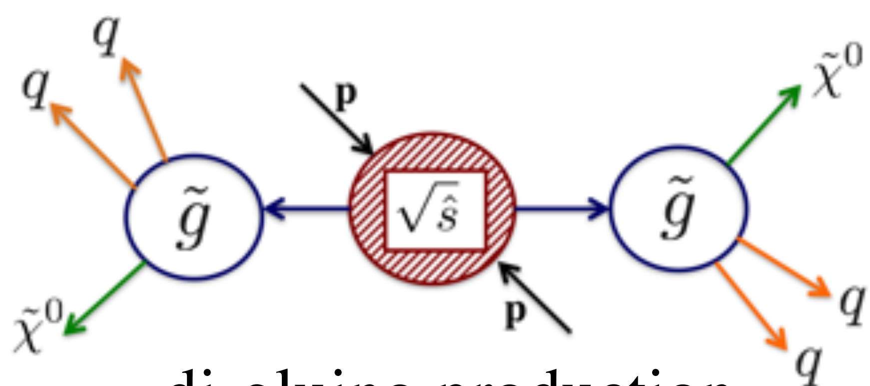
$$M_\Delta \equiv \frac{m^2_{\tilde{q}/\tilde{g}} - m^2_{\tilde{\chi}^0}}{m_{\tilde{q}/\tilde{g}}}$$

Example: Jets + MET search

Signals:

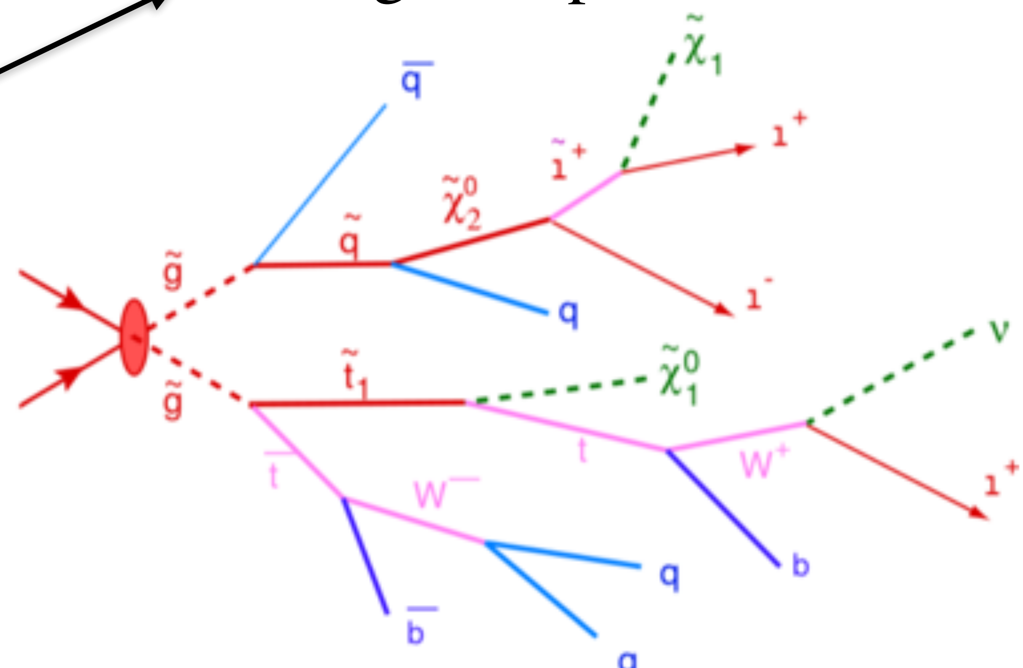


di-squark production



di-gluino production

“**simplified models**”



CMS jets+MET search with M_{T2}

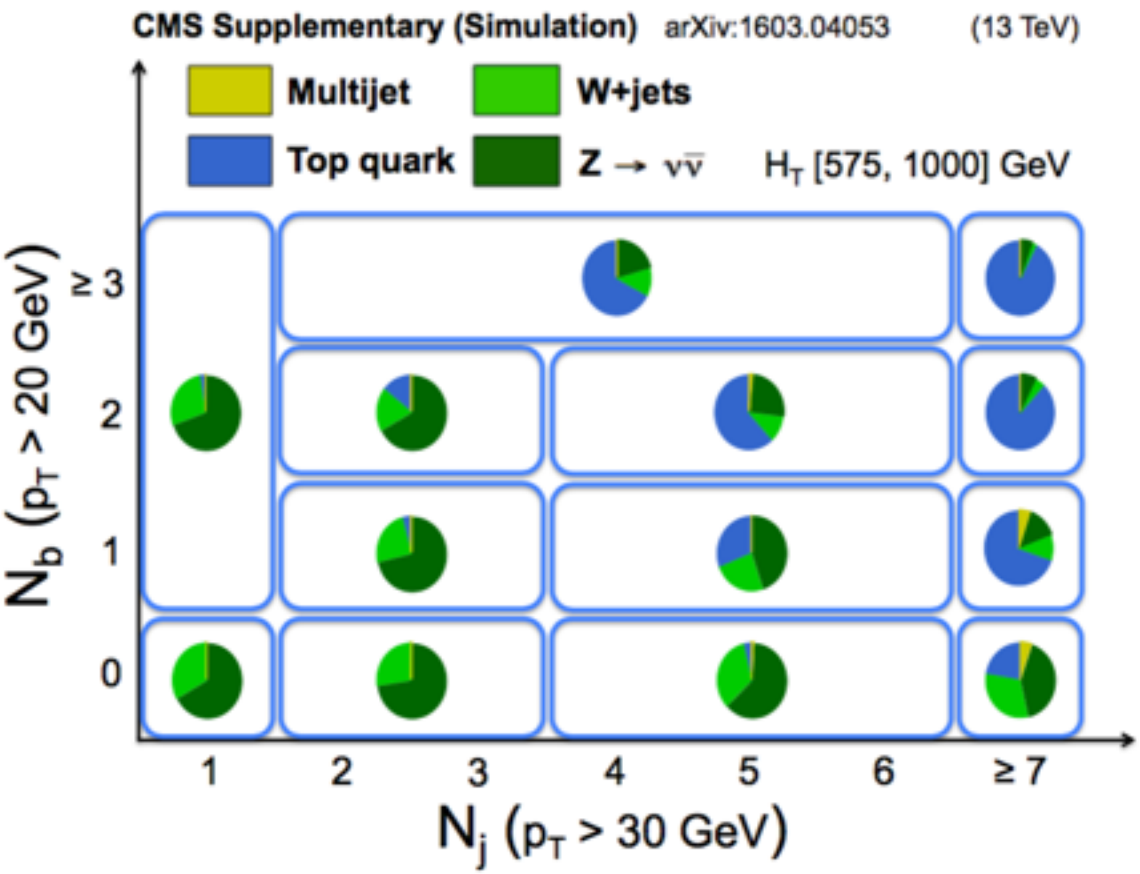
CMS PAS SUS-16-015

⇒ in zero lepton final state, partition phase-space in **N_{jet}, $N_{b\text{-}jet}$, and H_T**

⇒ in each region, search for NP in the **tails of M_{T2}**

Different regions have different compositions of backgrounds ($Z(\nu\nu)$ @ low jet multiplicity, increasing top contribution with more jets/b-jets)

Similarly, different signals will appear in different regions, dependent on final state multiplicity and mass-splitting scale

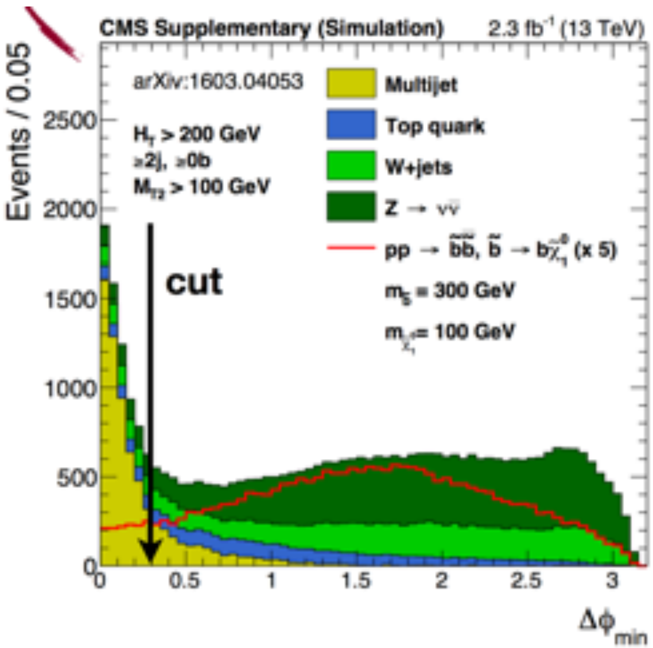


CMS jets+MET search with M_{T2}

Background estimation and control regions

CMS PAS SUS-16-015

QCD multi-jet events are an **instrumental background**, with MET resulting from jet mis-measurements



Can isolate this background by looking at minimum $\Delta\phi$ between jets and MET

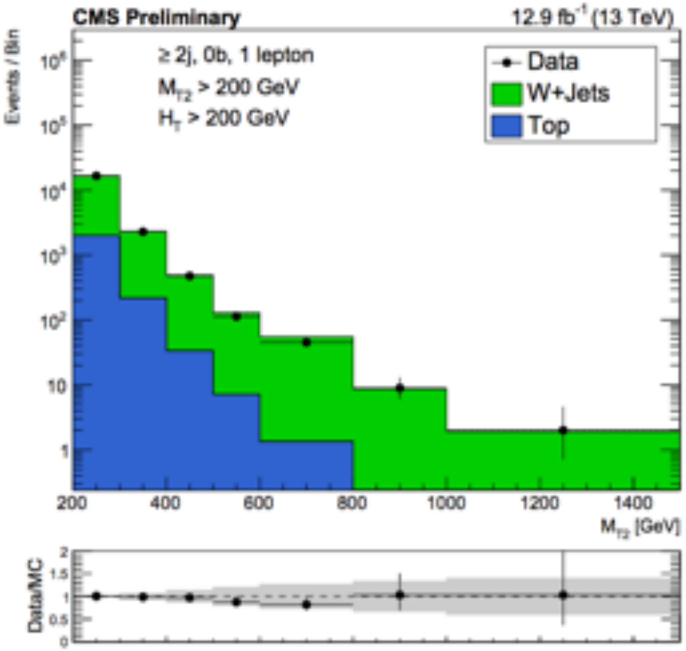
$\Delta\phi_{\min}$ used to both suppress background and estimate it (by inverting requirement)

CMS jets+MET search with M_{T2}

Background estimation and control regions

CMS PAS SUS-16-015

W($l\nu$) events (from W+jets and top processes) enter as backgrounds when **the decay lepton is not identified as such**

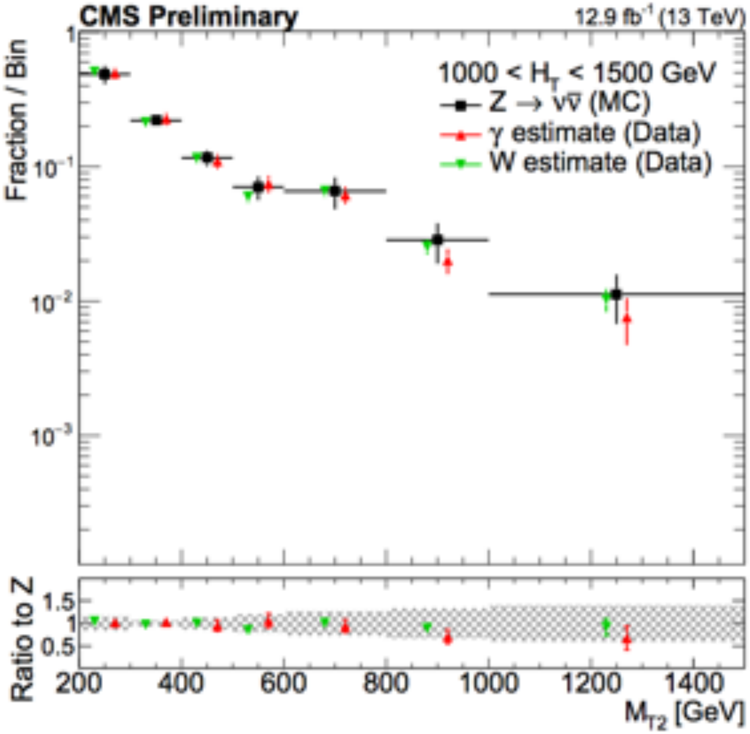


Can estimate this background using a control region in a **different object final state (one lepton)**, in similar kinematic phase-space

CMS jets+MET search with M_{T2}

Background estimation and control regions **CMS PAS SUS-16-015**

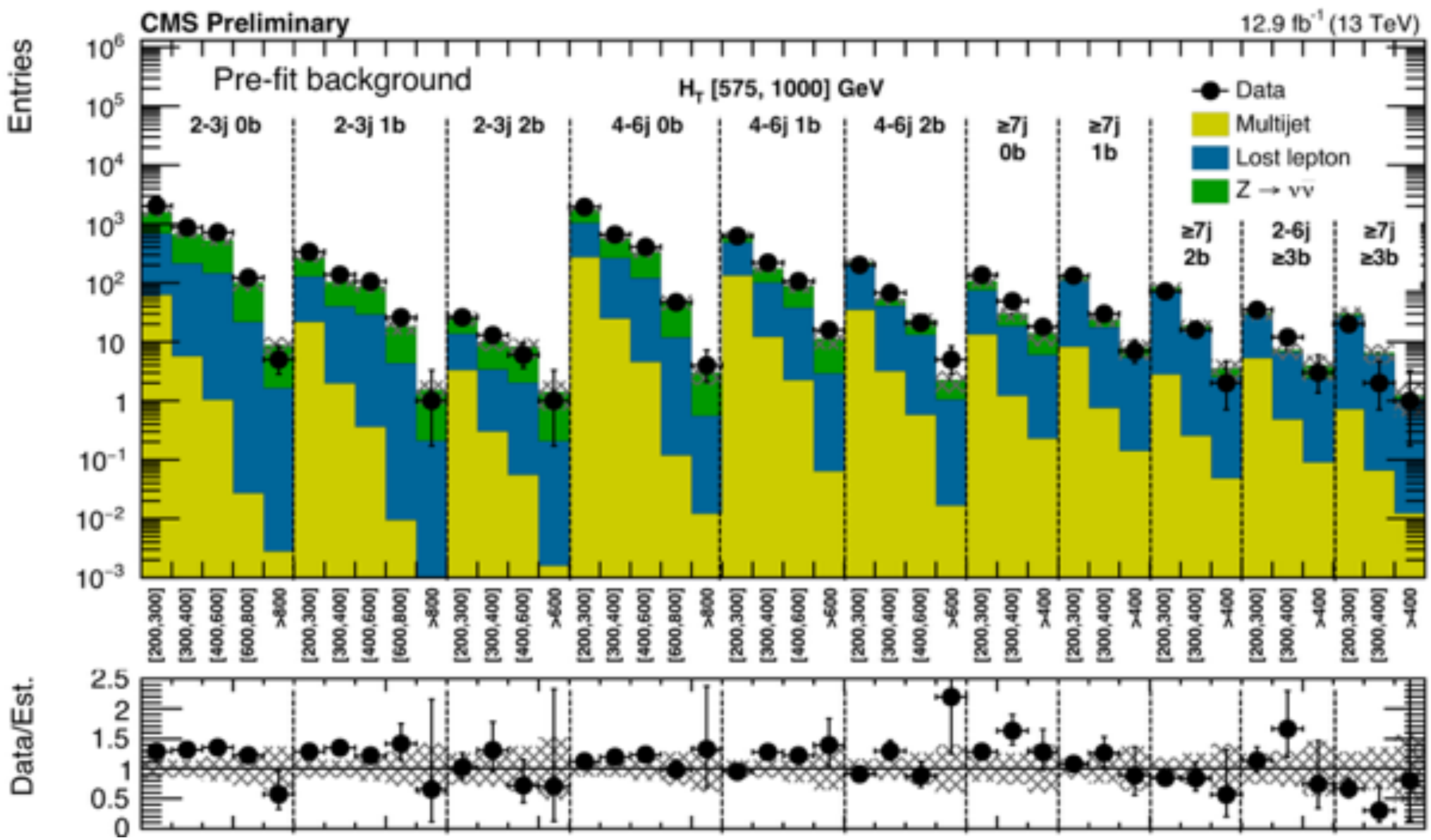
Z($\nu\nu$) events constitute a **~irreducible background**, particularly at low jet/b-jet multiplicity



Can estimate this background using a control region based on a **different SM process (γ+jets)**, in similar kinematic phase-space

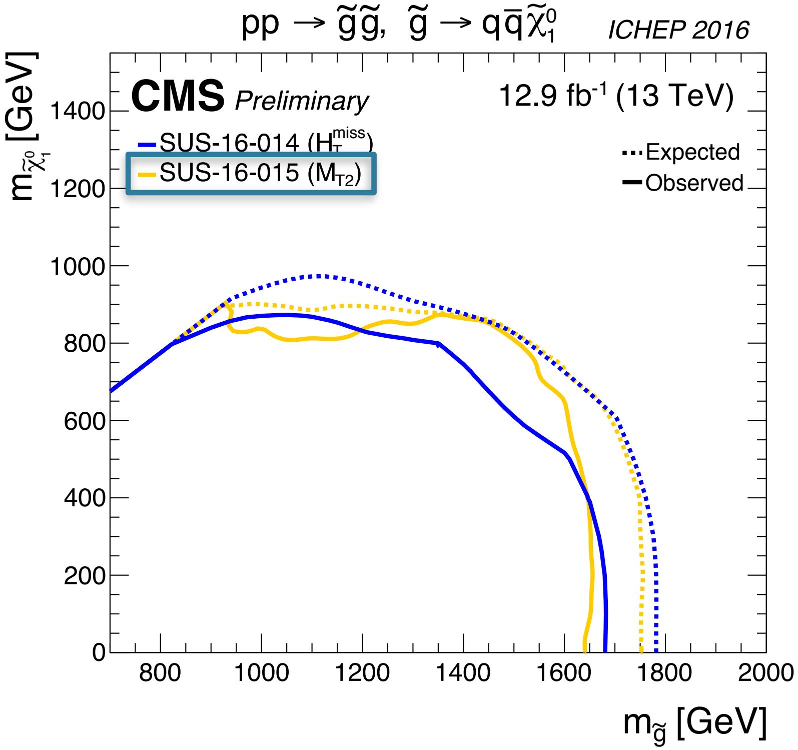
CMS jets+MET search with M_{T2}

CMS PAS SUS-16-015

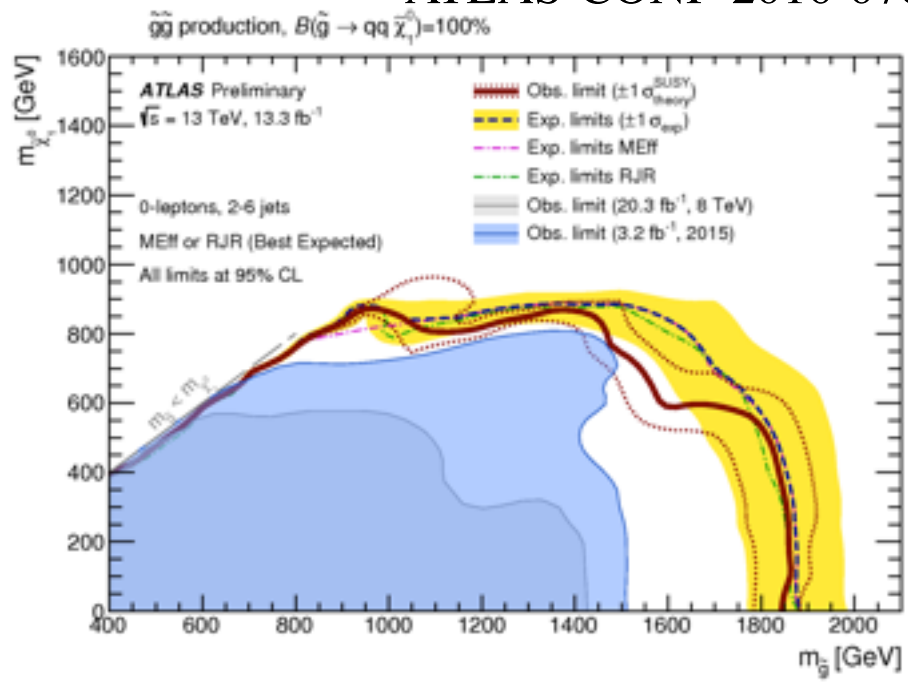


Observed yields (along with background predictions) in each partitioned region of phase-space combined to constrain SUSY

RPC SUSY constraints



ATLAS-CONF-2016-078



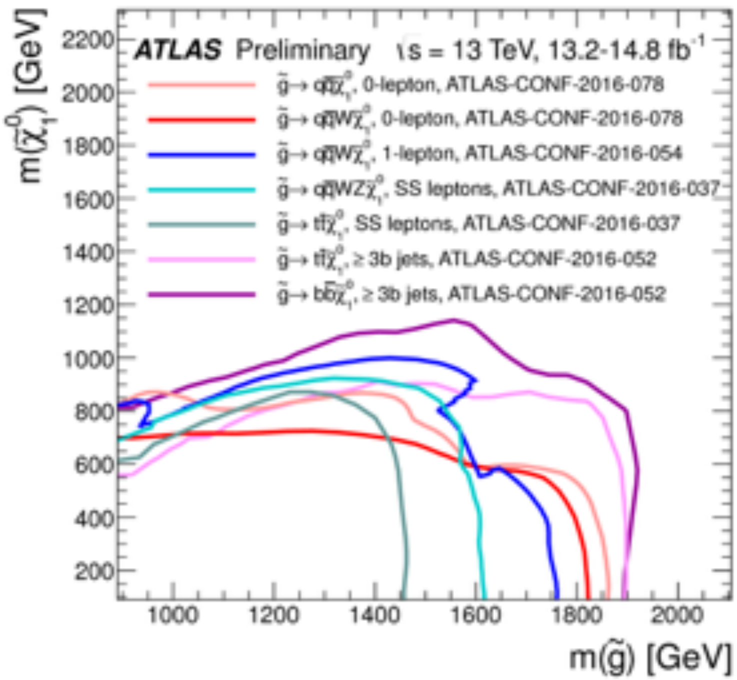
CMS and ATLAS searches yield qualitatively (and quantitatively) similar constraints:

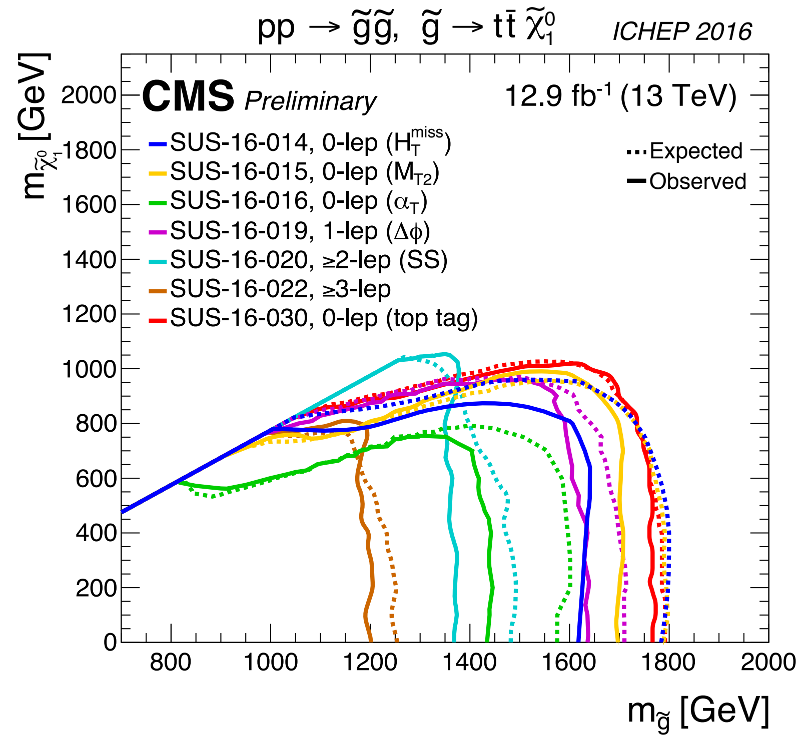
⇒ Similar control region/background estimation strategies

⇒ Different choices for phase-space partitioning (observables)

⇒ Larger sparticle masses constrained at lower LSP masses (cross-section upper limits scale with mass-splitting)

RPC SUSY constraints





CMS and ATLAS searches yield qualitatively (and quantitatively) similar constraints **in many different final states**:

⇒ Similar control region/background estimation strategies

⇒ Different choices for phase-space partitioning (observables)

⇒ Larger sparticle masses constrained at lower LSP masses (cross-section upper limits scale with mass-splitting)

Compressed Signals

Generally, in scenarios with weakly interacting particles, mass-sensitive observables scale as: $\sim m_{\tilde{P}} - m_{\tilde{\chi}}$

parent particle mass

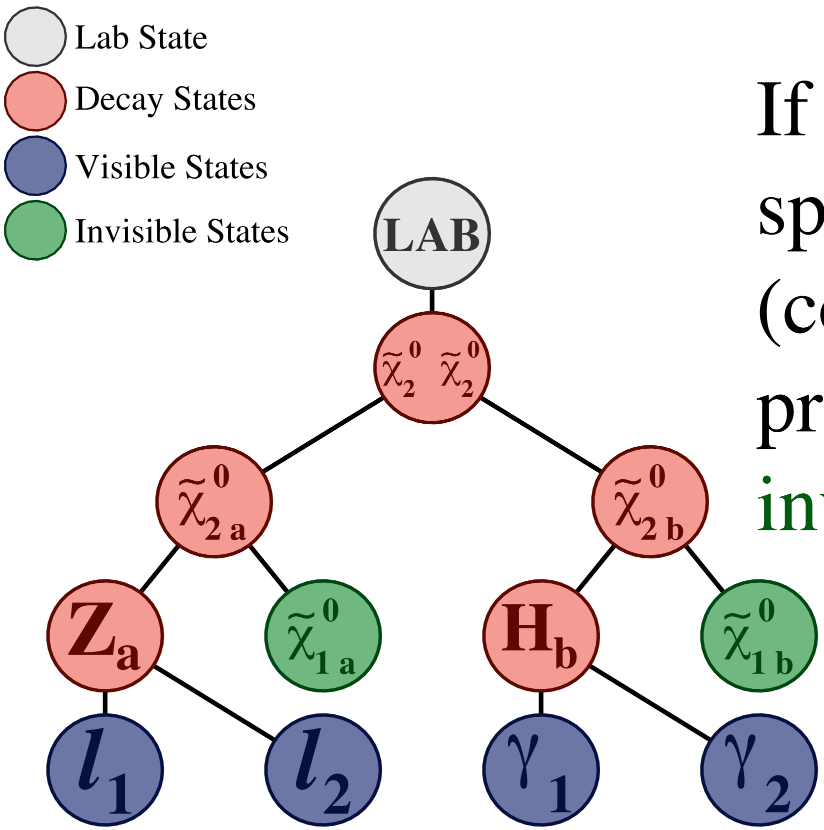
weakly-interacting particle mass

At large $m_{\tilde{P}} - m_{\tilde{\chi}}$, relevant SM backgrounds yields are falling quickly in the matching phase-space $\Rightarrow$
expect good S/B in the tails of mass-splitting-sensitive observables

As $m_{\tilde{P}} - m_{\tilde{\chi}}$ becomes smaller, SM decay products become softer (more difficult to identify), while backgrounds are larger $\Rightarrow$
no longer in the tails of mass-splitting-sensitive background observables

Compressed Signals

Consider SUSY EWK-ino production

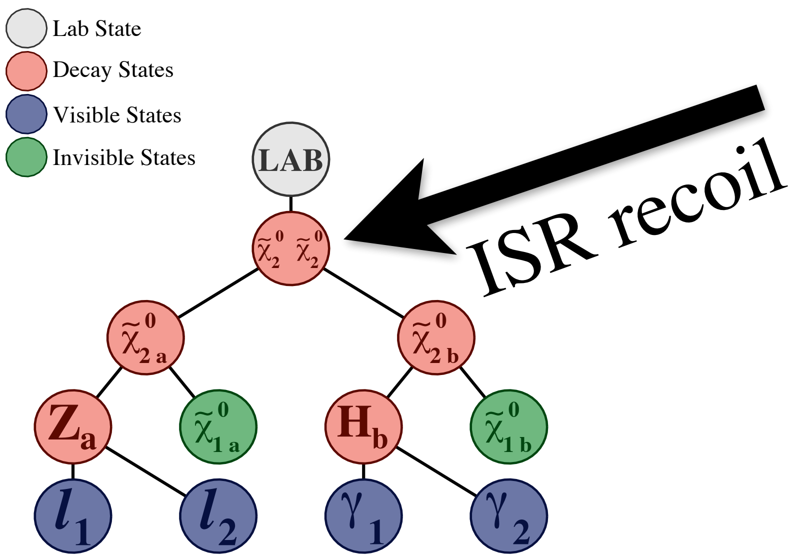


If the mass-splitting between sparticles, $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$, is small (compressed) then the decay products (both visible and invisible) will be soft

Can still calculate masses/splittings, but they may not be distinctive from background…

Sparticles in Motion

We can instead consider observables sensitive to the **absolute mass** of missing sparticles



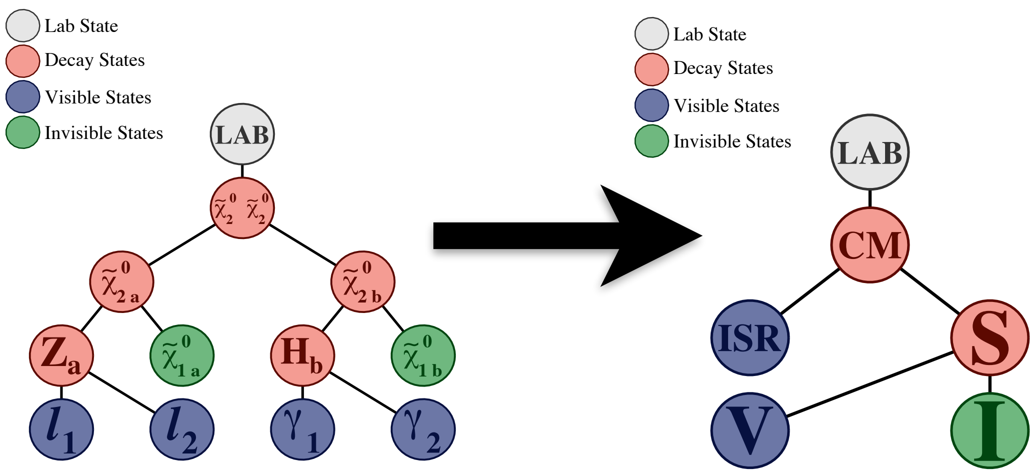
Identifying events with hard strong radiation means that soft particles will get momentum from recoil

In the limit of extreme compression the

$$\vec{\cancel{E}}_T \sim -\vec{p}_T^{\,\mathrm{ISR}} \times \frac{m_{\tilde{\chi}}}{m_{\tilde{P}}}$$

momentum of missing particles is sensitive to their mass

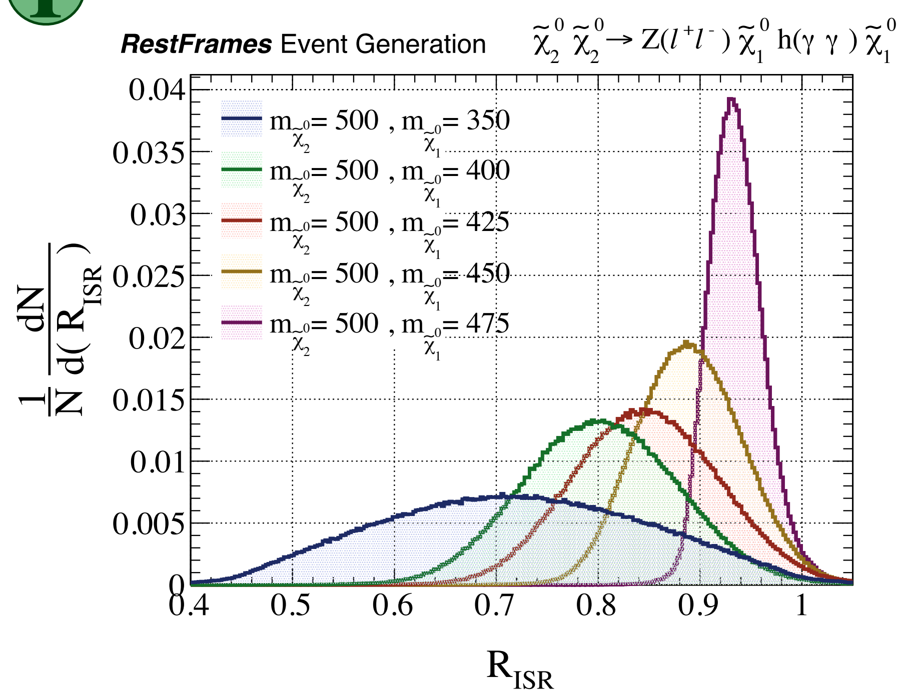
Sparticles in Motion



By analyzing each event in a simplified decay topology…

We can extract information about missing particle masses

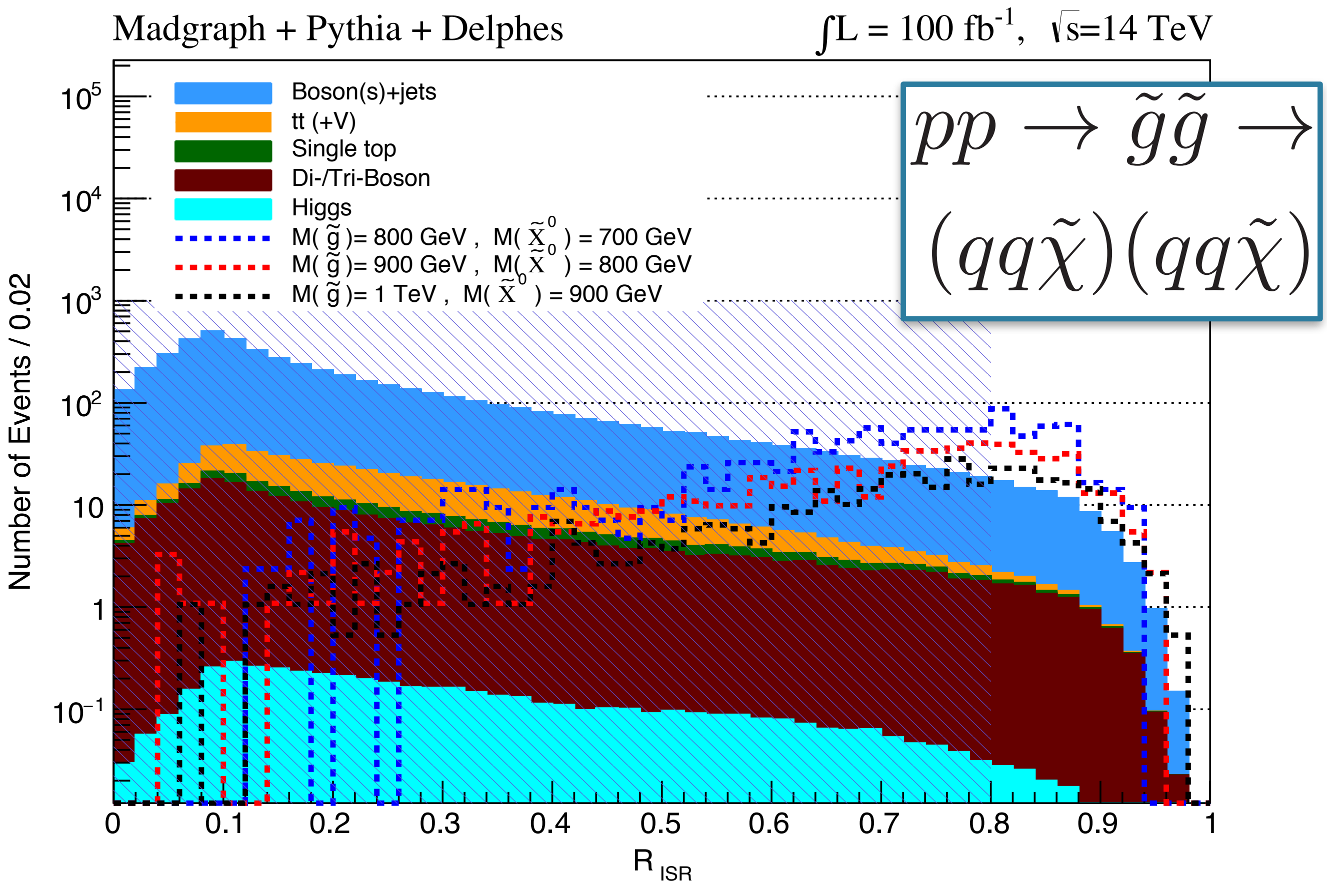
$$R_{\mathrm{ISR}} \equiv \frac{\vec{p}_{\mathrm{I}}^{\;\mathrm{CM}} \cdot \hat{p}_{\mathrm{ISR}}^{\;\mathrm{CM}}}{p_{\mathrm{ISR}}^{\mathrm{CM}}} \sim \frac{m_{\tilde{\chi}}}{m_{\tilde{P}}}$$



arXiv.1607.08307

Sparticles in Motion

arXiv.1607.08307

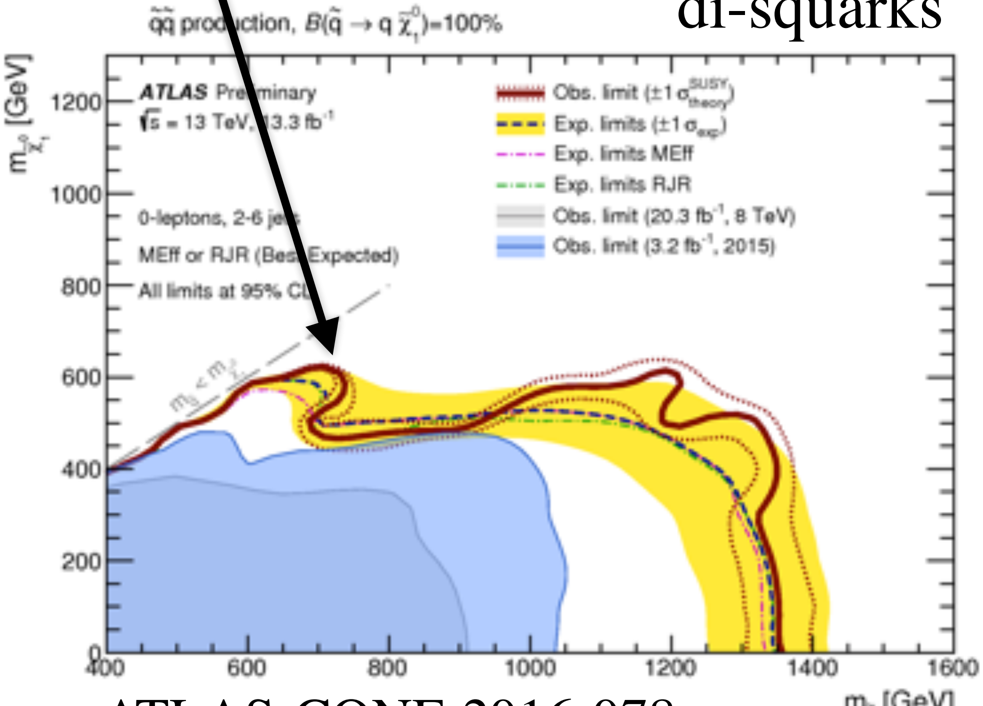


Can recover good S/B even in very-compressed scenarios

13 TeV Compressed Constraints

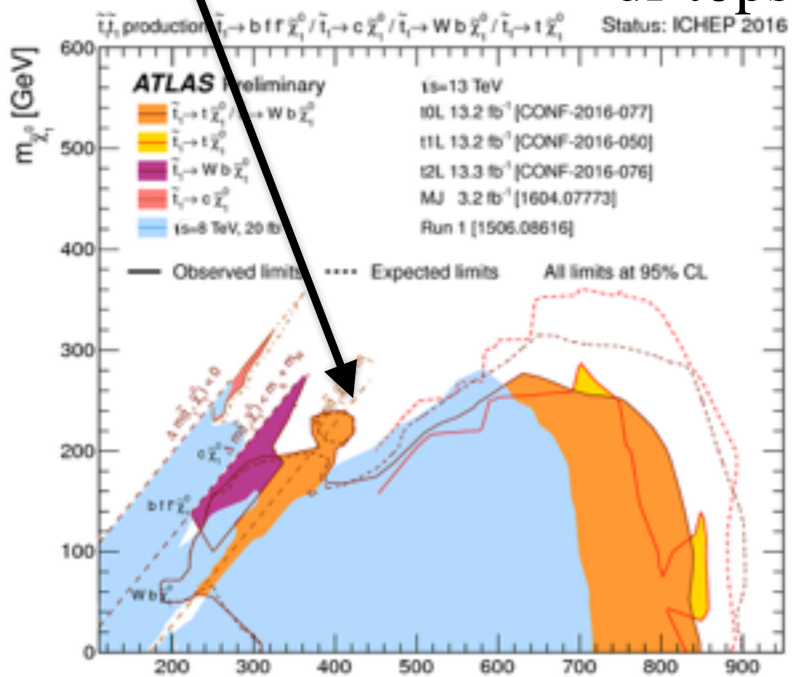
ISR-assisted compressed analysis technique already employed in ATLAS zero-lepton searches for strongly-interacting sparticles:

$m_{\tilde{q}} - m_{\tilde{\chi}} \sim 0$ di-squarks



ATLAS-CONF-2016-078

$m_{\tilde{t}} - m_{\tilde{\chi}} \sim m_{top}$ di-tops

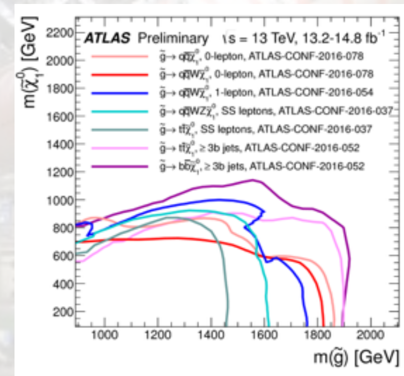


ATLAS-CONF-2016-077

Searching the TeV energy frontier for evidence of BSM physics involves boot-strapping our understanding of the SM and detectors from the “poles”

Searching the TeV energy frontier for evidence of BSM physics involves boot-strapping our understanding of the SM and detectors from the "poles"

Existing constraints on new particle masses up to ~2 TeV - will continue to probe increasingly high masses (up to 13 TeV) with more data



Searching the TeV energy frontier for evidence of BSM physics involves boot-strapping our understanding of the SM and detectors from the “poles”

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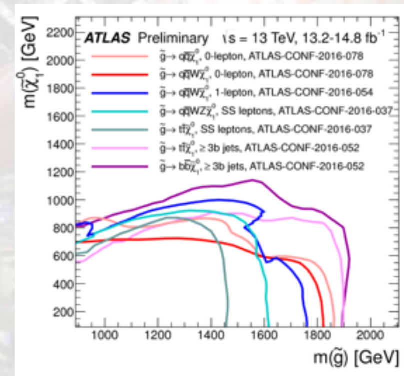
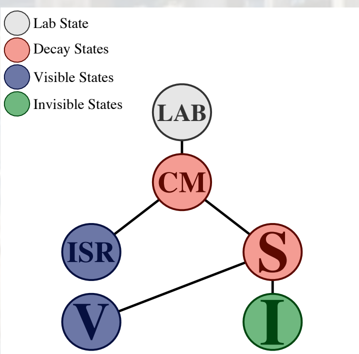
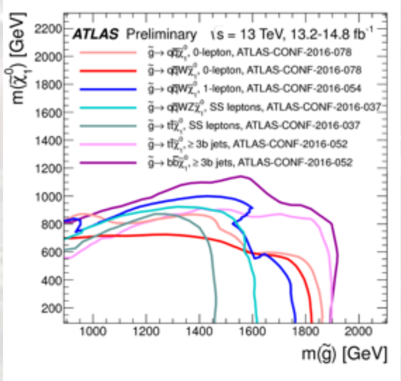


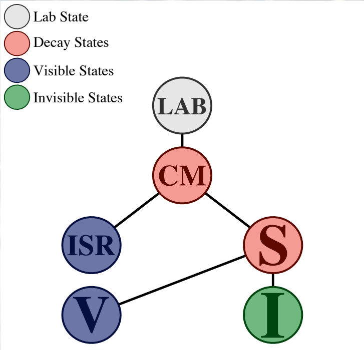


New searches for more difficult signals underway (compressed masses, rare decays, more complicated spectra…)

Searching the TeV energy frontier for evidence of BSM physics involves boot-strapping our understanding of the SM and detectors from the “poles”

Existing constraints on new particle masses up to ~2 TeV - will continue to probe increasingly high masses (up to 13 TeV) with more data





New searches for more difficult signals underway (compressed masses, rare decays, more complicated spectra…)

Still hoping that nature is as *natural* as some claim it should be - stay tuned for discovery!

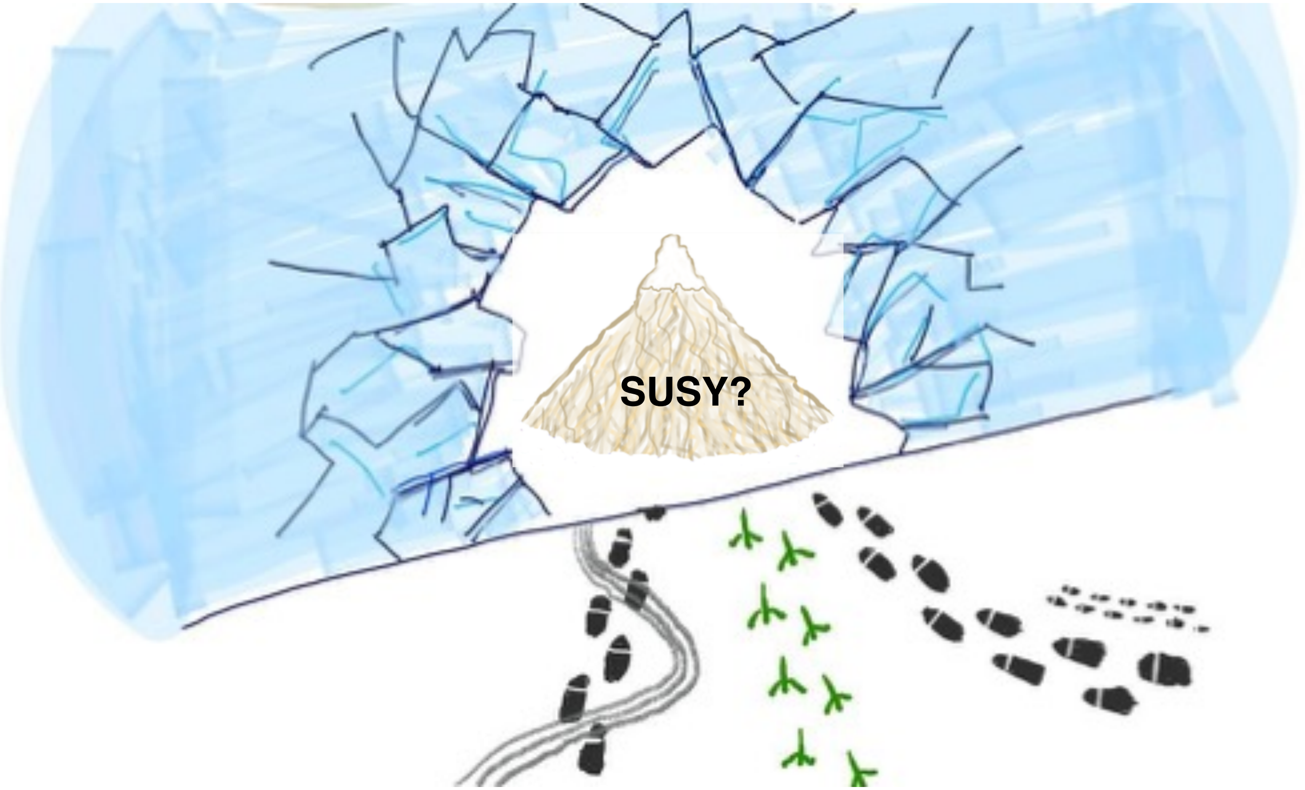
For more information about the topics covered in this lecture:

http://cern.ch

http://atlas.ch

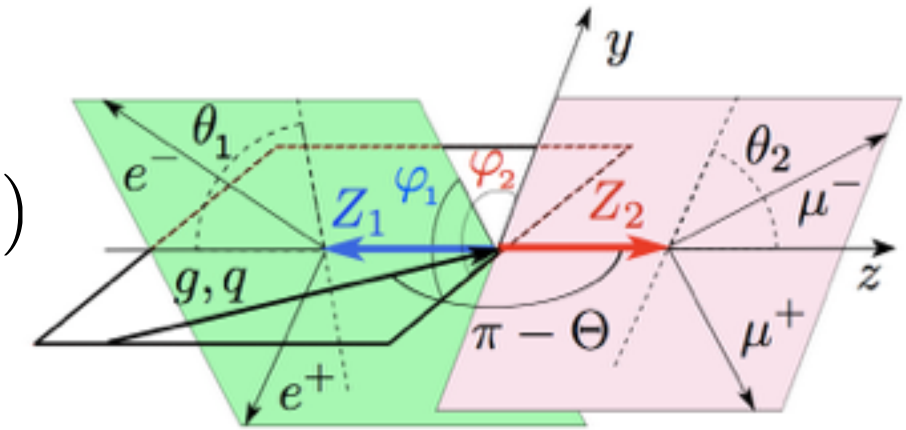
http://cms.cern.ch

Thank you for your attention!



BACKUP SLIDES

Open vs. closed final states



CLOSED $H \to Z(\ell\ell)Z(\ell\ell)$

Can calculate all masses, momenta, angles

Can use masses for discovery, can use information to measure spin, CP, etc.

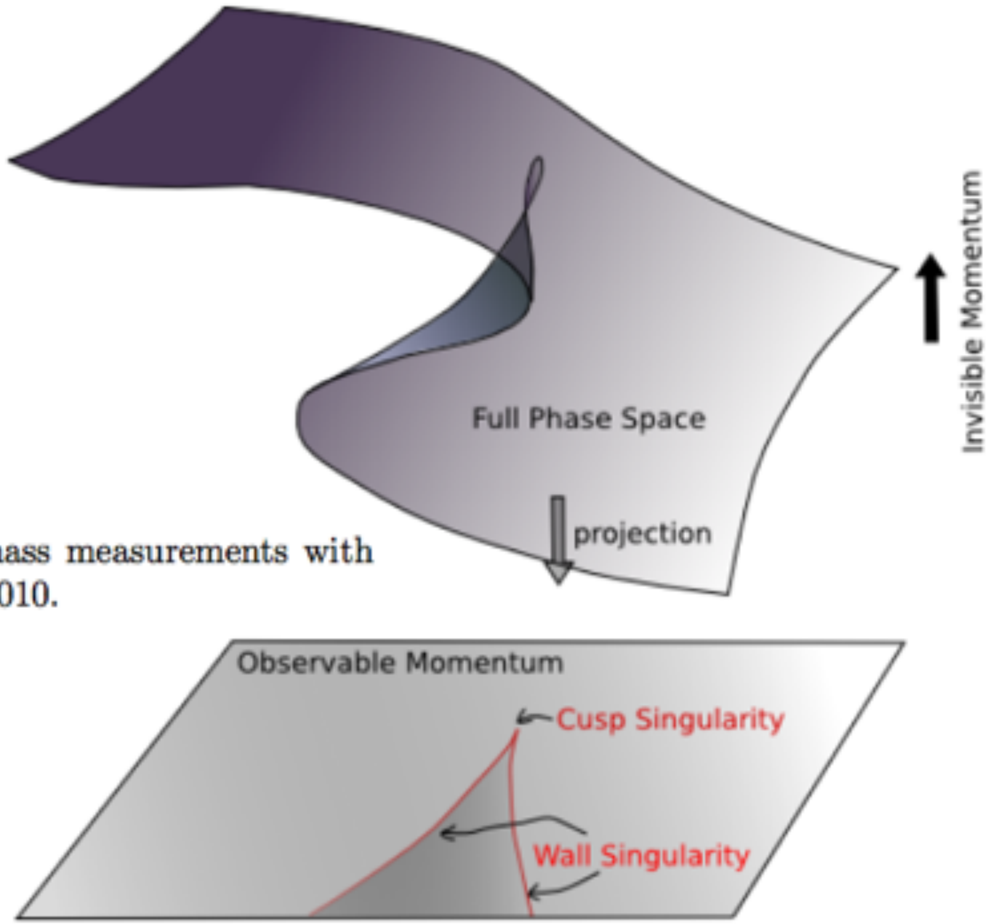
OPEN $H \to W(\ell\nu)W(\ell\nu)$

Under-constrained system with multiple weakly interacting particles – can't calculate all the kinematic information

What useful information can we calculate?
What can we measure?

Singularity variables

Kinematic Singularities. A singularity is a point where the local tangent space cannot be defined as a plane, or has a different dimension than the tangent spaces at non-singular points.

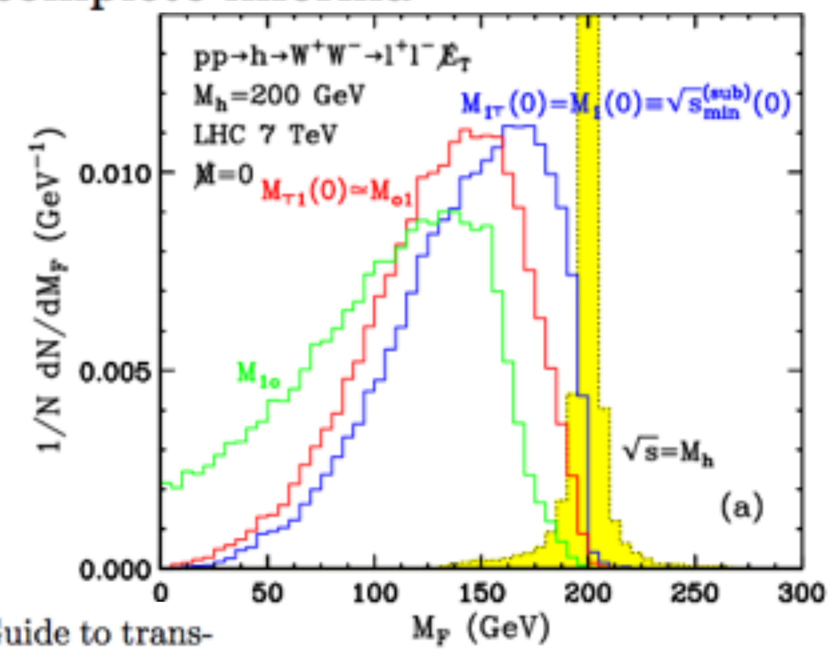


From:

Ian-Woo Kim. Algebraic singularity method for mass measurements with missing energy. *Phys. Rev. Lett.*, 104:081601, Feb 2010.

Singularity variables

The guiding principle we employ for creating useful hadron-collider event variables, is that: *we should place the best possible bounds on any Lorentz invariants of interest, such as parent masses or the center-of-mass energy* $\hat{s}^{1/2}$*, in any cases where it is not possible to determine the actual values of those Lorentz invariants due to incomplete event information.* Such incomplete informa-



From:

A.J. Barr, T.J. Khoo, P. Konar, K. Kong, C.G. Lester, et al. Guide to transverse projections and mass-constraining variables. *Phys.Rev.*, D84:095031, 2011.

The Family of Singularity Variables

- Transverse mass-bounding variables

$M_{2\top}, M_{\top 2}, M_{\circ 2}$ and $M_{2\circ}$ PRD 84, 095031 [1108.5182]

- 3D (3+1) generalizations, possibly with constraints

JHEP 1408 070 [1401.1449]

Example:

test masses

$$M_{2CC} \equiv \min_{\vec{q}_1, \vec{q}_2} \{\max [M_{P_1}(\vec{q}_1, \tilde{m}), \; M_{P_2}(\vec{q}_2, \tilde{m})]\}$$

Extremization over 3D momenta

$$\vec{q}_{1T} + \vec{q}_{2T} = \vec{\not{P}}_T$$
$$M_{P_1} = M_{P_2}$$
$$M^2_{R_1} = M^2_{R_2}$$

subject to constraints

The Family of Singularity Variables

- Transverse mass-bounding variables

  $M_{2\top}, M_{\top 2}, M_{\circ 2}$ and $M_{2\circ}$ PRD 84, 095031 [1108.5182]

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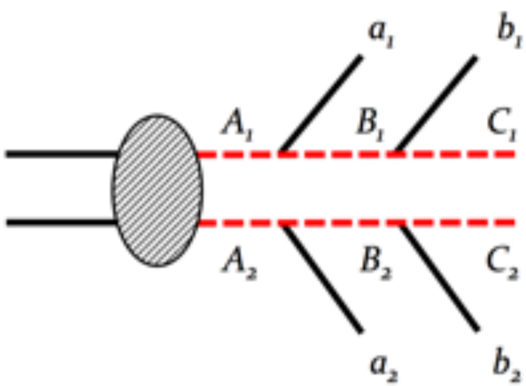
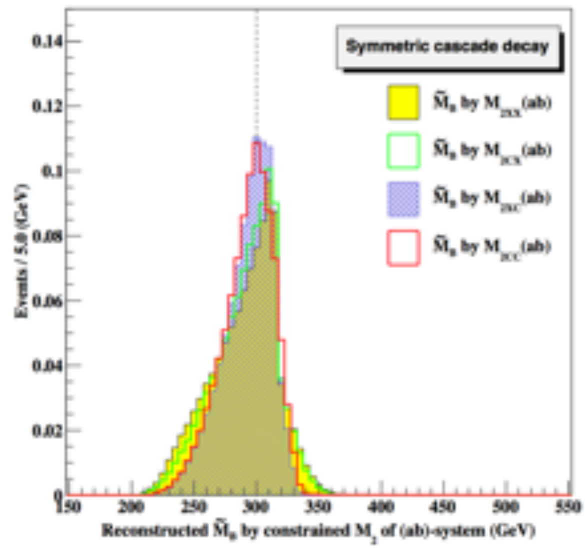
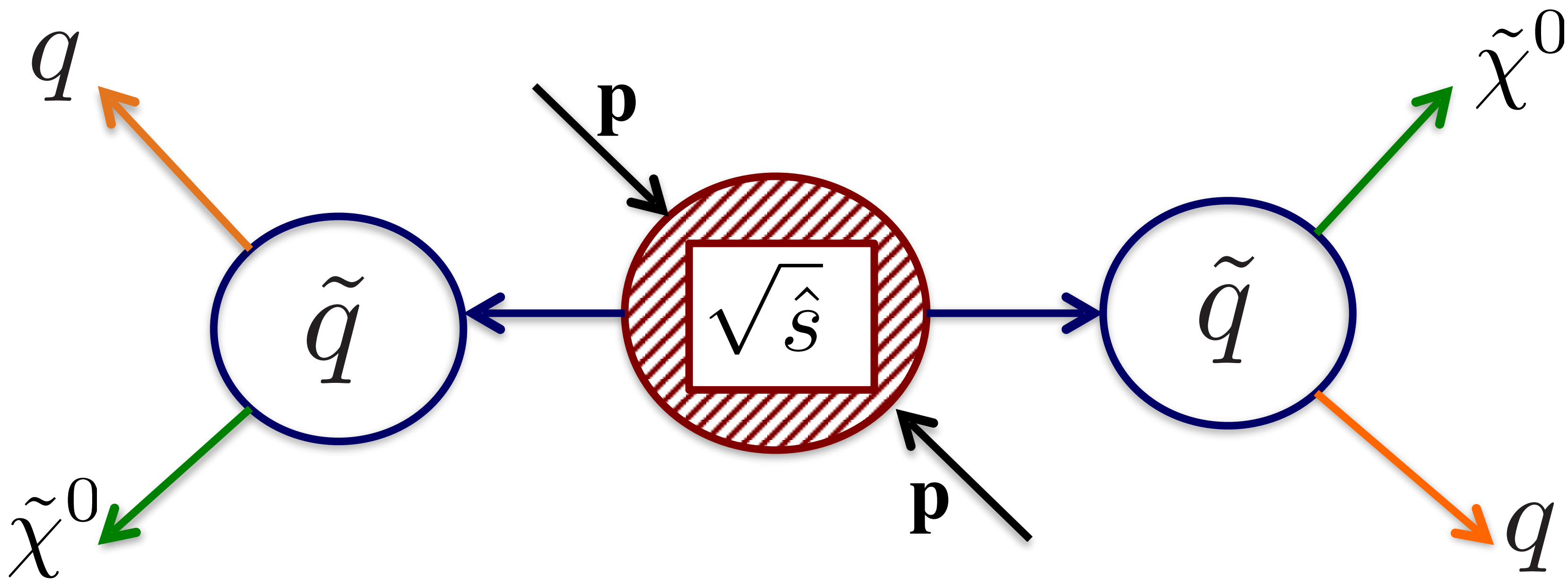
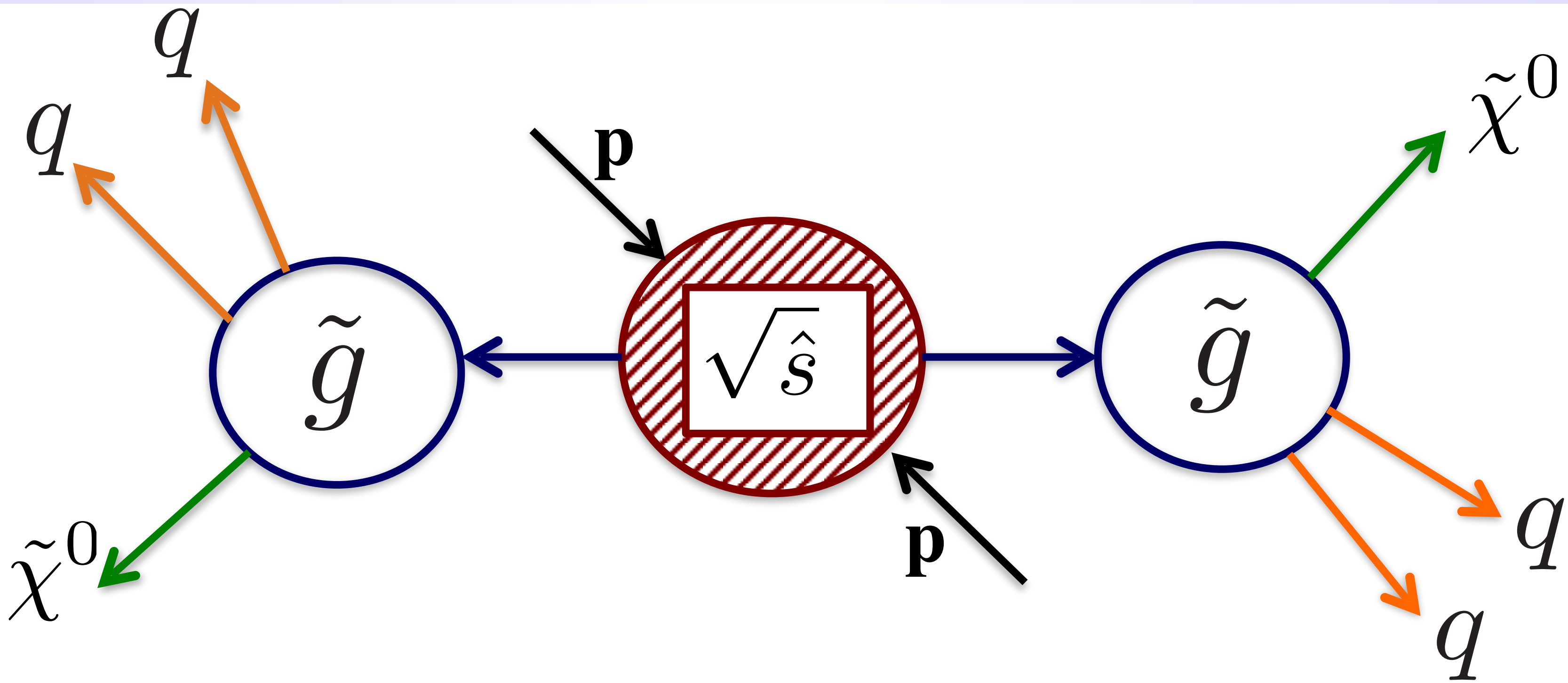




Jets + MET search



Jets + MET search



Partitioning LHC phase-space

- A list (incomplete) of observables used in recent LHC searches:

$$E_T^{\text{miss}},\ H_T^{\text{miss}},\ H_T,\ S_T,\ L_T,\ M_{eff},\ \frac{E_T^{\text{miss}}}{M_{eff}}$$

$$\frac{E_T^{\text{miss}}}{\sqrt{H_T}},\ M_{T2},\ M_{CT},\ M_{CT\perp},\ M_R,\ R$$

$$L_p,\ \ \min \Delta\phi_{\text{jet},\ E_T^{miss}},\ \alpha_T,\ dE/dx,\ \beta$$

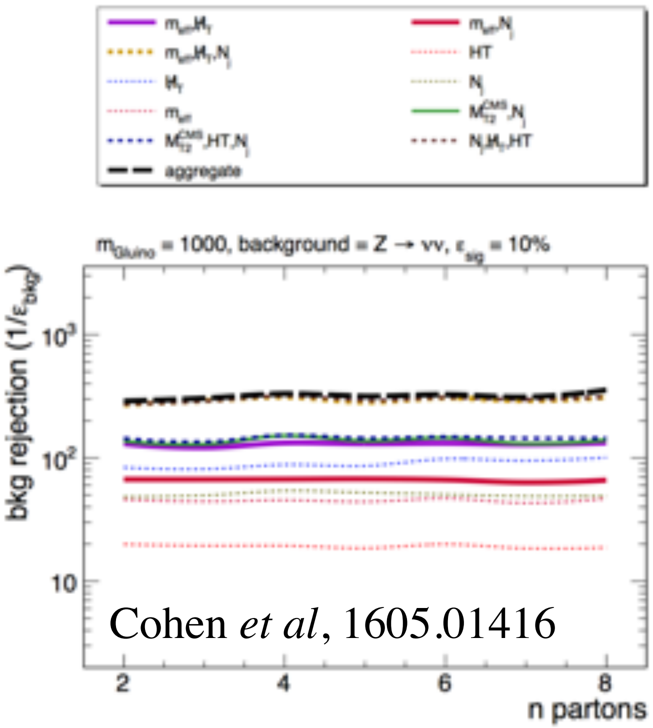
$$M_{jj},\ \Sigma M_{\text{jet}},\ \bar{M}_{\text{jet}},\ M_{\text{fat jet}},\ M_{\gamma\gamma},\ M_{\ell\ell}$$

$$N_{\text{jet}},\ N_{\text{b}-\text{tag}},\ N_{\ell},\ N_{\gamma},\ \cdots$$

- Many different ways to partition LHC phase-space…

SUSY Search Variables

- Which variables is/are the best?
  - Depends on final state, background composition, sparticle/particle masses, instantaneous luminosity, integrated luminosity, …



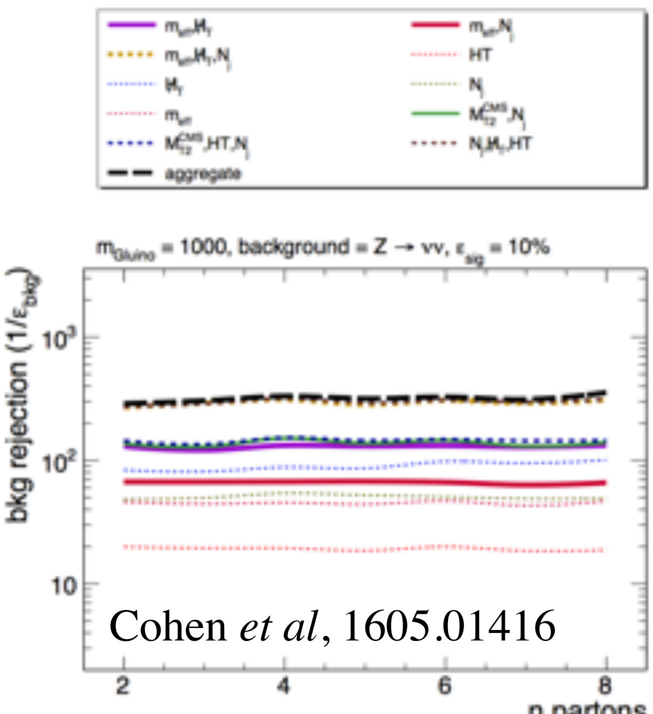
[1605.01416]

Study of Jets and MET searches for *n*-parton simplified models

Varying *n*, sparticle masses, compression and comparing different variables/combinations

SUSY Search Variables

- ~~Which variableis/are the best?~~ **wrong question**
  - Depends on final state, background composition, sparticle/particle masses, instantaneous luminosity, integrated luminosity, …



[1605.01416]
Study of Jets and MET searches for *n*-parton simplified models

Varying *n*, sparticle masses, compression and comparing different variables/combinations

- Which <u>combination/basis</u> is the best?

SUSY Search Variable Basis “wish-list”

- Complete
  - contains all the event information that’s useful
- Always well-defined
  - not over-constrained as to prevent real solutions
- Orthogonal/~uncorrelated
  - as little redundant information as possible (“minimal”)
- “Diagonalized”
  - Ideally, matched to the particle masses, decay angles, etc. that we hope to study/discover