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SUSY Phenomenology & Experimental searches

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Slides available at:

http://www.hep.ph.ic.ac.uk/~tapper/lecture.html

Reminder

- Supersymmetry is a theory which postulates a new symmetry between fermions and bosons
- Best studied extension to the Standard Model with vast literature
- Has the potential to solve some of the most serious problems in the Standard Model quite naturally

- Now how we search for Supersymmetry at colliders?

Outline

- What's the strategy?
- Detailed example of hadronic search
- What if we find something?
- Next steps

Reading list

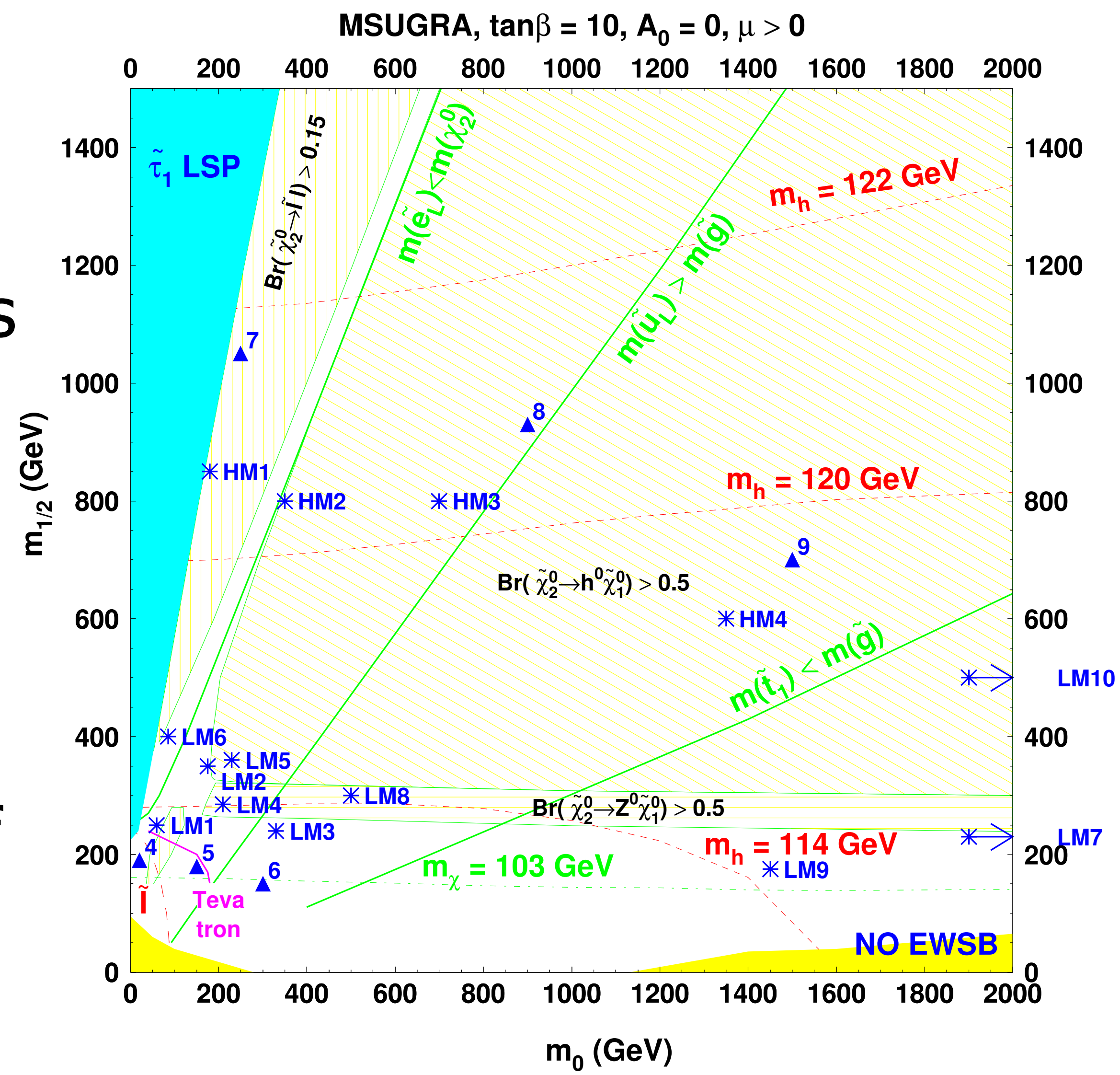
- Vast literature on Supersymmetry

- Latest results from the LHC
  - ATLAS SUSY group
    - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
  - CMS SUSY group
    - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

- Check any day on hep-ex to see latest papers
    - http://arxiv.org/archive/hep-ex

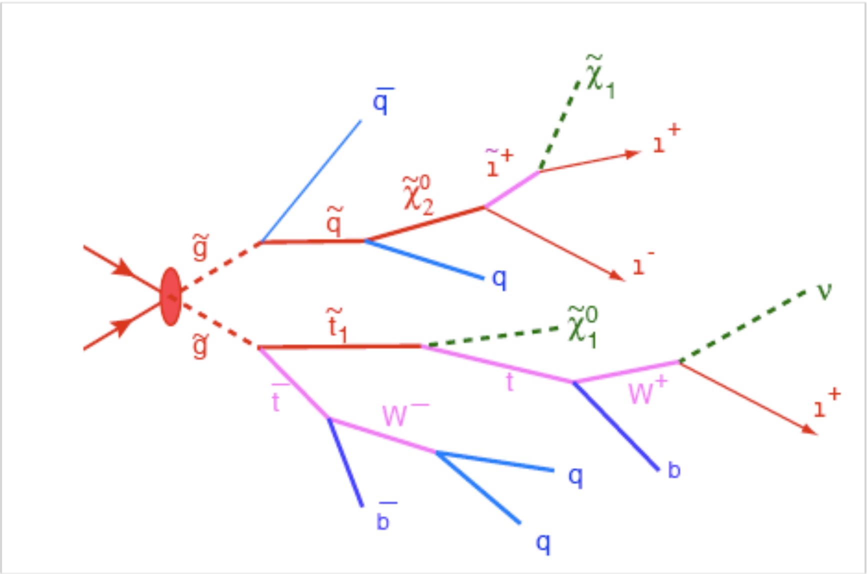
SUSY search strategy

- Be as model independent as possible
  - But the MSSM has > 100 parameters
  - Need more constrained models
  - Choose a set of benchmark points that are representative of a range of topologies and areas of phase space
  - Points usually used CMSSM at low masses, just above the (LMx)



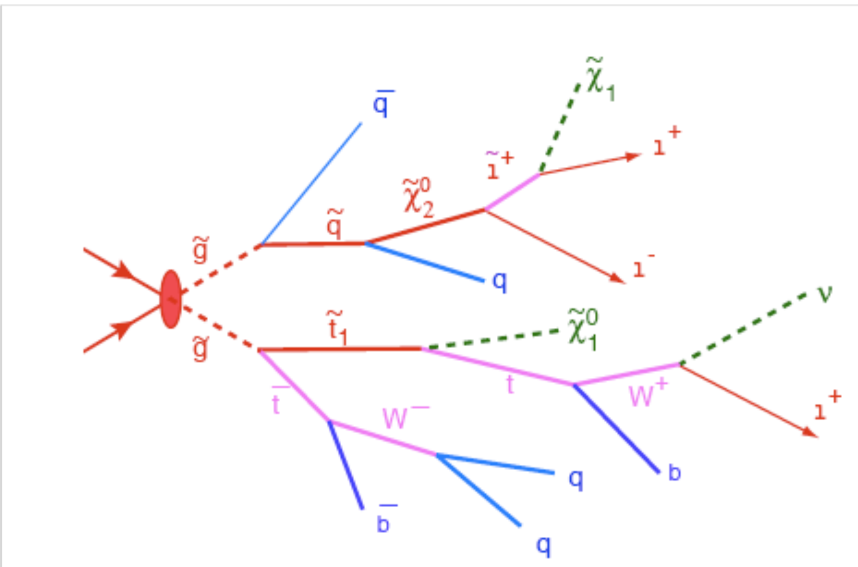
J. Phys. G: Nucl. Part. Phys. 34 (2006)

SUSY search strategy



- Production
  - Squark and gluino expected to dominate
  - Strong production so high cross section
  - Cross section depends only on masses
  - Approx. independent of SUSY model

SUSY search strategy



- Production
  - Squark and gluino expected to dominate
  - Strong production so high cross section
  - Cross section depends only on masses
  - Approx. independent of SUSY model
- Decay
  - Details of decay chain depend on SUSY model (mass spectra, branching ratios, etc.)
  - Assume RP conserved ➔ decay to lightest SUSY particle (LSP)
  - Assume squarks and gluinos are heavy ➔ long decay chains
- Signatures
  - MET from LSPs, high-E_T jets and leptons from long decay chain
  - Focus on robust and simple signatures
  - Common to wide variety of models
- Background and detector performance define searches not models

Backgrounds

- Physics
  - Standard Model processes that give the same signatures as SUSY
  - Rely on Monte Carlo predictions? ➔ measure in data
- Detector effects
  - Detector noise, mis-measurements etc. that generate MET or extra jets
  - Commissioning and calibration
- Beam related
  - Beam-halo muons (and cosmic-ray muons), beam-gas events
  - Data and simulation already ➔ measure in situ too

Search strategy (what and how?)

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

- Generic missing energy signatures
- Categorised by numbers of leptons and photons
- Many include jets ➔ strong production

Search strategy (what and how?)

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

– Very challenging due to large amount and wide range of backgrounds

– However most sensitive search for strongly produced SUSY

– CMS pursues several complementary strategies based on kinematics and detector understanding

– Extend to b, τ and top-tagged final states

Search strategy (what and how?)

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

- Lepton (electron or muon) requirement reduces background considerably
- Only ttbar and W+jets left

Search strategy (what and how?)

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

- Adding a second lepton (electron or muon) reduced W background
- Several techniques including opposite-sign opposite-flavour subtraction
- Shape information and mass edges

Search strategy (what and how?)

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
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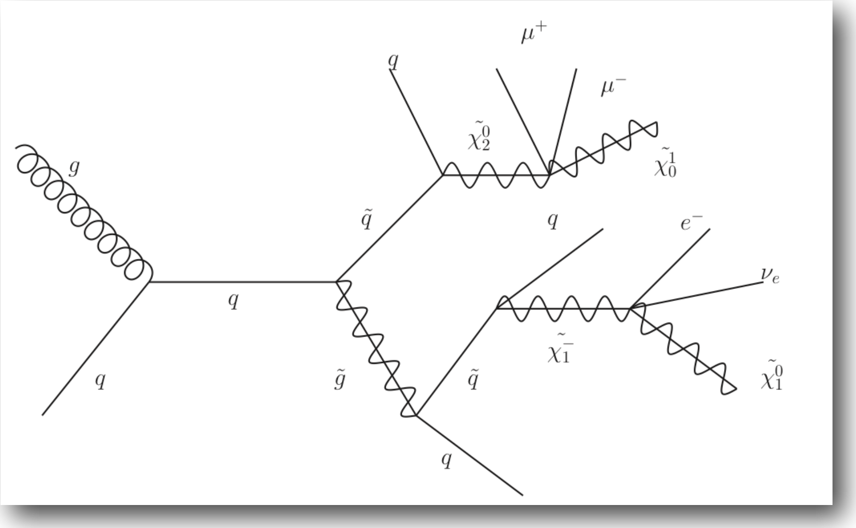


- A natural SUSY signature
- Very small Standard Model backgrounds
- Include all three generations of leptons and all cross channels

Search strategy (what and how?)

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

- Very clean events with very low Standard Model background
- Include all three generations of leptons and all combinations
- Search inclusively, on the Z peak, with and without MET
- Some striking Standard Model events observed

Search strategy (what and how?)

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

- Many gauge-mediated models predict photons in final state
- Di-photon searches dominated by QCD multijet and γ+jet backgrounds

Search strategy (what and how?)

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

– Many gauge mediated models predict photons in final state
– Lepton reduces QCD multijet and γ+jet backgrounds

Search strategy (what and how?)

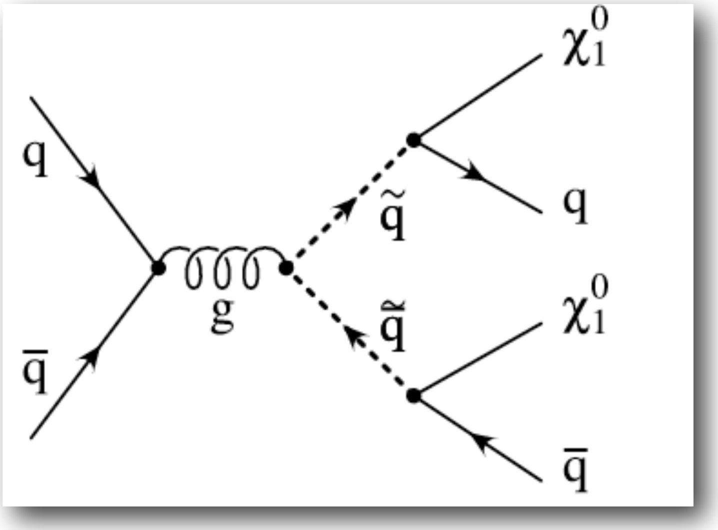
0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

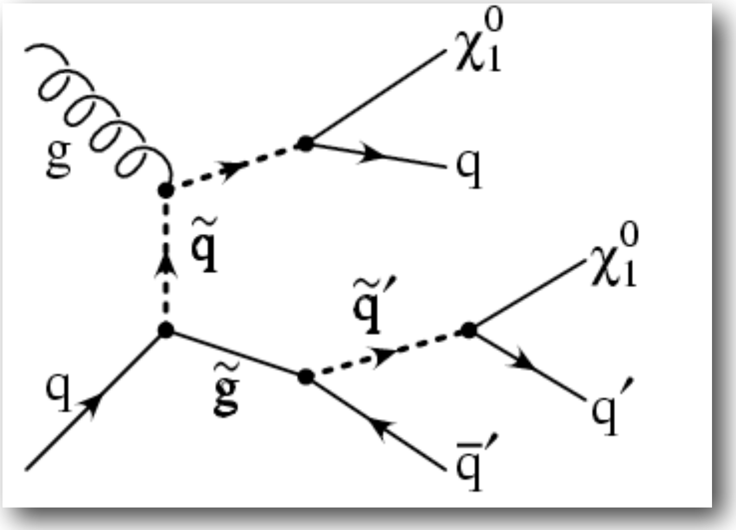
RPV	"Exotic"
R-Parity violating searches	Long-lived particles etc.

- Non-MET based searches
- R-parity conserving and "exotic" SUSY
- Examples are long-lived particles

All-hadronic SUSY search

- SUSY particles produced strongly and decay through long cascade



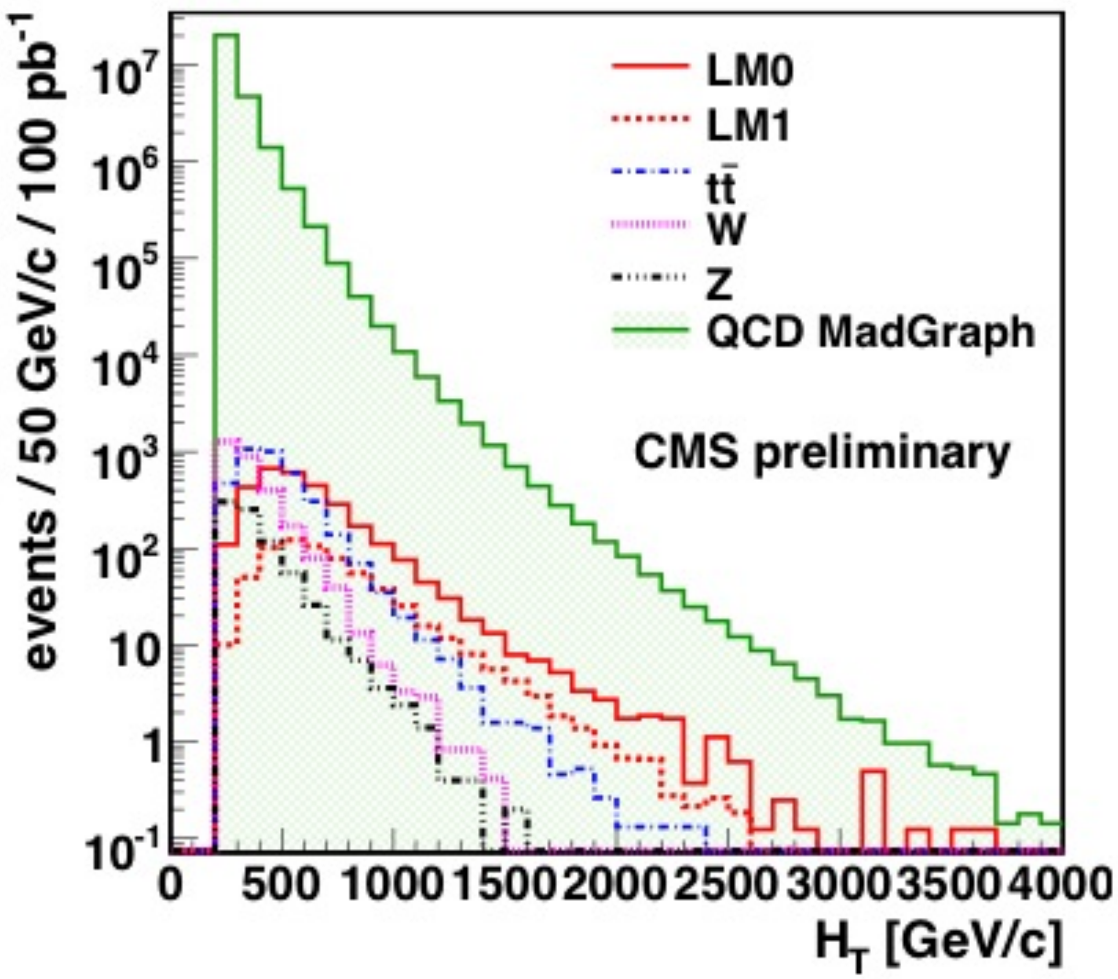


- Search for excess of events with large MET (from LSP) and several hadronic jets
- Veto events with leptons

All-hadronic SUSY search

- Simple (pre)selection
  - At least two jets with E_T>50 GeV and $|\eta|<3.0$
  - Veto events with an electron or muon P_T>10 GeV
- Use energy sums based on jets
  - More robust since you can put minimum E_T cut
  - H_T scalar sum of jet E_T
  - MHT vector sum of jet E_T
- Enhance SUSY-like processes
  - E_T of two highest E_T jets > 100 GeV $|\eta_{j1}|<2.0$
- Look at simulation to see what processes form backgrounds to your signal →

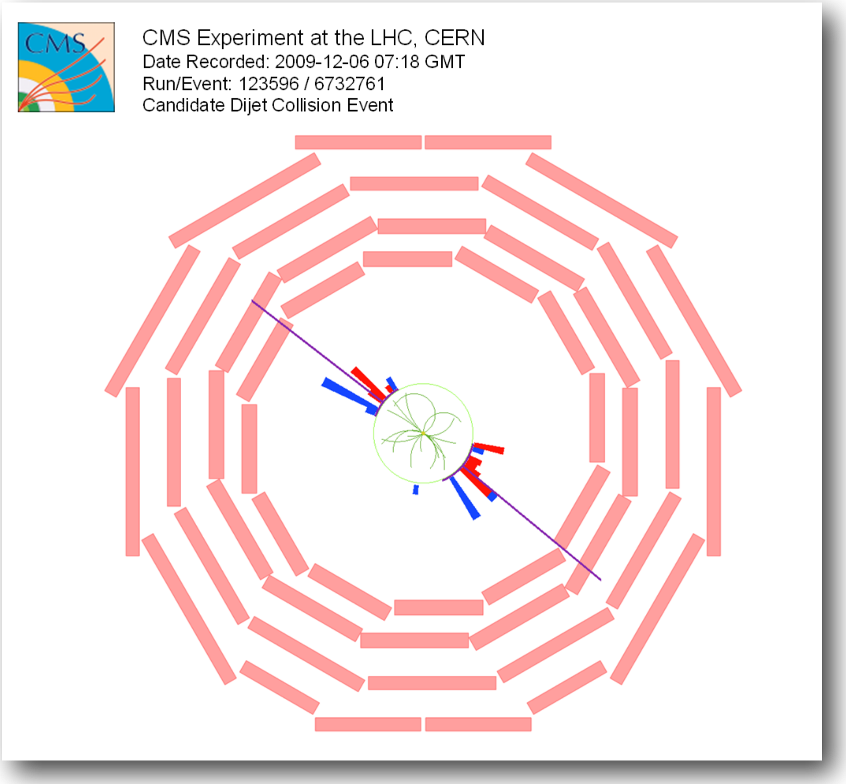
All-hadronic SUSY search

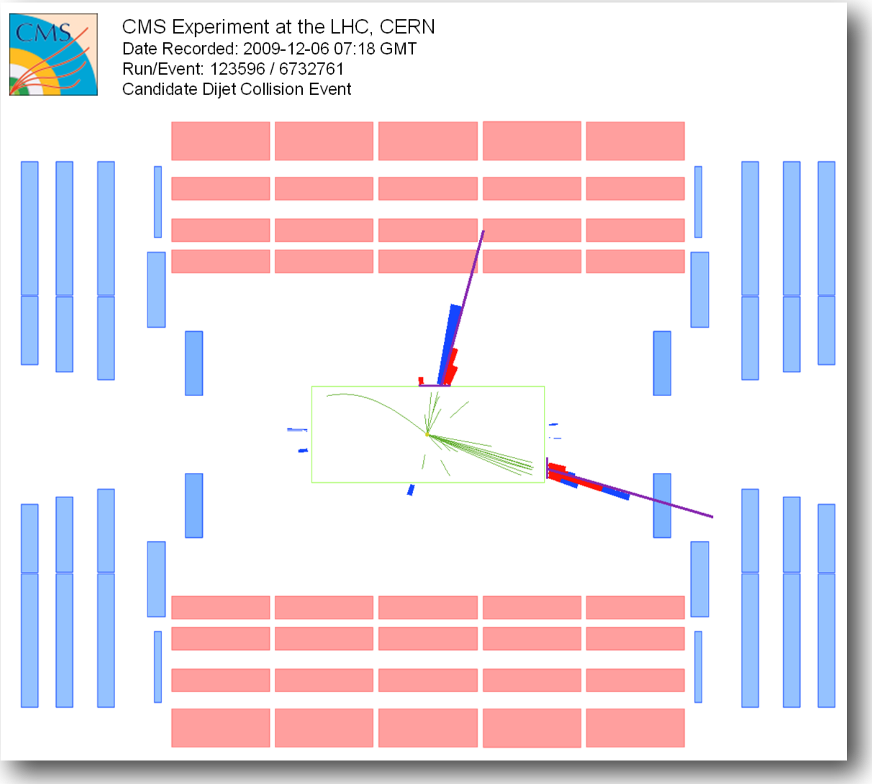


CMS-PAS-SUS-08-005
CMS-PAS-SUS-09-001
CMS-PAS-SUS-11-001
Phys. Lett. B698:196 (2011)
arXiv:1109.2352

- QCD is by far largest background
- Z-boson decays to neutrinos
- Top-pair production and W-boson decays

Background from QCD

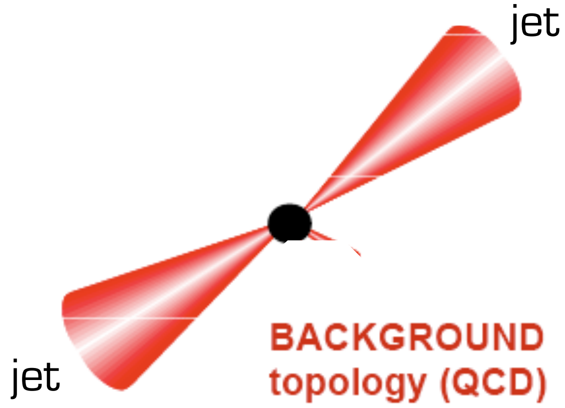


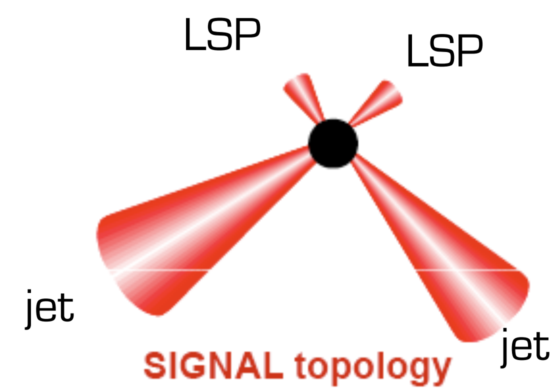


- QCD processes lead to di-jet events
- Gluon radiation gives >2 jets
- When perfectly measured no MET but...
  - Not a perfect detector
  - Semi-leptonic decays in jets (b and c quarks)

All-hadronic search

Phys. Rev. Lett. 101:221803 (2008)



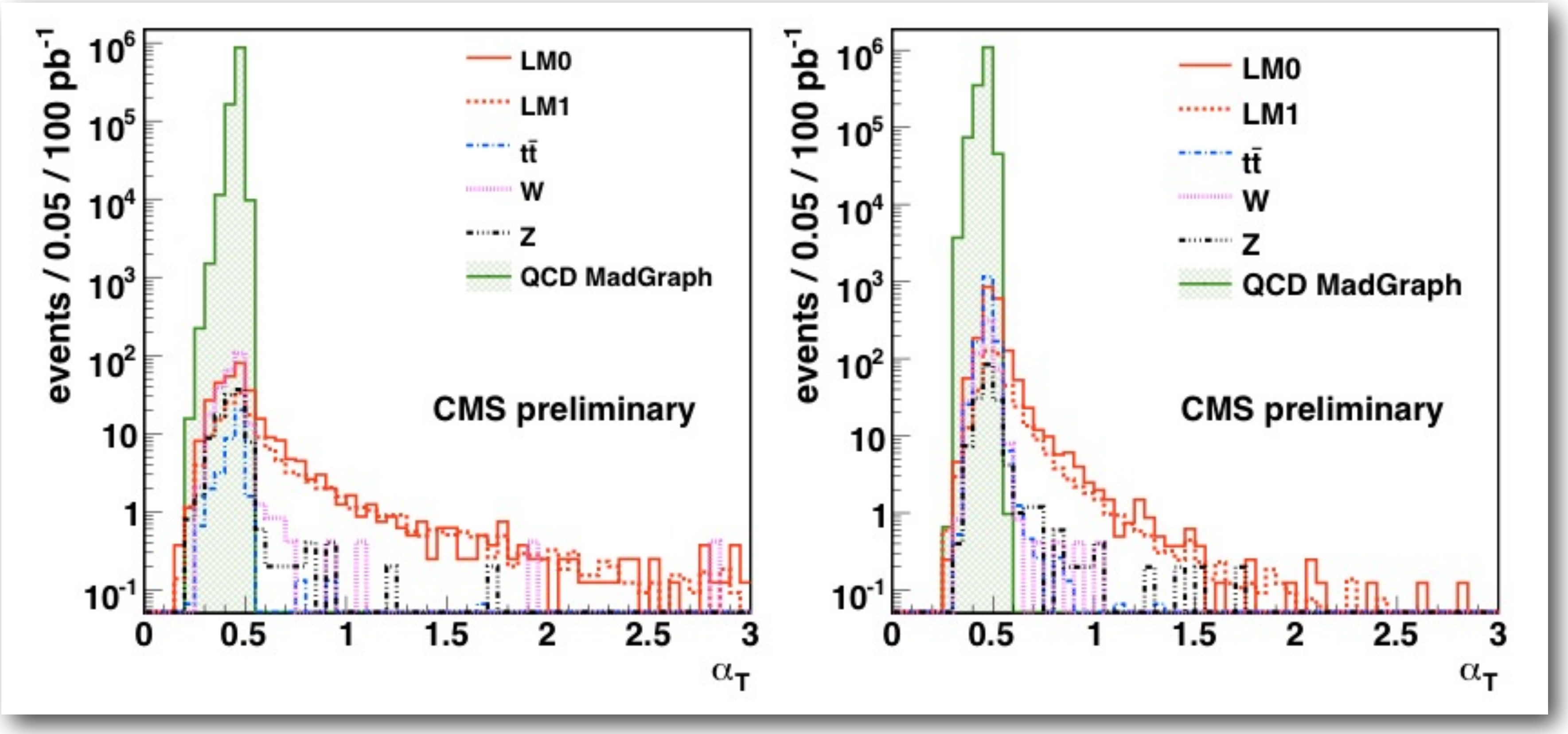


- A novel approach combining angular and energy measurements

$$\alpha_T = \frac{E_{T\ j2}}{M_{T\ j1j2}} = \frac{\sqrt{E_{T\ j2}/E_{T\ j1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$

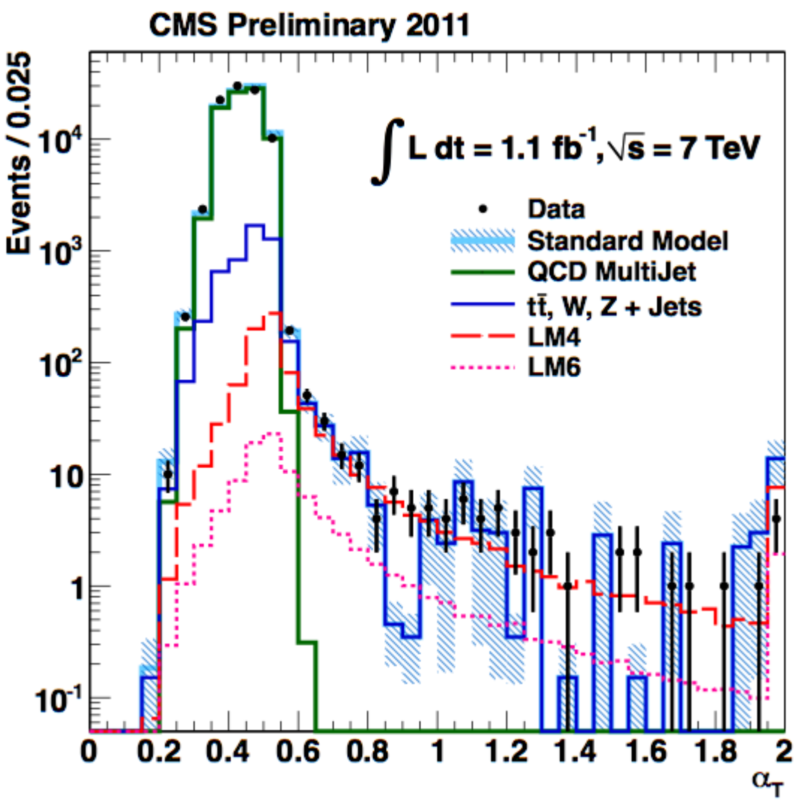
- Perfectly balanced events have α_T=0.5
- Mis-measurement of either jet leads to lower values

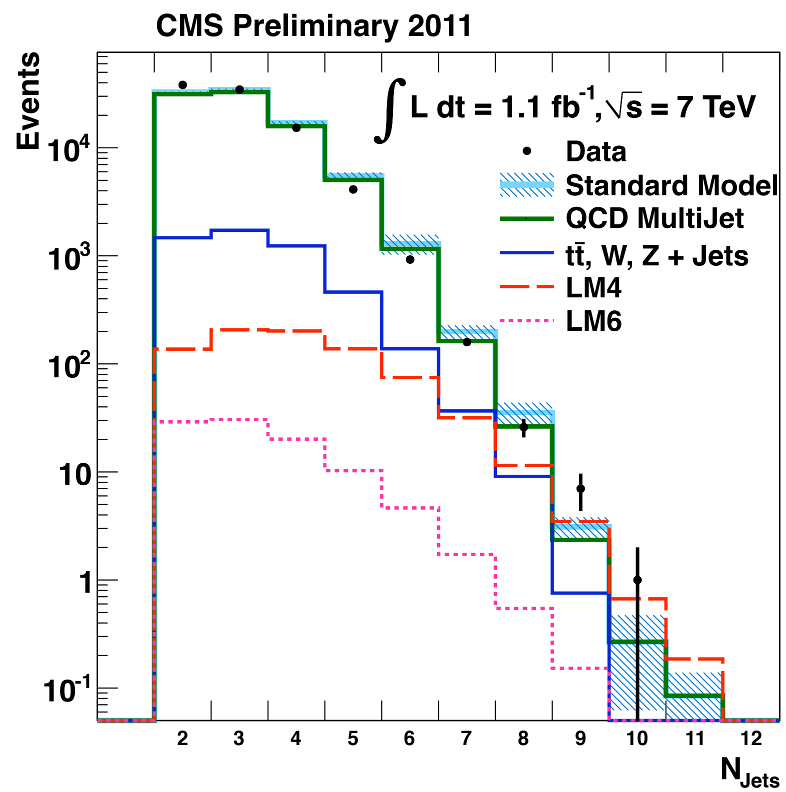
All-hadronic search

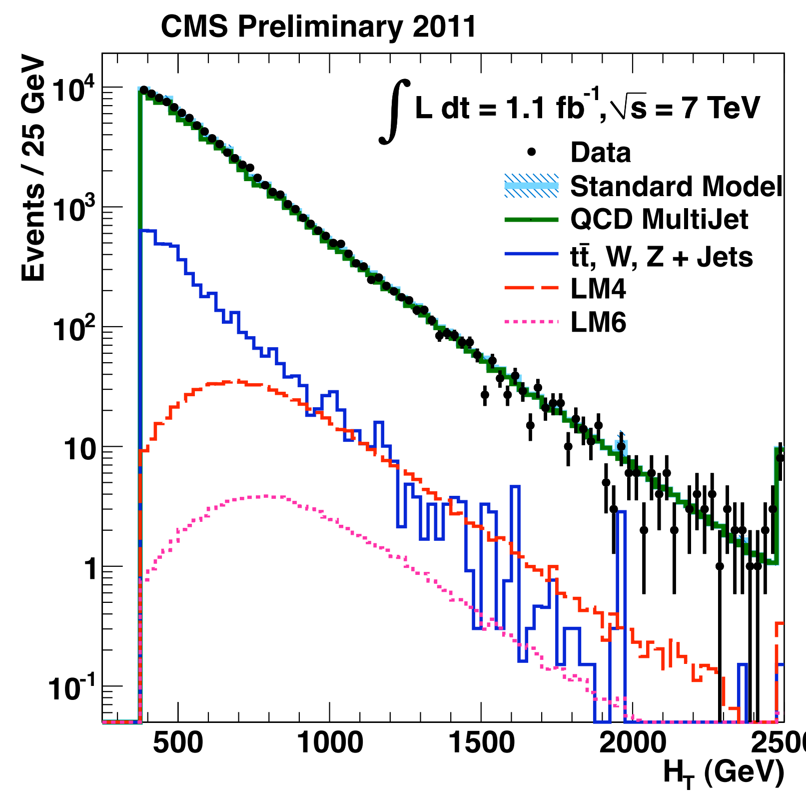


- Originally proposed for di-jet events ➔ generalised up to six jets
- Perfectly balanced events have α_T=0.5 (cut at α_T>0.55)
- Mis-measurement of either jet leads to lower values

All-hadronic SUSY search



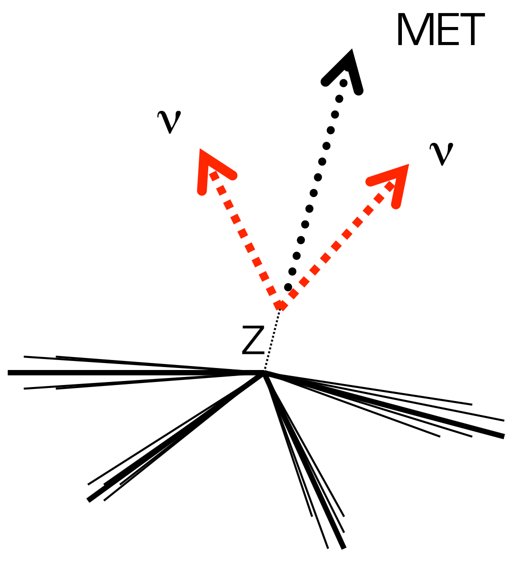


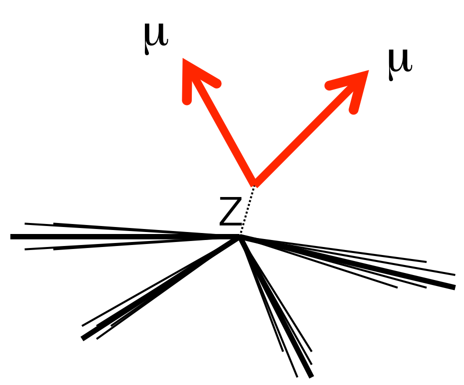


- Make cut on $\alpha_T > 0.55$ QCD under control
- Look at other backgrounds →

Z-boson background

- Data-driven background estimate
  - Find a **control region** in phase space where SM background dominates
  - Use measurements in this region to infer SM background in signal region
  - Example Z → νν + jets ➔ irreducible background
  - **Replacement technique**

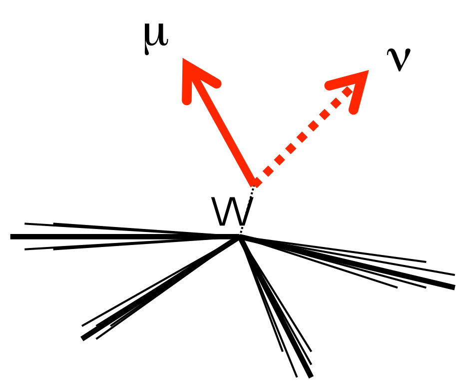




$Z \rightarrow ll$ + jets

Strength: very clean

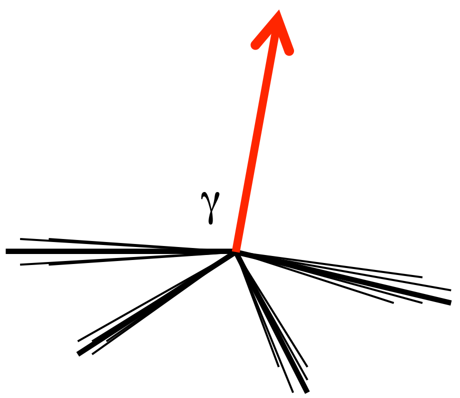
Weakness: low statistics



$W \rightarrow l\nu$ + jets

Strength: larger statistics

Weakness: background from SM and SUSY



γ + jets

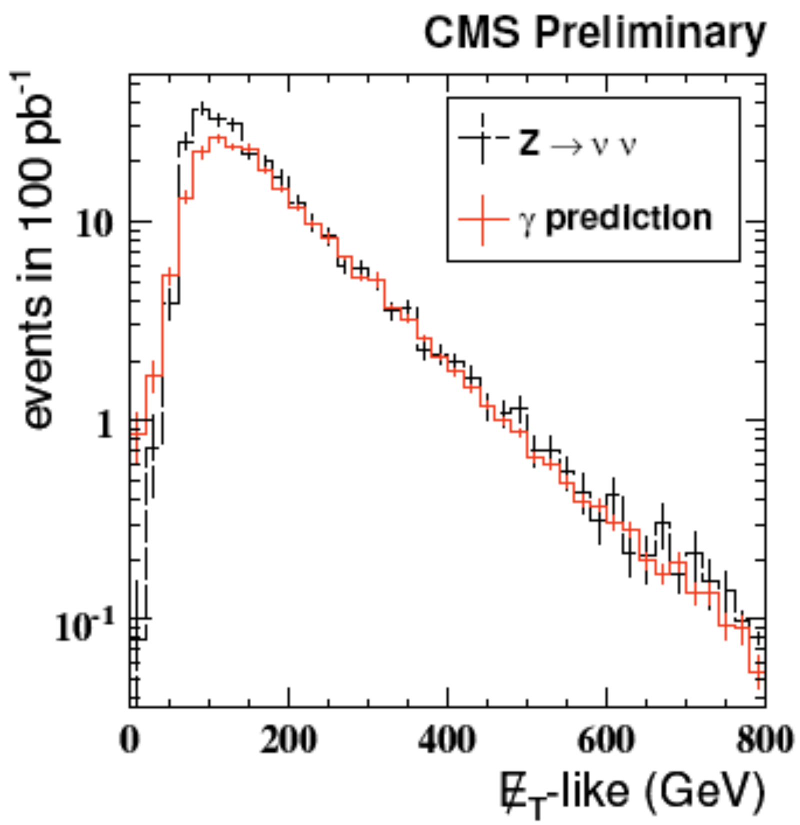
Strength: large statistics and clean at high E_T

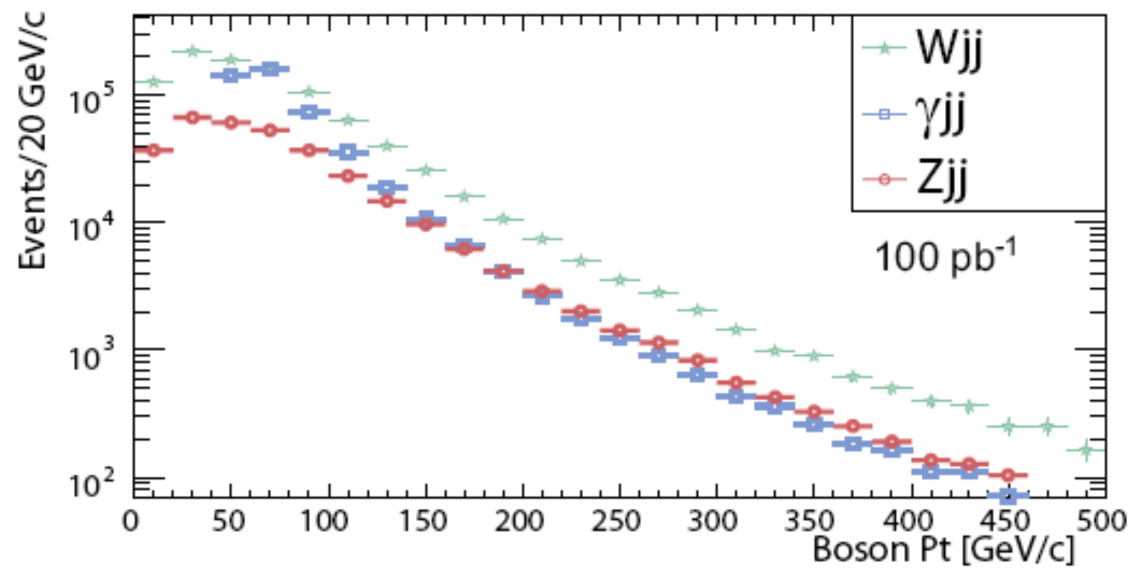
Weakness: background at low E_T, theoretical errors

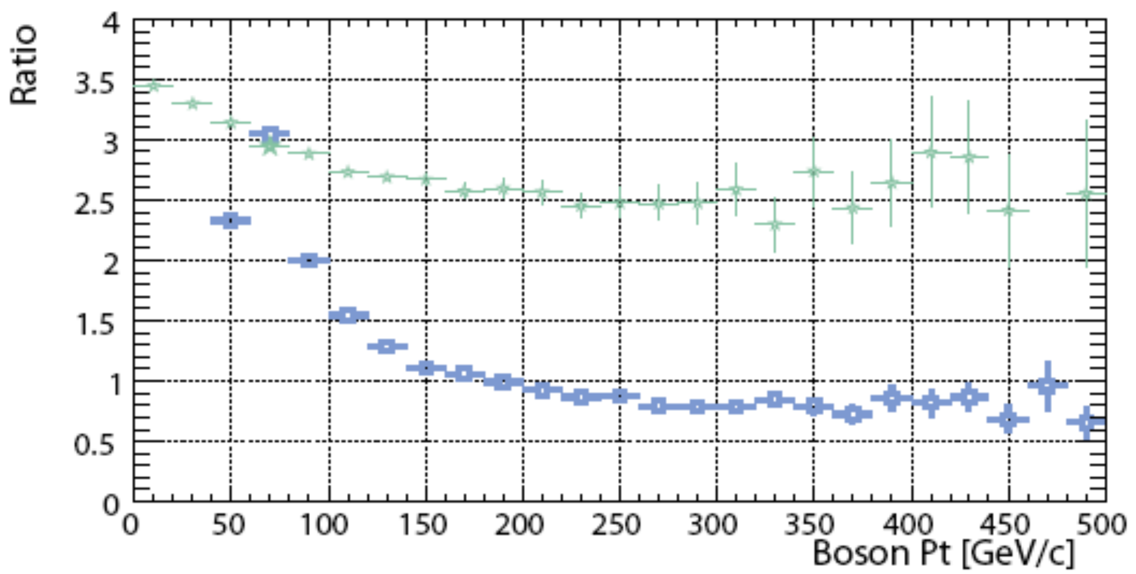
Z-boson background

CMS-PAS-SUS-08-002

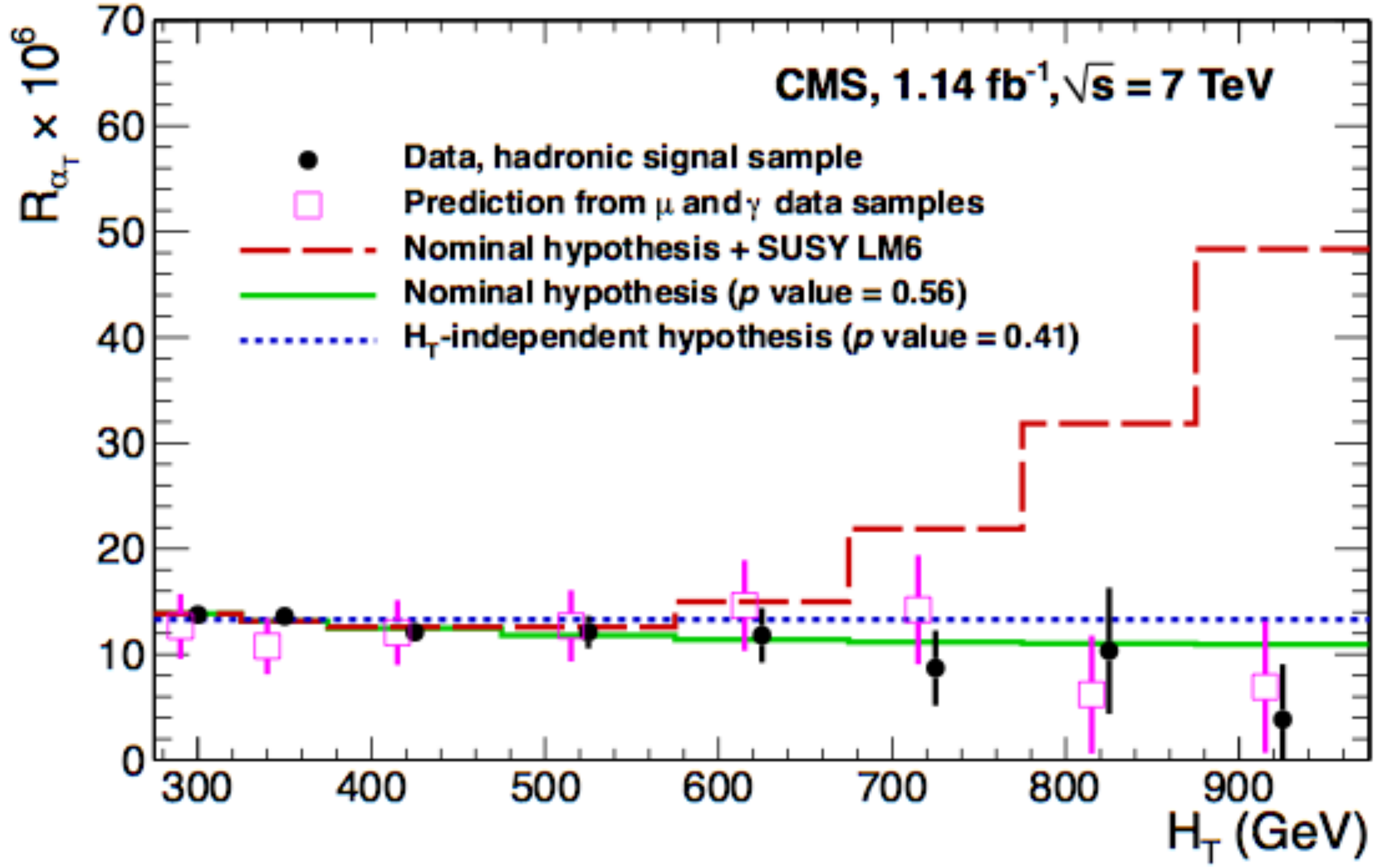
- Select γ + ≥3 jets with Eγ>150 GeV
  - Clean sample S/B>20
  - Remove photon from the event
  - Recalculate MET
  - Normalise with σ(Z+jets)/σ(γ+jets) from MC or measurements





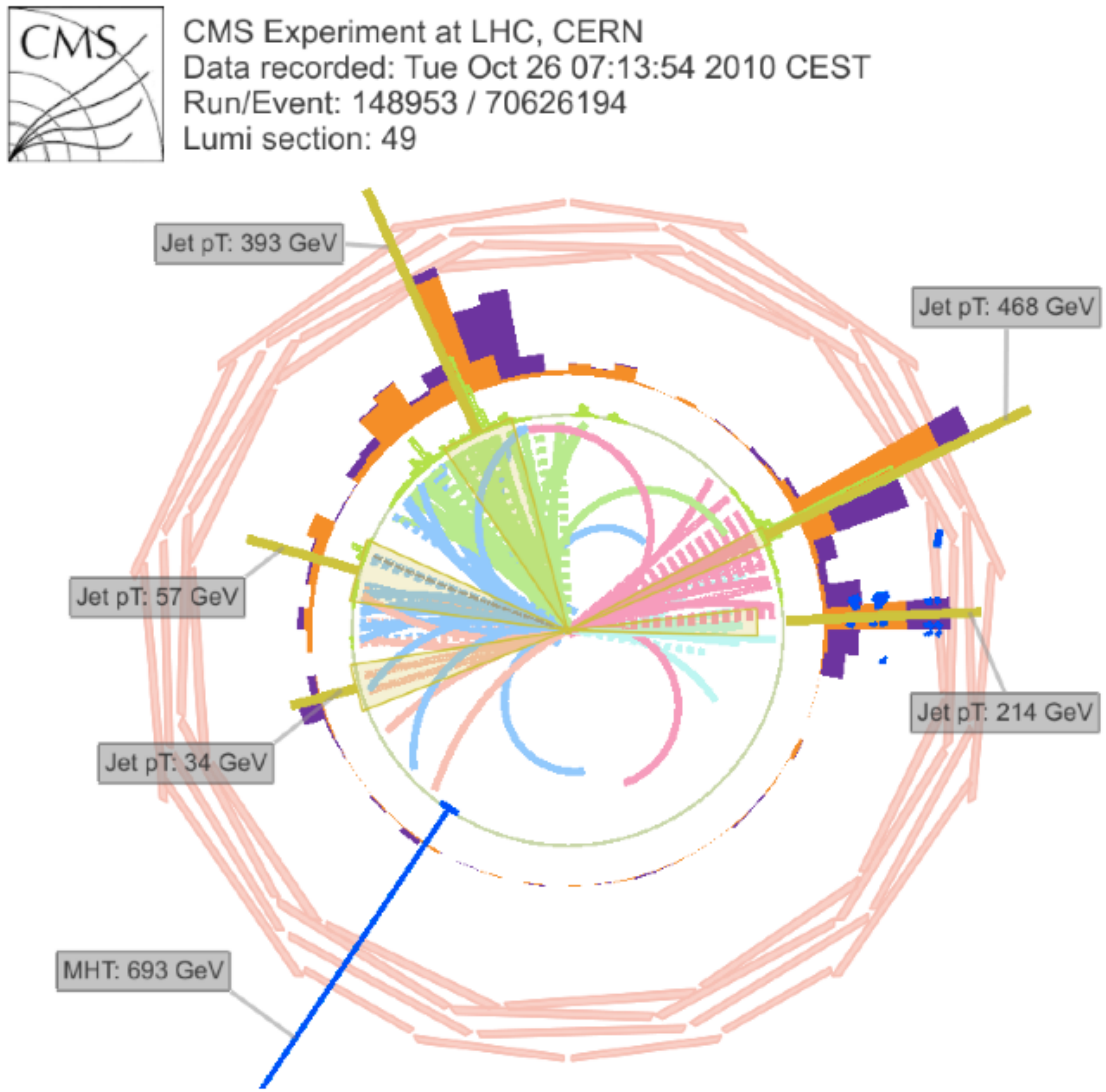


Results

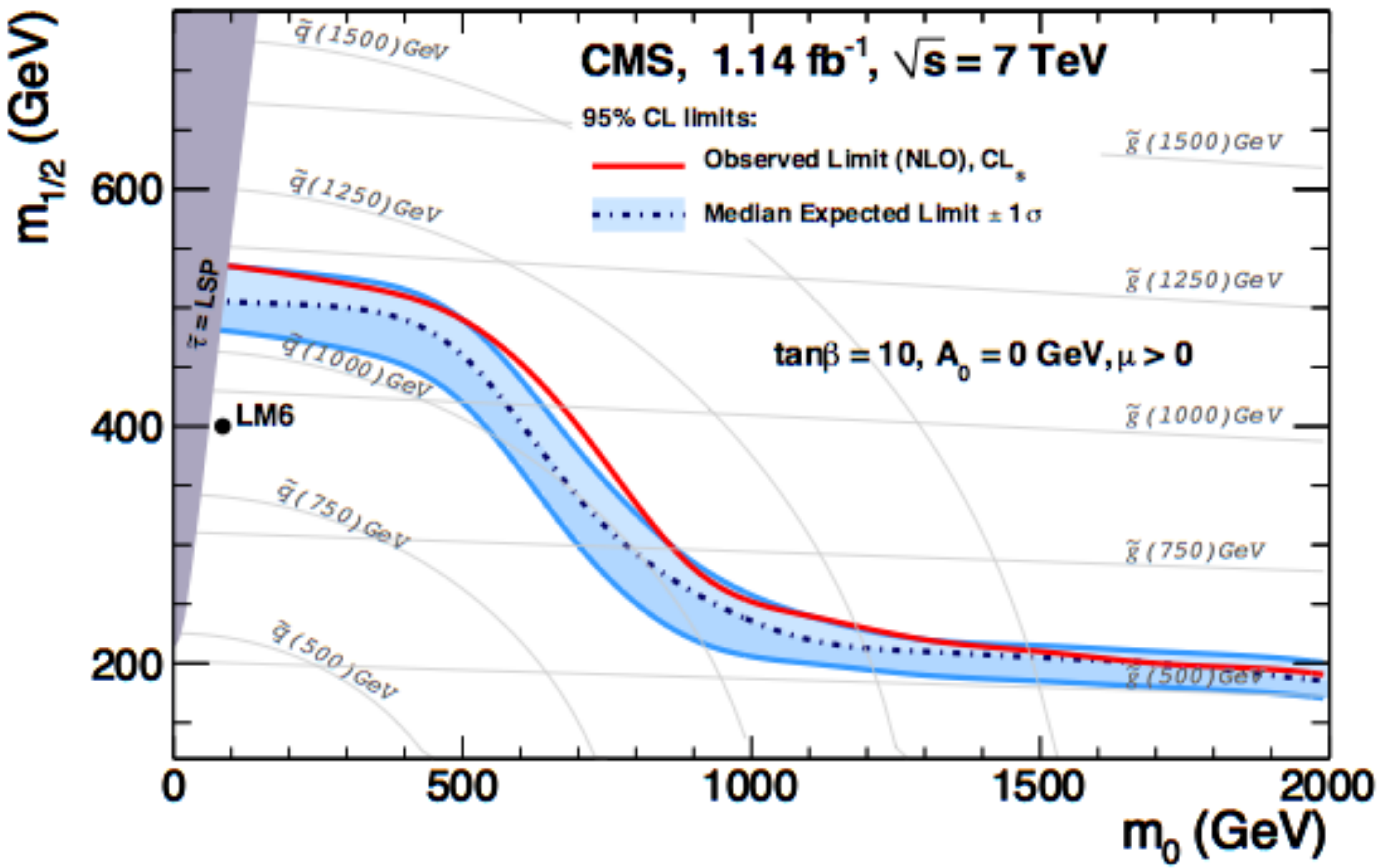


H_T bin (GeV)	275–325	325–375	375–475	475–575	575–675	675–775	775–875	>875
SM hadronic	787^{+32}_{-22}	310^{+8}_{-12}	202^{+9}_{-9}	$60.4^{+4.2}_{-3.0}$	$20.3^{+1.8}_{-1.1}$	$7.7^{+0.8}_{-0.5}$	$3.2^{+0.4}_{-0.2}$	$2.8^{+0.4}_{-0.2}$
Data hadronic	782	321	196	62	21	6	3	1
SM μ + jets	367^{+15}_{-15}	182^{+8}_{-9}	113^{+8}_{-7}	$36.5^{+3.8}_{-3.3}$	$13.4^{+2.2}_{-1.8}$	$4.0^{+1.4}_{-1.2}$	$0.8^{+0.9}_{-0.1}$	$0.7^{+0.9}_{-0.1}$
Data μ + jets	389	156	113	39	17	5	0	0
SM γ + jets	834^{+28}_{-30}	325^{+17}_{-17}	210^{+12}_{-12}	$64.7^{+6.9}_{-7.0}$	$21.1^{+3.9}_{-4.3}$	$10.5^{+2.5}_{-2.6}$	$6.1^{+0.9}_{-1.7}$	$5.5^{+0.9}_{-1.6}$
Data γ + jets	849	307	210	67	24	12	4	4

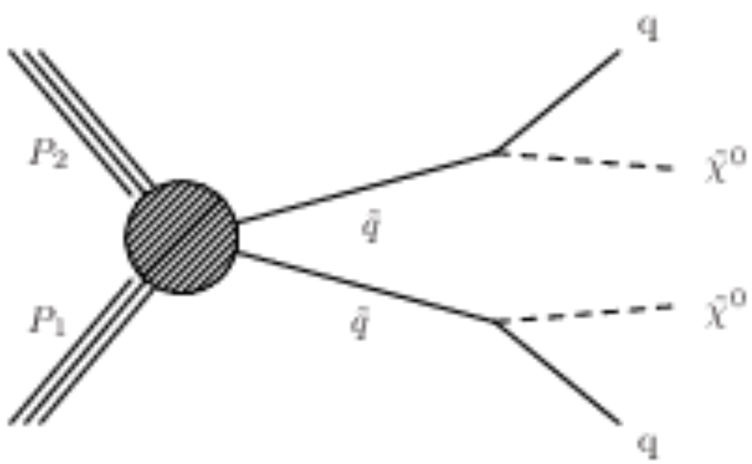
Candidate event

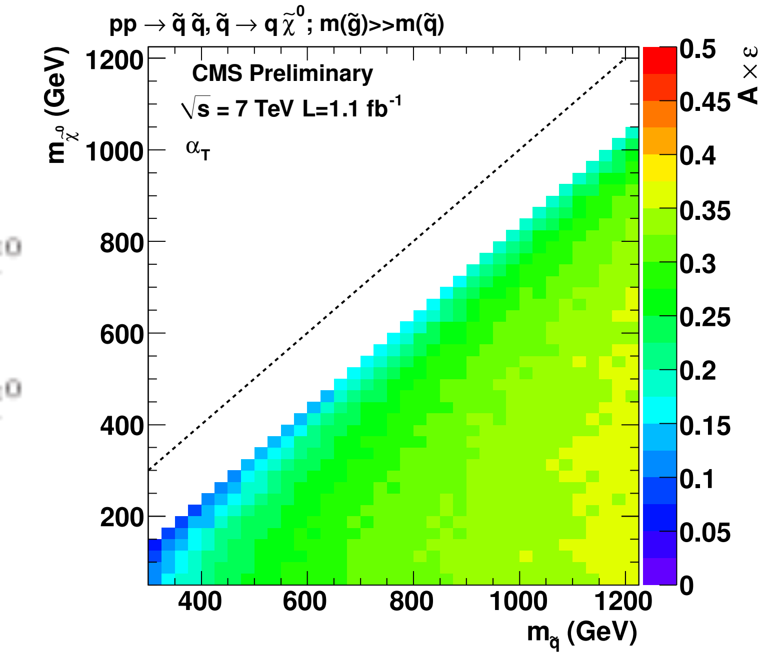


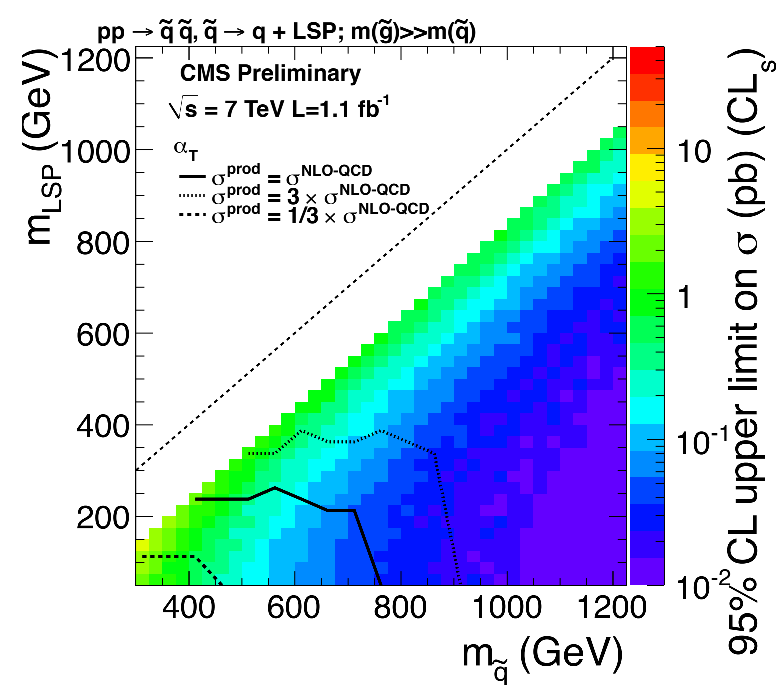
Limit in the CMSSM

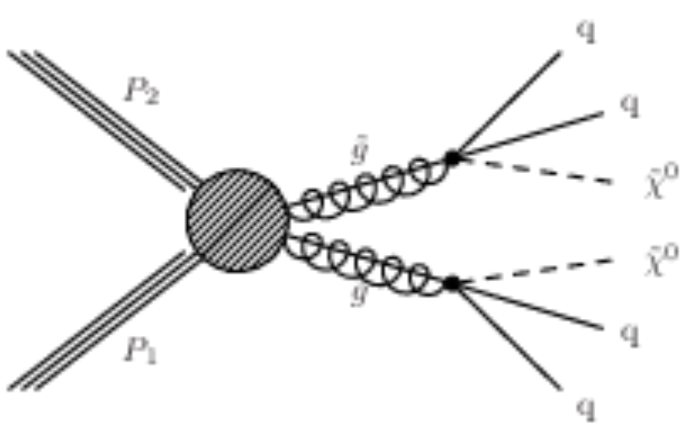


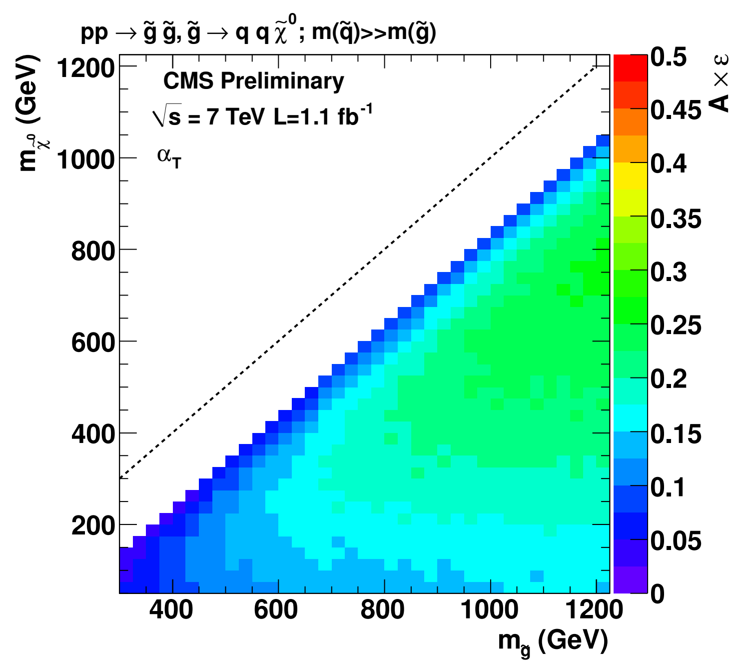
Simplified Models

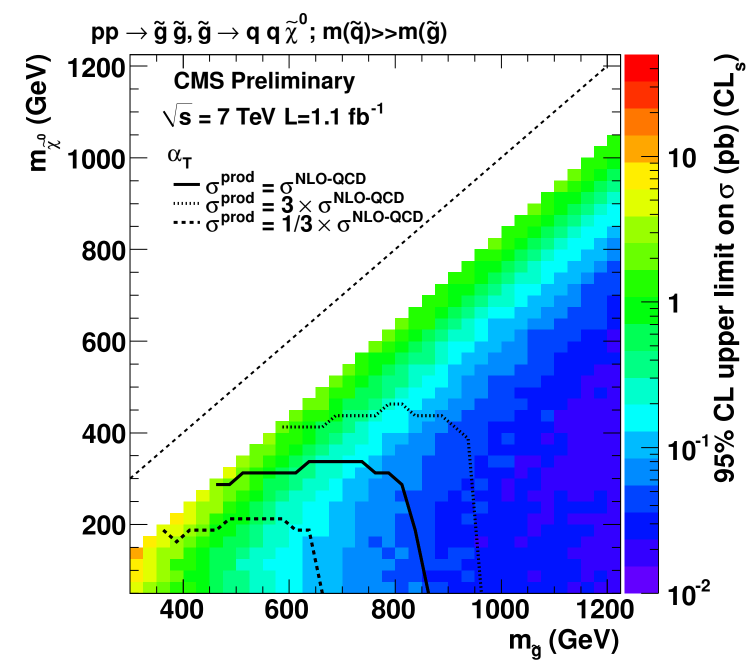




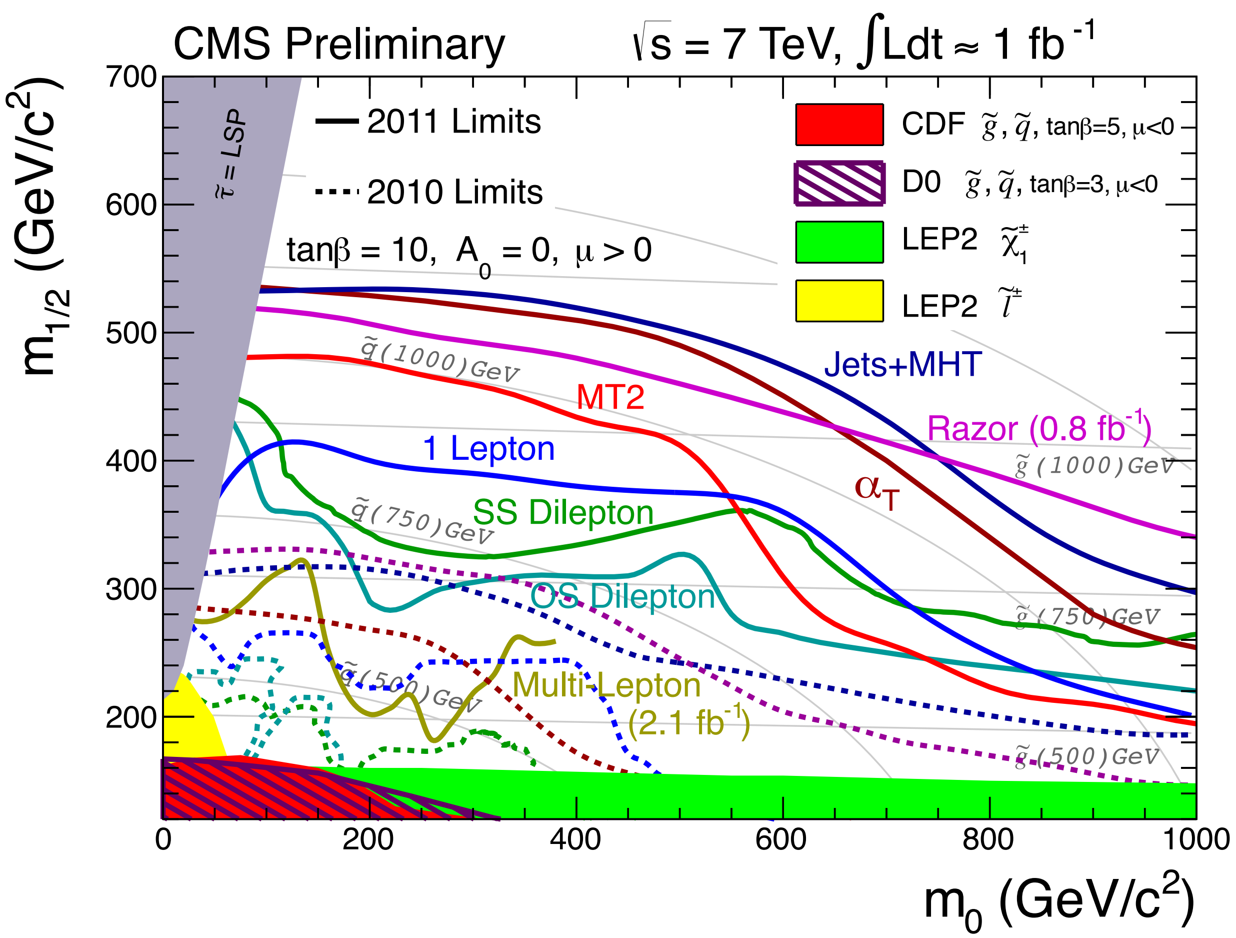


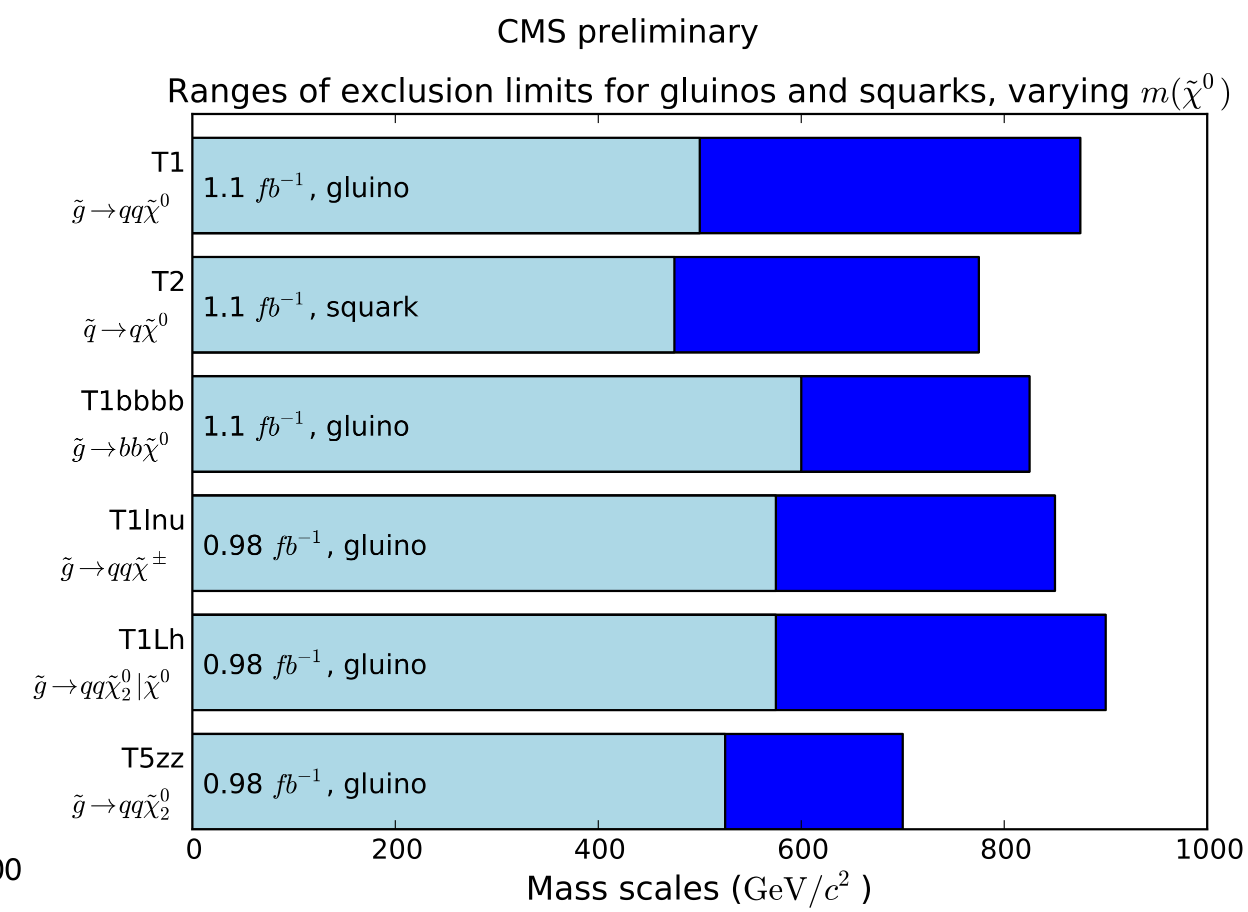






Summary of limits





For limits on $m(\tilde{g}), m(\tilde{q}) >> m(\tilde{g})$ (and vice versa). $\sigma^{\mathrm{prod}} = \sigma^{\mathrm{NLO-QCD}}$.

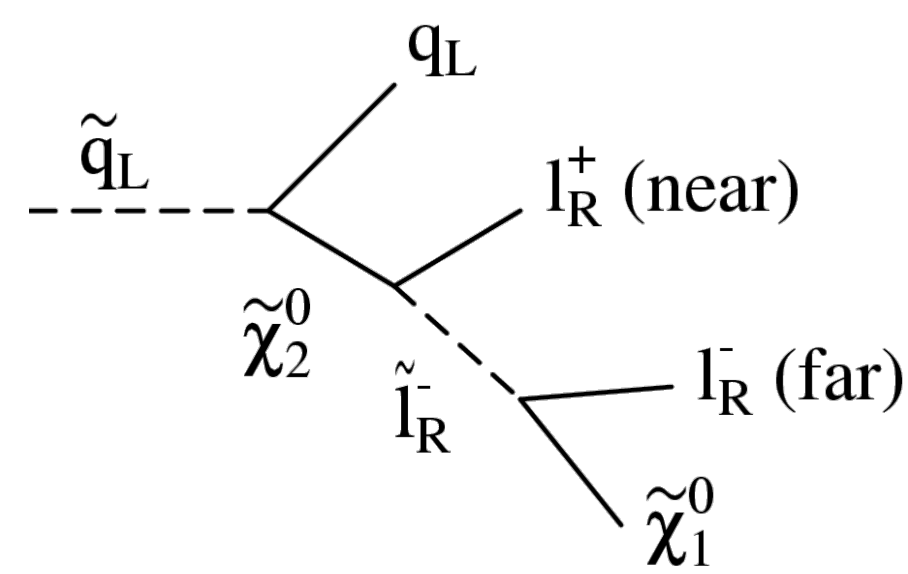
$m(\tilde{\chi}^{\pm}), m(\tilde{\chi}^0_2) \equiv \frac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}$.

$m(\tilde{\chi}^0)$ is varied from 0 GeV/c^2 (dark blue) to $m(\tilde{g}) - 200\ GeV/c^2$ (light blue).

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Mass determination example

- Two undetected LSPs per event
  - No mass peaks
  - Constraints from edges and endpoints in kinematic distributions

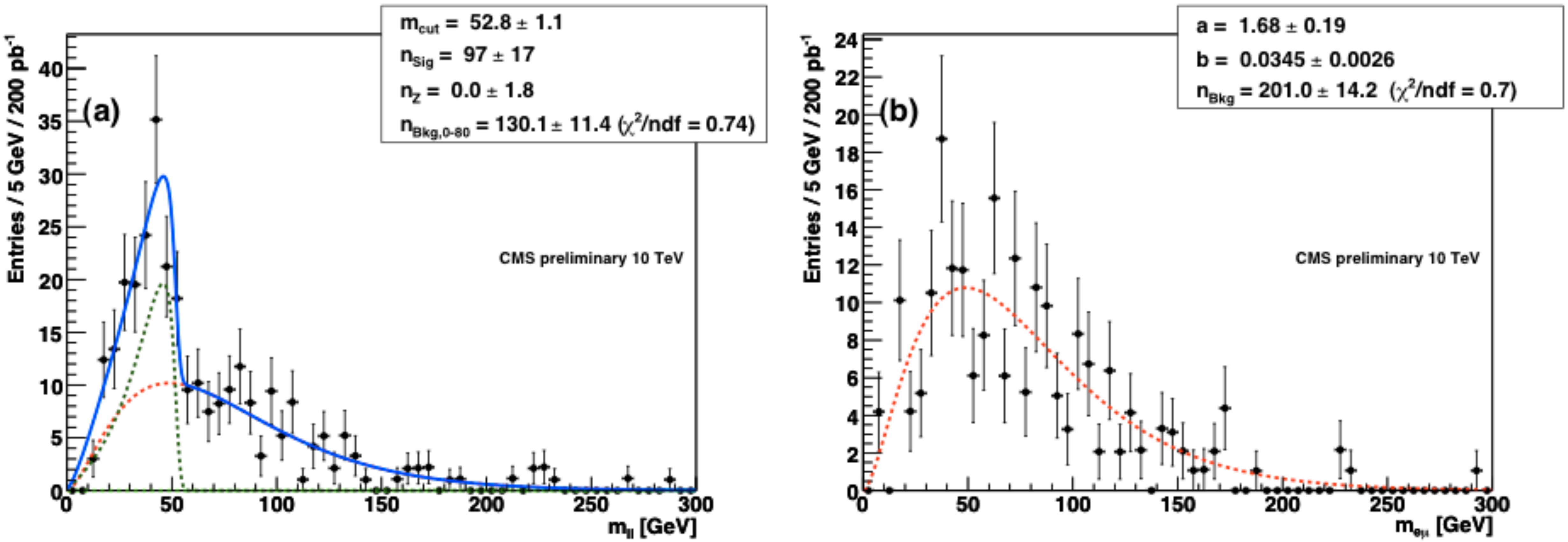


  - Two-body $$(m_{ll}^{max})^2 = \frac{\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}}\right)\left(m^2_{\tilde{l}} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{l}}}$$
  - Three-body $$S(m_{ll}) = \frac{1}{\sqrt{2\pi}\sigma}\int_0^{m_{cut}} dy \cdot y \frac{\sqrt{y^4 - y^2\left(m^2 + M^2\right) + (m\,M)^2}}{\left(y^2 - m_Z^2\right)^2} \times \left(-2y^4 - y^2\left(m^2 + 2M^2\right) + (m\,M)^2\right) e^{-}$$

- Simplest example - many others with endpoints, thresholds and other variables (M_{T2} and friends)
- Vast literature ➔ recommended review Barr & Lester arXiv: 1004.2732

Mass determination example

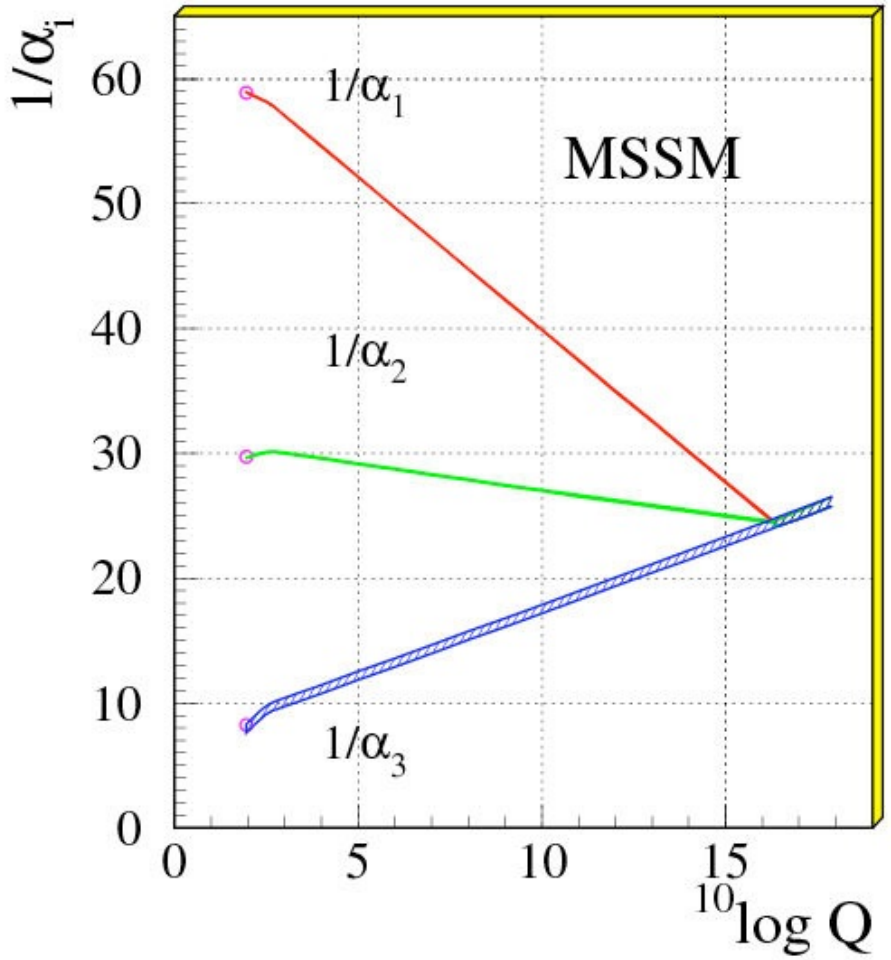
CMS PAS-SUS-09-002



- Fit ee, μμ and eμ distributions simultaneously
  - Monte Carlo study for 200 pb^{-1} @ 10 TeV (600-700 pb^{-1} @ 7 TeV)
  - Di-leptonic end-point $m_{ll,max}$=51.3 ± 1.5 (stat.) ± 0.9 (syst.) GeV [52.7 GeV]
- Can also determine spins given enough data ➔ need upgraded LHC

Where next?

- What constrains SUSY masses?
  - First lecture reminder



Superpartners could be @ 10 TeV (scalars anywhere)

Where next?

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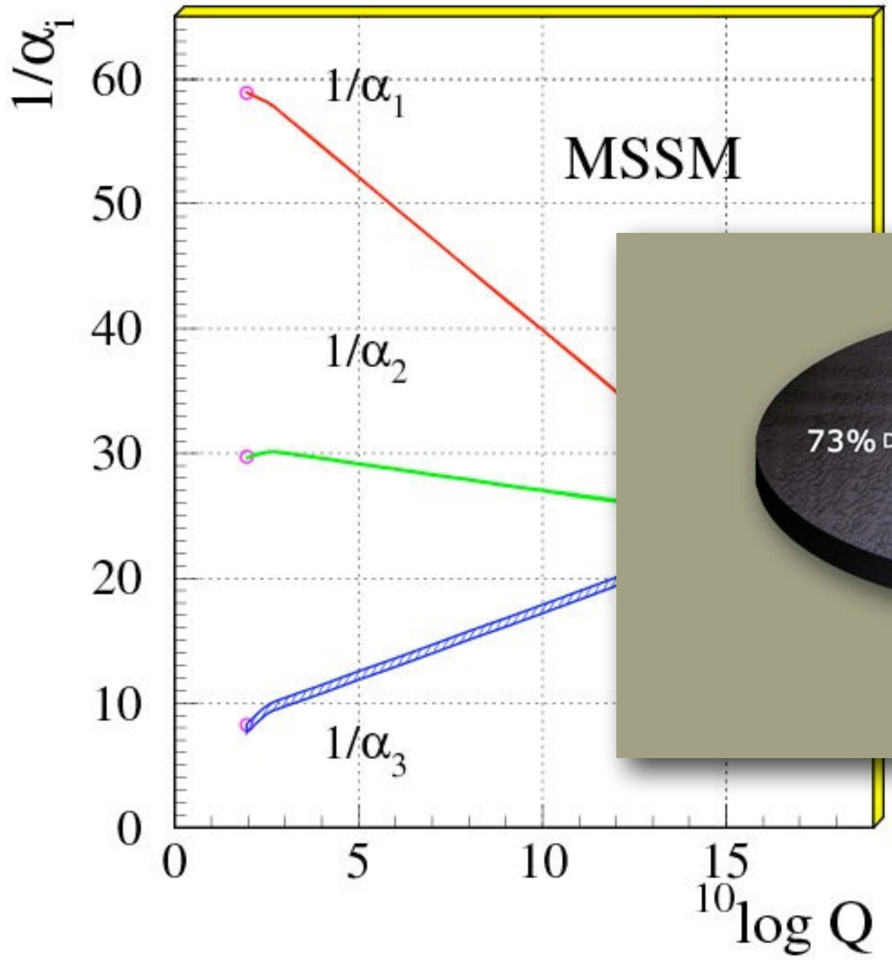

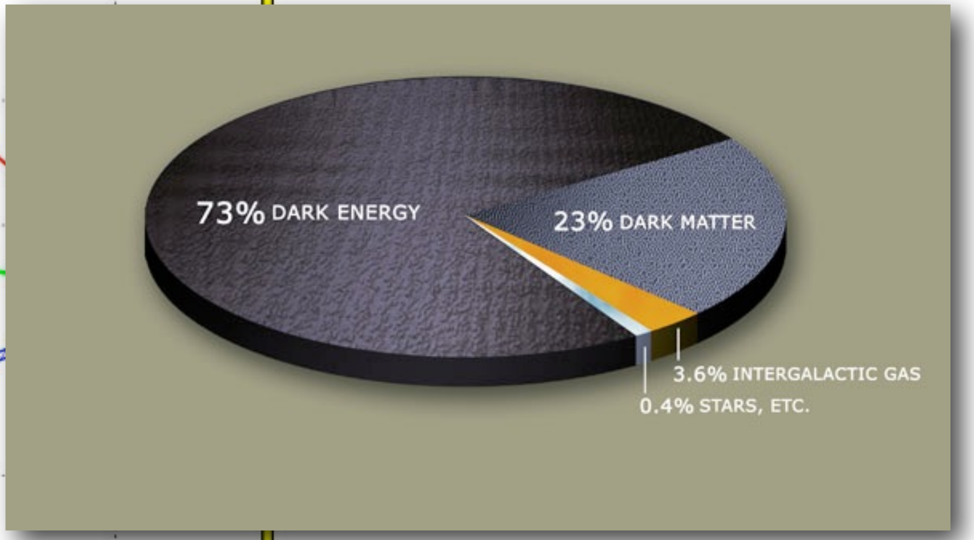

WIMP Dark Matter
Wino LSP @ 3 TeV

Where next?

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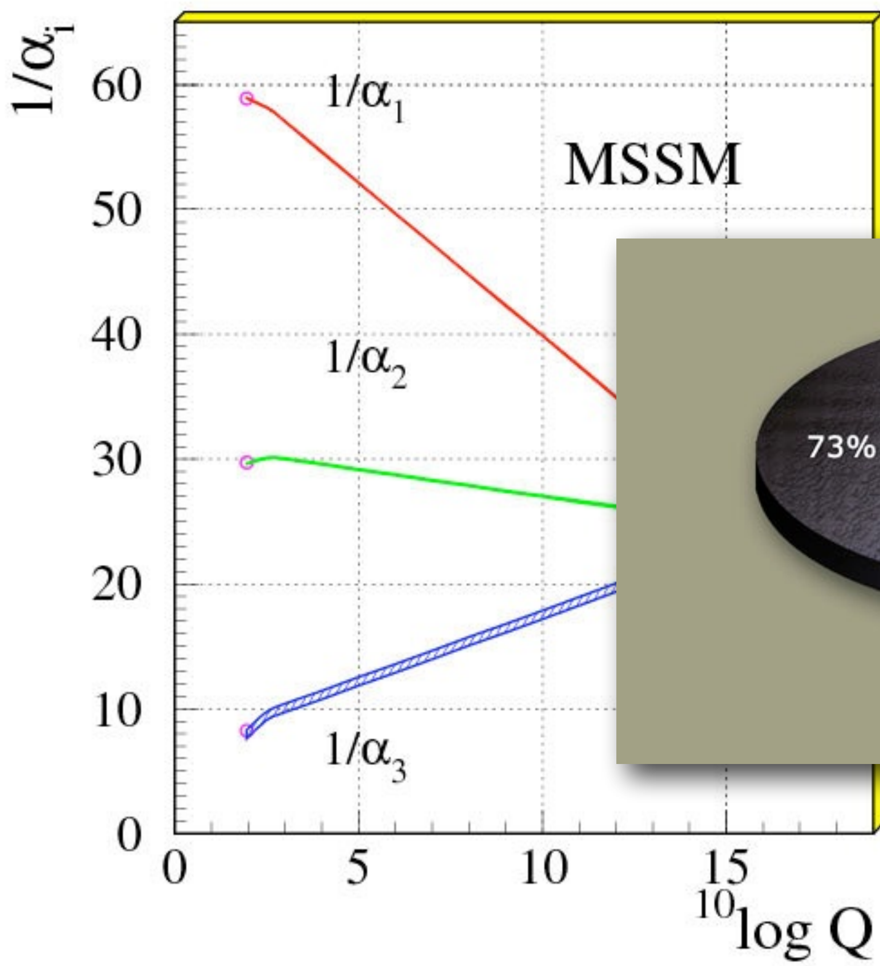
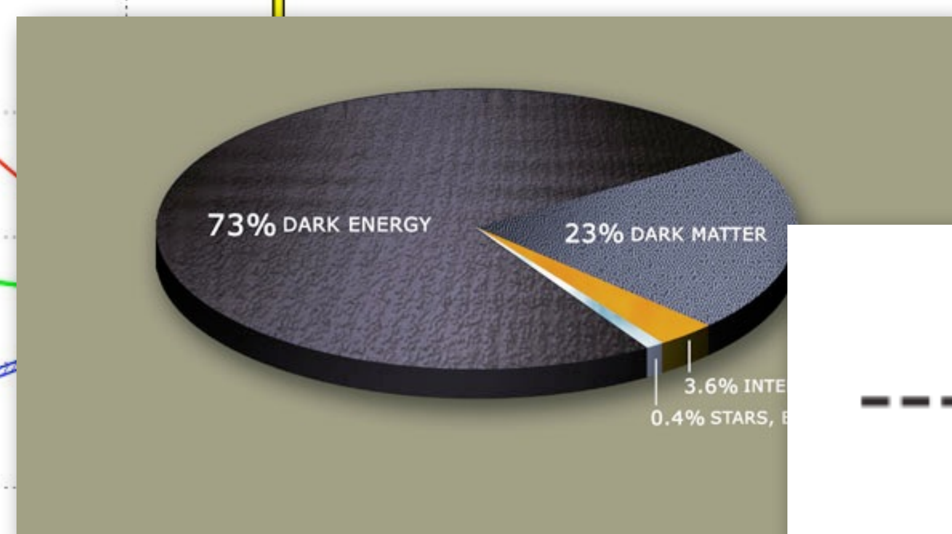
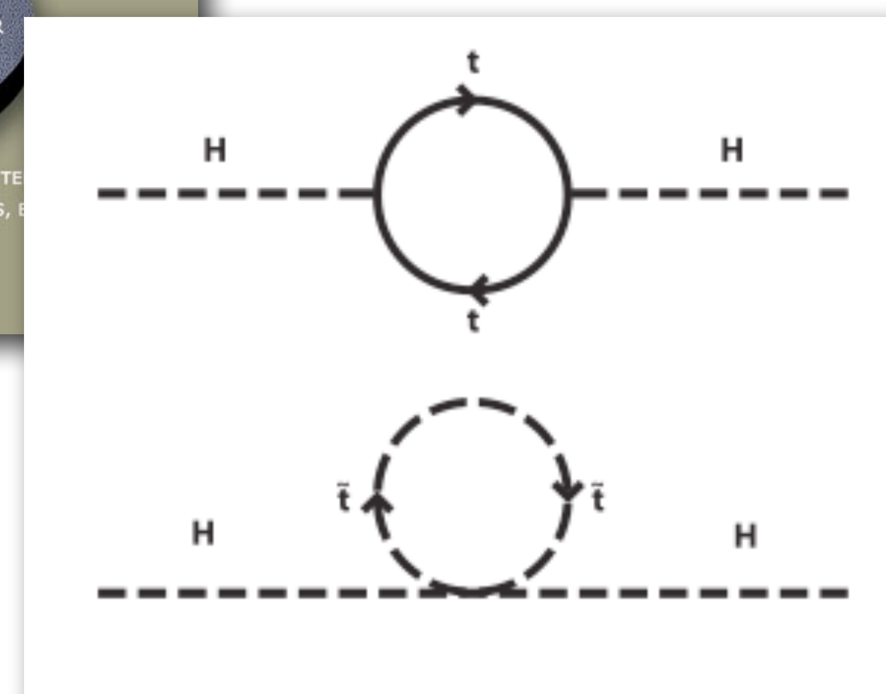
  - First lecture reminder

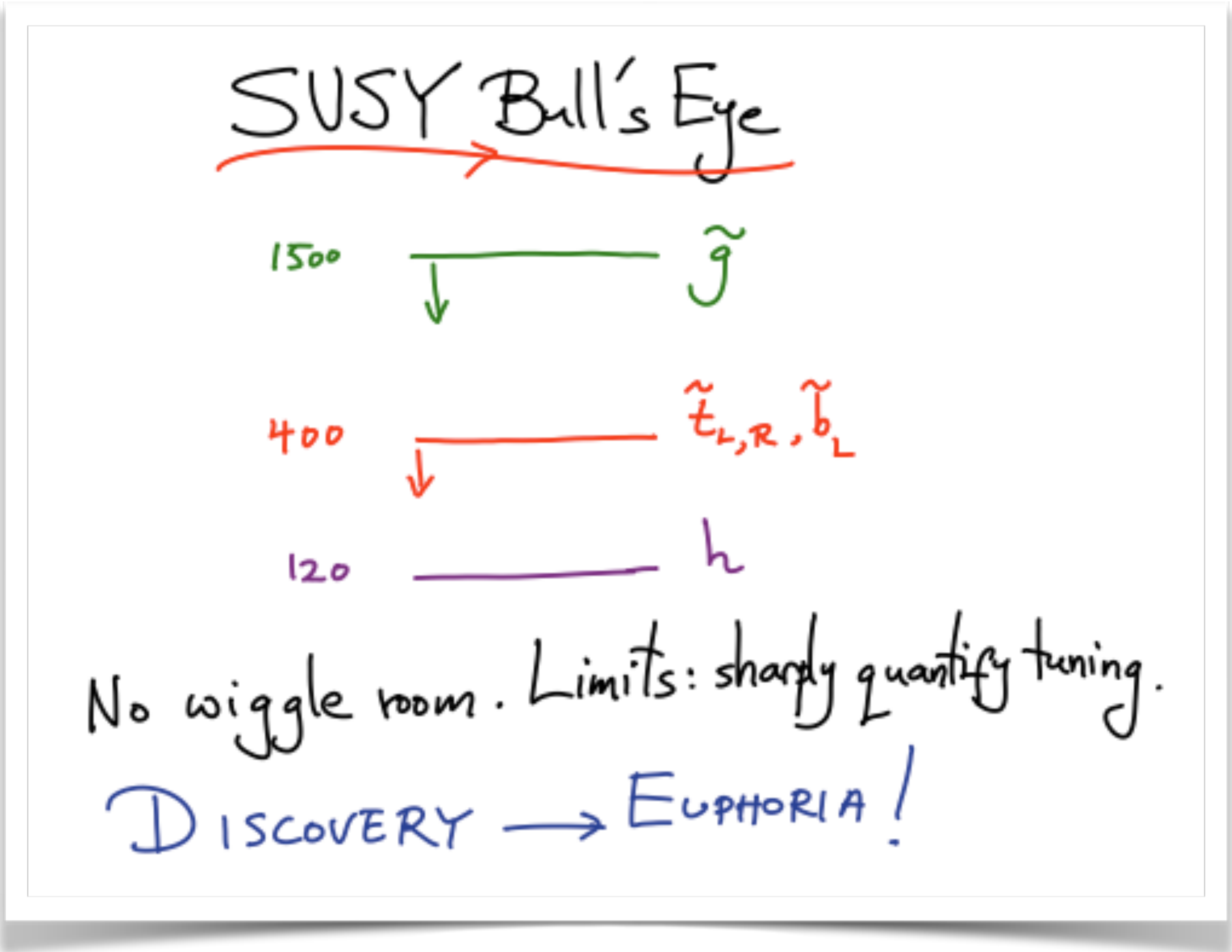


For 120 GeV Higgs need coloured top partners ≈ 400 GeV





Where next?



N. Arkani-Hamed @ Implications of LHC results for TeV-scale physics

Where next?

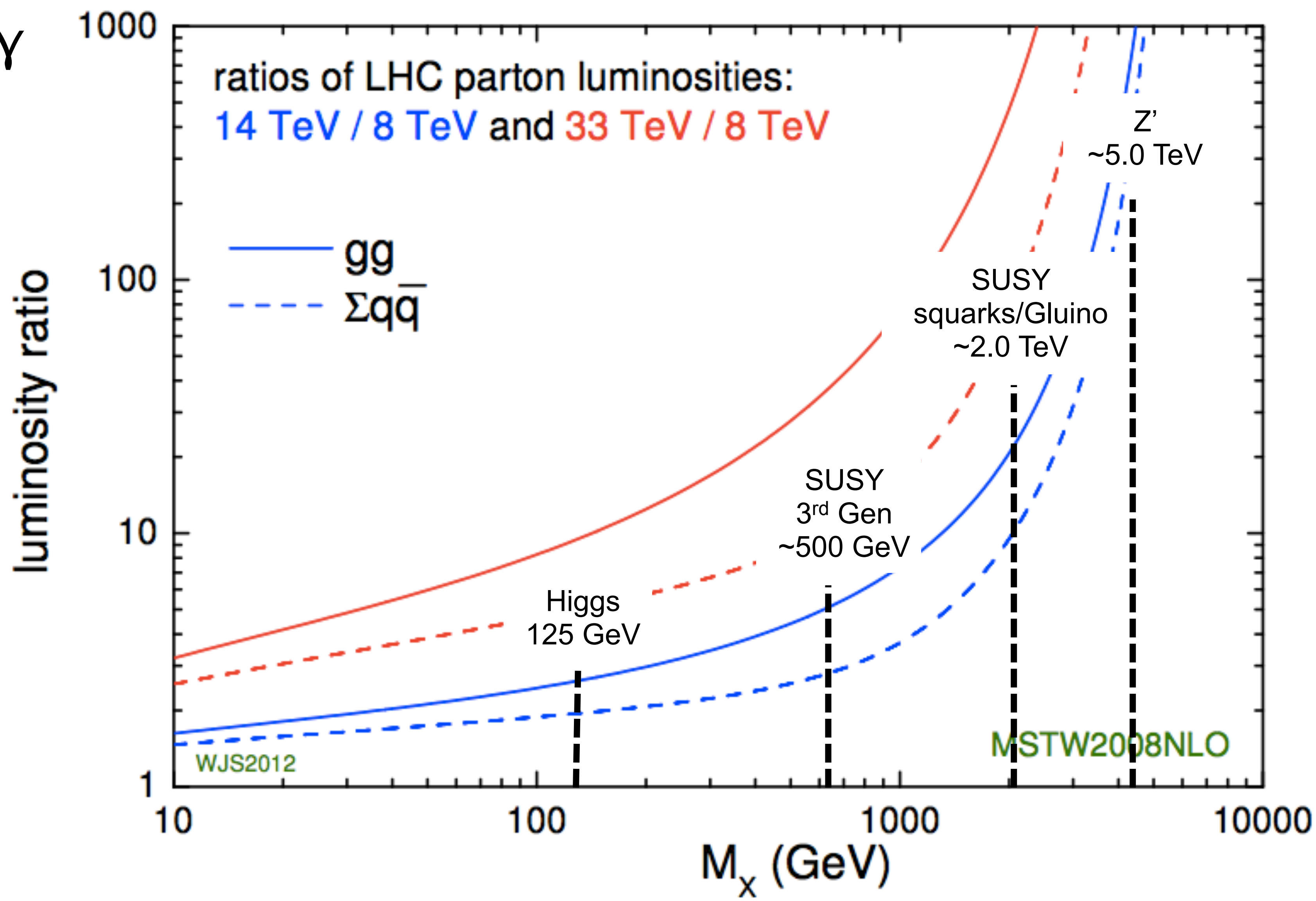
- Use parton luminosities to illustrate gain from 8 TeV to 14 TeV

Higgs
pp → H, H→WW, ZZ and γγ
mainly gg: factor ~2

SUSY – 3rd Generation
Mass scale ~ 500 GeV
qq and gg: factor ~2 to 4

SUSY – Squarks/Gluino
Mass scale ~ 2.0 TeV
qq,gg,qg: factor ~6 to 10

Z′
Mass scale ~ 5 TeV
qq: factor ~200



Summary

- Wide range of searches underway at the LHC
- Unfortunately no signs of Supersymmetry yet
- Tools in place to measure masses and spins of any discovery
- The next few years should be very exciting!