Searching for SUSY at CMS

Frédéric Ronga (ETH Zurich)

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Outline

- SUSY: why and how?
- The CMS detector (at a glance)
- SUSY searches at CMS (showcases)
- Interpretation and outlook

Supersymmetry (in one slide)

- New fundamental symmetry between bosons and fermions

$$Q\,|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle \qquad Q\,|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle$$

- For example

$$Q\,|\mathrm{top}\rangle = |\mathrm{s(calar)\ top}\rangle$$

$$Q\,|g\rangle = |\tilde{g}\rangle$$

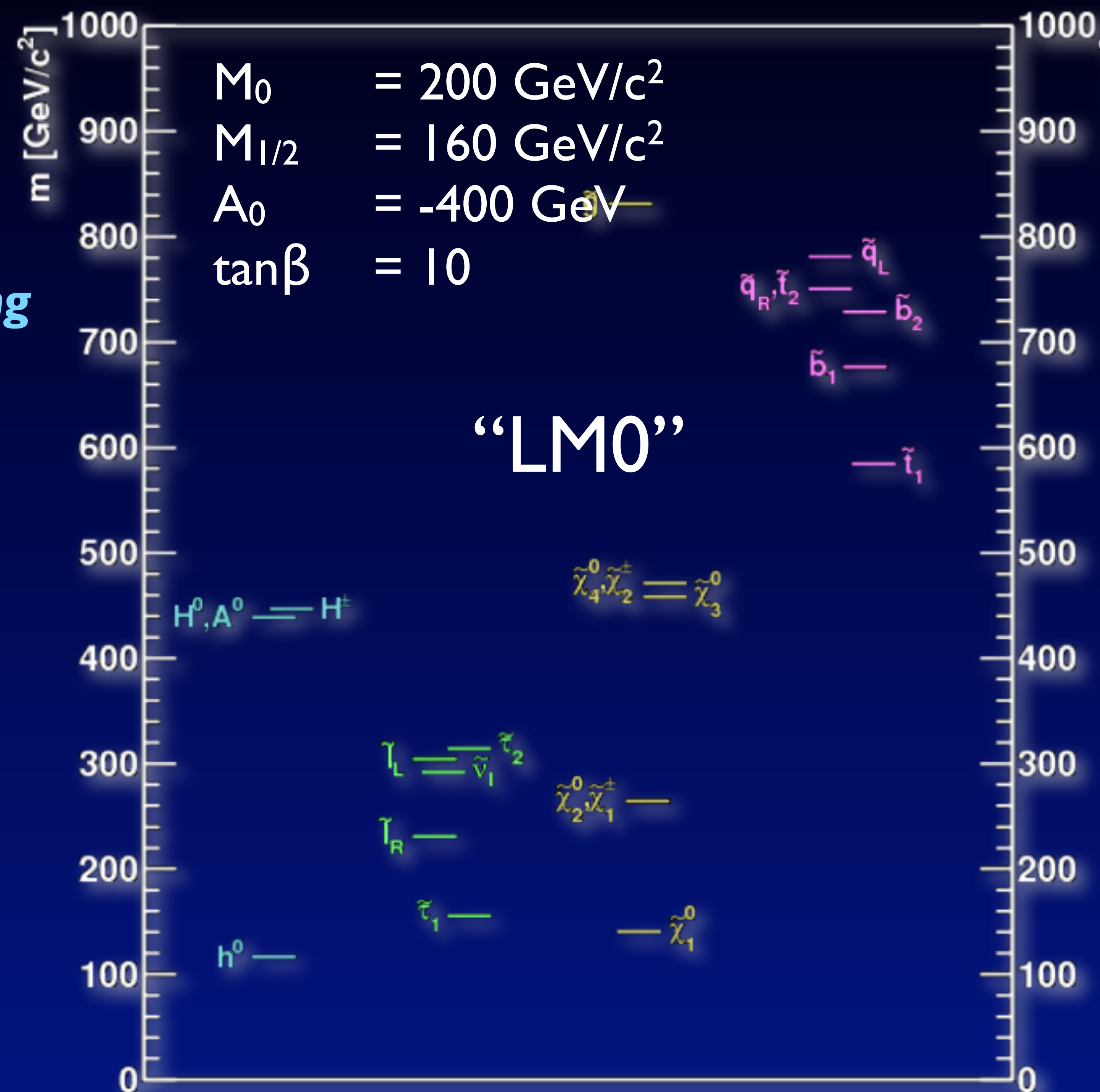
- Each standard model multiplet doubled in size
  - **this gives the "Minimal Supersymmetric Standard Model" (MSSM)**
  - **if SUSY conserved: all members of a multiplet have the same mass**

$$m_\ell = m_{\tilde{\ell}}$$

- Clearly, SUSY is broken: SUSY partners are *heavy*
  - **but "matter parity" ➟ the *number* of superpartners is conserved**
    - consequence: lightest SUSY particle (LSP) is stable

Towards a SUSY phenomenology

- MSSM has 124 parameters…
- Simplifying
  - **hypotheses on the SUSY *breaking mechanism***
  - **define parameters at GUT scale**
  - **generate mass spectra and couplings at EWK scale (RGE)**
- Famous example: CMSSM
  - M1/2 – gaugino mass (sfermions)
  - M0 – scalar mass
  - A0 – trilinear coupling
  - tanβ – Higgs VEV ratio



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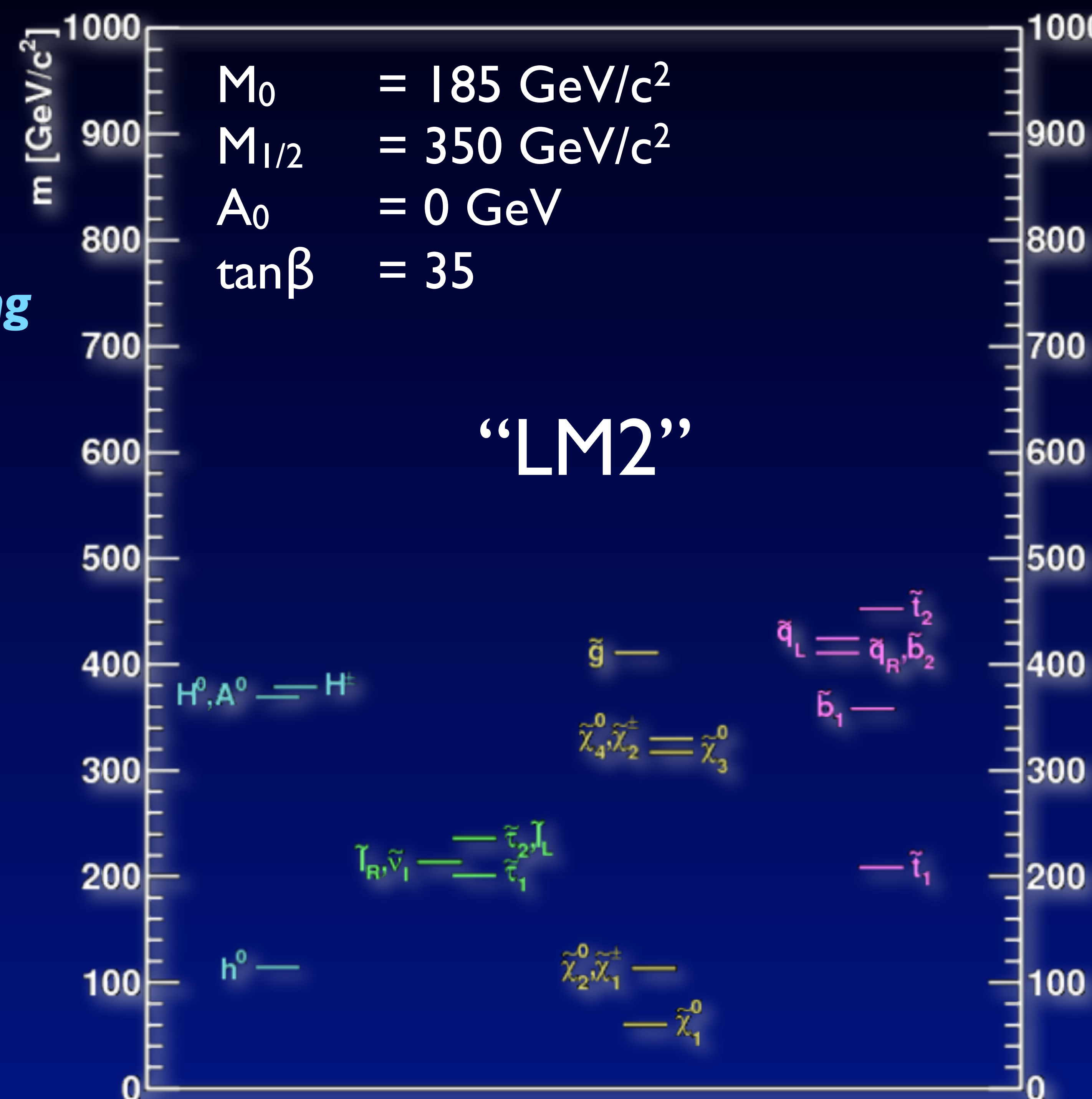
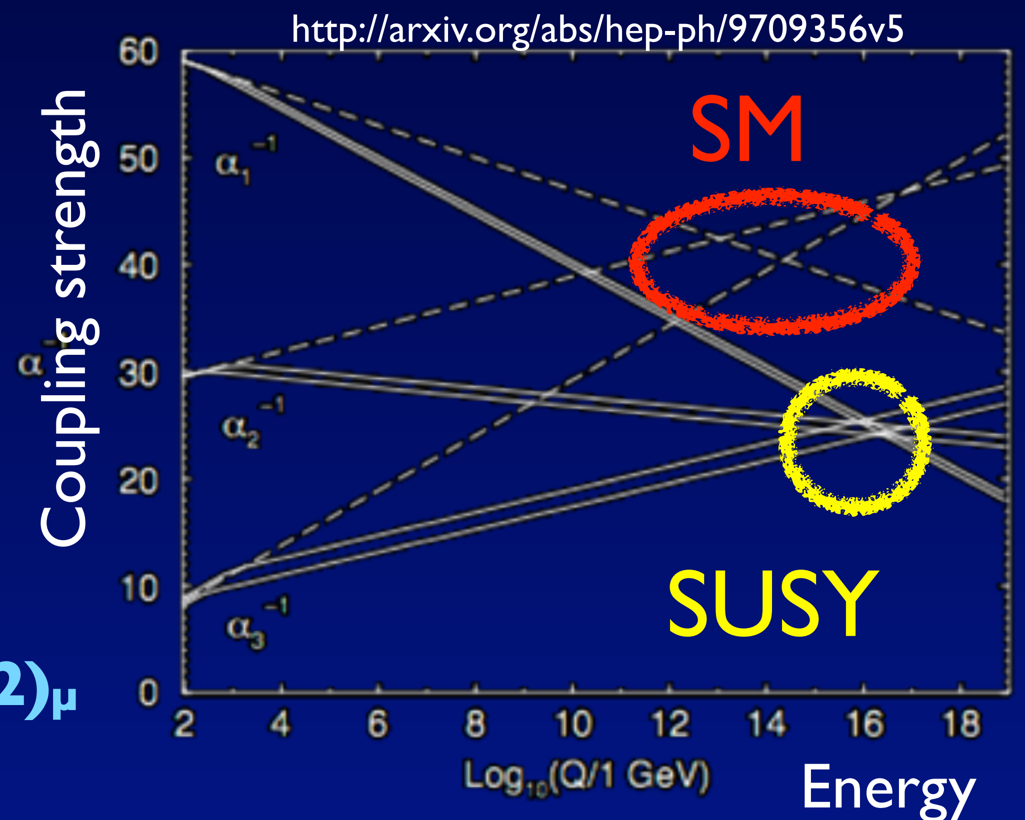


Why care about SUSY?

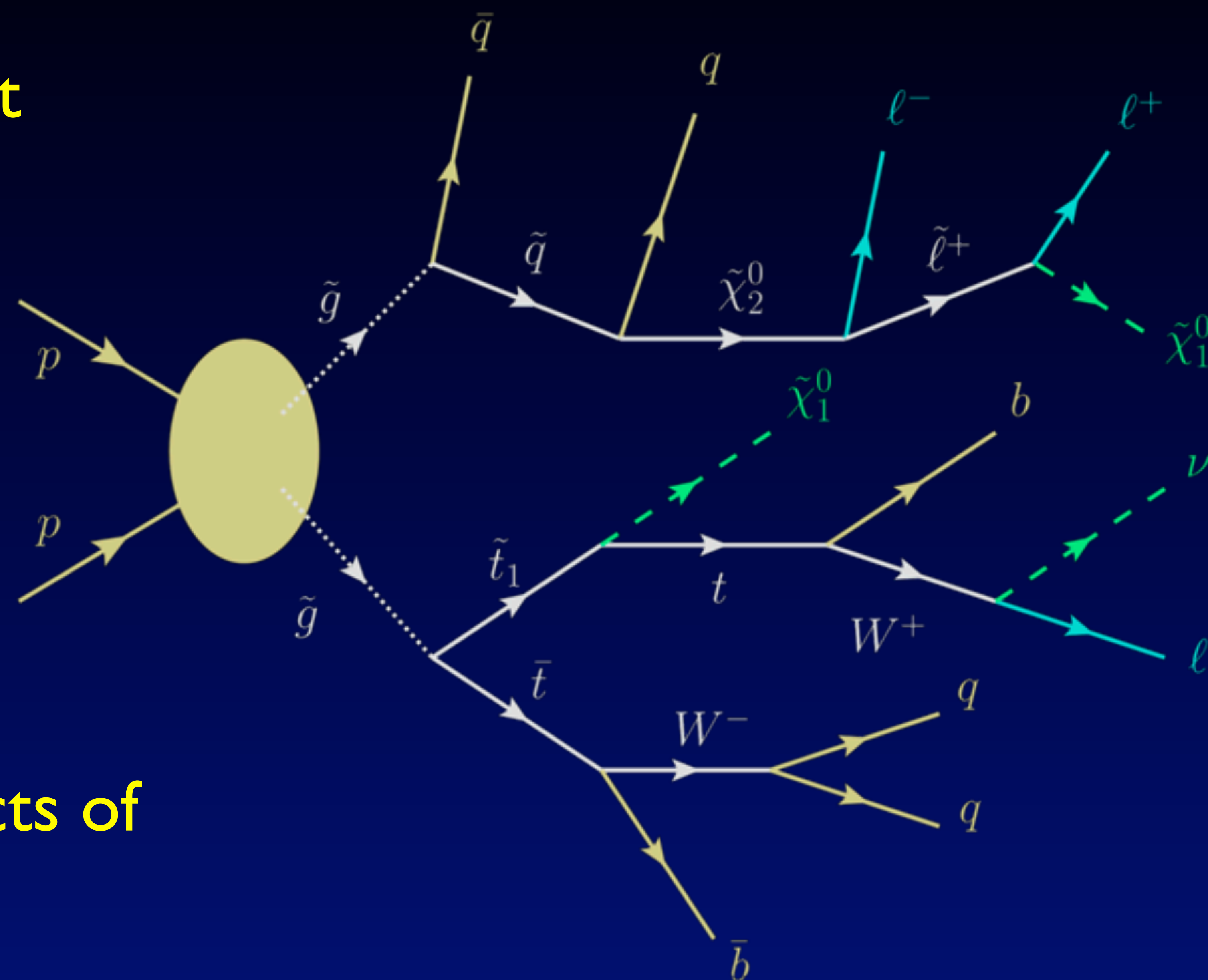
- The standard model is not the final word
  - **“Effective theory” at low energy?**
  - **LHC: high-energy regime, *beyond the standard model (BSM)***
    - Experimental challenge: what to look for? ➠ Need a **guide**…
- Supersymmetry…
  - **… stabilises the mass hierarchy**
  - **… facilitates grand unification of forces**
  - **… provides new sources of CP violation**
  - **… has a candidate for “dark matter”**
  - **… could explain the discrepancy seen in $(g-2)_\mu$**



  - **… has been with us for 40 years: it is our duty to confront it to reality!**

Searching for SUSY at the LHC

- Topology of a SUSY event
  - **large *energy* release**
  - **large number of *jets***
  - **low-p_T *leptons***
  - ***missing energy* (MET)**
- Searches rely on all aspects of the reconstruction
  - **electrons, photons and muons**
  - **jets, total hadronic activity**
  - **missing energy (especially tails)**



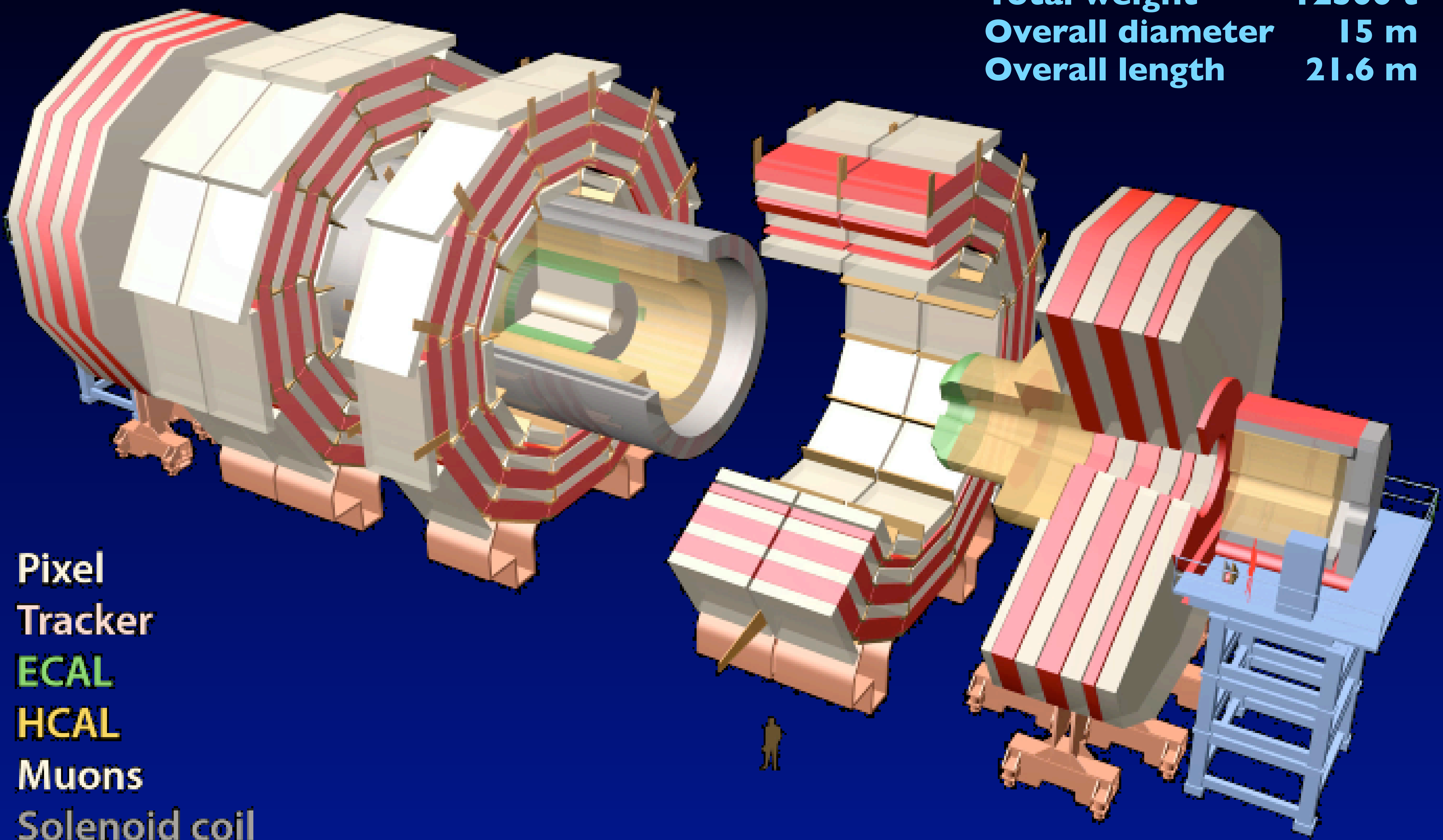
A "typical" SUSY event
many jets, leptons and missing energy

N.B. key is to try and stay as model-independent as possible

CMS

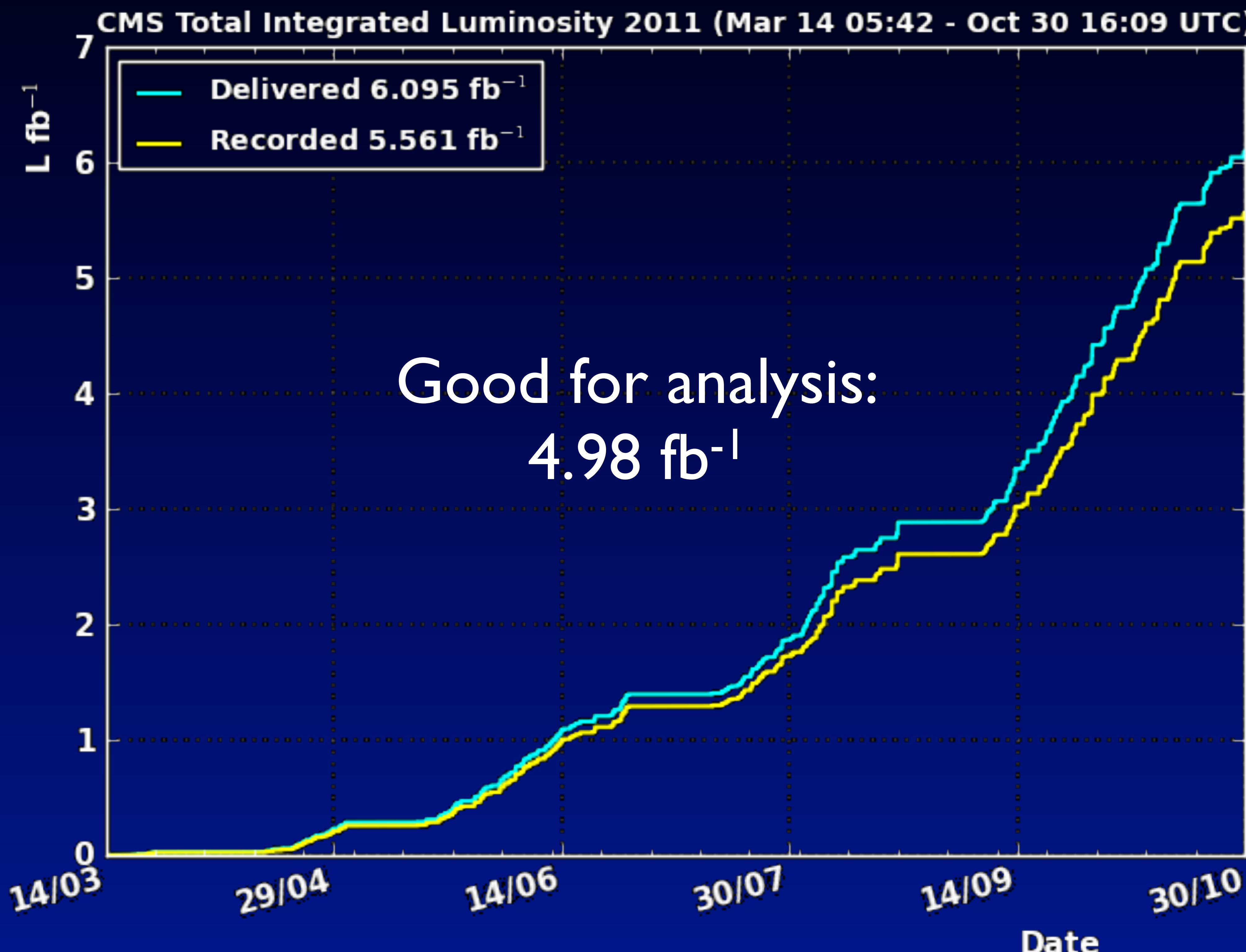
The Compact Muon Solenoid

Total weight	**12500 t**
Overall diameter	**15 m**
Overall length	**21.6 m**



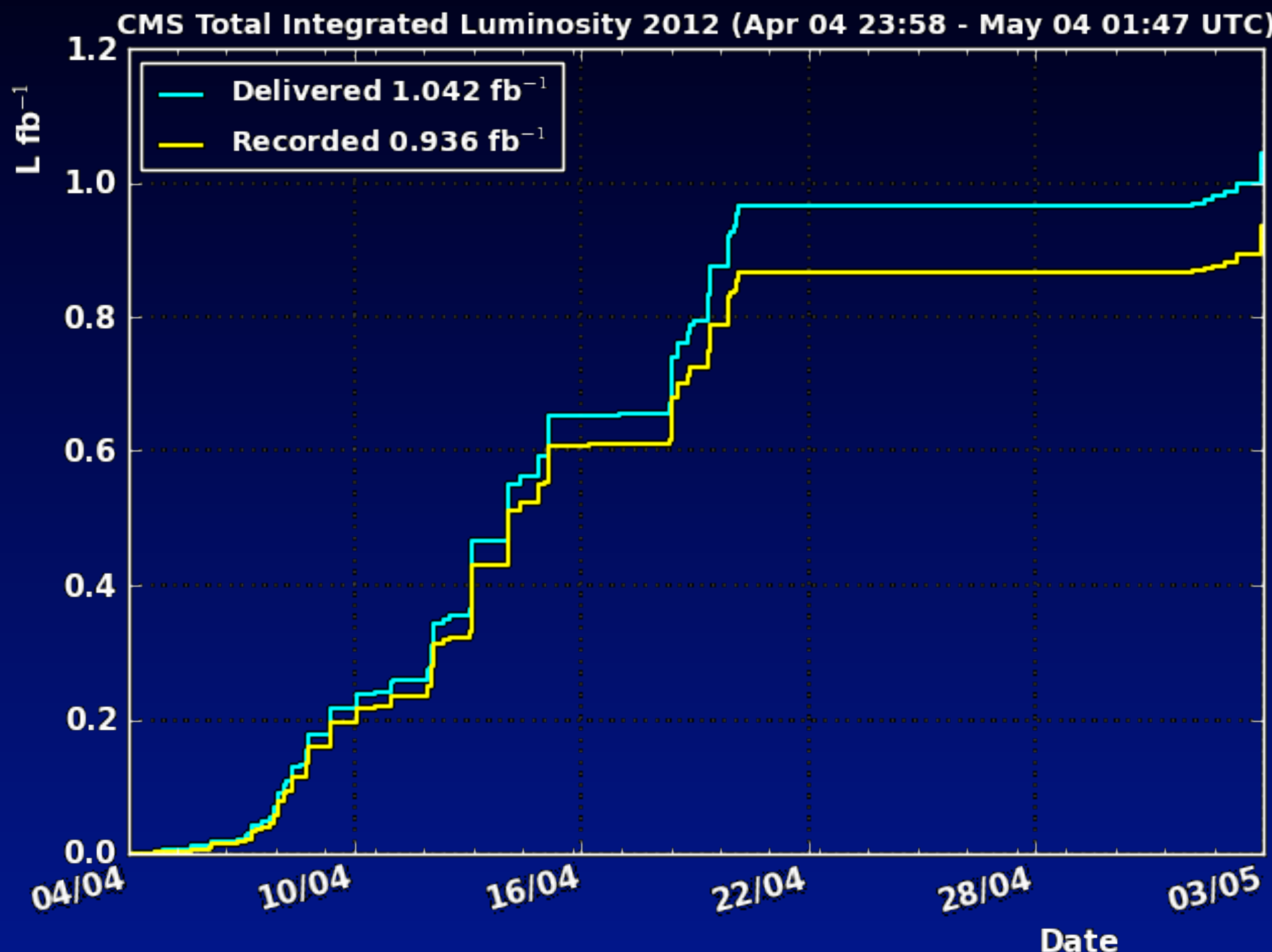
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

The 2011 sample



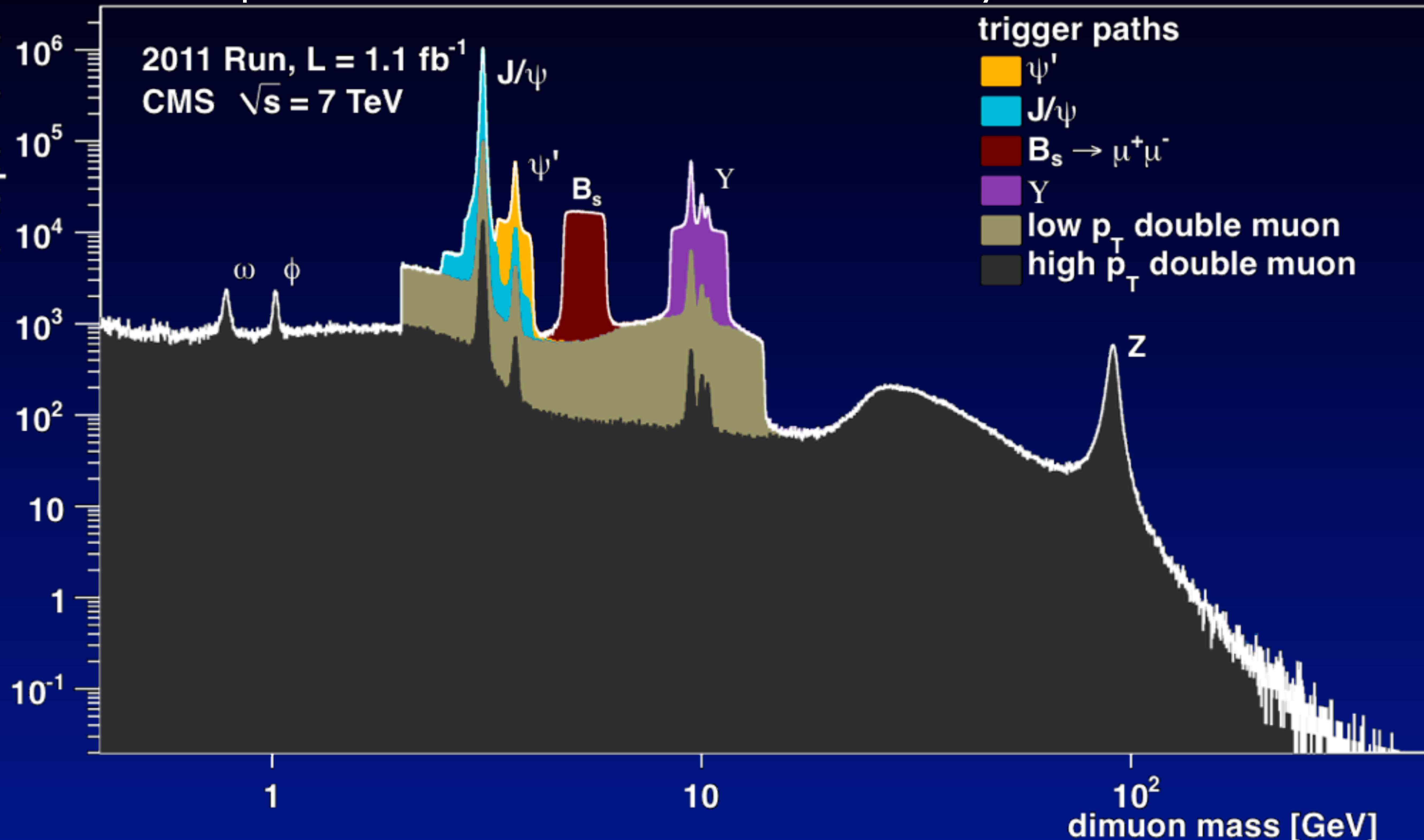
Good for analysis:
4.98 fb^{-1}

The ~~2011~~ 2012 sample



The Compact **Muon** Solenoid

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



SUSY searches

SUSY searches at CMS

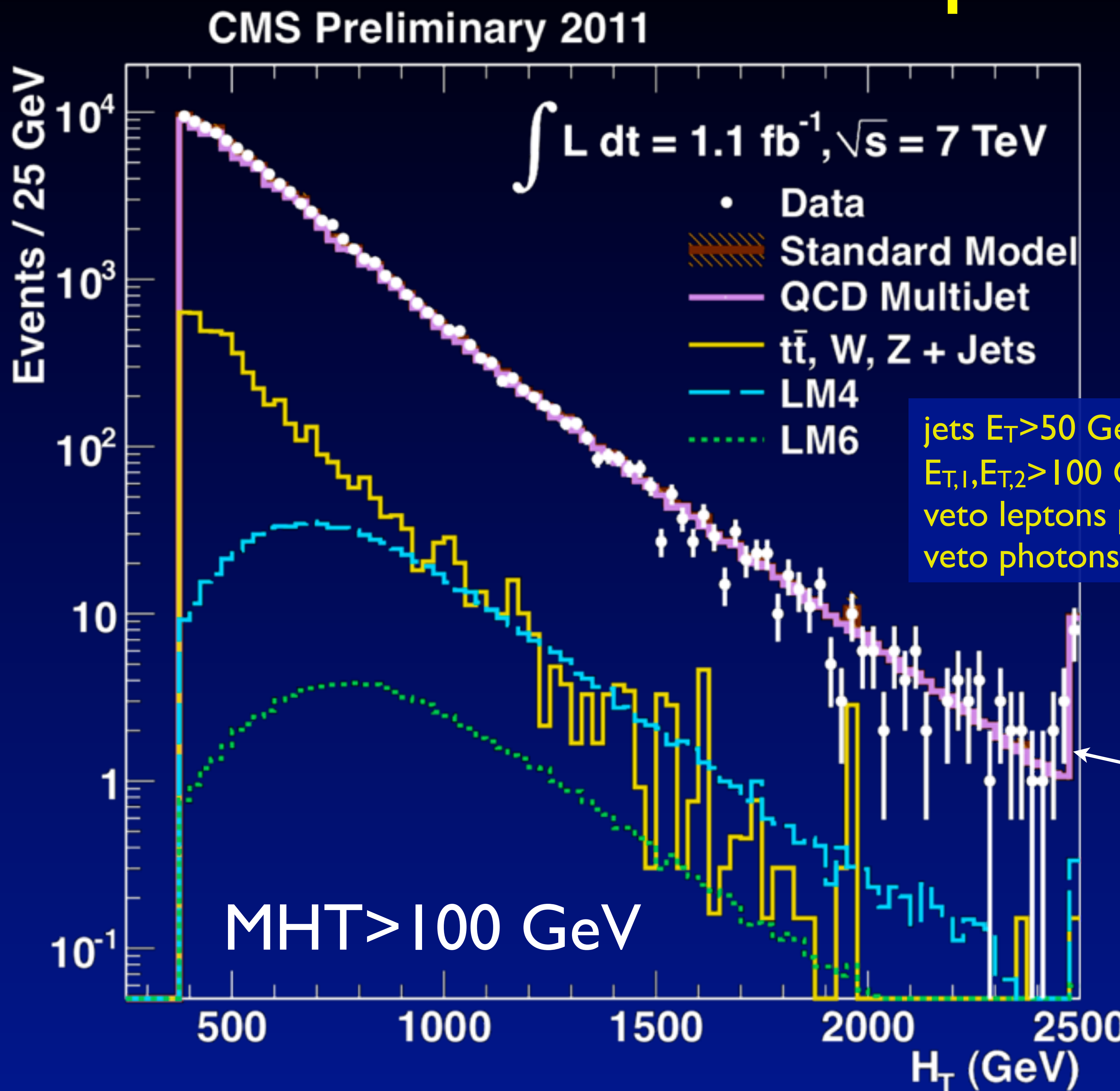
Topologies	Purely hadronic	1 lepton	2 leptons same sign	2 leptons opposite sign	≥ 3 leptons	2 photons	photon + lepton
Dominant backgrounds	QCD Z→νν ttbar W+jets	ttbar W+jets QCD	*fakes* (ttbar)	ttbar Z+jets	*fakes* (ttbar)	QCD	Wγ

Higher sensitivity ⟵ ⟶ Lower SM background ⟷ GMSB

- General strategy
  - **suppress Standard Model processes ("background")**
  - **estimate remainder** ➠ different strategies depending on final state (different bkgds)
    - "data-driven" techniques developed
  - **BSM physics will manifest itself as an "excess"**

PRL 107, 221804 (2011)

Purely hadronic search: the problem



jets E_T>50 GeV/c, $|\eta|$<3.0
$E_{T,1}$,$E_{T,2}$>100 GeV, $|\eta_1|$<2.5
veto leptons p_T > 10 GeV/c
veto photons p_T > 25 GeV/c

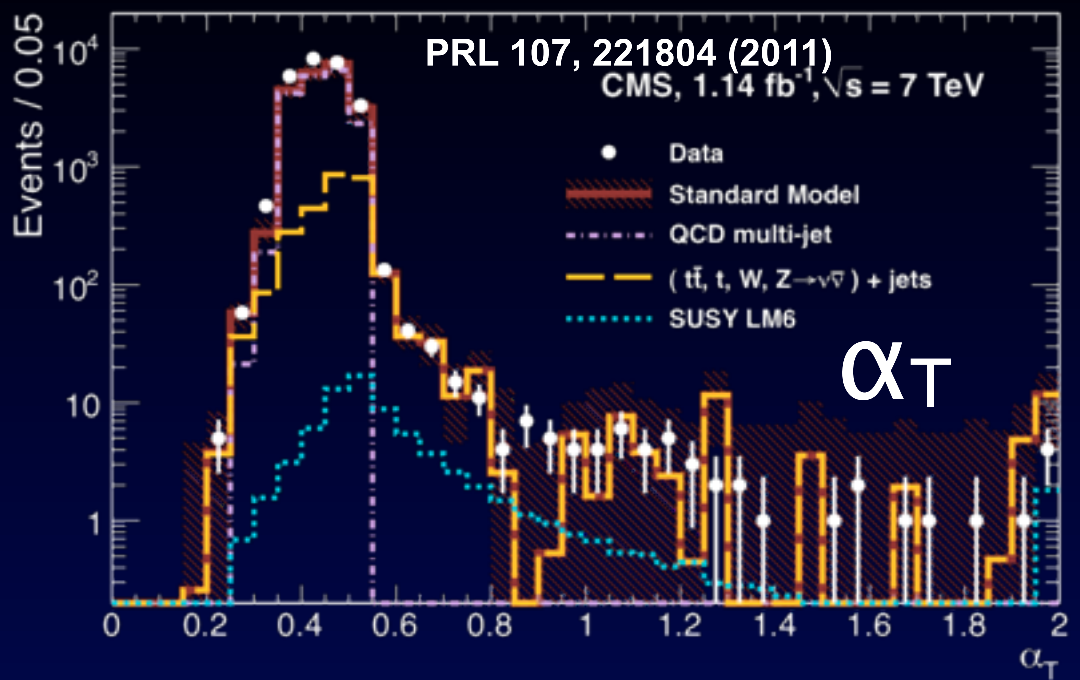
Last *bin* contains overflow

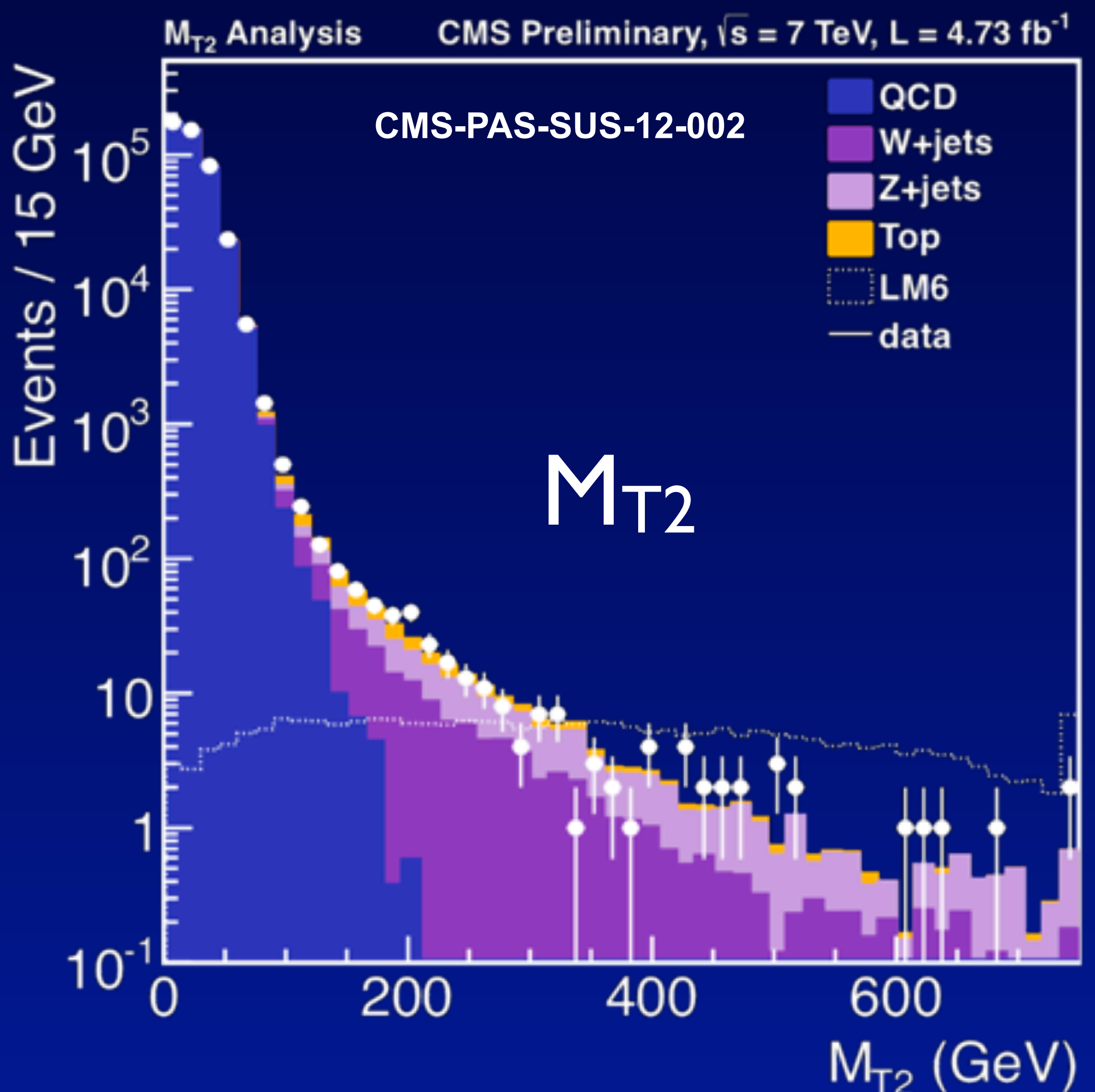
Purely hadronic search: solutions

- QCD "shifters"
  - **alpha_T**
  - **M_{T2}**
  - **Razor**

➠ Suppress multijet bkgd

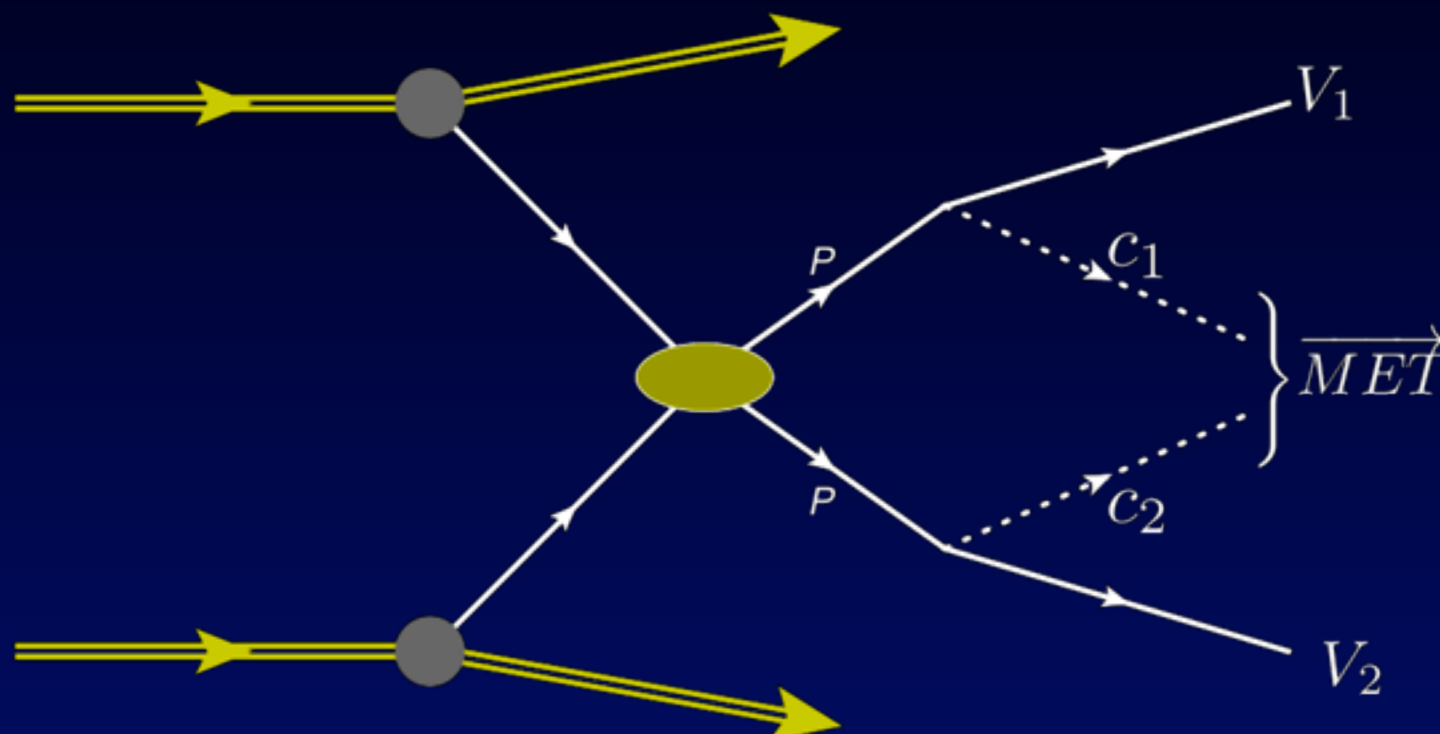
➠ Estimate remainder (various techniques)





M_{T2} in a nutshell

$$M_{\mathrm{T2}}(m_c) = \min_{p_{\mathrm{T}}^c(1)+p_{\mathrm{T}}^c(2)=p_{\mathrm{T}}^{\mathrm{miss}}} \left[\max(m_T^{(1)}, m_T^{(2)})\right]$$

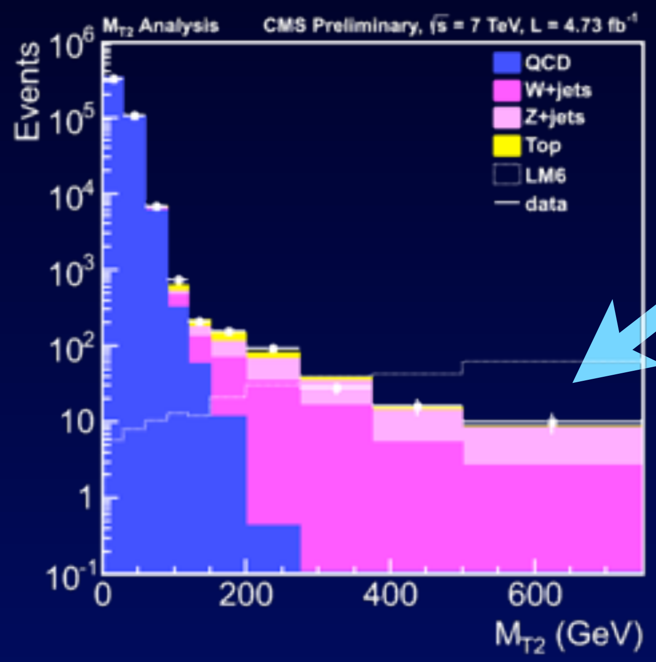


- function of mass of unobserved child (LSP)
  - **if m_c known, endpoint at parent mass m_P**
- visible systems V_1, V_2
  - **particles/jets, or pseudo-jets formed of multiple jets**
- originally designed to measure SUSY masses after discovery
  - **use here purely as a discovery variable**

M_{T2} Analysis strategy

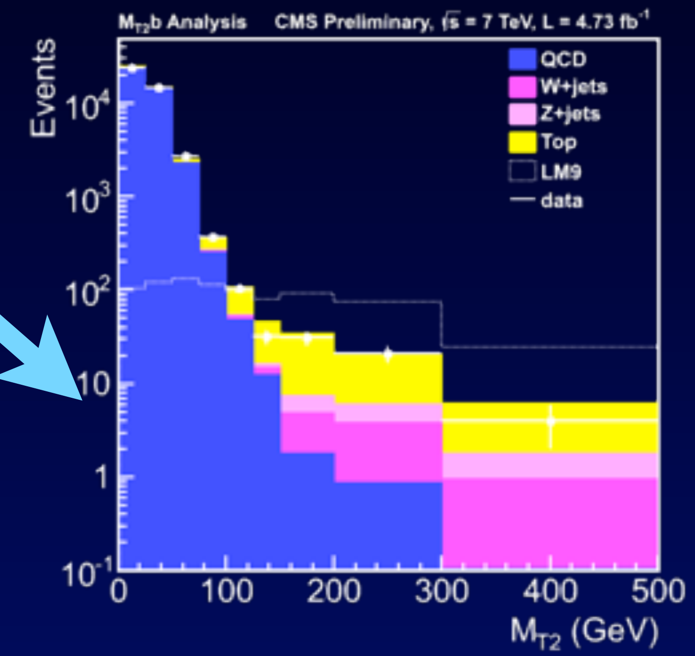
- select events with large hadronic activity (H_T)

Baseline selection
H_T > 750 GeV
≥ 3 jets
lepton veto



"M_{T2} analysis"
high M_{T2} signal region
➠ targeting at SUSY with large MET

dominant bkgds
leptonic W+jets
invisible Z(νν)+jets

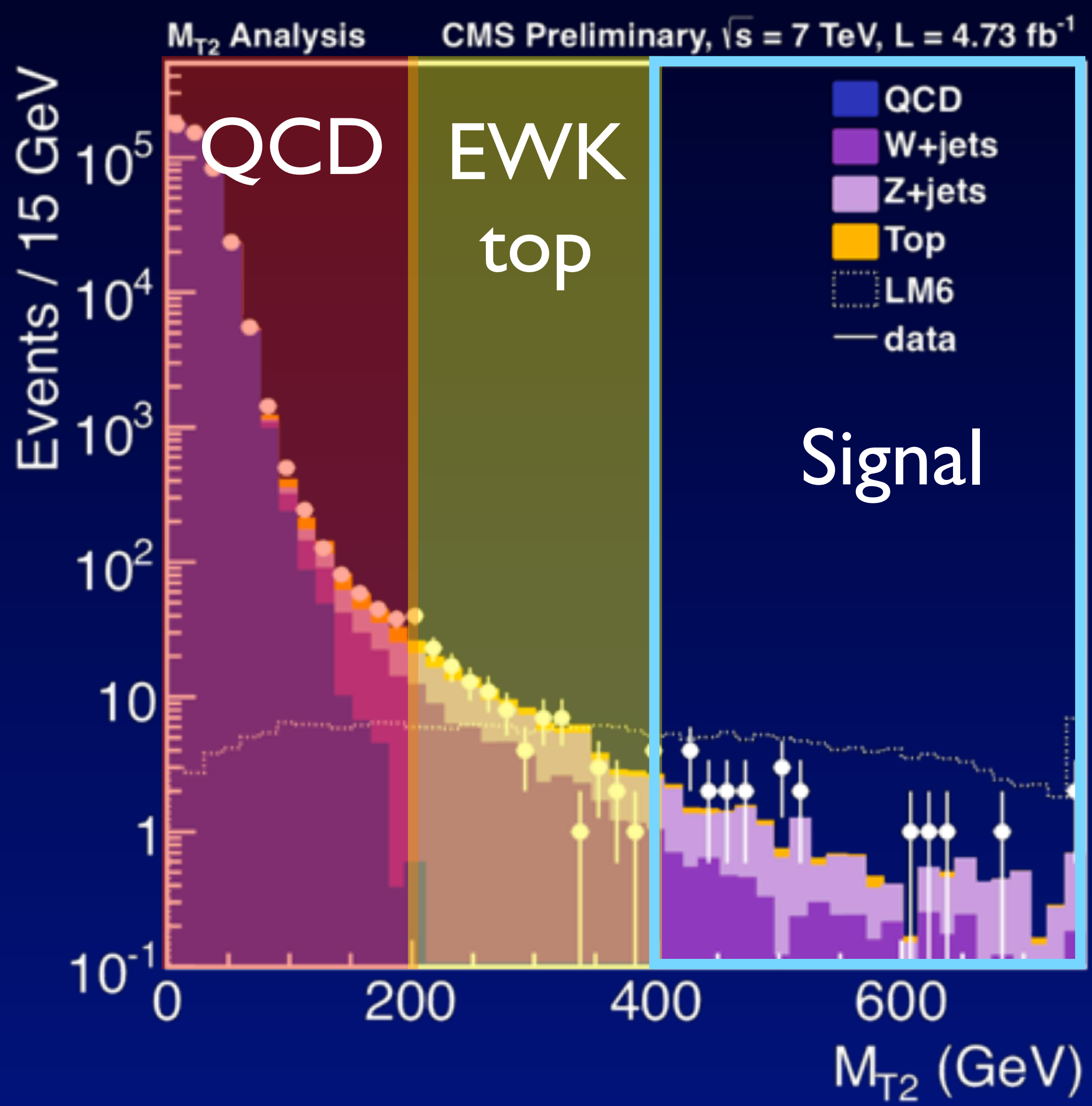


"M_{T2}b analysis"
≥ 4 jets
require 1 b-jet
➠ targeting at light gluino or stop/sbottom

dominant bkgd
ttbar

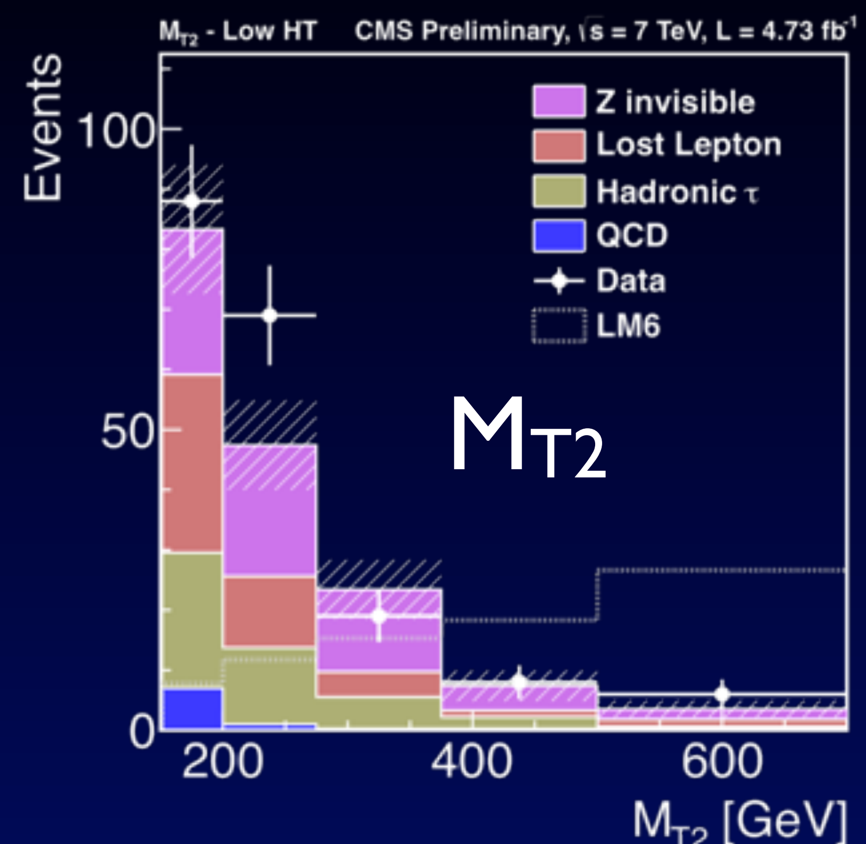
Background prediction strategy

- QCD background
  - factorization method based on jet kinematics
- W+jets / ttbar
  - estimate number of events with one lepton, correct with lost lepton probability
- Z(νν) + jets
  - γ+jets
  - W(μν) + jets (EWK region)

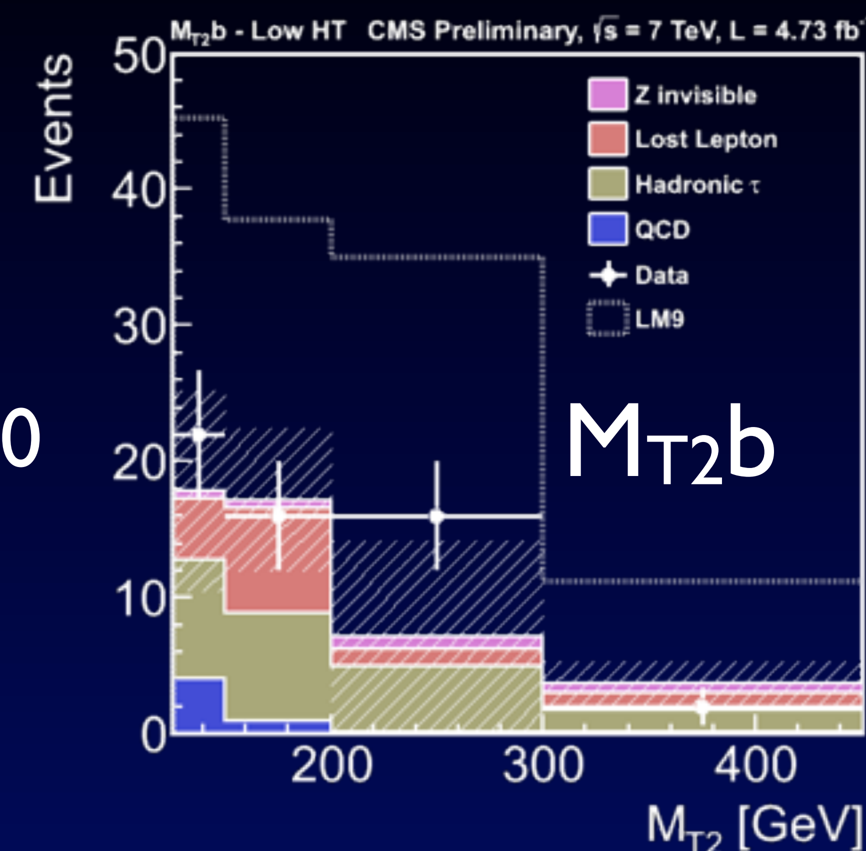


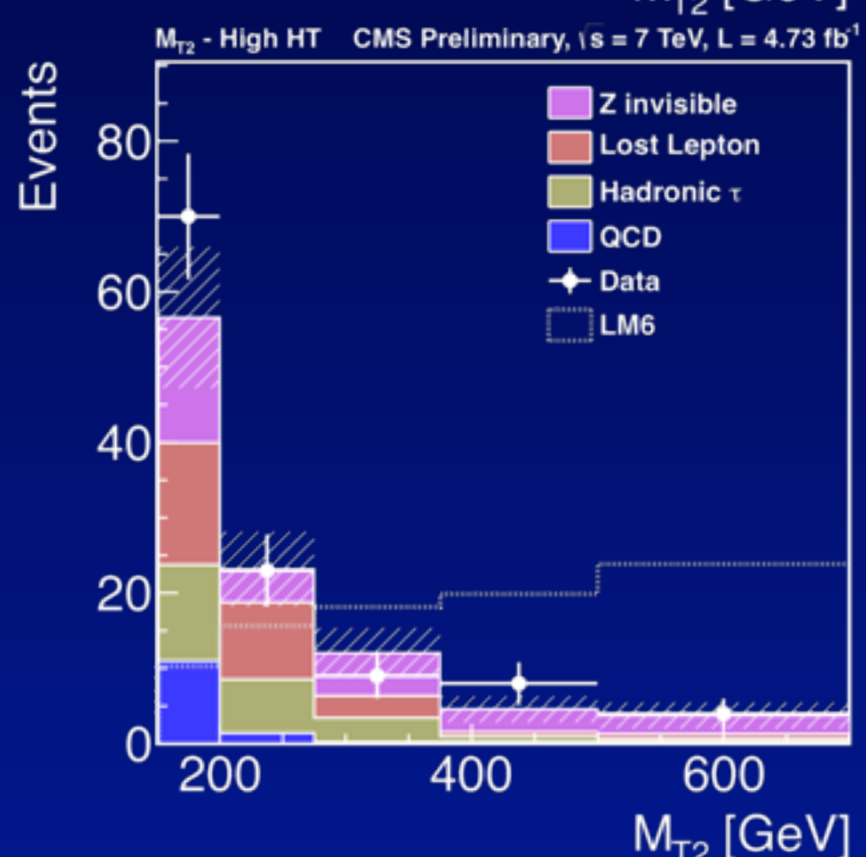
- Relies somewhat on MC shapes, validated in control regions

M_{T2}(b) Results

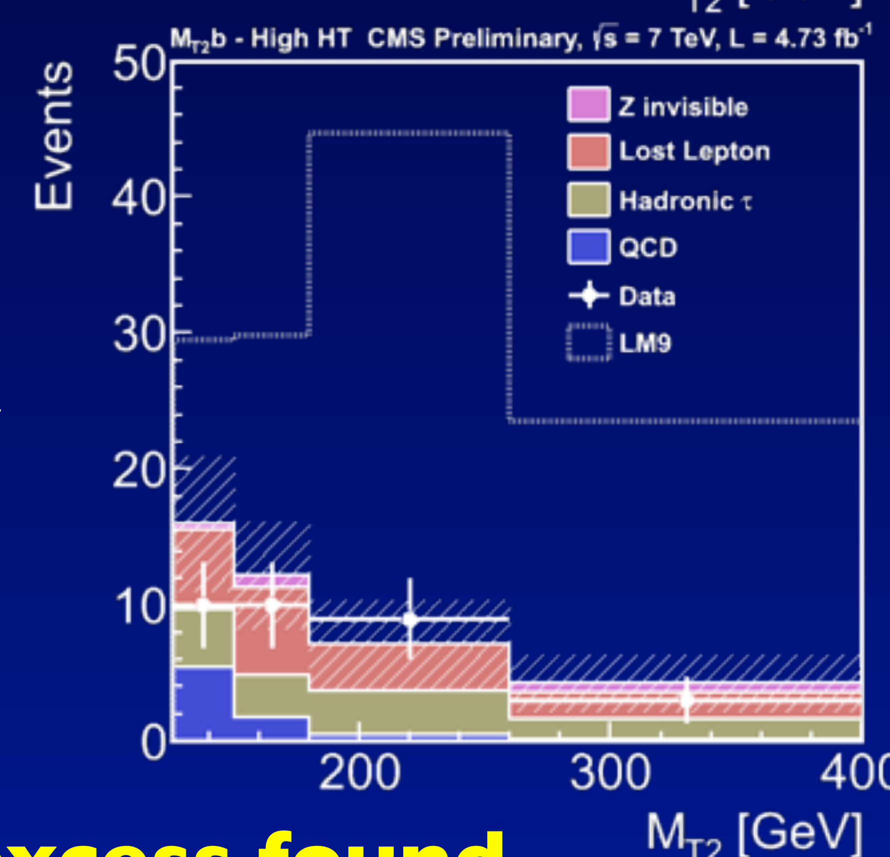


$750 \leq HT \leq 950$





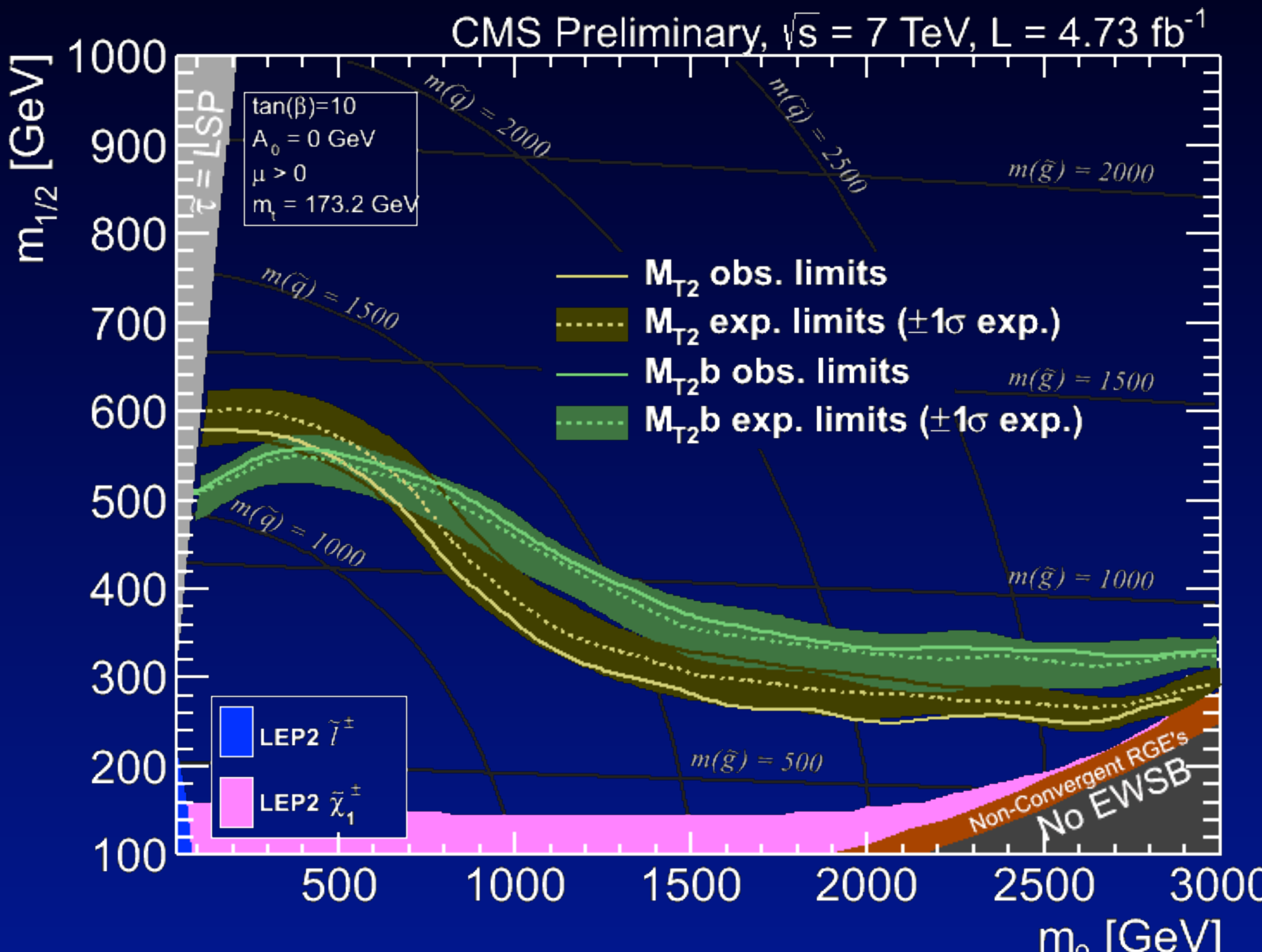
HT > 950 GeV



No excess found...

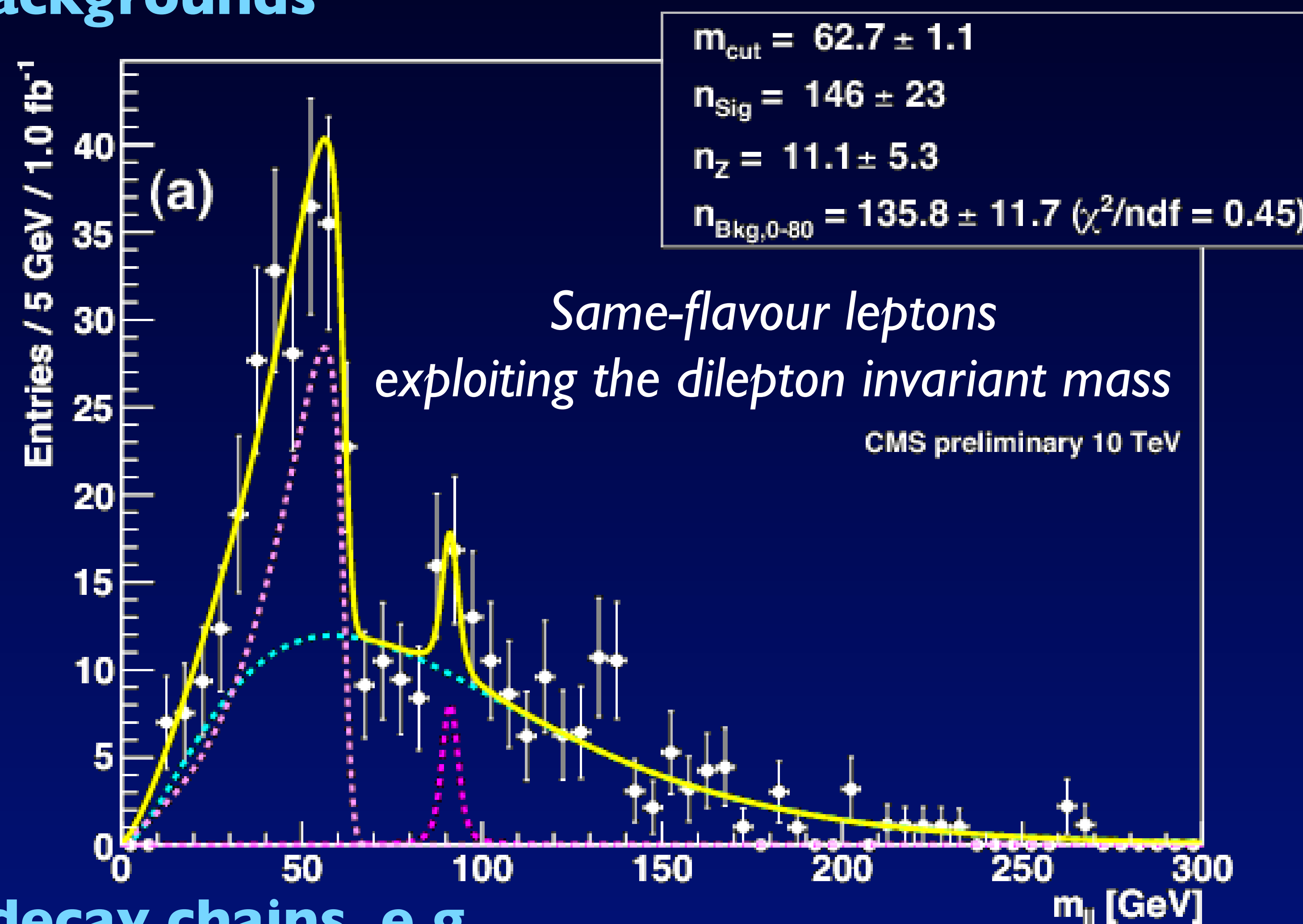
M_{T2} vs. CMSSM

- 95% C.L. exclusion limit in the CMSSM



Exploiting leptons

- *Discovery*: excess over standard model processes
  - **requires good knowledge of “backgrounds”**
  - **Leptons can help!**
    - reduce hadronic backgrounds, more difficult to model
    - provide additional handles to estimate leptonic backgrounds
    - exploit kinematic constraints



Same-flavour leptons
exploiting the dilepton invariant mass

- *Characterisation*: unraveling mass relations
  - **using kinematic constraints in decay chains, e.g.,**

$$\tilde{q} \rightarrow q + \tilde{\chi}_2^0 \rightarrow q + \tilde{\chi}_1^0 + \underbrace{\ell^+ + \ell^-}_{Z?}$$

Z + jets + MET

- Good example of "generic" topology

$$\tilde{q} \to q + \tilde{\chi}_2^0 \to q + \tilde{\chi}_1^0 + Z^0 \qquad \tilde{q} \to q + \tilde{\chi}_1^0 \to q + \tilde{G} + Z^0$$

  - **present in various extensions of the standard model**

See, e.g., arXiv:1103.6083 [hep-ph]

- Basic topology:
  - **≥ 3 jets**
  - **missing energy**
  - **two leptons compatible with a Z boson hypothesis**
- SM background estimation methods
  - **leptons from a Z boson (mainly Z+jets) → Jet-Z balance [next slide]**
  - **uncorrelated lepton pair (mainly ttbar) → opposite-flavour events**

arXiv:1204.3774 [hep-ex]

The Jet-Z balance method

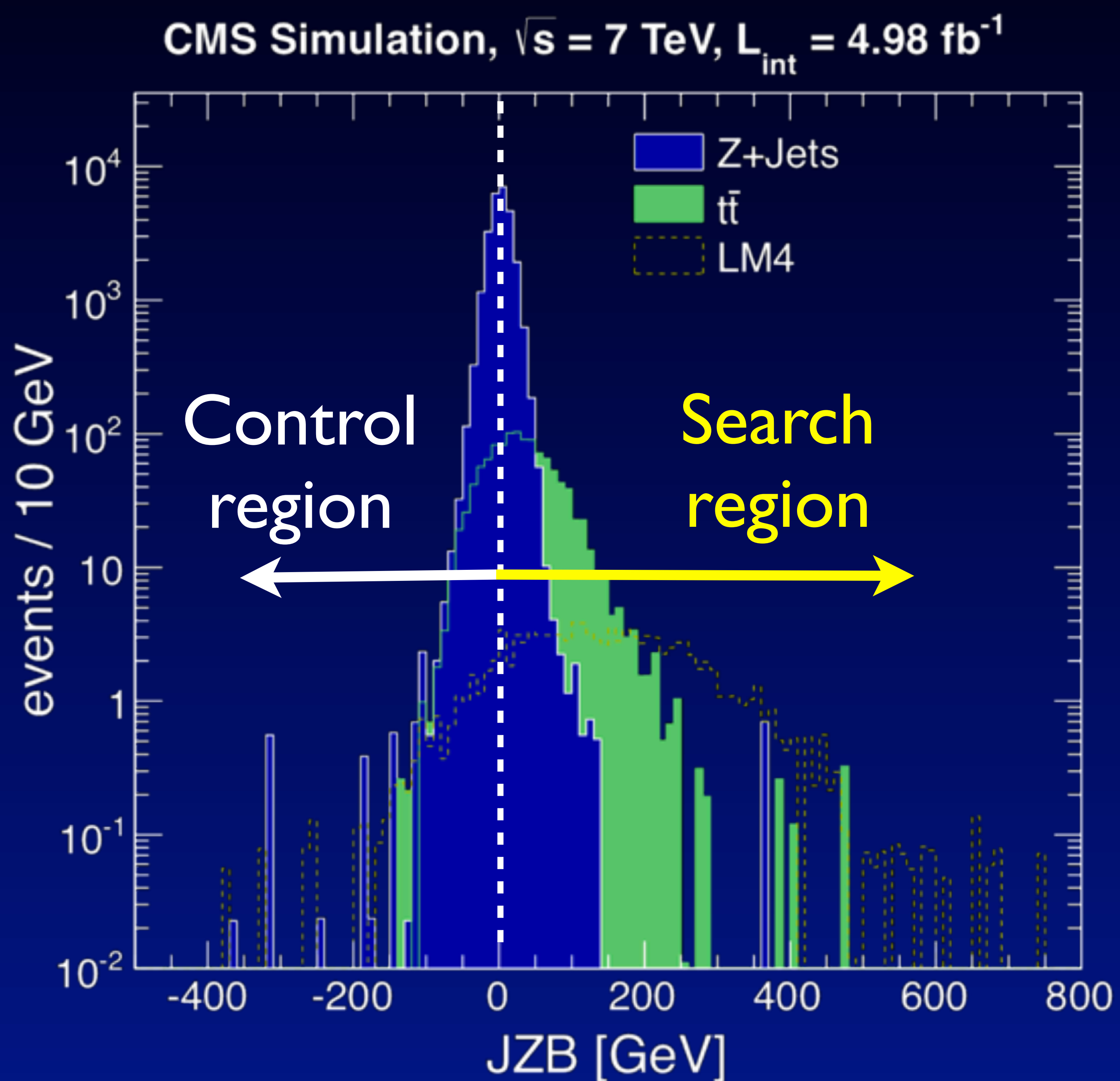
- Define

$$JZB = \left|\sum_{\text{jets}} \vec{p}_{\mathrm{T}}\right| - \left|\vec{p}_{\mathrm{T}}^{(Z)}\right|$$

  - **Z+jets events evenly populate JZB>0 and JZB<0 regions**
  - **Signal stretches to JZB≫0**

- Use JZB<0 to predict JZB>0

- Purely based on data
  - **Monte Carlo simulation only used to validate and assess systematic error**



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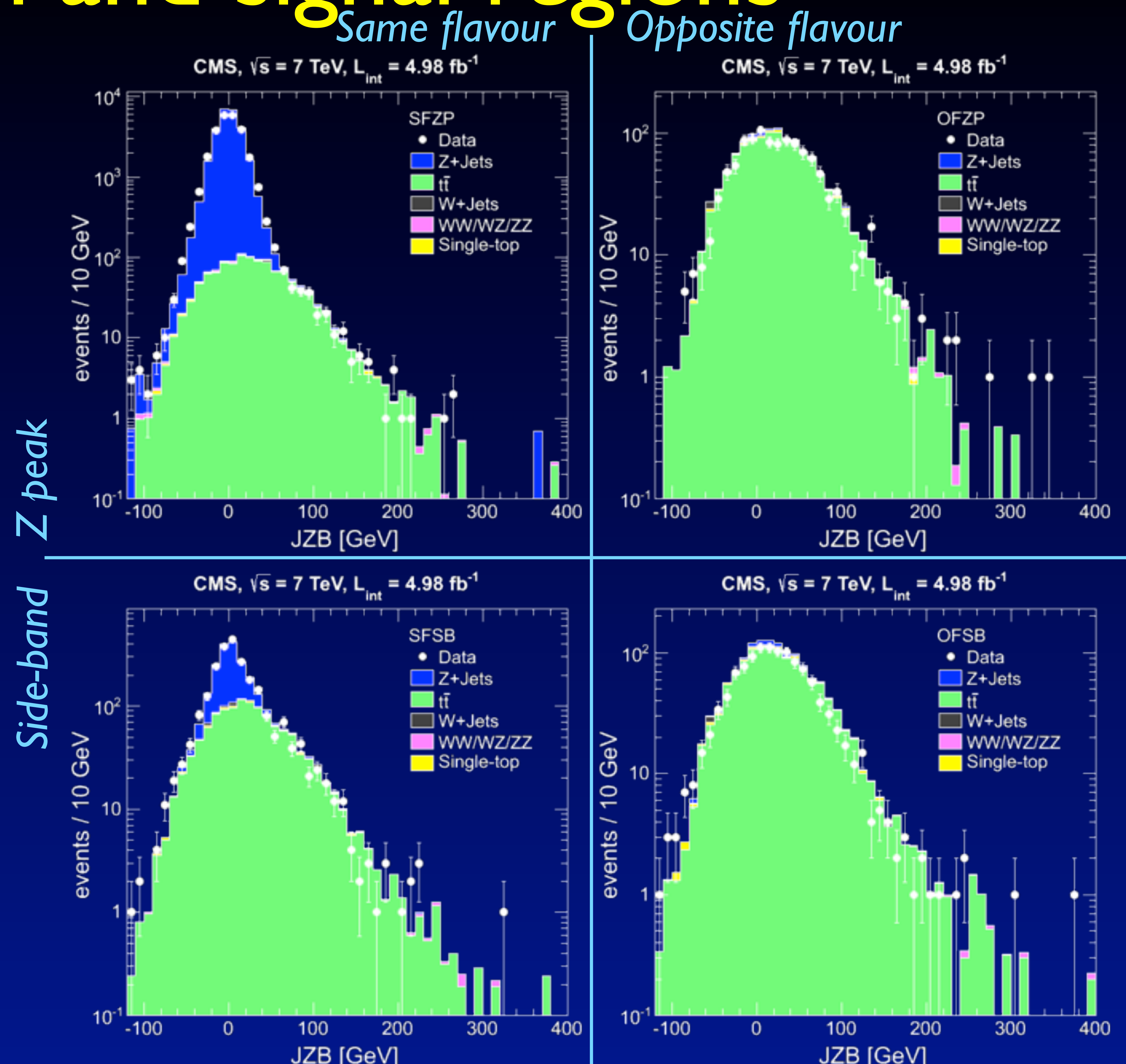
JZB control and signal regions



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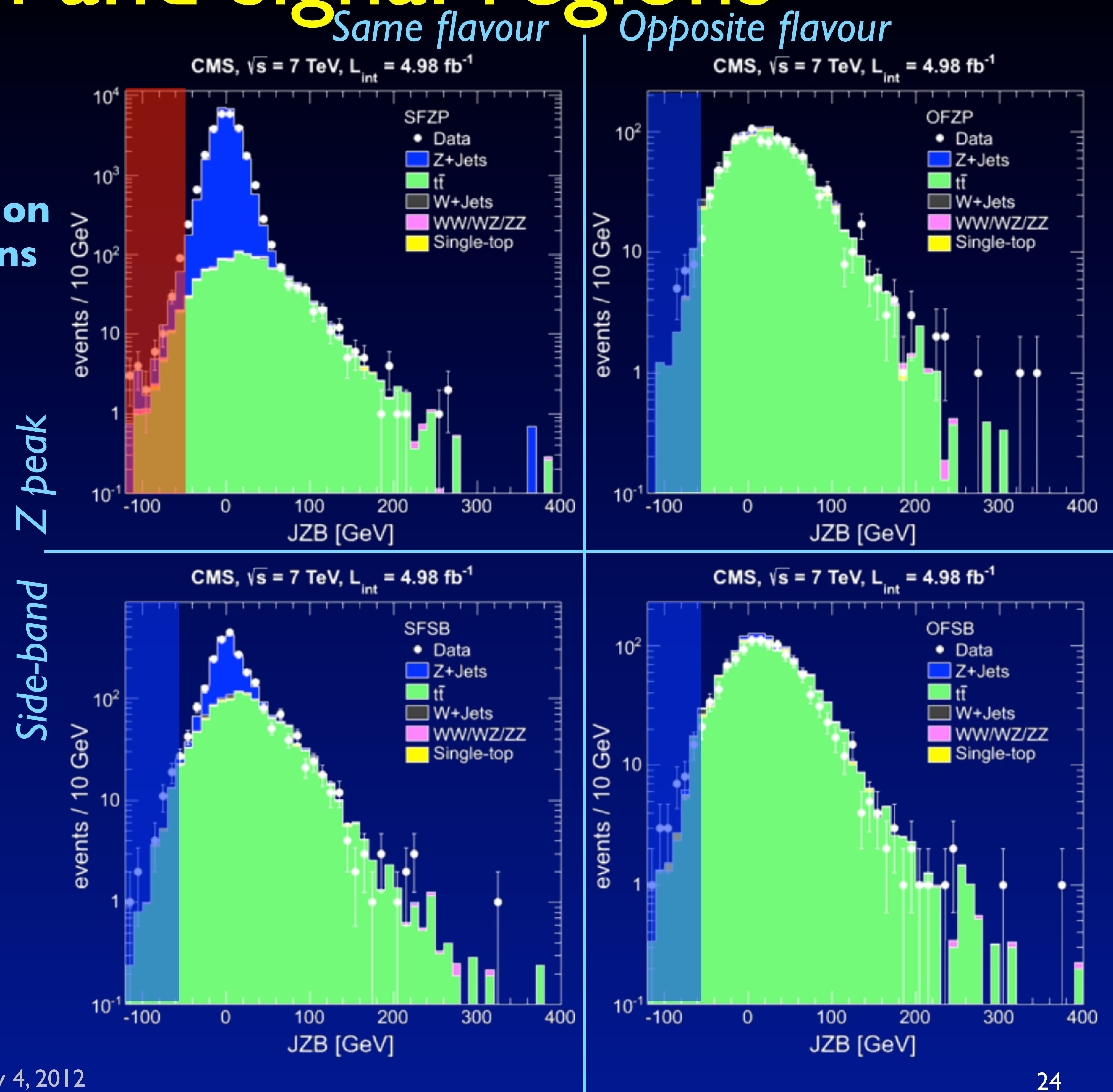
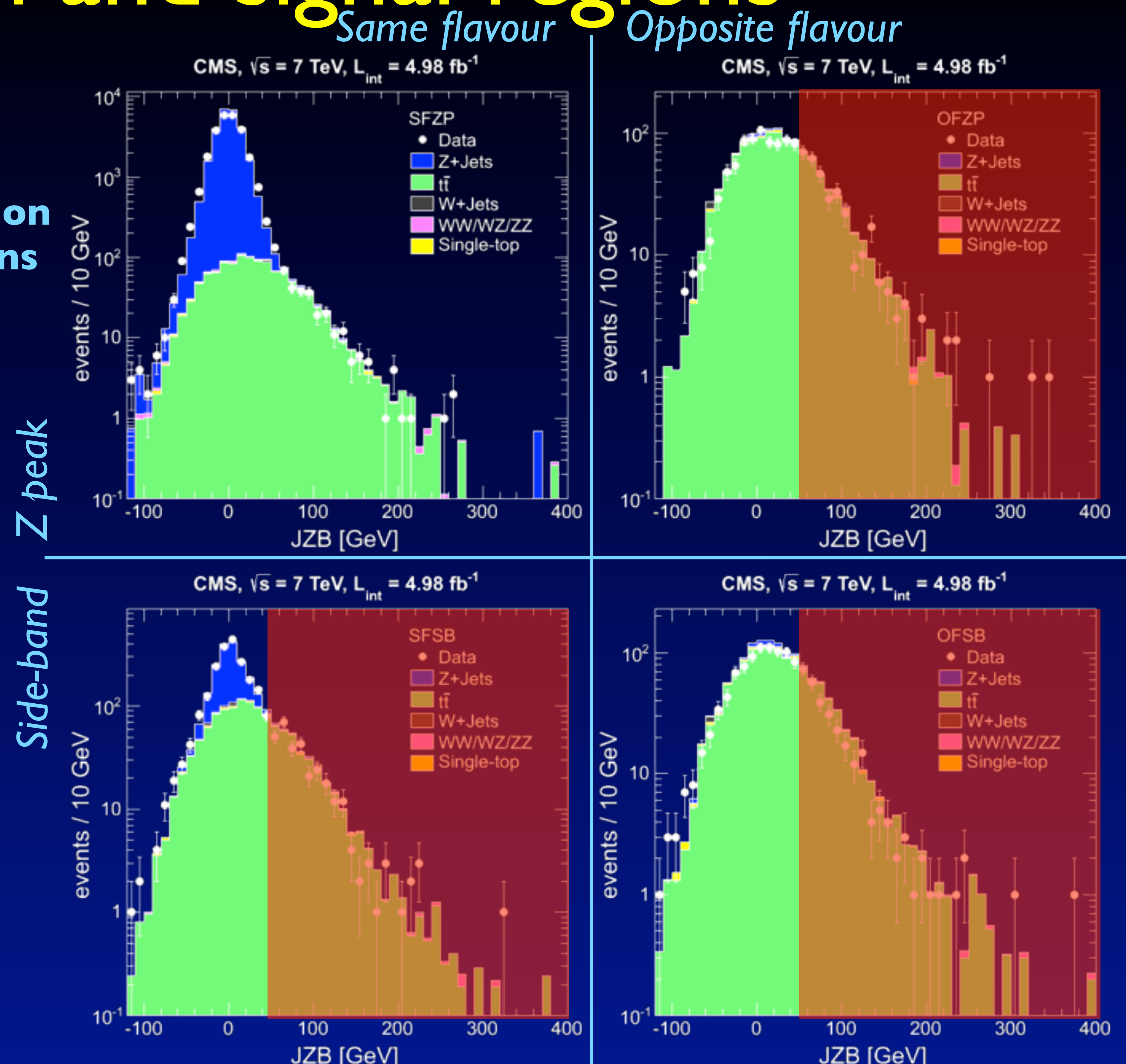
JZB control and signal regions

- Z+jets from JZB<0
  - **after ttbar subtraction from 3 control regions**



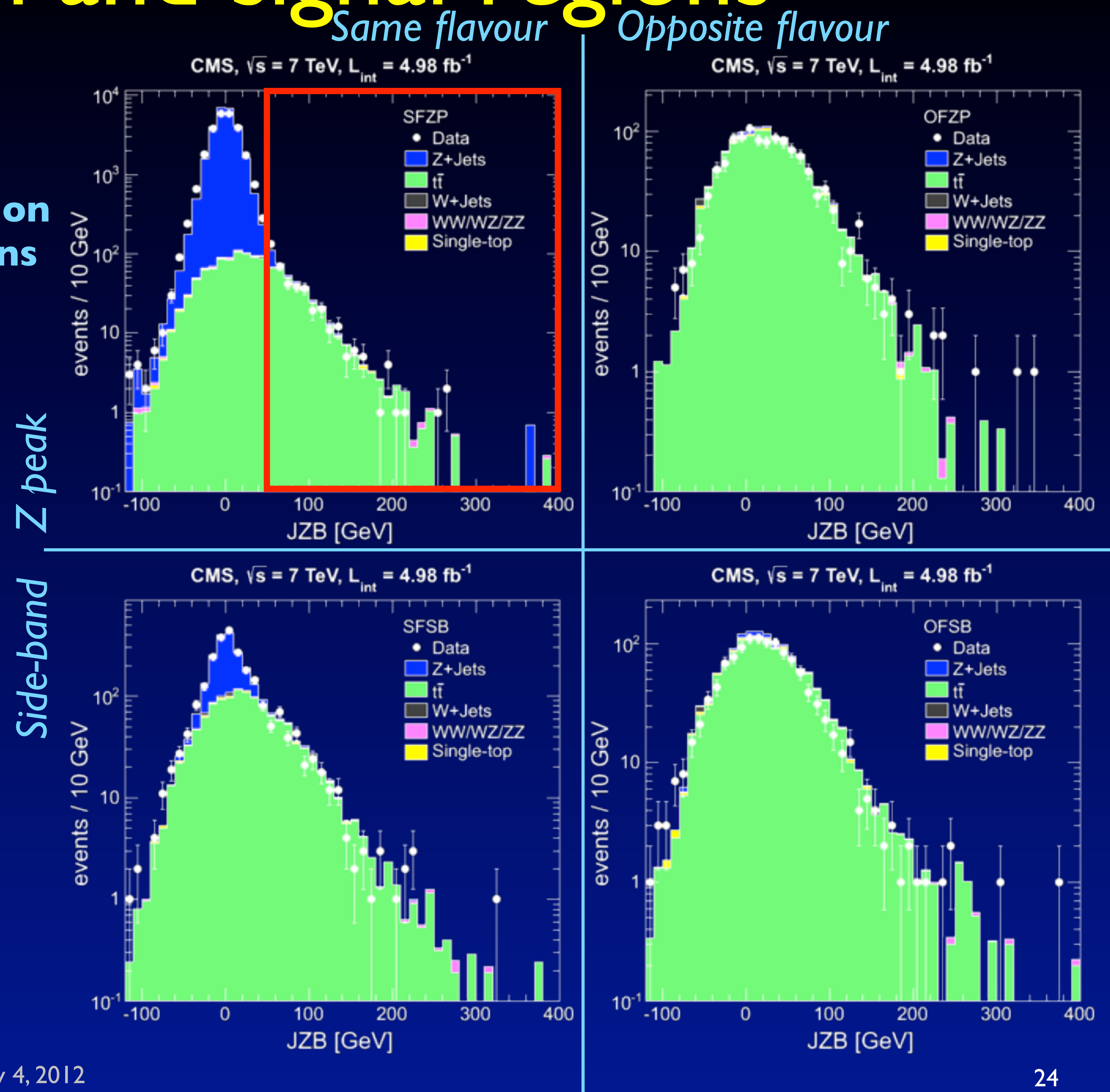
JZB control and signal regions

- Z+jets from JZB<0
  - **after ttbar subtraction from 3 control regions**
- ttbar JZB>0 from 3 control regions

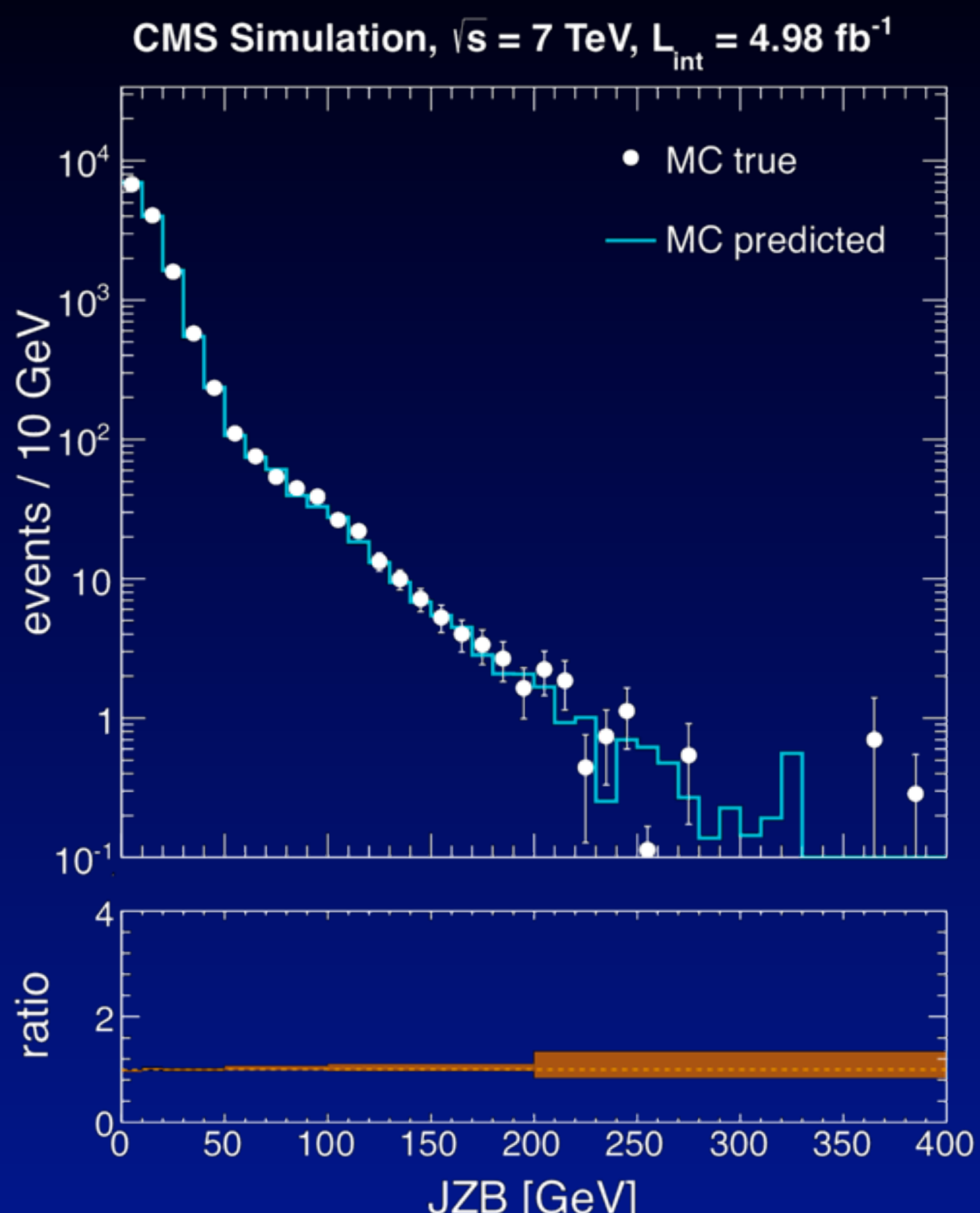


JZB control and signal regions

- Z+jets from JZB<0
  - **after ttbar subtraction from 3 control regions**
- ttbar JZB>0 from 3 control regions
- search in JZB>0



Monte Carlo "closure test"



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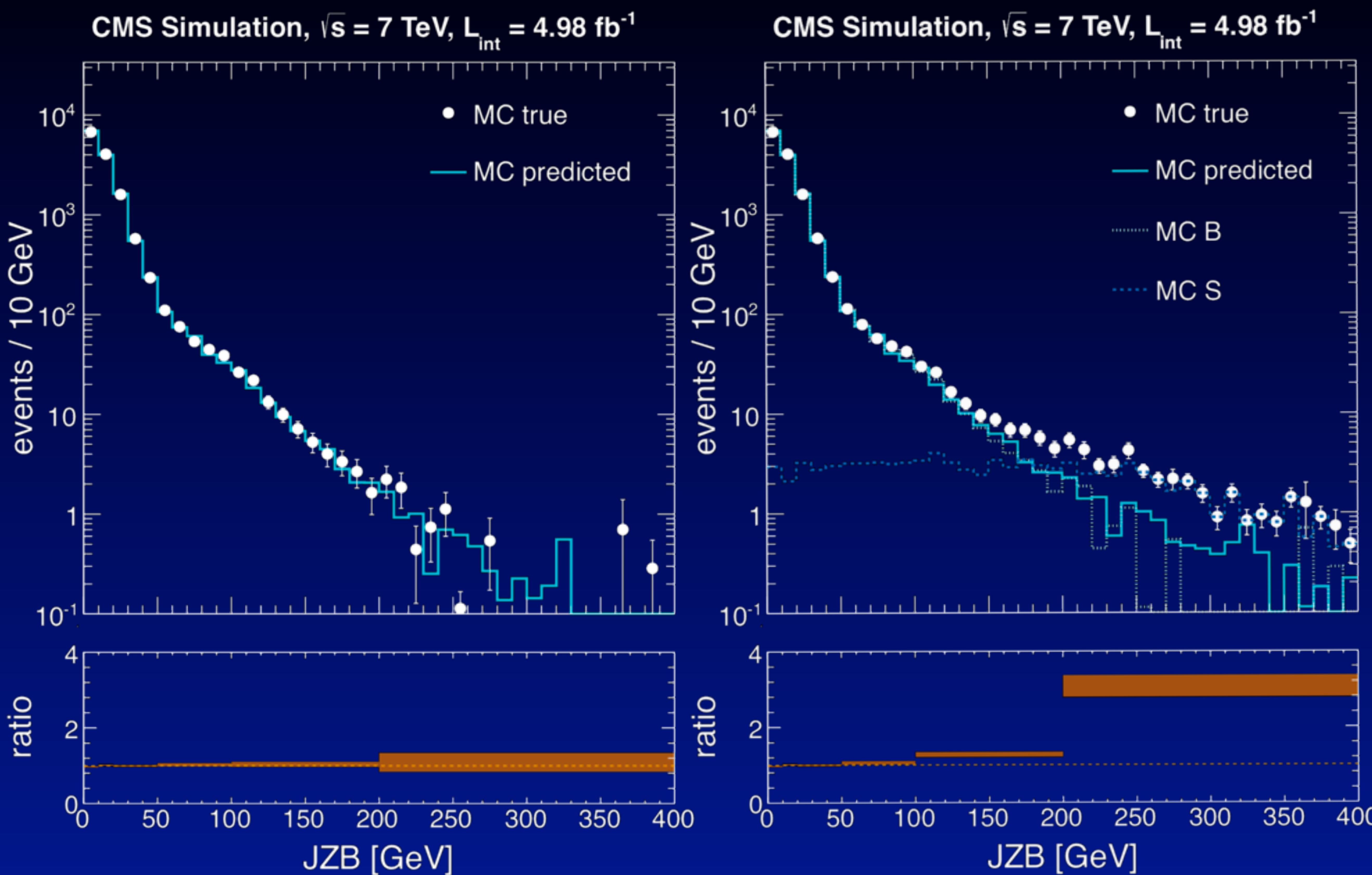

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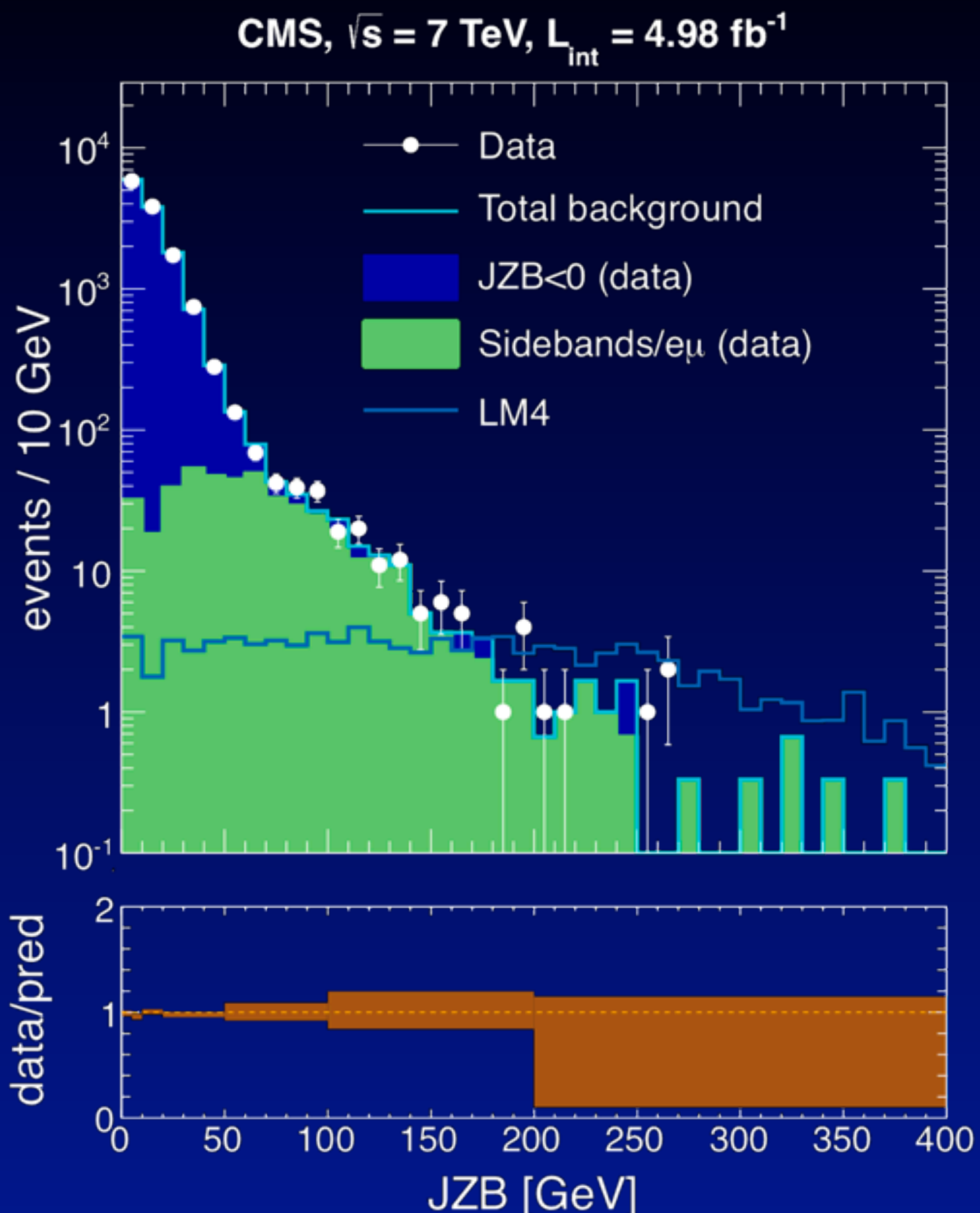
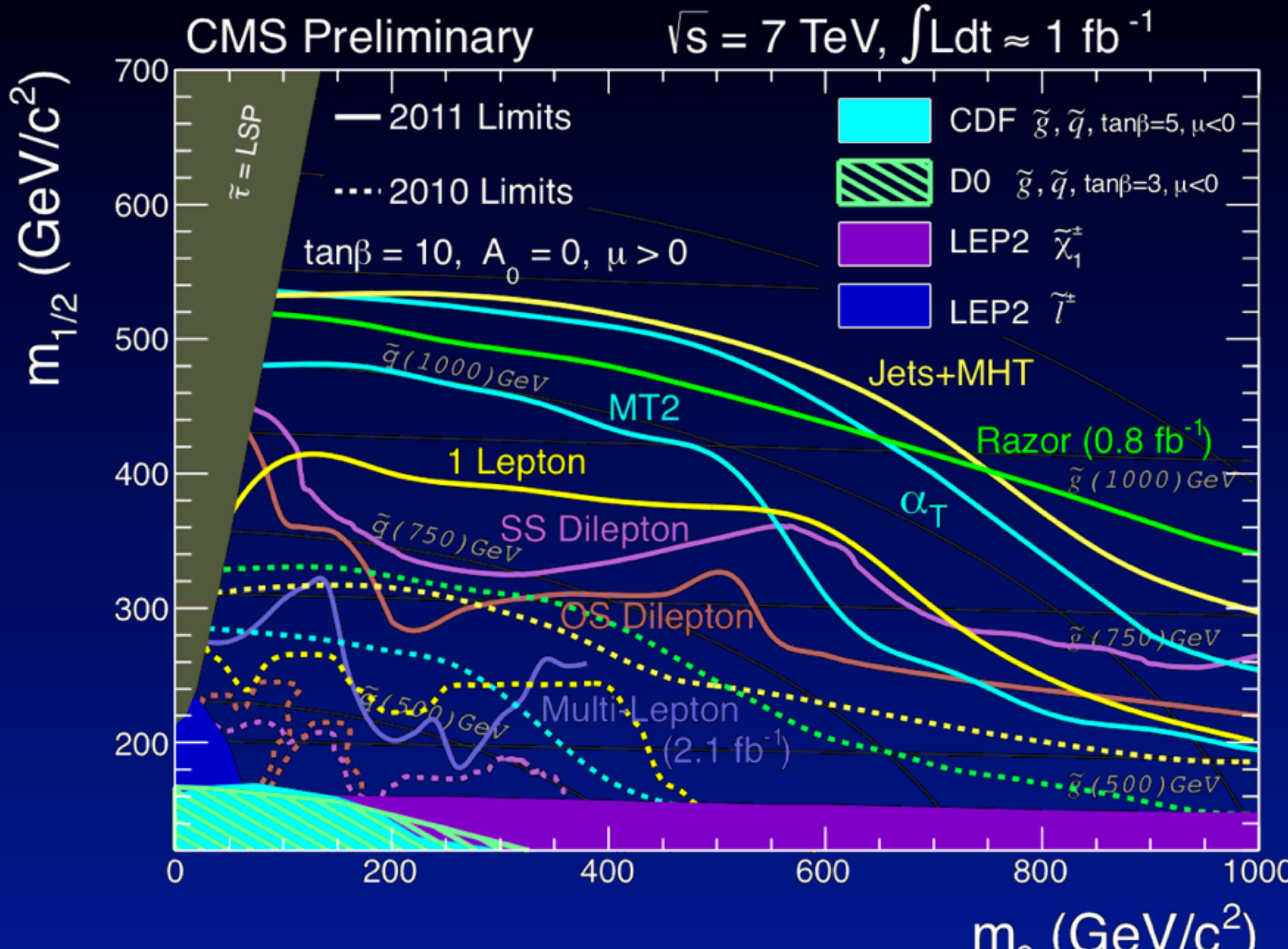
Z + jets + MET search results



Region [GeV]	Observed #(events)	Predicted #(events)
> 50	408	408±16±59
> 100	88	89±6±12
> 150	21	22±3±3
> 200	5	8±2±1
> 250	3	2.0±0.8±0.3

Interpretation & Outlook

Interpretation & Communication



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

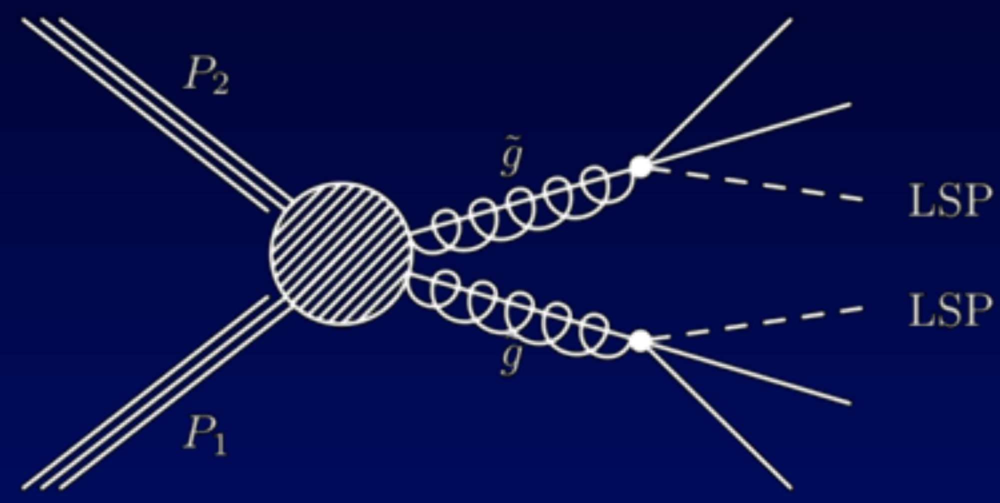
Interpretation & Communication

- Project the result on a particular **model**
  - **95% exclusion in the (m0,m1/2) plane in the CMSSM**
  - **comparison with previous searches (and other experiments...)**
- Simplified "models" of SUSY (SMS)
  - **"bottom-up" approach: adapt model to search**
  - **probe kinematic regions not accessible in constrained model**
- Global fits
  - **"top-down": integrate results in global fit of parameter space**
- Provide "outreach" information required for model testing
  - **acceptance, efficiency, detector response**

Simplified models of SUSY

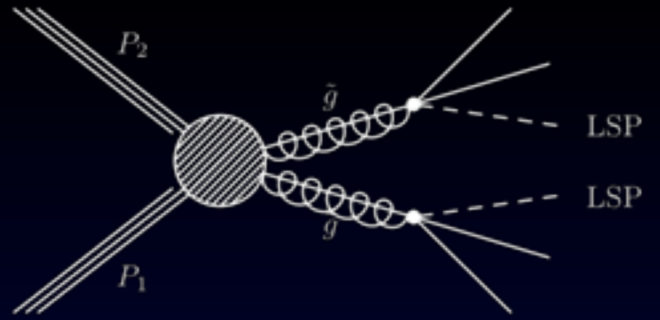
- Simplified topologies with limited number of particles
  - **inspired by theoretical work**
- Example: hadronic models
  - **gluino pair production with decay to quark-antiquark + LSP**
  - **kinematics specified by masses**
    - present limits in 2D mass plot

$$\tilde{g}\tilde{g} \rightarrow (q\bar{q}\tilde{\chi}_1^0)(q\bar{q}\tilde{\chi}_1^0)$$

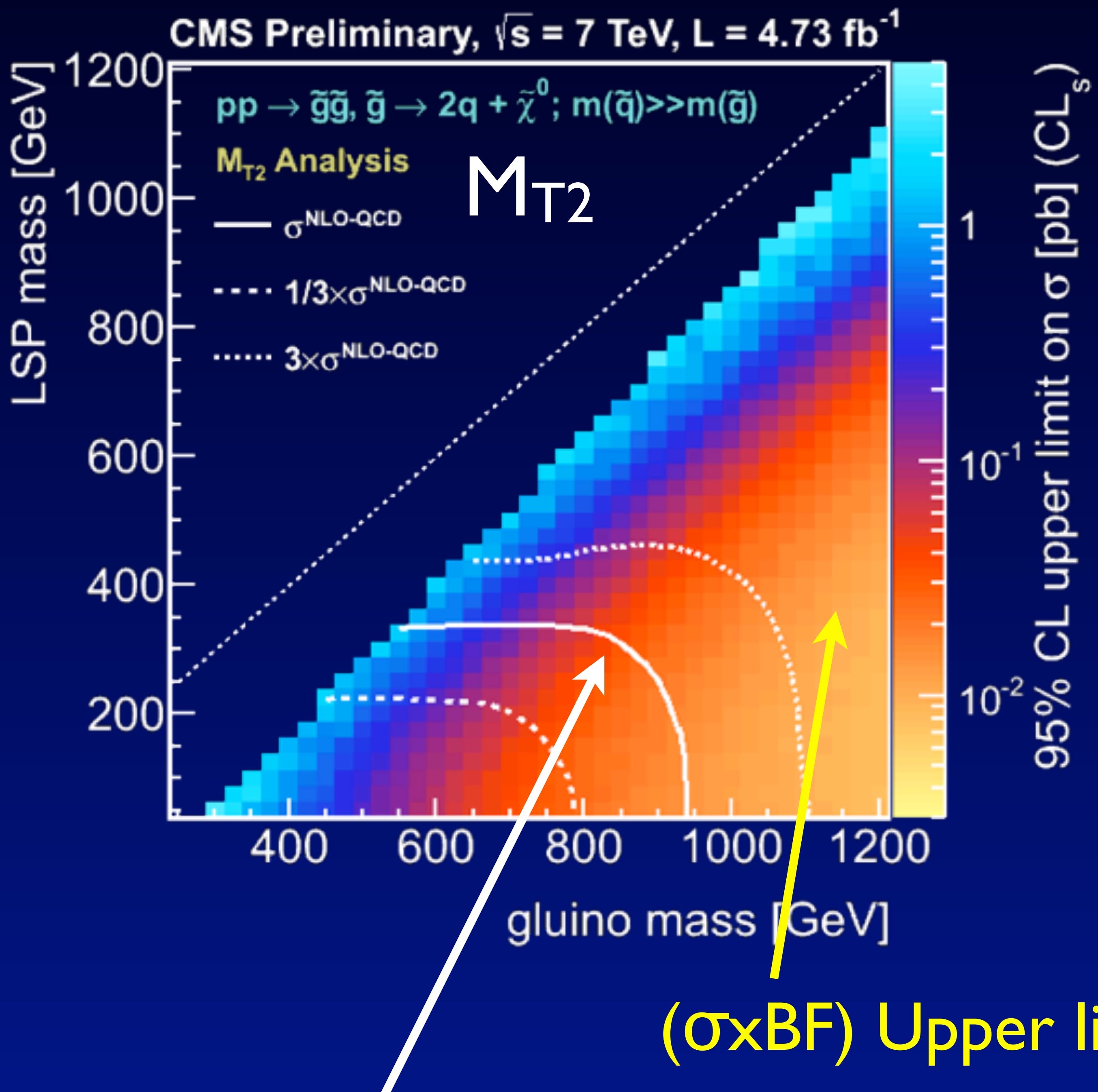


- Motivations
  - **compare analyses & uncover “holes” in covered ground**
  - **get away from constrained models**
  - **provide additional information for model testing**

M_{T2} limits: SMS mass plane



- example limits in simplified models

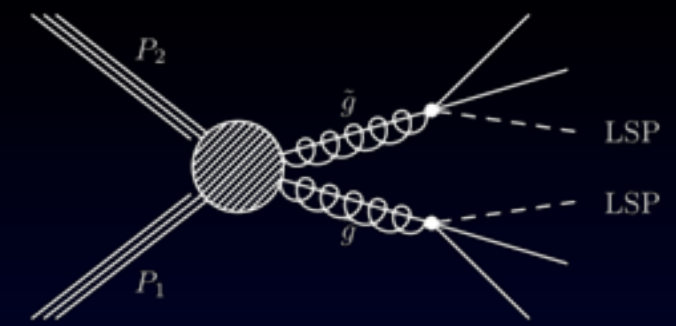


(σxBF) Upper limit in 2D mass plane

Assume $\sigma^{NLO-QCD}$ and BF = 1

CMS-PAS-SUS-11-016

M_{T2} limits: SMS mass plane



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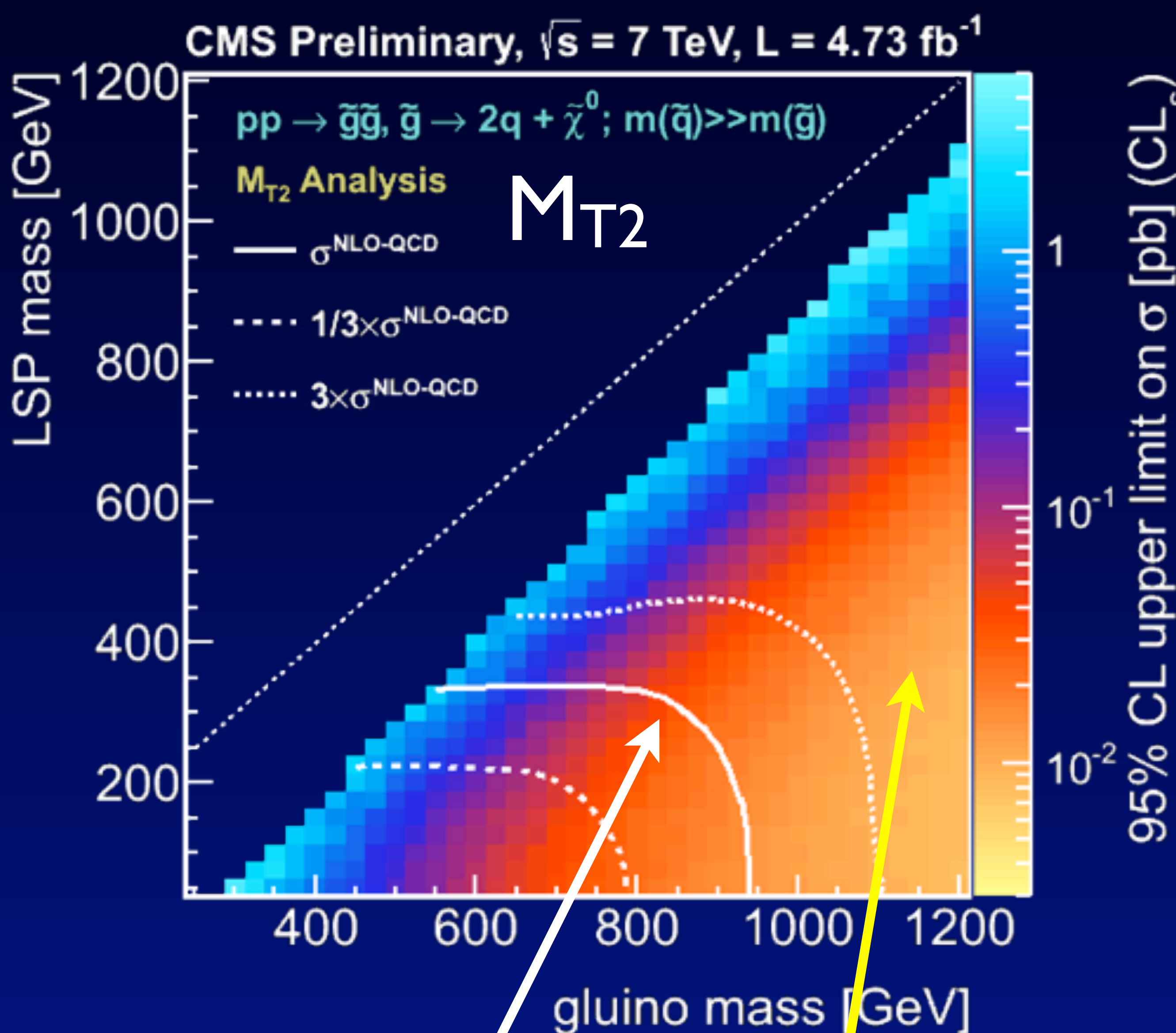

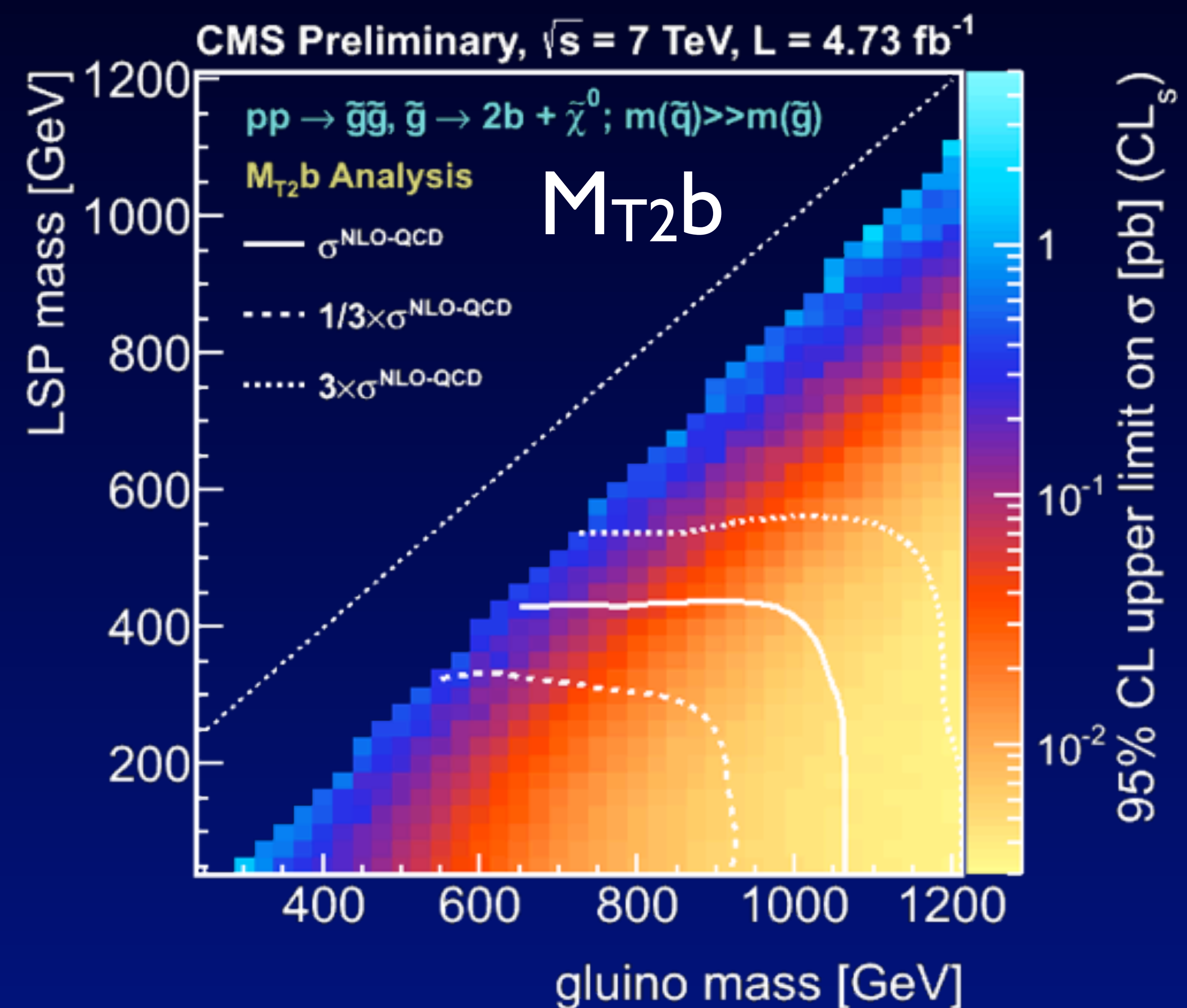

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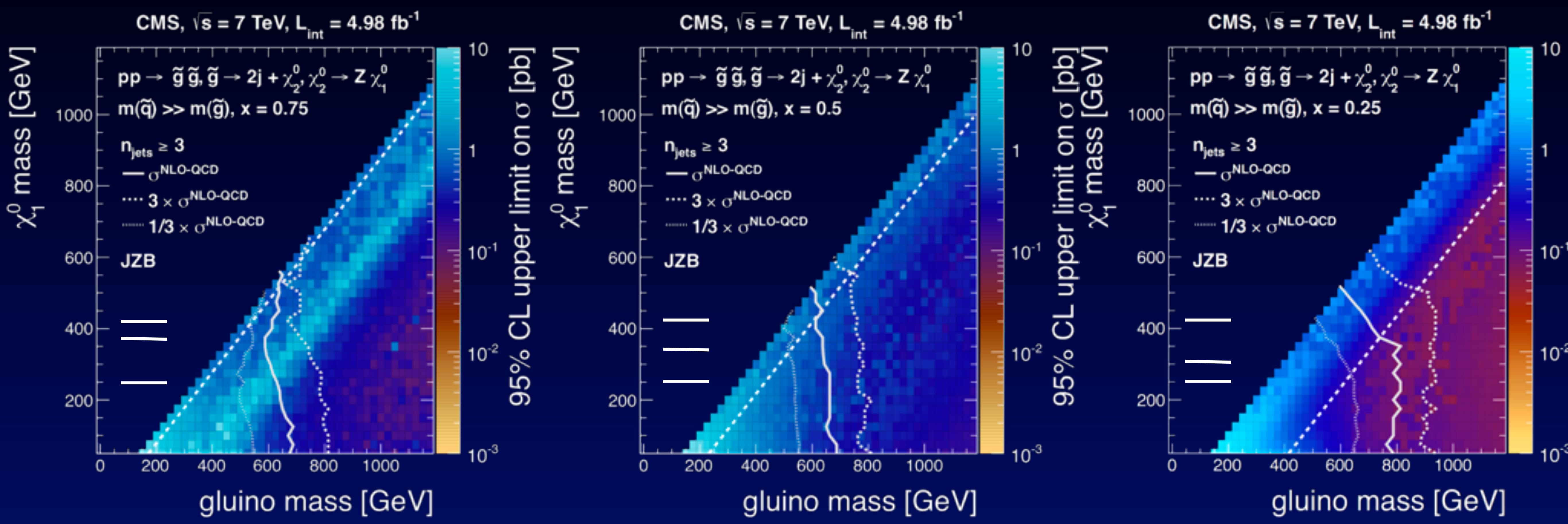
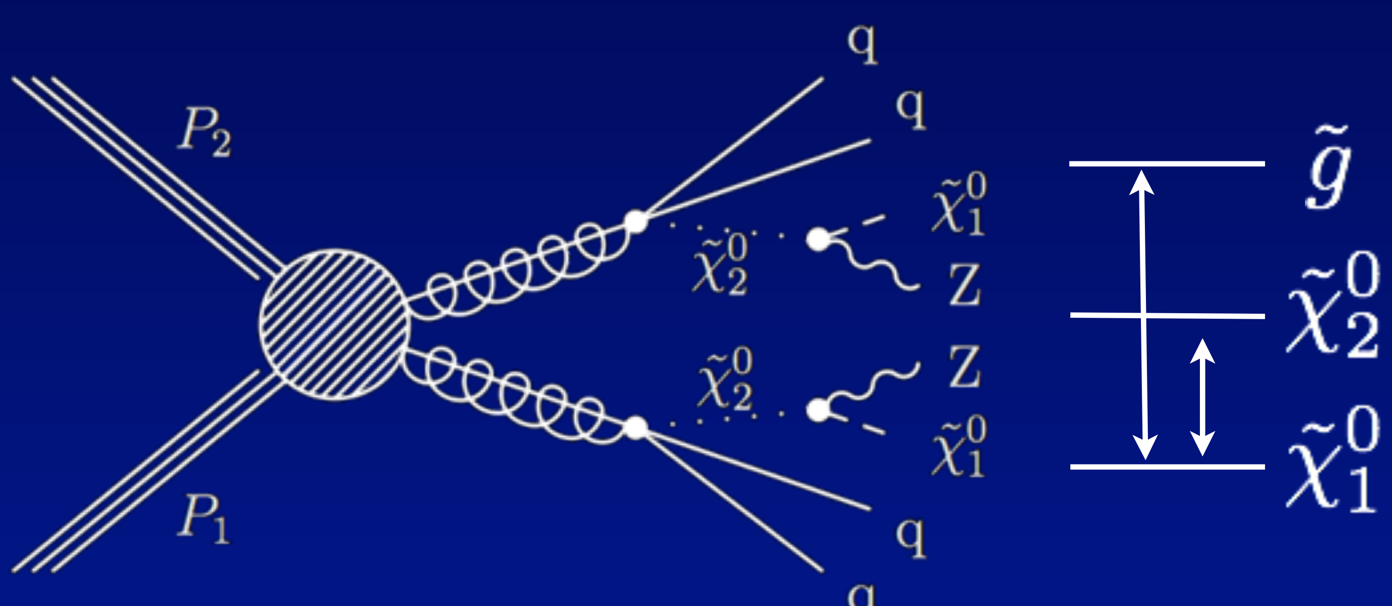
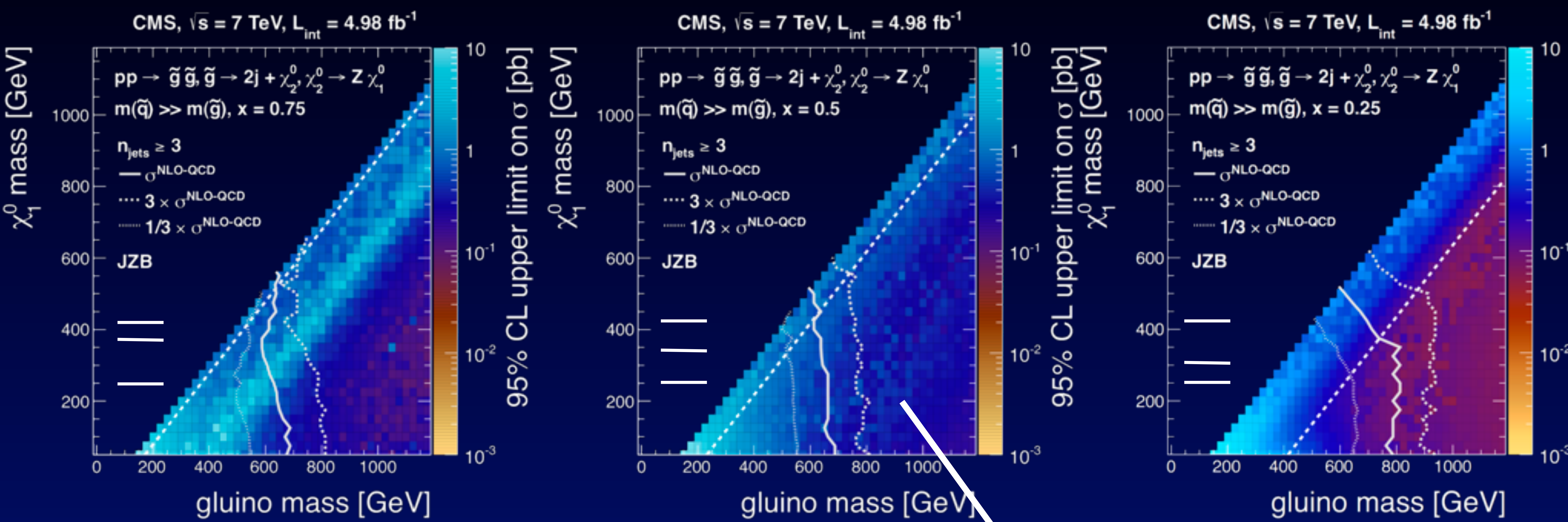
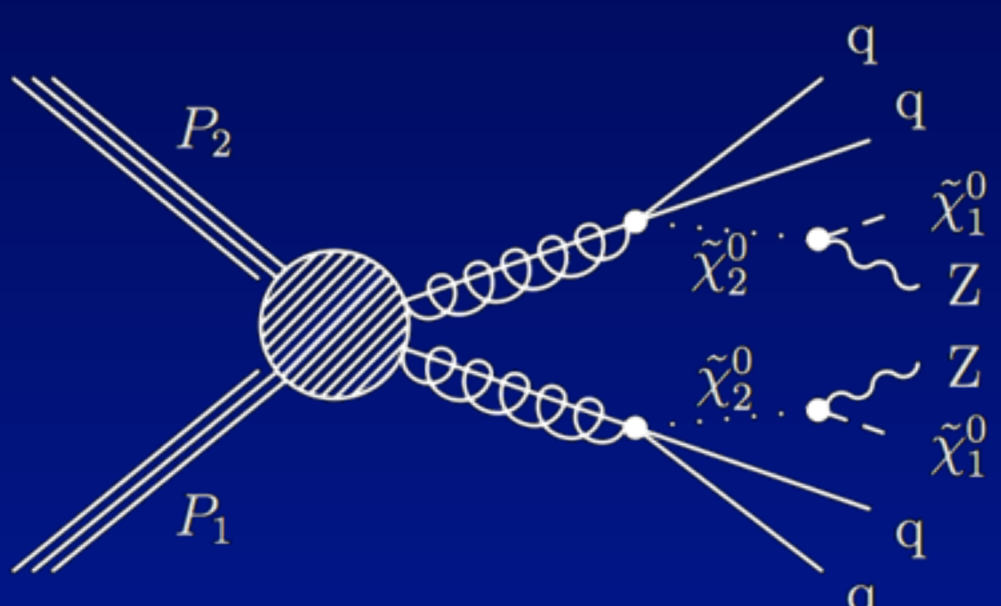
JZB limits: sensitivity to masses

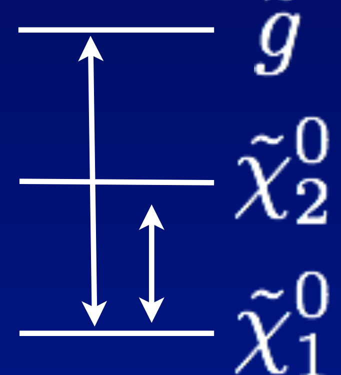


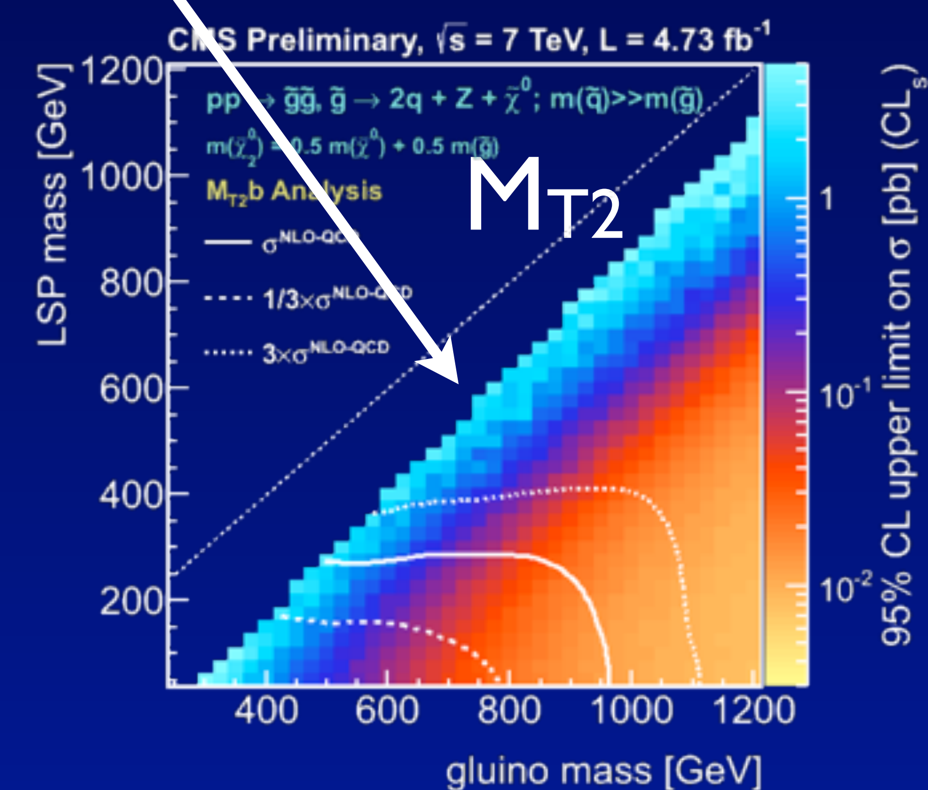


JZB limits: sensitivity to masses

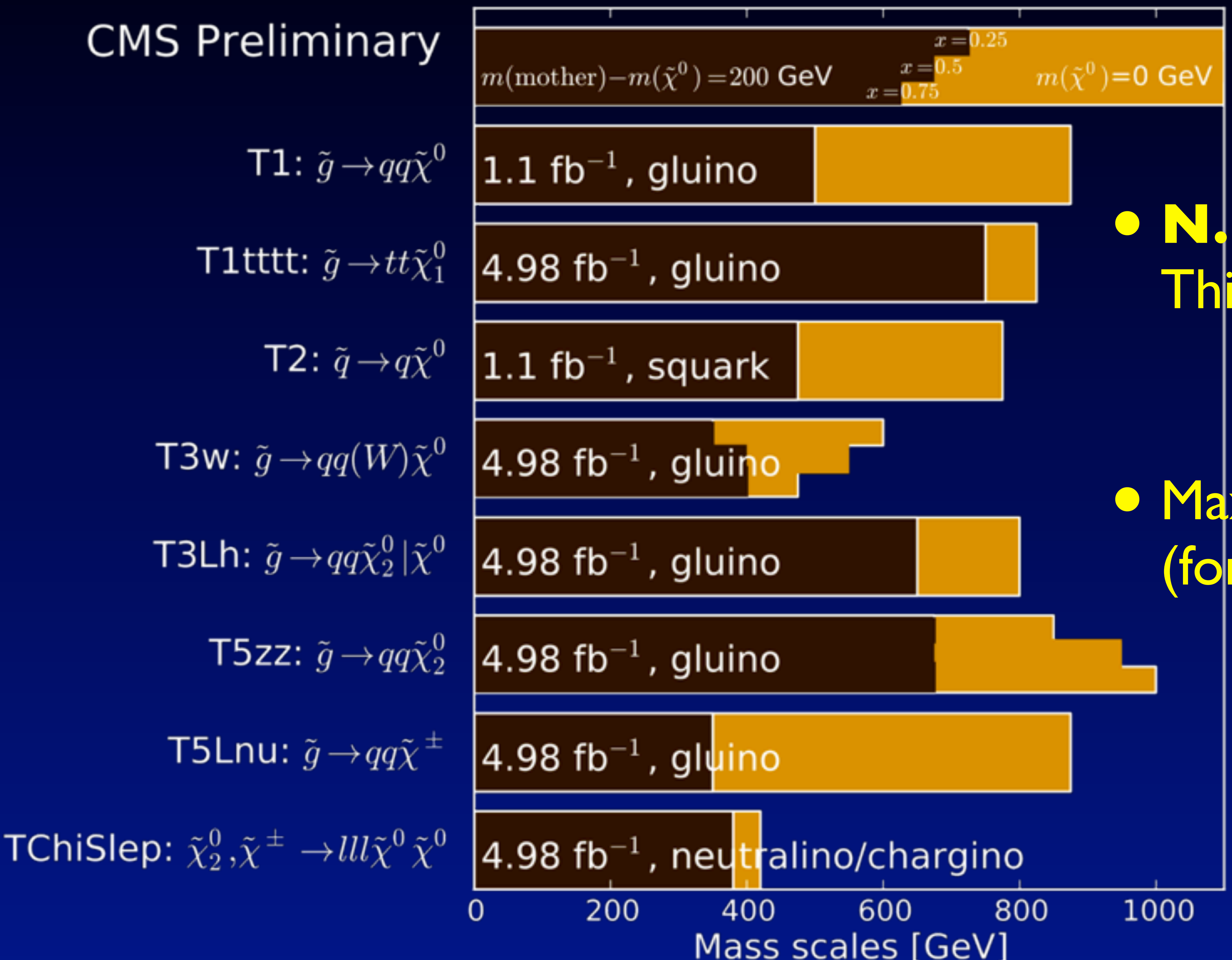








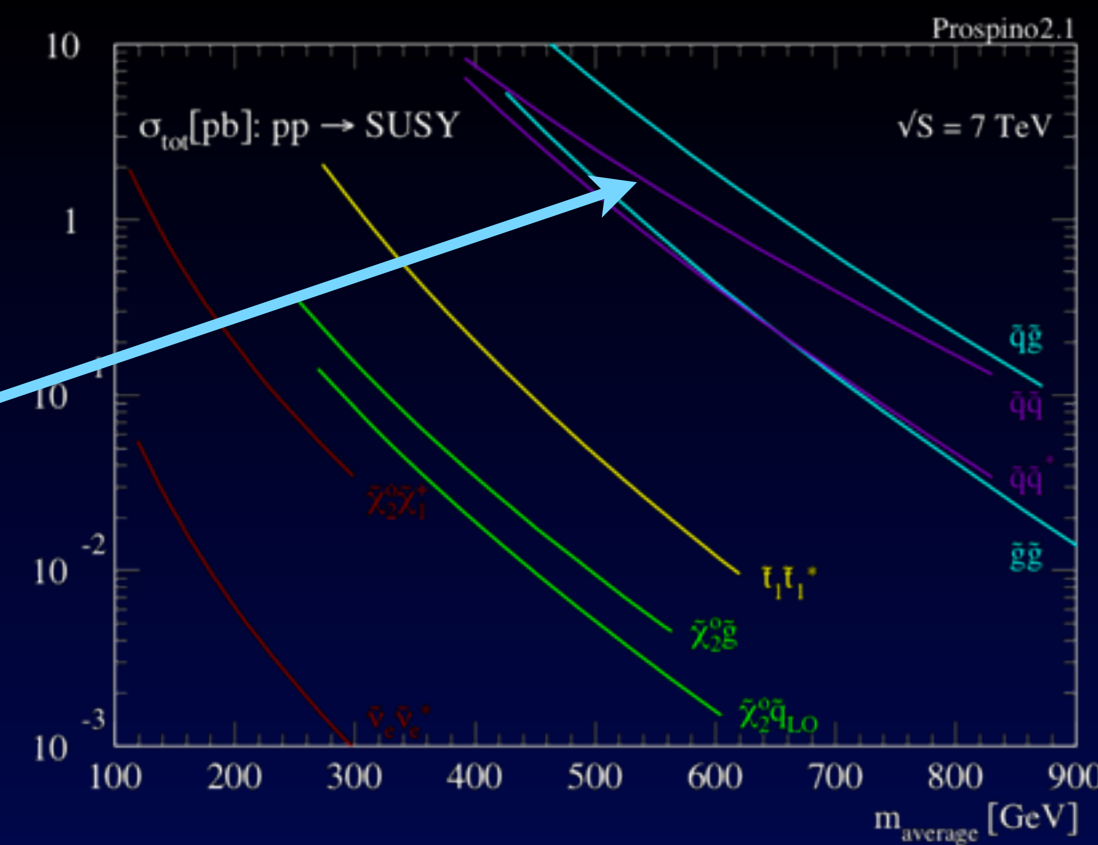
A picture is worth 1000 words (?)

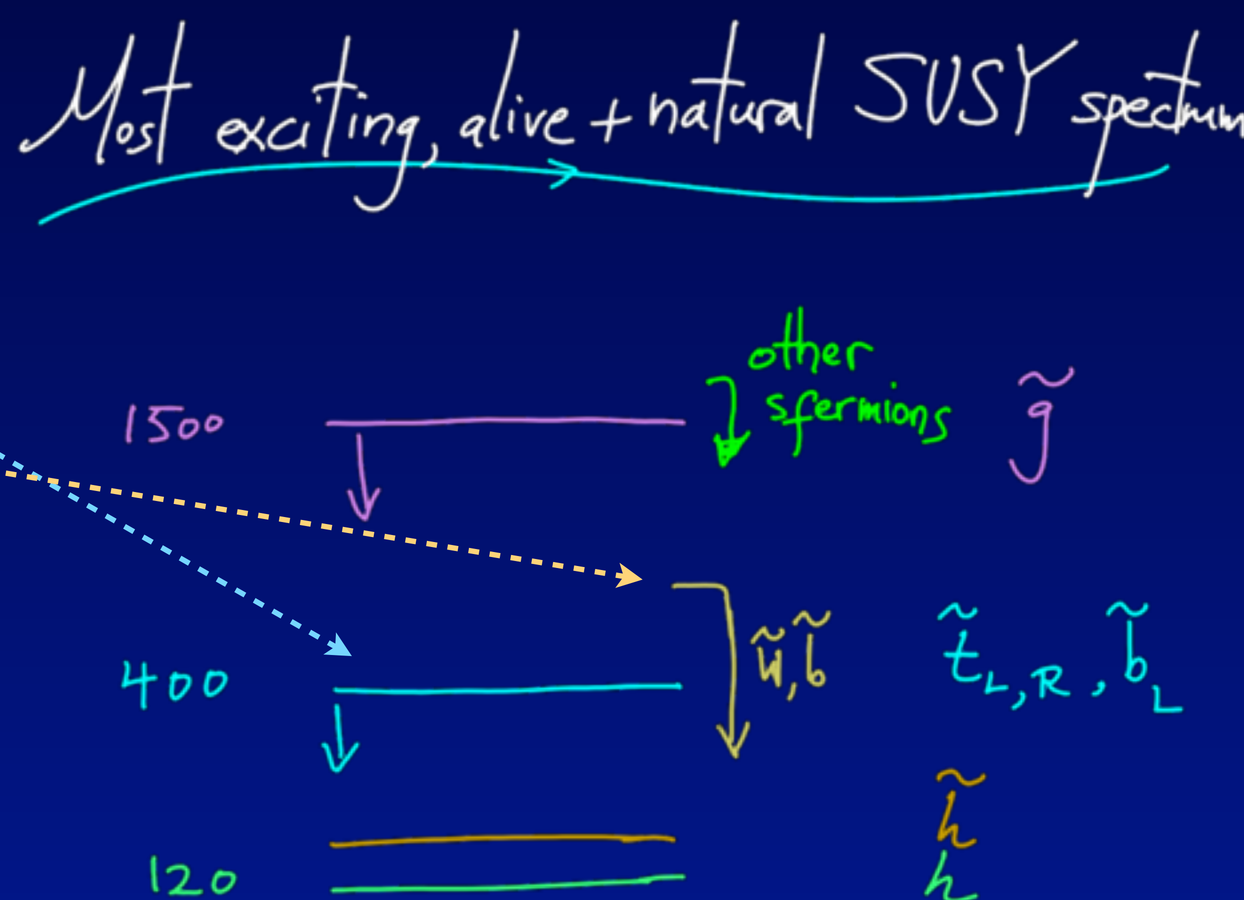


- **N.B.**
  This assumes **BF=1**
- Maximum reach *1 TeV* (for massless LSP)

Outlook

- Have we excluded SUSY yet?
  - **went for “low-hanging fruit” first**
  - **is it still hiding at higher masses?**
    - how high can we go?
- Have we missed SUSY?
  - **stop production**
    - third generation searches
  - **EWK production**
    - ≥3 lepton searches
  - **“compressed spectra”**
    - low H_T, low MET, low p_T

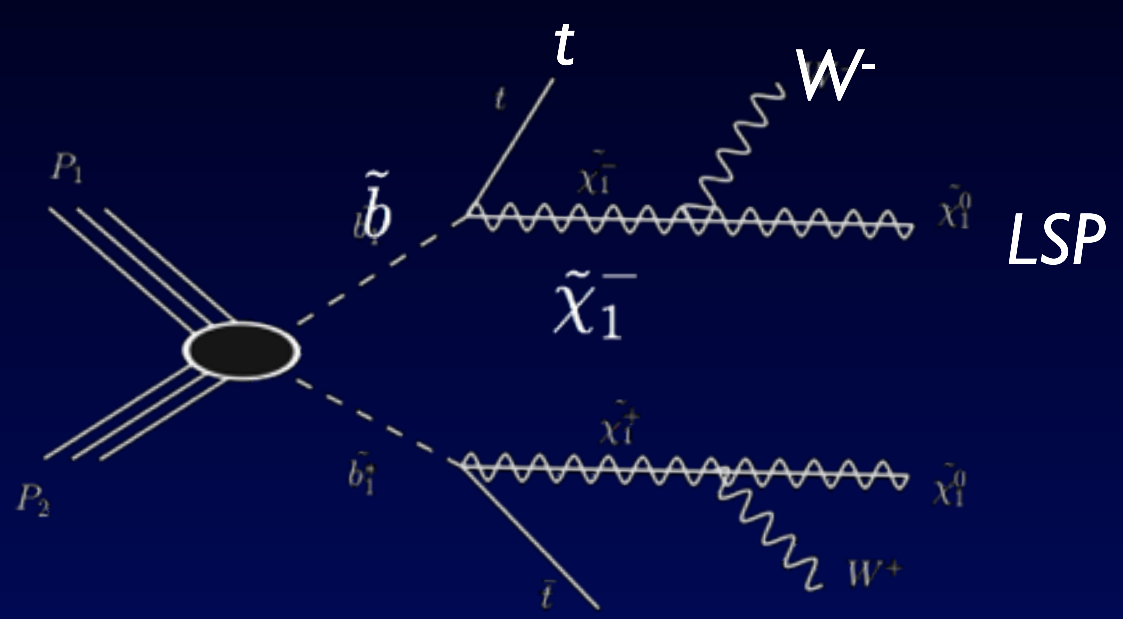


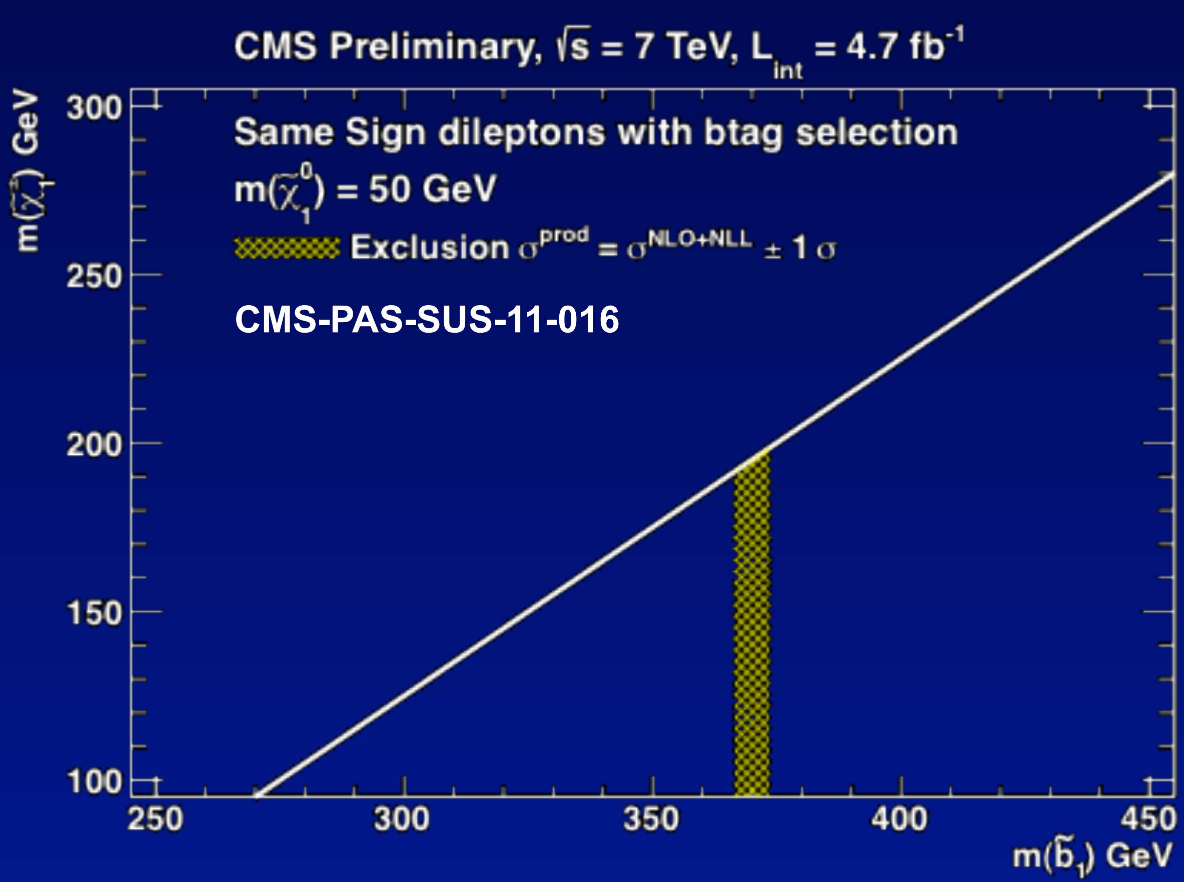


N. Arkani-Hamed, Oct. 2011

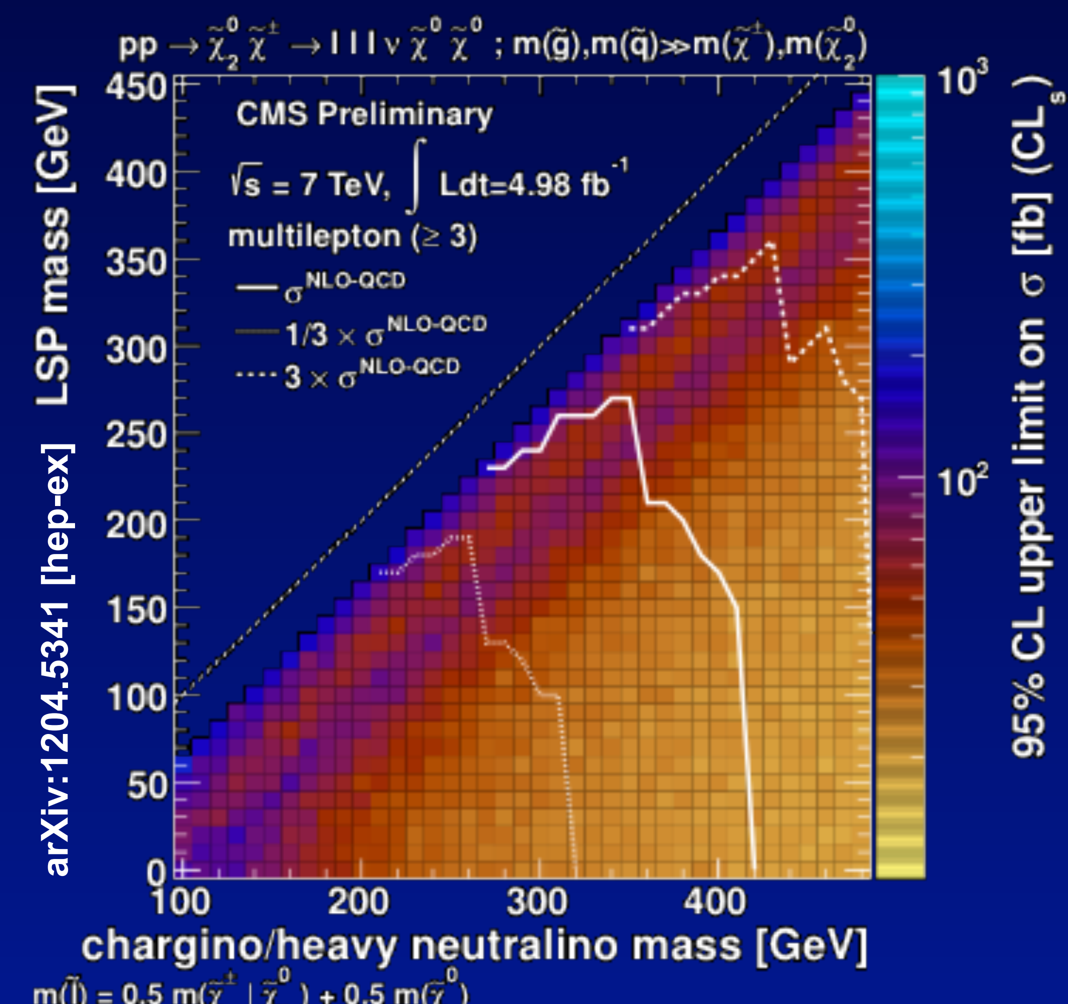
3rd generation and EWK*ino*

- Same-sign leptons + 1 b-jet





- $\geq$3 leptons (e,μ,τ)



Conclusion

Summary

- Excellent performance of LHC and CMS allowed broad range of SUSY searches
  - **a wealth of robust data modeling techniques successfully exploited**
    - remember: we are doing a *search*
  - **no excess found…**
- Interpretation: making best use of the absence of signal…
  - **various approaches to maximise "outreach"**
  - **Simplified models help uncover new grounds**
- The future remains bright
  - **more challenging topologies under study (stop, EWK, compressed)**
  - **more data, higher energy ➠ higher sensitivity in 2012**

More information

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

Journal Publications with 2011 7 TeV Data

Analysis	Approved Plots	CDS Entry	Luminosity	Comment
Search for Anomalous Production of Multilepton Events in pp Collisions at $\sqrt{s}$ = 7 TeV NEW	EXO11045/SUS11013	CMS-SUS-11-013	4.98/fb	Submitted to JHEP: arXiv:1204.5341
Search for physics beyond the standard model in events with a Z boson, jets and missing transverse energy NEW	SUS11021	CMS-SUS-11-021	4.98/fb	Submitted to PLB: arXiv:1204.3774
Search for supersymmetry in all-hadronic events with αT	SUS11003	CMS-SUS-11-003	1.1/fb	arxiv:1109.2352, PRL 107, 221804 (2011)

Recent Preliminary Results with 2011 7 TeV Data

Analysis	Approved Plots	CDS Entry	Luminosity	Comment
Interpretation of Searches for Supersymmetry NEW	SUS11016	PAS-SUS-11-016	up to 4.98/fb	
Search for new physics in the multijets + missing transverse energy final state NEW	SUS12011		4.98/fb	Update of 1.1/fb result
Search for Supersymmetry in hadronic final states using MT2 with the CMS detector at 7 TeV NEW	SUS12002	PAS-SUS-12-002	4.73/fb	
Search for supersymmetry in events with a single lepton and jets using a neural network NEW	SUS11026	PAS-SUS-11-026	4.98/fb	
Search for supersymmetry in events with a lepton and missing energy at the LHC NEW	SUS12010	PAS-SUS-12-010	4.7/fb	
Search for new physics in events with opposite-sign leptons, jets and missing transverse energy NEW	SUS11011		4.7/fb	Update of 0.98/fb result
Search for supersymmetry with the razor variables at $\sqrt{s}$ = 7 TeV NEW	SUS12005	PAS-SUS-12-005	4.4/fb	
Search for supersymmetry in events with photons and missing energy NEW	SUS12001	PAS-SUS-12-001	4.7/fb	
Search for new physics in events with same-sign dileptons, b-tagged jets and missing energy		PAS-SUS-		