Searches at the LHC

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Contents

PHYSICS AT THE TERASCALE
Helmholtz Alliance

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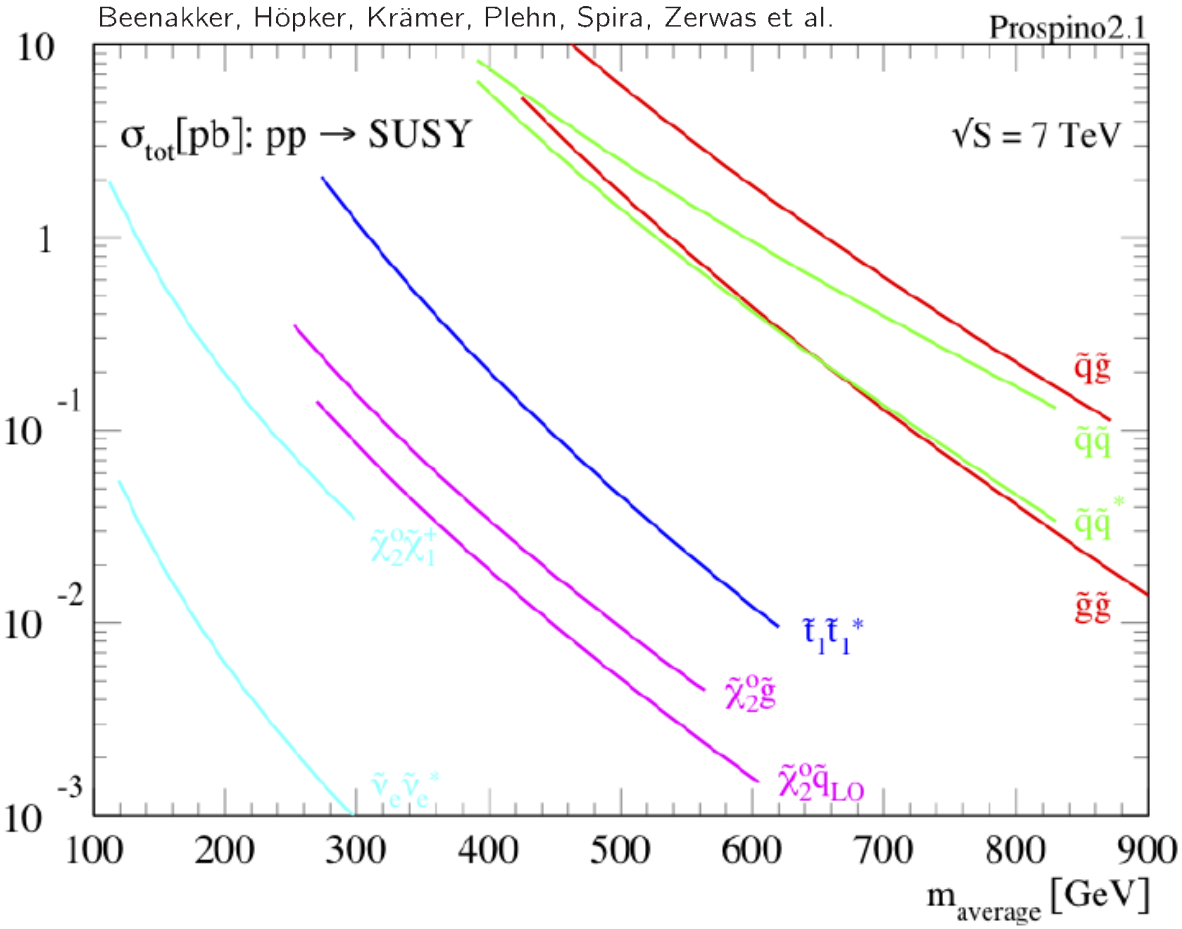
All limits at 95% confidence level (CL) if not specified otherwise

Searches for Supersymmetry (SUSY)

SUSY production cross-section



- Colored SUSY particles preferentially produced at LHC
  - Strong interaction, large cross-section
- Primary search channels: squark squark ($\tilde{q}\tilde{q}$), squark gluino ($\tilde{q}\tilde{g}$), gluino gluino ($\tilde{g}\tilde{g}$)
  - Subsequent SUSY decay chains produce many jets, high-MT, high-MET, ...

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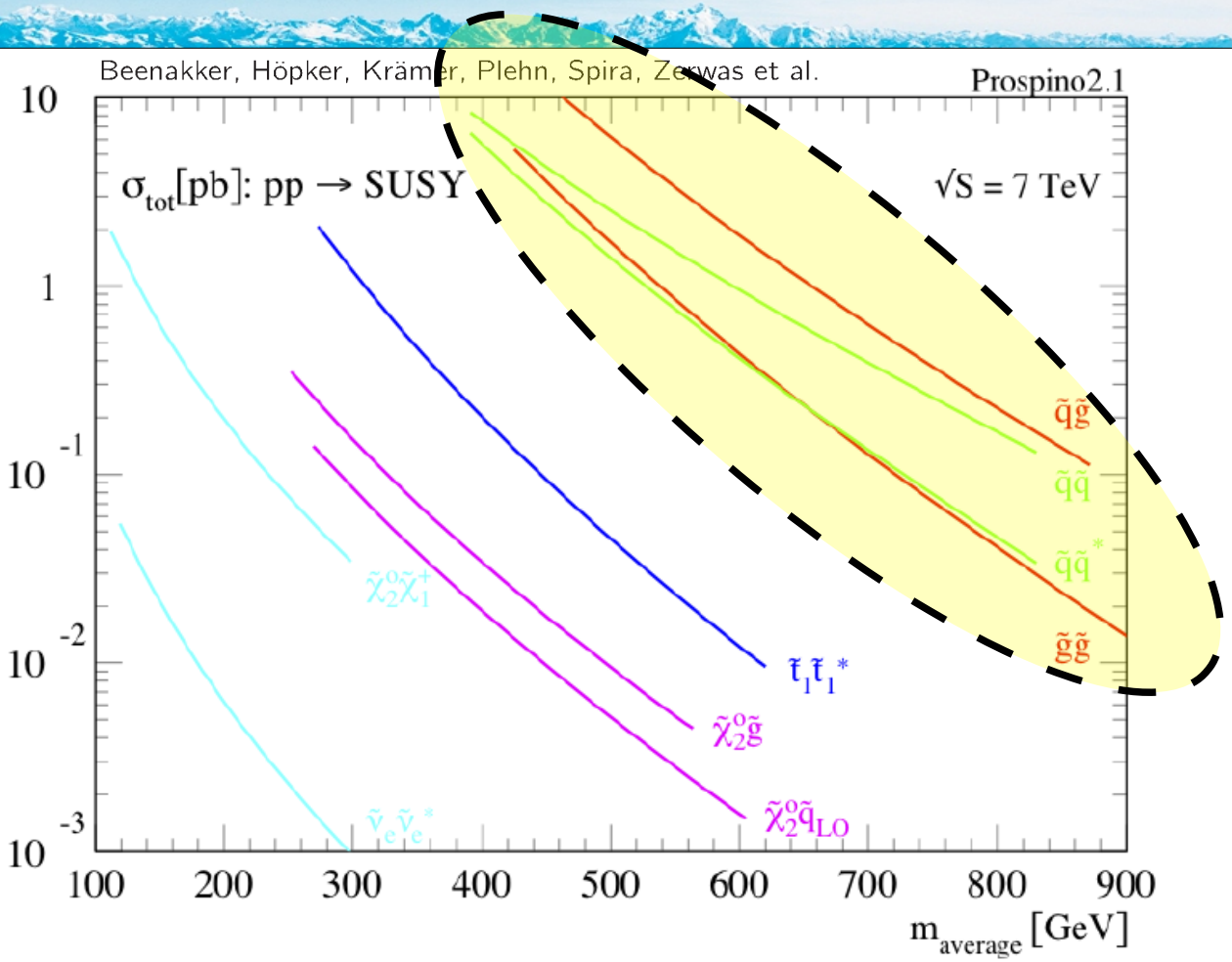

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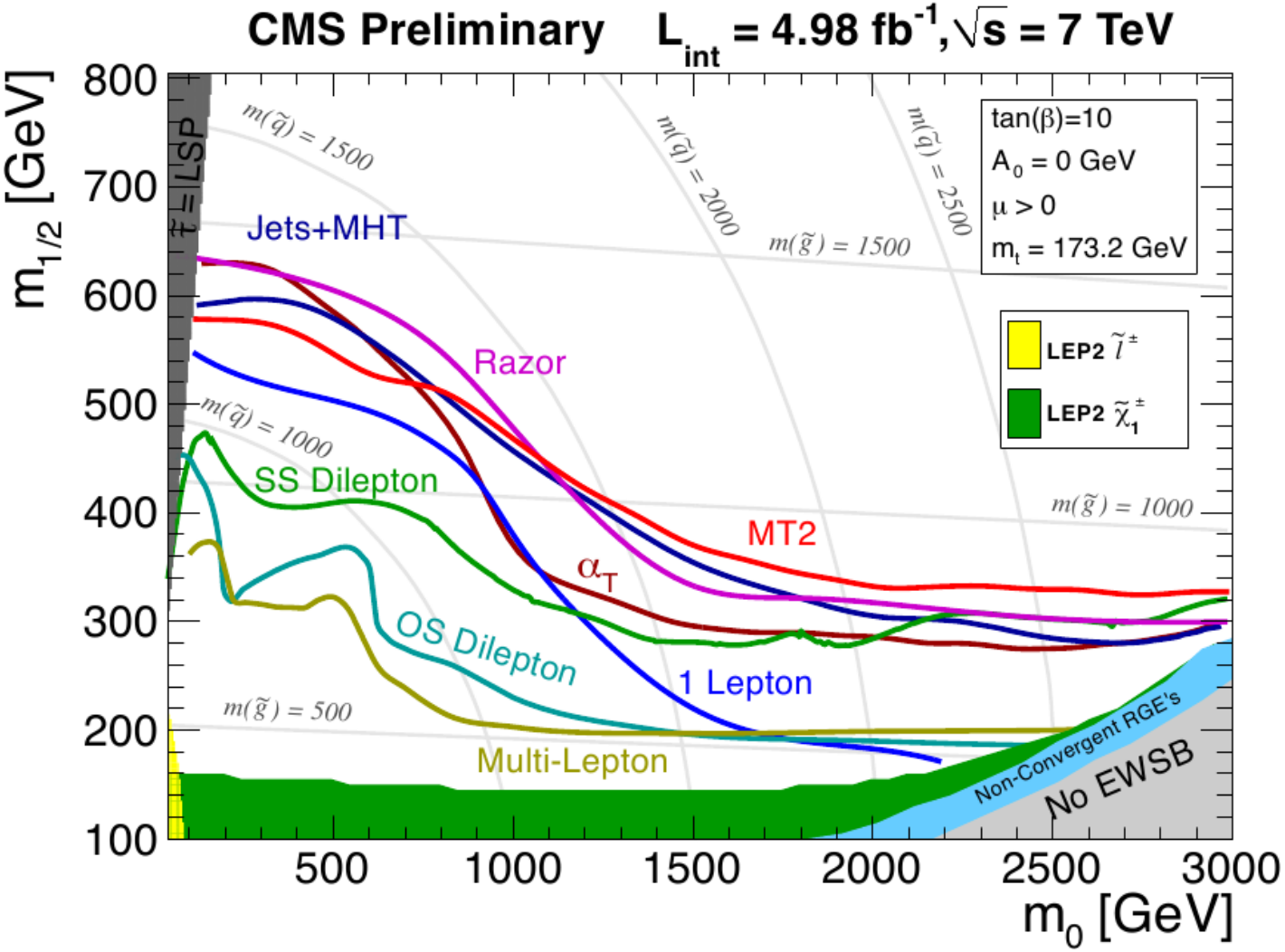
CMS SUSY CMSSM summary

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



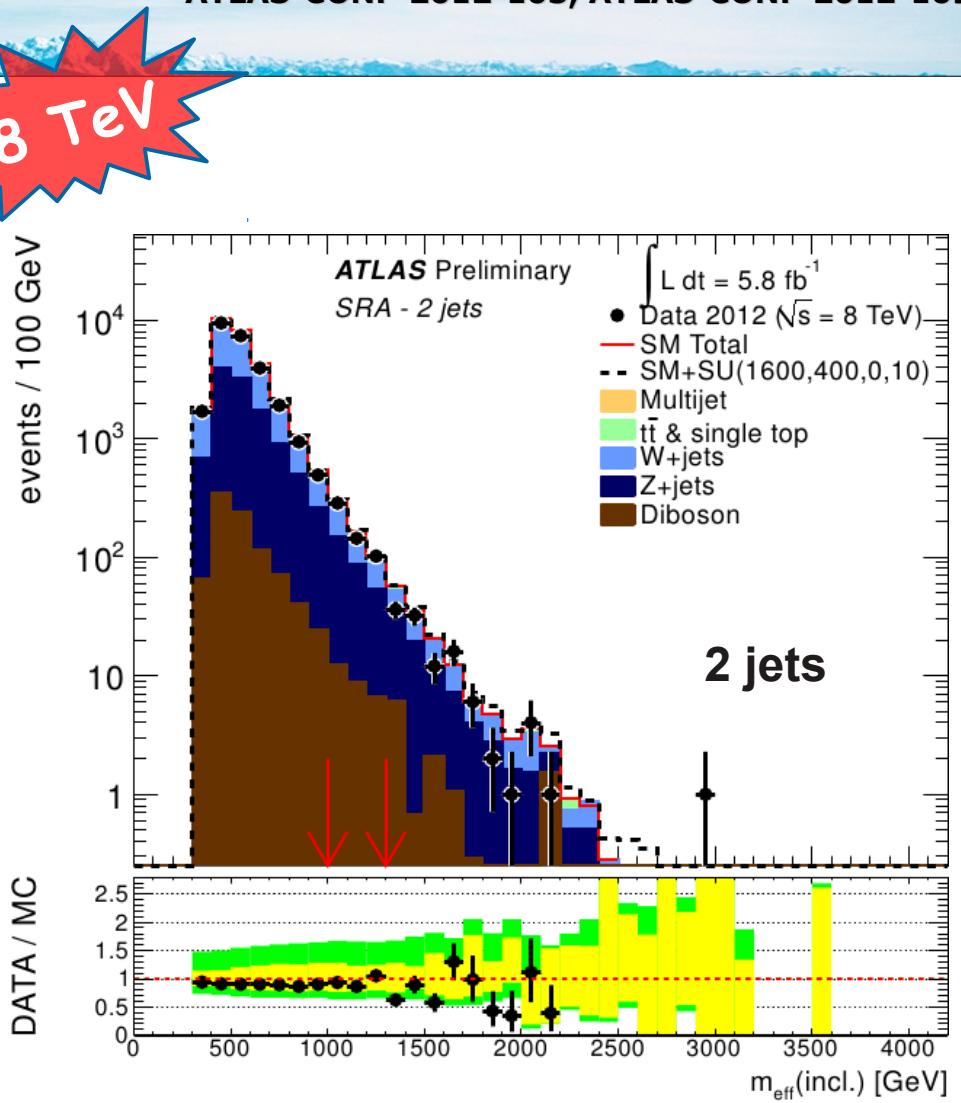
- CMSSM exclusion limits from CMS, ATLAS limits similar
- No signs for SUSY — Exclusion limits from previous experiments largely improved

ATLAS search for squarks and gluinos

ATLAS-CONF-2012-103, ATLAS-CONF-2012-109

Pair production:

- Typical decays:
  - $\tilde{q} \to q\chi_1^0$ and $\tilde{g} \to q\bar{q}\chi_1^0$
- Typical topology:
  - $\tilde{q}\tilde{q} \to$ 2 jets
  - $\tilde{q}\tilde{g} \to$ 3 jets,
  - $\tilde{g}\tilde{g} \to$ 4 jets
- 5 Signal regions $N = 2, 3, 4, 5, 6$ jets
- Define $m_{eff} = \sum_{i=1}^{N} p_T^{jet,i} + E_T^{miss}$
- Backgrounds estimated from data by control regions



Tue 9:30 M. C. Rammensee

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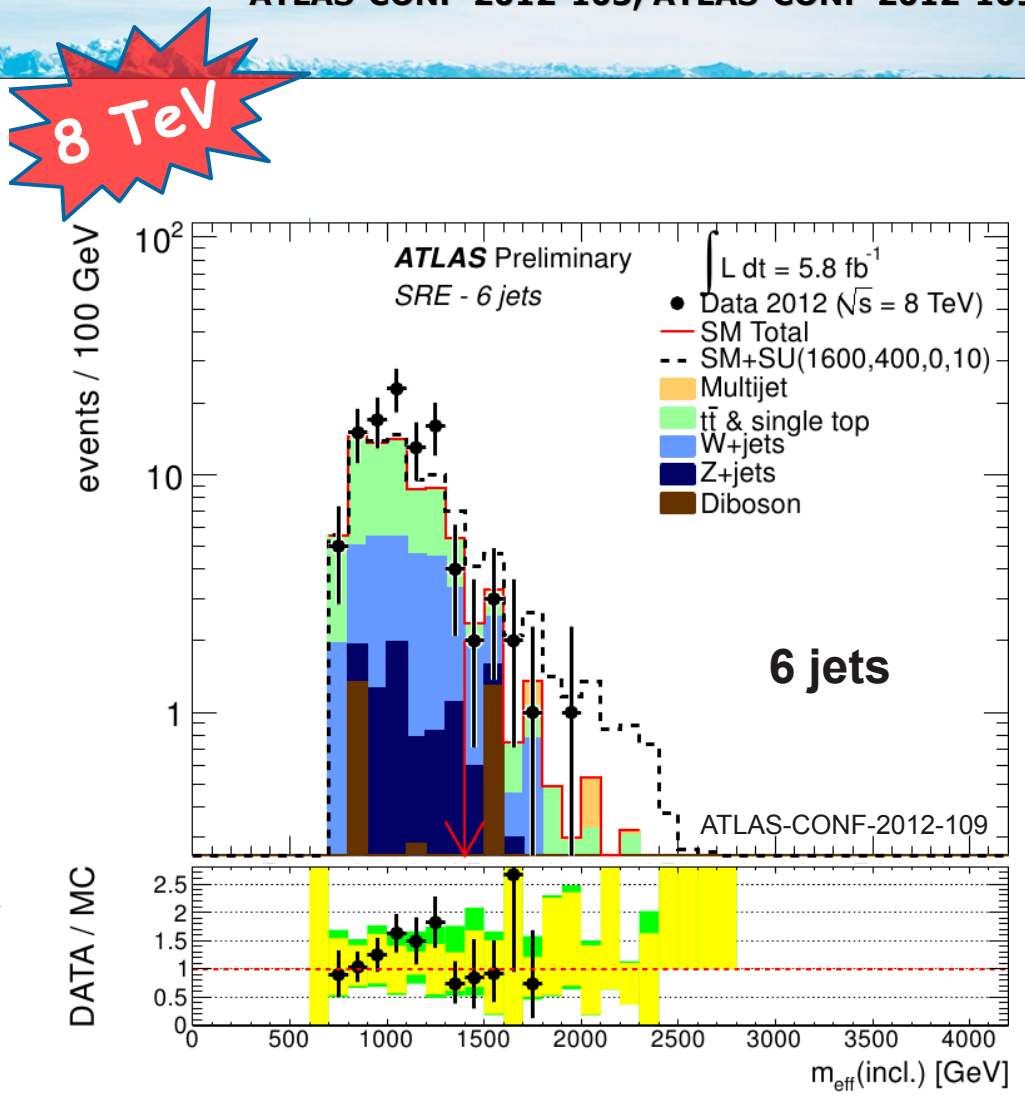
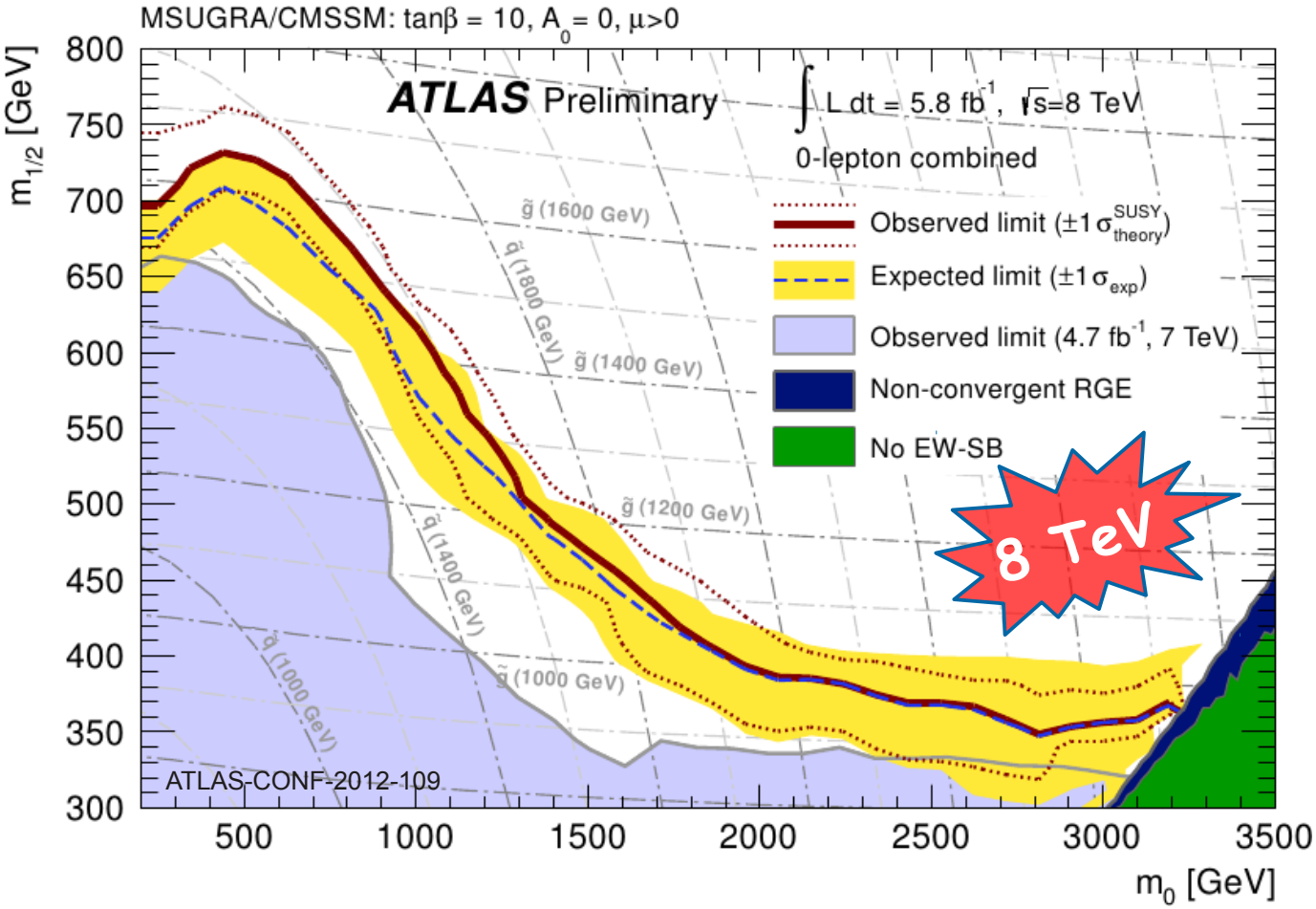


- Good agreement observed

Tue 9:30 M. C. Rammensee

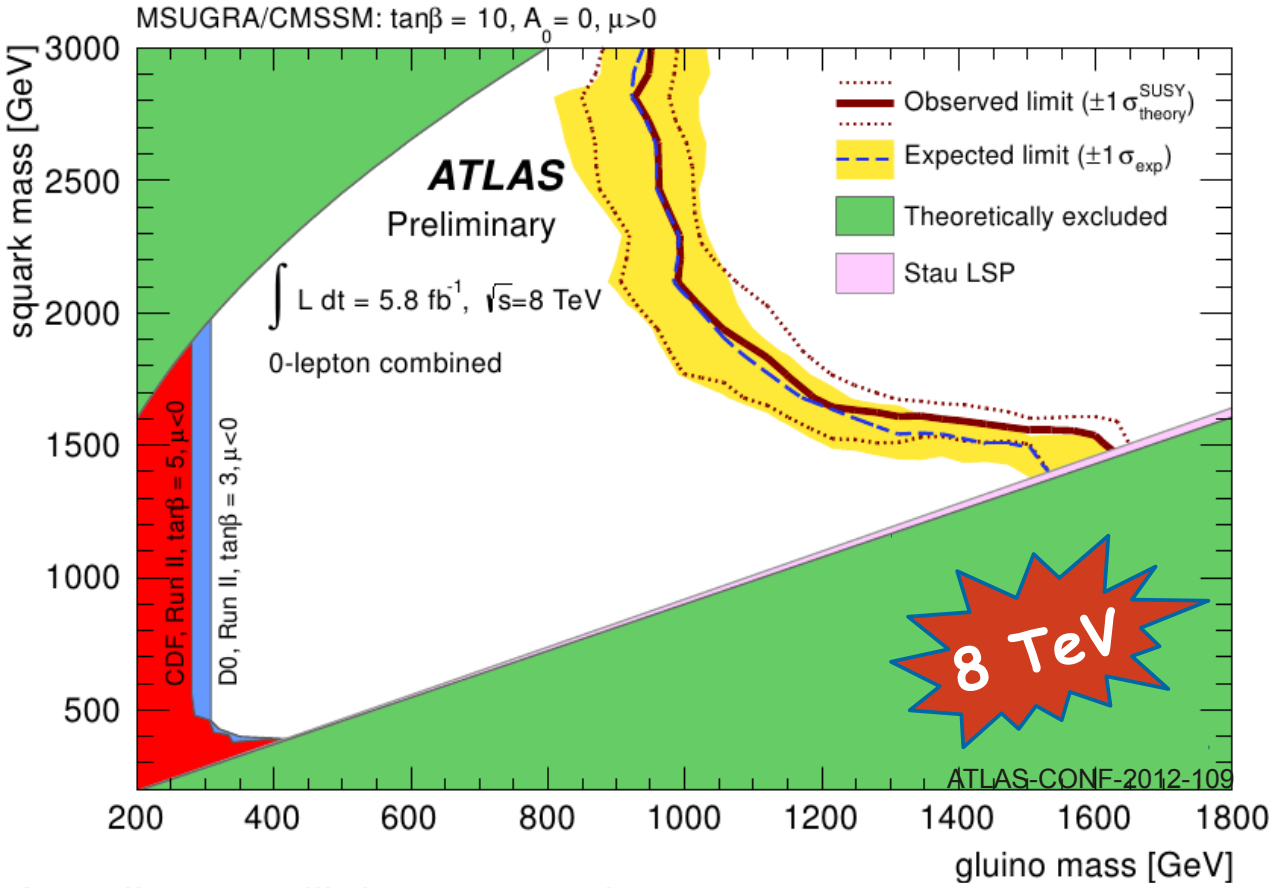
Interpretations: CMSSM parameters



CMSSM / MSUGRA interpretation

- Limits from 2011 extended $\sim 50\,\text{GeV}$ in $m_{1/2}$

Interpretations: CMSSM sparticle masses



More "natural" interpretation: $m_{\tilde{q}}$ vs. $m_{\tilde{g}}$

- Large excluded space
- Large "theoretically excluded" areas
  - Feature of CMSSM: $m_0, m_{1/2}, A_0, \tan\beta, \operatorname{sgn}\mu$
  - Validity of the model?

The end of SUSY?

New Scientist: "... konnte der Zerfall von B_s Mesonen in jeweils zwei Myonen registriert werden. [...] möglicherweise der Sargnagel für die vieldiskutierte SUSY."

NewScientist

Wissen, was kommt

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Home > Astronomie > CERN: Zerfallsreaktion stellt Supersymmetrie infrage

Elementarteilchen

Das Ende der Supersymmetrie?

Der LHC - nicht nur scharf auf Higgs-Bosonen. dapd

Das Higgs-Teilchen wird meist im gleichen Atemzug mit dem Large Hadron Collider (LHC) des Cern erwähnt. Erkenntnisse zu einem anderen Teilchen, dem Bs-Meson, könnte nun das Weltbild der Physiker auf den Kopf stellen.

Es ist die vermutlich wichtigste Entdeckung am , abgesehen vom Nachweis des Higgs-Teilchens. Die Wissenschaftler waren dennoch fast unter sich, als sie am 13. November im Auditorium des Forschungszentrums Cern in Genf feierten: Zum ersten Mal konnte der Zerfall von B_s-Mesonen in jeweils zwei Myonen registriert werden. Die Messungen fanden am LHCb-Experiment statt, einem von sechs Detektoren des größten Teilchenbeschleunigers der Welt. Obwohl die beteiligten Elementarteilchen nur kurz existieren, ist ihre Reaktion zentral für das Weltbild der Physiker – und möglicherweise der Sargnagel für die vieldiskutierte (Susy).

Lediglich fünf Zerfälle bei einer Menge von knapp zwei Milliarden B_s-Mesonen konnten die Forscher messen. Der Zerfall ist deshalb so

Datum: Montag 19.11.2012 | 14:36 Uhr

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Artikel versenden

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THEMA

Astronomie

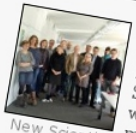
Physik

Zur Themenübersicht

MEHR AUF NEW SCIENTIST

Nachschlag: Woher kommt das Higgs-Boson?

DAS IST DER NEW SCIENTIST



New Scientist Deutschland

Willkommen auf der Website des deutschen New Scientist. Die Website ist unser erster Schritt, in Deutschland ein wöchentliches Wissensmagazin zu etablieren. Wir werfen einen prüfenden Blick auf Wissenschaft und Technik – und deren Folgen für unsere Gesellschaft. Mit kritischer Distanz, Sinn für Ironie – aber

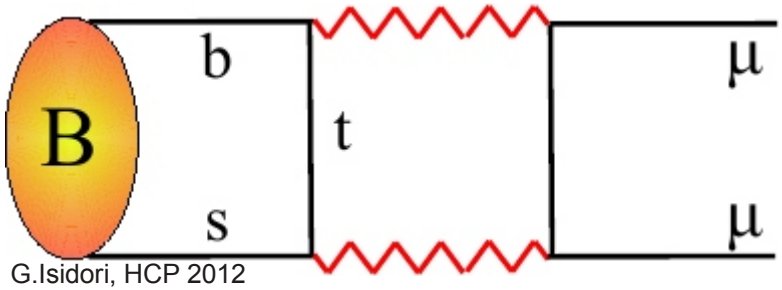
$B_s \to \mu\mu$ theory

$B_s \to \mu^+\mu^-$ doubly suppressed in Standard Model (FCNC, helicity suppressed)

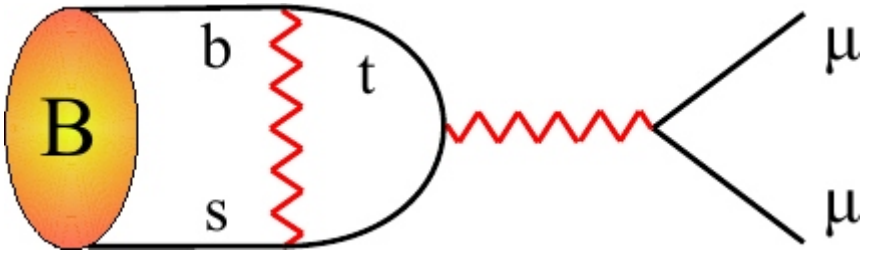
- SM Prediction: $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.54 \pm 0.30) \times 10^{-9}$

  Buras, Isidori: arXiv:1208.0934; De Bruy et al. arXiv:1204.1737

Standard Model diagrams:

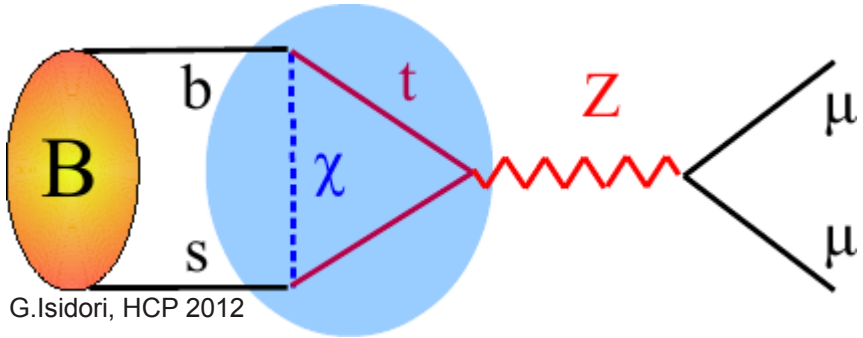


G.Isidori, HCP 2012



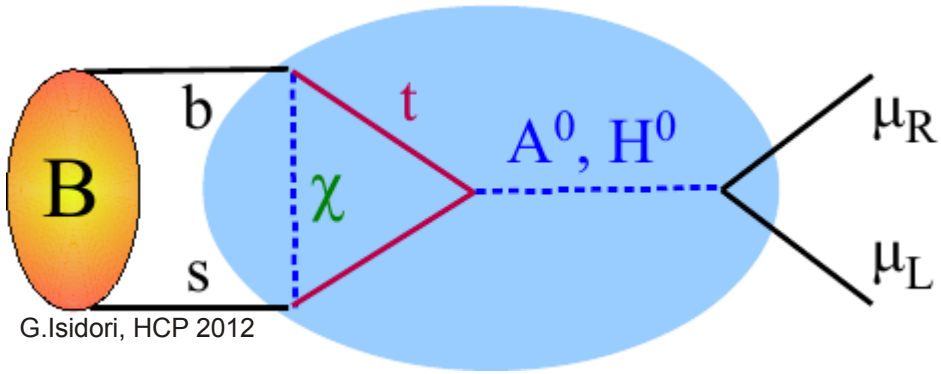
G.Isidori, HCP 2012

Possible SUSY contributions:



G.Isidori, HCP 2012

- Important if $\mathcal{B} \sim$ SM



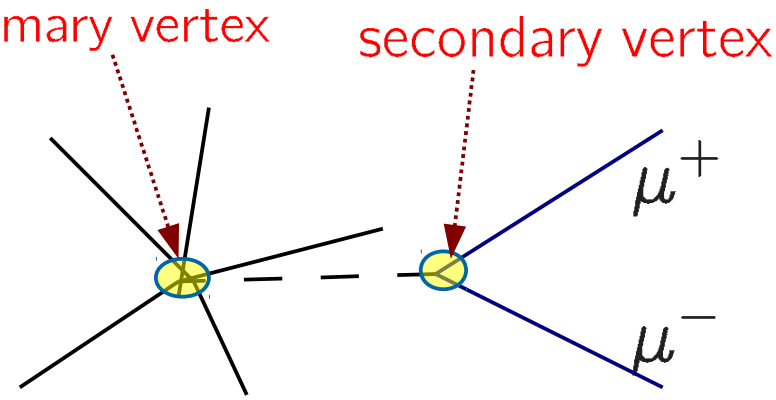
G.Isidori, HCP 2012

- Large effect at high $\tan\beta$

LHCb measurement BR($B_s \to \mu\mu$)

Selection

- Difficult analysis, use **B**oosted **D**ecision **T**ree for signal ↔ background separation



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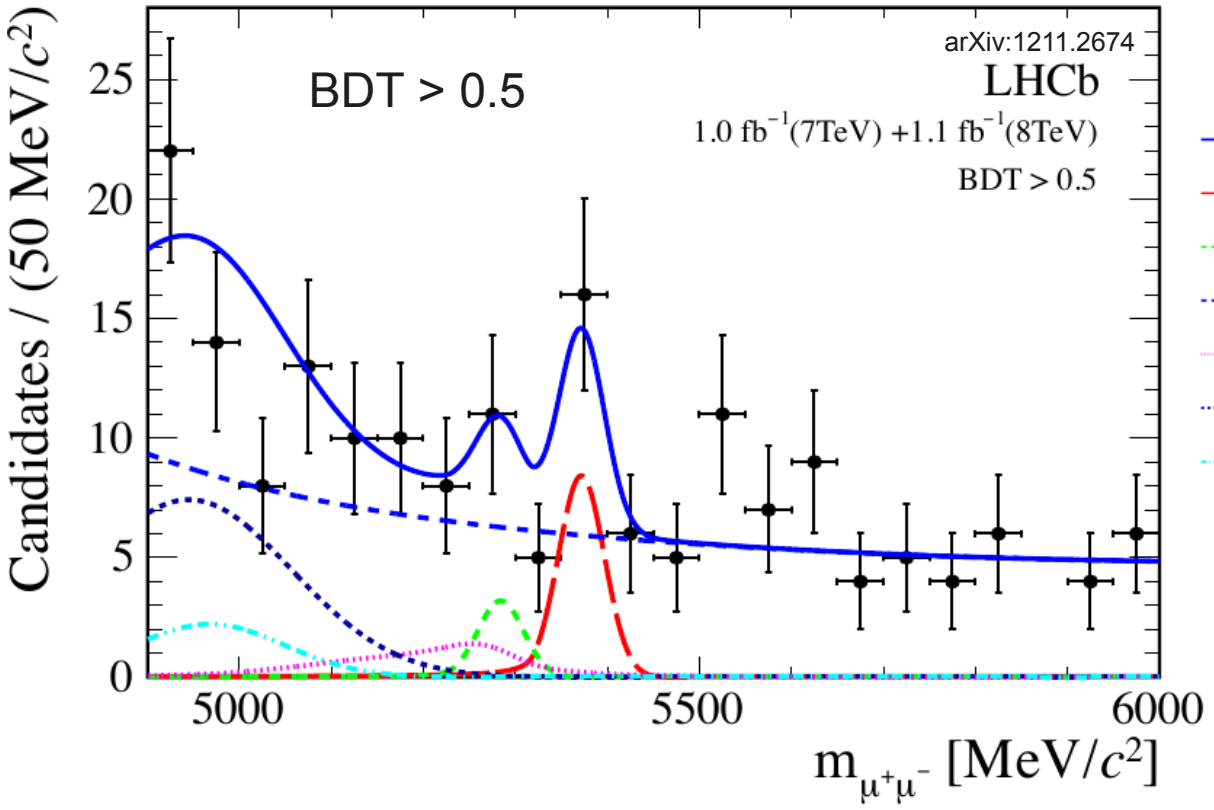

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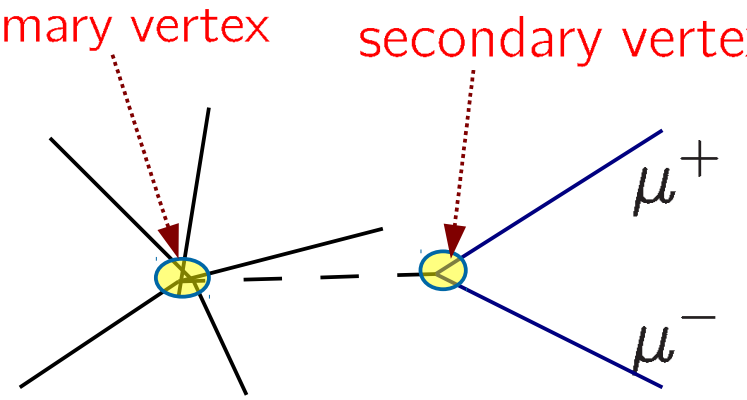

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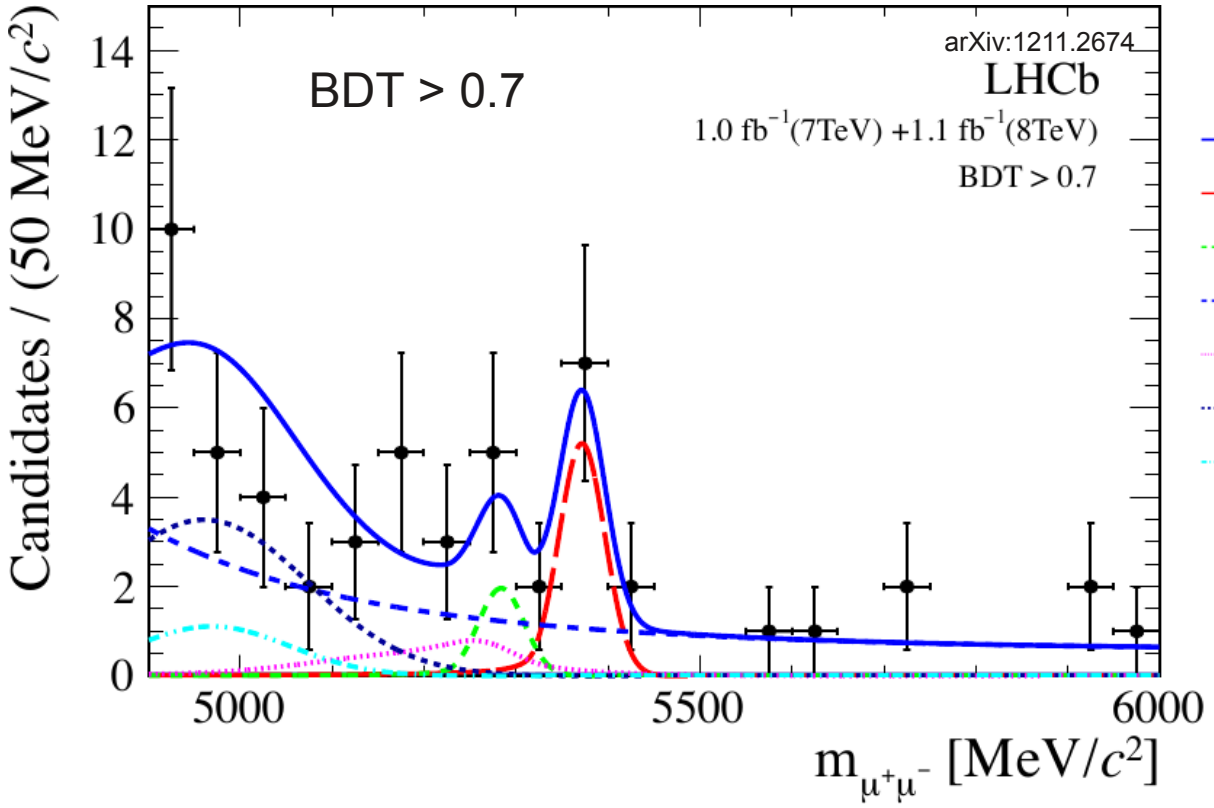

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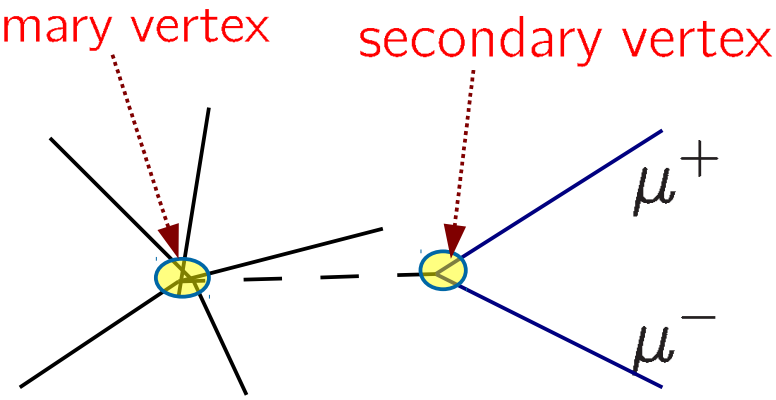

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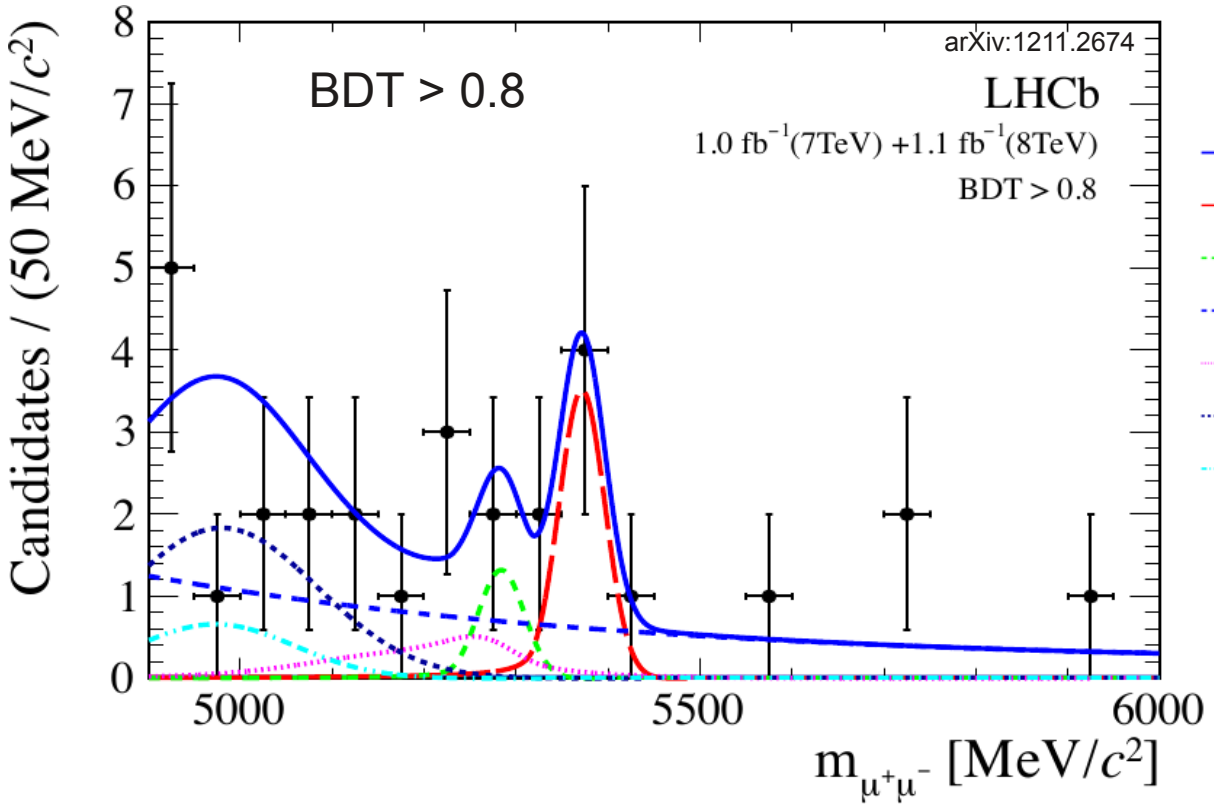
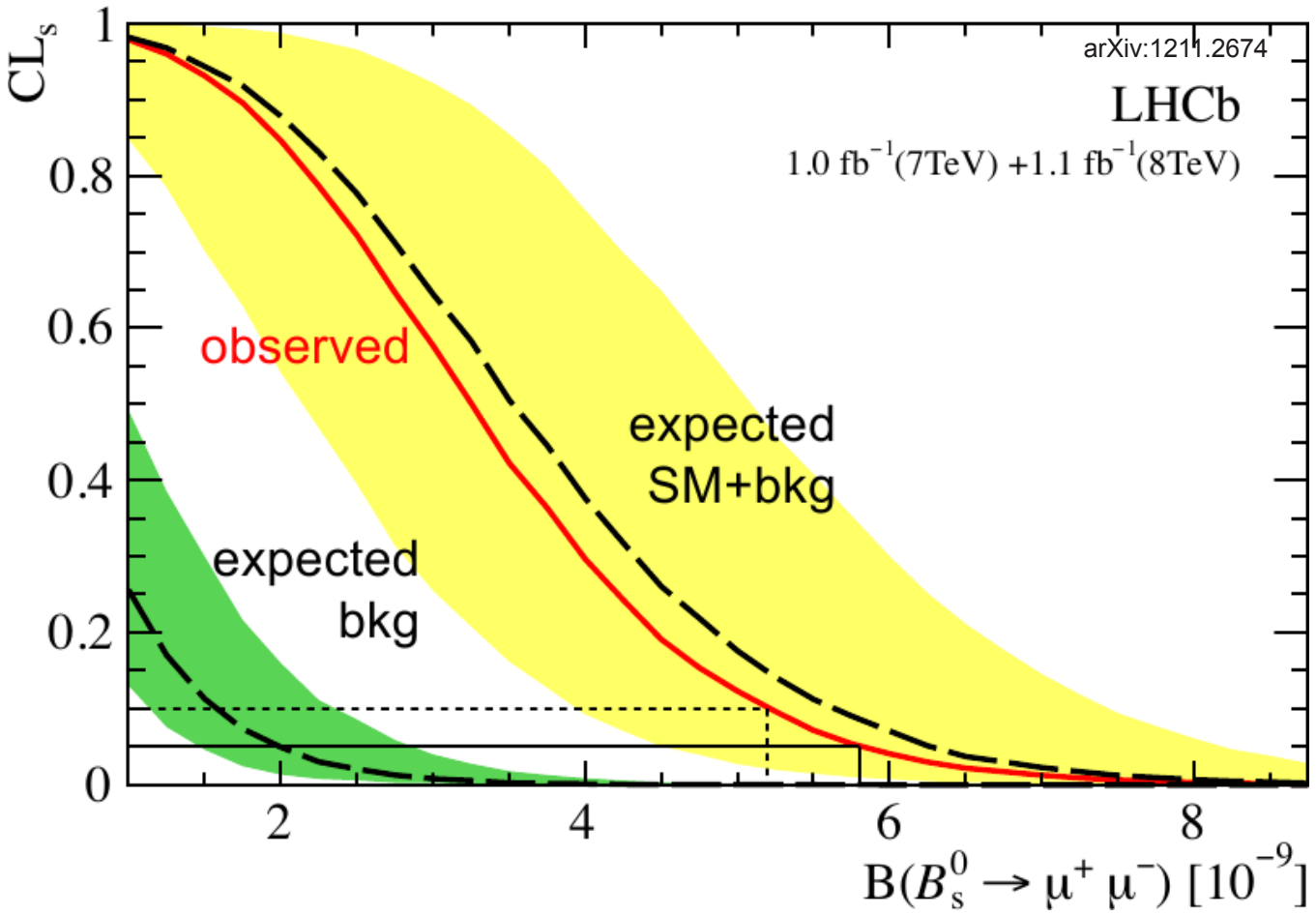


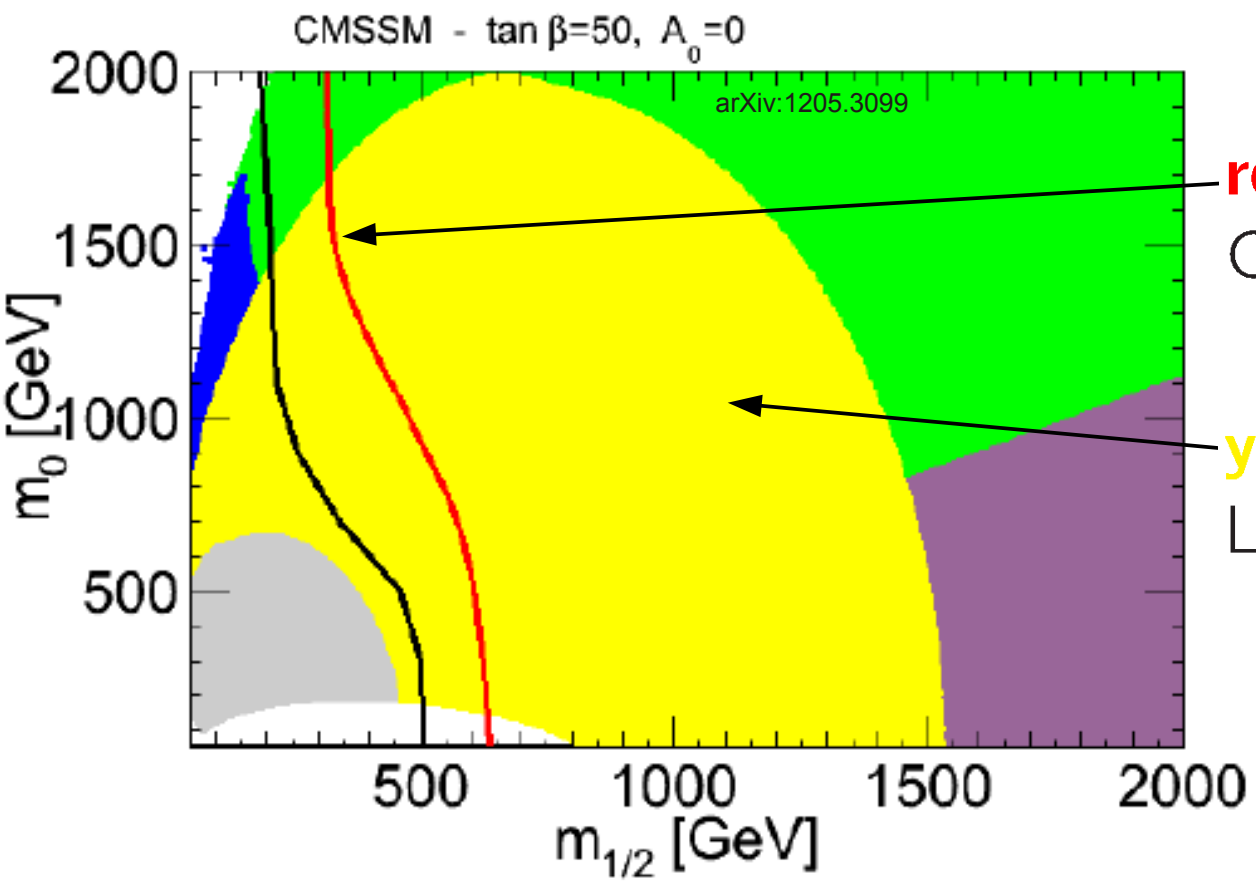
LHCb: $B_s \to \mu\mu$ evidence



- Use $BDT > 0.8$ for measuring $\mathcal{B}$
- p-Value for background-only hypothesis: $5.3 \cdot 10^{-4} = 3.5\,\sigma$

$$\text{LHCb evidence:} \quad \mathcal{B}(B_s \to \mu^+\mu^-) = 3.2^{+1.4}_{-1.2}(\text{stat})^{+0.5}_{-0.3}(\text{syst}) \quad \cdot 10^{-9}$$
$$\text{SM Prediction:} \quad \mathcal{B}(B_s \to \mu^+\mu^-) = 3.54 \pm 0.30 \quad \cdot 10^{-9}$$

LHCb: Bs → μμ interpretation



red line:
CMS jets+E_T^{miss}@7TeV

yellow area:
LHCb $B_s \to \mu^+\mu^-$ @ 7 TeV

F. Mahmoudi, arXiv:1205.3099

- LHCb result cutting deep in CMSSM space
- More stringent bounds than direct searches for large $\tan\beta$

A look at the CMSSM with Fittino

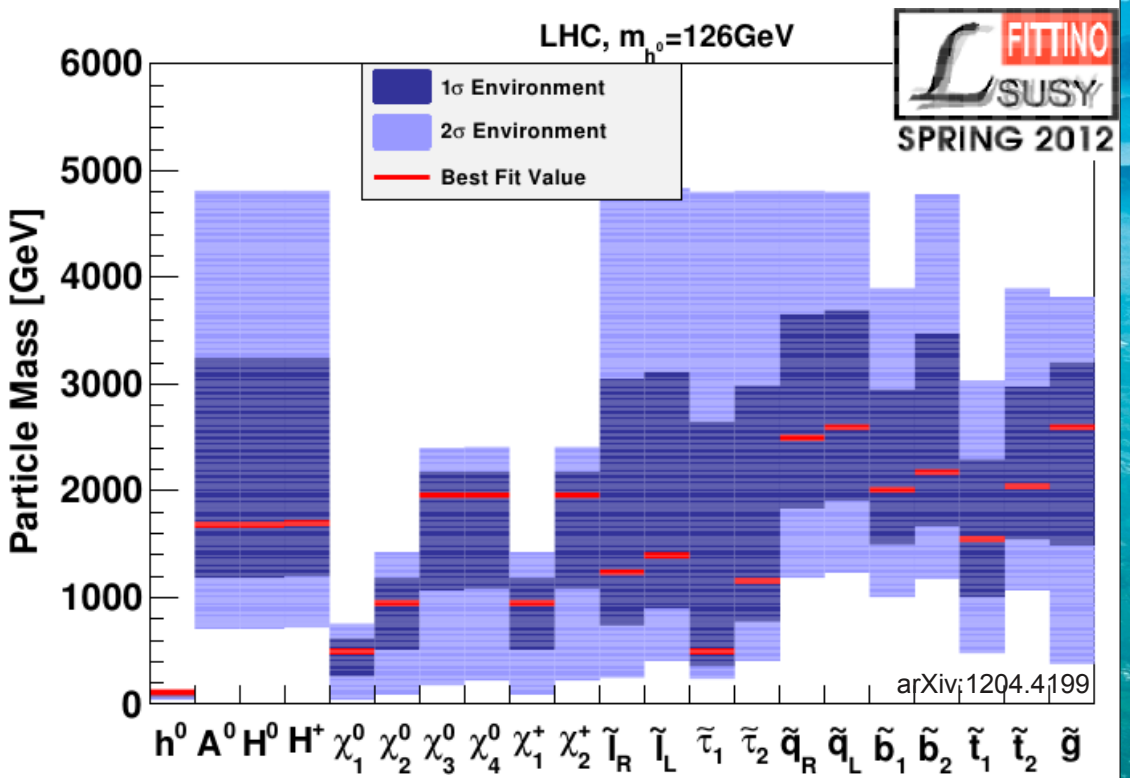
arXiv:1204.4199

Fittino:

- Estimate CMSSM parameters from measurements
- Quantify compatibility with CMSSM

Input sets of observables to CMSSM fits

- Indirect constraints:
  $\mathcal{B}(b \to s\gamma)$, $\mathcal{B}(B \to \mu\mu)$,
  $\mathcal{B}(B \to \tau\nu)$, Δm_{B_s},
  $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM}$.
- Astrophysical observations:
  $\Omega_{CDM}h^2$, XENON,
  γ-rays from dwarf galaxies
- Collider results:
  LHC SUSY & Higgs & $B_S \to \mu\mu$,
  LEP $m_{\chi^\pm}$



- **Multi-TeV $\tilde{q}, \tilde{g}$, most sparticles $\gtrsim 1\,TeV$**

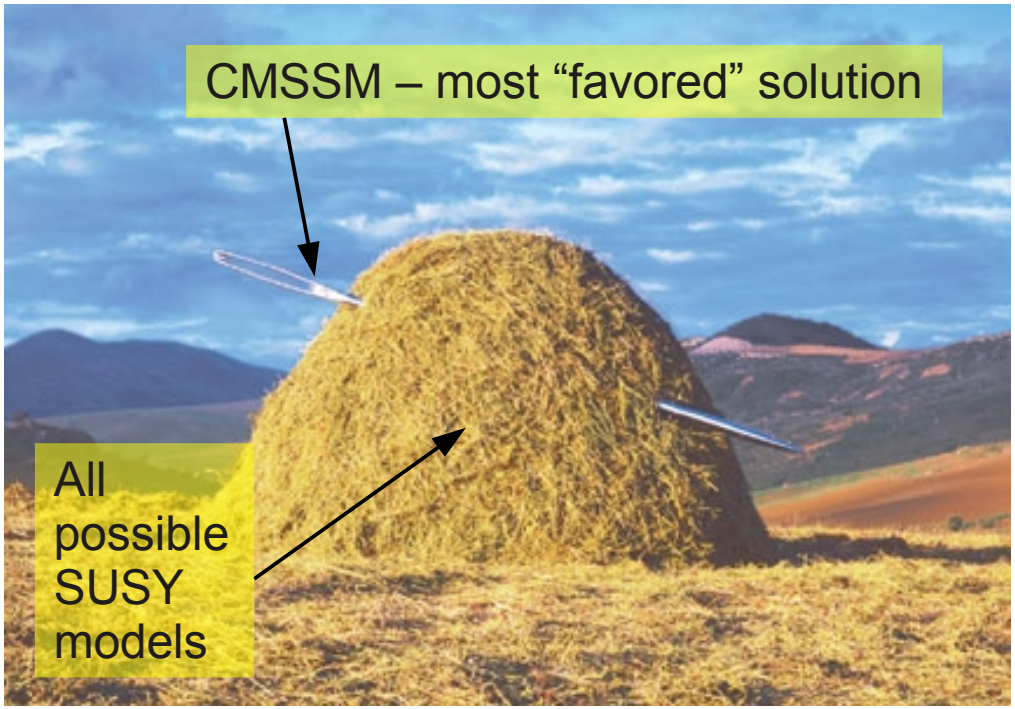
Input measurements	χ^2/ndf
low energy +astrophysics (LEO)	10.3/8
LEO+SUSY limits	13.1/9
LEO+SUSY+M(Boson)=126	18.4/9

- **Bad overall compatibility when Higgs is included!**

Tue 17:15 X. Prudent

Alternative scenarios

- Alternative SUSY scenarios
  - NUHM
    - additional Higgs deegres of freedom
  - pMSSM
    - 19 parameters, less assumption on SUSY breaking
  - Split SUSY / high-scale SUSY
    - High mass scalars
  - GMSB, AMSB
    - SUSY breaking mechanisms
  - R-Parity violation
    - Neutralino lifetime, stau LSP, …



- Experimental approach:
  - Use “simplified model spectra (SMS)”
  - Look in all possible production/decay topologies

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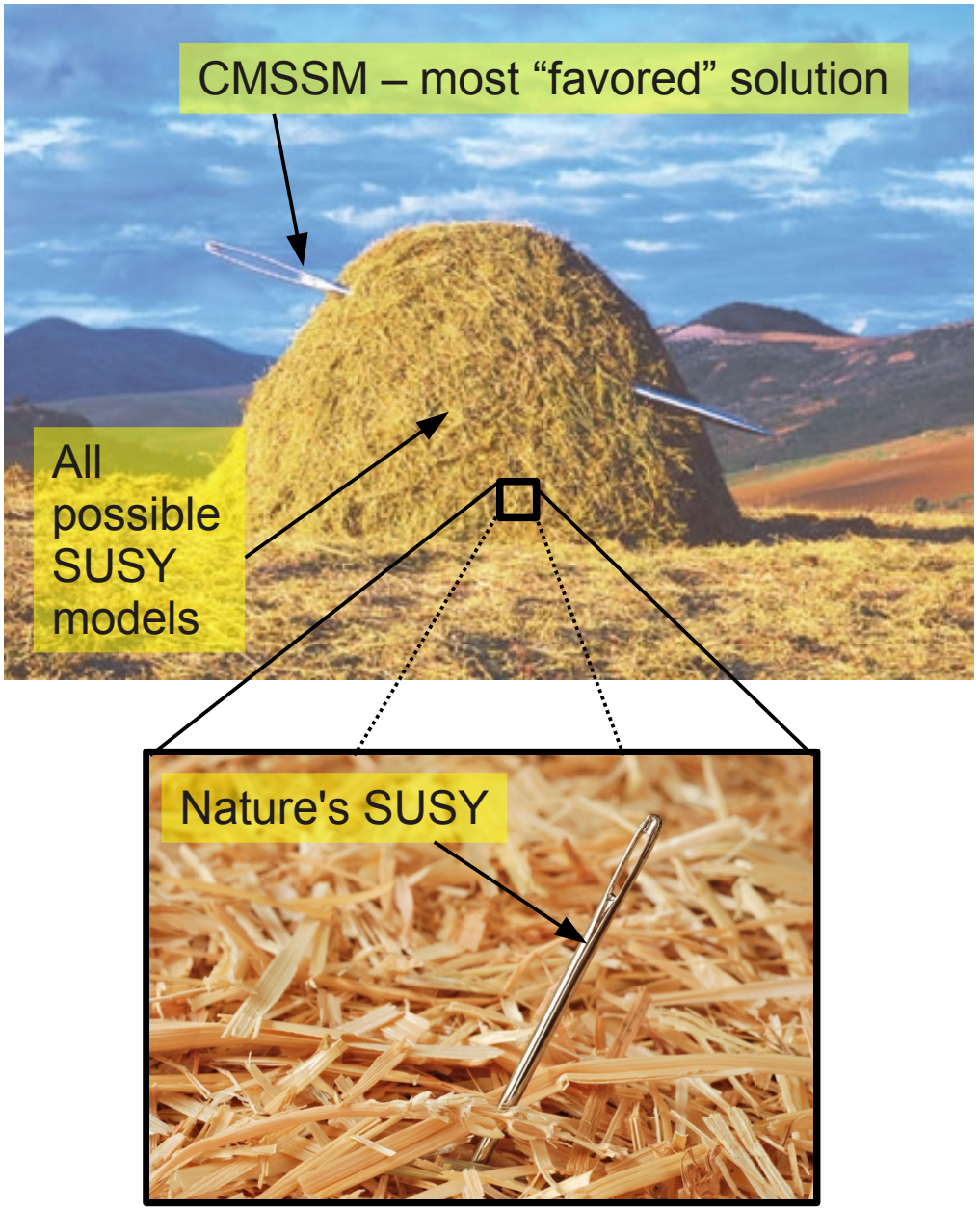
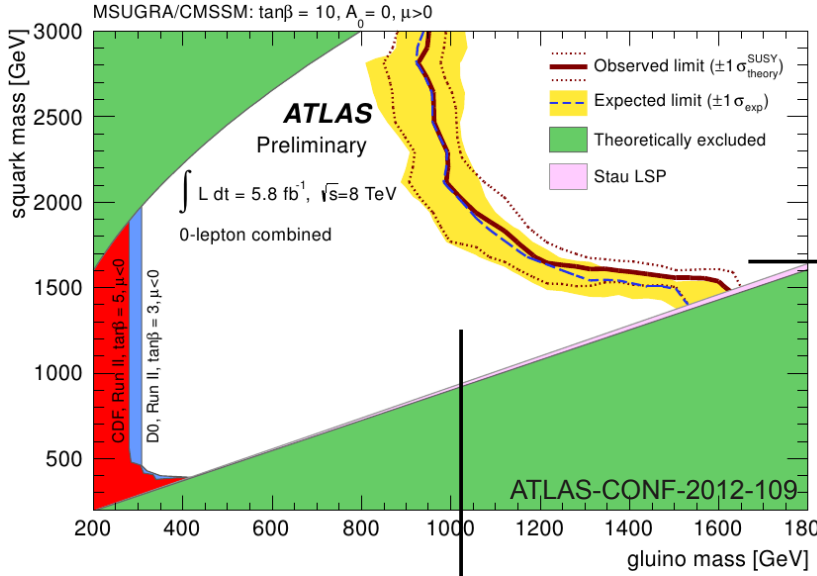
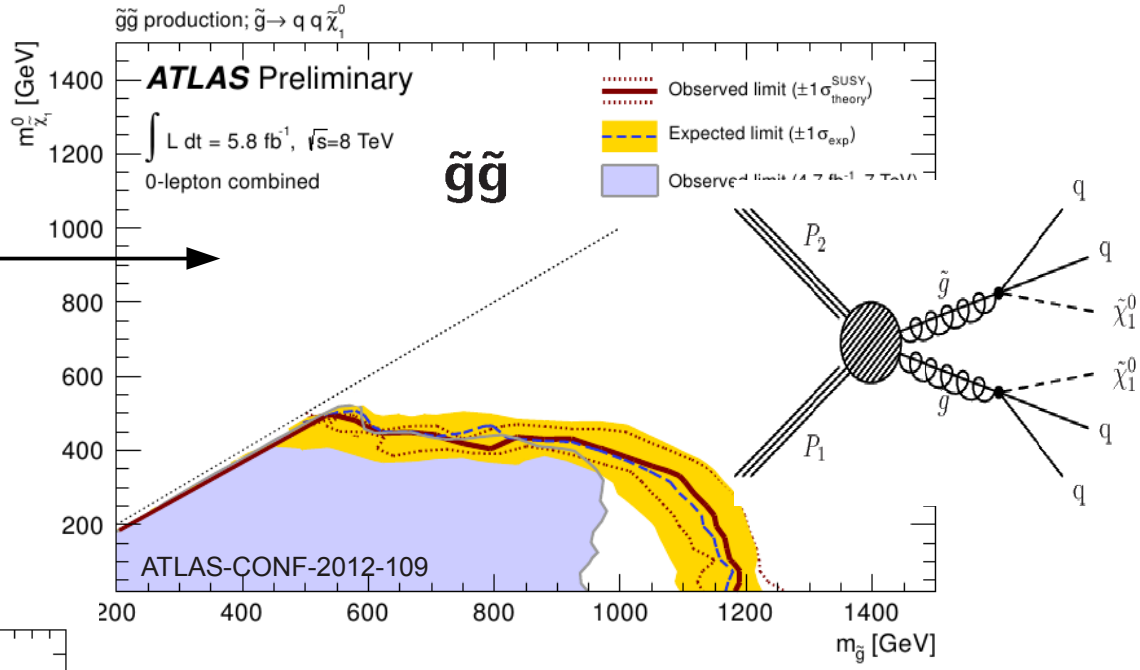
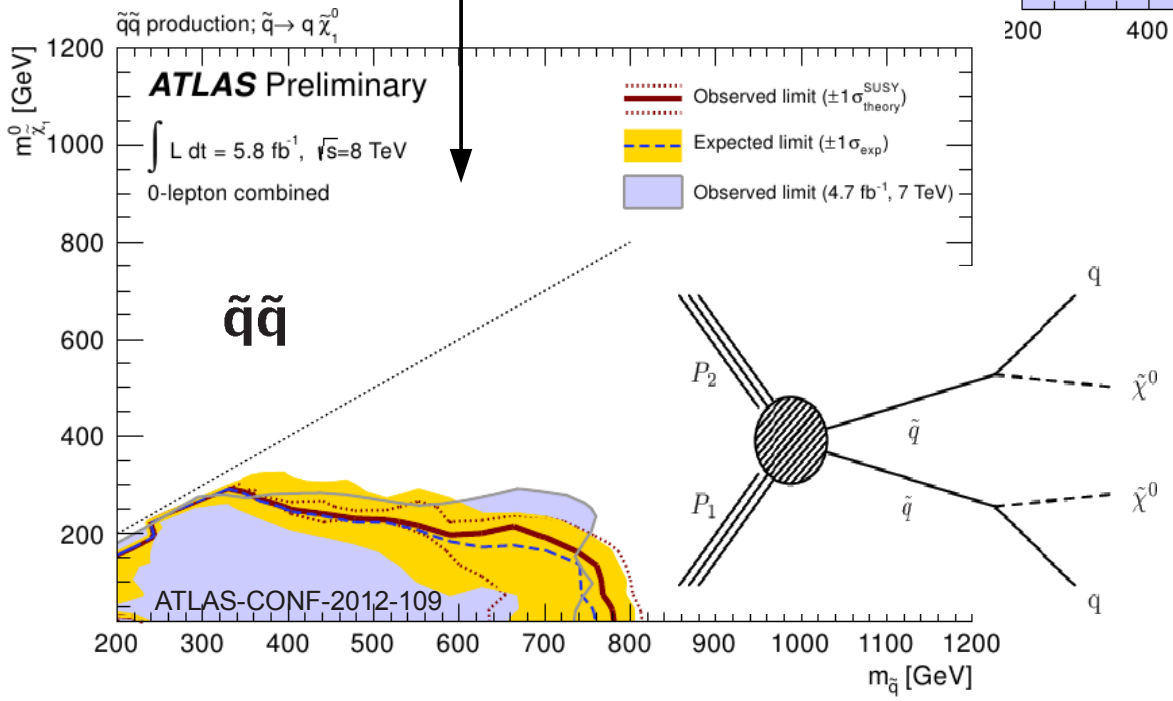


Simplified model interpretation I



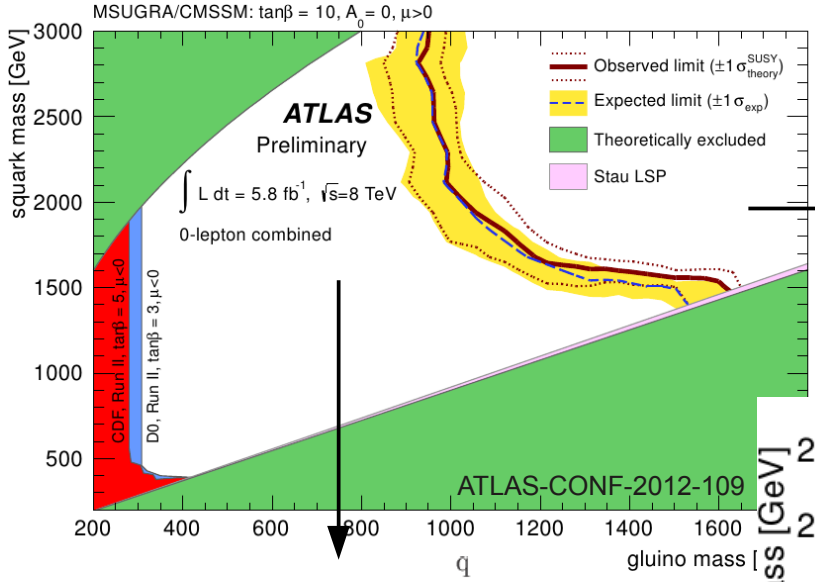


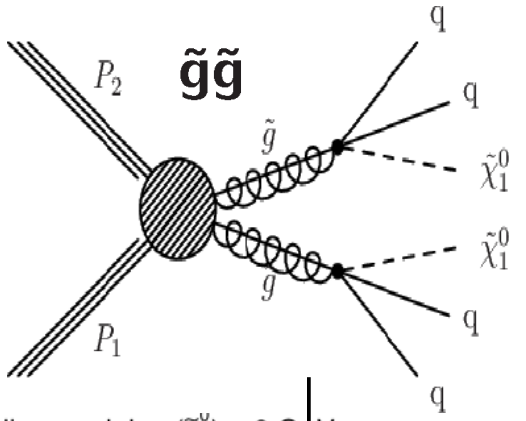


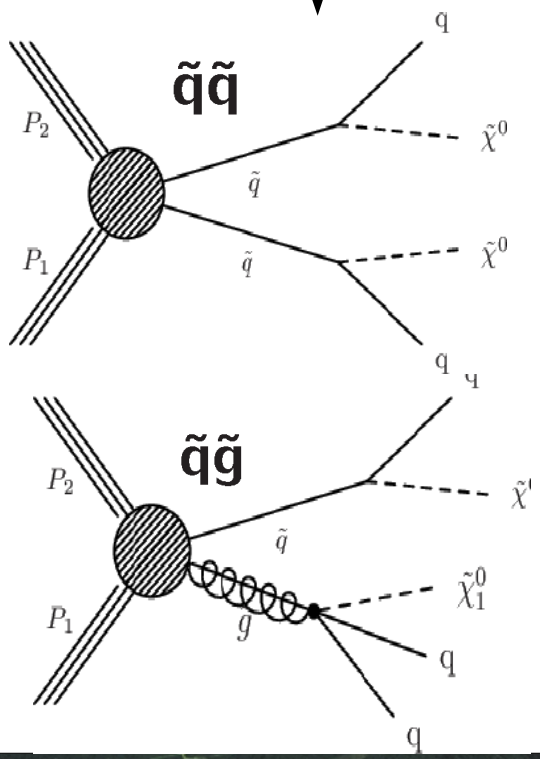
Use same analysis, change interpretation

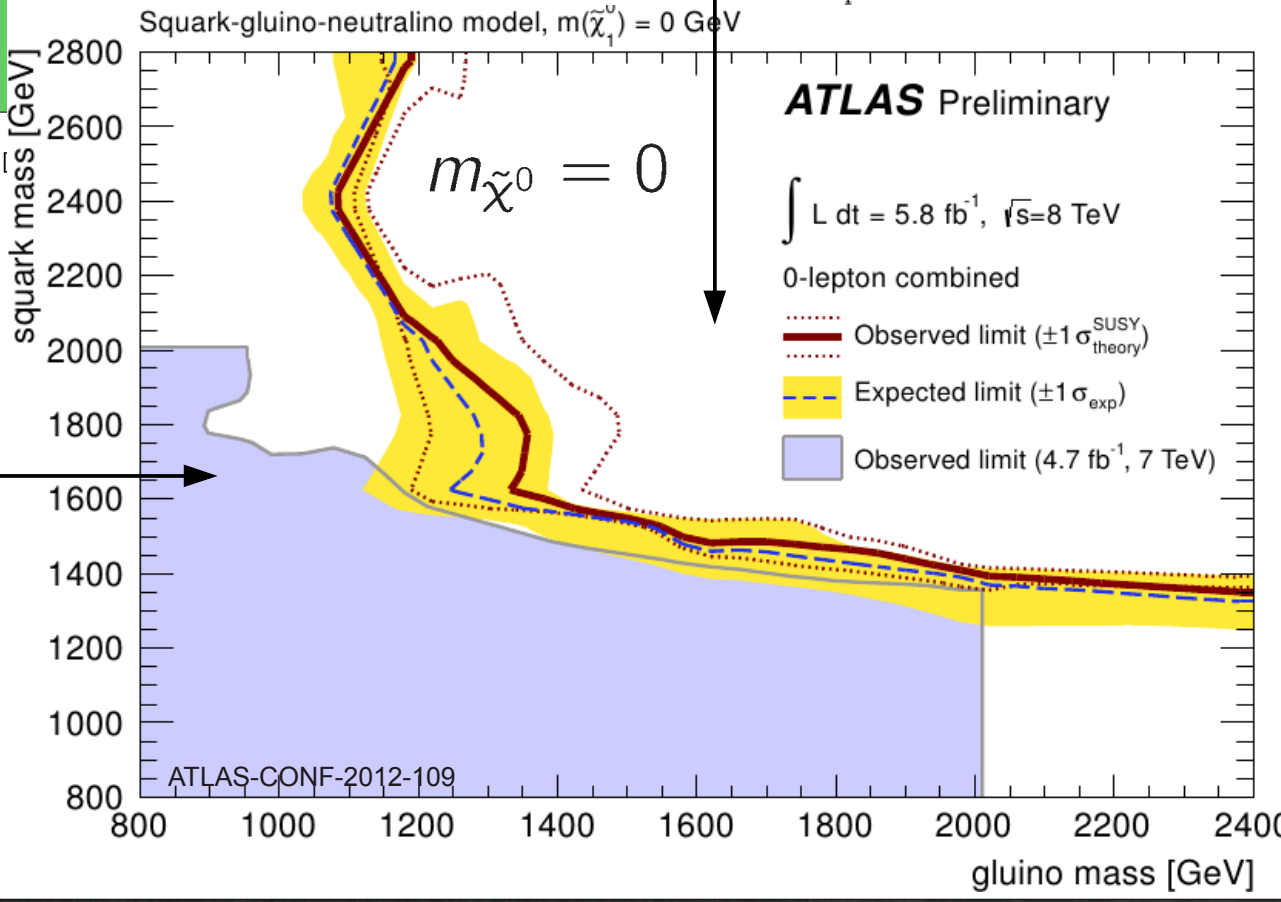
- Typically just 2...3 particles
- Couplings fixed by SUSY
- Masses free parameters

Simplified model interpretation II



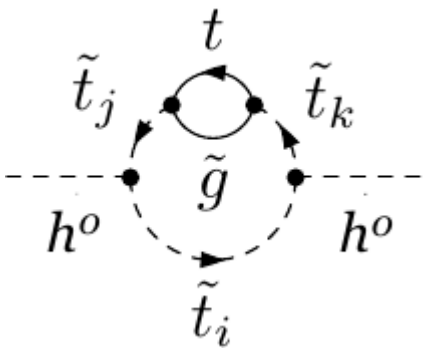


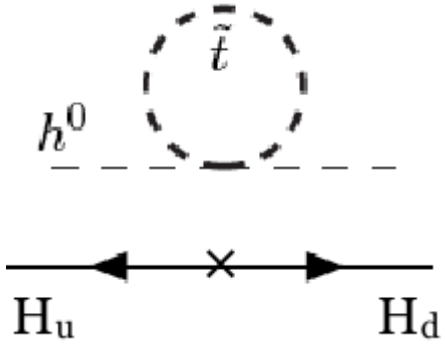




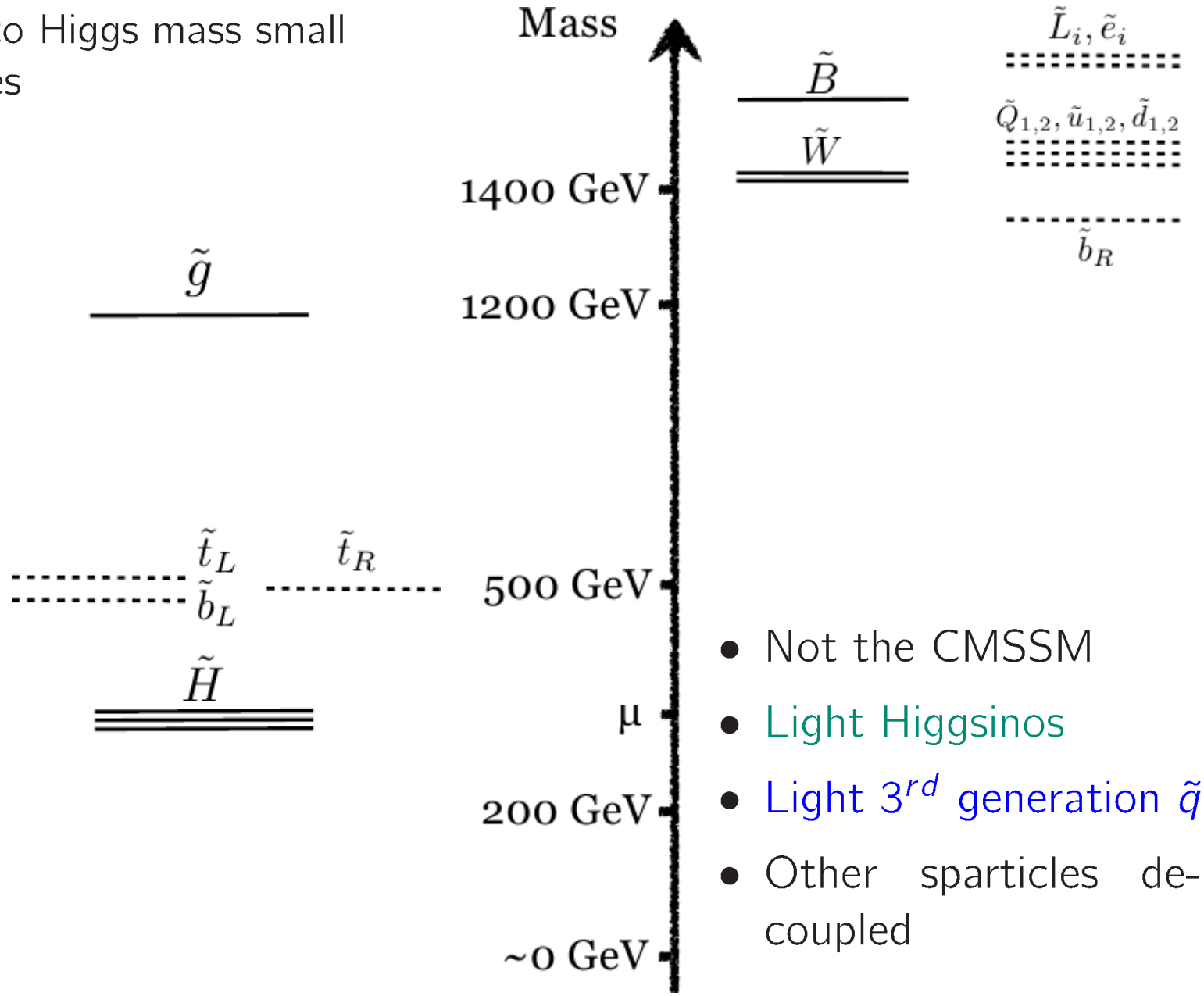
Natural SUSY?

- Keep corrections to Higgs mass small
  $\rightarrow$ limits on masses



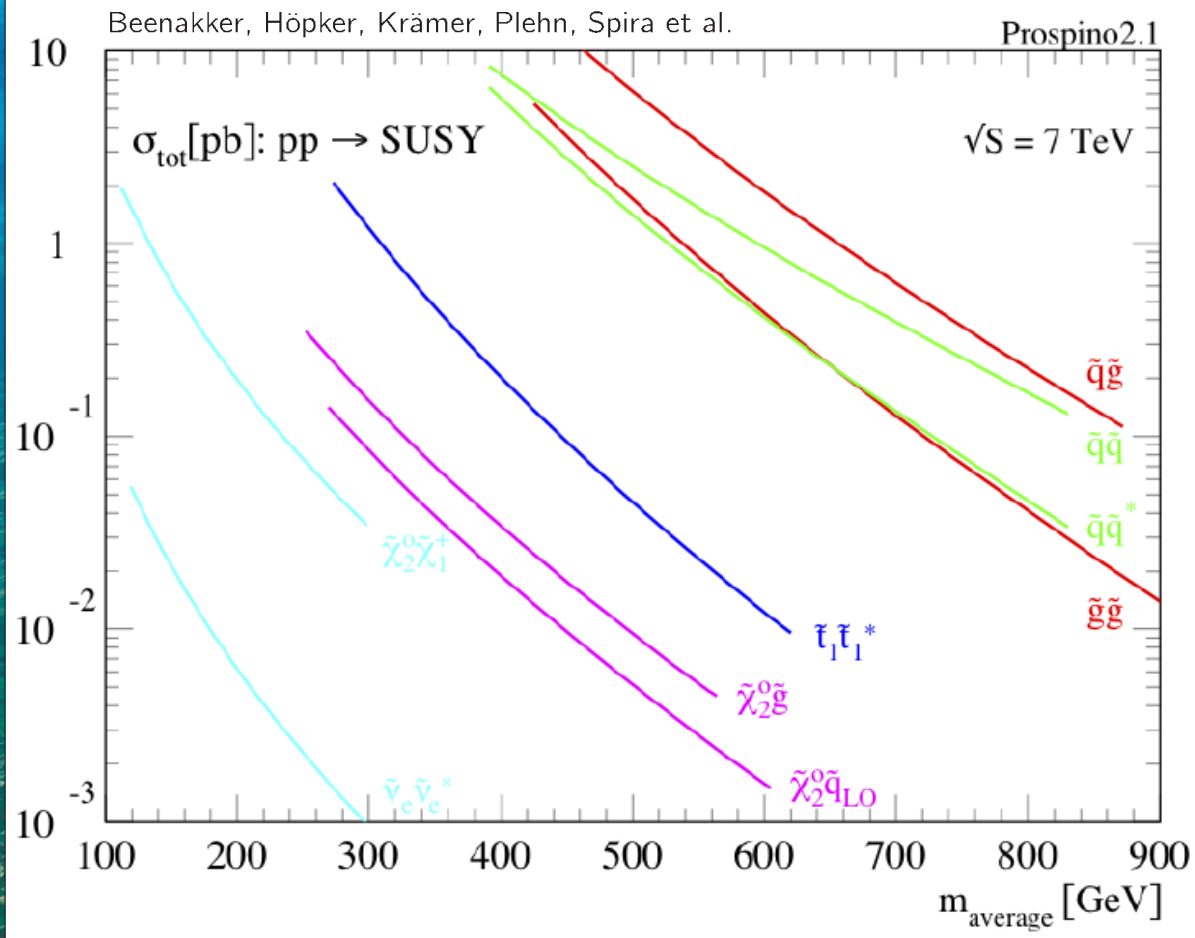


Graphics from Ch. Grojean, HCP



- Not the CMSSM
- Light Higgsinos
- Light 3rd generation $\tilde{q}$
- Other sparticles decoupled

SUSY production cross-section



$m(\tilde{t}, \tilde{b}) \leq 500$ GeV ,
Higgsinos $\sim$ electroweak scale

- Comparable cross-section

Fruitful activity by experiments

- Direct $\tilde{t}$, $\tilde{b}$ production
- 3^{rd} generation sparticles $(\tilde{\tau}, \tilde{b}, \tilde{t})$ in the decay
- Spartners of Higgs, W, Z: charginos $\chi^{\pm}$, neutralinos χ^0

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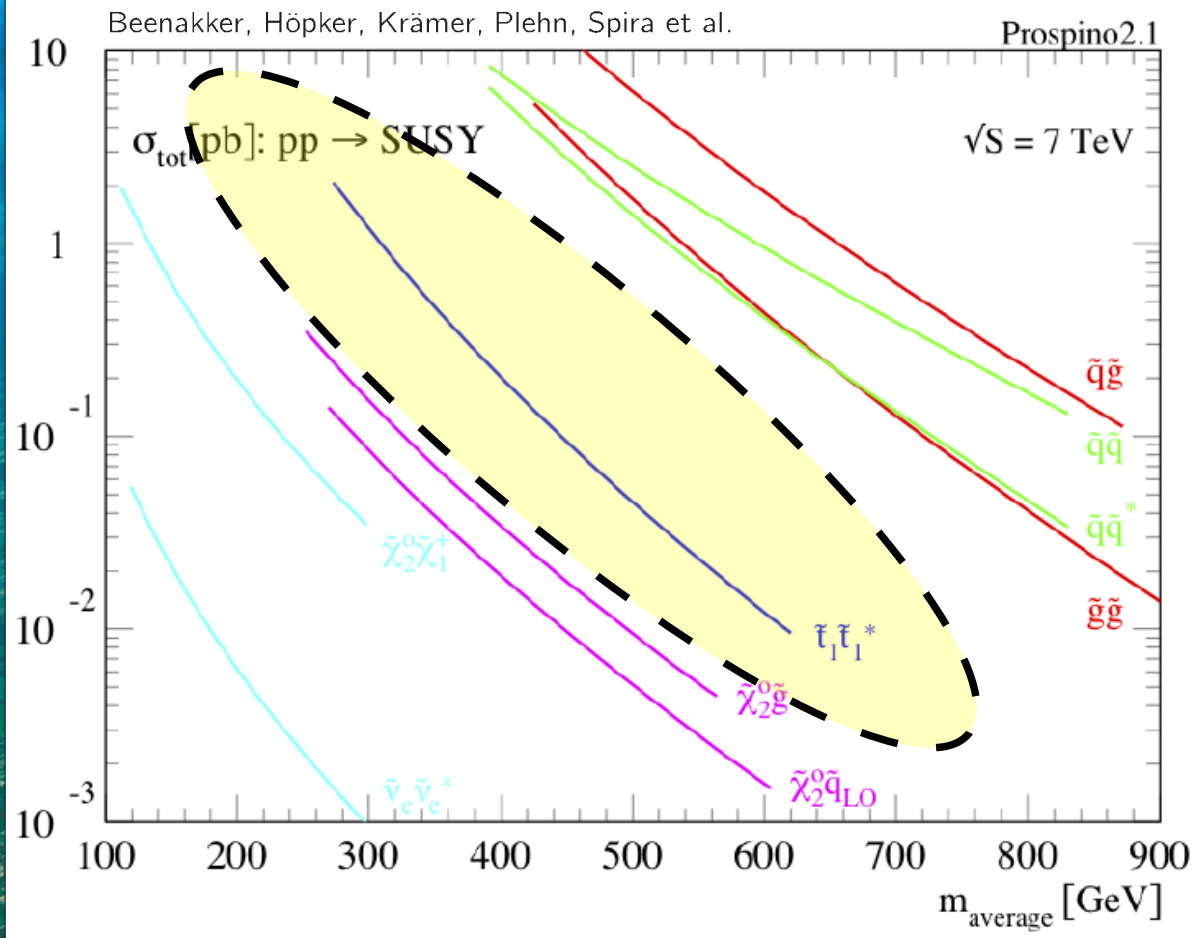

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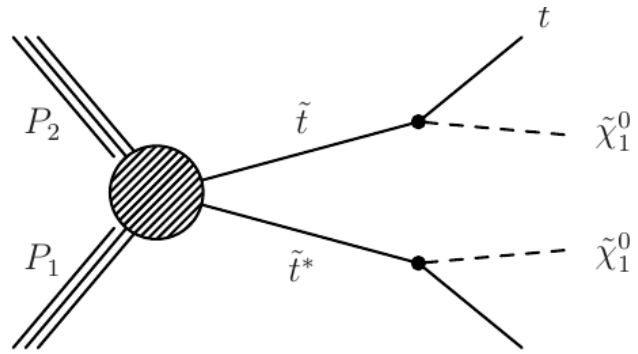
Search for direct stop pair production

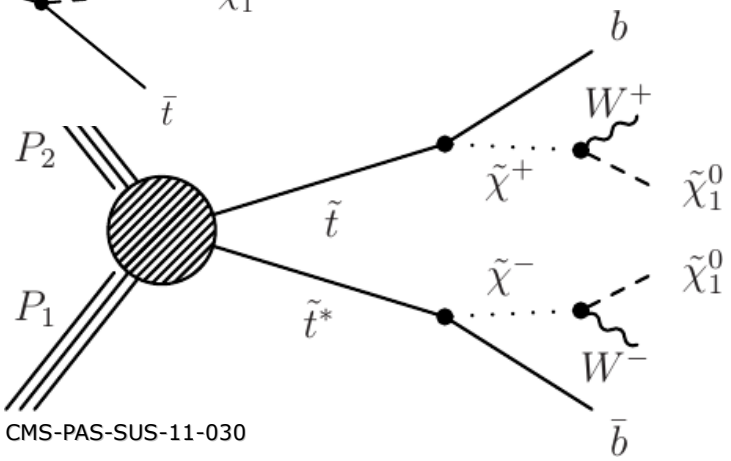
CMS-PAS-SUS-11-030

Simplified model, $\tilde{t} \to t\tilde{\chi}_0^1$ and $\tilde{t} \to \tilde{\chi}^+ b$

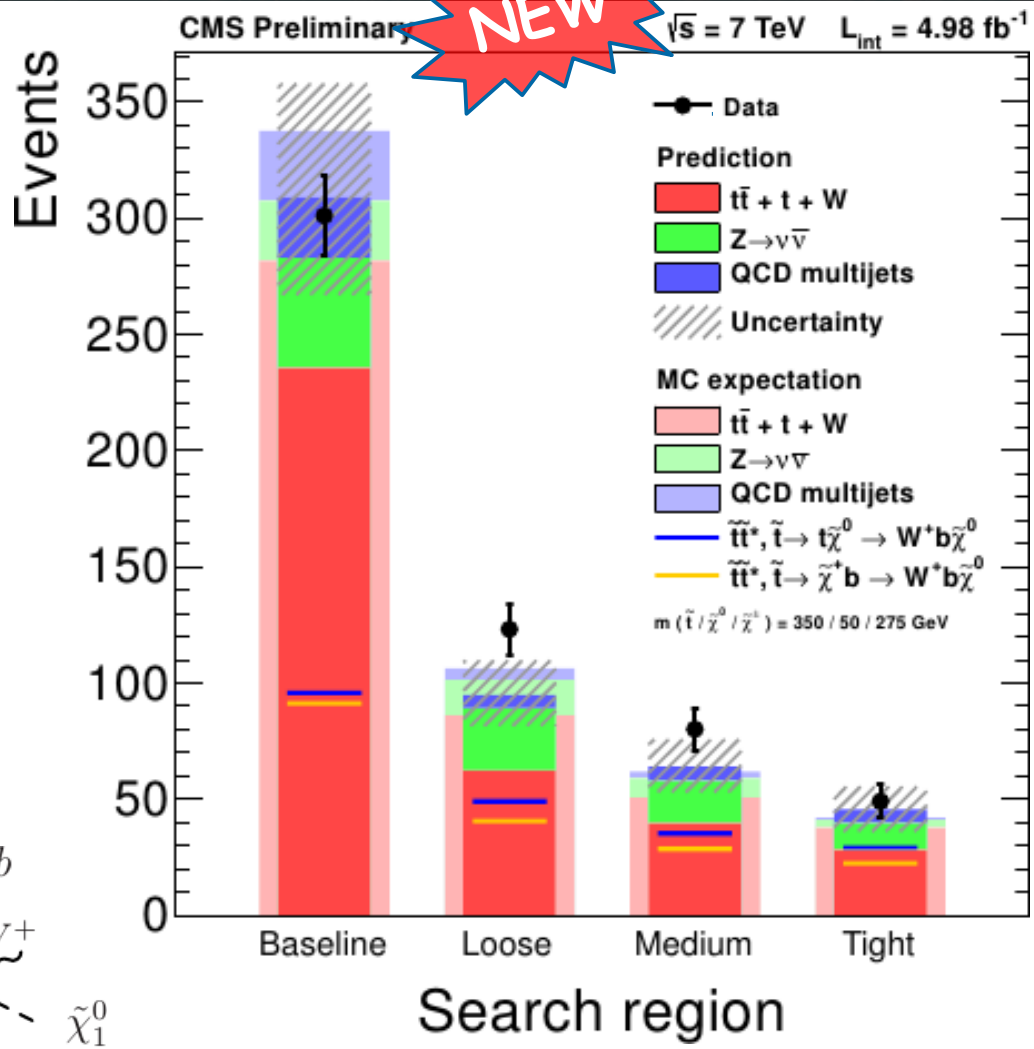
- ≥ 5 jets, ≥ 1 b-jet
- Largest background:
  - Semi-leptonic $t\bar{t}$ with real E_T^{miss}
- Use $E_T^{miss} > 175$ GeV to discriminate
- Look at 5,6 and 7 jet final states, with loose, medium and tight cuts



CMS-PAS-SUS-11-030

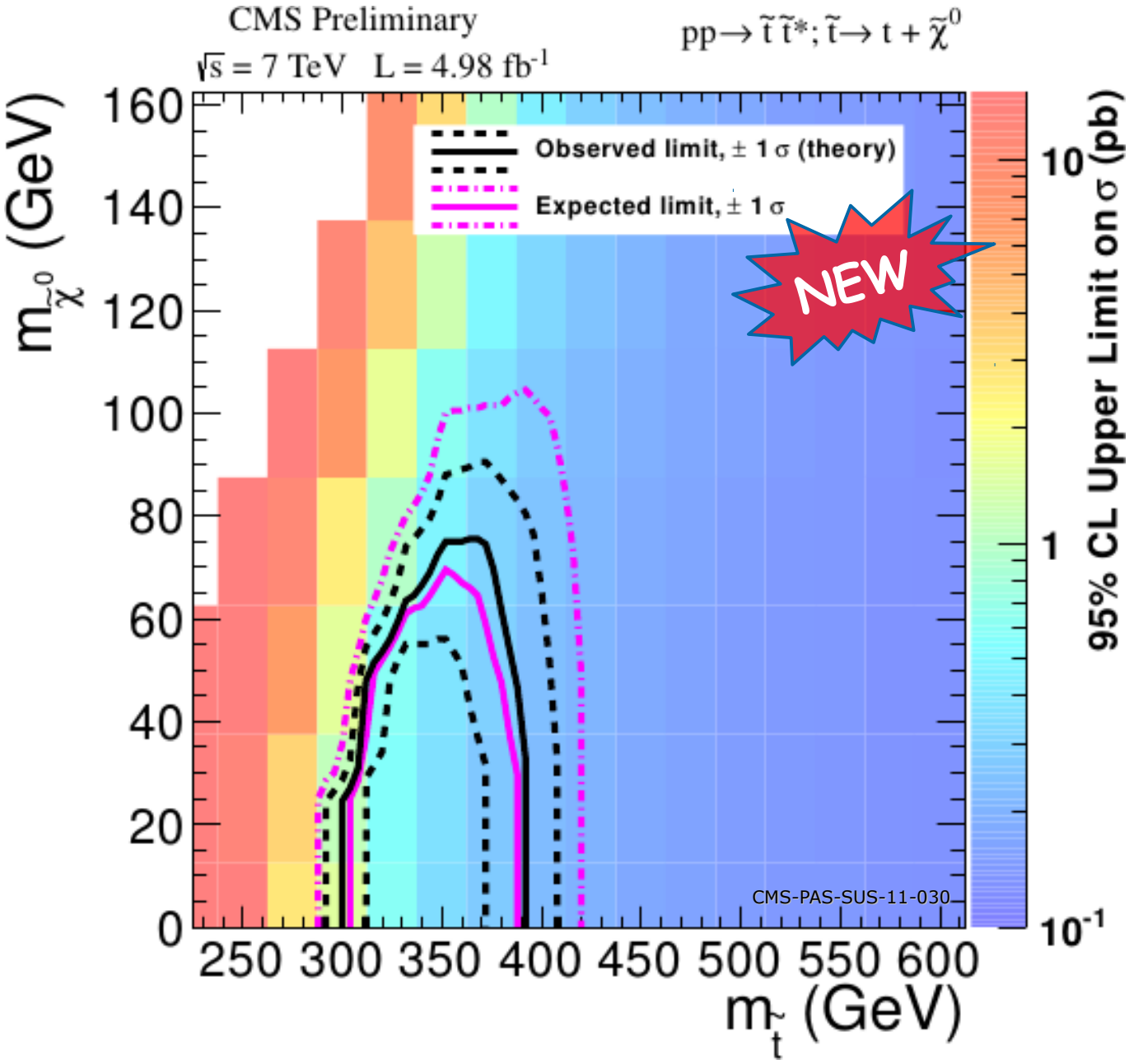


CMS-PAS-SUS-11-030

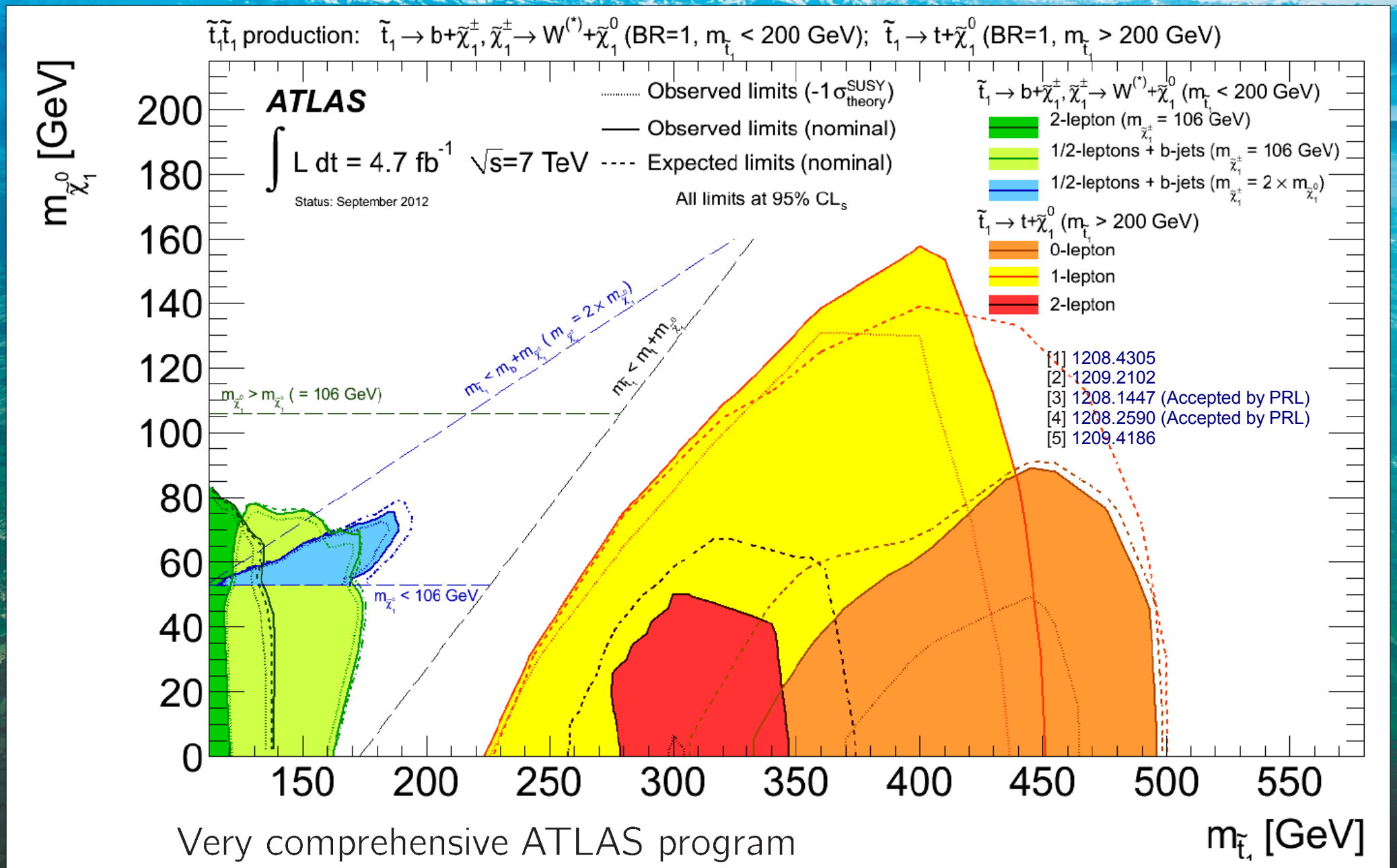


CMS stop mass limits

- Limits
  - $\tilde{t} \to t + \tilde{\chi}^0$
- More $\tilde{t}$ results from CMS available, just one example

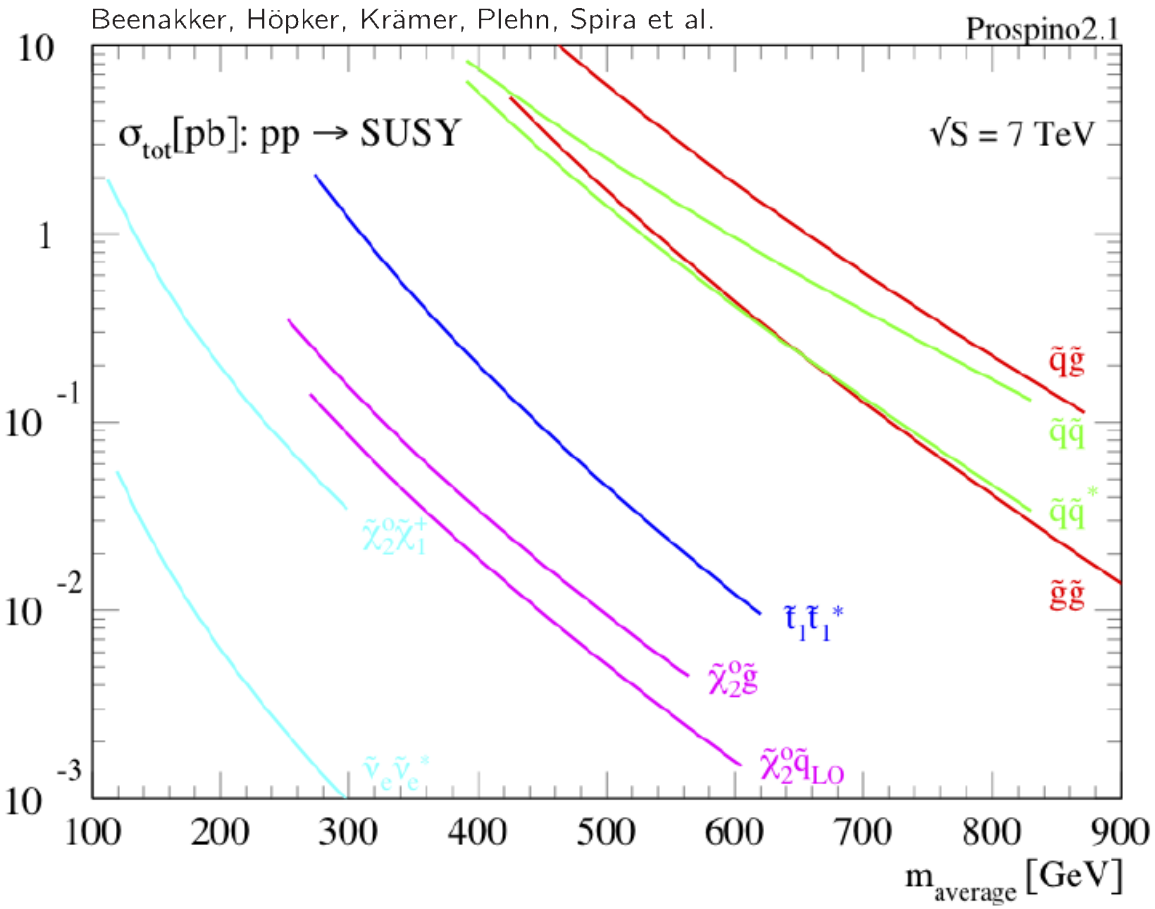


ATLAS stop mass limits



Very comprehensive ATLAS program

SUSY production cross-section



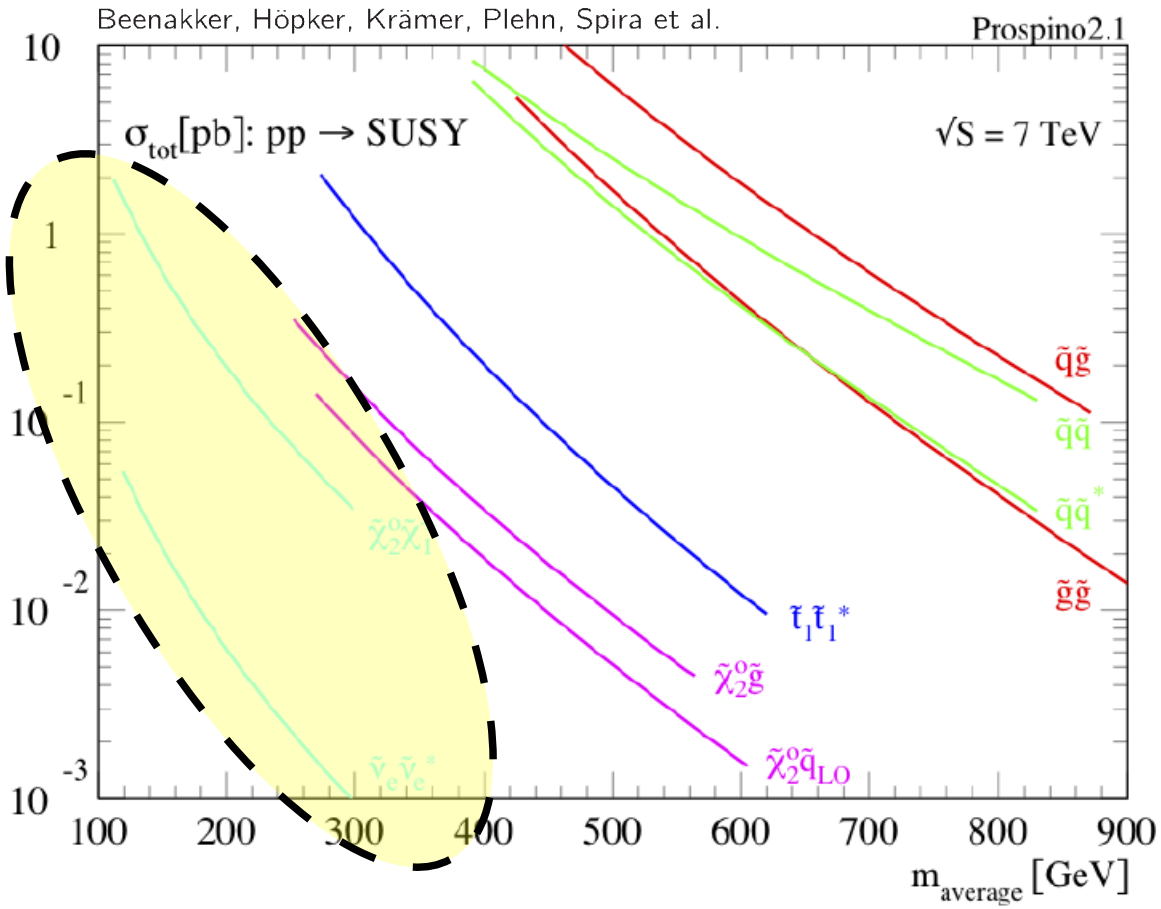
$m(\tilde{t}, \tilde{b}) \leq 500$ GeV ,
Higgsinos $\sim$ electroweak scale

- Comparable cross-section

Fruitful activity by experiments

- Direct $\tilde{t}$, $\tilde{b}$ production
- 3^{rd} generation sparticles $(\tilde{\tau}, \tilde{b}, \tilde{t})$ in the decay
- Spartners of Higgs, W, Z: charginos $\chi^{\pm}$, neutralinos χ^0

SUSY production cross-section



$m(\tilde{t}, \tilde{b}) \leq 500$ GeV ,
Higgsinos $\sim$ electroweak scale

- Comparable cross-section

Fruitful activity by experiments

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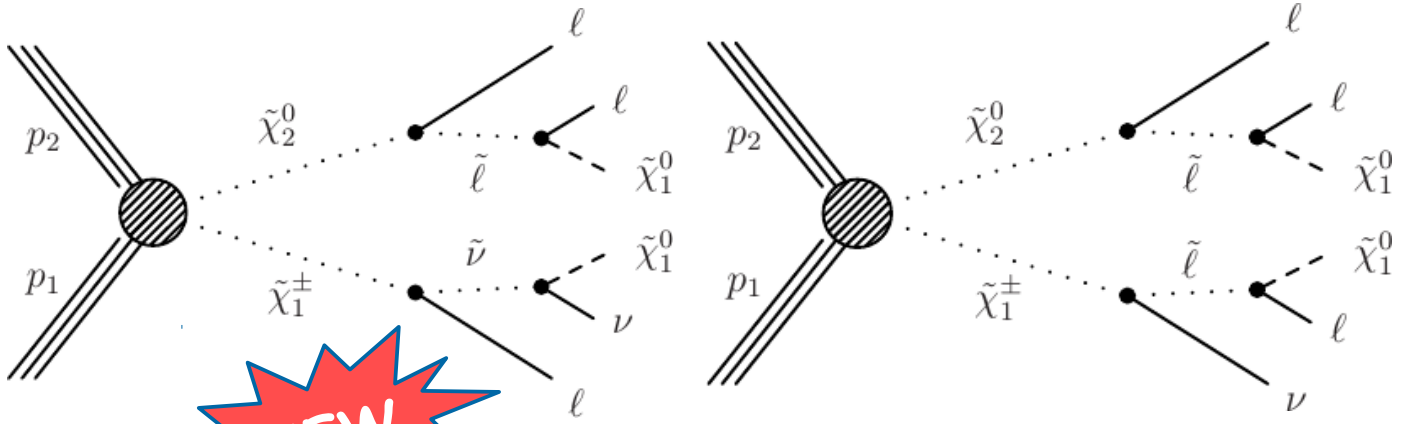
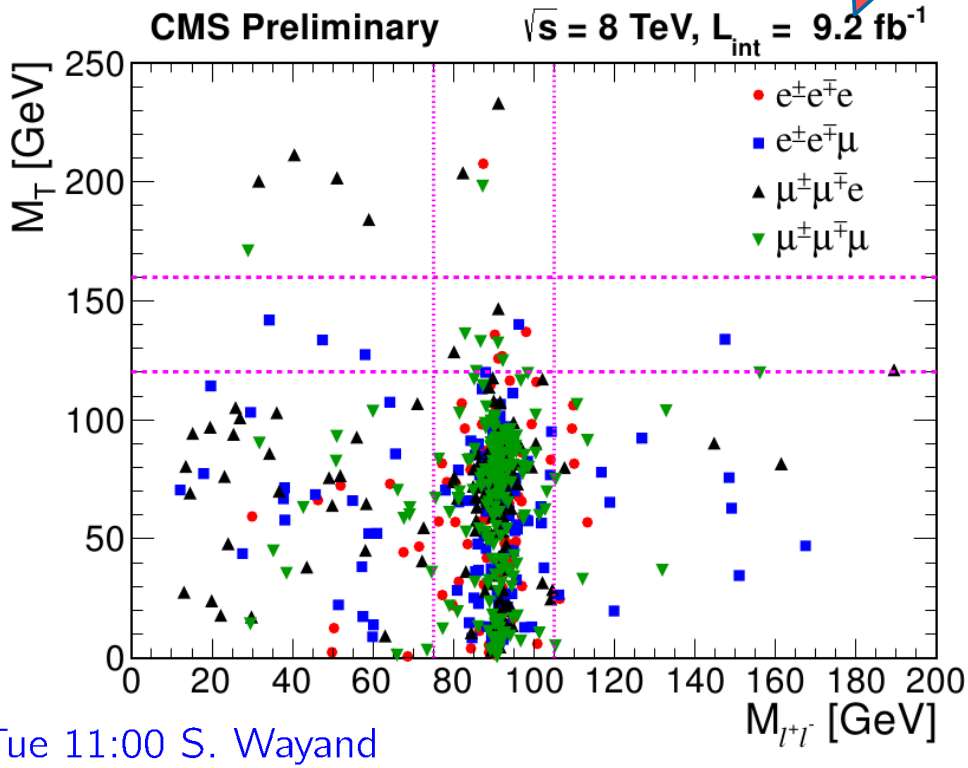
- Spartners of Higgs, W, Z: charginos $\chi^{\pm}$, neutralinos χ^{0}

CMS: Direct production of χ^0 and $\chi^{\pm}$

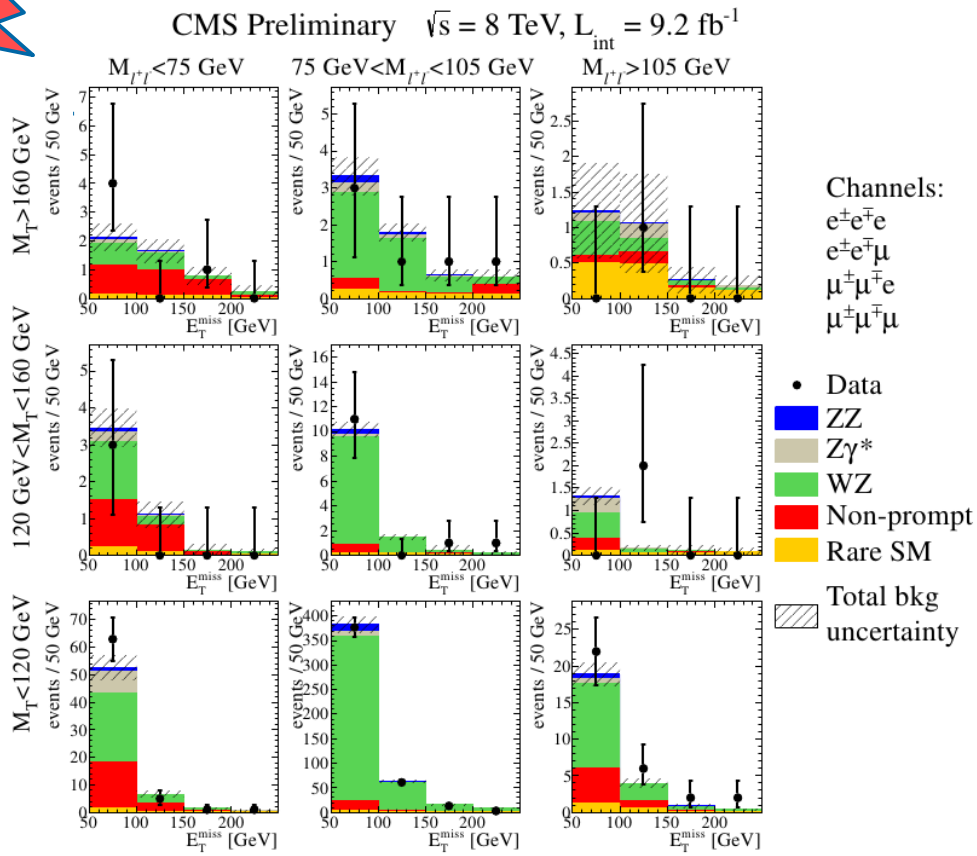
- Simplified model spectra (SMS) with few parameters
- Decay to three-lepton final states
- Same-sign leptons from $\tilde{\chi}^0$ decay



NEW



Tue 11:00 S. Wayand



CMS: Direct production of χ^0 and $\chi^{\pm}$

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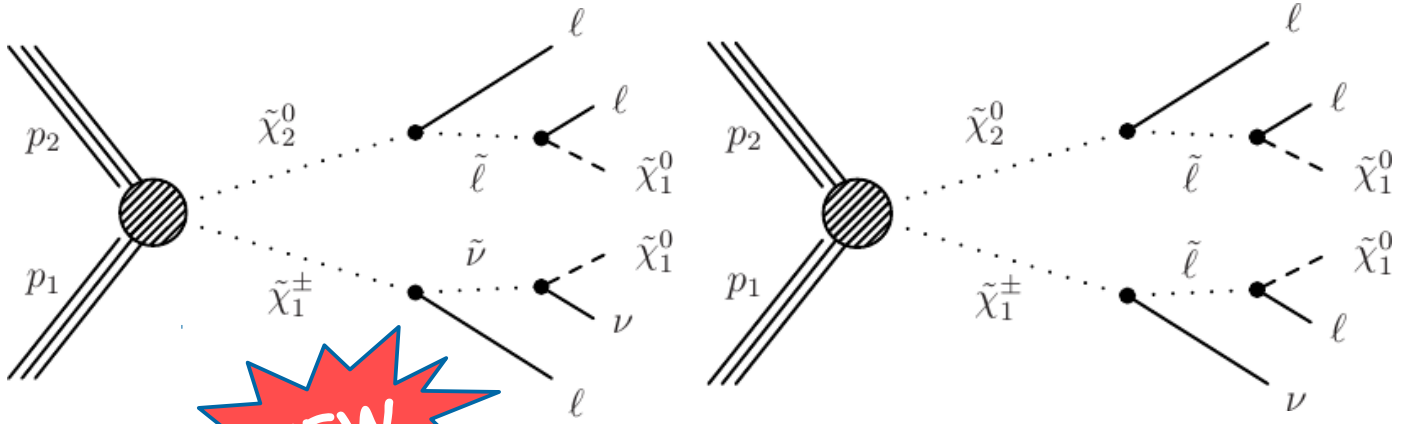
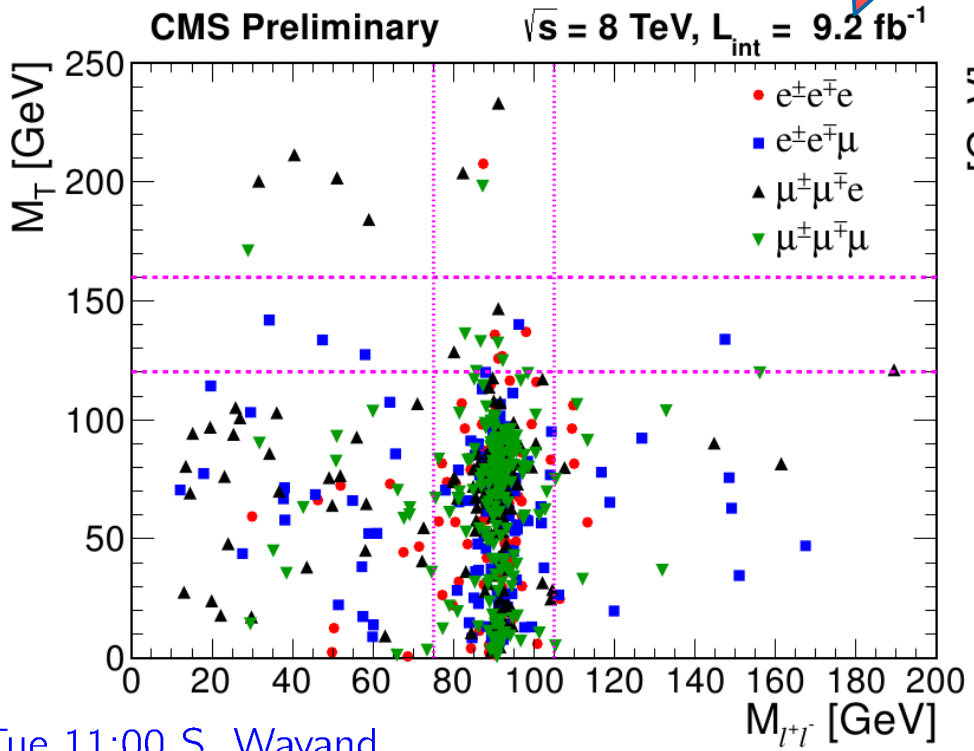
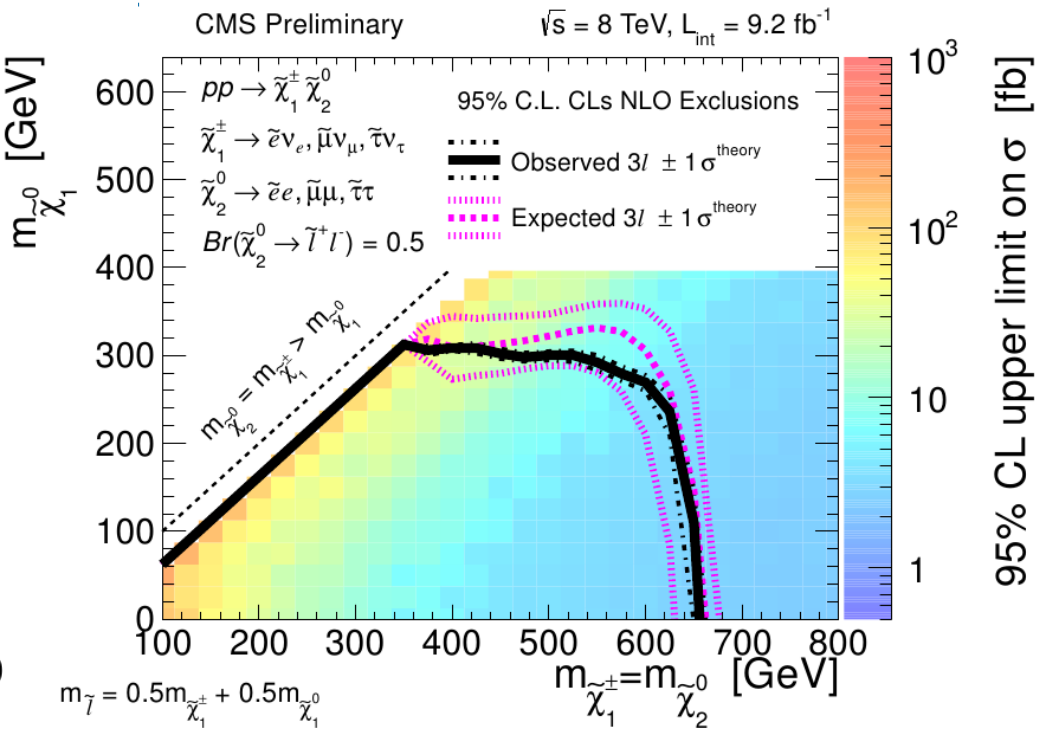


NEW

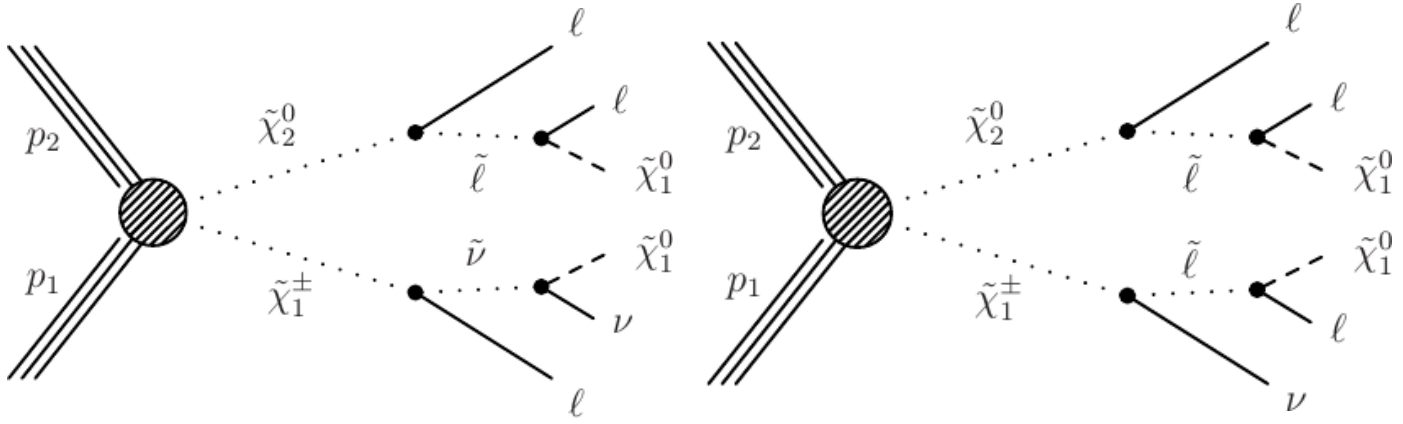




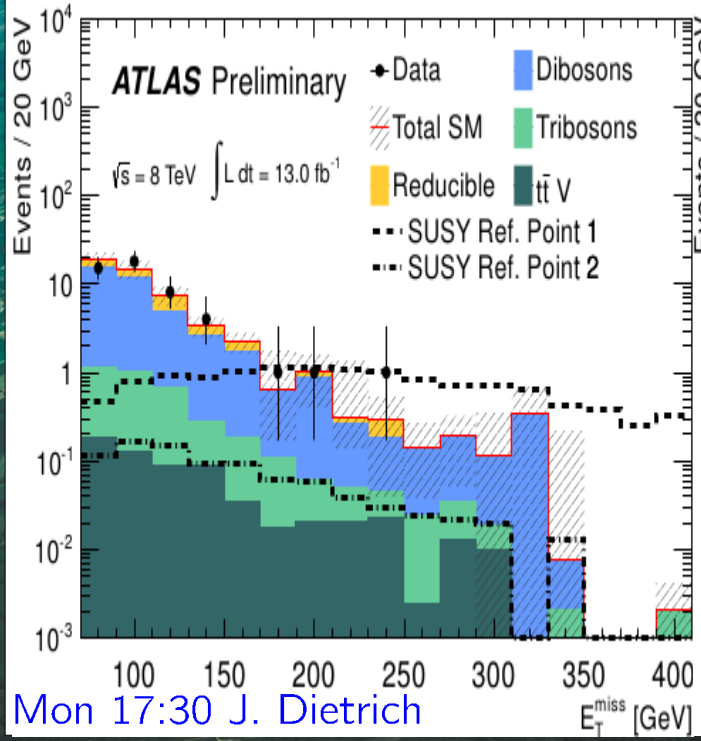
Tue 11:00 S. Wayand

ATLAS: Direct production of χ^0 and $\chi^\pm$

- Simplified model spectra (SMS) with few parameters
- Decay to three-lepton final states
- Same-sign leptons from $\tilde{\chi}^0$ decay

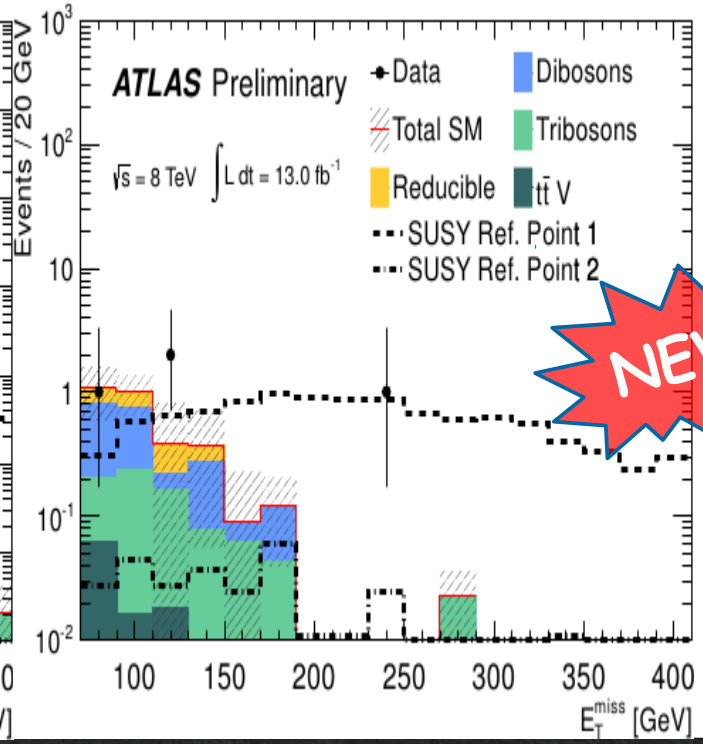


Z veto, small M_T

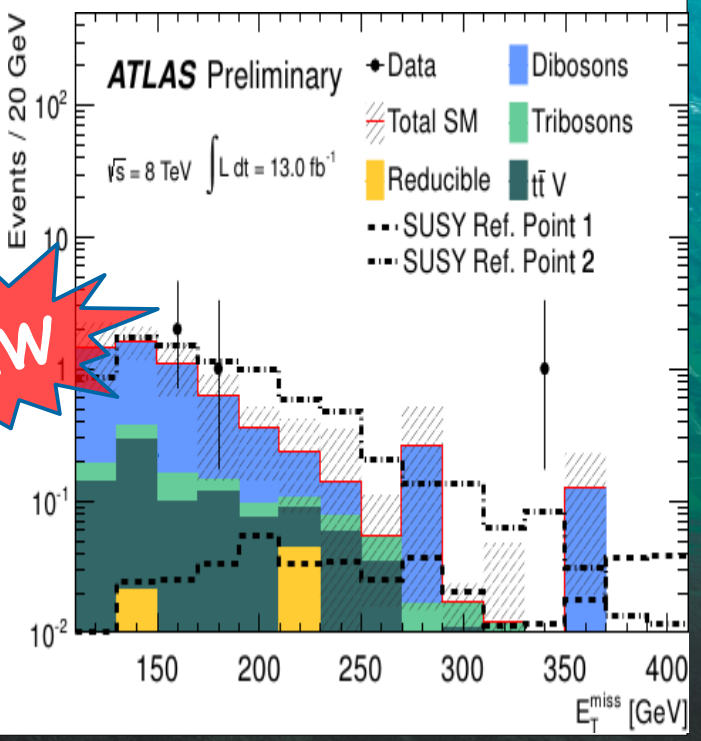


Mon 17:30 J. Dietrich

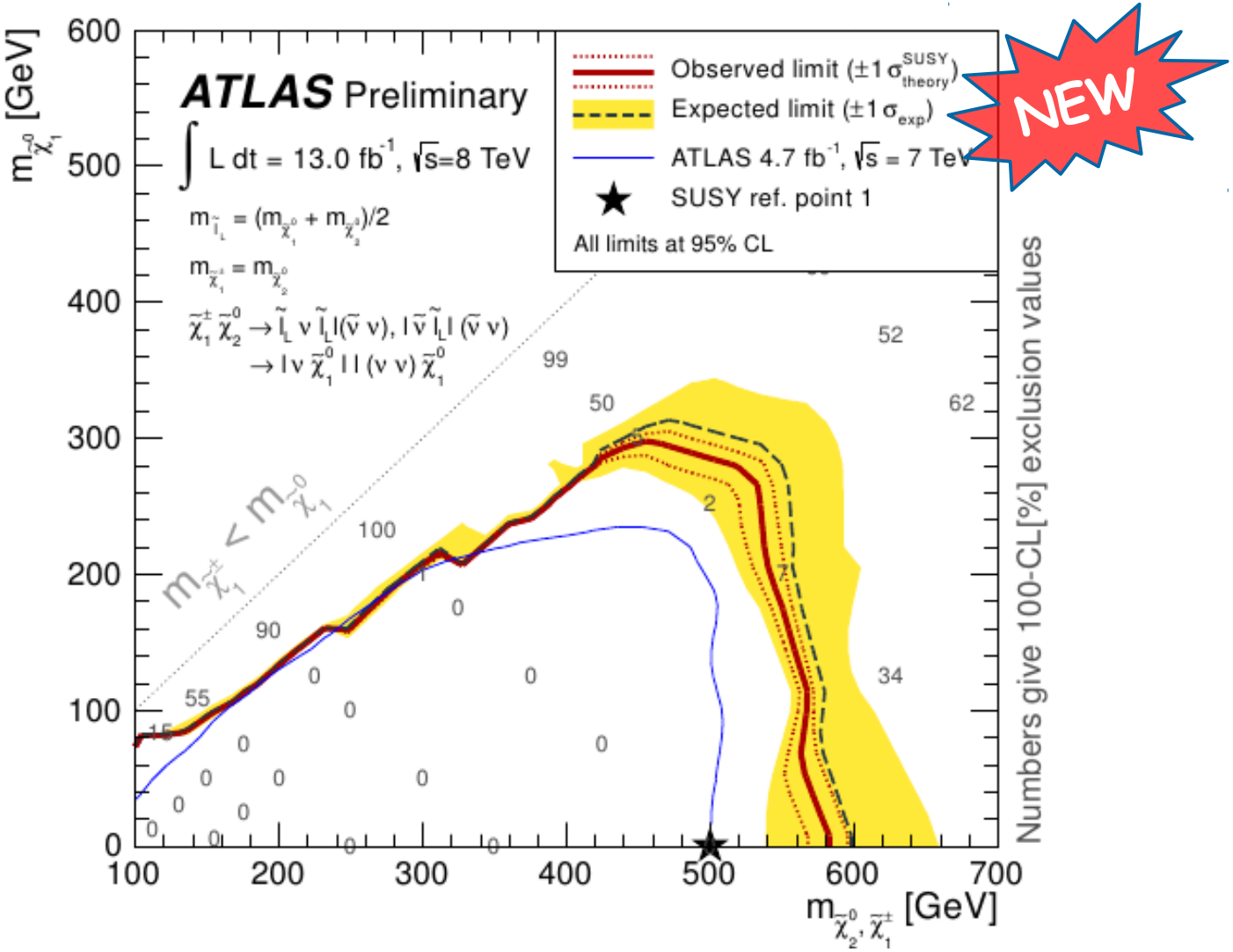
Z veto, large M_T



Z on-shell



Direct production of χ^0 and $\chi^\pm$

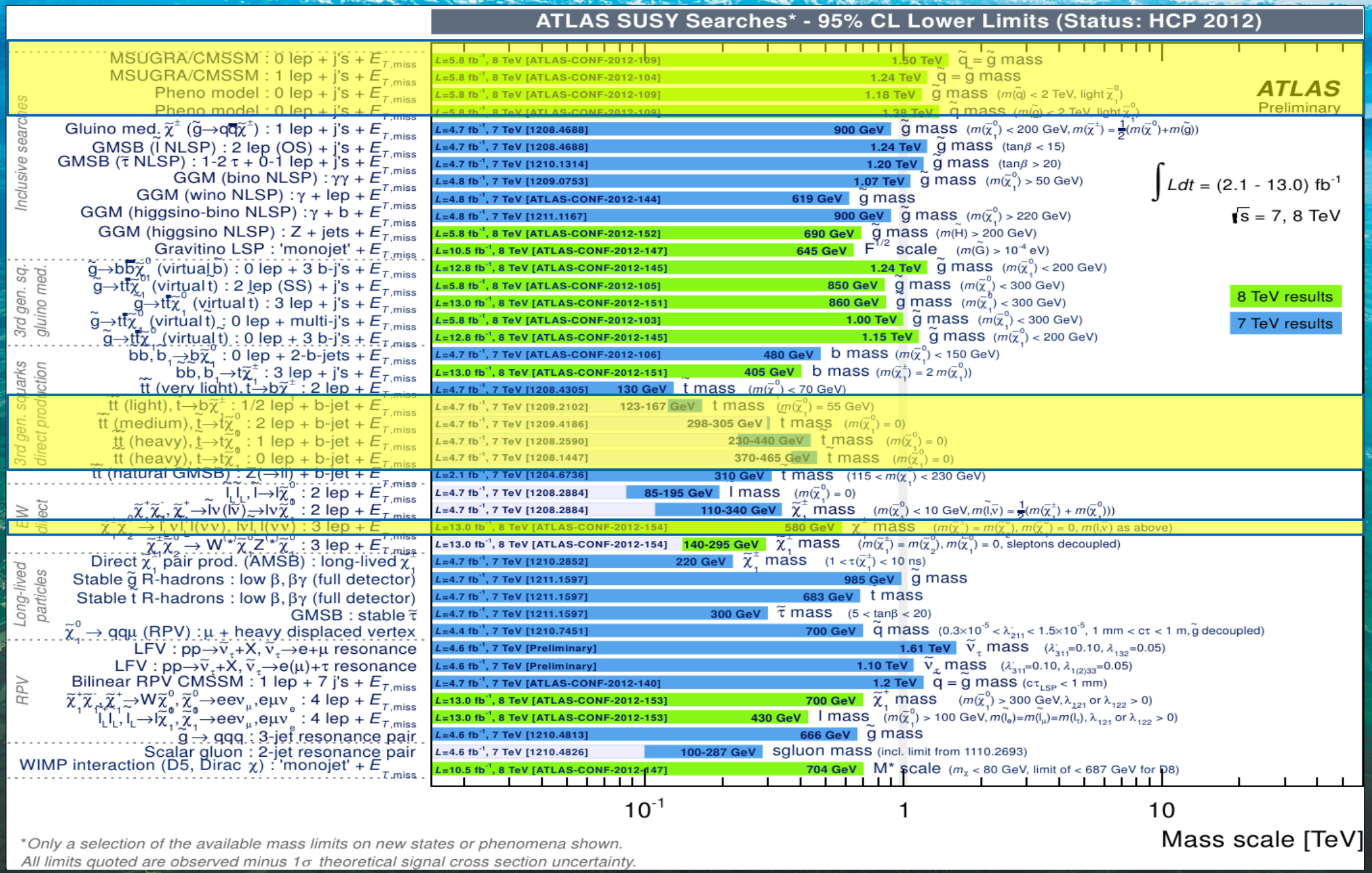


- Additional limits for (off-shell) W and Z decays of $\tilde{\chi}_2^0$ and in pMSSM

Mon 17:30 J. Dietrich

ATLAS SUSY summary

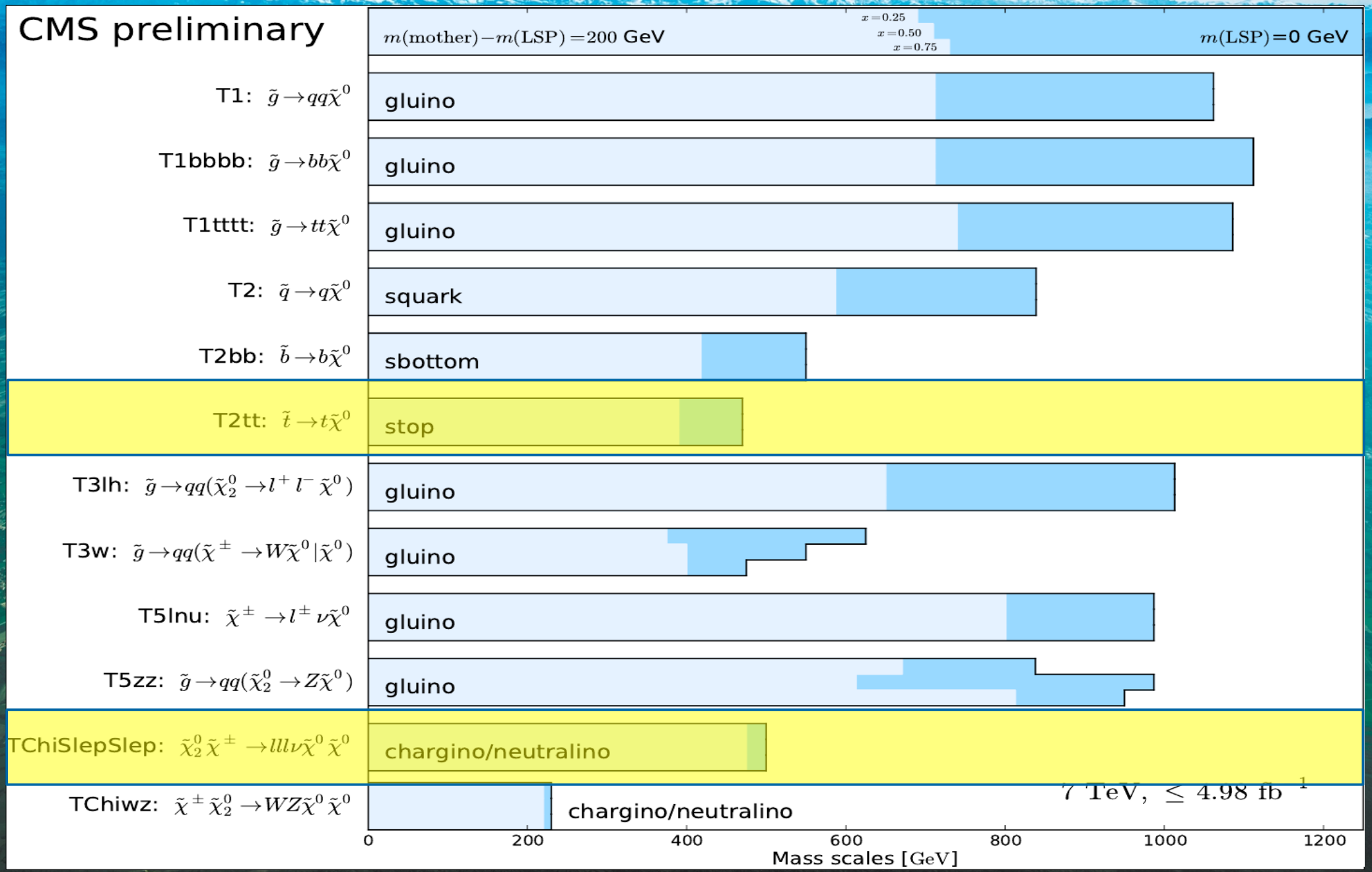
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

CMS SUSY summary

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



Non-SUSY searches (Exotica)

Searches with leptons

Z'

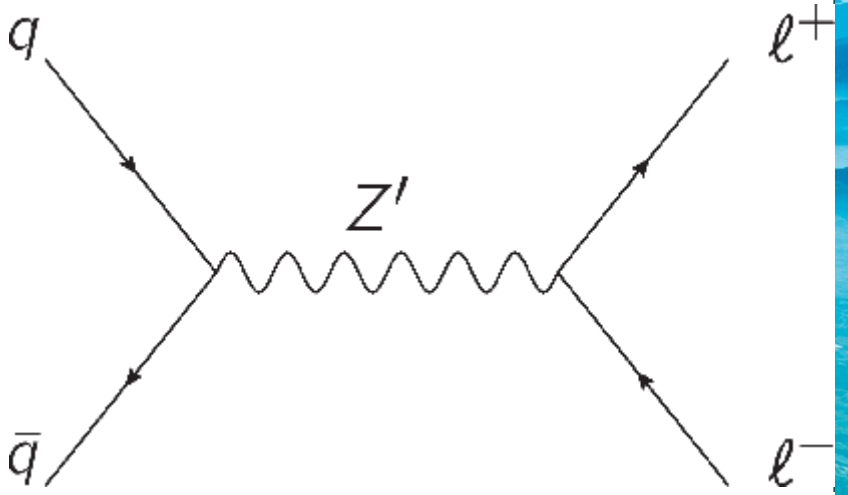
Z' → ee, μμ in 2012 data

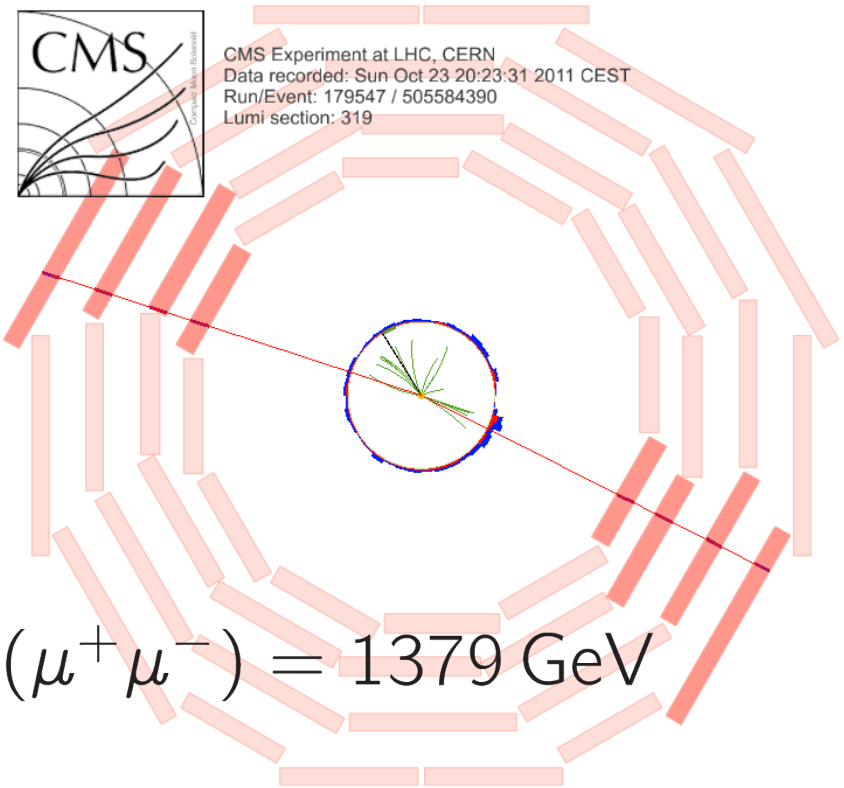
CMS search strategy:

- Require isolated $\ell = e, \mu$
- Require opposite sign muons

Backgrounds:

- Drell-Yan (Z/γ^*) shape taken from simulation, scaled at Z peak
- Top-Pair-Production from simulation, validated with data in $e^{\pm}\mu^{\mp}$
- Fake leptons from QCD multijets, γ+jets and W+jets estimated from data

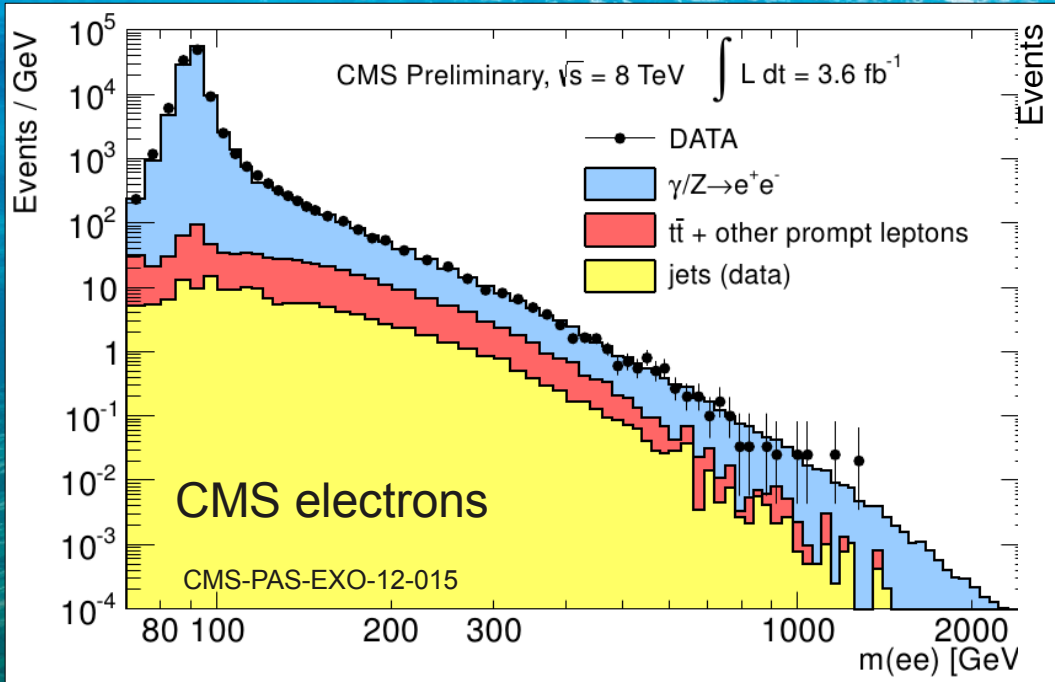


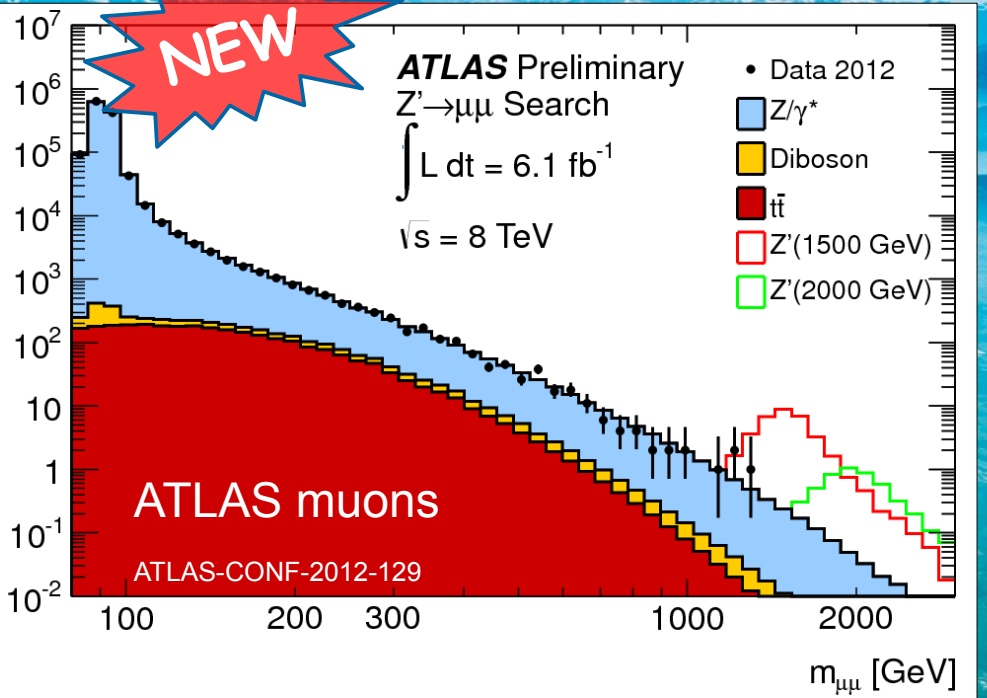


$m(\mu^+\mu^-) = 1379\,\text{GeV}$

Mo 16:30 J. Caudron

Test distribution: m(ll)



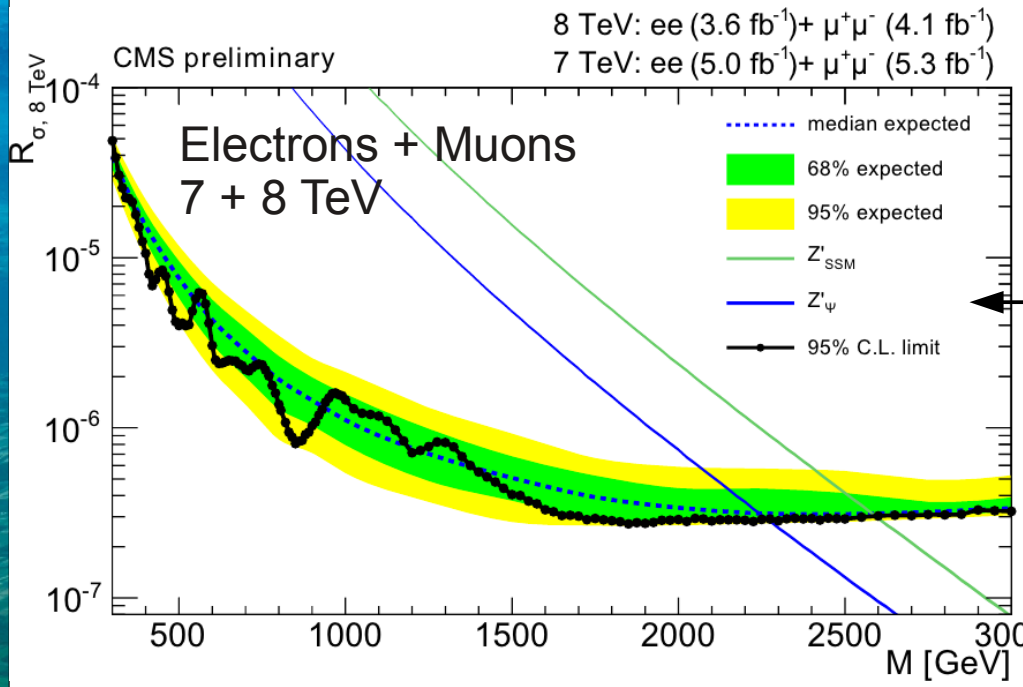


Both CMS and ATLAS:

- No signs of excess at high mass in 8 TeV data
- Consistently observed in electron and muon final state
- Set exclusion limits

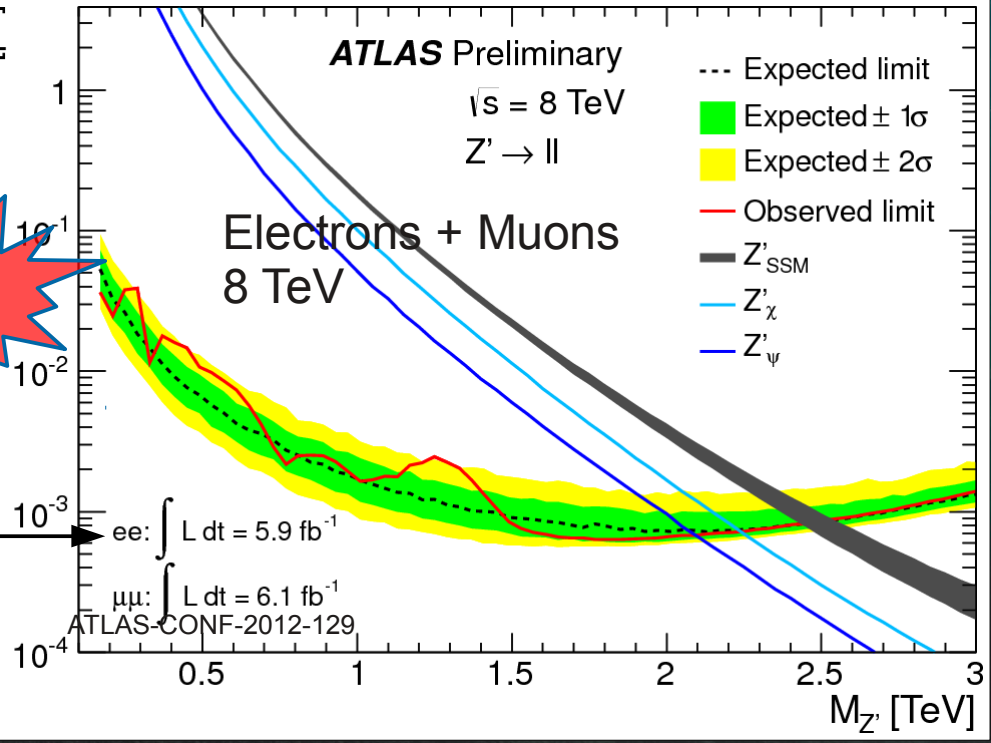
Mo 16:30 J. Caudron

Z': New limits



CMS: Combination of 7 TeV and 8 TeV data

- $M(Z'_{SSM}) > 2590$ GeV
- $M(Z'_\psi) > 2260$ GeV



NEW

ATLAS limits 8 TeV:

- $M(Z'_{SSM}) > 2.49$ TeV
- $M(Z'_\psi) > 2.09$ TeV
- $M(Z'_\chi) > 2.24$ TeV

Mo 16:30 J. Caudron

Searches with leptons

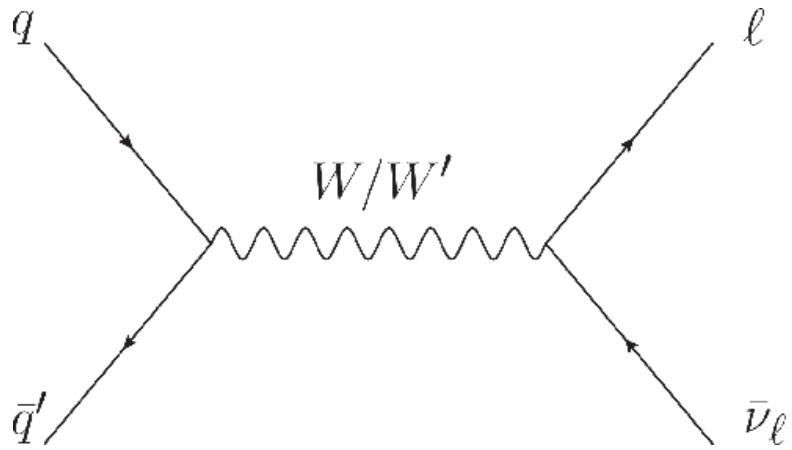
W'

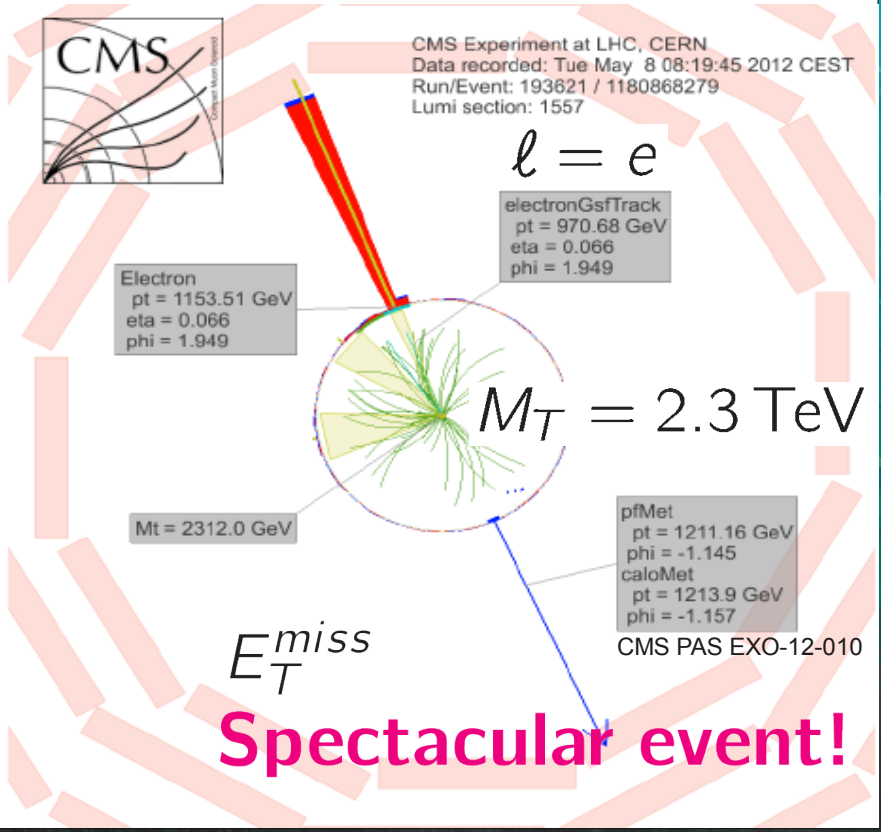
Theory:

- Sequential Standard Model, W' a carbon-copy of Standard Model W
- Possible Right-Handed W'_R, consider interference as well

CMS search strategy (ATLAS very similar):

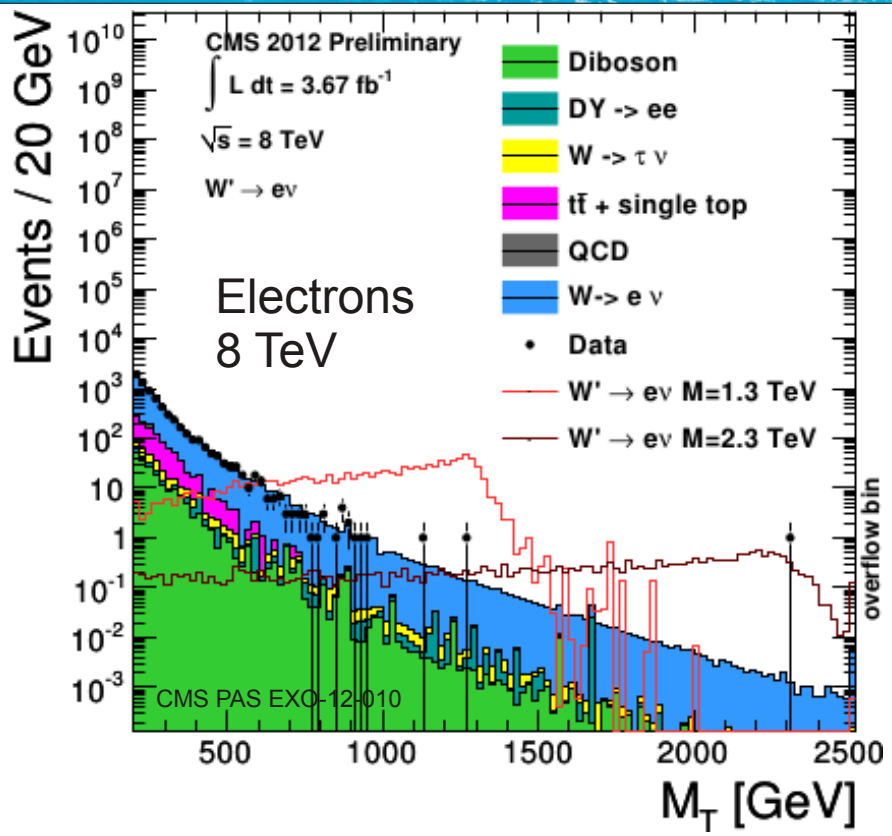
- Require well reconstructed, isolated $\ell = e, \mu$
- Measure $E_T^{miss} = |-\sum_i \vec{p}_T^{\,i}|$ with energy flow
- Require $0.4 < p_T^{\ell}/E_T^{miss} < 1.5$ and $\Delta\phi > 2.5$

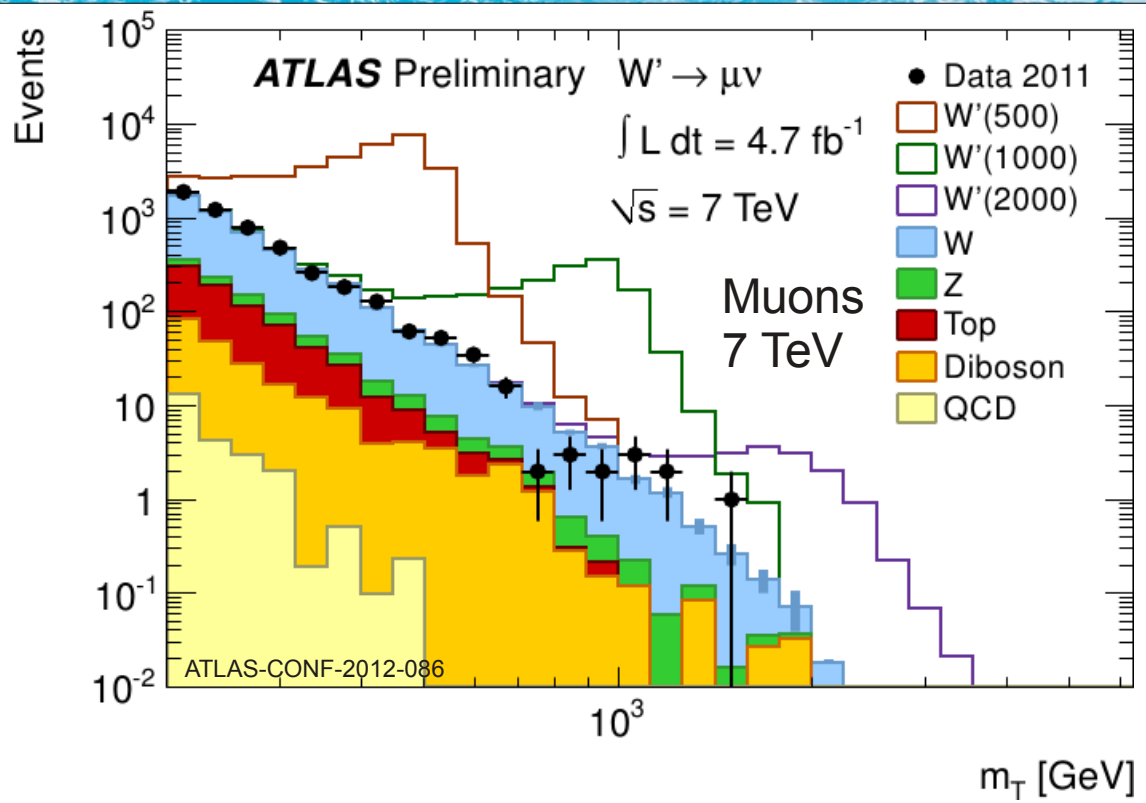




ATLAS-CONF-2012-086
CMS PAS-EXO-12-010

Transverse mass distribution

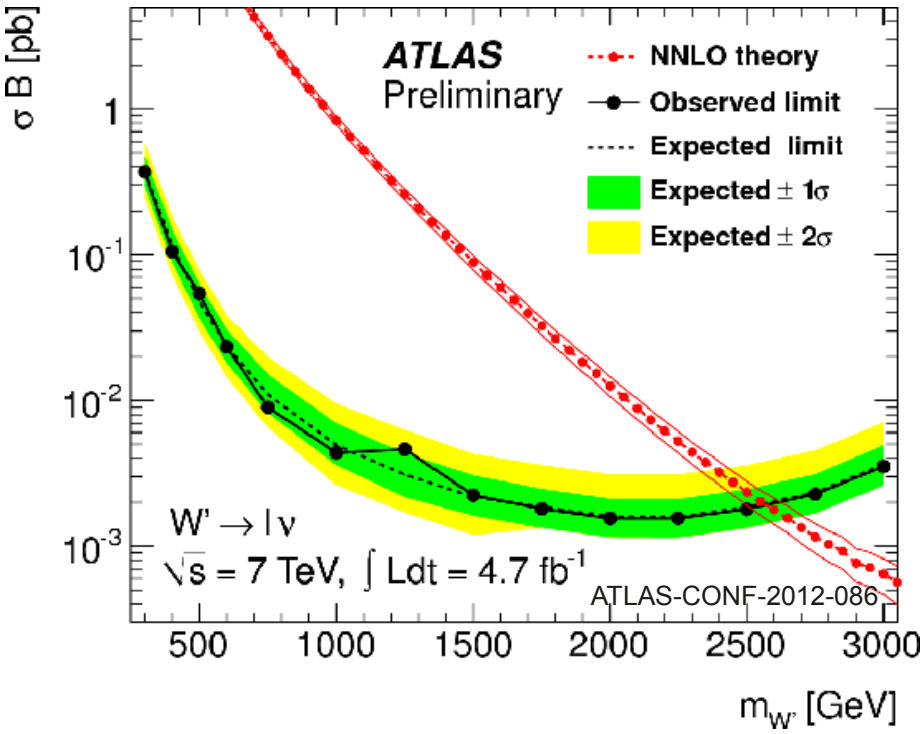




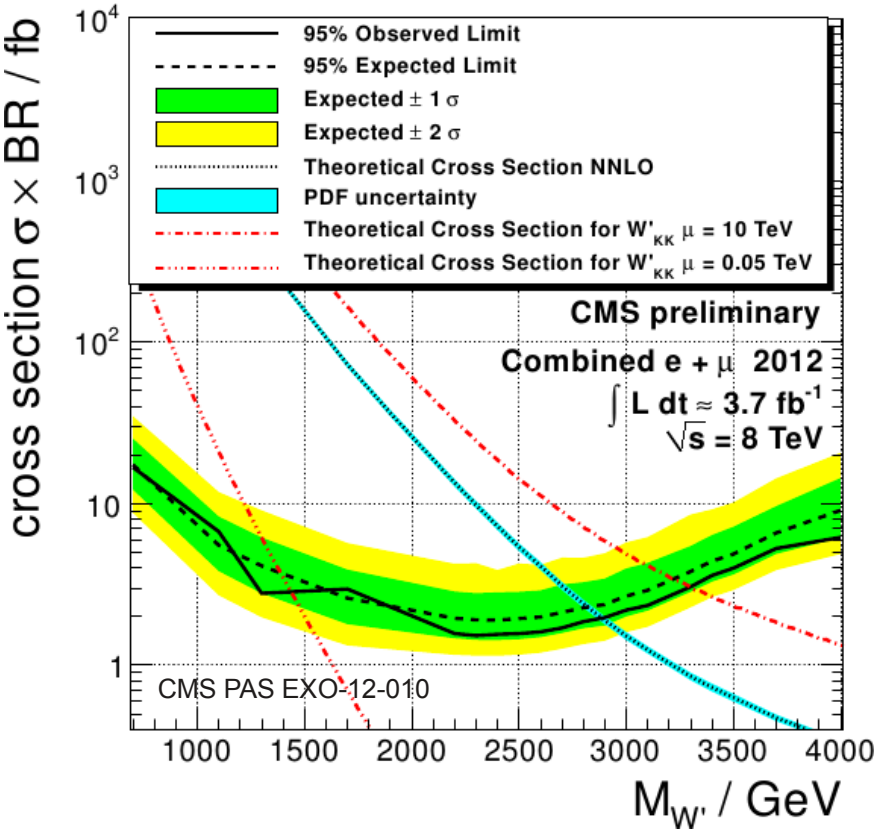
- Test distribution: Transverse mass $M_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{miss} \cdot (1 - \cos\Delta\phi)}$
- Shown: Simulation of a $M(W')$ signal for various masses
- W' mass at kinematic limit $\rightarrow$ no clear Jacobian peak, mainly virtual W
- Good agreement with Standard Model

W' limits

ATLAS limit: 2011 data, 7 TeV, 4.7 fb^{-1}



CMS limit: 2012 data, 8 TeV, 3.7 fb^{-1}



	Luminosity	Expected limit	Observed limit
ATLAS $e+\mu$, 2011	4.7	2.55 TeV	2.55 TeV
CMS $e+\mu$, 2012	3.7	2.80 TeV	2.85 TeV
CMS $e+\mu$, 2011+2012	5.0+3.7	2.85 TeV	2.85 TeV

Resonances in dijets

ATLAS dijet resonances

Theory: Small width resonance, strong couplings

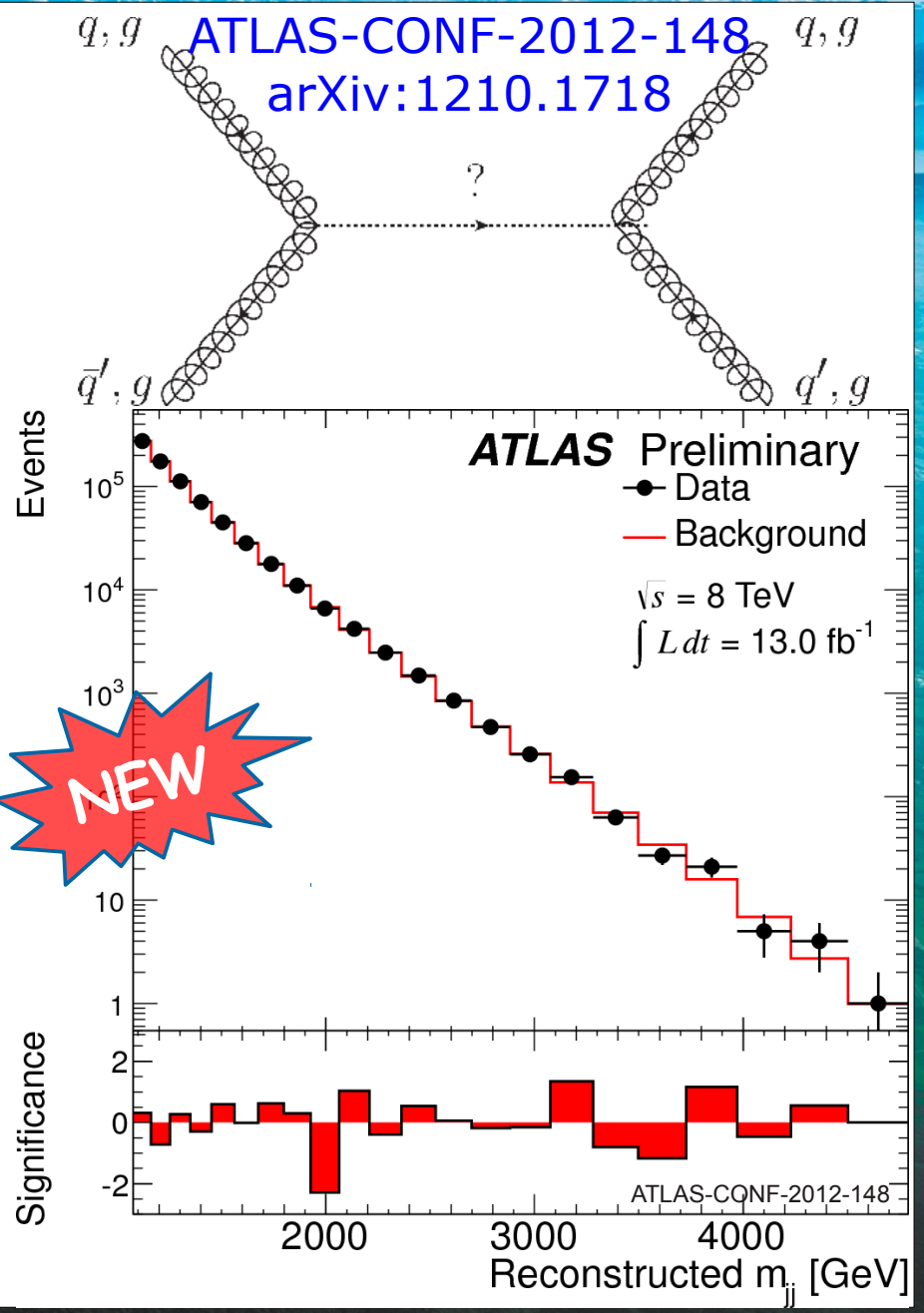
- String resonances, E_6 diquarks, excited quarks, axigluons, colorons, W', Z', RS gravitons, ...

ATLAS search strategy:

- ≥ 2 jets
- Rapidities $|y_1|, |y_2| < 2.8$, $|y^*| = |\pm(y_1 - y_2)/2| < 0.6$, $|y_B| = |(y_1 + y_2)/2| < 1.1$
- $m_{jj} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$
- Smooth fit, $\chi^2/\text{ndof} = 15.5/18$

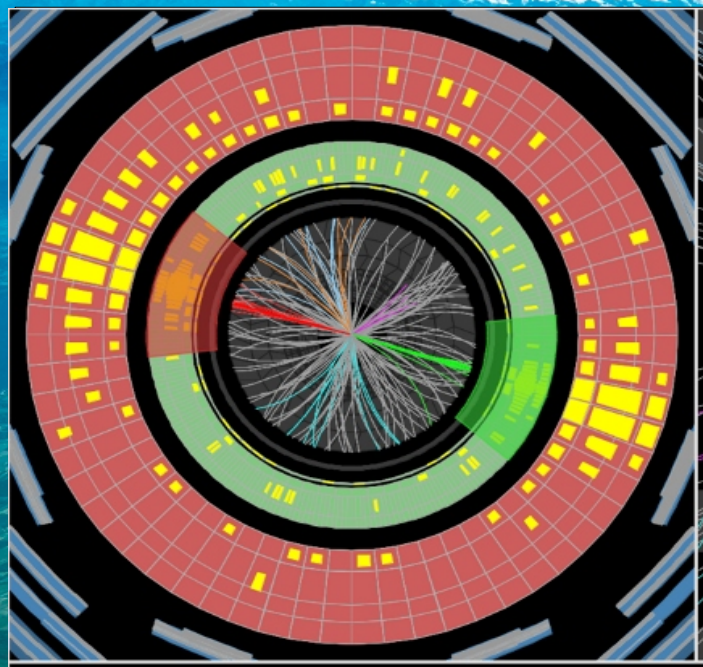
$$\frac{d\sigma}{dm} = \frac{P_0(1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2 + P_3 \ln(m/\sqrt{s})}}$$

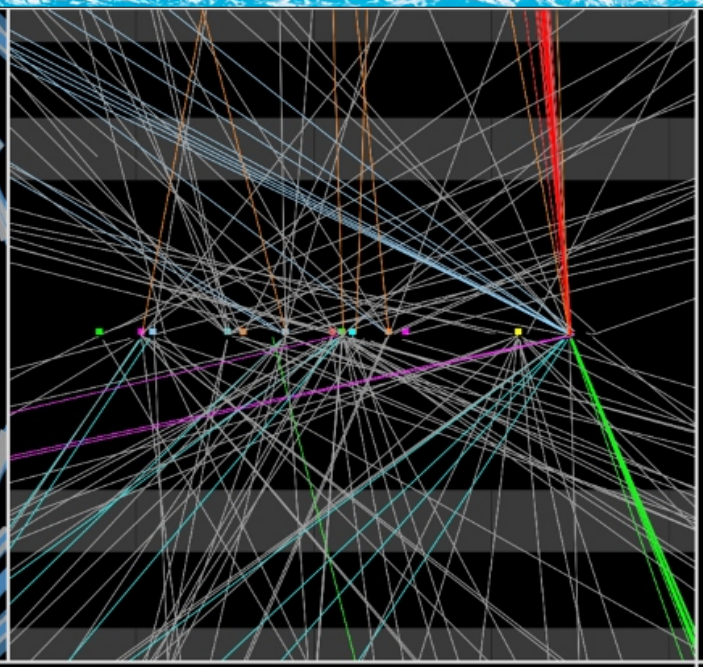
ATLAS-CONF-2012-148
arXiv:1210.1718



Mo 16:00 O. Endner

ATLAS highest mass dijet event



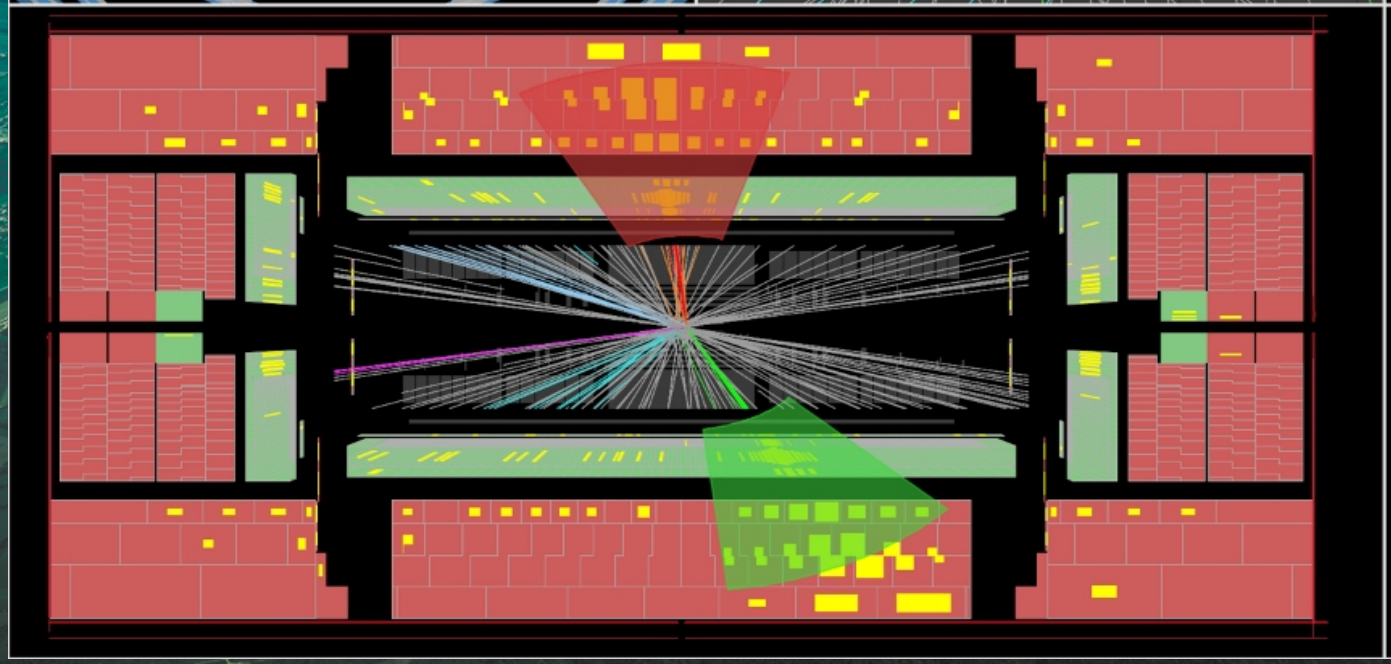


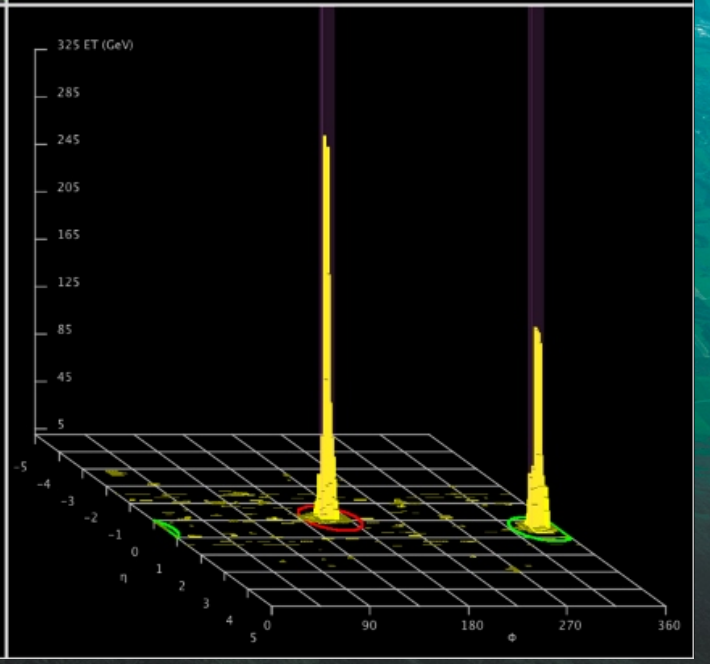
ATLAS EXPERIMENT

Run Number: 209580, Event Number: 179229707

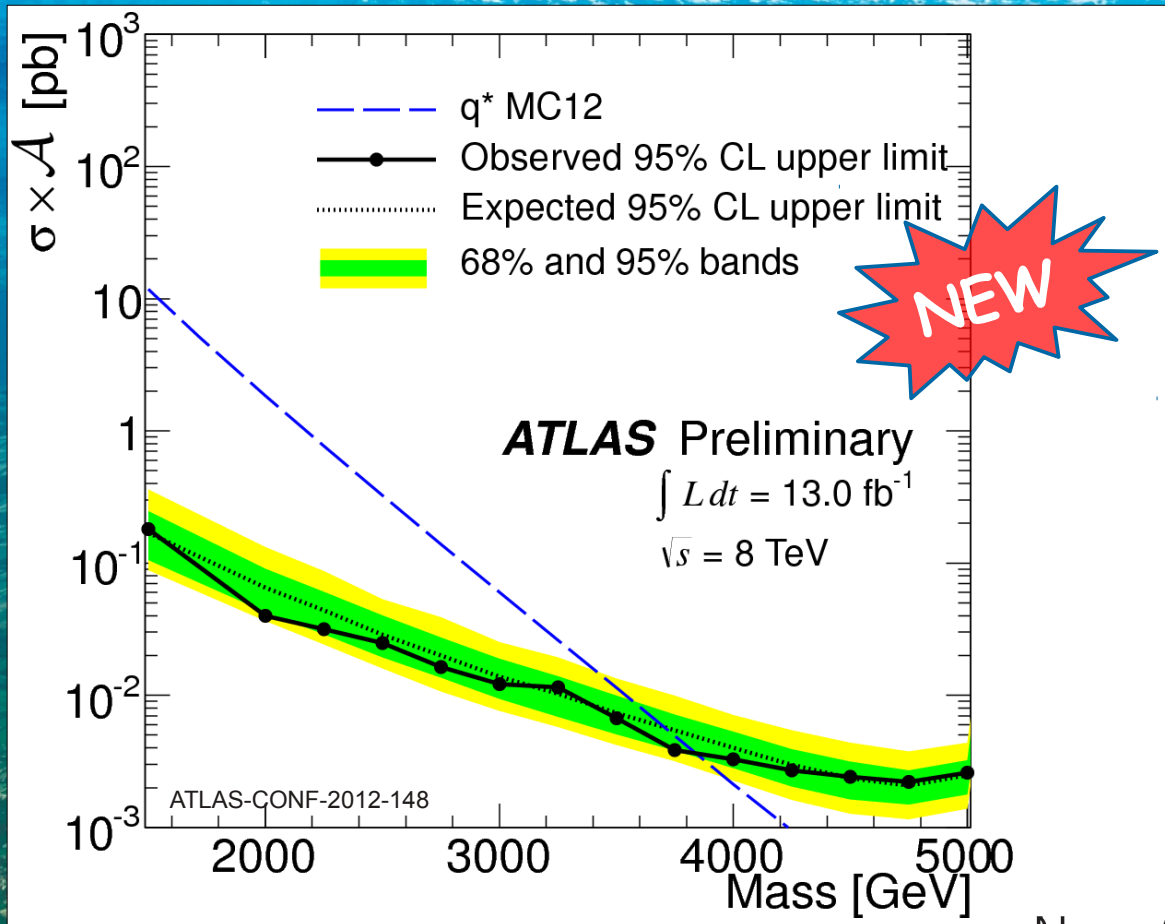
Date: 2012-08-31 20:24:29 CEST

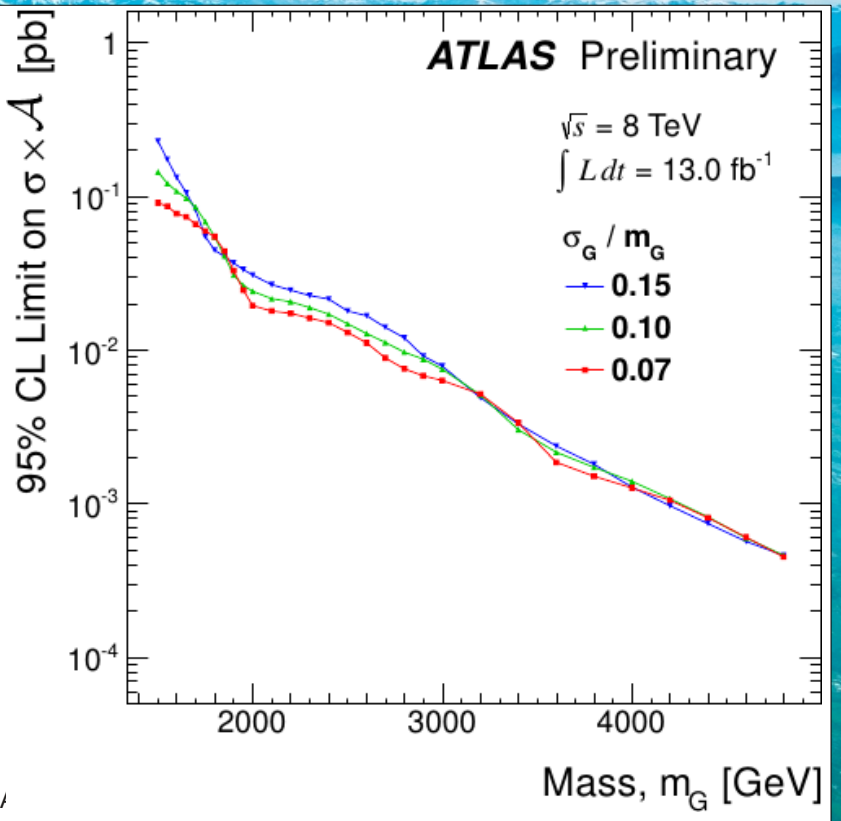
$m_{jj} = 4.69\,\text{TeV}$





ATLAS dijet limits





Model	Expected	Observed
q^*	$m > 3.09$ TeV	$m > 3.84$ TeV

New ATLAS result:

- Model independent limits
- Assuming Gaussian signal, Mass m_G, Width σ_G, $m_G/\sigma_G = 0.07...0.15$

Mo 16:00 O. Endner

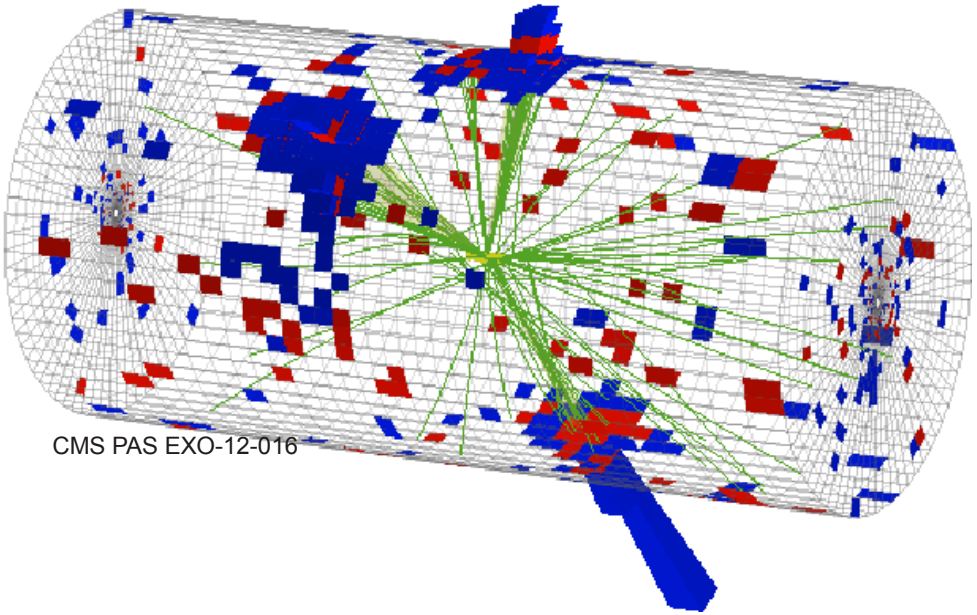
CMS dijet resonances

CMS: very similar search strategy

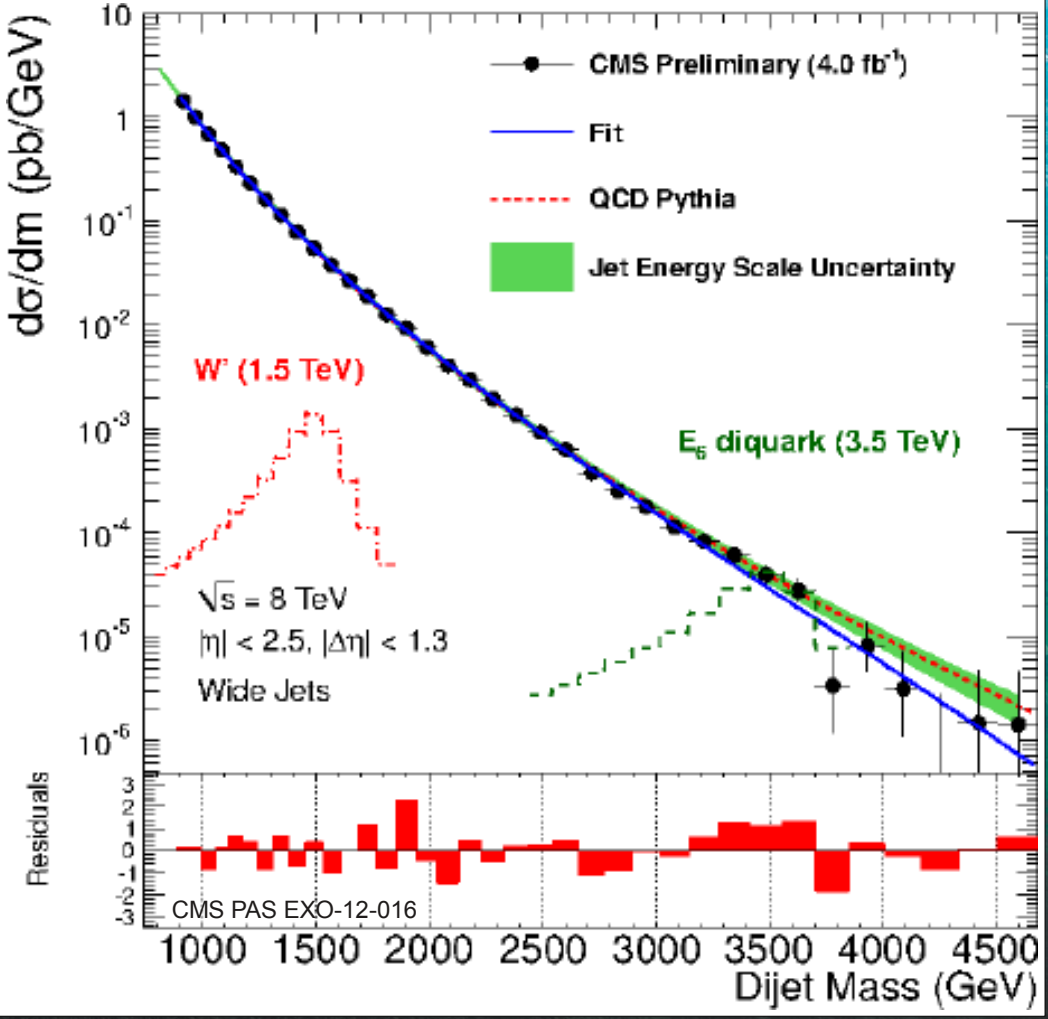
- $m_{jj} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$
- Same fit function
- Fit $\chi 2/\text{ndof} = 25.7/32$

CMS Experiment at LHC, CERN
Data recorded: Sat May 26 13:25:29 2012 CEST
Run/Event: 195016 / 425646417
Lumi section: 384

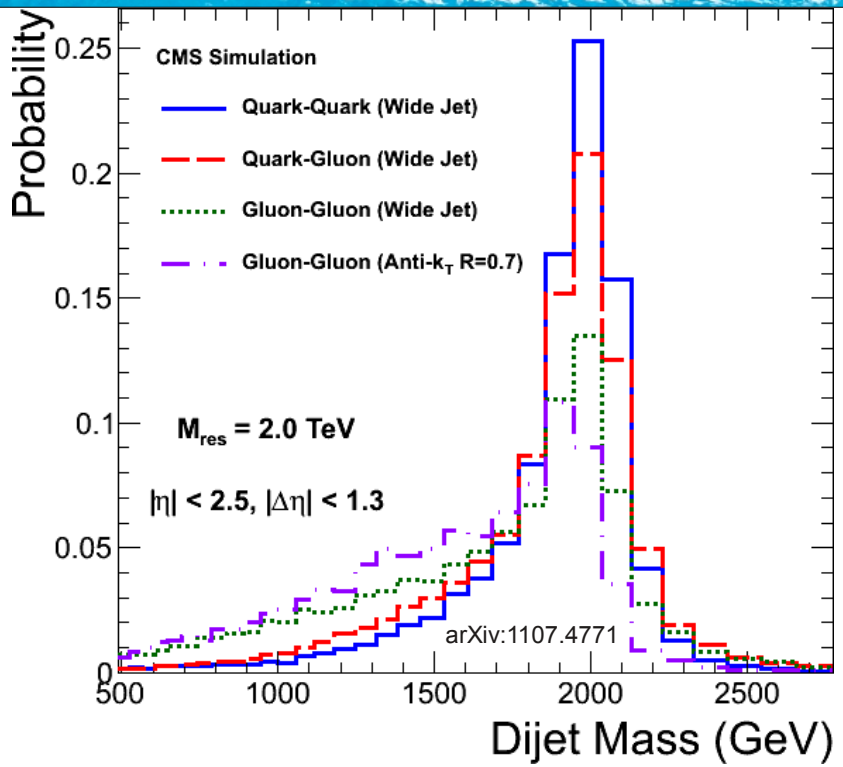
$$m_{jj} = 4.5\,\text{TeV}$$

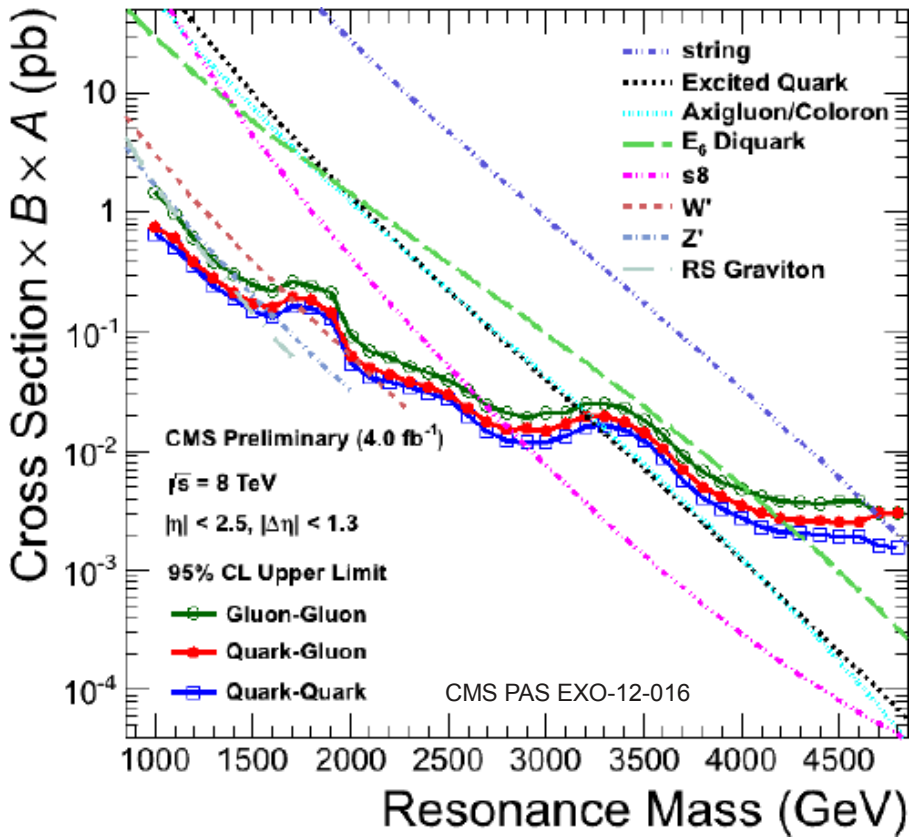


CMS PAS EXO-12-016



CMS: Narrow width resonance exclusion





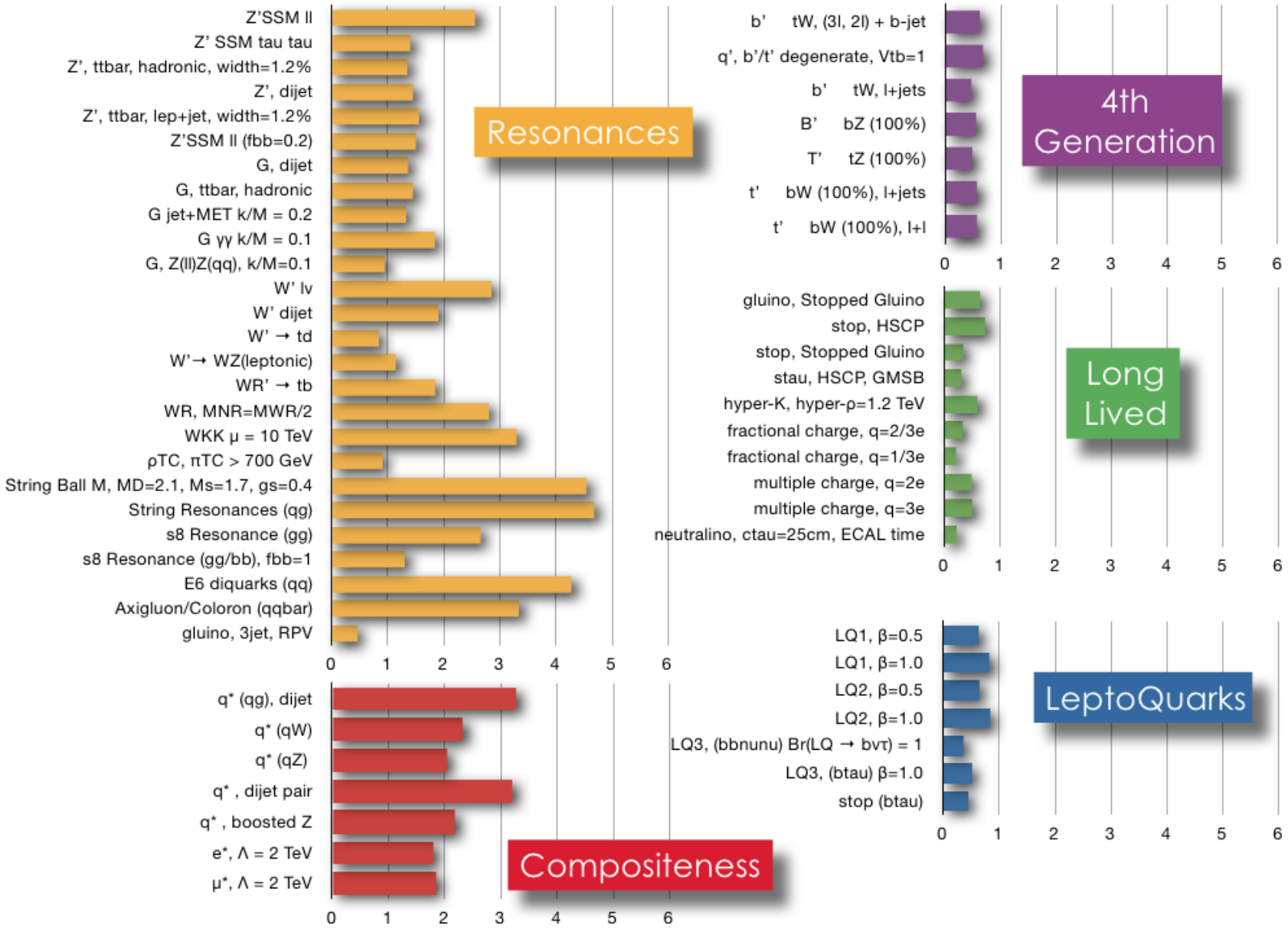
Specific feature:

- If model resonance width narrow compared to dijet mass resolution → possible to exclude with just one template!
- Depending on particle decay, use qq, qg or gg mass template

Model	Final State	Obs. Mass Excl. [TeV]	Exp. Mass Excl. [TeV]
String Resonance (S)	qg	[1.0, 4.69]	[1.0,4.64]
Excited Quark (Q*)	qg	[1.0, 3.19]	[1.0,3.43]
E_6 Diquark (D)	qq	[1.0, 4.28]	[1.0,4.12]
Axigluon (A)/Coloron (C)	$q\bar{q}$	[1.0, 3.28]	[1.0,3.55]
s8 Resonance (s8)	gg	[1.0, 2.66]	[1.0,2.53]
W′ Boson (W′)	$q\bar{q}$	[1.0, 1.74] [1.97, 2.12]	[1.0,1.92]
Z′ Boson (Z′)	$q\bar{q}$	[1.0, 1.60]	[1.0,1.50]
RS Graviton (RSG)	$q\bar{q}$+gg	[1.0, 1.36]	[1.0,1.20]

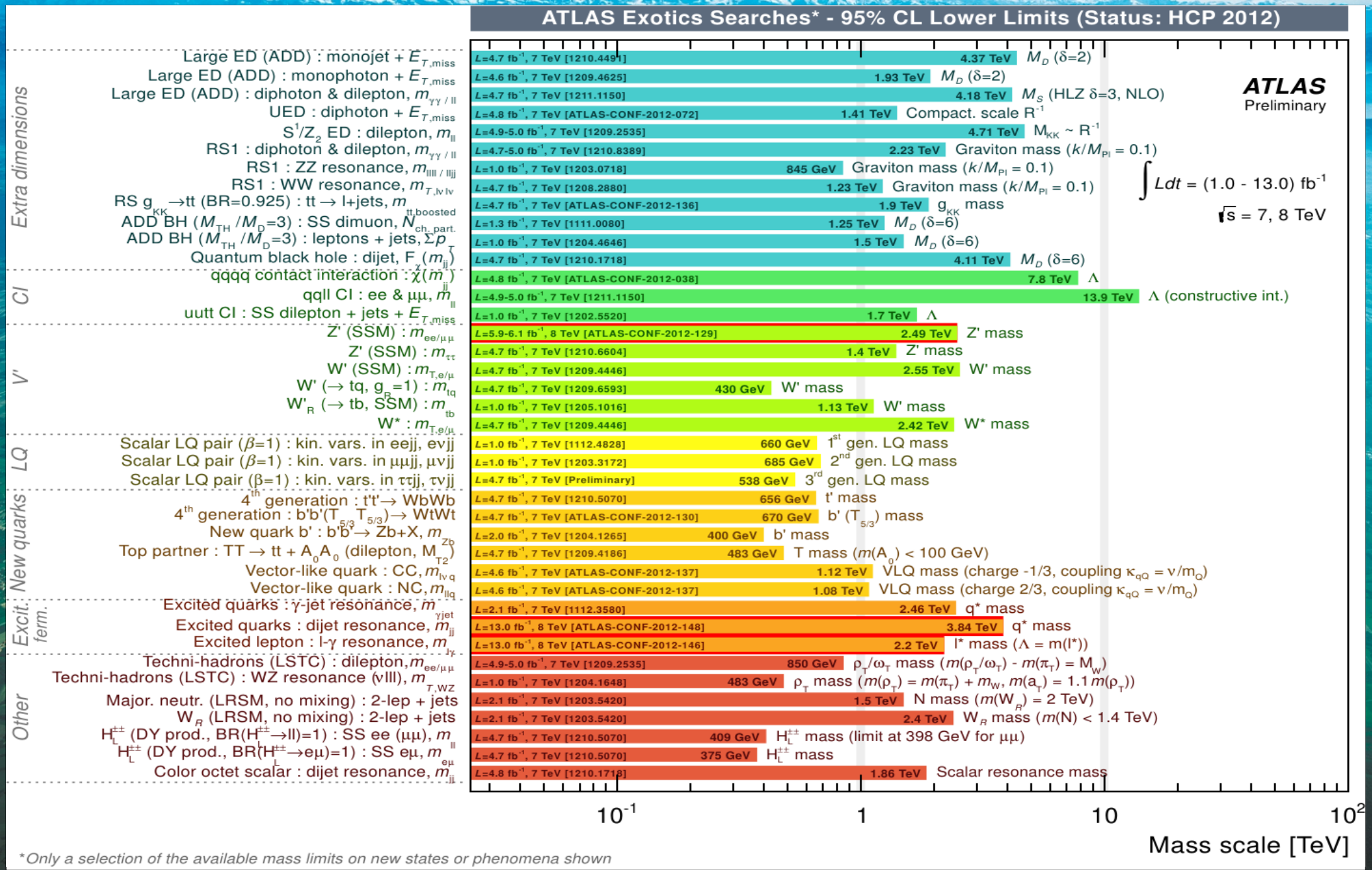
CMS exotica results overview

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



ATLAS exotica results overview

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults



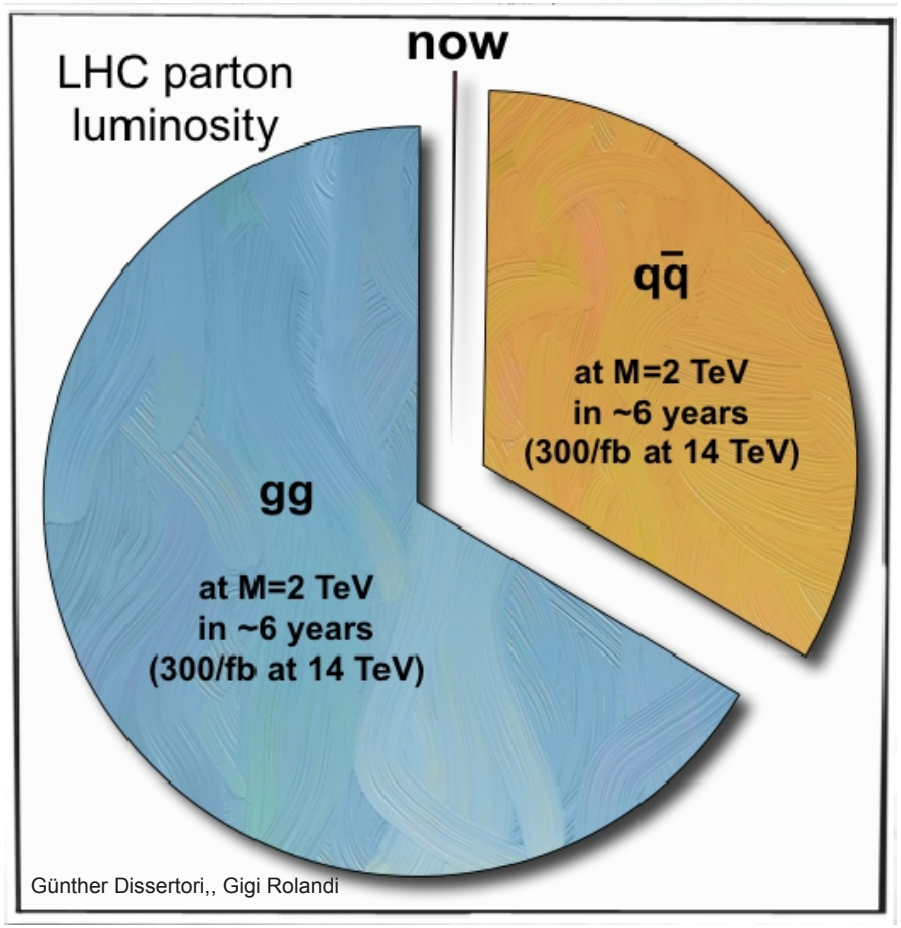
*Only a selection of the available mass limits on new states or phenomena shown

Summary and outlook

Conclusion

- ATLAS and CMS searched for physics beyond the Standard Model
- Great LHC, ATLAS and CMS performance in 2011 and 2012
  - Many 8 TeV results available
  - Constantly new 7 TeV + 8 TeV results being made public
- SUSY results
  - Searches excluding wide range of sparticle masses for different production mechanisms
  - CMSSM under tension, other ("simplified", "natural") models being explored
- Exotica results
  - A large variety of exotic models covered
- Summary: No signs for physics beyond the Standard Model!

Outlook



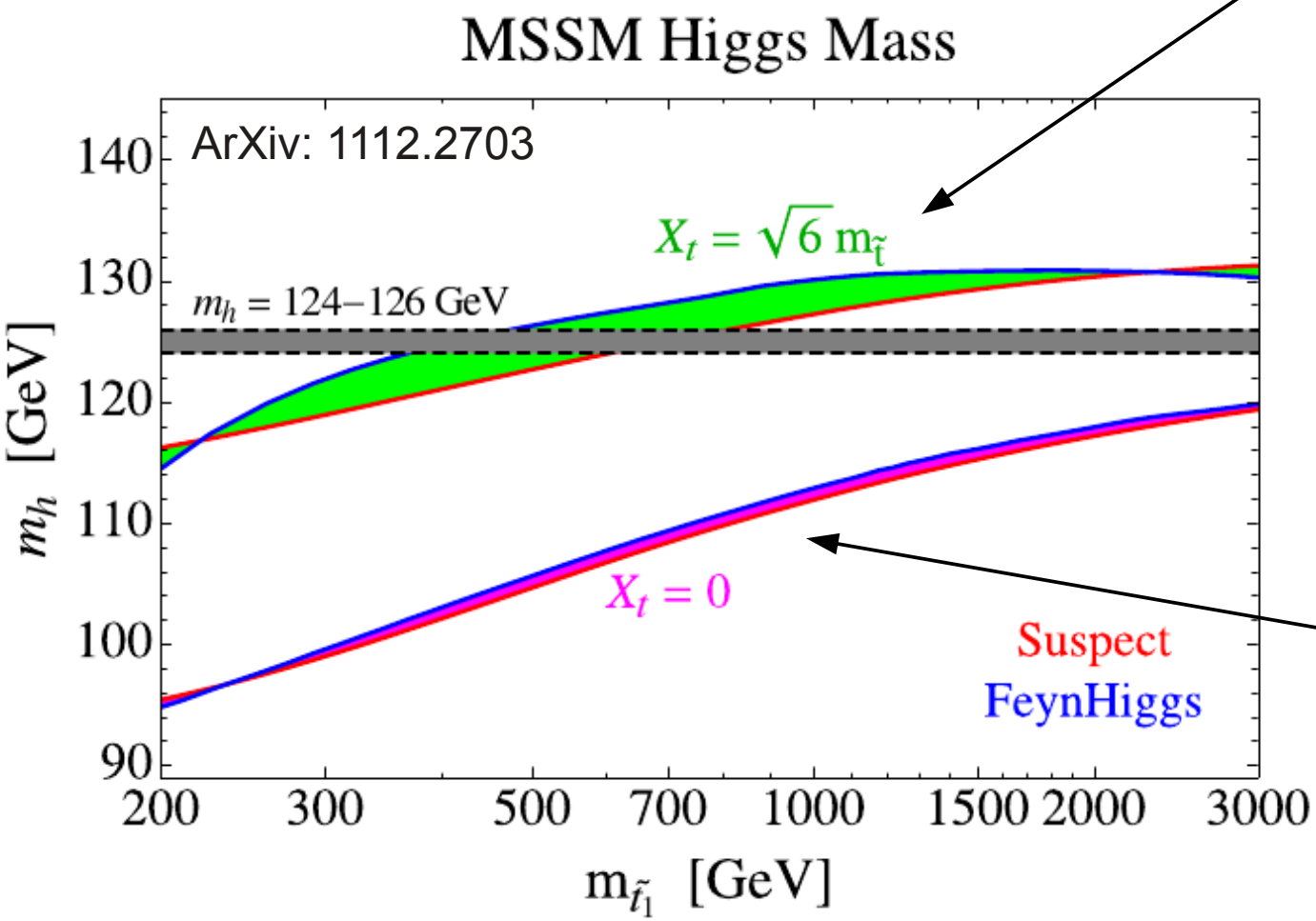
- Up to now, small parton luminosity at high masses
- Large discovery potential at our fingertips
  - 14 TeV
  - 300/fb

Thank you!

- For plots, notes, and additional information see
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoPublicResults
  http://lhcb.web.cern.ch/lhcb/Physics-Results/LHCb-Physics-Results.html

Supplementary information

Higgs mass in the MSSM



Maximal mixing

No mixing

SUSY models and Higgs mass