Constraints on new physics from the LHC

selected topics

Slava Krutelyov (UCSB>Texas A&M)
for ATLAS,CMS,LHCb Collaborations

BEAUTY 2013
Bologna, Italy

April 8, 2013

Outline

- Unanswered questions
- Direct and indirect contributions from new physics
- Supersymmetry, excited fermions and other resonances
- LHC and experiments: ATLAS, CMS, LHCb
- Beauty of the third generation
- B->μμ
- Highlights of searches for direct new particle production
- Natural SUSY

Unanswered questions

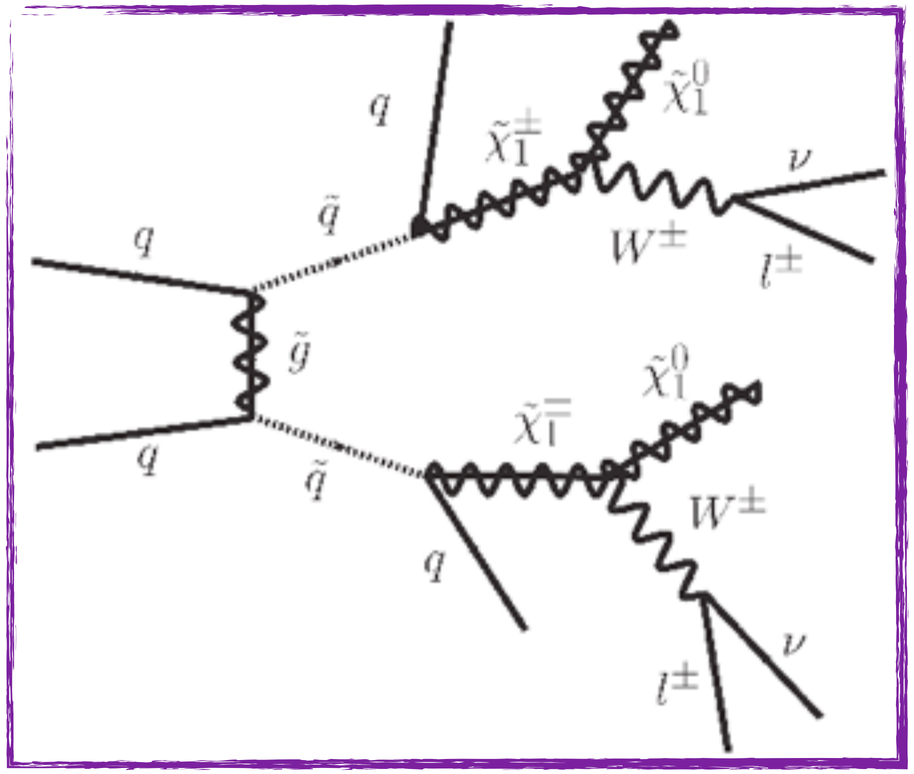
- Origins of various puzzles are not cleared by the Standard Model
  - ➡ Some may be within experimental (direct or indirect) grasp, some may be addressed by new theories (with observable predictions?)
    - ✓ baryogenesis and CP violation
    - ✓ dark energy
    - ✓ nature of inflation
    - ✓ dark matter
    - ✓ EWK symmetry breaking (is the SM Higgs enough?)
    - ✓ neutrino masses and mixing
    - ✓ fermion mass hierarchy
    - ✓ scale hierarchy (Higgs mass and fine tuning in going from "low-energy" to "Plank")
      - ⊙ The hierarchy problems may stay in "that's accidental" domain (dark energy too?)
  - ➡ Don't forget a coherent description of gravity with EWK+strong interactions
- Many different theories address these puzzles.
  - ➡ I pick supersymmetry more frequently in later slides
  - ➡ Not going into theoretical review here

Remarkable year

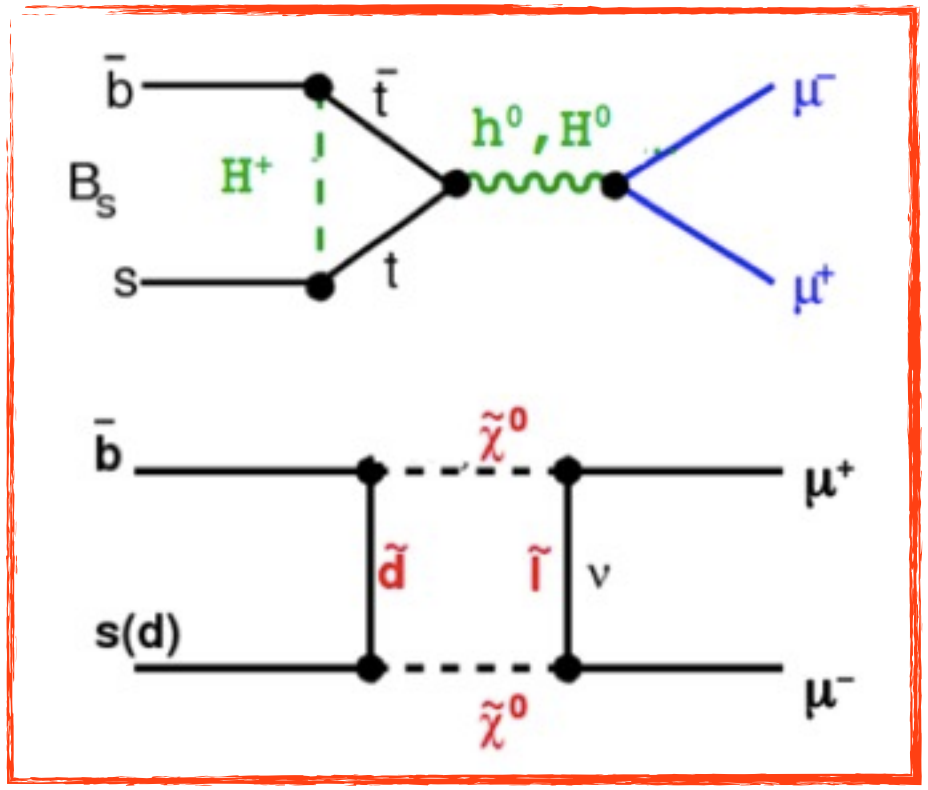
- We had a remarkable year, which brought HEP to the headlines
  - ➡ Collider experiments and cosmology
- Cosmology and astro-particle physics with stark advances, naming a few
  - ➡ South Pole Telescope and IceCube
  - ➡ Plank and AMS-2 satellites
- Collider experiments with the LHC in the lead at the energy frontier

Direct and virtual signs of NP

- Collider experiments deliver two ways of detecting new physics
  - ➡ Direct: NP particles are produced "on-shell"
  - ➡ Indirect/virtual: NP particles contribute virtually through loops or tree level
- BEAUTY13 conference program includes a great coverage of the latter
  - ➡ Signs of virtual contributions can be sensitive to NP "mass" far beyond reach of direct production in experiments
- This talk will give you (mostly) highlights on the direct production



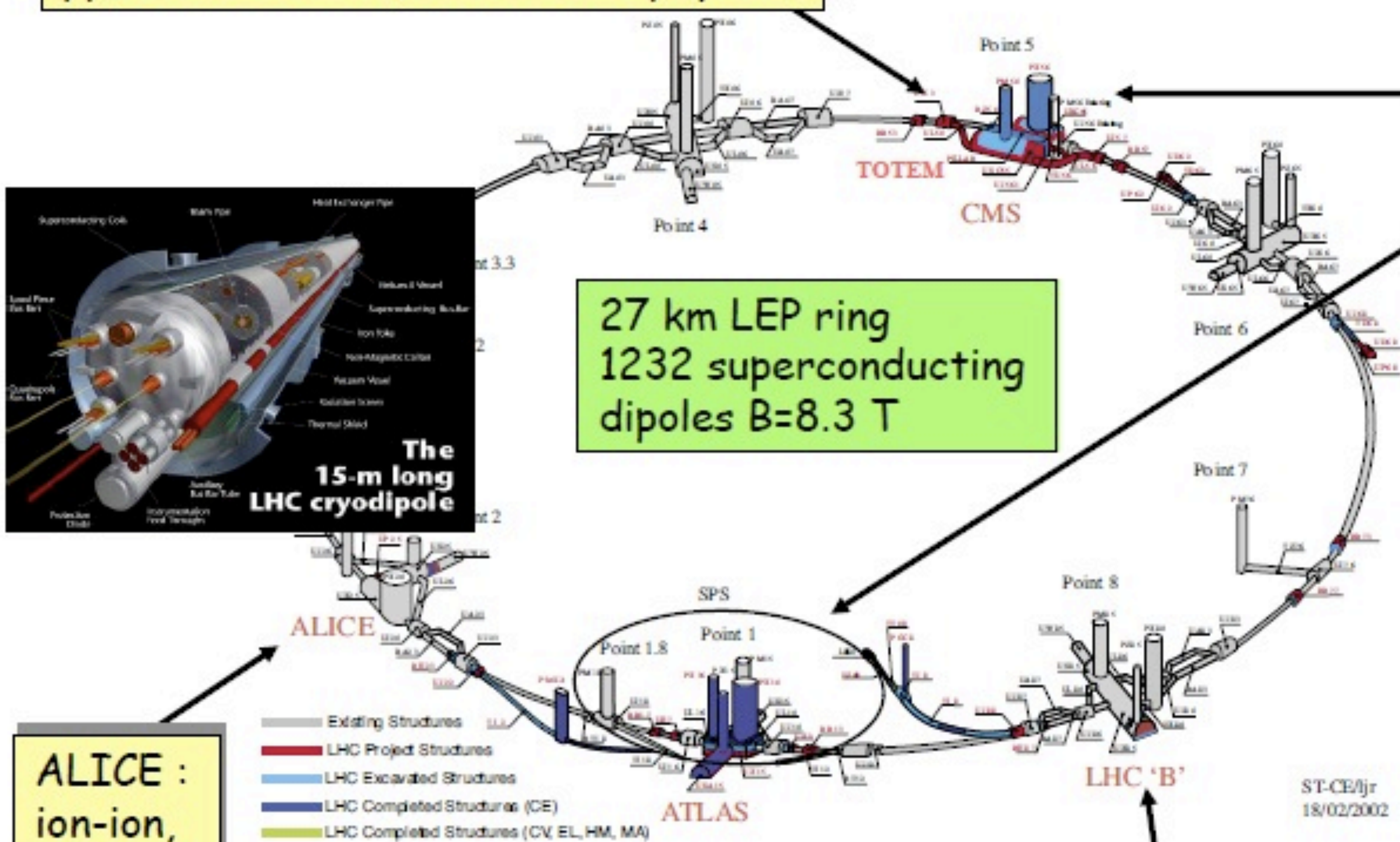
VS



LHC: the machine

TOTEM (integrated with CMS):
pp, cross-section, diffractive physics

ATLAS and CMS :
general purpose



27 km LEP ring
1232 superconducting
dipoles B=8.3 T

Design parameters:
pp collisions at $\sqrt{s}$ = 14 TeV
L = 10^{34} $cm^{-2}s^{-1}$ ≈ 100 fb^{-1}/year

"Run 1" operation parameters
- $\sqrt{s}$ = 8 TeV (2012), 7 TeV ('10-'11)
L(peak)= 7.6 x10^{33} $cm^{-2}s^{-1}$

ALICE :
ion-ion,
p-ion

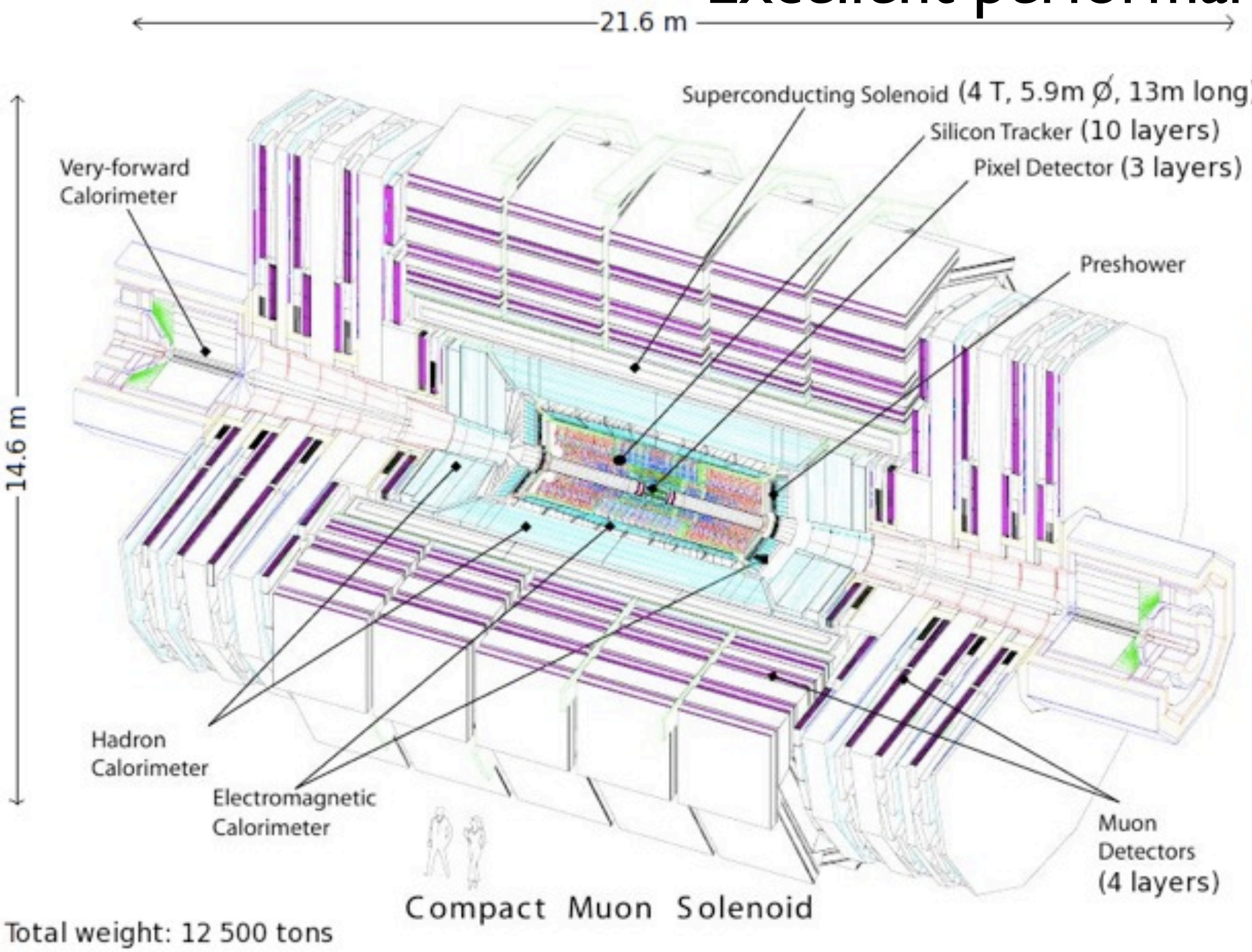
LHCb :
pp, B-physics, CP-violation

- Run 1 is over.
- Now time to upgrade to work at higher energy (13.5 TeV?) and make a new stride to discoveries in 2015 and beyond

CMS Detector: 2008 JINST 3 S08004

CMS Detector

Excellent performance from first days of collisions



Tracker: $\sigma/p_T \simeq 1.5\times10^{-4}\times p_T \oplus 0.005$

Muon standalone @ 1 TeV: $\sigma/p_T \simeq 0.10$

Electromagnetic energy resolution

$$\frac{\sigma(\mathrm{E})}{\mathrm{E}}=\frac{3\%}{\sqrt{\mathrm{E}}}+0.3\%$$

Hadronic energy resolution

$$\frac{\sigma(\mathrm{E})}{\mathrm{E}}=\frac{100\%}{\sqrt{\mathrm{E}}}+5\%$$

- Trigger system setup to reduce input rate of 40MHz down to 100-200 Hz
  - ✓ Hardware level-1 40MHz → 100 kHz followed by PC farm with near-final reconstruction resolution
  - ➡ No triggering on inner tracks at L1 (available only in a couple of years)
  - ➡ Final trigger stage can select muons, electrons, photons, jets, MET, displaced vertices

ATLAS detector

ATLAS

A Toroidal LHC Apparatus

Calorimetry $|\eta| < 4.9$

- **EMBC, EMEC** accordion LAr + Pb $|\eta|<3.2$
- **Tile** Hadronic Fe + scintillator $|\eta|<1.7$
- **HEC** Hadr end cap Cu+Lar $1.5<|\eta|<3.2$
- **FCAL** Forward calo Cu+W+Lar $3.1<|\eta|<4.9$

Muon spectrometer $|\eta| < 2.7$

High precision tracking

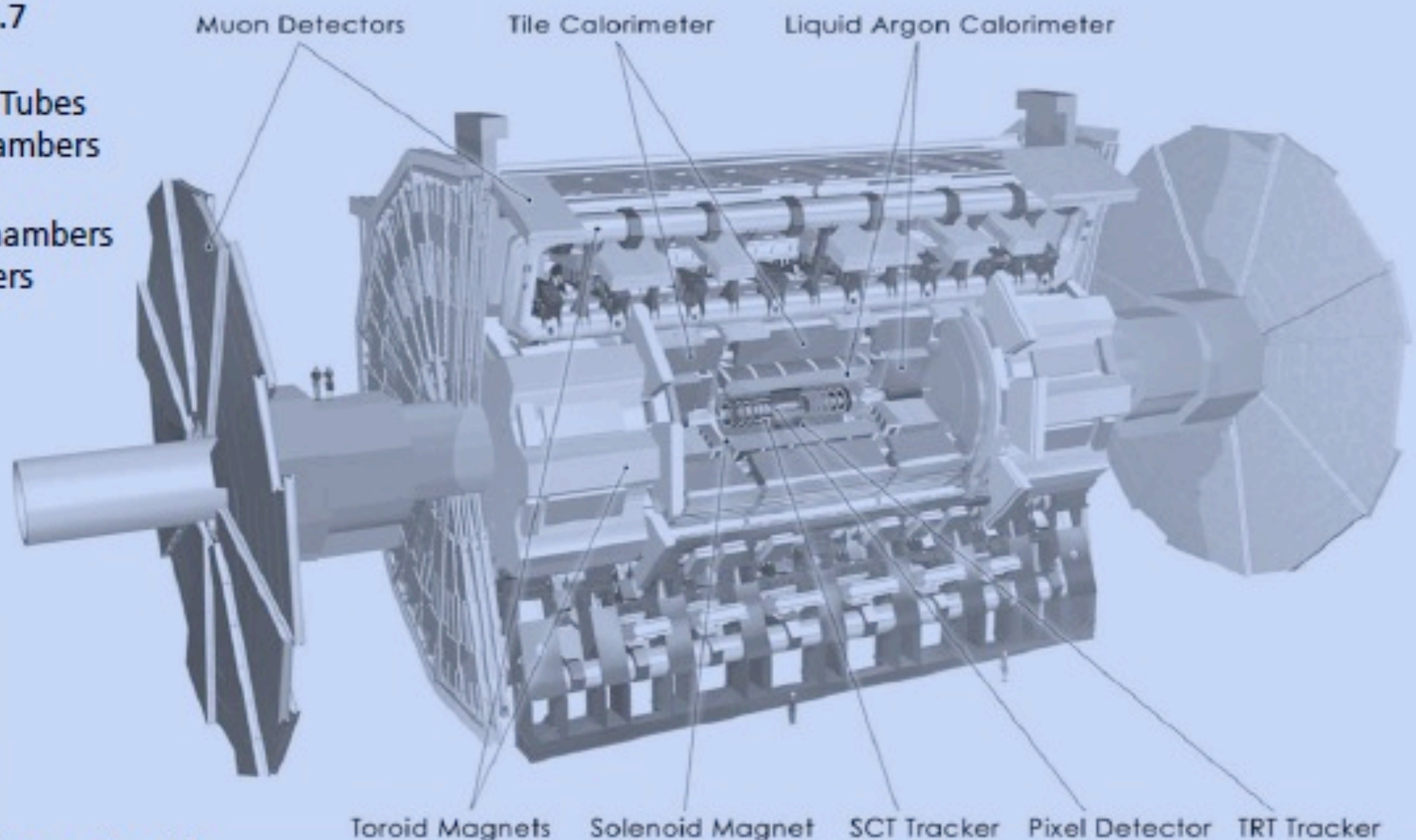
- **MDT** Monitored Drift Tubes
- **CSC** Cathode Strip Chambers

Trigger chambers

- **RPC** Resistive Plate Chambers
- **TGC** Thin Gap Chambers

Air core toroid system

→ strong bending power in large volume



Inner Detector

~6m long 1.1m radius inside 2T **Solenoid**

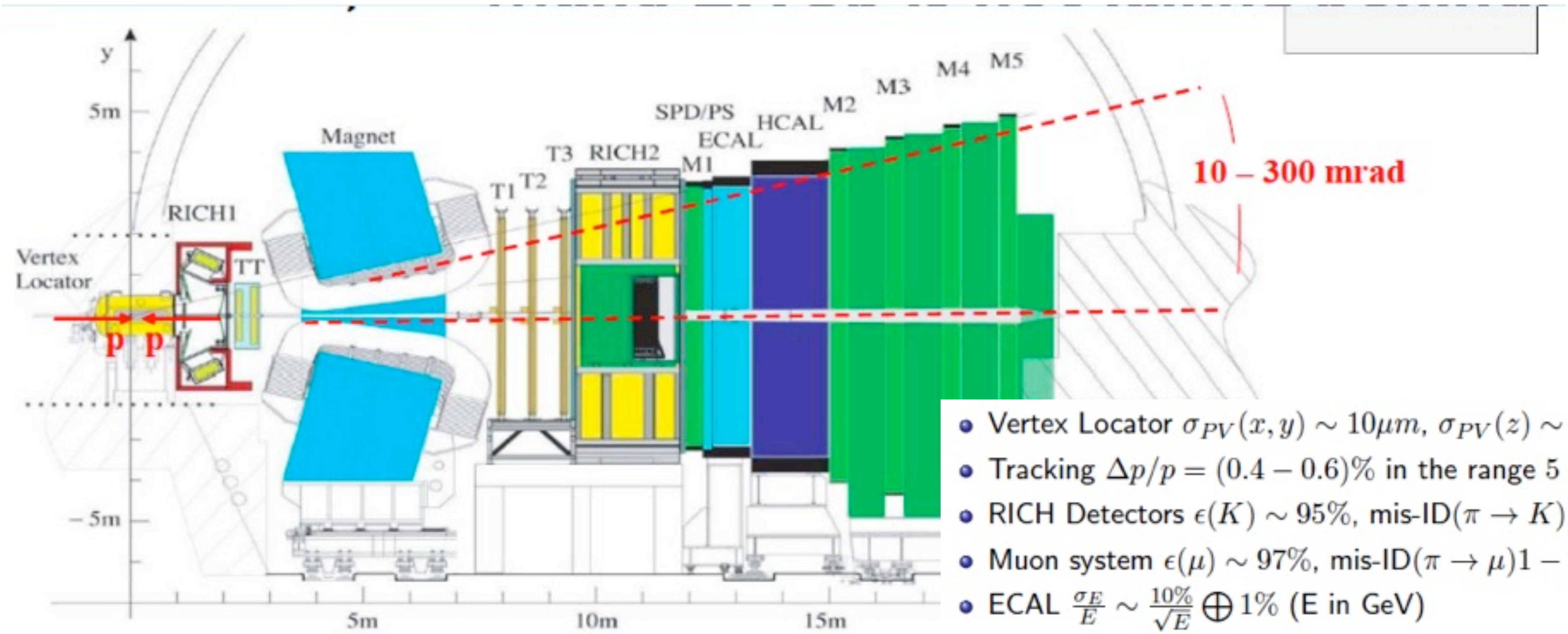
- **Pixels**
- **SCT** Silicon Strips
- **TRT** Transition Radiation Tracker e/π separation

3 trigger levels : L1, L2, Event Filter (L2+EF=HLT)

40 MHz → 200 Hz

24

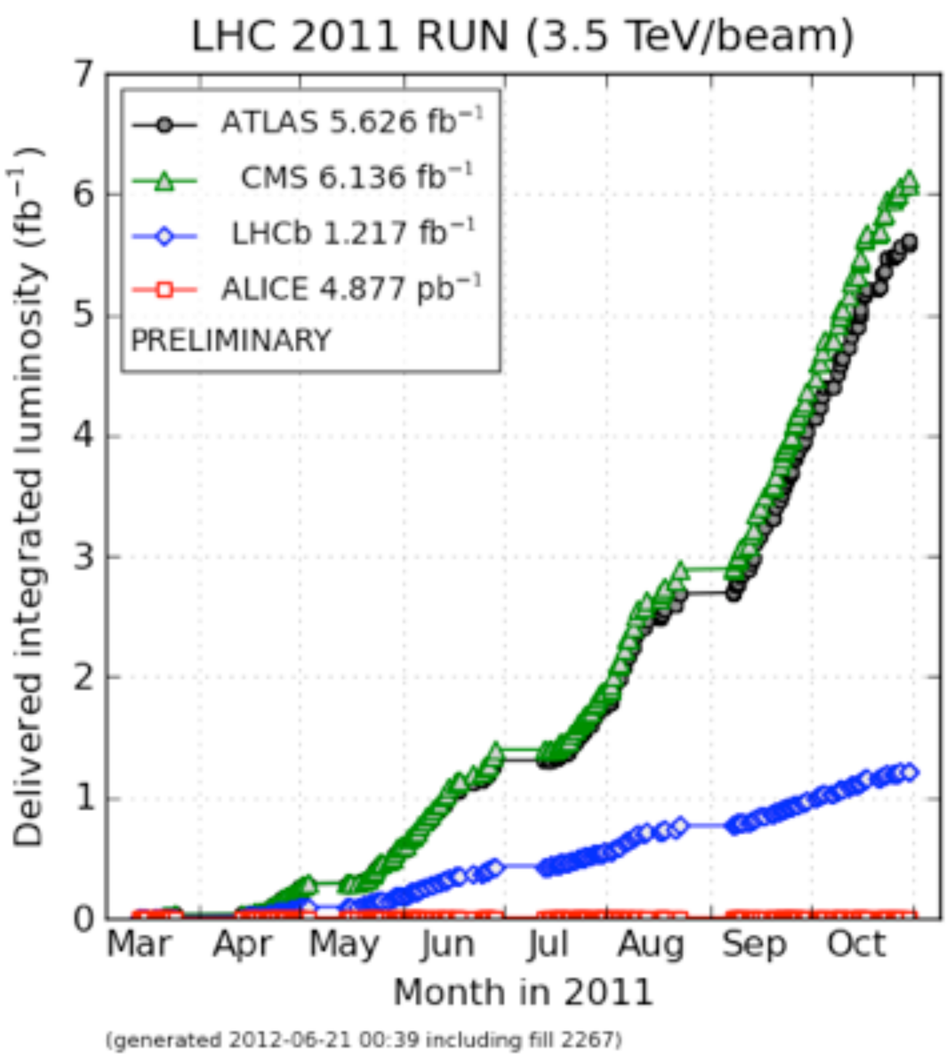
LHCb detector

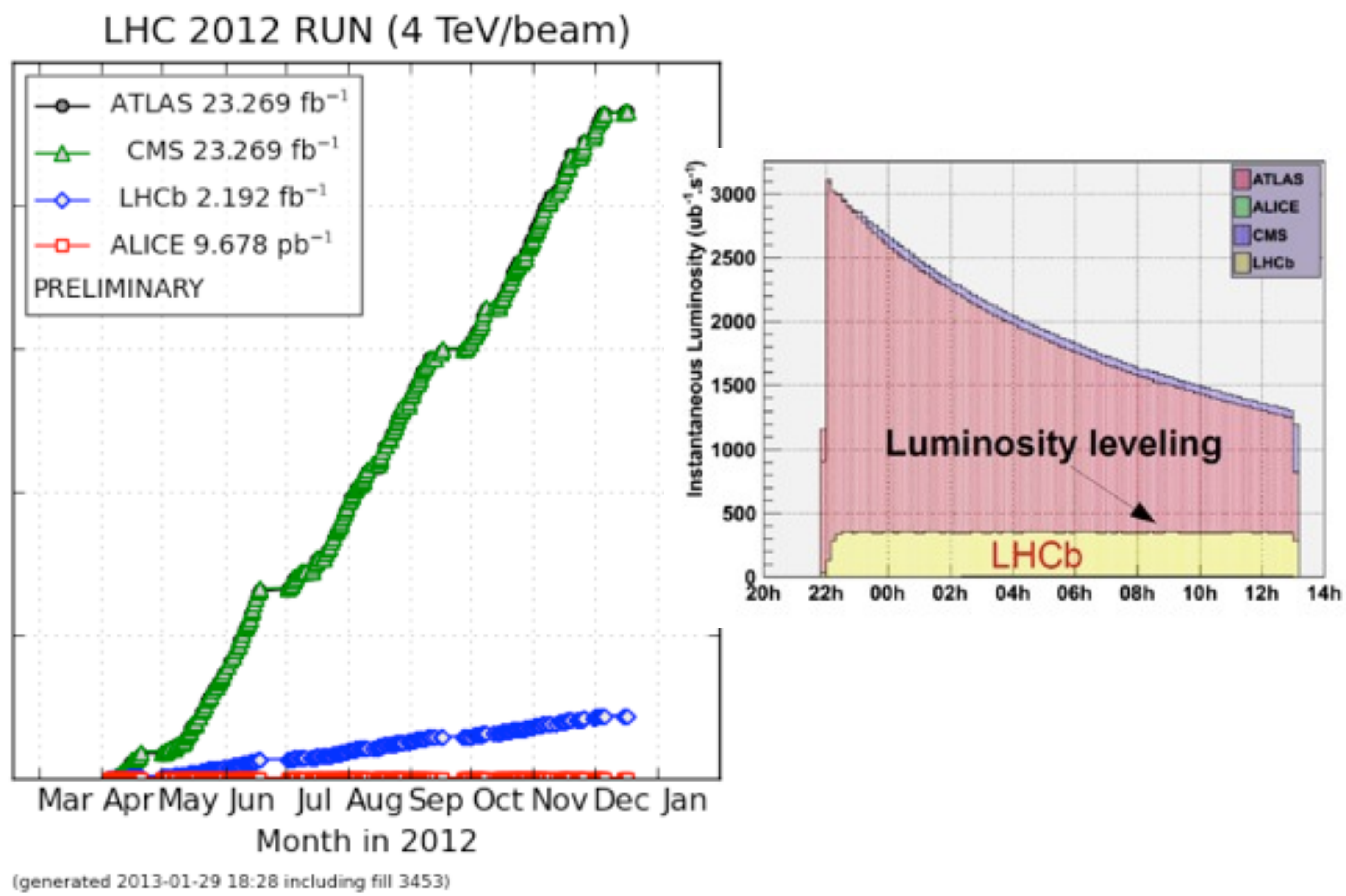


- Vertex Locator $\sigma_{PV}(x,y) \sim 10\mu m$, $\sigma_{PV}(z) \sim 60\mu m$
- Tracking $\Delta p/p = (0.4 - 0.6)\%$ in the range $5 - 100$GeV/c
- RICH Detectors $\epsilon(K) \sim 95\%$, mis-ID$(\pi \to K) \sim 5\%$
- Muon system $\epsilon(\mu) \sim 97\%$, mis-ID$(\pi \to \mu) 1 - 3\%$
- ECAL $\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E}} \bigoplus 1\%$ (E in GeV)
- HCAL $\frac{\sigma_E}{E} \sim \frac{70\%}{\sqrt{E}} \bigoplus 10\%$ (E in GeV)

- Different geometry, fitting well the purpose of observing boosted/displaced b-hadrons and alike
- Two-level triggering system selecting up to 1MHz at L0 for a final rate from HLT of up to 5 kHz

LHC: delivered data



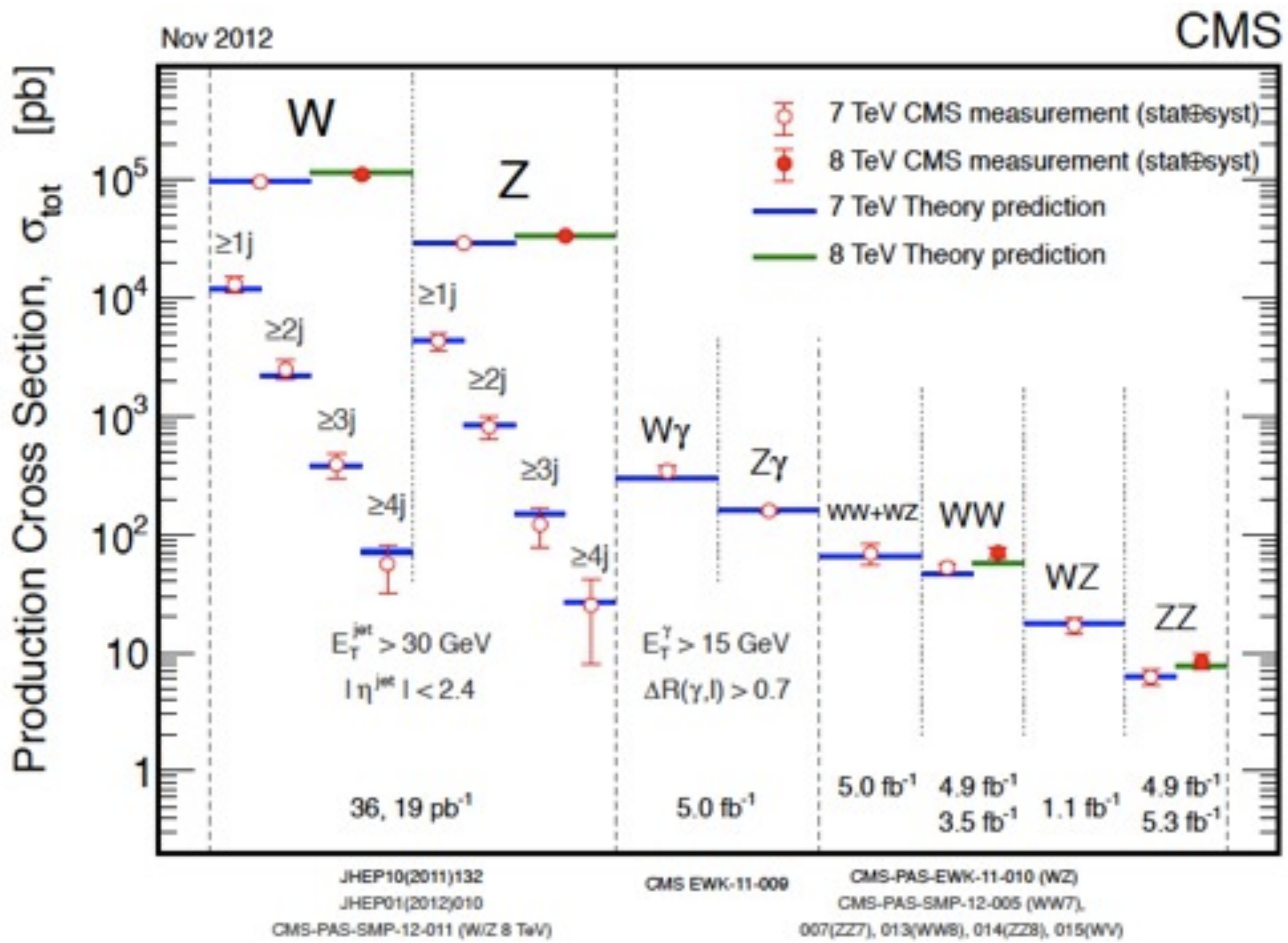


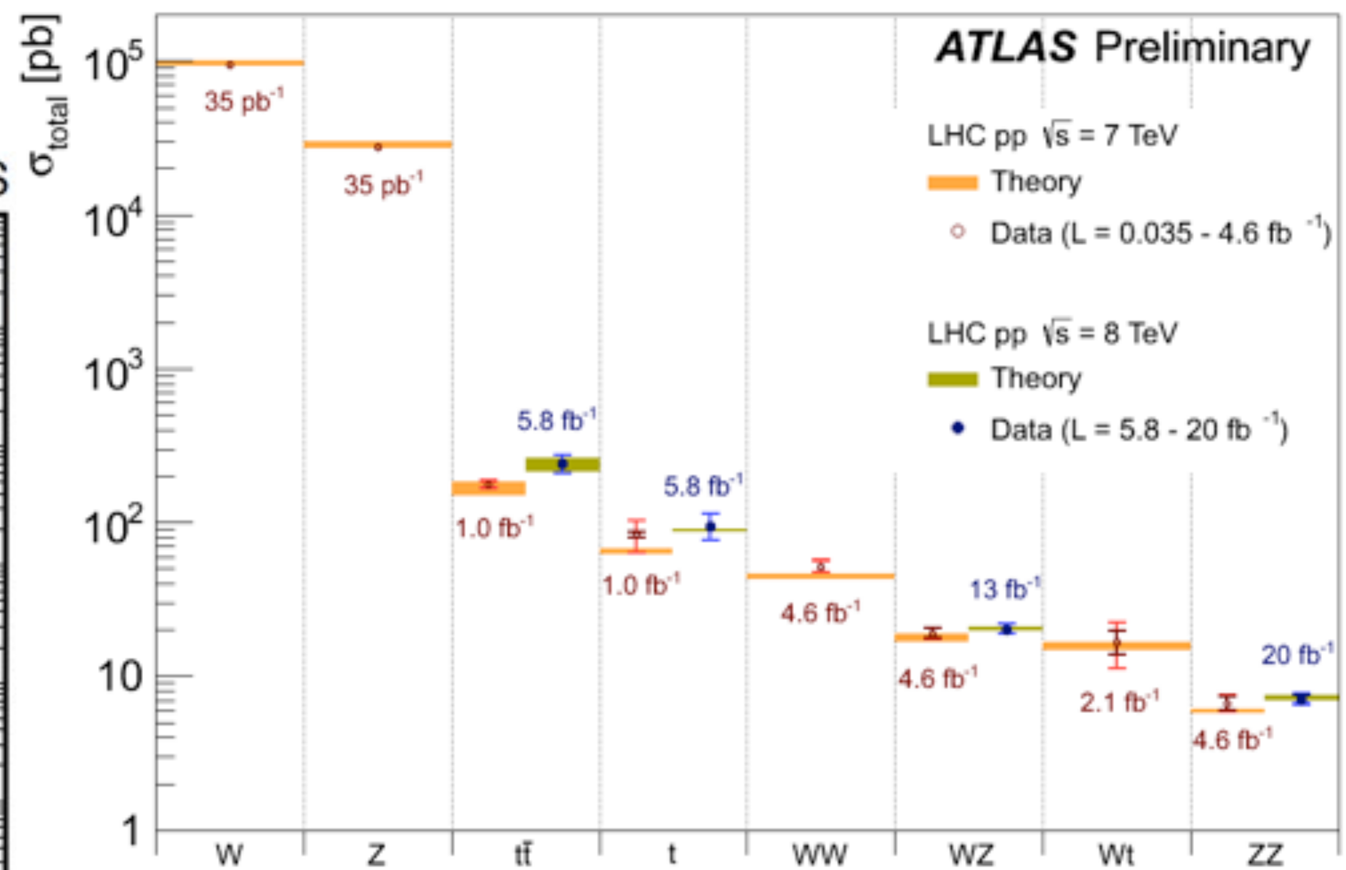
- Counting just pp collision program:
  - ✓ about 25 fb^{-1} (20@8TeV +5@7TeV) to ATLAS and CMS
  - ✓ about 3 fb^{-1} (2@8TeV + 1@7TeV) for LHCb

Highlights of work by experiments

- Many physics results are being reported by ATLAS, CMS, LHCb
  - ✓ Full available data has been analyzed in many cases. Most publications with full dataset are in preparation.
- Physics program is reflected in publications (over 100 each)
  - ✓ https://cds.cern.ch/ submitted papers by Apr 5, 2013: 103 LHCb, 263 CMS, 249 ATLAS
  - ➡ Balance by area is similar in ATLAS and CMS. LHCb clearly dominates heavy flavor hadron research topics.
  - ✓ SM Higgs-related topics: about 20 papers each from ATLAS/CMS
    - Probably the largest impact, especially in public
  - ✓ B/c-physics related: under 10% ATLAS/CMS, and over 90% at LHCb
  - ✓ SM W/Z/gamma/jets/top: about 20% ATLAS/CMS, several in LHCb
  - ✓ BSM searches, direct production: about 40% in ATLAS/CMS
- Broad program in searches for physics beyond Standard Model with new particles in the final state or other high-mass phenomena
  - ✓ SUSY, resonances (Z'/W', H, RS/KK), excited fermions, leptoquarks, long-lived particles ...
  - ➡ I focus mostly on these topics here, will pick just one from B-physics

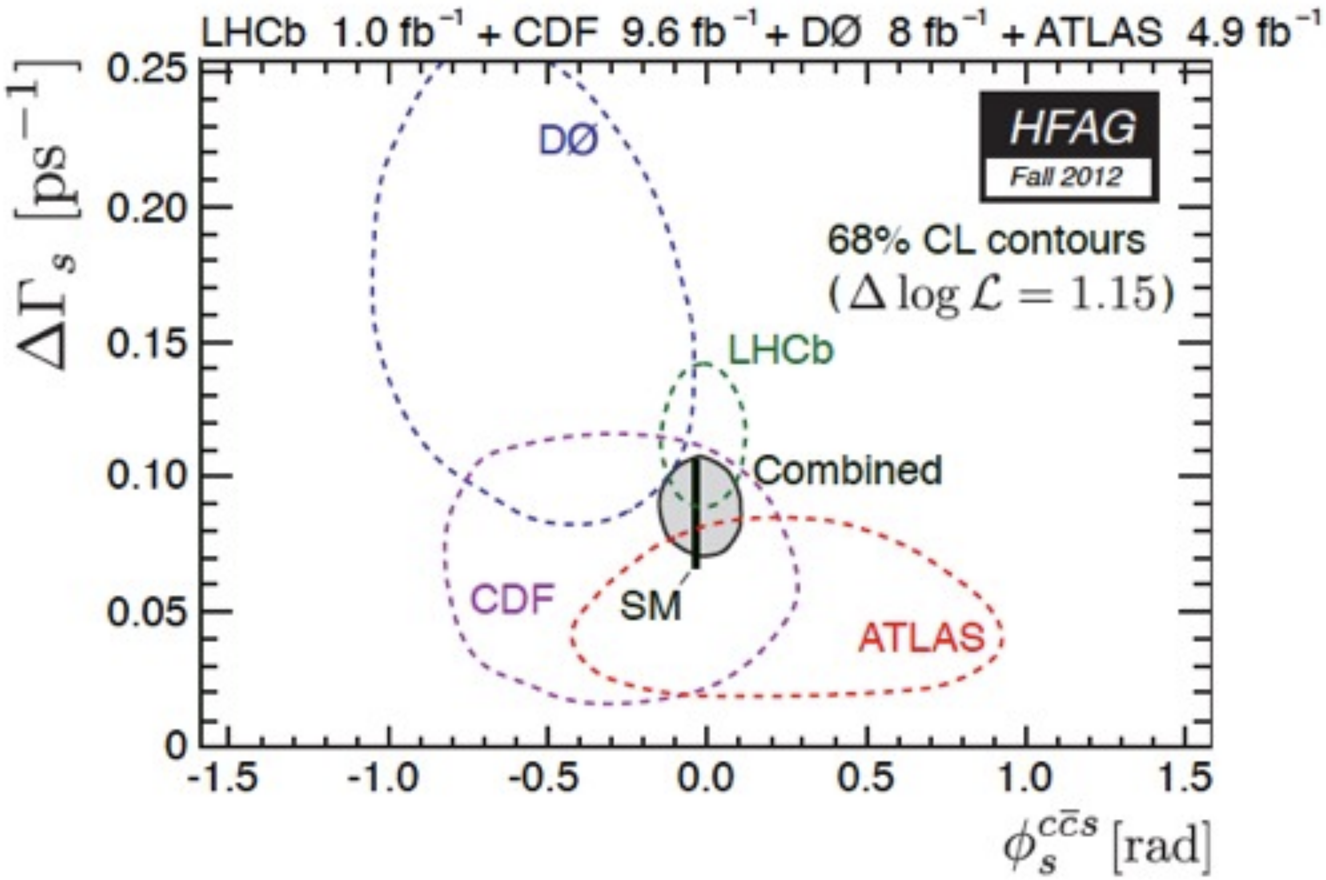
The SM is alive and well



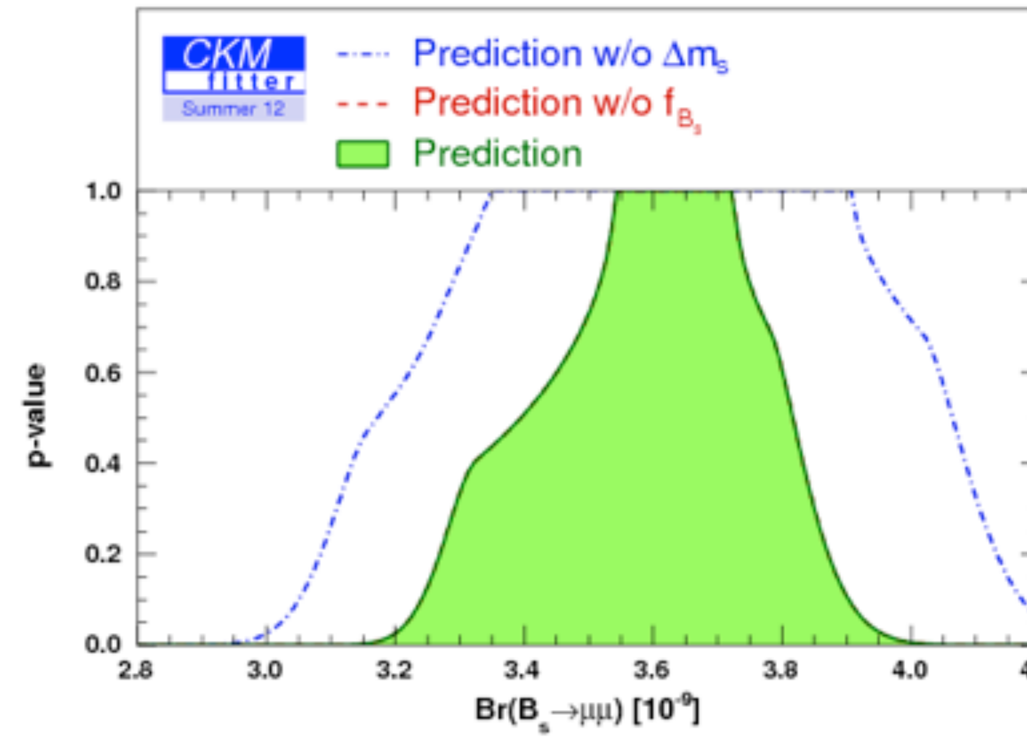


- A crucial step to a successful search beyond the Standard Model is understanding of the SM itself.
  - ➡ Spectacular agreement overall (If all we had was the LHC data ...)

The SM is alive and well



See session on Friday for updates …



LHCb

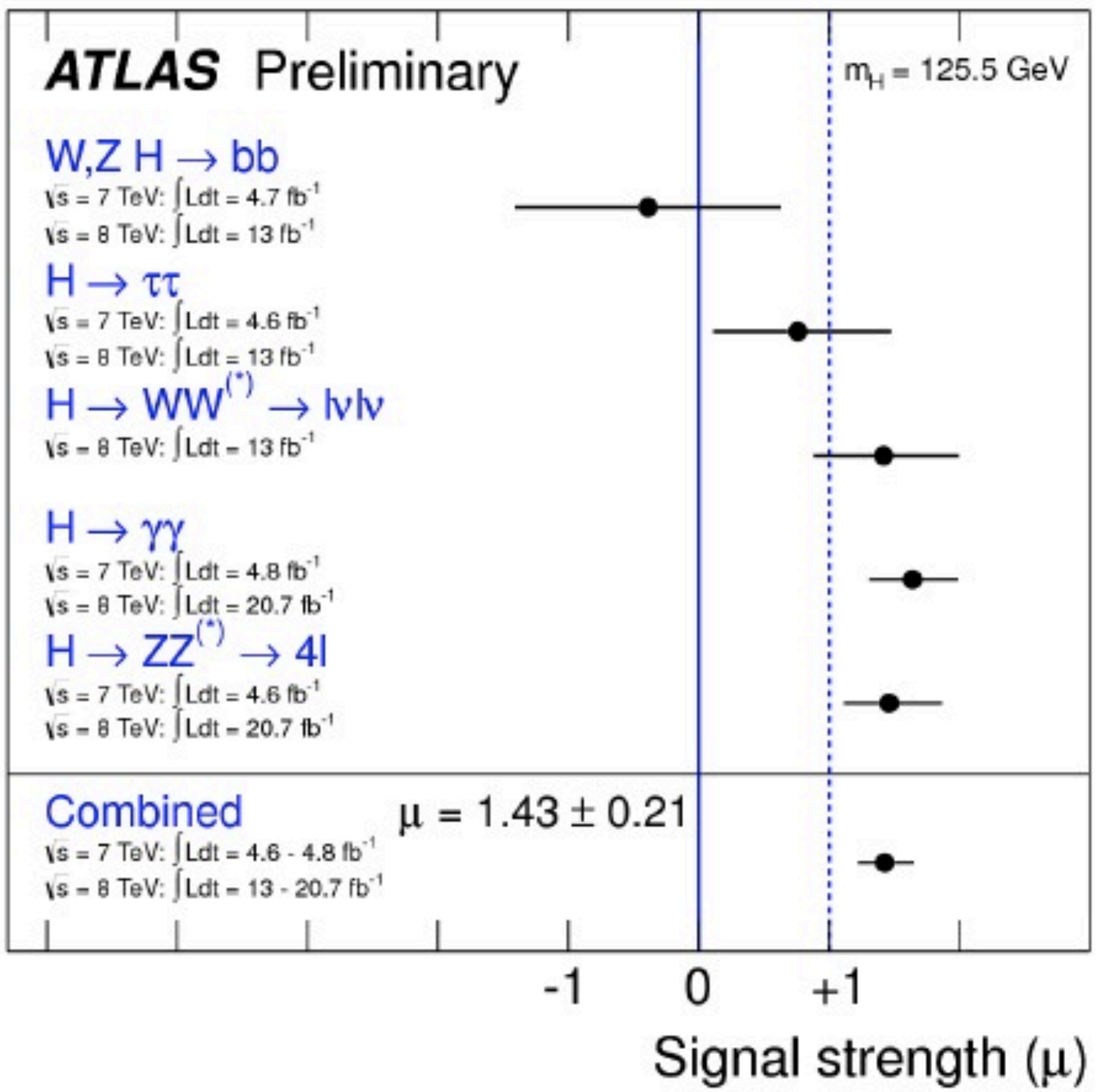
$BR(B_s^0 \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}(\text{stat.}) \pm 0.2(\text{syst.})) \times 10^{-9}$

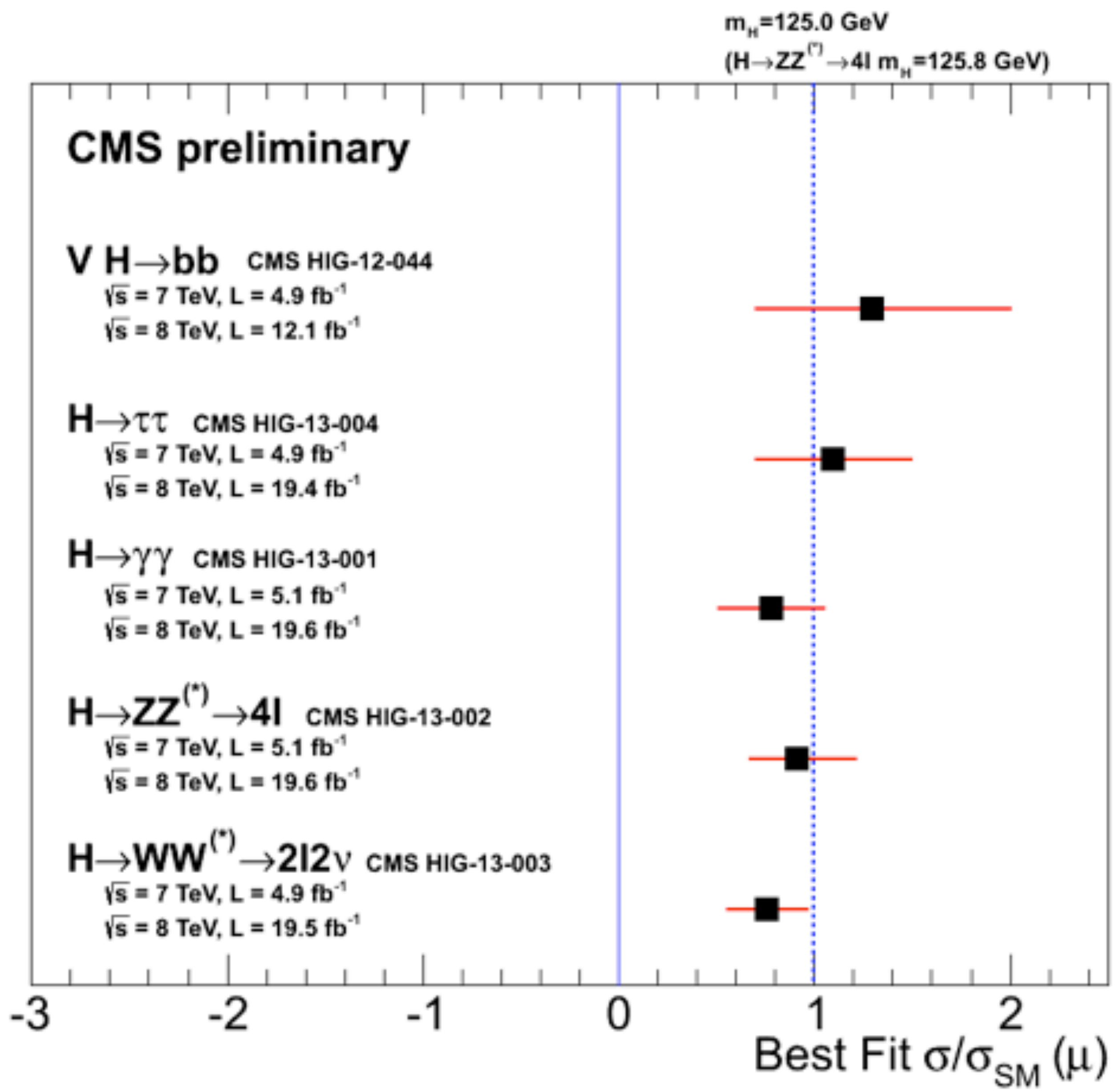
Probability of background-only fluctuations: 5×10^{-4} ⇔ 3.5 σ **(first evidence!)**

See session on Tuesday for updates …

- More, many more B-physics results later in the conference schedule

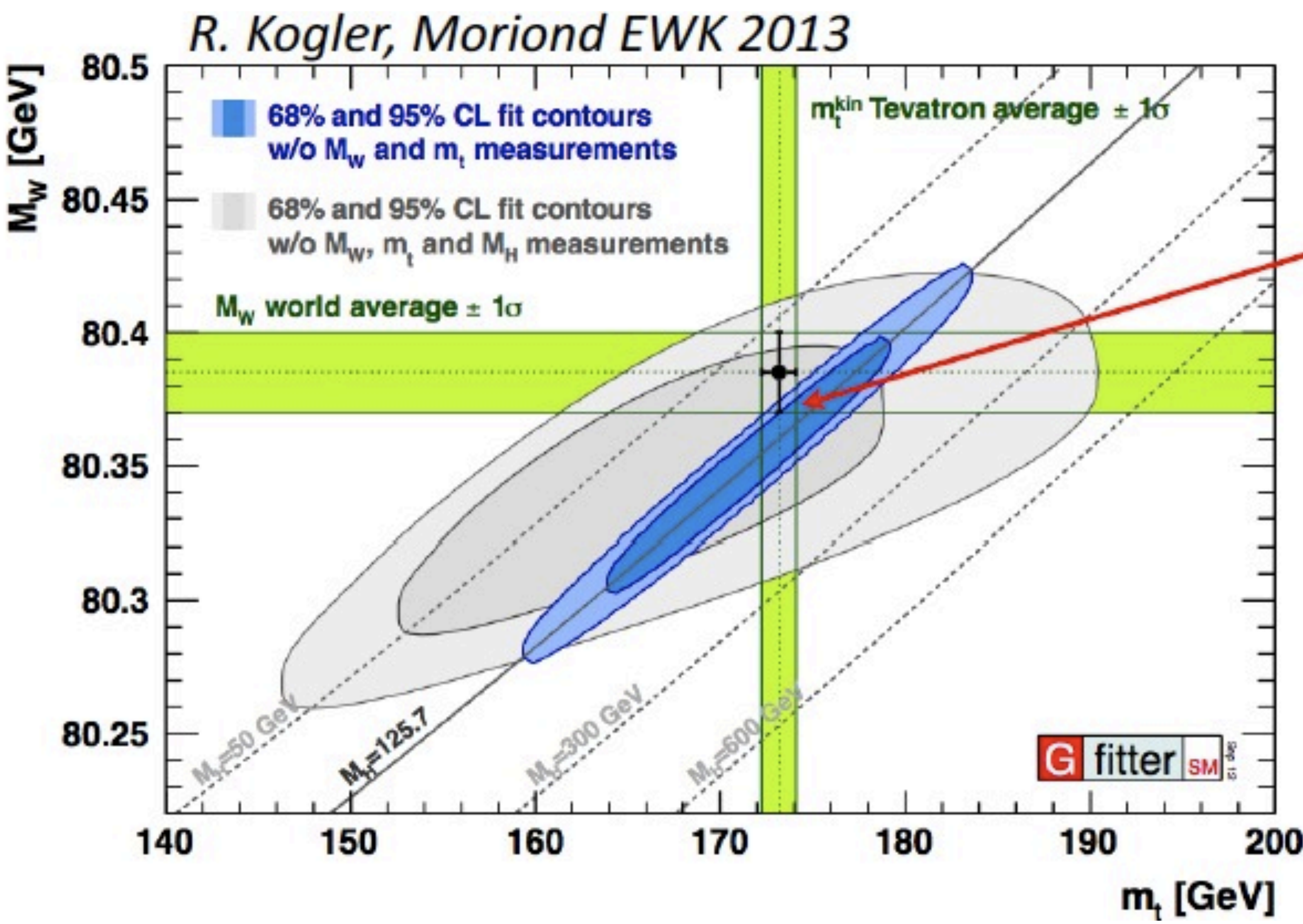
The SM is alive and well





- More on the Higgs boson in the previous talk

The SM is alive and well



Once M_H is fixed, we cornered the SM!

Effects of new physics through loop corrections!

⇒ improve measurements of EW precision observables

- EW precision measurements in the next talk

Beauty of the third generation

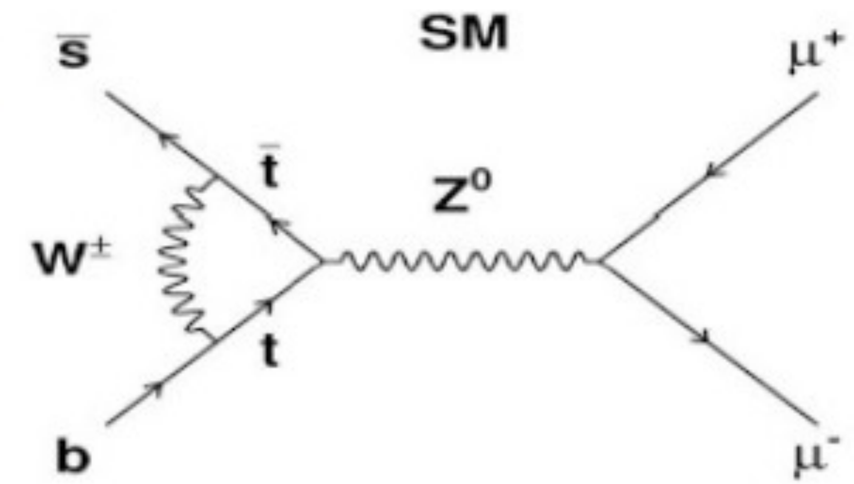
- Studies of processes with b- and t-quarks provide some of the deepest connections across experimental and theoretical HEP

- b-hadron physics, the theme of this conference, has the t-quarks of big importance considering the large value of V_{tb}
  - ✓ b and t go hand in hand in many processes
- t (and b) play vital role in the NP model building due to large mass (large Yukawa couplings)
  - ✓ Higgs production, SUSY "naturalness", FCNC processes just to pick from the popular topics
- Final states with top quarks are very reach in possible final state signatures: isolated leptons, neutrinos, jets, b-jets in the final states; become more interesting in associated production
  - ✓ Demands high quality of detector performance
  - ✓ Allows to support findings by combining different modes
  - ✓ Gives a wide field of new experimental methods and techniques

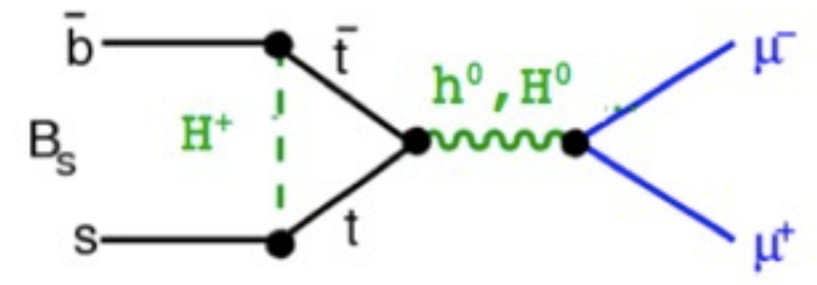
B_s->μμ: search turning SM measurement

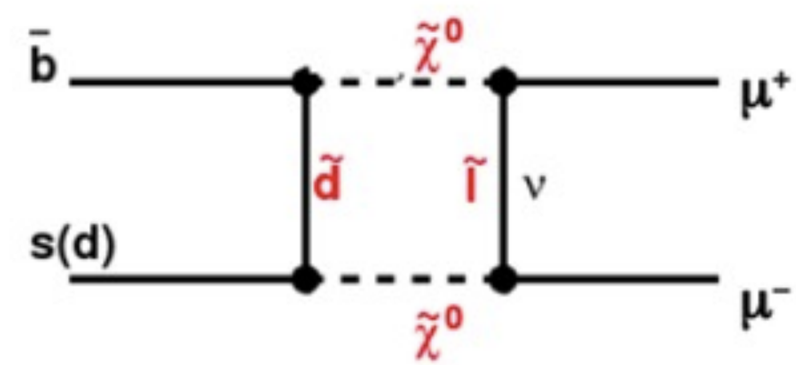
Mode	SM
$B_s \to \mu^+\mu^-$, time averaged	$(3.54 \pm 0.30) \times 10^{-9}$
$B^0 \to \mu^+\mu^-$	$(0.107 \pm 0.01) \times 10^{-9}$

Buras, Isidori: arXiv:1208.0934
De Bruyn, et al [1204.1737] uses LHCb-CONF-2012-002



- Can be enhanced in many models
  - ✓ *Suppression possible too*
  - ➡ 2HDM has $\tan^4\beta$ dependence
  - ➡ SUSY has $\tan^6\beta$ dependence
    - ✓ *This makes it very popular for SUSY model building*
    - ✓ *Many parameters are still at play in SUSY*
      - ◉ this can easily wash away the enhancement



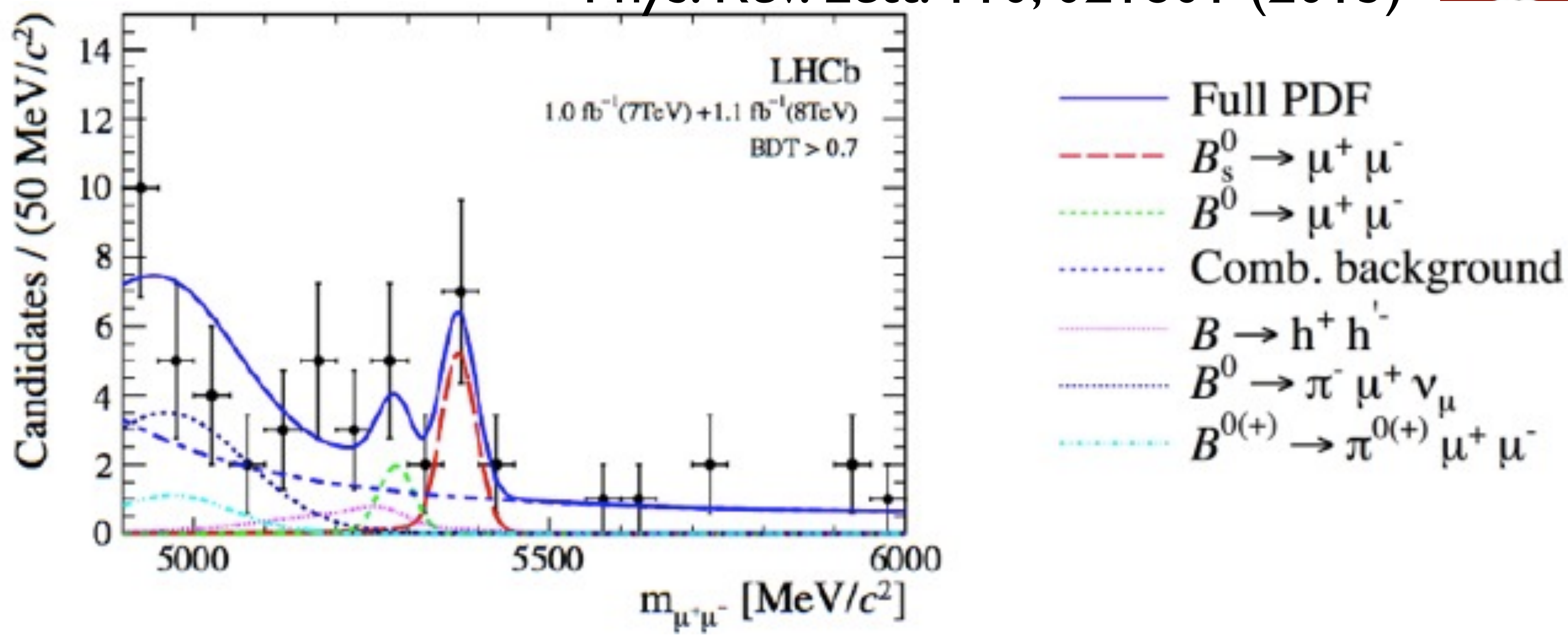


- History of 25 years searching for this mode is now at its closing chapter

B_s->μμ: search turning SM measurement

Phys. Rev. Lett. 110, 021801 (2013)

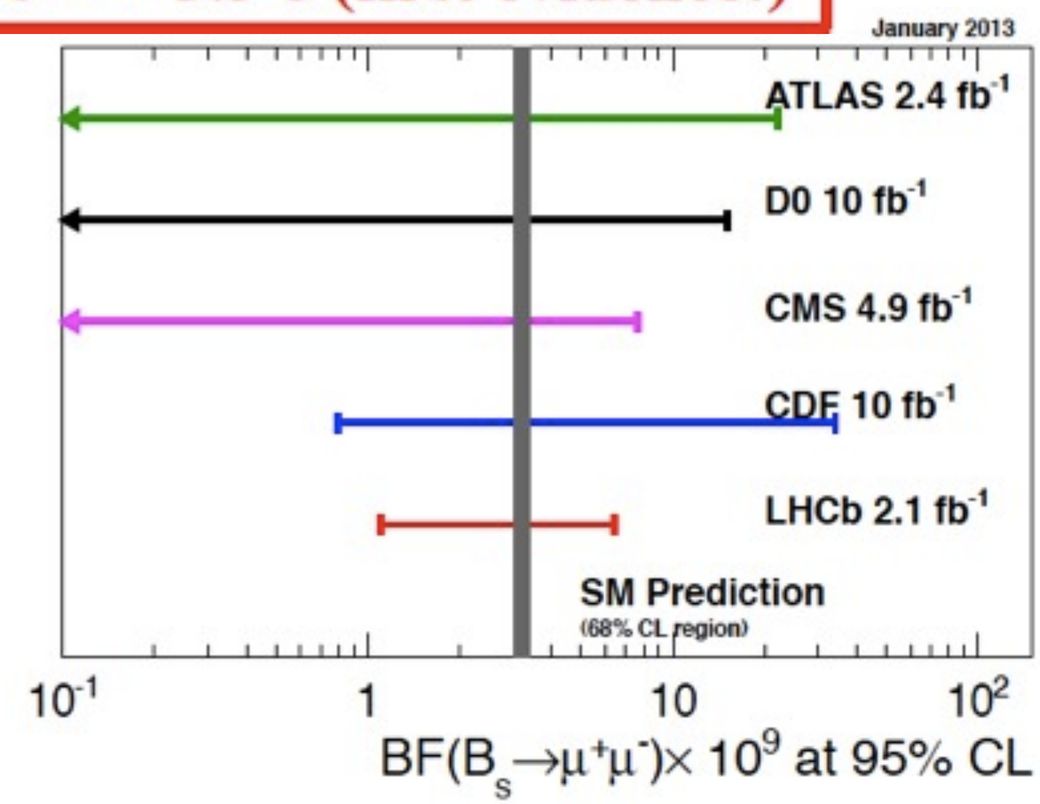
- LHCb:
  - ➡ use BDT to select signal
  - ➡ fit in mass as well
  - ➡ calibrate BDT with B->hh



$$BR(B_s^0 \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}(\text{stat.}) \pm 0.2(\text{syst.})) \times 10^{-9}$$

Probability of background-only fluctuations: 5×10^{-4} ⇔ 3.5 σ **(first evidence!)**

- LHCb is not the leader in this mode
  - ➡ first evidence in Nov '12
  - ➡ In agreement with SM
- Talks from ATLAS/CMS/LHCb tomorrow



On to the new physics constraints

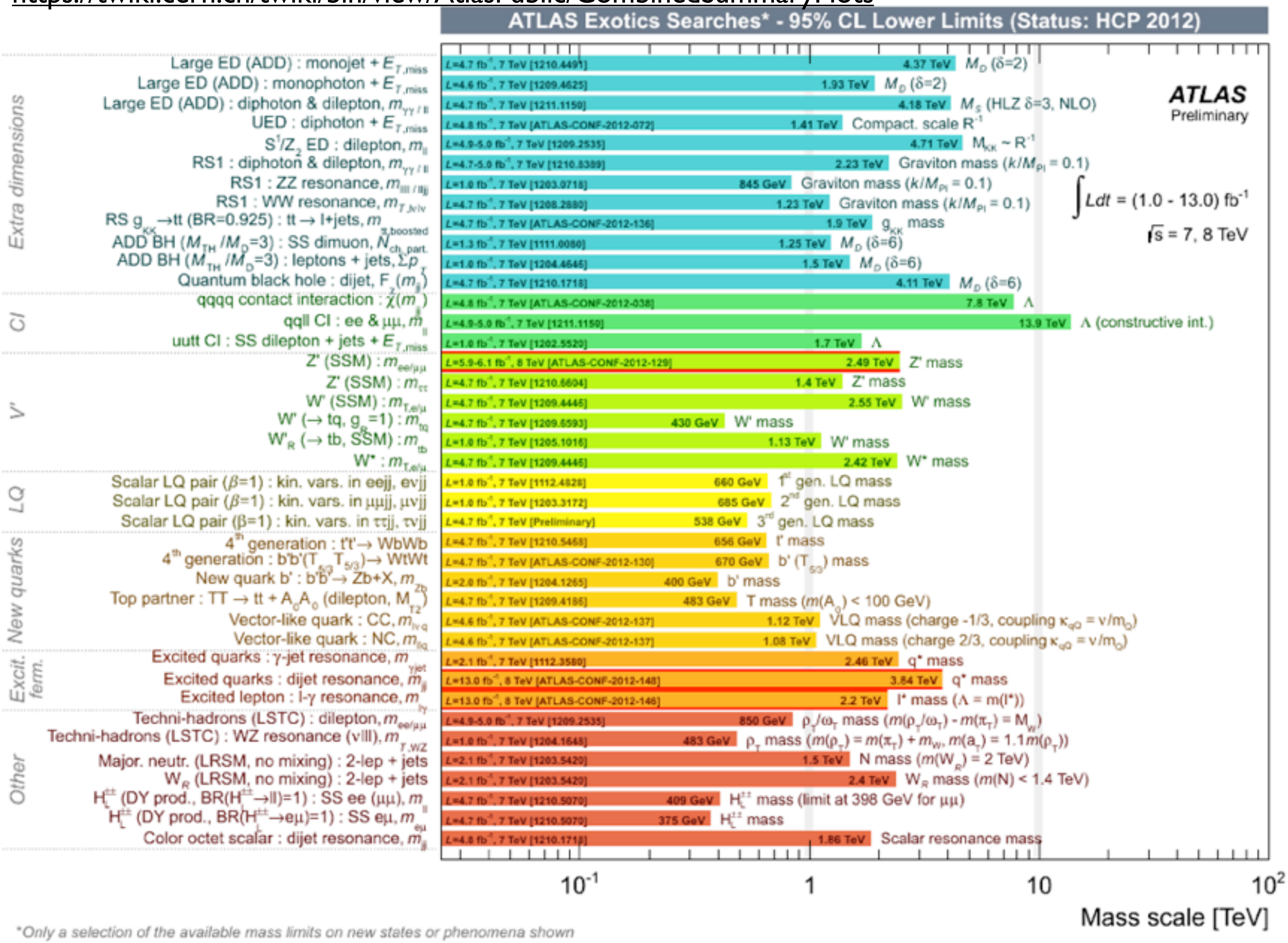
- Following slides summarize searches for NP by ATLAS and CMS
- Not surprisingly, reach for similar/same models is similar
  - ✓ Mileage varies, but not dramatically
- High-mass reach depends on the couplings in the model
  - contact interaction and alike extend to 10 TeV
  - weakly coupled bosons at 1-2 TeV

➡ Flavor or other symmetries may force pair production ==> lower m in reach

  - SUSY searches are in this category

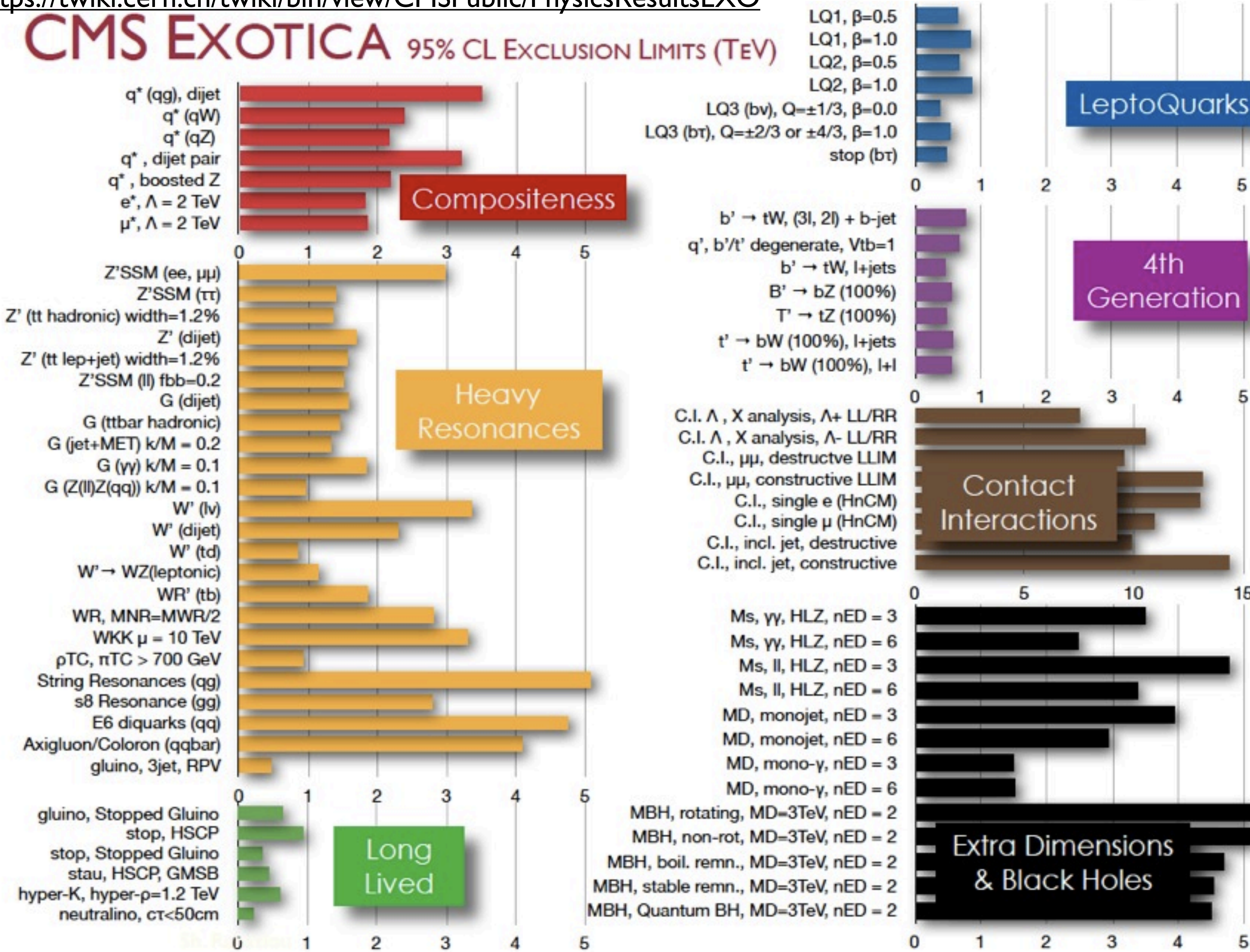
NP limits: bird eye view (nonSUSY)

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



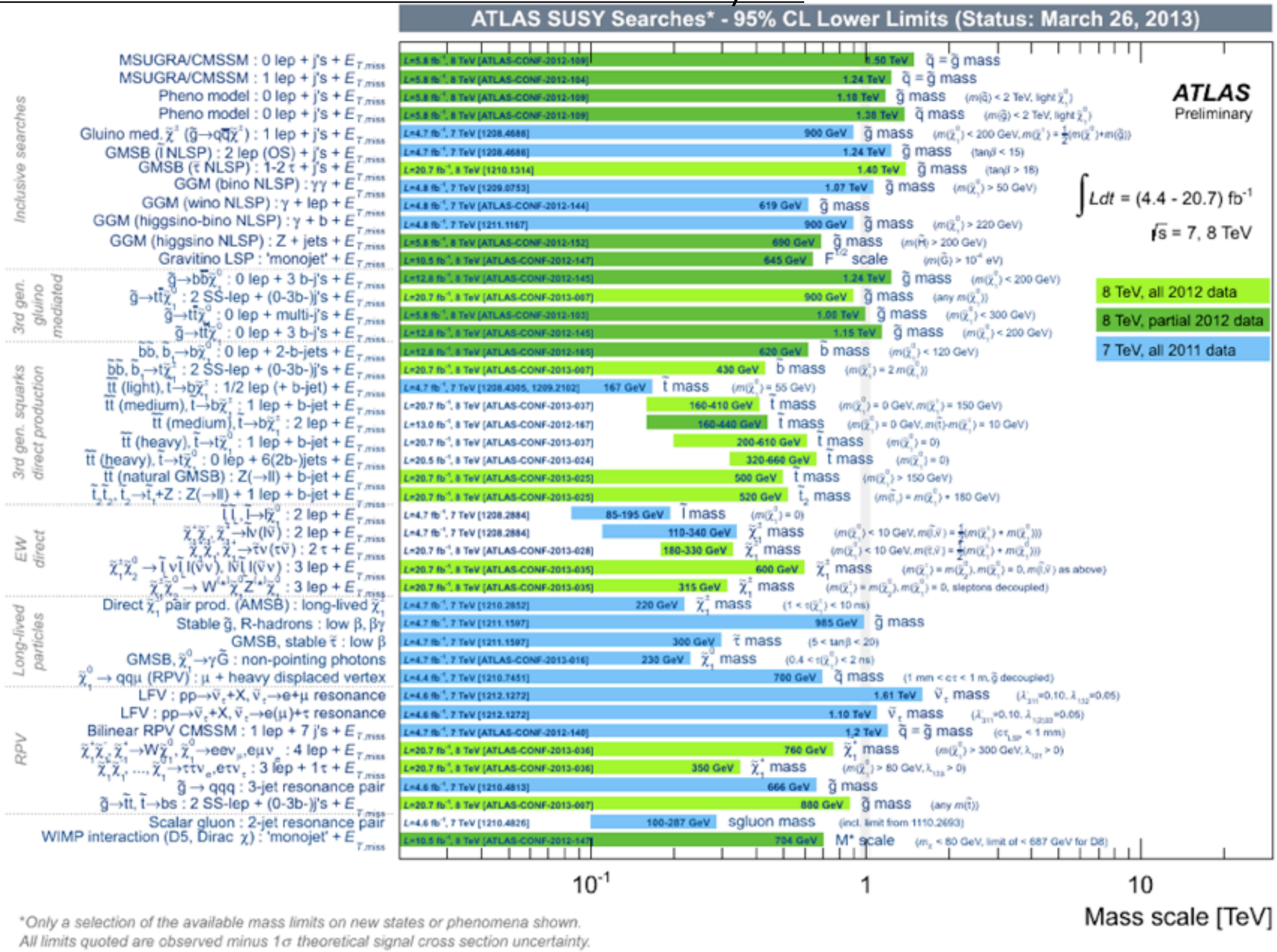
NP limits: bird eye view (nonSUSY)

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



NP limits: bird eye view (SUSY)

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



SUSY

- SUSY: brought to you from a simple extension of Poincare group
  - ✓ connect bosons and fermions
  - ✓ everyone gets a partner

$$\{Q_\alpha, \bar{Q}_{\dot{\beta}}\} = 2(\sigma^\mu)_{\alpha\dot{\beta}} P_\mu$$

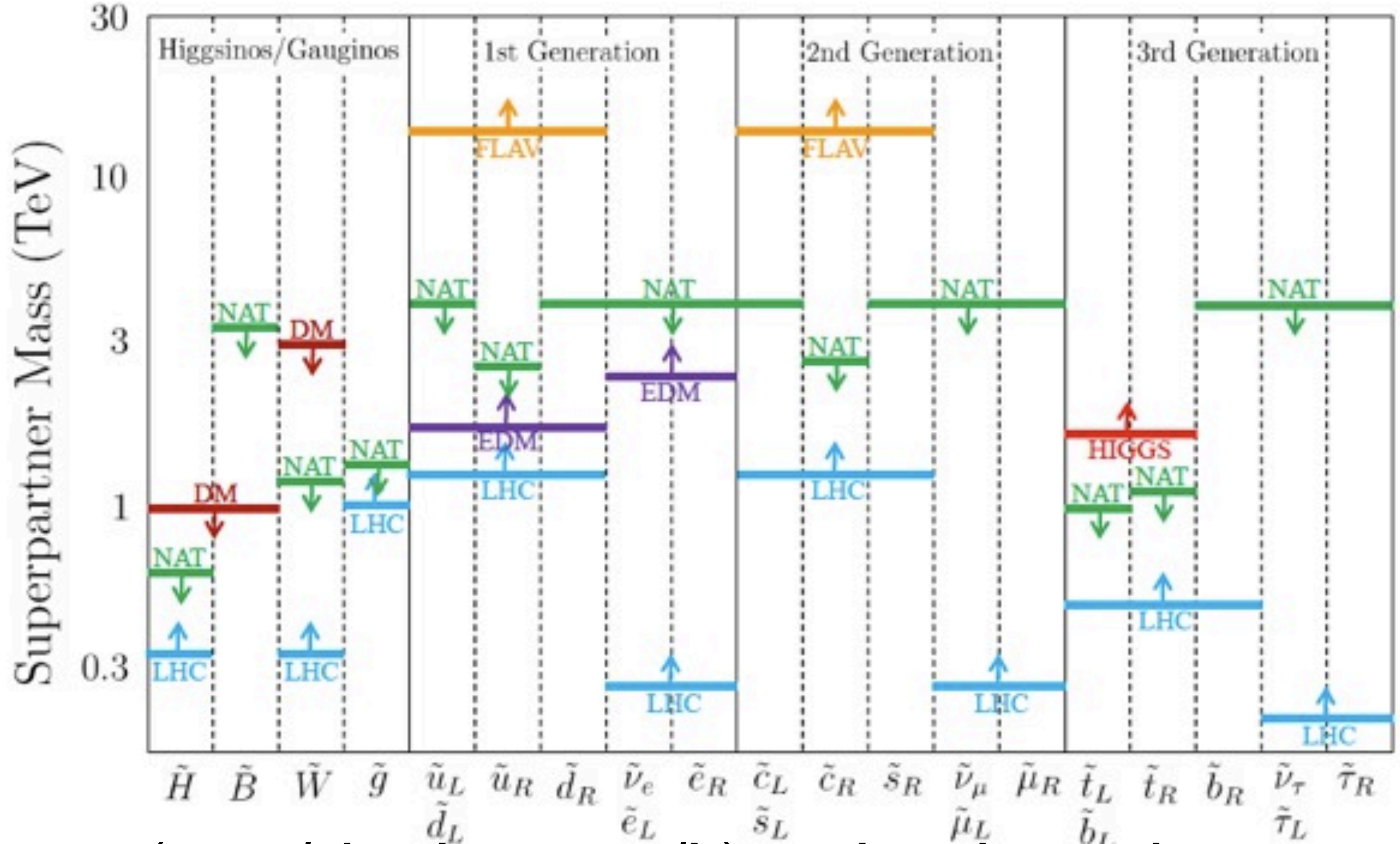
- This immediately makes it attractive to extend SM
  - ✓ Higgs mass corrections become logarithmic and allow running to Plank energies without much fine-tuning
  - ✓ R-parity conservation gives a nice dark matter candidate
  - ✓ Points to a grand unification of EWK and QCD
  - ✓ works well (even required) in string theories
  - ✓ ...

- Sadly, it's badly broken and generic (pheno) fixes open a Pandora box of parameters and require assumptions on how to break it

- While searches for SUSY were a large part of HEP program, it still remains around the corner

SUSY and naturalness

- Higgs mass in SUSY connects t-quark and 3rd generation masses
  - Recall that it would be mZ ~ mH without loop corrections
  - ➡ Once you restrict fine-tuning, the masses of the stops can't be large
    - ✓ this eventually drags gluino and electroweakino masses to "could be" naturally low

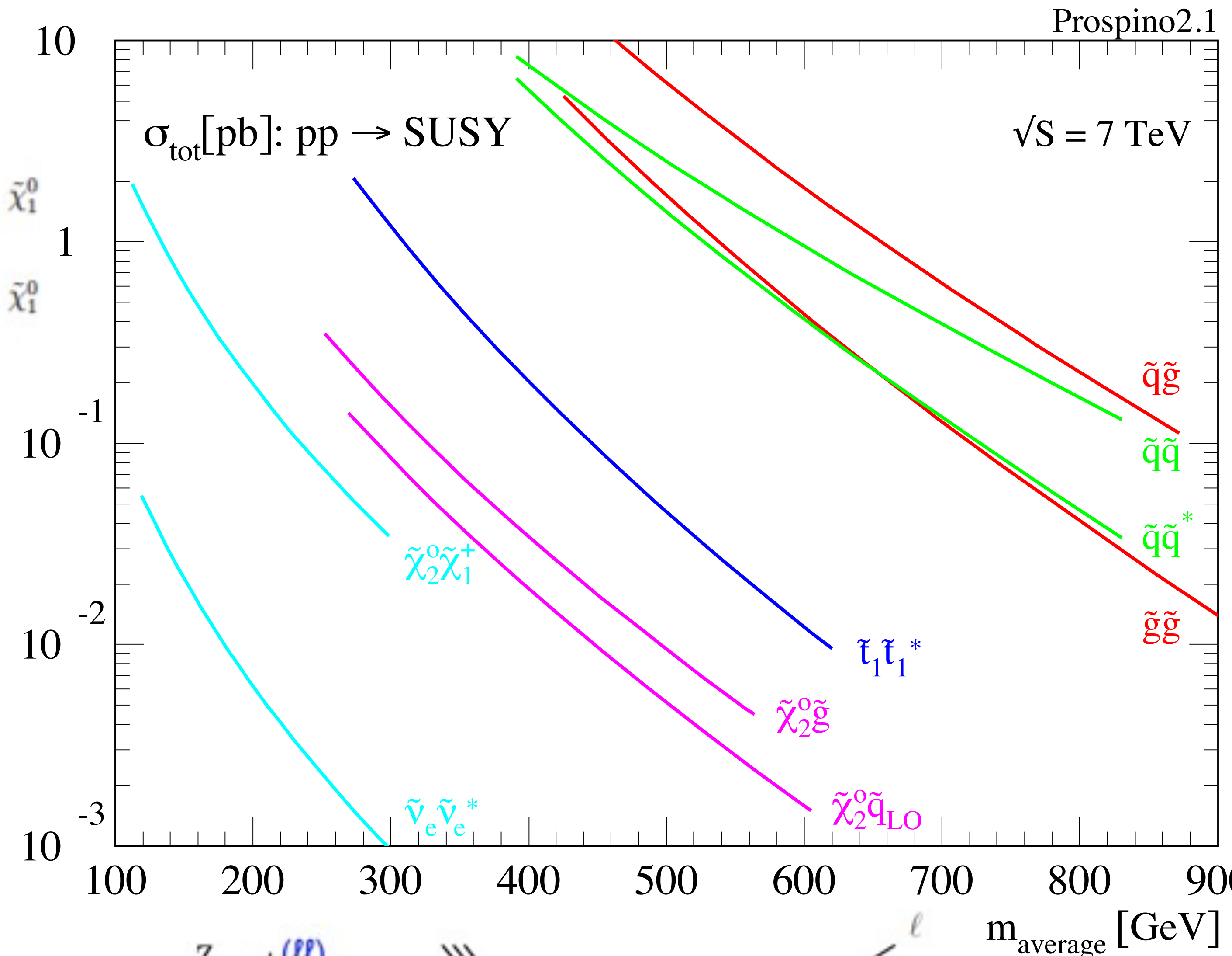


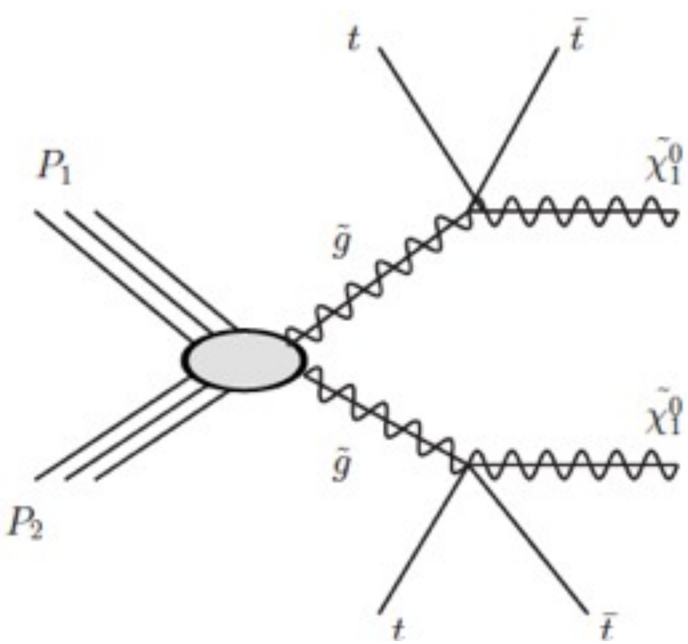
J.Feng : arXiv1302.6587

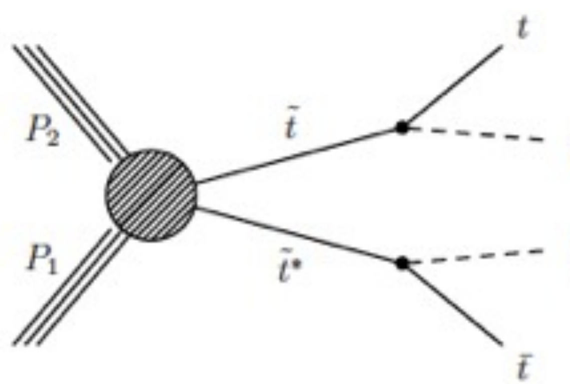
- 3rd generation (stop/sb, gluino->t/b) and ewkinos become the low-hanging fruits in SUSY searches
  - ➡ Drives the focus of searches for SUSY in the 3rd generation

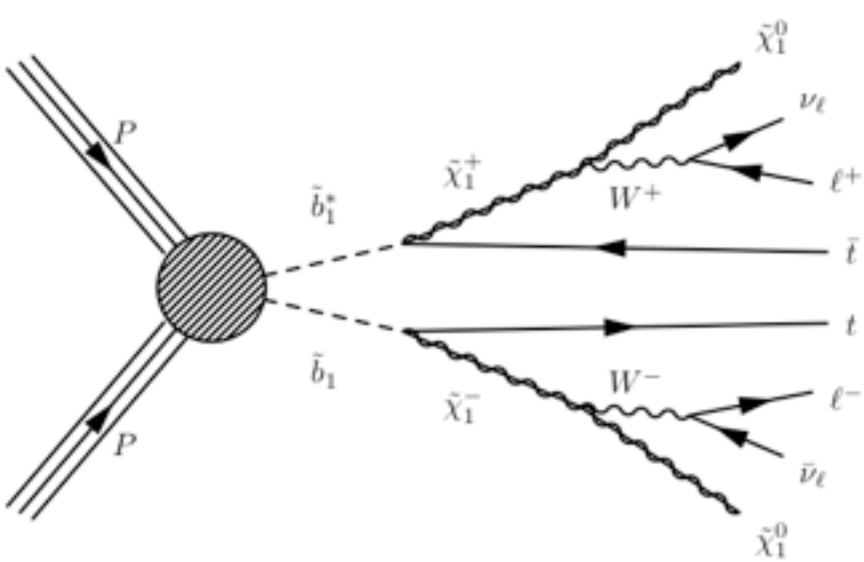
SUSY: simplified models

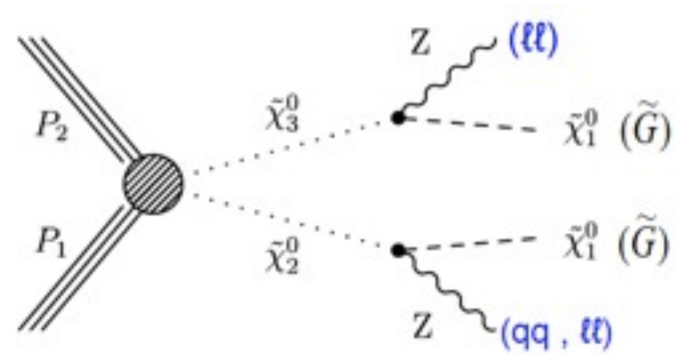
- While some complete model assumptions are better on theory side, we use simplified model approach and look for sensitivity individually in selected topologies

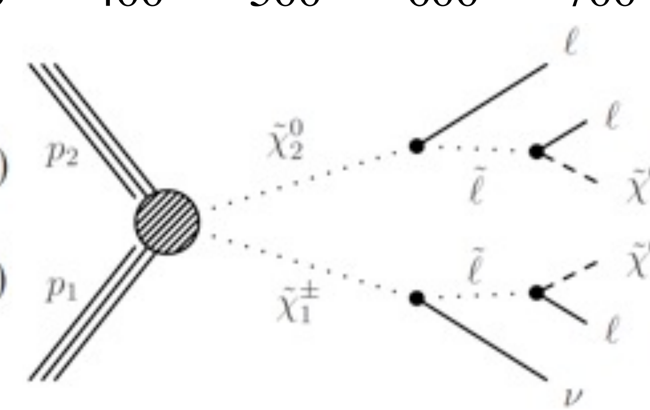








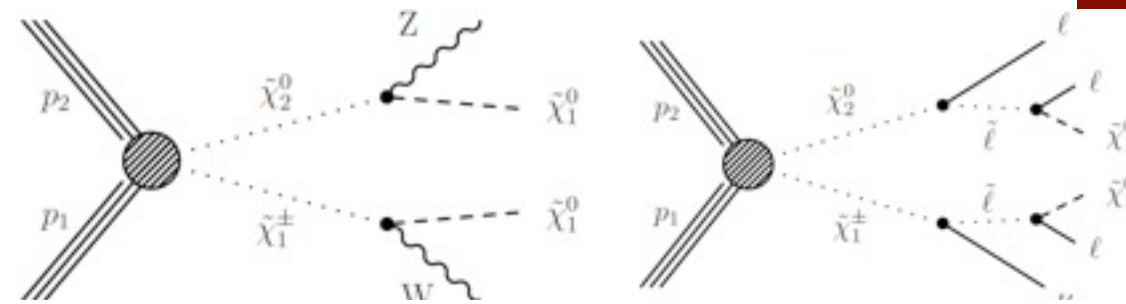




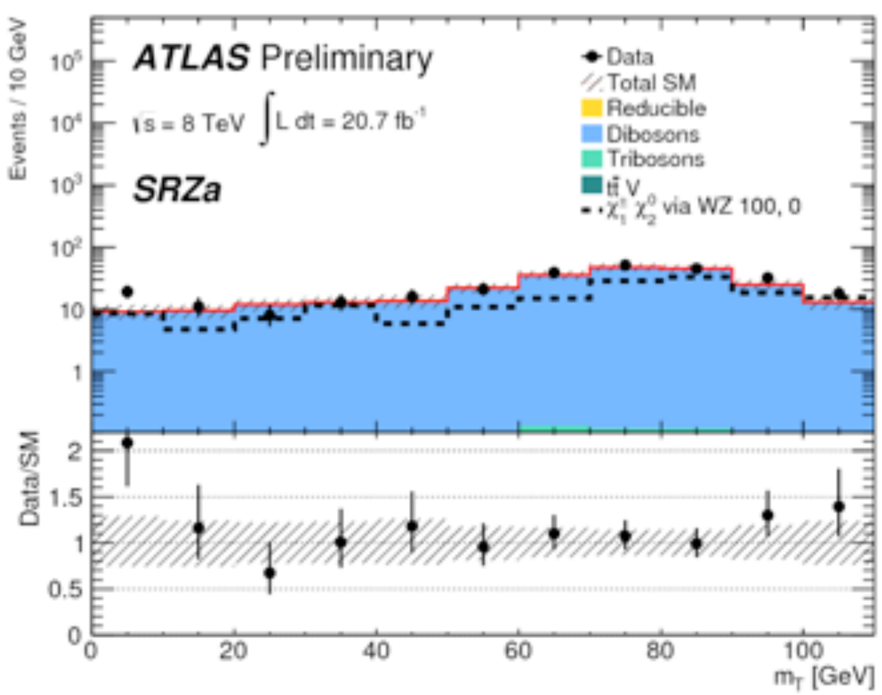
Electroweakinos: 3 leptons (ATLAS)

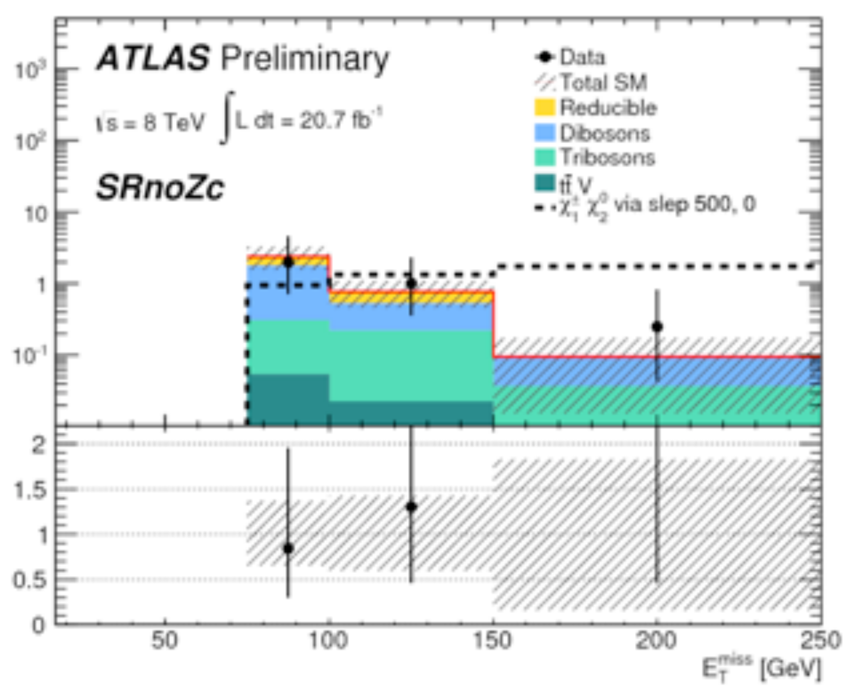
ATLAS-CONF-2013-035

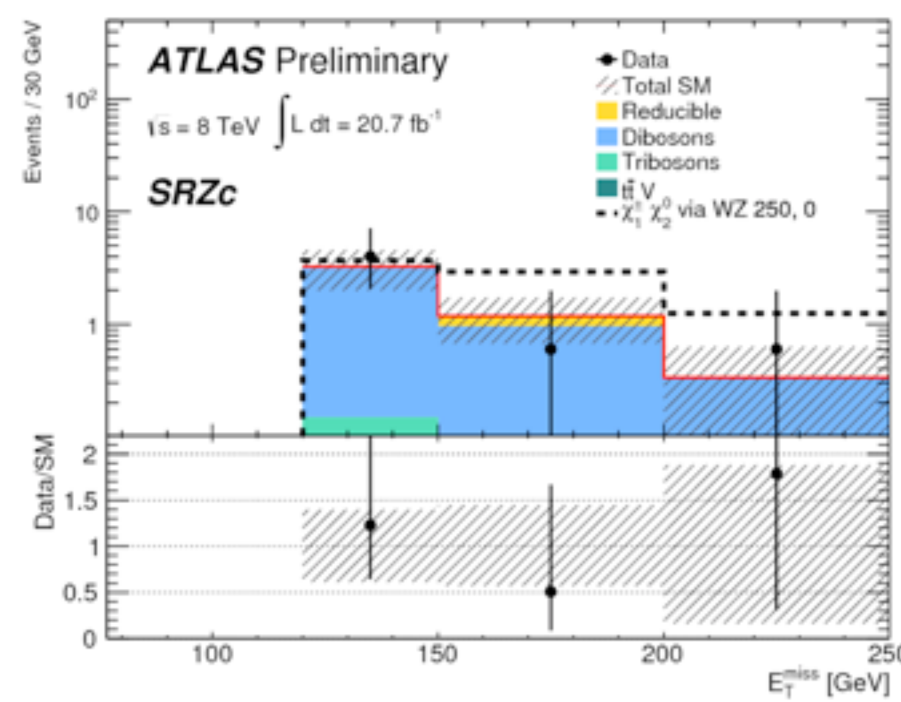
- Leptons appear "naturally" from sleptons or W/Z bosons in decay chains
- 3-lepton configurations here
- Selections:
  - ✓ Signal regions with MET
  - ✓ 3 leptons, on/off Z-peak
- Backgrounds
  - ✓ mainly ZZ/WZ "irreducible"
  - ✓ also some j->lepton misid



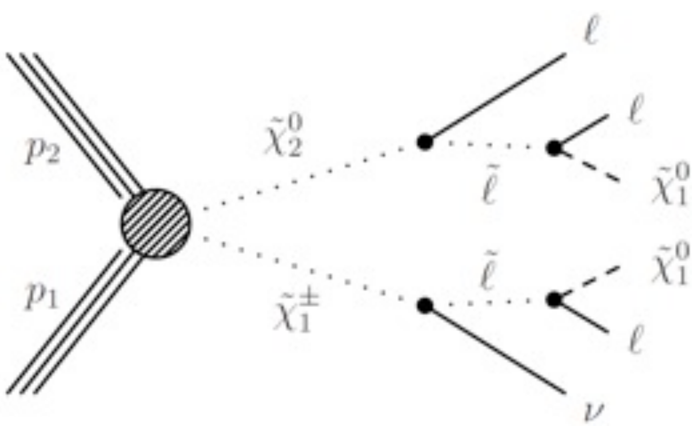
Selection	SRnoZa	SRnoZb	SRnoZc	SRZa	SRZb	SRZc
Tri-boson	1.7 ± 1.7	0.6 ± 0.6	0.8 ± 0.8	0.5 ± 0.5	0.4 ± 0.4	0.29 ± 0.29
ZZ	14 ± 8	1.8 ± 1.0	0.25 ± 0.17	8.9 ± 1.8	1.0 ± 0.4	0.39 ± 0.28
$t\bar{t}V$	0.23 ± 0.23	0.21 ± 0.19	$0.21^{+0.30}_{-0.21}$	0.4 ± 0.4	0.22 ± 0.21	0.10 ± 0.10
WZ	50 ± 9	20 ± 4	2.1 ± 1.6	235 ± 35	19 ± 5	5.0 ± 1.4
Σ SM irreducible	65 ± 12	22 ± 4	3.4 ± 1.8	245 ± 35	20 ± 5	5.8 ± 1.4
SM reducible	31 ± 14	7 ± 5	1.0 ± 0.4	4^{+5}_{-4}	1.7 ± 0.7	0.5 ± 0.4
Σ SM	**96 ± 19**	**29 ± 6**	**4.4 ± 1.8**	**249 ± 35**	**22 ± 5**	**6.3 ± 1.5**
Data	**101**	**32**	**5**	**273**	**23**	**6**
p_0-value	0.41	0.37	0.40	0.23	0.44	0.5

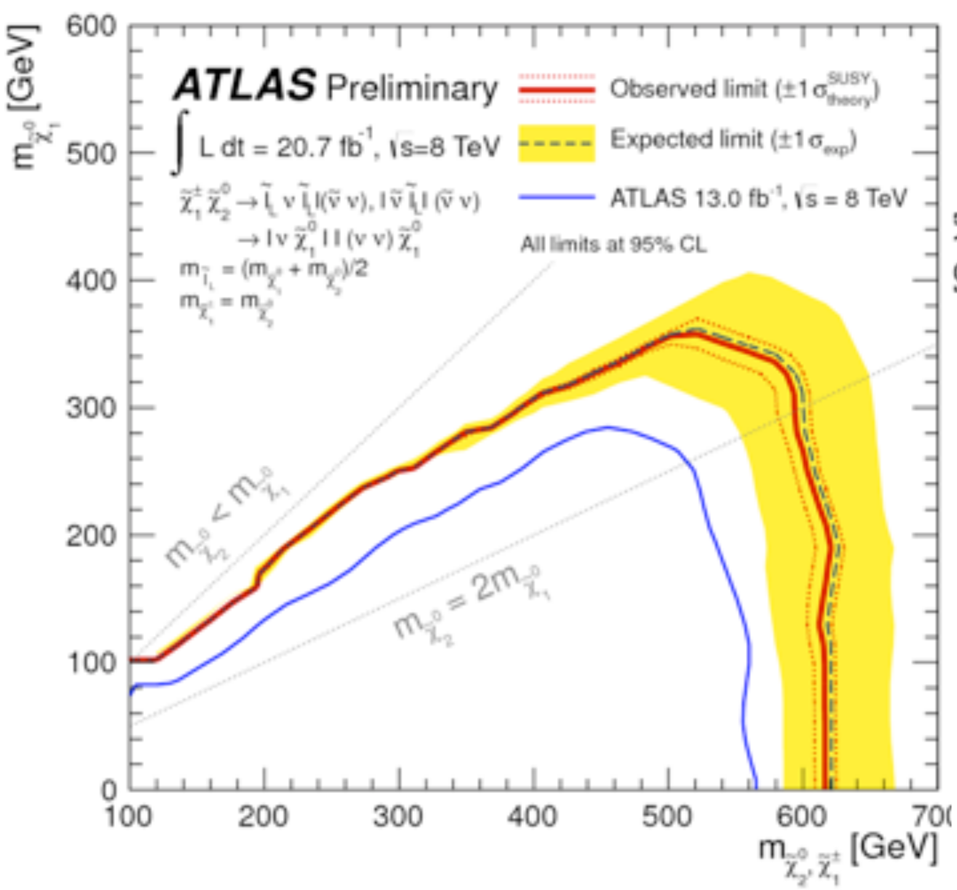




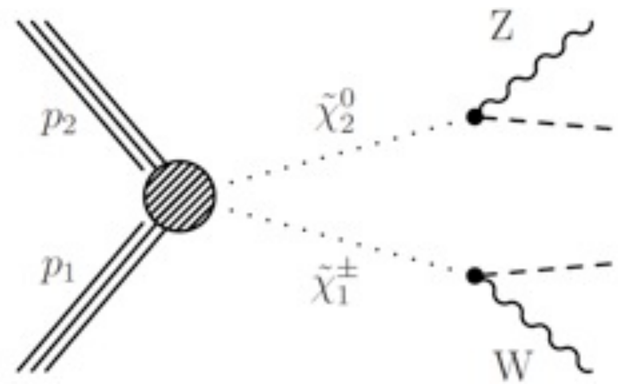


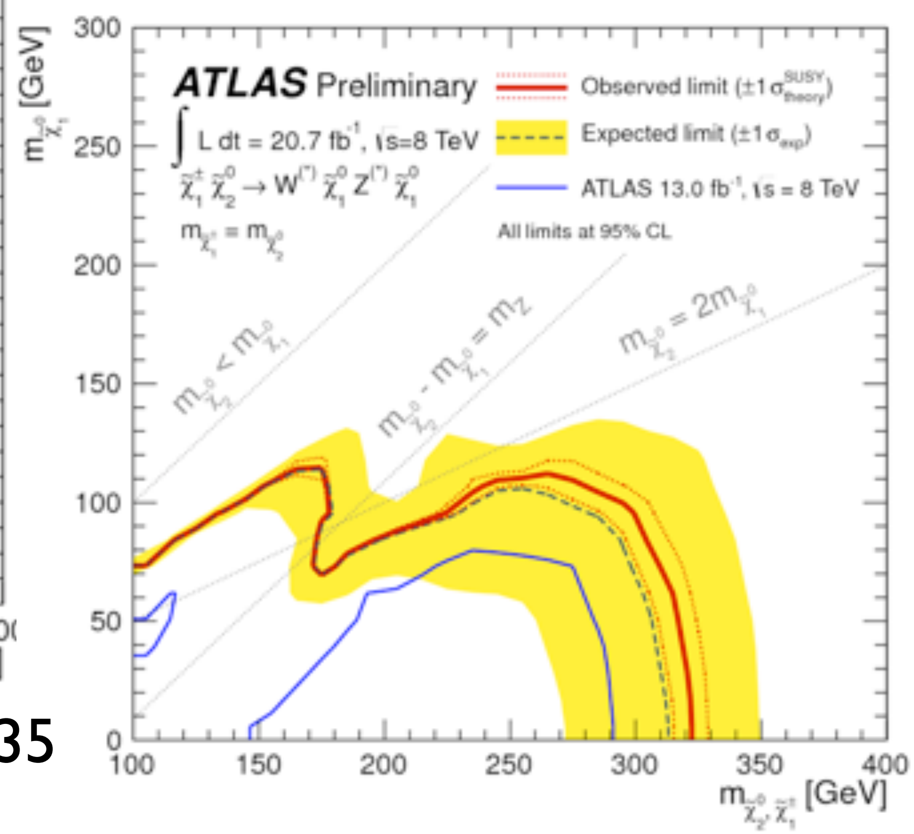
Electroweakinos: summary for 3L



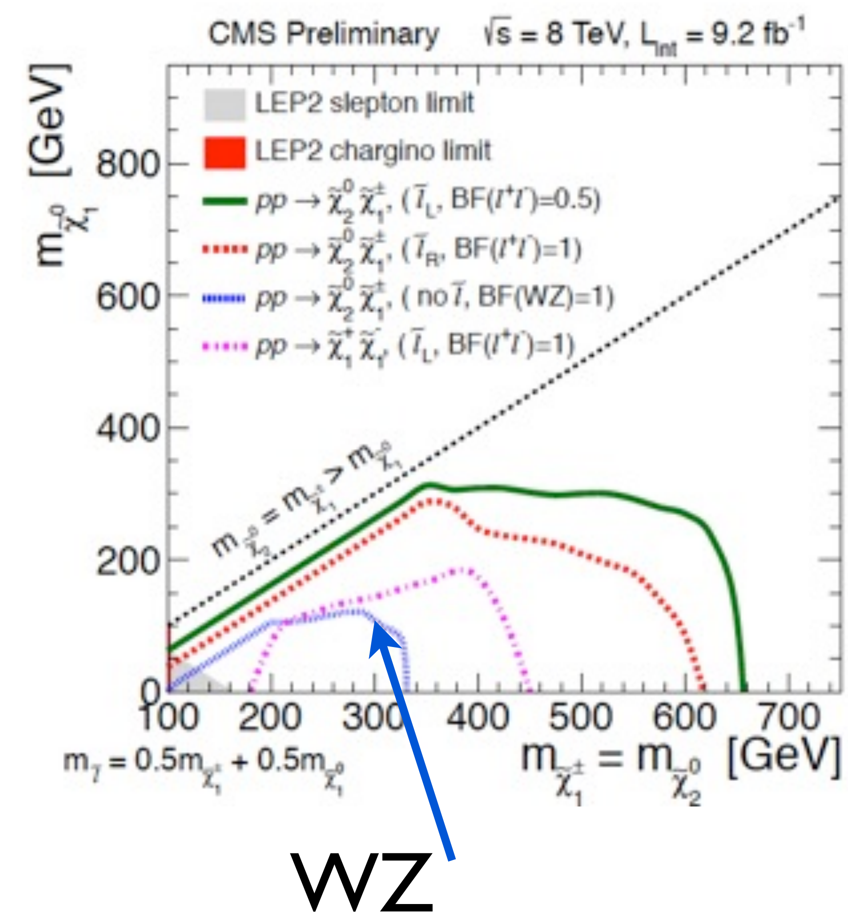


ATLAS-CONF-2013-035





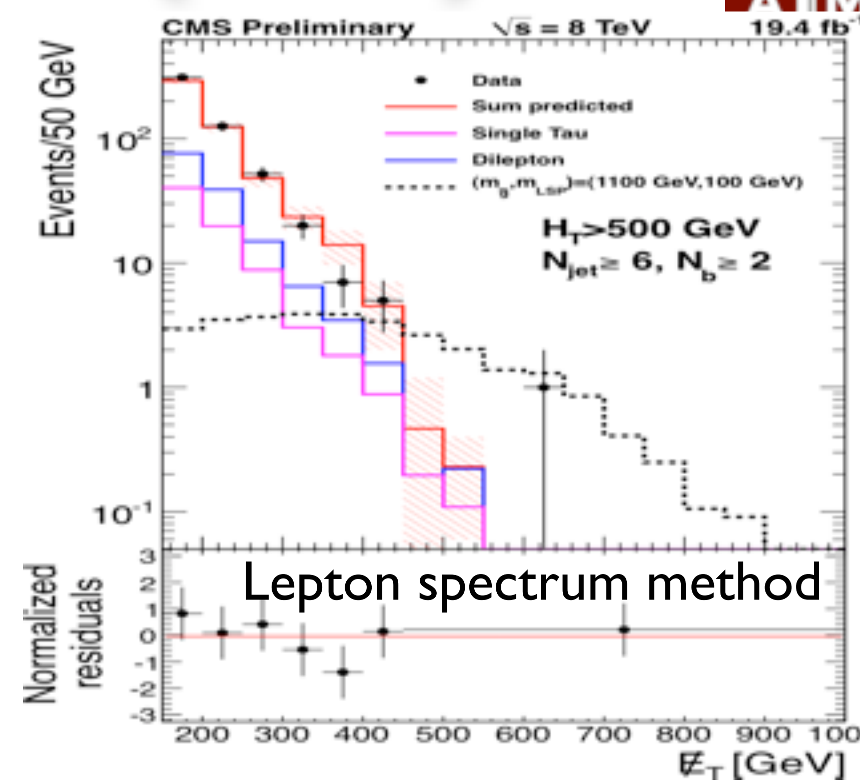
CMS SUS-12-022

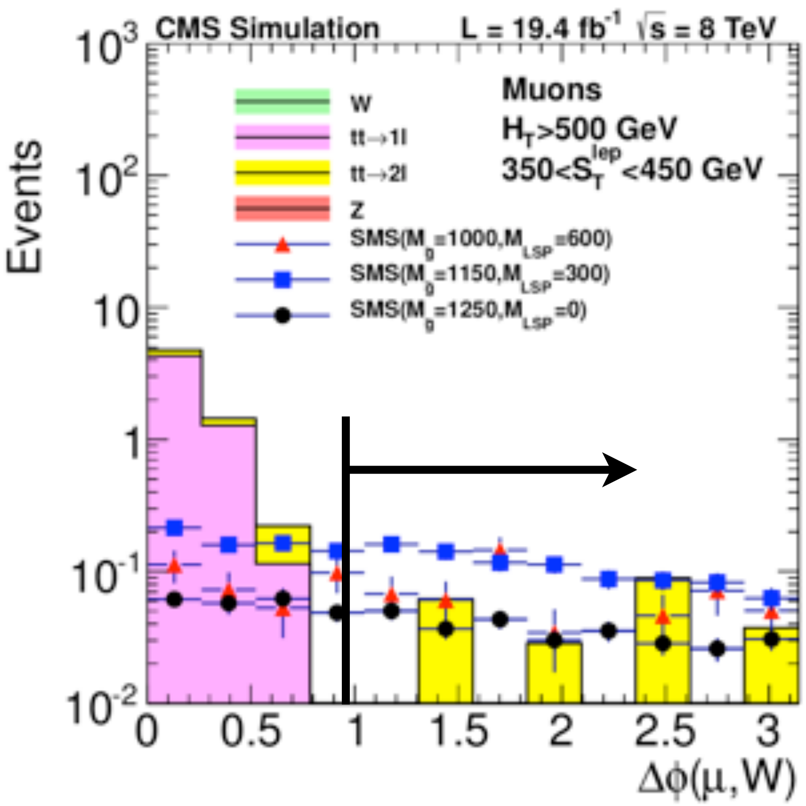


Gluino pairs via stops: l+jets (CMS)

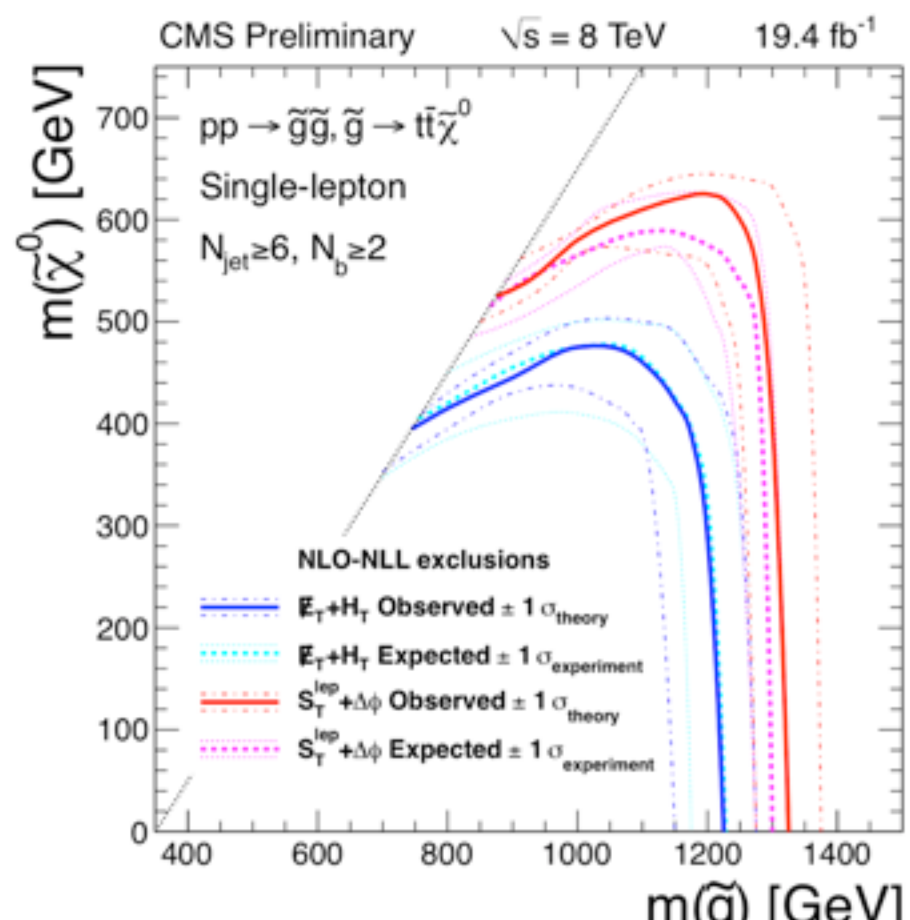
CMS-PAS-SUS-13-007

- High-pt lepton, 6 or more jets, 2 or 3 b-tags
- Bin in HT(Σpt^{jet}), ST($pt^{e/mu}$+MET), and Nbtags
- Main discriminant is $\Delta\varphi$(W, lepton)
- Alternative (lepton spectrum method) uses lepton pt spectrum to predict MET spectrum
- Exclude m_gluino below ~1.35 TeV

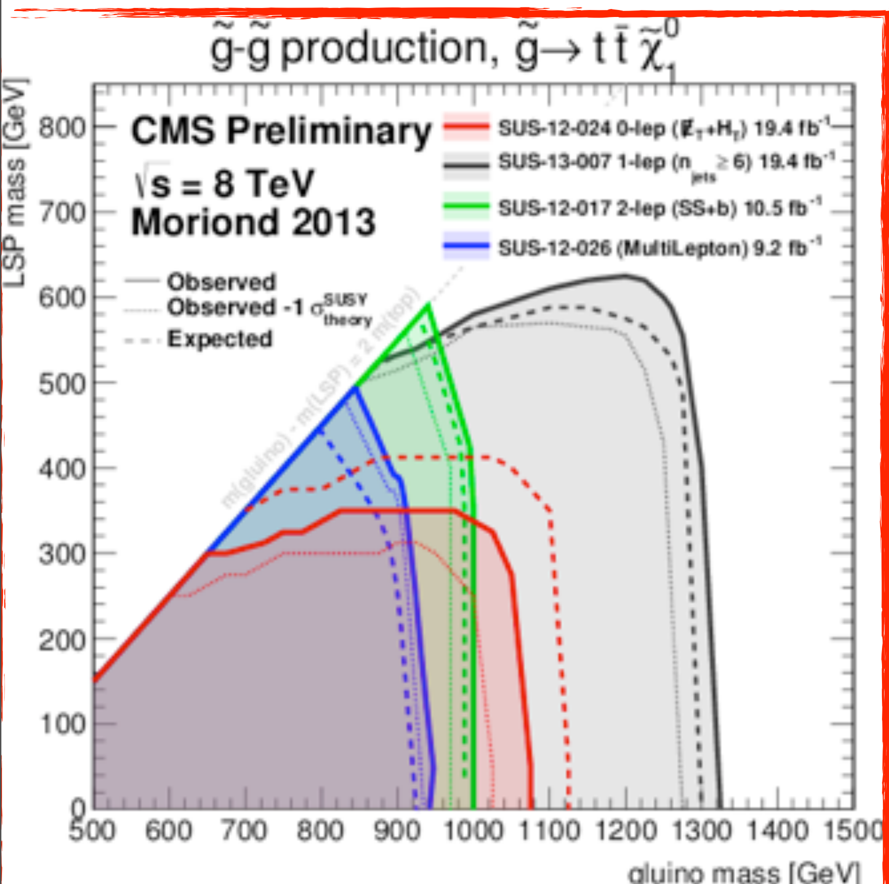


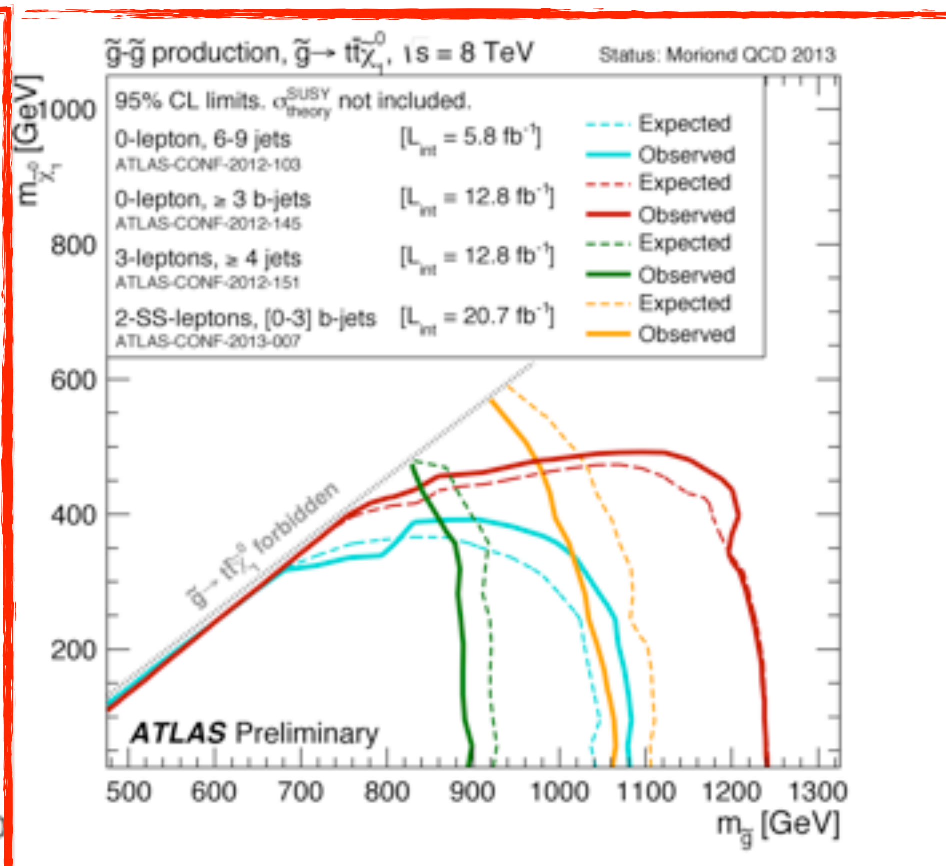


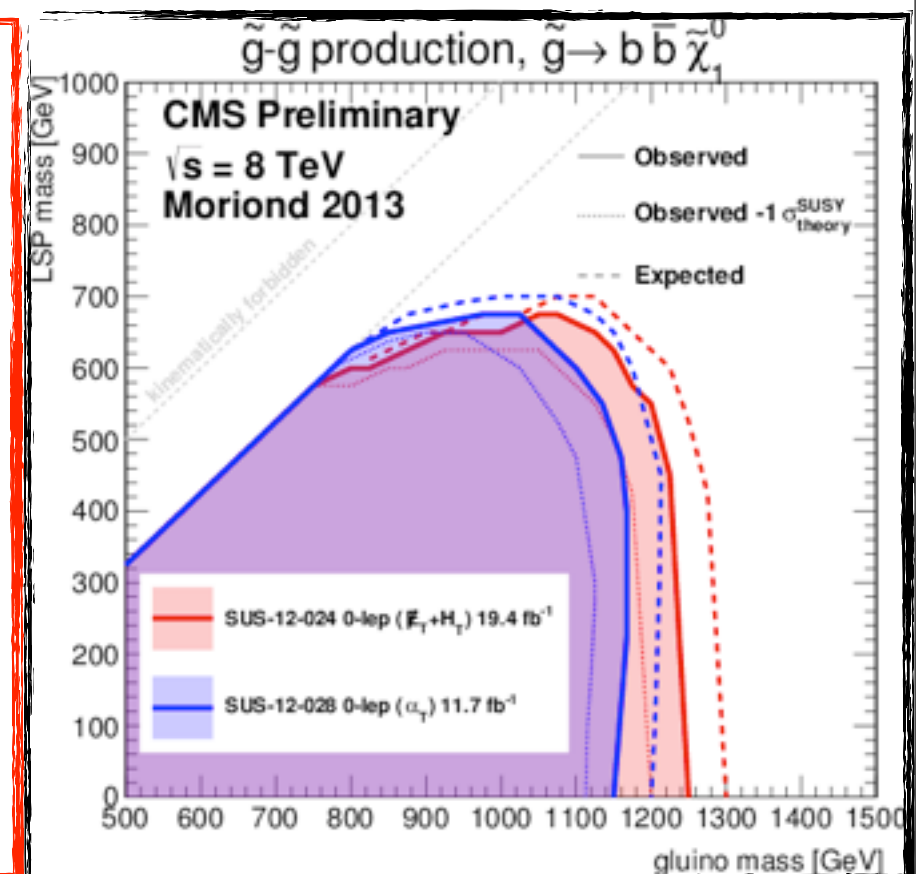
		S_T^{lep} [GeV]	prediction	observation
N_b=2	Muons	[250,350]	6.00 ± 2.40 (2.23)	9
		[350,450]	1.37 ± 1.19 (1.12)	2
		>450	0.0 ± 0.66 (0.66)	0
	Electr.	[250,350]	3.83 ± 1.84 (1.75)	9
		[350,450]	2.74 ± 2.02 (1.86)	2
		>450	0.0 ± 0.42 (0.42)	0
$N_b\geq3$	Muons	[250,350]	1.92 ± 0.95 (0.84)	0
		[350,450]	0.57 ± 0.58 (0.52)	0
		>450	0.0 ± 0.22 (0.22)	0
	Electr.	[250,350]	1.89 ± 1.03 (0.94)	4
		[350,450]	0.85 ± 0.80 (0.70)	0
		>450	0.0 ± 0.08 (0.08)	0



Gluino pairs via stops and sbottoms





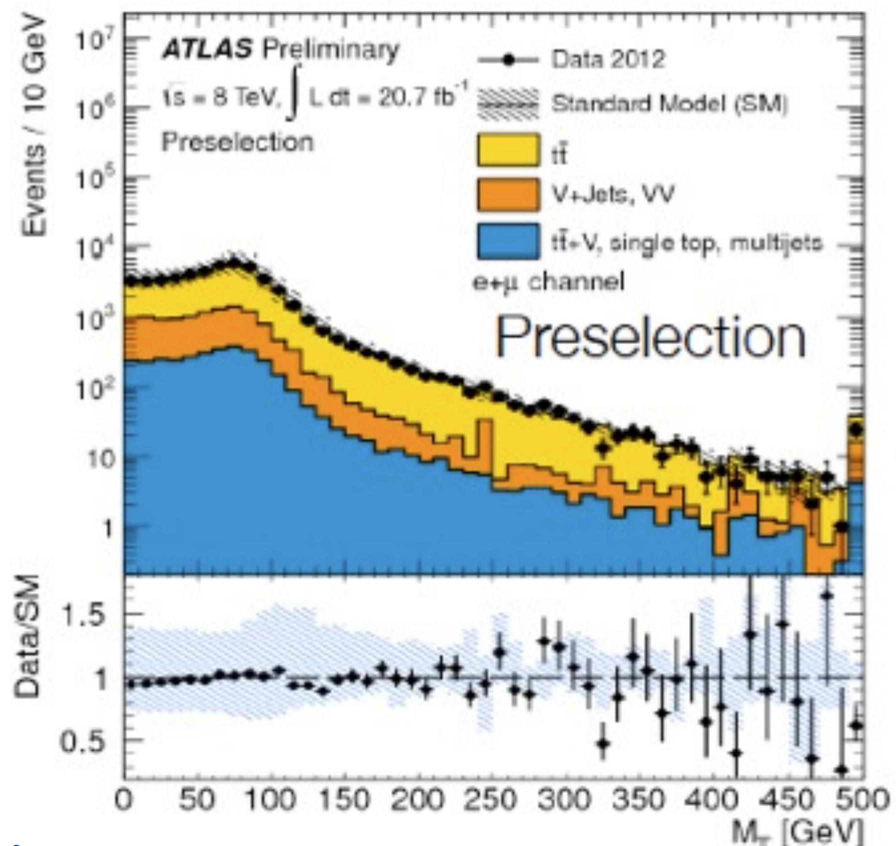


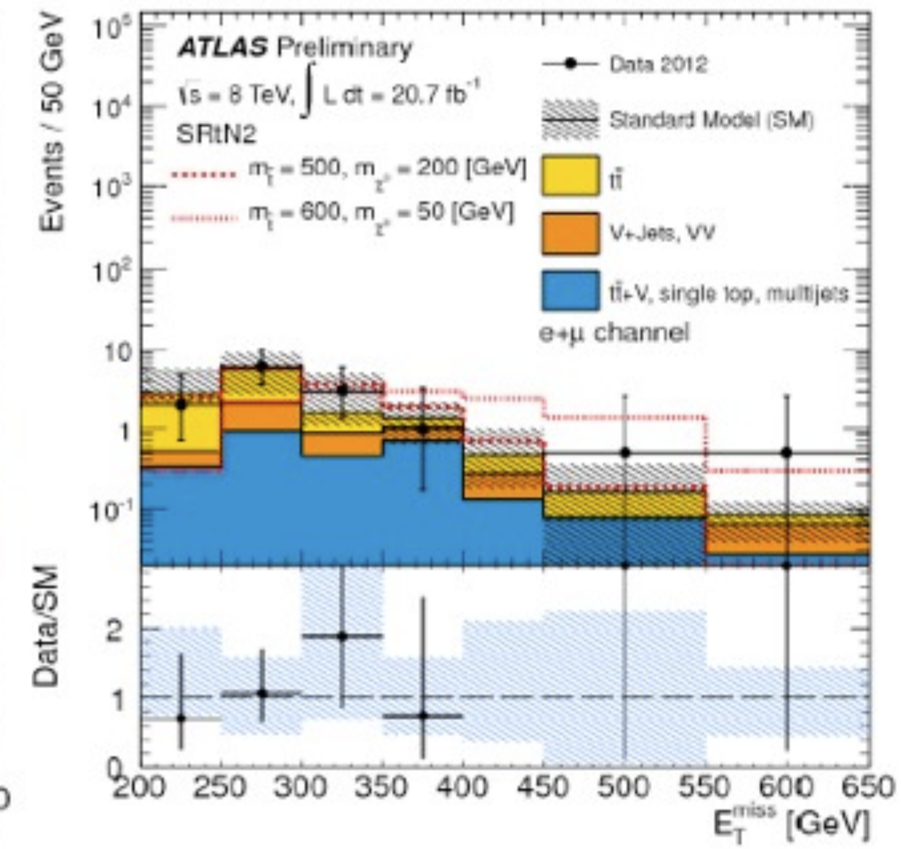
- 4b+MET is in b-jets+MET final state alone
- 4t+MET takes contributions from final states with leptons
  - ✓ Multiple analyses are sensitive

Stop quark production (ATLAS)

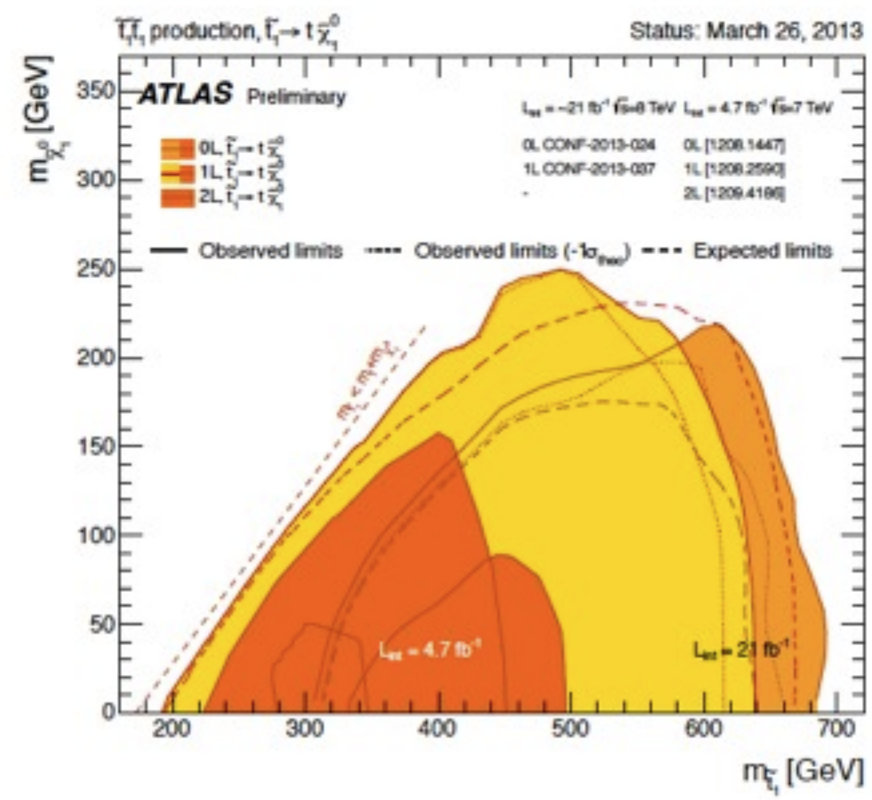
ATLAS-CONF-2013-037

- stop-> top+LSP
  - NB on 0-lepton mode:
    - **reconstruct both hadronic top decays**
    - **look for excess in high-MET**



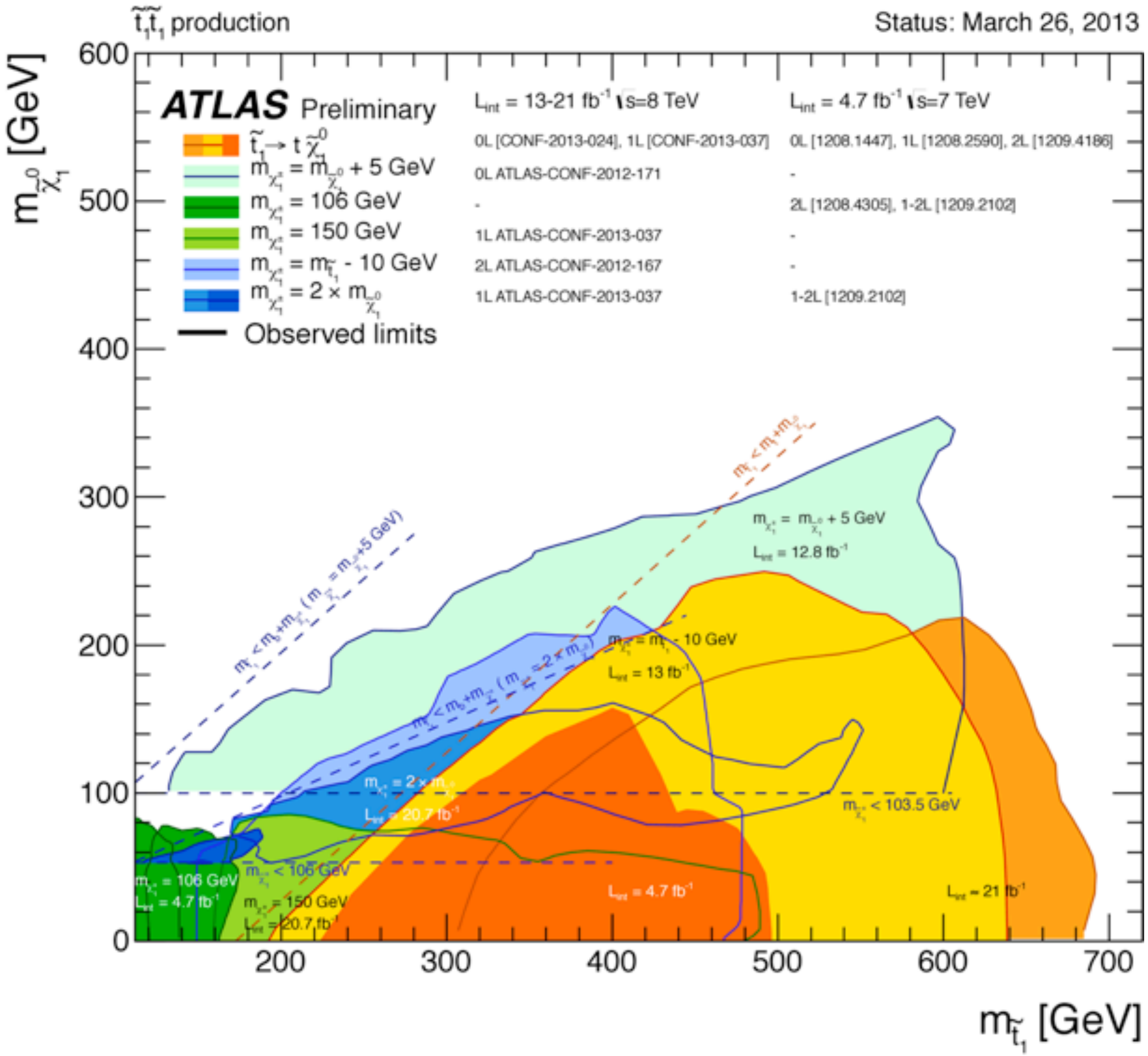


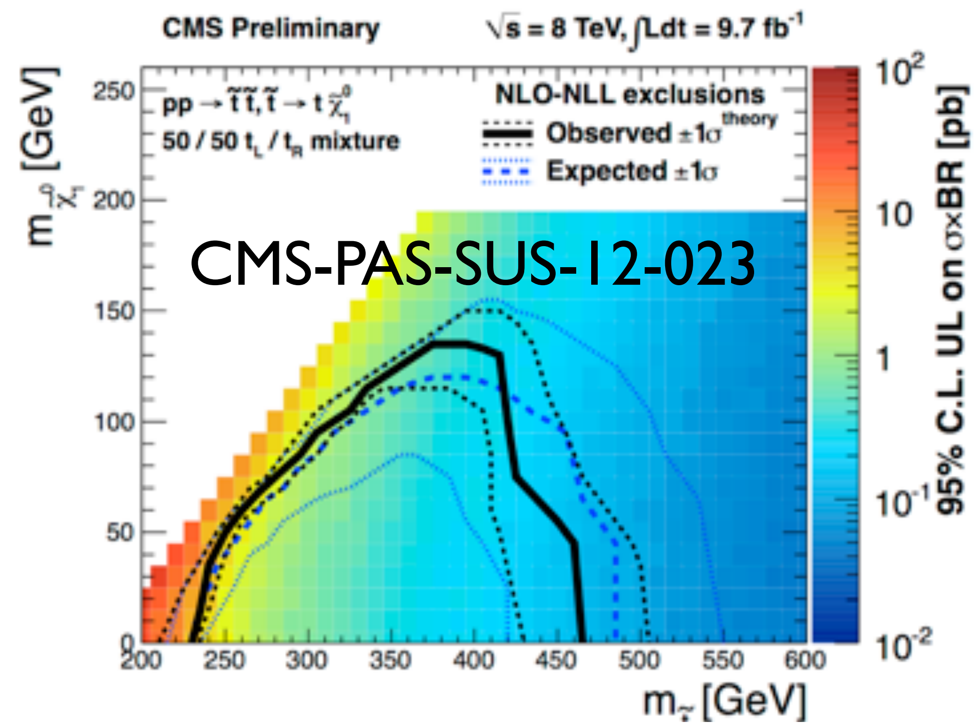
- 1-lepton mode:
  - ✓ energetic lepton, ≥1 bjet
  - ✓ reconstruct other hadronic top
  - ✓ look for excess in high-m_T, high-MET region
- Background control:
  - ✓ Mainly from ttbar->2l+jets

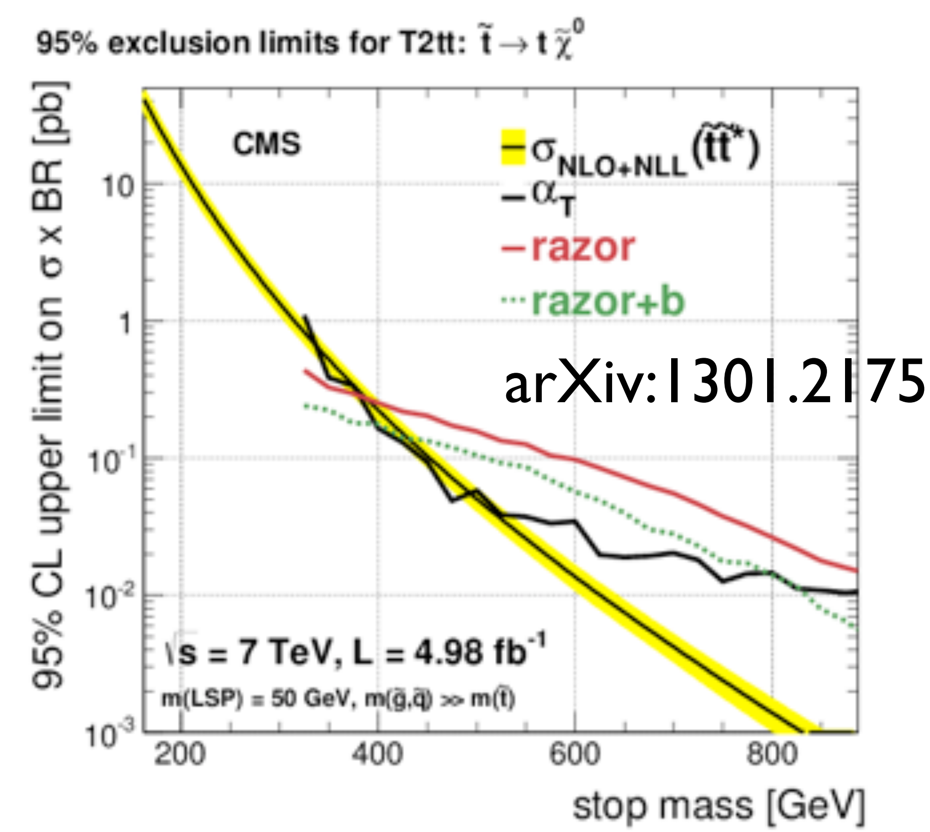


- l+jets analysis extends reach to regions near production threshold

Stop quark production: summary







- ATLAS results for full dataset, CMS results in preparation

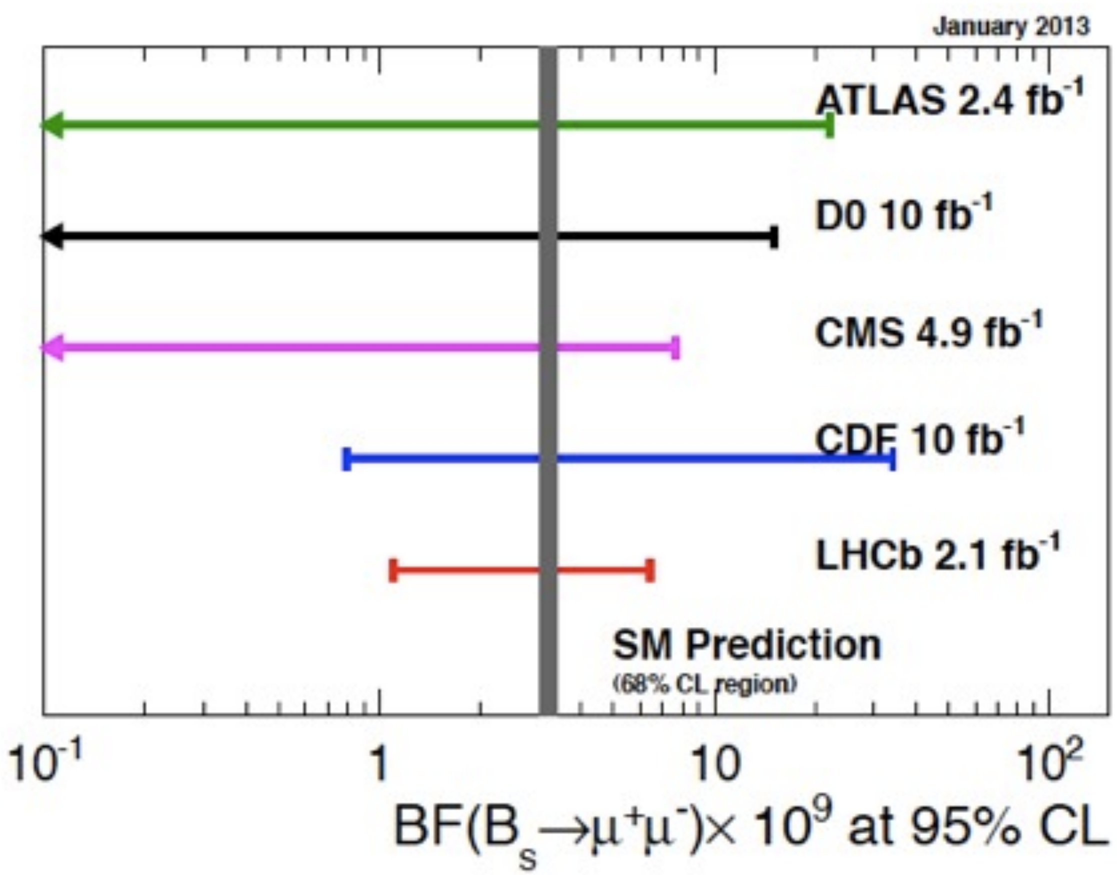
Summary

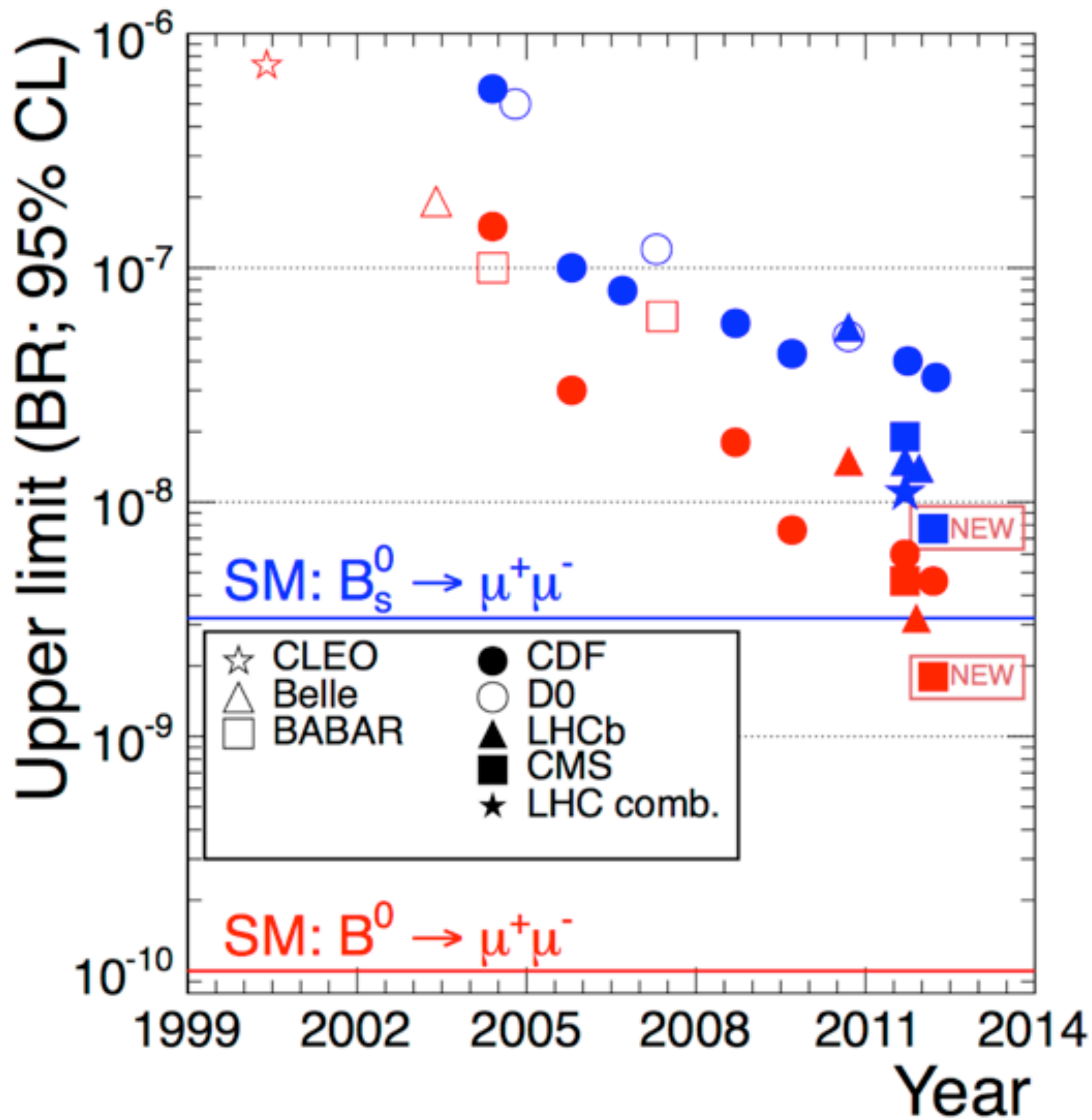
- Searches for physics beyond the Standard Model play major role in the programs of the LHC experiments
  - ➡ Rare b-physics processes at the LHCb
    - ✓ B->mumu essential for all 3 experiments
  - ➡ Direct production of heavy particles at ATLAS and CMS
- On the theory side, SUSY is being very attractive
  - ➡ Naturalness considerations bring predictions within reach of LHC
  - ➡ Final states with top/b quarks become the most interesting
- Alas, no evidence for physics beyond the SM has been found yet
- Next major step in NP program in ATLAS and CMS is post-LS1 ("Run-2")
  - ➡ The energy increase is paramount
- More exciting times are ahead of us

What’s next?

Backup

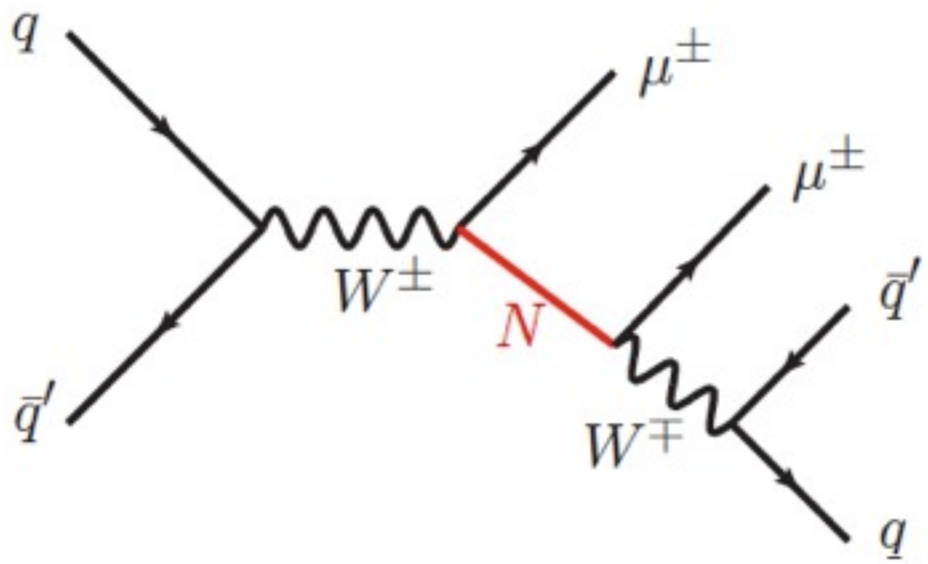
Bsmm history

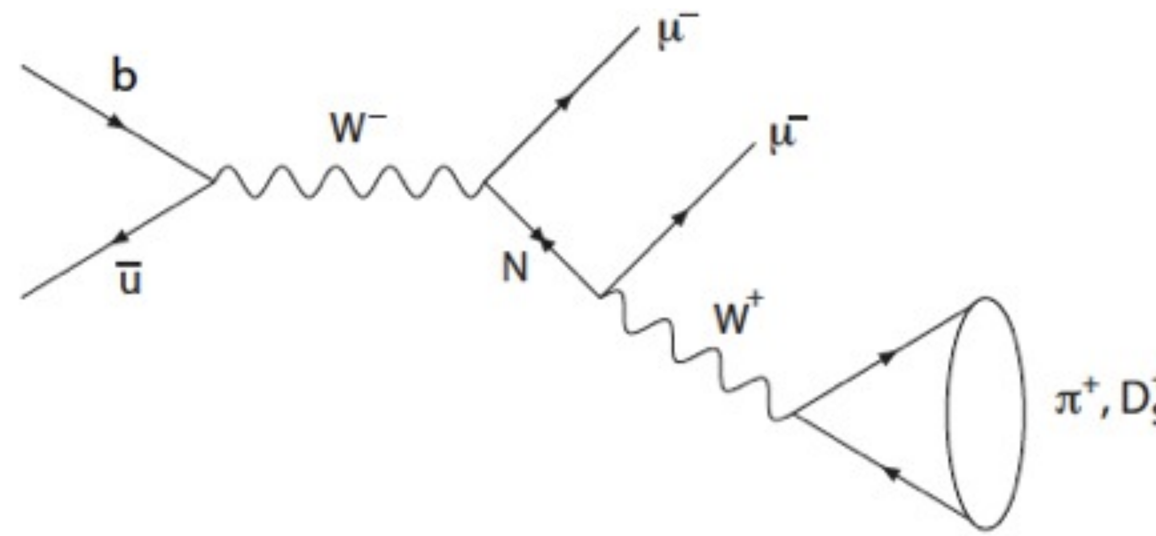




- 25 years in the making

Majorana neutrinos



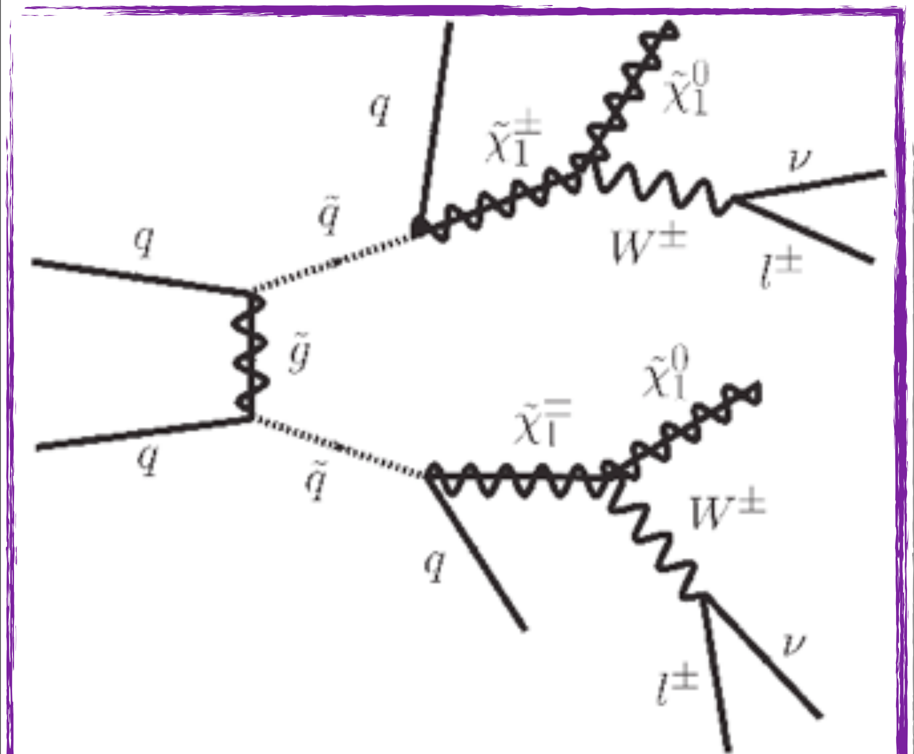


- A curious cross between NP searches with direct and virtual contribution

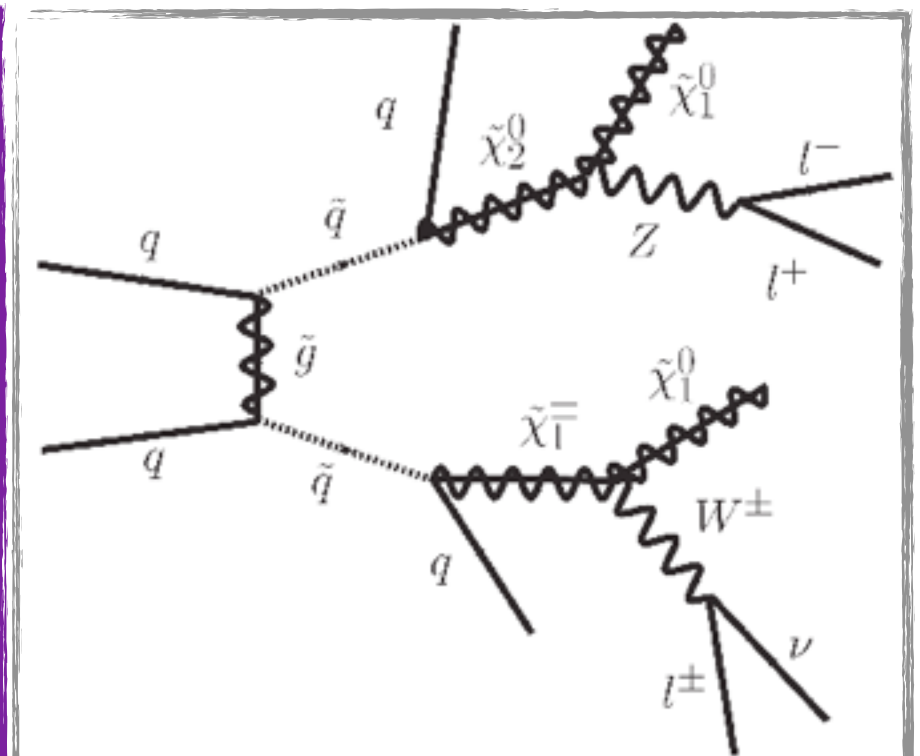
SUSY: di/multi-leptons

- Plenty of ways to get multiple leptons in SUSY
- Start from colored superpartners ==> pick up leptons from decays of charginos/neutralinos directly, or W/Z or sleptons coming off of them
  - ✓ All cases here give extra jets
  - ✓ R-parity conservation gives Missing Energy from LSP
  - ✓ R-parity violation means no MET from LSP, but still some MET from W/chargino decays

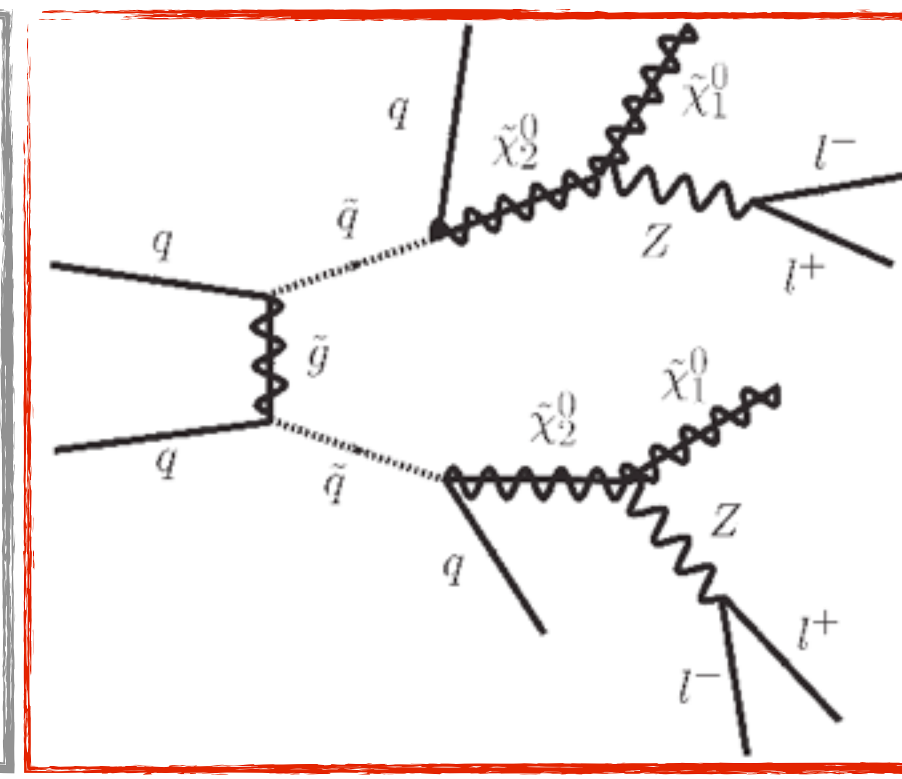
Same-sign dilepton



Tri-lepton



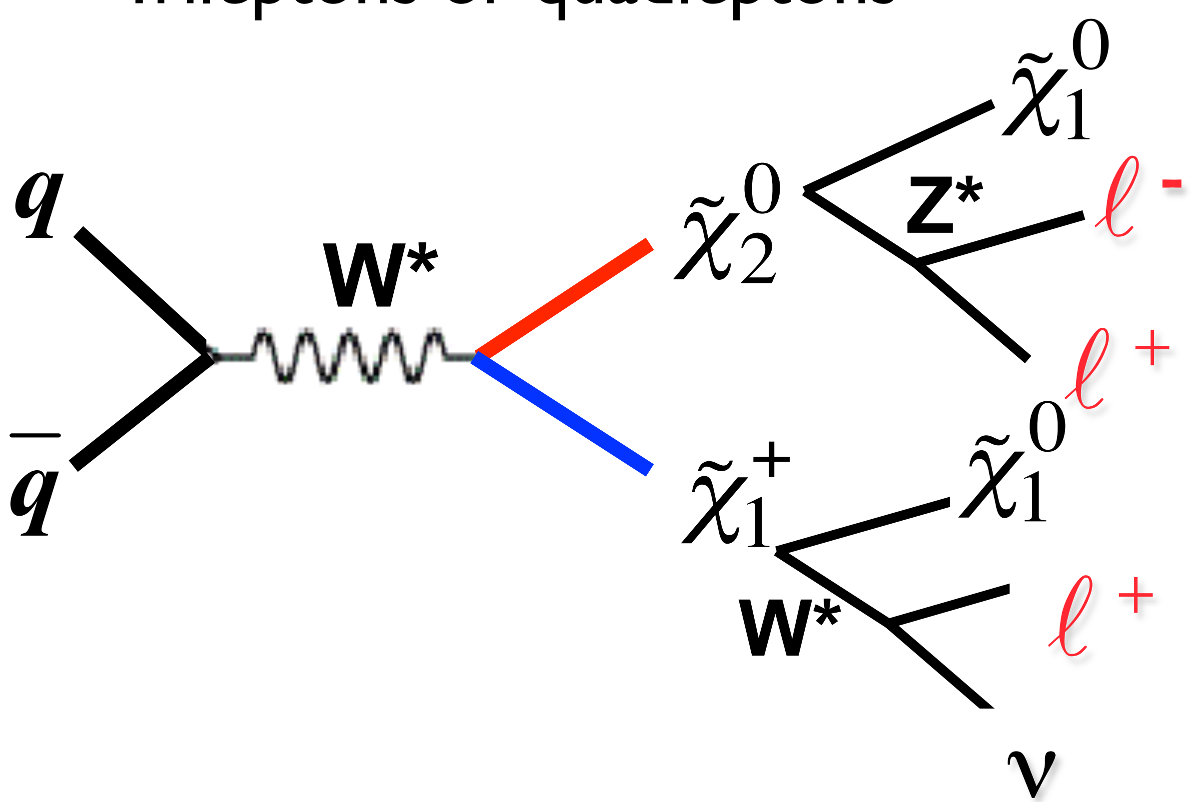
Four-lepton



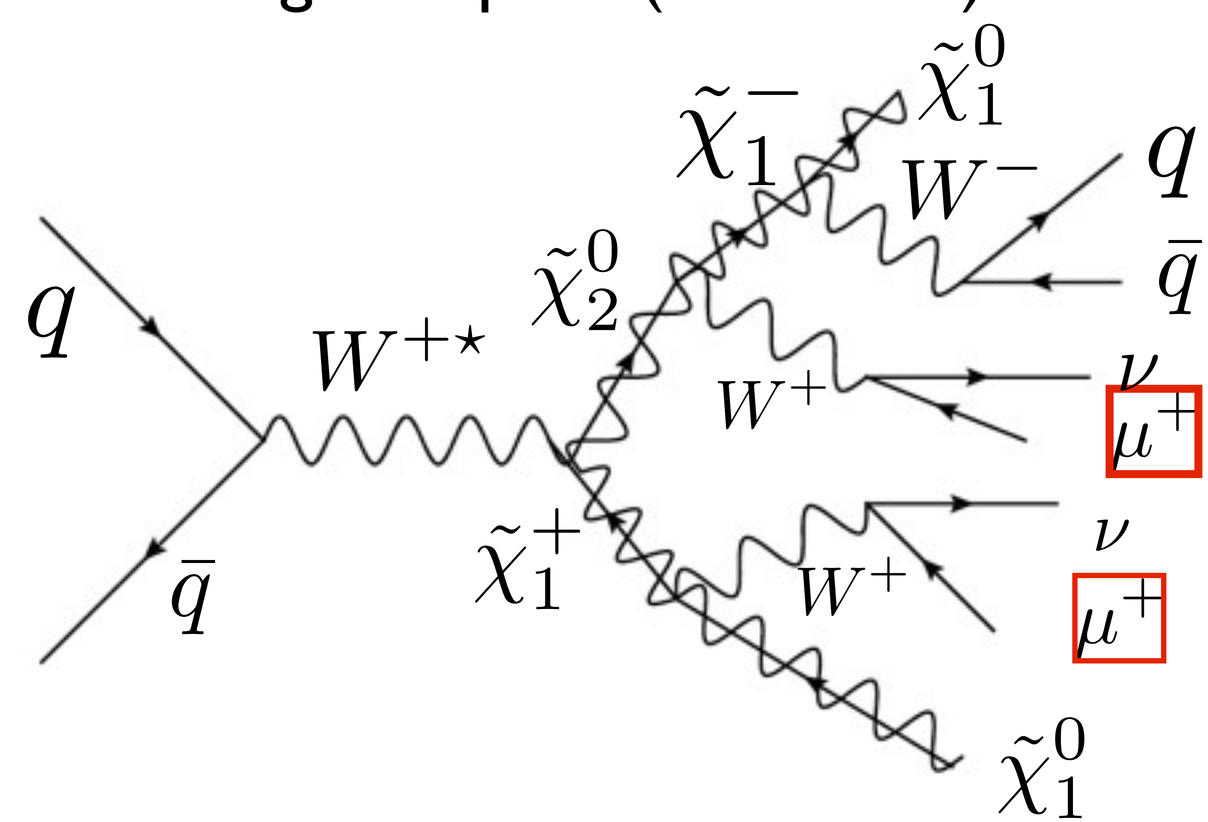
SUSY: di/multi-leptons

- Plenty of ways to get multiple leptons in SUSY
- Start from no-color superpartners ==> same ways to get leptons
  - ✓ 3 or more leptons more "natural" than same-sign only
  - ✓ Fewer jets, if any
  - ✓ Similar situation with MET for R-parity conserving or violating cases

Trileptons or quadleptons

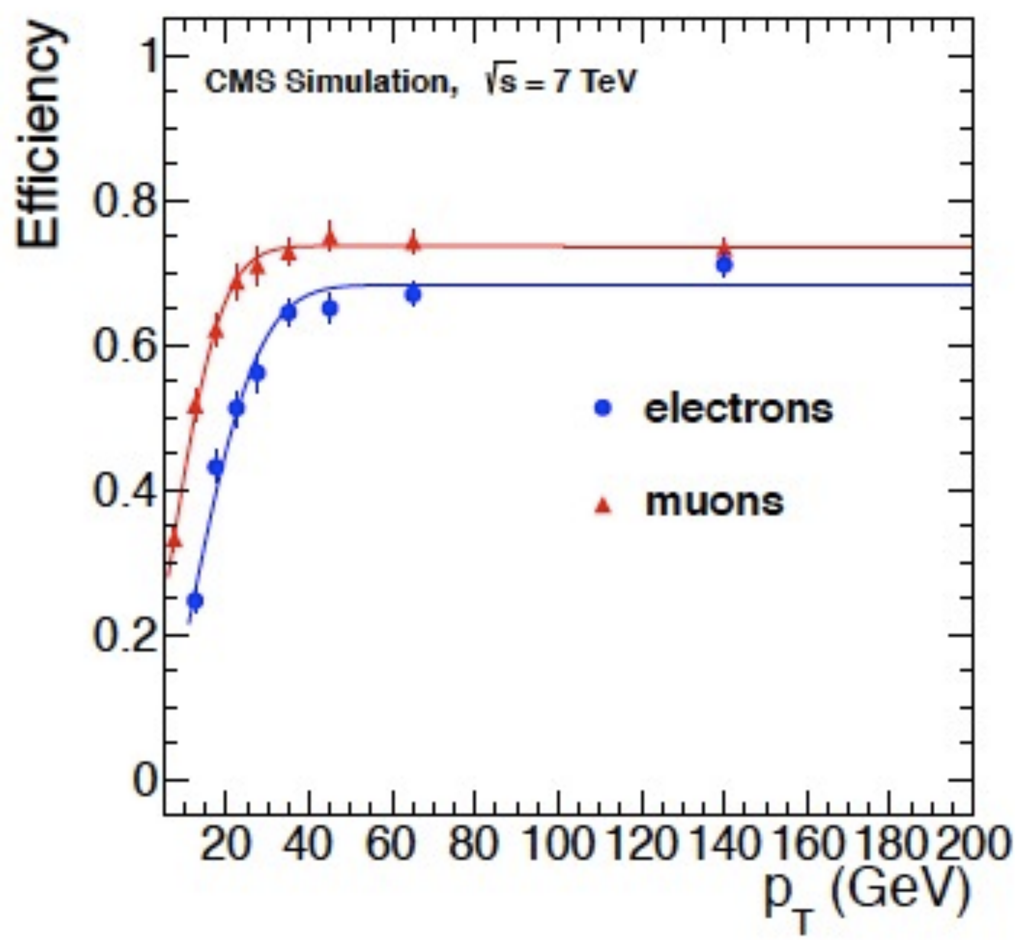


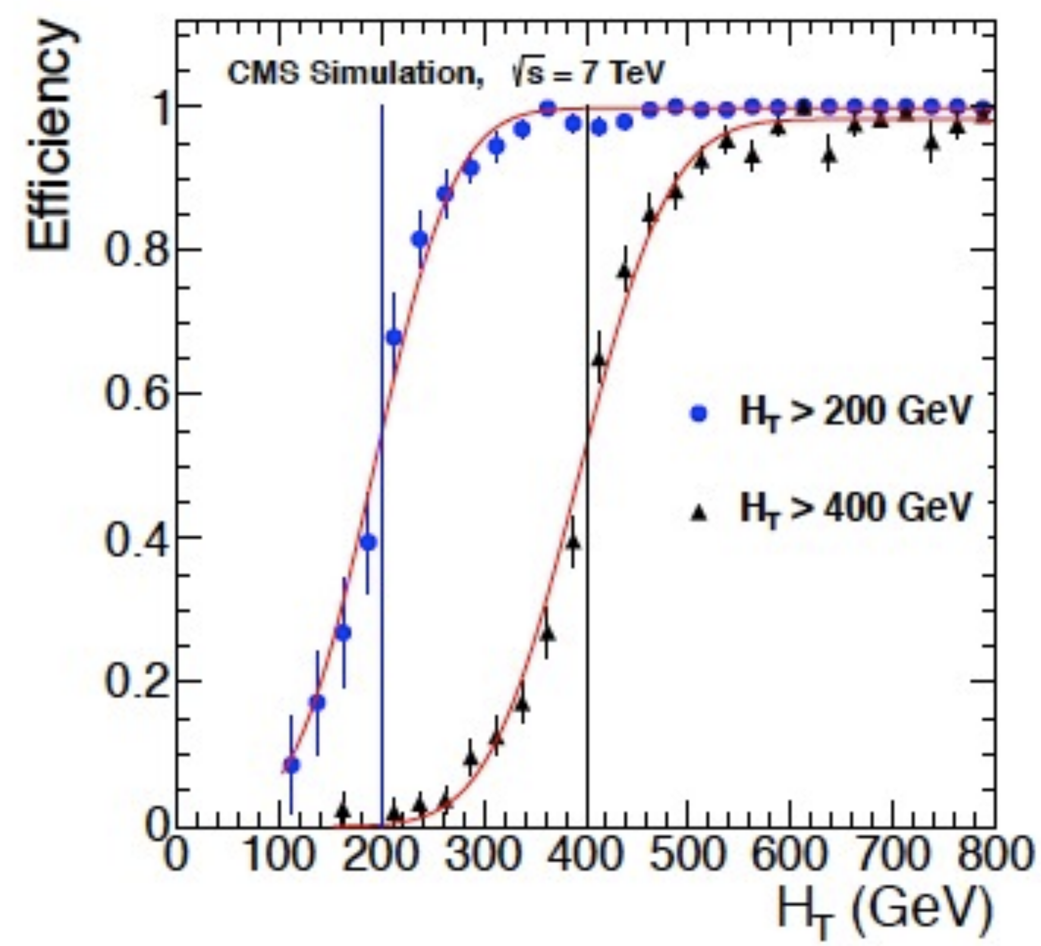
Same-sign dilepton (less trivial)



Outreach

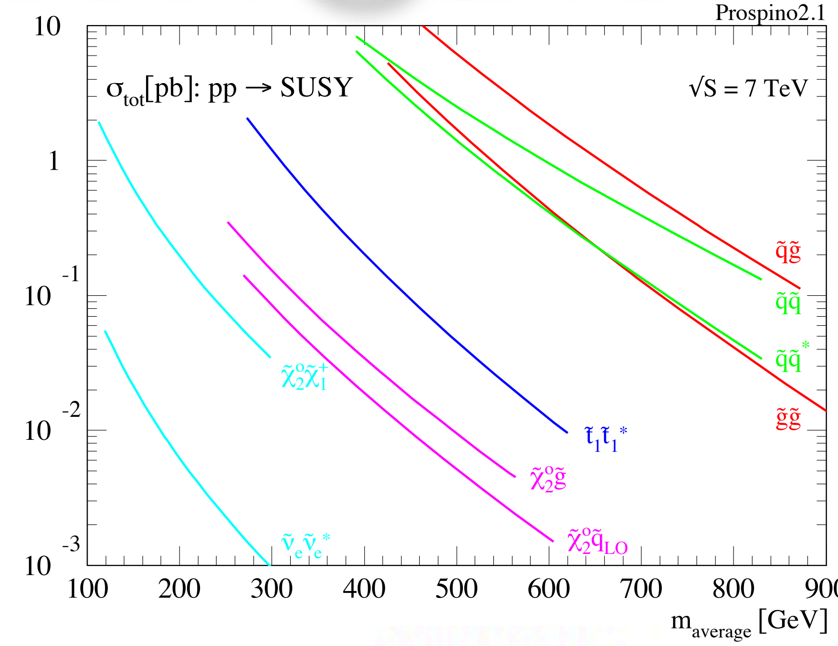
- The interpretation of results is quite specific and implies someone had to use the full detector simulation/response in analysis
- We provide information (efficiency/response curves) for each given selection as a function of generator level (hard scattering) kinematics



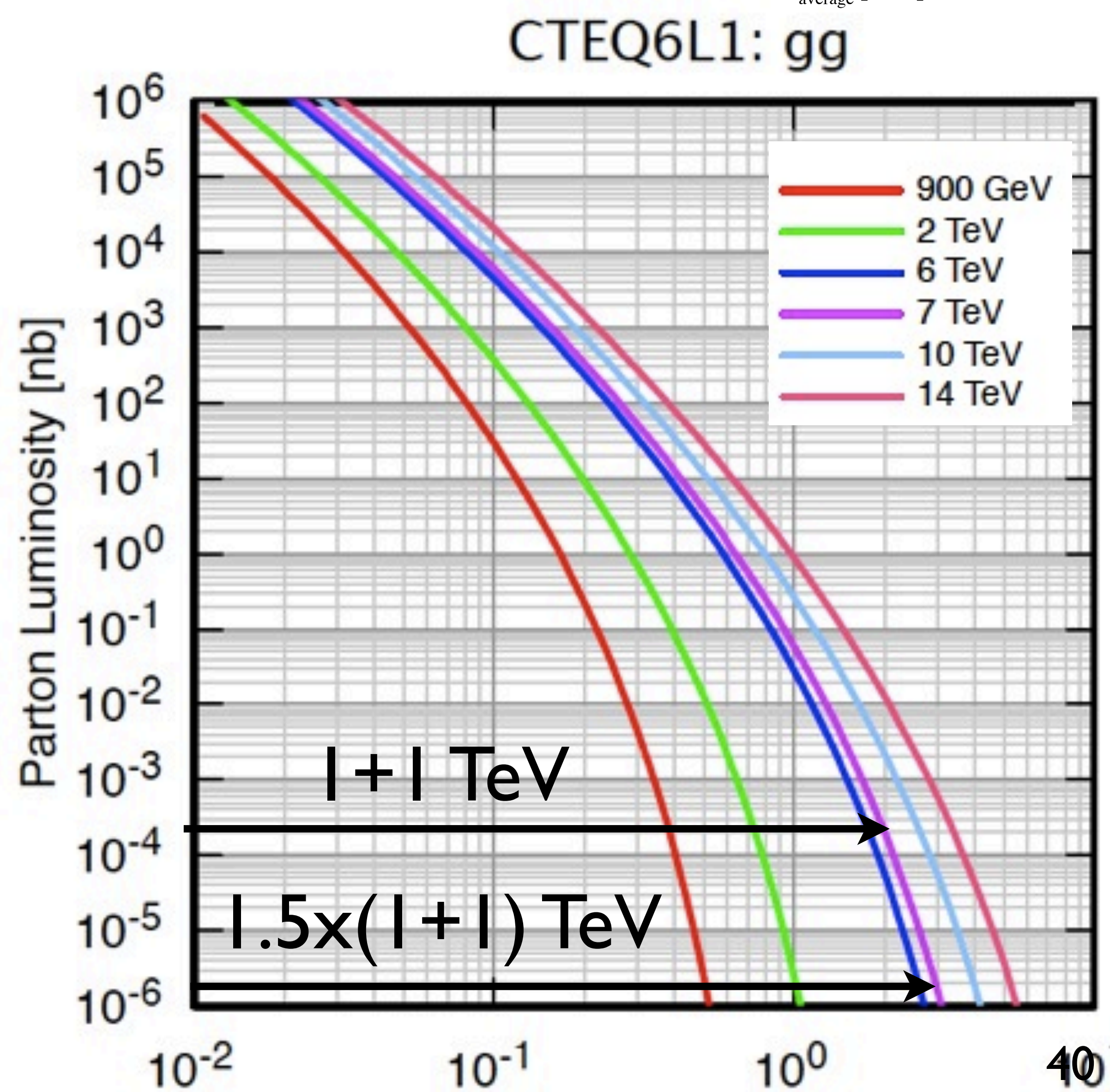


- Can be used to emulate selection efficiency for any model

Future prospects for SUSY@LHC

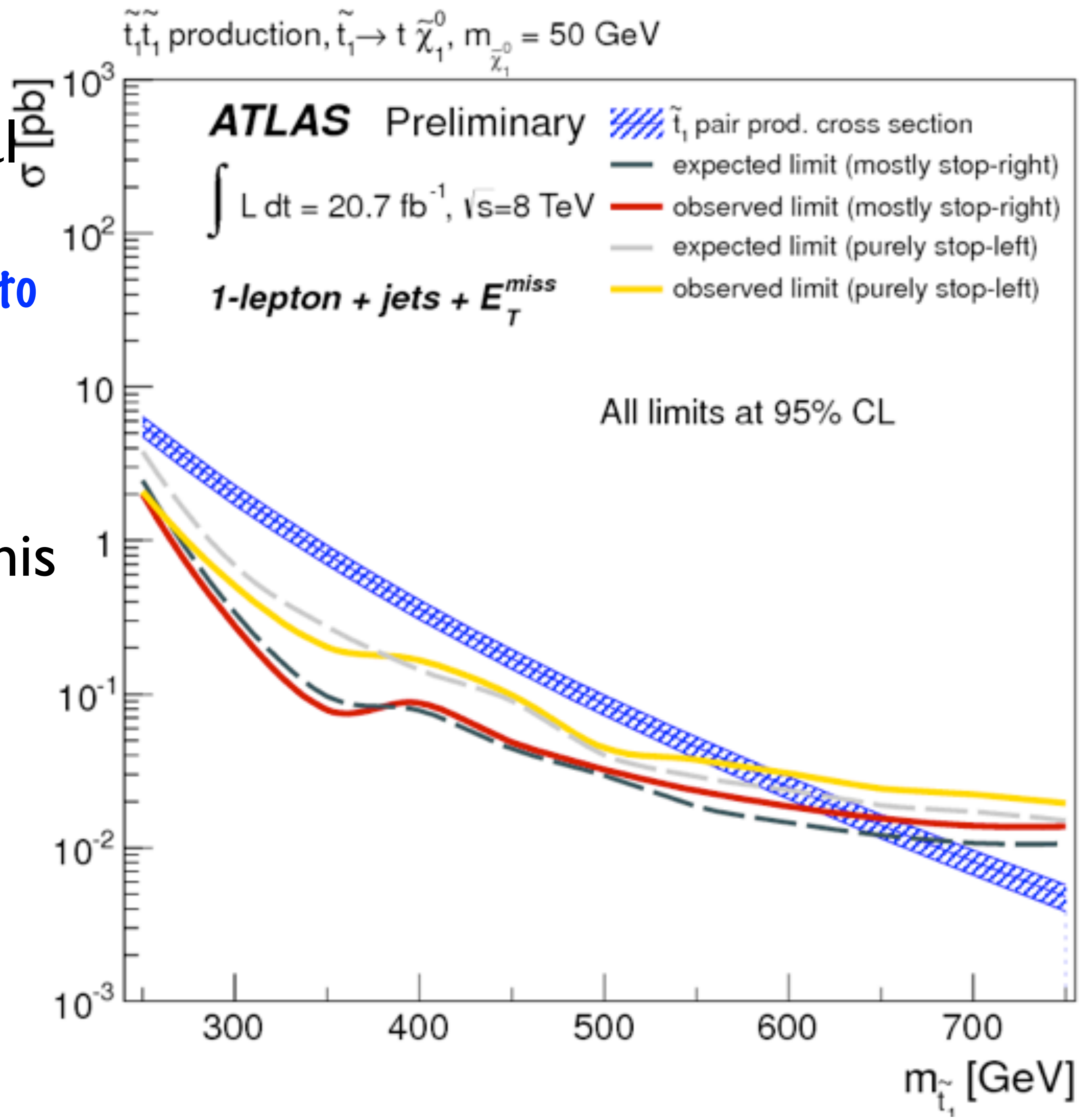


- Look at how sensitivity can increase with more luminosity
- Parton luminosities begin to turn over:
  - ✓ next 50% in reach will require 100 times more lumi (even forgetting backgrounds)
- We need more energy to go to higher masses than 7 or 8 TeV
  - ✓ For now (most 2012) direct heavy production reach is near saturation
- Next most reasonable strategy is go after processes with lower mass and lower xsections.

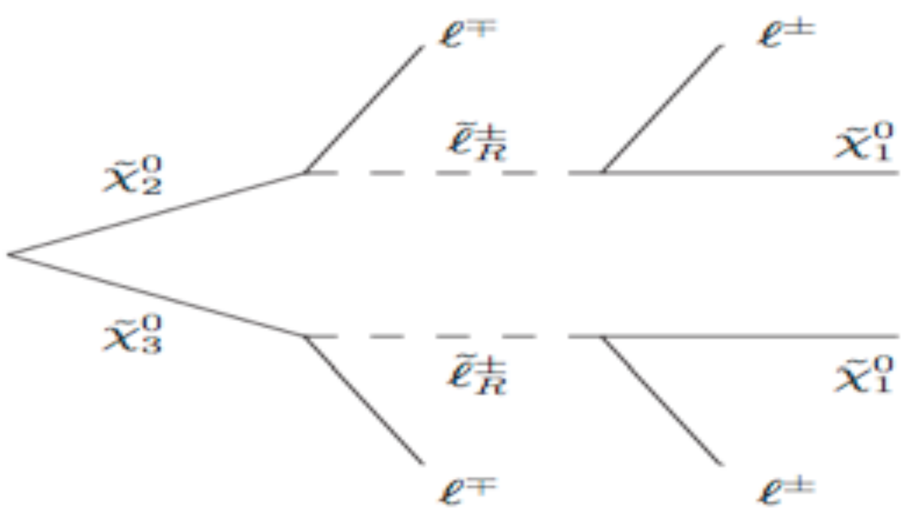


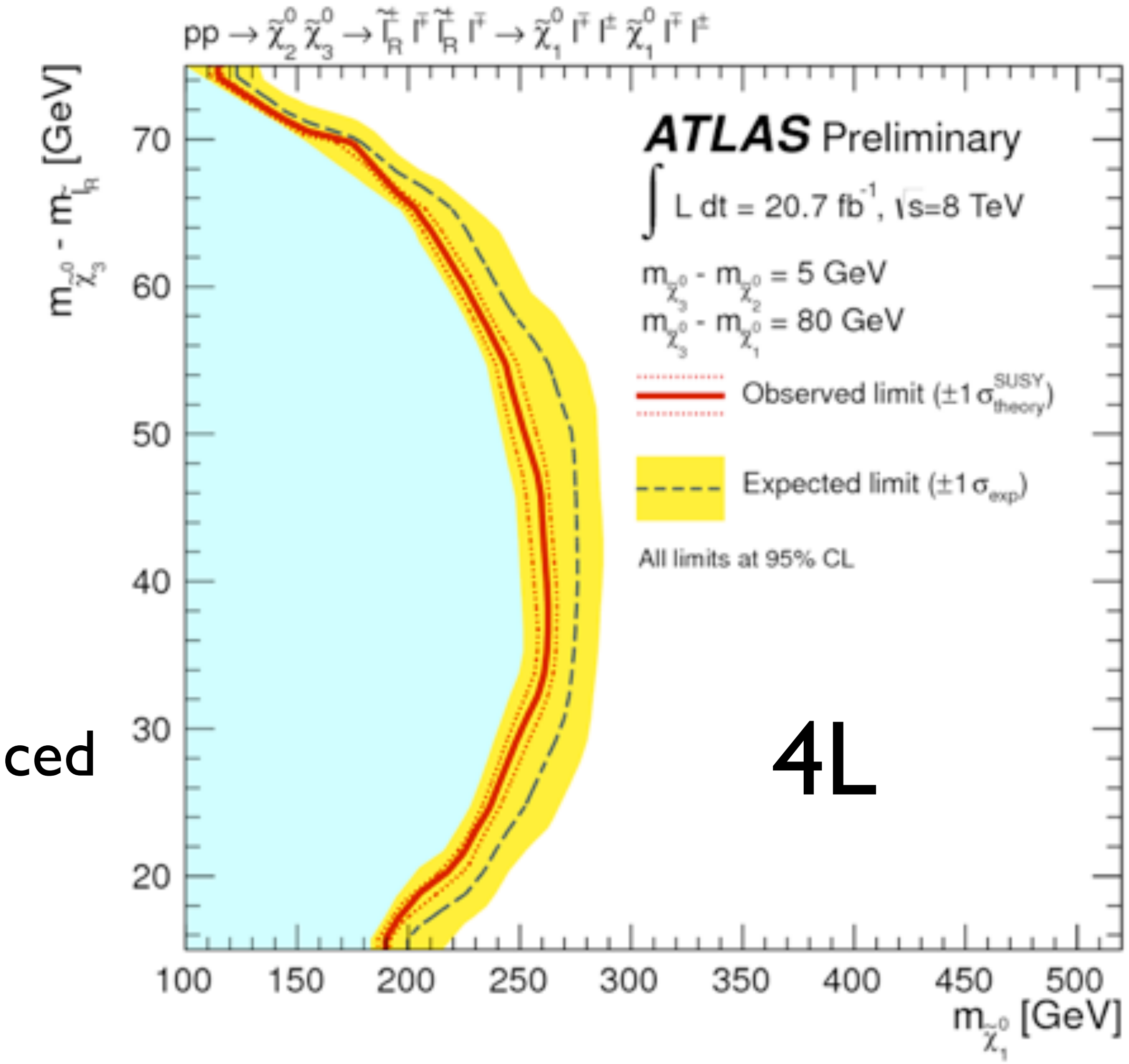
Stop production: chirality matters

- Mixing of L/R in t_l matters to final state kinematics with leptons
  - ✓ t_R leads to leptons with higher pt due to the t-quark polarization
  - ✓ More in arXiv:0811.1024
- Hadronic final states don't have this dependence
- NB re main slides:
  - ✓ CMS has 50/50 L/R
  - ✓ ATLAS has mostly (70%) R
  - ➡ Here
  - ✓ "mostly" means 70% R as well



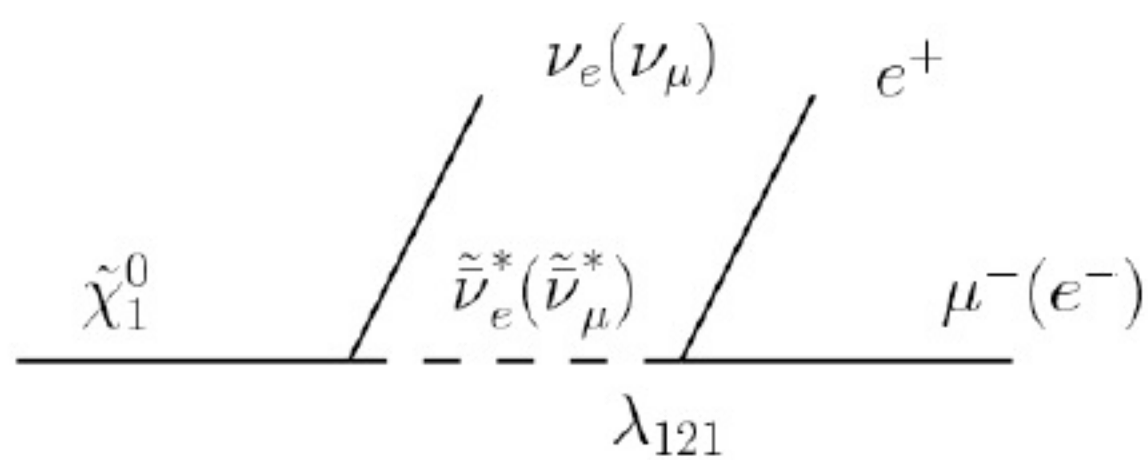
Electroweakinos: 4L





4L appear for 2 neutralinos produced
<== similar method as 3L

- RPV is yet another way to make 4leptons
  - ✓ *see talks at Moriond for details*



Definitions of some variables

$$m_{\mathrm{T}}^{2} = 2 p_{\mathrm{T}}^{\mathrm{lep}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos(\Delta\phi))$$

$$m_{T2} \equiv \min_{\vec{p}_{Ta}^{\,C} + \vec{p}_{Tb}^{\,C} = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}} \{\max(m_{Ta}, m_{Tb})\}$$