Prospects of LHC Run II

a phenomenologist view

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“Developments in String Theory and Quantum Field Theory”
YITP Workshop, Kyoto, Nov 9-13, 2015

Plan of Talk

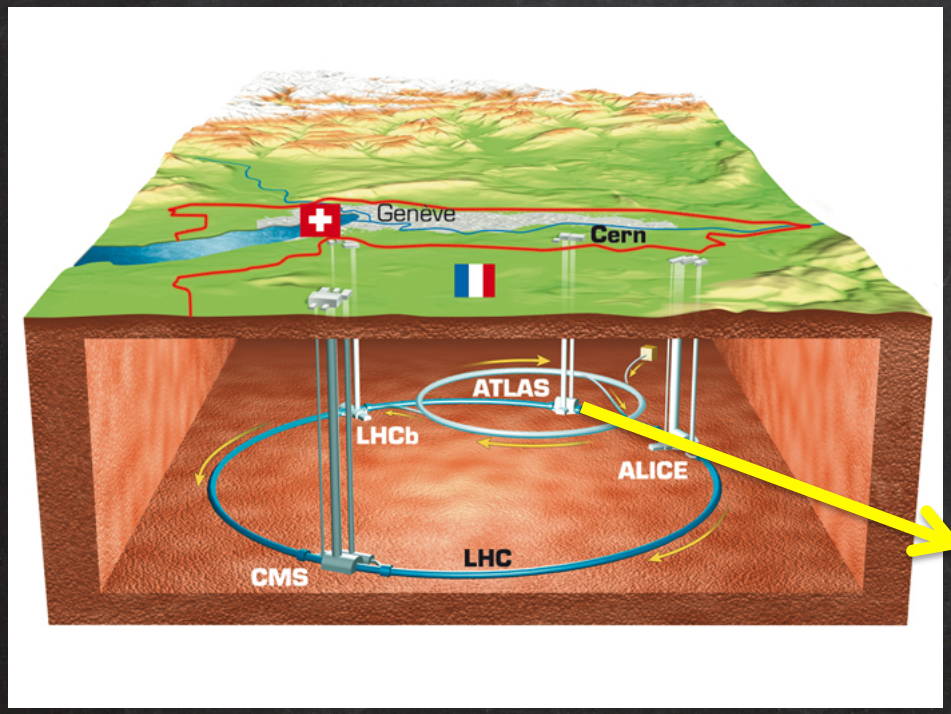
- LHC Status
- Run I Summary

  SM Discovery / BSM Exclusion / Anomalies
- Run II Early Data

LHC Status

Large Hadron Collider (LHC)

26.7 km proton (heavy ion) Accelerator

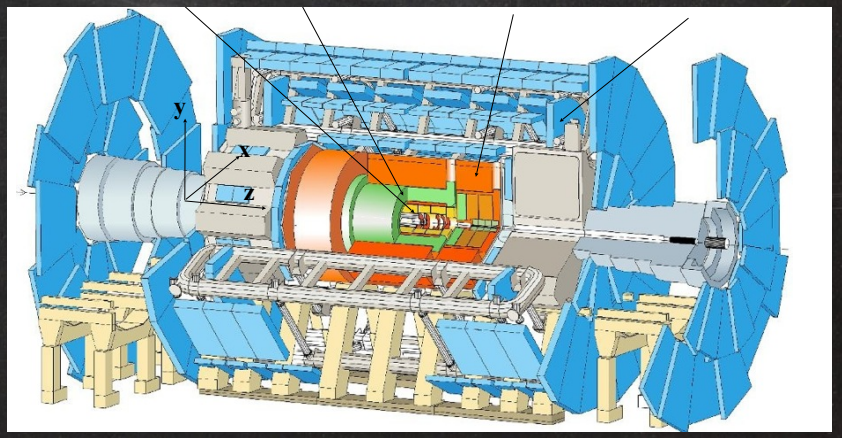


Detector

Multi-purpose : ATLAS / CMS

B physics : LHCb

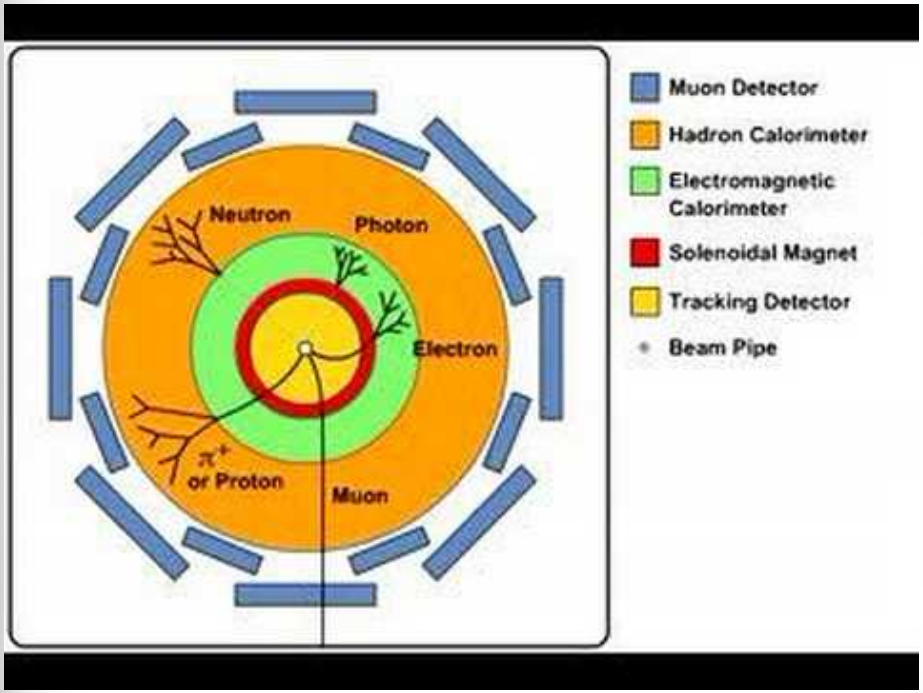
Heavy Ion : ALICE



Detector

Multi-layer structure

Vertex detector EM calorimeter Hadron calorimeter Muon System



Collider Observable

of Events

$$N = \sigma \text{ (cross section)} \times L \text{ (luminosity)}$$

QFT (+ Your model) + Energy

Distributions

$dN/dM,\ dN/d\Theta,\ \cdots$

Collider

of Events

N = σ (cross section)

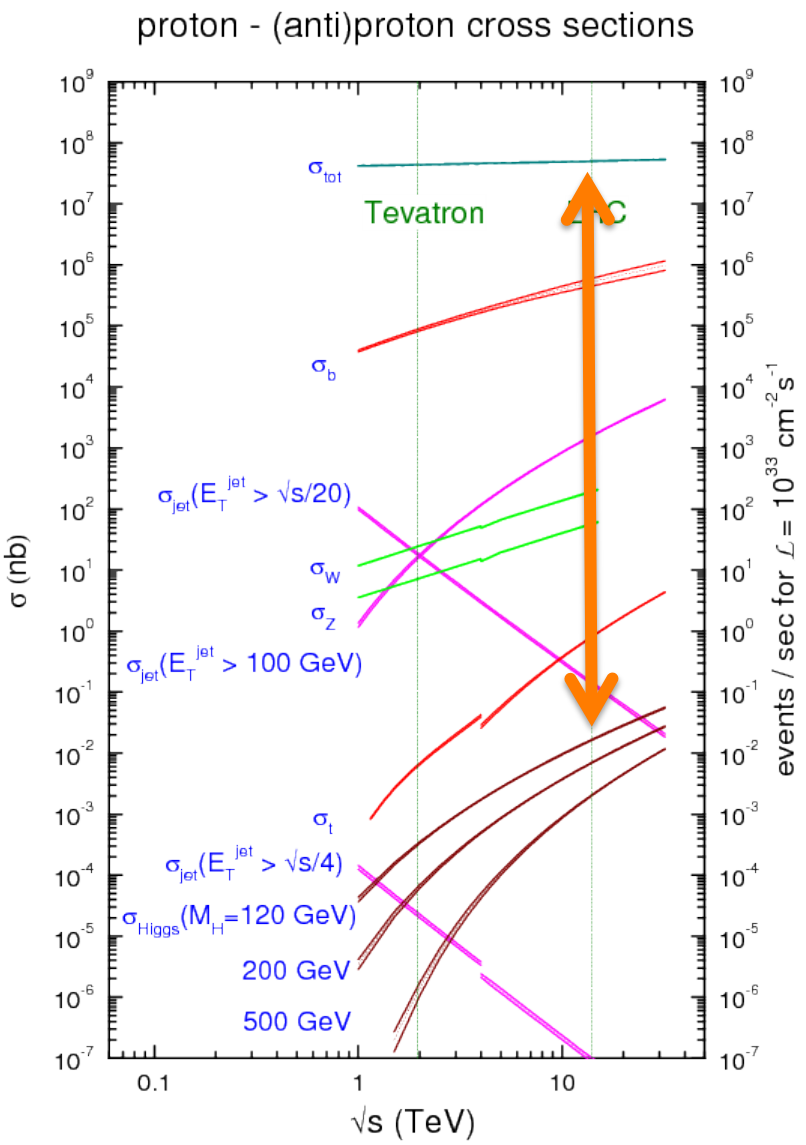
Too Many Data

Signal is 10 orders of magnitude smaller than BG

Need to Reduce Data → Trigger, Selection Cut

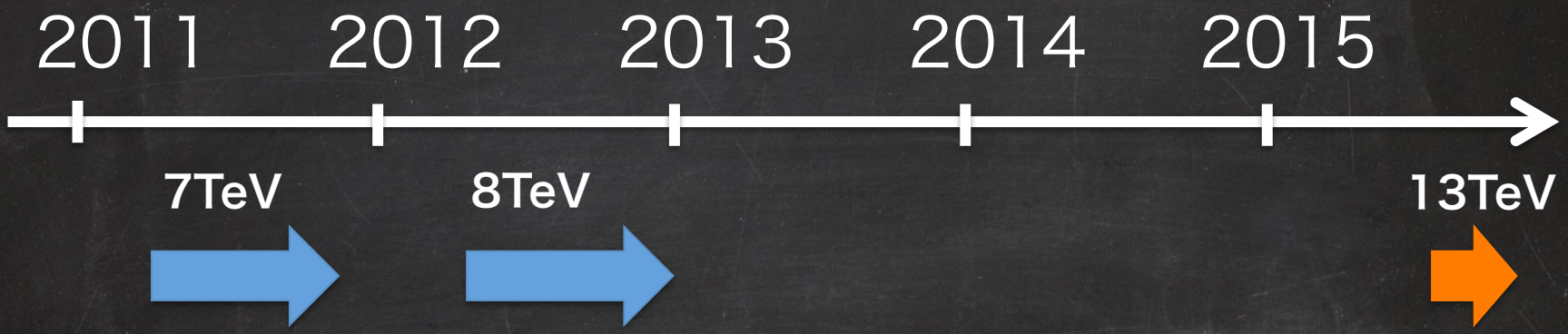
Experimental Challenge

Phenomenologist Idea

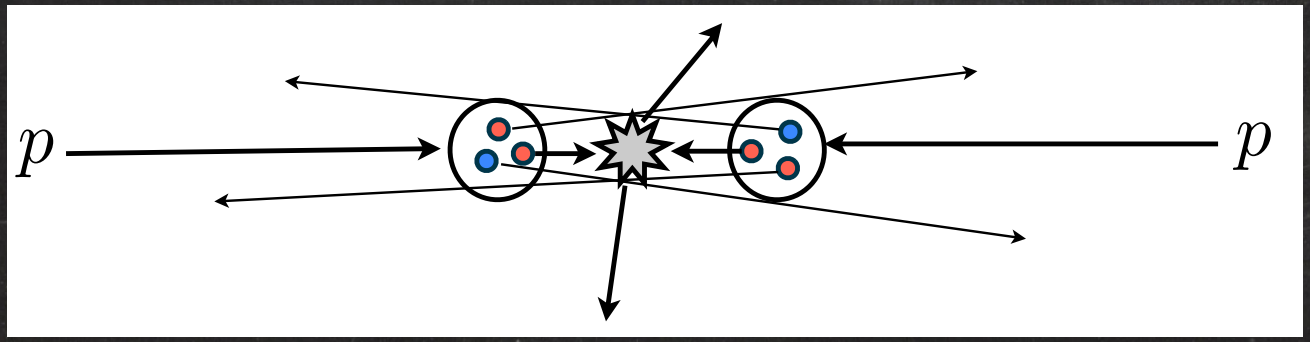


Function of Energy

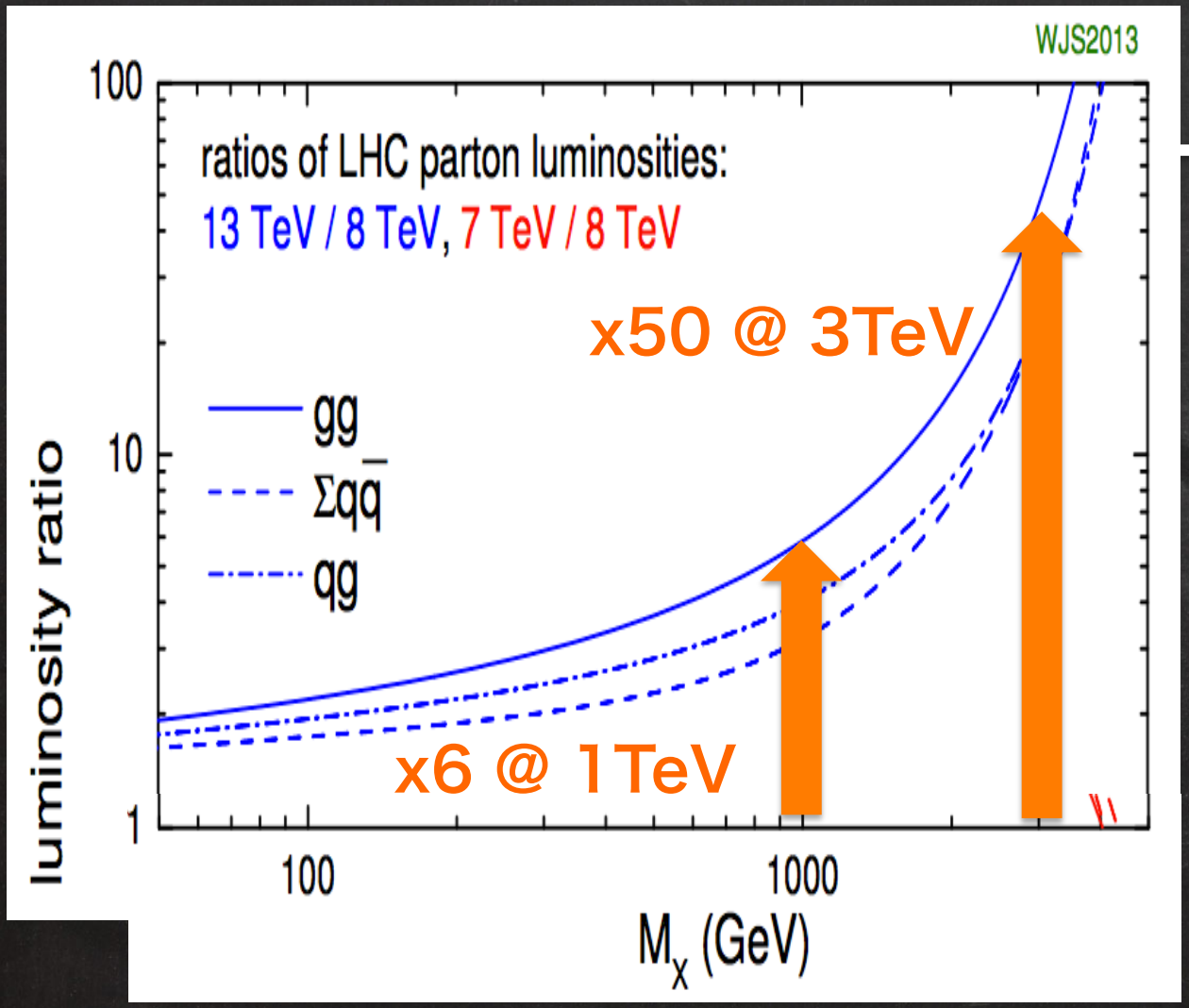
Energy



Run I **Run II**



Energy



2015

13TeV

Run II

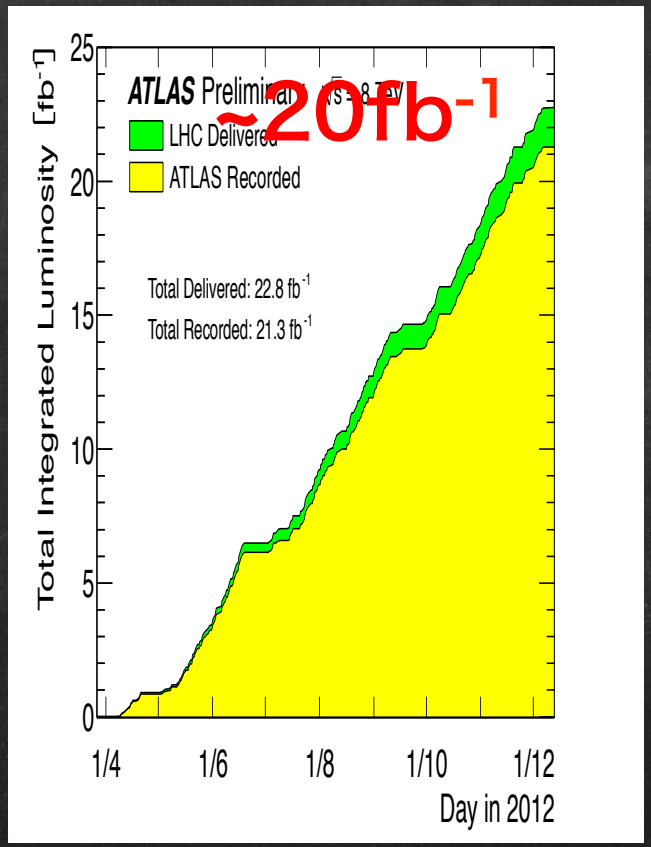
Integrated Luminosity

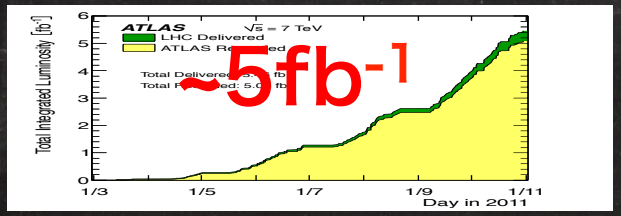
2011 2012 2013 2014 2015

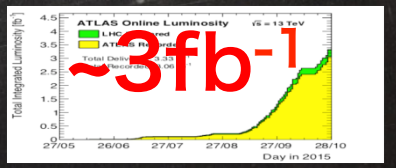
7TeV → 8TeV → 13TeV

Run I

Run II





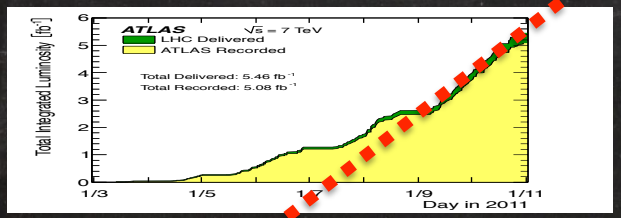


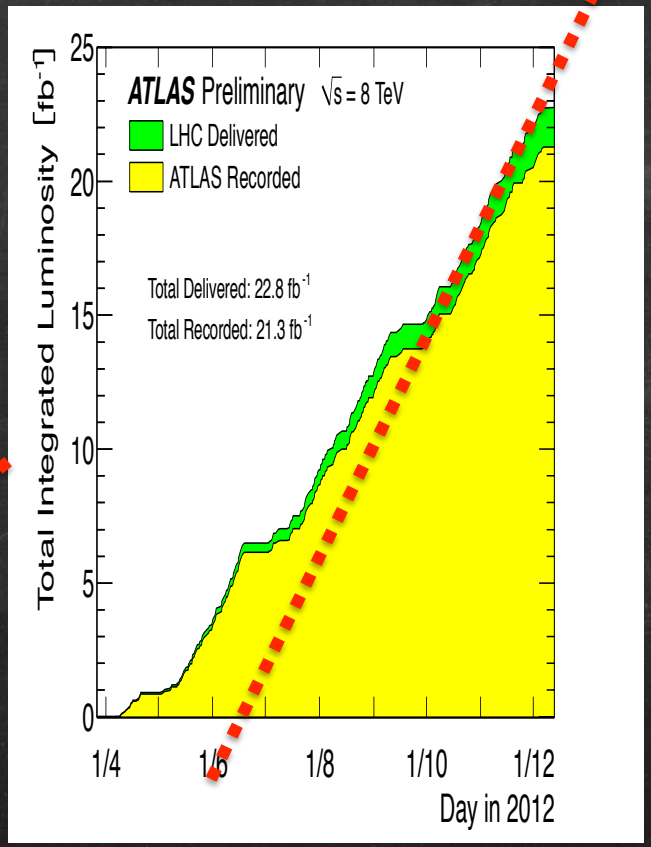
Peak Luminosity

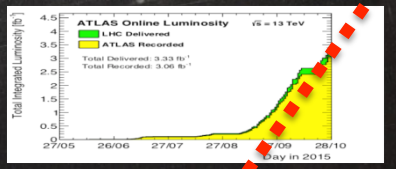
2011 2012 2013 2014 2015

7TeV 8TeV 13TeV

Run I Run II







Peak Luminosity

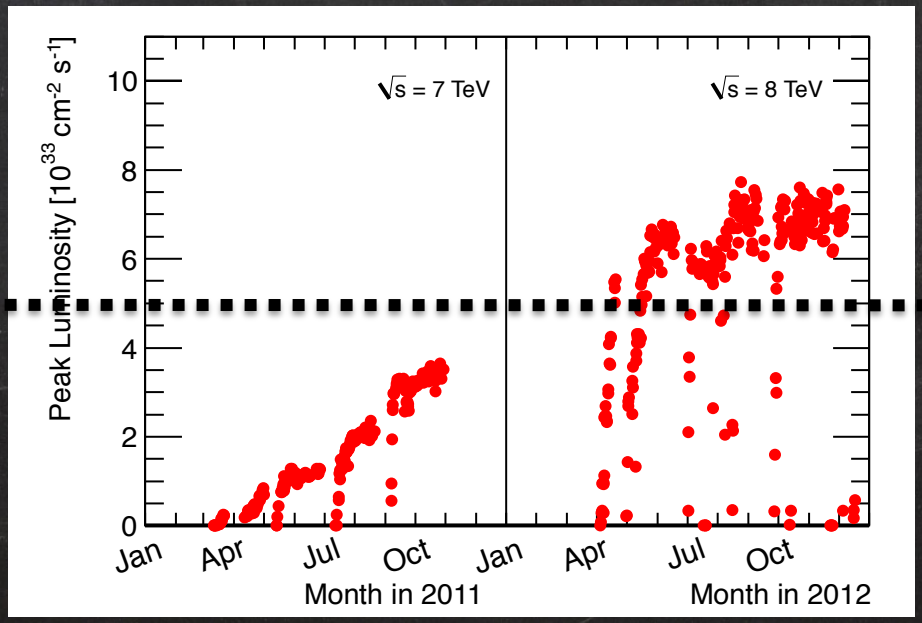
2011 2012 2013 2014 2015

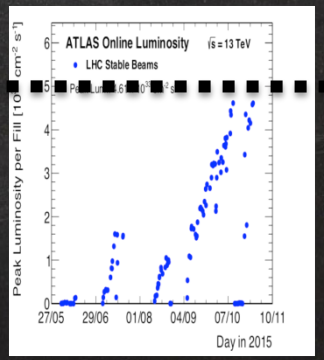
7TeV 8TeV 13TeV

Run I

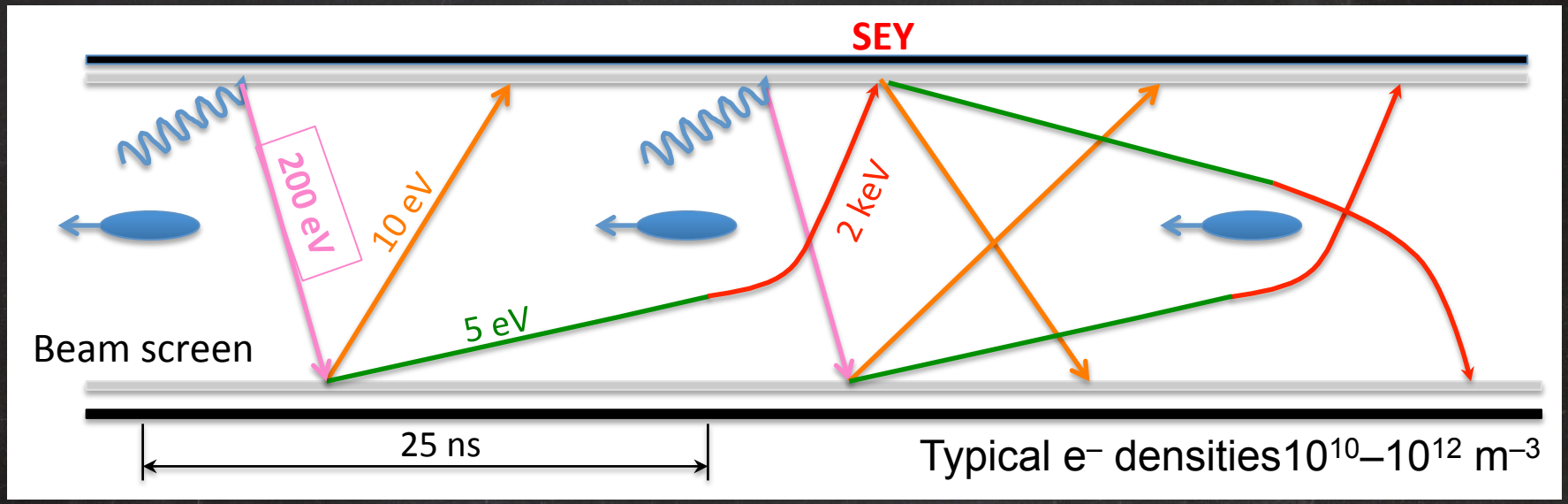
Run II

$5 \times 10^{33}\ cm^{-2}s^{-1}$





Electron Cloud



Synchrotron Rad. → Photo-elec. @ Beam Screen Wall

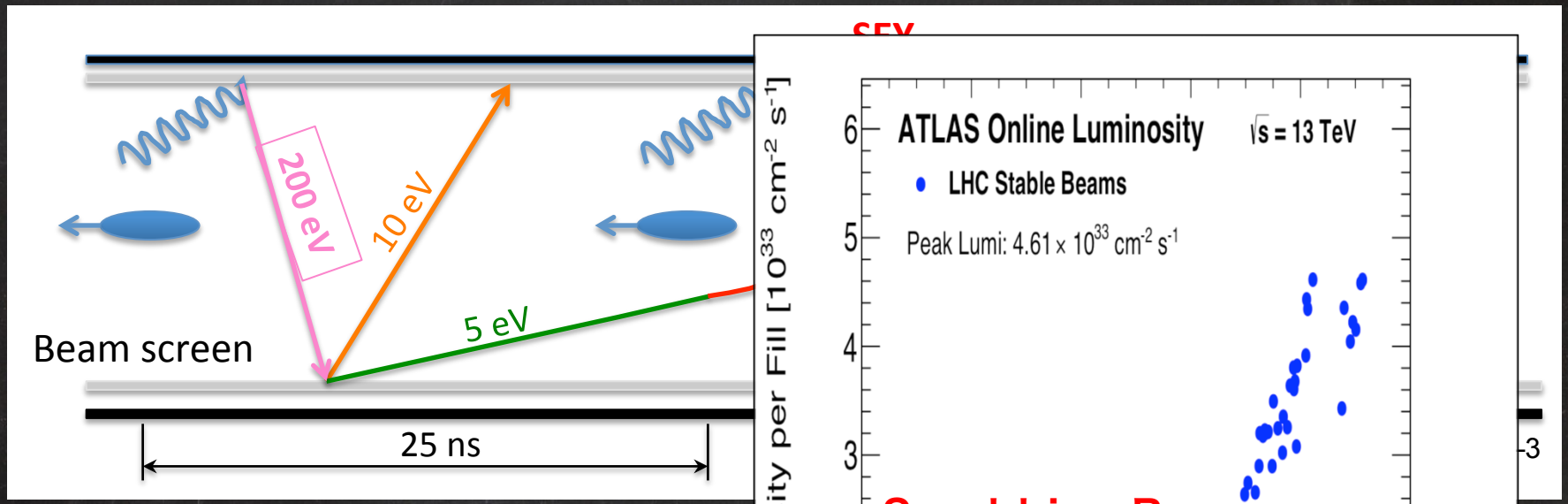
→ Accelerate Electron by Bunch

→ Hit Wall & Emit Secondary Electron

→ **Electron Cloud**

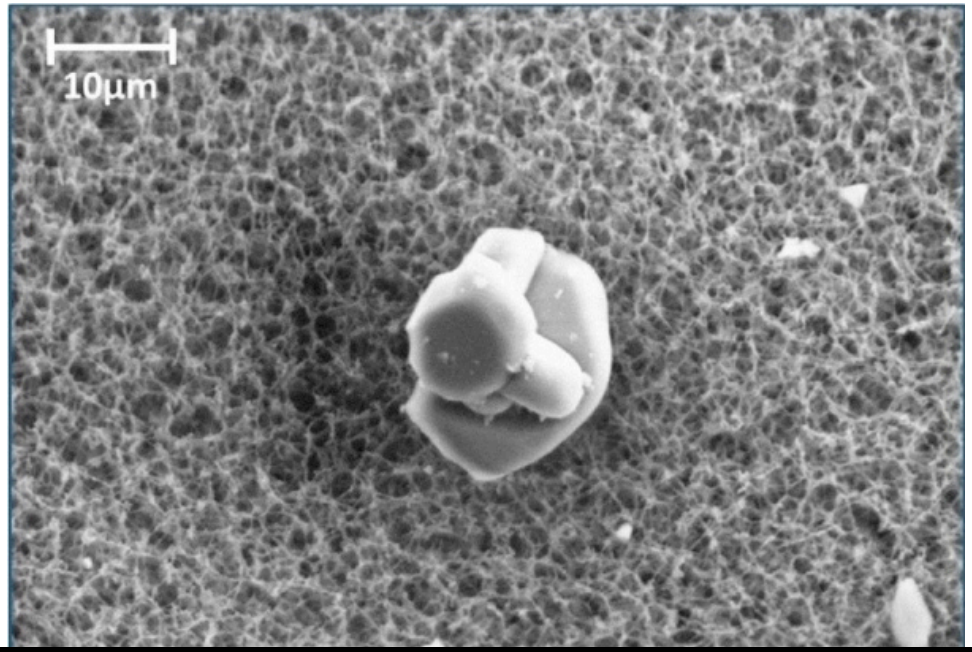
➔ **Emittance growth, Unstable Beam, Heat Cryogenic System**

Electron Cloud



UFO (Undefined Falling Object)

A nice picture of some dust



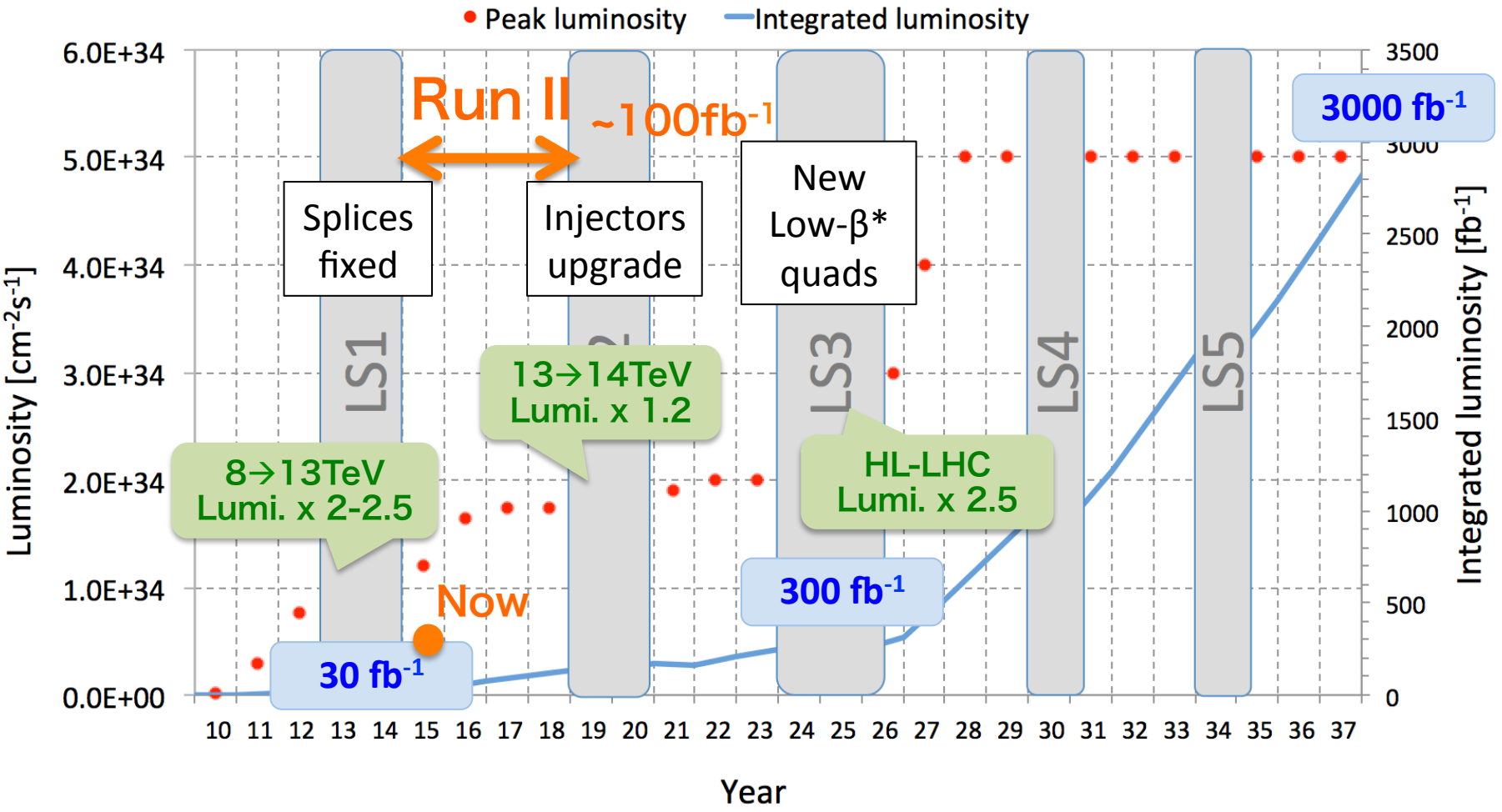
UFOs (dust?) **dropping from upper beam shield**

→ Hit the Beam (Collision outside Detector)

→ Beam Loss ?

→ **Beam Bump** (Need 8hrs for reboot)

Next 20 years



Physics Results

Timeline of Analysis

Run I **Run II**

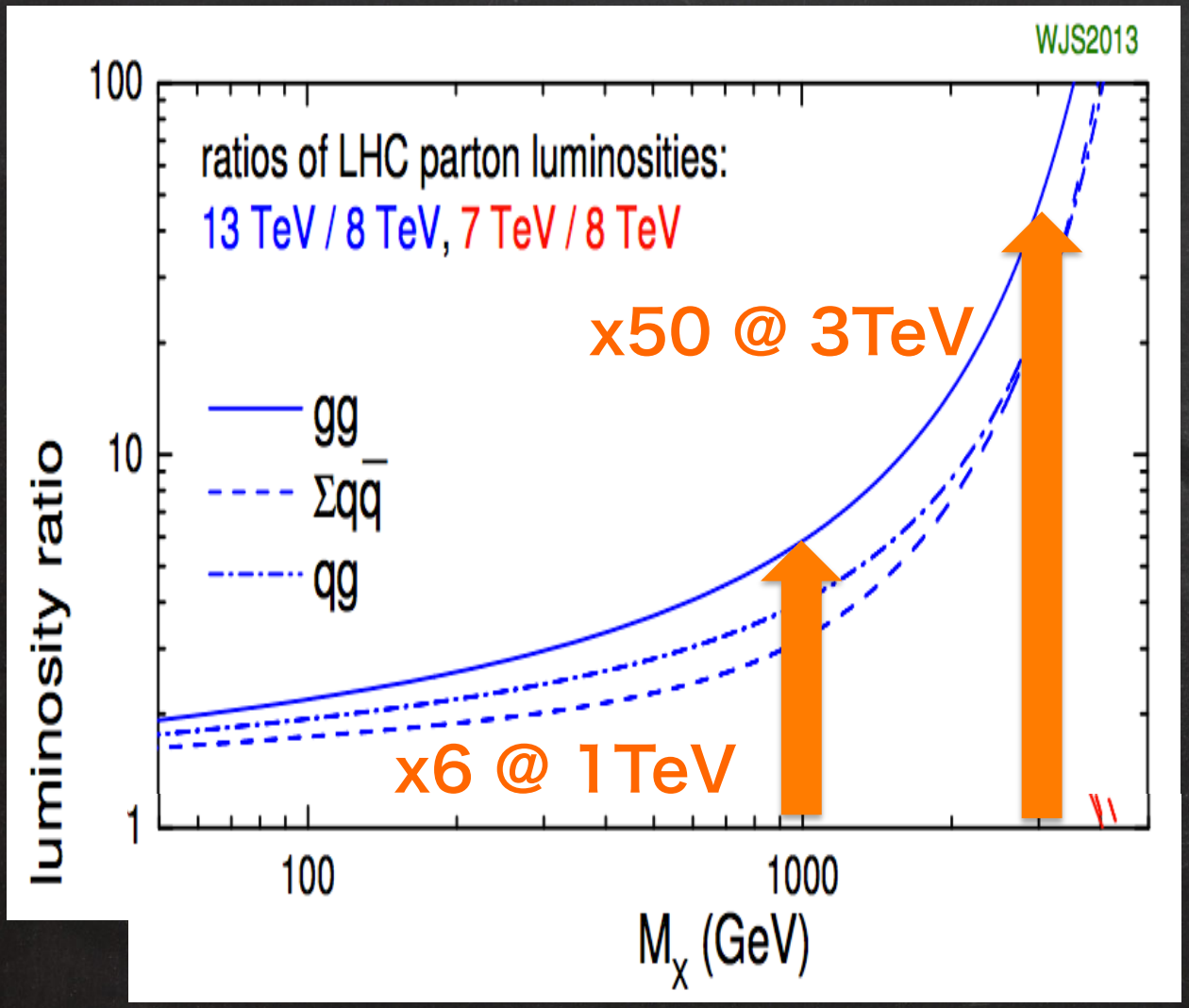
SM Discovery

Simple New Phys.

Higgs

Complicated New Phys., Minor New Phys.

Run II Prospects



Run I ~25fb^{-1} (analyzed)

Run II ~ 3fb^{-1} (collected)

Run II ~ 100pb^{-1} (partly analyzed)

Run I (7/8 TeV)

Dictionary

- Discovery / Observation
  > 5σ [99.99994%]
- Evidence
  > 3σ [99.7%]
- Anomaly (Excess / Deficit / …)
  > 2σ [95.5%]

- Exclusion
  BG only > 2σ [95.5%]

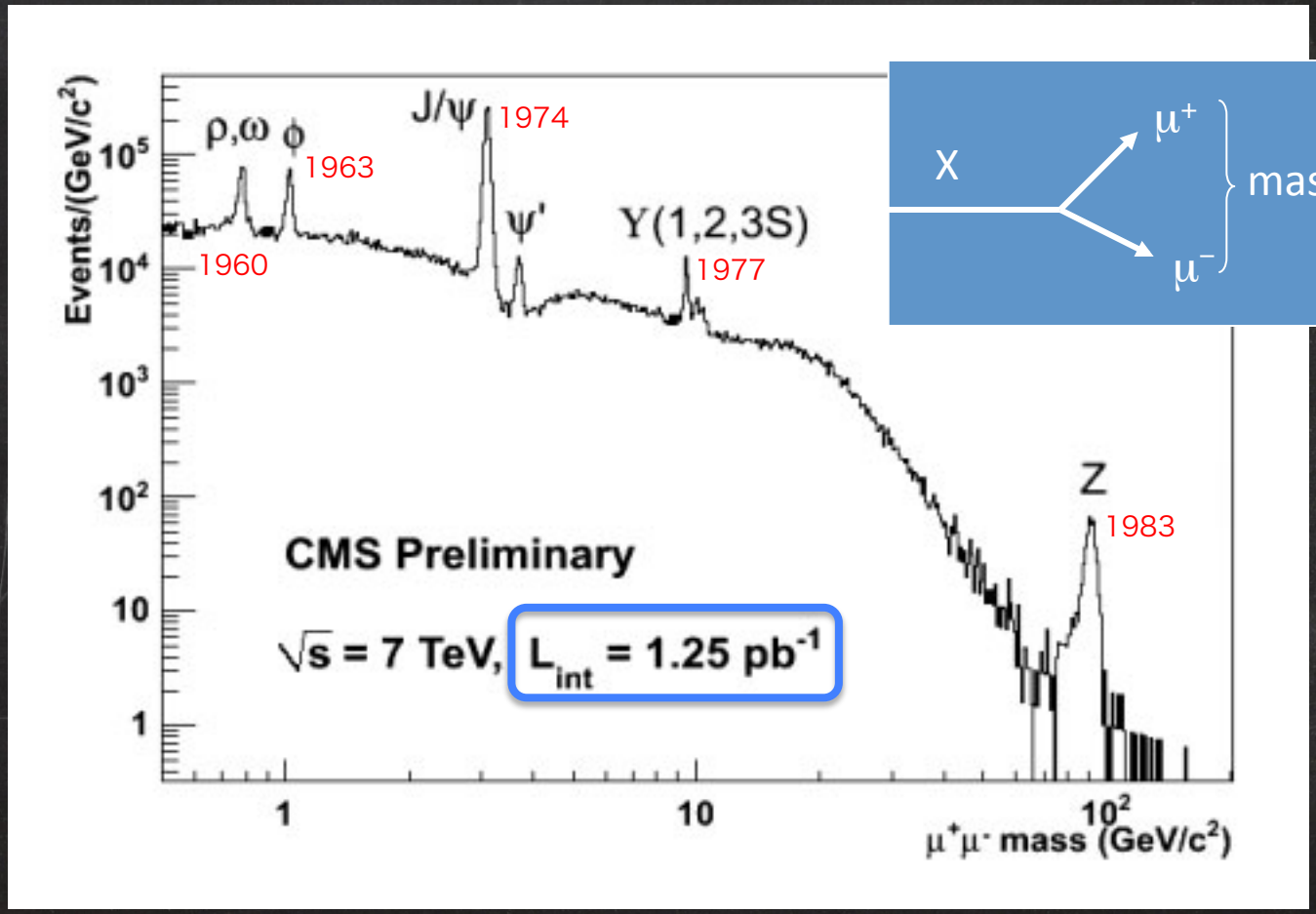
Discovery / Observation

$> 5\sigma$

1/1744278 : Every 4776 years
(Once in recorded history)
99.99994%

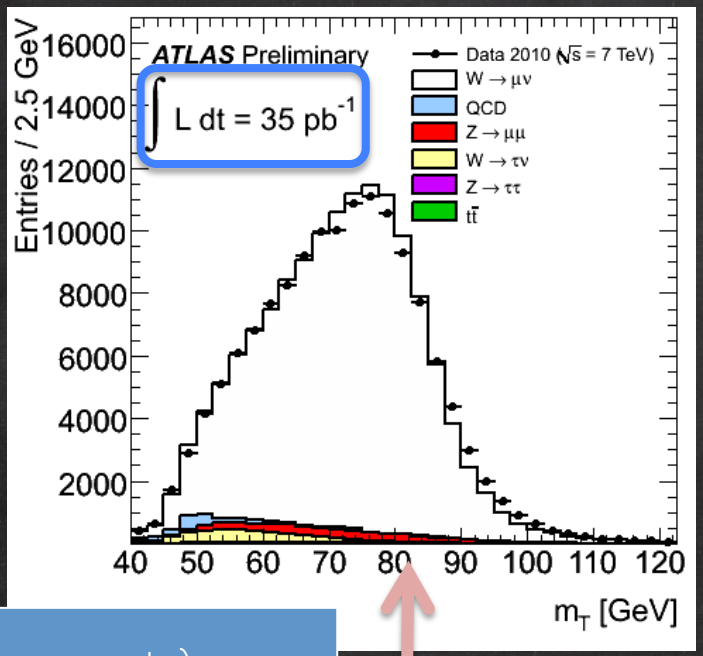
Re-Discovery of the SM

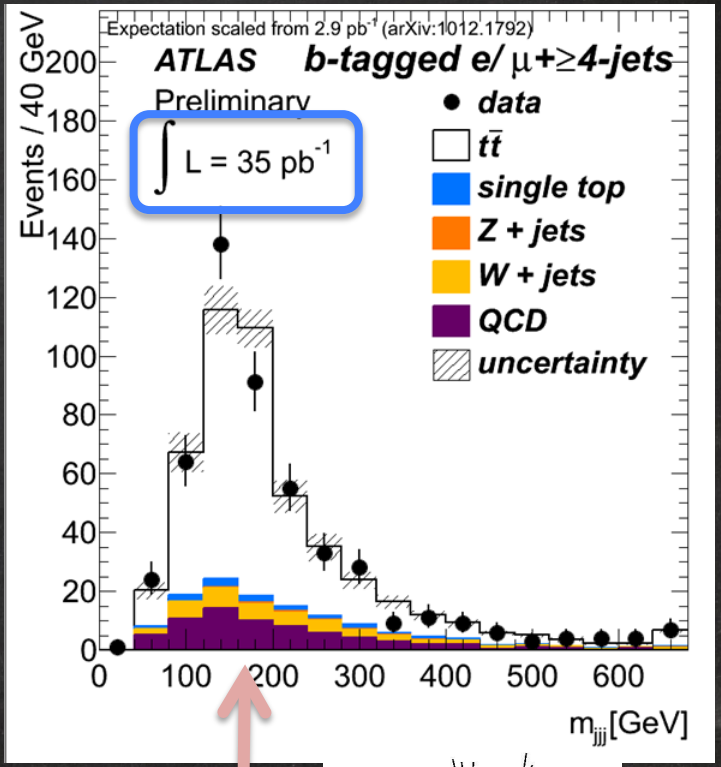
$M_{\mu\mu} = \sqrt{(p_{1\mu} + p_{2\mu})^2}$: Di-Muon Invariant Mass

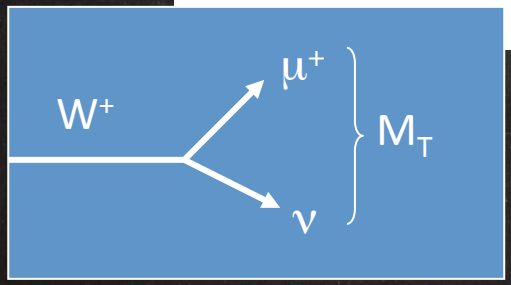


Re-Discovery of W, top

lepton + Missing E_T(ν) [w/ p_T conservation]

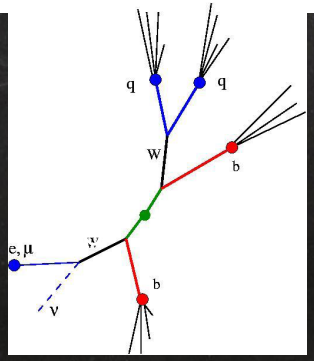






M_W

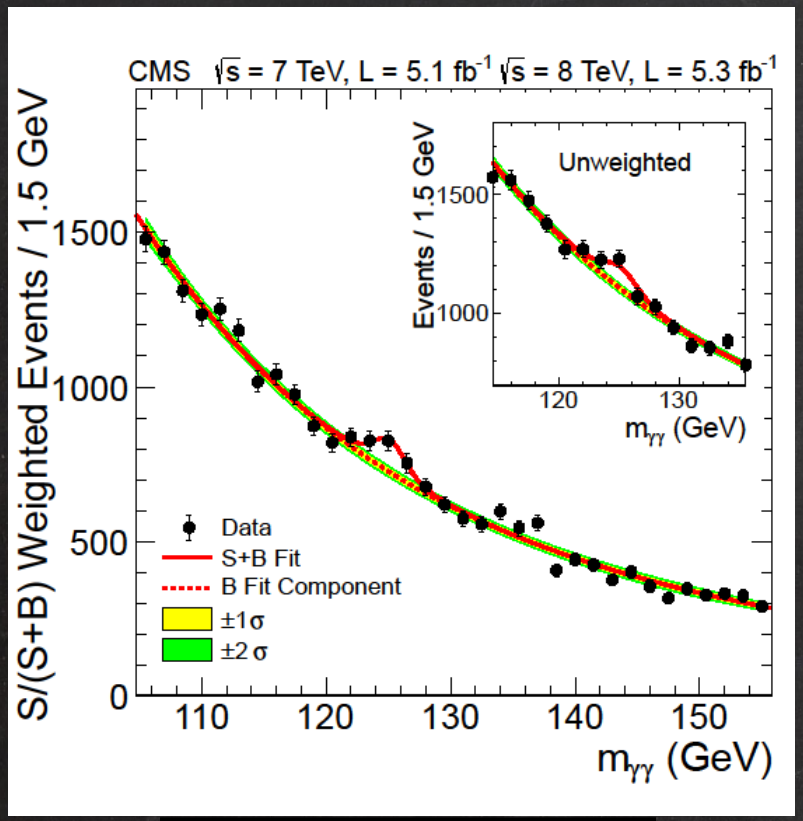
M_t

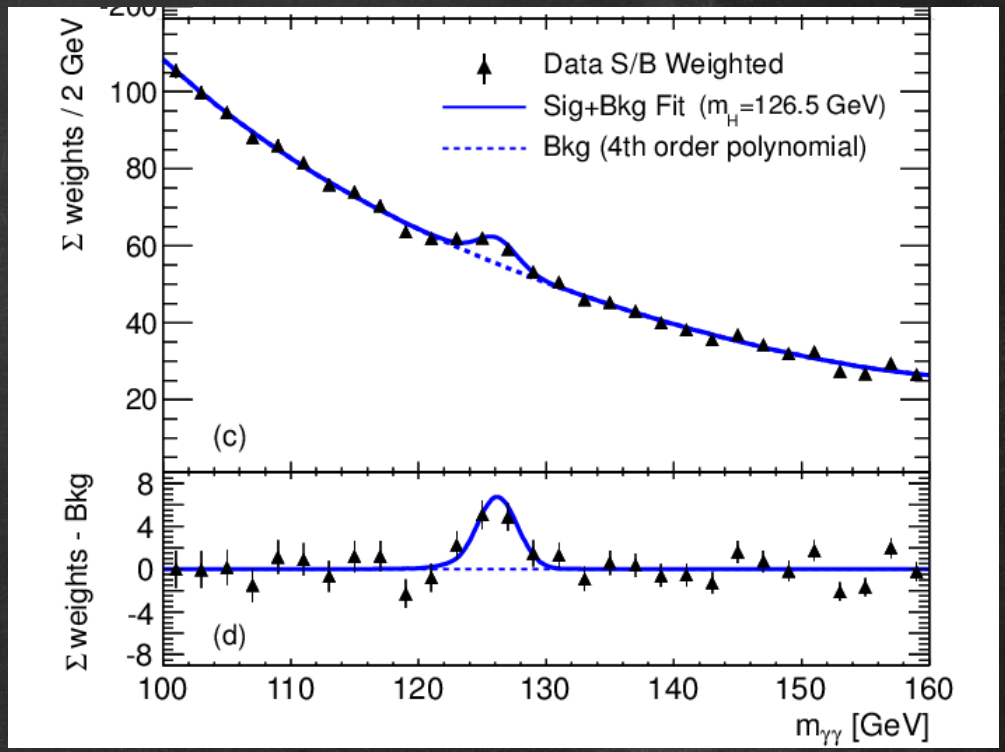


$$M_T = \sqrt{2p_T^{\ell} p_T^{\nu} \left(1 - \cos(\phi^{\ell} - \phi^{\nu})\right)}$$

Higgs

Higgs Discovery





PDG 2015 update

New, Oct 2015 (cutoff 15th Jan)

H^0

$J = 0$

Now, we can make precise predictions

Mass $m = 125.09 \pm 0.24$ GeV

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)

$WW^* = 0.81 \pm 0.16$

$ZZ^* = 1.15^{+0.27}_{-0.23}$ (S = 1.2)

$\gamma\gamma = 1.17^{+0.19}$

$b\bar{b}$

$\mu^+\mu^-$ <

$\tau^+\tau^- = 0.79 \pm 0.26$

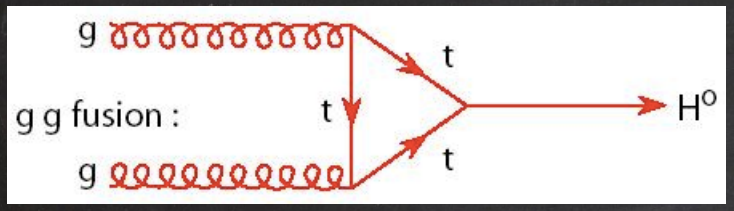
$Z\gamma <$ 9.5, CL = 95%

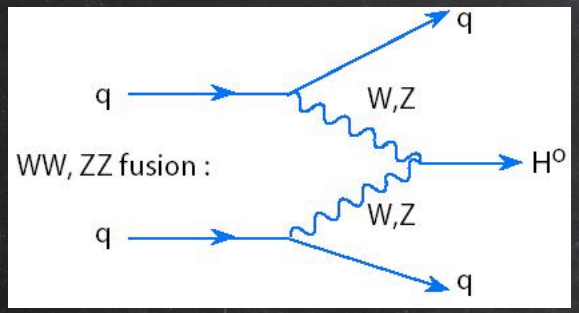
$t\bar{t}H^0$ Production $= 2.5^{+0.9}_{-0.8}$

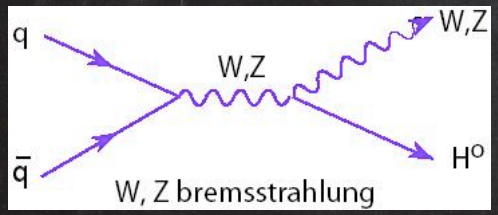
Official Combination

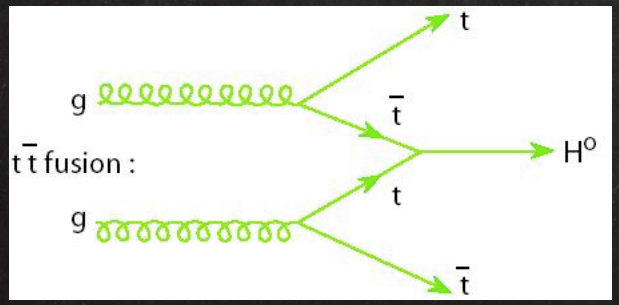
H^0 DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
invisible	<58 %	95%	–

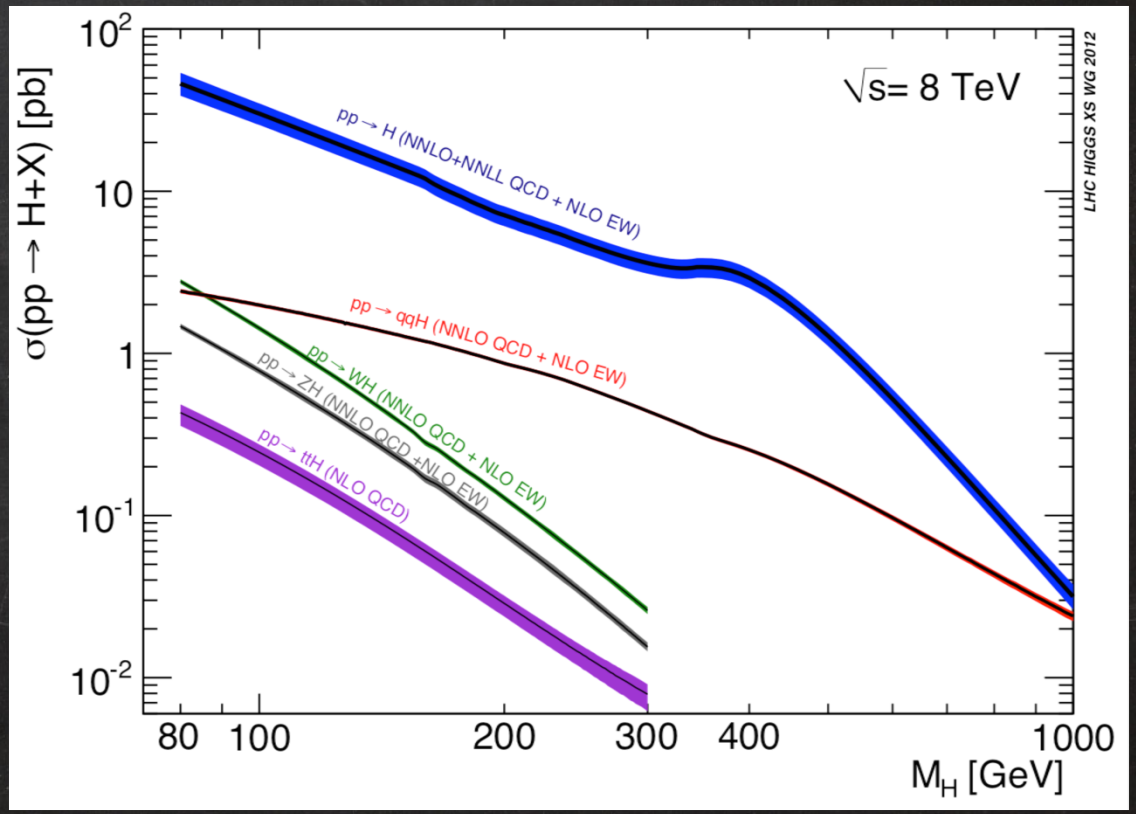
Higgs Production



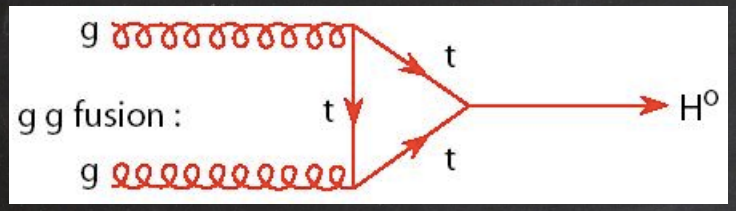


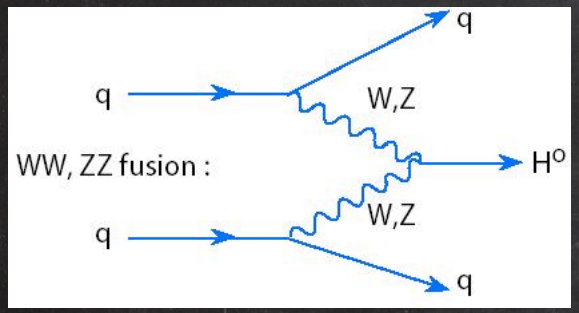


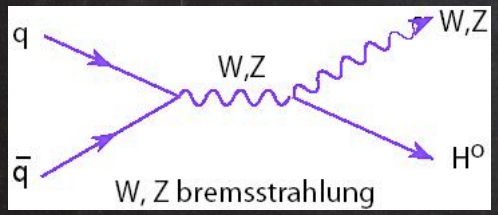


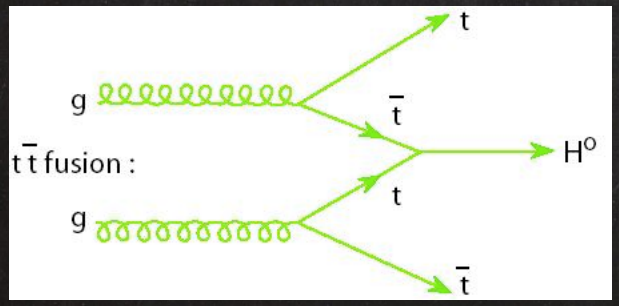


Higgs Production



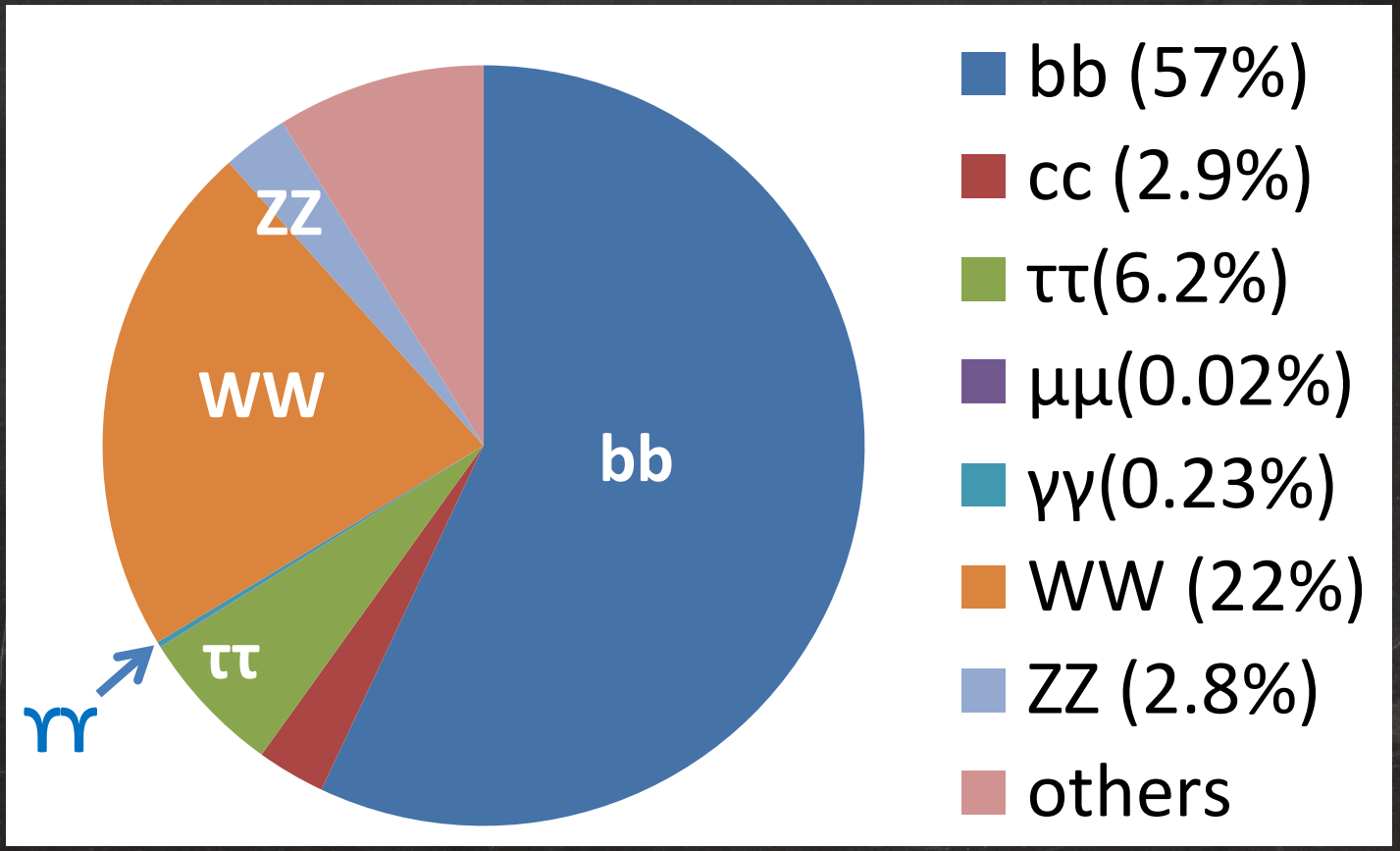






	σ (pb) @7TeV	σ (pb) @14TeV	14TeV /7TeV
Gluon Fusion (ggF)	15.3	50.0	3.3
Vector Boson Fusion (VBF)	1.2	4.2	3.5
Higgs-strahlung (WH, ZH)	0.6, 0.3	1.5, 0.9	2.5, 3.0
ttH	0.1	0.6	6.0
ttbar [BG]	170	830	4.9

Higgs Decay


bb
cc
ττ
μμ
γγ
WW
ZZ
bb (57%)
cc (2.9%)
ττ(6.2%)
μμ(0.02%)
γγ(0.23%)
WW (22%)
ZZ (2.8%)
others

New, 15th Sep 2015

Official Combination

Individual Results

μ = Observed / Expected

Channel	Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	$1.15^{+0.27}_{-0.25}$ ($^{+0.26}_{-0.24}$)	$1.12^{+0.25}_{-0.23}$ ($^{+0.24}_{-0.22}$)	5.0 (4.6)	5.6 (5.1)
$H \to ZZ \to 4\ell$	$1.51^{+0.39}_{-0.34}$ ($^{+0.33}_{-0.27}$)	$1.05^{+0.32}_{-0.27}$ ($^{+0.31}_{-0.26}$)	6.6 (5.5)	7.0 (6.8)
$H \to WW$	$1.23^{+0.23}_{-0.21}$ ($^{+0.21}_{-0.20}$)	$0.91^{+0.24}_{-0.21}$ ($^{+0.23}_{-0.20}$)	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	$1.41^{+0.40}_{-0.35}$ ($^{+0.37}_{-0.33}$)	$0.89^{+0.31}_{-0.28}$ ($^{+0.31}_{-0.29}$)	4.4 (3.3)	3.4 (3.7)
$H \to bb$	$0.62^{+0.37}_{-0.36}$ ($^{+0.36}_{-0.37}$)	$0.81^{+0.45}_{-0.42}$ ($^{+0.45}_{-0.43}$)	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	-0.7 ± 3.6 (± 3.6)	0.8 ± 3.5 (± 3.5)		
ttH production	$1.9^{+0.8}_{-0.7}$ ($^{+0.72}_{-0.66}$)	$2.9^{+1.0}_{-0.9}$ ($^{+0.88}_{-0.80}$)	2.7 (1.6)	3.6 (1.3)

20-30%

30-40%

>5σ

>3σ

Observation of gg, ZZ, WW

Evidence of $\tau\tau$, (tt)

Need more data for bb (Run II)
for μμ, Zγ (HL-LHC)

New, 15th Sep 2015

Official Combination

Individual Results

Channel	Signal strength [μ]		Signal significance [σ]	
	from results in this paper (Section 5.2)			
	ATLAS	CMS	ATLAS	CMS
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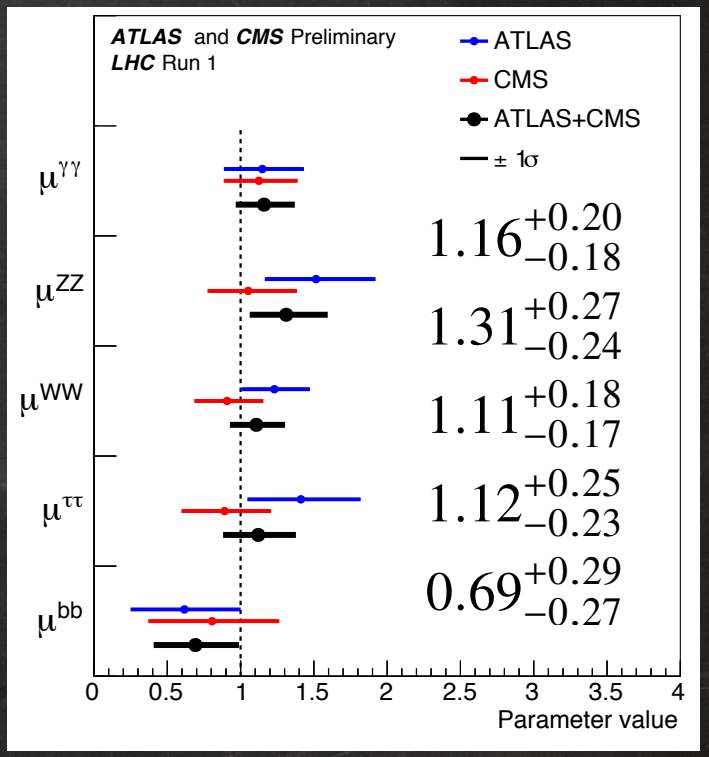
20-30%

30-40%

>5σ

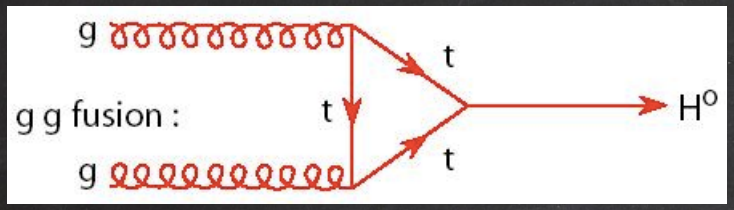
>3σ

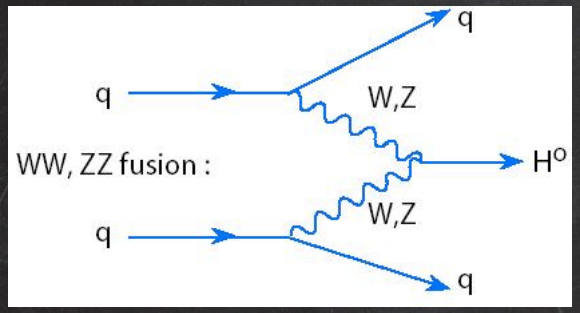
Combined Results

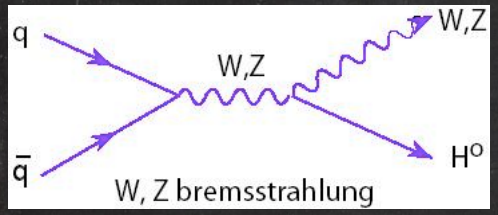


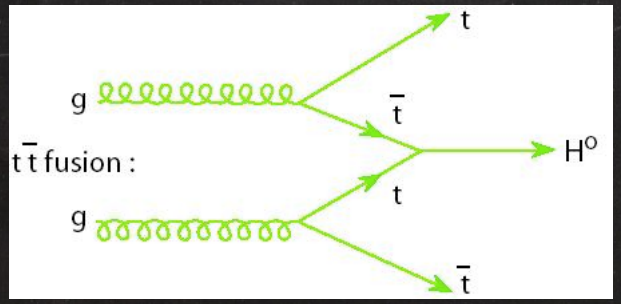
New, 15th Sep 2015

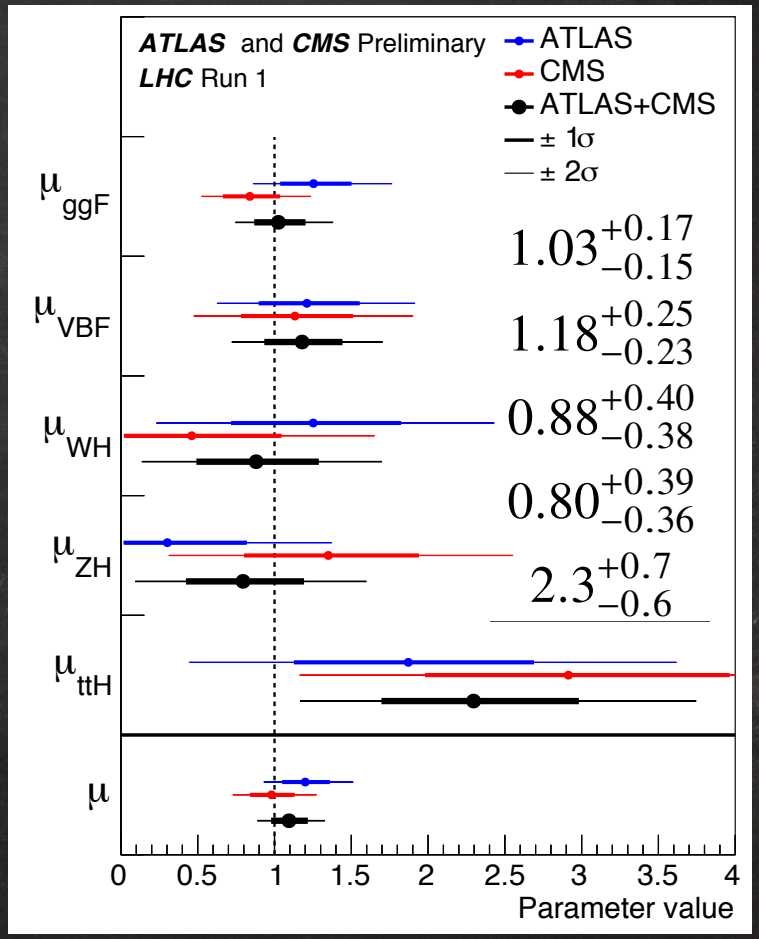
Testing Higgs Production



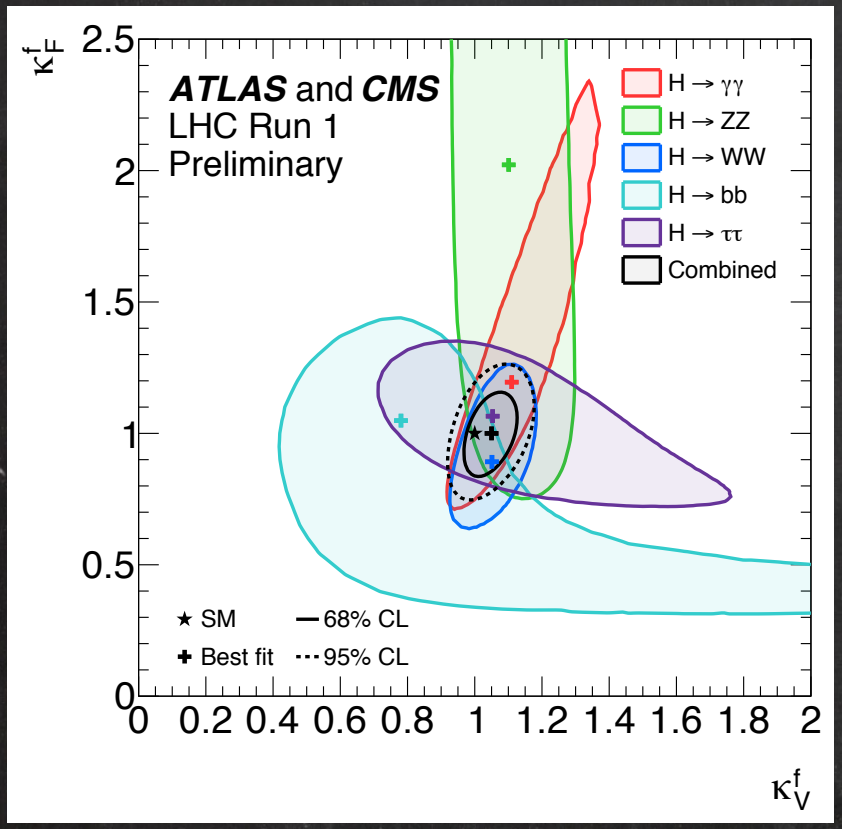


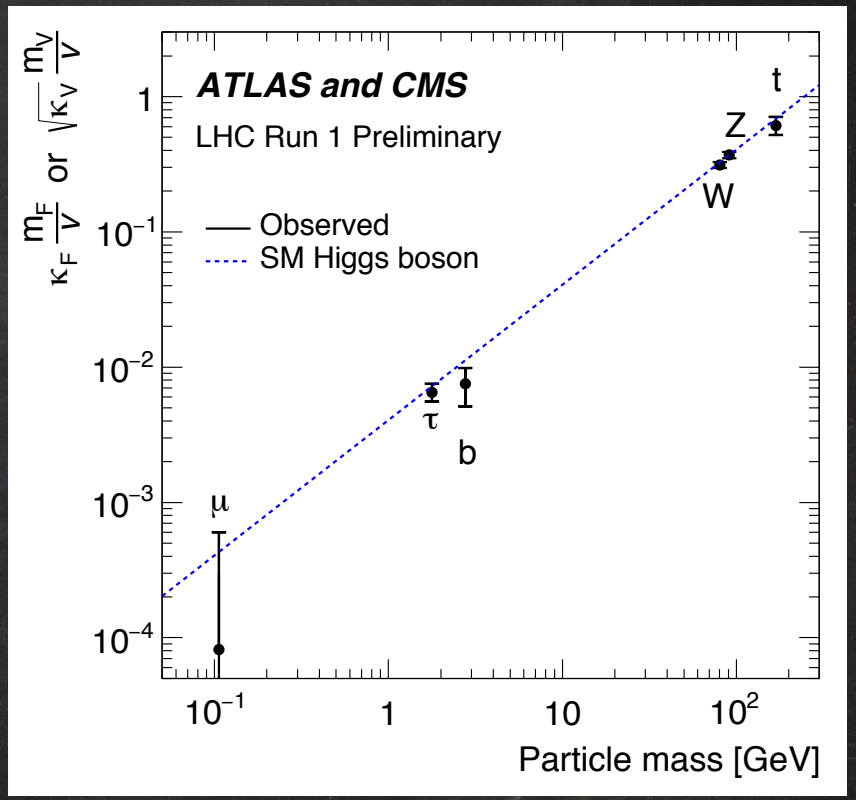






Testing Higgs Coupling





Indirect Test of BSM w/o New Particles

Exclusion / Non-discovery

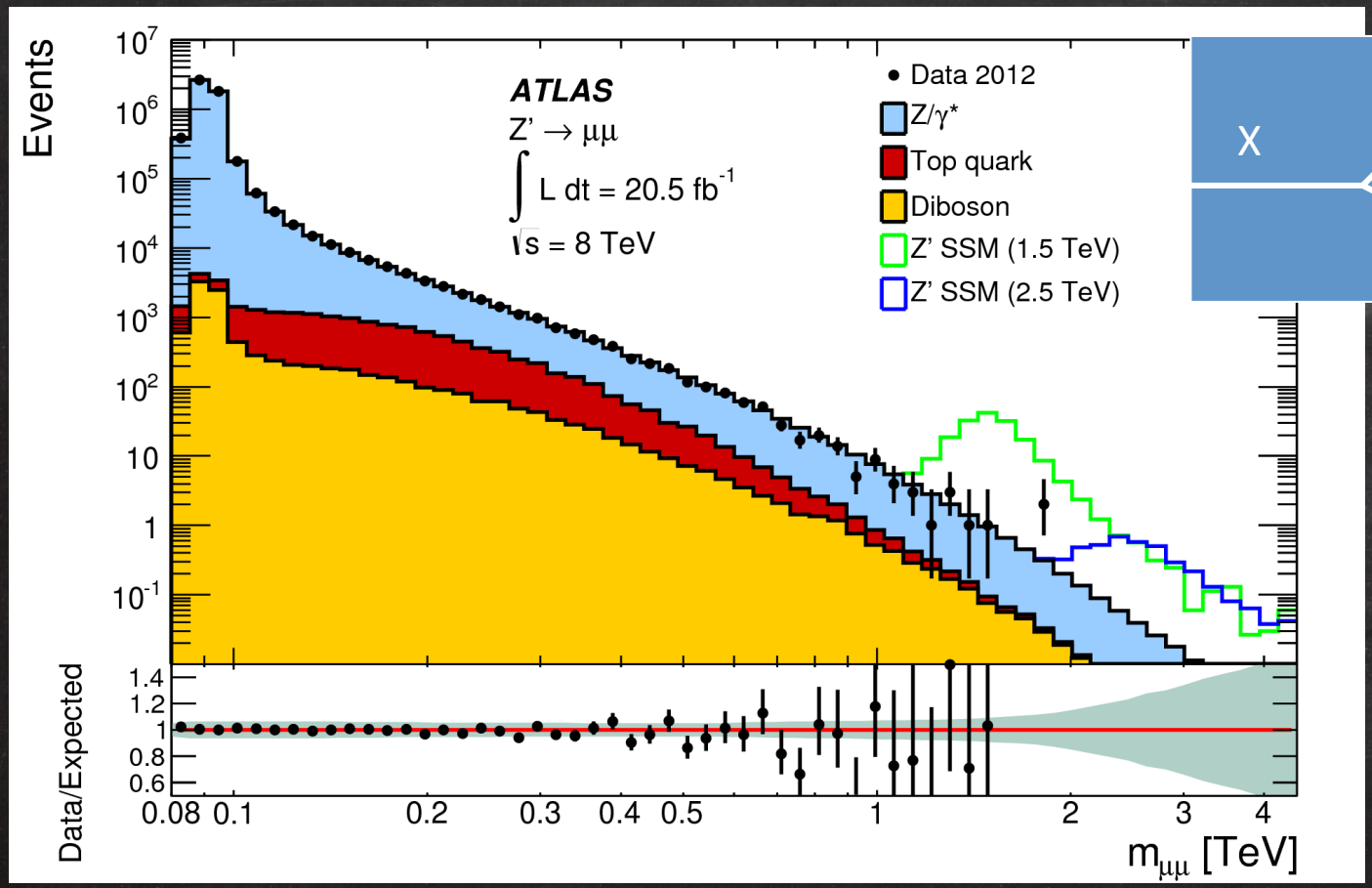
BG Only Hypothesis > 2σ

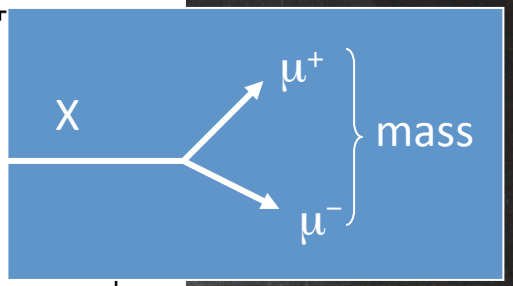
1/22 : Every 3 weeks
95.5%

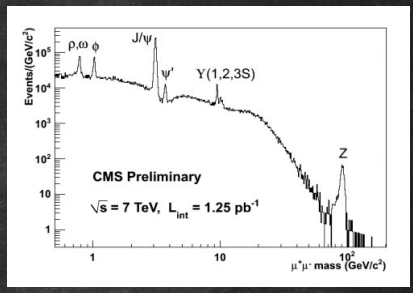
Z' search (resonance search)

$M_{\ell\ell} = \sqrt{(p_{1\ell} + p_{2\ell})^2}$: di-lepton Invariant Mass

Event Topology

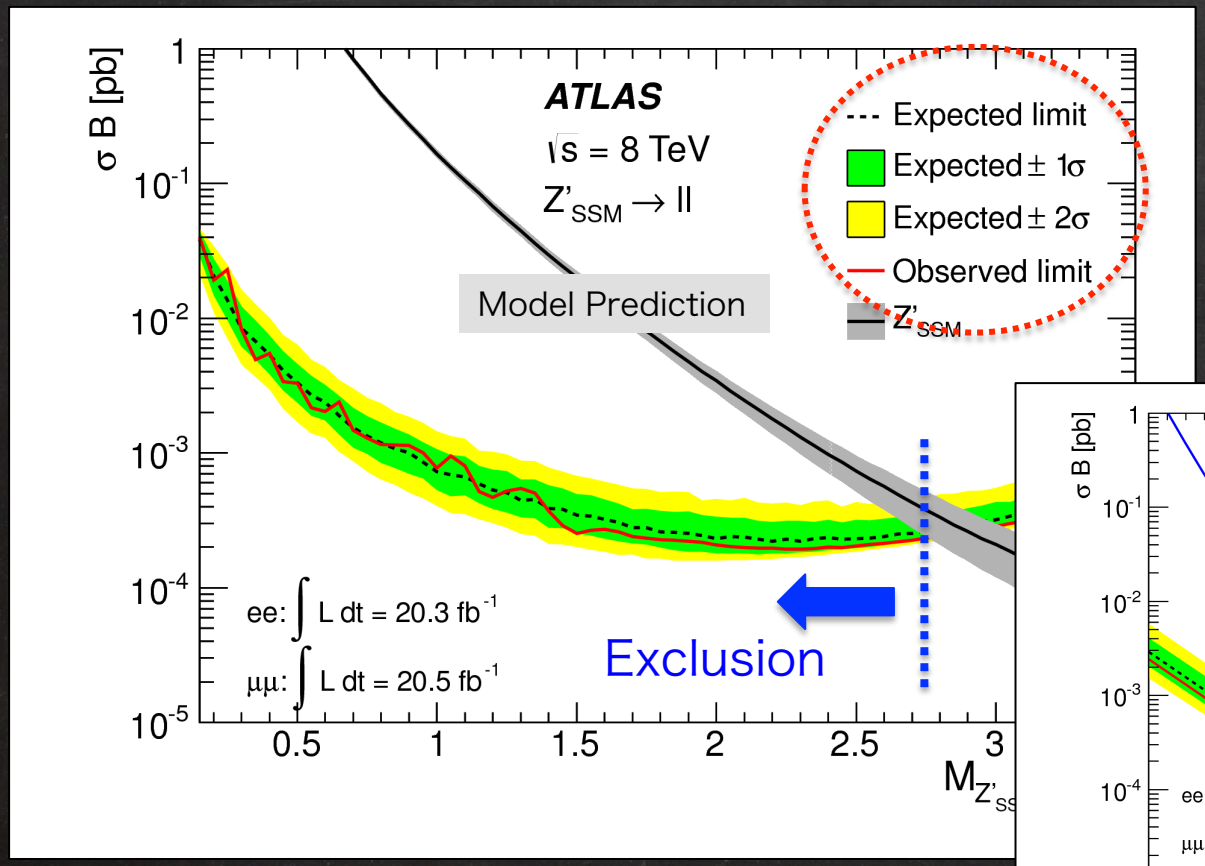


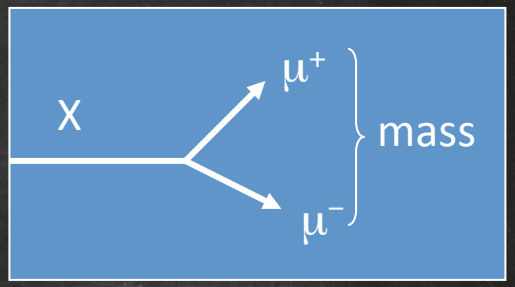


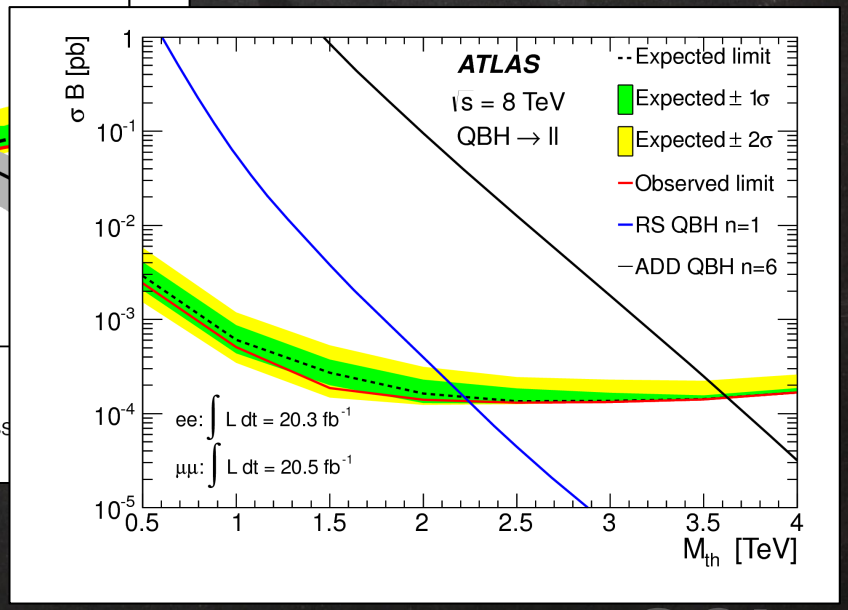


Z' search (resonance search)

$M_{\ell\ell} = \sqrt{(p_{1\ell} + p_{2\ell})^2}$: di-lepton Invariant Mass

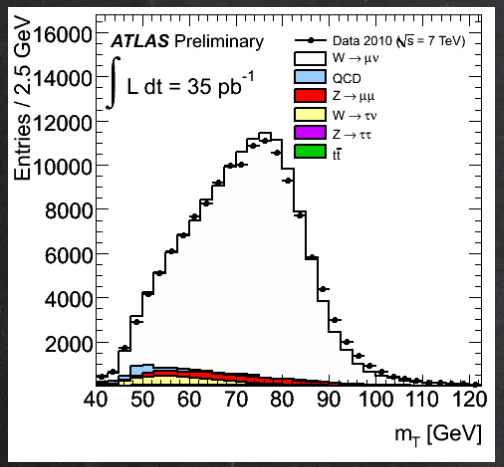


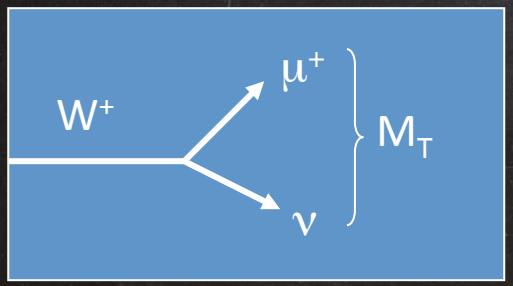


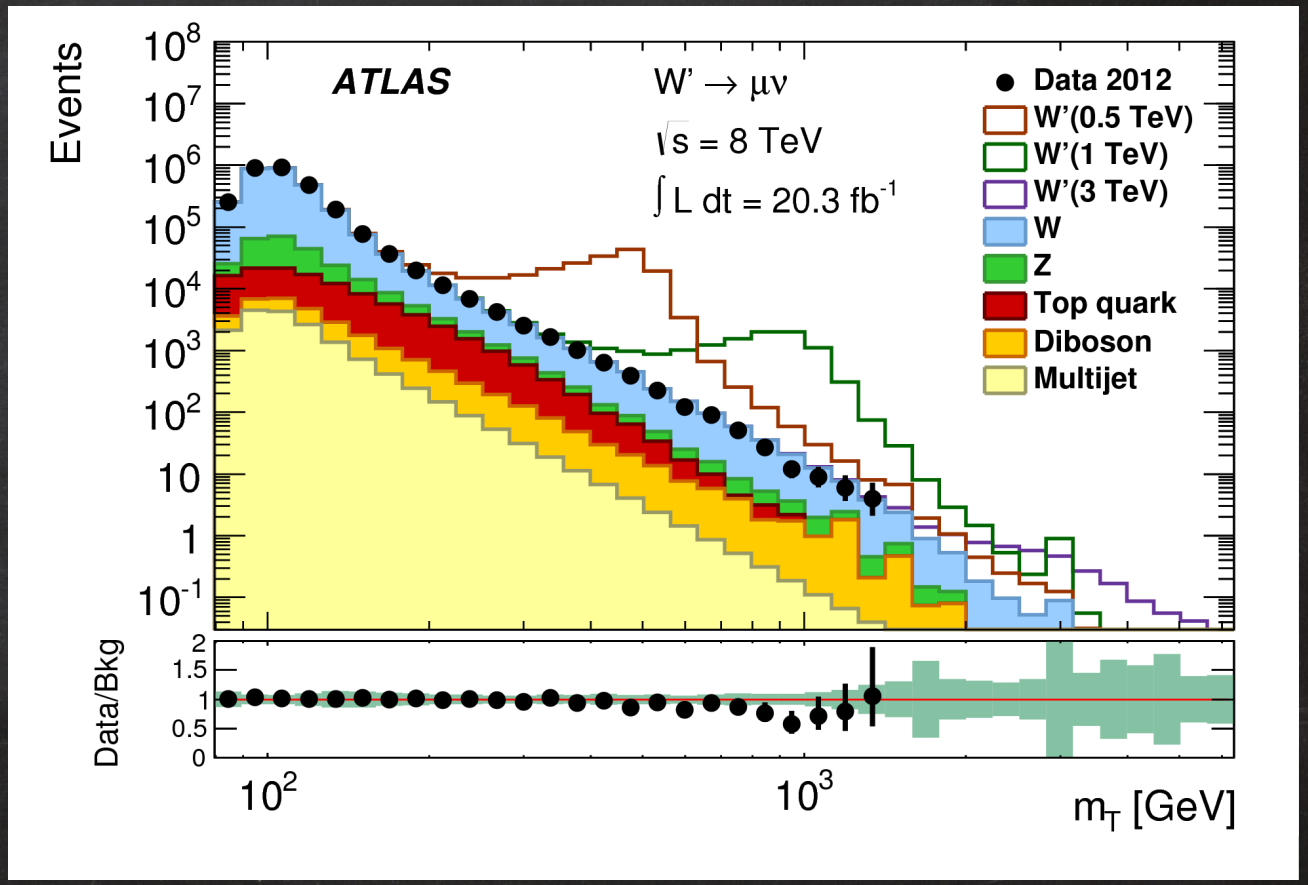


W' search (edge search)

lepton + Missing E_T(ν) [w/ p_T conservation]



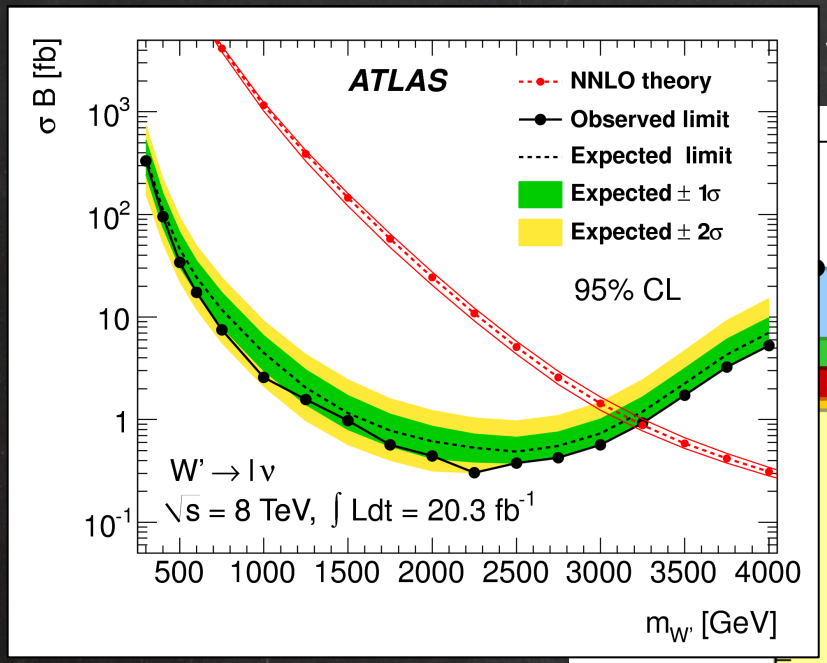


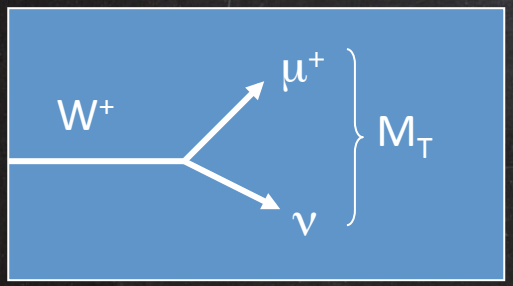


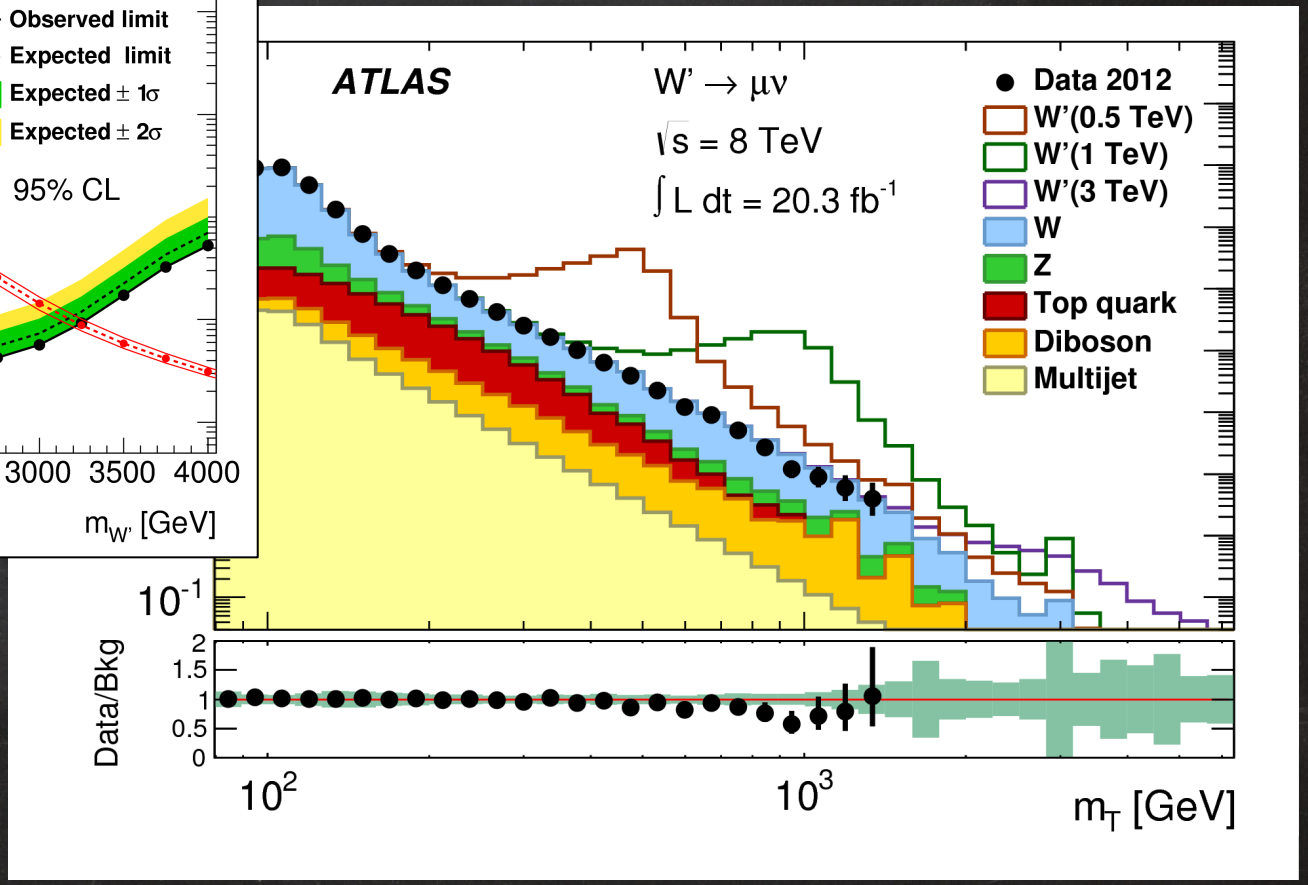
$$M_T = \sqrt{2p_T^{\ell} p_T^{\nu} \left(1 - \cos(\phi^{\ell} - \phi^{\nu})\right)}$$

W' search (edge search)

w/ p_T conservation]





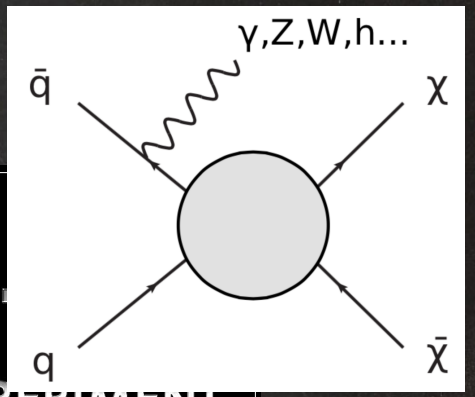


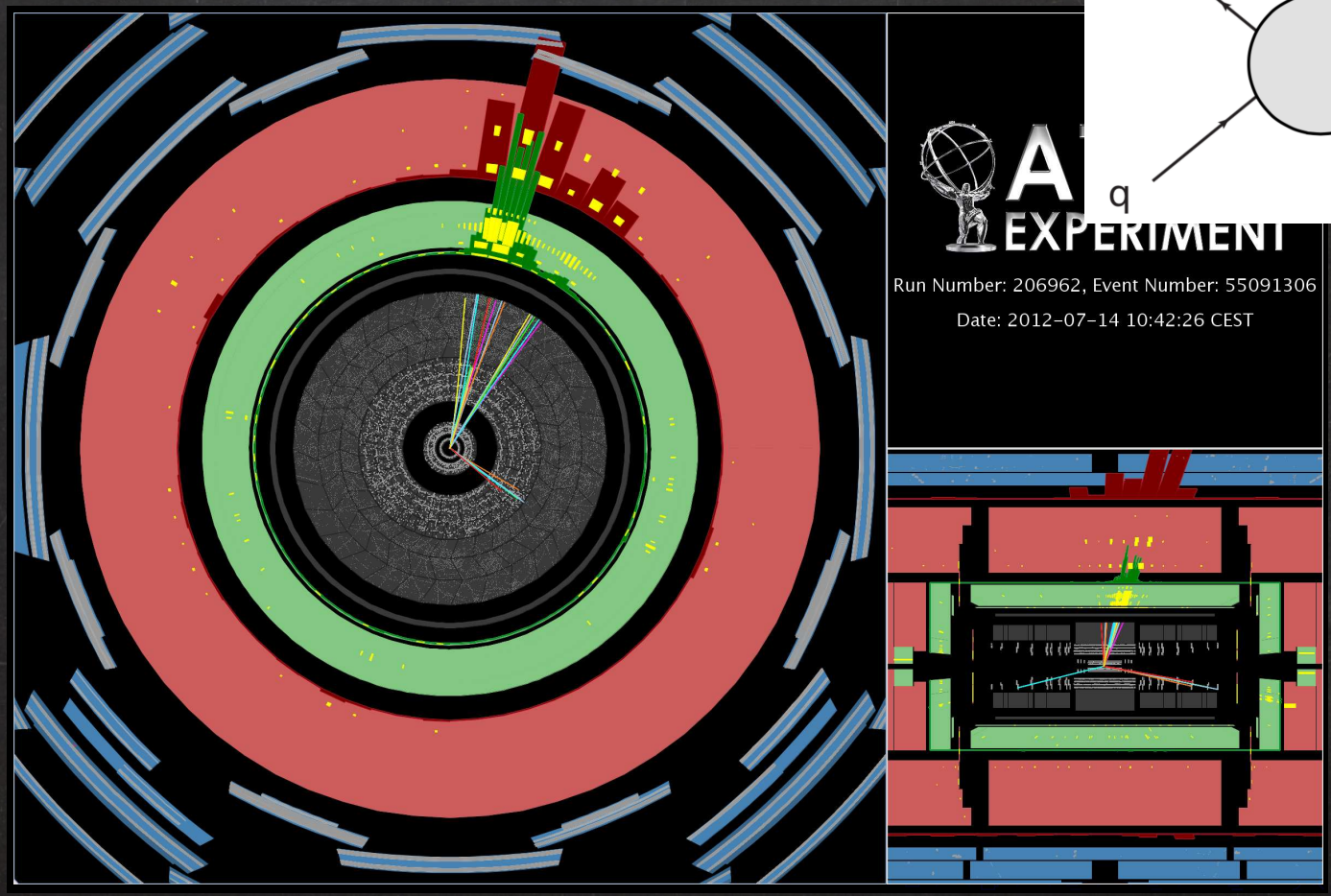
$$M_T = \sqrt{2p_T^{\ell} p_T^{\nu} \left(1 - \cos(\phi^{\ell} - \phi^{\nu})\right)}$$

DM search (invisible search)

Mono-X : Large Missing E_T(~p_T)

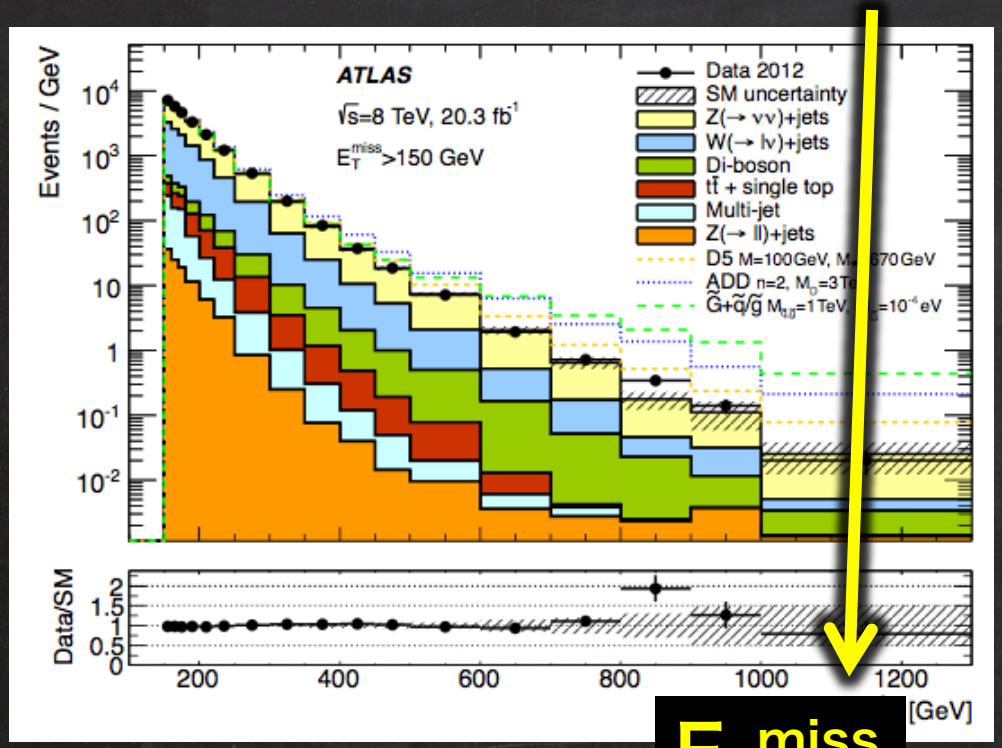
testing p_T non-conservation by recoil energy



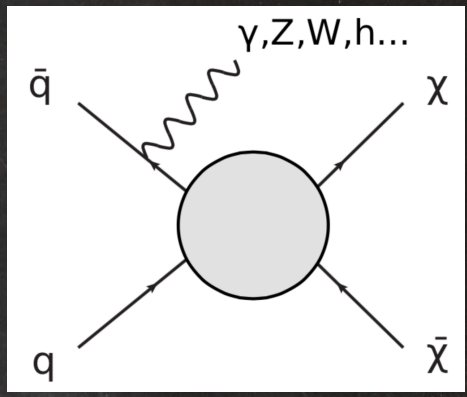


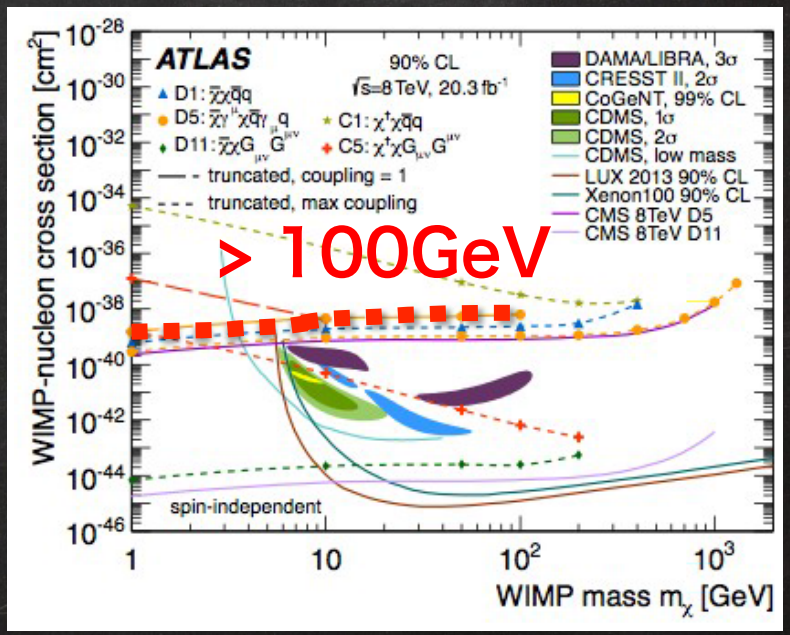
DM search (invisible search)

Mono-X : Large Missing E_T($\sim p_T$)



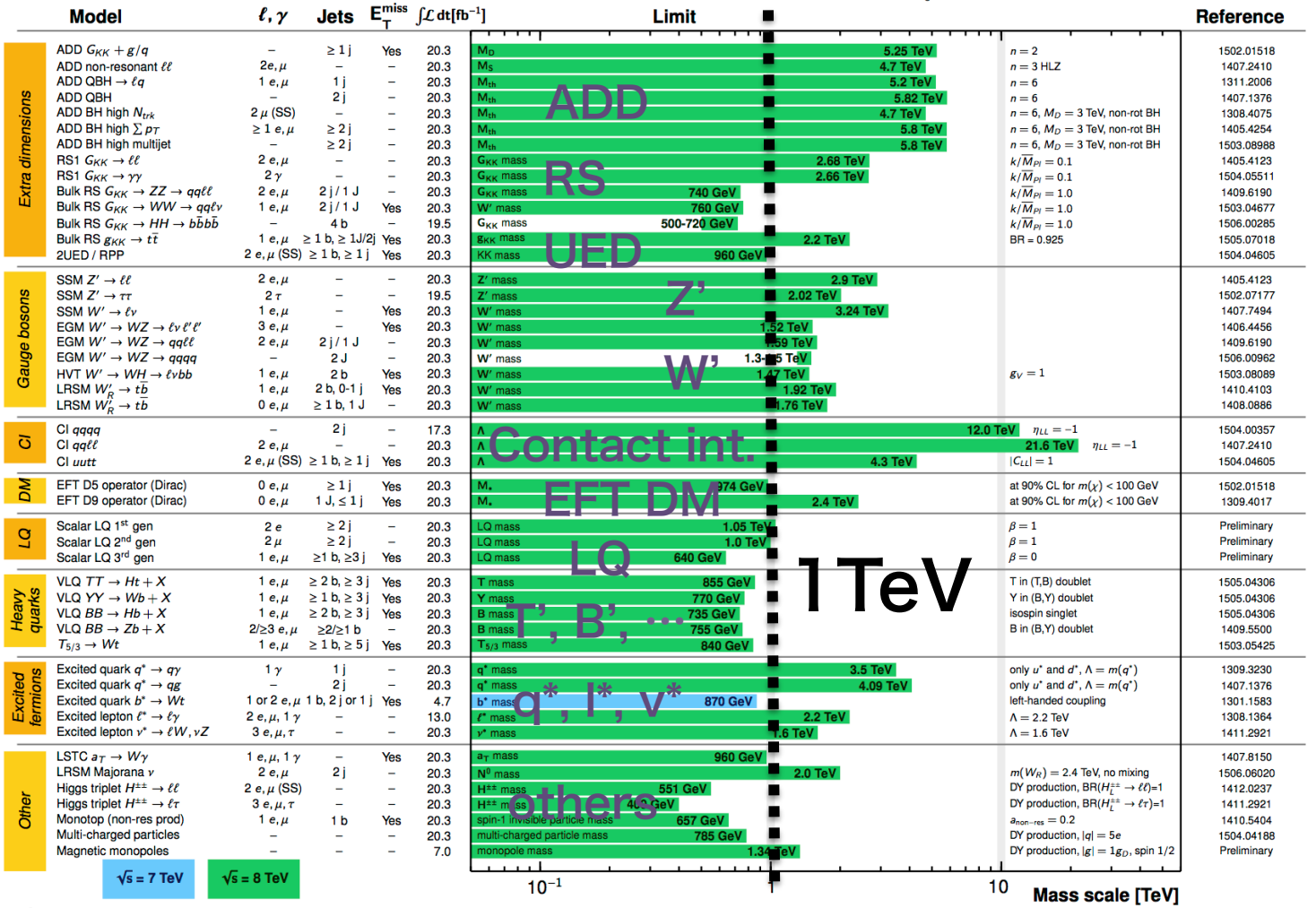
E_T^{miss}





Results are interpreted as σ bound

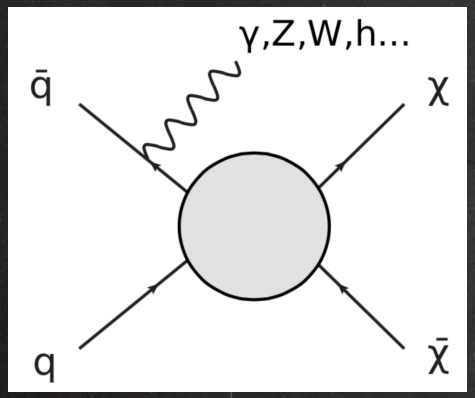
Exotics (non-SUSY)



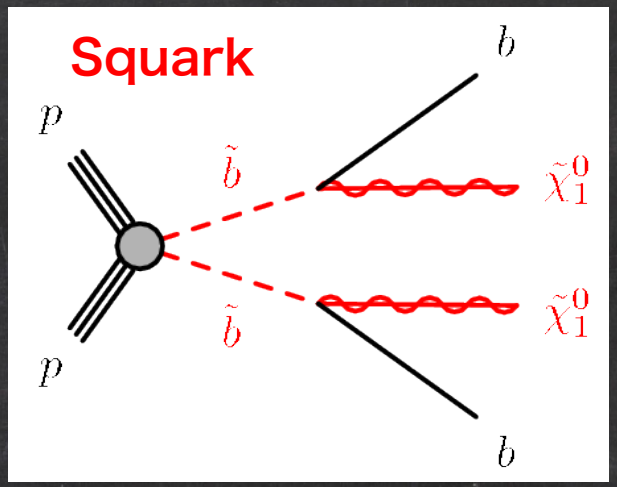
SUSY search

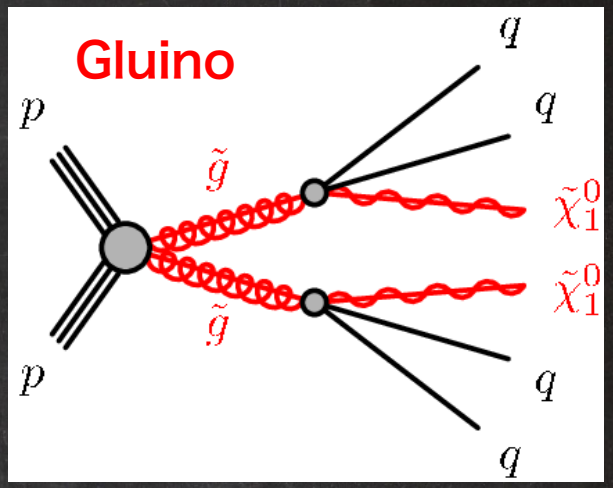
EW production

Large Missing E_T(~p_T)



QCD production + Cascade decay





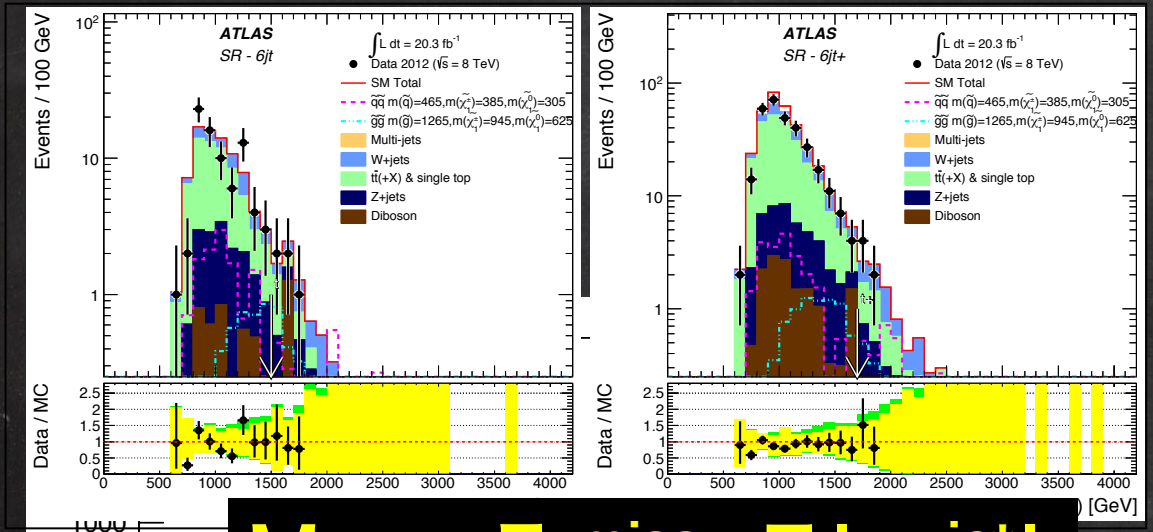
Large p_T object + Large Missing E_T(~p_T)

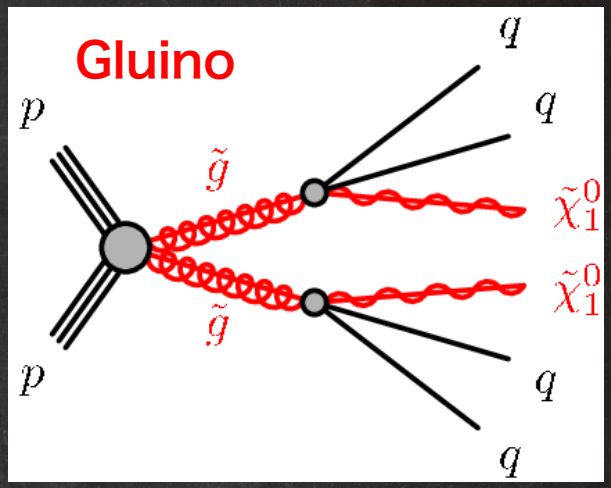
Good : Large σ + Multi-jet ➔ Stronger Limit

Bad : Bounds depend on Mass Spectrum

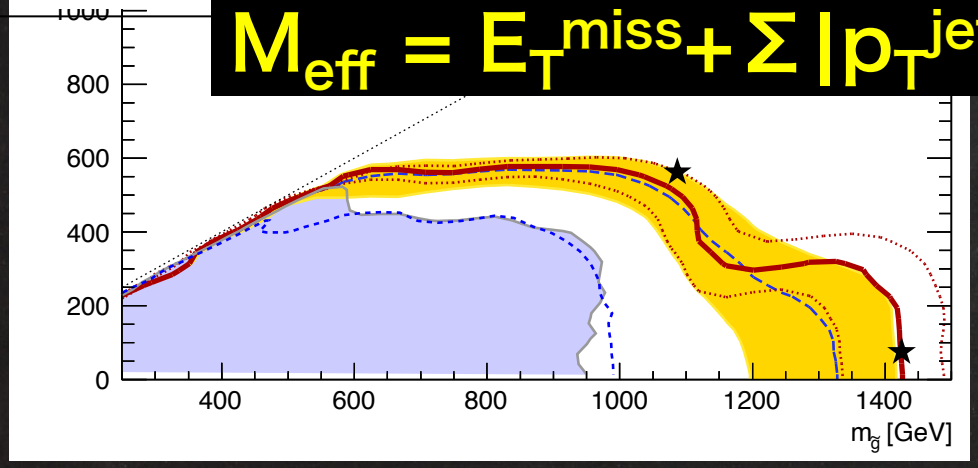
SUSY search

Any excess is observed in M_{eff} dist. ➔ bound



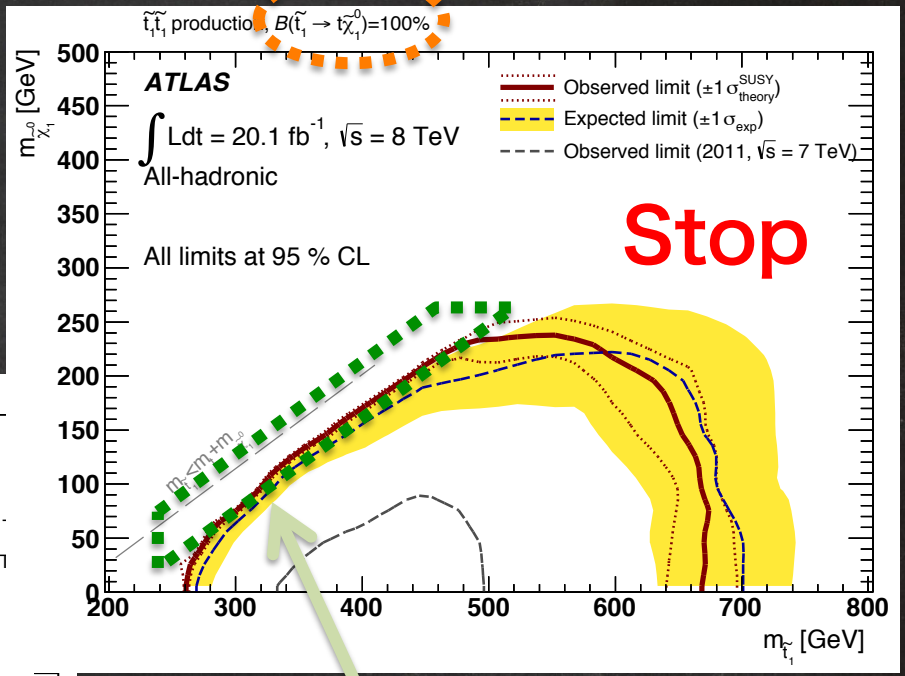


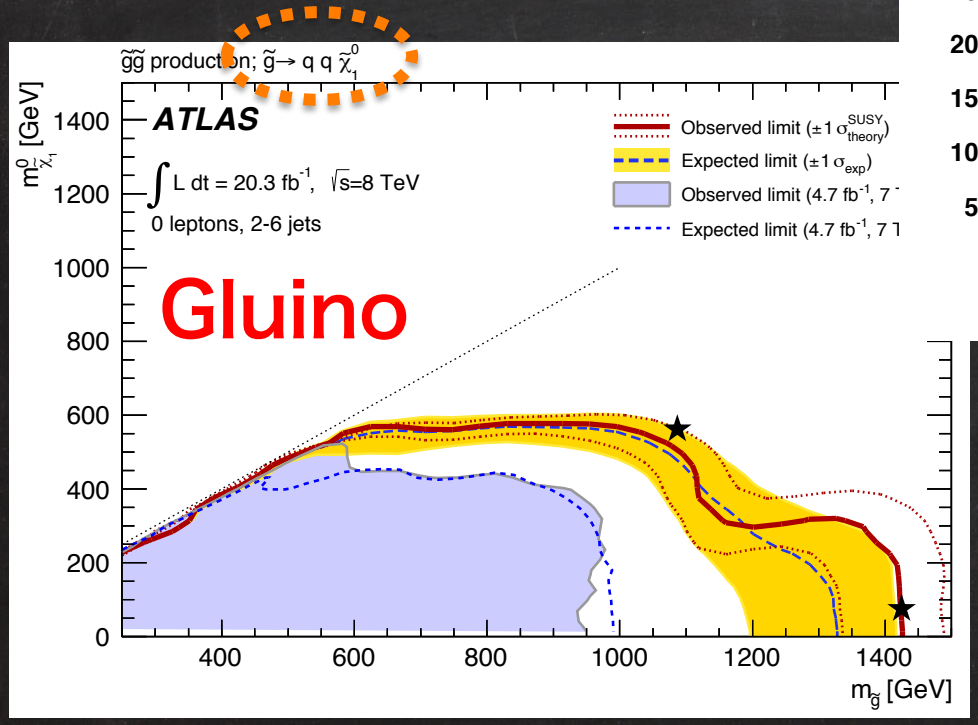
$$M_{eff} = E_T^{miss} + \Sigma |p_T^{jet}|$$



SUSY search

Different Decay chains
➔ Different Bounds

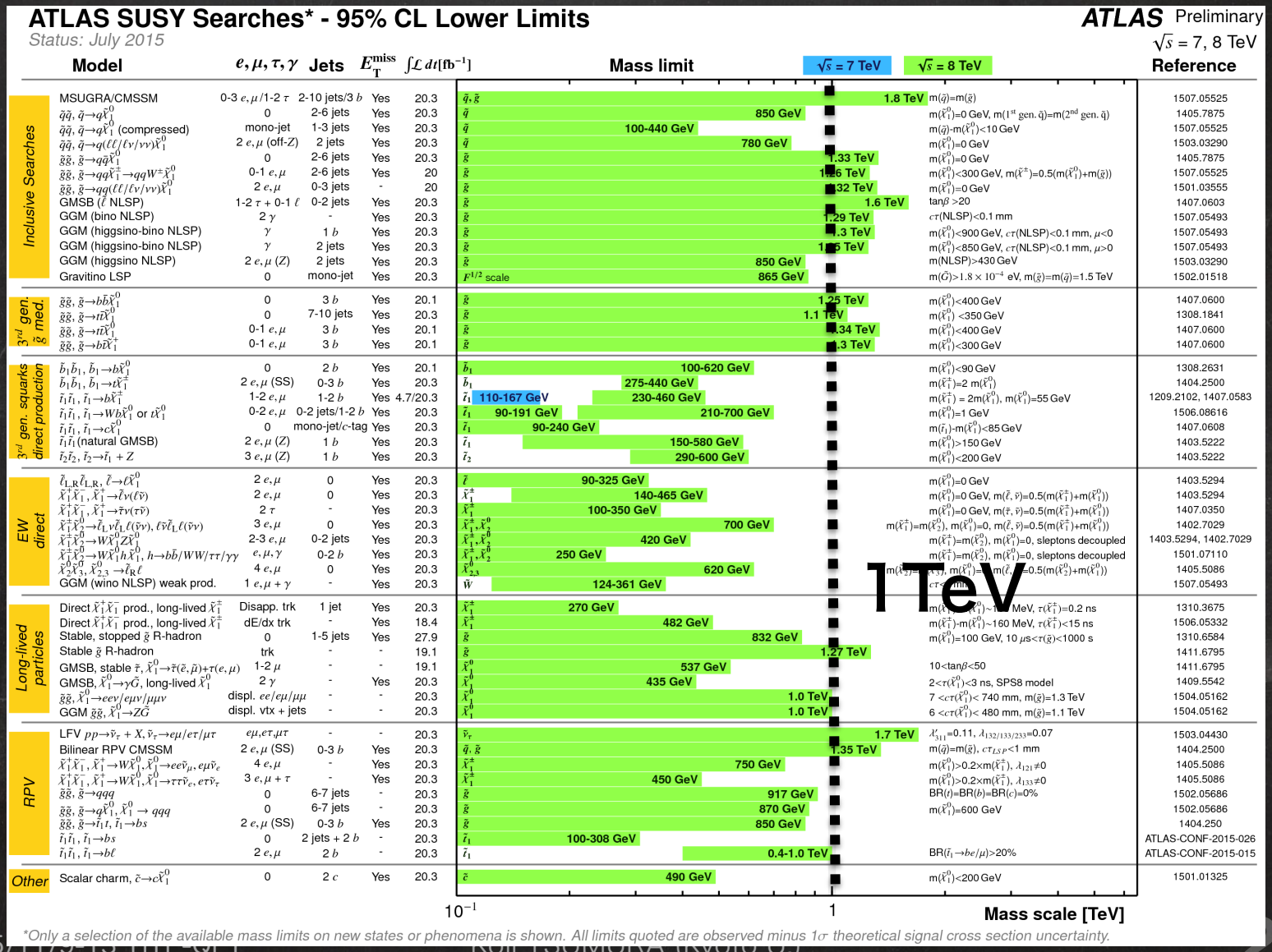




Degenerate Spectrum
➔ Difficult (Soft)

Many Loopholes

SUSY Summary



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

Evidence / Anomaly (Excess / Deficit / ⋯)

Phenomenologists Start To CHASE

$> 3\sigma$ (2σ)

1/370 : Yearly
99.7%

1/22 : Every 3 weeks
95.5%

2.5σ = 1/81 : Quarterly

Rules of The Game

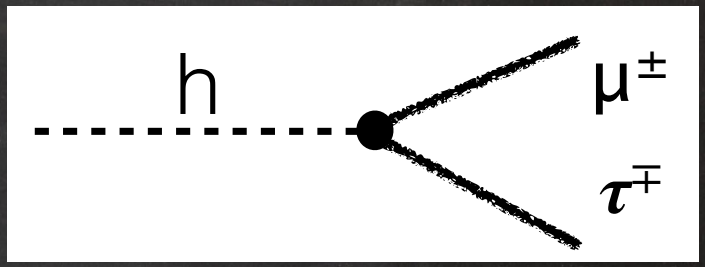
Criteria is dependent on the 'strangeness' of Anomaly

- **Very Exotic Anomaly**
  - Stay tuned
  - Interpretation by a minimal model → Make Predictions
- **Exotic Anomaly**
  - Interpretation by popular / favorite models (SUSY, ED, TC, ...)
  - Interpretation by a model & relate to New Physics (Neutrino, DM, ...)
  - Interpretation by a model & relate to other Anomaly (g-2, ...)

Evidence of Anomalies

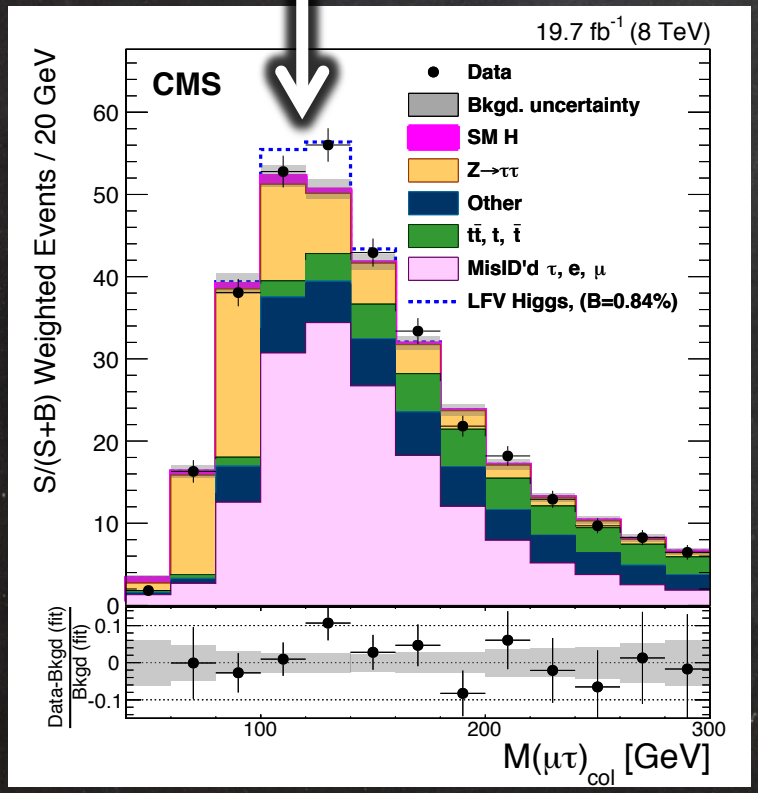
- h → τμ
- W_R
- SUSY
- Diboson Excesses
- …

h → τμ



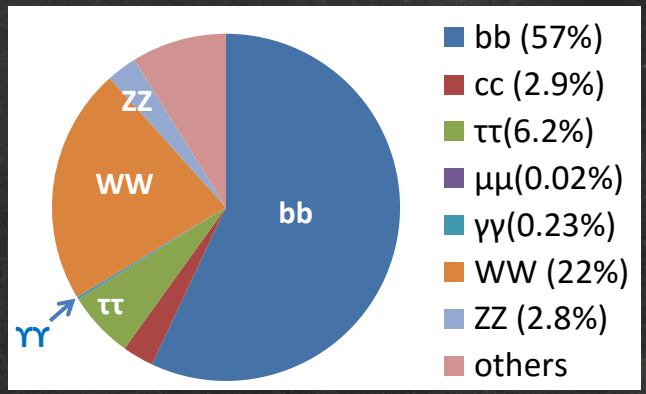
Lepton Flavor Violating Higgs Decay

2.6 σ Excess in CMS



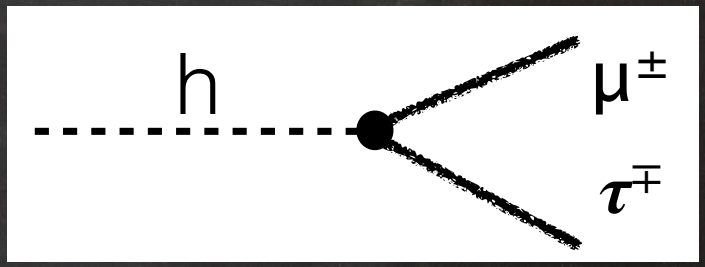
Not so small fraction

$$\mathcal{B}(h \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%$$



ATLAS $(0.77^{+0.62}_{-0.62})\%$ 1.3σ

h → τμ



Lepton Flavor Violating Higgs Decay

Interpretations

- **2HDM [2nd Higgs doublet]**
  - → Misaligned-Yukawa coupling

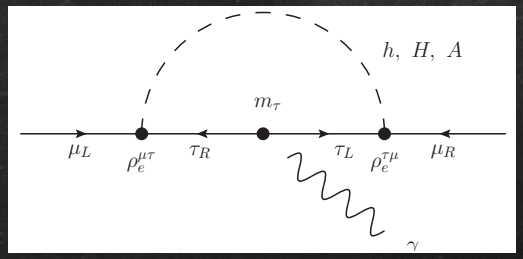
$$\mathcal{L} = +\overline{L_i}\frac{\sqrt{2}(M_\ell)_{ij}}{v}\ell_{jR}H_1 + \overline{L_i}(Y'_\ell)_{ij}\ell_{jR}H_2$$

SM-like doublet

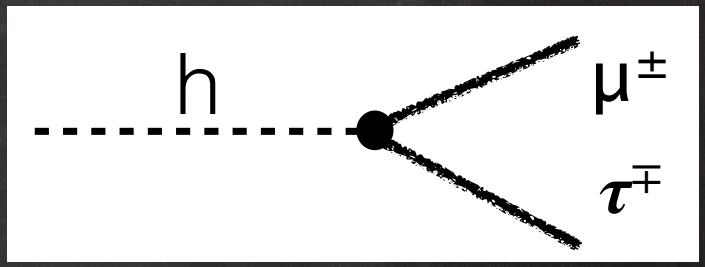
Mixing

➔ Prediction : Large LFV in 2nd doublet (very exotic)

➔ Relate to the g-2 anomaly (exotic)



h → τμ



Lepton Flavor Violating Higgs Decay

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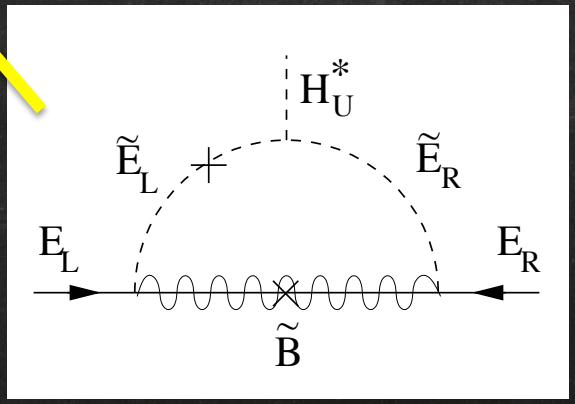
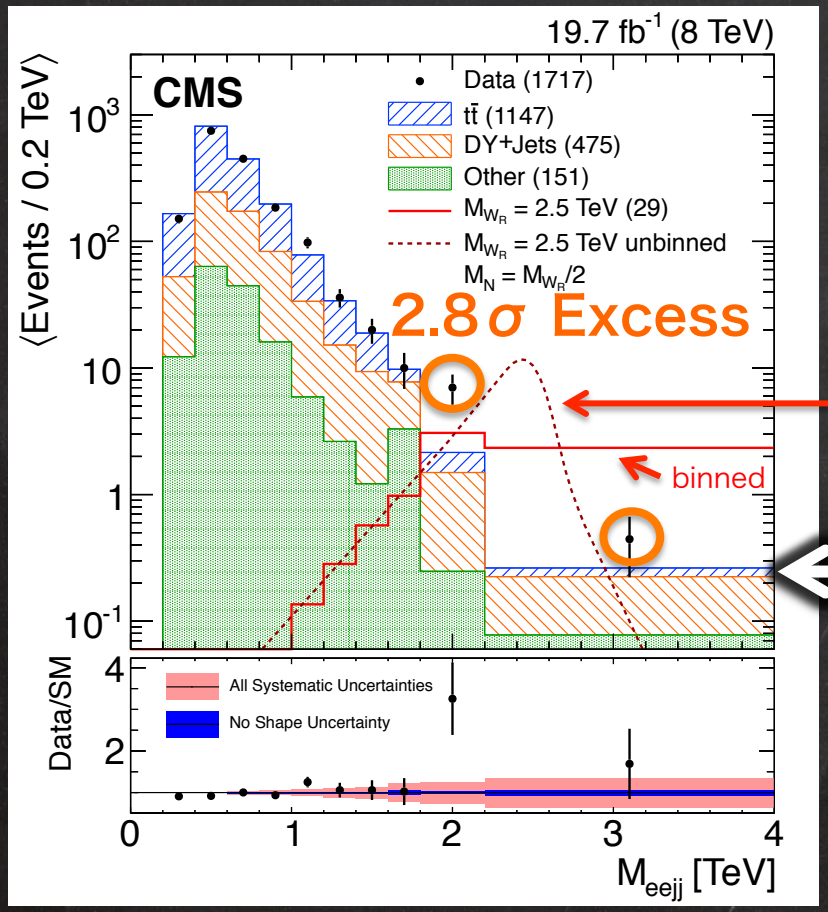
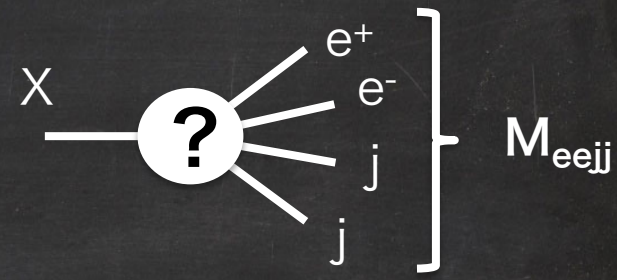
$$\mathcal{L} = +\overline{L_i}\frac{\sqrt{2}(M_\ell)_{ij}}{v}\ell_{jR}H_1 + \overline{L_i}(Y'_\ell)_{ij}\ell_{jR}H_2$$

SUSY interpretation (slepton mixing)



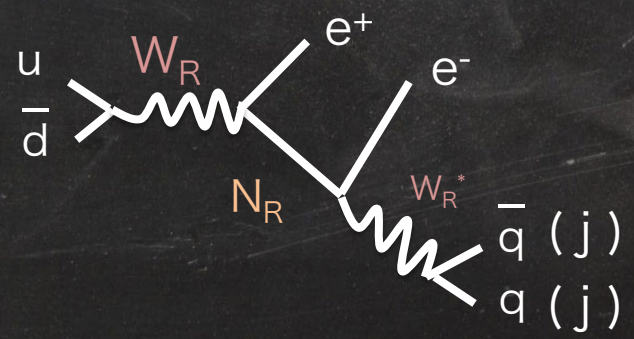
W_R @ 2.5TeV





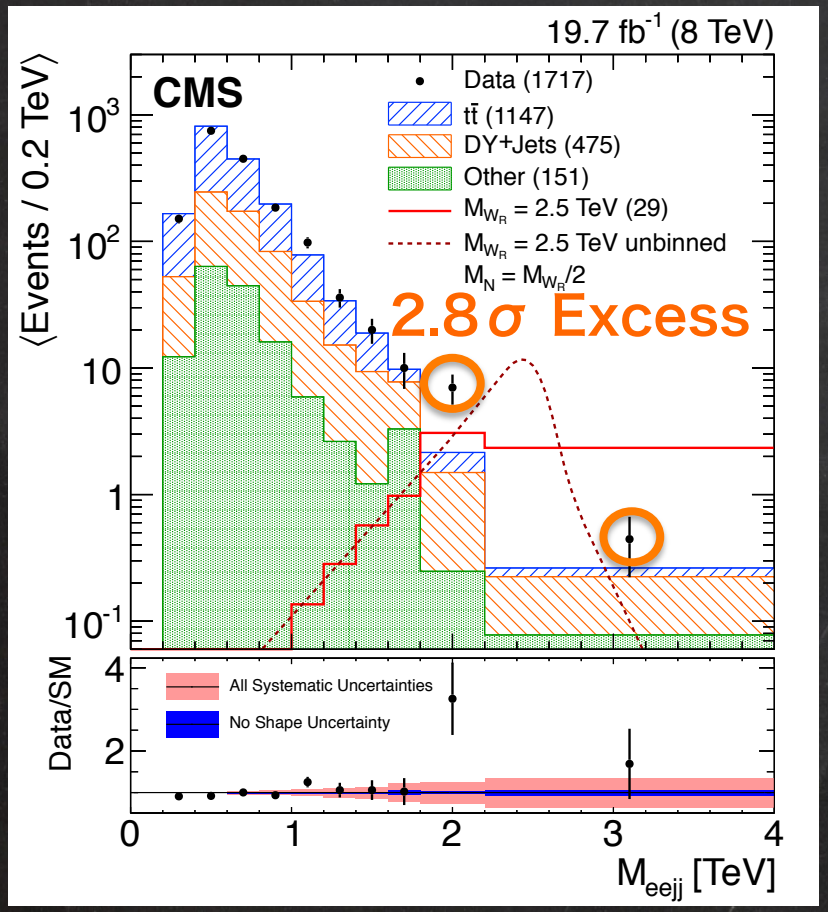
unbinned W_R signal

Shaded : SM Backgrounds



W_R decay via right-handed neutrinos

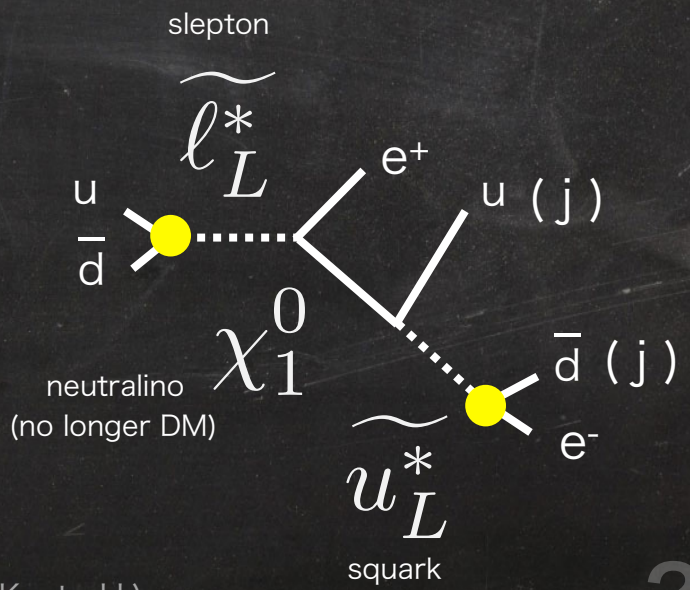
RPV SUSY @ 2.5TeV



R-Parity Violating SUSY

Dangerous for the proton decay in general,
but some couplings can be introduced.

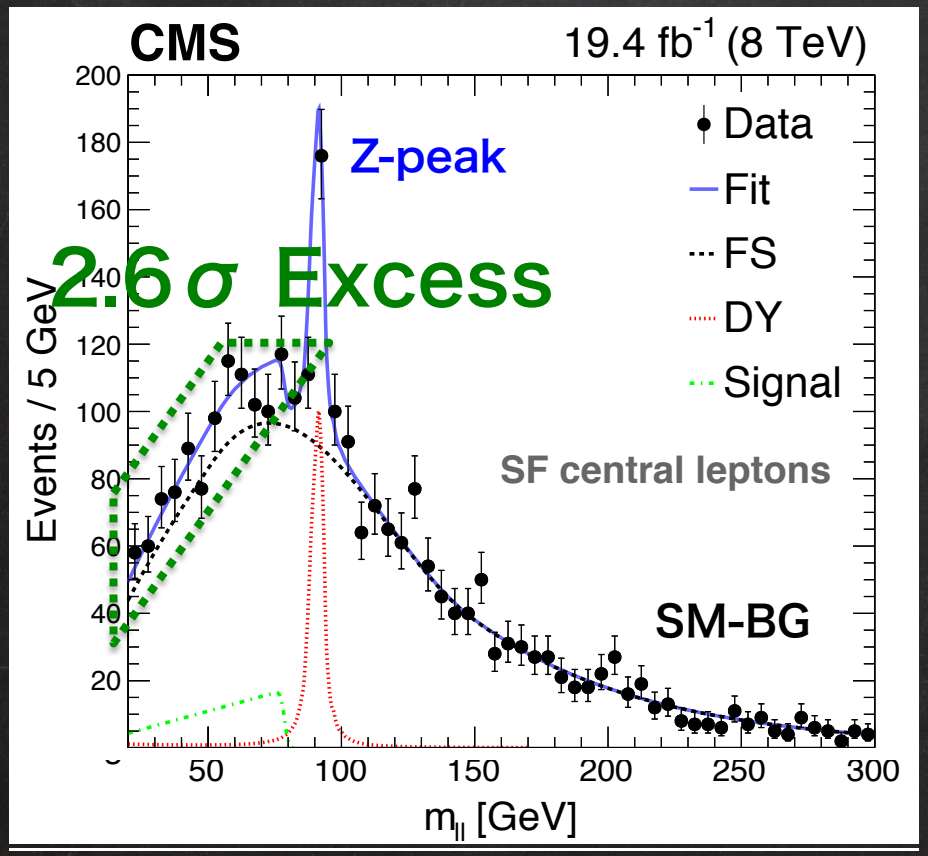
$$W_{\mathrm{RPV}} = \lambda'_{111} L Q d^c$$

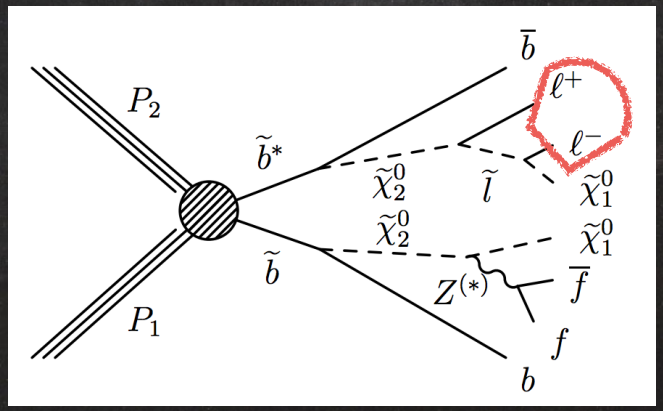


(R-parity conserving) # SUSY

Large p_T object + Large Missing E_T + dilepton

Additional Kinematical Cut

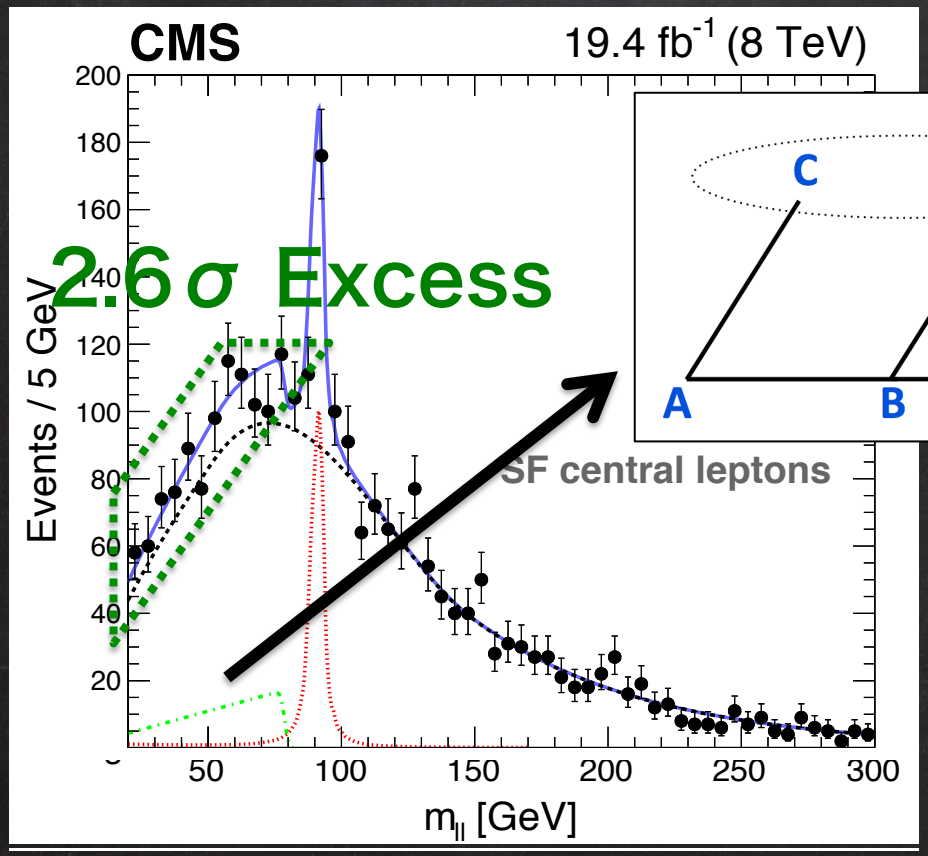




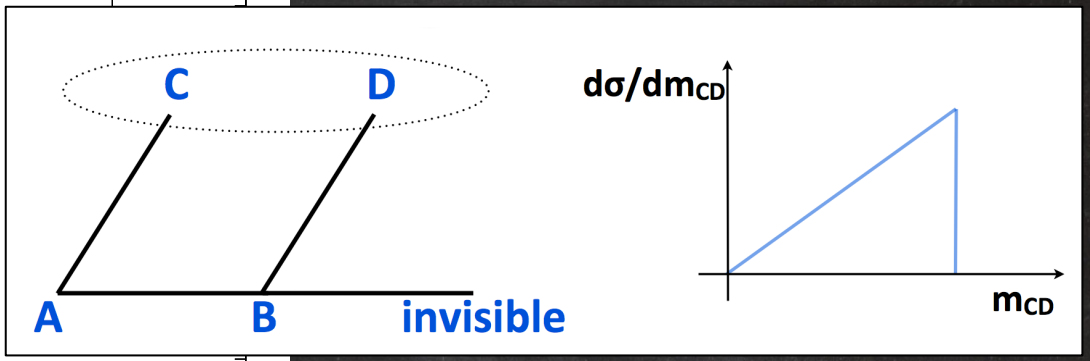
(R-parity conserving)

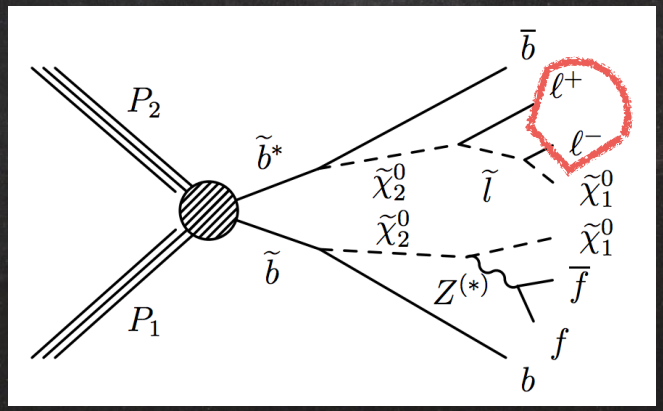
SUSY

Large p_T object + Large Missing E_T + dilepton



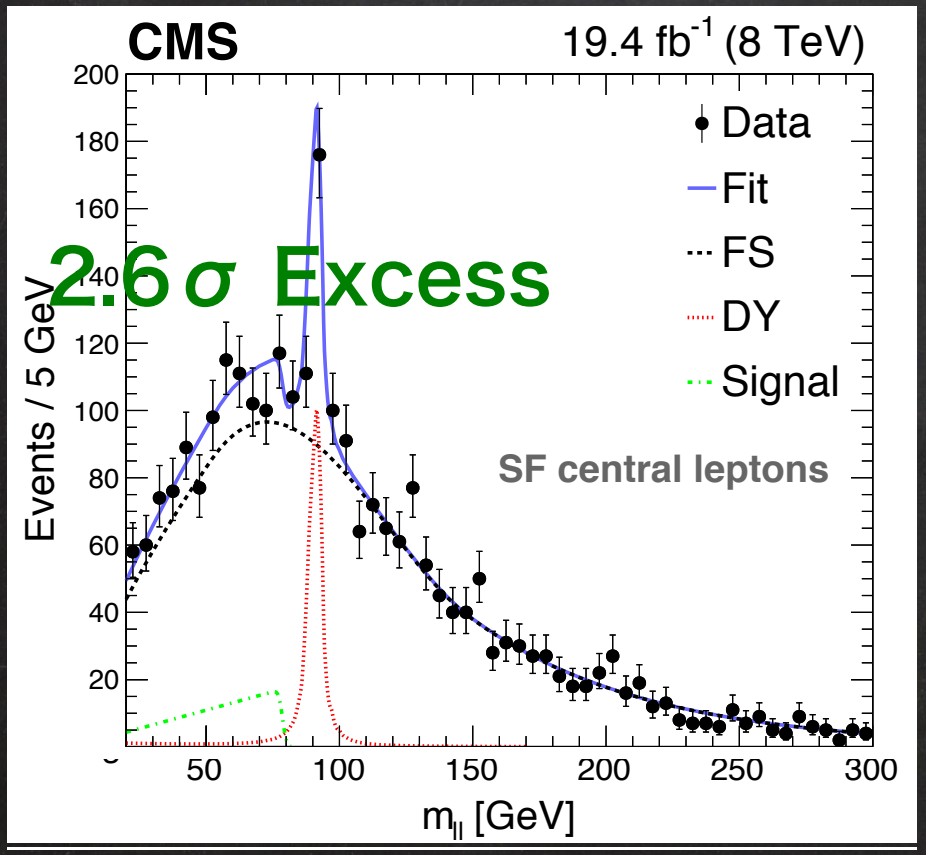
Kinematical Edge of SUSY



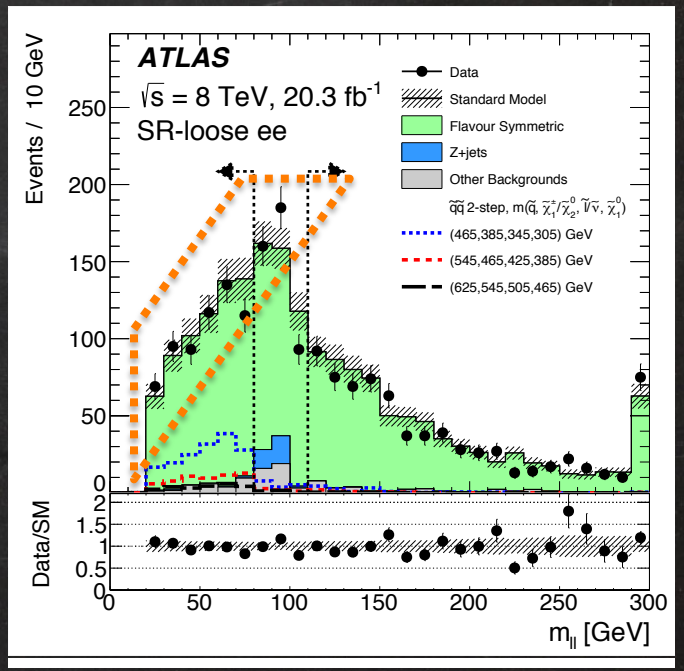


(R-parity conserving) # SUSY

Large p_T object + Large Missing E_T + dilepton

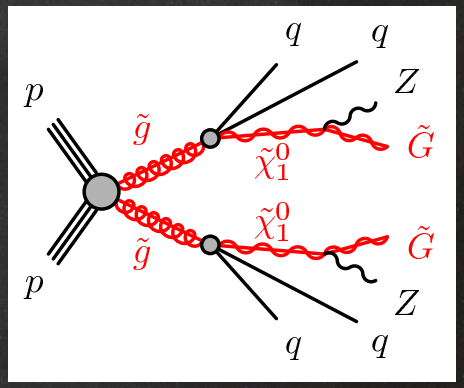


No Excess Observed in ATLAS

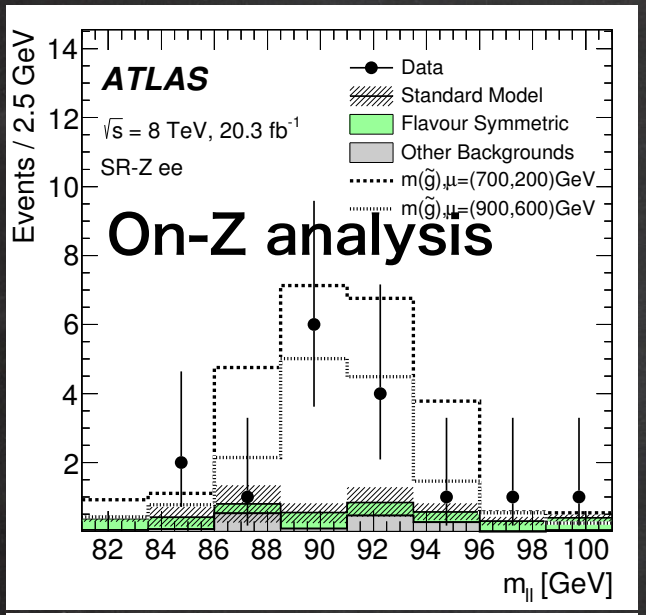


SUSY

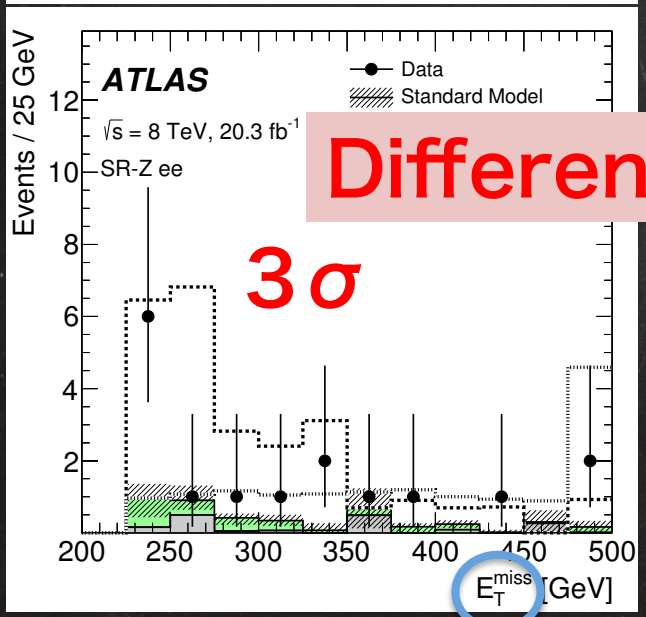
Missing E_T + dilepton



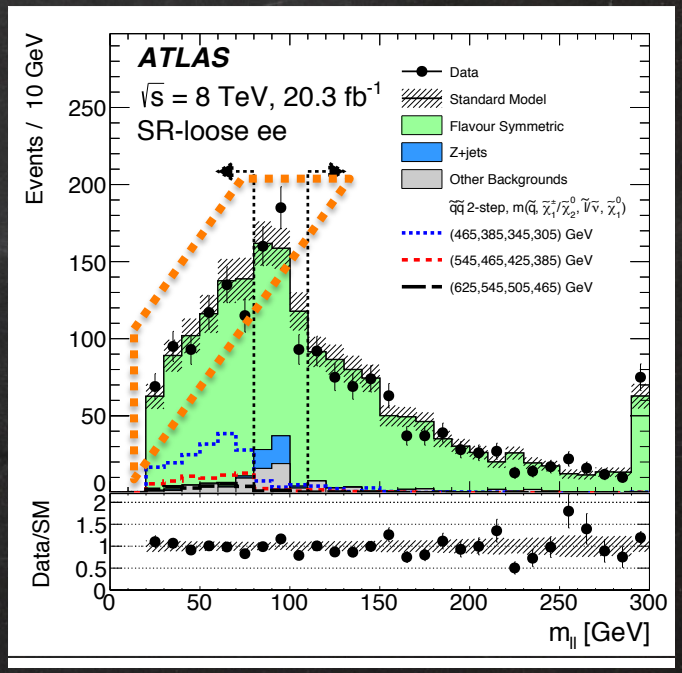
~~No Excess Observed @ ATLAS~~



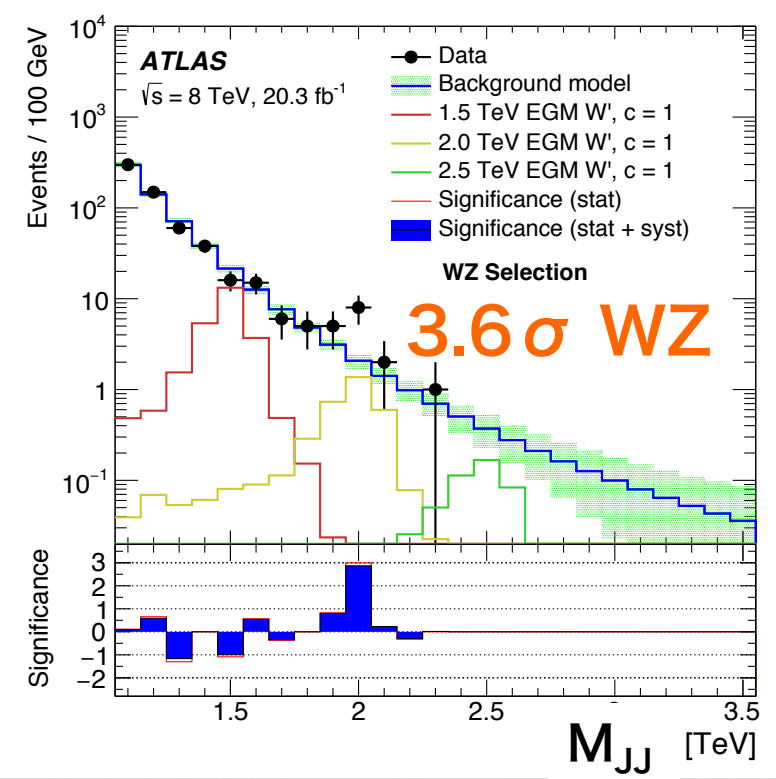
$M_{ll} \approx M_Z$

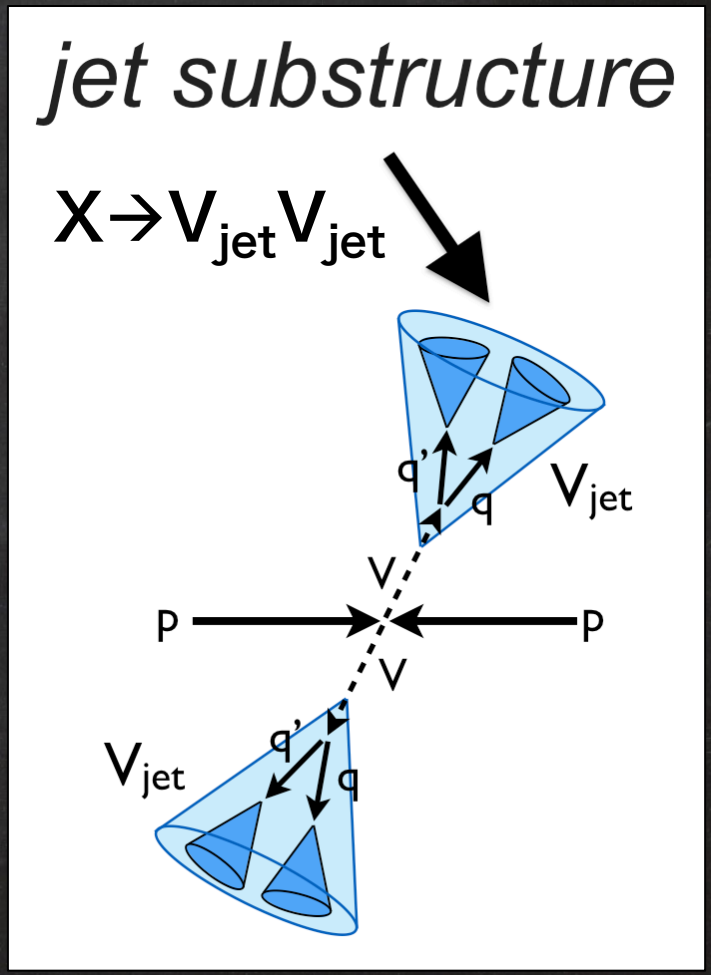


Missing E_T



Diboson Excess @ 2TeV

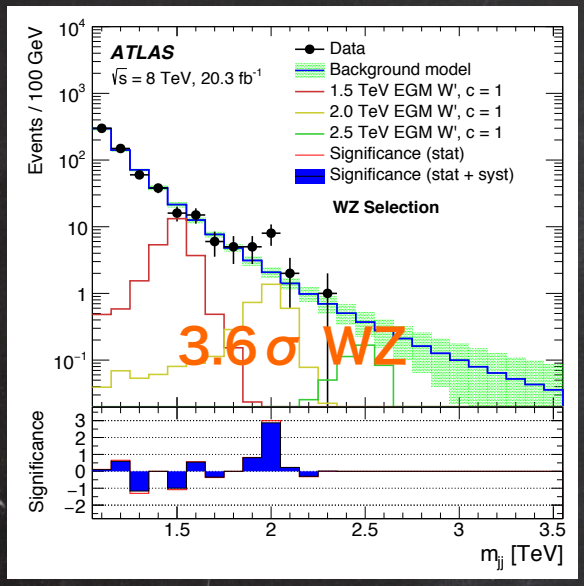


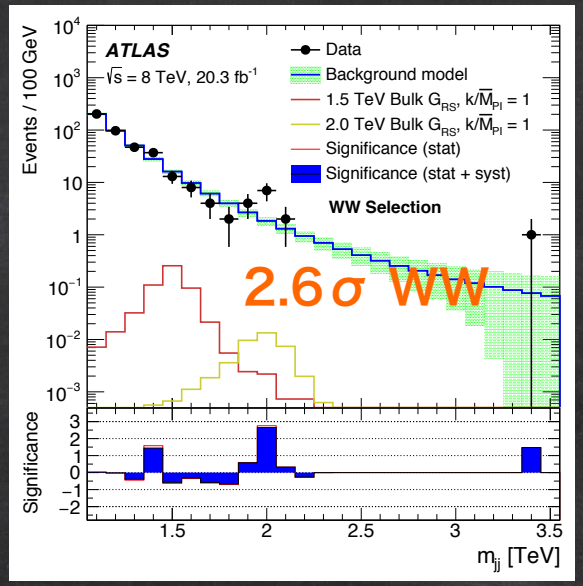


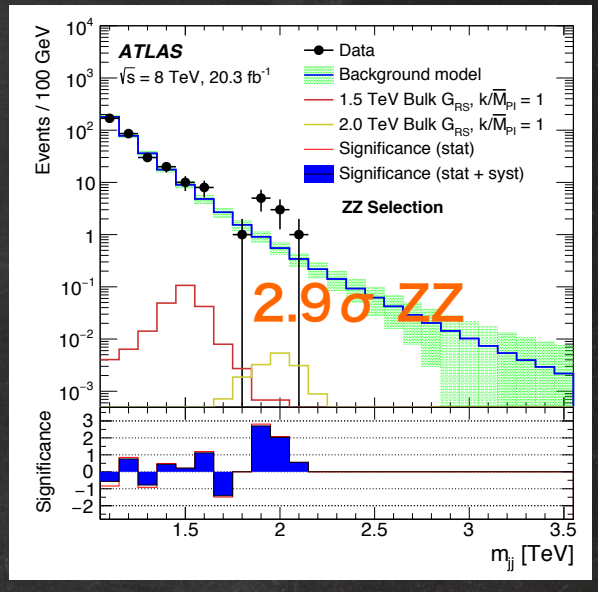
Additional Selection Cut :

Tag 2 Fat Jets (J) with $M_J \approx M_W$ or M_Z

Diboson Excesses @ 2TeV







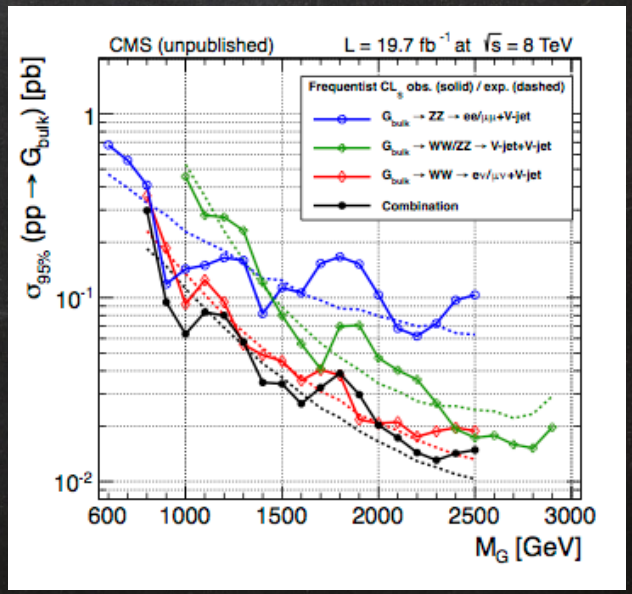
- 3 different channels have excesses

[20% overlap]

- Excess @ 1.8TeV in CMS

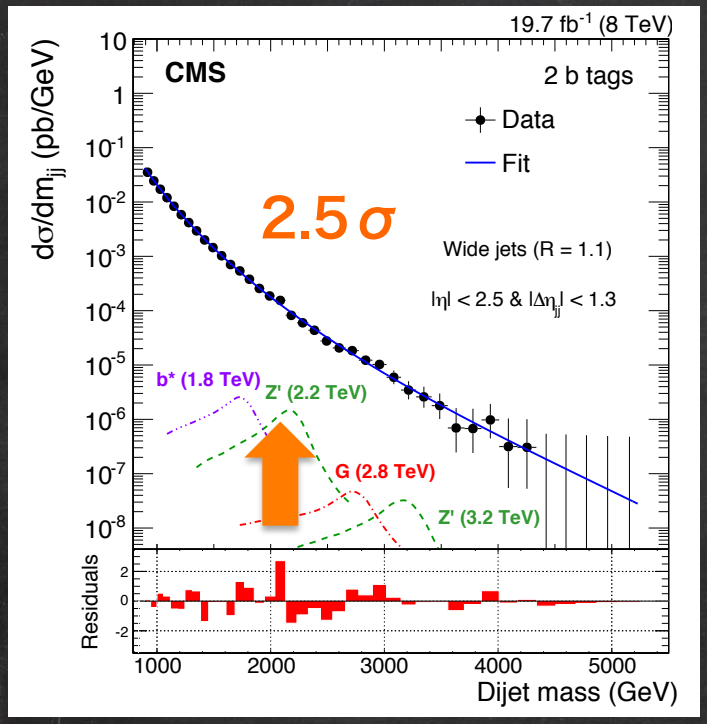
Many Interpretations (W',Z',TC-ρ,H',⋯)

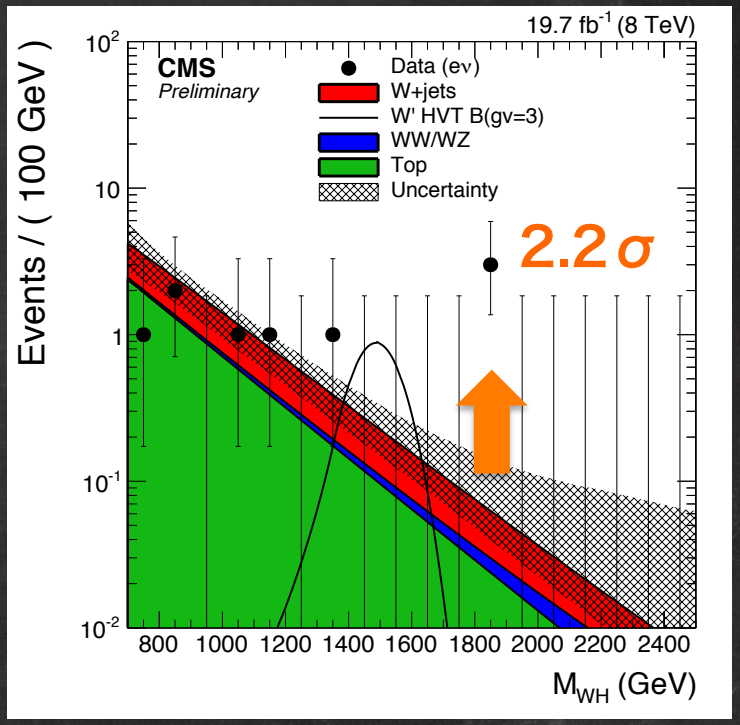
> 40 Theory Papers

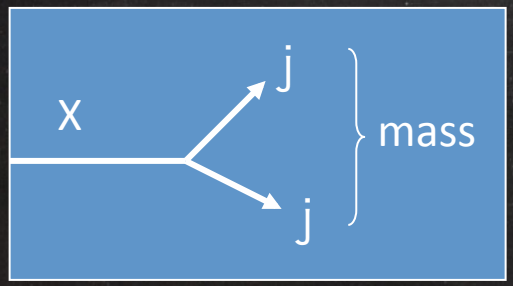


Koji TSUMURA (Kyoto U.)

2TeV in Other Channels?

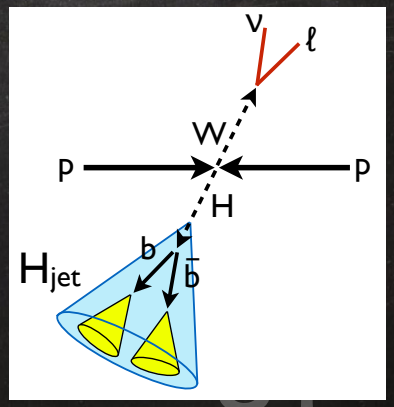






X → jj

X → Wh



Evidence of Anomalies

- h → τμ (2nd H) 2.6σ
- W_R (RPV SUSY) 2.8σ
- SUSY 2.6σ 3σ (Edge, on-Z)
- Diboson Excesses 3.6σ 2.6σ 2.9σ (WZ, WW, ZZ)
- Dijet Excess 2.5σ
- WH search 2.2σ
- …

Different SUSY

3σ = 1/370 : Yearly
2.5σ = 1/81 : Quarterly
2σ = 1/22 : Every 3 weeks

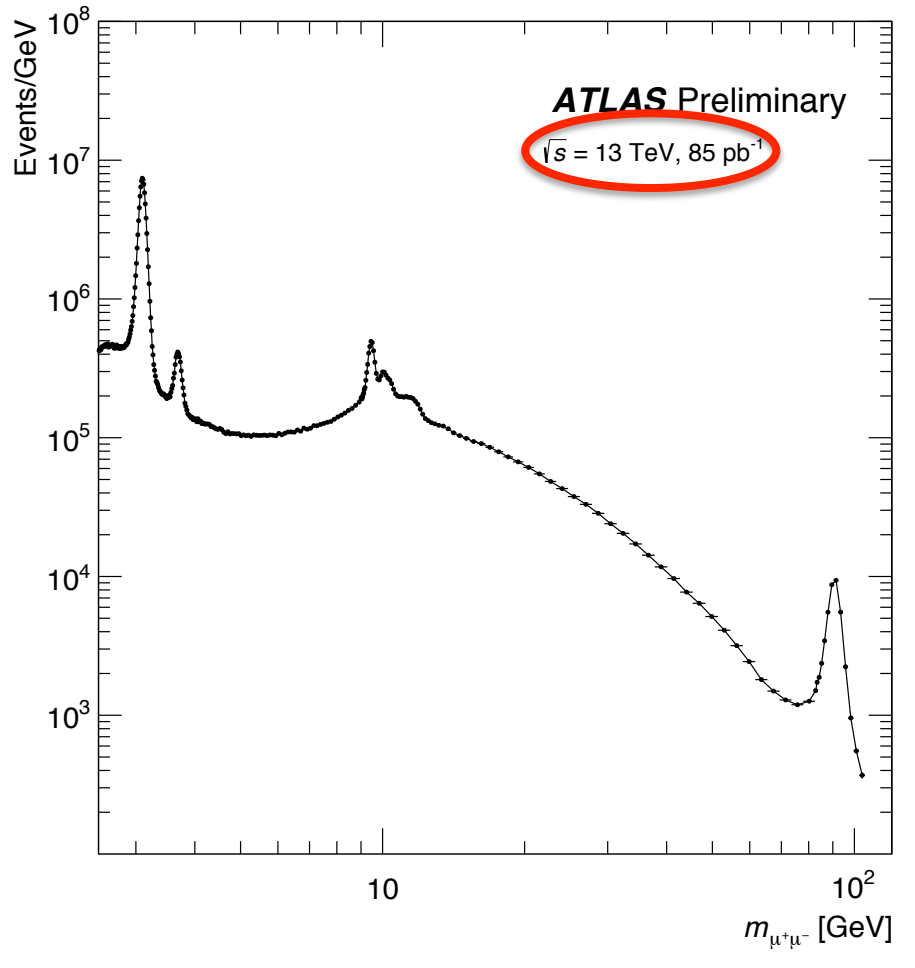
~~Evidence of New Physics !!~~

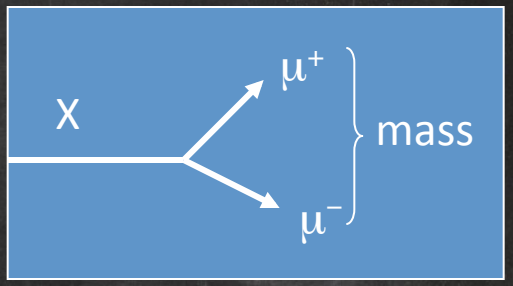
We can't say No New Physics

Run II (13 TeV)

Re-Discovery of the SM

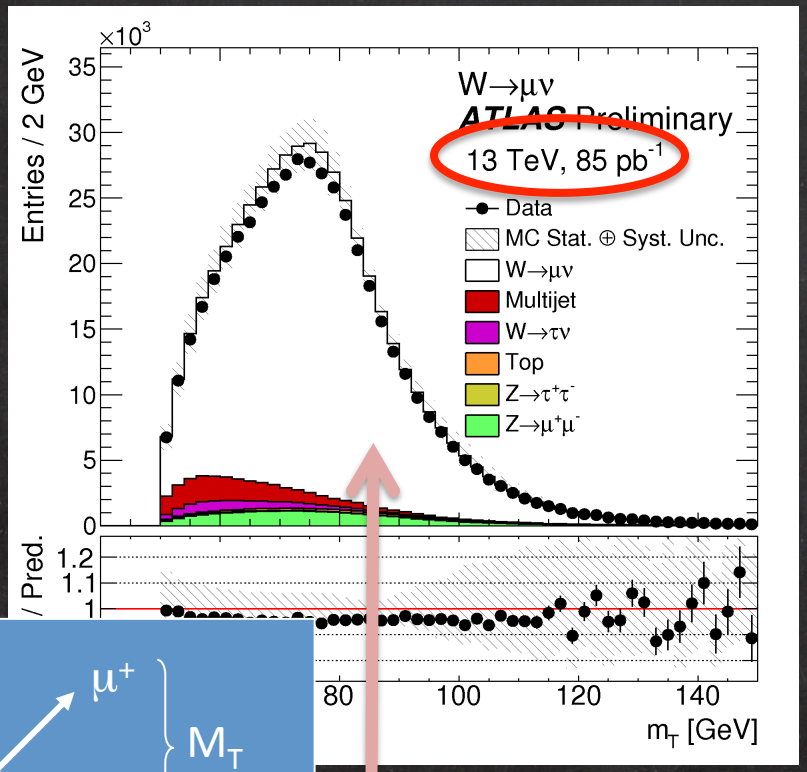
$M_{\ell\ell} = \sqrt{(p_{1\ell} + p_{2\ell})^2}$: di-lepton Invariant Mass

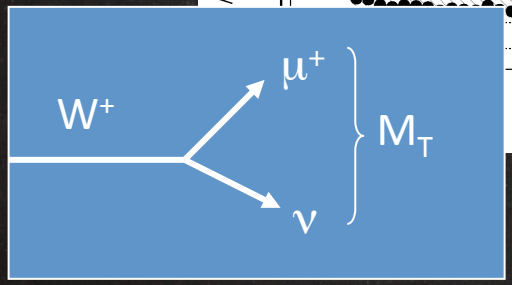




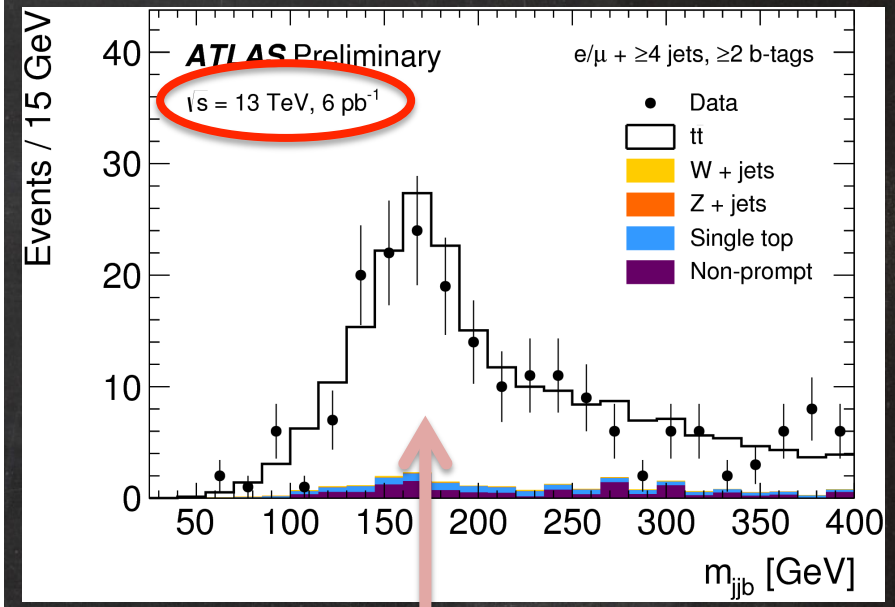
Re-Discovery of W, top

lepton + Missing $E_T(\nu)$ [w/ p_T conservation]

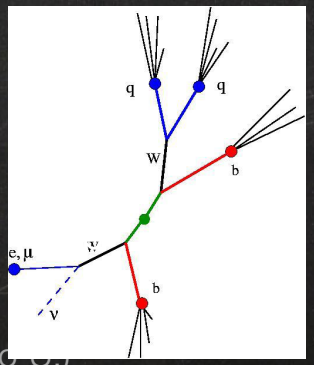




M_W



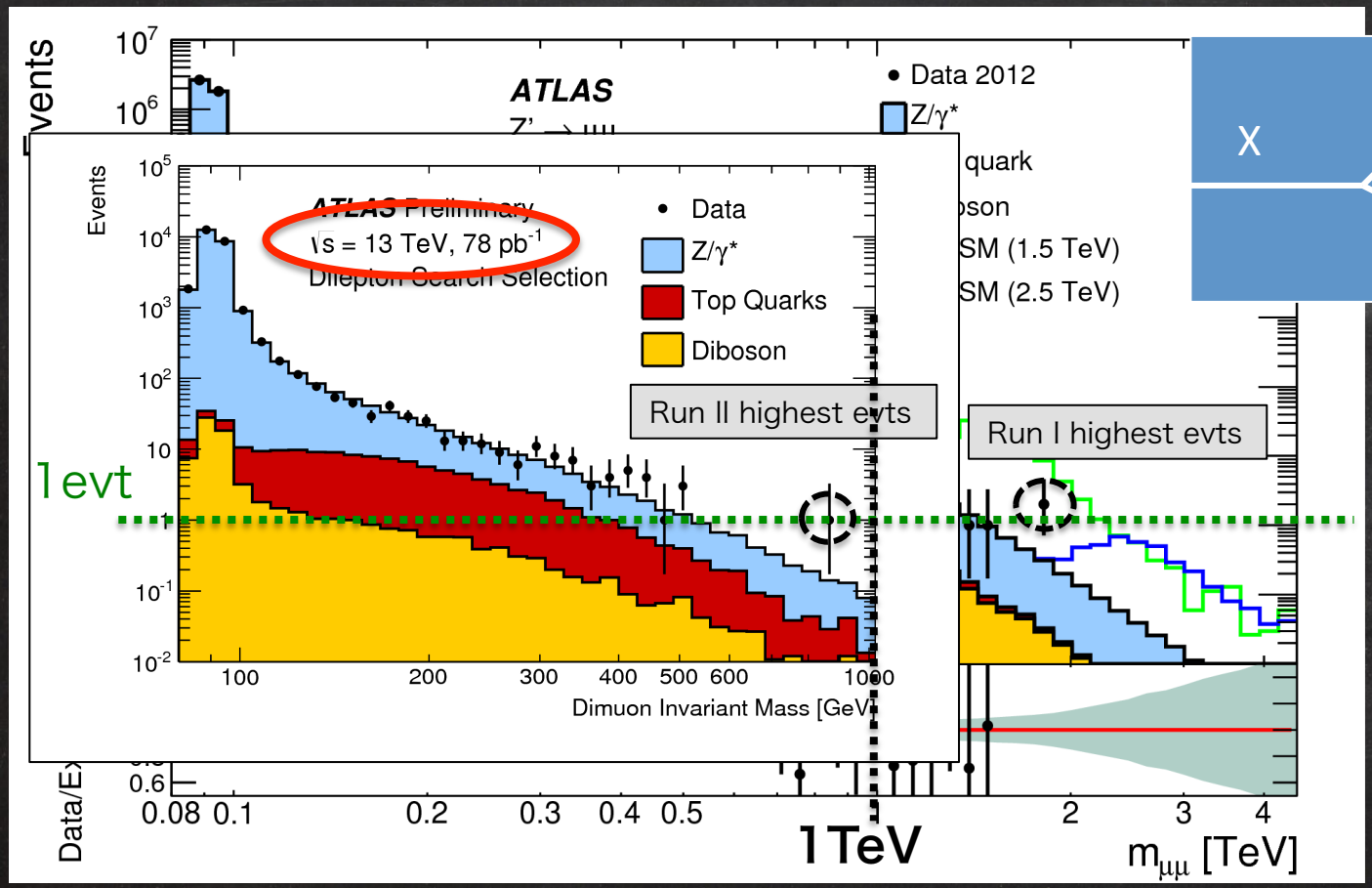
M_t

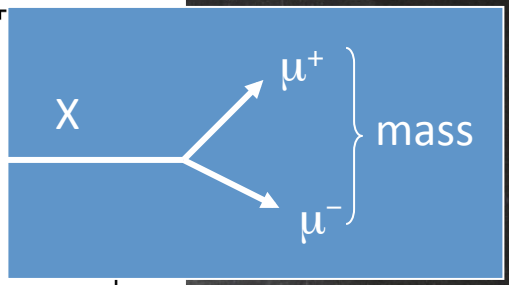


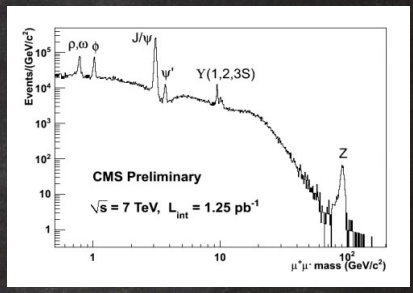
$$M_T = \sqrt{2p_T^{\ell} p_T^{\nu} \left(1 - \cos(\phi^{\ell} - \phi^{\nu})\right)}$$

Z' search

$M_{\ell\ell} = \sqrt{(p_{1\ell} + p_{2\ell})^2}$: di-lepton Invariant Mass





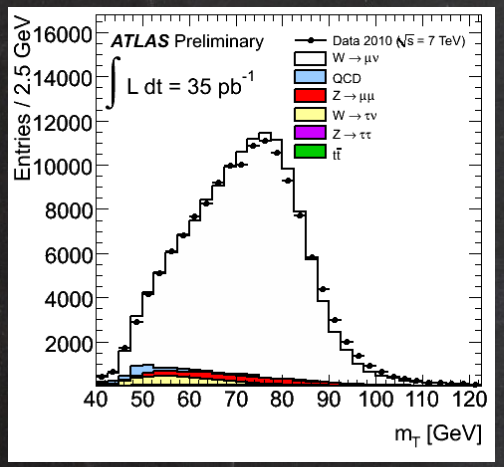


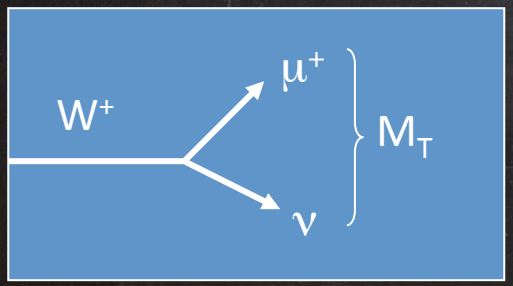
~3fb^{-1} @ Run II

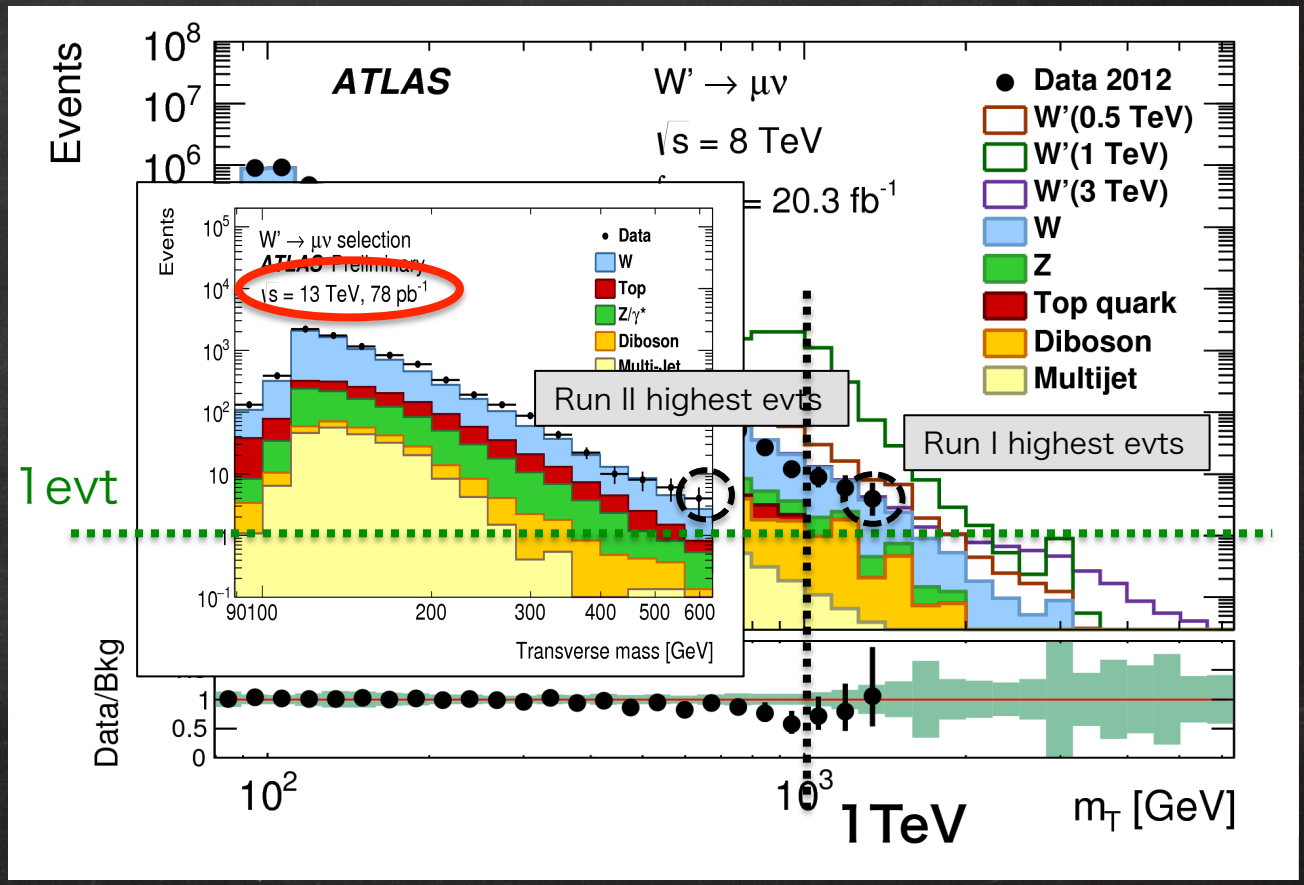
Beyond Run I Sensitivity

W' search

lepton + Missing E_T(ν) [w/ p_T conservation]





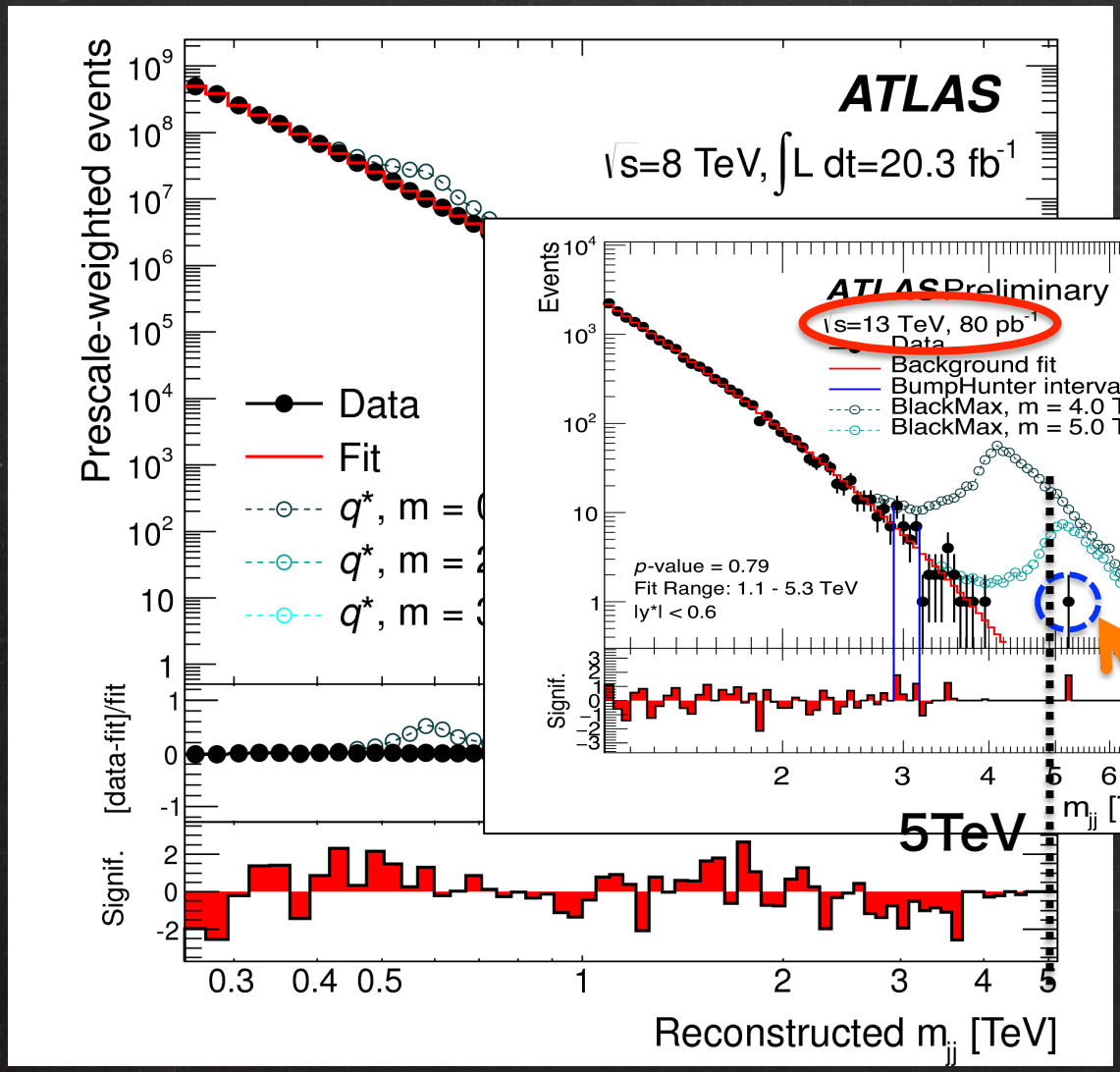


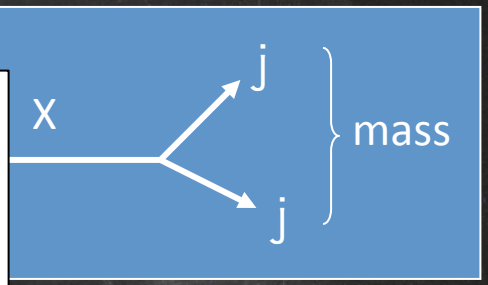
$$M_T = \sqrt{2p_T^{\ell} p_T^{\nu} \left(1 - \cos(\phi^{\ell} - \phi^{\nu})\right)}$$

~3fb^{-1} @ Run II

Beyond Run I Sensitivity

Dijet (q*, Z', W') search

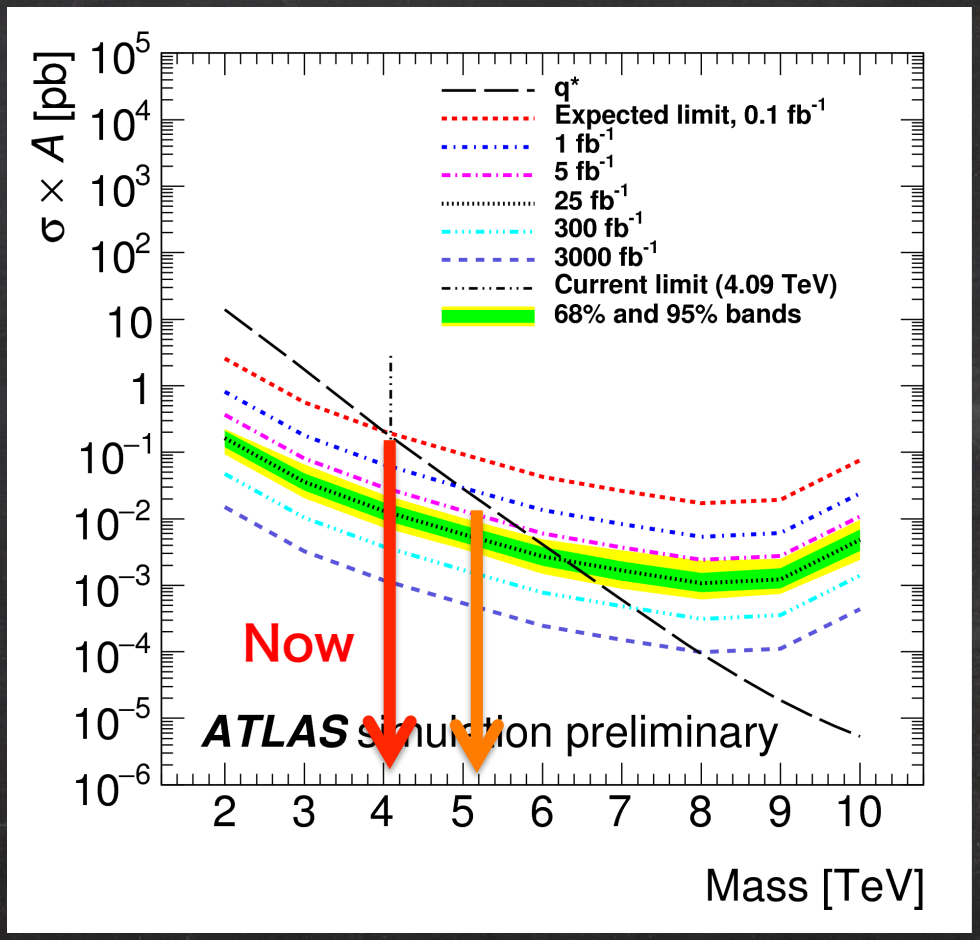




The Highest Mass event

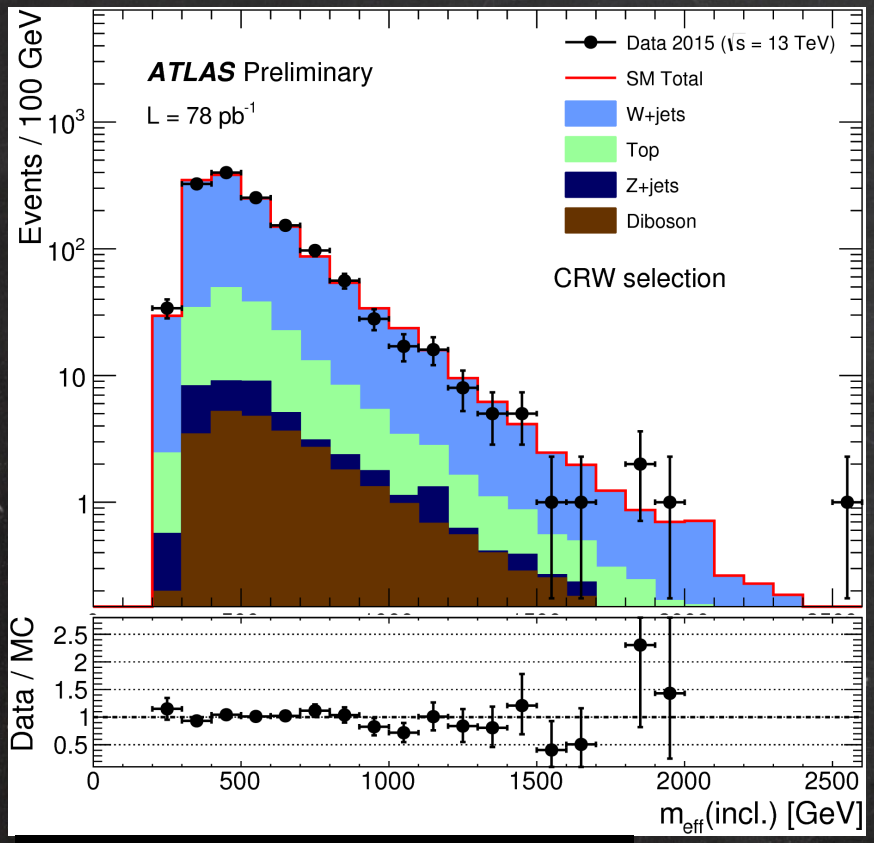
Need more statistics

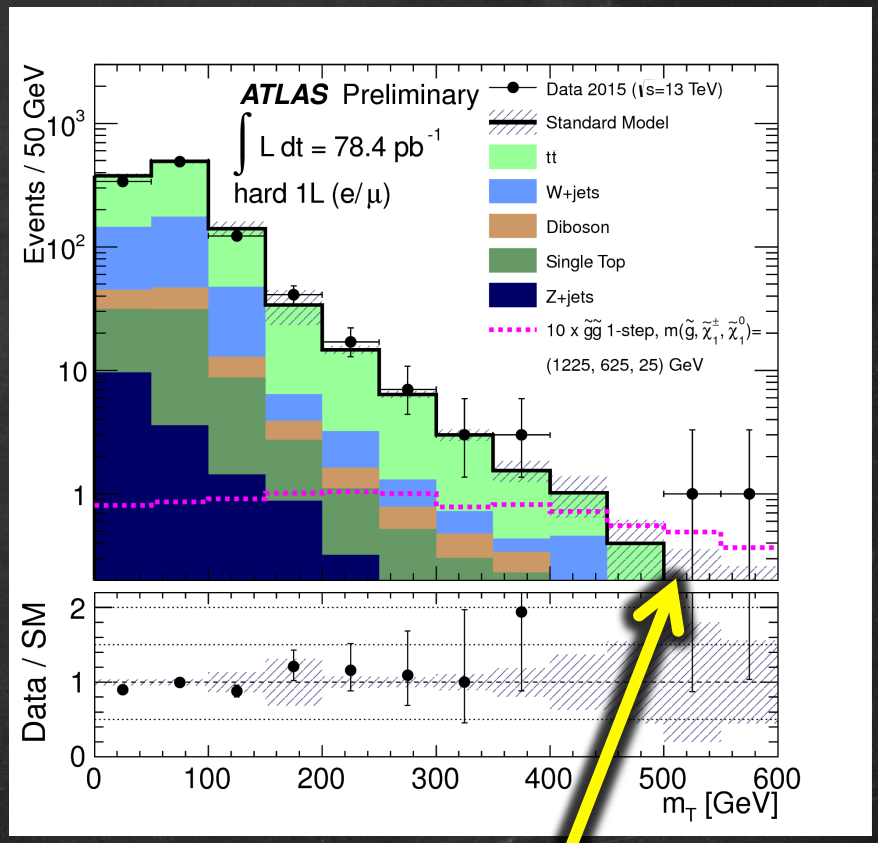
Dijet (q*, Z', W') search



~3fb^{-1} @ Run II (Mar 2016???)

Ready for SUSY search

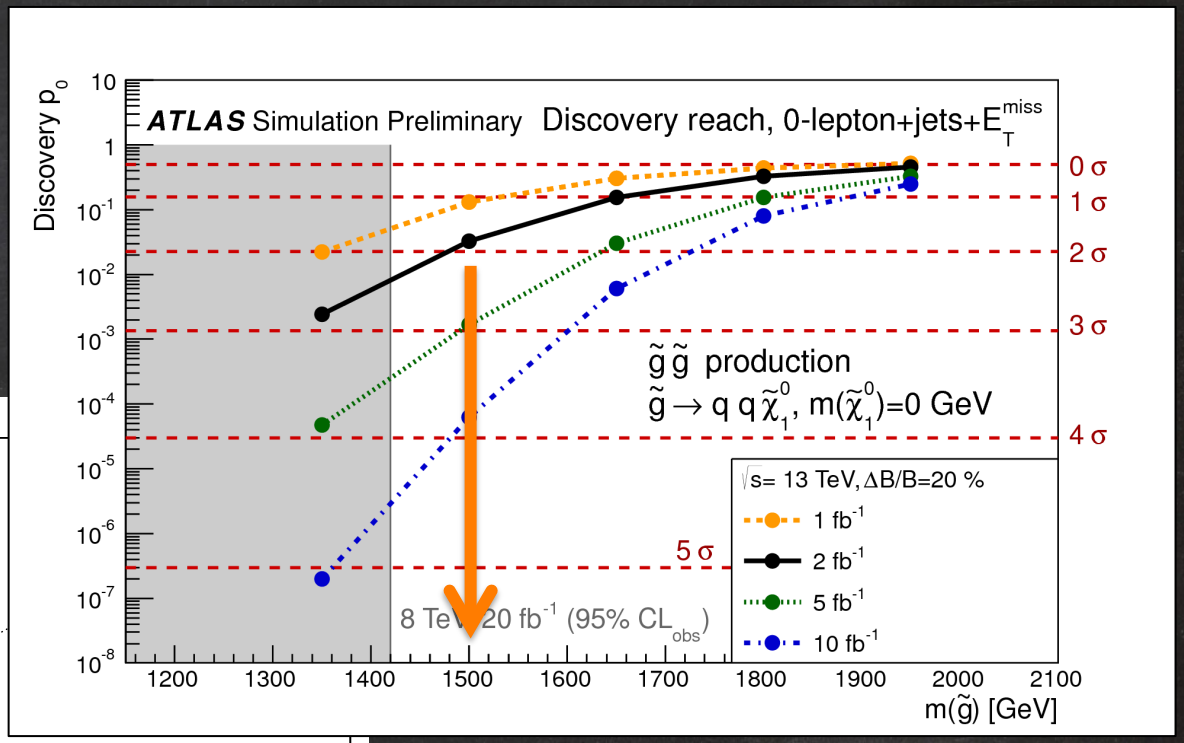


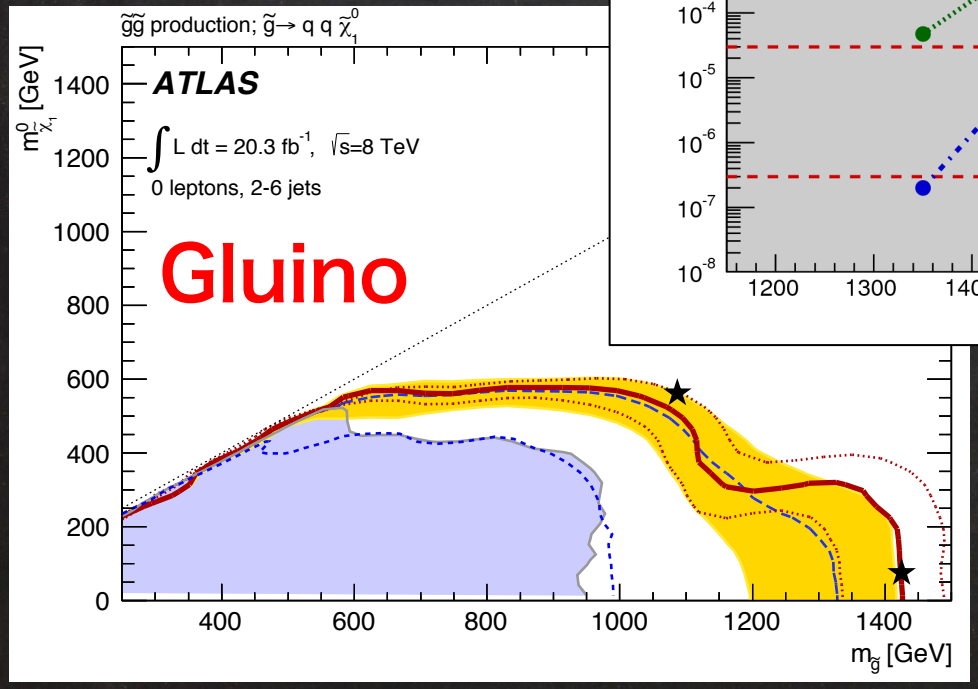


$M_{eff} = E_T^{miss} + \Sigma |p_T^{jet}|$

No bound is obtained so far

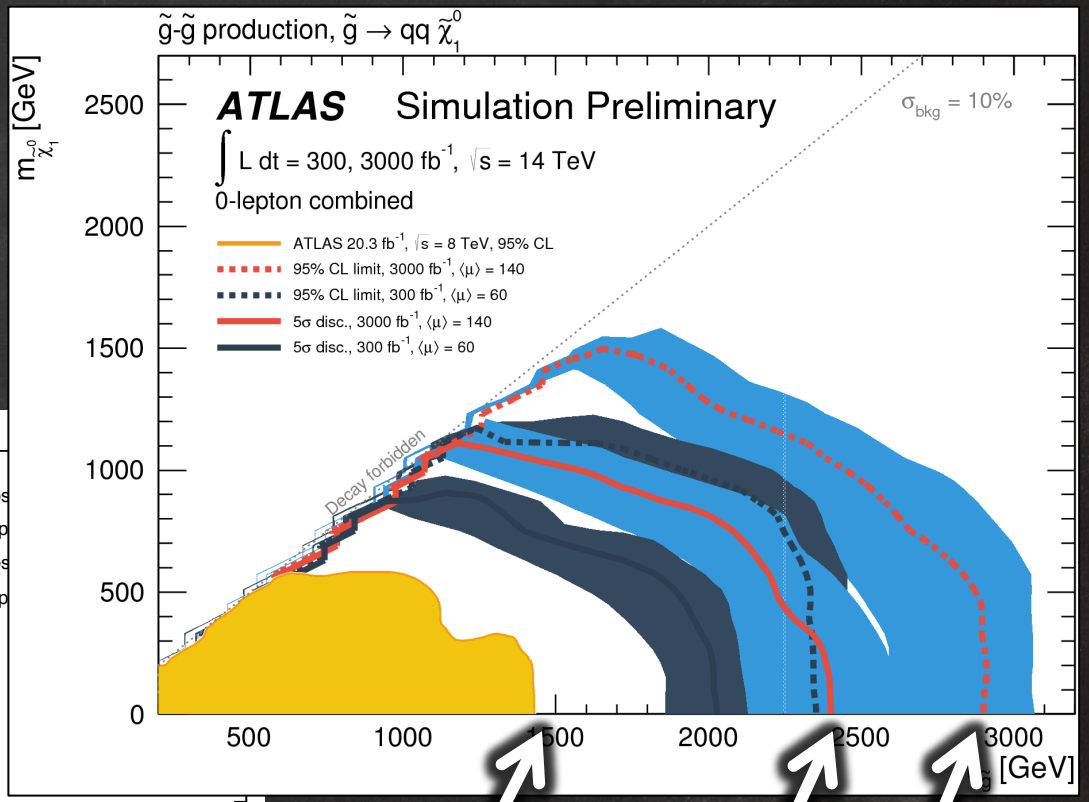
SUSY Prospects

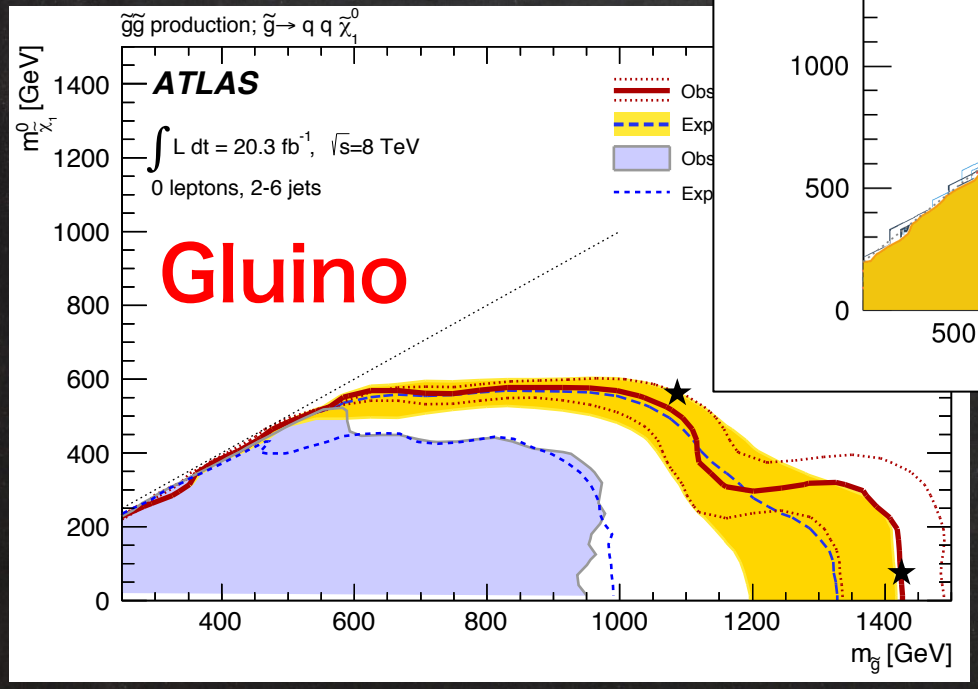




~3fb^{-1} @ Run II (Mar 2016???)

SUSY Prospects





3fb^{-1}, ~2015

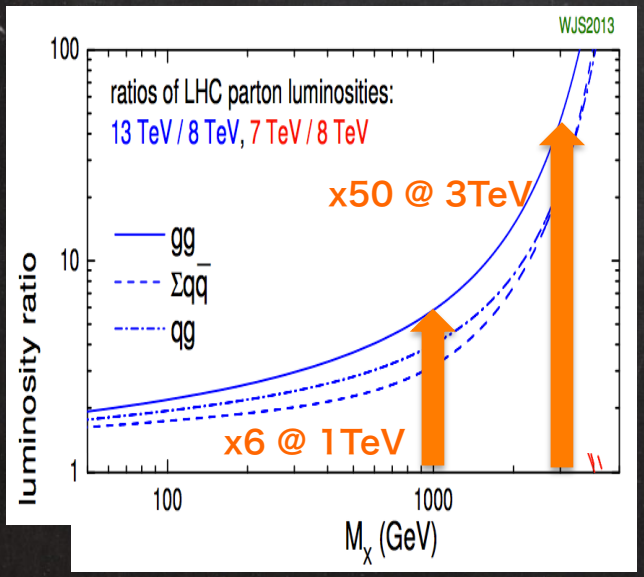
300fb^{-1}, ~2023

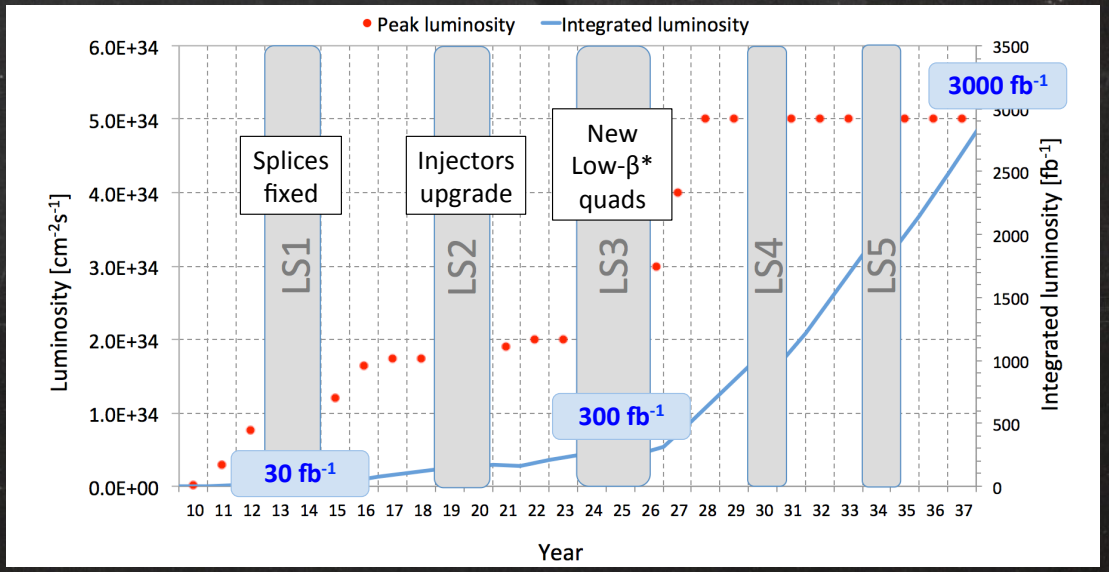
3000fb^{-1}, ~2037

Summary

Summary

- LHC Status
  - Energy Upgraded
  - Some Troubles (EC, UFO)
  - Next 20 years Plan
- Run I Summary and Run II Early Data
  - SM Re-Discovery incl. Higgs
  - BSM Non-Discovery / Exclusion
  - Evidence / Anomalies
  - Analysis Ready
  - Need More Data





Fin.

Stay Tuned