

# Prospects of LHC Run II

a phenomenologist view

Koji TSUMURA (Kyoto U.)

“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

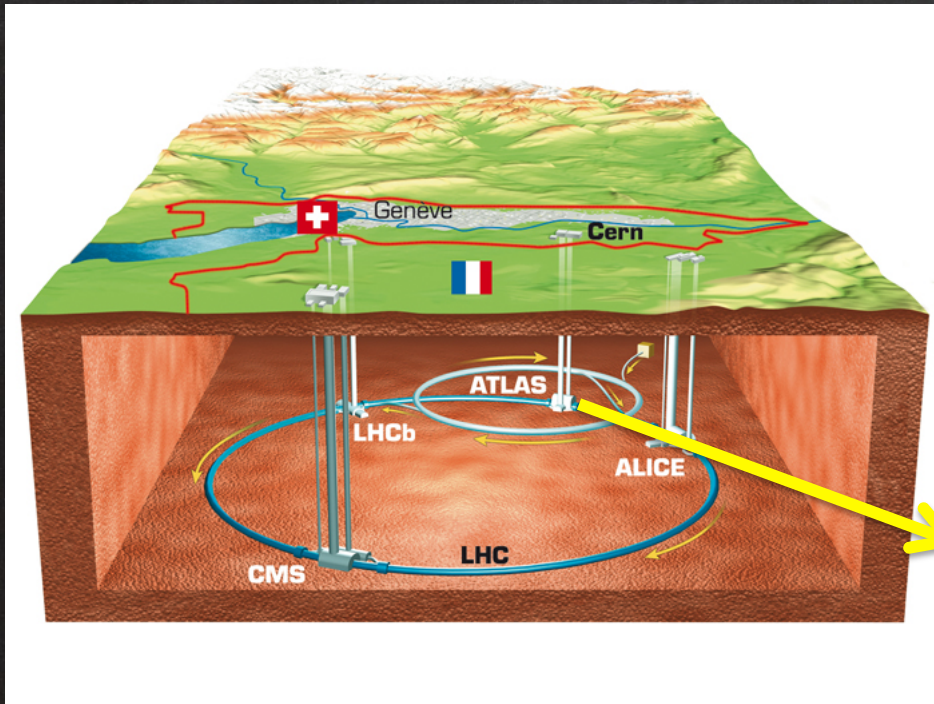


# LHC Status



# Large Hadron Collider (LHC)

26.7 km proton (heavy ion) Accelerator

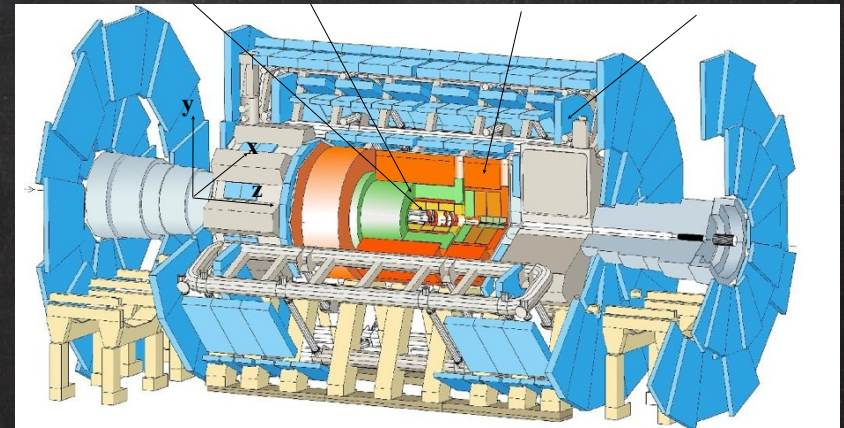


## Detector

Multi-purpose : ATLAS / CMS

B physics : LHCb

Heavy Ion : ALICE

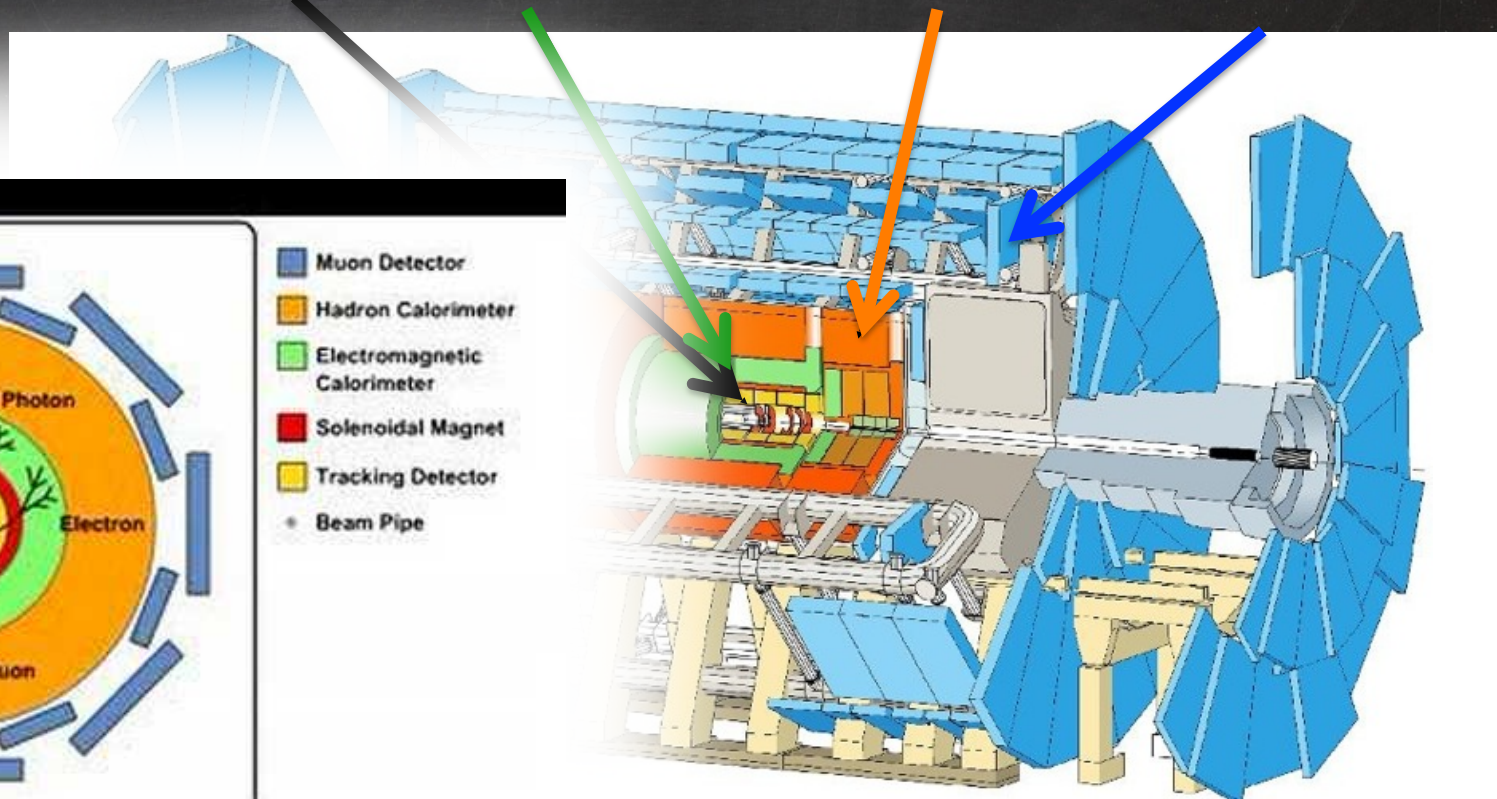
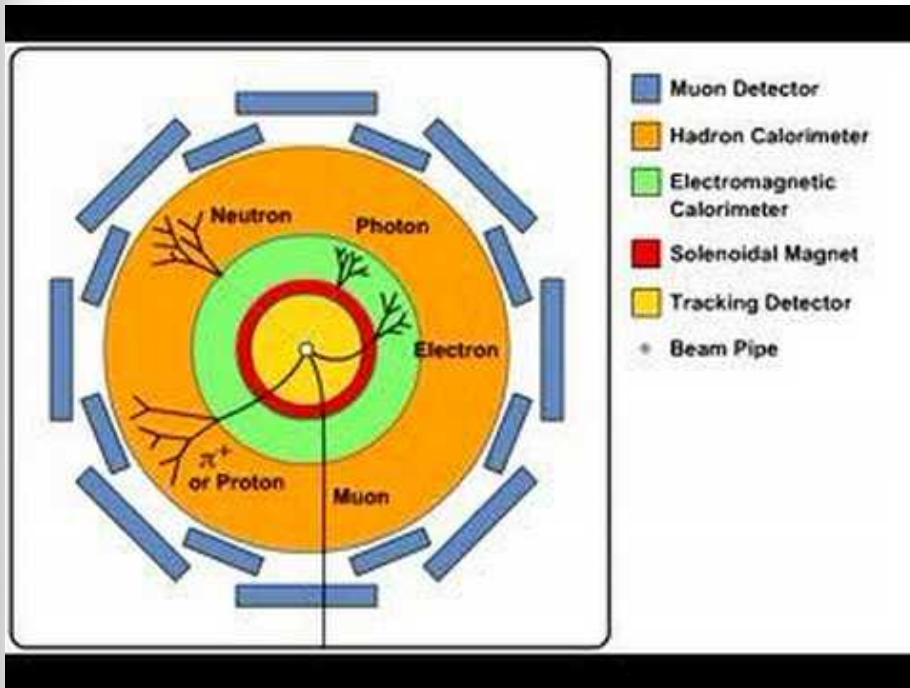




# Detector

## 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

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



# Collider

# of Events

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

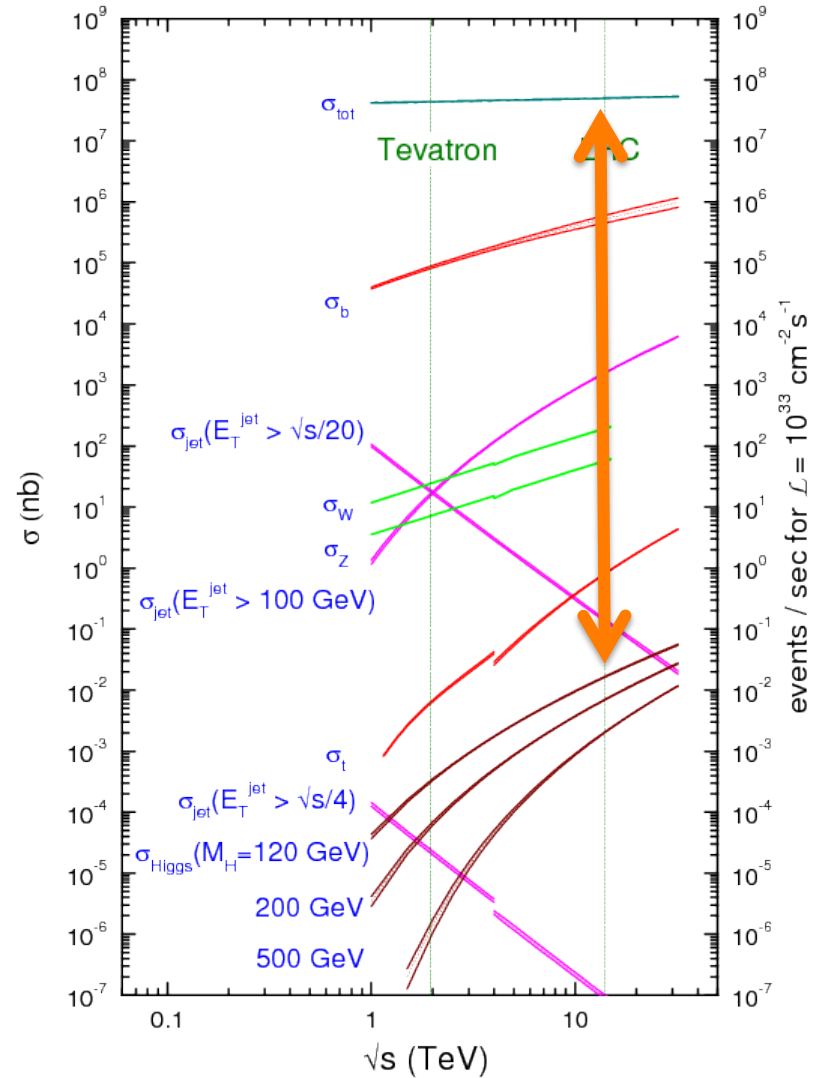
## Too Many Data

Signal is 10 orders of magnitude smaller than BG  
Need to Reduce Data → Trigger, Selection Cut

Experimental Challenge

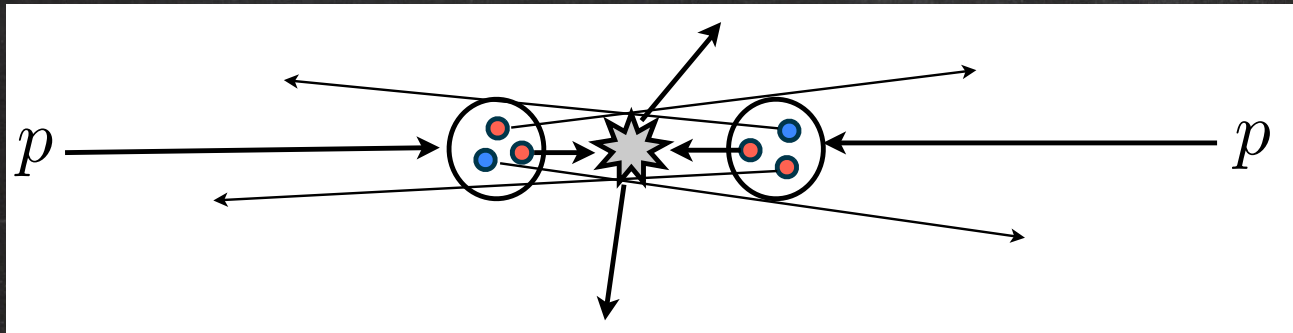
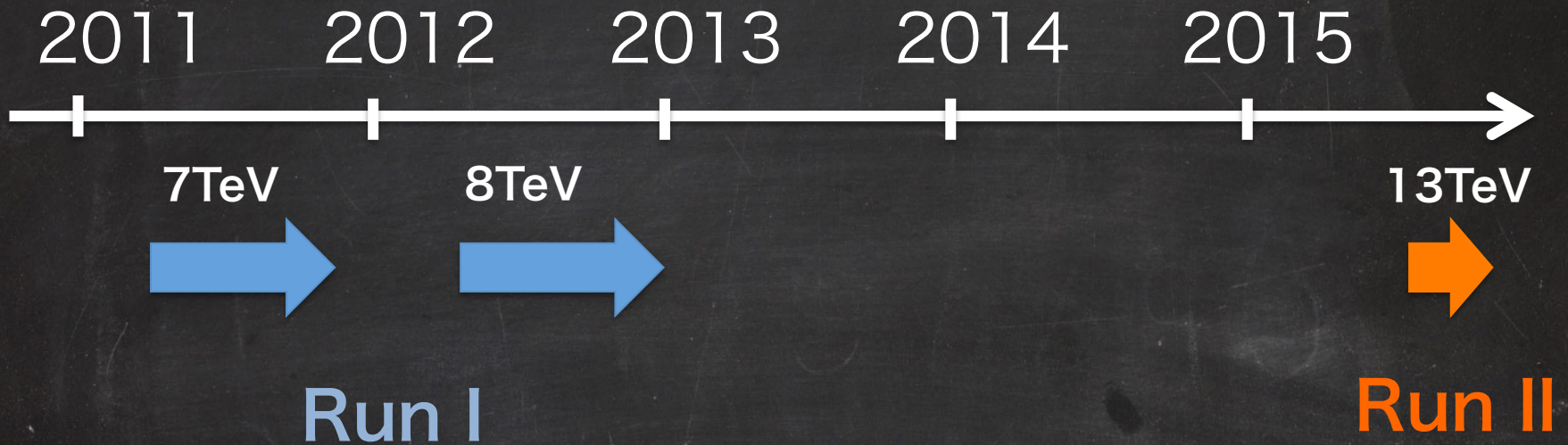
Phenomenologist Idea

proton - (anti)proton cross sections



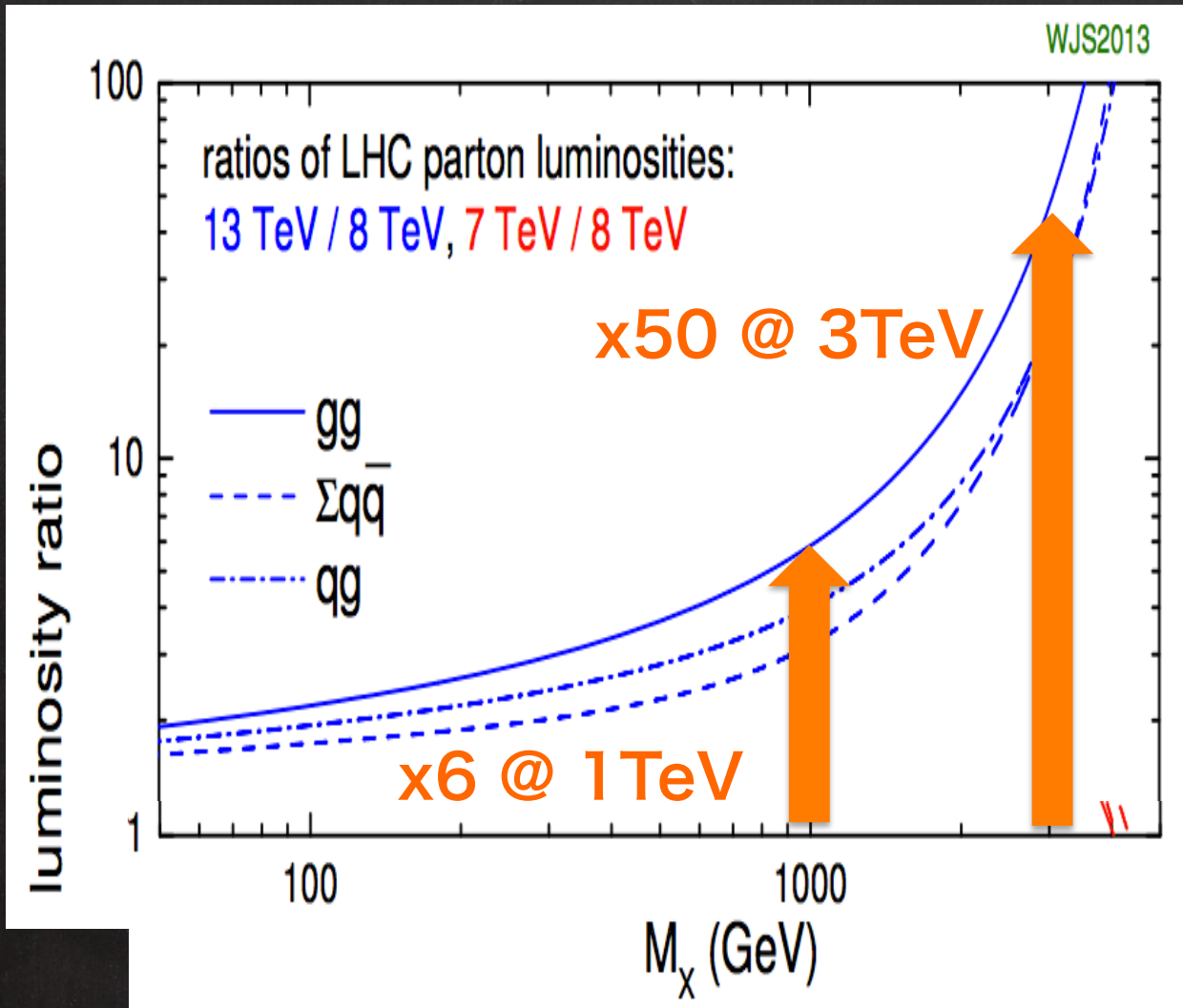
Function of Energy

# Energy





# Energy



2015



13TeV



Run II

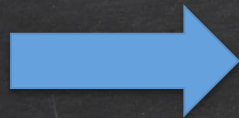
# Integrated Luminosity

2011      2012      2013      2014      2015

7TeV

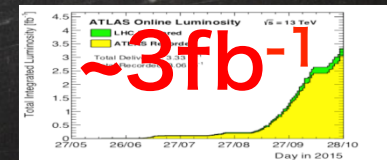
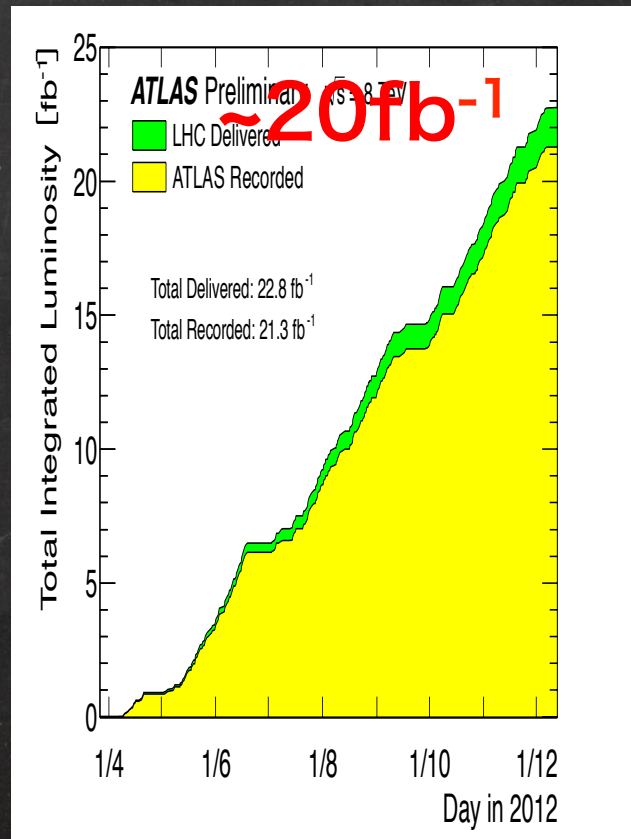
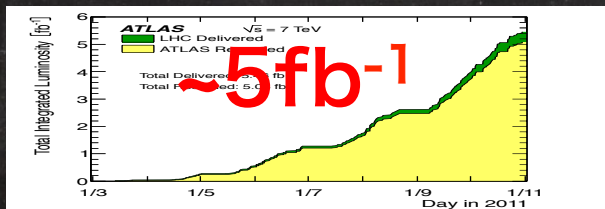
8TeV

13TeV



Run I

Run II





# Peak Luminosity

2011

2012

2013

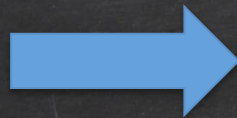
2014

2015

7TeV

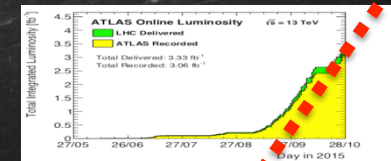
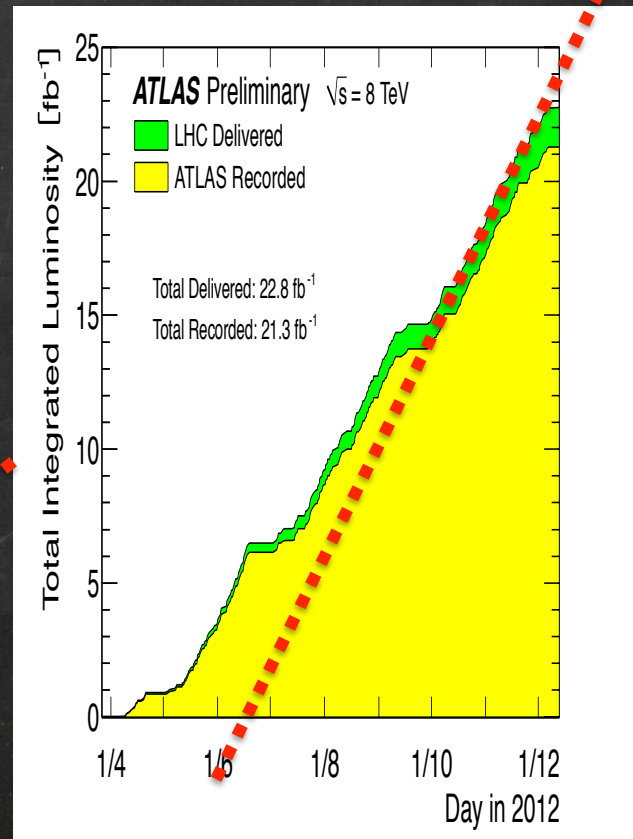
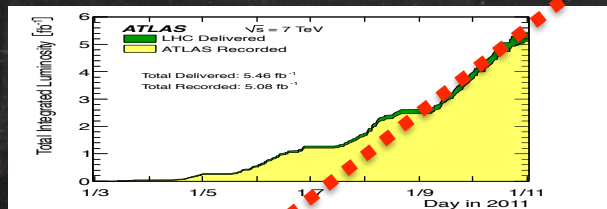
8TeV

13TeV



Run I

Run II



# Peak Luminosity

2011

2012

2013

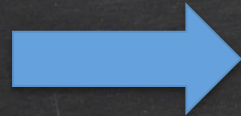
2014

2015

7TeV

8TeV

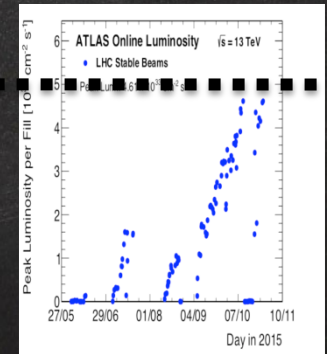
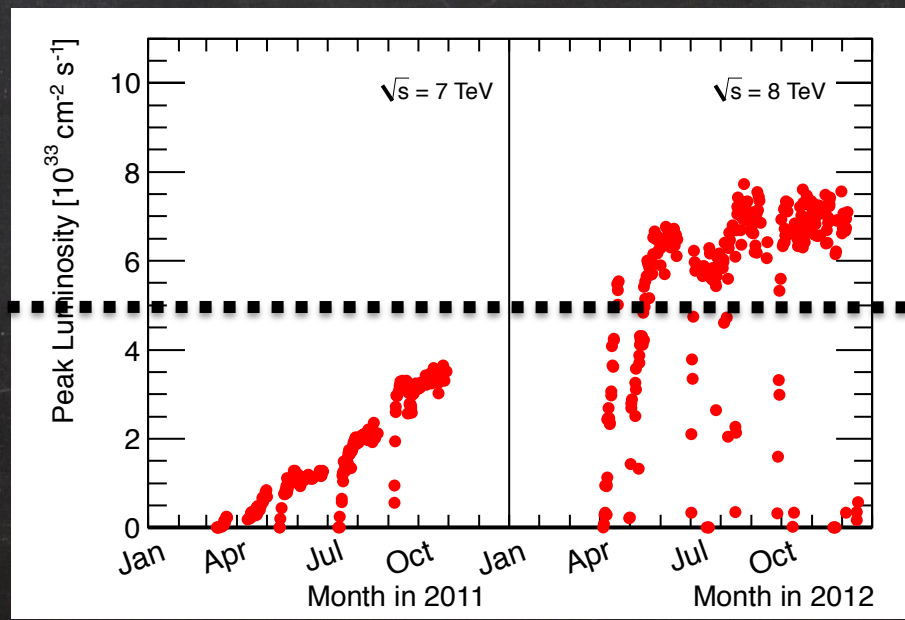
13TeV



Run I

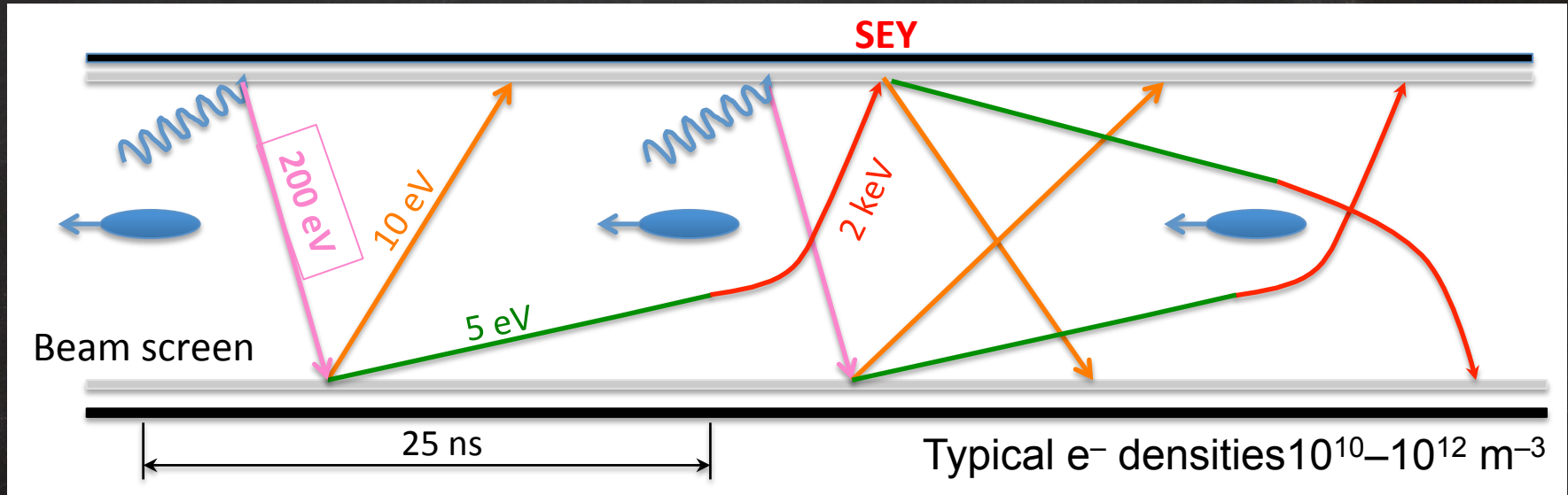
Run II

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





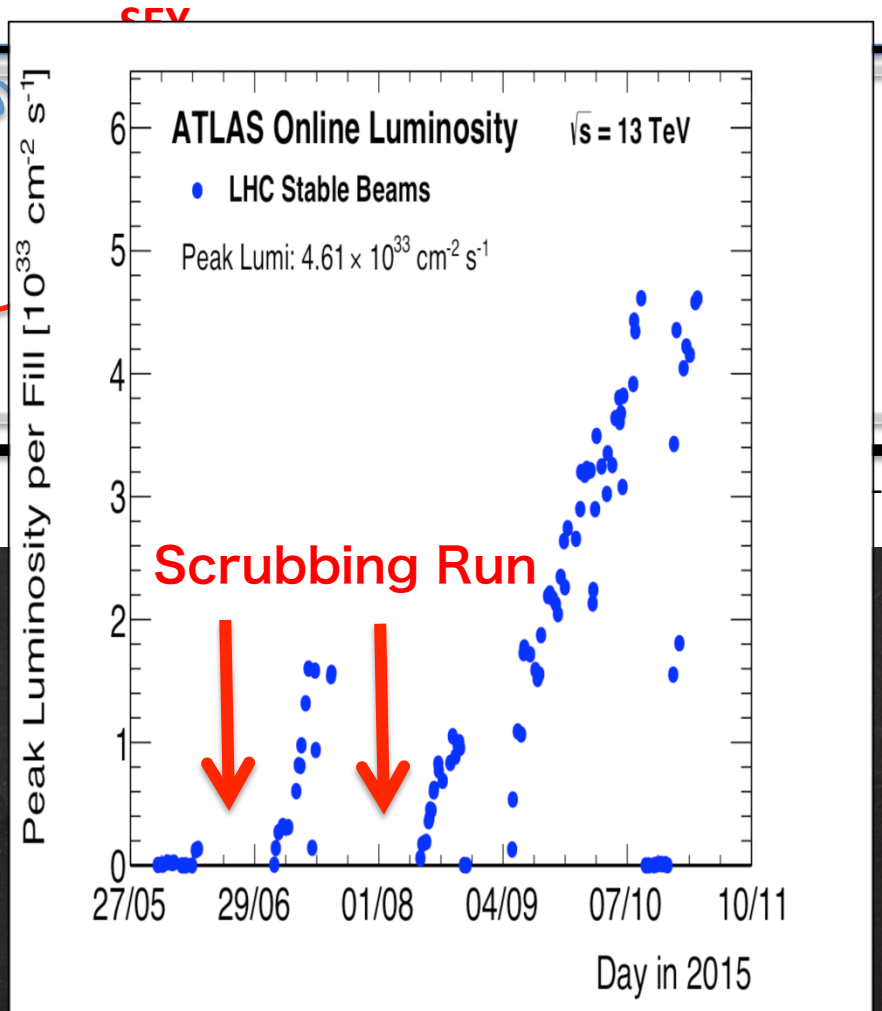
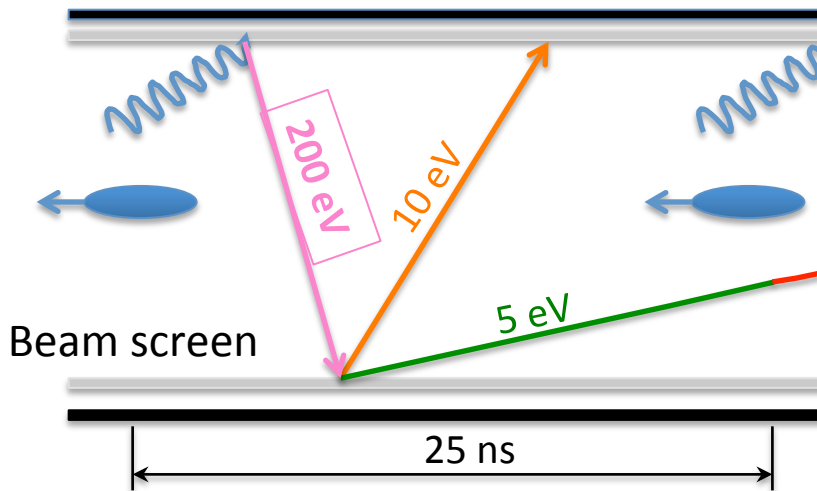
# Electron Cloud



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**

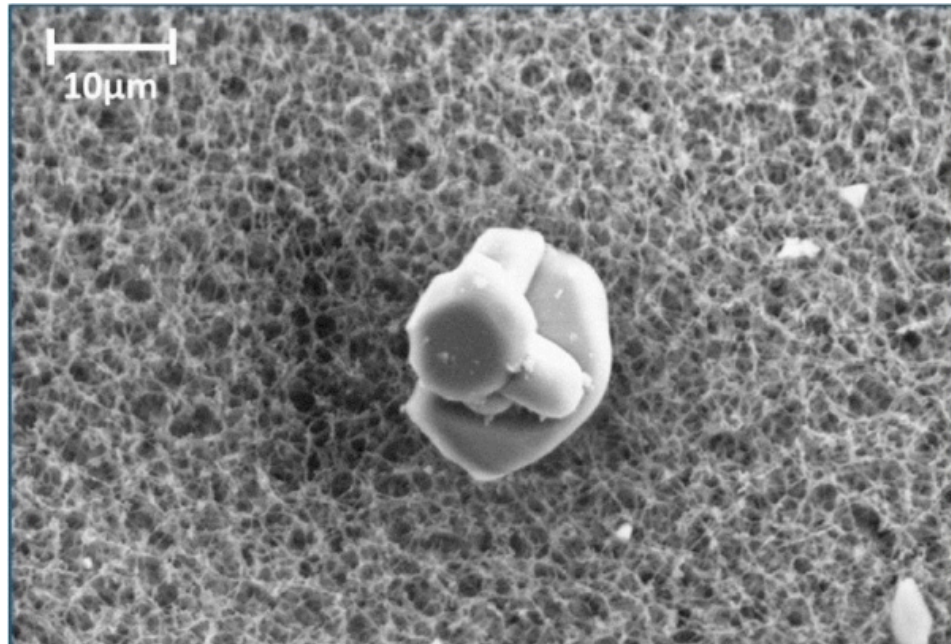
# Electron Cloud





# UFO (Undefined Falling Object)

A nice picture  
of some dust



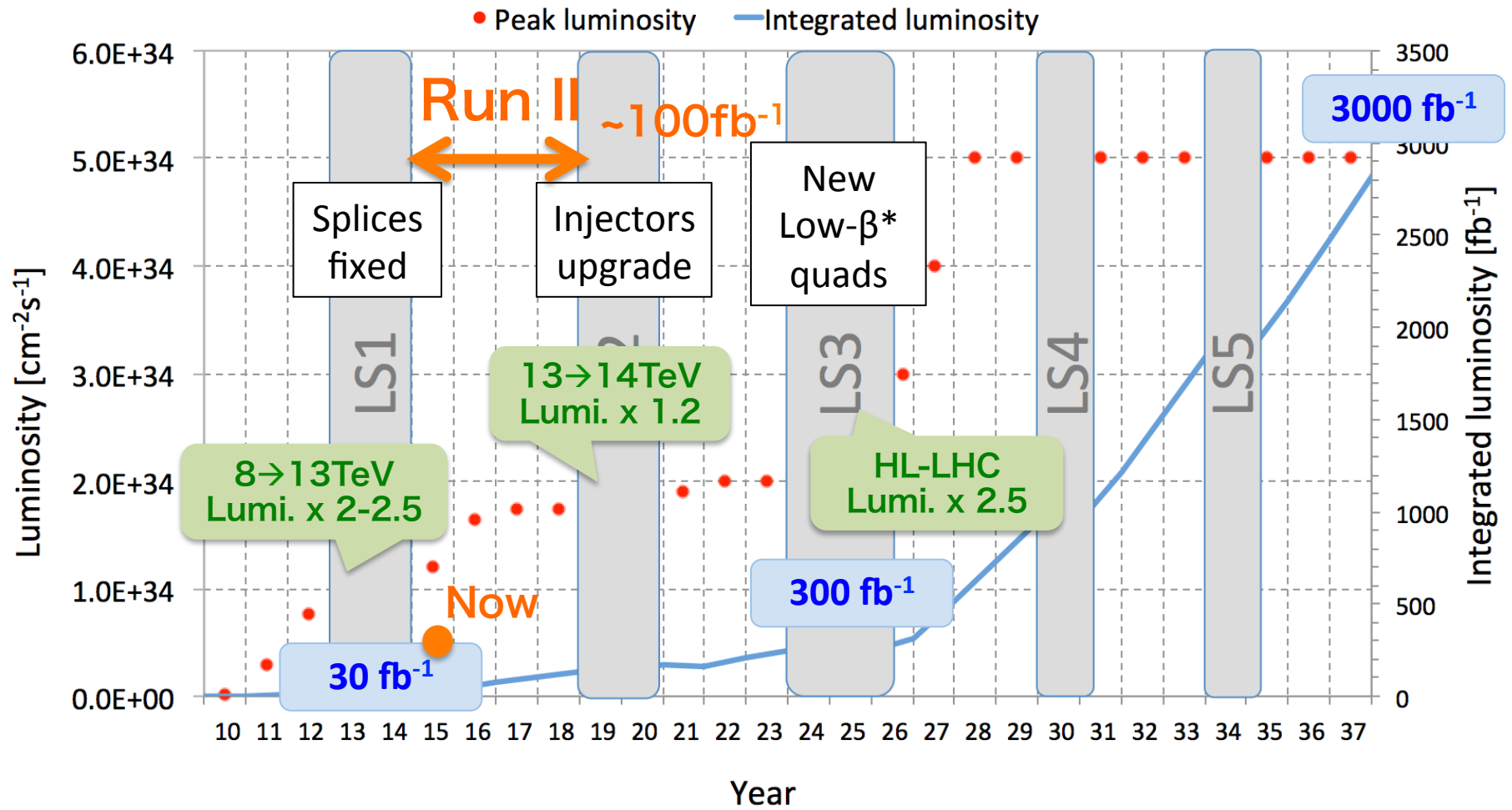
**UFOs (dust?) dropping from upper beam shield**

→ Hit the Beam (Collision outside Detector)

→ Beam Loss ?

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

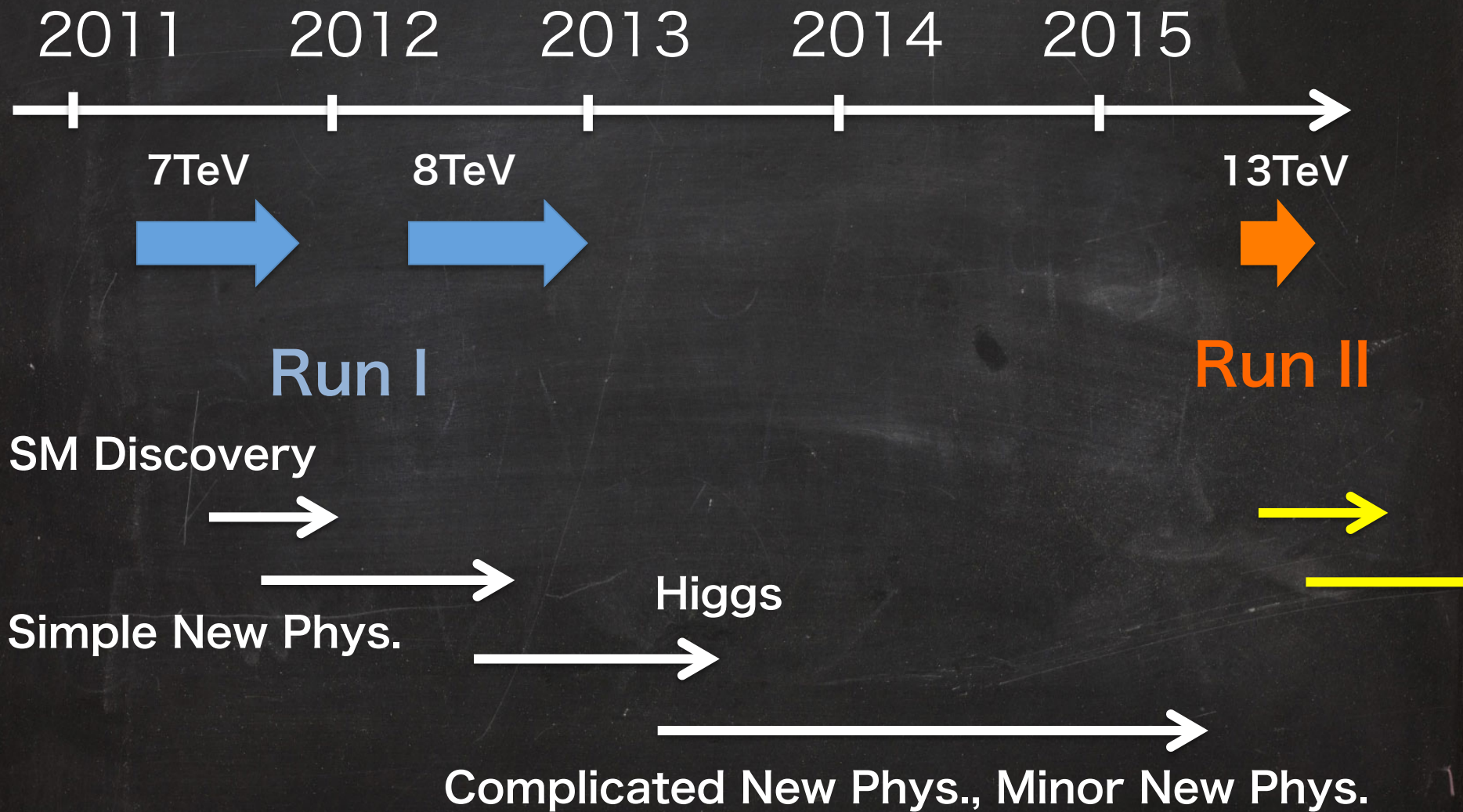
# Next 20 years





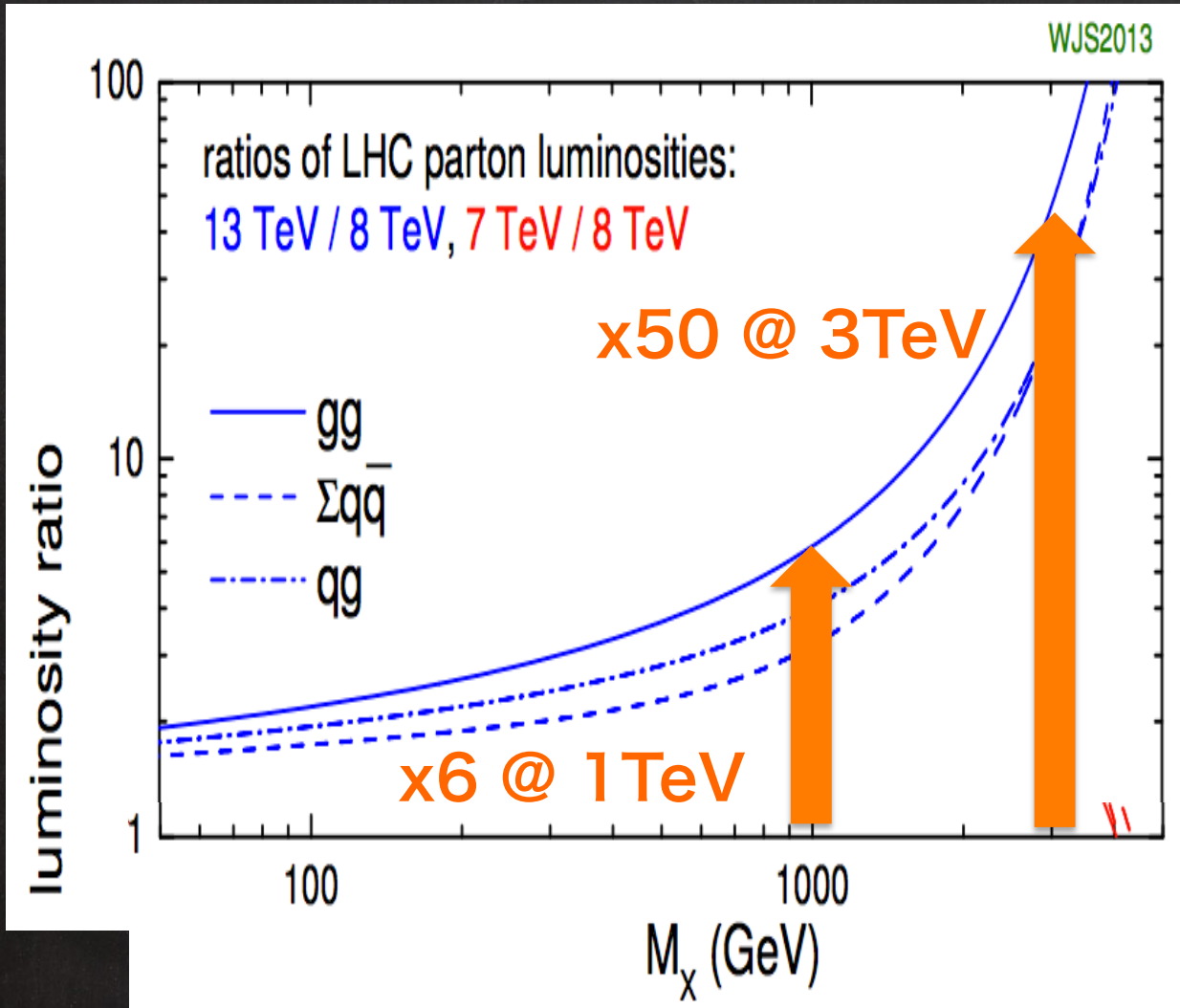
# Physics Results

# Timeline of Analysis





# Run II Prospects



Run I  $\sim 25\text{fb}^{-1}$   
(analyzed)

Run II  $\sim 3\text{fb}^{-1}$   
(collected)

Run II  $\sim 100\text{pb}^{-1}$   
(partly analyzed)

# Run I ( 7/8 TeV )



# Dictionary

- **Discovery / Observation**  
 $> 5\sigma$  [ 99.99994% ]
- **Evidence**  
 $> 3\sigma$  [ 99.7% ]
- **Anomaly** ( Excess / Deficit / ... )  
 $> 2\sigma$  [ 95.5% ]
- **Exclusion**  
BG only  $> 2\sigma$  [ 95.5% ]

# Discovery / Observation

$> 5\sigma$

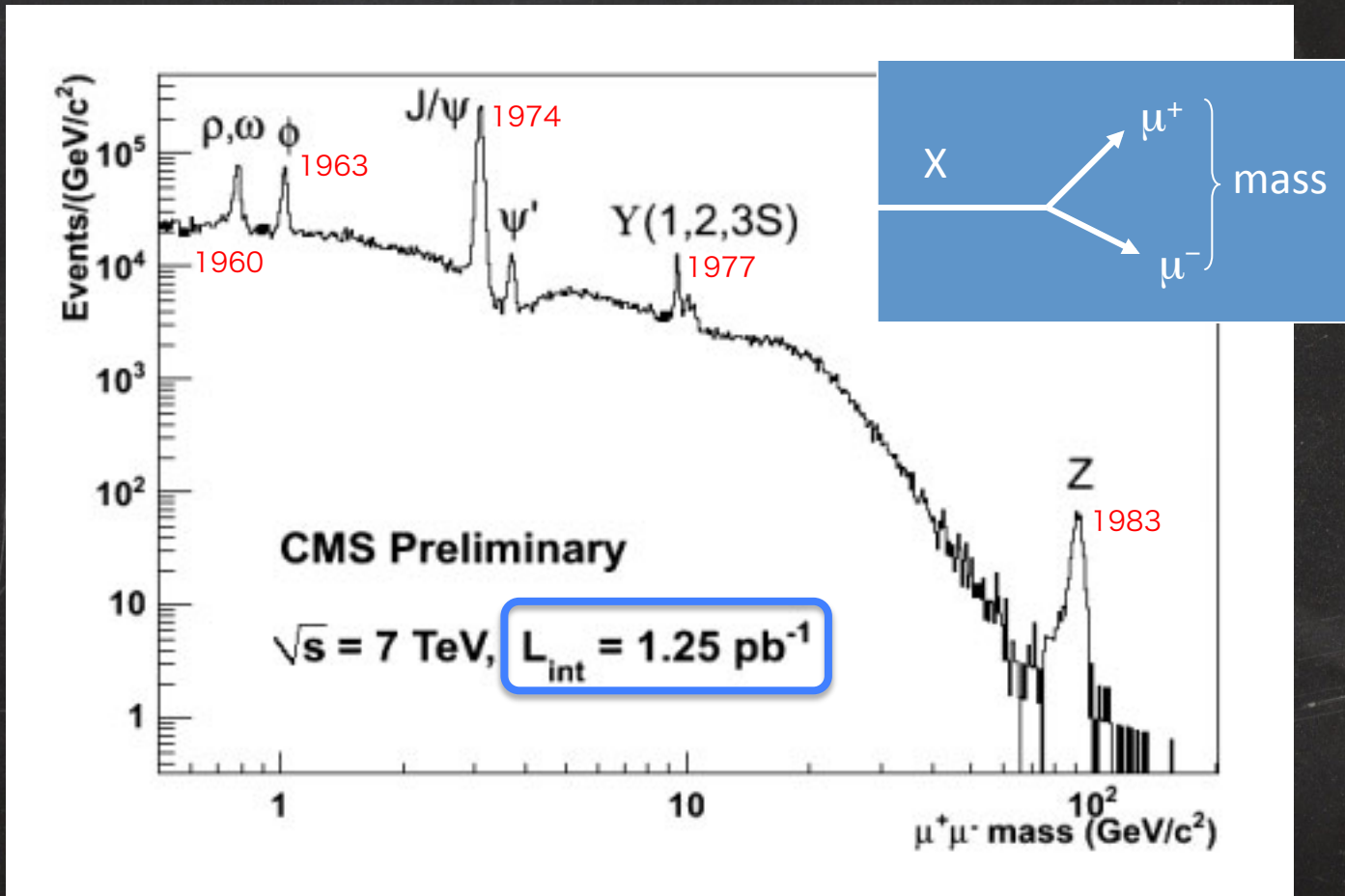
1/1744278 : Every 4776 years  
(Once in recorded history)

99.99994%



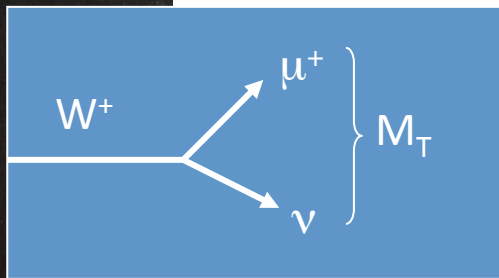
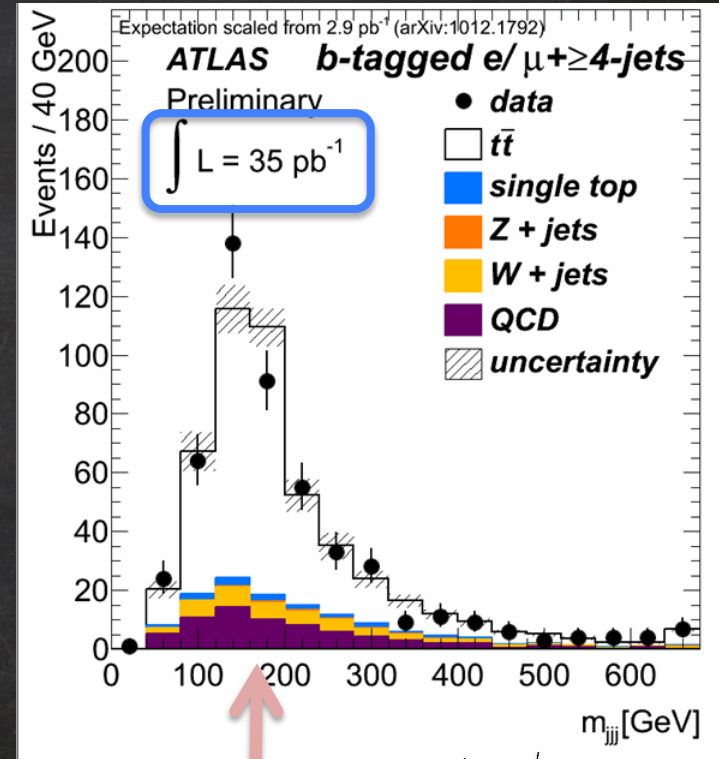
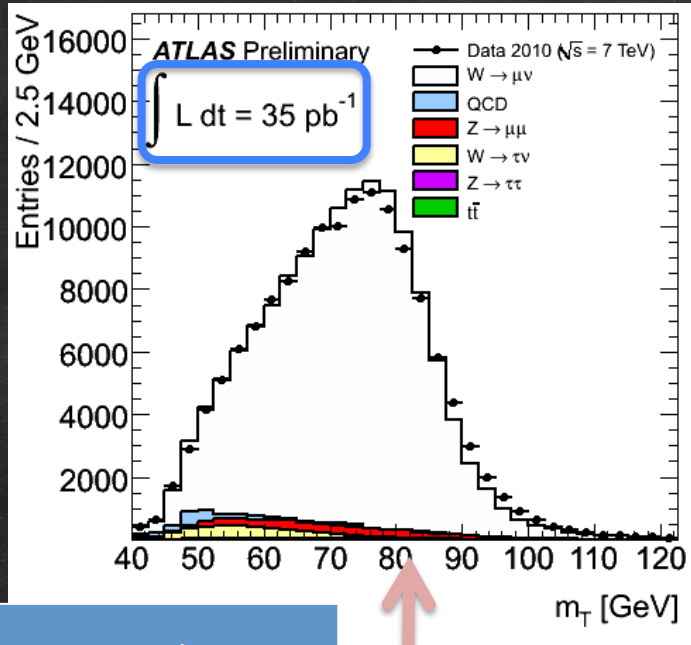
# Re-Discovery of the SM

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



# Re-Discovery of W, top

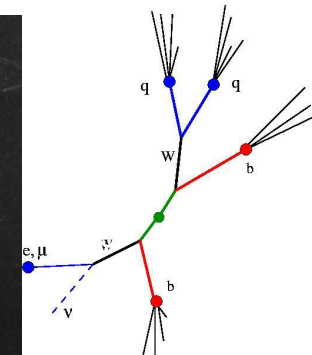
lepton + Missing  $E_T(\nu)$  [ w/  $p_T$  conservation ]



$M_W$

$M_t$

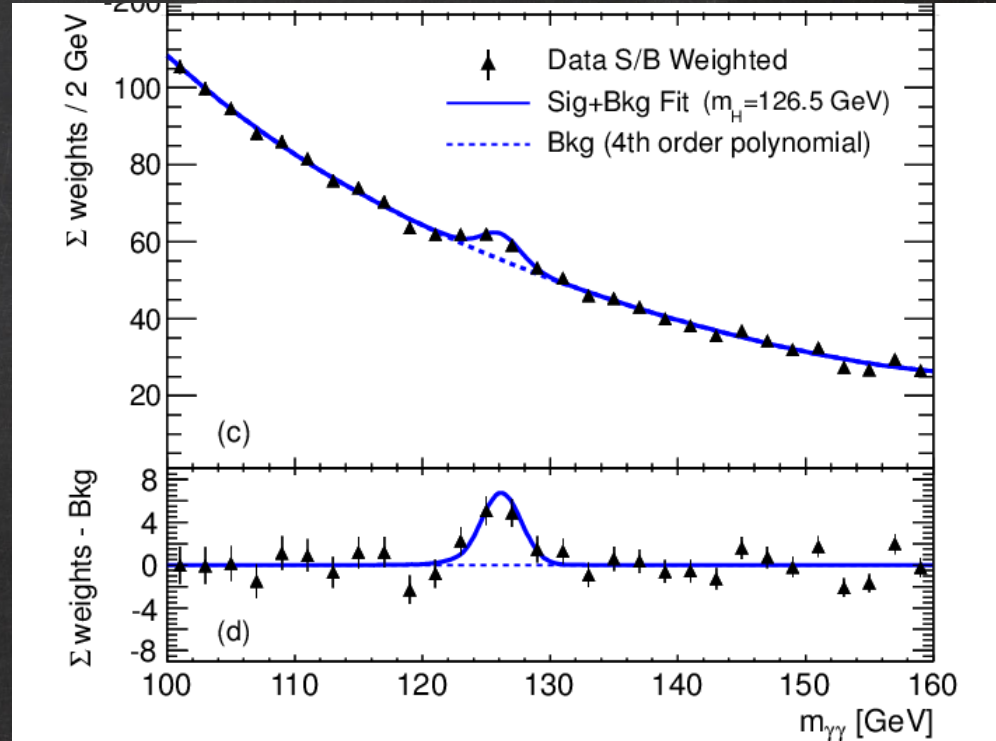
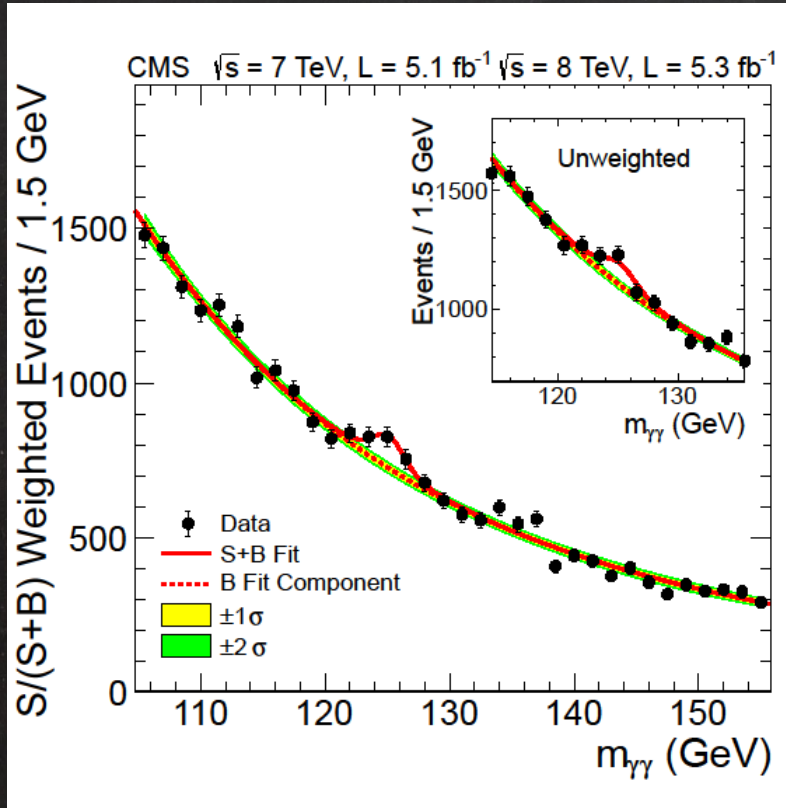
$$M_T = \sqrt{2p_T^\ell p_T^\nu (1 - \cos(\phi^\ell - \phi^\nu))}$$





# Higgs

# Higgs Discovery



2015/

Koji TSUMURA (Kyoto U.)



13



**H<sup>0</sup>**

$J = 0$

Now, we can make precise predictions

Mass  $m = 125.09 \pm 0.24$  GeV

### H<sup>0</sup> Signal Strengths in Different Channels

See Listings for the latest unpublished results.

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

$W W^* = 0.81 \pm 0.16$

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

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

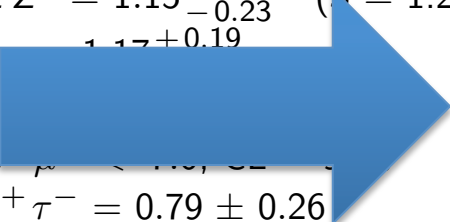
$b\bar{b}$

$\mu\bar{\mu}$

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

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

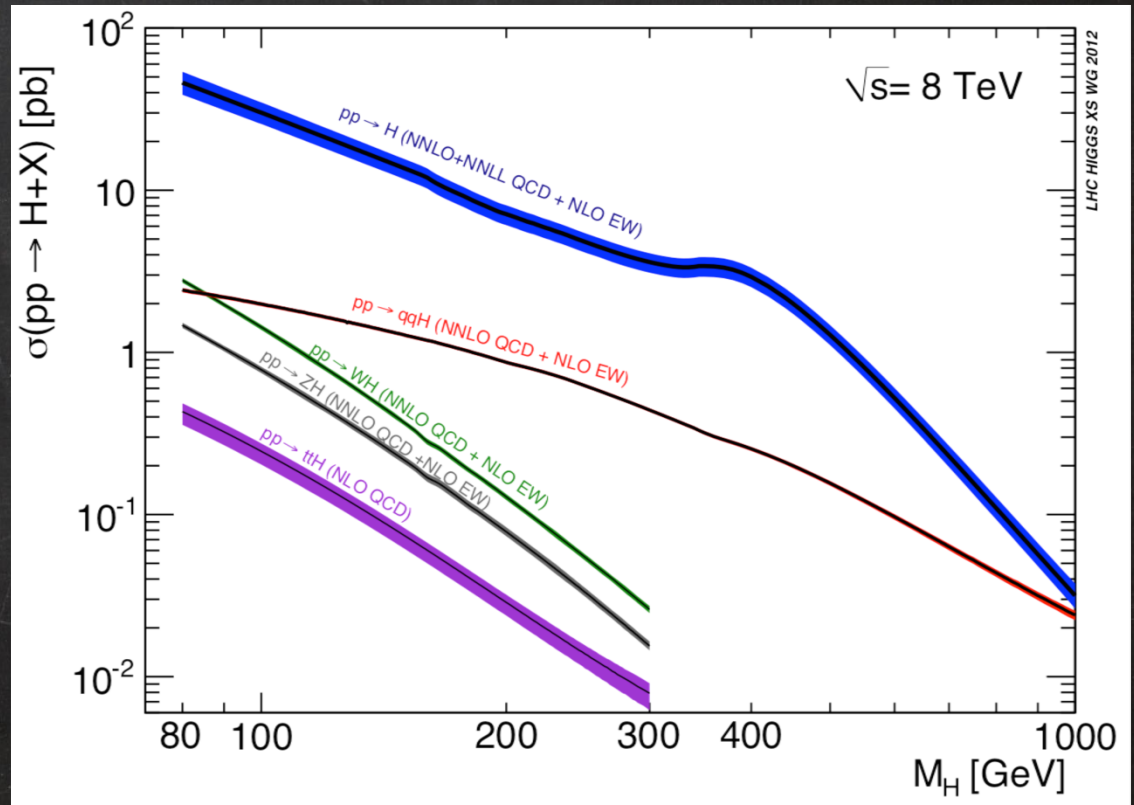
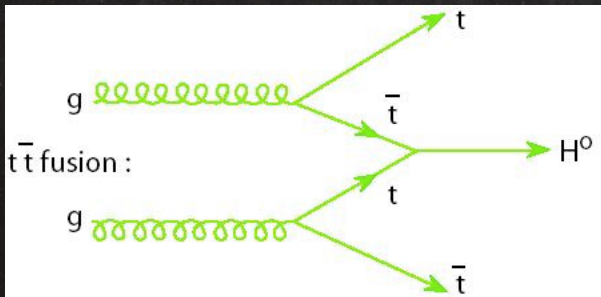
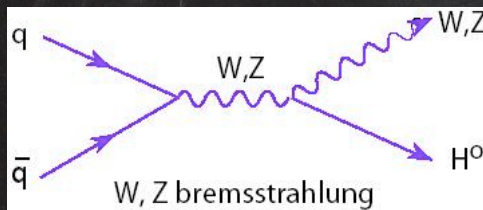
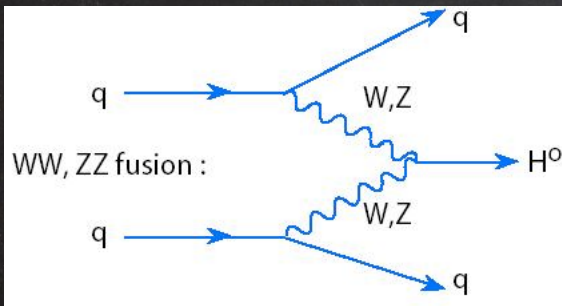
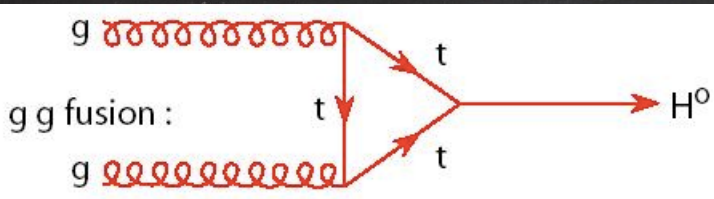
$t\bar{t}H^0$  Production =  $2.5^{+0.9}_{-0.8}$



Official Combination

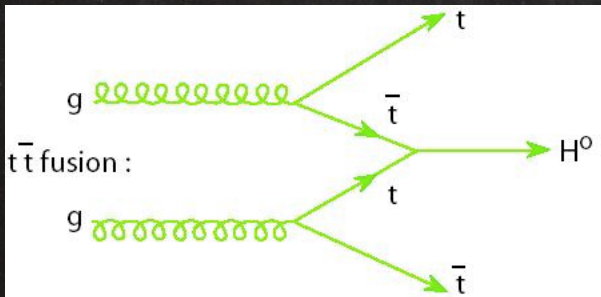
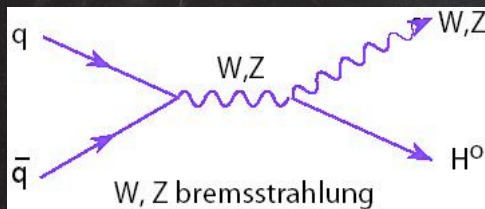
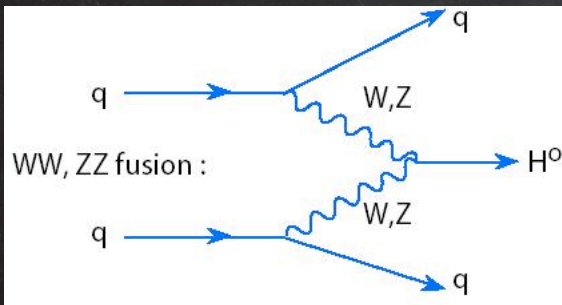
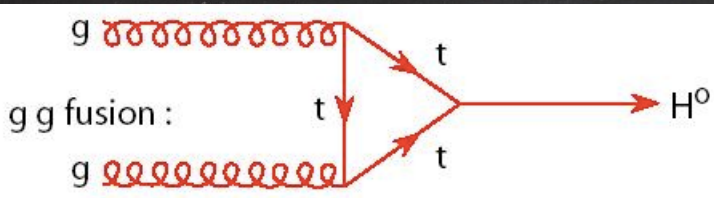
| H <sup>0</sup> DECAY MODES | Fraction ( $\Gamma_i/\Gamma$ ) | Confidence level | $p$<br>(MeV/c) |
|----------------------------|--------------------------------|------------------|----------------|
| invisible                  | <58 %                          | 95%              | —              |

# Higgs Production



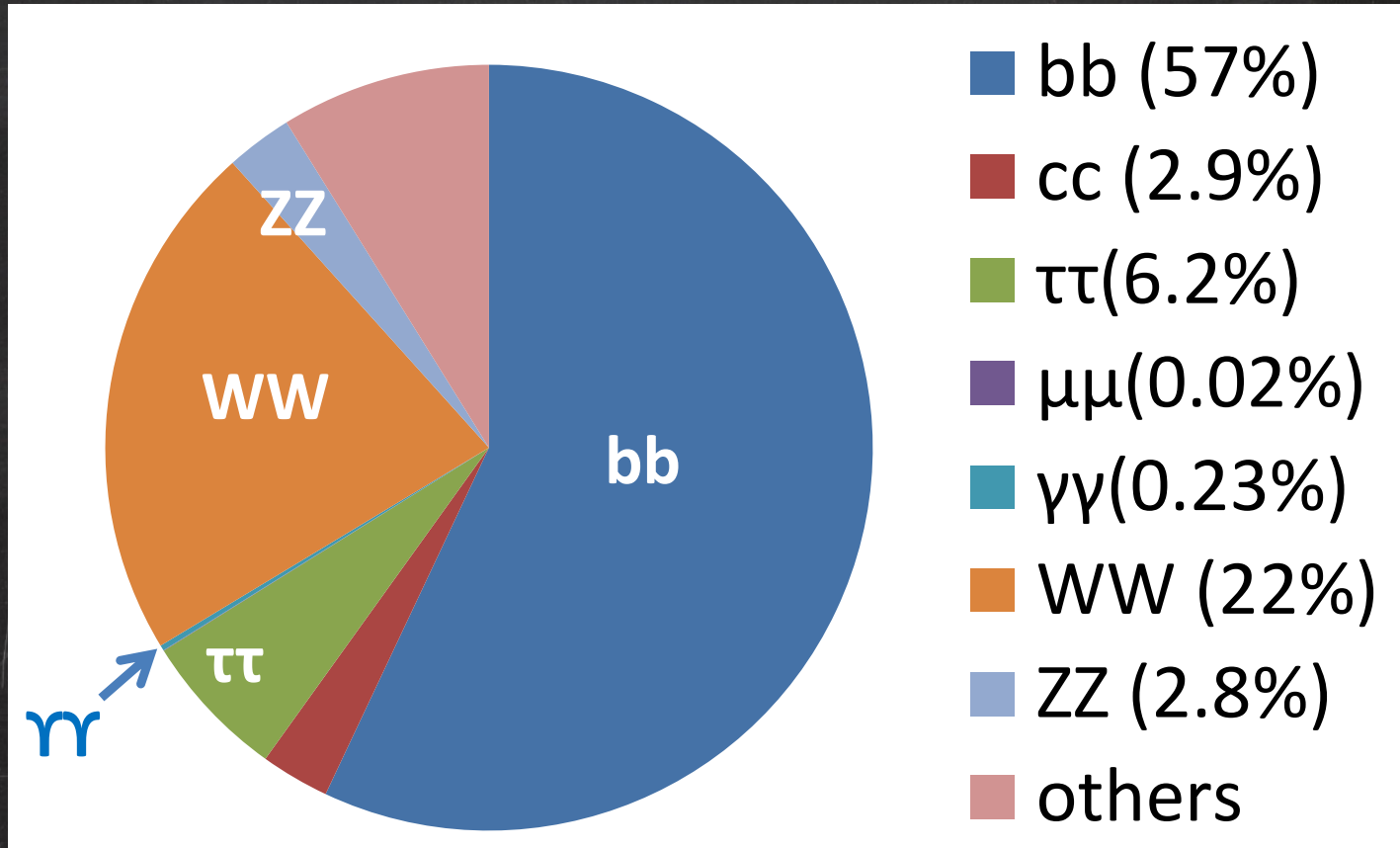


# Higgs Production



|                           | $\sigma$ (pb)<br>@7TeV | $\sigma$ (pb)<br>@14TeV | 14TeV<br>/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





# Official Combination

## Individual Results

$\mu = \text{Observed} / \text{Expected}$

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

20-30%

30-40%

3.5  $\sigma$

3.0  $\sigma$

Observation of gg, ZZ, WW

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

Need more data for bb (Run II)  
for  $\mu\mu$ ,  $Z\gamma$  (HL-LHC)

# Official Combination

## Individual Results

| Channel                              | Signal strength [ $\mu$ ]                    |  | Signal significance [ $\sigma$ ] |              |
|--------------------------------------|--|--|----------------------------------|--------------|
|                                      | ATLAS  | CMS  | ATLAS                            | CMS          |
| $H \rightarrow \gamma\gamma$         | $1.15^{+0.27}_{-0.25}$<br>(+0.26)<br>(-0.24) | $1.12^{+0.25}_{-0.23}$<br>(+0.24)<br>(-0.22) | 5.0<br>(4.6)                     | 5.6<br>(5.1) |
| $H \rightarrow ZZ \rightarrow 4\ell$ | $1.51^{+0.39}_{-0.34}$<br>(+0.33)<br>(-0.27) | $1.05^{+0.32}_{-0.27}$<br>(+0.31)<br>(-0.26) | 6.6<br>(5.5)                     | 7.0<br>(6.8) |
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| $H \rightarrow bb$                   | $0.62^{+0.37}_{-0.36}$<br>(+0.39)<br>(-0.37) | $0.81^{+0.43}_{-0.42}$<br>(+0.45)<br>(-0.43) | 1.7<br>(2.7)                     | 2.0<br>(2.5) |
| $H \rightarrow \mu\mu$               | $-0.7 \pm 3.6$<br>( $\pm 3.6$ )              | $0.8 \pm 3.5$<br>( $\pm 3.5$ )               |                                  |              |
| $ttH$ production                     | $1.9^{+0.8}_{-0.7}$<br>(+0.72)<br>(-0.66)    | $2.9^{+1.0}_{-0.9}$<br>(+0.88)<br>(-0.80)    | 2.7<br>(1.6)                     | 3.6<br>(1.3) |

from results in this paper (Section 5.2)

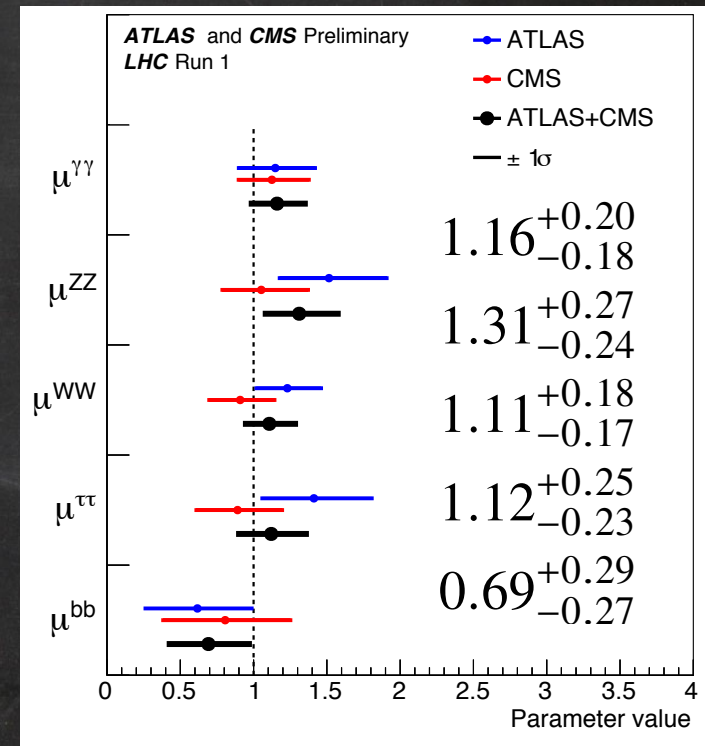
20-30% (green boxes)

30-40% (orange boxes)

>5 $\sigma$  (red boxes)

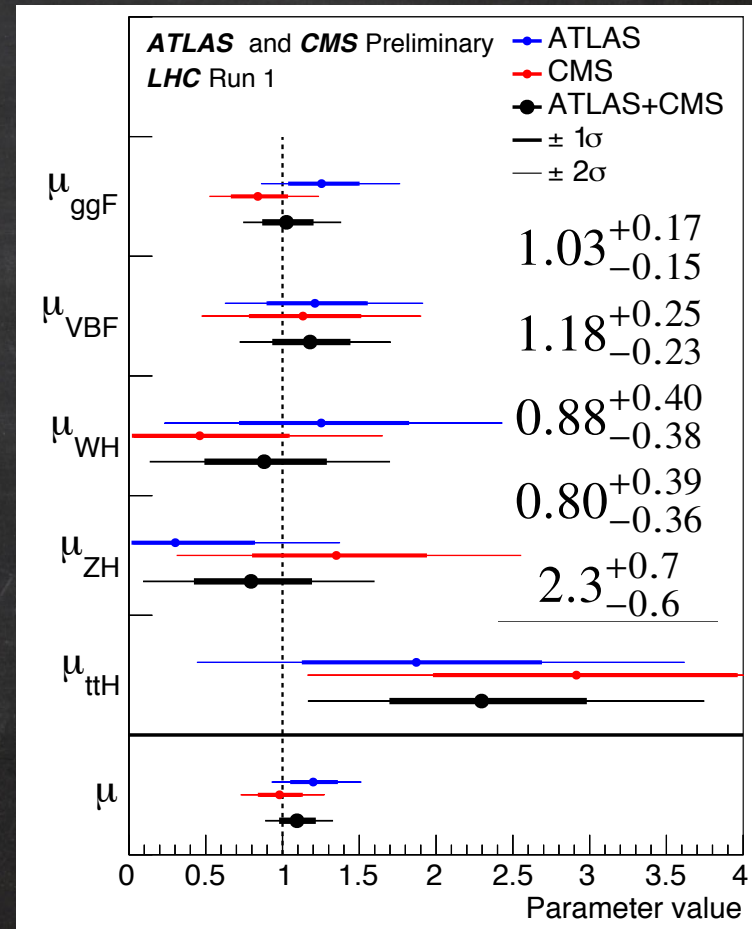
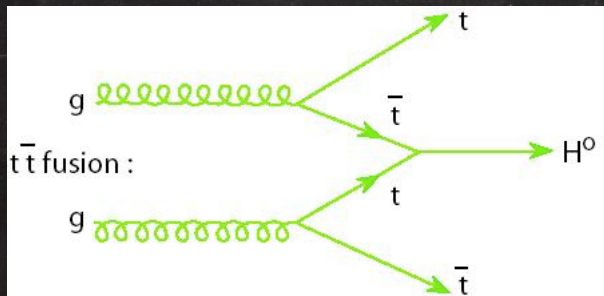
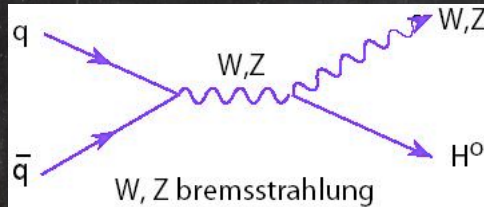
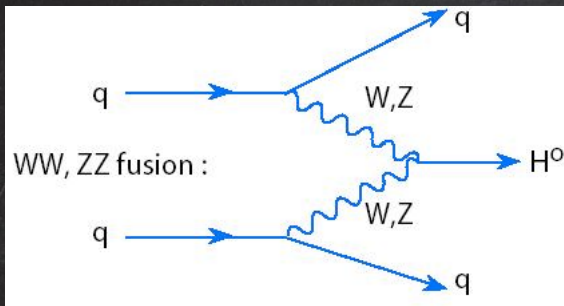
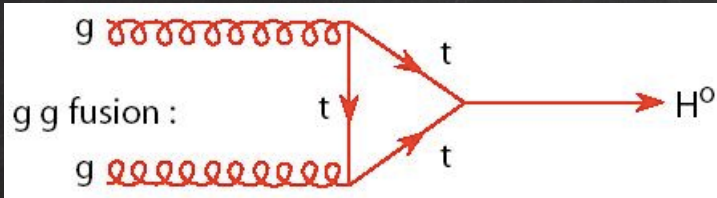
>3 $\sigma$  (blue boxes)

## Combined Results

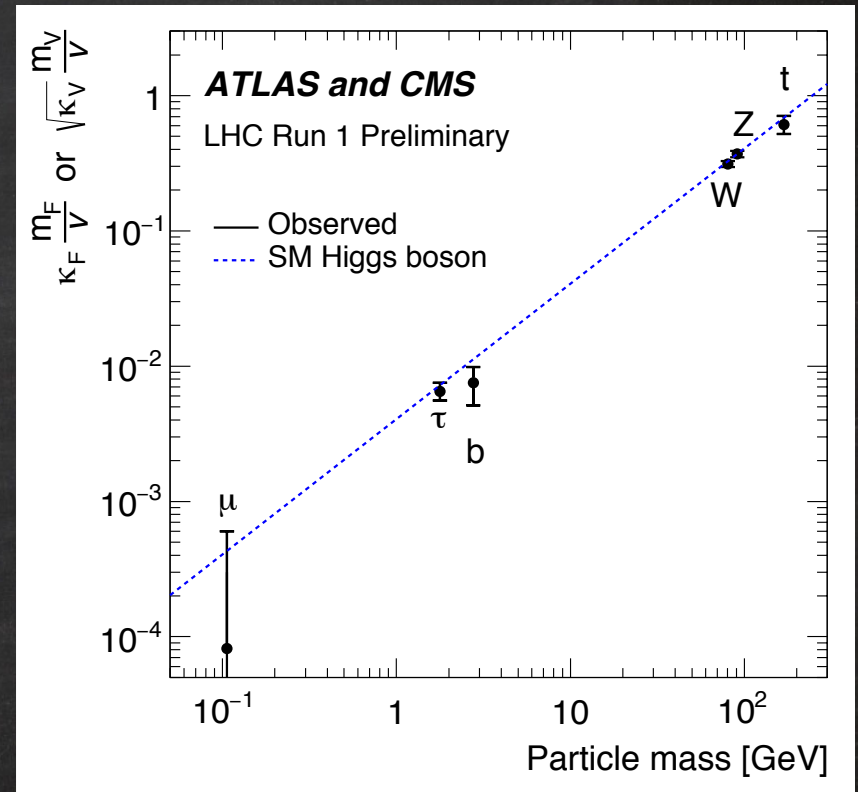
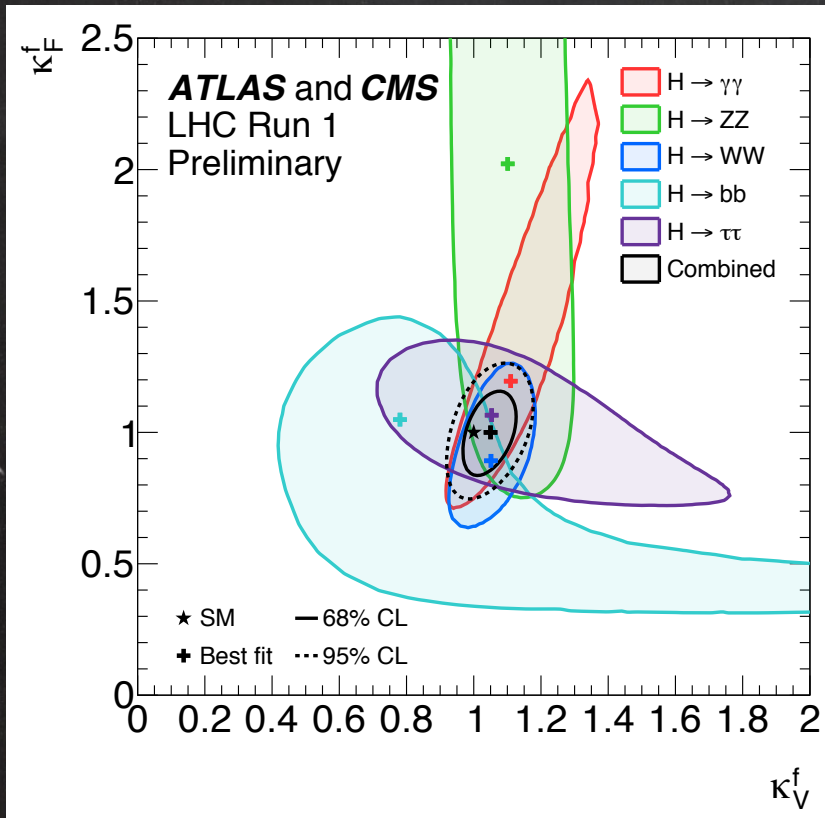




# Testing Higgs Production



# Testing Higgs Coupling



Indirect Test of BSM w/o New Particles



# Exclusion / Non-discovery

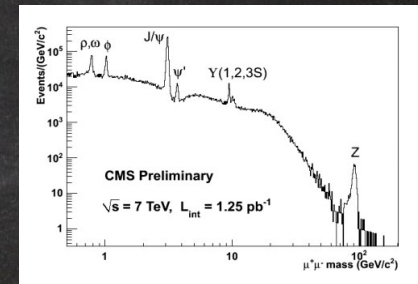
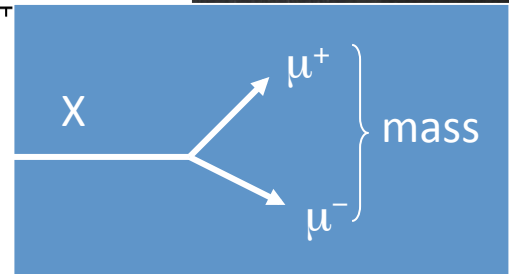
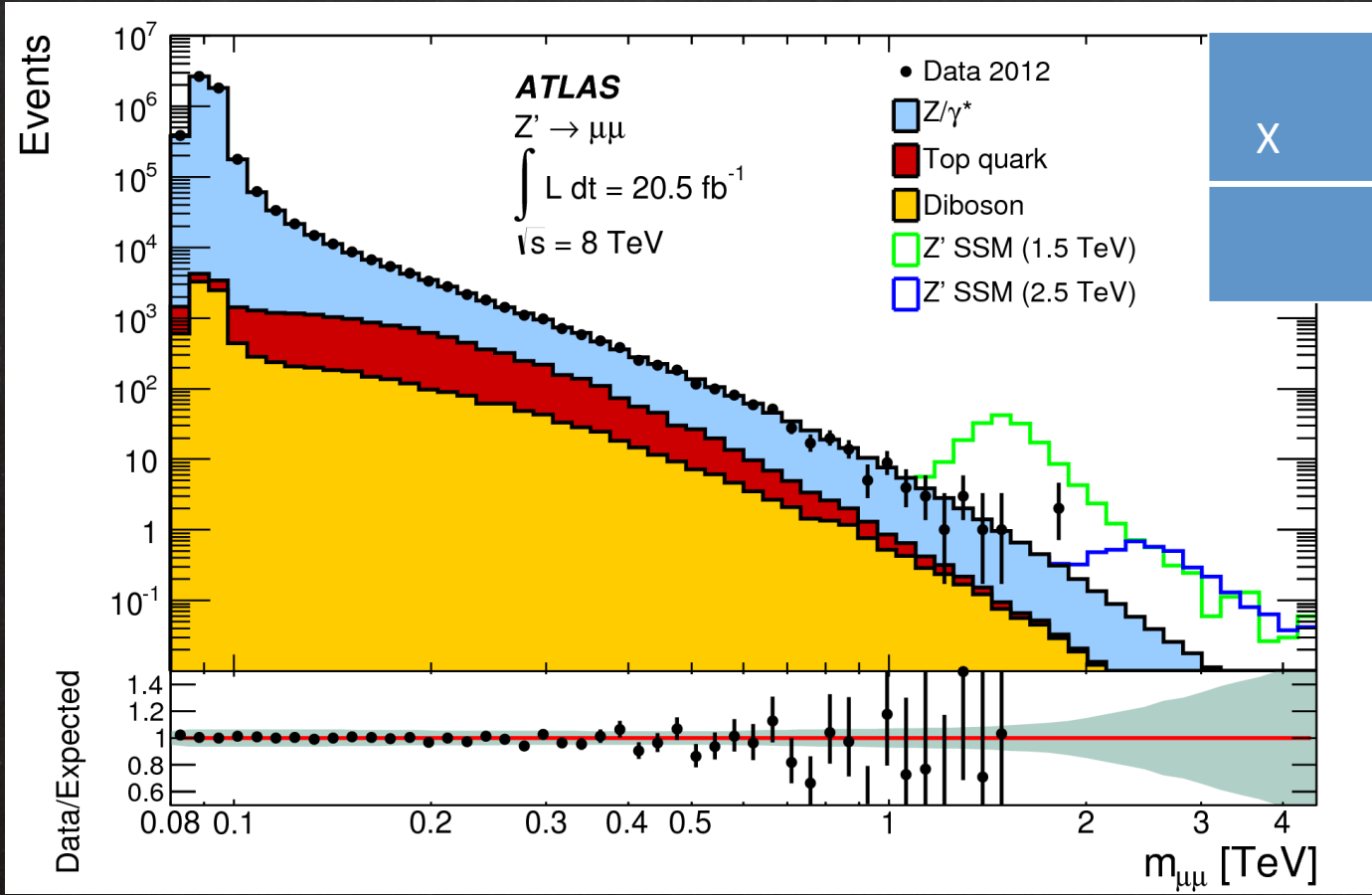
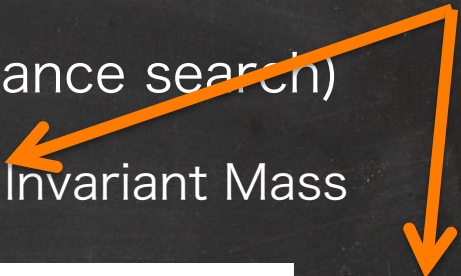
**BG Only Hypothesis  $> 2\sigma$**

1/22 : Every 3 weeks  
95.5%

# Z' search (resonance search)

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

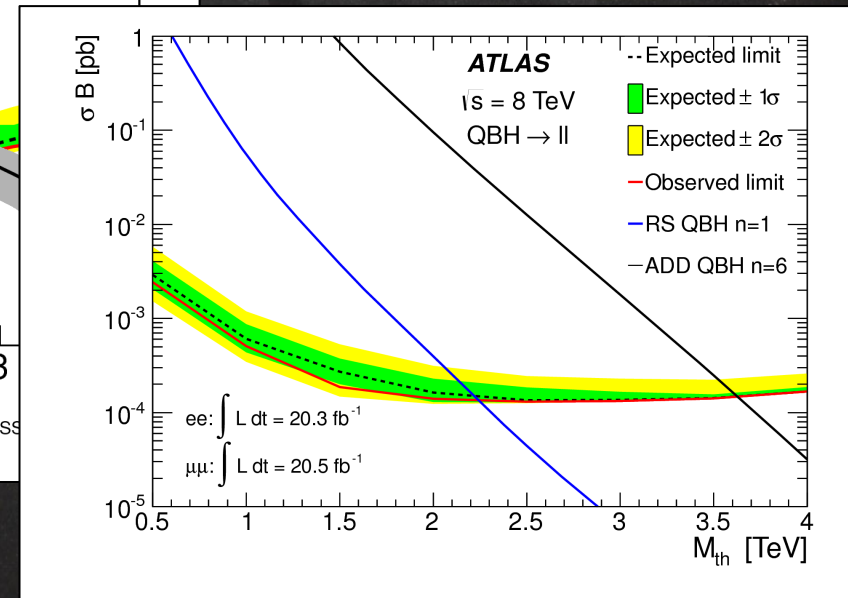
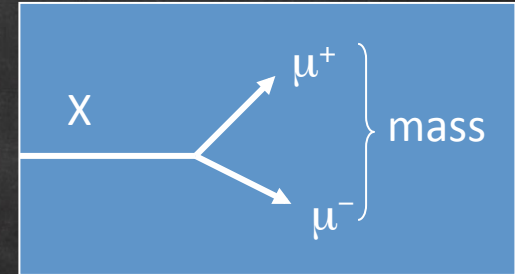
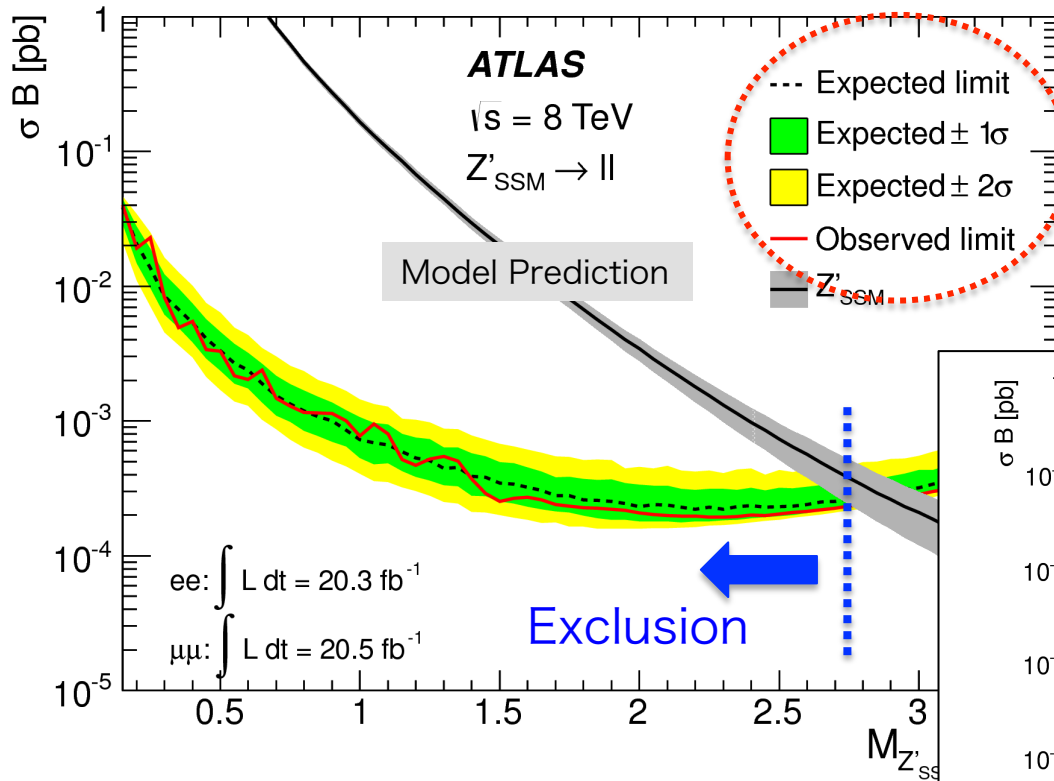
Event Topology





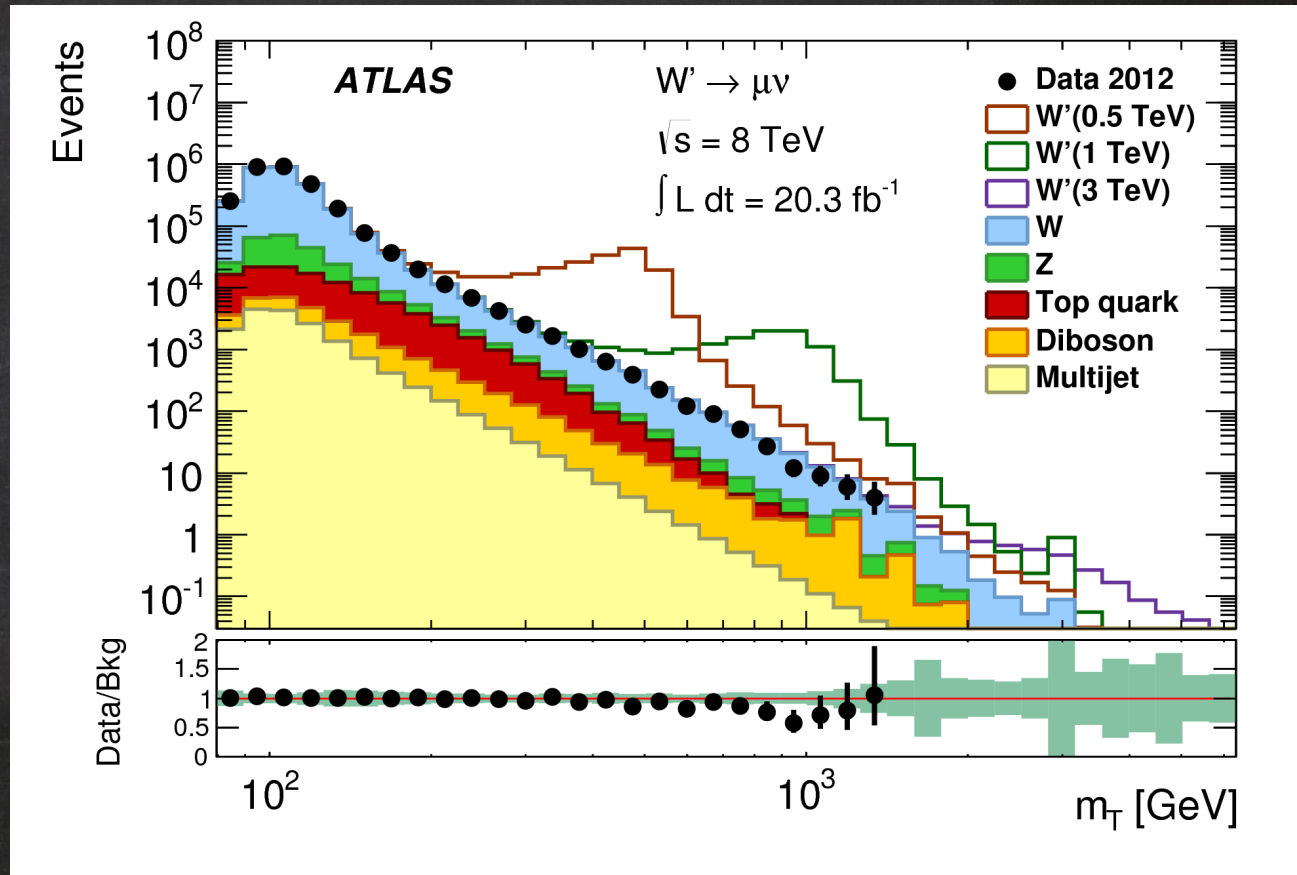
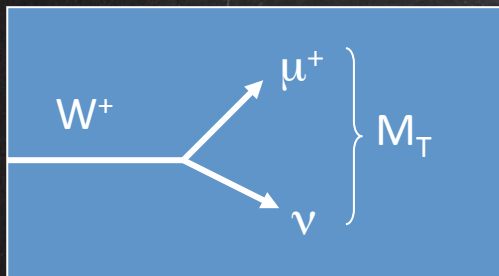
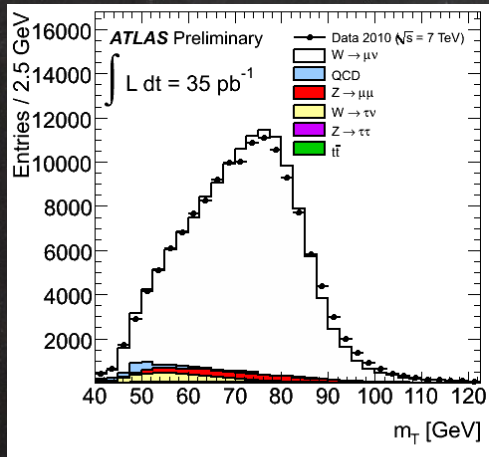
# Z' search (resonance search)

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



# W' search (edge search)

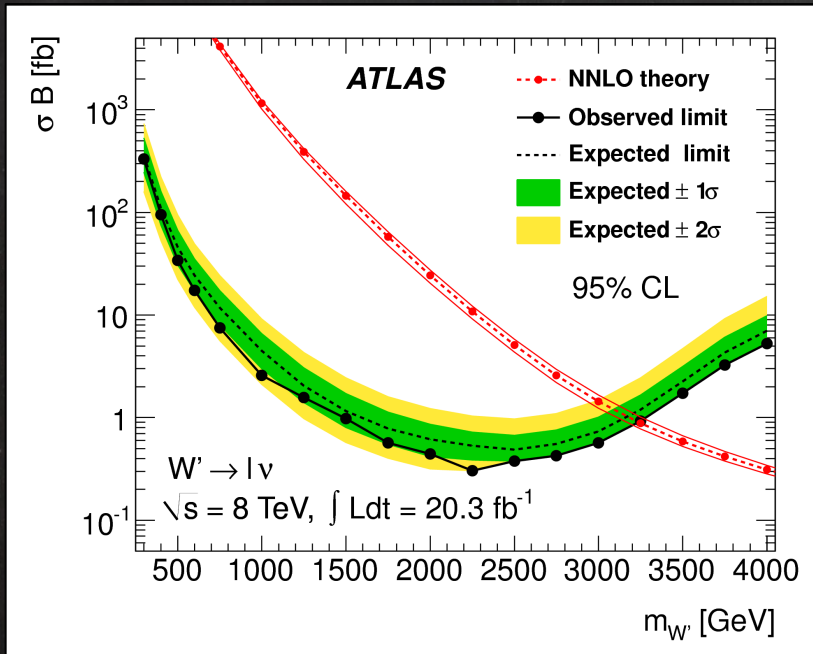
lepton + Missing  $E_T(\nu)$  [ w/  $p_T$  conservation ]



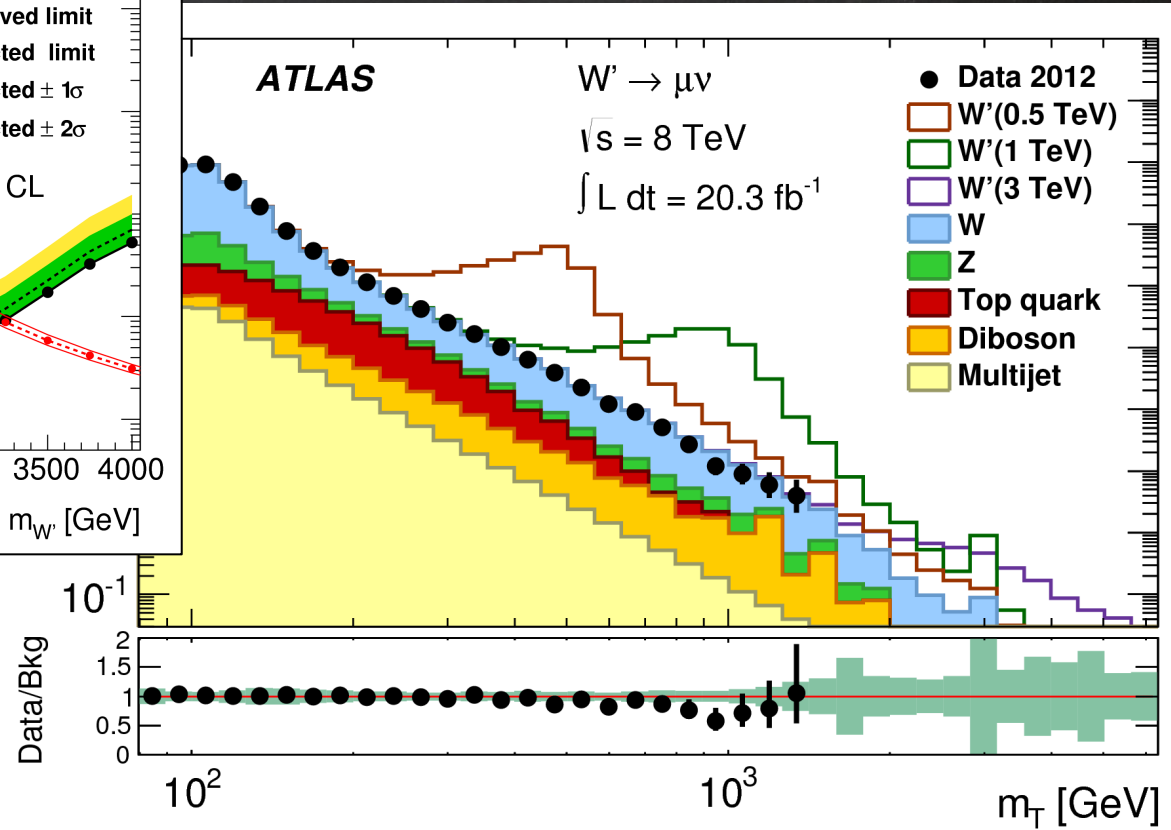
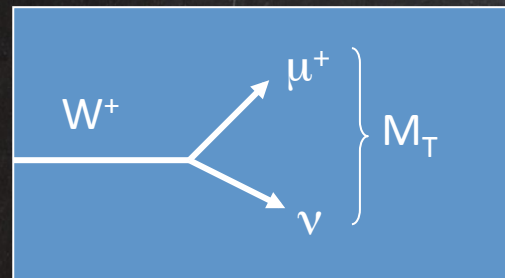
$$M_T = \sqrt{2p_T^\ell p_T^\nu (1 - \cos(\phi^\ell - \phi^\nu))}$$



# W' search (edge search)



w/  $p_T$  conservation]

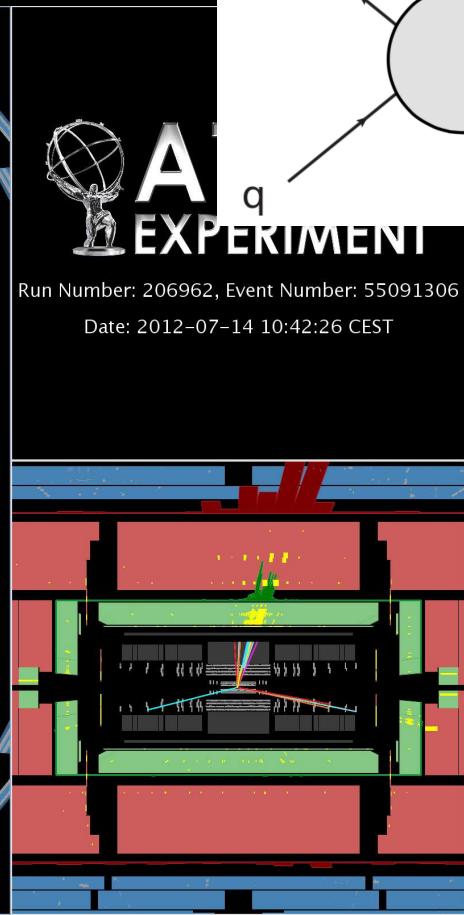
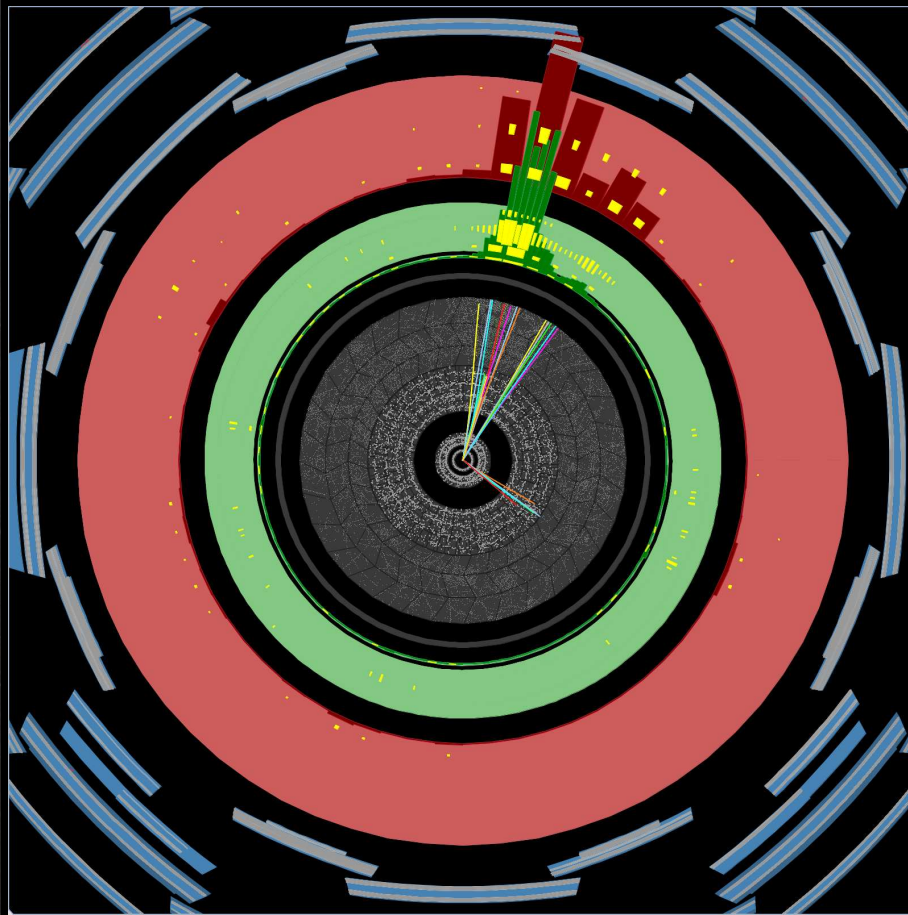
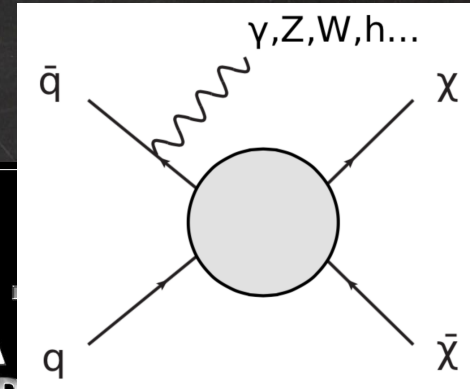


$$M_T = \sqrt{2p_T^\ell p_T^\nu (1 - \cos(\phi^\ell - \phi^\nu))}$$

# DM search (invisible search)

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

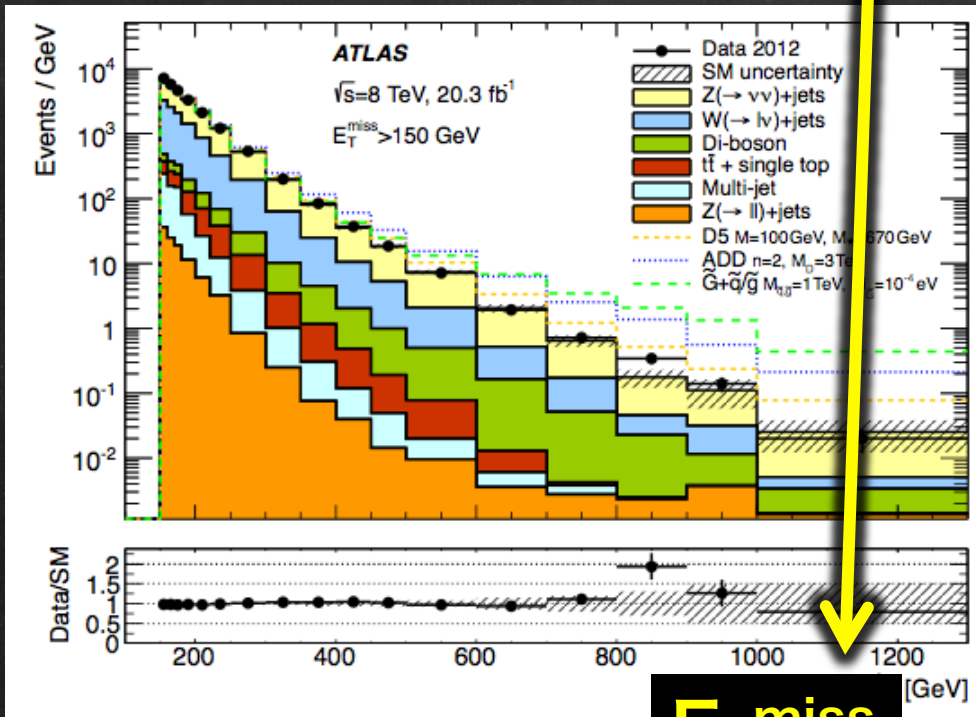
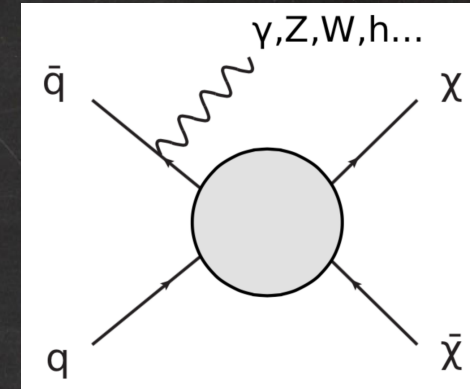
testing  $p_T$  non-conservation by recoil energy





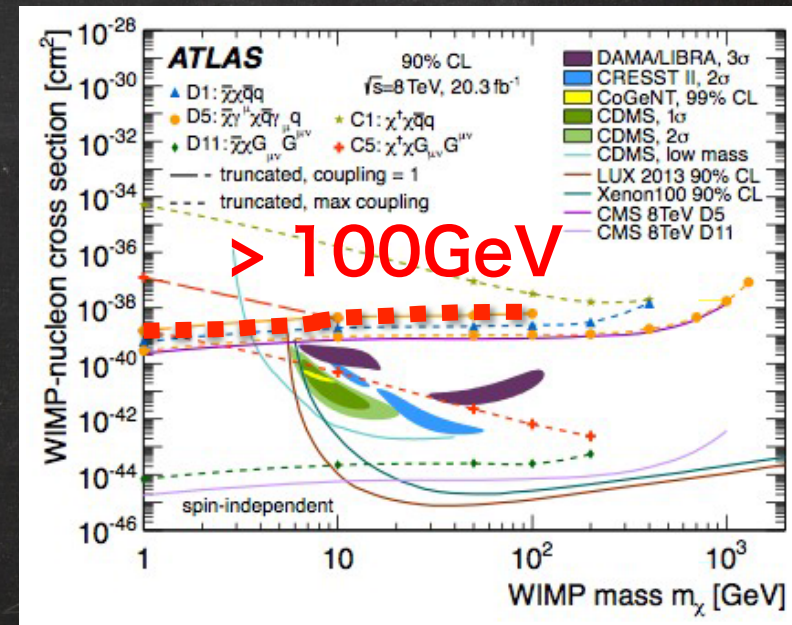
# DM search (invisible search)

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



$E_T^{\text{miss}}$

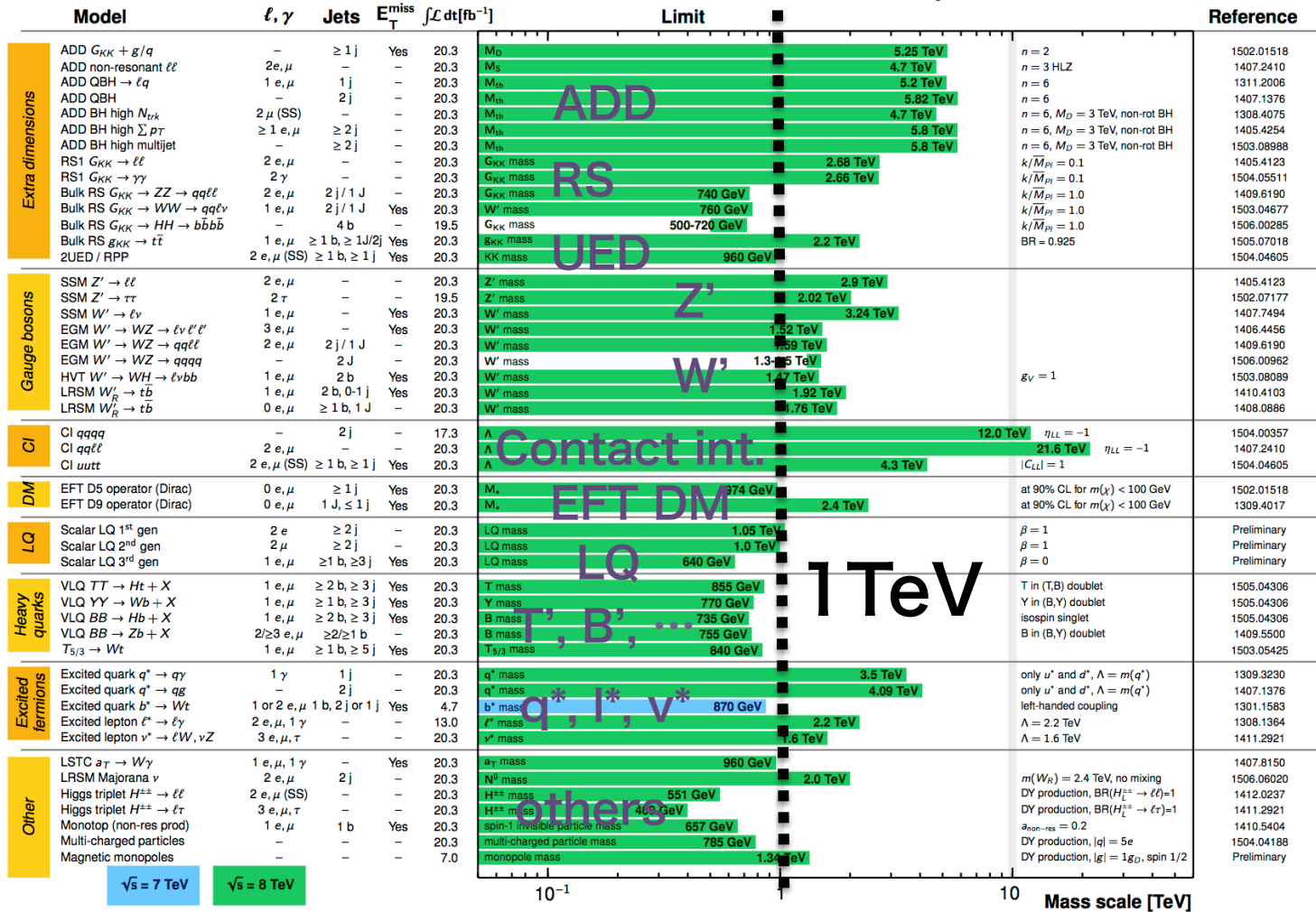
Results are interpreted as  $\sigma$  bound



# Exotics (non-SUSY)

**ATLAS Exotics Searches\* - 95% CL Exclusion**  
 Status: July 2015

**ATLAS Preliminary**  
 $\sqrt{s} = 7, 8 \text{ TeV}$   
 $\int \mathcal{L} dt = (4.7 - 20.3) \text{ fb}^{-1}$



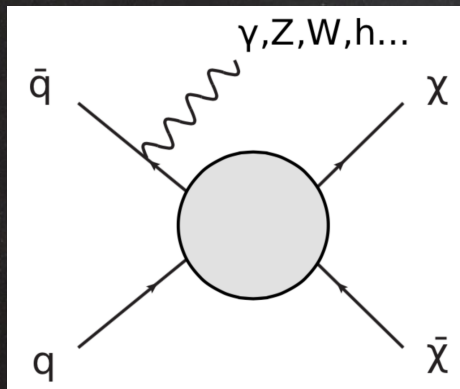
\*Only a selection of the available mass limits on new states or phenomena is shown.



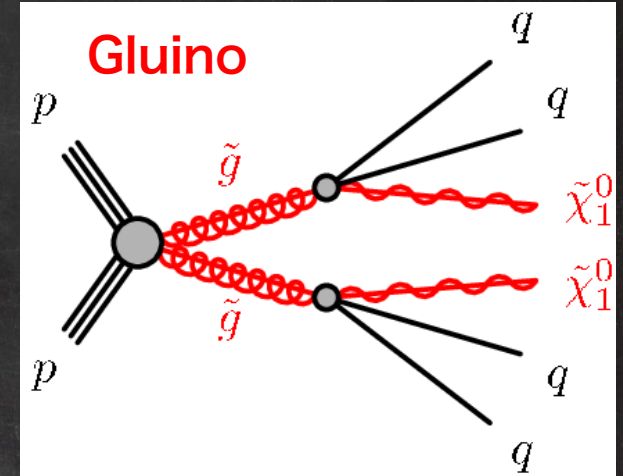
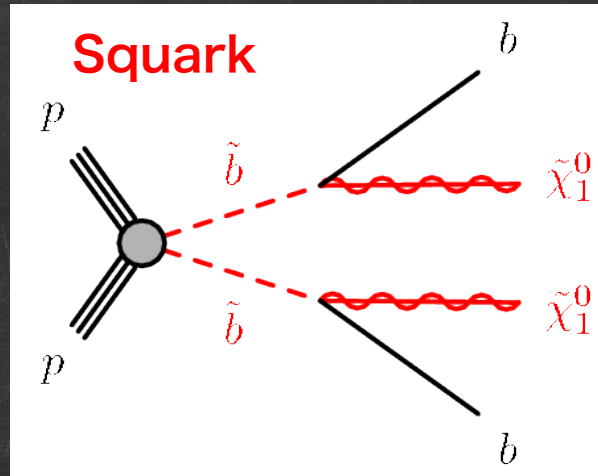
# SUSY search

## EW production

Large Missing  $E_T(\sim p_T)$



## QCD production + Cascade decay



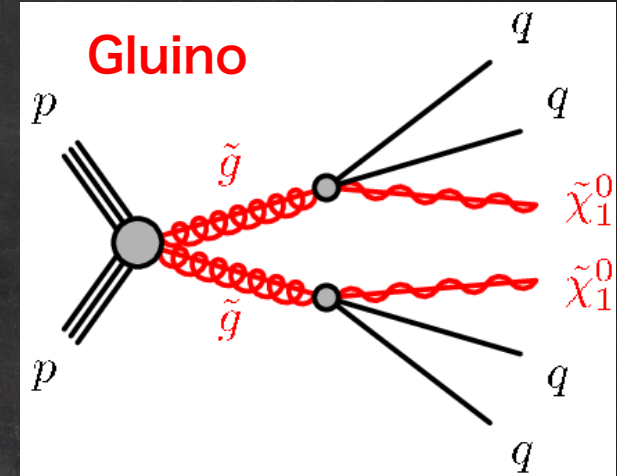
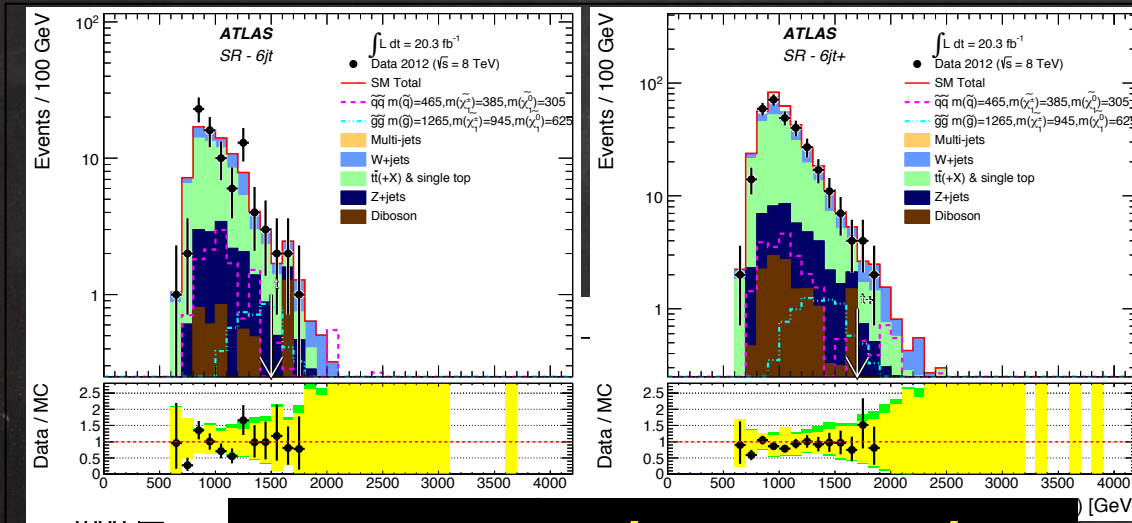
Large  $p_T$  object + Large Missing  $E_T(\sim p_T)$

Good : Large  $\sigma$  + Multi-jet  $\rightarrow$  Stronger Limit

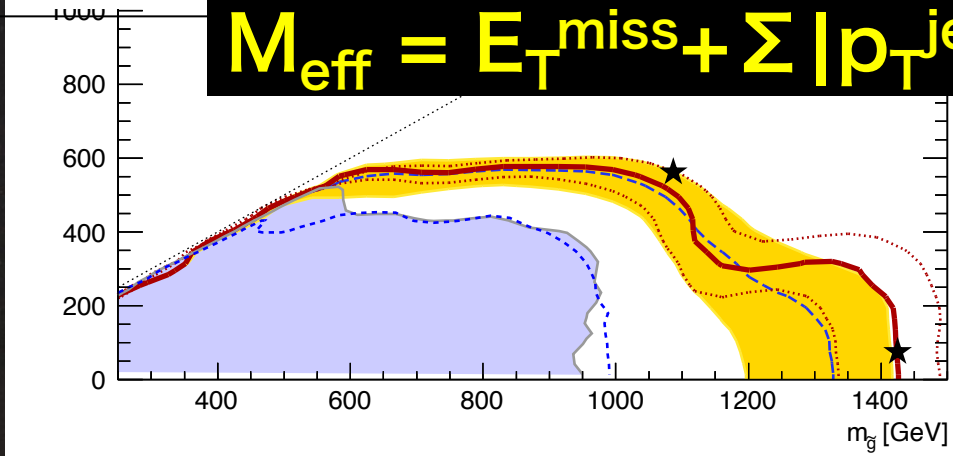
Bad : Bounds depend on Mass Spectrum

# SUSY search

Any excess is observed in  $M_{\text{eff}}$  dist.  $\rightarrow$  bound



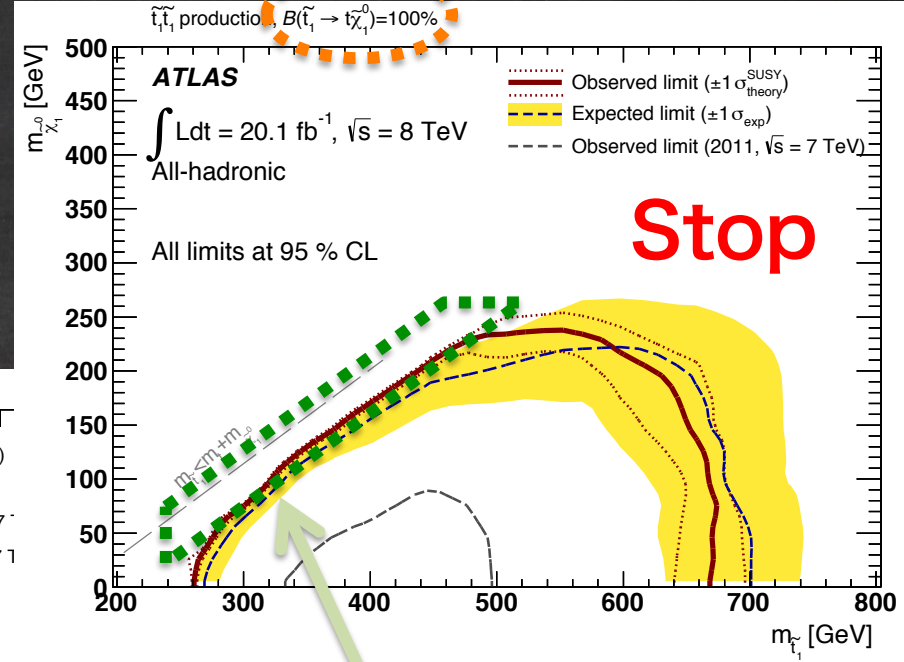
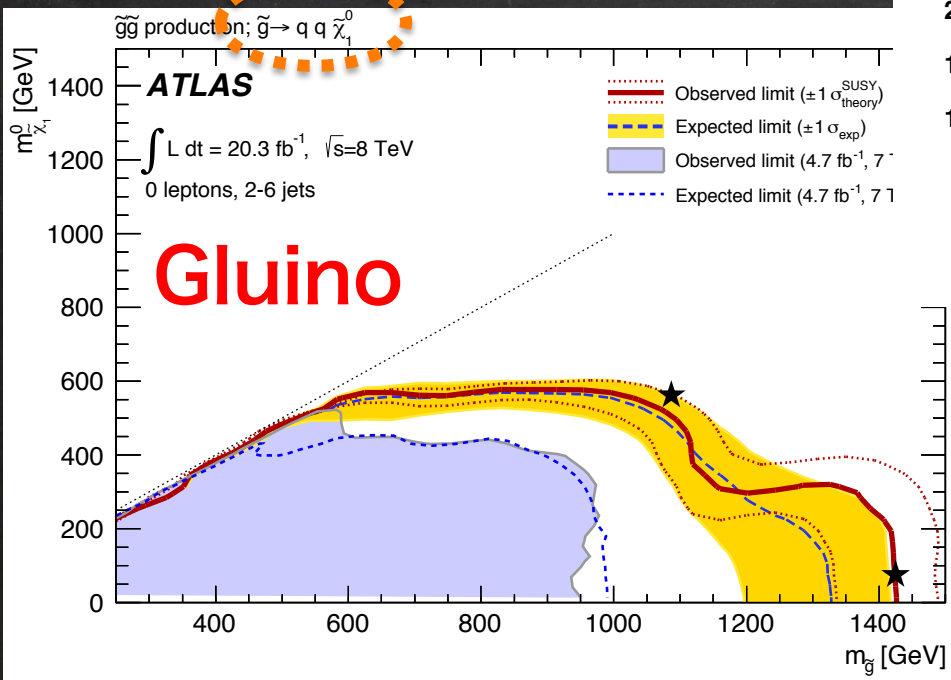
$$M_{\text{eff}} = E_T^{\text{miss}} + \sum |p_T^{\text{jet}}|$$





# SUSY search

Different Decay chains  
 → Different Bounds



Degenerate Spectrum  
 → Difficult (Soft)

**Many Loopholes**

# SUSY Summary

## ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

$\sqrt{s} = 7, 8 \text{ TeV}$

| Model   | $e, \mu, \tau, \gamma$   | Jets  | $E_T^{\text{miss}}$ | $\int \mathcal{L} dt (\text{fb}^{-1})$ | Mass limit                      | $\sqrt{s} = 7 \text{ TeV}$ | $\sqrt{s} = 8 \text{ TeV}$   | Reference   |                                       |
|---|--|---|---------------------|--|---------------------------------|----------------------------|--|---|---------------------------------------|
| Inclusive Searches  | MSUGRA/CMSSM   | 0-3 $e, \mu$ /1-2 $\tau$                                | 2-10 jets/3 $b$     | Yes                                    | 20.3                            | $\tilde{q}, \tilde{g}$     | 1.8 TeV  | $m(\tilde{g})=m(\tilde{q})$   | 1507.05525                            |
|   | $\tilde{q}\tilde{q}, \tilde{g} \rightarrow g\tilde{\chi}_1^0$  | 0   | 2-6 jets            | Yes                                    | 20.3                            | $\tilde{q}$                | 850 GeV  | $m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$                              | 1405.7875                             |
|   | $\tilde{q}\tilde{q}, \tilde{g} \rightarrow g\tilde{\chi}_1^0$ (compressed)   | mono-jet  | 1-3 jets            | Yes                                    | 20.3                            | $\tilde{q}$                | 100-440 GeV  | $m(\tilde{g})-m(\tilde{\chi}_1^0)<10 \text{ GeV}$   | 1507.05525                            |
|   | $\tilde{q}\tilde{q}, \tilde{g} \rightarrow g(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$   | 2 $e, \mu$ (off-Z)                                      | 2 jets              | Yes                                    | 20.3                            | $\tilde{q}$                | 780 GeV  | $m(\tilde{\chi}_1^0)=0 \text{ GeV}$   | 1503.03290                            |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow g\tilde{q}\tilde{q}^*$  | 0   | 2-6 jets            | Yes                                    | 20.3                            | $\tilde{g}$                |  | $m(\tilde{\chi}_1^0)=0 \text{ GeV}$   | 1405.7875                             |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow gq\tilde{\chi}_1^{\pm} \rightarrow qqW^{\pm}\tilde{\chi}_1^0$   | 0-1 $e, \mu$  | 2-6 jets            | Yes                                    | 20                              | $\tilde{g}$                |  | $m(\tilde{\chi}_1^0)<300 \text{ GeV}, m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$  | 1507.05525                            |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow gq\ell(\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$  | 2 $e, \mu$  | 0-3 jets            | -                                      | 20                              | $\tilde{g}$                |  | $m(\tilde{\chi}_1^0)=0 \text{ GeV}$   | 1501.03555                            |
|   | GMSB ( $\tilde{\ell}$ NLSP)  | 1-2 $\tau + 0-1 \ell$                                   | 0-2 jets            | Yes                                    | 20.3                            | $\tilde{g}$                |  | $\tan\beta > 20$  | 1407.0603                             |
|   | GGM (bino NLSP)  | 2 $\gamma$  | -                   | Yes                                    | 20.3                            | $\tilde{g}$                |  | $c\tau(\text{NLSP})<0.1 \text{ mm}$   | 1507.05493                            |
|   | GGM (higgsino-bino NLSP)   | $\gamma$  | 1 $b$               | Yes                                    | 20.3                            | $\tilde{g}$                |  | $m(\tilde{\chi}_1^0)<900 \text{ GeV}, c\tau(\text{NLSP})<0.1 \text{ mm}, \mu<0$   | 1507.05493                            |
|   | GGM (higgsino-bino NLSP)   | $\gamma$  | 2 jets              | Yes                                    | 20.3                            | $\tilde{g}$                |  | $m(\tilde{\chi}_1^0)<850 \text{ GeV}, c\tau(\text{NLSP})<0.1 \text{ mm}, \mu>0$   | 1507.05493                            |
|   | GGM (higgsino NLSP)  | 2 $e, \mu$ (Z)  | 2 jets              | Yes                                    | 20.3                            | $\tilde{g}$                | 850 GeV  | $m(\text{NLSP})=430 \text{ GeV}$  | 1503.03290                            |
| Gravitino LSP   | 0  | mono-jet  | Yes                 | 20.3                                   | $\tilde{g}^{1/2} \text{ scale}$ | 865 GeV                    | $m(\tilde{G})>1.8 \times 10^{-4} \text{ eV}, m(\tilde{g})=m(\tilde{q})=1.5 \text{ TeV}$  | 1502.01518  |                                       |
| $\tilde{g}$ gen. $\tilde{g}$ med.   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$   | 0   | 3 $b$               | Yes                                    | 20.1                            | $\tilde{g}$                | 1.25 TeV   | $m(\tilde{\chi}_1^0)<400 \text{ GeV}$   | 1407.0600                             |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$   | 0   | 7-10 jets           | Yes                                    | 20.3                            | $\tilde{g}$                | 1.1 TeV  | $m(\tilde{\chi}_1^0)<350 \text{ GeV}$   | 1308.1841                             |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{b}\tilde{\chi}_1^0$   | 0-1 $e, \mu$  | 3 $b$               | Yes                                    | 20.1                            | $\tilde{g}$                | 1.34 TeV   | $m(\tilde{\chi}_1^0)<400 \text{ GeV}$   | 1407.0600                             |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^0$   | 0-1 $e, \mu$  | 3 $b$               | Yes                                    | 20.1                            | $\tilde{g}$                | 1.3 TeV  | $m(\tilde{\chi}_1^0)<300 \text{ GeV}$   | 1407.0600                             |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^0$   | 0   | 3 $b$               | Yes                                    | 20.1                            | $\tilde{g}$                |  |   |                                       |
| $\tilde{g}$ gen. squarks direct production  | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$  | 0   | 2 $b$               | Yes                                    | 20.1                            | $\tilde{b}_1$              | 100-620 GeV  | $m(\tilde{\chi}_1^0)<90 \text{ GeV}$  | 1308.2631                             |
|   | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^0$  | 2 $e, \mu$ (SS)   | 0-3 $b$             | Yes                                    | 20.3                            | $\tilde{b}_1$              | 275-440 GeV  | $m(\tilde{\chi}_1^0)=2 \text{ m}(\tilde{\chi}_1^0)$   | 1404.2500                             |
|   | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$  | 1-2 $e, \mu$  | 1-2 $b$             | Yes                                    | 4.7/20.3                        | $\tilde{t}_1$              | 110-167 GeV  | $m(\tilde{\chi}_1^0)=2 \text{ m}(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=55 \text{ GeV}$   | 1209.2102, 1407.0583                  |
|   | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $\tilde{\chi}_1^0$   | 0-2 $e, \mu$  | 0-2 jets/1-2 $b$    | Yes                                    | 20.3                            | $\tilde{t}_1$              | 90-191 GeV   | $m(\tilde{\chi}_1^0)=1 \text{ GeV}$   | 1506.08616                            |
|   | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$  | 0   | mono-jet/c-tag      | Yes                                    | 20.3                            | $\tilde{t}_1$              | 90-240 GeV   | $m(\tilde{t}_1)-m(\tilde{\chi}_1^0)<85 \text{ GeV}$   | 1407.0608                             |
|   | $\tilde{t}_1\tilde{t}_1$ (natural GMSB)  | 2 $e, \mu$ (Z)  | 1 $b$               | Yes                                    | 20.3                            | $\tilde{t}_1$              | 150-580 GeV  | $m(\tilde{\chi}_1^0)>150 \text{ GeV}$   | 1403.5222                             |
|   | $\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$  | 3 $e, \mu$ (Z)  | 1 $b$               | Yes                                    | 20.3                            | $\tilde{t}_2$              | 290-600 GeV  | $m(\tilde{\chi}_1^0)<200 \text{ GeV}$   | 1403.5222                             |
|   | $\tilde{t}_1\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$  | 3 $e, \mu$ (Z)  | 1 $b$               | Yes                                    | 20.3                            | $\tilde{t}_2$              | 290-600 GeV  |   |                                       |
| EW direct   | $\tilde{\ell}_L\tilde{\ell}_R, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$  | 2 $e, \mu$  | 0                   | Yes                                    | 20.3                            | $\tilde{\ell}$             | 90-325 GeV   | $m(\tilde{\chi}_1^0)=0 \text{ GeV}$   | 1403.5294                             |
|   | $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow \ell\nu(\ell\nu)$  | 2 $e, \mu$  | 0                   | Yes                                    | 20.3                            | $\tilde{\chi}_1^{\pm}$     | 140-465 GeV  | $m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$                                  | 1403.5294                             |
|   | $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow \tau\nu(\tau\nu)$  | 2 $\tau$  | 0                   | Yes                                    | 20.3                            | $\tilde{\chi}_1^{\pm}$     | 100-350 GeV  | $m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$                                  | 1407.0350                             |
|   | $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \rightarrow \tilde{\ell}_L, \tilde{\nu}_L(\tilde{\ell}\tilde{\nu}), \tilde{\nu}\tilde{\ell}_L(\tilde{\nu}\tilde{\nu})$ | 3 $e, \mu$  | 0                   | Yes                                    | 20.3                            | $\tilde{\chi}_1^{\pm}$     | 700 GeV  | $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ | 1402.7029                             |
|   | $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$   | 2-3 $e, \mu$  | 0-2 jets            | Yes                                    | 20.3                            | $\tilde{\chi}_1^{\pm}$     | 420 GeV  | $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=0, \text{ sleptons decoupled}$  | 1403.5294, 1402.7029                  |
|   | $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h \rightarrow b\tilde{b}/W\tilde{W}/\tau\tau/\gamma\gamma$            | $e, \mu, \gamma$  | 0-2 $b$             | Yes                                    | 20.3                            | $\tilde{\chi}_1^{\pm}$     | 250 GeV  | $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=0, \text{ sleptons decoupled}$  | 1501.07110                            |
|   | $\tilde{\chi}_2^0\tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R\tilde{\ell}$  | 4 $e, \mu$  | 0                   | Yes                                    | 20.3                            | $\tilde{\chi}_2^0$         | 620 GeV  | $m(\tilde{\chi}_2^0)=m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$            | 1405.5086                             |
|   | GGM (wino NLSP) weak prod.   | 1 $e, \mu + \gamma$                                     | -                   | Yes                                    | 20.3                            | $\tilde{W}$                | 124-361 GeV  | $c\tau < 1 \text{ mm}$  | 1507.05493                            |
|   | Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$   | Disapp. trk   | 1 jet               | Yes                                    | 20.3                            | $\tilde{\chi}_1^{\pm}$     | 270 GeV  | $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_1^0)=1 \text{ MeV}, \tau(\tilde{\chi}_1^{\pm})=0.2 \text{ ns}$  | 1310.3675                             |
|   | Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$   | dE/dx trk   | 0                   | Yes                                    | 18.4                            | $\tilde{\chi}_1^{\pm}$     | 482 GeV  | $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)<160 \text{ MeV}, \tau(\tilde{\chi}_1^{\pm})<15 \text{ ns}$   | 1506.05332                            |
| Stable, stopped $\tilde{g}$ R-hadron  | 0  | 1-5 jets  | Yes                 | 27.9                                   | $\tilde{g}$                     | 832 GeV                    | $m(\tilde{\chi}_1^0)=100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$ | 1310.6584   |                                       |
| Stable $\tilde{g}$ R-hadron   | trk  | -   | -                   | 19.1                                   | $\tilde{g}$                     | 1.27 TeV                   |  | 1411.6795   |                                       |
| GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tau(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$ | 1-2 $\mu$  | -   | -                   | 19.1                                   | $\tilde{\tau}$                  | 537 GeV                    | $10 < \tan\beta < 50$  | 1411.6795   |                                       |
| GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ , long-lived $\tilde{\chi}_1^0$                  | 2 $\gamma$   | -   | Yes                 | 20.3                                   | $\tilde{\chi}_1^0$              | 435 GeV                    | $2 < \tau(\tilde{\chi}_1^0) < 3 \text{ ns}, \text{SPS8 model}$                           | 1409.5542   |                                       |
| $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow e\bar{e}\nu/\mu\bar{\mu}\nu$                        | displ. $e\bar{e}/\mu\bar{\mu}$   | -   | -                   | 20.3                                   | $\tilde{\chi}_1^0$              | 1.0 TeV                    | $7 < c\tau(\tilde{\chi}_1^0) < 740 \text{ mm}, m(\tilde{g})=1.3 \text{ TeV}$             | 1504.05162  |                                       |
| GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow Z\tilde{G}$                                     | displ. vtx + jets  | -   | -                   | 20.3                                   | $\tilde{\chi}_1^0$              | 1.0 TeV                    | $6 < c\tau(\tilde{\chi}_1^0) < 480 \text{ mm}, m(\tilde{g})=1.1 \text{ TeV}$             | 1504.05162  |                                       |
| RPV   | LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu/\mu\tau$   | $e\mu, e\tau, \mu\tau$                                  | -                   | -                                      | 20.3                            | $\tilde{\nu}_\tau$         | 1.7 TeV  | $A_{11}^{\tau\tau}=0.11, A_{12/13/23/33}=0.07$  | 1503.04430                            |
|   | Bilinear RPV CMSSM   | 2 $e, \mu$ (SS)   | 0-3 $b$             | Yes                                    | 20.3                            | $\tilde{q}, \tilde{g}$     | 1.35 TeV   | $m(\tilde{g})=m(\tilde{q}), c\tau_{LS} < 1 \text{ mm}$  | 1404.2500                             |
|   | $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow e\bar{e}\nu_e, e\mu\nu_e$            | 4 $e, \mu$  | -                   | Yes                                    | 20.3                            | $\tilde{\chi}_1^{\pm}$     | 750 GeV  | $m(\tilde{\chi}_1^0)>0.2 \text{ m}(\tilde{\chi}_1^{\pm}), A_{121} \neq 0$   | 1405.5086                             |
|   | $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\tau\nu_e, e\bar{\nu}_\tau$      | 3 $e, \mu + \tau$                                       | -                   | Yes                                    | 20.3                            | $\tilde{\chi}_1^{\pm}$     | 450 GeV  | $m(\tilde{\chi}_1^0)>0.2 \text{ m}(\tilde{\chi}_1^{\pm}), A_{133} \neq 0$   | 1405.5086                             |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{q}$  | 0   | 6-7 jets            | -                                      | 20.3                            | $\tilde{g}$                | 917 GeV  | $\text{BR}(\tilde{t})-\text{BR}(\tilde{b})-\text{BR}(\tilde{c})=0\%$  | 1502.05686                            |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow g\tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{q}$  | 0   | 6-7 jets            | -                                      | 20.3                            | $\tilde{g}$                | 870 GeV  | $m(\tilde{\chi}_1^0)=500 \text{ GeV}$   | 1502.05686                            |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}, \tilde{t}_1 \rightarrow b\tilde{s}$   | 2 $e, \mu$ (SS)   | 0-3 $b$             | Yes                                    | 20.3                            | $\tilde{g}$                | 850 GeV  |   | 1404.2500                             |
|   | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$   | 0   | 2 jets + 2 $b$      | -                                      | 20.3                            | $\tilde{t}_1$              | 100-308 GeV  |   | ATLAS-CONF-2015-026                   |
|   | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\ell}$  | 2 $e, \mu$  | 2 $b$               | -                                      | 20.3                            | $\tilde{t}_1$              | 0.4-1.0 TeV  | $\text{BR}(\tilde{t}_1 \rightarrow b\tilde{e}/\mu)>20\%$  | ATLAS-CONF-2015-015                   |
|   | Other  | Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$ | 0                   | 2 $c$                                  | Yes                             | 20.3                       | $\tilde{c}$  | 490 GeV   | $m(\tilde{\chi}_1^0)<200 \text{ GeV}$ |

10<sup>-1</sup> 1 Mass scale [TeV]

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



# Evidence / Anomaly ( Excess / Deficit / ...)

## Phenomenologists Start To CHASE

>  $3\sigma$  ( $2\sigma$ )

1/370 : Yearly  
99.7%

1/22 : Every 3 weeks  
95.5%

2.5 $\sigma$  = 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**

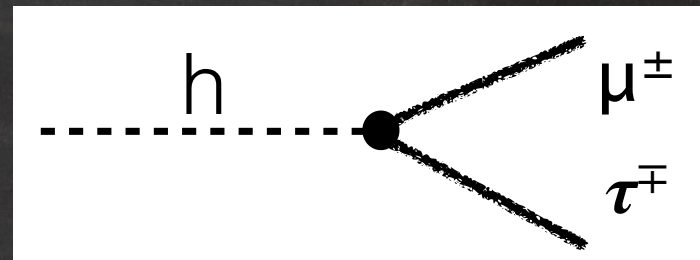
- Interpretation by **popular / favorite models** (SUSY, ED, TC, ...)
- Interpretation by a model & relate to **New Physics** (Neutrino, DM, ...)
- Interpretation by a model & relate to **other Anomaly** (g-2, ...)



# Evidence of Anomalies

- $h \rightarrow \tau\mu$
- $W_R$
- SUSY
- Diboson Excesses
- ...

$$h \rightarrow \tau\mu$$

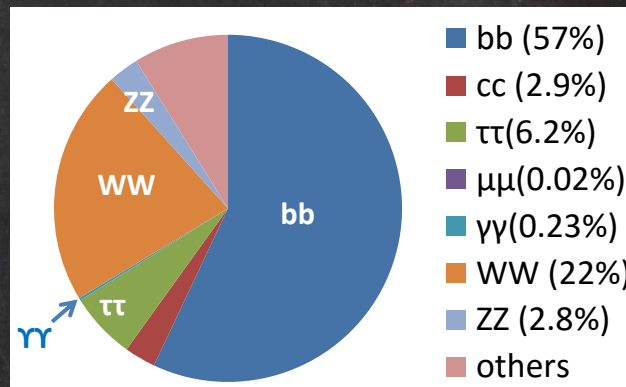
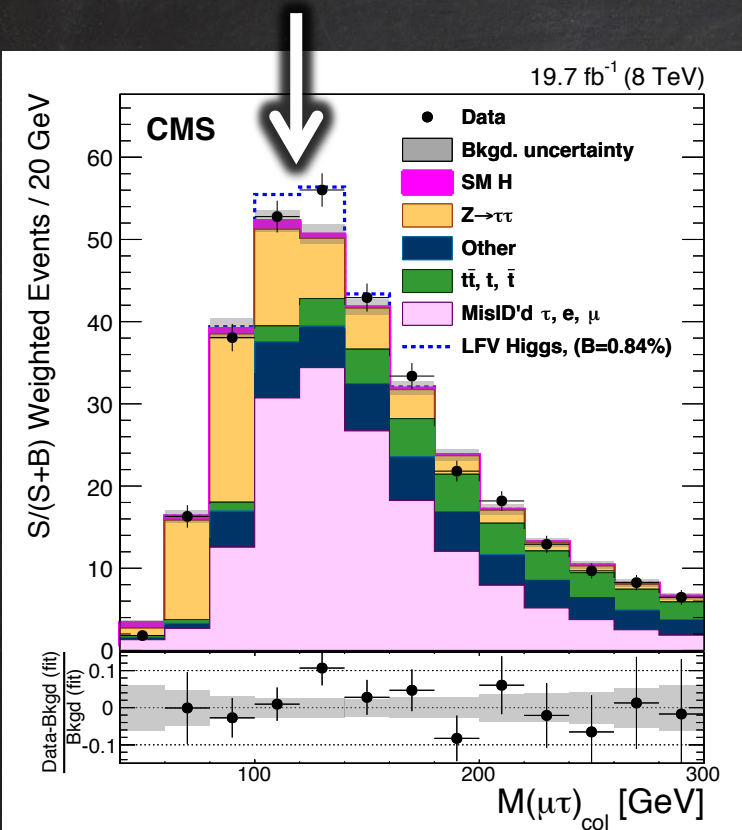


Lepton Flavor Violating Higgs Decay

2.6  $\sigma$  Excess in CMS

Not so small fraction

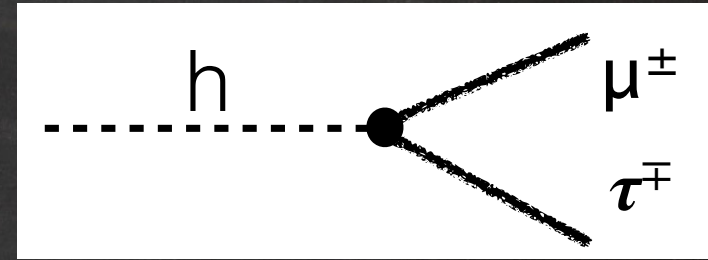
$$\mathcal{B}(h \rightarrow \tau\mu) = (0.84^{+0.39}_{-0.37})\%$$



$$\text{ATLAS } (0.77^{+0.62}_{-0.62})\% \quad 1.3 \sigma$$



$$\underline{h \rightarrow \tau\mu}$$



Lepton Flavor Violating Higgs Decay

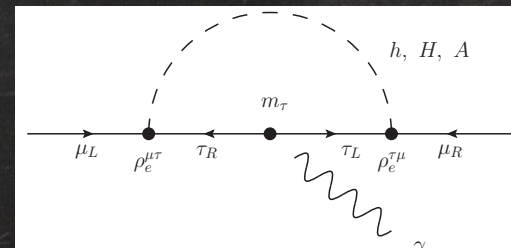
## Interpretations

- 2HDM [ 2<sup>nd</sup> Higgs doublet ]  
 → Misaligned-Yukawa coupling

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

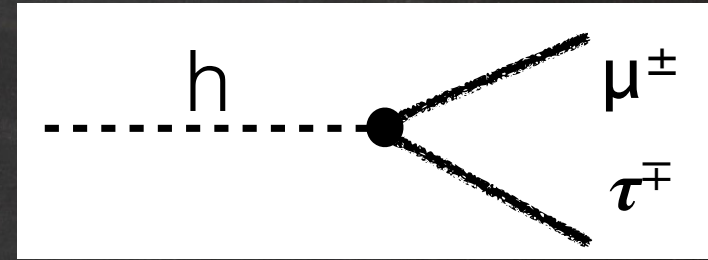
SM-like doublet
Mixing

- Prediction : Large LFV in 2<sup>nd</sup> doublet (very exotic)
- Relate to the g-2 anomaly (exotic)



$$\underline{h \rightarrow \tau\mu}$$

Lepton Flavor Violating Higgs Decay

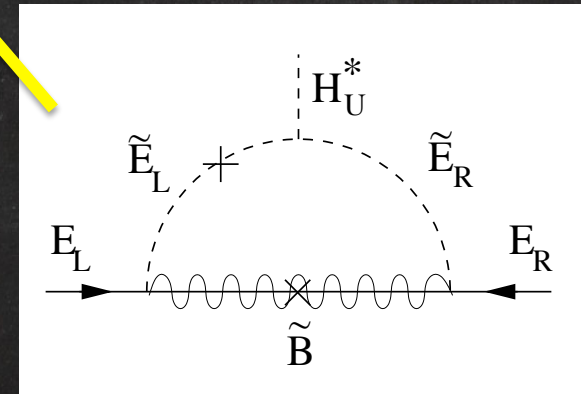


## Interpretations

- 2HDM [ 2<sup>nd</sup> Higgs doublet ]  
 → Misaligned-Yukawa coupling

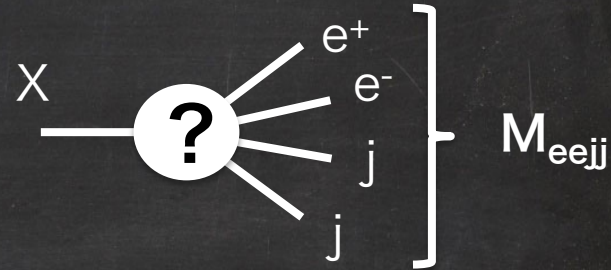
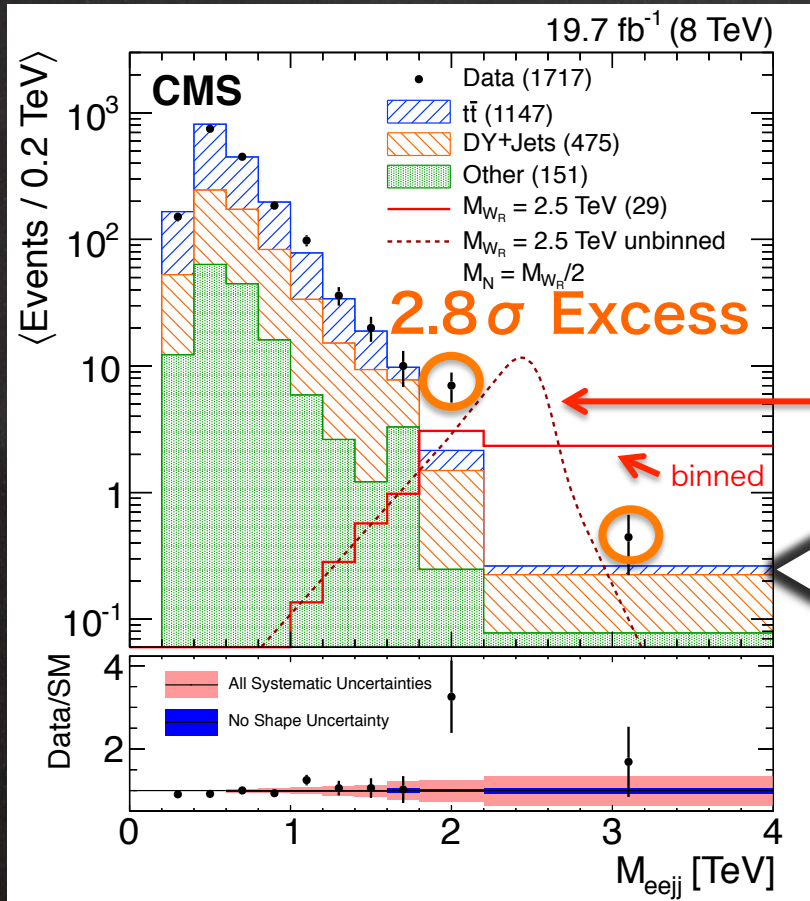
$$\mathcal{L} = +\overline{L}_i \frac{\sqrt{2}(M_\ell)_{ij}}{v} \ell_{jR} H_1 + \overline{L}_i (Y'_\ell)_{ij} \ell_{jR} H_2$$

SUSY interpretation (slepton mixing)



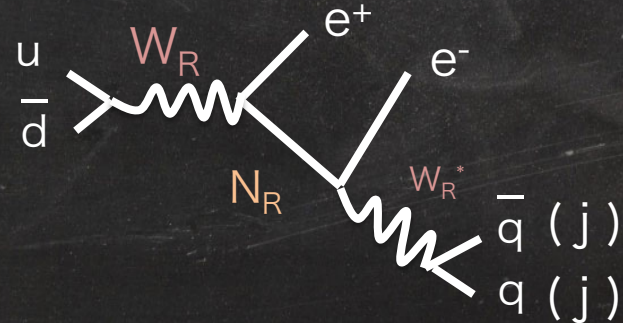


# $W_R$ @ 2.5 TeV



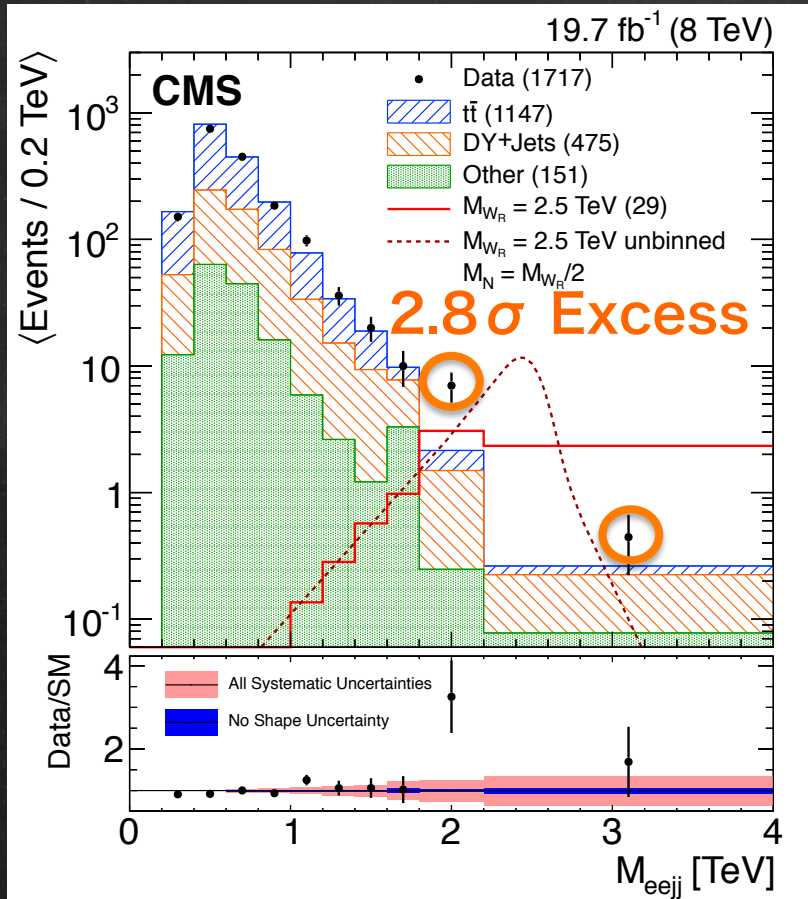
unbinned  $W_R$  signal

Shaded : SM Backgrounds



$W_R$  decay via right-handed neutrinos

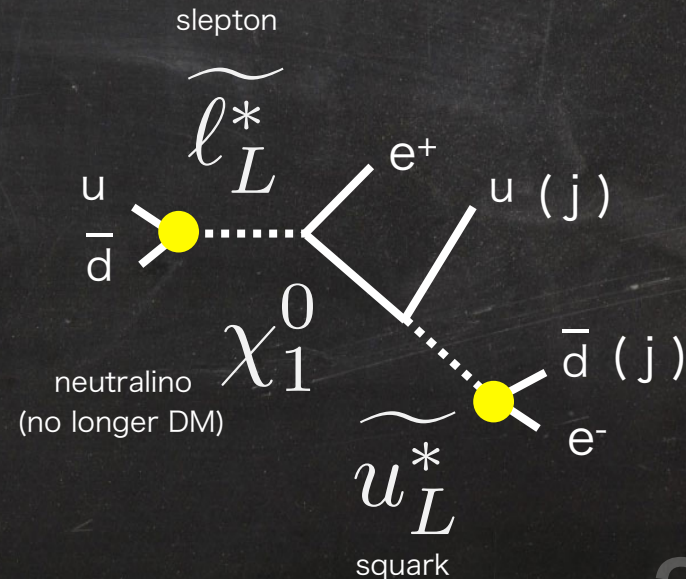
# RPV SUSY @ 2.5TeV



## R-Parity Violating SUSY

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

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



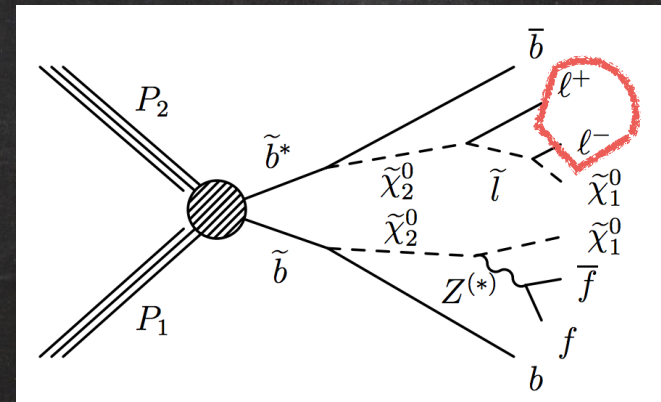
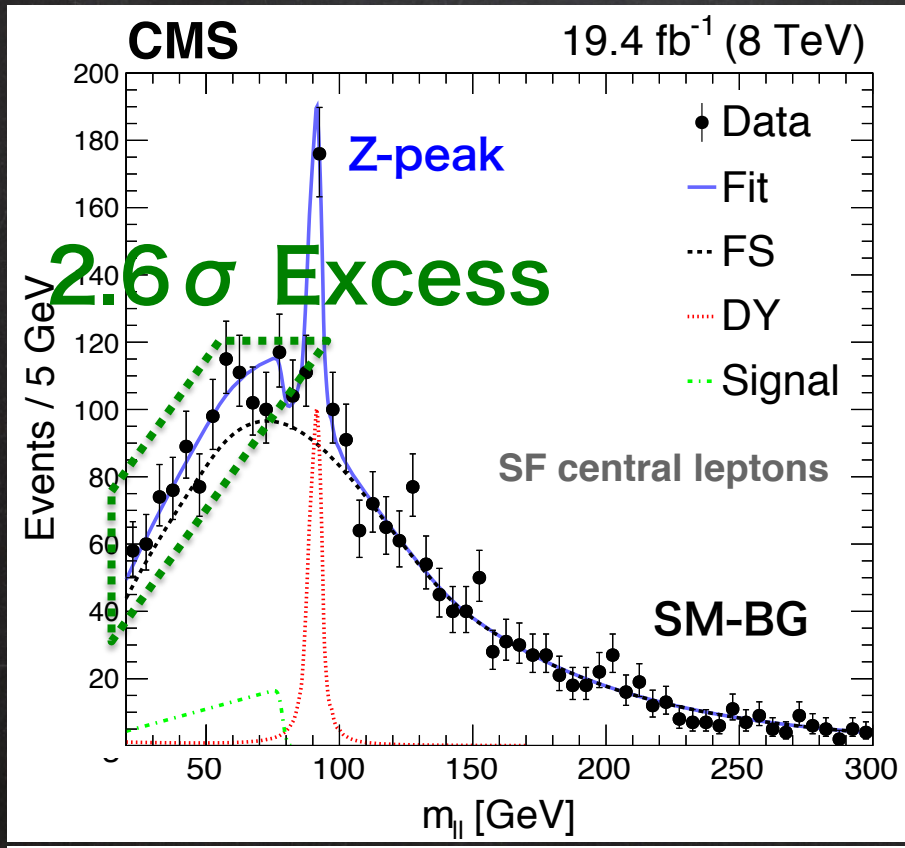


(R-parity conserving)

# SUSY

Large  $p_T$  object + Large Missing  $E_T$  + dilepton

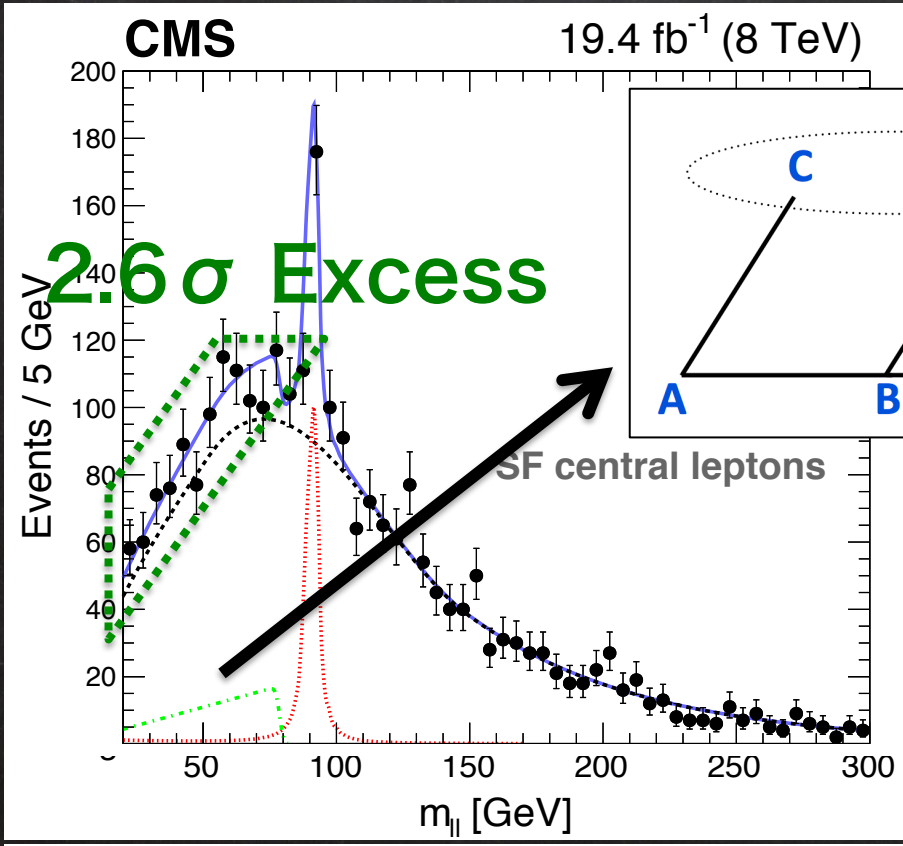
Additional Kinematical Cut



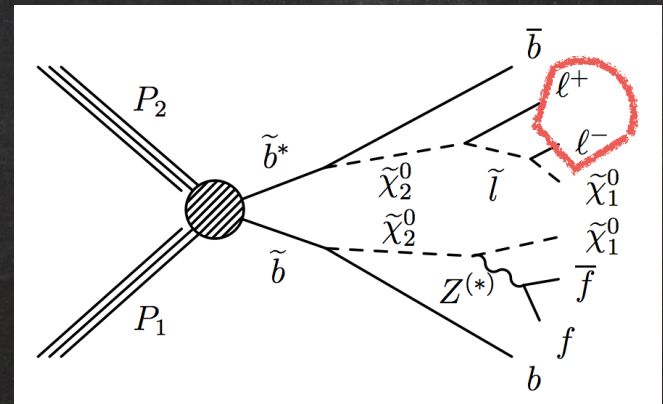
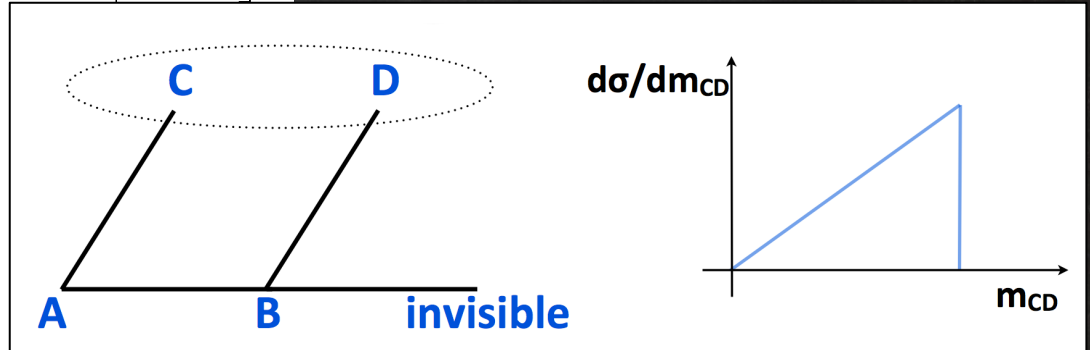
(R-parity conserving)

# SUSY

Large  $p_T$  object + Large Missing  $E_T$  + dilepton



## Kinematical Edge of SUSY

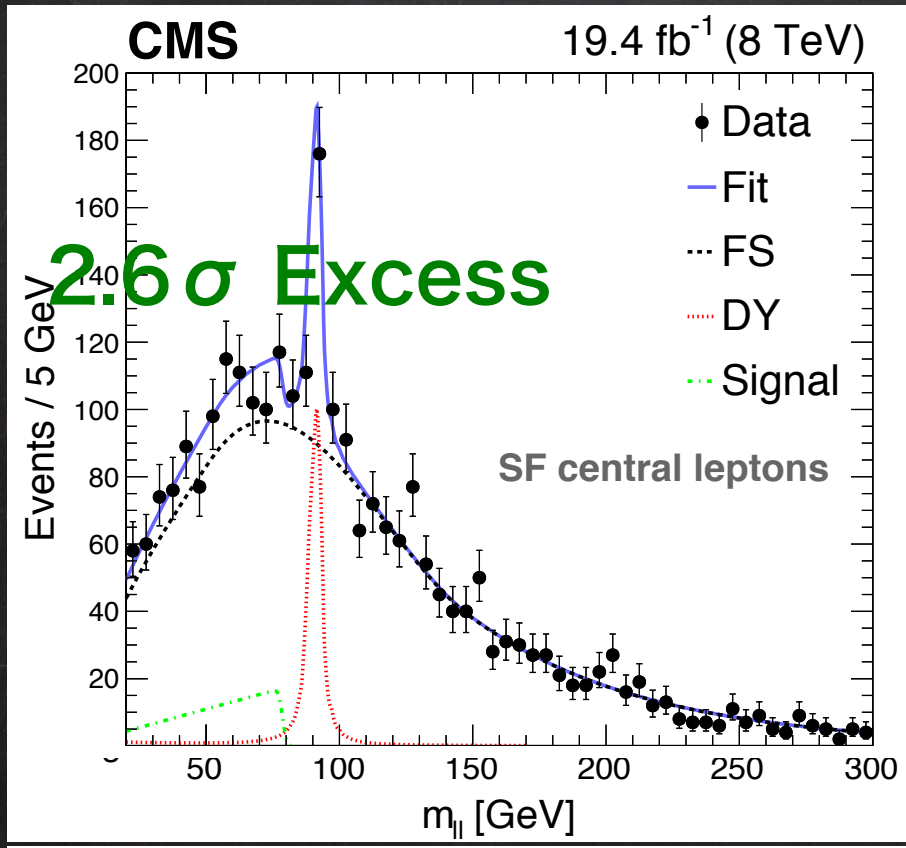




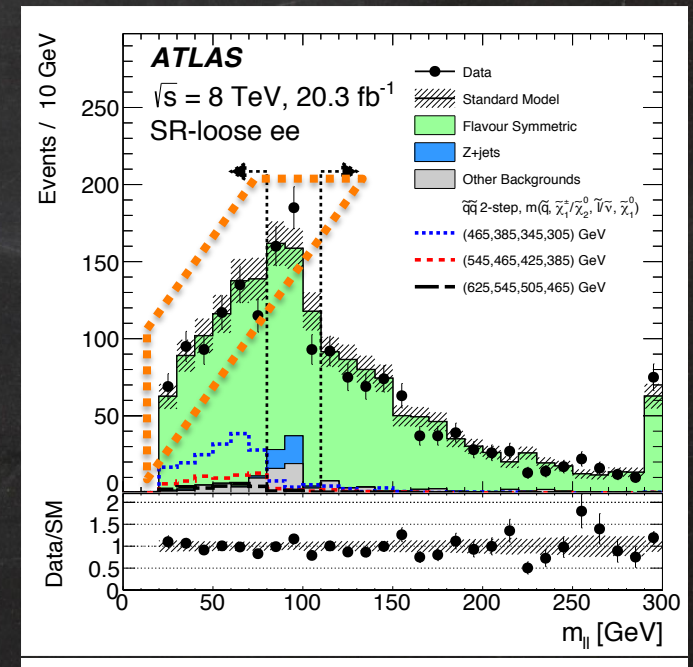
(R-parity conserving)

# SUSY

Large  $p_T$  object + Large Missing  $E_T$  + dilepton

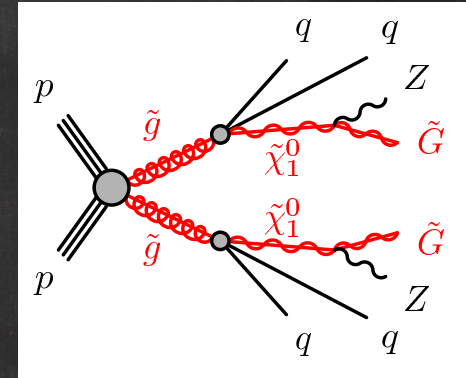


**No Excess Observed in ATLAS**

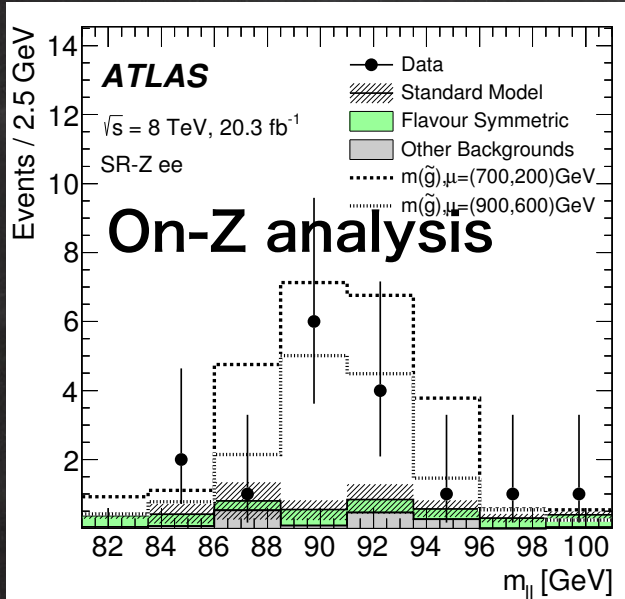


# SUSY

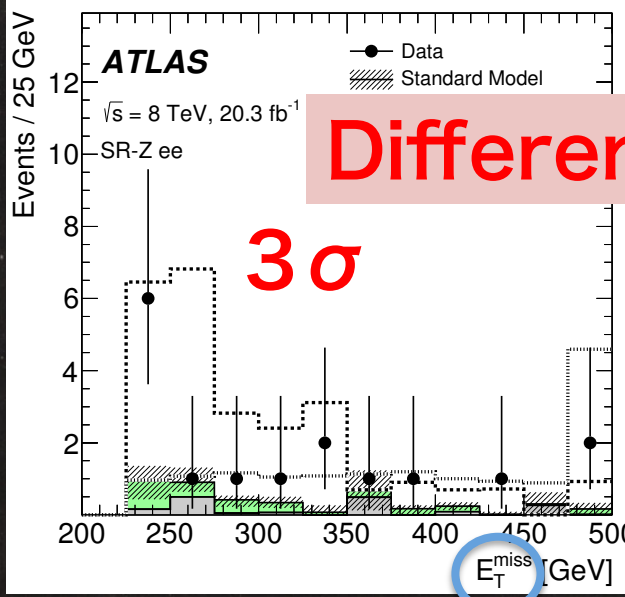
Missing  $E_T$  + dilepton



~~No Excess Observed @ ATLAS~~

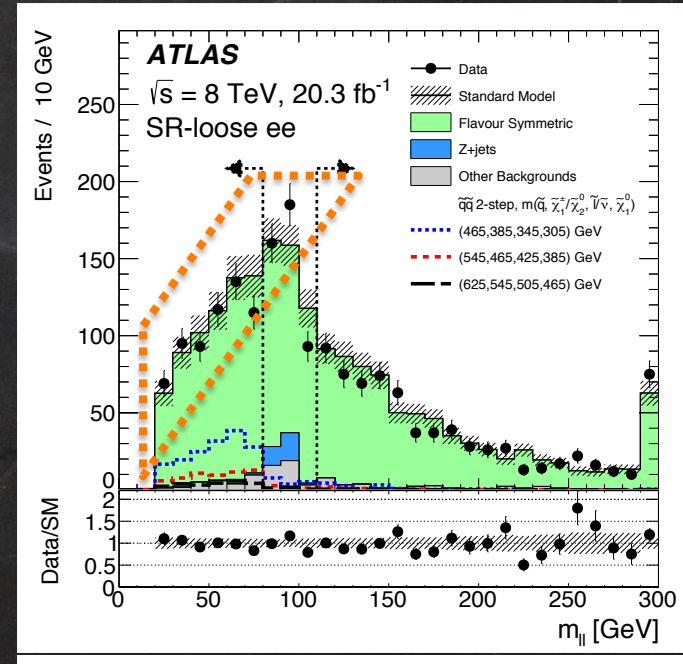


$$M_{II} \approx M_Z$$



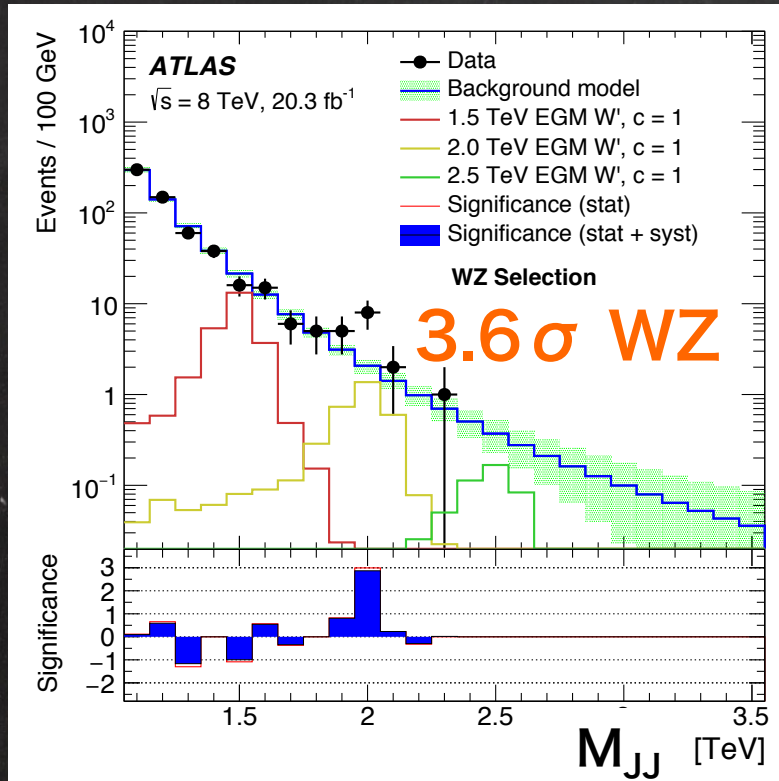
Different Excess

Missing  $E_T$

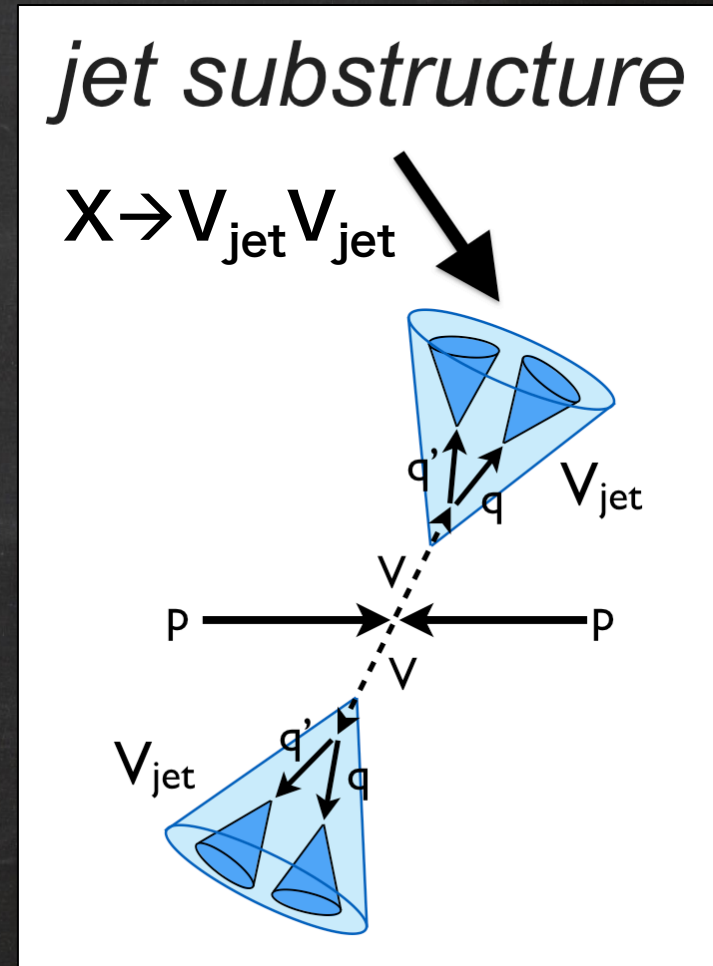




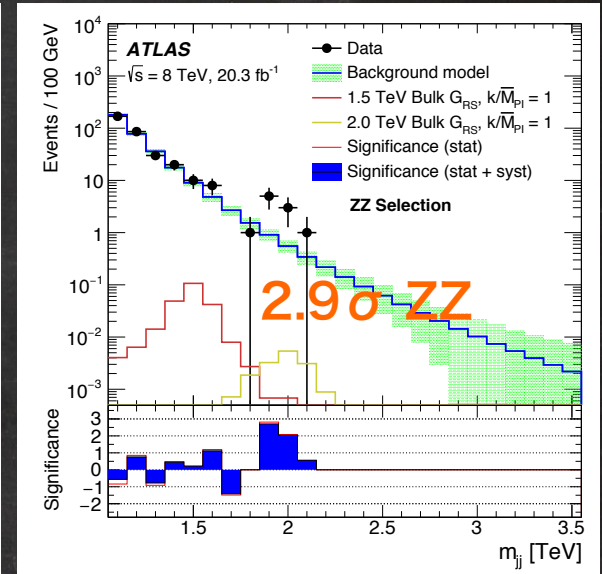
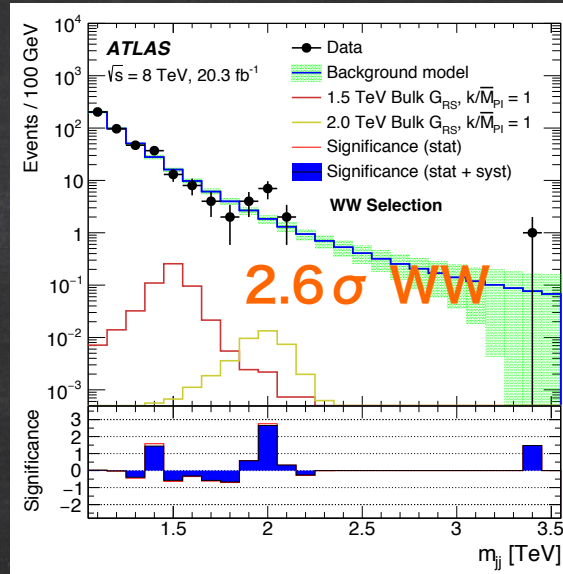
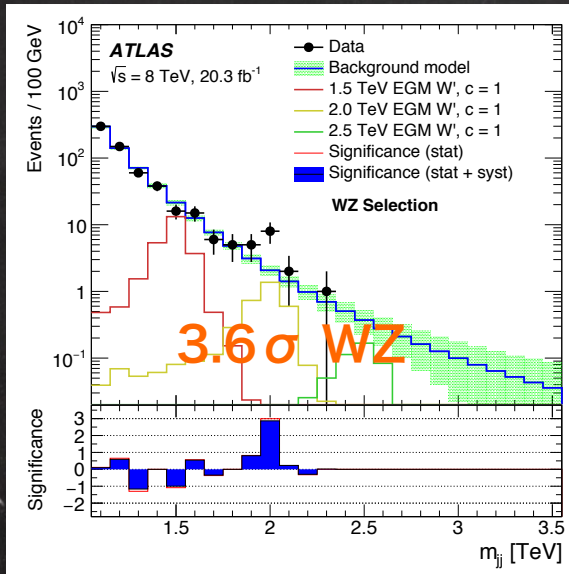
# Diboson Excess @ 2TeV



**Additional Selection Cut :**  
**Tag 2 Fat Jets (J) with  $M_J \approx M_W$  or  $M_Z$**



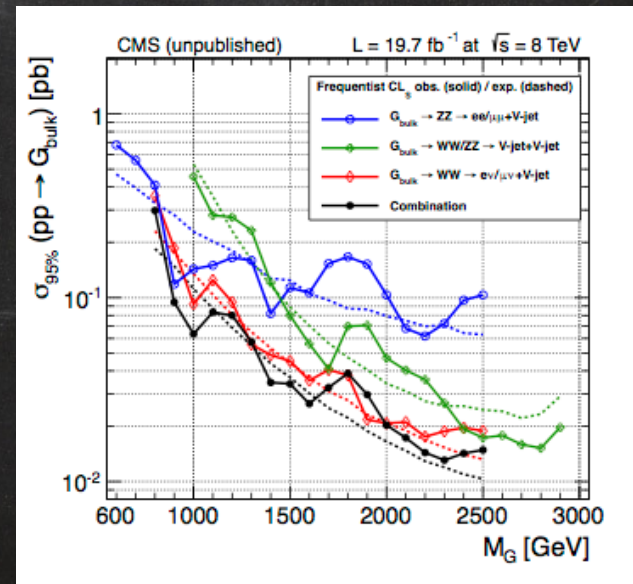
# Diboson Excesses @ 2TeV



- 3 different channels have excesses [ 20% overlap ]
- Excess @ 1.8TeV in CMS

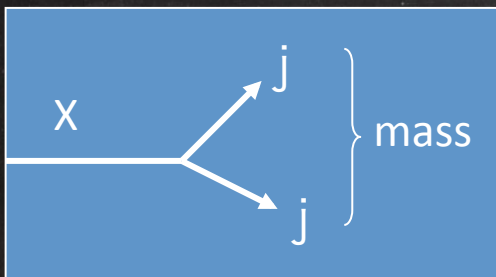
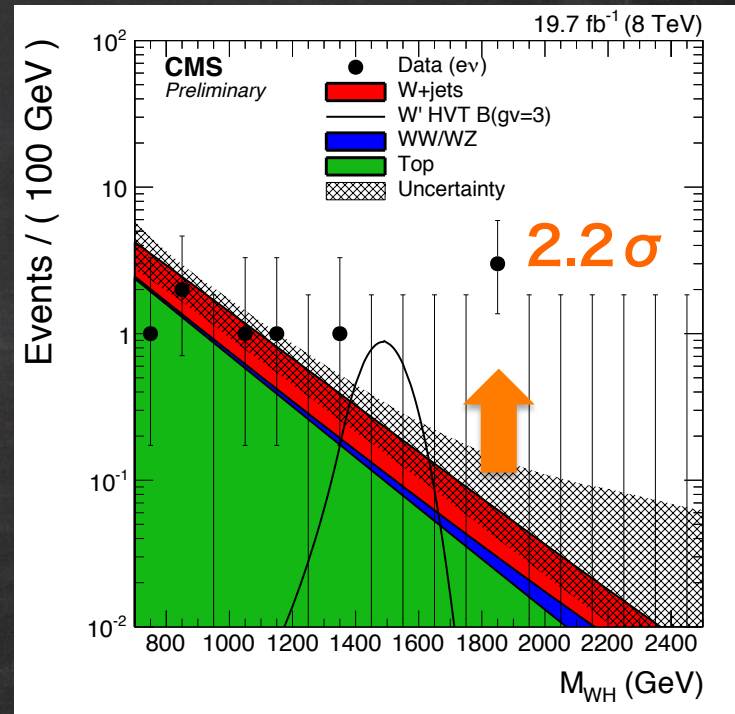
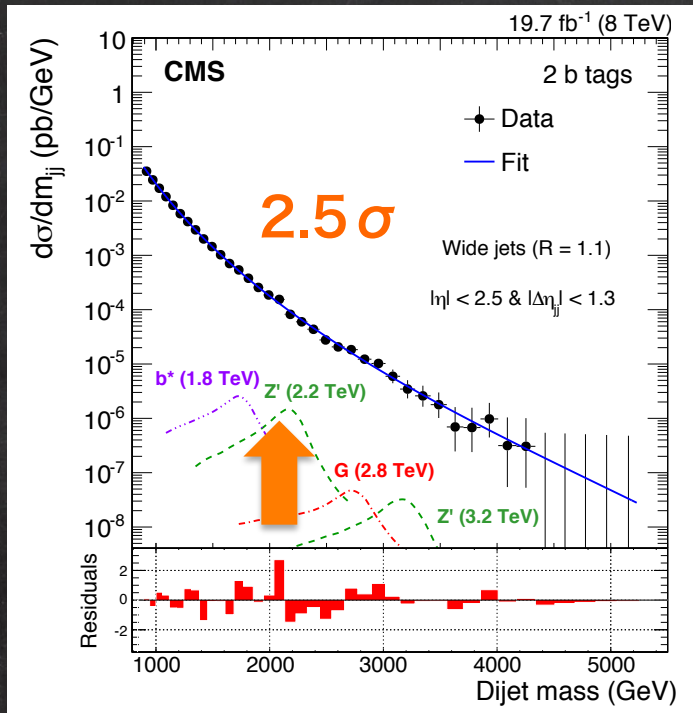
Many Interpretations ( $W', Z', \text{TC-}\rho, H', \dots$ )

> 40 Theory Papers



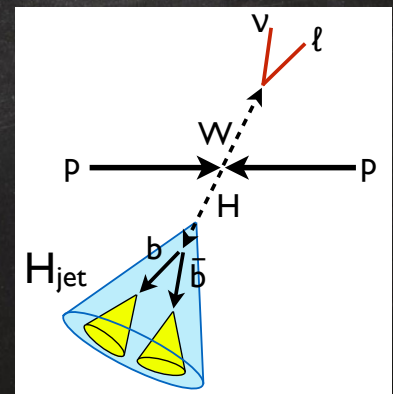


# 2TeV in Other Channels?



$$X \rightarrow jj$$

$$X \rightarrow Wh$$



# Evidence of Anomalies

- $h \rightarrow \tau\mu$  (2<sup>nd</sup> H)  $2.6\sigma$
  - $W_R$  (RPV SUSY)  $2.8\sigma$
  - SUSY (Edge, on-Z)  $2.6\sigma$   $3\sigma$
  - Diboson Excesses (WZ, WW, ZZ)  $3.6\sigma$   $2.6\sigma$   $2.9\sigma$
  - Dijet Excess  $2.5\sigma$
  - WH search  $2.2\sigma$
  - ...
- Different SUSY
- $3\sigma = 1/370$  : Yearly  
 $2.5\sigma = 1/81$  : Quarterly  
 $2\sigma = 1/22$  : Every 3 weeks
- ~~Evidence of New Physics !!~~

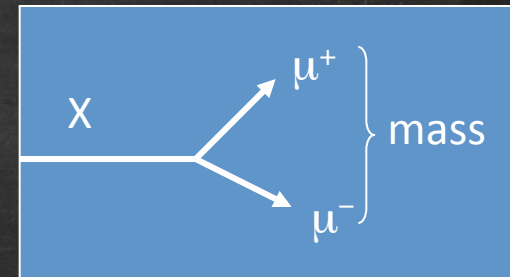
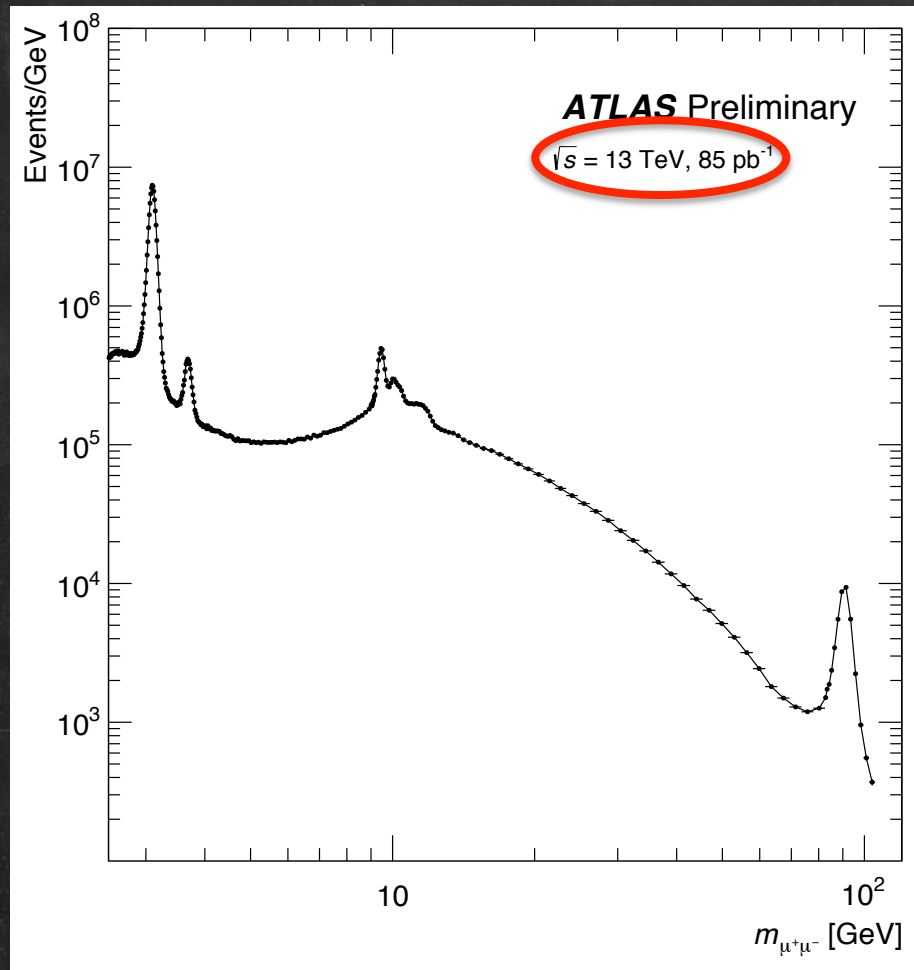
**We can't say No New Physics**



# Run II ( 13 TeV )

# Re-Discovery of the SM

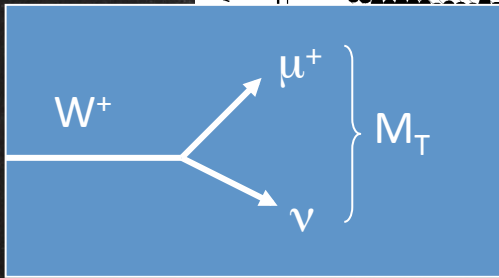
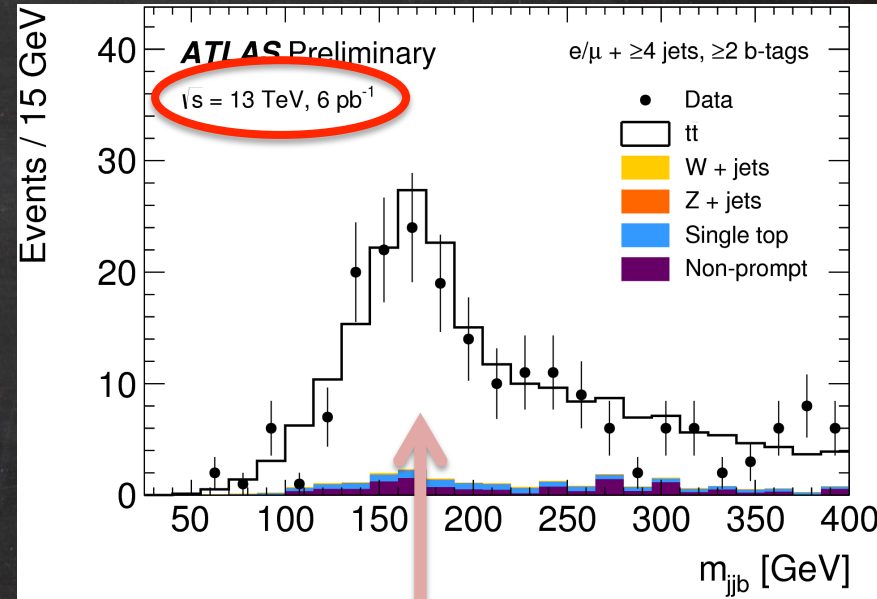
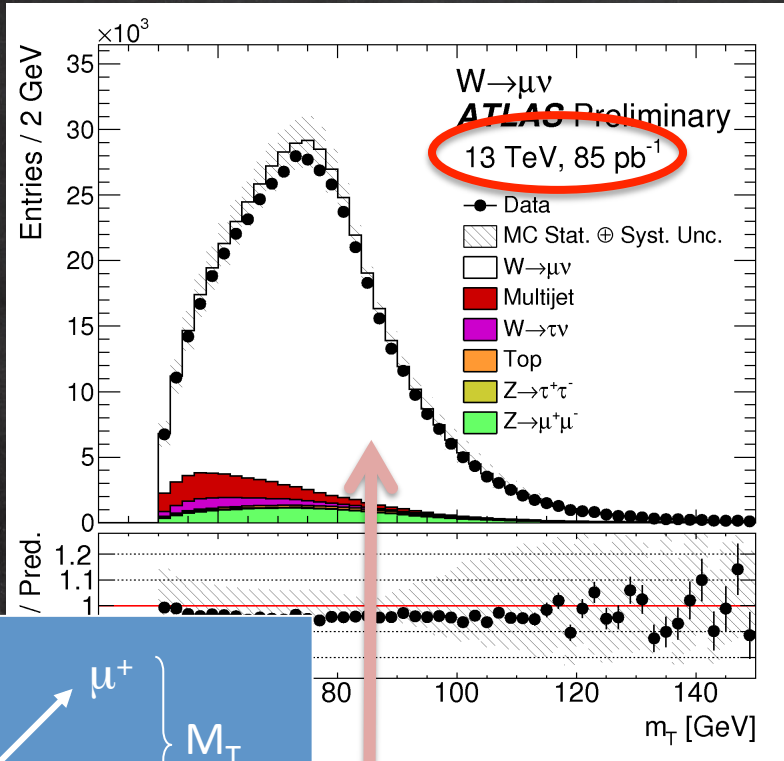
$$M_{\ell\ell} = \sqrt{(p_{1\ell} + p_{2\ell})^2} : \text{di-lepton Invariant Mass}$$



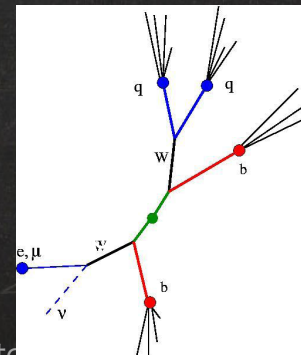


# Re-Discovery of W, top

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



$M_W$

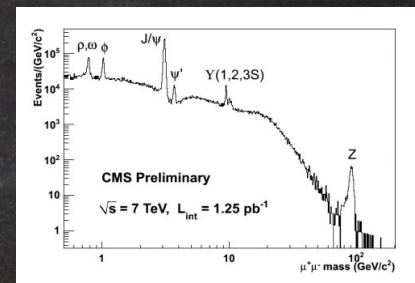
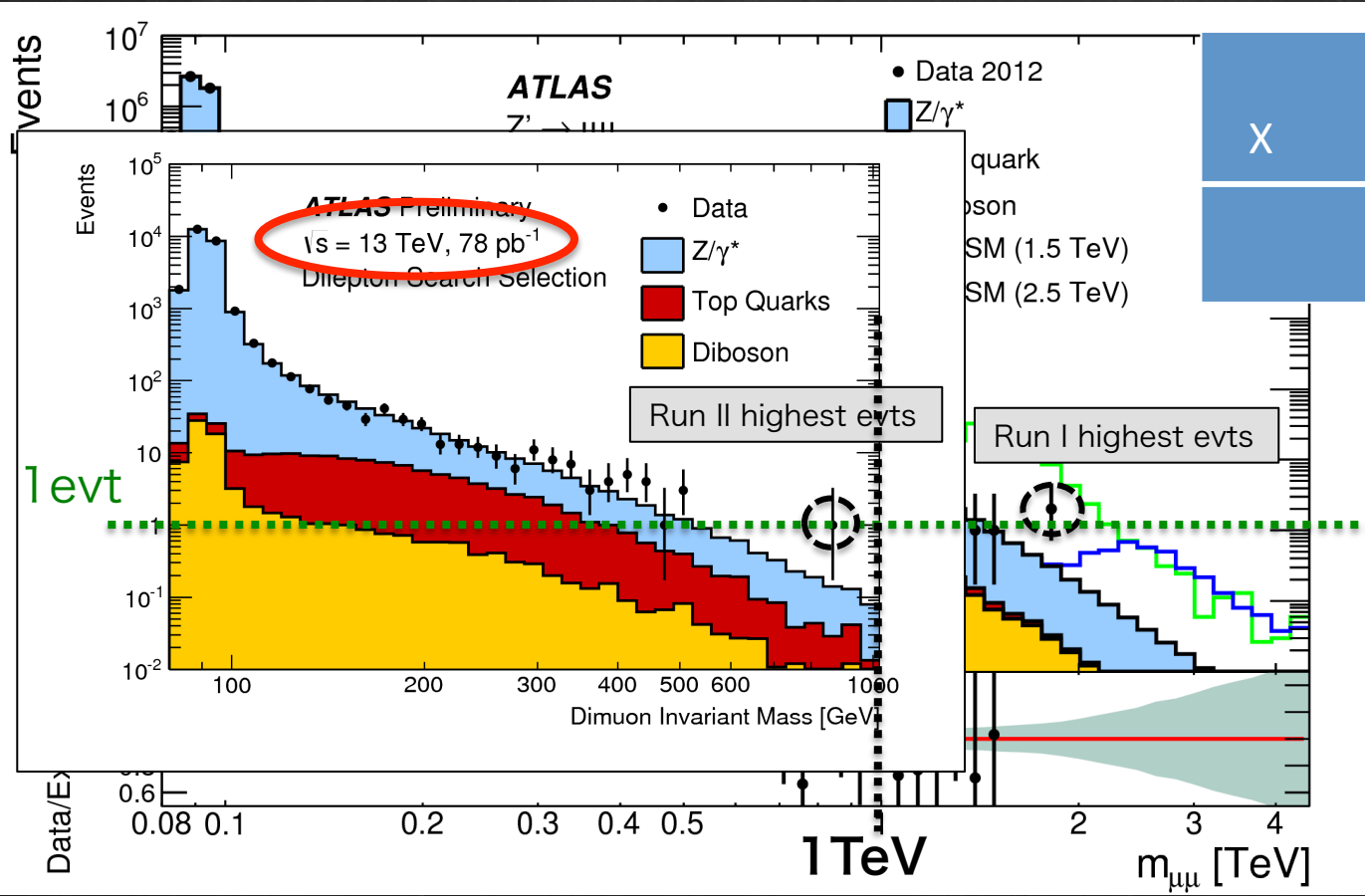


$M_t$

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

# Z' search

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

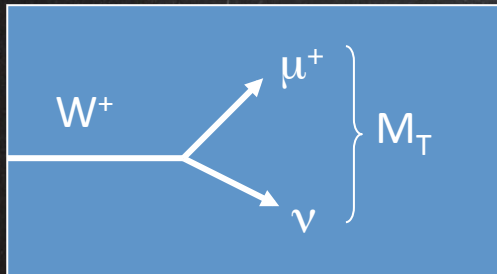
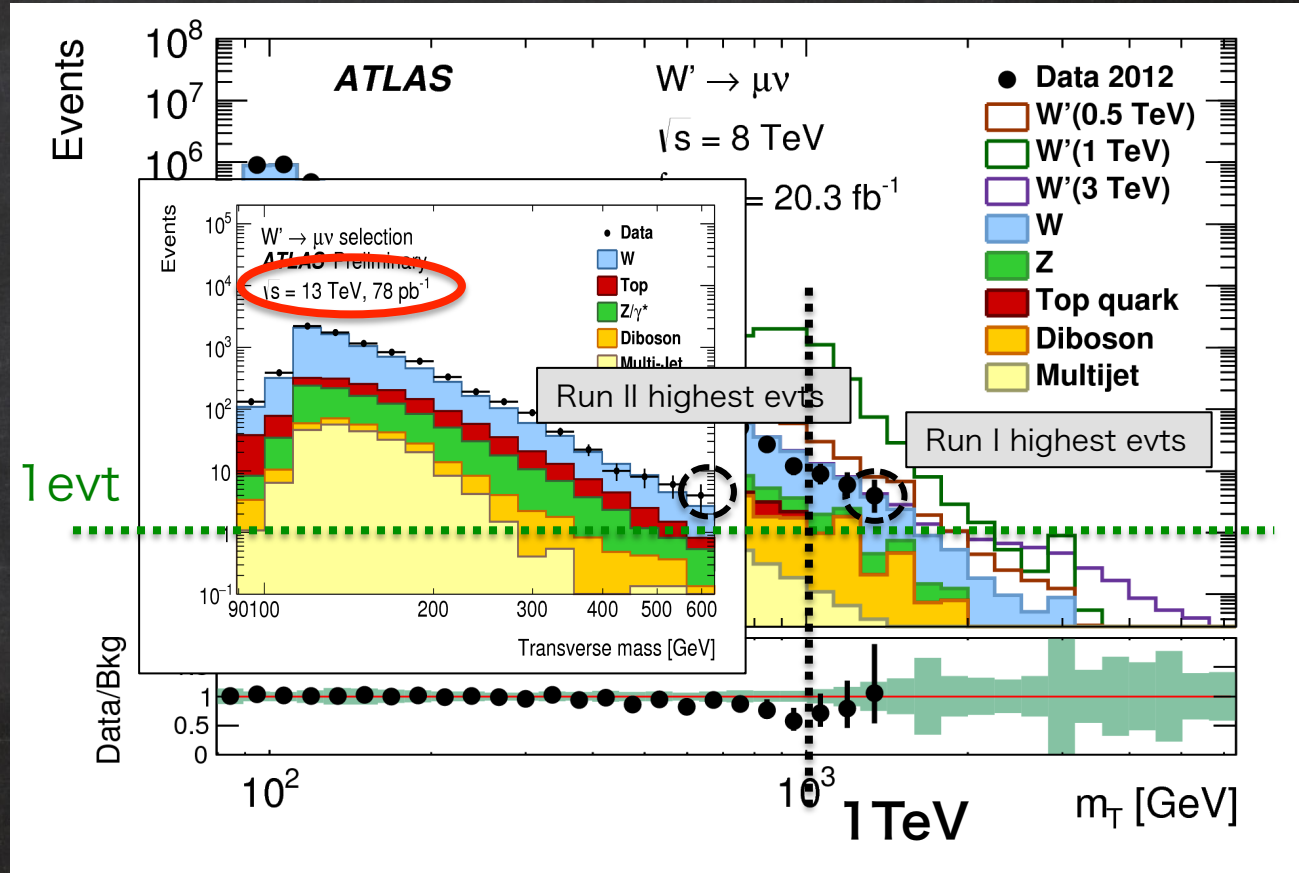
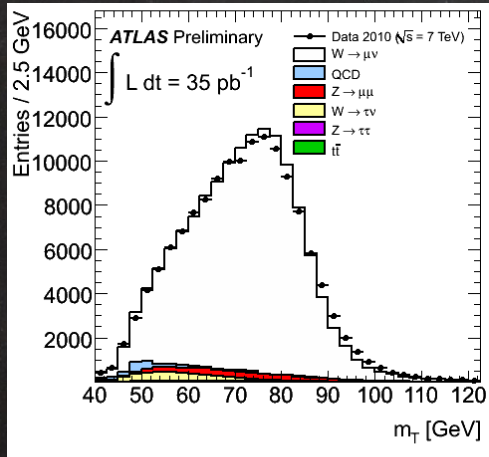


**~3fb<sup>-1</sup> @ Run II**  
Beyond Run I Sensitivity



# W' search

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

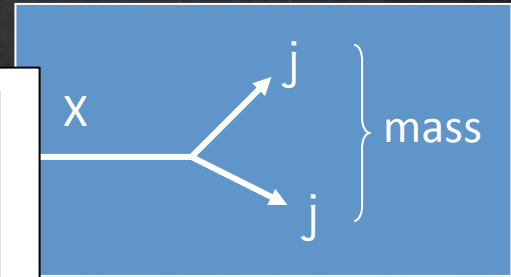
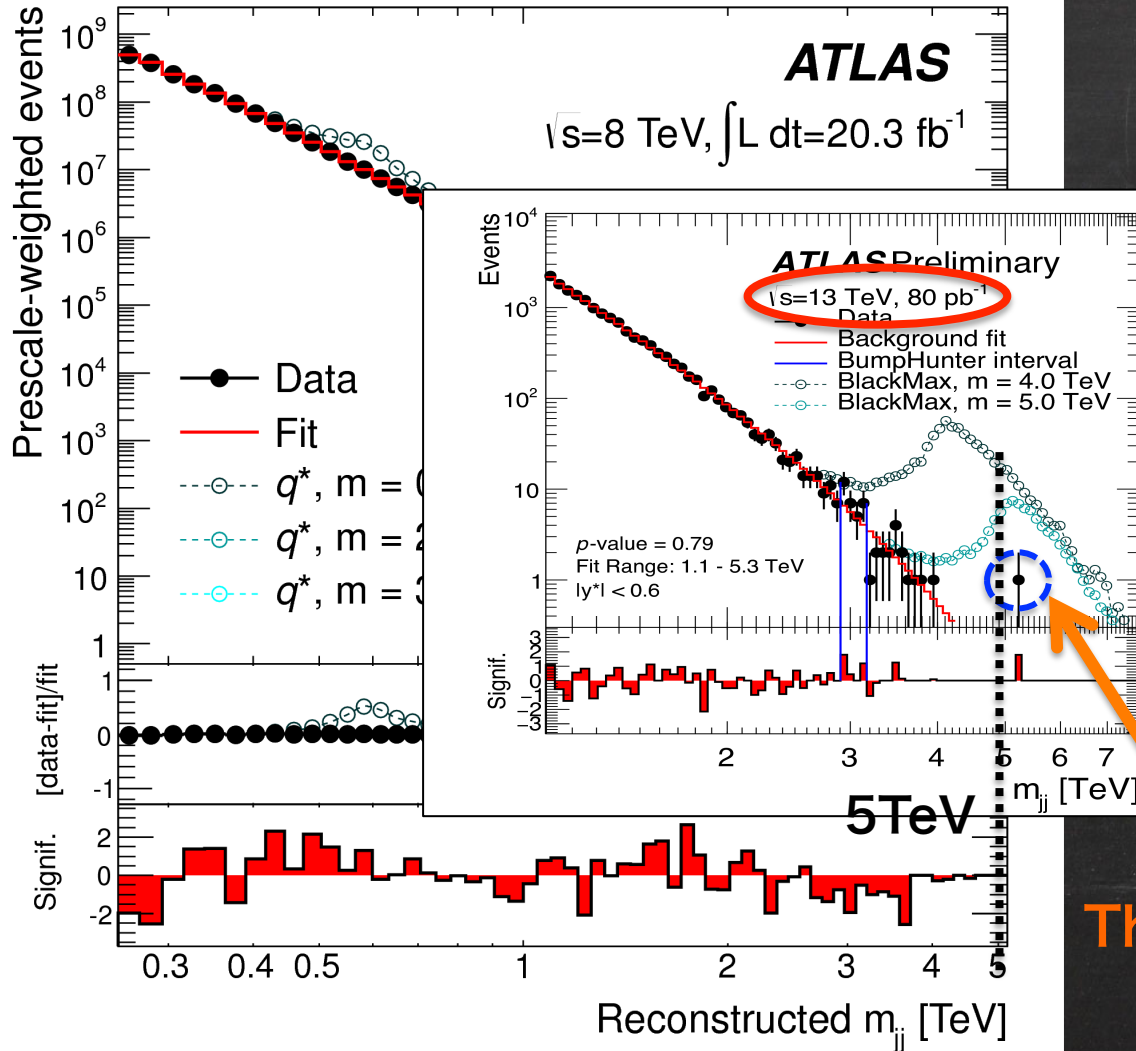


$$M_T = \sqrt{2p_T^\ell p_T^\nu (1 - \cos(\phi^\ell - \phi^\nu))}$$

~3fb<sup>-1</sup> @ Run II

Beyond Run I Sensitivity

# Dijet ( $q^*$ , $Z'$ , $W'$ ) search

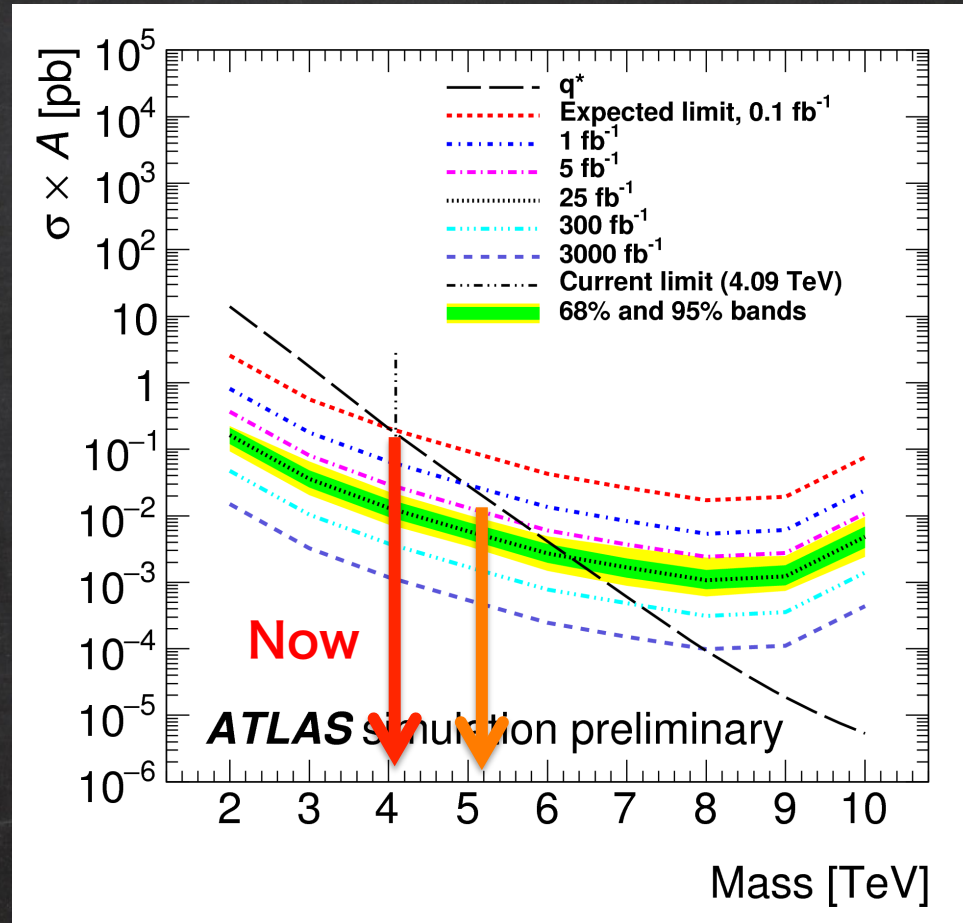


The Highest Mass event

Need more statistics

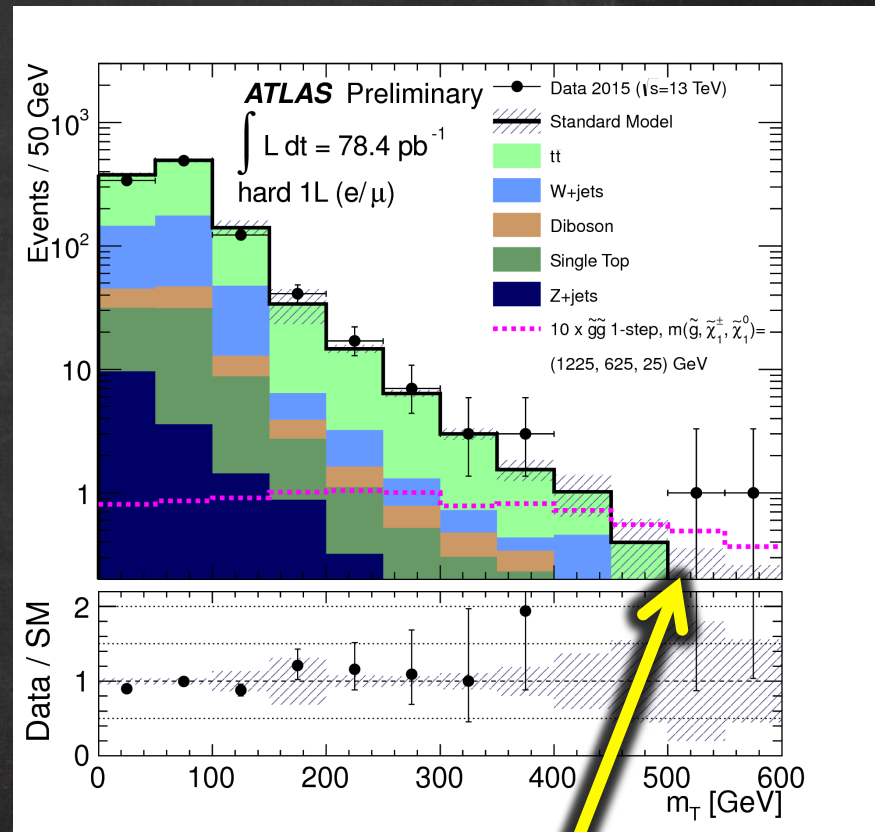
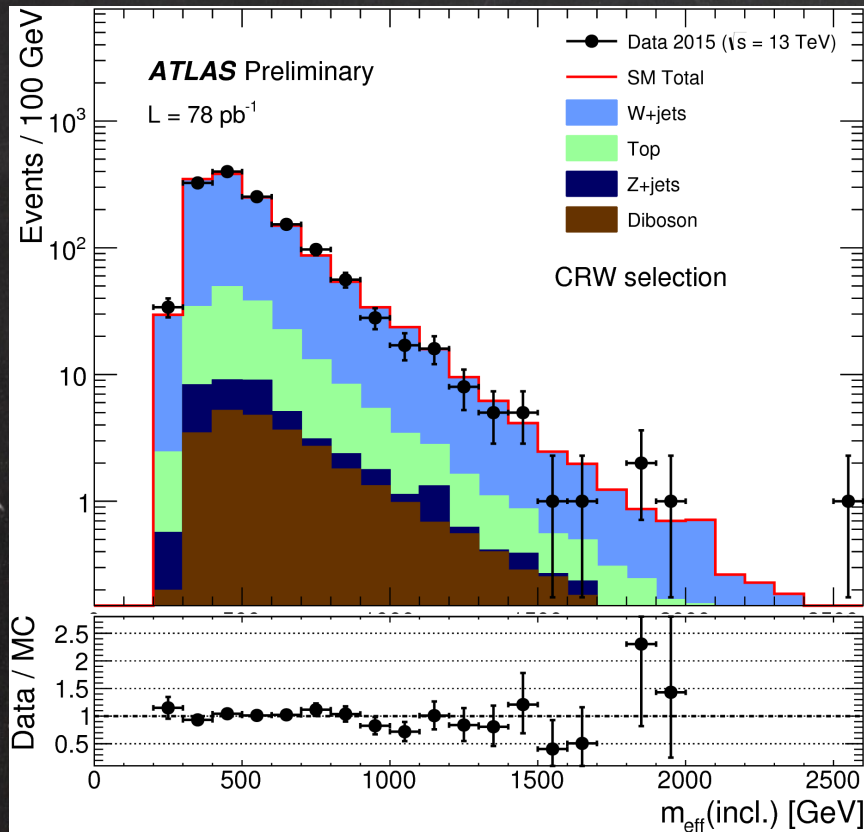


# Dijet ( $q^*$ , $Z'$ , $W'$ ) search



**~3fb<sup>-1</sup> @ Run II** (Mar 2016???)

# Ready for SUSY search

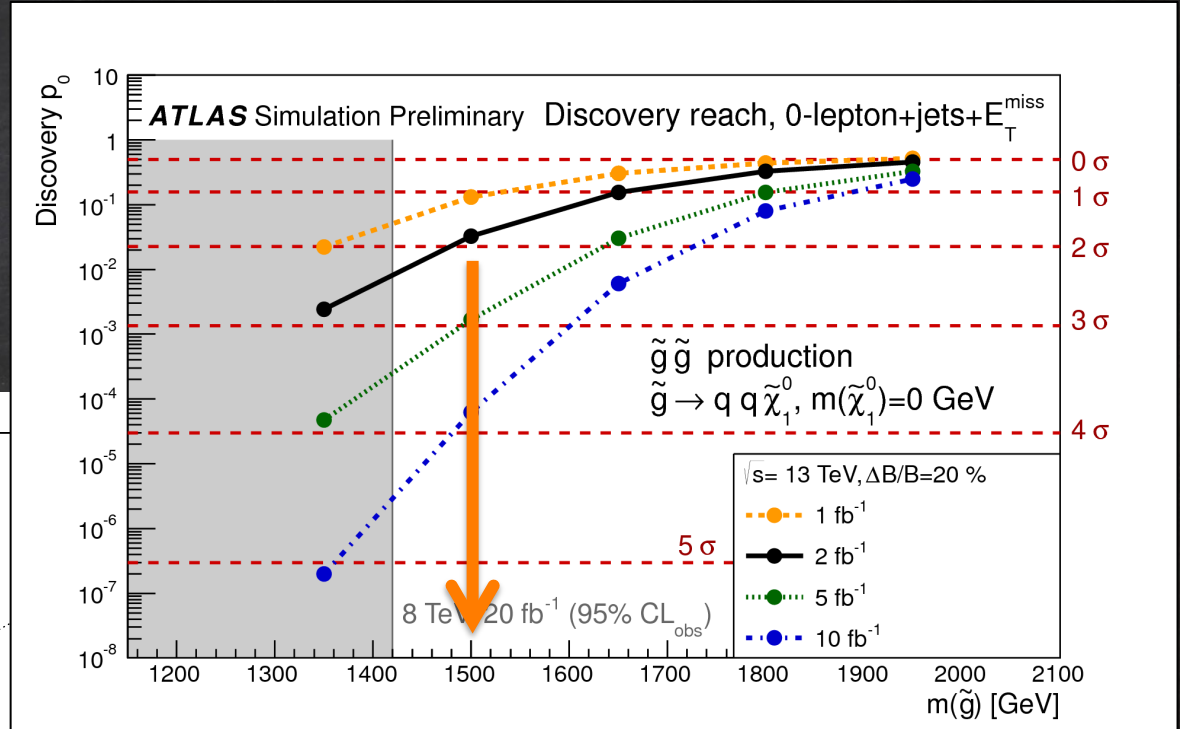
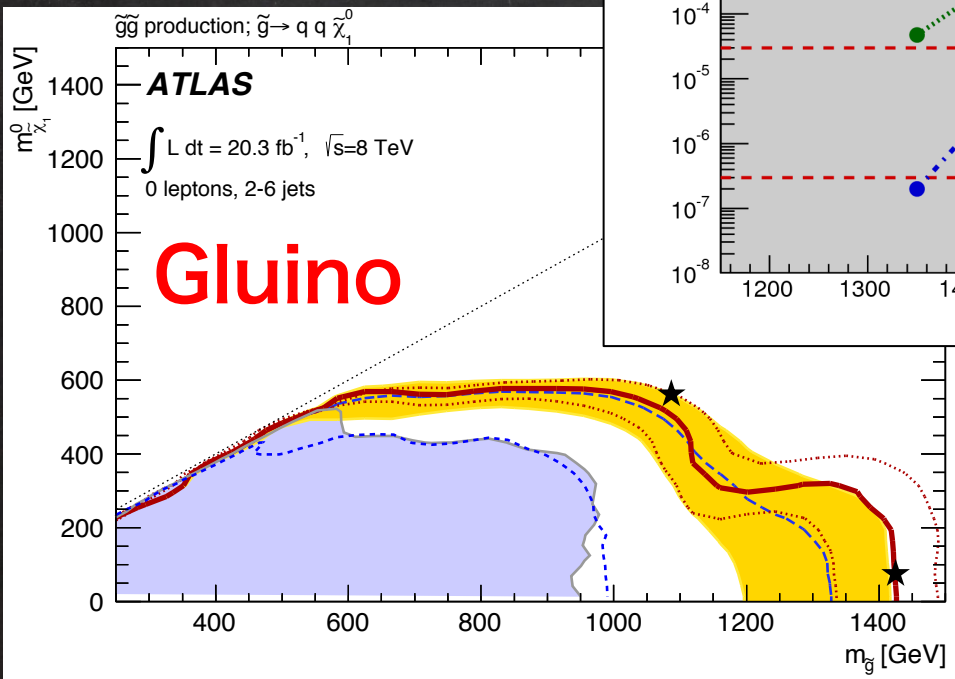


$$M_{\text{eff}} = E_T^{\text{miss}} + \sum |p_T^{\text{jet}}|$$

No bound is obtained so far

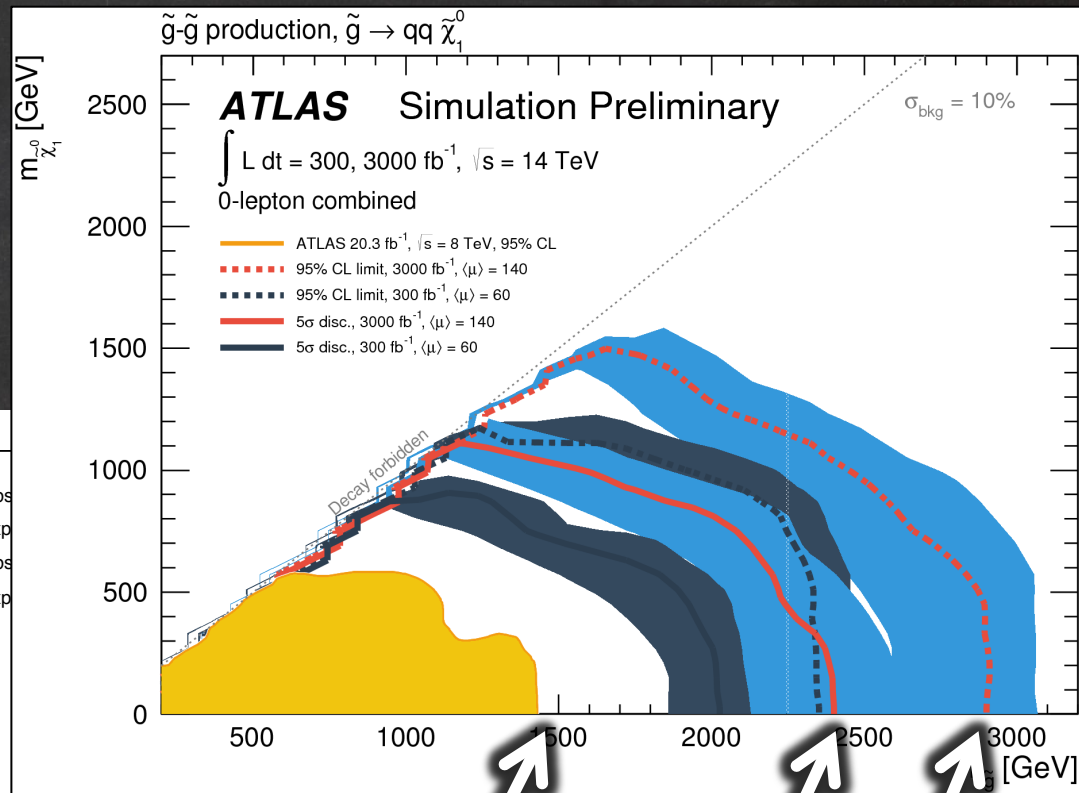
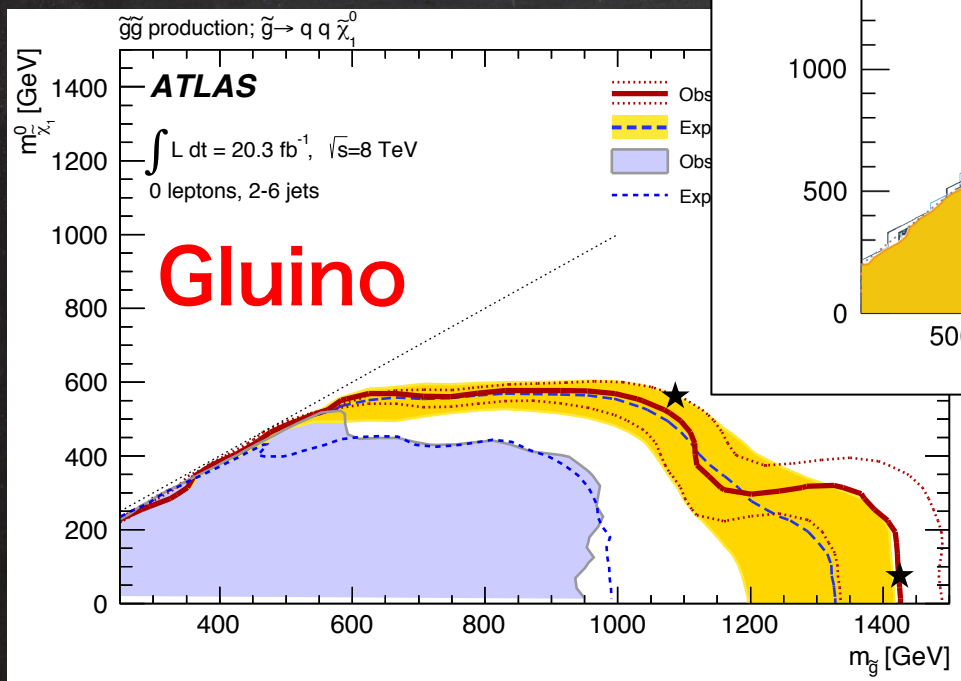


# SUSY Prospects



$\sim 3 \text{ fb}^{-1}$  @ Run II (Mar 2016???)

# SUSY Prospects



3 $\text{fb}^{-1}$ , ~2015

300 $\text{fb}^{-1}$ , ~2023

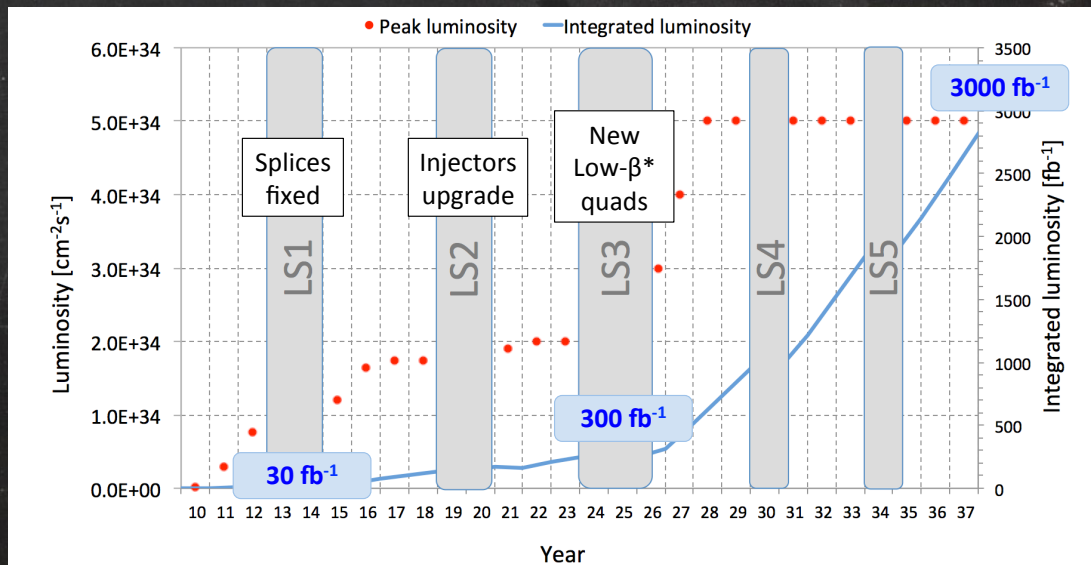
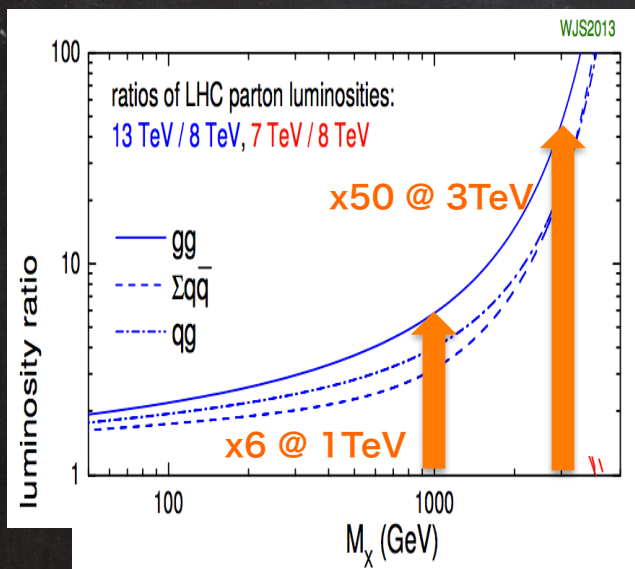
3000 $\text{fb}^{-1}$ , ~2037



# 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





# Stay Tuned