



# Quest for the Unknown: Search for Supersymmetry with the ATLAS Detector

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*PhD Defense*

Friday, July 7th, 2017

# Outline

- What is our goal?
- Why we want to achieve it?
- How to do it?
- Where are we at?

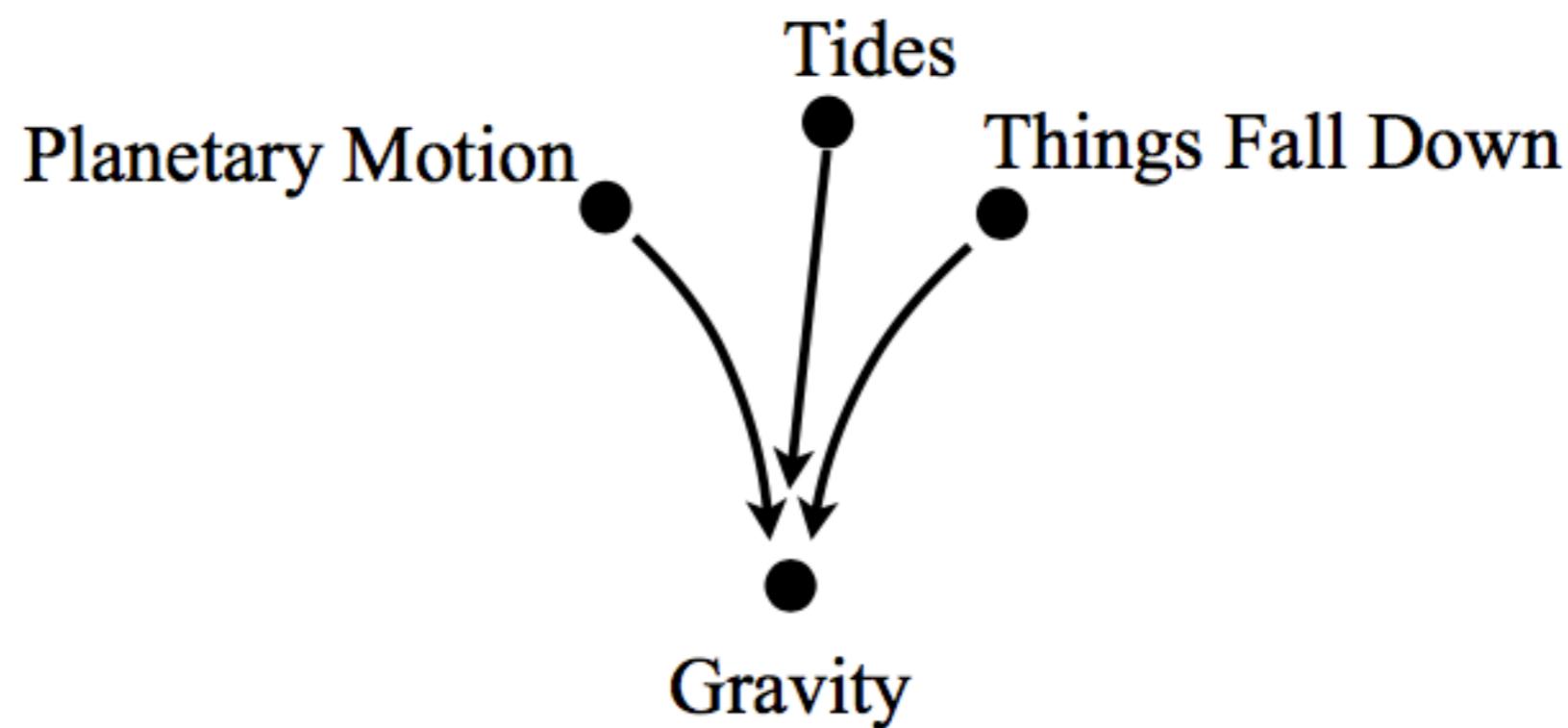
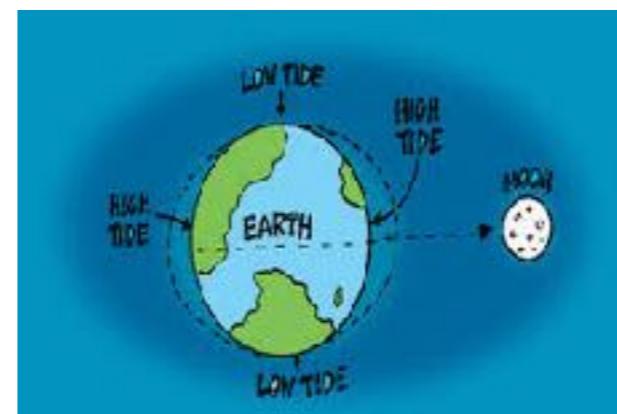
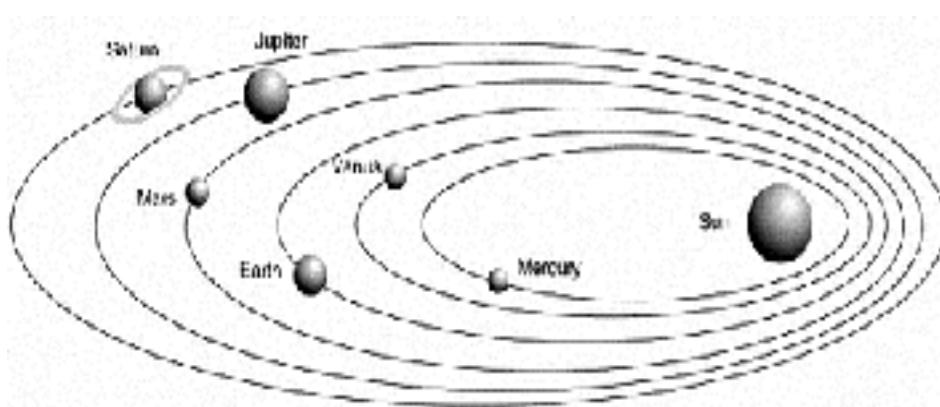
# What is our goal?

# Goal

The multitude of phenomena observed around us can be described by fundamental elements obeying simple principles

# Why we want to achieve it?

# Scientific description

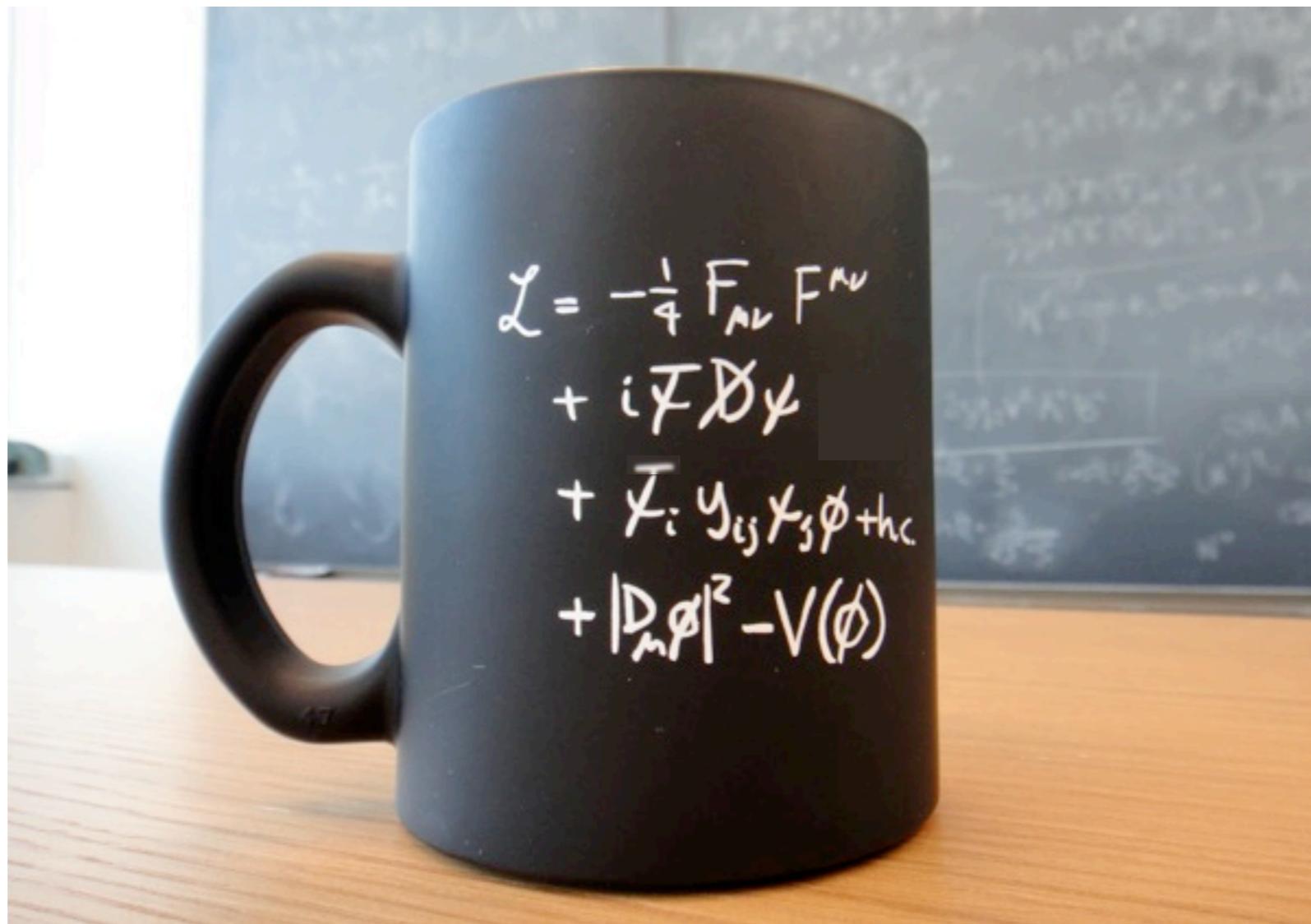


# Goal



- **Particle physics** aims at answering all basic questions of everyday world at the deepest level
- **Standard Model** of particle physics is the culmination of this endeavor

# Standard Model (SM)



$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \quad \mu^2 < 0 \quad \lambda > 0$$

# Standard Model

Simple description of elementary particles and their interactions based on Quantum Field Theory and global/gauge symmetries

Gauge invariance  $SU(3) \times SU(2) \times U(1)$

Matter particles:

$$\begin{pmatrix} v_e \\ e \end{pmatrix} \quad \begin{pmatrix} v_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} v_\tau \\ \tau \end{pmatrix} \quad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Gauge bosons:

$$g \quad W \quad Z \quad \gamma$$

Gauge invariance implies massless Matter Particles and Gauge Bosons

Higgs boson:

Spontaneous symmetry breaking allows for massive fermions, weak bosons while preserving gauge invariance

Prediction of an additional particle: Higgs boson

# Standard Model

Simple description of elementary particles and their interactions  
based on gauge theories

Gauge  
Matter

Gauge

Gauge bosons

Higgs boson

Spoof: Higgs boson

while Higgs boson

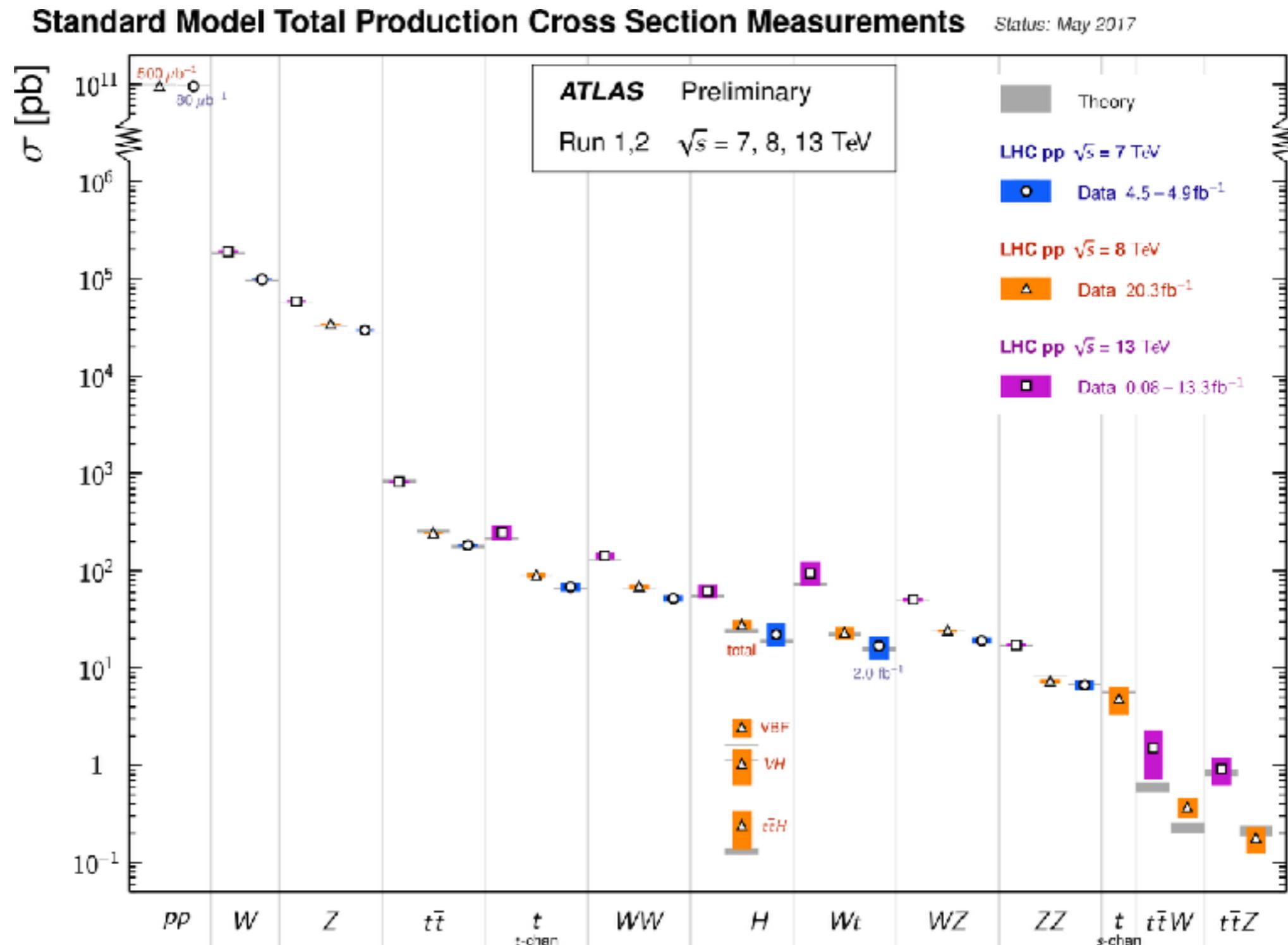


**Nobel Prize**

Prediction of an additional particle: Higgs boson

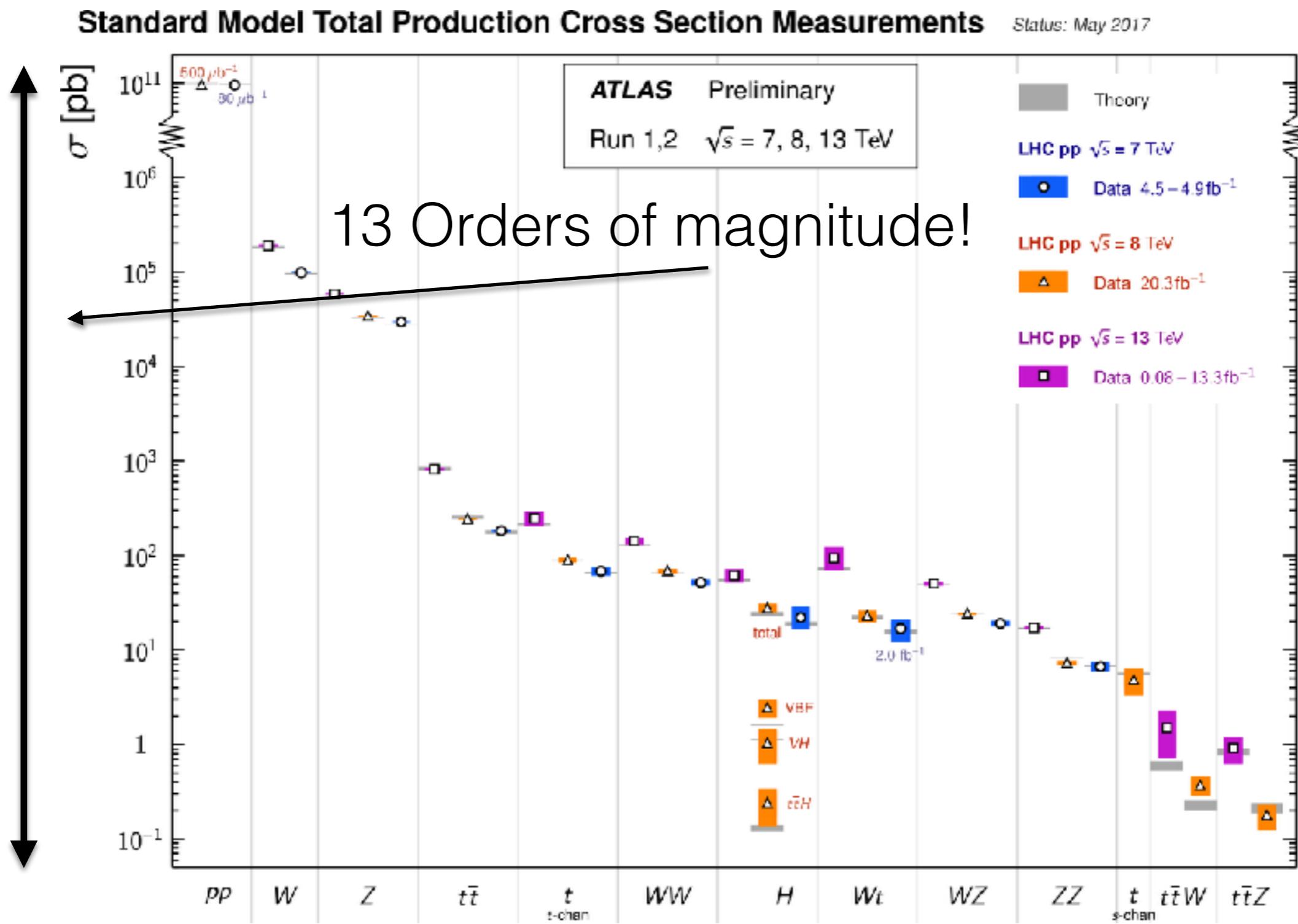
# Standard Model

Standard Model works incredibly well!



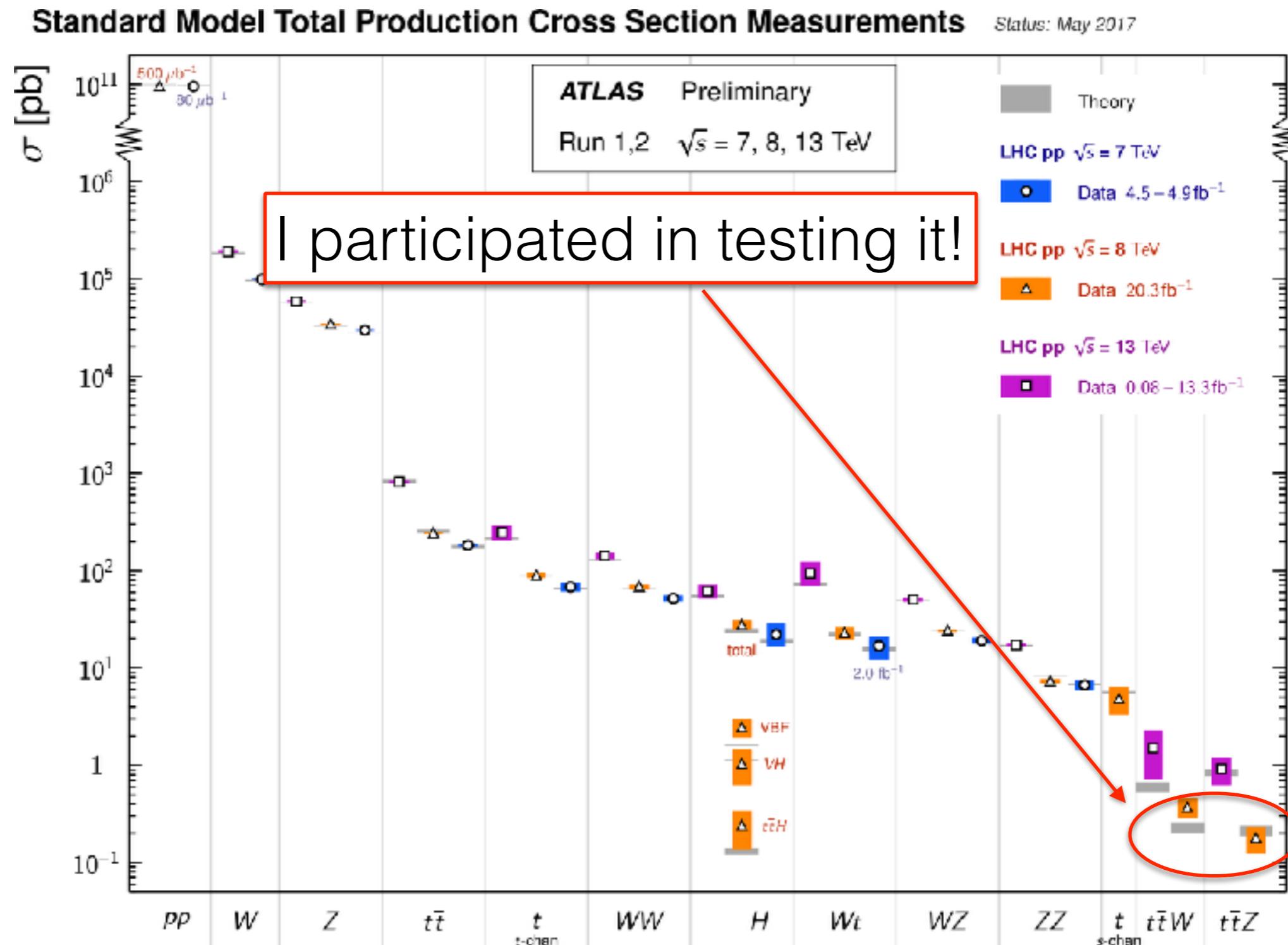
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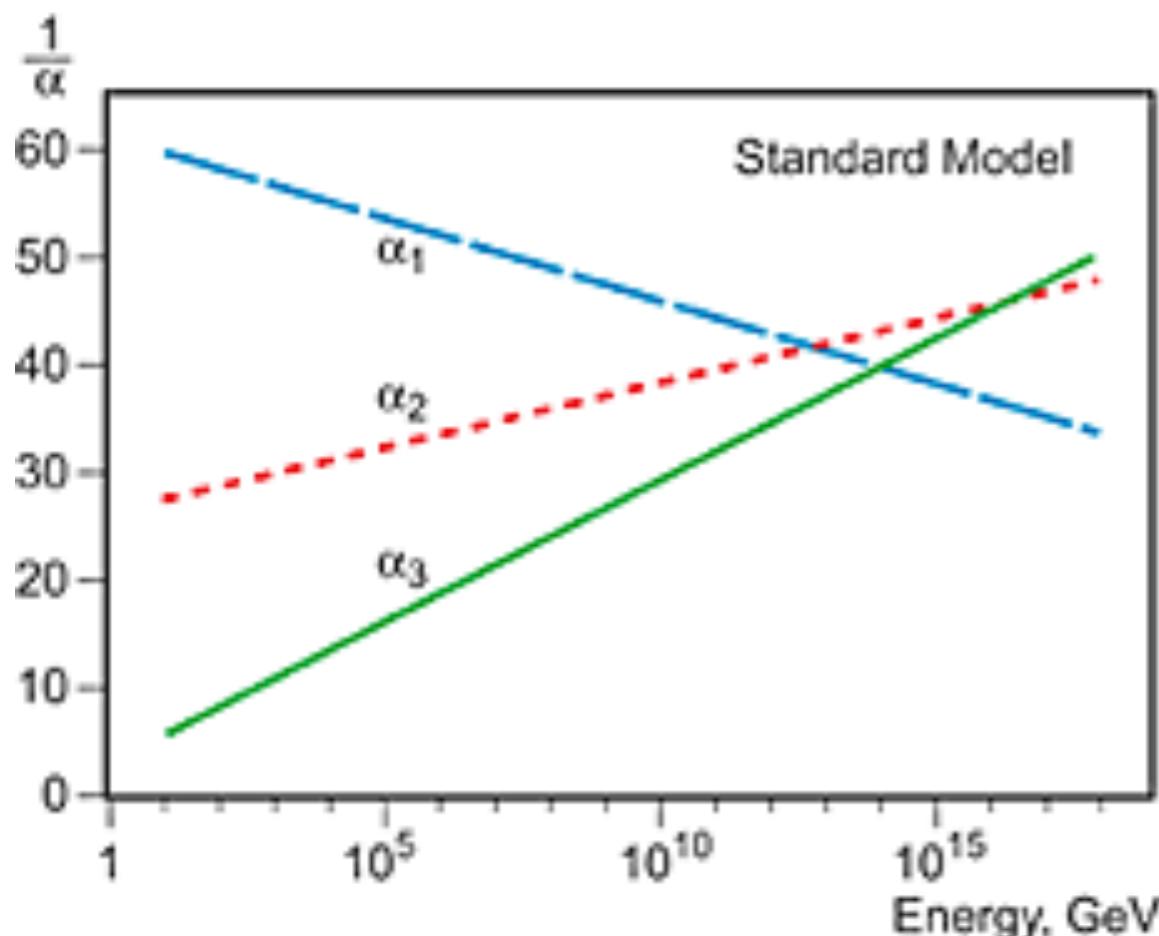
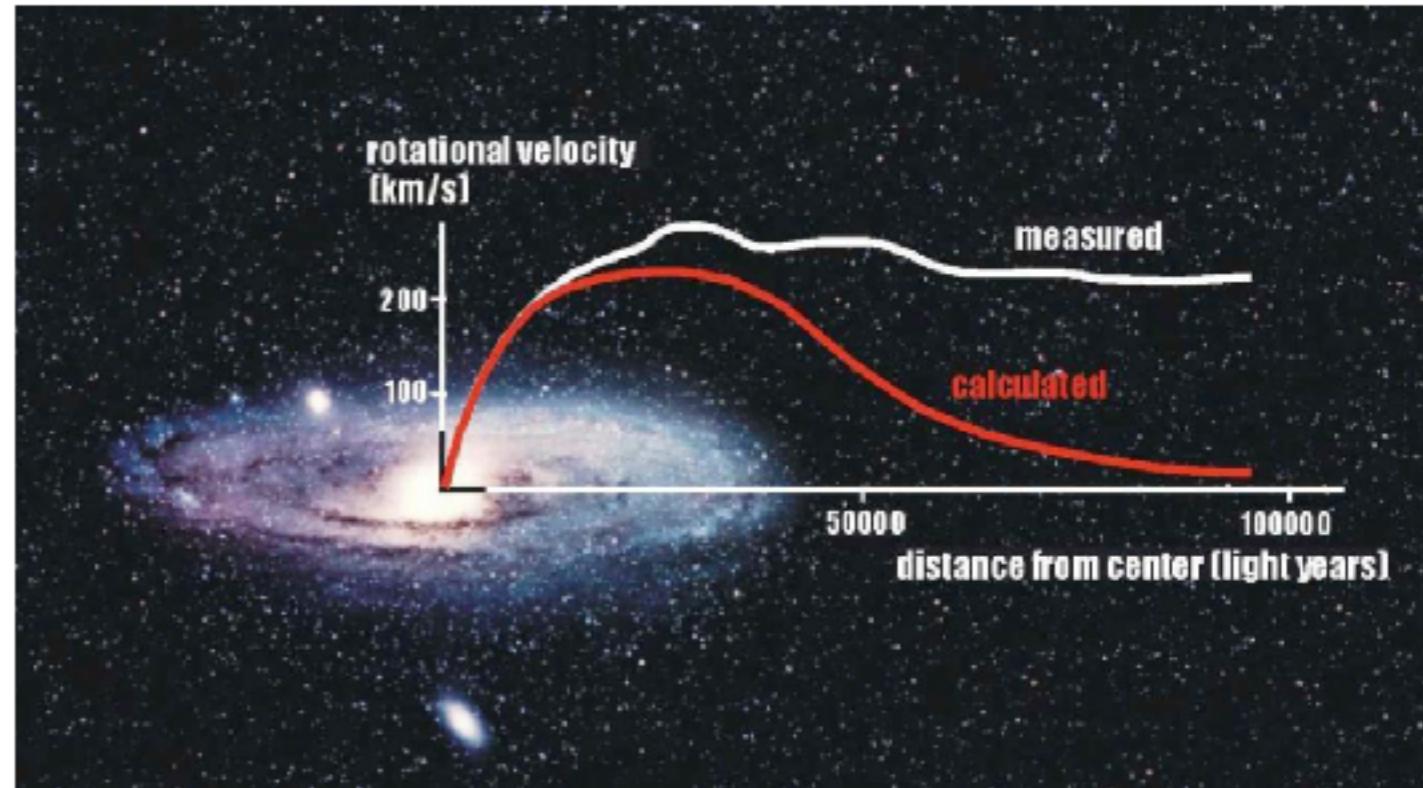
# Standard Model

Standard Model works incredibly well!



# Open Questions of the SM

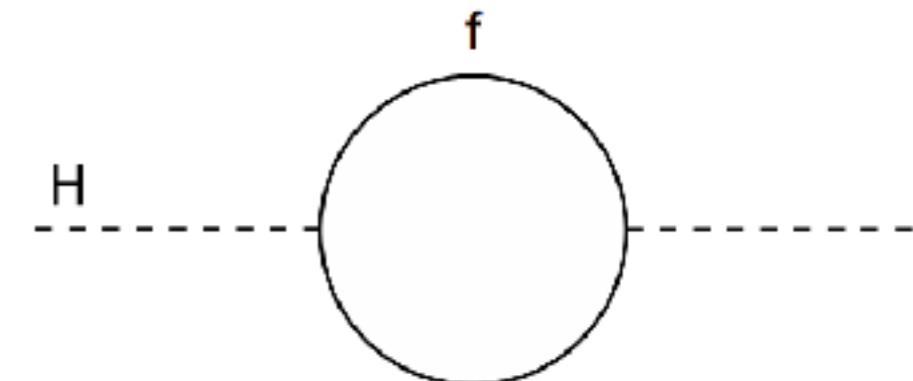
- **Dark matter:** Cosmological data suggests presence of dark matter → No explanation within the SM



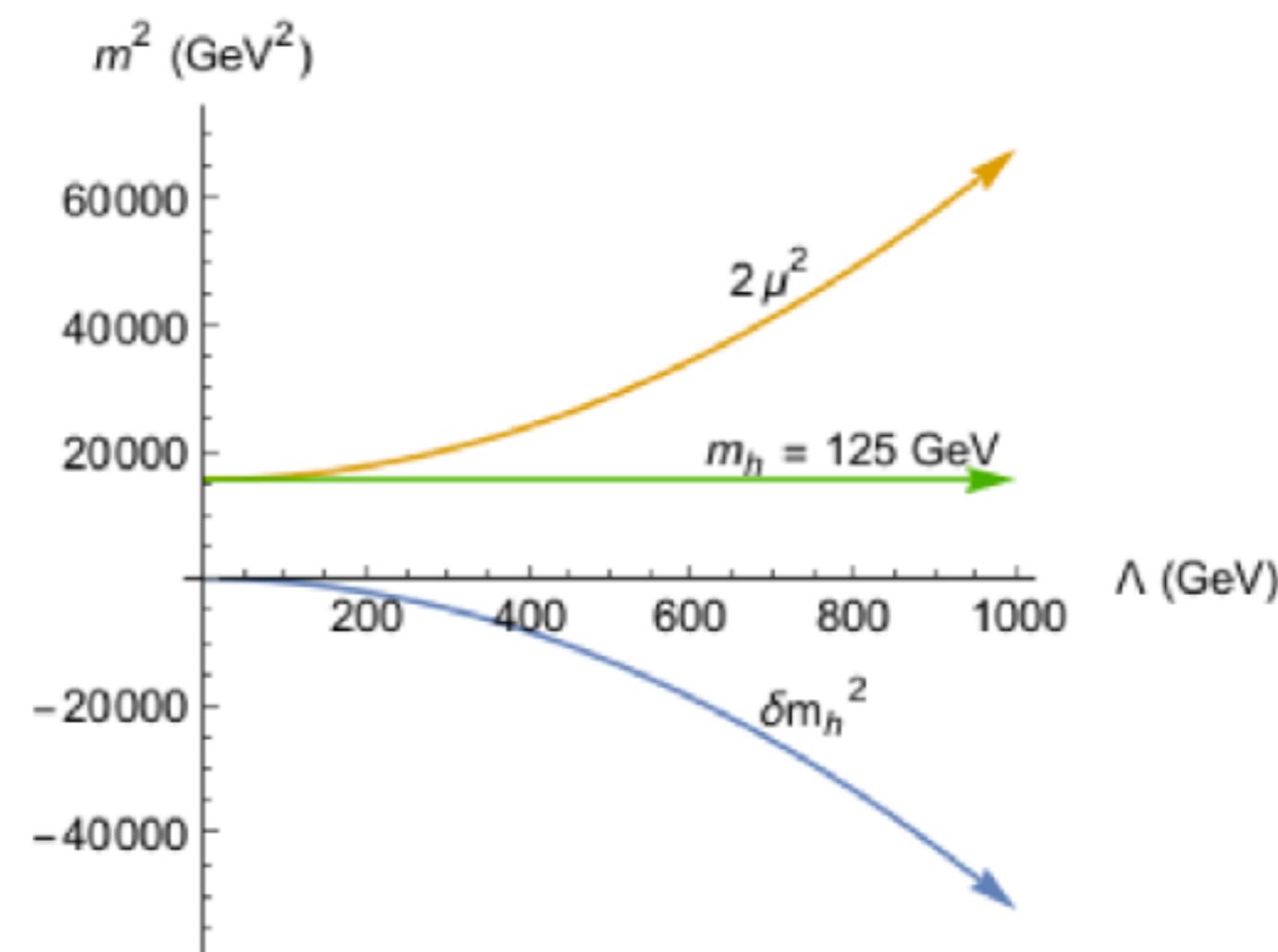
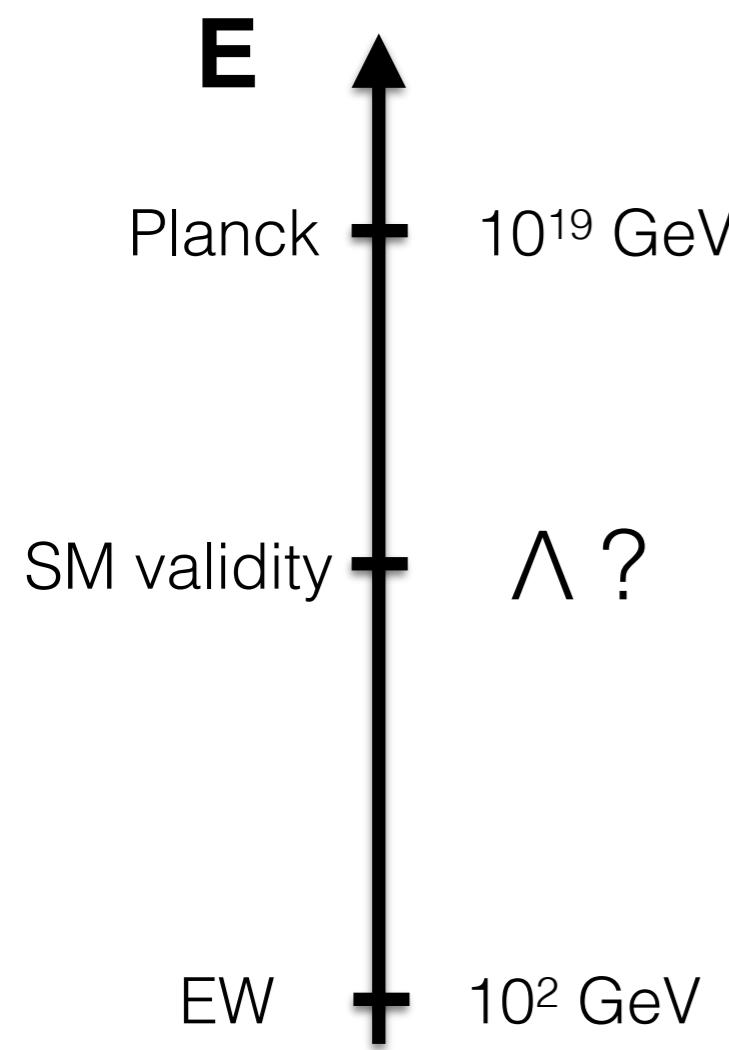
- **Grand unification:** Standard model coupling constants do not unify at high scales  
→ SM does not imply a Grand Unified Theory

# Open Questions of the SM

- **Hierarchy problem:** Corrections to the Higgs self-energy can be far larger than the mass itself

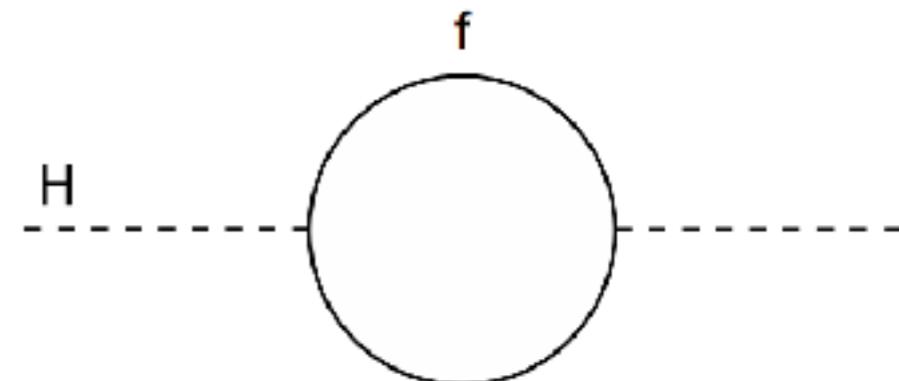


$$m_{h,\text{physical}}^2 \simeq m_h^2 + \frac{C}{16\pi^2} \Lambda^2$$

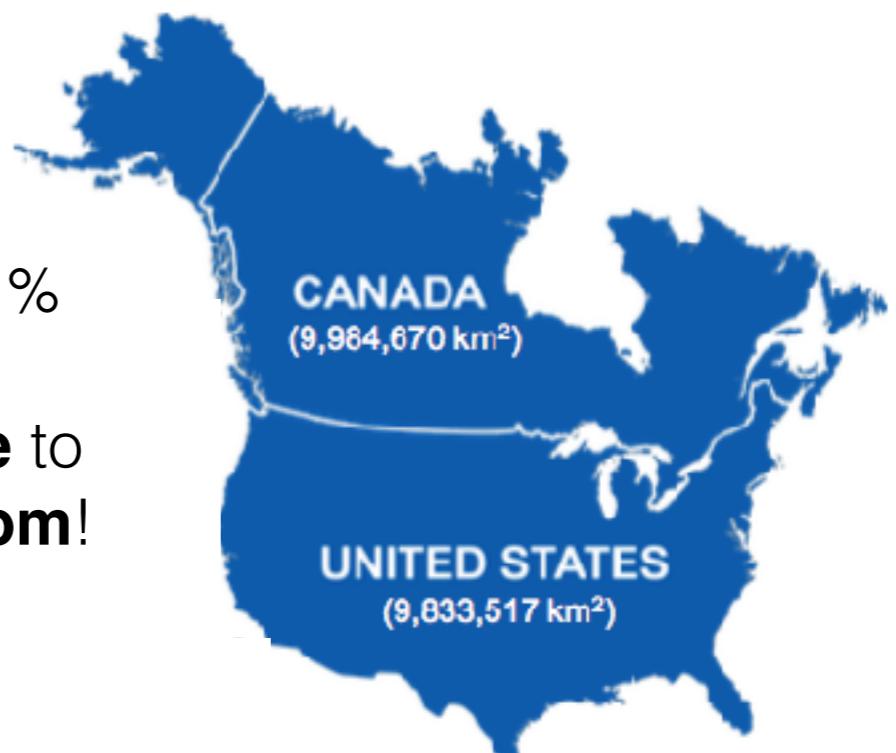
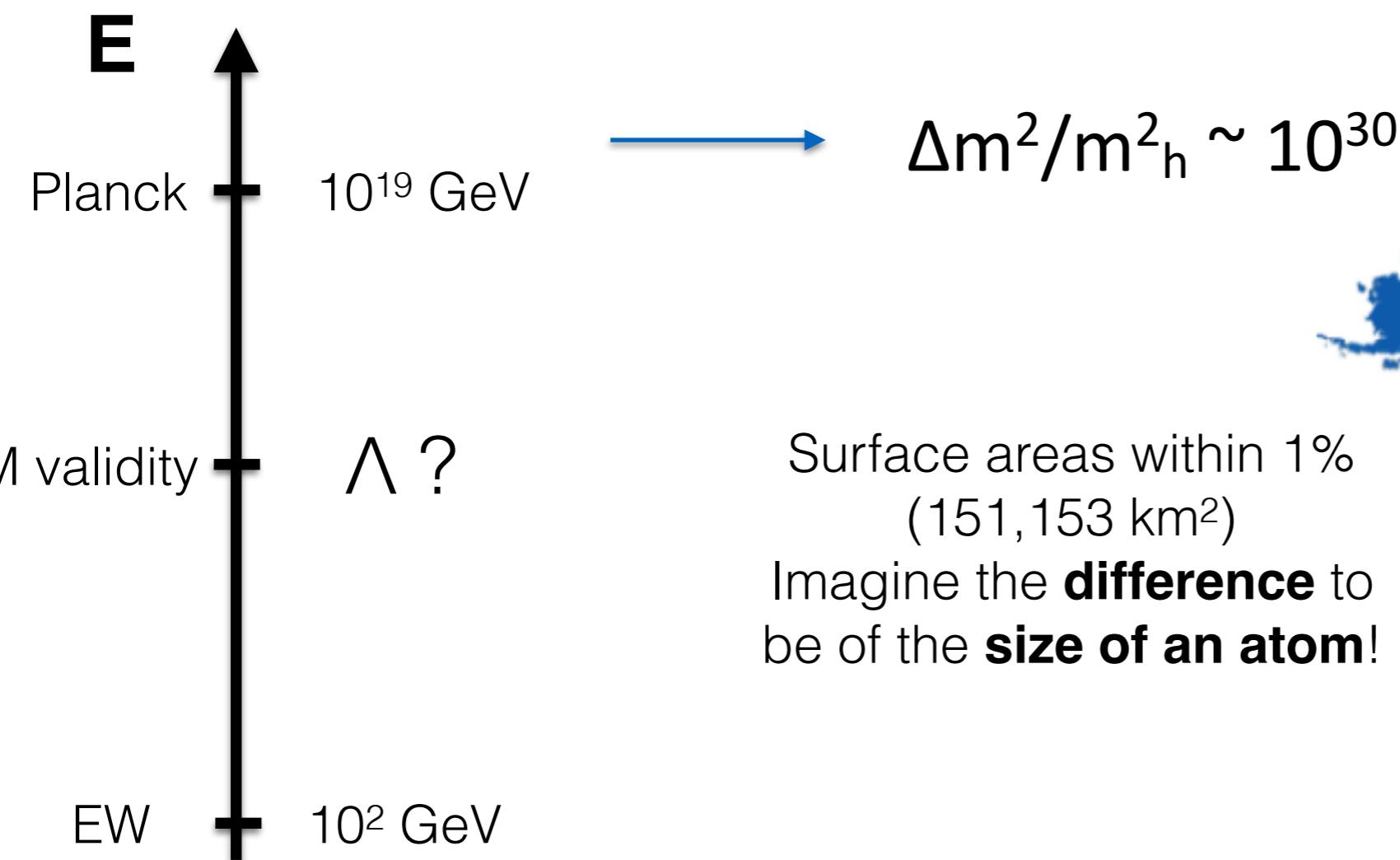


# Open Questions of the SM

- **Hierarchy problem:** Corrections to the Higgs self-energy can be far larger than the mass itself



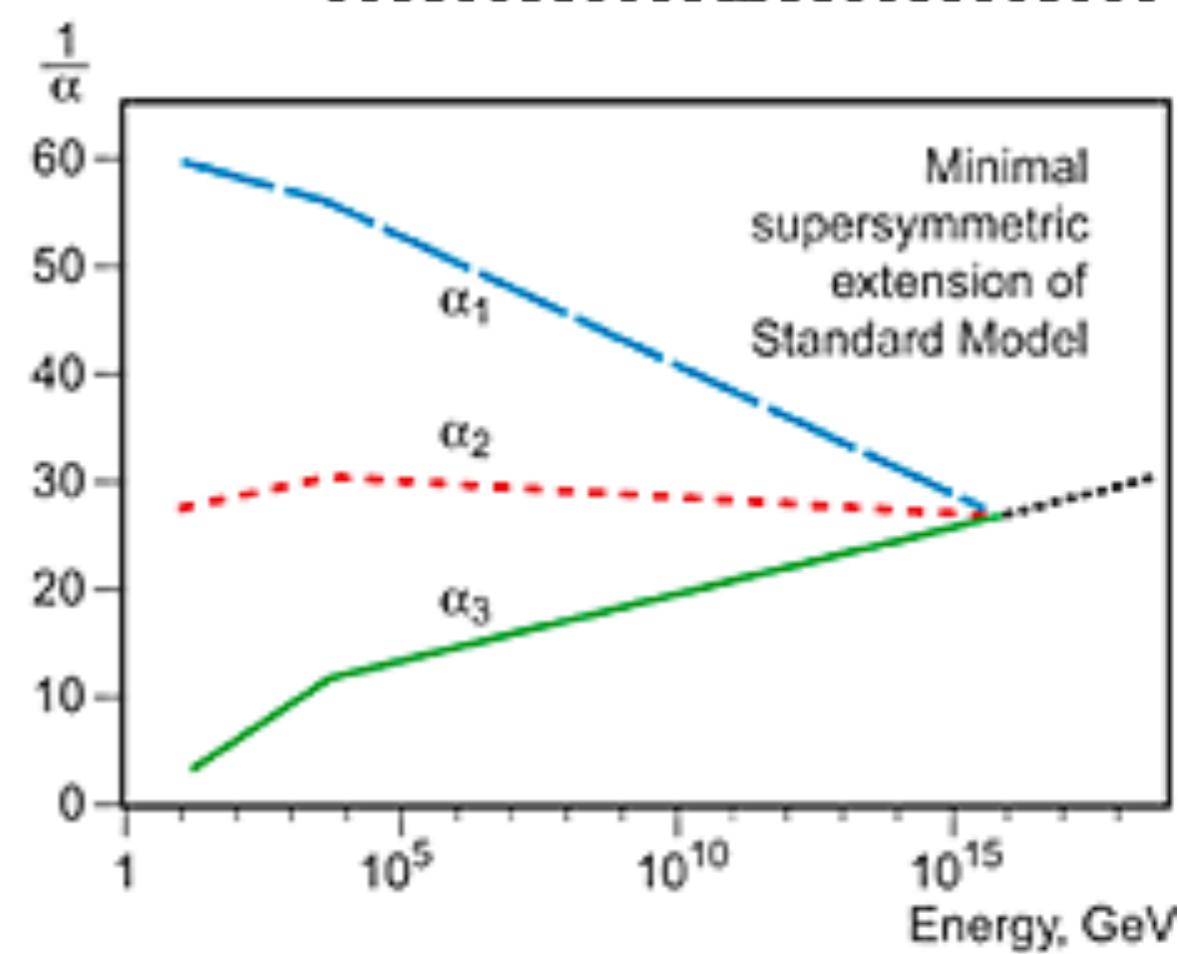
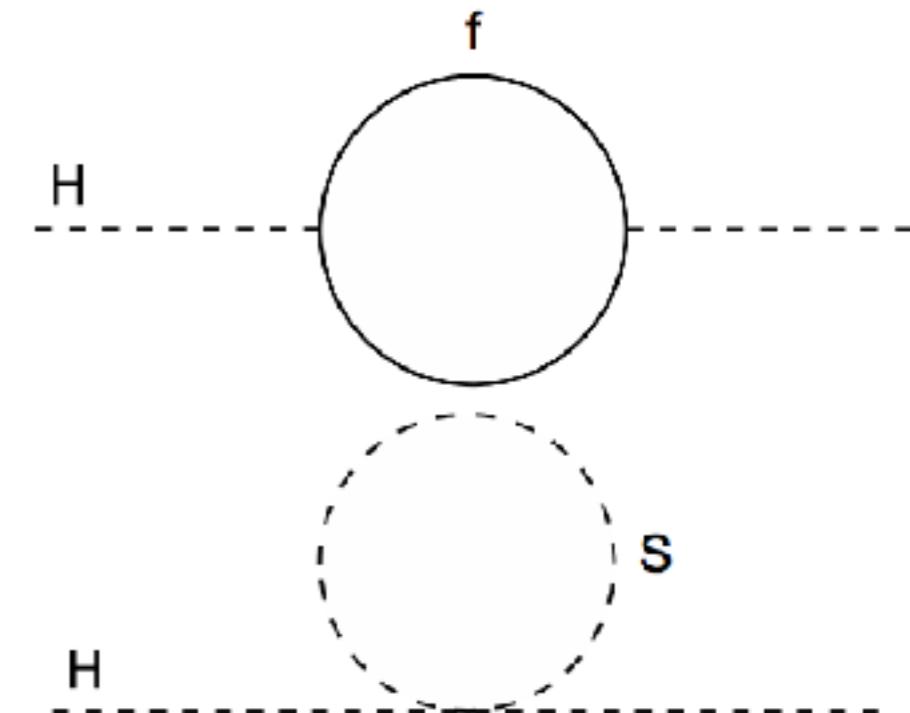
$$m_{h,\text{physical}}^2 \simeq m_h^2 + \frac{C}{16\pi^2} \Lambda^2$$



Analogy only for illustration!

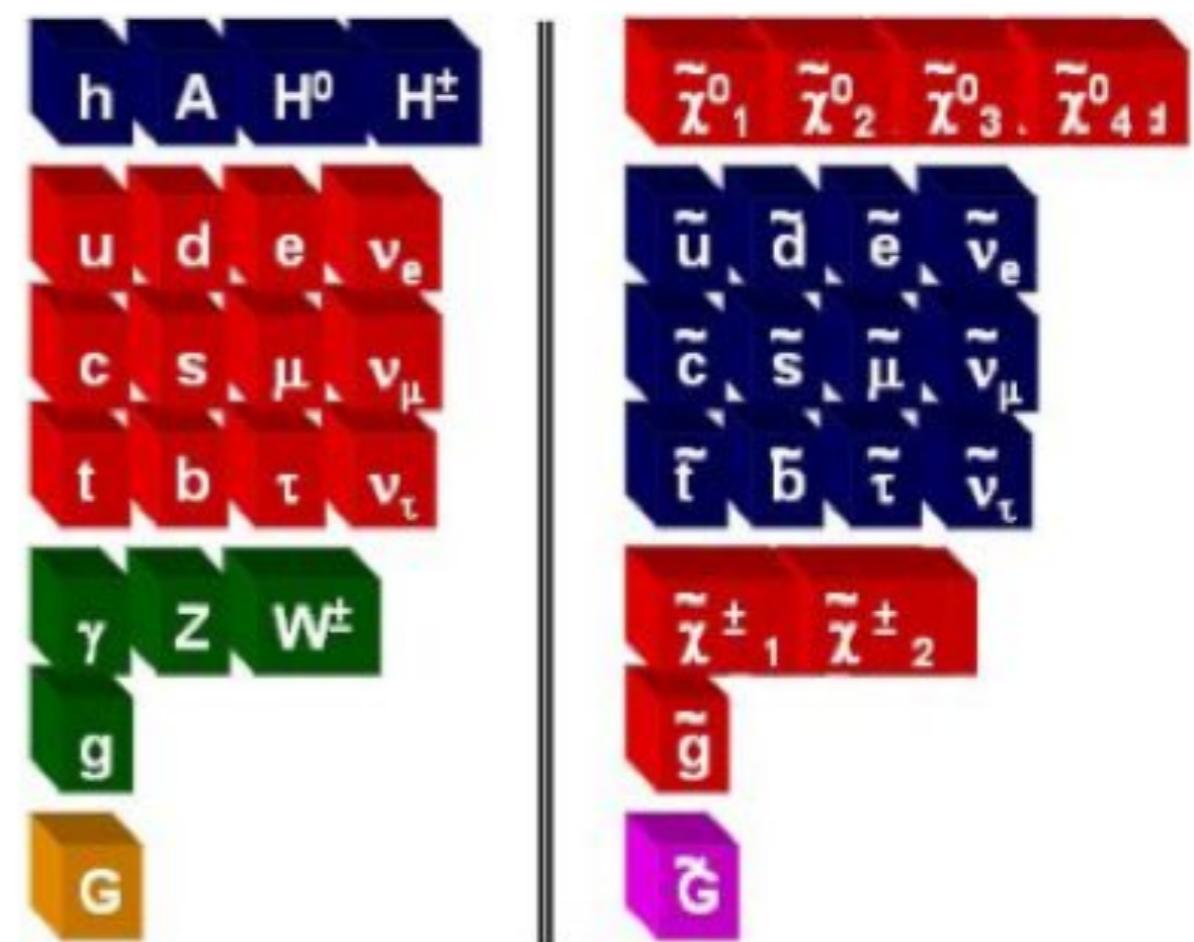
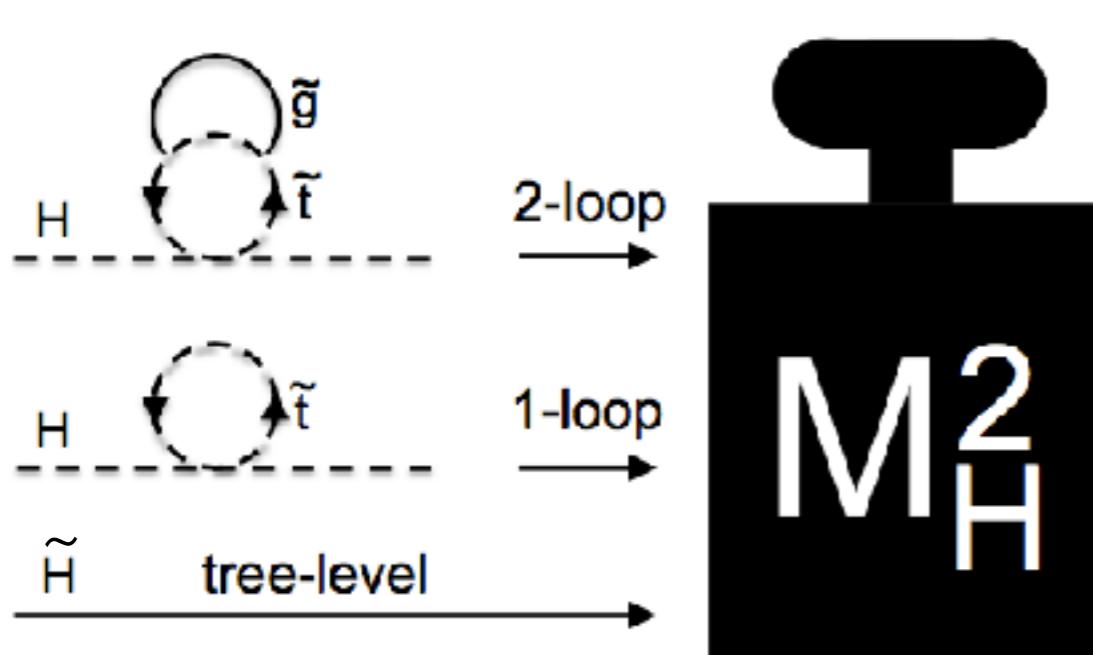
# We need ... Supersymmetry (SUSY)!

- **Fundamental symmetry** between **fermions** and **bosons** introducing a set of new partner particles to the SM particles with half-spin difference
- ✓ Opposite-sign loop corrections from SUSY particles → **Quadratic divergences cancel**
- ✓ If R-parity conserved: Lightest SUSY Particle (LSP) stable  
→ Good candidate for dark matter
- ✓ **Unification** of gauge couplings at  $M_{\text{GUT}} \sim 10^{16} \text{ GeV}$



# Not any SUSY

- No SUSY particles with the same mass as the SM partners
- Stop and gluino masses enter at 1 and 2 loop level into the Higgs mass matrix, the Higgsino mass parameter at tree level
- Search efforts focus around “**Natural SUSY**” with relatively **light gluinos, stops, and higgsinos**
- Remaining SUSY particles can be decoupled at high masses



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# How to do it?

# Our Tools

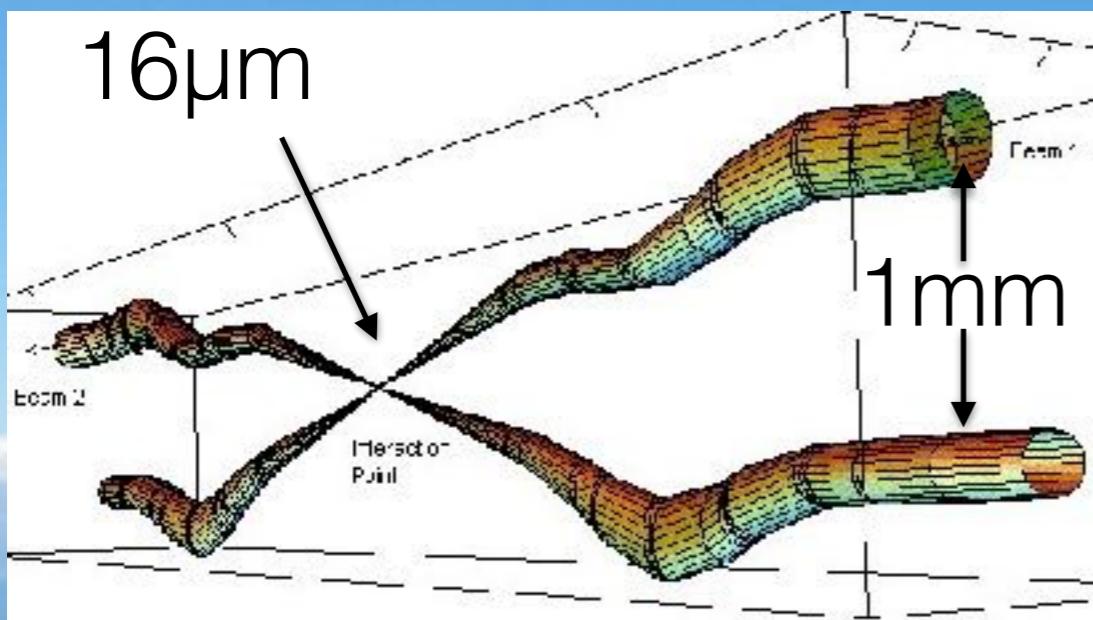
- Large Hadron Collider (**LHC**)
- A Toroidal LHC ApparatuS (**ATLAS**)
- Computing resources (Grid)



# The LHC Accelerator



# The LHC Accelerator



17 miles

Geneva Airport

CMS

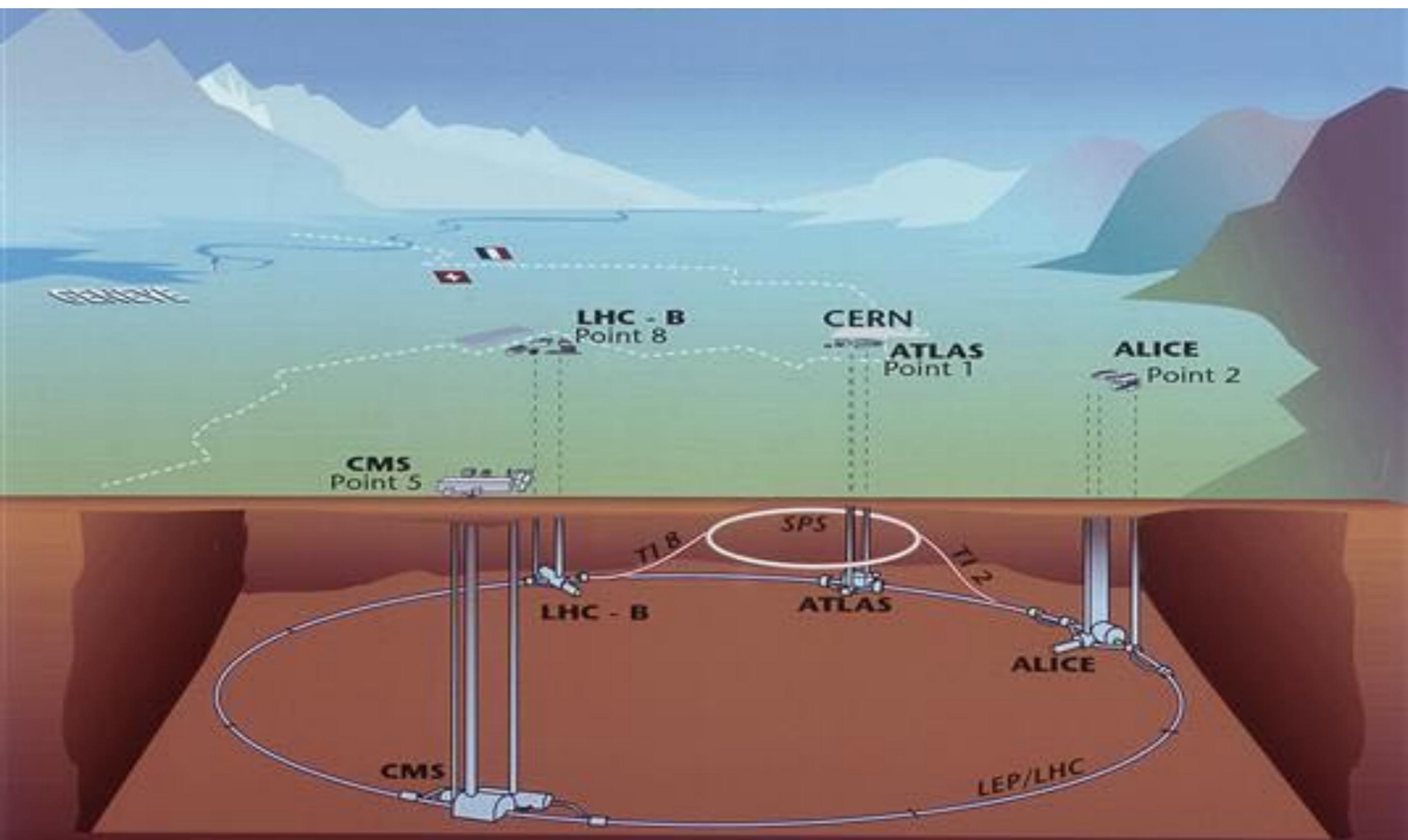
ATLAS

protons

protons

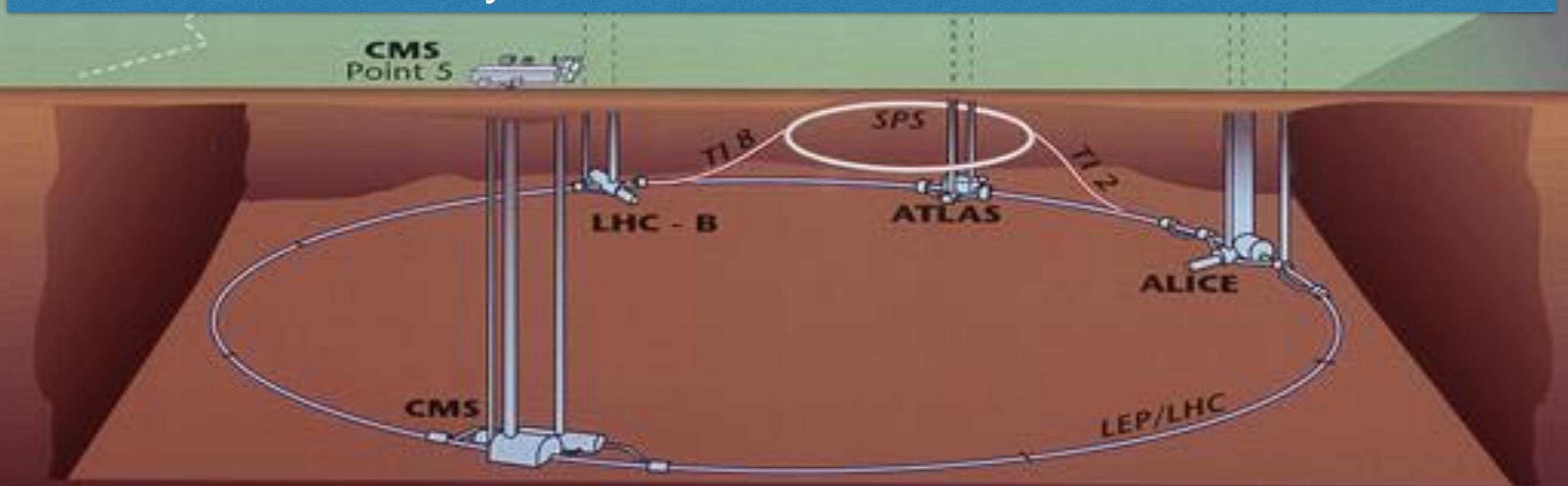


# The LHC Accelerator



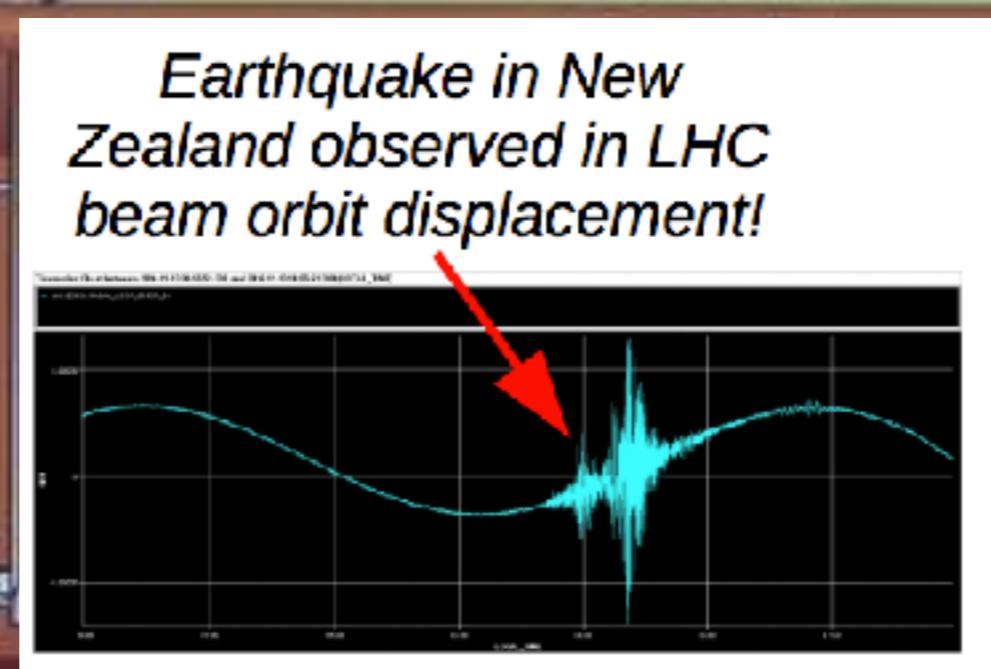
# The LHC Accelerator

- Largest fridge in the world ( $1.9\text{ K} \sim -271\text{ C}$ )
- 300000 billion protons circling 27km 11,245 times/s
- Time with 6 digits, beam dump if 1ms off
- Energy stored in magnet  $\sim$  A380 of 560 t at 700 km/h
- Total budget  $\sim$  10 billion dollars
- Tidal variations by  $\sim 1\text{ mm}$

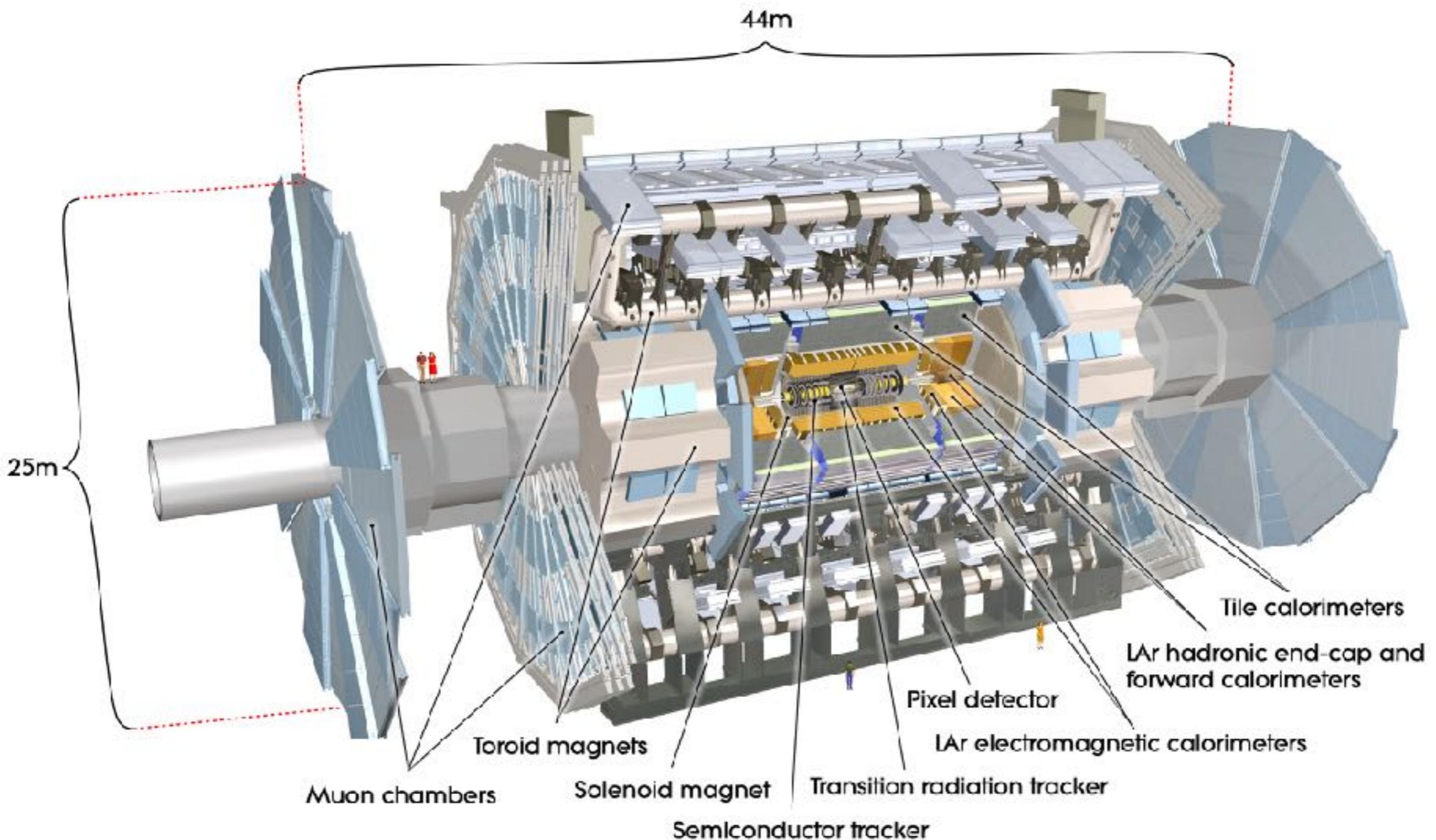


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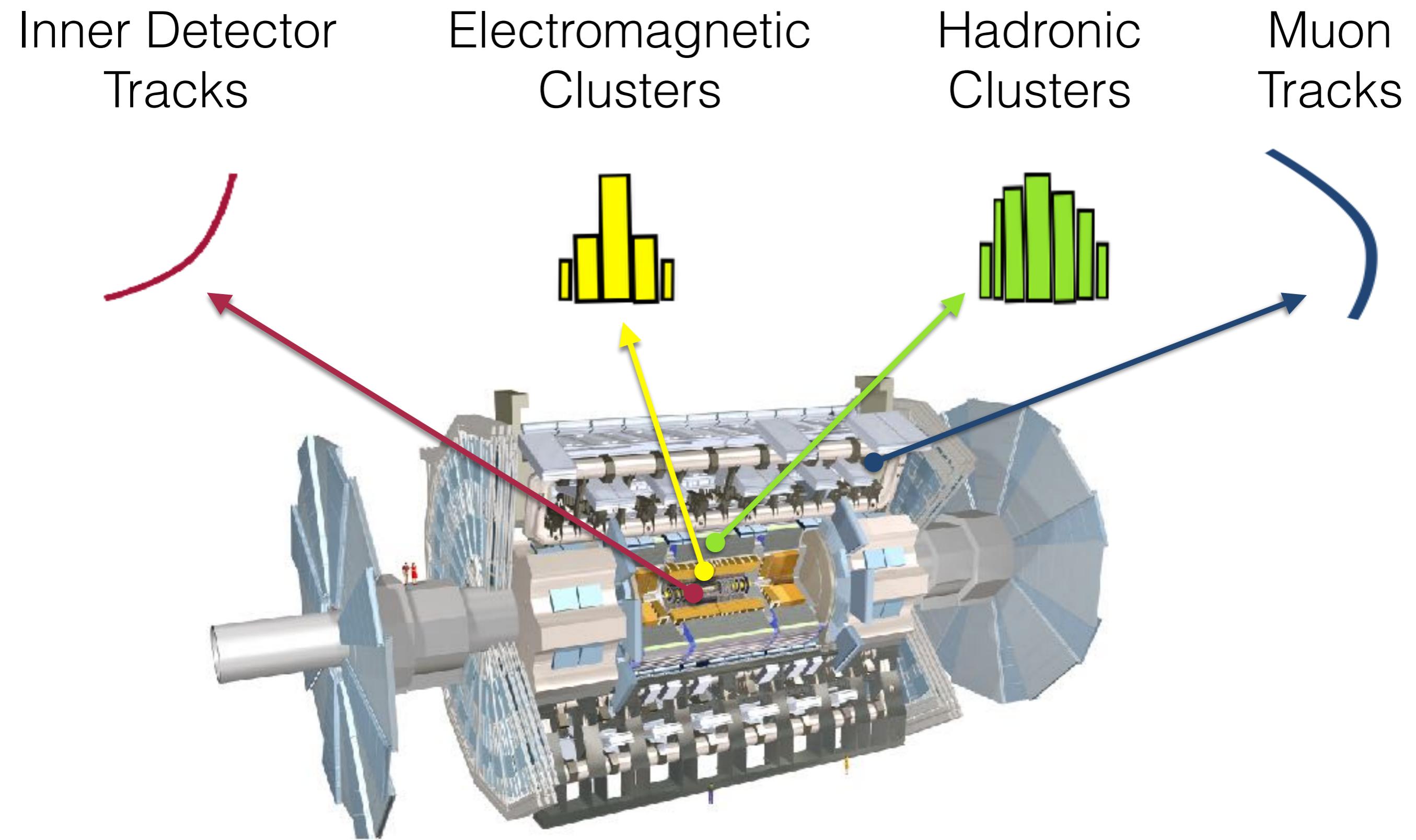
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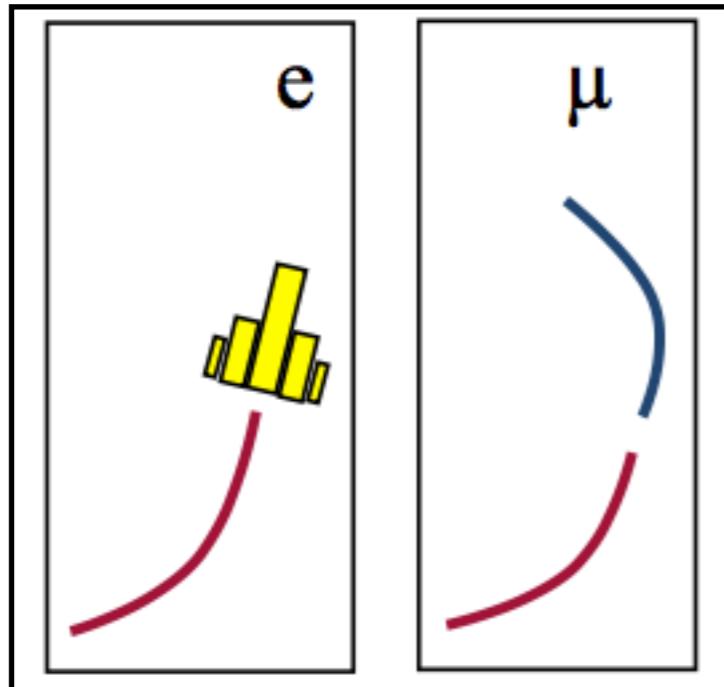
# ATLAS



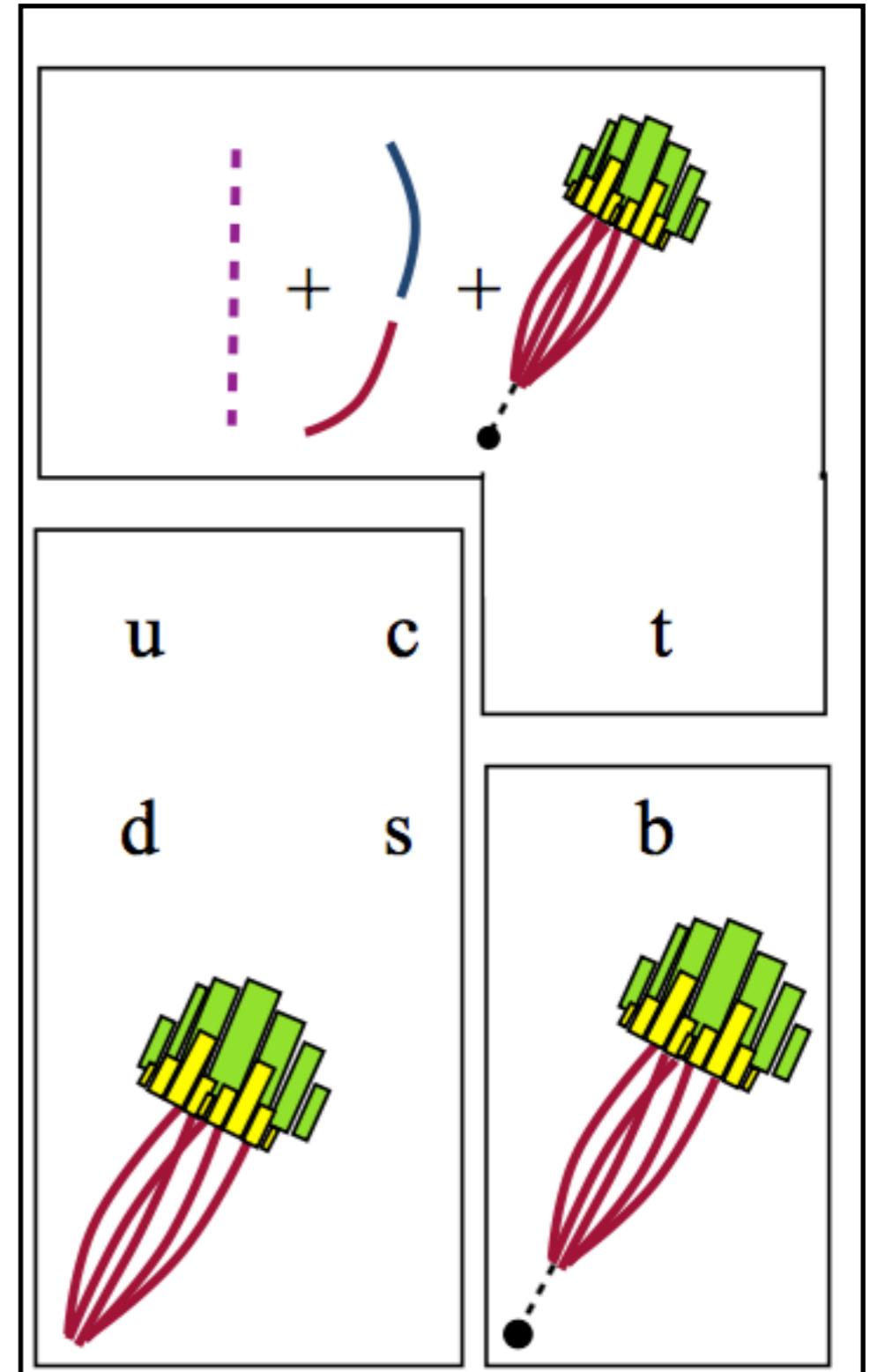
# Detector Outputs



# Identifying Particles



A lot of effort goes in the algorithms that identify these particles



# Data Challenge

40 million beam crossing/s



1 billion p-p/s



1000 p-p/s

# Data Challenge

40 million beam crossing/s

1 billion p-p/s

1000 p-p/s

**Rejection  $10^6$   
in real time**

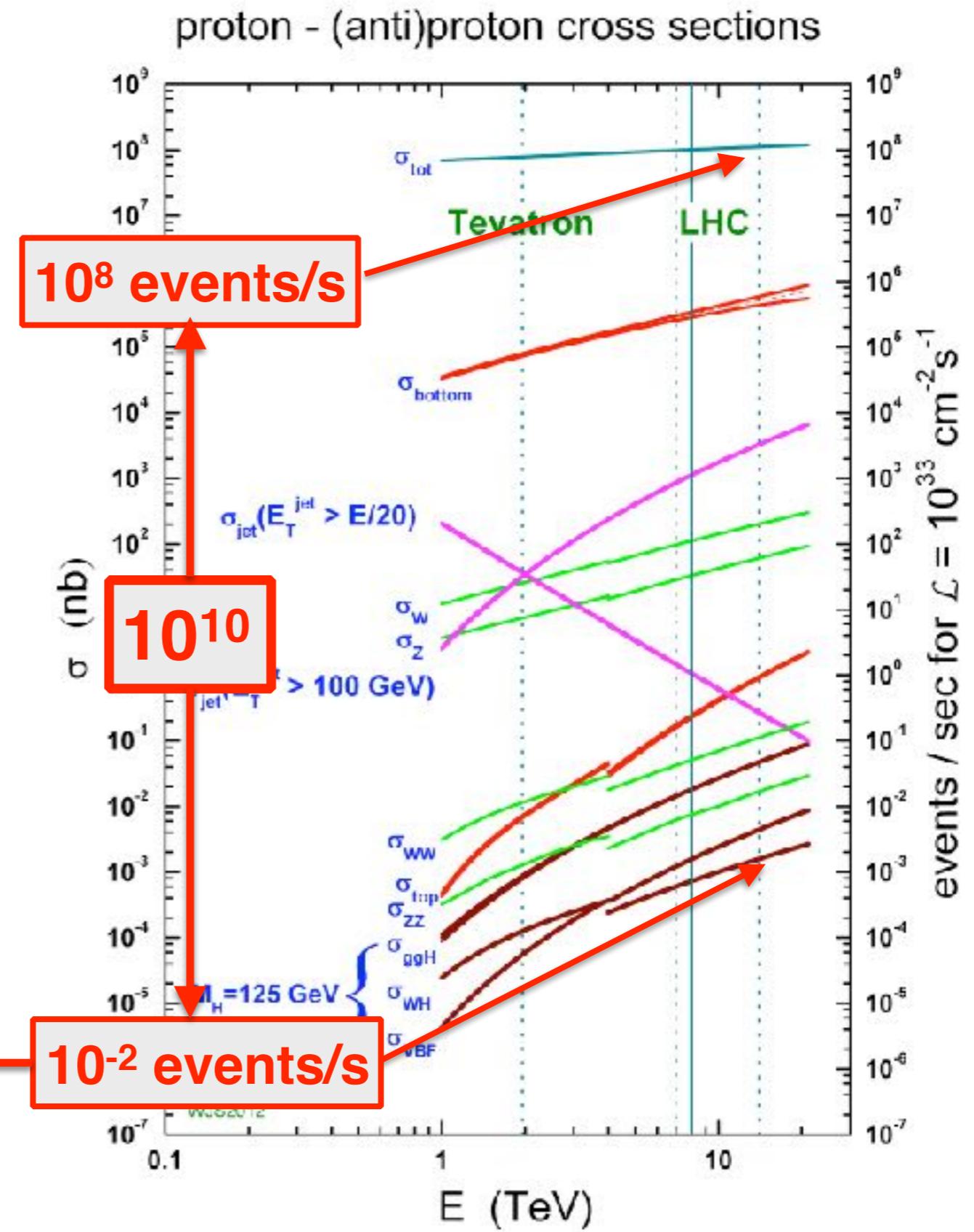
# Data Challenge

40 million beam crossing/s

1 h  
10<sup>6</sup> p/p/s  
**Rejection 10<sup>6</sup>**

1000 p-p/s

Higgs to 4l 1 in 10<sup>12</sup> p-p



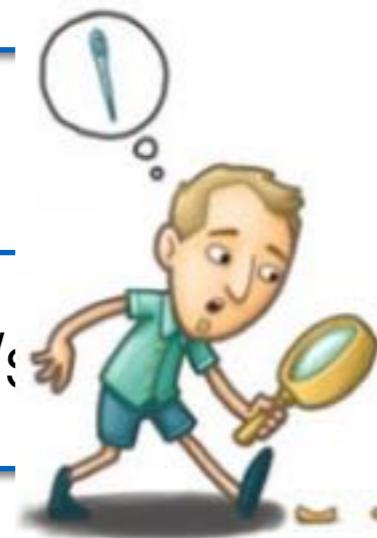
# Data Challenge

40 million beam crossings/s

SUSY signals are even more rare!

Rejected

1000 p-p/s



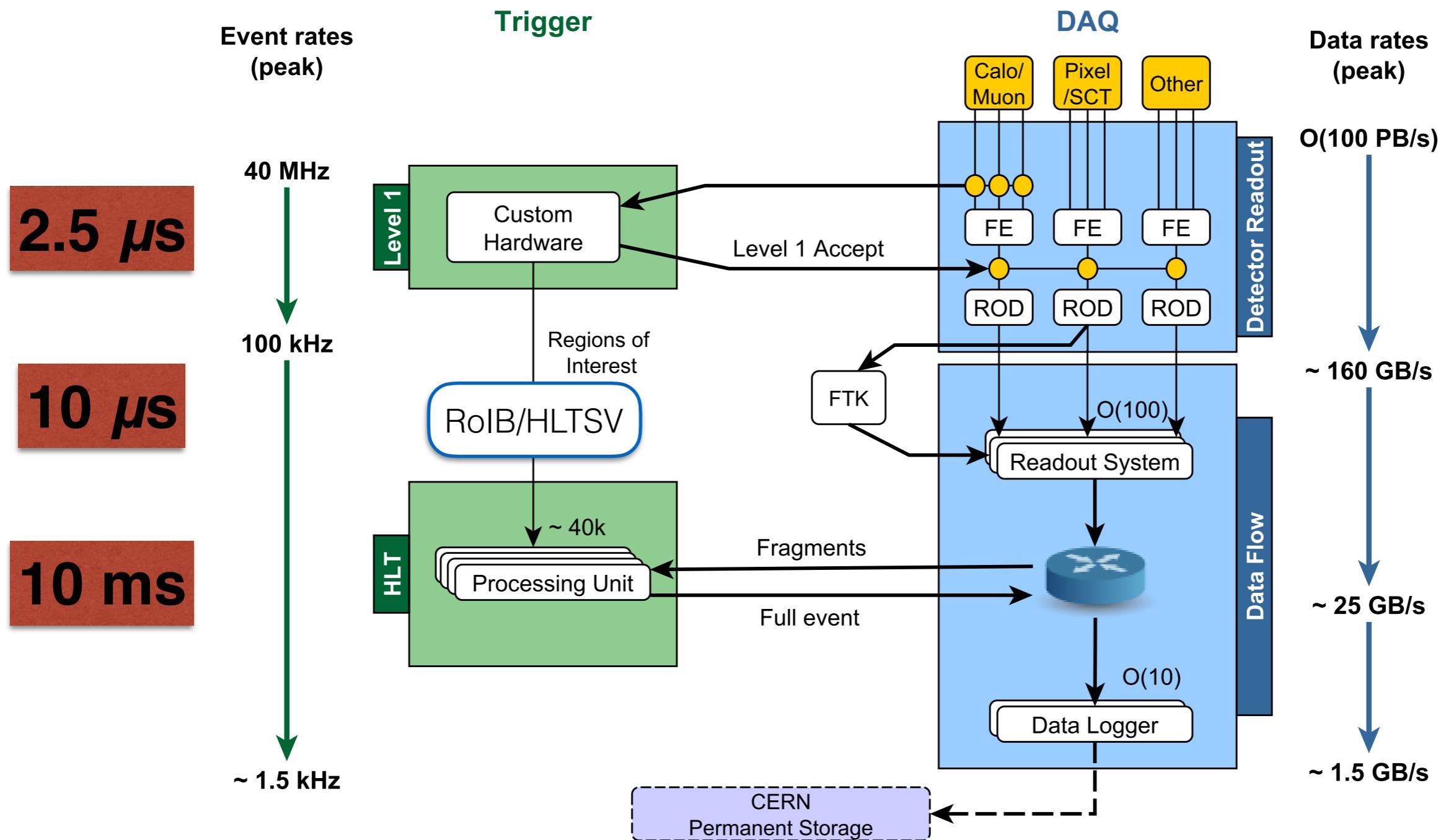
Higgs to 4l 1 in  $10^{12}$  p-p

**10<sup>-2</sup> events/s**

proton - (anti)proton cross sections



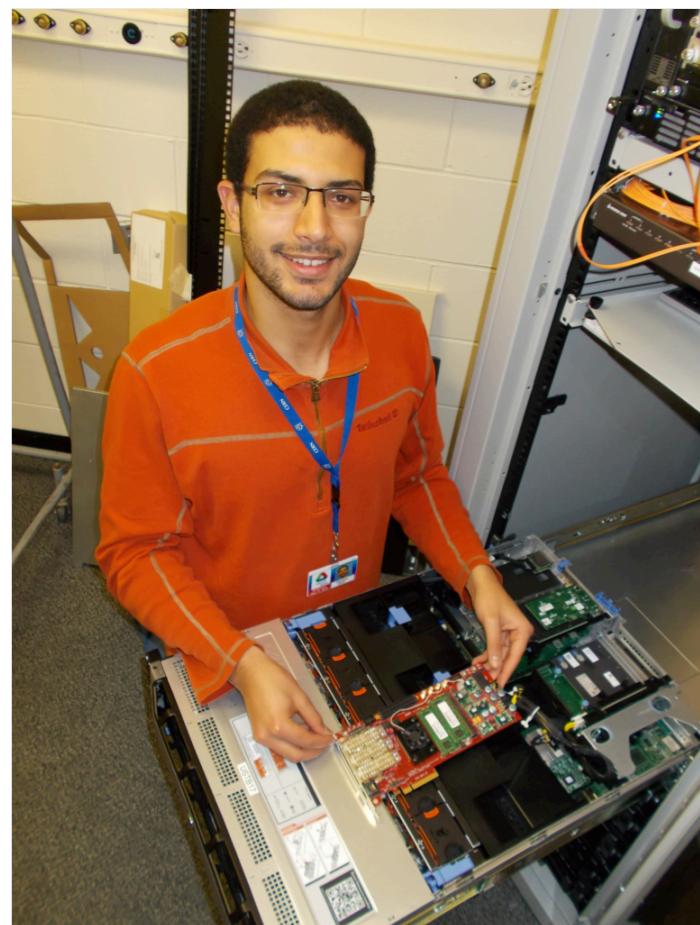
# Trigger and Data Acquisition



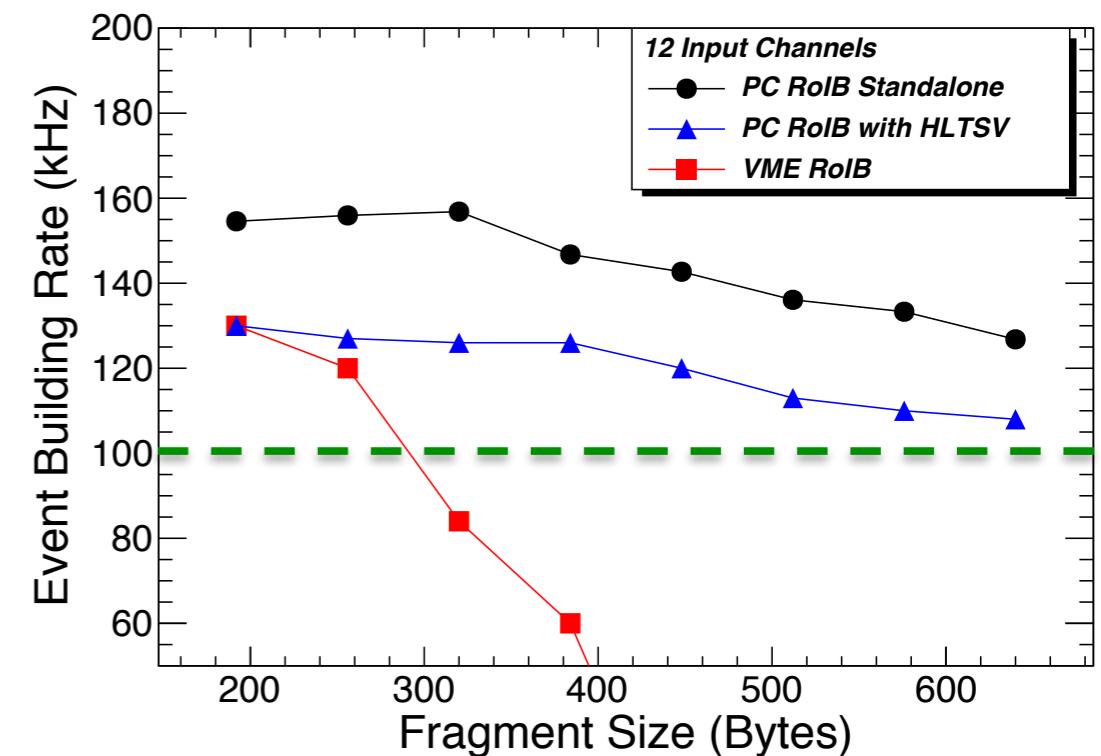
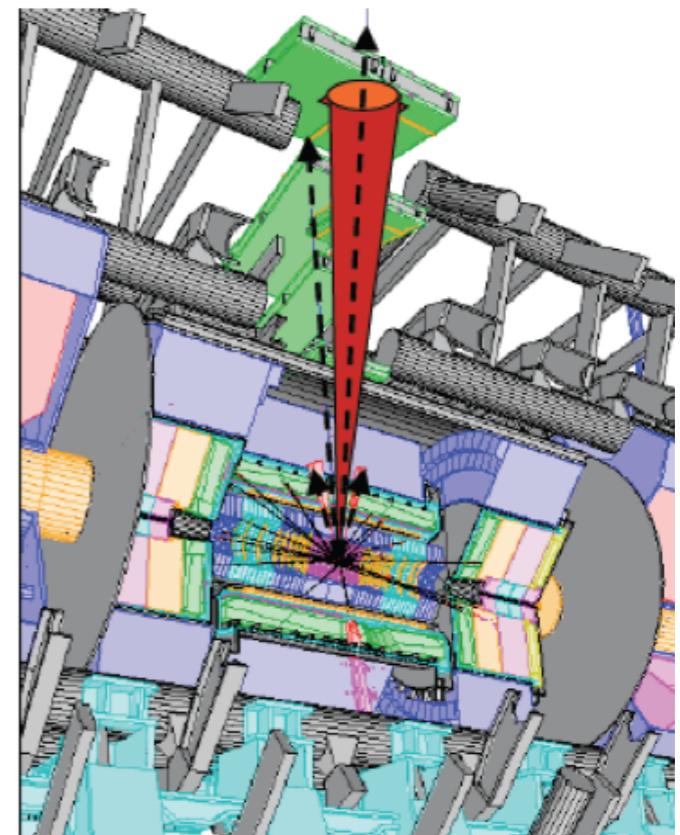
# Region of Interest Builder

Every event recorded by ATLAS is processed by the RoIB

Argonne



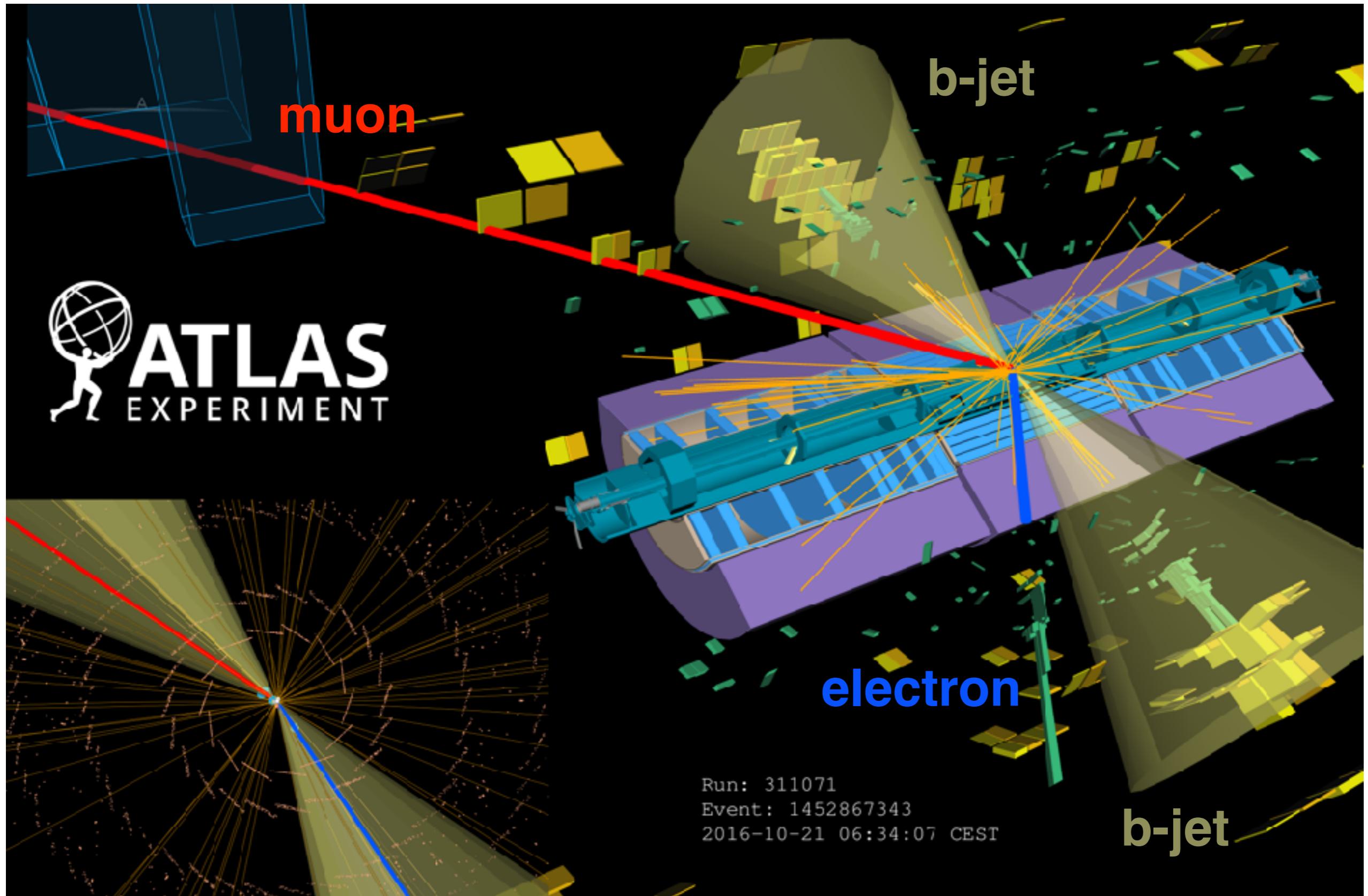
CERN



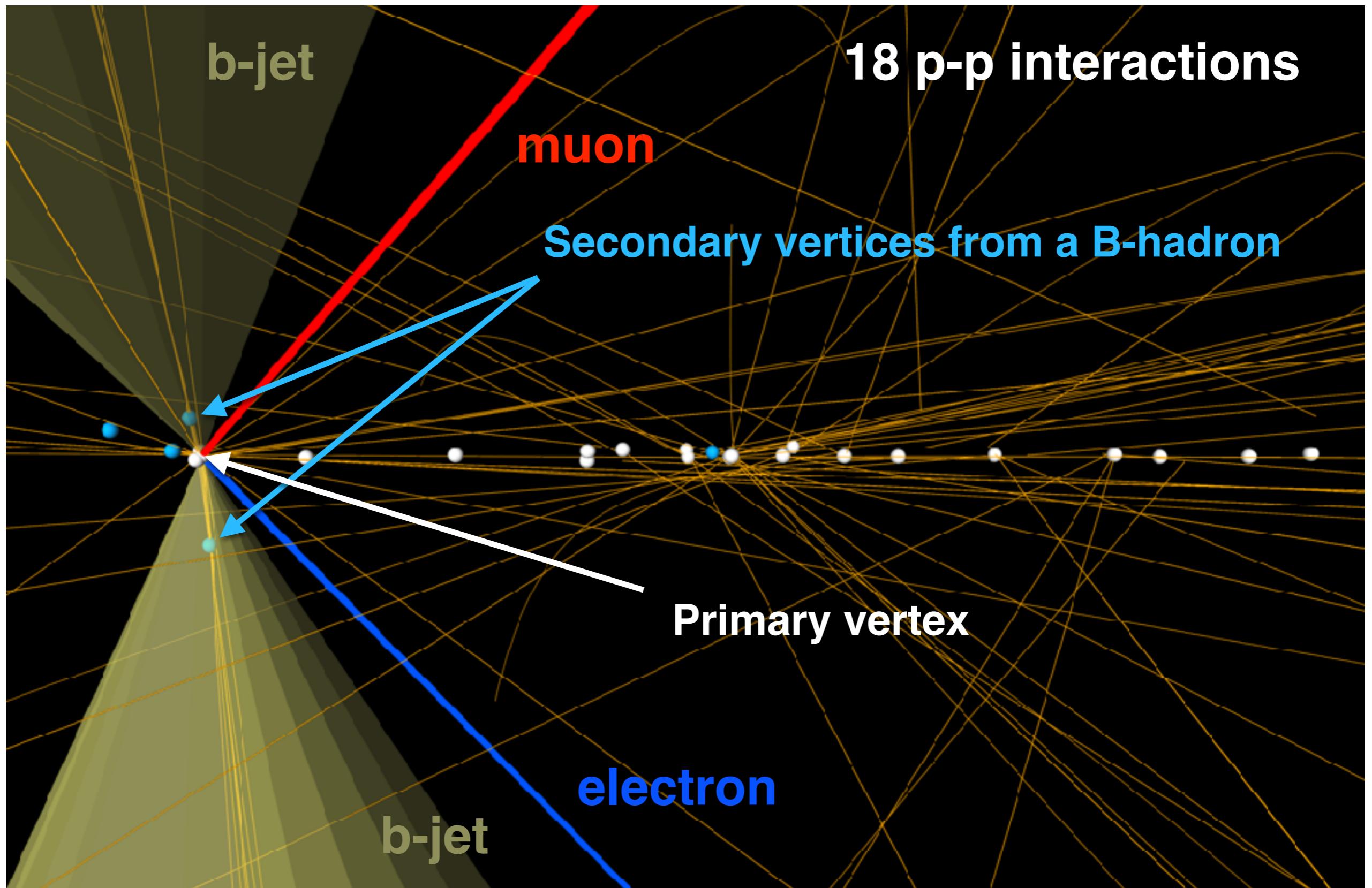
# ATLAS Control Room



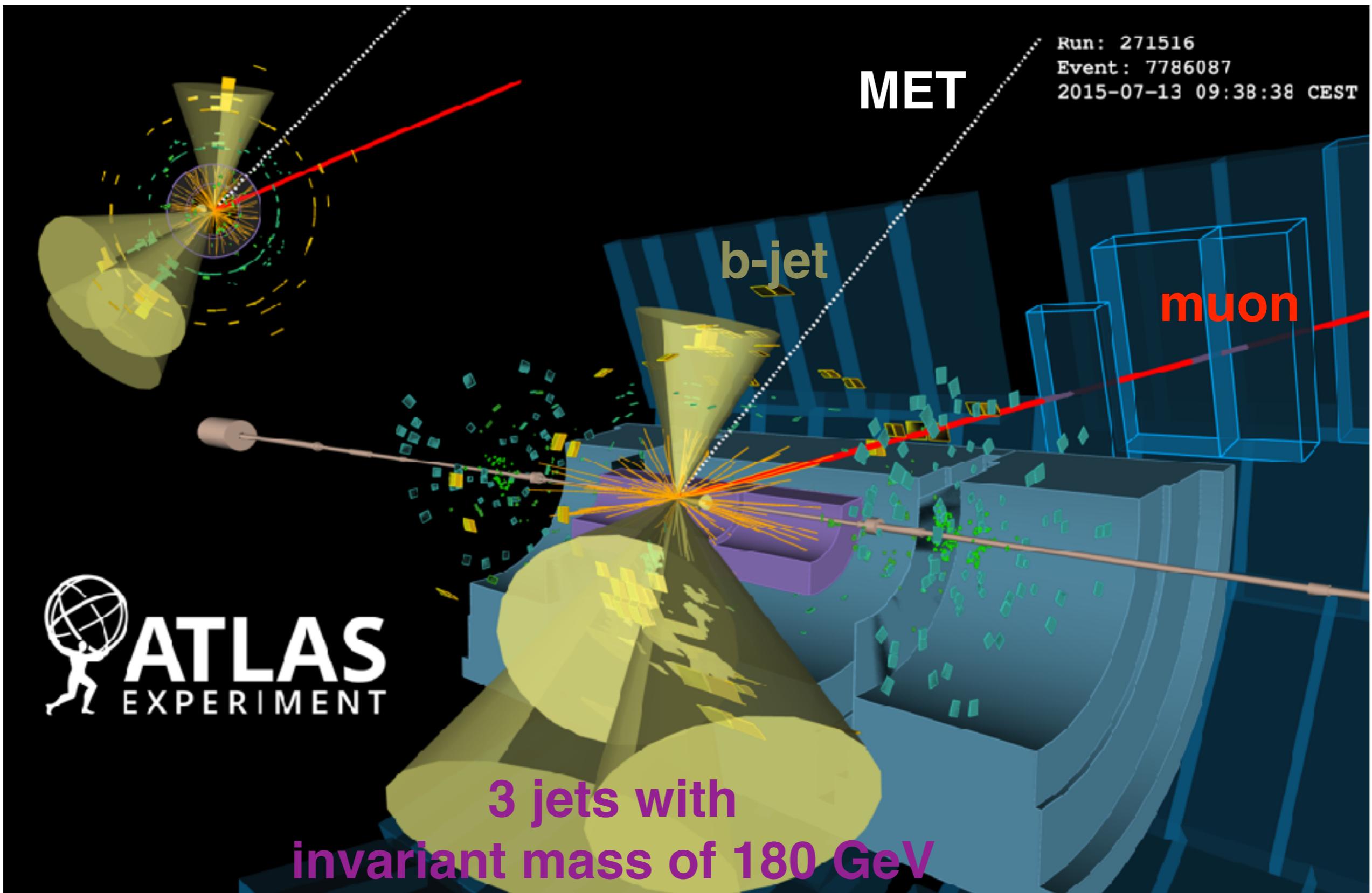
# Top anti-top candidate 1



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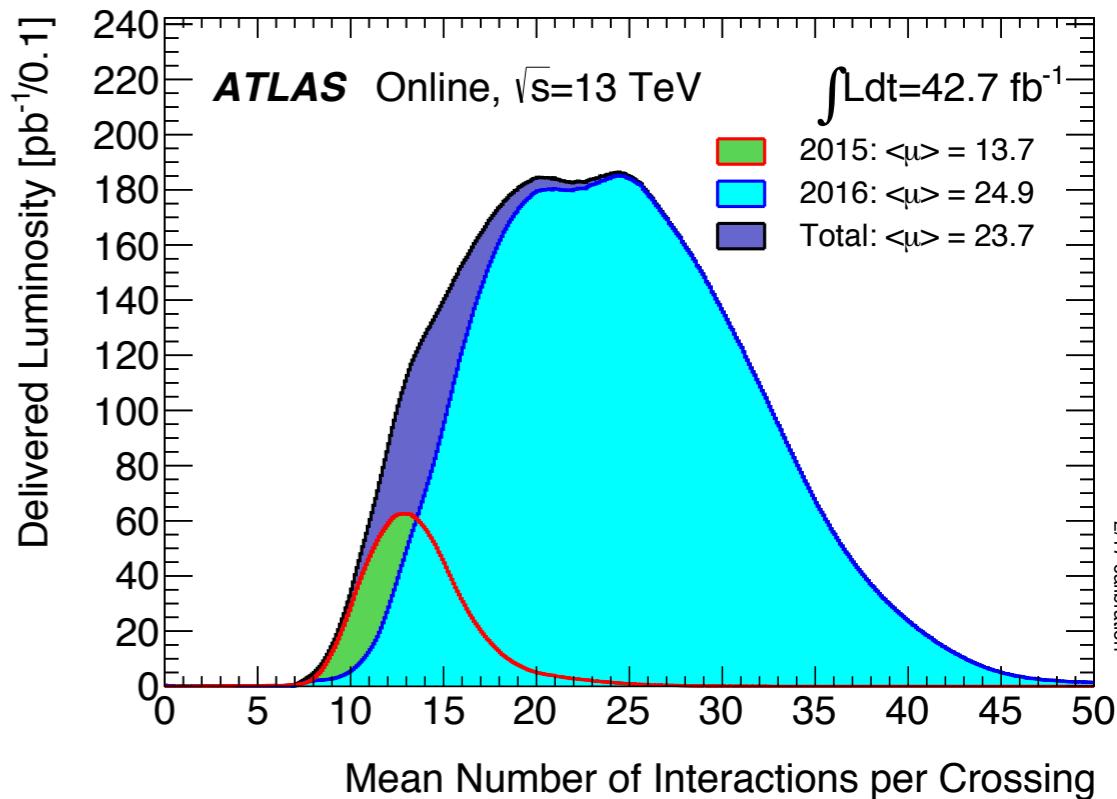
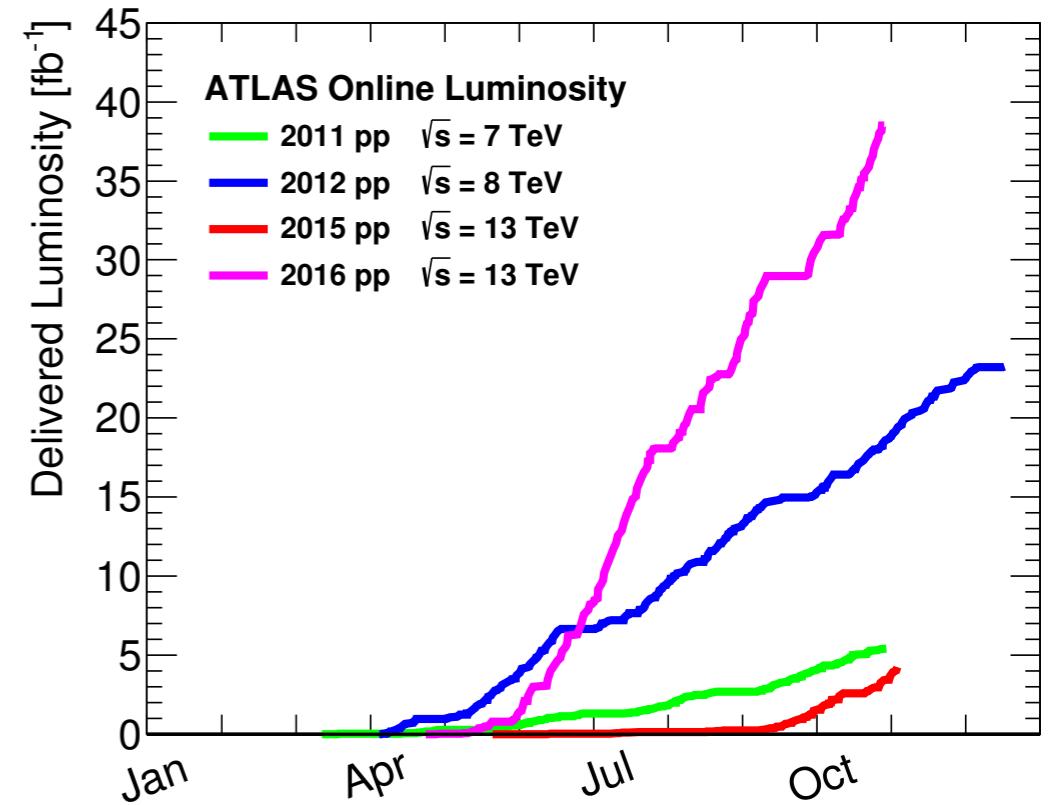


# Top anti-top candidate 2

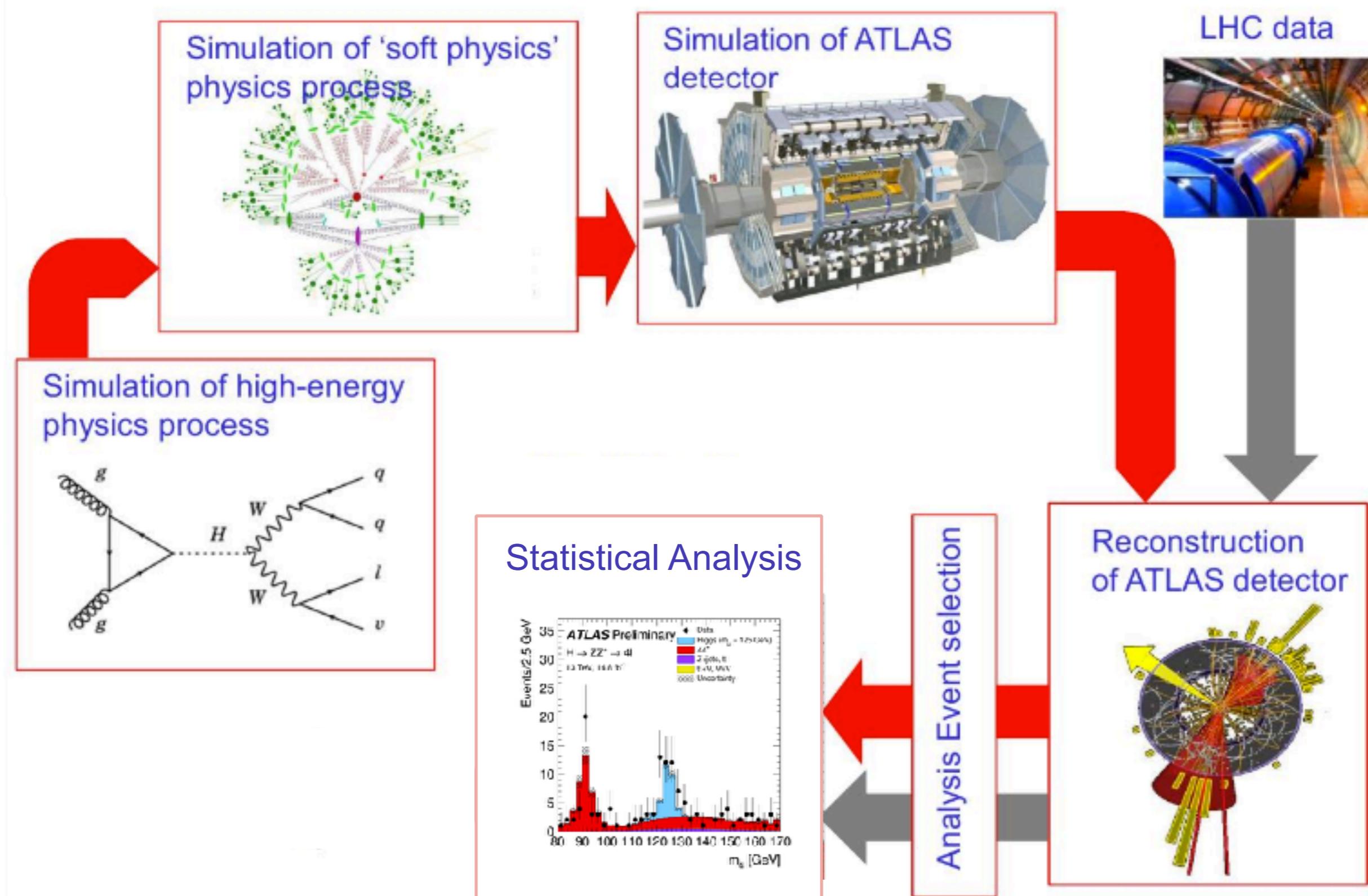


# Data-taking 2015/2016

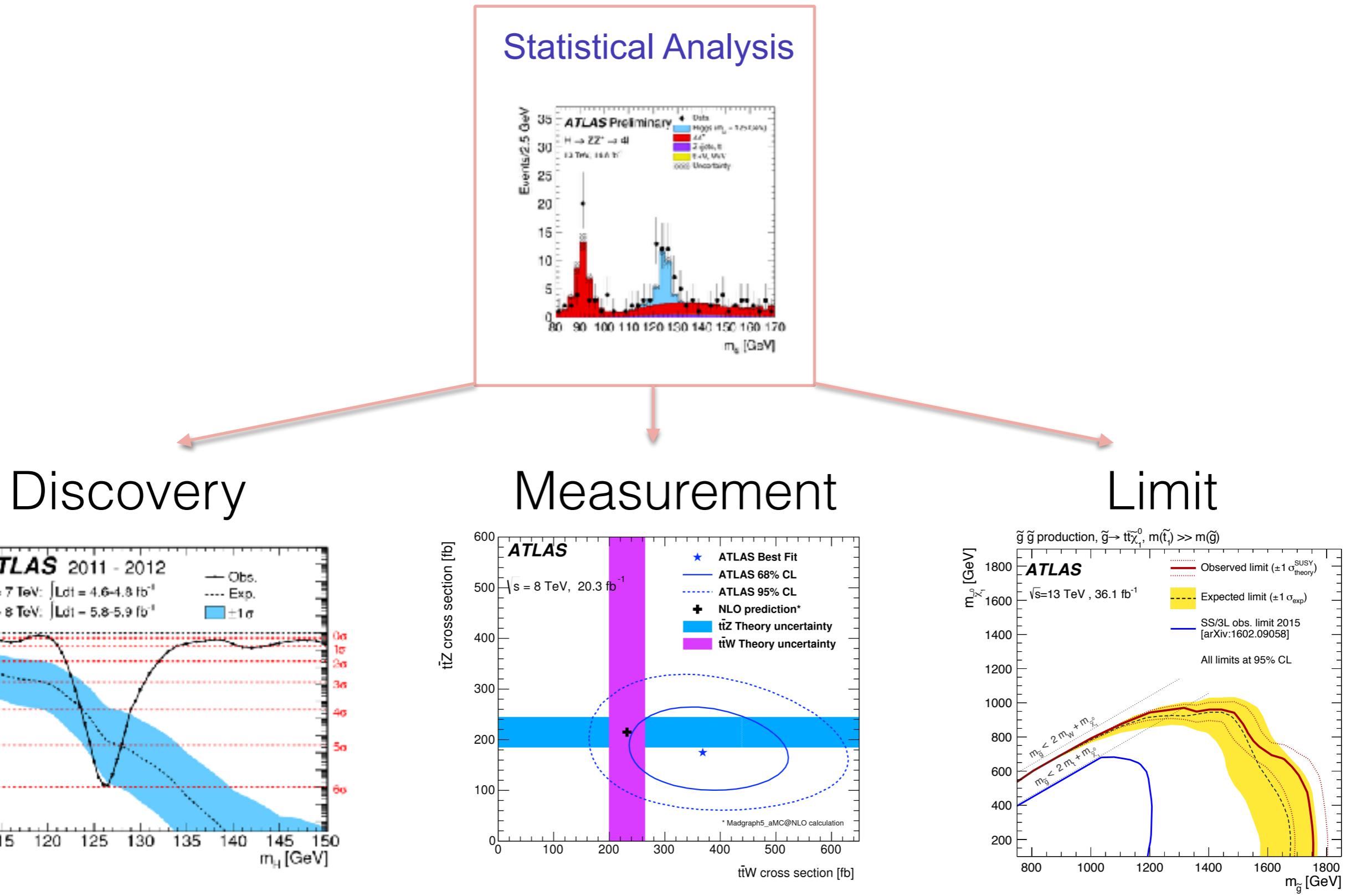
- Record performance of the LHC in 2016:
  - **1680 hours** of **13 TeV** stable beams data-taking
  - Peak luminosity of  **$1.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$**  40% higher than design
  - Pile-up of **50** interactions per crossing
- Excellent Run-2 data-taking campaign for ATLAS:
  - **$3.9 \text{ fb}^{-1} + 35.6 \text{ fb}^{-1}$**  recorded in 2015 + 2016
  - In total  **$36.1 \text{ fb}^{-1}$**  (i.e. 91.4%) good for **SUSY searches!**



# Workflow



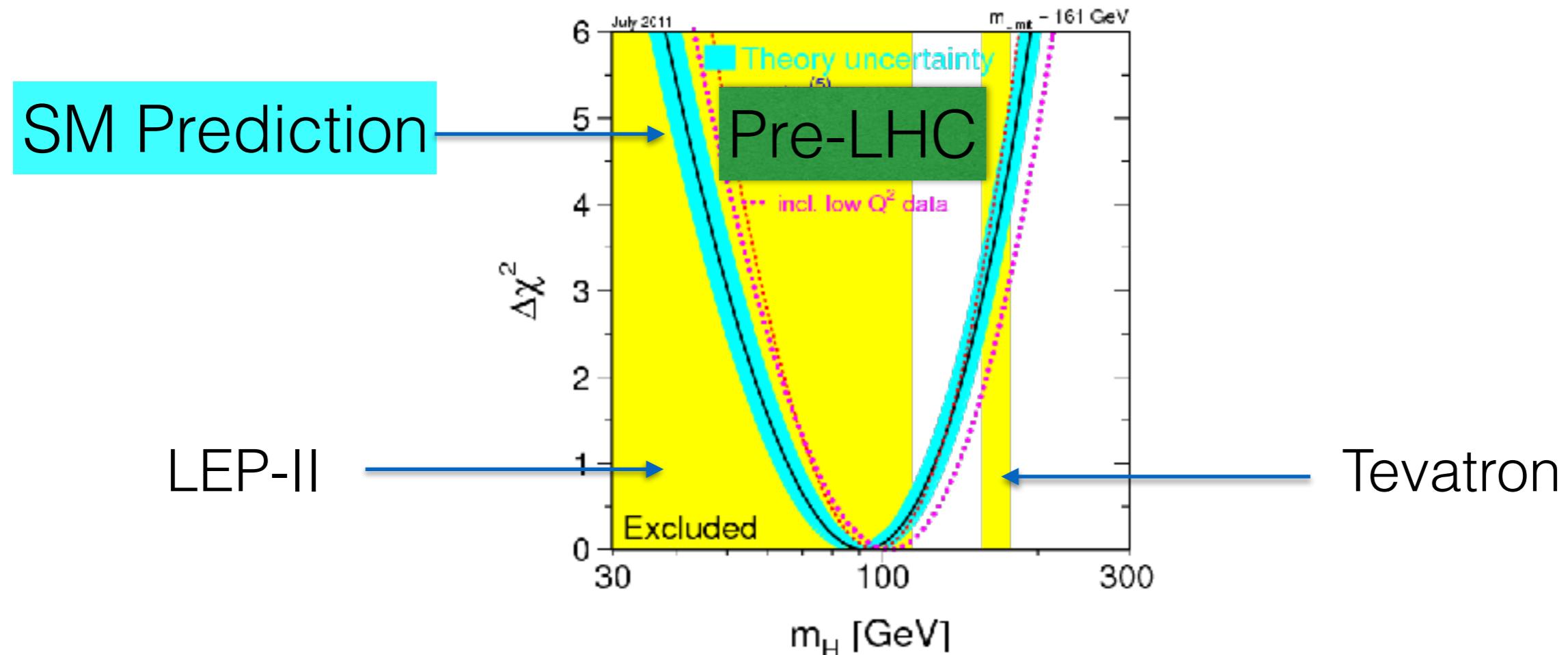
# Workflow



# Where are we at?

# Signals of Discovery

- Discoveries of W, Z, top, and Higgs were anticipated

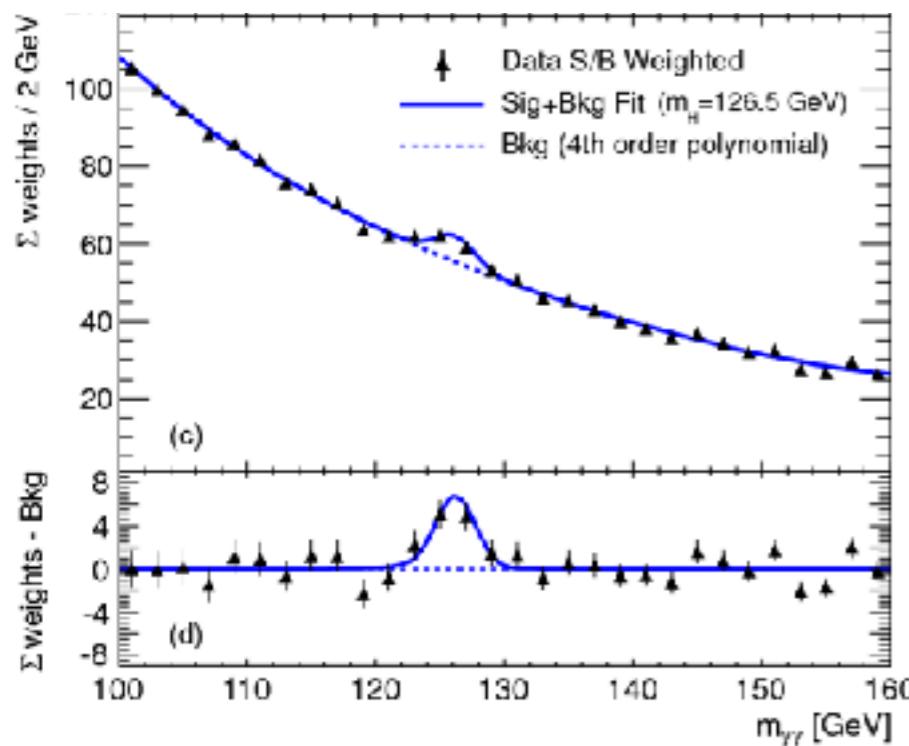


- Today, **we don't know what/where the unknown physics is**
- Discovery will most likely follow two steps:
  - Establish a deviation from the SM
  - Understand what this deviation corresponds to

# Signals of Discovery

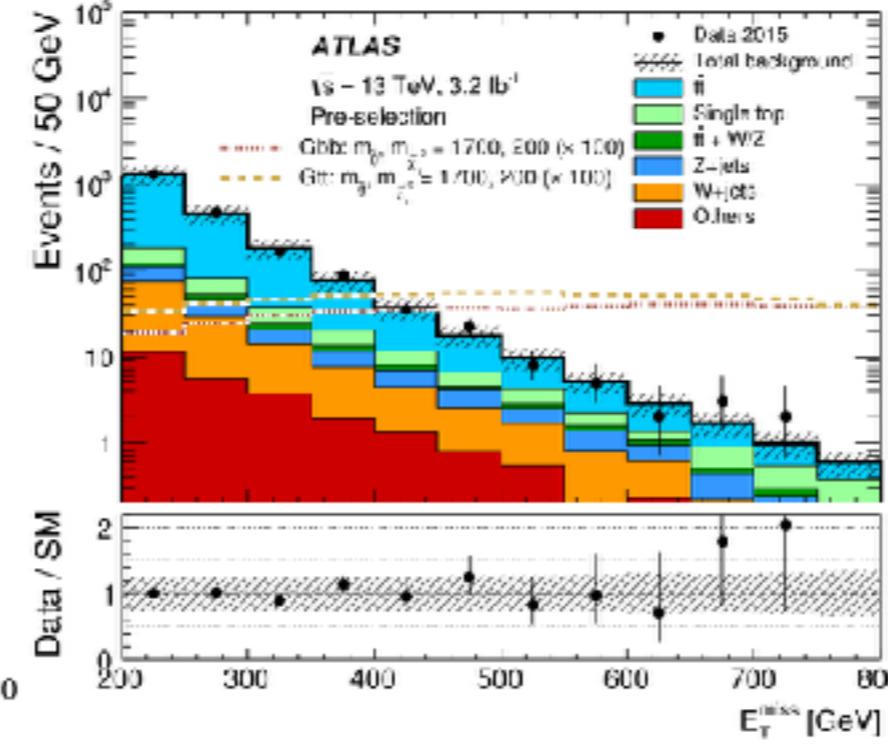
In hadron colliders, deviations in roughly three categories:

Mass Peak



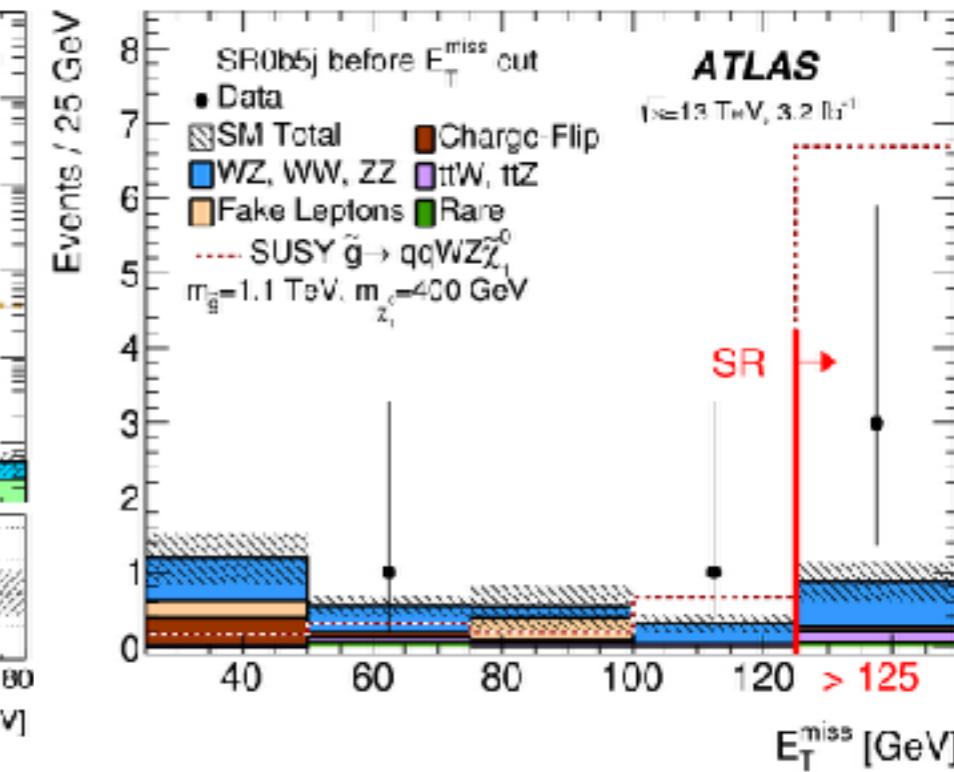
Most robust  
signature

Shape Discrepancies



Requires careful background  
estimation

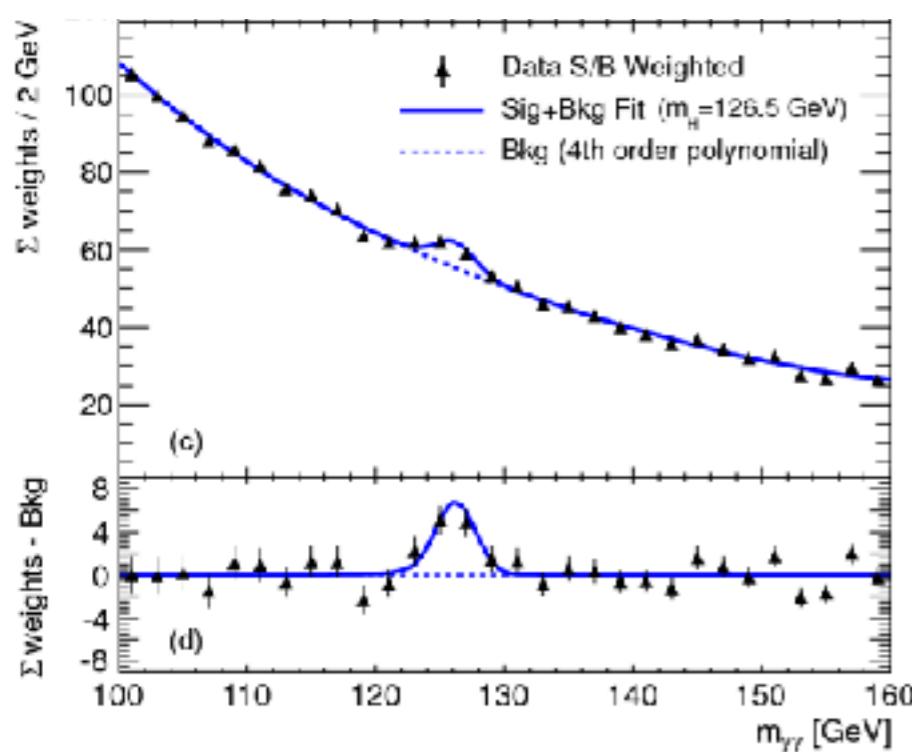
Counting experiment



# Signals of Discovery

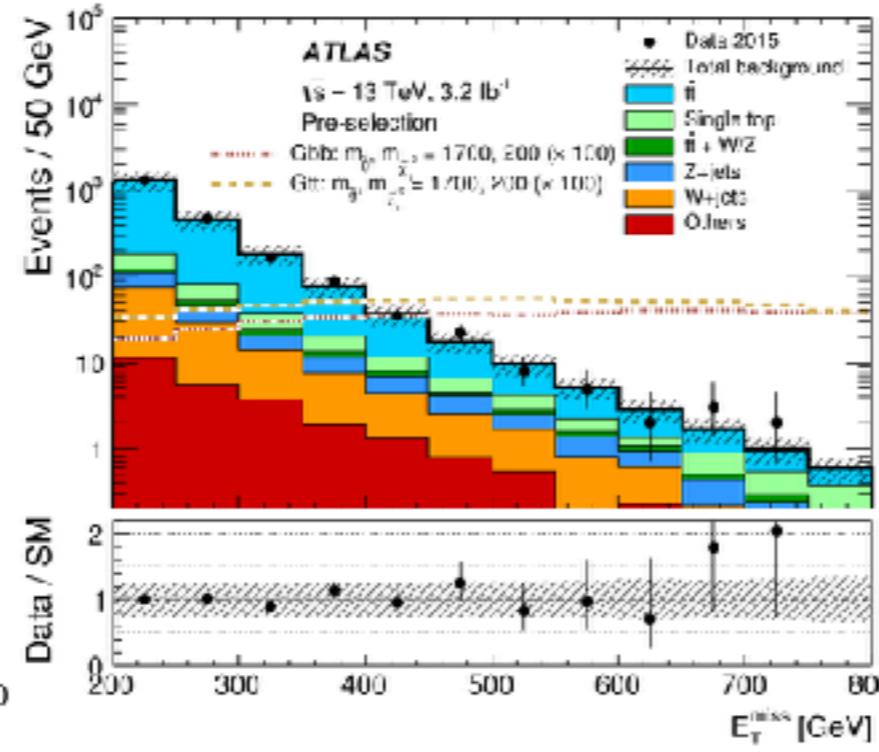
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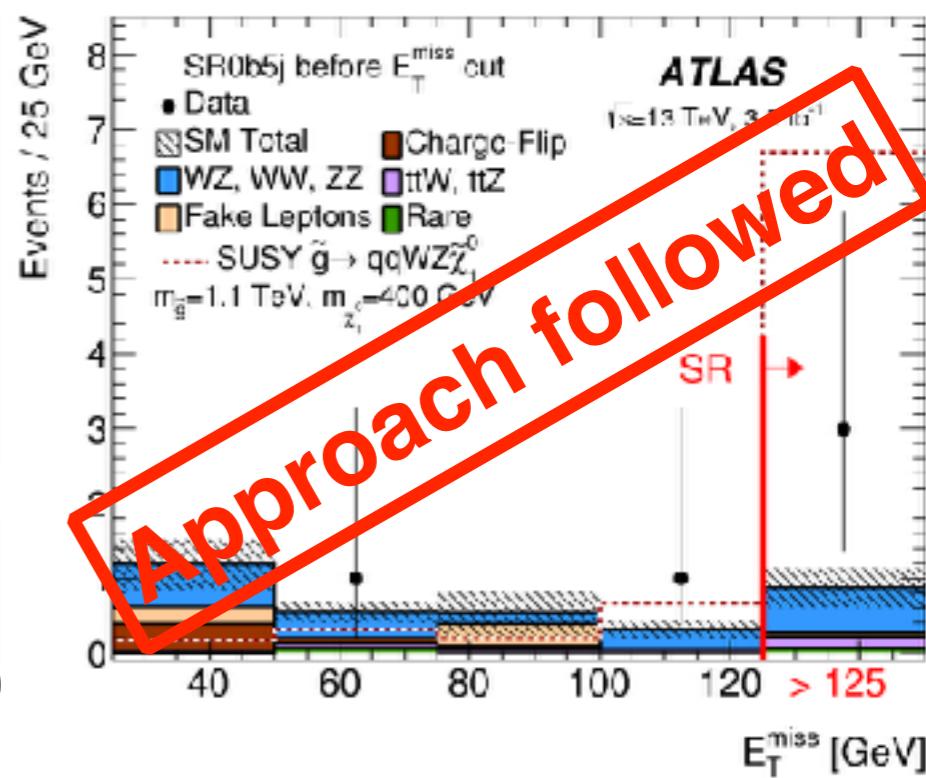
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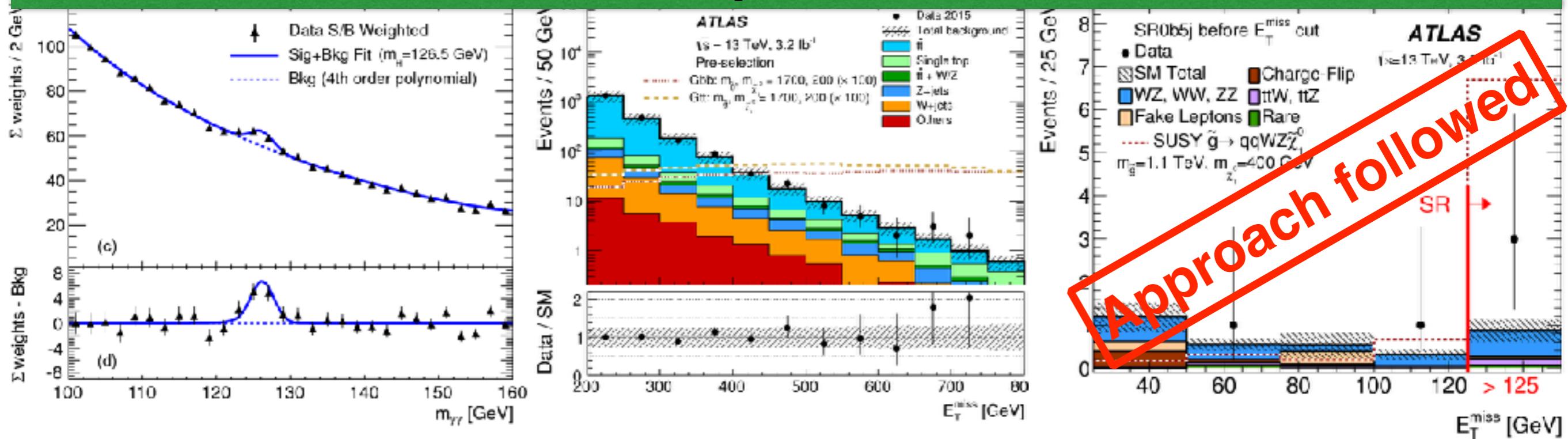


Approach followed

# Signals of Discovery

In hadron colliders, possible deviations in roughly three categories:

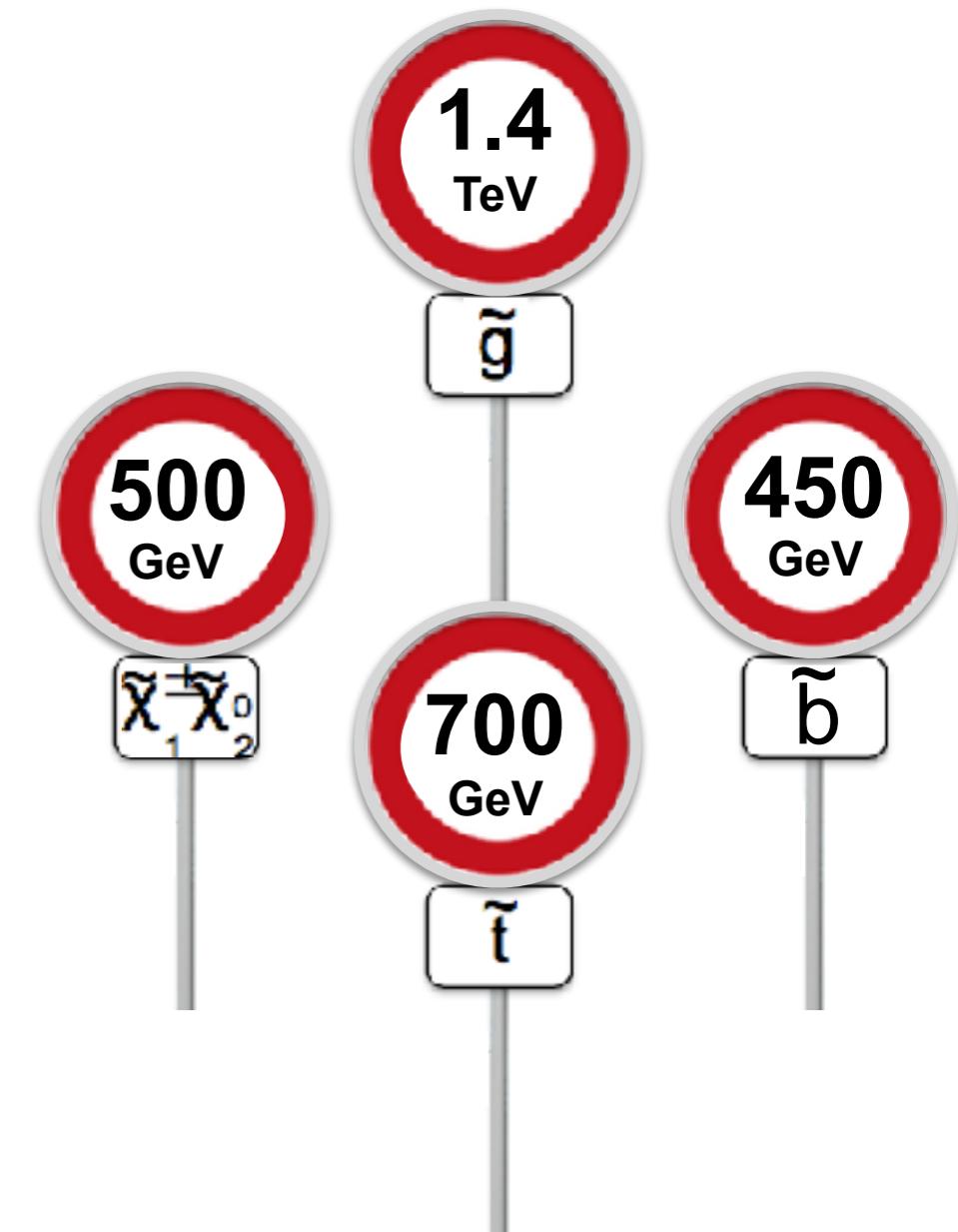
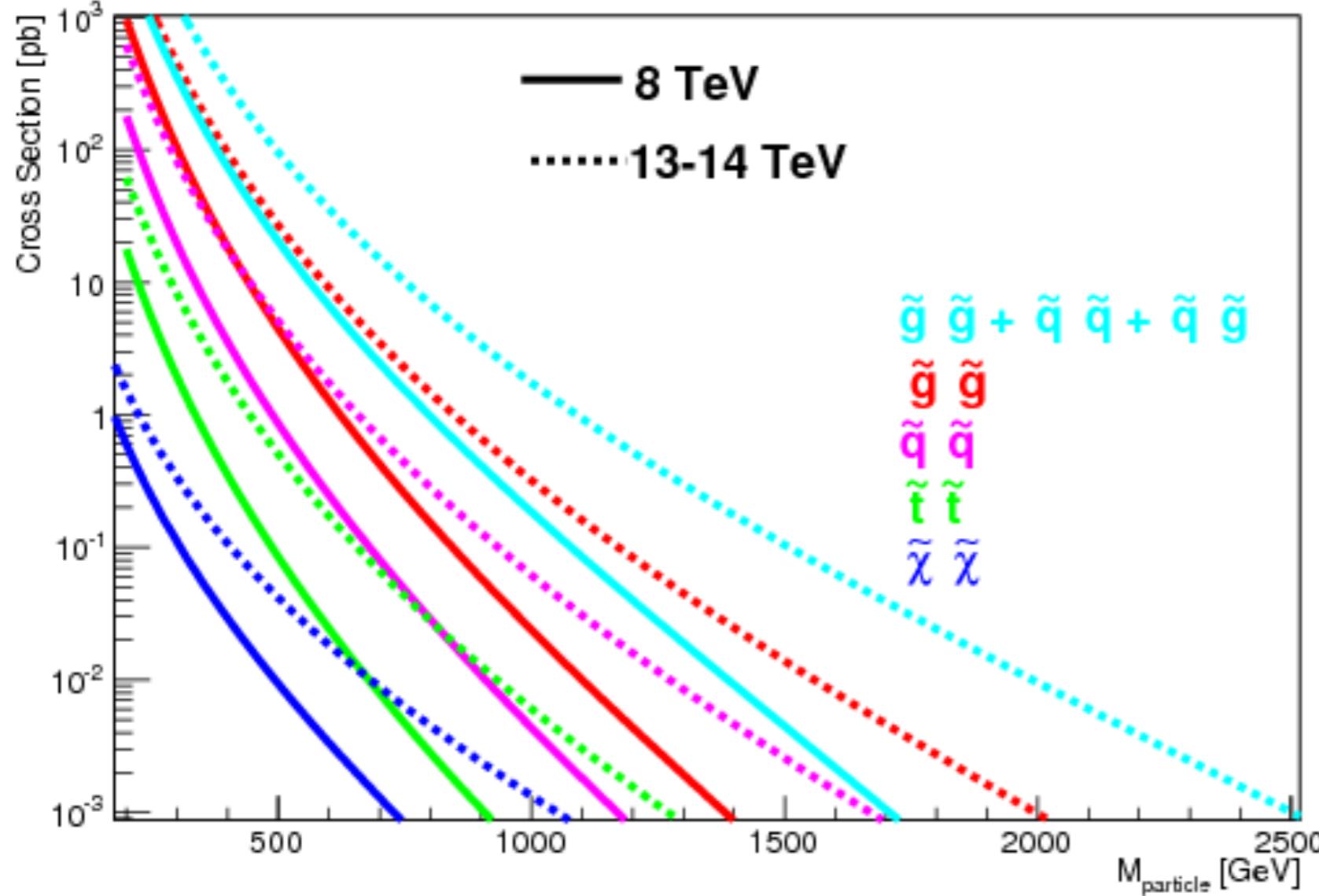
**Claim of discovery is too important to just trust the Monte Carlo prediction**



Most robust  
signature

Requires careful background  
estimation

# Run-1 at 8 TeV status



# Run-2 at 13 TeV starts...



# Search for Supersymmetry

arXiv:1706.03731v2 [hep-ex] 13 Jun 2017

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

 **ATLAS**  
EXPERIMENT

Submitted to: JHEP

 CERN  
CERN-EP-2017-108  
14th June 2017

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**Search for supersymmetry in final states with two same-sign or three leptons and jets using  $36 \text{ fb}^{-1}$  of  $\sqrt{s} = 13 \text{ TeV}$   $pp$  collision data with the ATLAS detector**

The ATLAS Collaboration

A search for strongly produced supersymmetric particles using signatures involving multiple energetic jets and either two isolated same-sign leptons ( $e$  or  $\mu$ ), or at least three isolated leptons, is presented. The analysis relies on the identification of  $b$ -jets and high missing transverse momentum to achieve good sensitivity. A data sample of proton-proton collisions at  $\sqrt{s} = 13 \text{ TeV}$  recorded with the ATLAS detector at the Large Hadron Collider in 2015 and 2016, corresponding to a total integrated luminosity of  $36.1 \text{ fb}^{-1}$ , is used for the search. No significant excess over the Standard Model prediction is observed. The results are interpreted in several simplified supersymmetric models featuring  $R$ -parity conservation or  $R$ -parity violation, extending the exclusion limits from previous searches. In models considering gluino pair production, gluino masses are excluded up to  $1.87 \text{ TeV}$  at 95% confidence level. When bottom squarks are pair-produced and decay to a chargino and a top quark, models with bottom squark masses below  $700 \text{ GeV}$  and light neutralinos are excluded at 95% confidence level. In addition, model-independent limits are set on a possible contribution of new phenomena to the signal region yields.

# Analysis Motivation

Search for **strongly produced gluino** and **squark** initiated decay chains with multi-leptons in the final state:

- Majorana gluinos or long cascade decays can give **same-sign lepton pair (SS)** or **three or more leptons (3L)** and jets
- Low SM background: Looser kinematic requirements with high sensitivity to **compressed spectra**
- Evaluated sensitivity to 6 **R-parity conserving** scenarios with 13 search regions
- Explored a novel experimental signature of **three leptons of the same electric charge (3LSS)**

# Analysis Strategy

1. Determine SUSY scenarios
  - Simplified models
  - Realistic models
2. Design search regions
  - Optimize for discovery
3. Estimate the background
  - SM background
  - Detector background
4. Evaluate the uncertainties
  - Statistical uncertainties
  - Experimental uncertainties
  - Theoretical uncertainties
5. Validate the estimates
6. Unblind the search regions

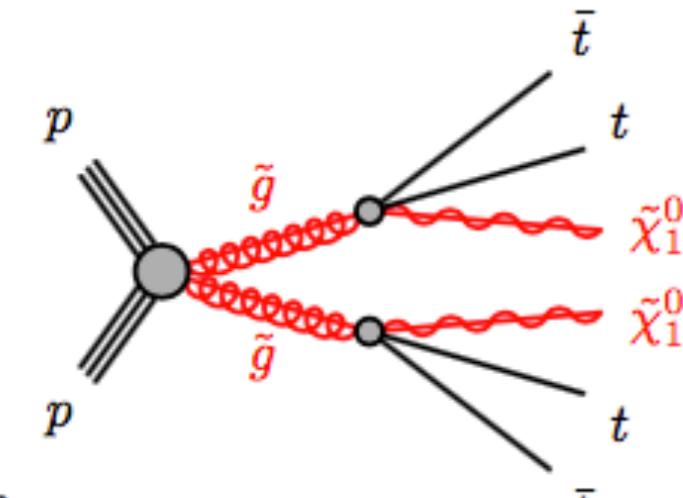
**Deviation:** establish the significance of the excess

**No deviation:** set exclusion limits on signal scenarios

# Simplified Models

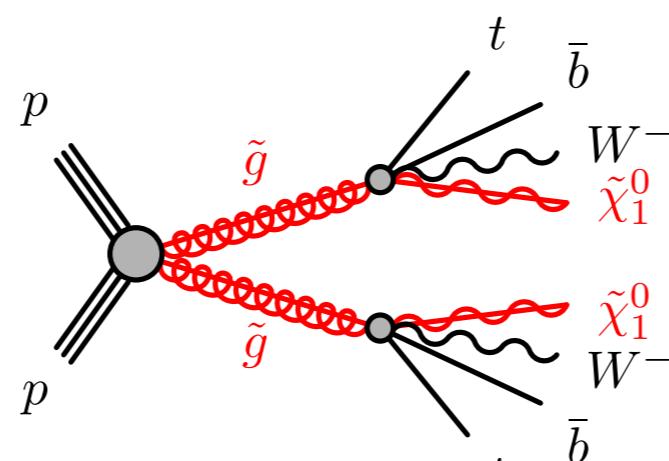
## Gluinos

**Many b-jets**



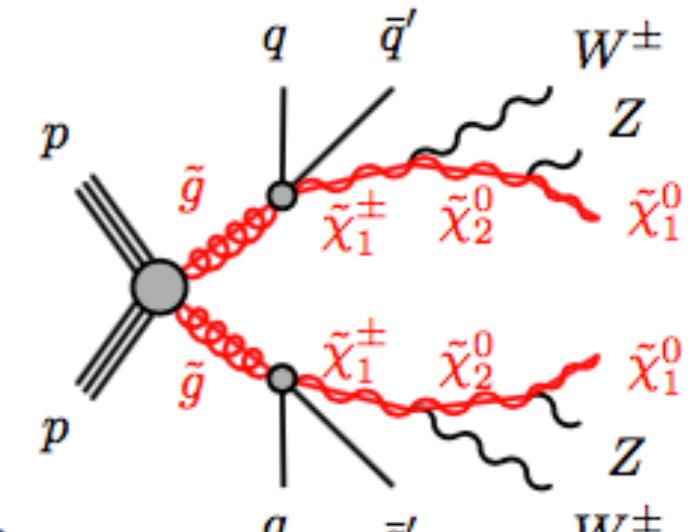
a)

**Off-shell tops**



b)

**High  $N_{\text{jets}}$**



c)

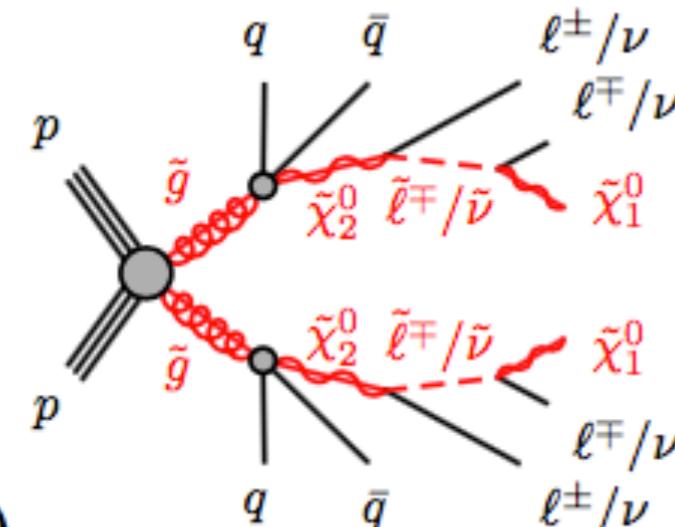
Signal region Name	$N_{\text{signal leptons}}$	$N_{b-\text{jets}}$	$N_{\text{jets}}$	$p_{\text{T,jet}}$ [GeV]	$E_T^{\text{miss}}$ [GeV]	$m_{\text{eff}}$ [GeV]	$E_T^{\text{miss}}/m_{\text{eff}}$	Other	Targeted Signal
Rpc2L2bS	$\geq 2\text{SS}$	$\geq 2$	$\geq 6$	$> 25$	$> 200$	$> 600$	$> 0.25$	–	Fig. a)
Rpc2L2bH	$\geq 2\text{SS}$	$\geq 2$	$\geq 6$	$> 25$	–	$> 1800$	$> 0.15$	–	Fig. a), NUHM2
Rpc2Lsoft1b	$\geq 2\text{SS}$	$\geq 1$	$\geq 6$	$> 25$	$> 100$	–	$> 0.3$	$20, 10 < p_T^{\ell_1}, p_T^{\ell_2} < 100 \text{ GeV}$	Fig. b)
Rpc2Lsoft2b	$\geq 2\text{SS}$	$\geq 2$	$\geq 6$	$> 25$	$> 200$	$> 600$	$> 0.25$	$20, 10 < p_T^{\ell_1}, p_T^{\ell_2} < 100 \text{ GeV}$	Fig. b)
Rpc2L0bS	$\geq 2\text{SS}$	= 0	$\geq 6$	$> 25$	$> 150$	–	$> 0.25$	–	Fig. c)
Rpc2L0bH	$\geq 2\text{SS}$	= 0	$\geq 6$	$> 40$	$> 250$	$> 900$	–	–	Fig. c)

# Simplified Models

Gluinos

3<sup>rd</sup> Gen Squarks

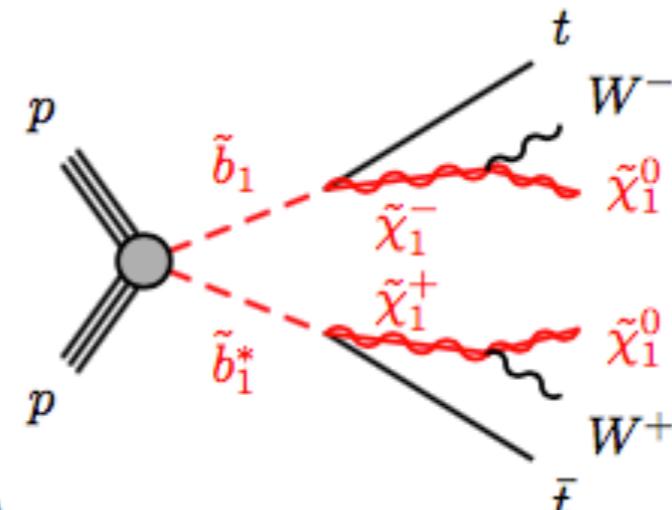
highest BR to leptons



d)

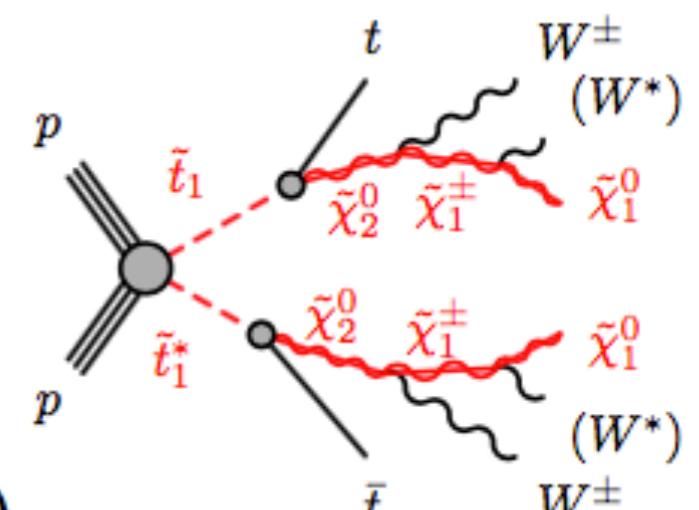
Completes

$$\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$$



e)

Novel 3LSS



f)

Signal region Name	$N_{\text{leptons}}^{\text{signal}}$	$N_{b-\text{jets}}$	$N_{\text{jets}}$	$p_{\text{T,jet}}$ [GeV]	$E_T^{\text{miss}}$ [GeV]	$m_{\text{eff}}$ [GeV]	$E_T^{\text{miss}}/m_{\text{eff}}$	Other	Targeted Signal
Rpc3L0bS	$\geq 3$	$= 0$	$\geq 4$	$> 40$	$> 200$	$> 600$	-	-	Fig. d)
Rpc3L0bH	$\geq 3$	$= 0$	$\geq 4$	$> 40$	$> 200$	$> 1600$	-	-	Fig. d)
Rpc3L1bS	$\geq 3$	$\geq 1$	$\geq 4$	$> 40$	$> 200$	$> 600$	-	-	
Rpc3L1bH	$\geq 3$	$\geq 1$	$\geq 4$	$> 40$	$> 200$	$> 1600$	-	-	
Rpc2L1bS	$\geq 2\text{SS}$	$\geq 1$	$\geq 6$	$> 25$	$> 150$	$> 600$	$> 0.25$	-	Fig. e)
Rpc2L1bH	$\geq 2\text{SS}$	$\geq 1$	$\geq 6$	$> 25$	$> 250$	-	$> 0.2$	-	Fig. e)
Rpc3LSS1b	$\geq \ell^\pm \ell^\pm \ell^\pm$	$\geq 1$	-	-	-	-	-	veto $81 < m_{e^\pm e^\pm} < 101$ GeV	Fig. f)

# Realistic Model

Non-Universal Higgs Model with 2 parameters (NUHM2)

- $m_{H_d}^2 \neq m_{H_u}^2 \neq m_0^2$  at the GUT scale
- All parameters set to respect  $m_h = 125$  GeV  
 $m_{1/2} = 300 - 800$  GeV,  $m_{\tilde{g}} \sim 2.5 m_{1/2}$
- Gtt-like signatures with different branching ratios to leptons

Example for  $m_{1/2} = 400$  GeV

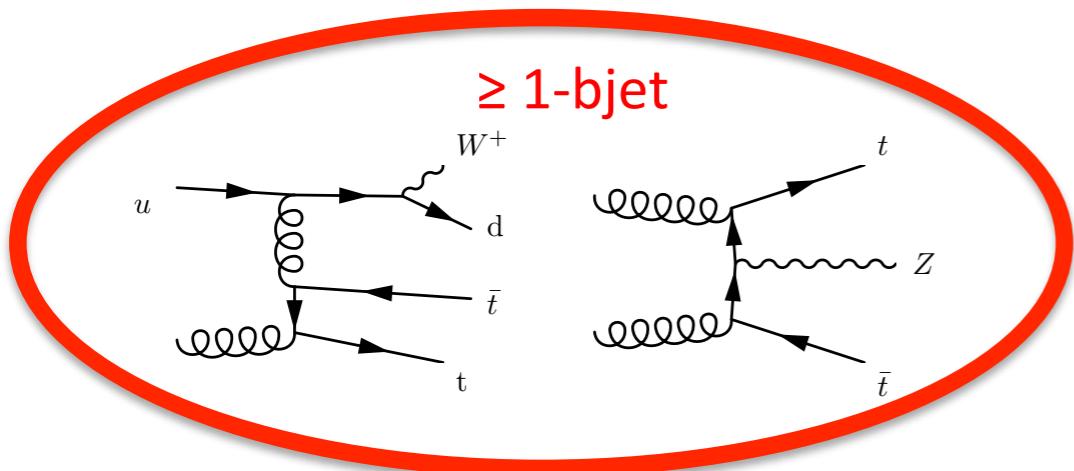
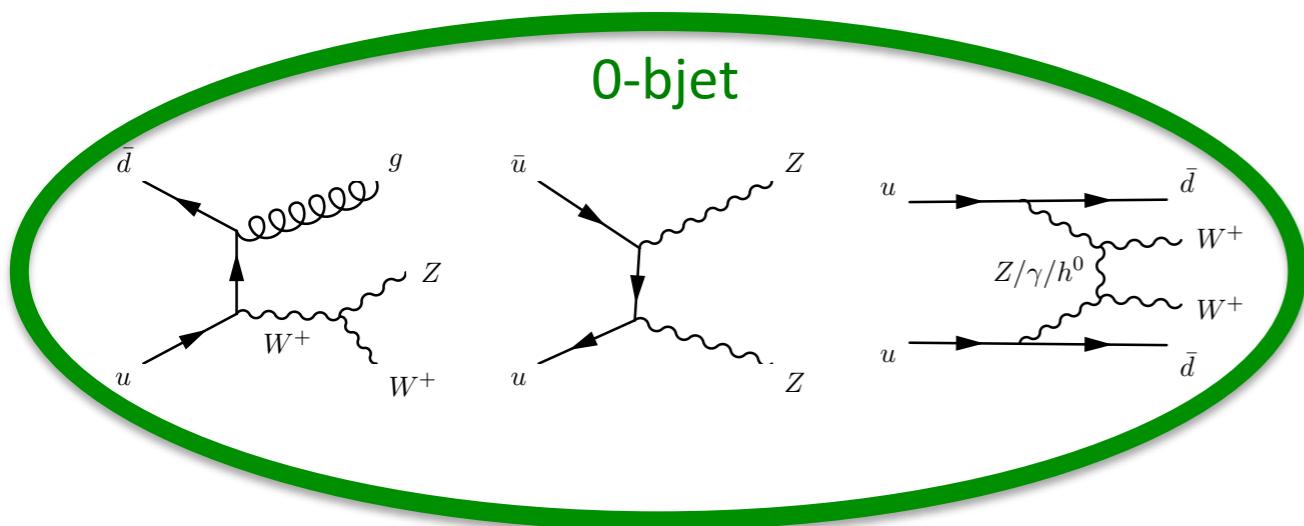
Decay	BR	Decay	BR
$t\bar{t}\chi_1^0$	0.13	$t\bar{b}\chi_1^\pm$	0.45
$t\bar{t}\chi_2^0$	0.21	$t\bar{b}\chi_2^\pm$	0.04
$t\bar{t}\chi_3^0$	0.13	-	-
$t\bar{t}\chi_4^0$	0.02	-	-
$t\bar{t}\chi_i^0$	0.49	$t\bar{b}\chi_i^\pm$	0.49

# Data and Simulation

- **Data** collected during 2015 and 2016 at **13 TeV**:  **$36.1 \text{ fb}^{-1} \pm 3.2\%$**
- Irreducible **SM background and SUSY signals** simulated using Monte Carlo event generators and processed through detector simulation
- Reducible **detector background** estimated using data-driven techniques

# SM Background

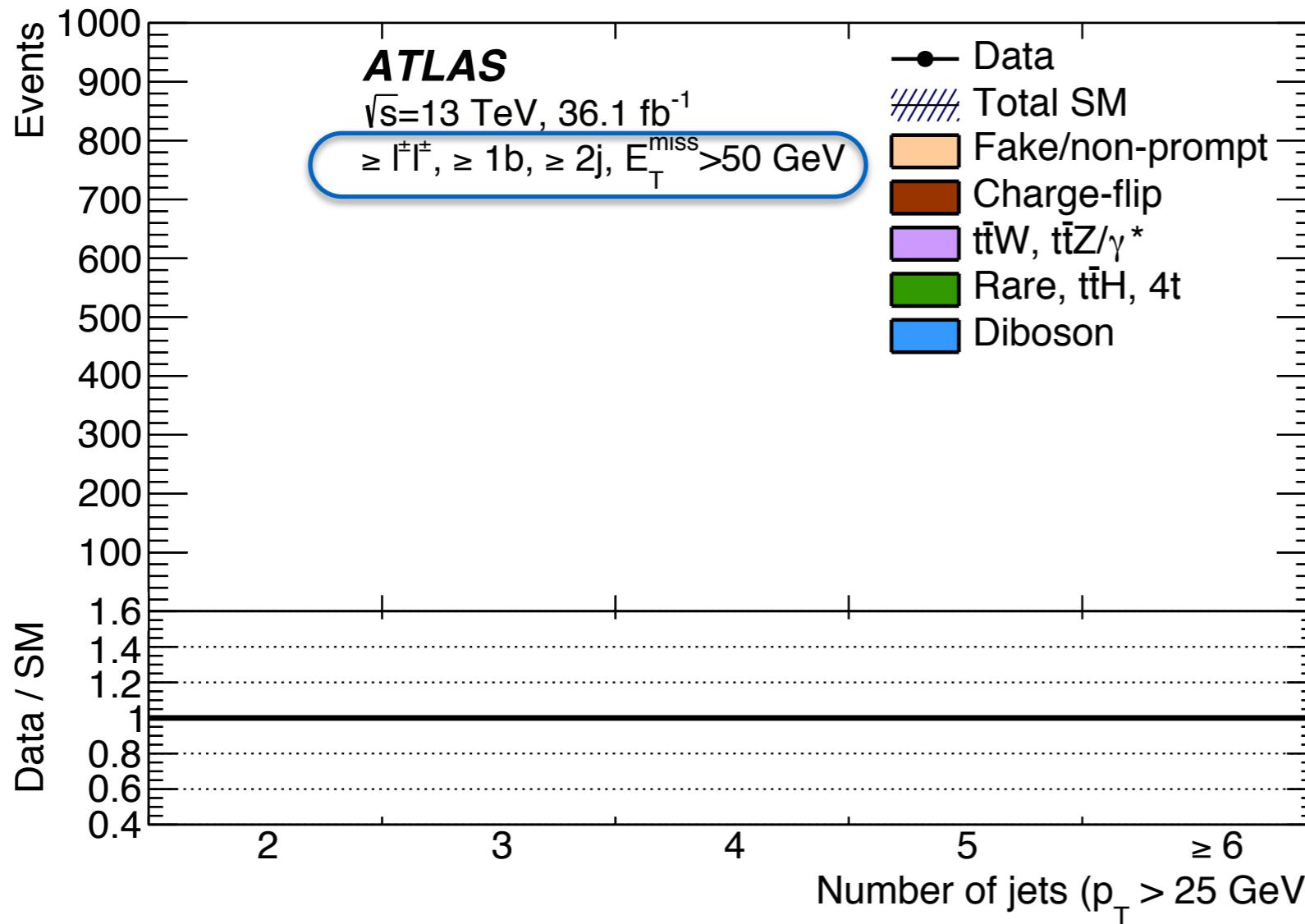
Determine all the SM processes  
with SS/3L



Process	Cross Section (pb)
$\tilde{g}\tilde{g}, m_{\tilde{g}} = 1000 \text{ GeV}$	0.163
$\tilde{g}\tilde{g}, m_{\tilde{g}} = 1400 \text{ GeV}$	0.025
$\tilde{b}\tilde{b}, m_{\tilde{b}} = 550 \text{ GeV}$	0.296
$\tilde{b}\tilde{b}, m_{\tilde{b}} = 700 \text{ GeV}$	0.067
$WZ$	44.87
$ZZ$	14.15
$W^\pm W^\pm jj$	0.325
$t\bar{t}Z$	0.760
$t\bar{t}W$	0.566
$WH$	1.419
$ZH$	0.767
$t\bar{t}H$	0.461
$VVV$	0.448
$tZ$	0.240
$tWZ$	0.016
$t\bar{t}WW$	0.010
$t\bar{t} t\bar{t}$	0.009

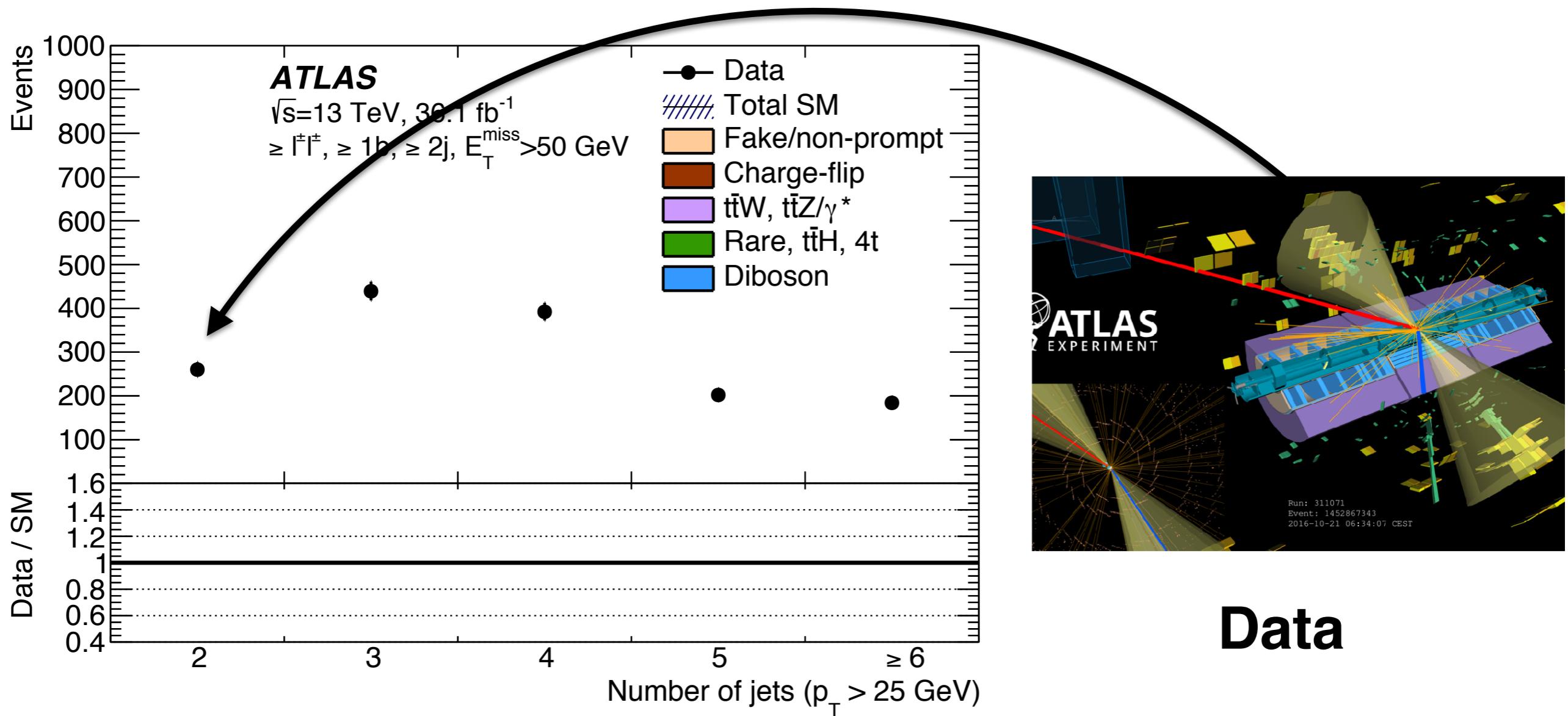
# Data vs. Expectation

Selection close to the search regions



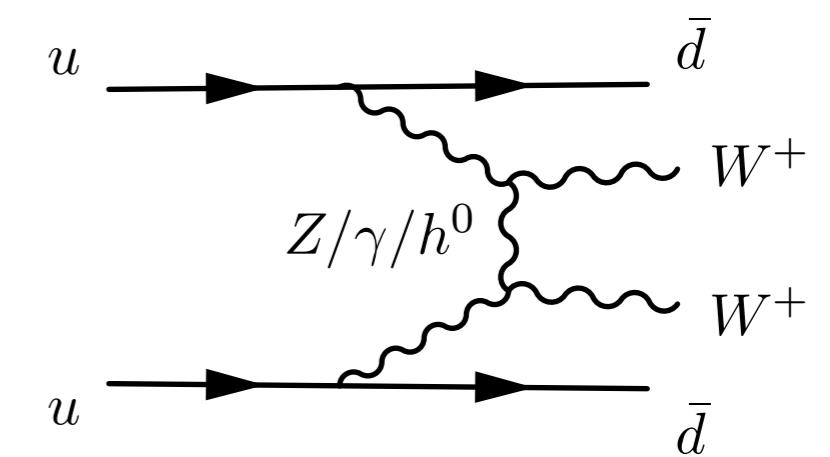
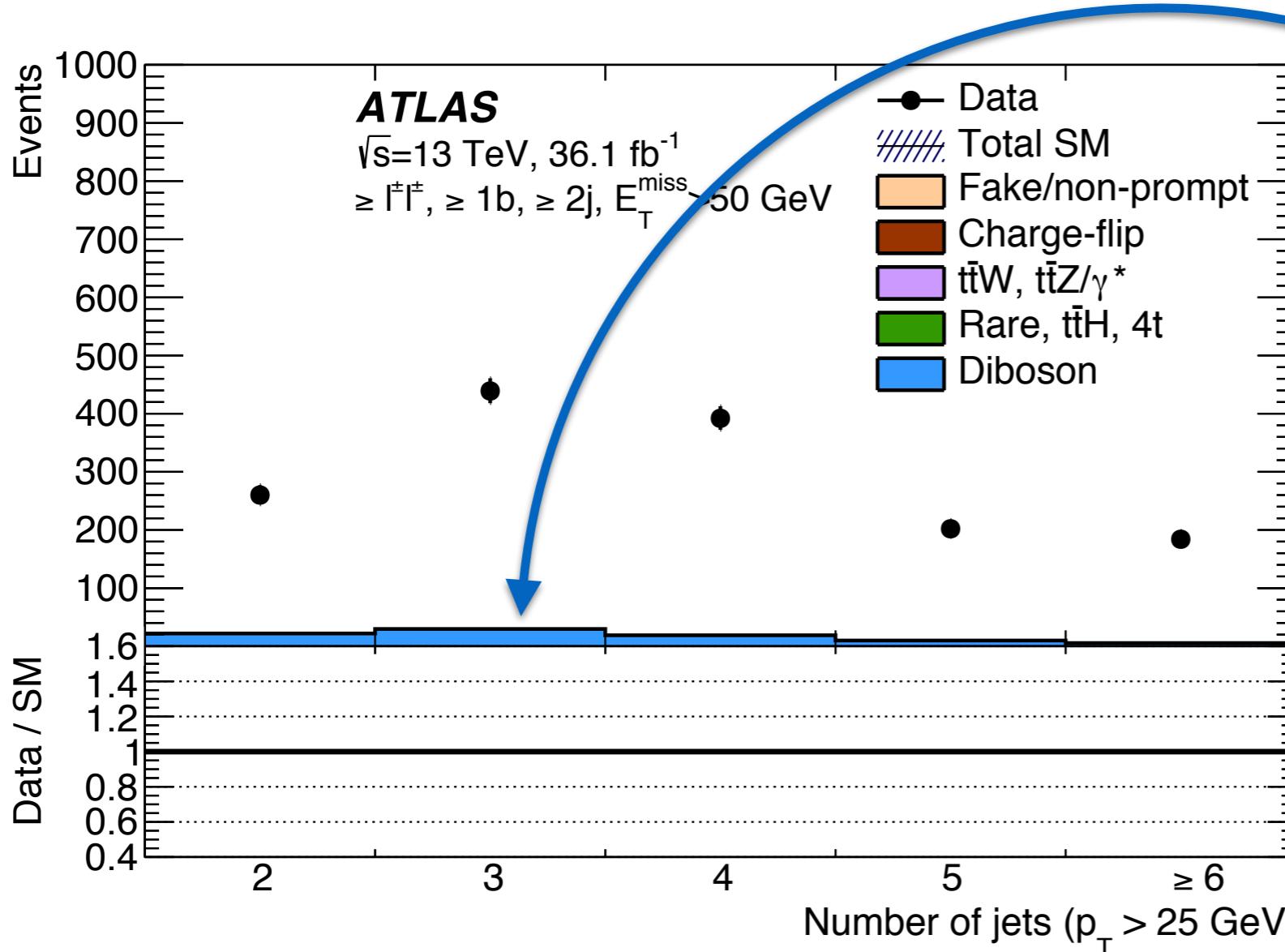
# Data vs. Expectation

Observed events in this selection



# Data vs. Expectation

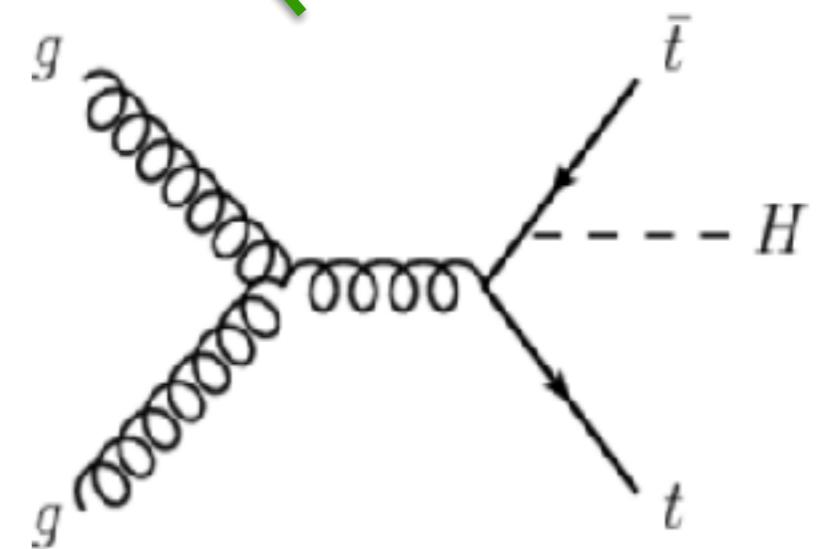
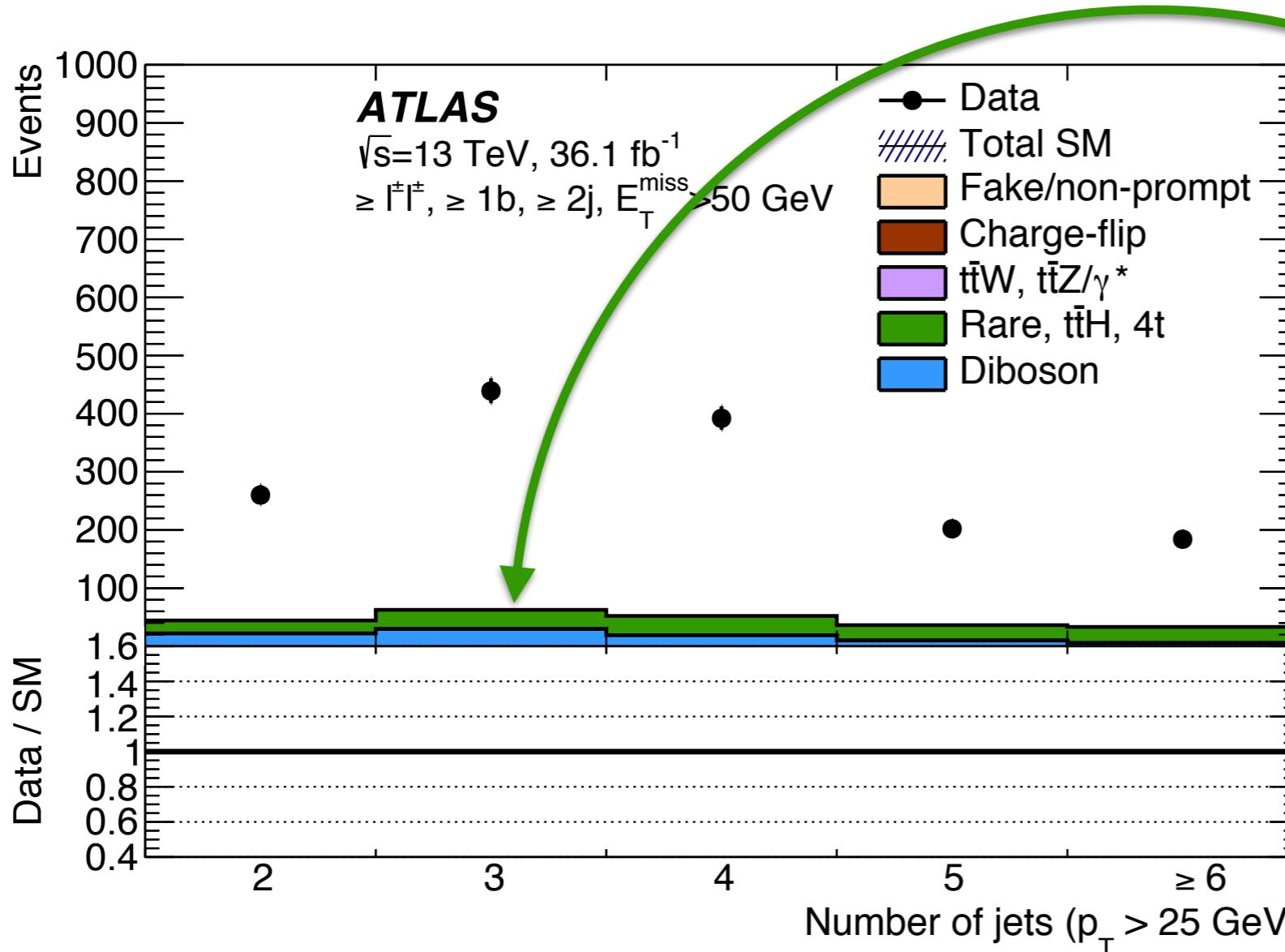
SM background from MC:



WW, WZ, ZZ

# Data vs. Expectation

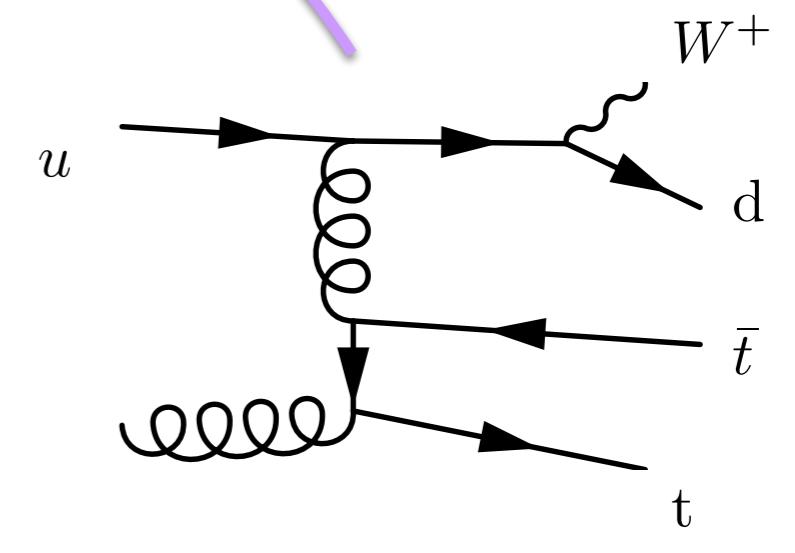
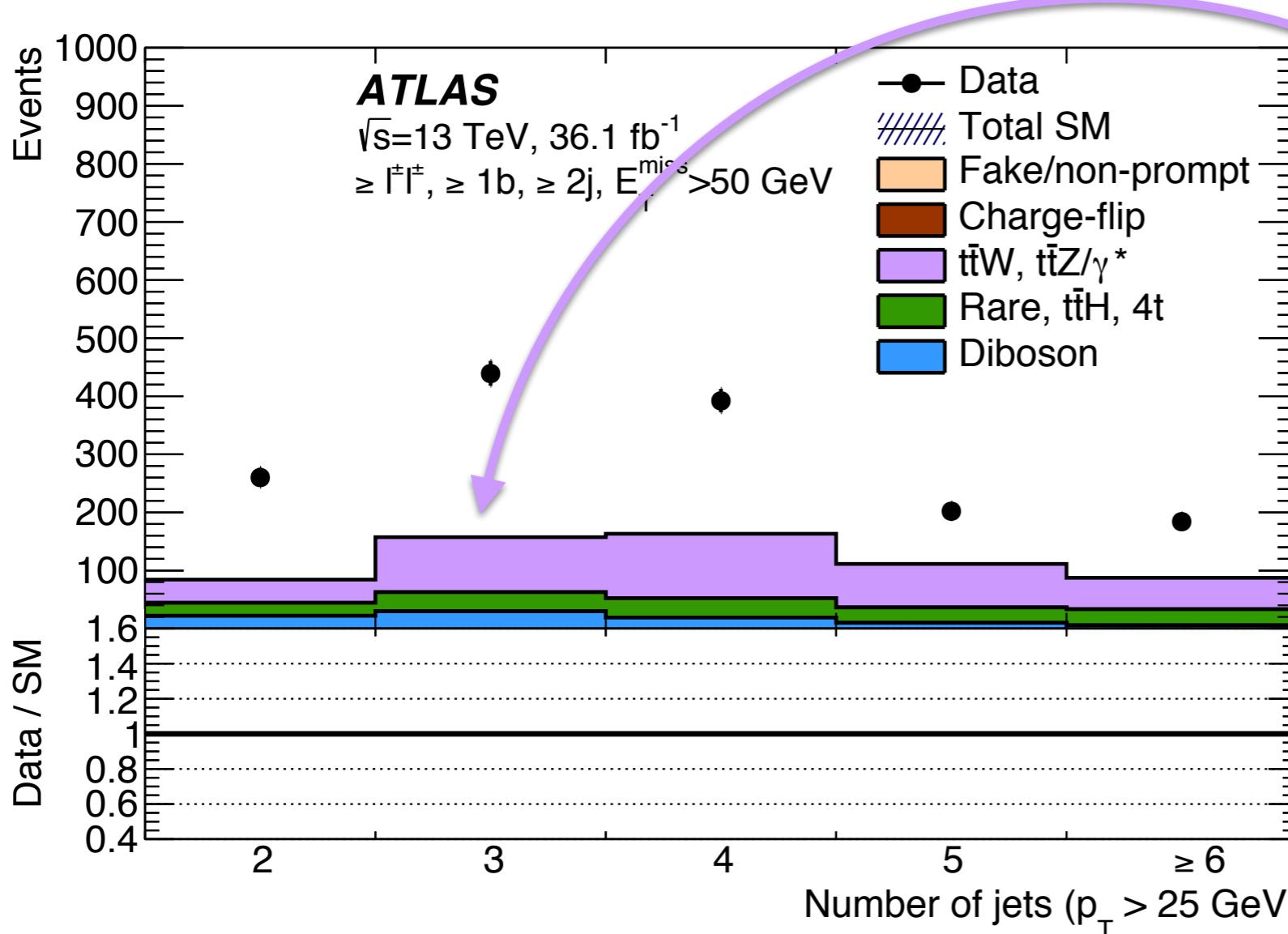
SM background from MC:



**ttH, 4t, 3t, VVV,  
tWZ, ttWW, VH**

# Data vs. Expectation

SM background from MC:

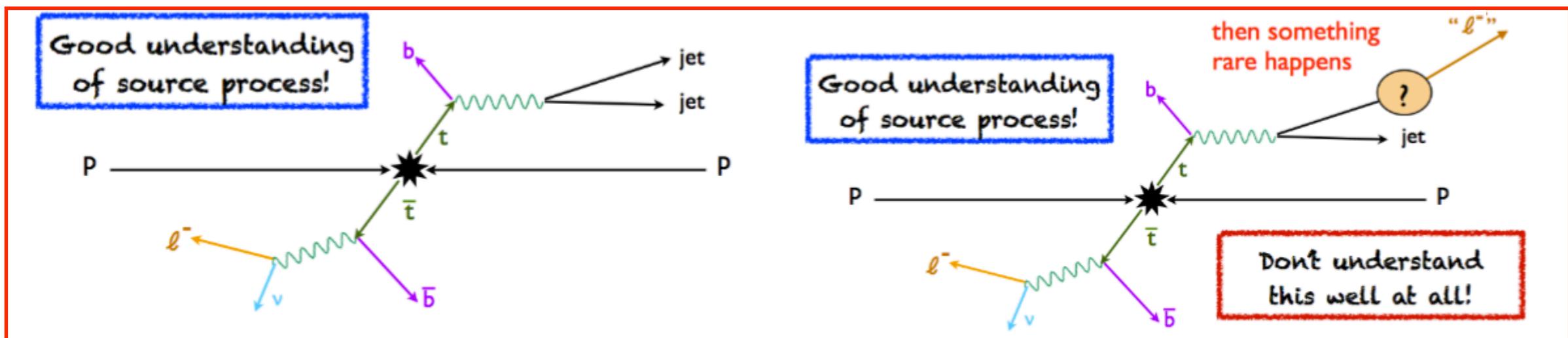
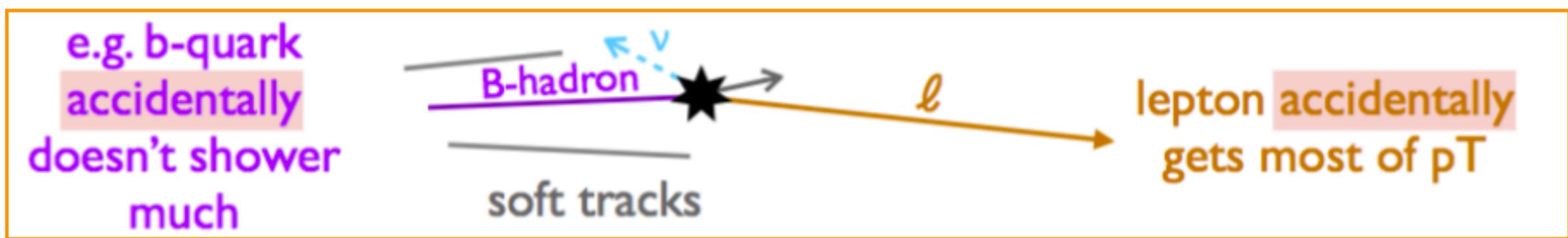
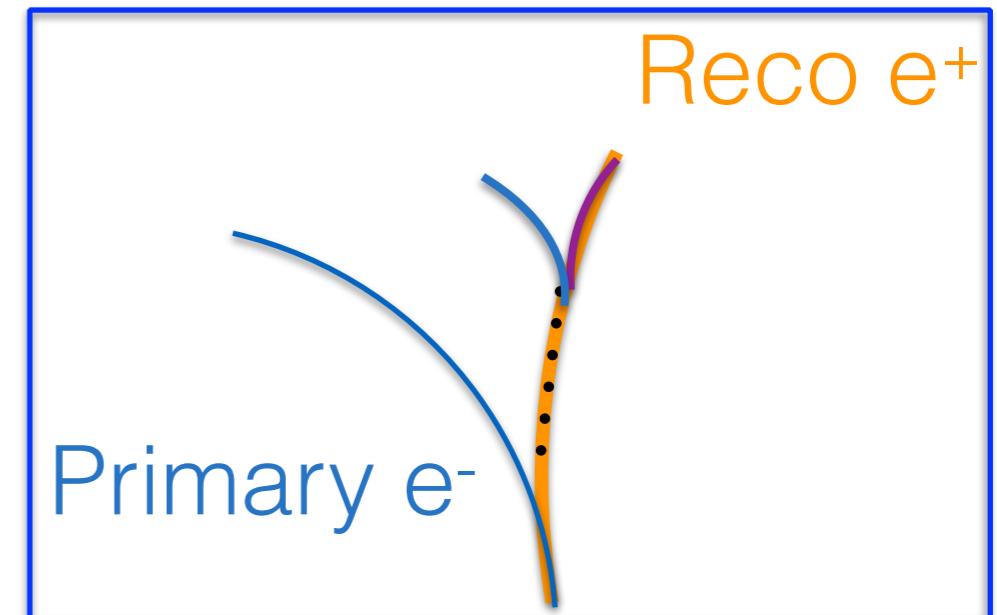


$ttW, ttZ$

**Clearly not done yet!**

# Detector background

- Electron charge mis-measured (charge-flip)
- Hadrons mis-identified as leptons (fake)
- Non-prompt leptons from heavy flavor jets (non-prompt)

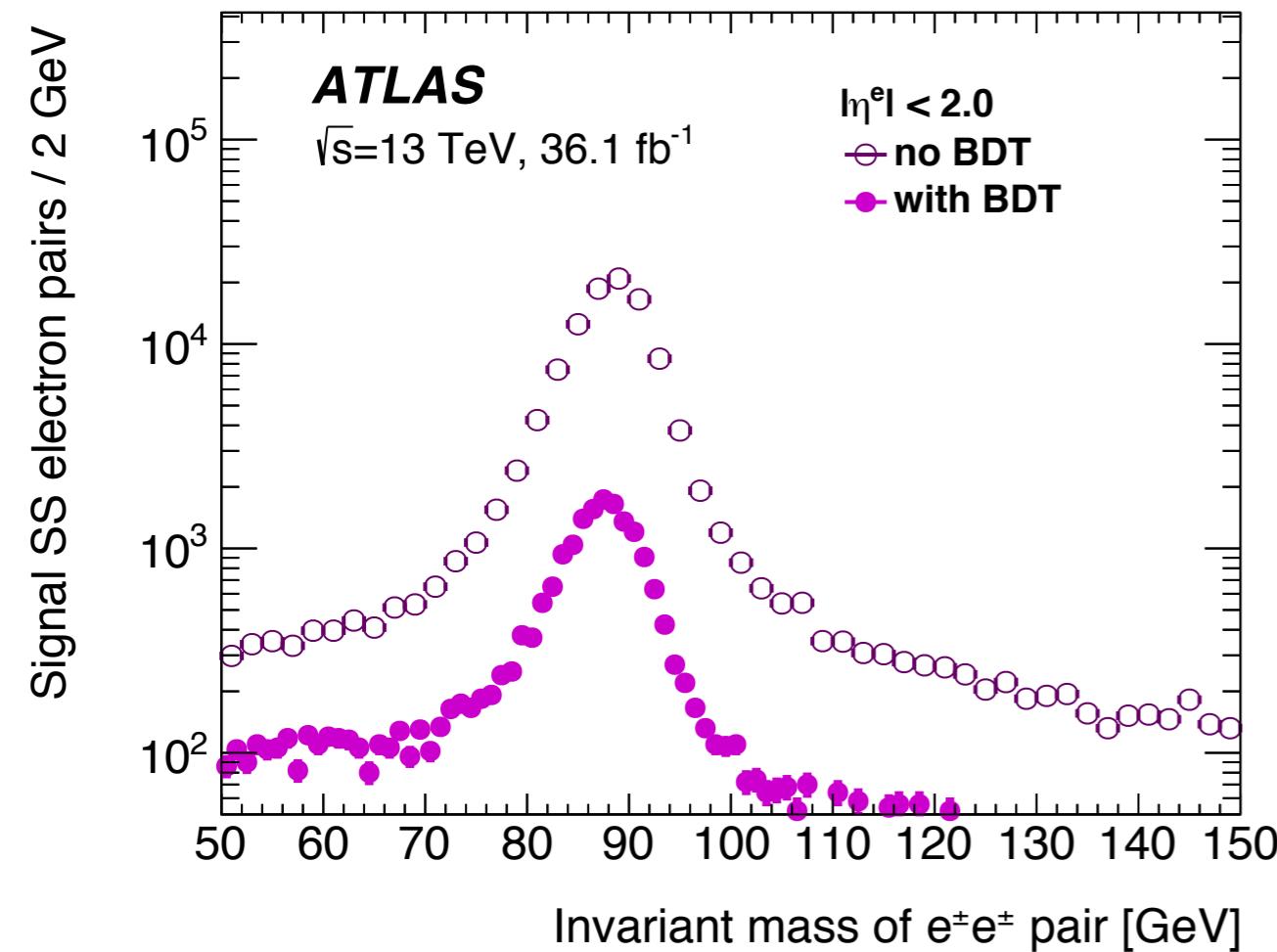


# Charge flip

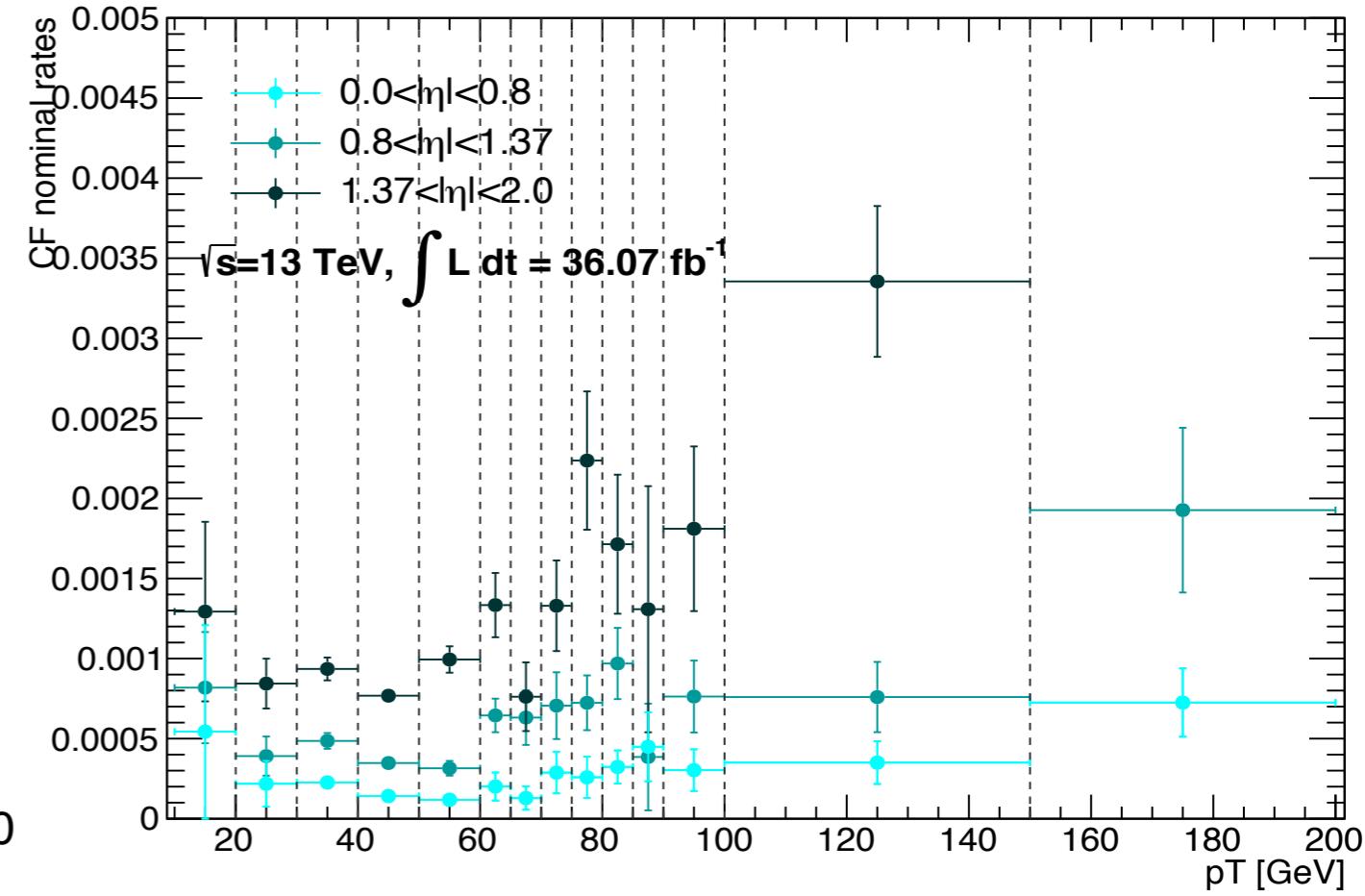
Electron charge mis-identification is relevant for same-sign lepton analyses

- Use electron properties to reduce charge mis-identification
- Re-weight opposite-sign data events by the **charge-flip rate** (prob. OS  $\rightarrow$  SS)
- Extract the charge-flip rates from a likelihood fit in  $Z \rightarrow ee$  data
  - Barrel <  $\sim 0.1\%$ , End-cap <  $\sim 0.5\%$

Charge-flip reduction

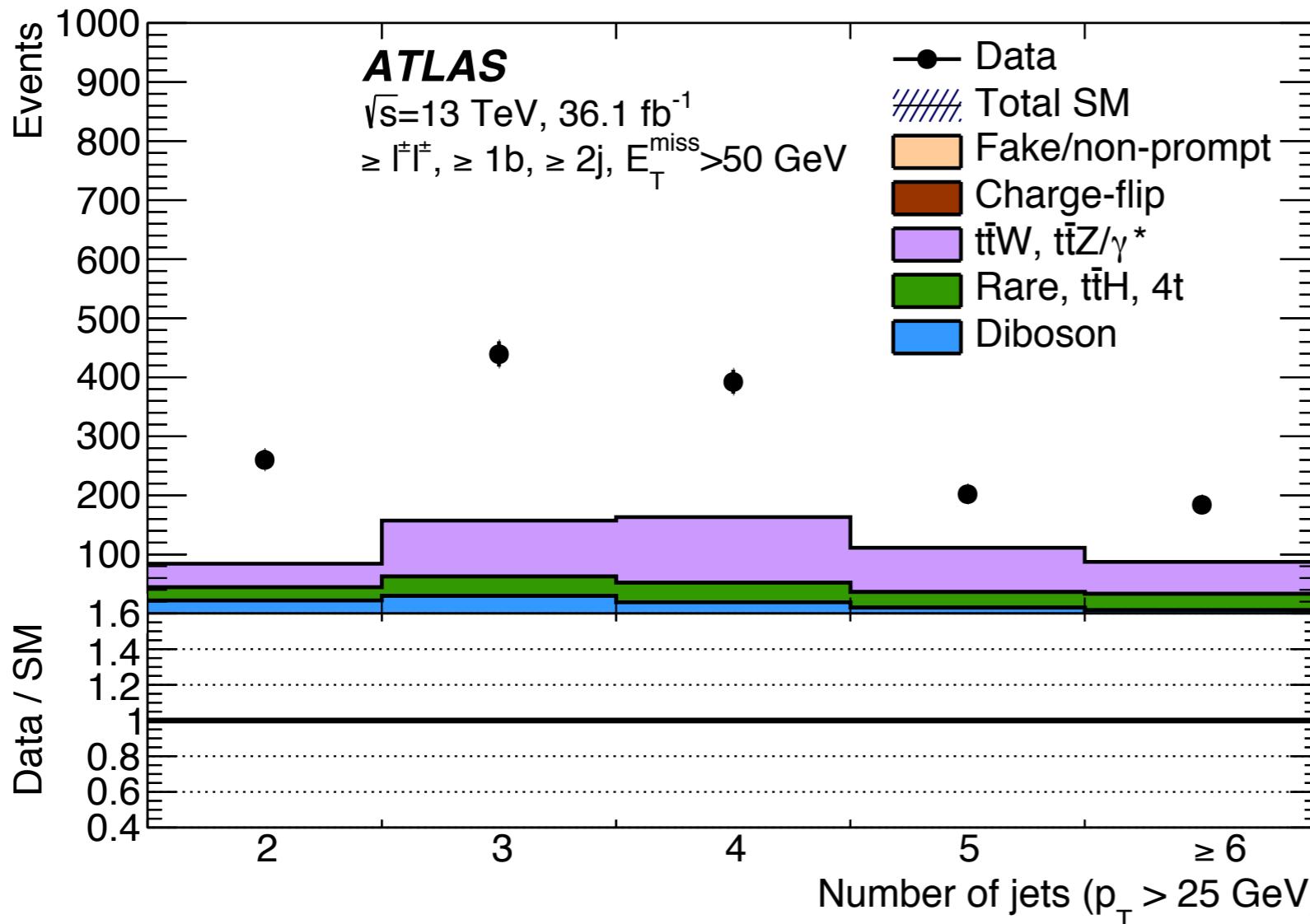


Charge-flip rates



# Data vs. Expectation

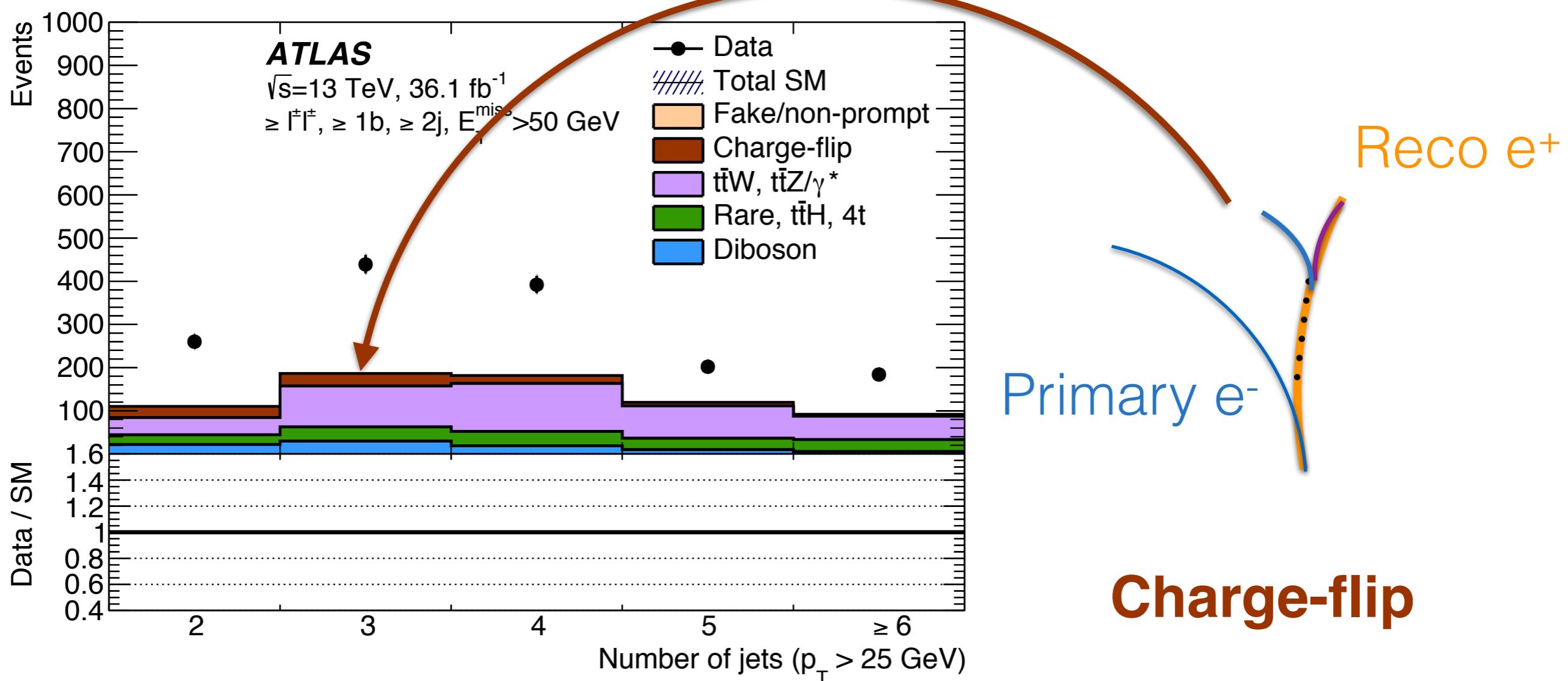
SM background from MC:



Remember!

# Data vs. Expectation

Detector background from data-driven:



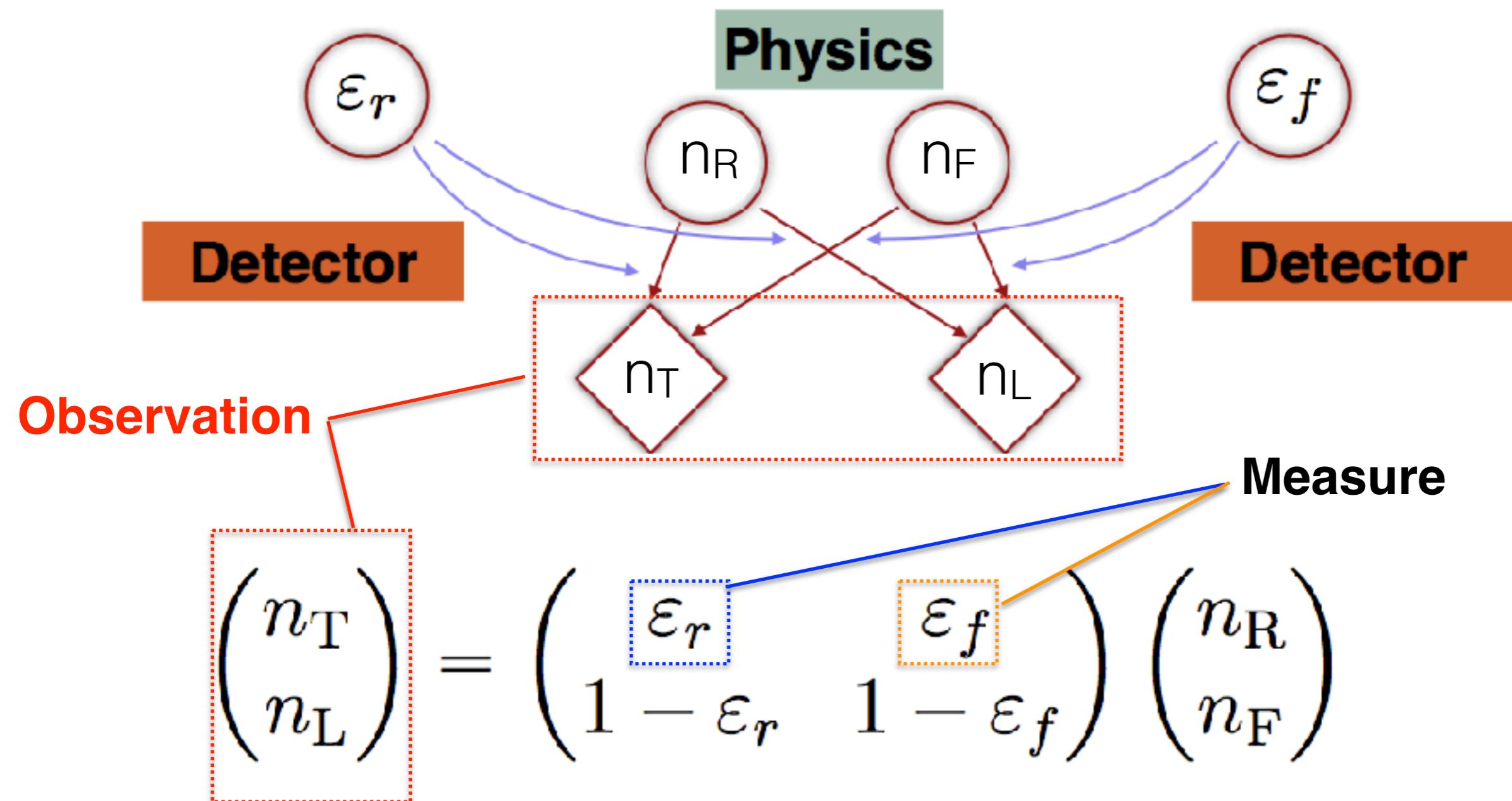
# Fake/Non-prompt background

- Dominant process: ttbar
- **Matrix Method**: relies on probabilities that loosely identified **real** or **fake** leptons pass tight isolation criteria
- **MC Template Method**: relies on MC simulation of fake processes corrected with data
- Statistical combination of the two estimates

# Matrix Method



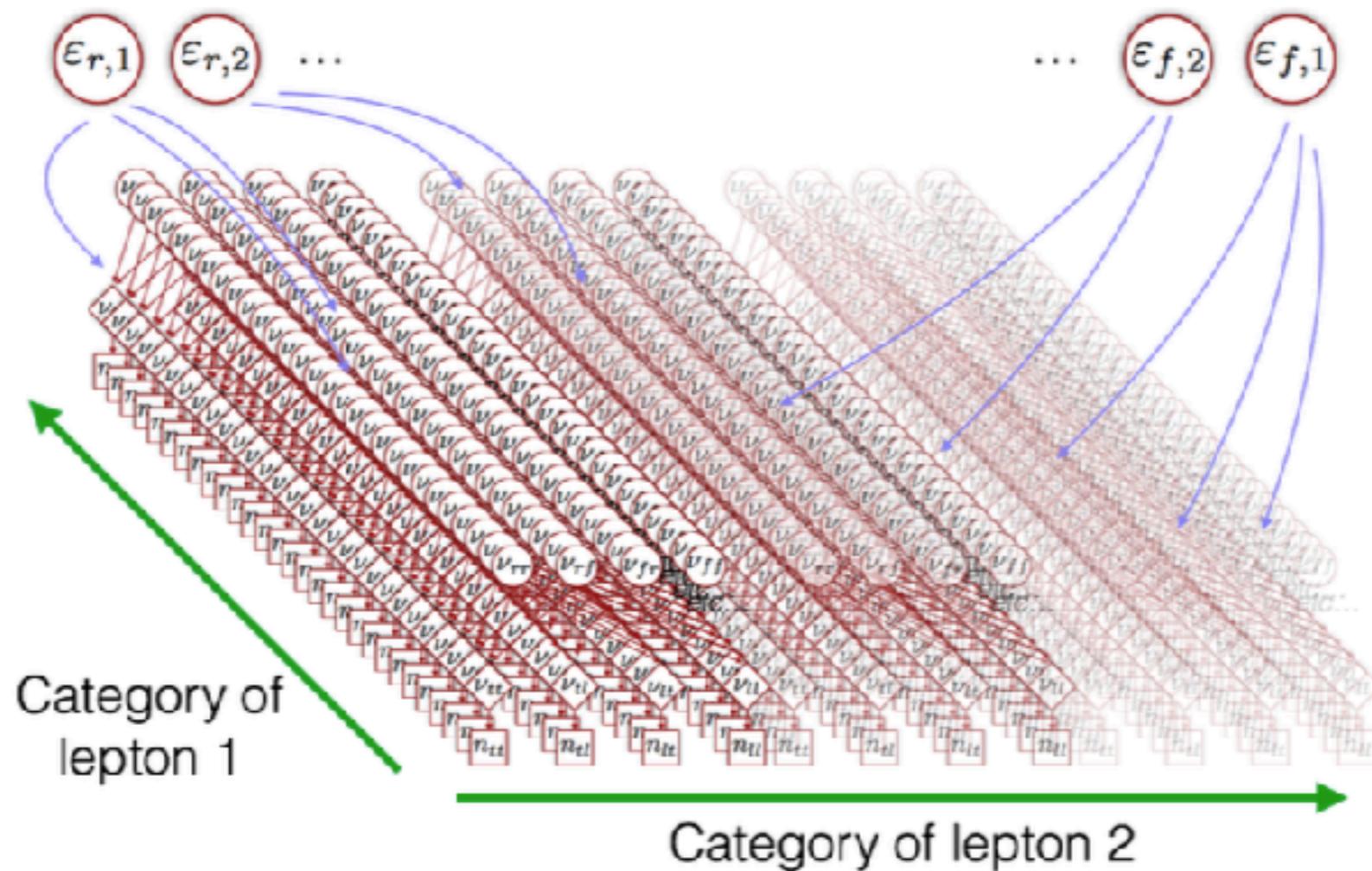
1-lepton case in one category:



# Matrix Method



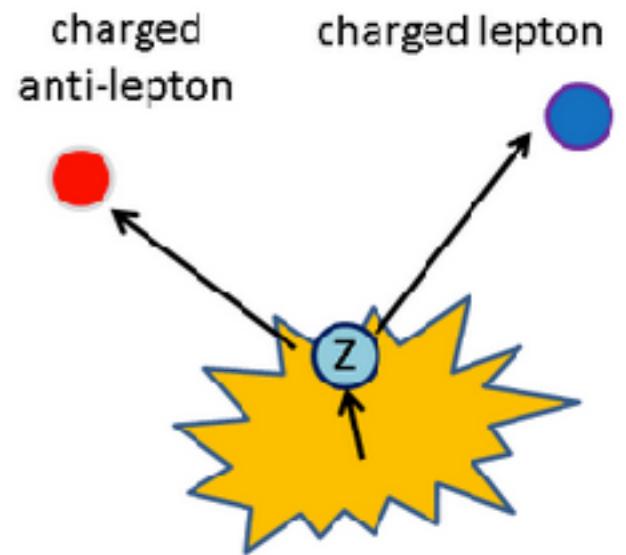
2-leptons case in multiple categories ( $\sim 100$ ):



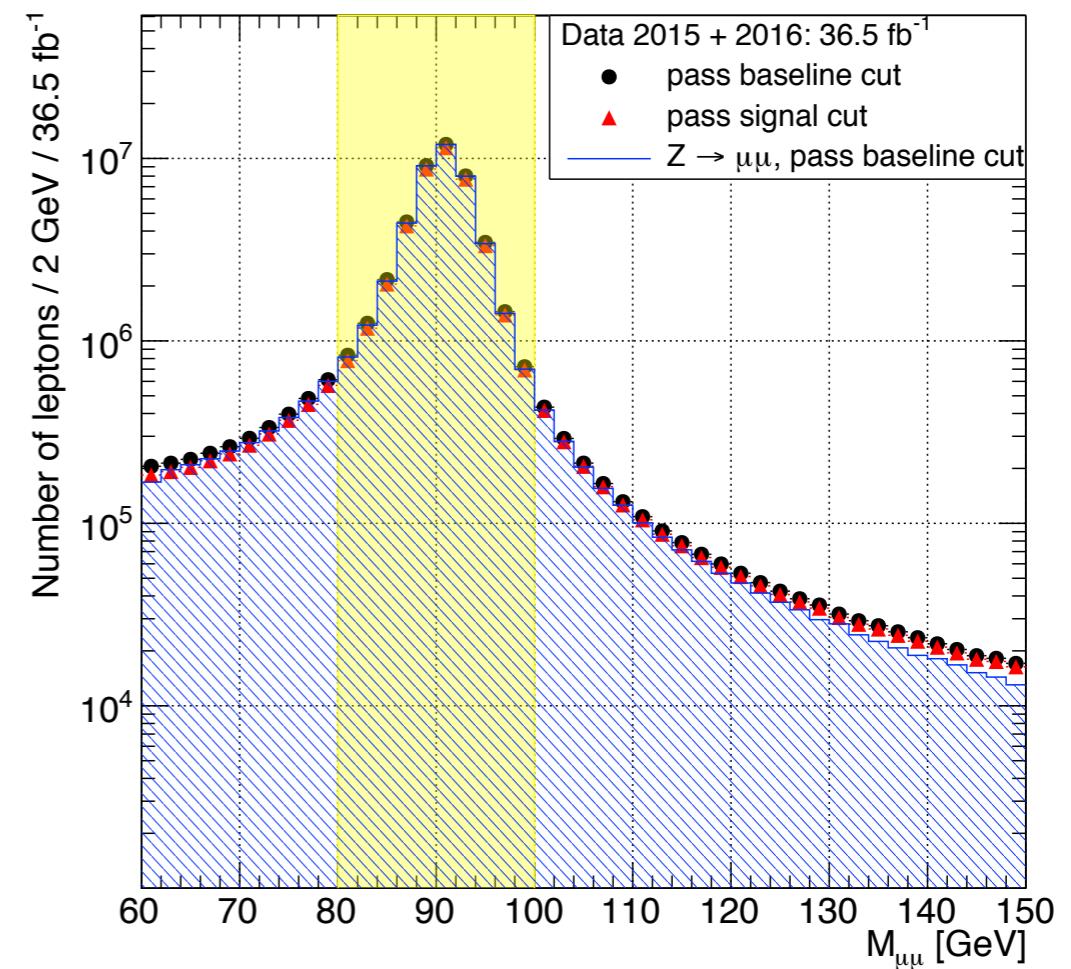
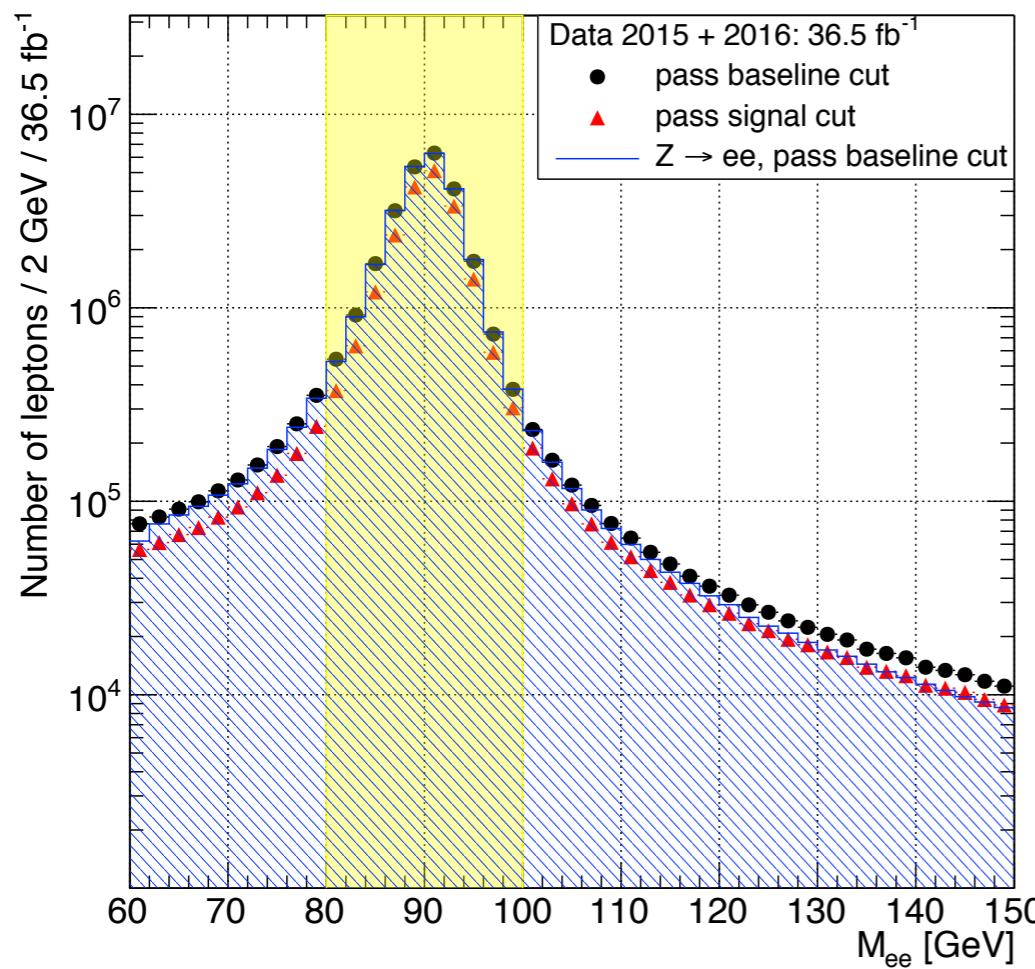
We have to deal with an arbitrary number of leptons with multiple categories, not trivial!

# Real efficiency

- Exploit  $Z \rightarrow l^+l^-$  which produces **real leptons**
- $Z$  resonance reconstructed with one leg passing signal (tag) and one leg passing baseline (probe)

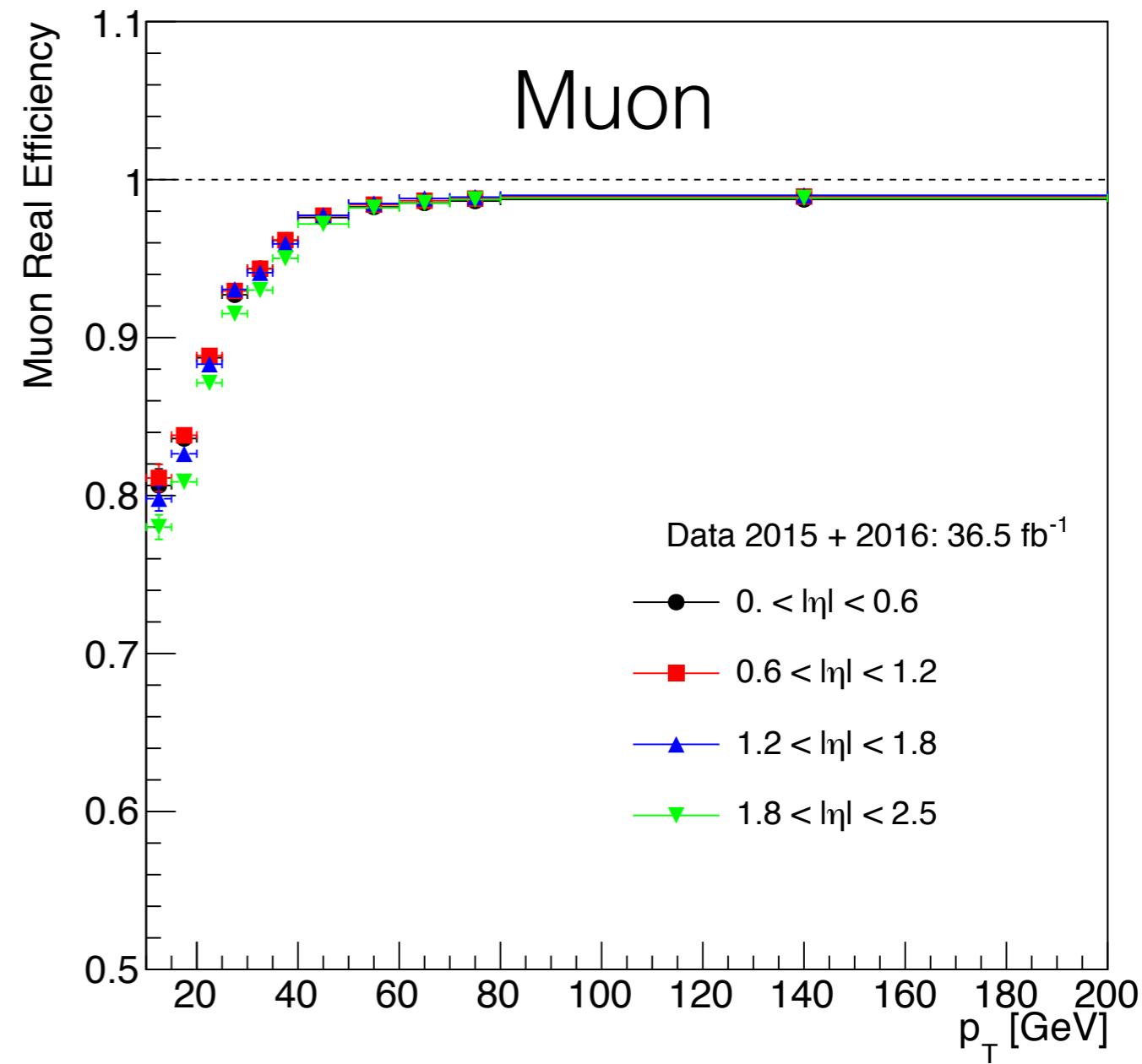
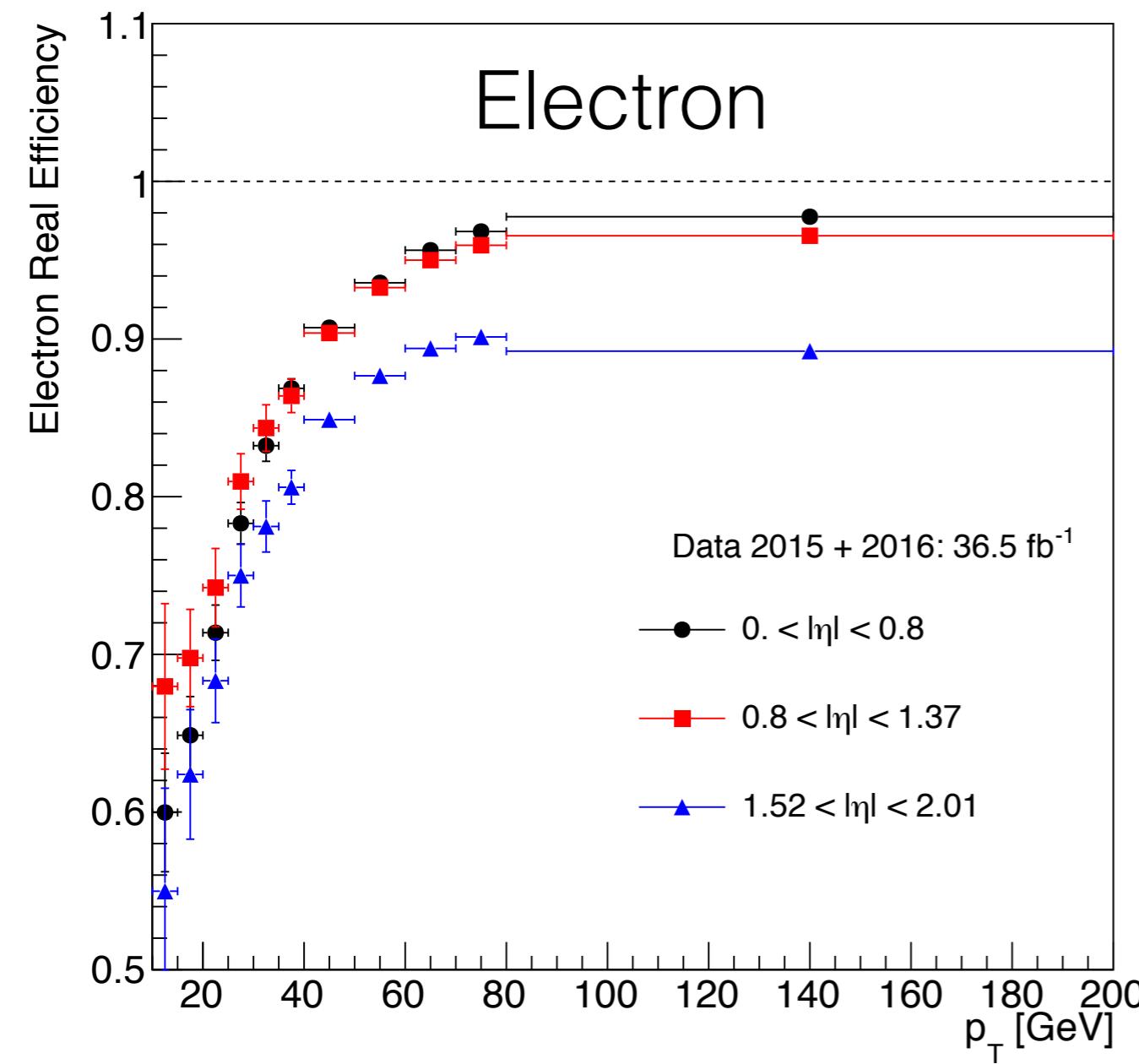


$$\varepsilon_r = \frac{n_{\text{signal}}^{\text{data}}}{n_{\text{baseline}}^{\text{data}} - n_{\text{baseline}}^{\text{BKG}}}$$



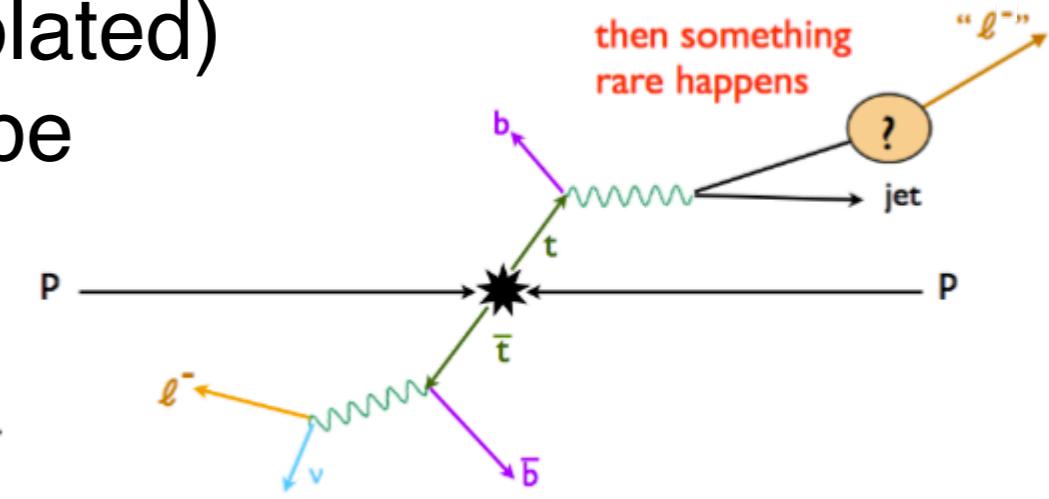
# Real efficiency

- Real efficiency in data (33 for  $e$ , 44 for  $\mu$ ):

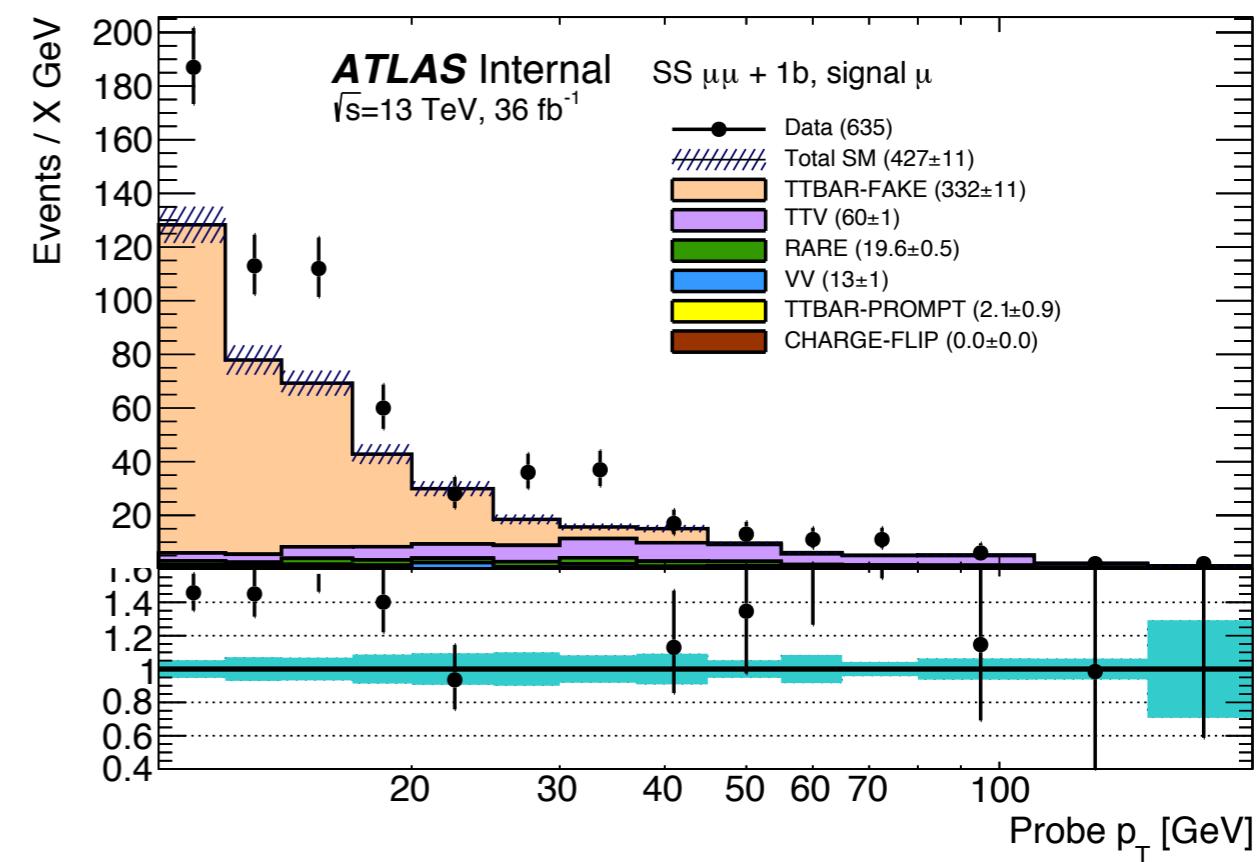
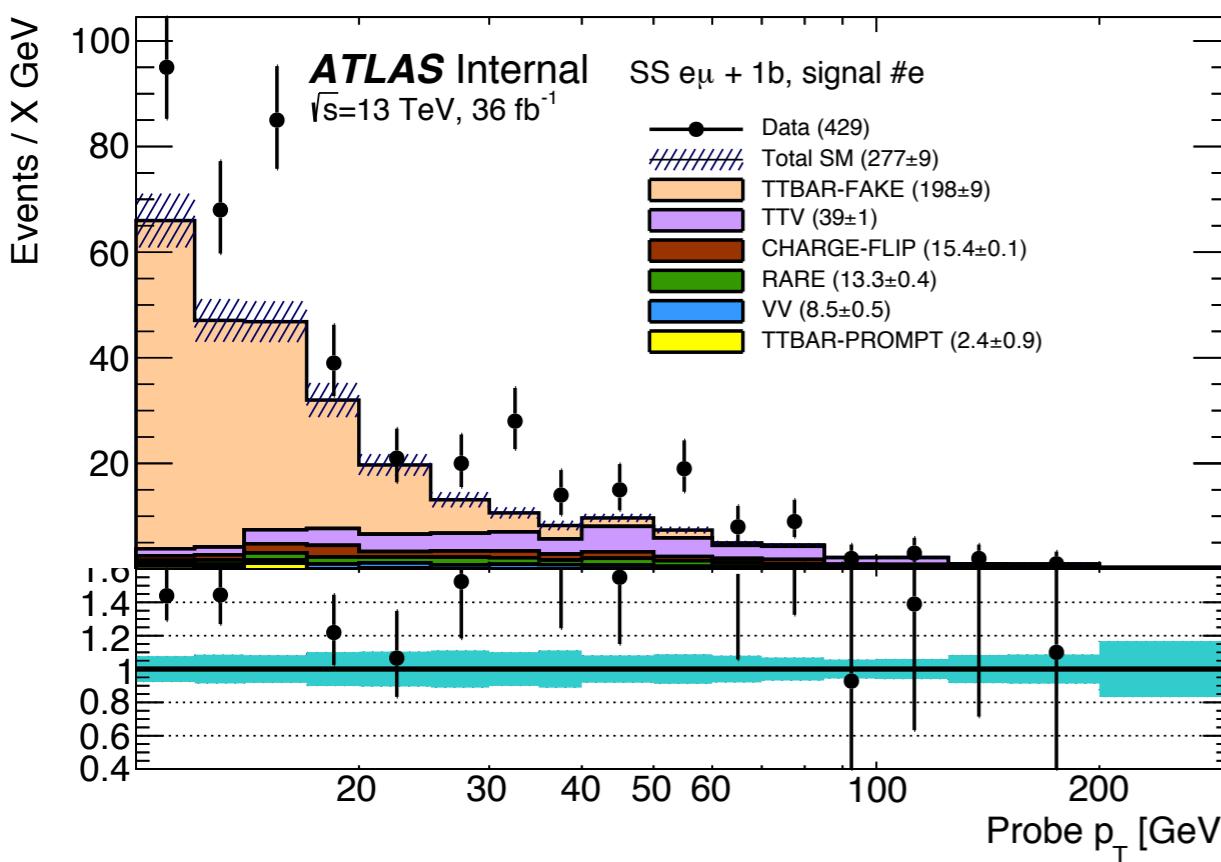


# Fake rate

- tt-enriched region:  $\geq 1$  b-jet, and  $\geq 3$  jets,  $e^\pm\mu^\pm$  and  $\mu^\pm\mu^\pm$
- Muon used as tag ( $p_T > 40$  GeV, well isolated)
- Electron fake rate: electron used as probe
- Muon fake rate: muon used as probe

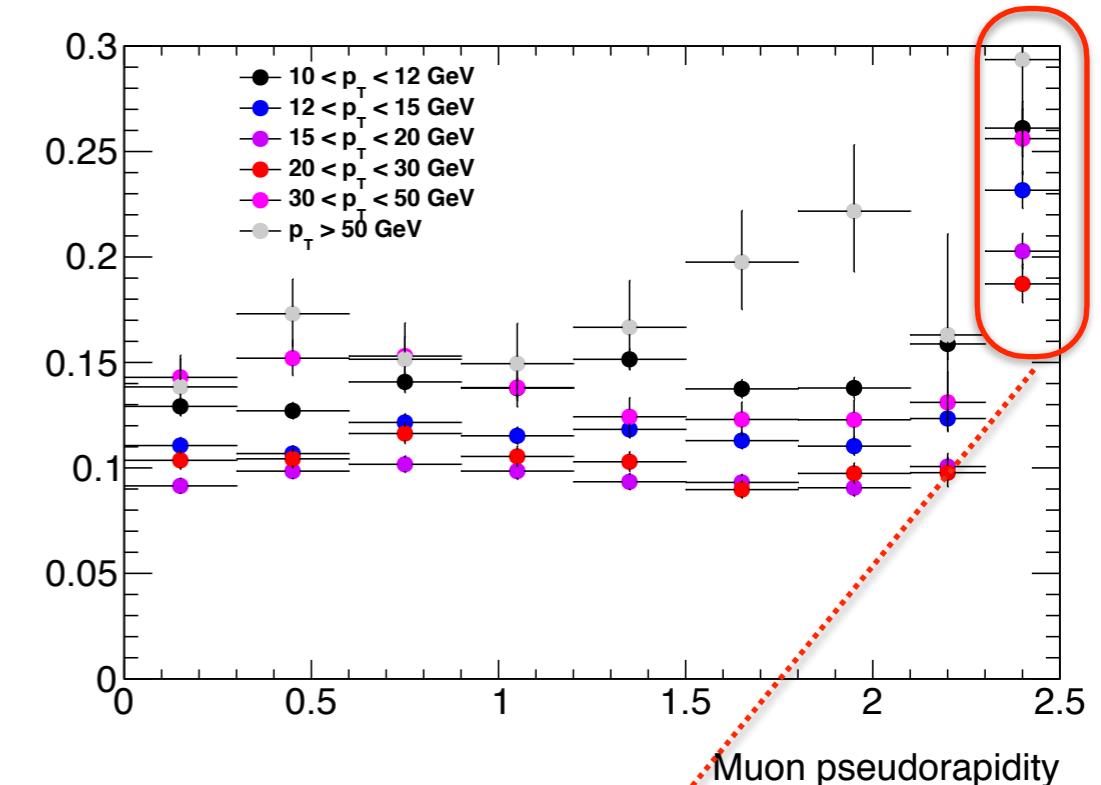
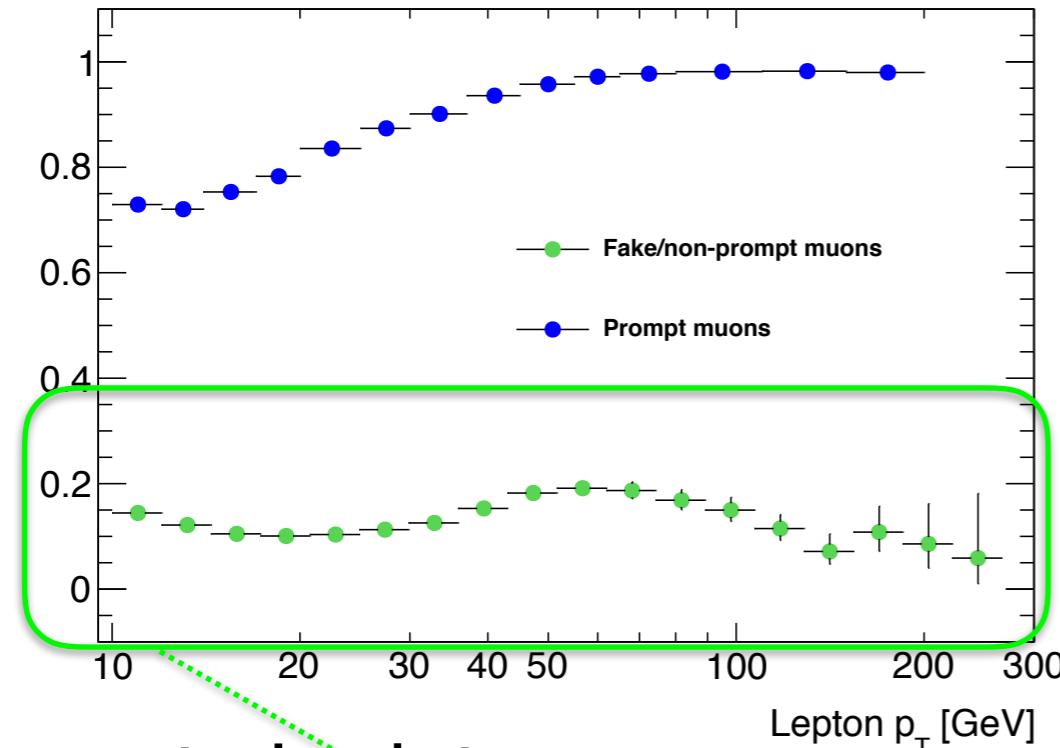


$$\varepsilon_f = \frac{n_{\text{signal}}^{\text{data}} - n_{\text{signal}}^{\text{MC}}}{n_{\text{baseline}}^{\text{data}} - n_{\text{baseline}}^{\text{MC}}}$$



# Muon fake rate

- Fake rate in ttbar MC:

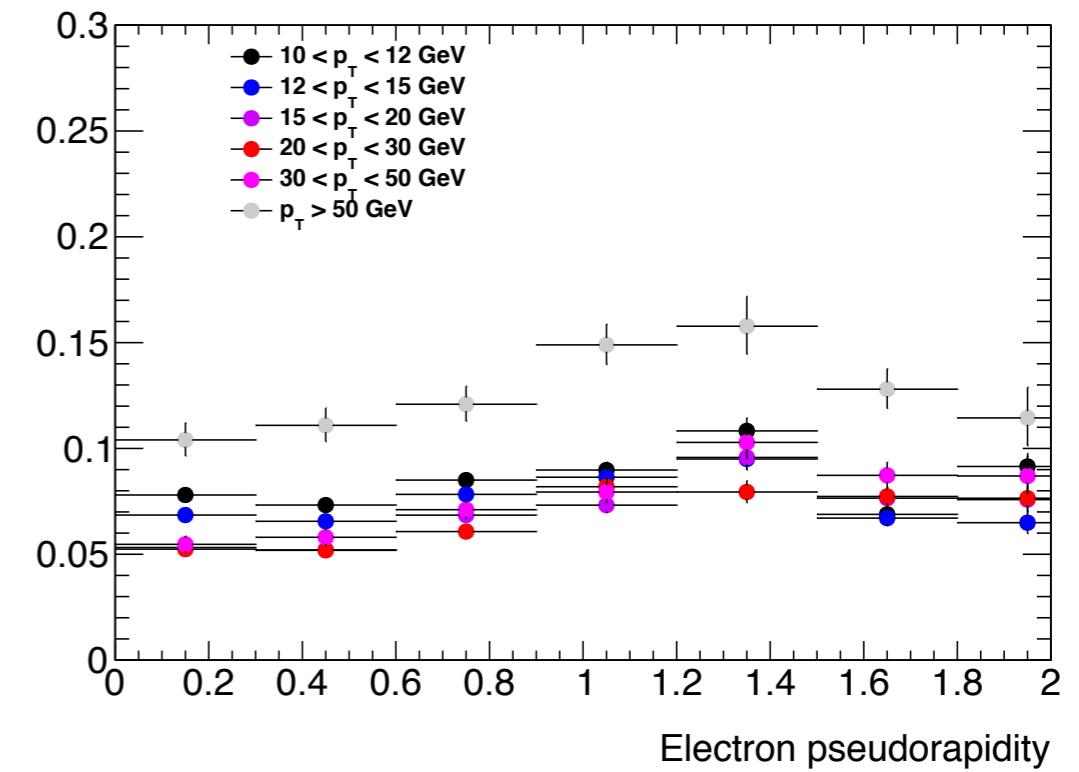
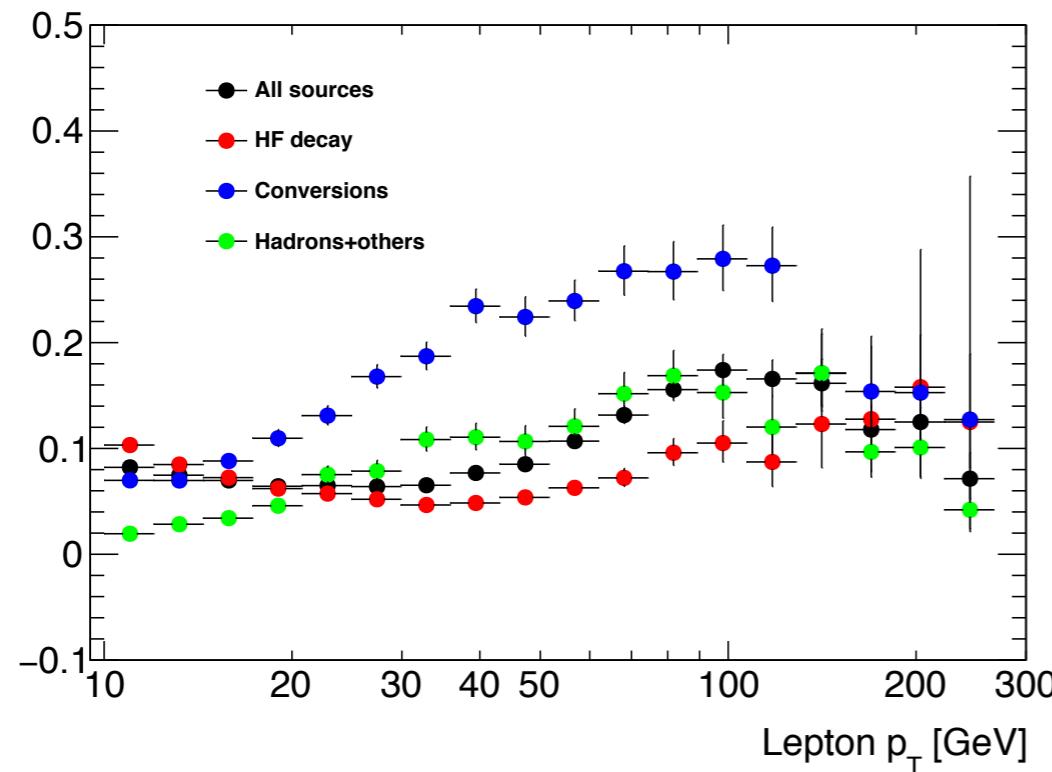


- Fake rate in data:

$10 < p_T < 12 \text{ GeV}$		$12 < p_T < 14 \text{ GeV}$	
$ \eta  < 2.3$	$ \eta  > 2.3$	$ \eta  < 2.3$	$ \eta  > 2.3$
$0.14 \pm 0.01 \pm 0.00$	$0.22 \pm 0.05 \pm 0.00$	$0.11 \pm 0.01 \pm 0.00$	$0.24 \pm 0.06 \pm 0.00$
$14 < p_T < 17$		$17 < p_T < 20 \text{ GeV}$	
$ \eta  < 2.3$	$ \eta  > 2.3$	$ \eta  < 2.3$	$ \eta  > 2.3$
$0.12 \pm 0.01 \pm 0.00$	$0.09 \pm 0.05 \pm 0.00$	$0.09 \pm 0.01 \pm 0.00$	$0.21 \pm 0.07 \pm 0.00$
$20 < p_T < 30$		$40 < p_T < 60$	$p_T > 60$
$0.07 \pm 0.02 \pm 0.00$	$0.12 \pm 0.05 \pm 0.01$	$0.16 \pm 0.09 \pm 0.04$	$0.49 \pm 0.10 \pm 0.07$

# Electron fake rate

- Fake rate in ttbar MC:



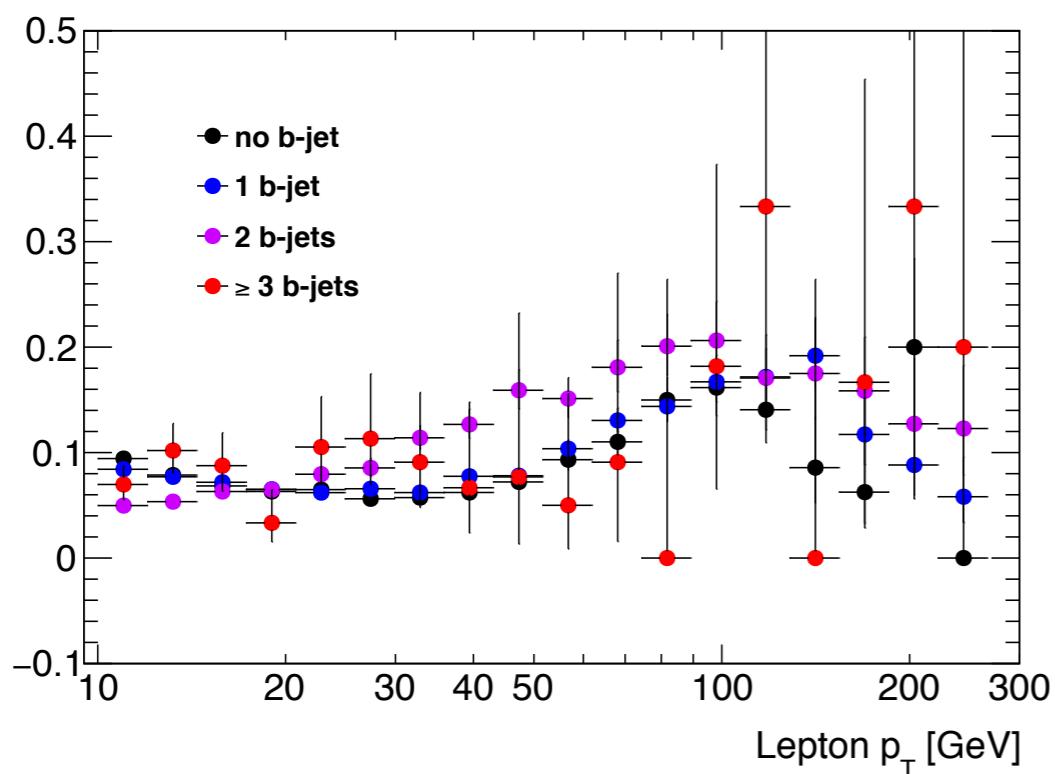
- Fake rate in data electrons:

$10 < p_T < 12$	$12 < p_T < 14$	$14 < p_T < 17$	$17 < p_T < 20$
$0.10 \pm 0.01 \pm 0.00$	$0.10 \pm 0.01 \pm 0.01$	$0.12 \pm 0.01 \pm 0.01$	$0.08 \pm 0.02 \pm 0.00$
$20 < p_T < 25$	$25 < p_T < 30$	$30 < p_T < 40$	$40 > p_T$
$0.07 \pm 0.02 \pm 0.01$	$0.11 \pm 0.03 \pm 0.01$	$0.20 \pm 0.07 \pm 0.03$	$0.25 \pm 0.10 \pm 0.05$

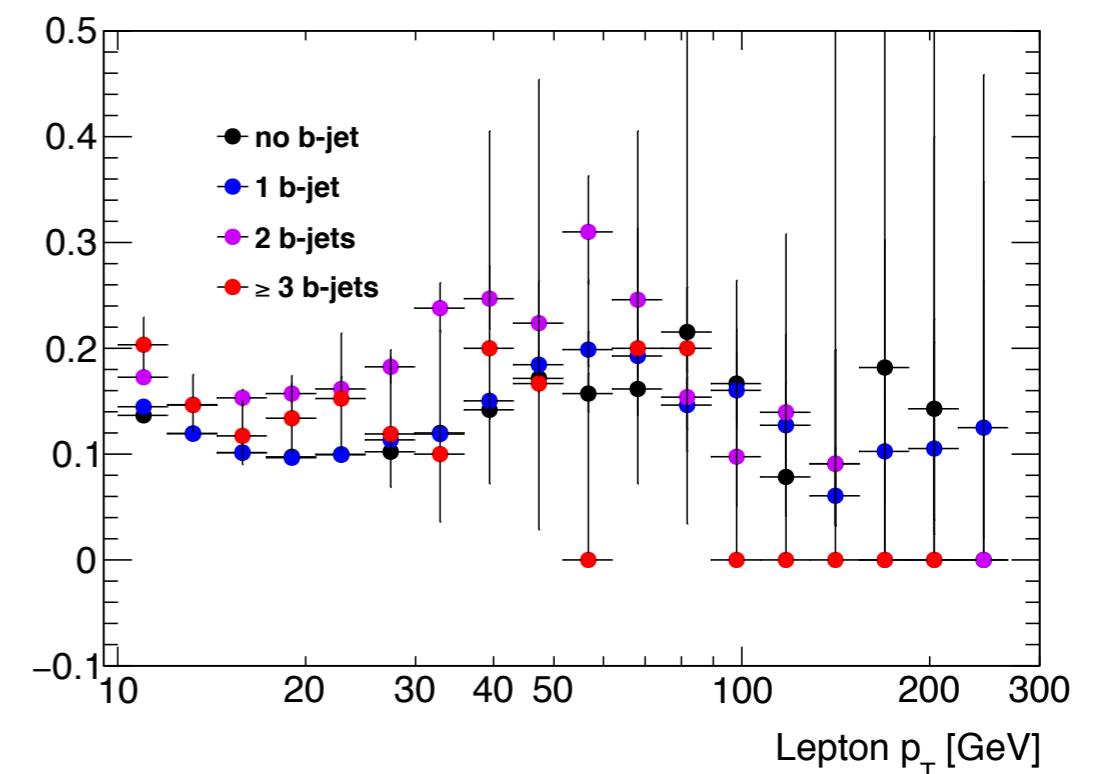
# Fake rate and b-jets

- Measurement done in  $\geq 1$  b-jet region, but some regions have 0-bjet or  $\geq 2$  b-jet: variable fraction of heavy flavor decays

Electron



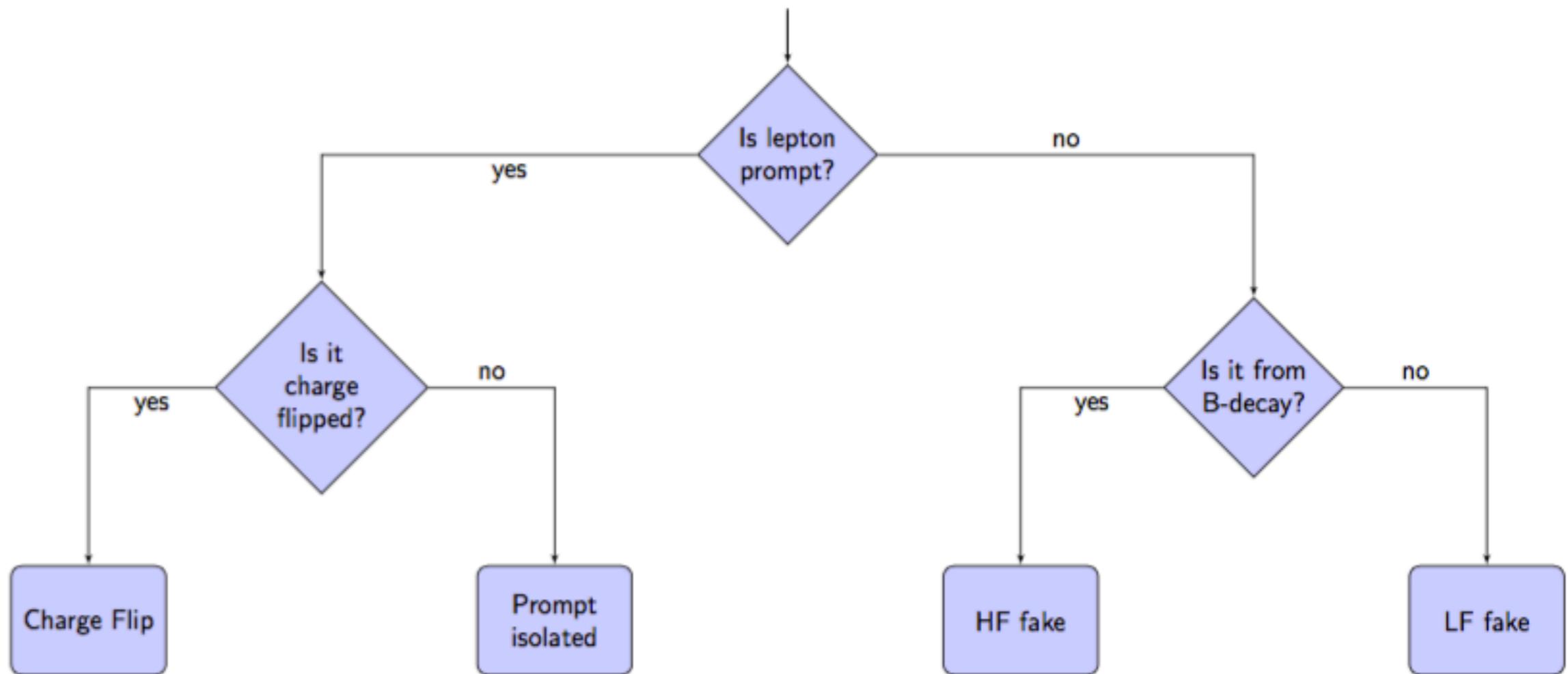
Muon



- Assign additional correction to the fake rate and systematic to account for differences

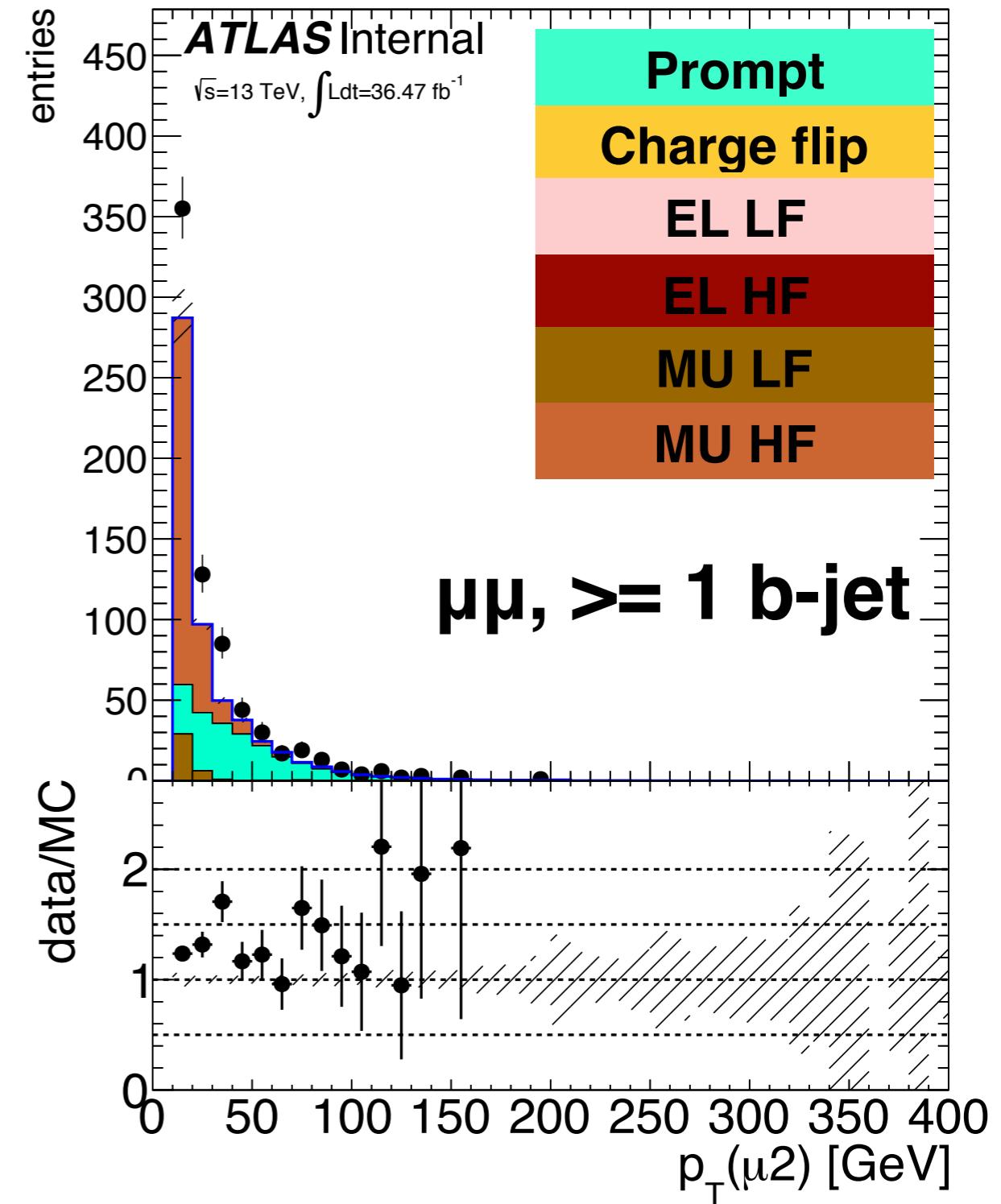
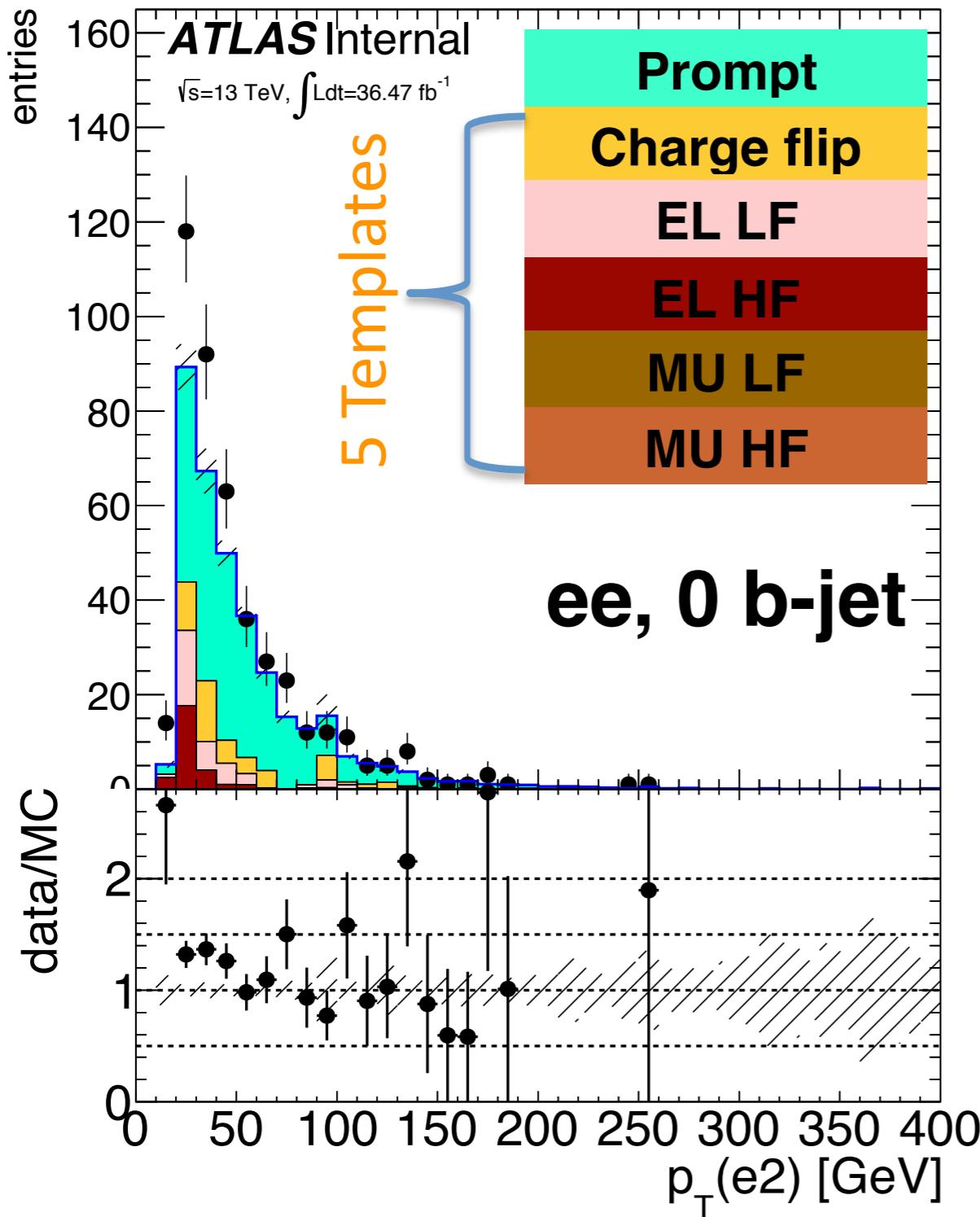
# MC Template Method

- Assume that the **kinematic distributions are modeled correctly** but the **rate is off** by a constant fraction independent of the selection
- Obtain **5 MC corrections** by a simultaneous fit in **6 CRs** with **0 b-jet and  $\geq 1$  b-jet** to constrain **LF and HF**, and **ee/e $\mu$ / $\mu\mu$**  to get different handles on **charge flip, e and  $\mu$  fake rates**



# MC Template Method

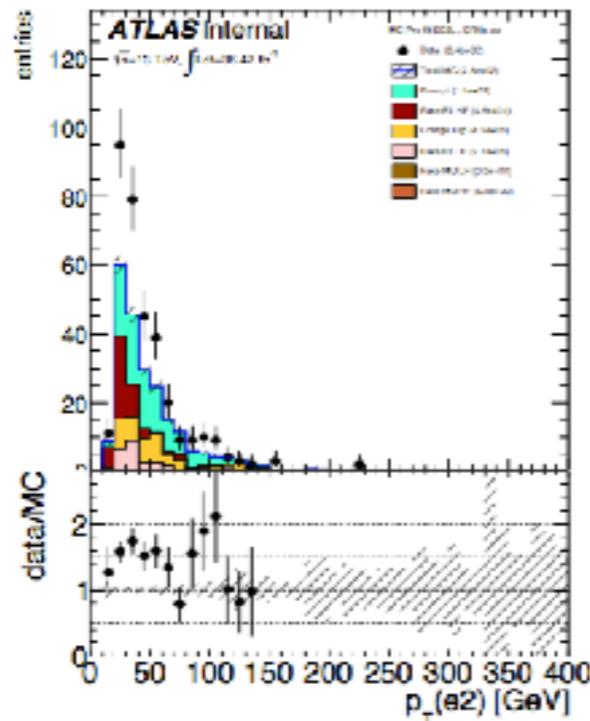
- Distributions chosen with discrimination power



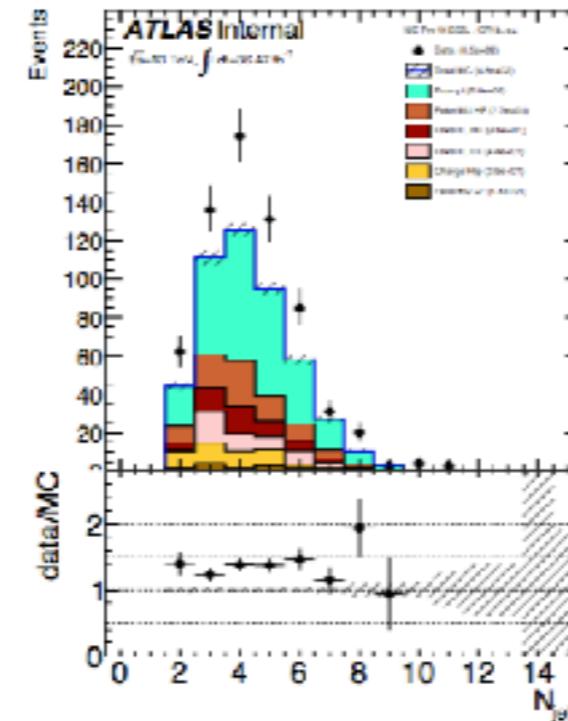
# MC Template Method

- Fit recovers MC mis-modeling in CR with 0 b-jet

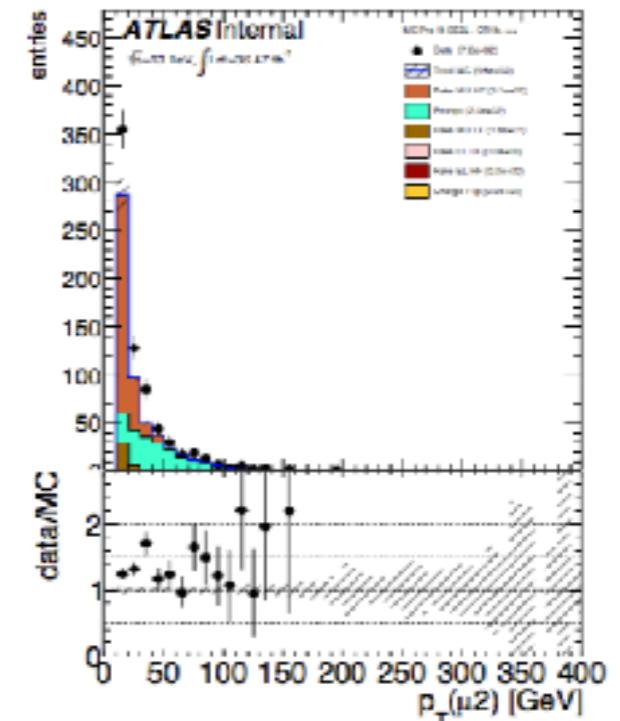
ee



e $\mu$

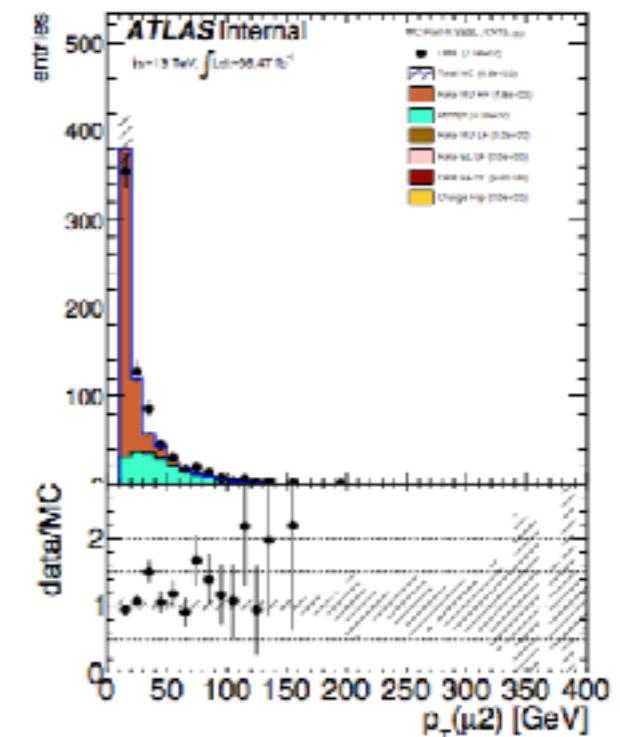
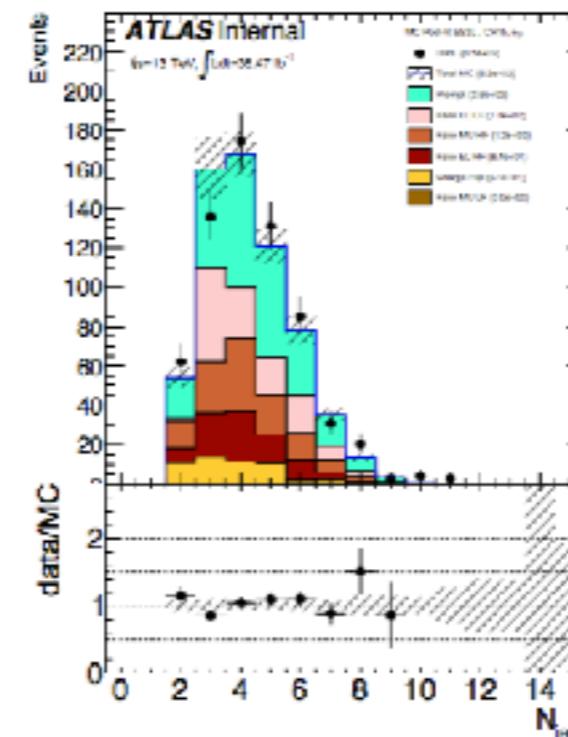
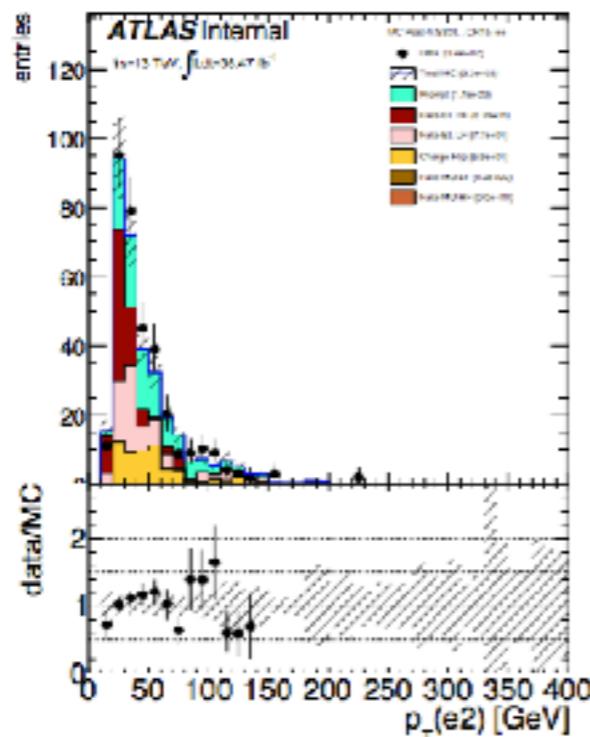


$\mu\mu$



Pre-fit

Post-fit



# MC Template Method

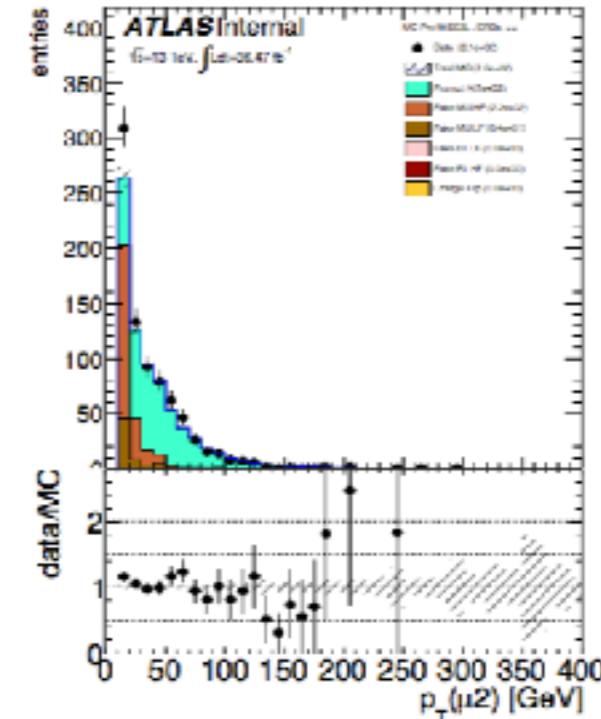
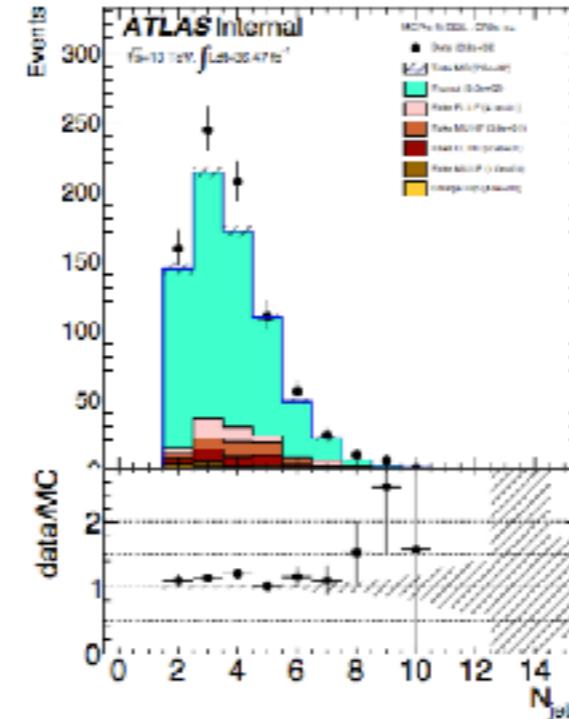
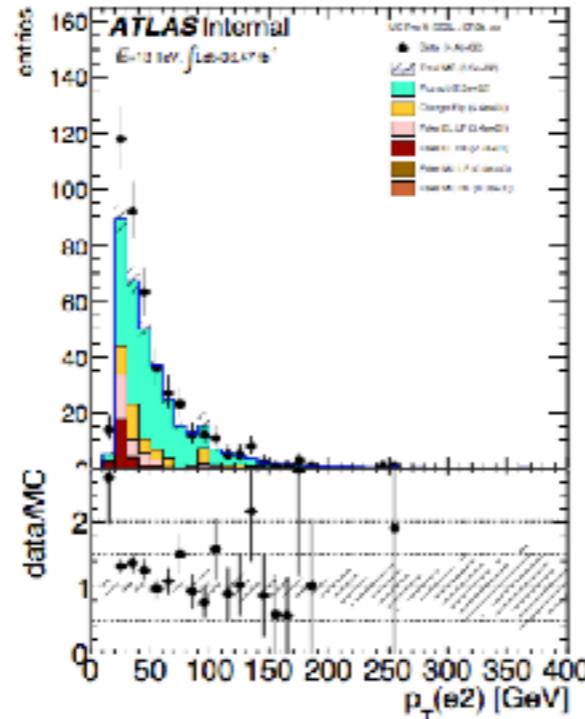
- Fit recovers MC mis-modeling in CR with  $\geq 1$  b-jet

ee

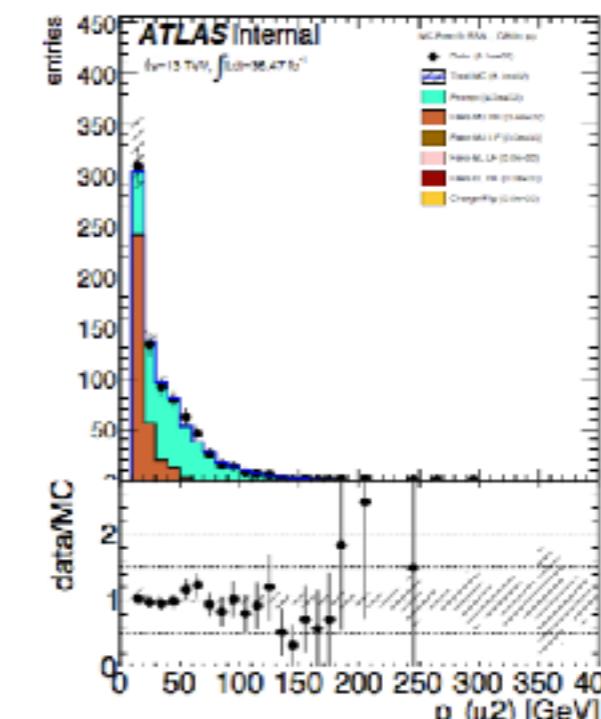
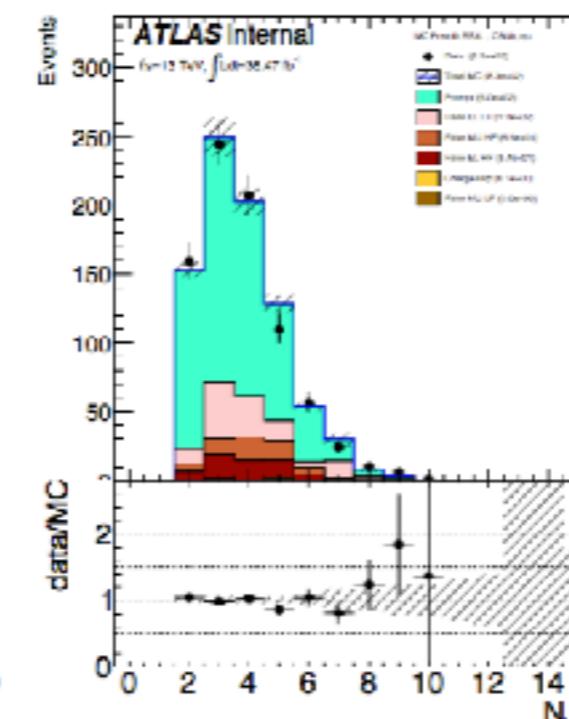
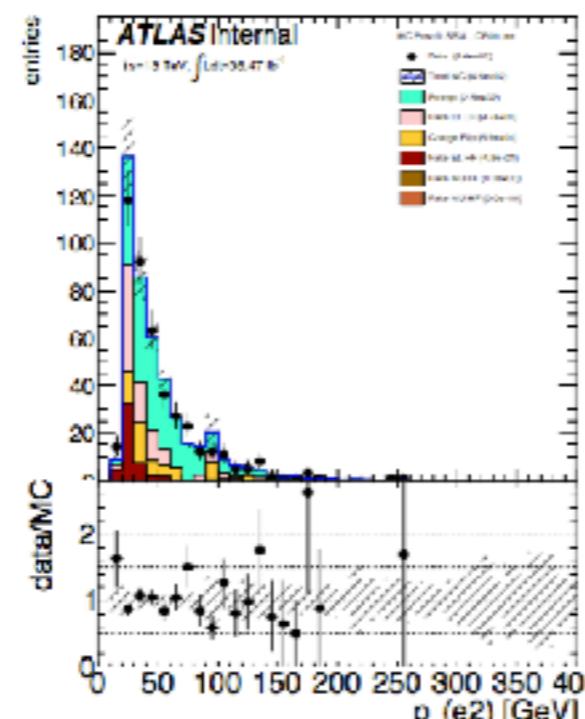
e $\mu$

$\mu\mu$

Pre-fit



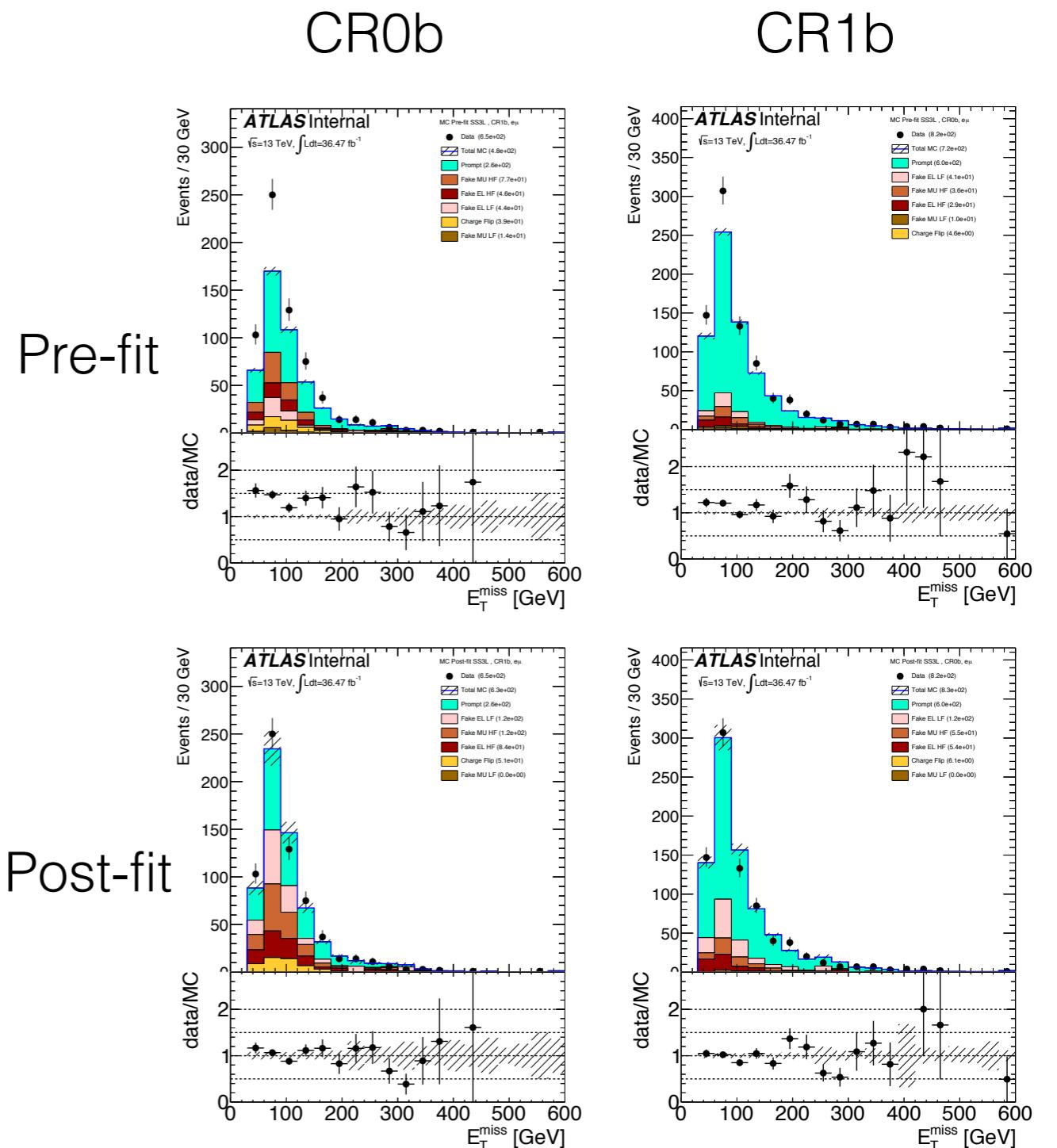
Post-fit



# MC Template Method

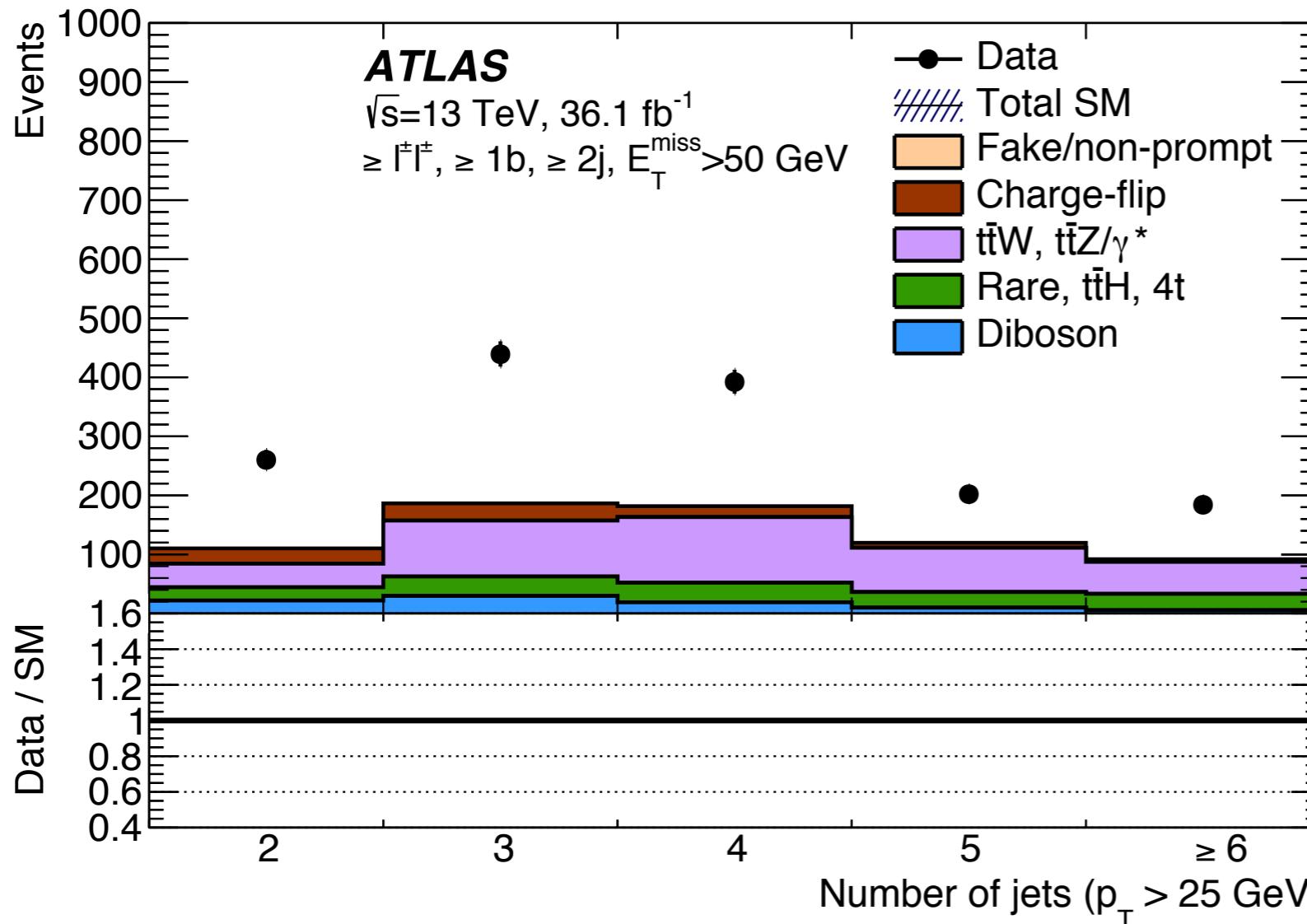
- Distributions other than the ones used in the fit show a reasonable agreement between Data/MC
- The optimization procedure relies on the MC template results

Category	Correction	Uncertainty
chFlip	1.34	0.58
HF EL	2.40	0.85
LF EL	1.83	1.04
HF MU	1.17	0.16
LF MU	2.40	0.81



# Data vs. Expectation

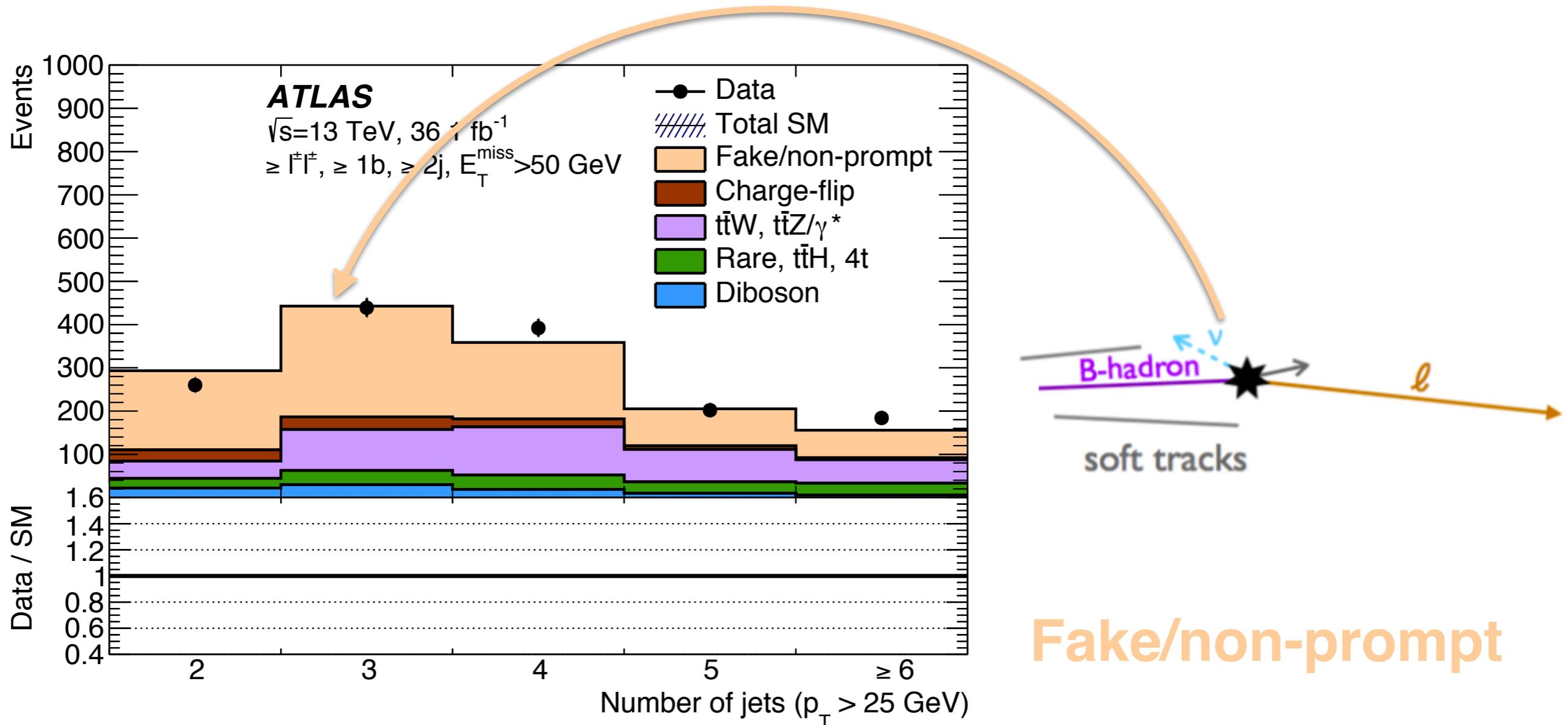
Detector background from data-driven:



Remember!

# Data vs. Expectation

Detector background from data-driven:



Much better! But need uncertainties

# Uncertainties

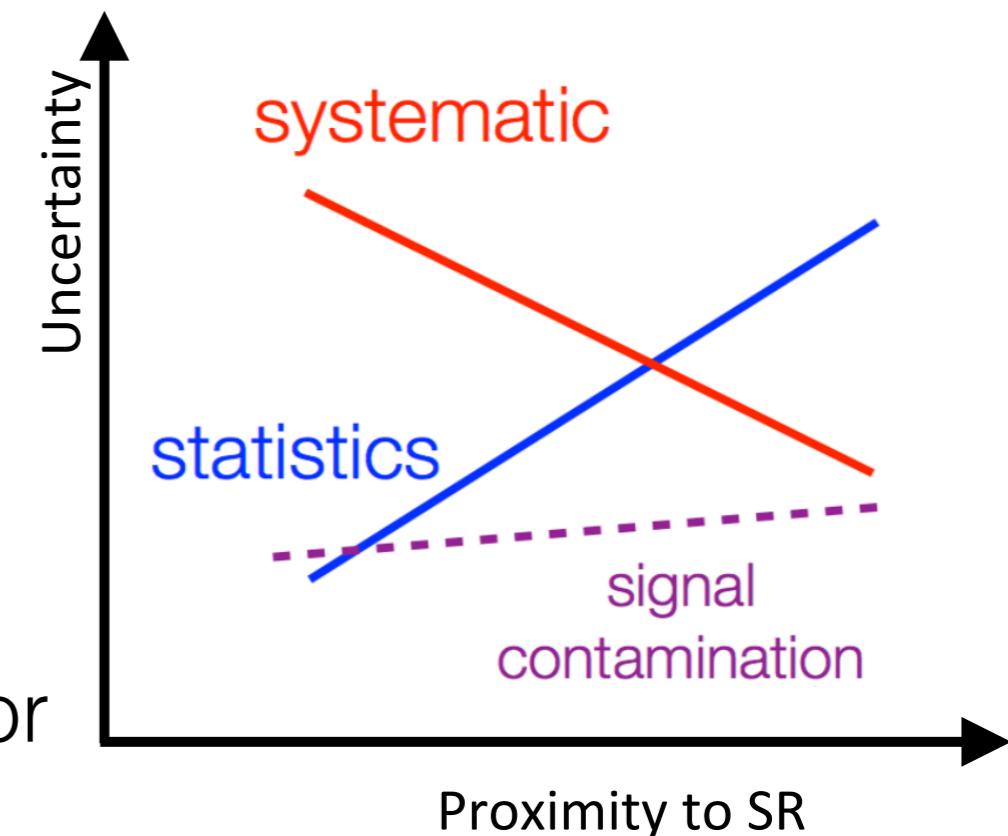
Accuracy of the theoretical and experimental modeling in the MC simulations

- Jet Energy Scale, Jet Energy Resolution, b-tagging, ...
- Theoretical modeling
  - ttV: different generators, renormalization and factorization scale variations -> **13-15% theory unc.**
  - VV: QCD and matching scales variations, parton shower, and recoil scheme -> **30-40% theory unc.**
  - Rare -> **50% theory unc.**
  - Cross-section uncertainties  
-> **13% for ttW, 12% for ttZ, 6% for VV, and 8% for ttH**
- Statistical unc. of the MC simulation

# Uncertainties

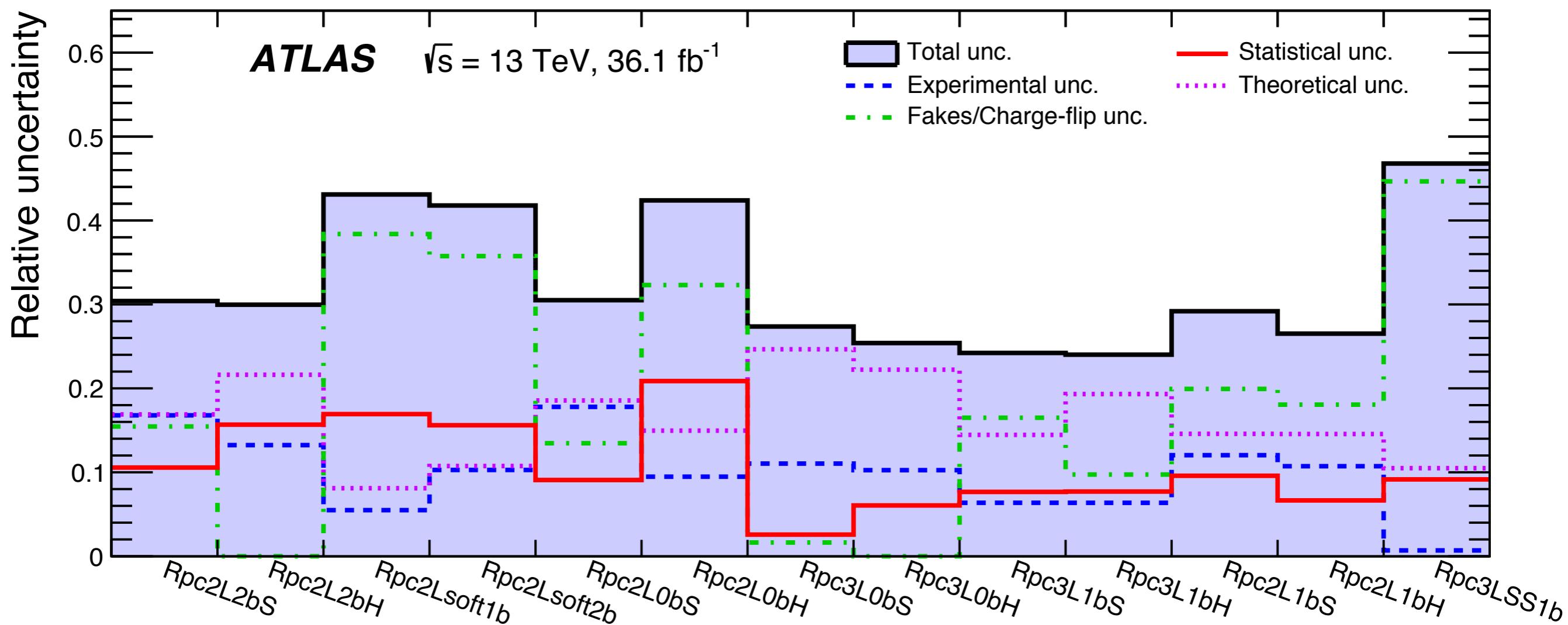
Detector background systematic uncertainties:

- Electron charge flip:
  - Lack of statistics, background subtraction  
-> **below 20%**
- Fake and non-prompt leptons:
  - MxM: different composition of fake leptons between the CR and SR  
-> **30%-85% for muons**  
-> **50% for electrons**
  - MC template: variation of the generator  
-> **35-85%**
- Final sys. unc. are propagated assuming a full correlation



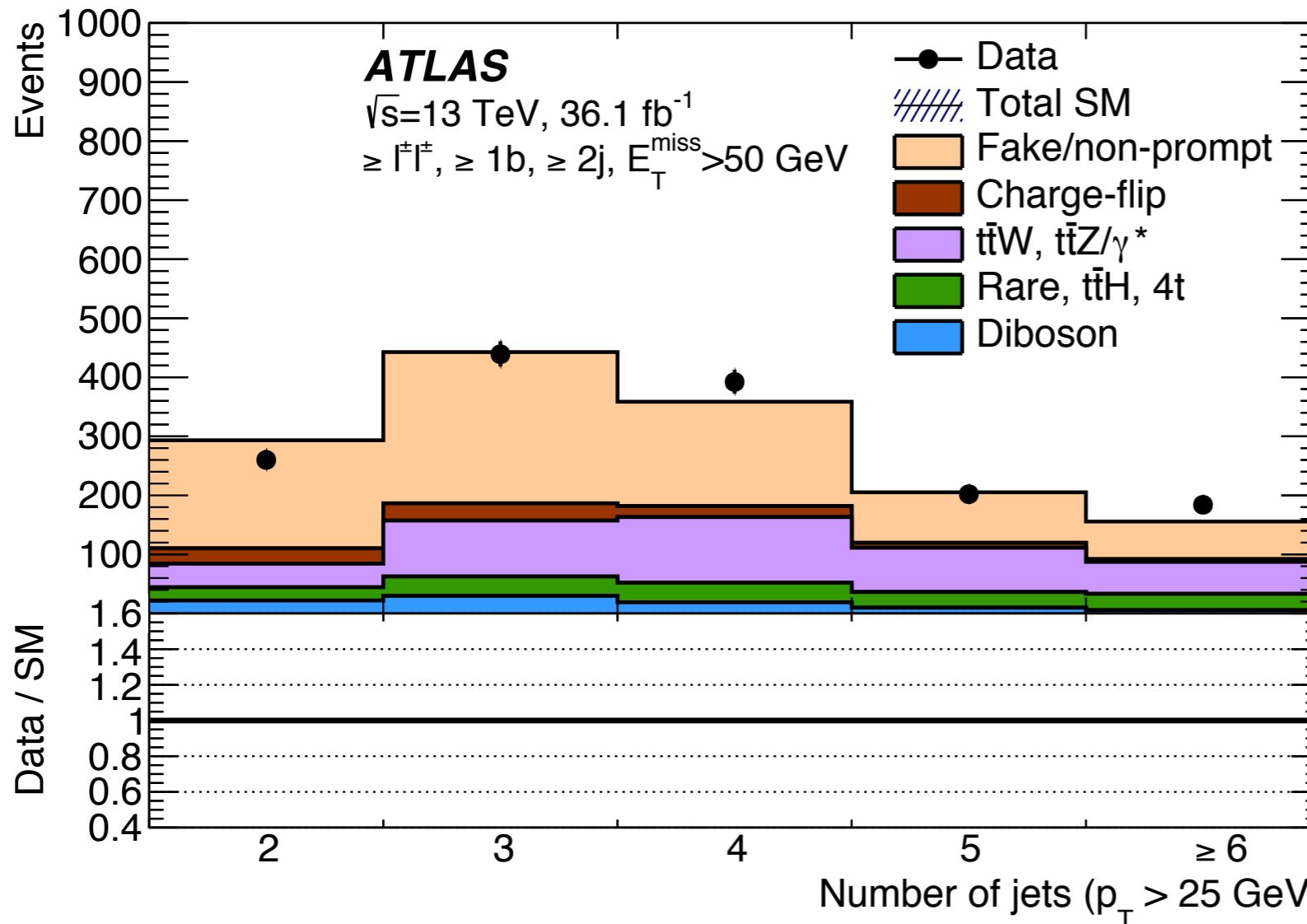
# Uncertainties

Summary of the uncertainties in the signal regions:  
dominated by detector uncertainties (green)



# Data vs. Expectation

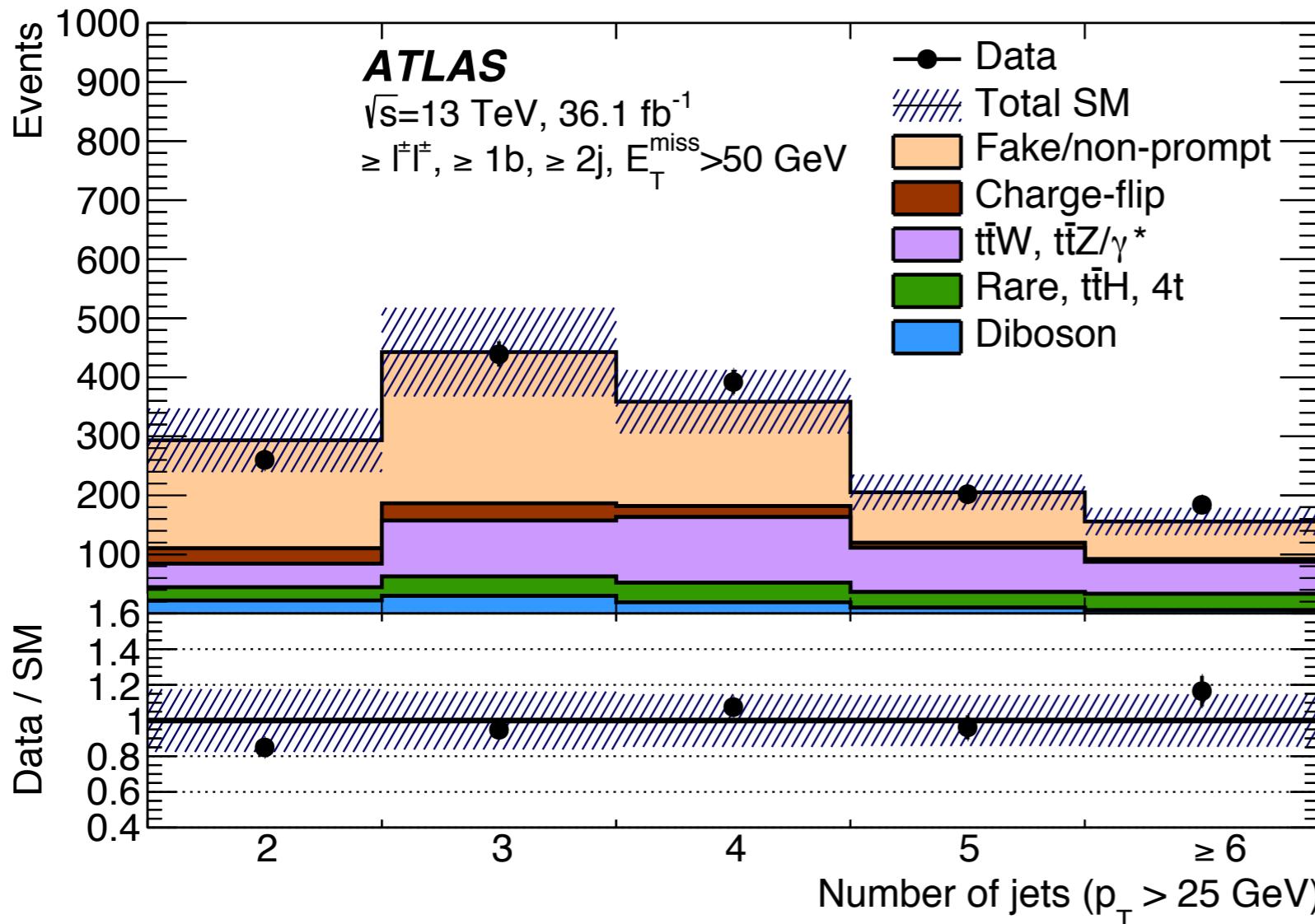
Detector background from data-driven:



Remember!

# Data vs. Expectation

Final estimate:

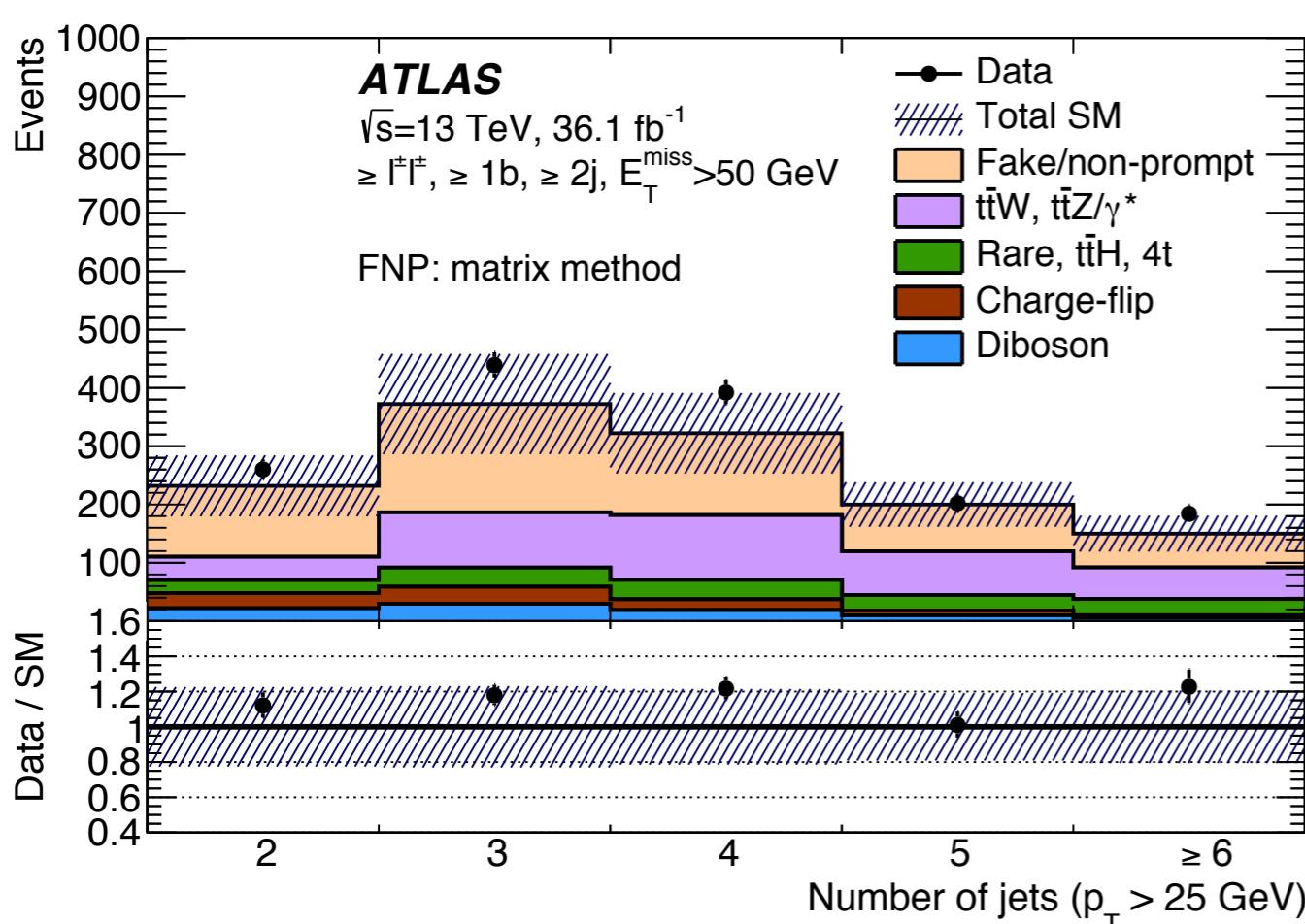


- Add ratio plot and uncertainties
- Good agreement!

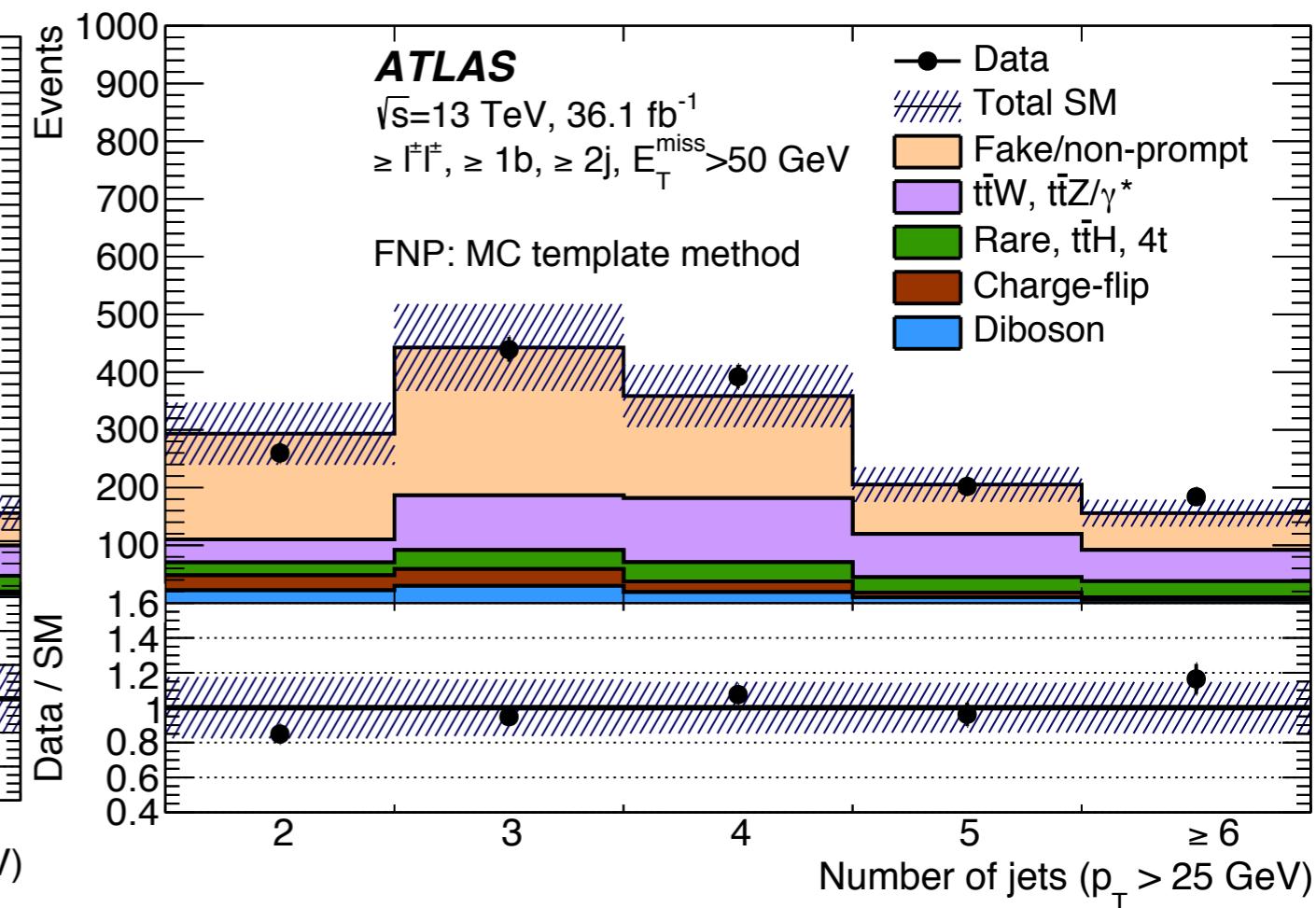
# MxM vs. MC template

Excellent agreement in fake enriched regions for both:

Matrix method



MC template

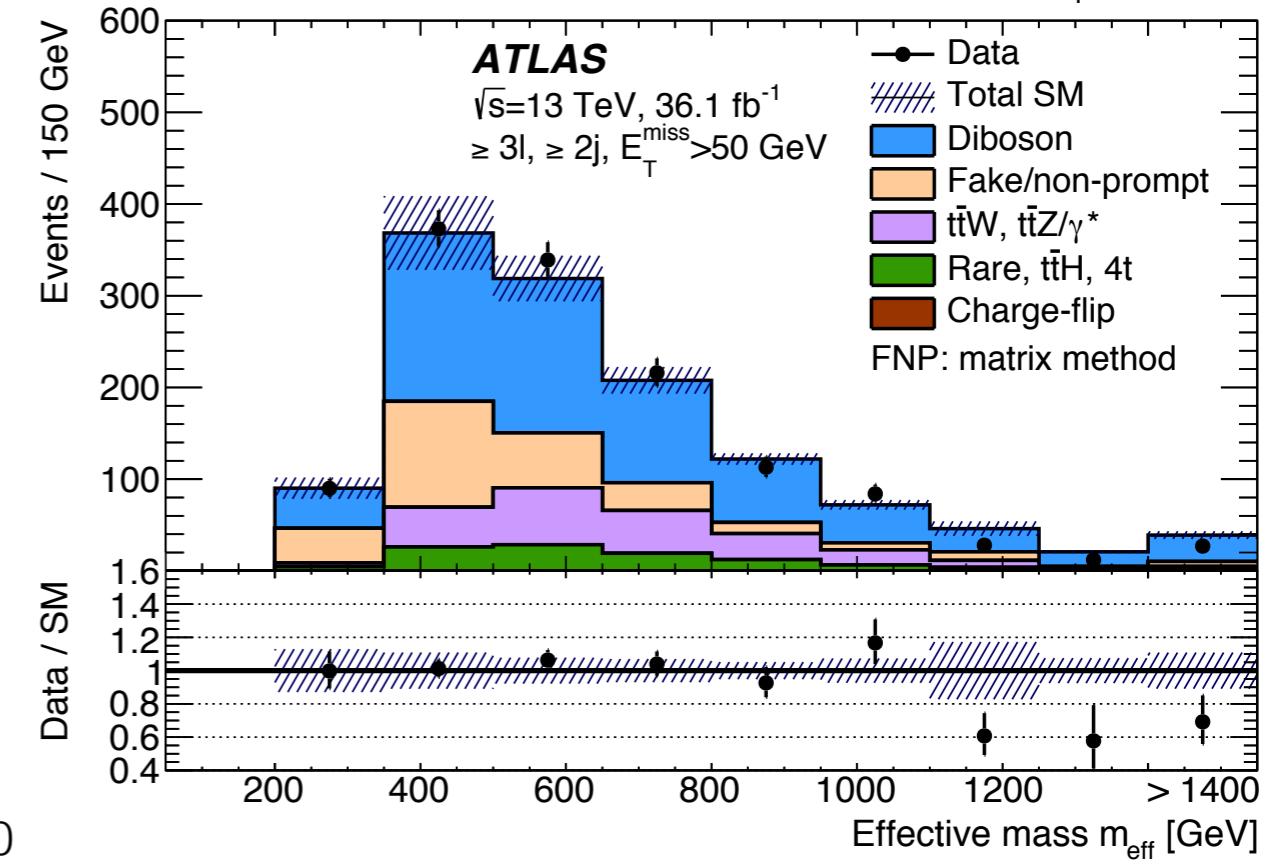
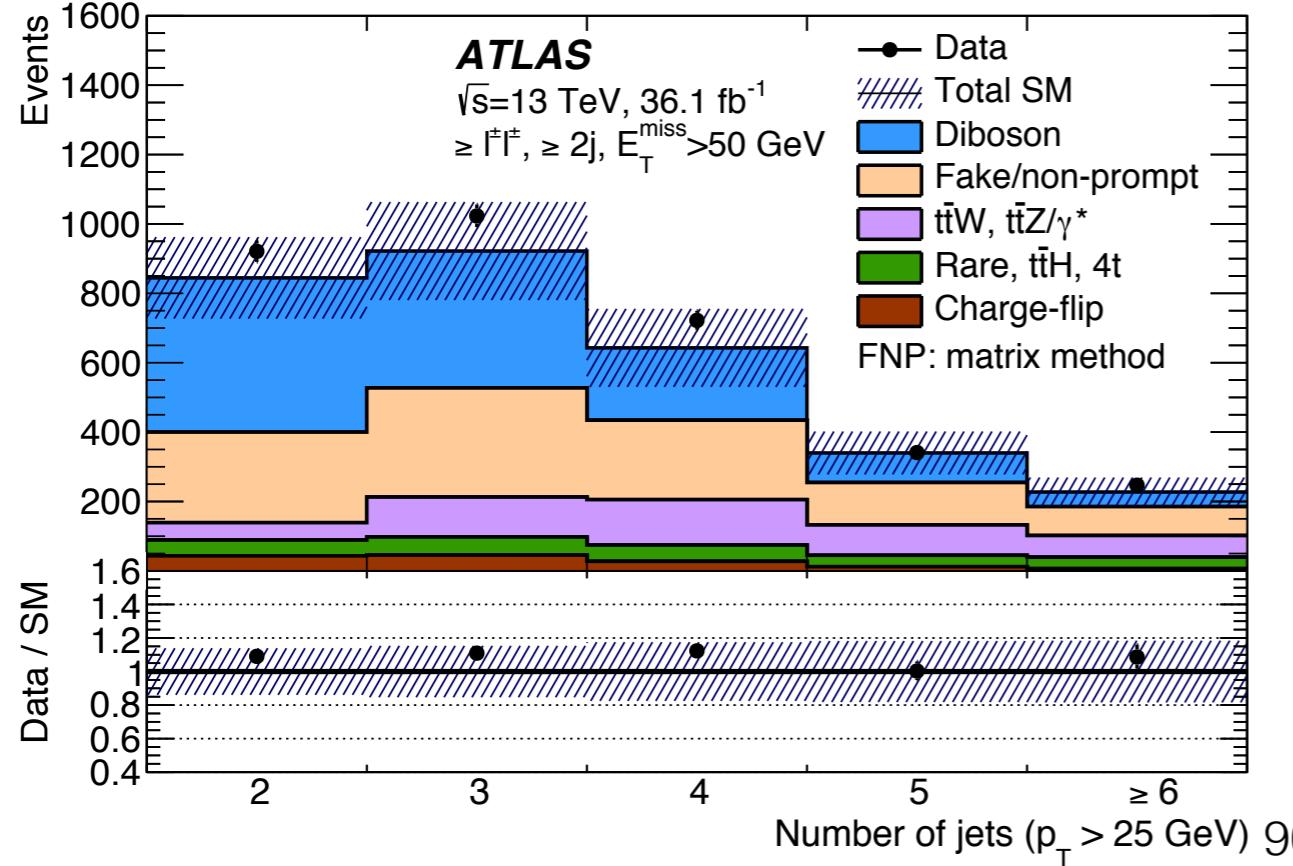
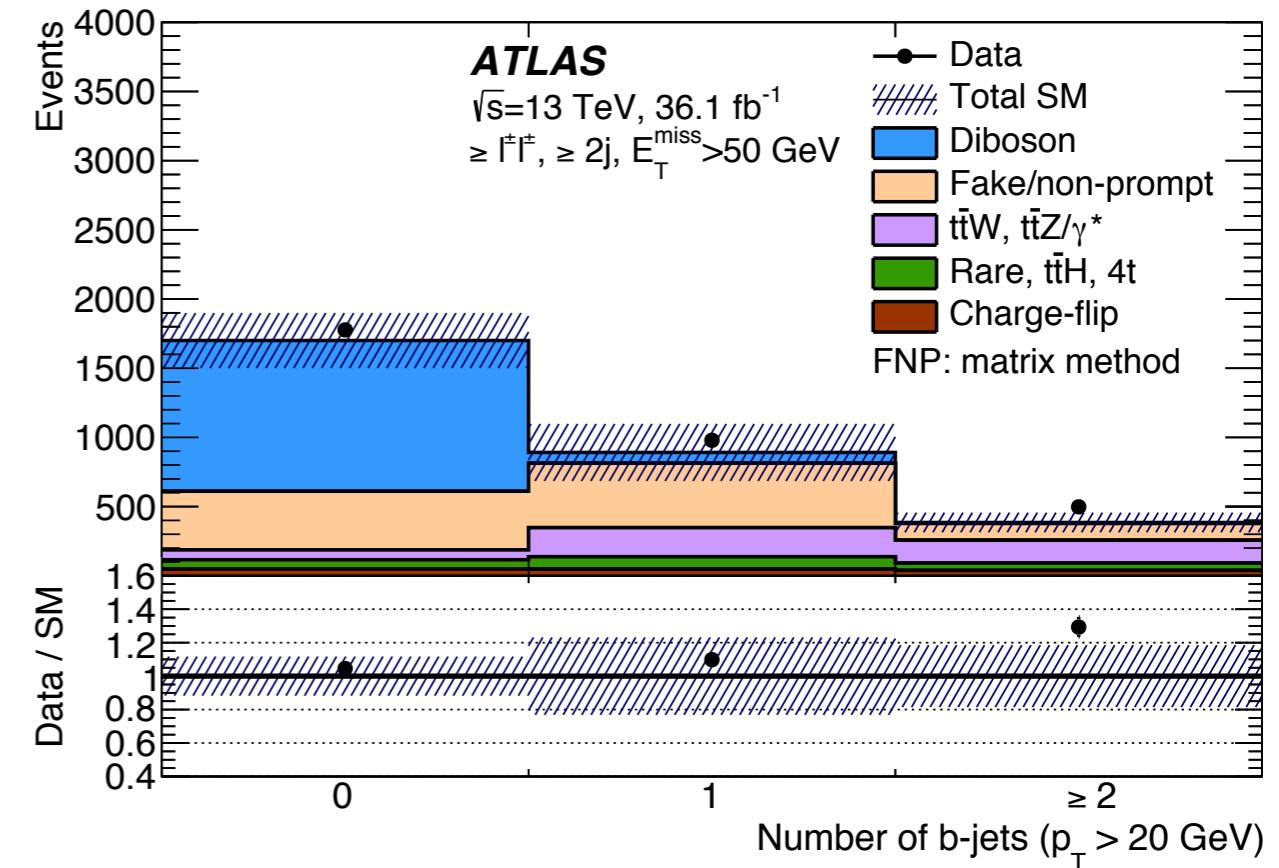
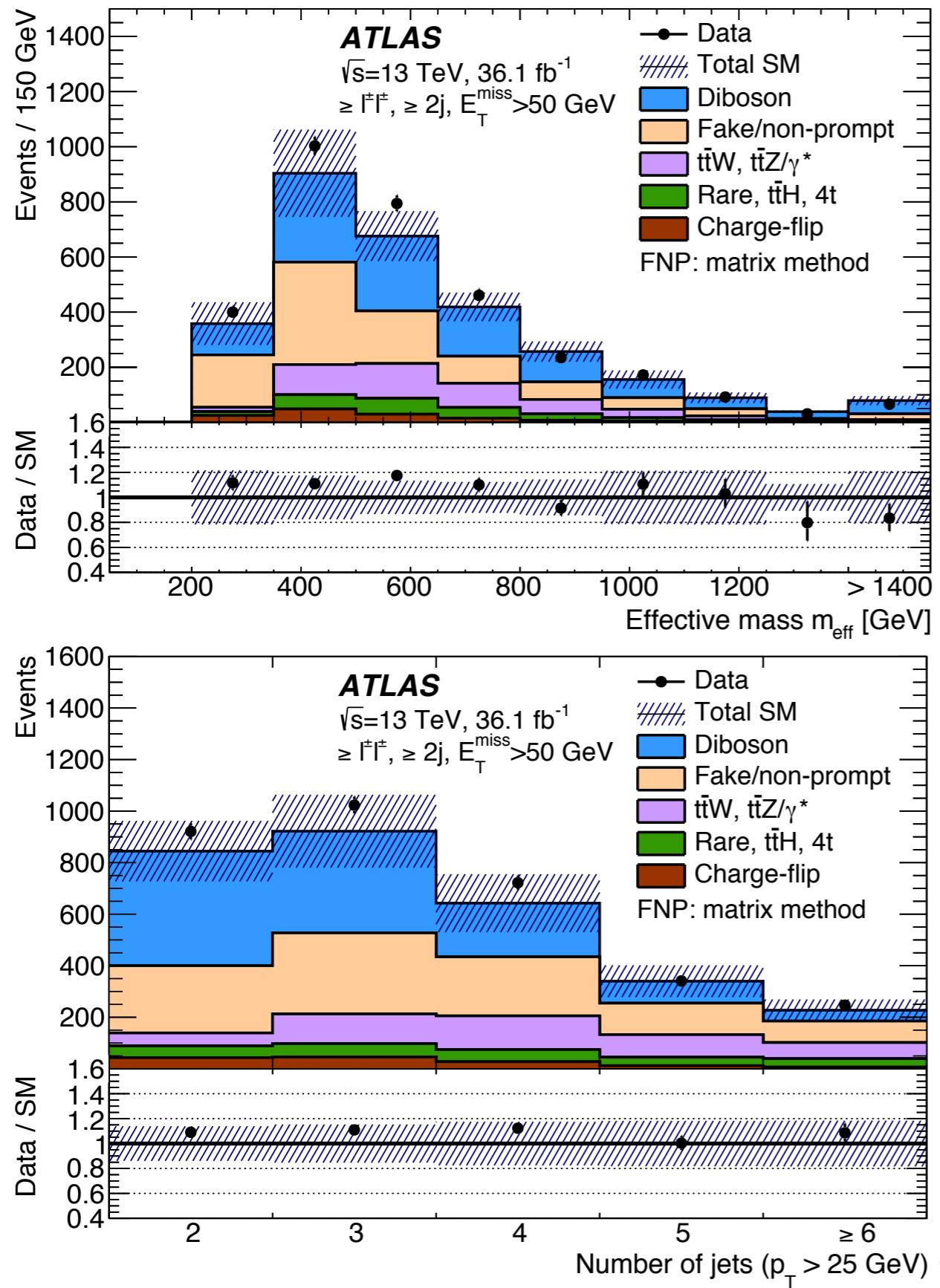


# Background validation

- Regions designed to verify the estimates of the dominant SM processes:  $t\bar{t}W$ ,  $t\bar{t}Z$ ,  $WZ$ , and  $W^\pm W^\pm$
- Overall **good agreement** between data and estimated SM background

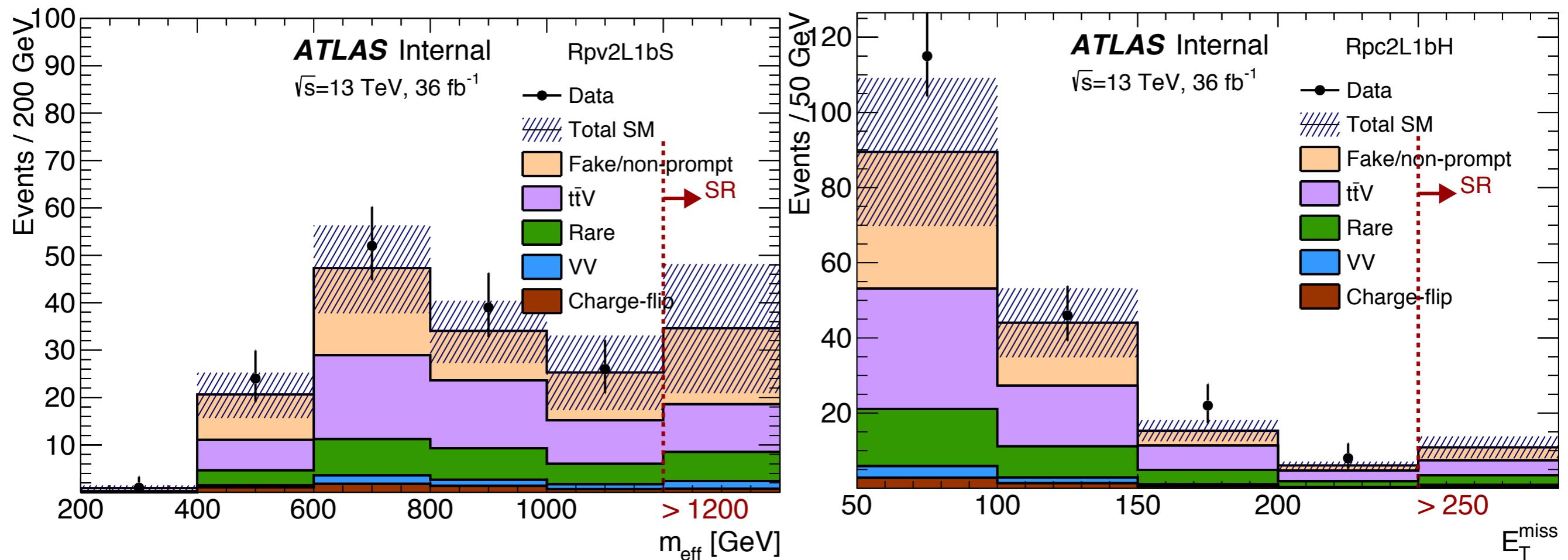
Validation Regions	$t\bar{t}W$	$t\bar{t}Z$	$WZ4j$	$WZ5j$	$W^\pm W^\pm jj$
$t\bar{t}Z/\gamma^*$	$6.2 \pm 0.9$	$123 \pm 17$	$17.8 \pm 3.5$	$10.1 \pm 2.3$	$1.06 \pm 0.22$
$t\bar{t}W$	$19.0 \pm 2.9$	$1.71 \pm 0.27$	$1.30 \pm 0.32$	$0.45 \pm 0.14$	$4.1 \pm 0.8$
$t\bar{t}H$	$5.8 \pm 1.2$	$3.6 \pm 1.8$	$1.8 \pm 0.6$	$0.96 \pm 0.34$	$0.69 \pm 0.14$
$t\bar{t}t\bar{t}$	$1.02 \pm 0.22$	$0.27 \pm 0.14$	$0.04 \pm 0.02$	$0.03 \pm 0.02$	$0.03 \pm 0.02$
$W^\pm W^\pm$	$0.5 \pm 0.4$	--	--	--	$26 \pm 14$
$WZ$	$1.4 \pm 0.8$	$29 \pm 17$	$200 \pm 110$	$70 \pm 40$	$27 \pm 14$
$ZZ$	$0.04 \pm 0.03$	$5.5 \pm 3.1$	$22 \pm 12$	$9 \pm 5$	$0.53 \pm 0.30$
Rare	$2.2 \pm 0.5$	$26 \pm 13$	$7.3 \pm 2.1$	$3.0 \pm 1.0$	$1.8 \pm 0.5$
Fake/non-prompt leptons	$18 \pm 16$	$22 \pm 14$	$49 \pm 31$	$17 \pm 12$	$13 \pm 10$
Charge-flip	$3.4 \pm 0.5$	--	--	--	$1.74 \pm 0.22$
<b>Total SM background</b>	$57 \pm 16$	$212 \pm 35$	$300 \pm 130$	$110 \pm 50$	$77 \pm 31$
<b>Observed</b>	71	209	257	106	99

# Background validation



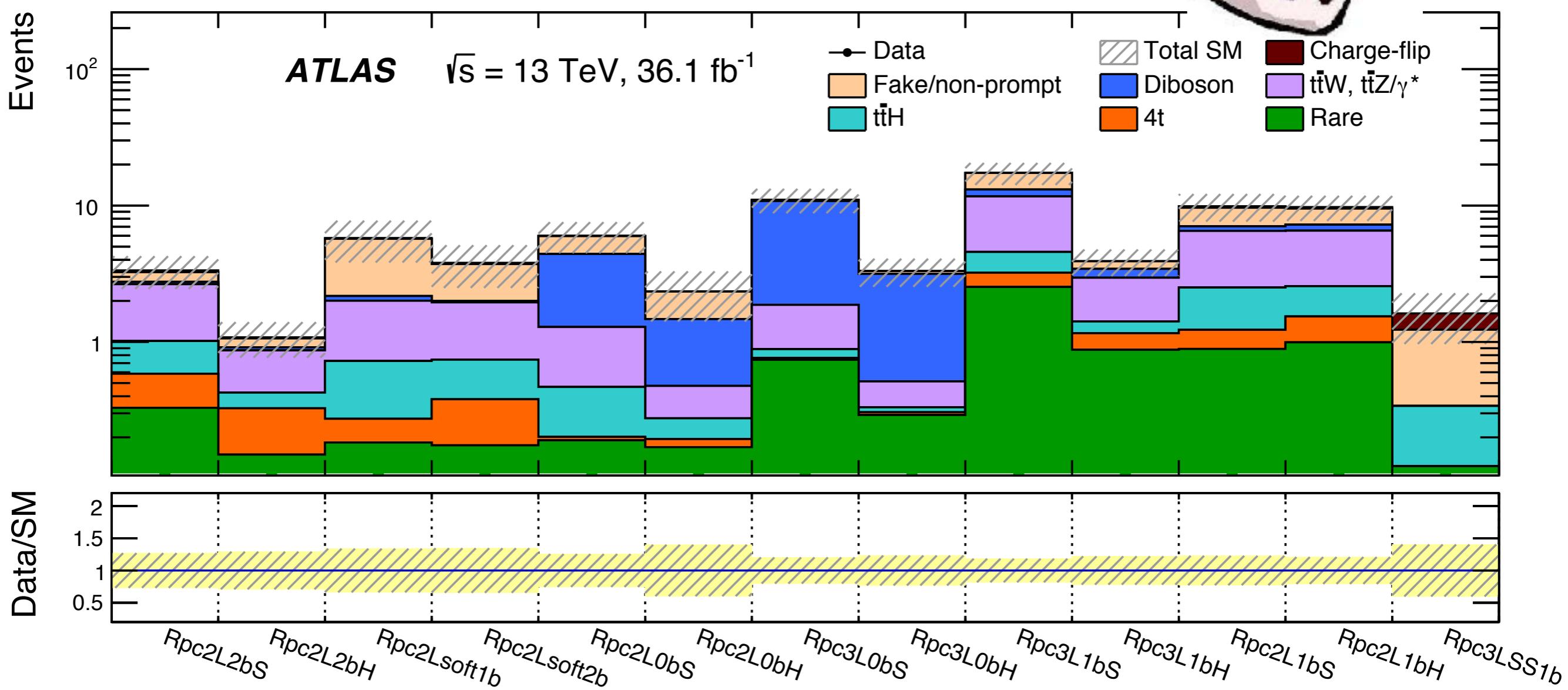
# Background validation

Very good agreement near the search regions (blinded)



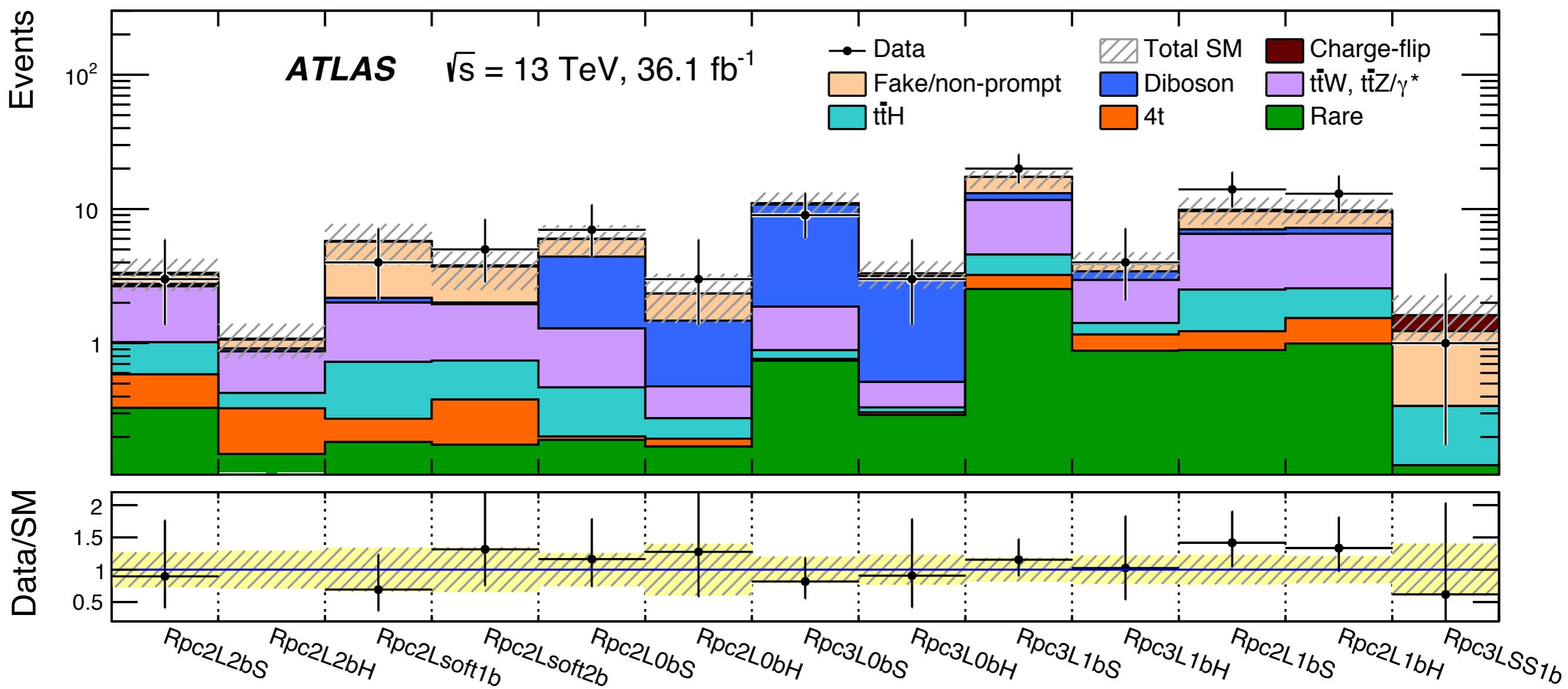
# Background Estimation

Background estimation completed,  
ready to open the box...



# Results

No significant deviation from the prediction



# Interpretation

- In the **absence** of any significant deviations from the predictions, model independent and model dependent exclusion limits are set at 95% CL ( $CL_s$ )

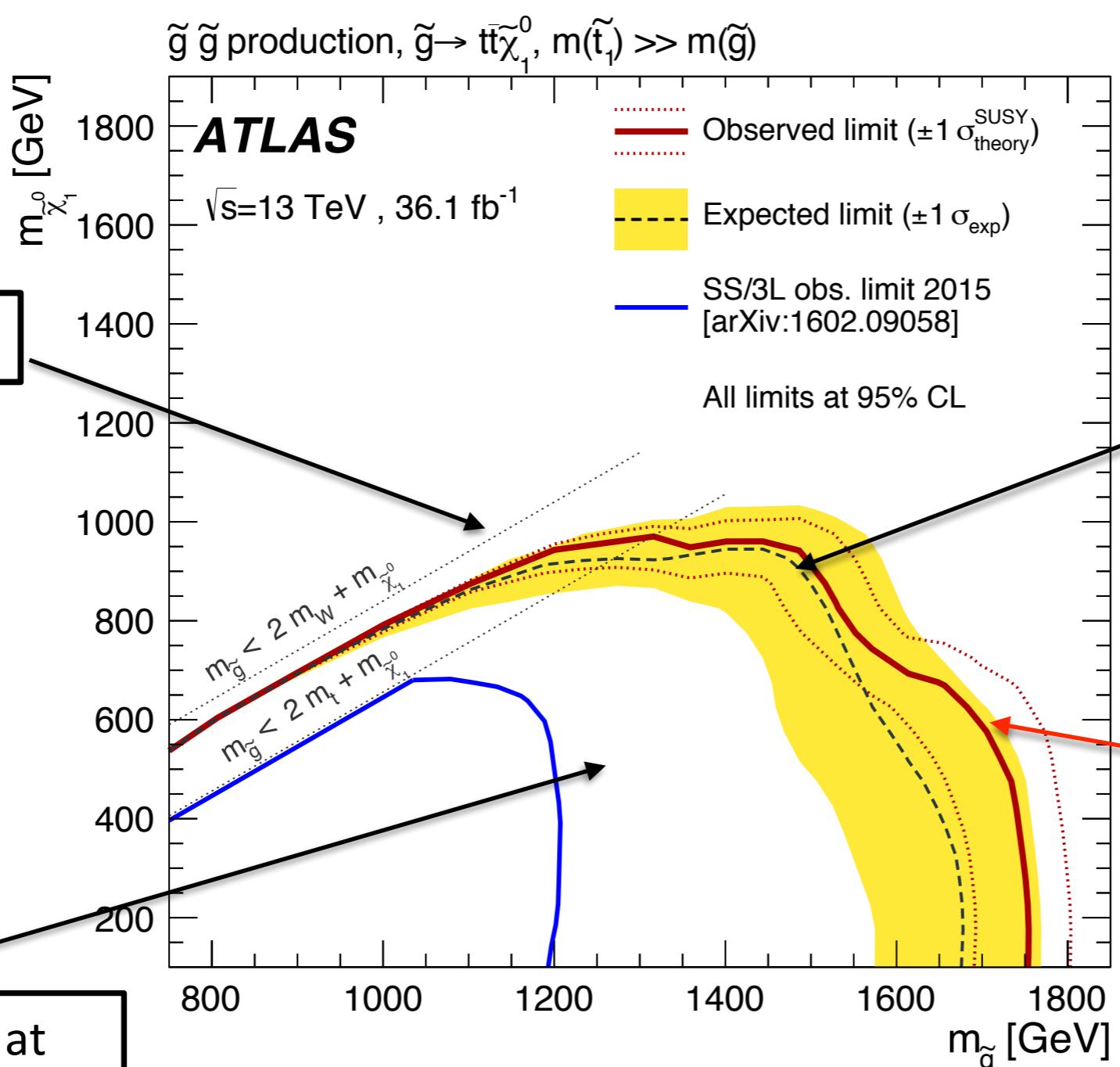
## Model Independent Limits

Signal Region	Rpc2L2bS	Rpc2L2bH	Rpc2Lsoft1b	Rpc2Lsoft2b	Rpc2L0bS	Rpc2L0bH
Total Background	$3.3 \pm 1.0$	$1.08 \pm 0.32$	$5.8 \pm 2.5$	$3.8 \pm 1.6$	$6.0 \pm 1.8$	$2.4 \pm 1.0$
Observed	3	0	4	5	7	3
$S_{\text{obs}}^{95}$ $p_0 (Z)$	5.5 0.71 (-)	3.6 0.91 (-)	6.3 0.69 (-)	7.7 0.30 ( $0.5\sigma$ )	8.3 0.36 ( $0.4\sigma$ )	6.1 0.35 ( $0.4\sigma$ )

Signal Region	Rpc3L0bS	Rpc3L0bH	Rpc3L1bS	Rpc3L1bH	Rpc2L1bS	Rpc2L1bH	Rpc3LSS1b
Total Background	$11.0 \pm 3.0$	$3.3 \pm 0.8$	$17 \pm 4$	$3.9 \pm 0.9$	$9.8 \pm 2.9$	$9.8 \pm 2.6$	$1.6 \pm 0.8$
Observed	9	3	20	4	14	13	1
$S_{\text{obs}}^{95}$ $p_0 (Z)$	8.3 0.72 (-)	5.4 0.85 (-)	14.7 0.32 ( $0.5\sigma$ )	6.1 0.46 ( $0.1\sigma$ )	13.7 0.17 ( $1.0\sigma$ )	12.4 0.21 ( $0.8\sigma$ )	3.9 0.56 (-)

Discovery:  $Z = 5\sigma \sim p_0 = 3.10^{-7}$

# Model dependent



Expected mass limit

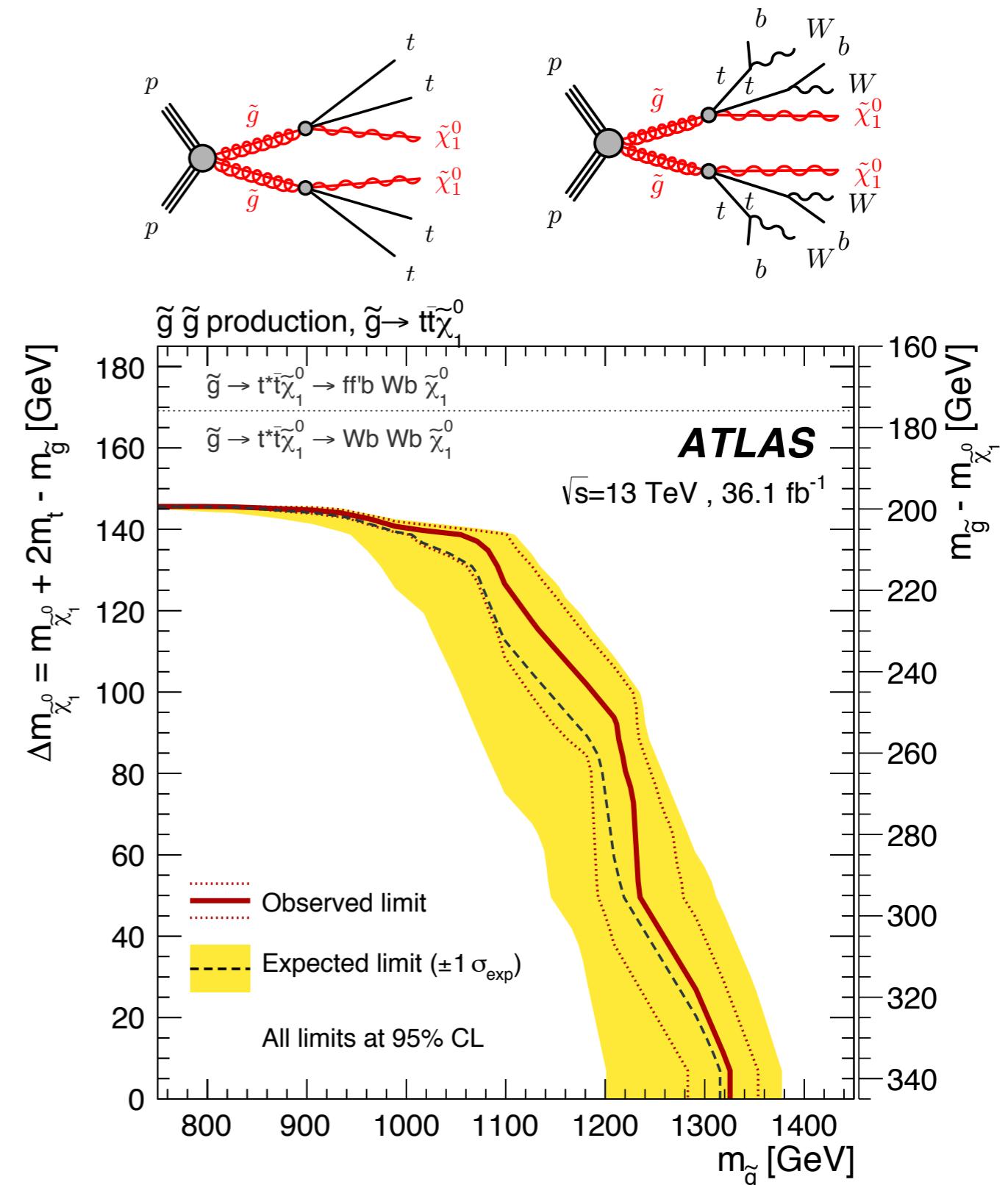
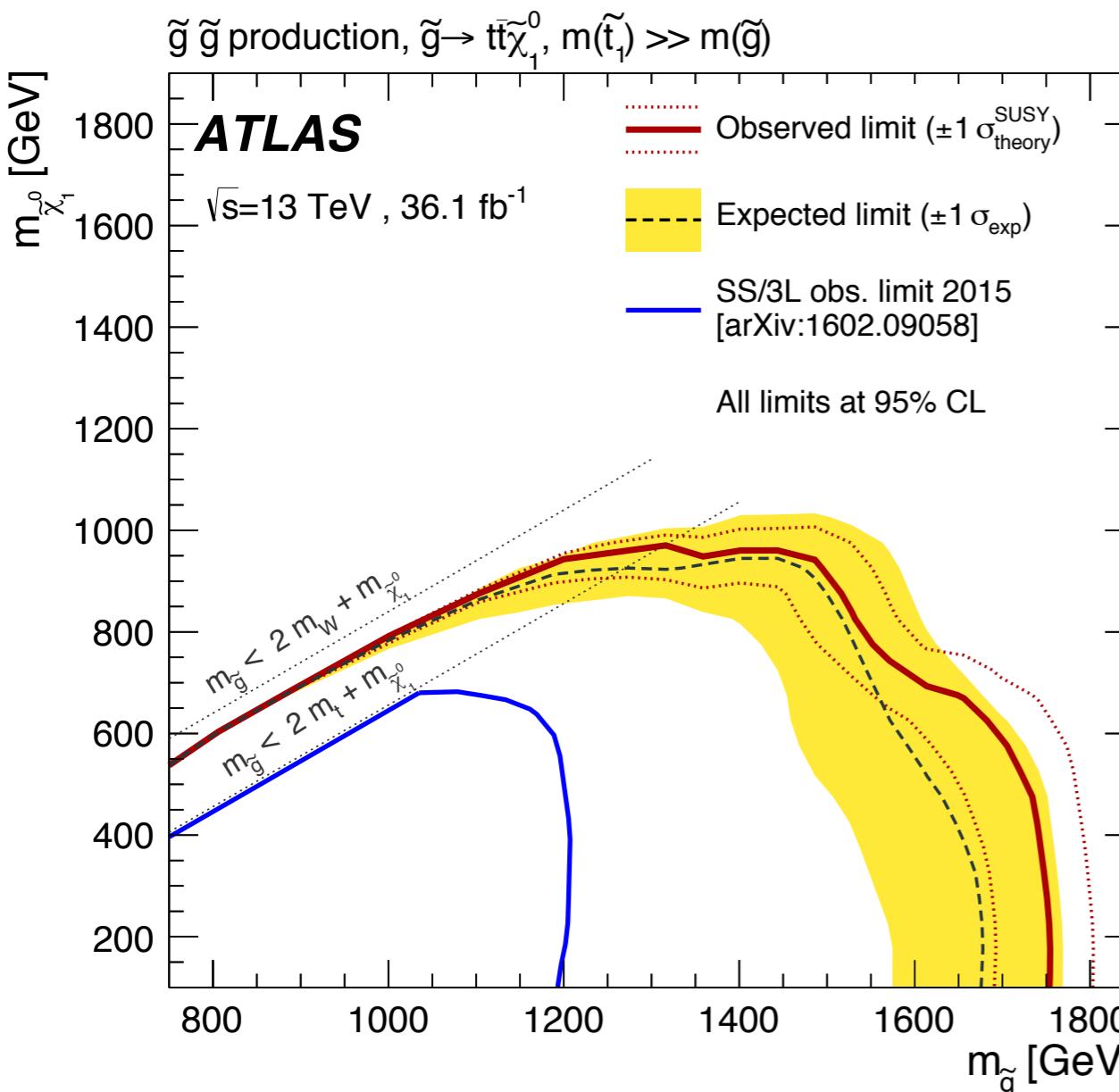
- At nominal production cross section
- $1\sigma$  variations due to stat+syst

Observed mass limit

- variations correspond to  $\pm 1\sigma$  uncertainty on total production cross section

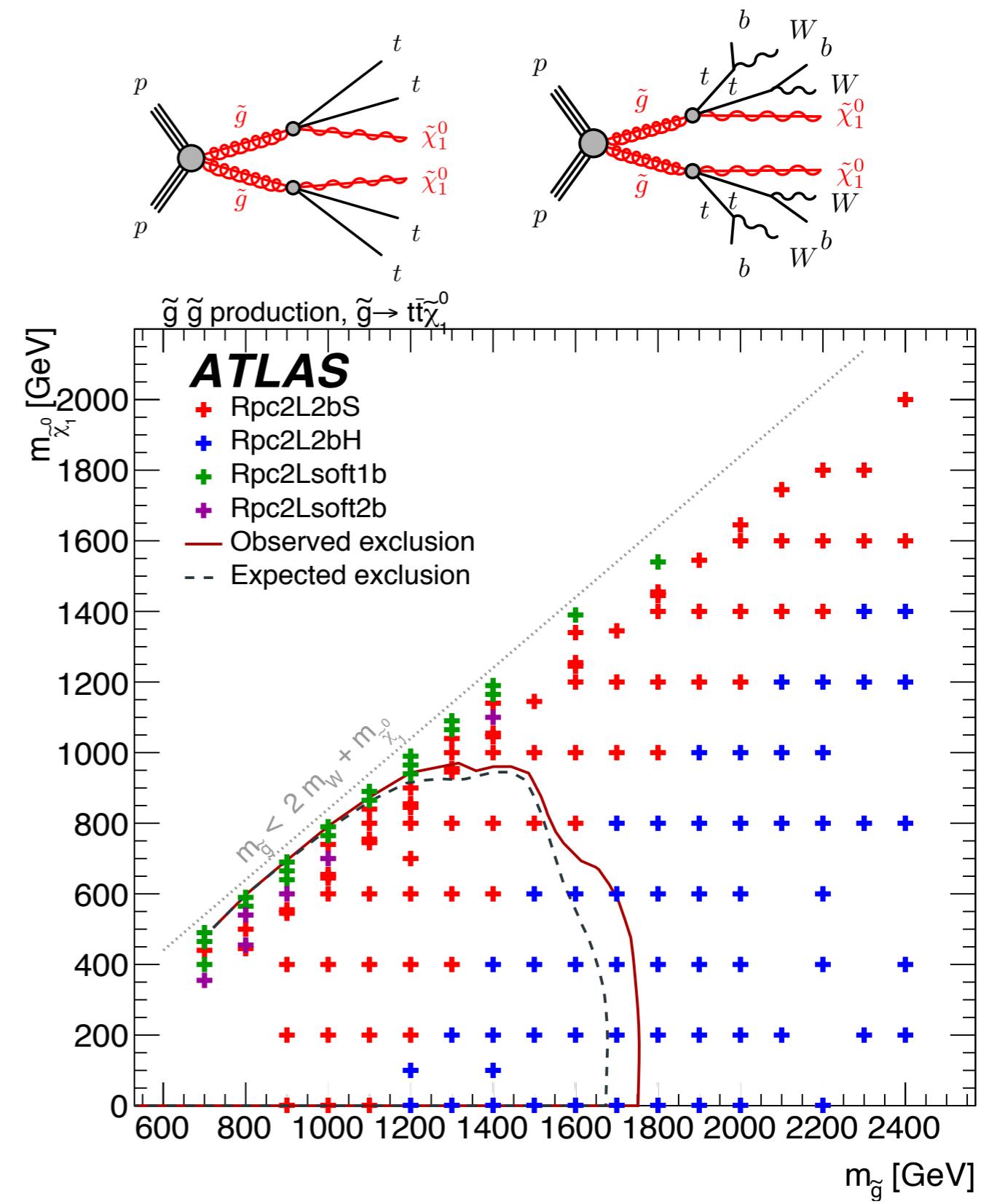
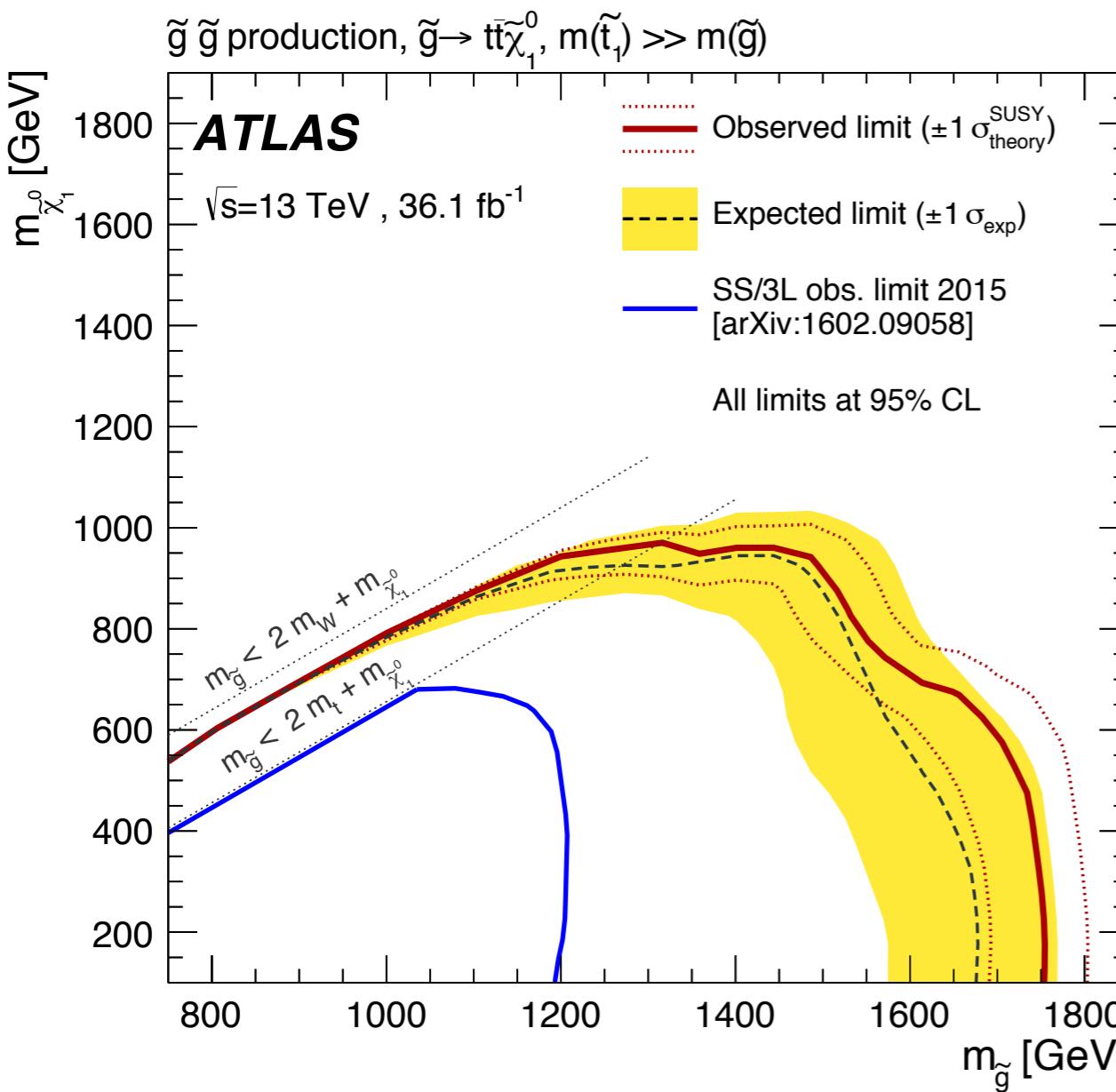
# Model dependent

- SRs: Rpc2L2bS, Rpc2L2bH, Rpc2Lsoft1b, Rpc2Lsoft2b



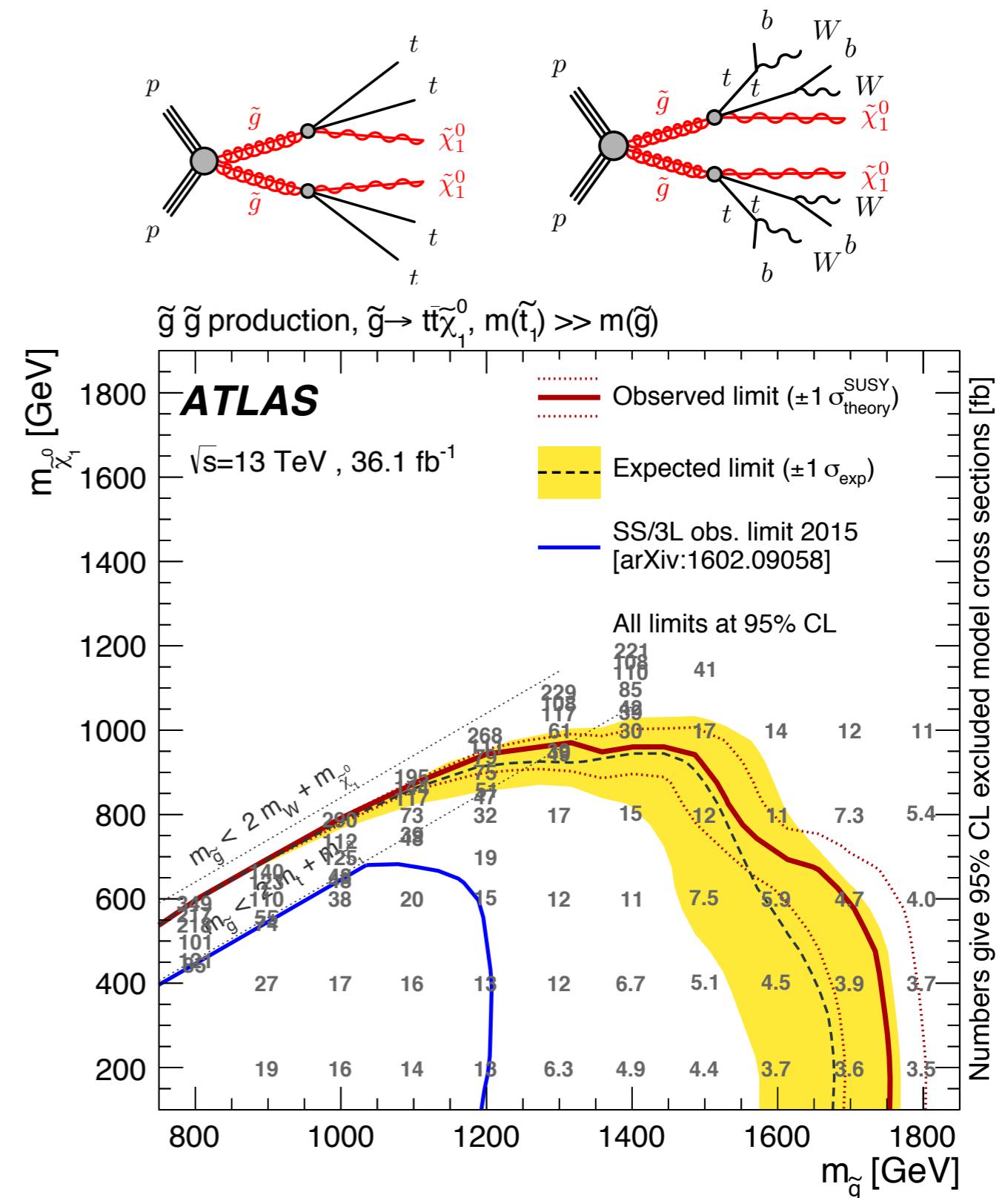
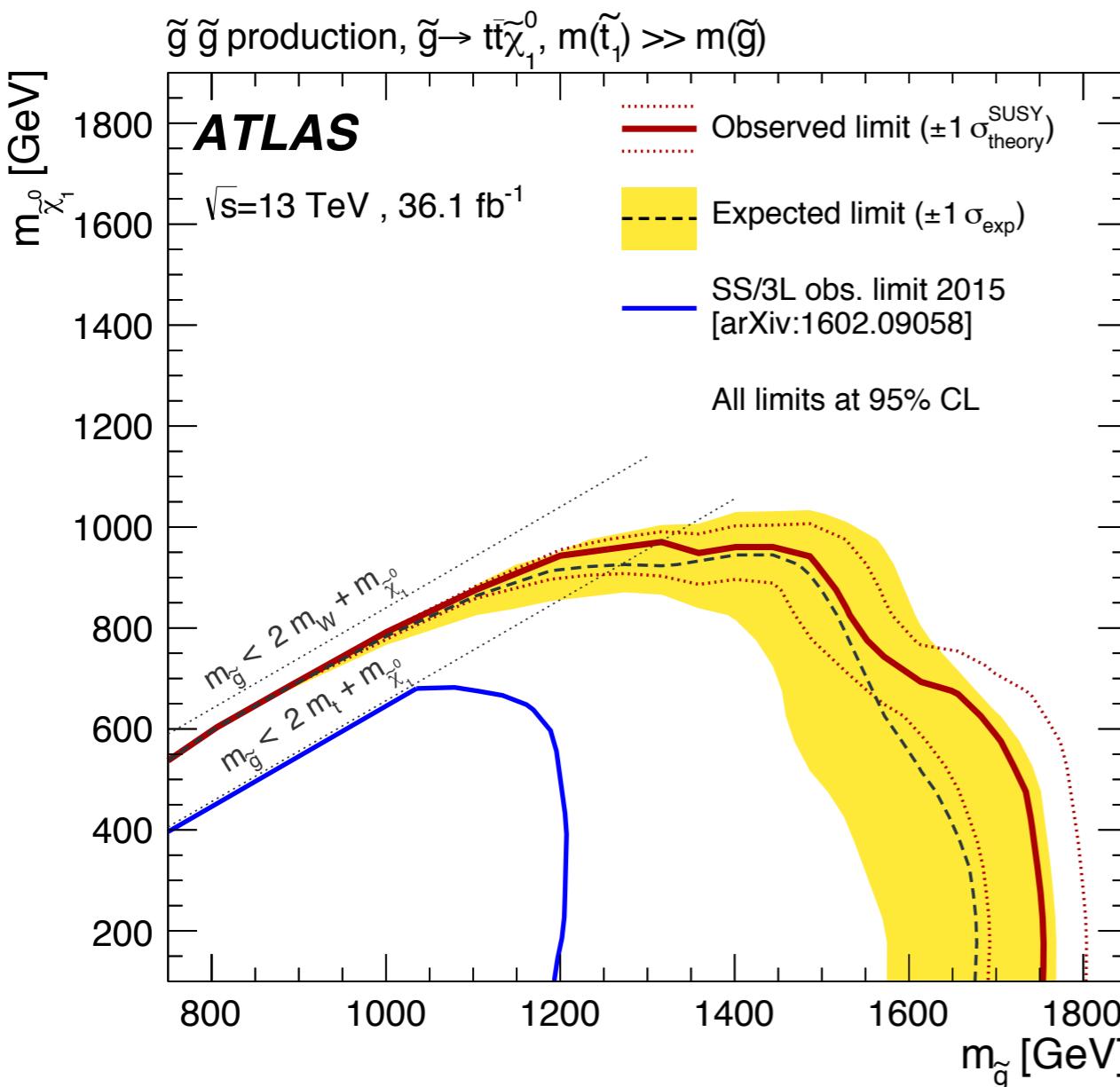
# Model dependent

- SRs: Rpc2L2bS, Rpc2L2bH, Rpc2Lsoft1b, Rpc2Lsoft2b



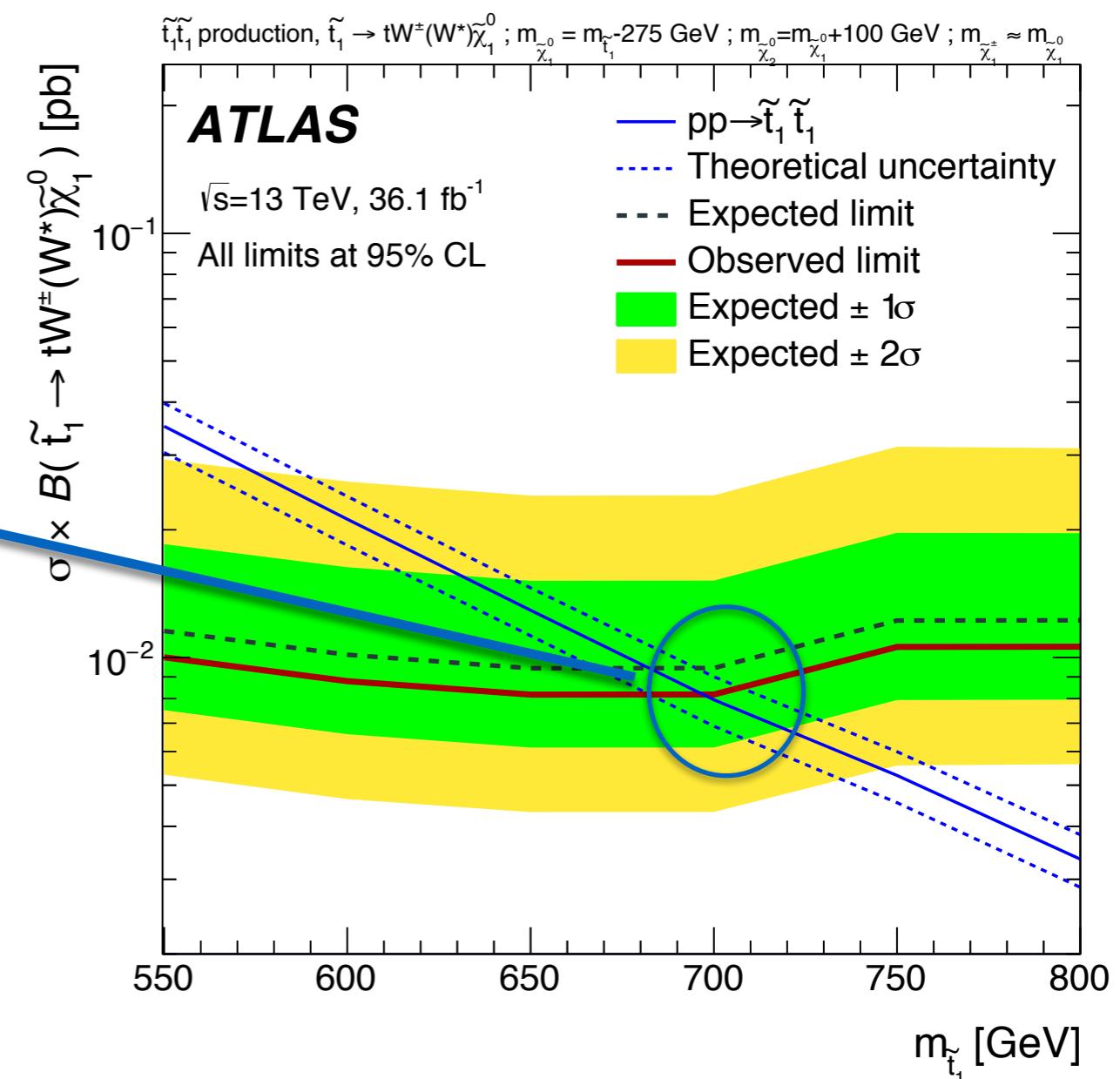
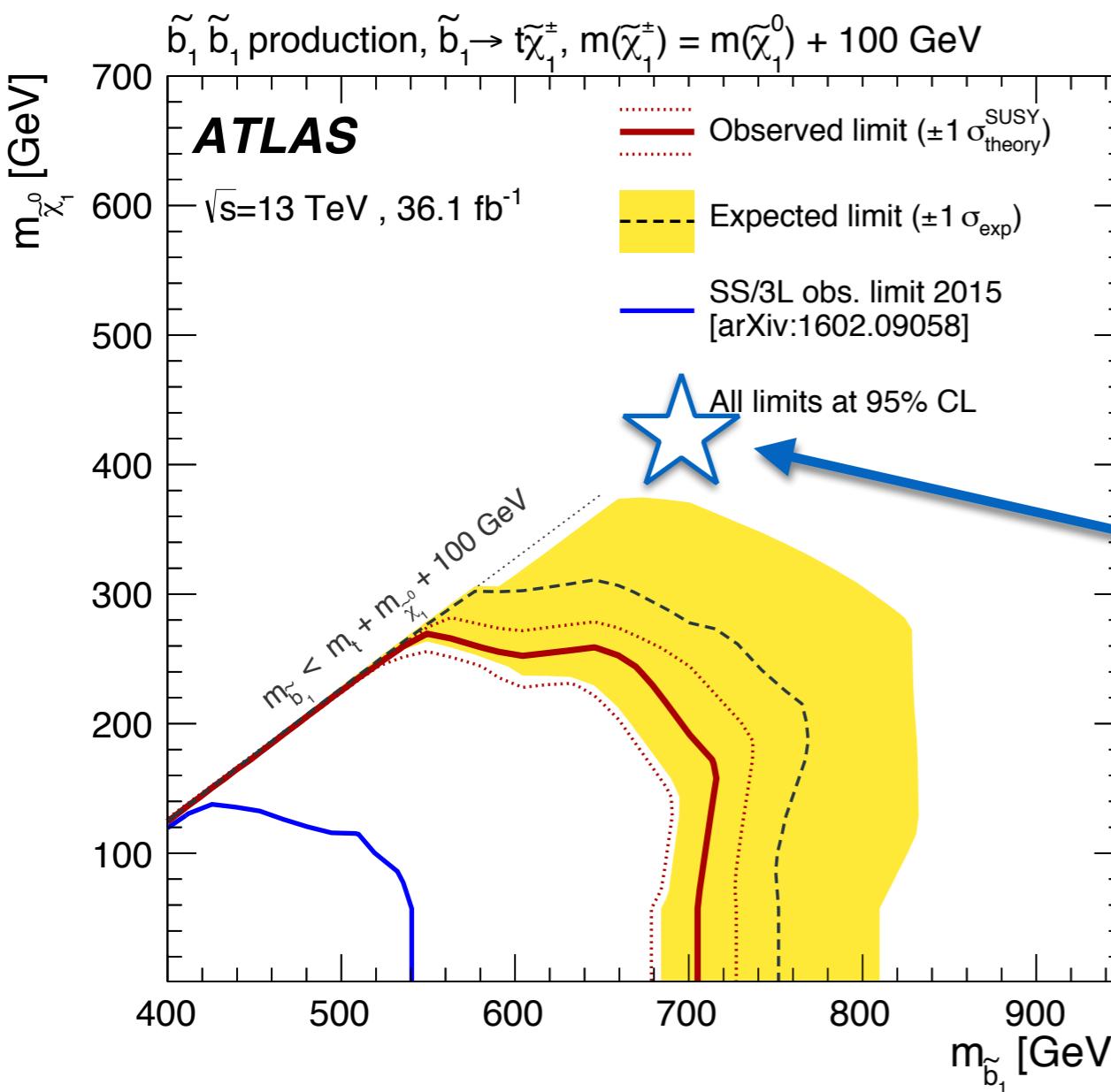
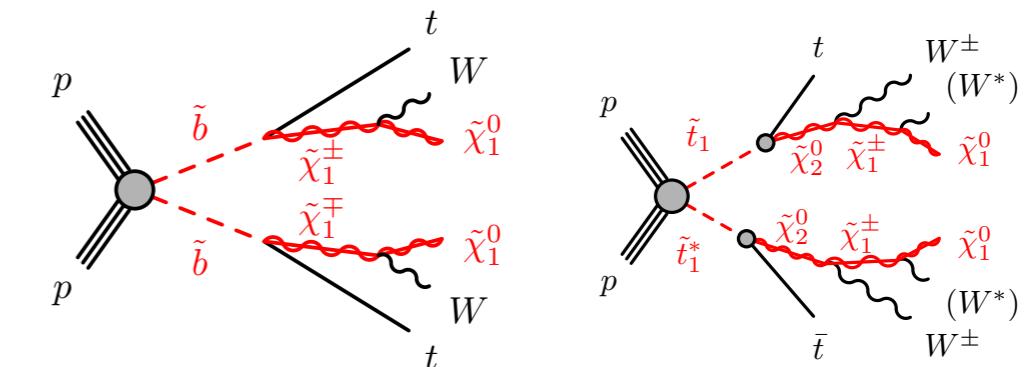
# Model dependent

- SRs: Rpc2L2bS, Rpc2L2bH, Rpc2Lsoft1b, Rpc2Lsoft2b



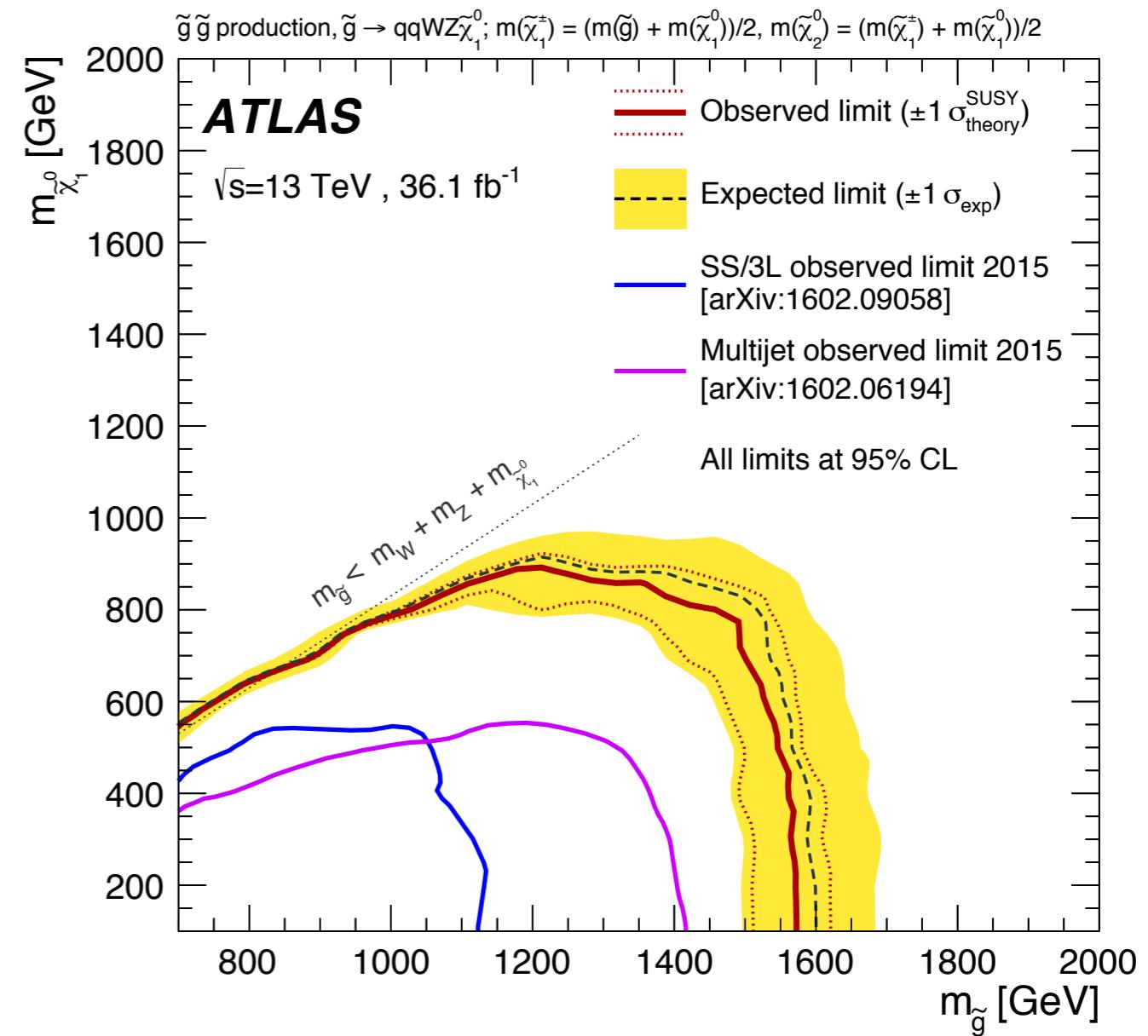
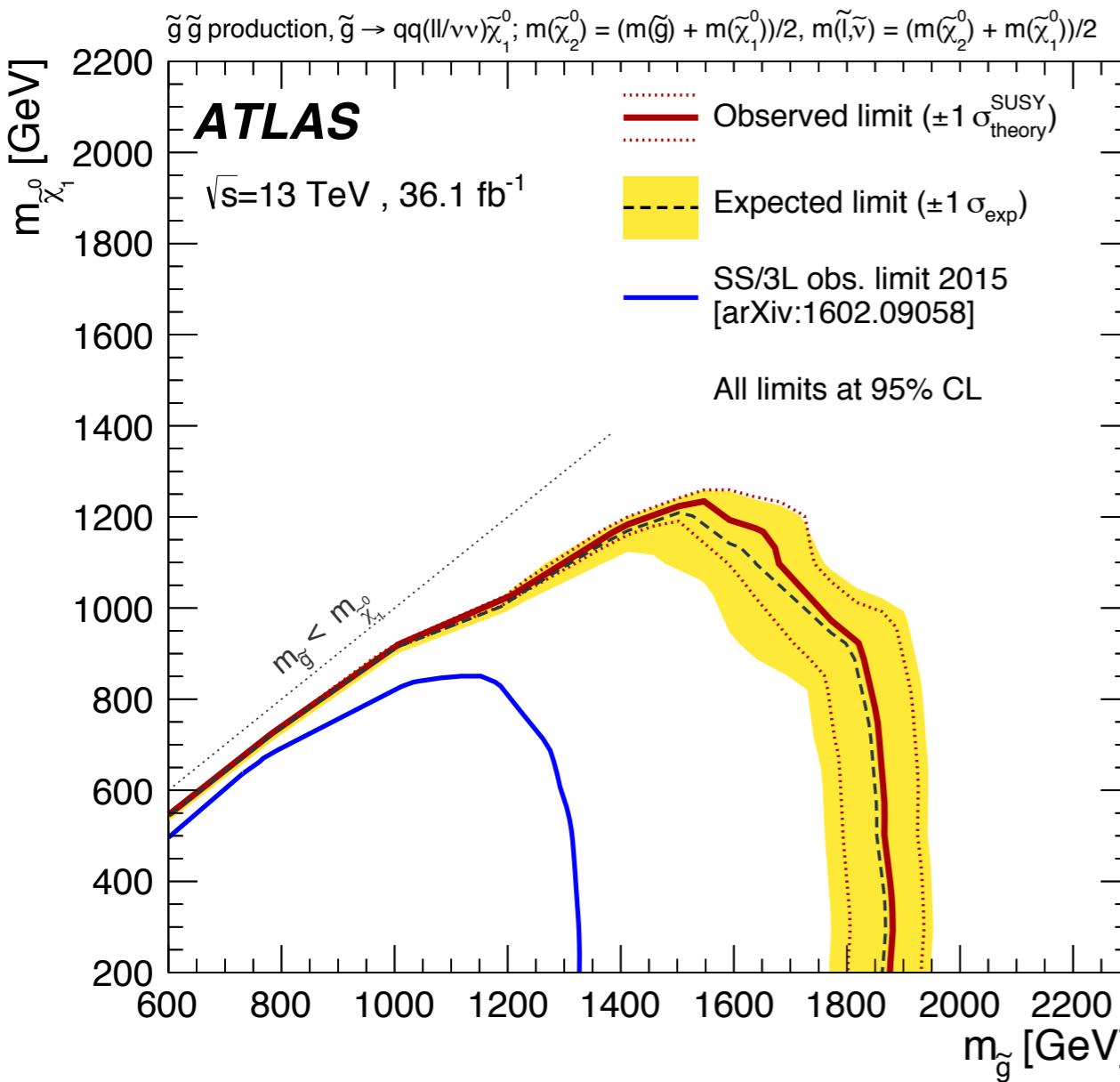
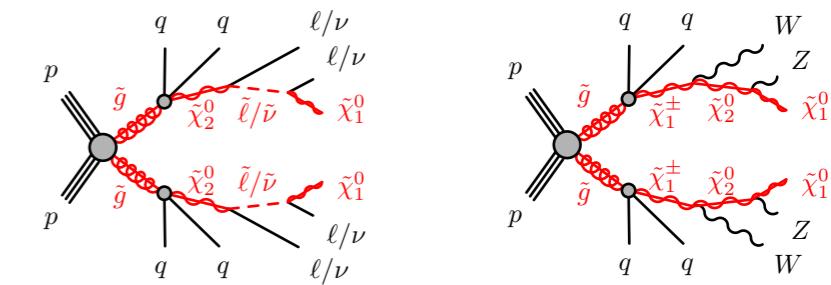
# RPC Interpretation: 3rd Gen

- SRs: Rpc2L1bS, Rpc2L1bH, Rpc3LSS1b



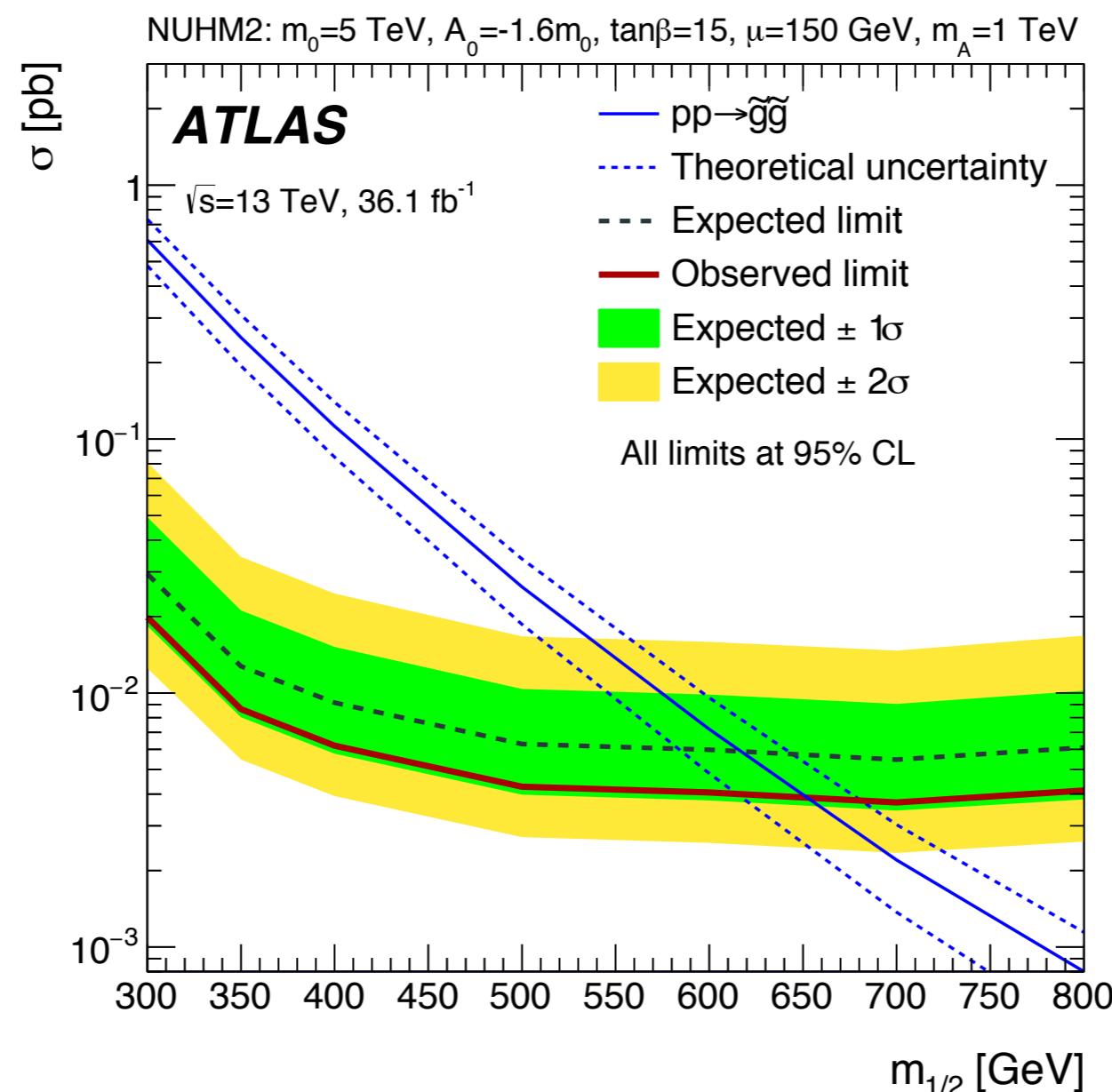
# RPC Interpretation: GSL and 2setp-WZ

- SRs: Rpc3L0bS and Rpc3L0bH ,  
Rpc2L0bS and Rpc2L0bH



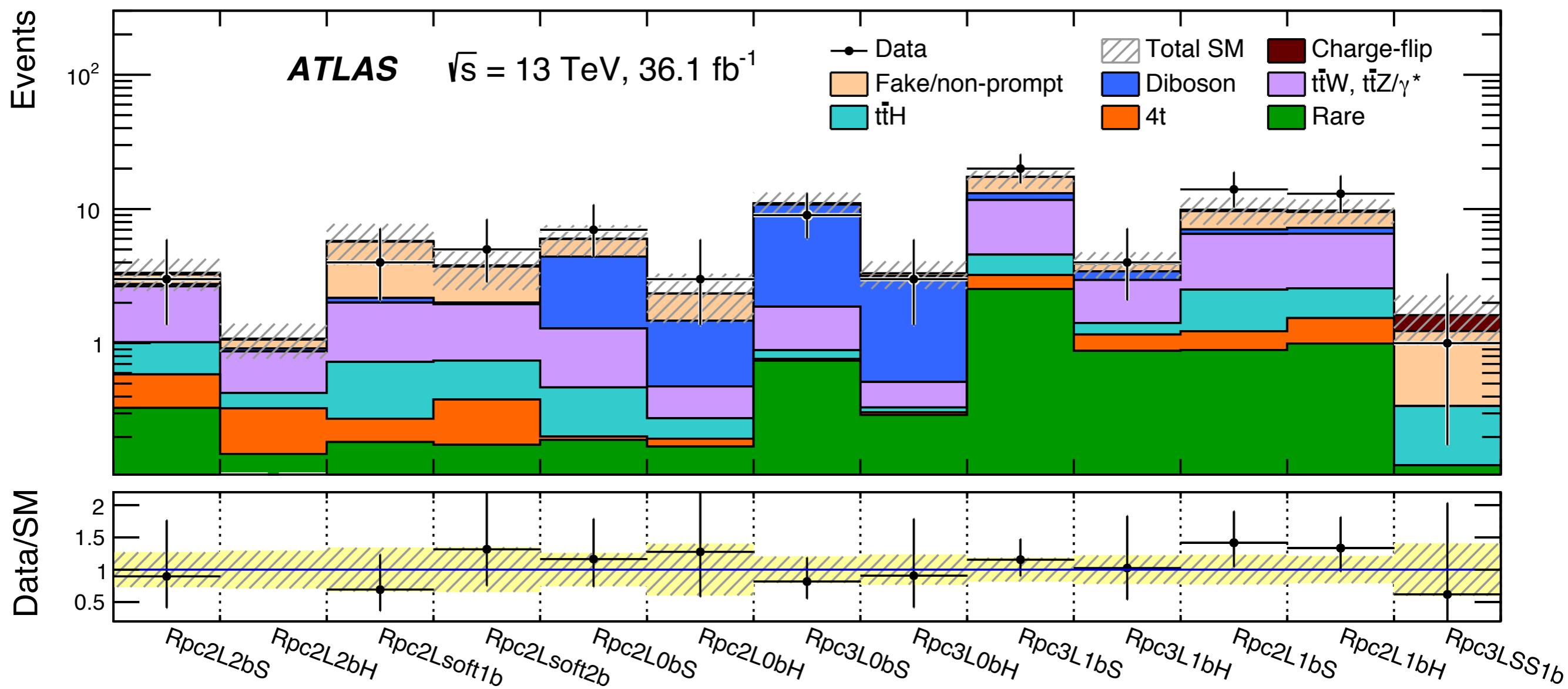
# RPC Interpretation: NUHM2

- SR: Rpc2L2bH



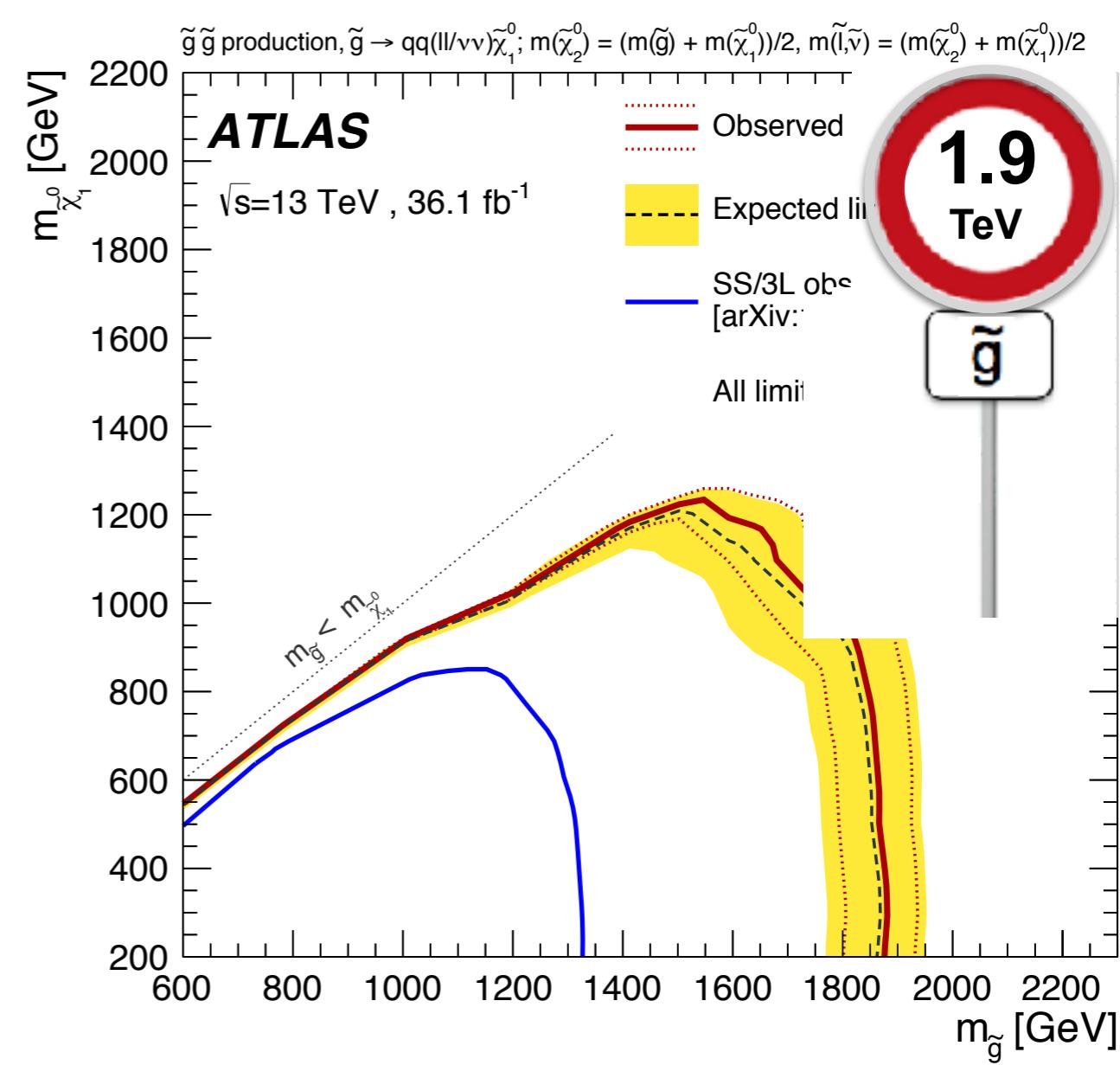
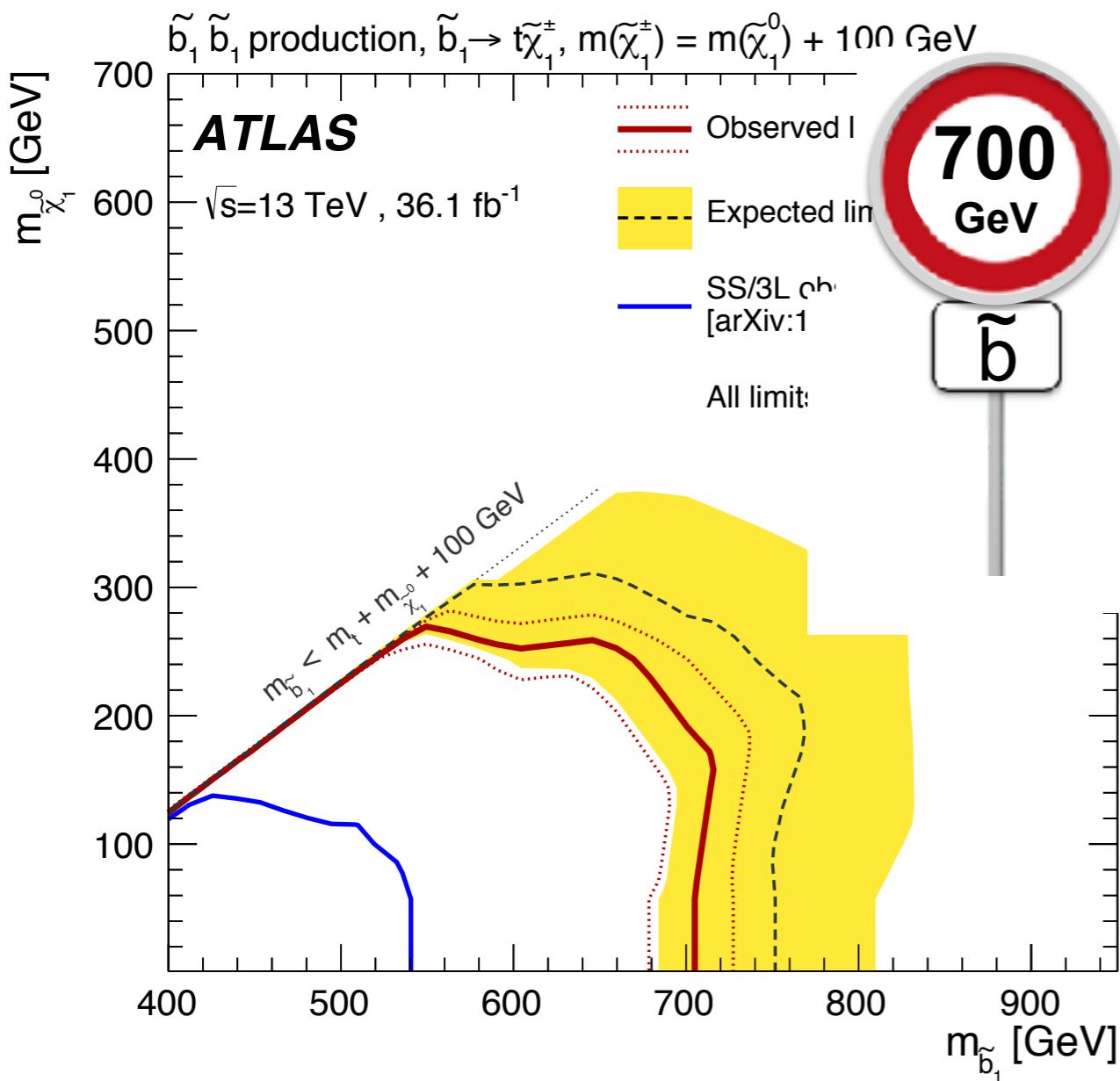
# Closing remarks...

I didn't find any evidence for supersymmetry in all the search regions:



# Closing remarks...

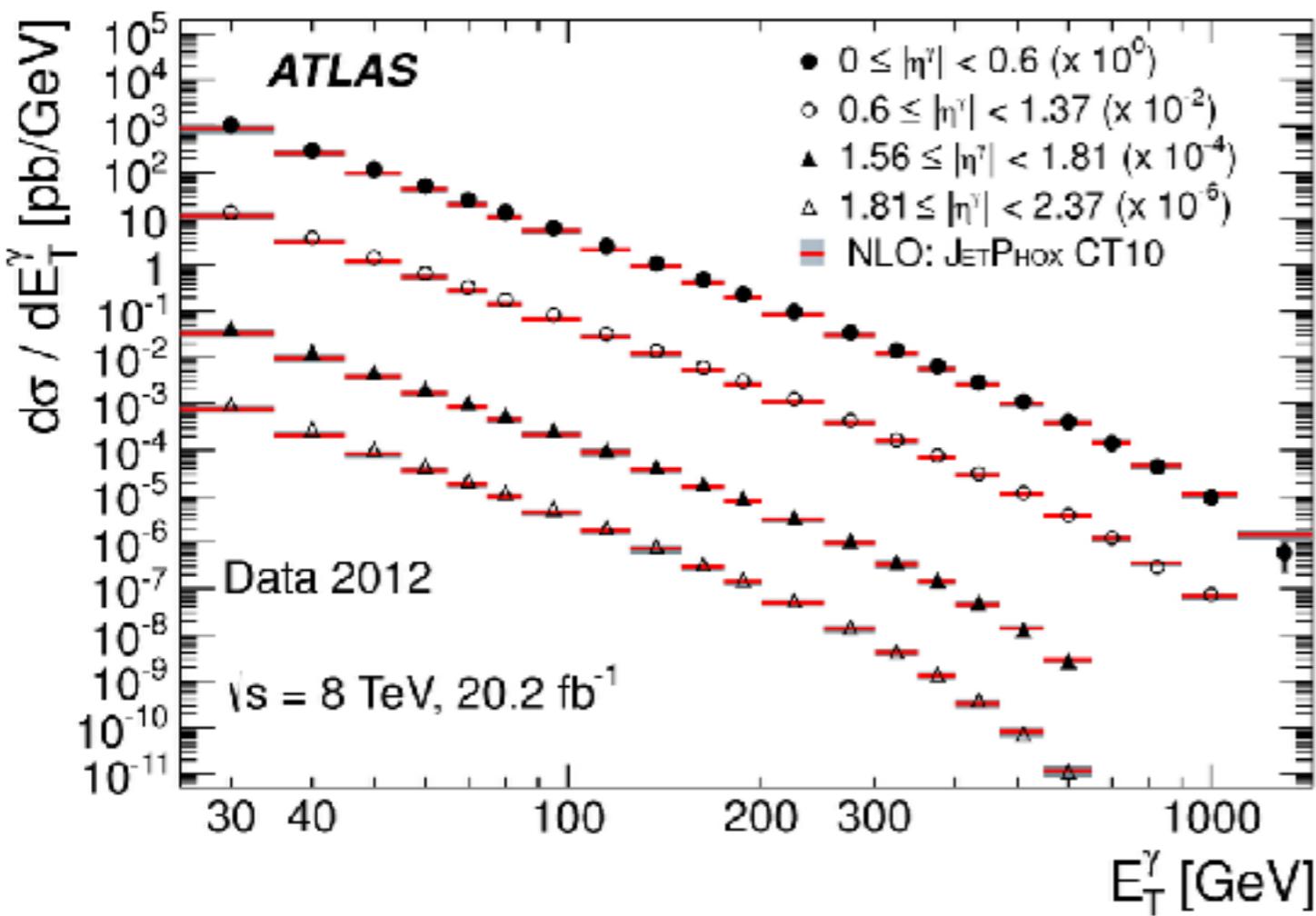
I improved the discovery sensitivity to SUSY beyond that of Run-1



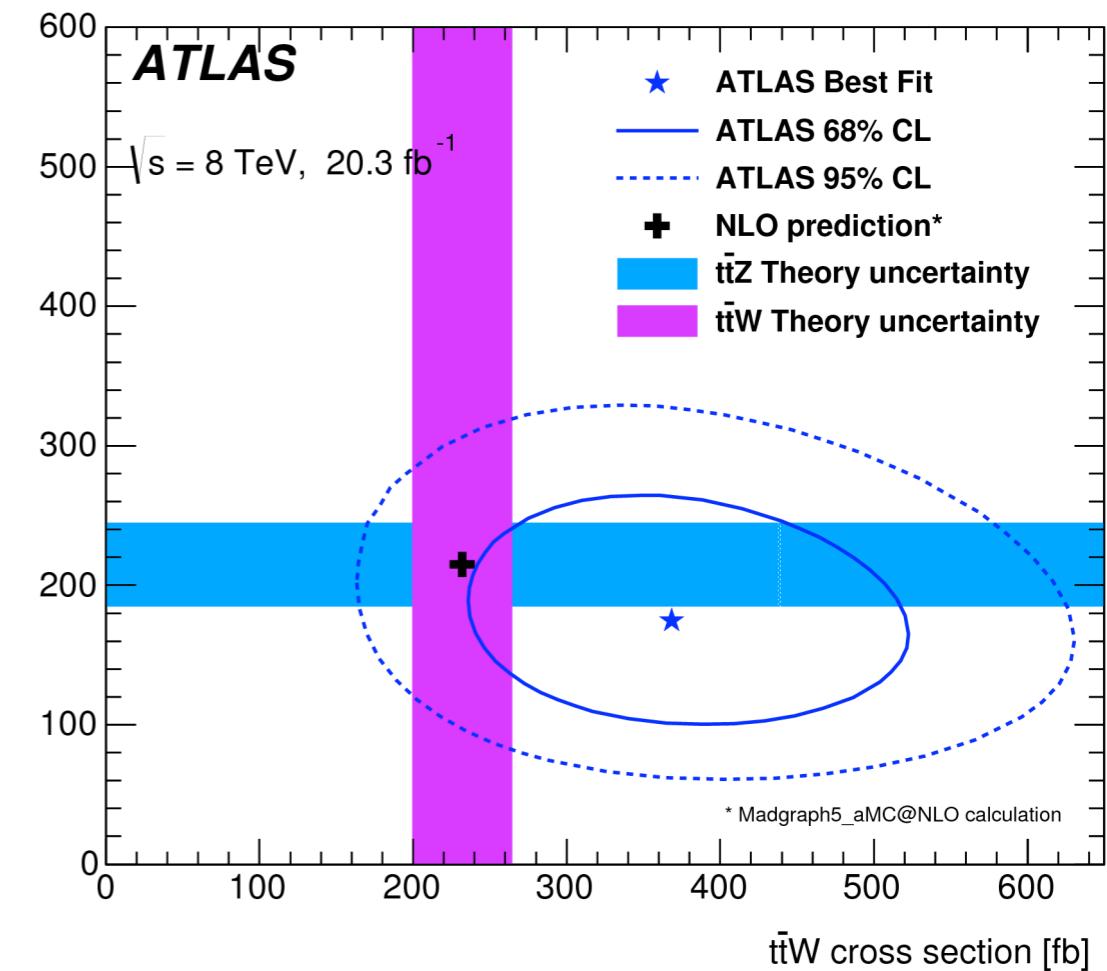
# Closing remarks...

I performed two standard model measurements

Photon cross-section

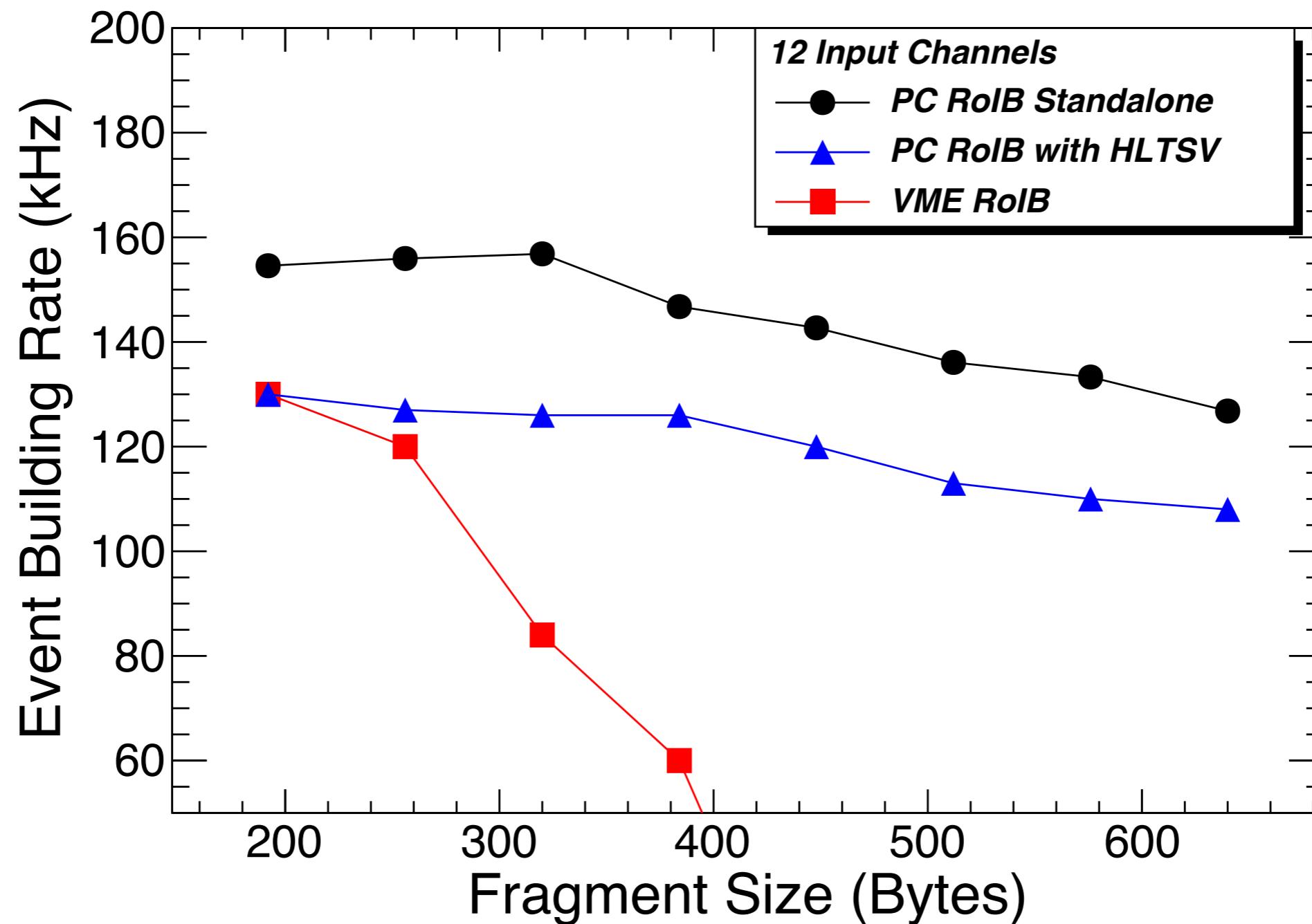


ttW, ttZ cross-section



# Closing remarks...

I enabled a simplified readout architecture of ATLAS



# Closing remarks...

and I had a great time at CERN while analyzing the LHC data



# Closing remarks...

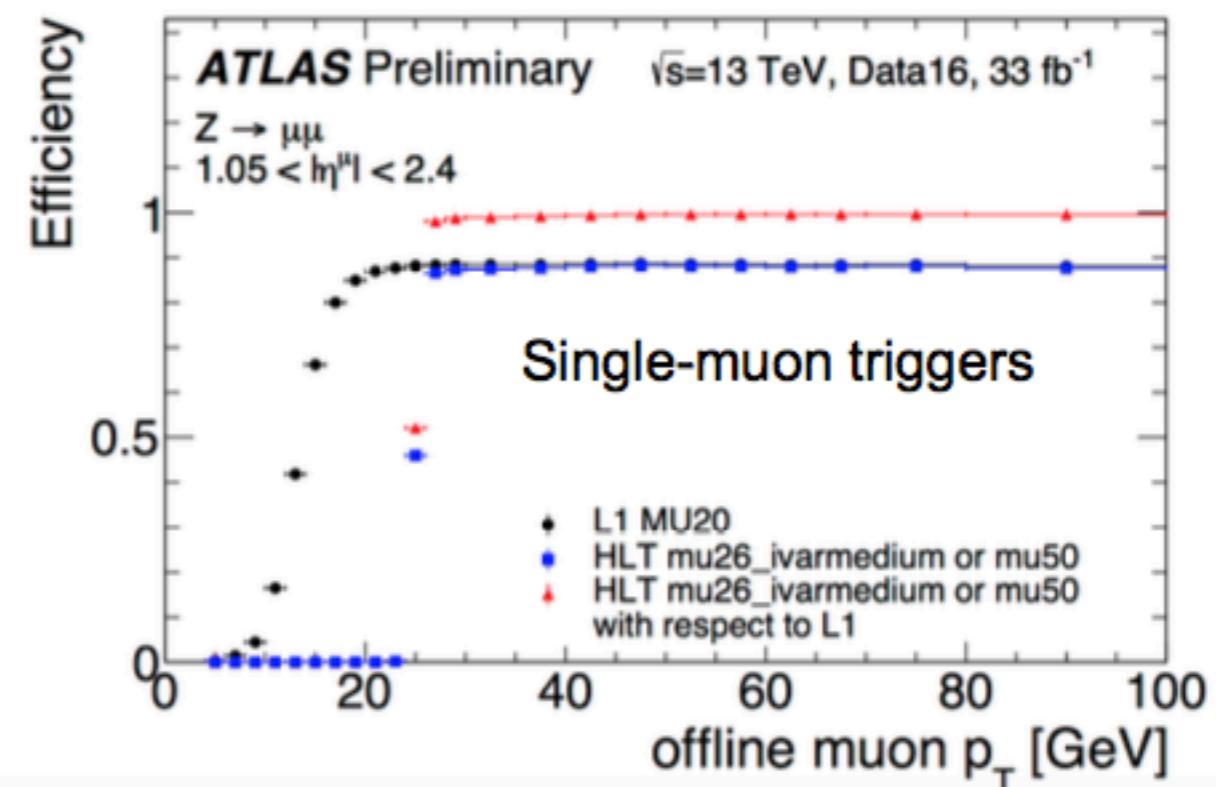
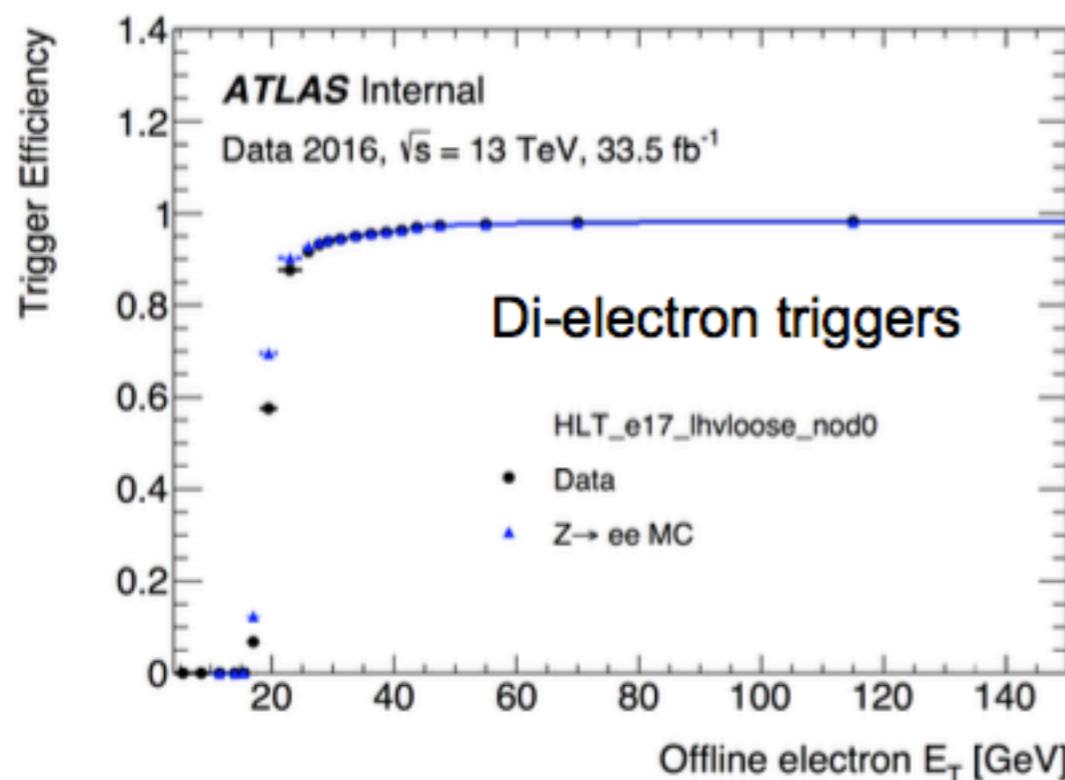
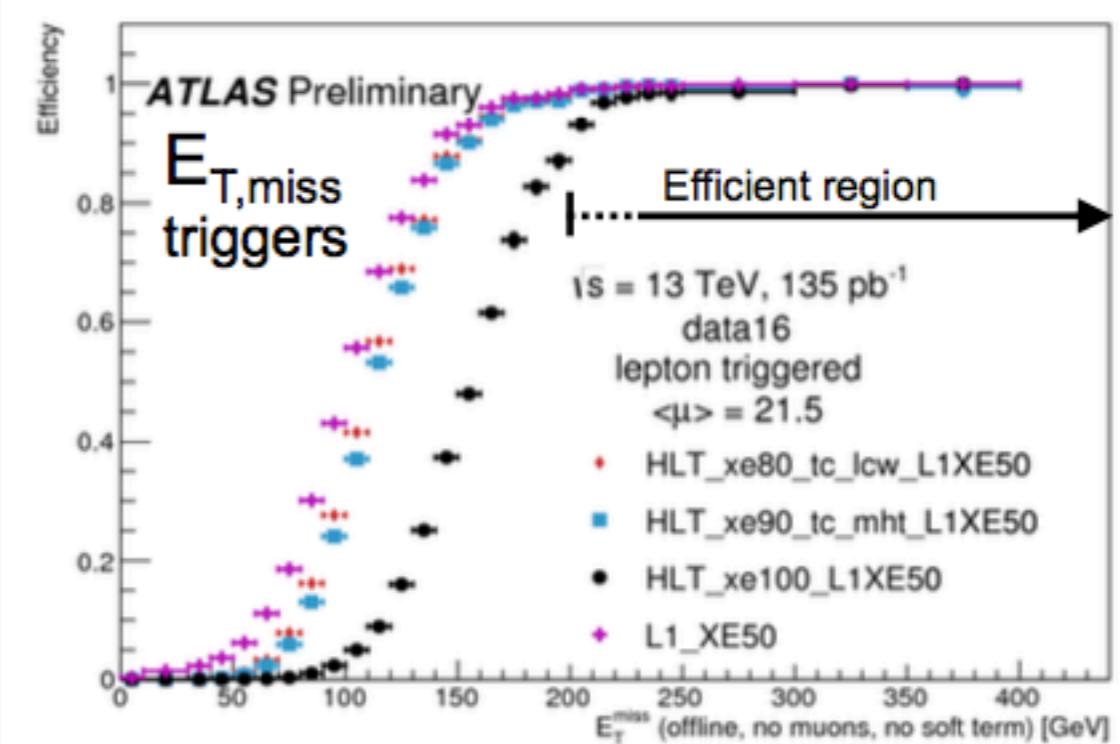


# Thank you for your attention!

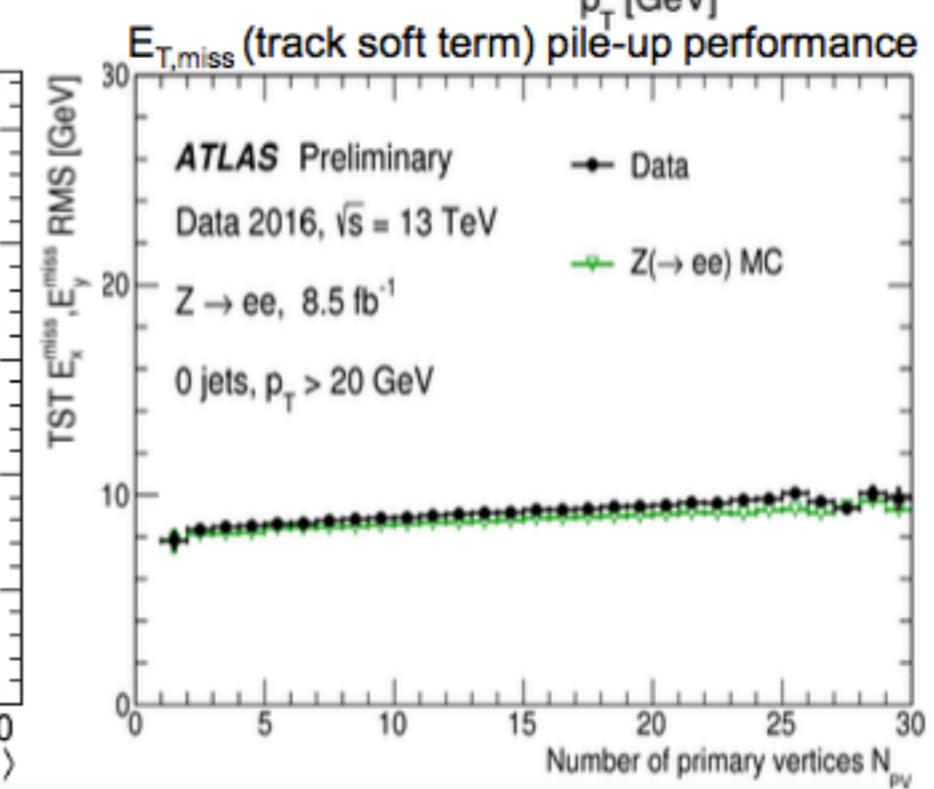
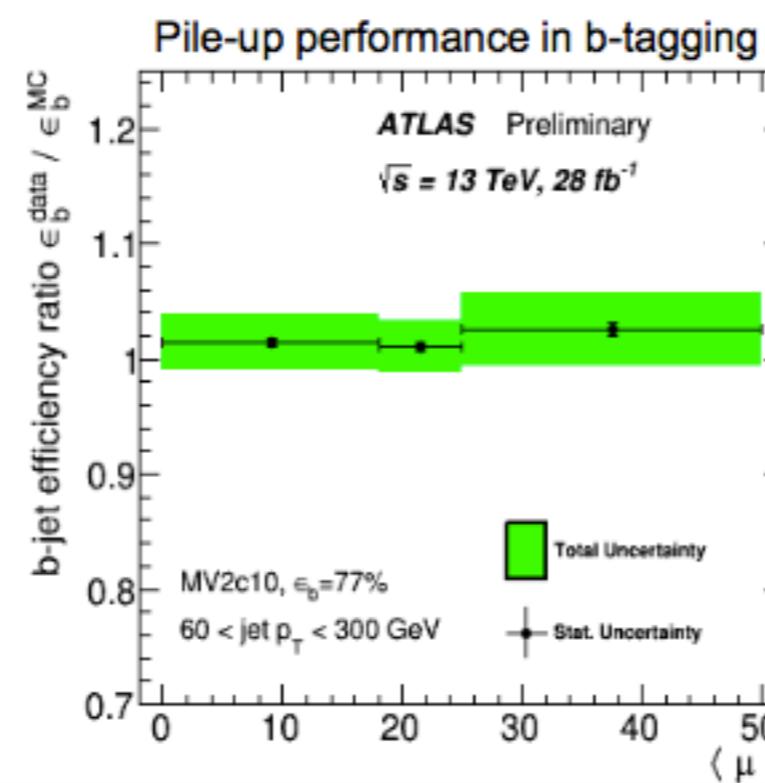
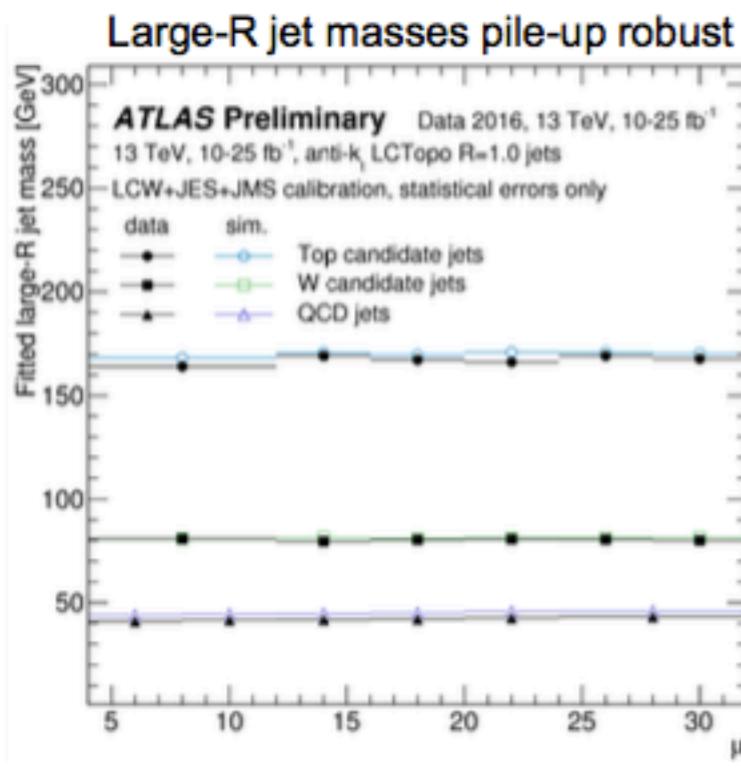
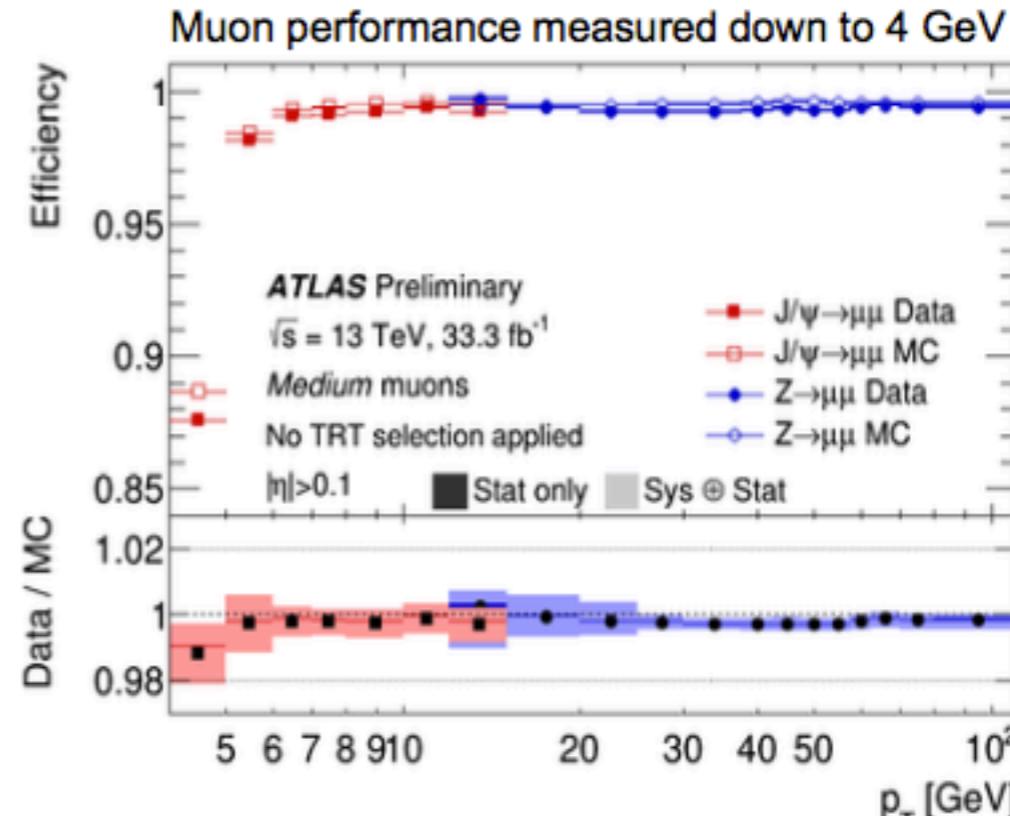
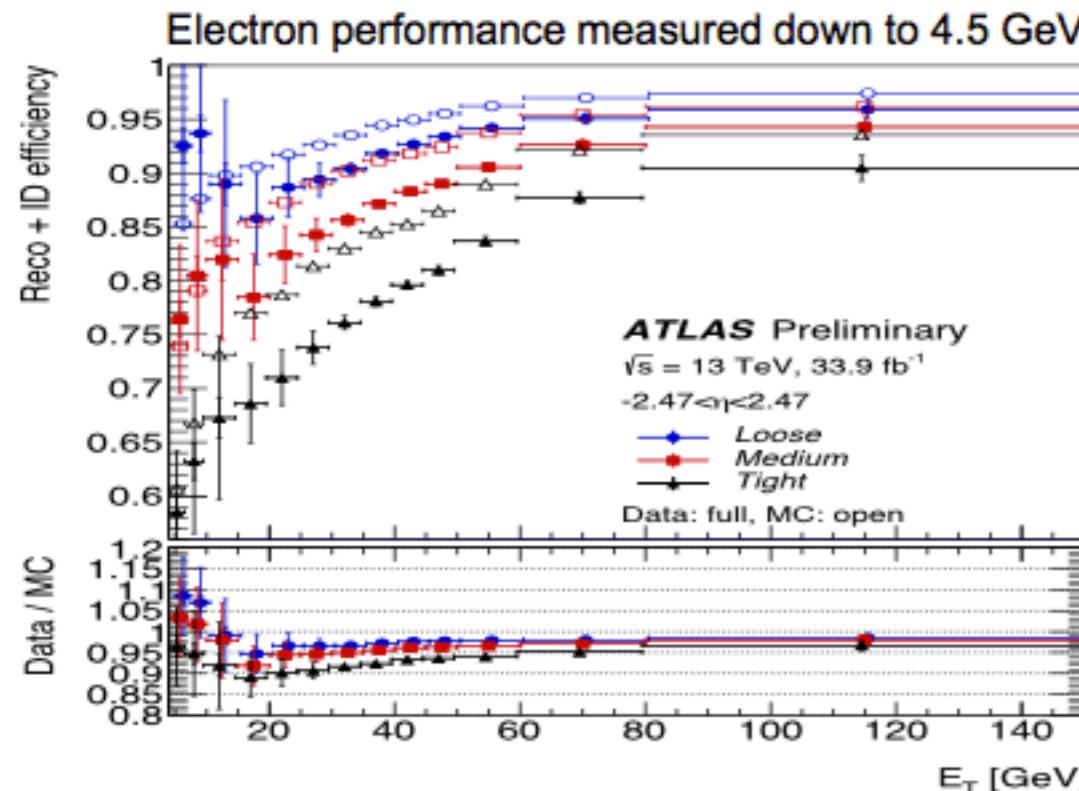
# Backup

# ATLAS Performance

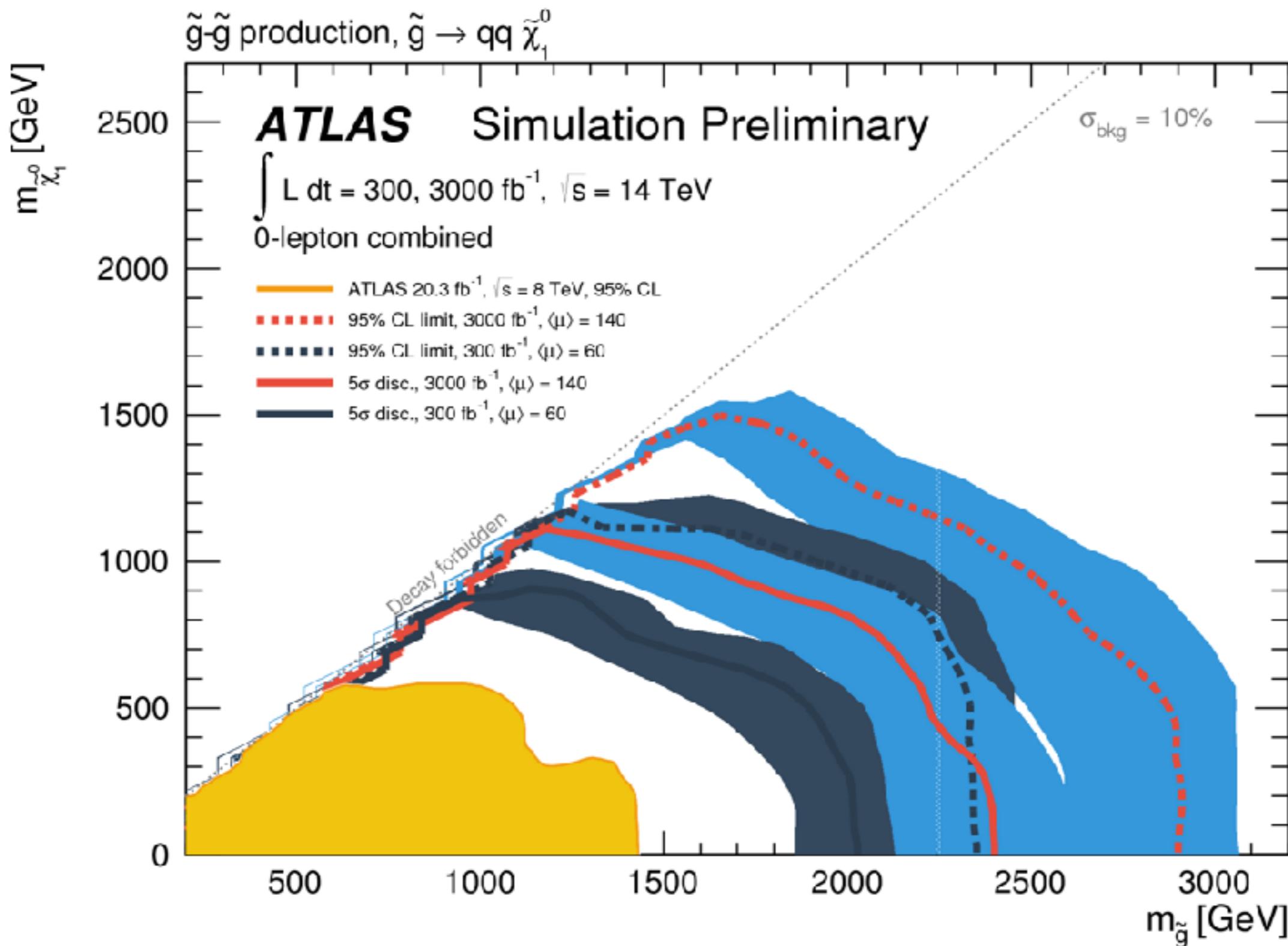
- **ATLAS trigger and DAQ systems form the basis for a successful data-taking**
- Major challenge in 2016: **Maintain trigger performance** in fierce luminosity & pile-up conditions
- Main physics triggers for SUSY searches: **Generic  $E_{T,\text{miss}}$ , jet, lepton triggers**



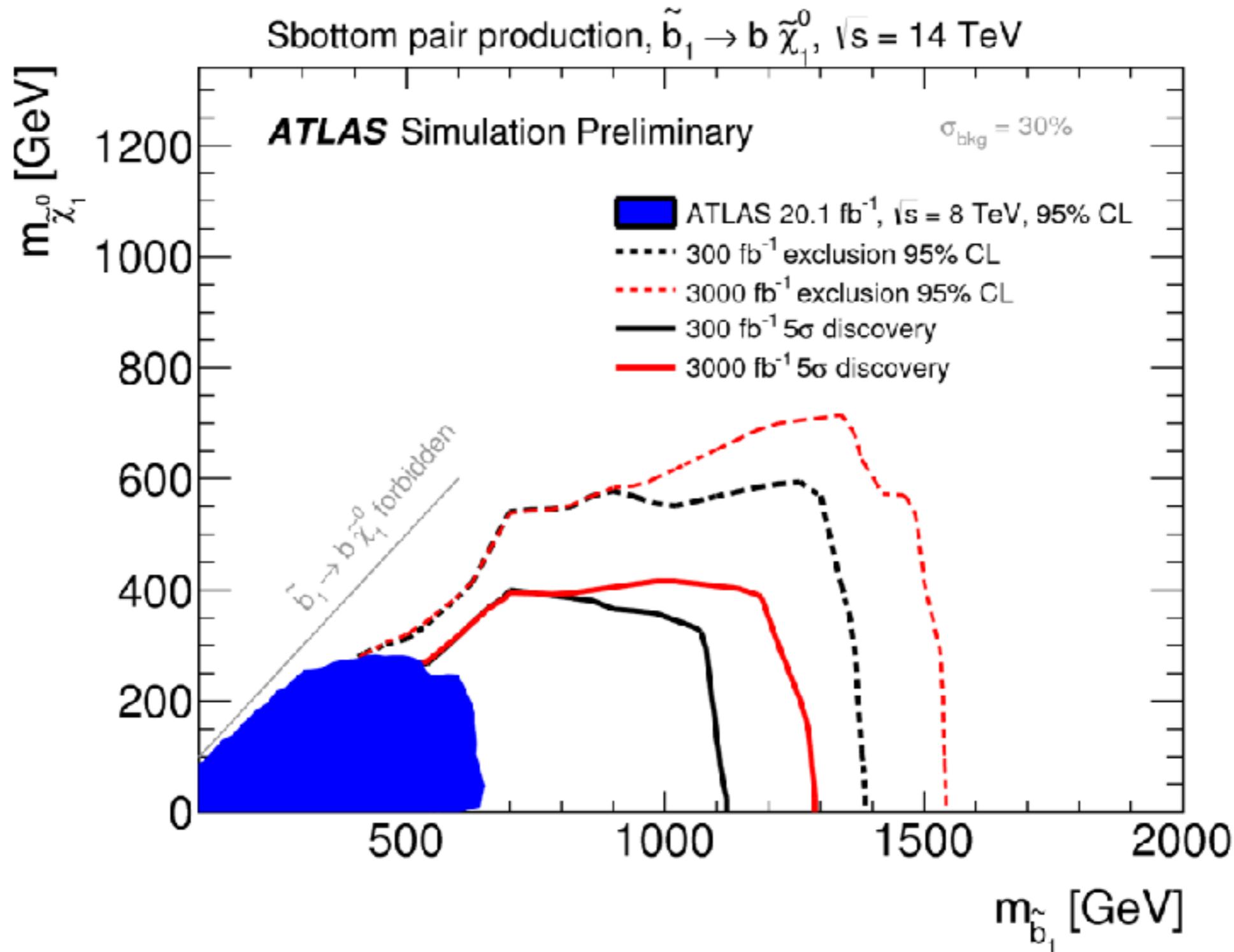
# ATLAS Performance



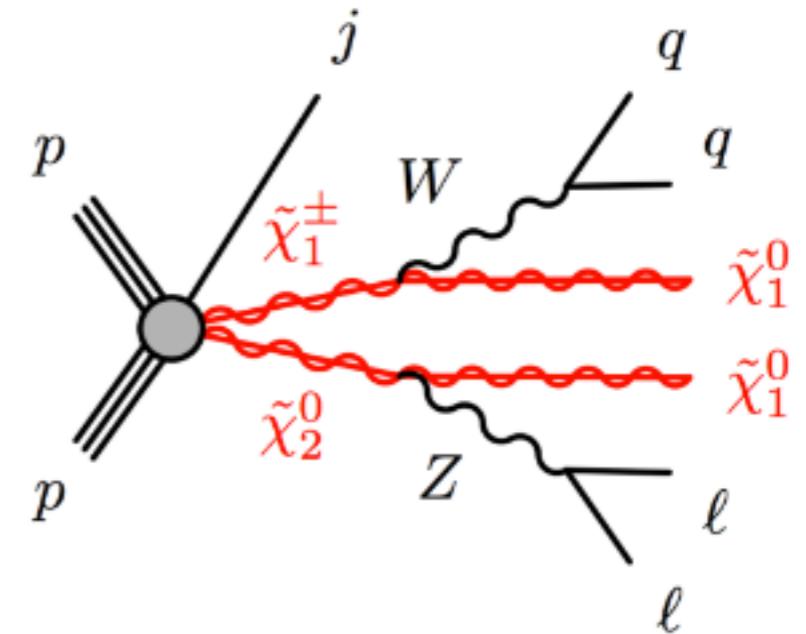
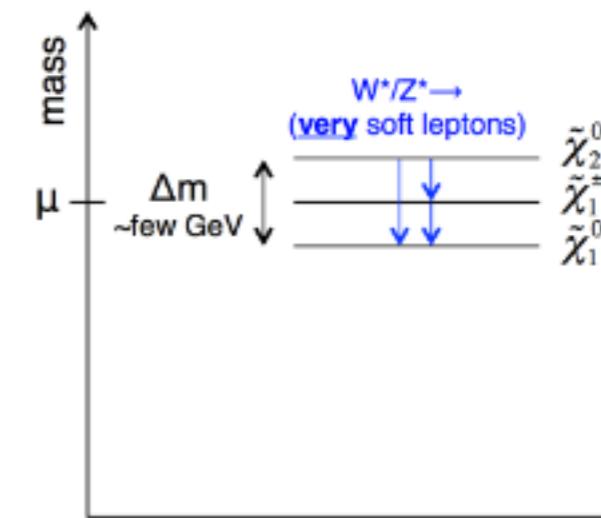
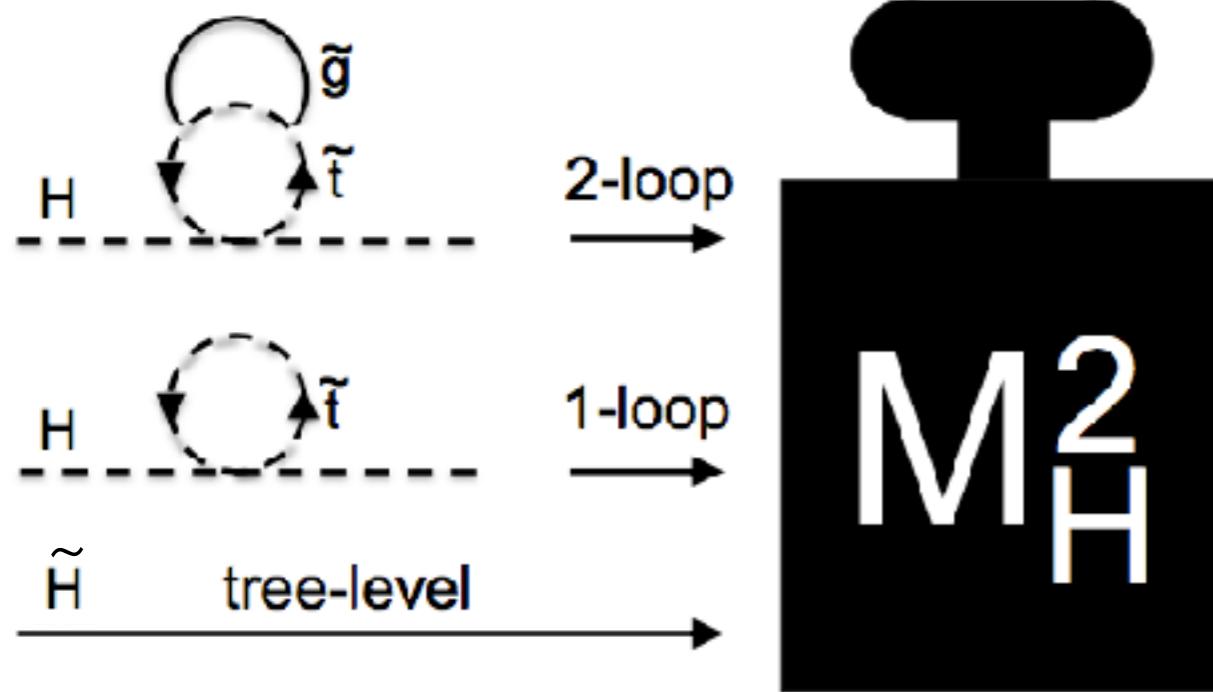
# What Next?



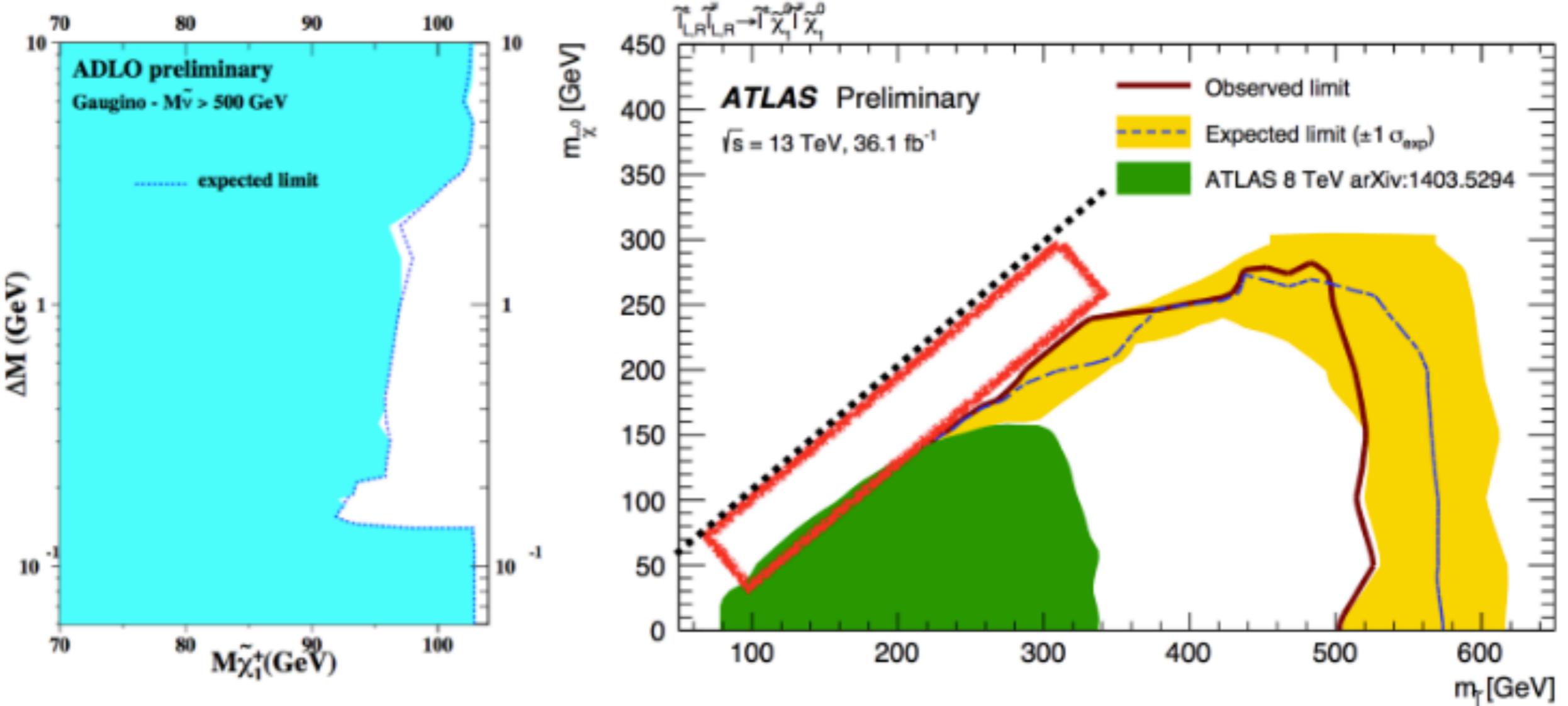
# What Next?



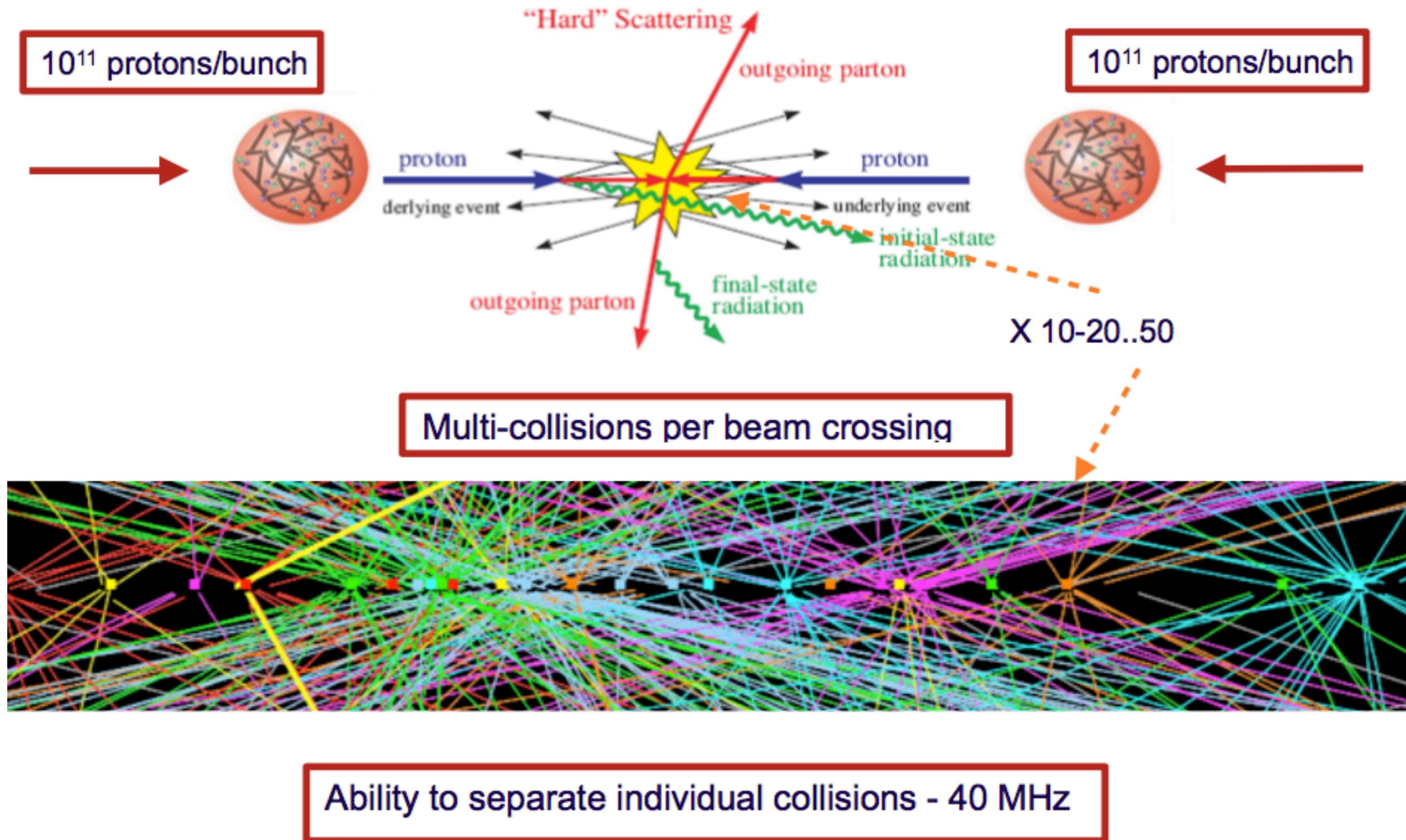
# What Next?



# What next?



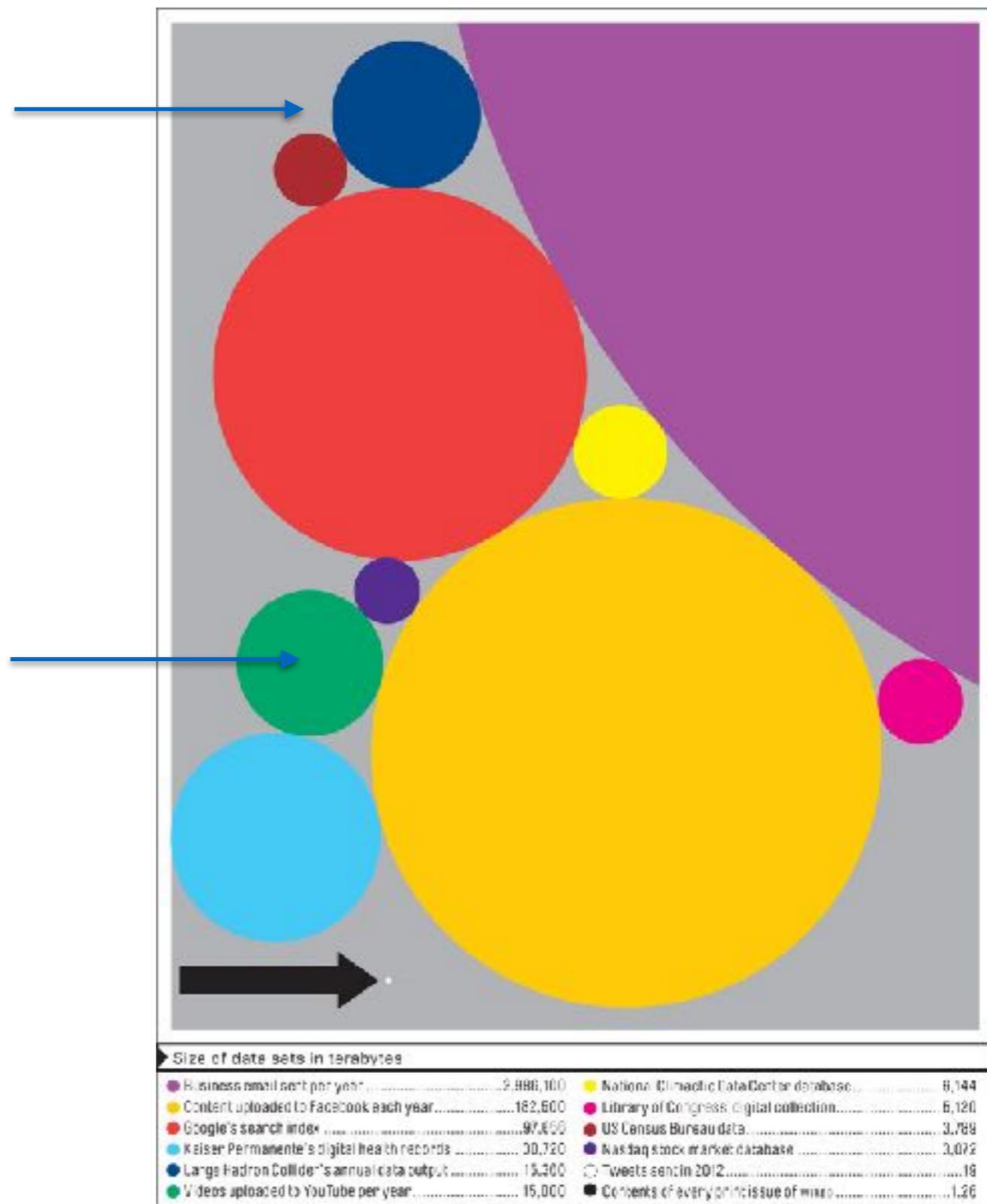
# Pileup



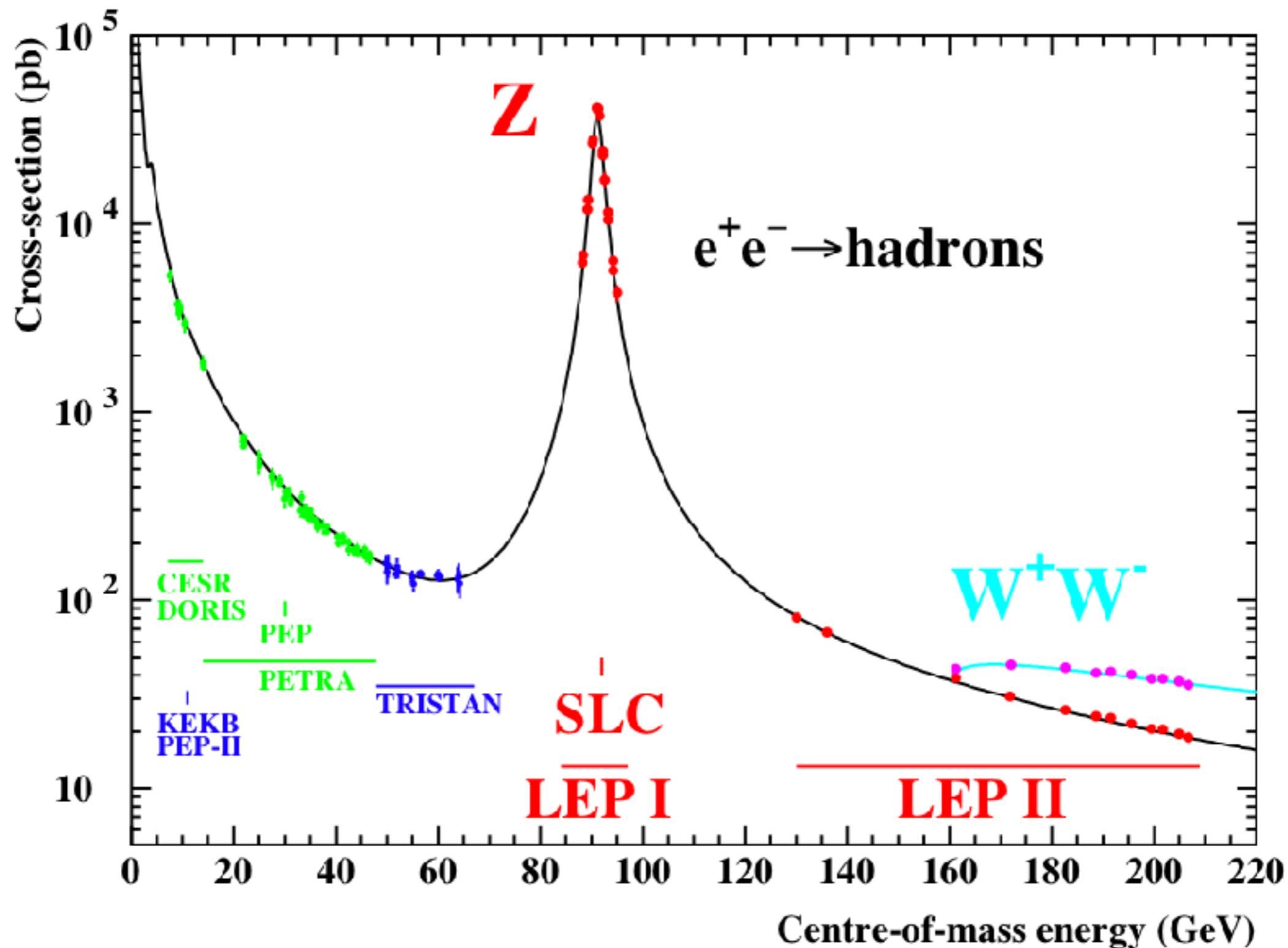
# Data, Data, Data

LHC ~ 15 petabytes/2012

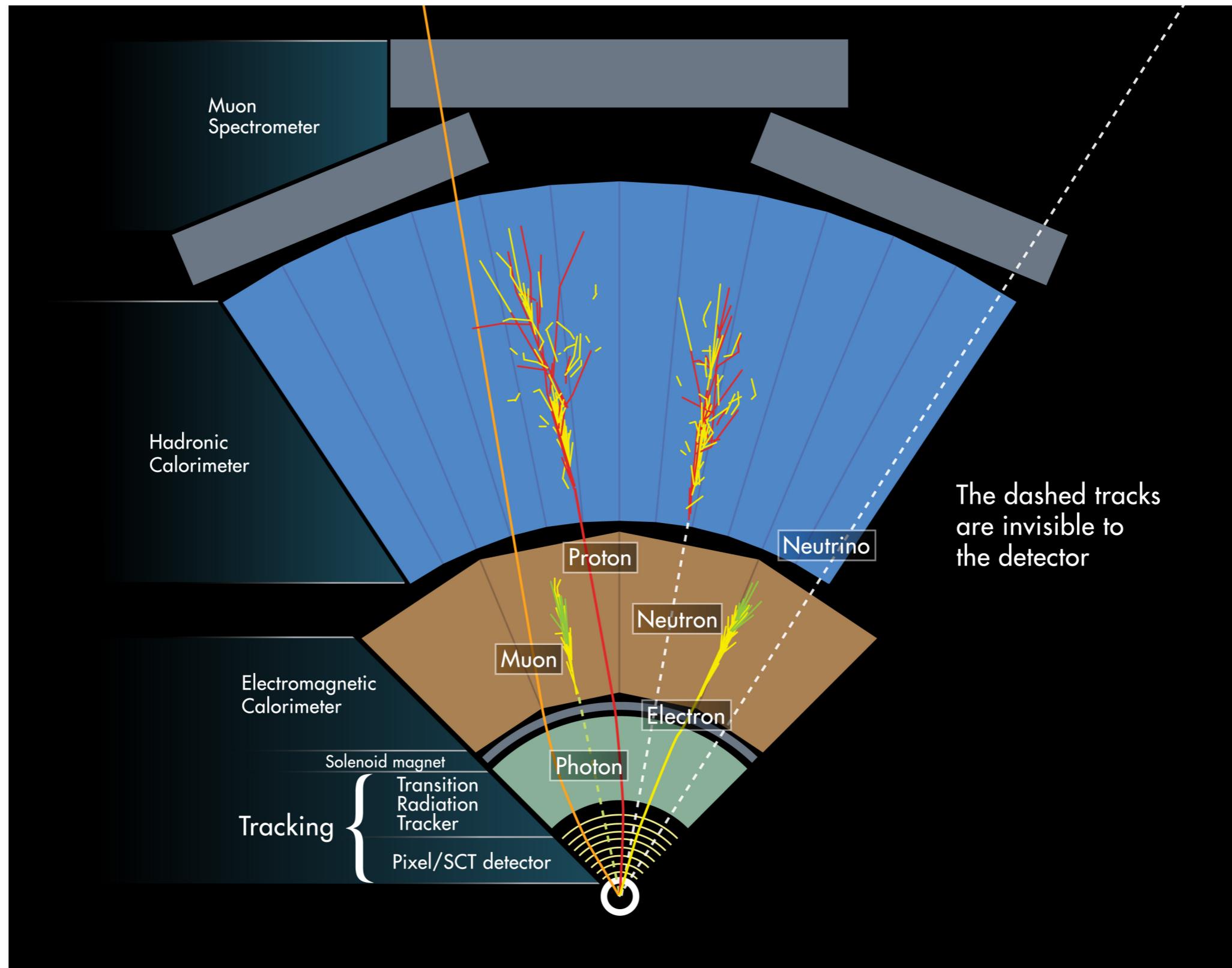
Youtube upload /year



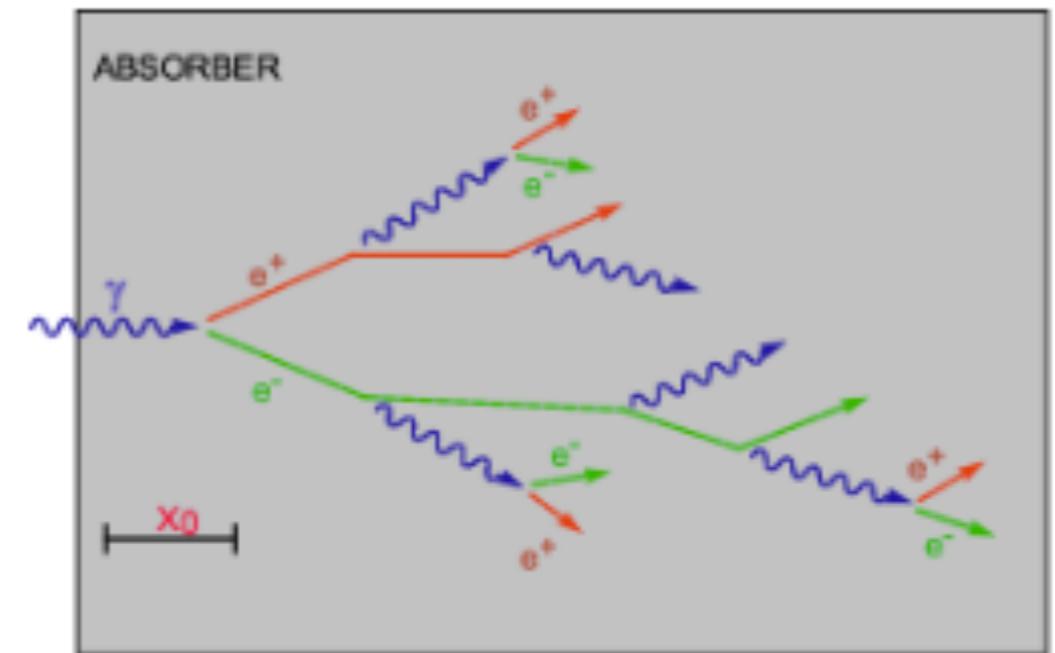
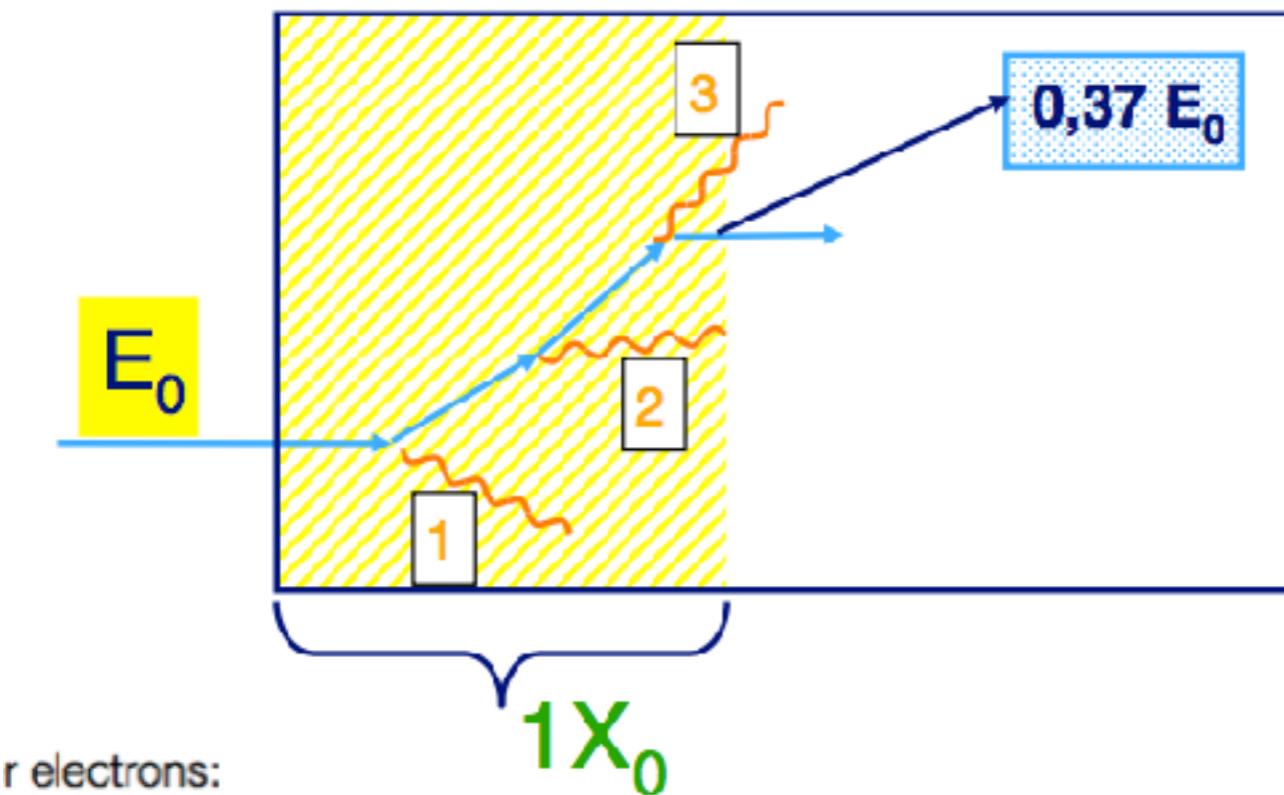
# LEP



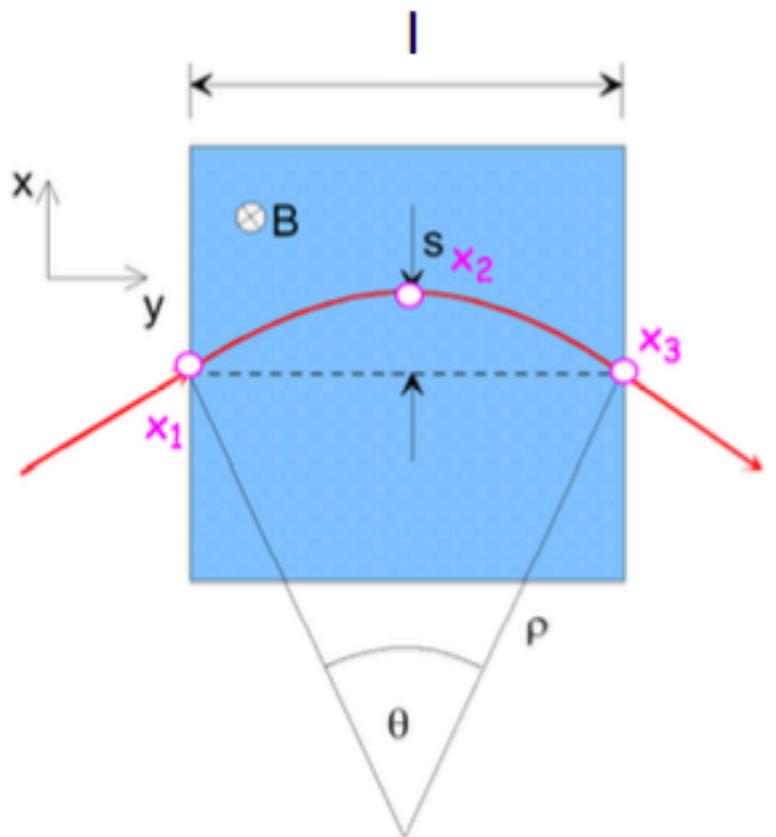
# Particle Identification



# Radiation Length



# Magnetic Analysis



$s$  = sagitta

$l$  = chord

$\rho$  = radius

$$\rho \simeq \frac{l^2}{8s}$$

$$p = 0.3 \frac{Bl^2}{8s}$$

$$\left| \frac{\delta p}{p} \right| = \left| \frac{\delta s}{s} \right|$$

Charged particle of momentum  $p$  in a magnetic field  $B$

$$\frac{d\vec{p}}{dt} = q\vec{\beta} \times \vec{B}$$

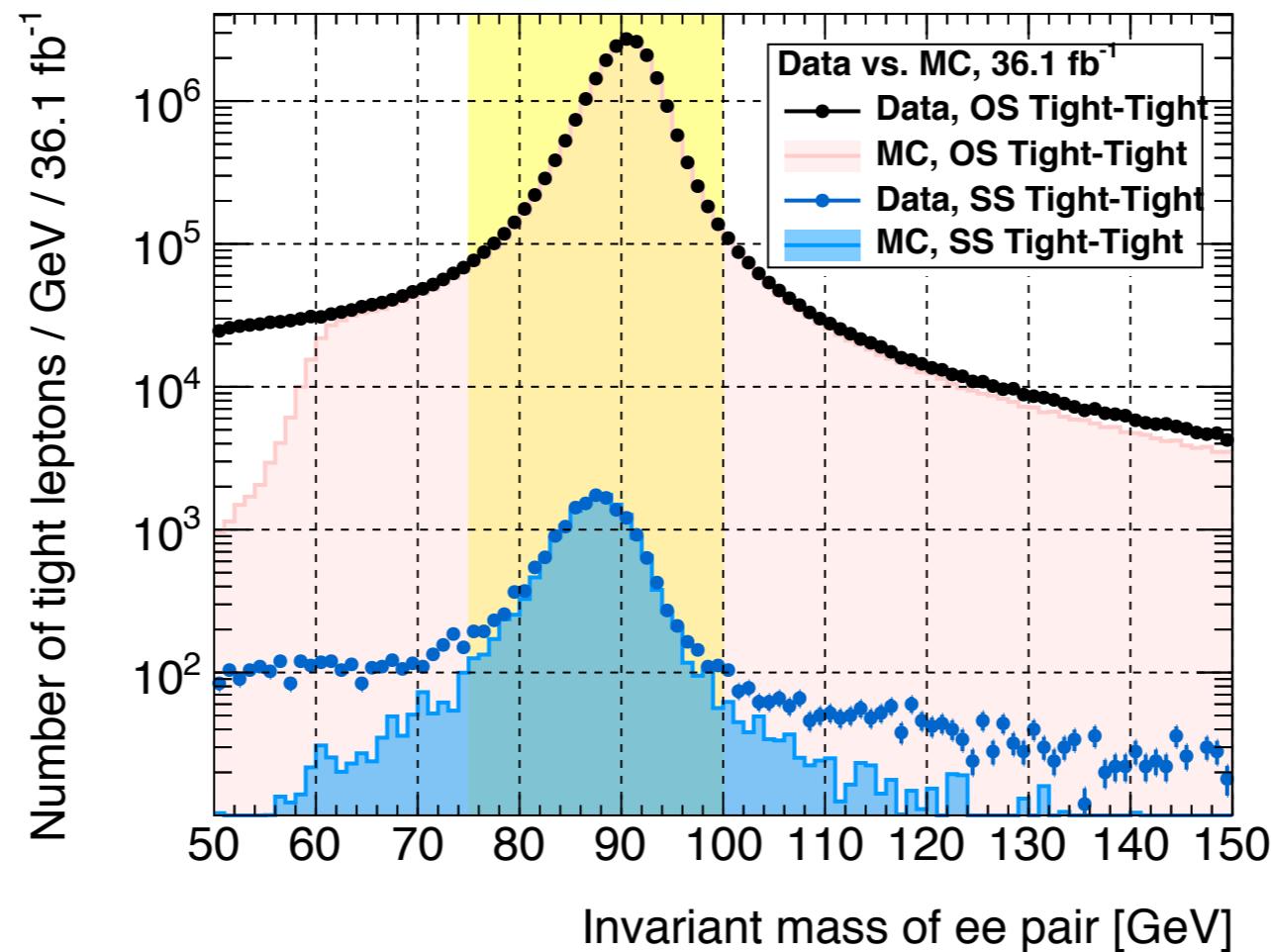
# MC Samples

Physics process	Event generator	Parton shower	Cross-section order	Cross-section value (fb)	PDF set	Set of tuned parameters
Signal	AMC@NLO 2.2.3 [42]	PYTHIA 8.186 [43]	NLO+NLL	See Table 5.4	NNPDF2.3LO [70]	A14 [71]
$t\bar{t} + X$						
$t\bar{t}W, t\bar{t}Z/\gamma^*$	AMC@NLO 2.2.2	PYTHIA 8.186	NLO [72]	600.8, 123.7	NNPDF2.3LO	A14
$t\bar{t}H$	AMC@NLO 2.3.2	PYTHIA 8.186	NLO [72]	507.1	NNPDF2.3LO	A14
$4t$	AMC@NLO 2.2.2	PYTHIA 8.186	NLO [42]	9.2	NNPDF2.3LO	A14
Diboson						
$ZZ, WZ$	SHERPA 2.2.1 [73]	SHERPA 2.2.1	NLO [74]	$1.3 \cdot 10^3, 4.5 \cdot 10^3$	NNPDF2.3LO	SHERPA default
inc. $W^\pm W^\pm$	SHERPA 2.1.1	SHERPA 2.1.1	NLO [74]	86	CT10 [75]	SHERPA default
Rare						
$t\bar{t}WW, t\bar{t}WZ$	AMC@NLO 2.2.2	PYTHIA 8.186	NLO [42]	9.9, 0.36	NNPDF2.3LO	A14
$tZ, tWZ, tt\bar{t}$	AMC@NLO 2.2.2	PYTHIA 8.186	LO	240, 16, 1.6	NNPDF2.3LO	A14
$WH, ZH$	AMC@NLO 2.2.2	PYTHIA 8.186	NLO [76]	$1.4 \cdot 10^3, 868$	NNPDF2.3LO	A14
Triboson	SHERPA 2.1.1	SHERPA 2.1.1	NLO [74]	14.9	CT10	SHERPA default
Irreducible (Incl.)						
$W+Jets$	POWHEG-BOX	PYTHIA 8.186	NNLO	$2.0 \cdot 10^7$	CT10	AZNLO[77]
$Z+Jets$	POWHEG-BOX	PYTHIA 8.186	NNLO	$1.9 \cdot 10^7$	CT10	AZNLO[77]
$t\bar{t}$	POWHEG-BOX	PYTHIA 6.428	NNLO+NNLL [78]	$8.3 \cdot 10^5$	CT10	PERUGIA2012 (P2012) [79]

# Charge flip

$$w_{\text{flip}} = \xi_1(1 - \xi_2) + (1 - \xi_1)\xi_2$$

$$L(\{N_{\varpi}^{\text{SS,obs}}\} | \{\xi(\eta, p_T)\}) = \prod_{\varpi} \mathcal{P}(N_{\varpi}^{\text{SS,obs}} | w_{\text{flip}}(\xi(\eta_1, p_{T,1}), \xi(\eta_2, p_{T,2})) \times N_{\varpi}^{\text{OS+SS,obs}})$$



# Combination of fake estimates

- To improve the robustness of the fake estimates and reduce uncertainties, we combine the MxM and MC template predictions
- Retained estimate is a weighted-average with weights based on the statistical component (fully uncorrelated)
- Systematic uncertainties propagated conservatively assuming full correlation
  - In fact, the two methods are largely independent!
- Central value and statistical/systematic uncertainties:

$$(w\xi_1 + (1-w)\xi_2) \pm \sqrt{w^2 (\Delta\xi_1^{(\text{stat})})^2 + (1-w)^2 (\Delta\xi_2^{(\text{stat})})^2} \pm (w\Delta\xi_1^{(\text{syst})} + (1-w)\Delta\xi_2^{(\text{syst})})$$

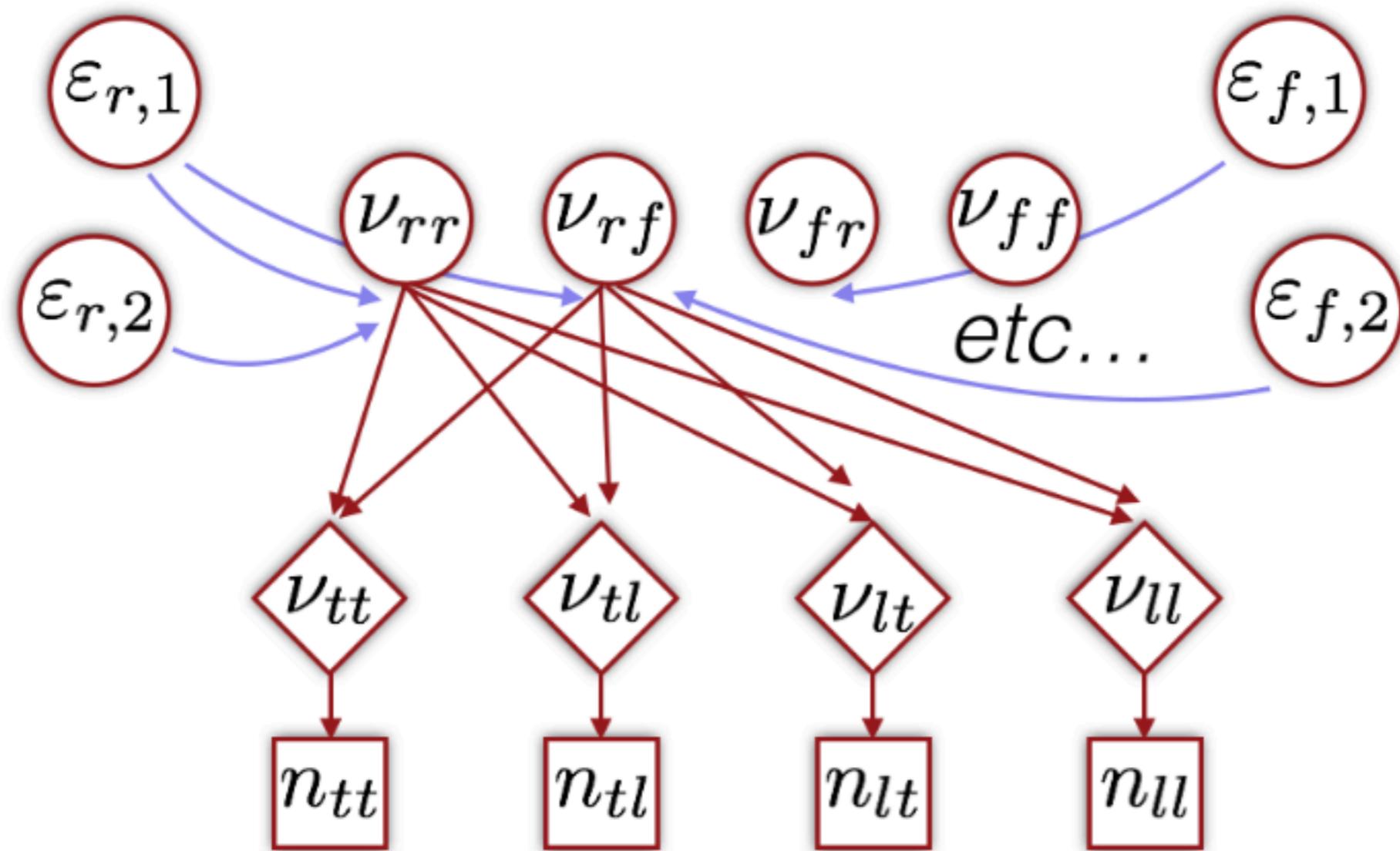
with  $w = \frac{(\Delta\xi_2^{(\text{stat})})^2}{(\Delta\xi_1^{(\text{stat})})^2 + (\Delta\xi_2^{(\text{stat})})^2}$

$\xi_1$ : estimate from MxM  
 $\xi_2$ : estimate from MC template

# Matrix Method



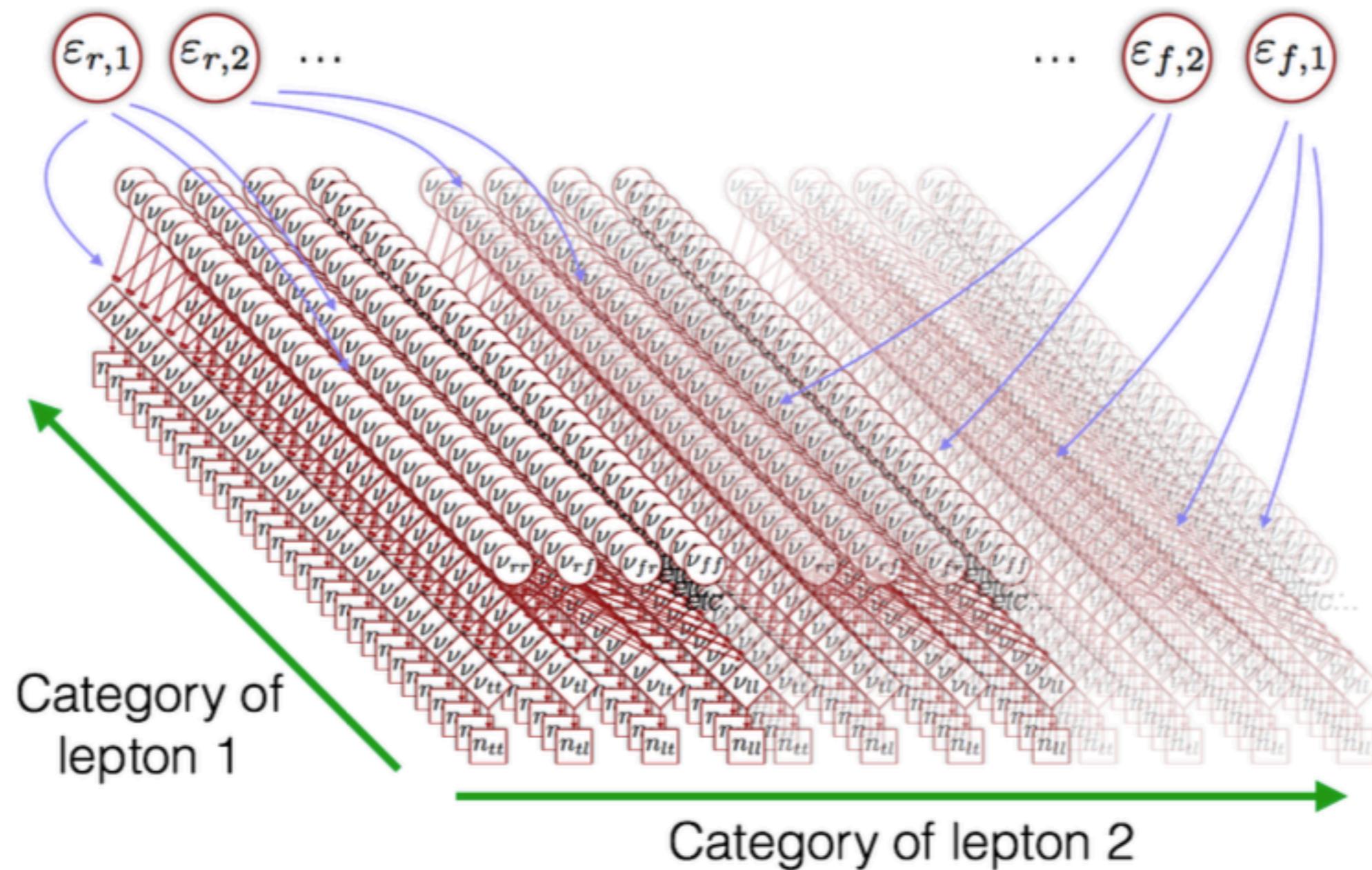
2-leptons case in one category:



# Matrix Method



2-leptons case in multiple categories:



# Real efficiency uncert.

- Dominant uncertainty: efficiency loss in busy environments, evaluated in MC samples featuring  $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$  with large  $\Delta M(\tilde{g}, \tilde{\chi}_1^0)$

$\Delta R(e, jet)$	efficiency loss (electrons)								
	[0, 0.1]	[0.1, 0.15]	[0.15, 0.2]	[0.2, 0.3]	[0.3, 0.35]	[0.35, 0.4]	[0.4, 0.6]	[0.6, 4]	
$10 < p_T < 20$	-	-	-	-	-	-	25%	7%	
$20 < p_T < 30$	-	-	-	-	-	73%	10%	0.4%	
$30 < p_T < 40$	-	-	-	98%	48%	16%	7%	1%	
$40 < p_T < 50$	-	-	-	53%	23%	17%	8%	1%	
$50 < p_T < 60$	-	-	-	30%	21%	20%	7%	3%	
$60 < p_T < 80$	-	-	56%	24%	17%	25%	6%	3%	
$80 < p_T < 150$	-	58%	30%	16%	13%	21%	4%	3%	
$150 < p_T < 200$	89%	40%	19%	8%	15%	17%	3%	2%	

$\Delta R(\mu, jet)$	efficiency loss (muons)								
	[0, 0.1]	[0.1, 0.15]	[0.15, 0.2]	[0.2, 0.3]	[0.3, 0.35]	[0.35, 0.4]	[0.4, 0.6]	[0.6, 4]	
$10 < p_T < 20$	-	-	-	-	-	-	34%	5%	
$20 < p_T < 30$	-	-	-	-	-	82%	22%	3%	
$30 < p_T < 40$	-	-	-	99%	56%	32%	14%	2%	
$40 < p_T < 50$	-	-	-	53%	21%	14%	7%	1%	
$50 < p_T < 60$	-	-	-	25%	14%	10%	4%	0.8%	
$60 < p_T < 80$	-	-	44%	14%	6%	5%	2%	0.2%	
$80 < p_T < 150$	-	30%	7%	3%	1%	1%	0.1%	0.6%	
$150 < p_T < 200$	82%	4%	1%	0.2%	0.3%	0.6%	1%	1%	

# Real lepton background subtraction

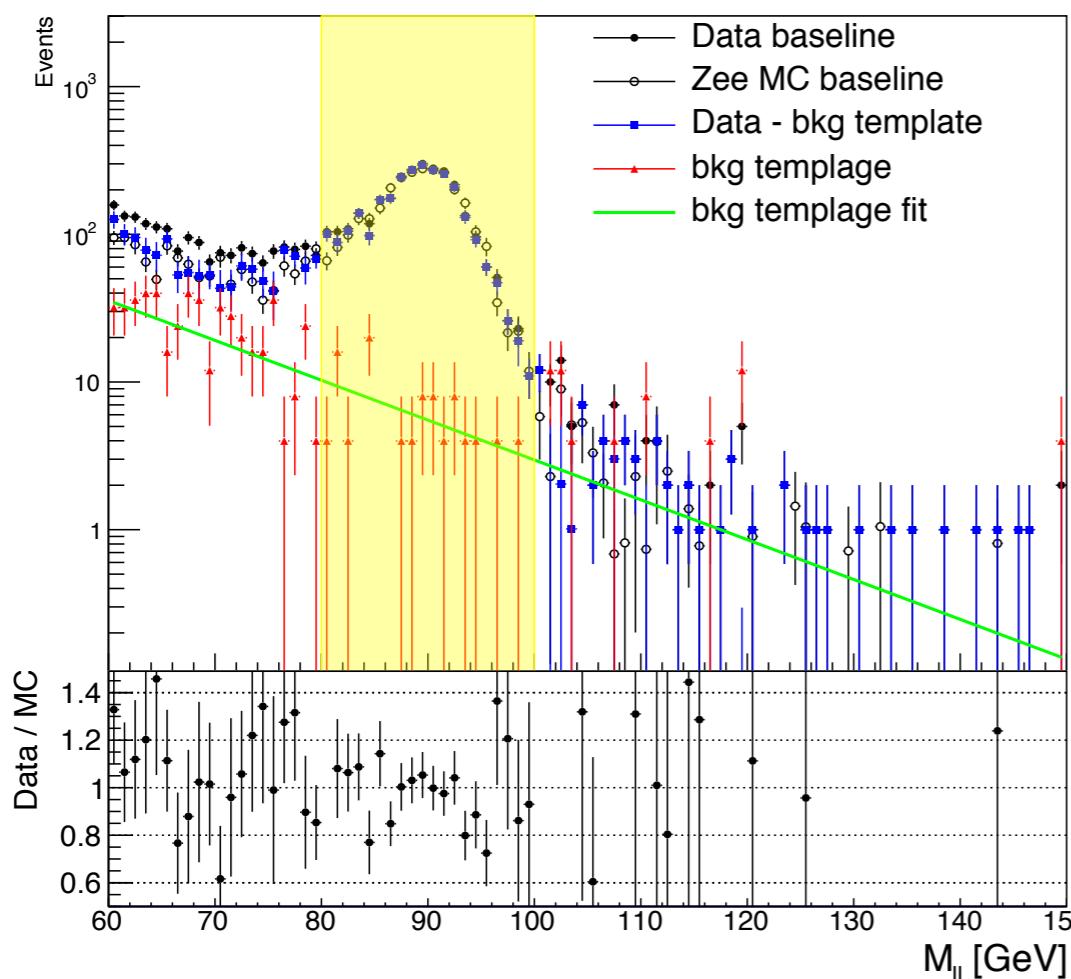
$$N_{\text{baseline}}^{\text{BKG}} = \int_{80}^{100} dM_{\ell\ell} N_{\text{Template}} \left[ \frac{N_{\text{baseline}}^{\text{Tail}} - N_{\text{signal}}^{\text{MC, Tail}} / \epsilon_{\text{real}}^{\text{MC}}}{N_{\text{Template}}^{\text{Tail}}} \right]$$

$$N_{\text{baseline}}^{\text{Tail}} = N_{\text{BKG}}^{\text{Tail}} + N_{\text{contamination}}^{\text{Tail}}$$

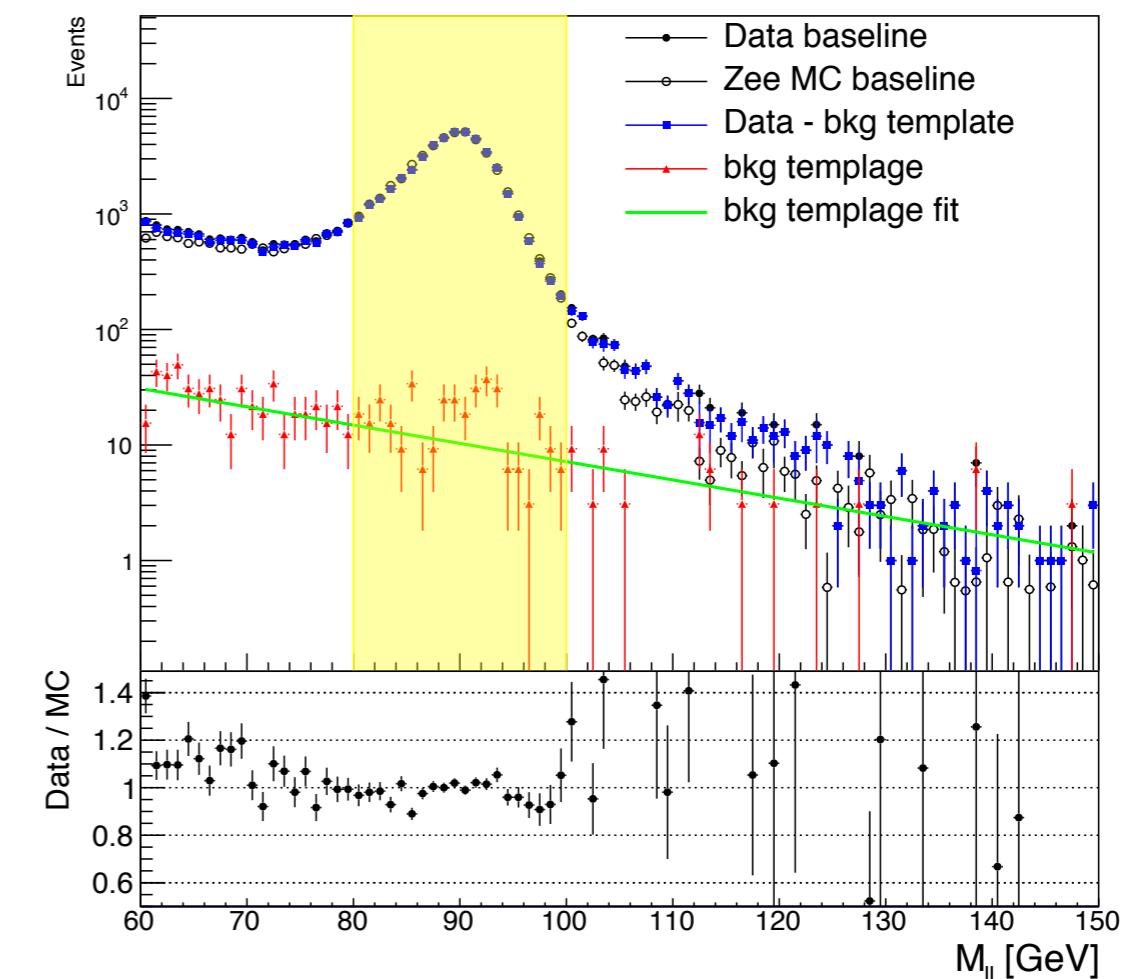
The signal contamination in the tail region are estimated using MC:

$$N_{\text{contamination}}^{\text{Tail}} = N_{\text{signal}}^{\text{MC, Tail}} / \epsilon_{\text{real}}^{\text{MC}}$$

$10 < pT < 15 \text{ GeV}$

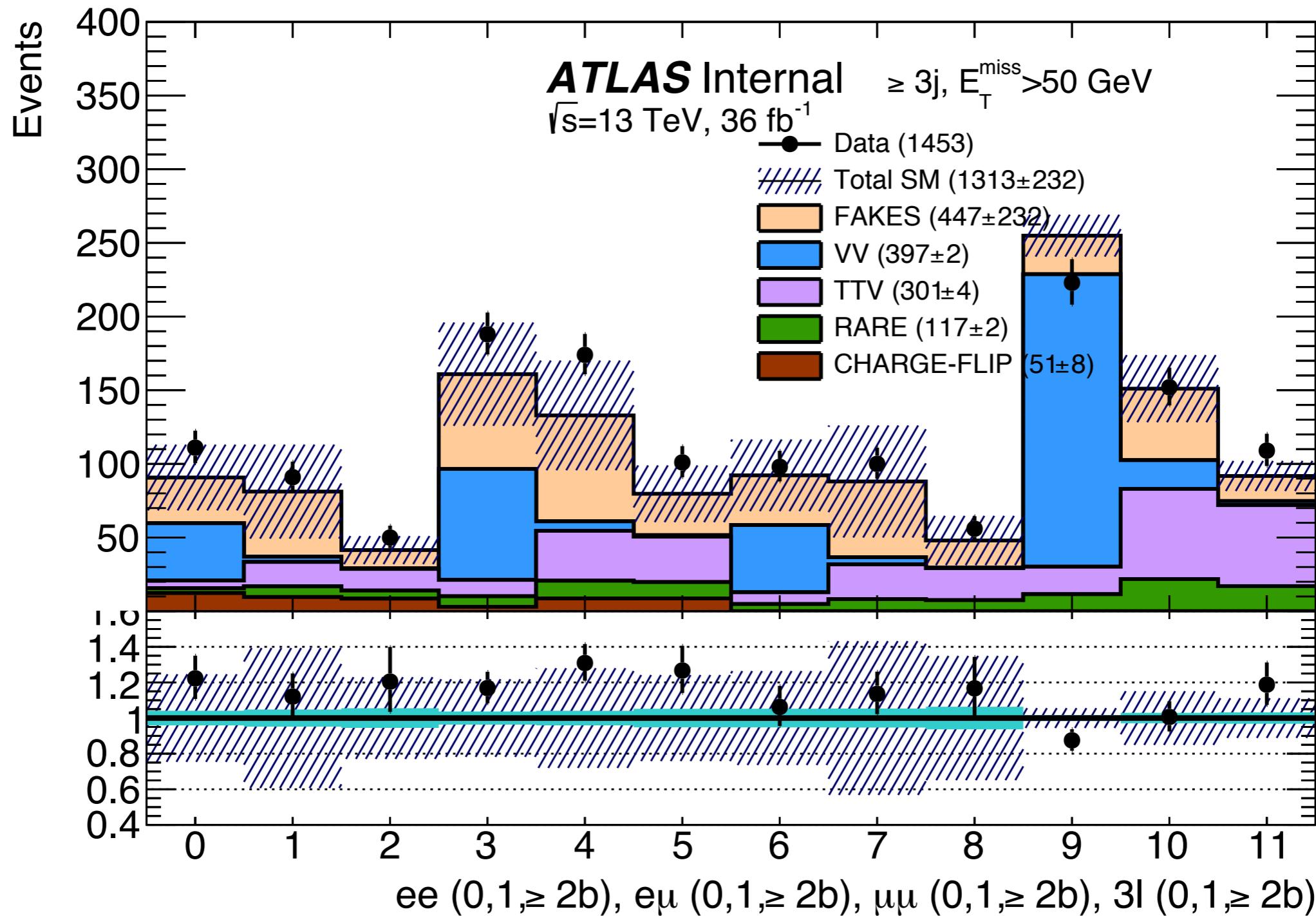


$15 < pT < 20 \text{ GeV}$



# Validation of fake estimates

- Good agreement in inclusive SS/3L selection with  $\text{MET} > 50\text{GeV}$ ,  $\geq 3j$



# Compared fake estimates

- **Remarkable agreement** from independent methods!
- Reduced uncertainty in the combination

Region	Matrix method	Template method	Retained estimate
Rpc2L0bH	$0.83 \pm 0.56 \pm 0.74$	$1.00 \pm 0.96 \pm 0.81$	$0.87 \pm 0.48 \pm 0.76$
Rpc2L0bS	$1.51 \pm 0.60 \pm 0.66$	$1.68 \pm 1.02 \pm 1.26$	$1.55 \pm 0.52 \pm 0.81$
Rpc2L1bH	$3.54 \pm 1.62 \pm 3.12$	$2.07 \pm 0.63 \pm 1.56$	$2.26 \pm 0.59 \pm 1.76$
Rpc2L1bS	$2.65 \pm 1.21 \pm 1.89$	$2.33 \pm 1.17 \pm 2.10$	$2.48 \pm 0.84 \pm 2.00$
Rpc2L2bH	$-0.11 \pm 0.11 \pm 0.18$	$< 0.5$	$0.15 \pm 0.15 \pm 0.00$
Rpc2L2bS	$1.31 \pm 1.07 \pm 1.65$	$0.41 \pm 0.33 \pm 0.45$	$0.49 \pm 0.32 \pm 0.55$
Rpc2Lsoft1b	$4.75 \pm 1.42 \pm 2.64$	$2.48 \pm 1.32 \pm 1.86$	$3.53 \pm 0.97 \pm 2.22$
Rpc2Lsoft2b	$1.91 \pm 1.18 \pm 1.63$	$1.66 \pm 0.66 \pm 1.28$	$1.72 \pm 0.58 \pm 1.36$
Rpc3L0bH	$-0.01 \pm 0.11 \pm 0.10$	$< 0.5$	$0.15 \pm 0.15 \pm 0.00$
Rpc3L0bS	$2.31 \pm 1.50 \pm 2.63$	$0.21 \pm 0.15 \pm 0.16$	$0.23 \pm 0.15 \pm 0.18$
Rpc3L1bH	$0.57 \pm 0.43 \pm 0.50$	$0.42 \pm 0.29 \pm 0.32$	$0.47 \pm 0.24 \pm 0.38$
Rpc3L1bS	$4.94 \pm 1.83 \pm 2.96$	$3.55 \pm 1.80 \pm 2.76$	$4.23 \pm 1.28 \pm 2.86$
Rpc3LSS1b	$-0.18 \pm 1.24 \pm 2.85$	$0.90 \pm 0.14 \pm 0.69$	$0.89 \pm 0.14 \pm 0.72$

# Validation regions

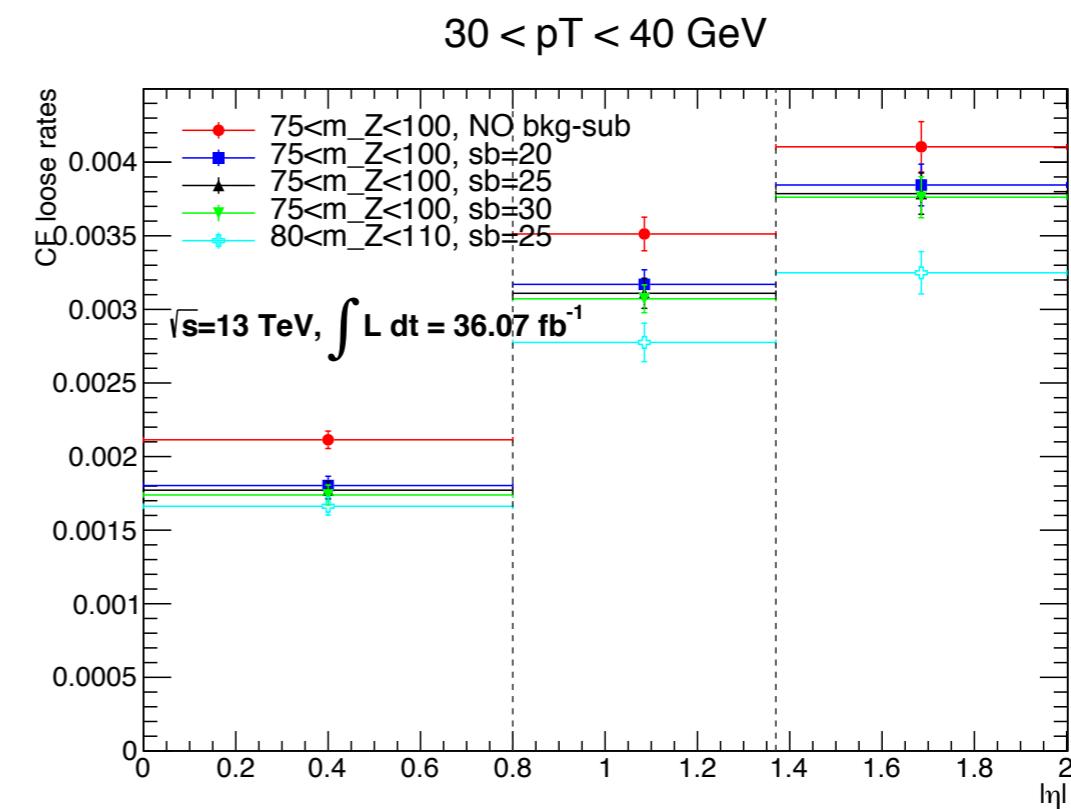
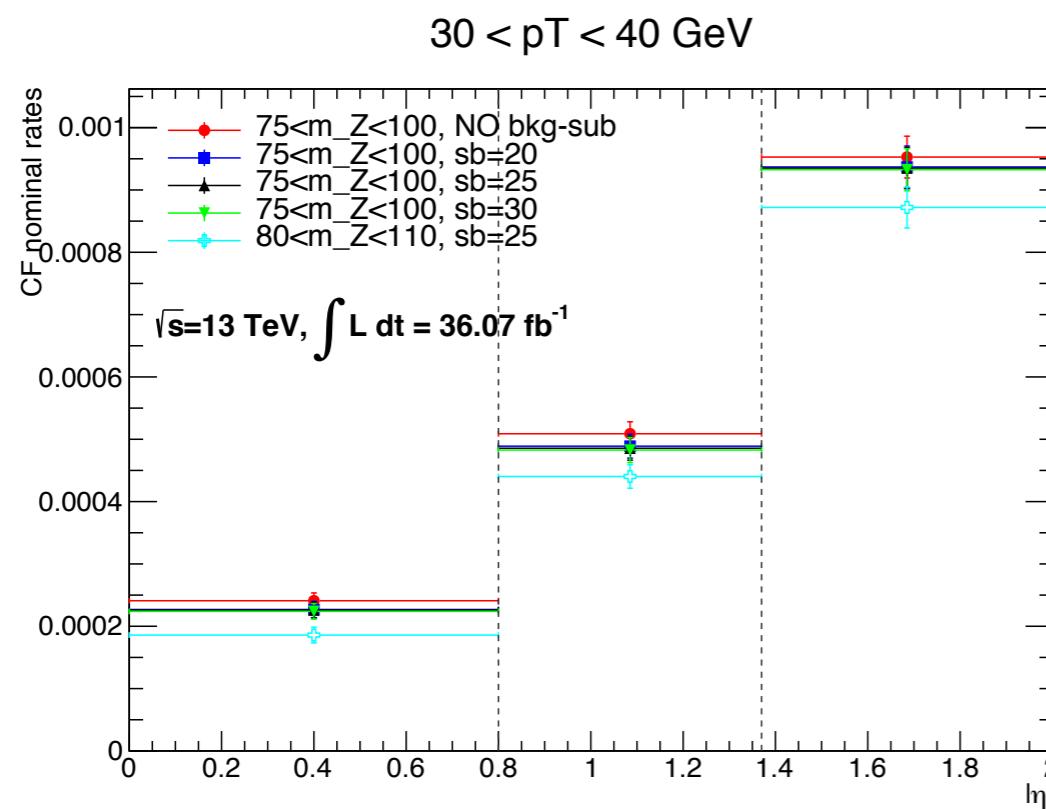
	$N_{\text{lept}}^{\text{signal}}$ ( $N_{\text{lept}}^{\text{base}}$ )	$N_{b-\text{jcts}}$	$N_{\text{jcts}}$	jet $p_T$ [GeV]	$E_T^{\text{miss}}$ [GeV]	$m_{\text{eff}}$ [GeV]	Other
$W^\pm W^\pm\text{-VR}$	=2 (=2) =1 SS pair	==0	$\geq 2$	> 50	> 55	> 650	veto $81 < m_{ee} < 101$ GeV $p_T(\ell_2) > 30$ GeV $\min\{\Delta R(\ell_{1,2}, j)\} > 0.7$ $\min\{\Delta R(\ell_1, \ell_2)\} > 1.3$
$WZ4j\text{-VR}$	==3 (==3)	==0	$\geq 4$	> 25	-	> 450	$E_T^{\text{miss}}/\sum p_T^\ell < 0.7$
$WZ5j\text{-VR}$	==3 (==3)	==0	$\geq 5$	> 25	-	> 450	$E_T^{\text{miss}}/\sum p_T^\ell < 0.7$
$t\bar{t}W\text{-VR}$	=2 (=2) =1 SS pair	$\geq 1$	$\geq 4 (e^\pm e^\pm, e^\pm \mu^\pm)$ $\geq 3 (\mu^\pm \mu^\pm)$	> 40 > 25	> 45	> 550	$p_T(\ell_2) > 40$ GeV $\sum p_T^{b-j} / \sum p_T^j > 0.25$
$t\bar{t}Z\text{-VR}$	$\geq 3 (-)$ $\geq 1$ SFOS pair	$\geq 1$	$\geq 3$	> 35	-	> 450	$81 < m_{\text{SFOS}} < 101$ GeV

separate estimates from the matrix and MC template methods:

	VR- $t\bar{t}W$	VR- $t\bar{t}Z$	VR- $WZ4j$	VR- $WZ5j$	VR- $W^\pm W^\pm$
Fakes DD	$23 \pm 5 \pm 24$	$30 \pm 4 \pm 14$	$53 \pm 6 \pm 27$	$21 \pm 4 \pm 10$	$14 \pm 3 \pm 10$
Fakes MC	$14 \pm 4 \pm 10$	$18 \pm 3 \pm 13$	$46 \pm 5 \pm 34$	$16 \pm 2 \pm 12$	$13 \pm 2 \pm 10$
Combined	$18 \pm 3 \pm 15$	$22 \pm 2 \pm 13$	$49 \pm 4 \pm 30$	$17 \pm 2 \pm 12$	$13 \pm 2 \pm 10$
Charge-flip DD	$3.4 \pm 0.1 \pm 0.5$	—	—	—	$1.7 \pm 0.1 \pm 0.2$
Charge-flip MC	$3.8 \pm 1.0 \pm 1.9$	—	—	—	$1.0 \pm 0.3 \pm 0.2$

# Charge flip background

- Systematics evaluated by comparing configurations 1,2,4, 5 to the nominal configuration 3:
  1.  $75 < m_{ee} < 100$  GeV, no background subtraction;
  2.  $75 < m_{ee} < 100$  GeV, sidebands of 20 GeV;
  3.  $75 < m_{ee} < 100$  GeV, sidebands of 25 GeV (nominal measurement);
  4.  $75 < m_{ee} < 100$  GeV, sidebands of 30 GeV;
  5.  $80 < m_{ee} < 100$  GeV, sidebands of 20 GeV.
- The largest deviation in each bin is taken as the systematic uncert,: 15% in SRs



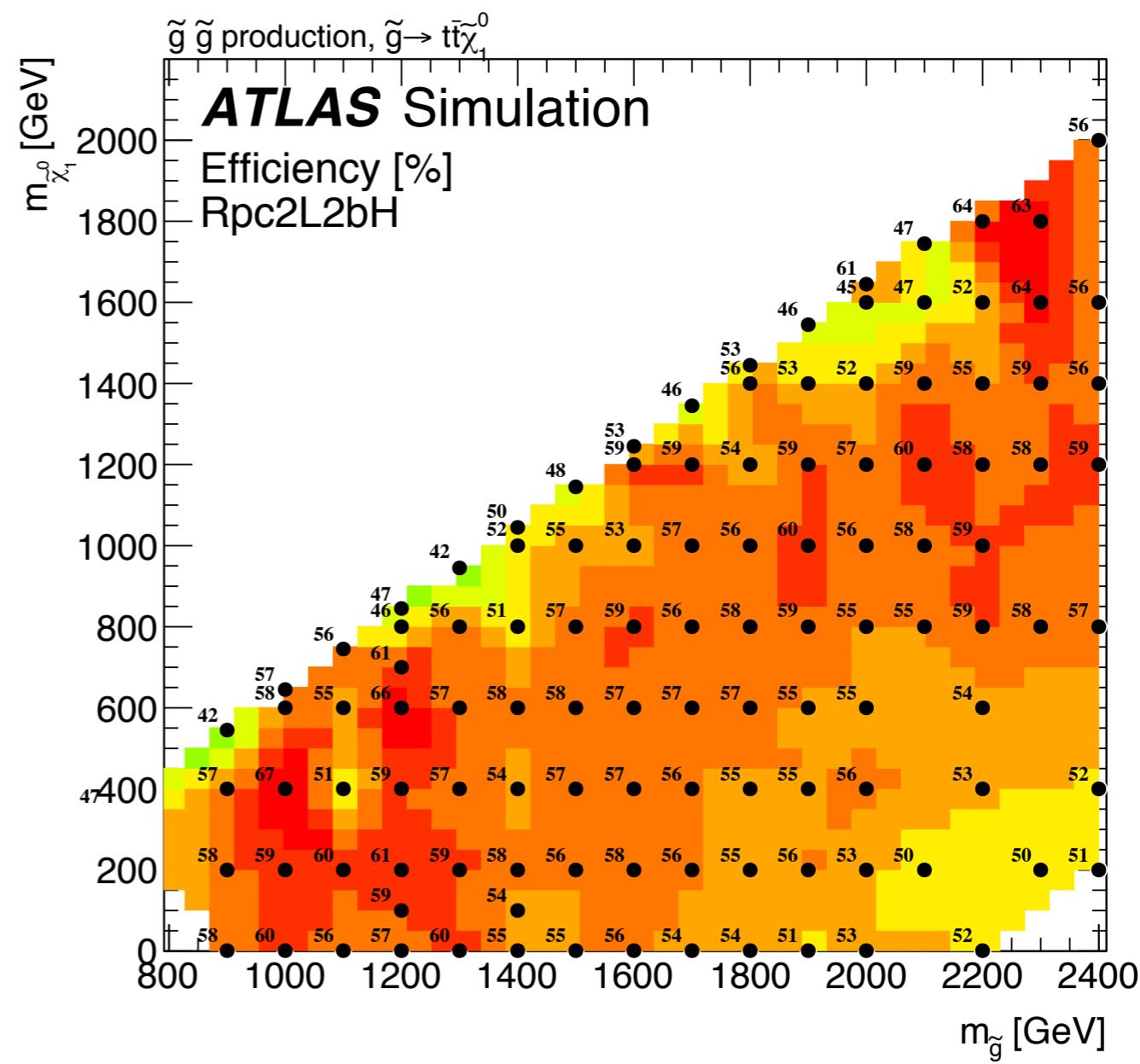
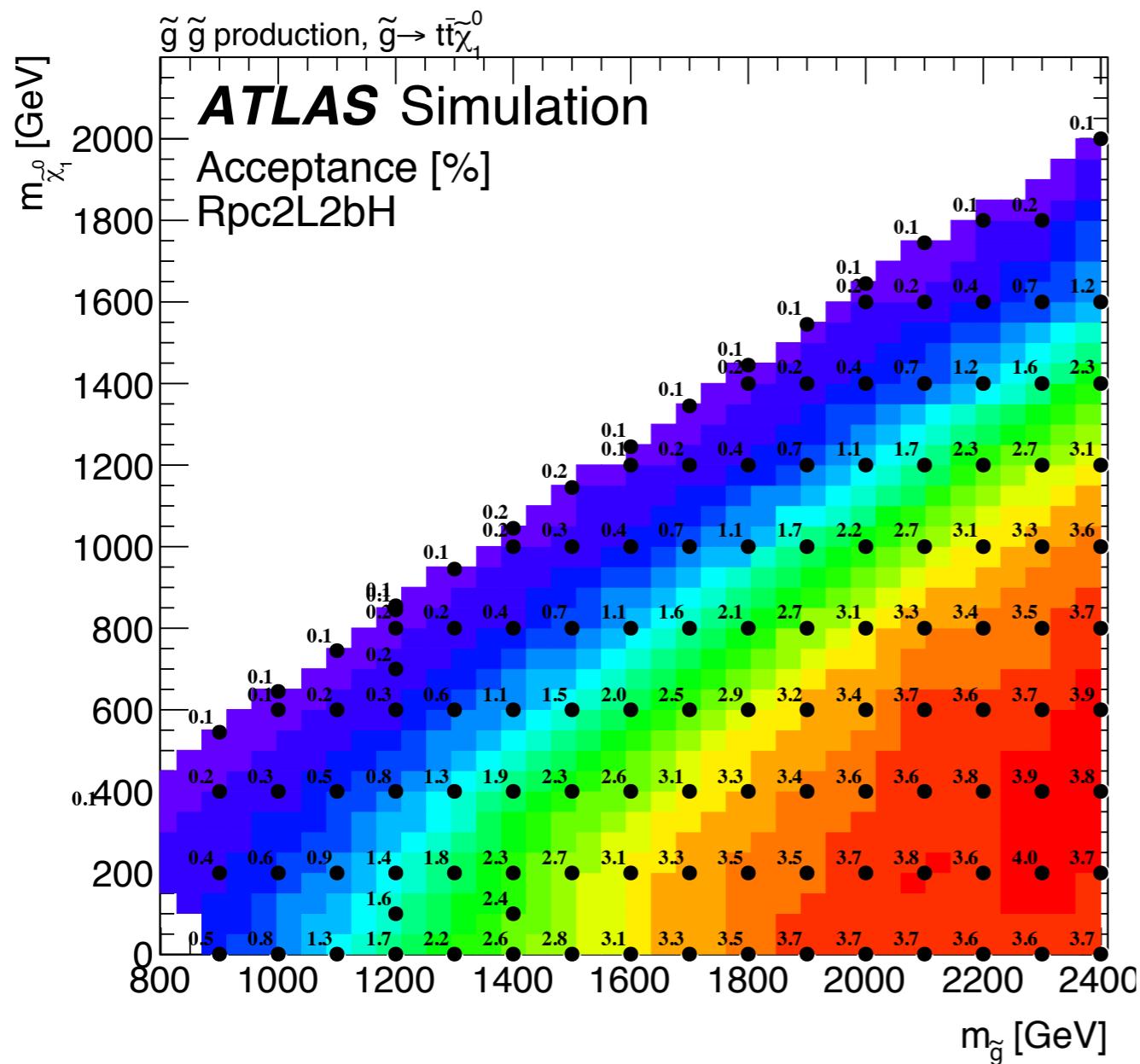
# Uncertainties

Signal Region	Rpc2L2bS	Rpc2L2bH	Rpc2Lsoft1b	Rpc2Lsoft2b	Rpc2L0bS	Rpc2L0bH
Total background expectation	3.35	1.08	5.78	3.80	6.02	2.35
Total statistical	10.56%	15.67%	16.93%	15.61%	9.08%	20.87%
Total background systematic	30.41%	29.97%	43.10%	41.79%	30.51%	42.39%
Fake/non-prompt	15.46%	0.00%	38.39%	35.75%	13.46%	32.31%
Charge-flip	0.06%	0.00%	0.35%	0.53%	0.17%	0.00%
Jet Energy Scale	15.19%	11.37%	5.27%	9.28%	17.28%	8.11%
Other Jet Unc.	2.09%	2.71%	0.80%	0.99%	2.31%	3.42%
Flavor Tagging	6.27%	5.55%	0.81%	3.96%	3.33%	3.27%
Electrons	1.20%	1.72%	0.51%	0.51%	0.76%	0.74%
Muons	0.90%	1.39%	0.35%	0.51%	0.83%	0.93%
Missing transverse momentum	2.24%	1.68%	0.85%	1.50%	0.65%	0.54%
Diboson Th. Unc.	1.07%	1.39%	1.07%	0.50%	17.68%	13.54%
ttV Th. Unc.	7.33%	8.86%	5.01%	4.48%	4.06%	2.44%
Rare Th. Unc.	15.18%	19.67%	6.28%	9.75%	3.89%	5.87%
PDF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Signal Region	Rpc3L0bS	Rpc3L0bH	Rpc3L1bS	Rpc3L1bH	Rpc2L1bS	Rpc2L1bH	Rpc3LSS1b
Total background expectation	11.02	3.31	17.33	3.90	9.88	9.75	1.62
Total statistical	2.57%	6.05%	7.66%	7.70%	9.59%	6.65%	9.15%
Total background systematic	27.37%	25.40%	24.22%	24.02%	29.19%	26.52%	46.79%
Fake/non-prompt	1.63%	0.00%	16.50%	9.73%	19.93%	18.05%	44.45%
Charge-flip	0.00%	0.00%	0.00%	0.00%	0.40%	0.41%	4.32%
Jet Energy Scale	9.78%	8.98%	5.54%	4.20%	11.71%	10.40%	0.02%
Other Jet Unc.	3.41%	2.55%	0.70%	2.30%	1.42%	1.46%	0.20%
Flavor Tagging	2.79%	2.93%	2.22%	2.82%	1.32%	1.38%	0.32%
Electrons	1.78%	2.16%	1.66%	2.47%	0.67%	0.89%	0.41%
Muons	1.73%	2.12%	1.25%	1.79%	0.80%	0.92%	0.41%
Missing transverse momentum	0.78%	0.53%	0.38%	0.59%	1.70%	1.06%	0.00%
Diboson Th. Unc.	24.28%	21.58%	2.57%	3.78%	1.87%	2.50%	0.00%
ttV Th. Unc.	1.49%	1.76%	5.34%	5.56%	6.96%	5.72%	0.00%
Rare Th. Unc.	4.02%	5.02%	13.19%	18.11%	12.68%	13.16%	10.49%
PDF	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

# Acceptance and Efficiency

$$S = L_{\text{int}} \cdot \sigma_{\text{prod}} \cdot A \cdot \epsilon$$



# NUHM2

## In CMSSM

- ▶ Four free continuous parameters:  $m_0, m_{1/2}, A_0, \tan \beta$ 
  - ★  $m_0$ : the universal scalar mass.
  - ★  $m_{1/2}$ : the universal gaugino mass.
  - ★  $A_0$ : the universal trilinear coupling
  - ★  $\tan \beta$ : the ratio of Higgs vacuum expectation values
- ▶  $m_0, m_{1/2}, A_0$  are defined at GUT scale.
- ▶  $\mu$  (the Higgs superpotential coupling) and  $m_A$  (the pseudoscalar Higgs boson mass):

$$\mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} - \frac{m_Z^2}{2}$$
$$m_A^2 = m_{H_d}^2 + m_{H_u}^2 + 2\mu^2$$

- ▶ The sign of  $\mu$  remains undetermined.
- ▶ The Higgs doublets have the same mass at GUT scale.
  - ★  $m_{H_d}^2 = m_{H_u}^2 = m_0^2$

# NUHM2

## NUHM2

- ▶ The Non-Universal Higgs Mass Model with two extra parameters.
- ▶  $m_{H_d}^2$  and  $m_{H_u}^2$  are no longer set equal to  $m_0$  at the GUT scale.

$$m_{H_d}^2 \neq m_{H_u}^2 \neq m_0^2$$

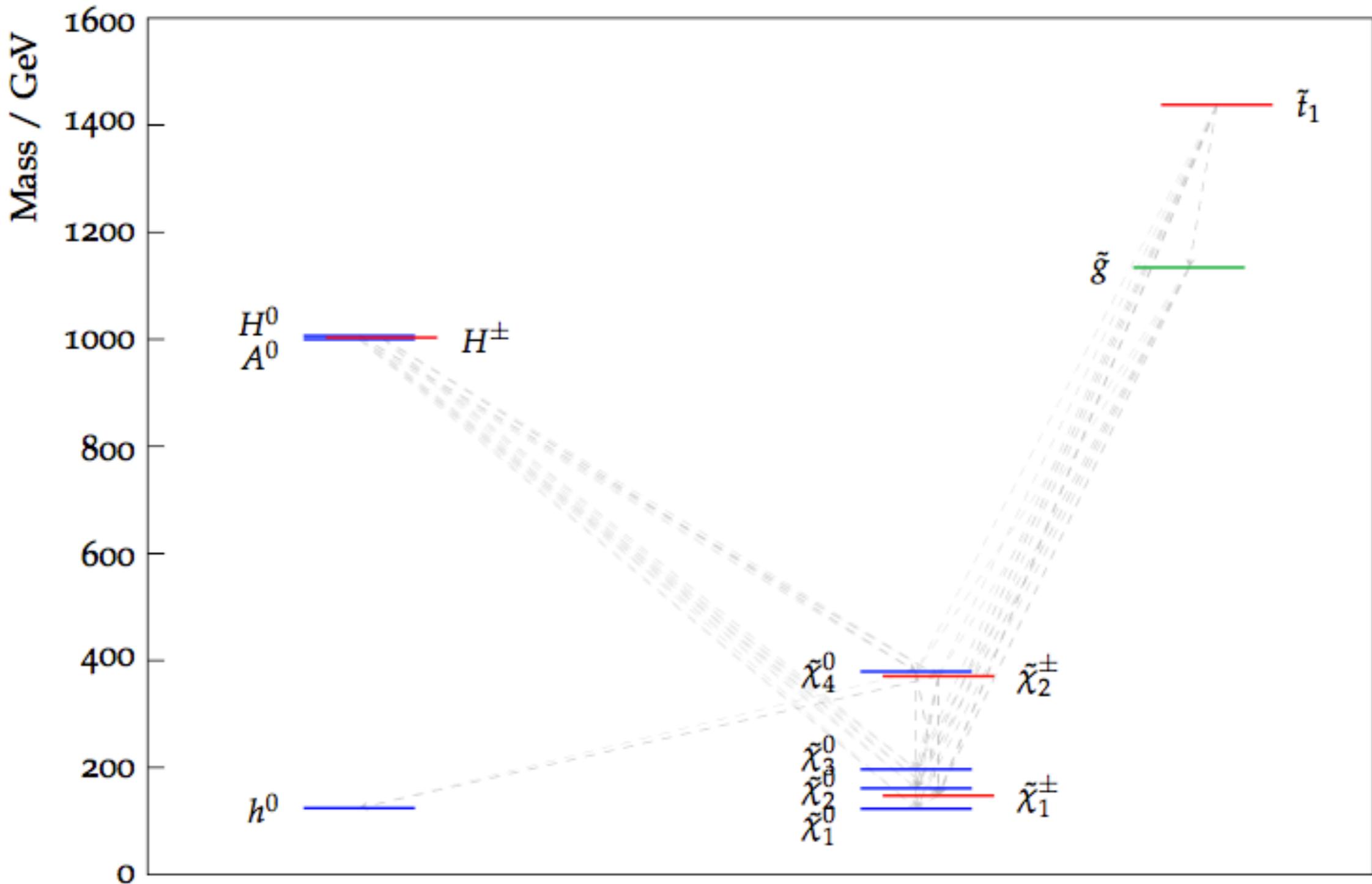
- ▶ Six free parameters:  $m_0$ ,  $m_{1/2}$ ,  $A_0$ ,  $\tan \beta$ ,  $\mu$ ,  $m_A$ .

$m_0 = 5$  TeV,  $A_0 = -1.6m_0$ ,  $\tan \beta = 15$ ,  $m_A = 1$  TeV, and  $\text{sign}(\mu) > 0$ .

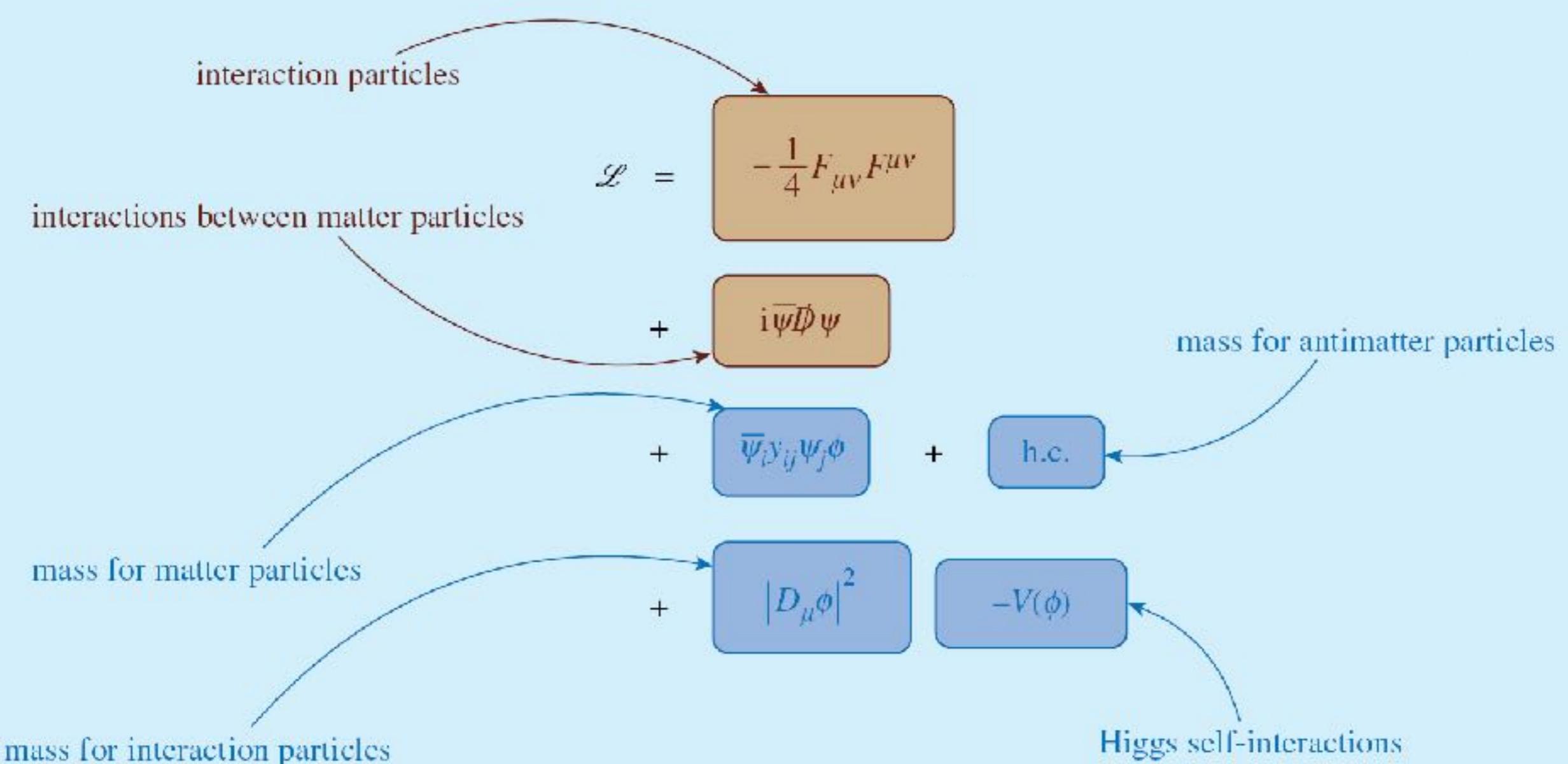
$$\mu = 150 \text{ GeV}$$

$$m_{1/2} = 300 - 800 \text{ GeV}$$

# NUHM2

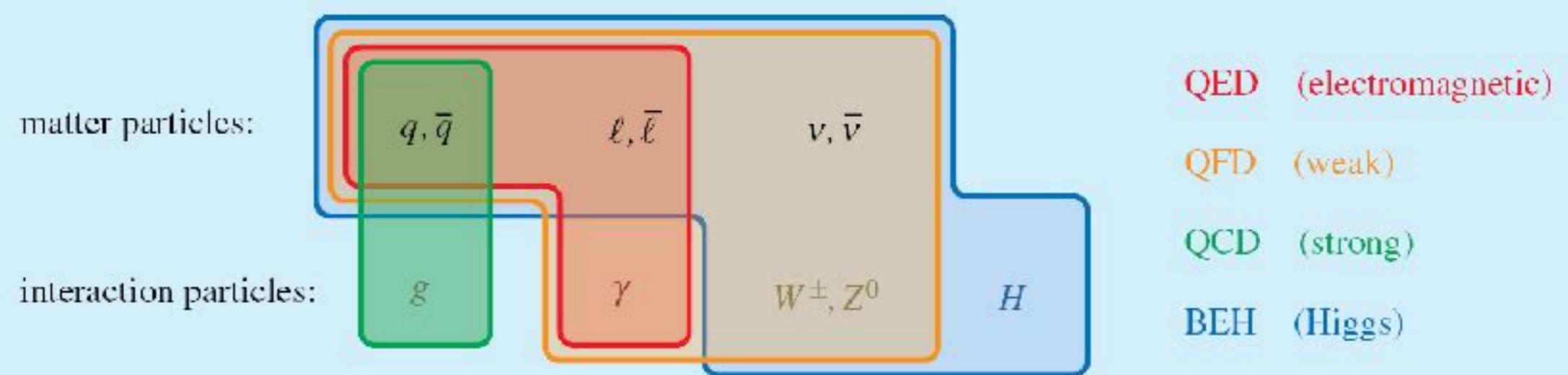


# Standard Model

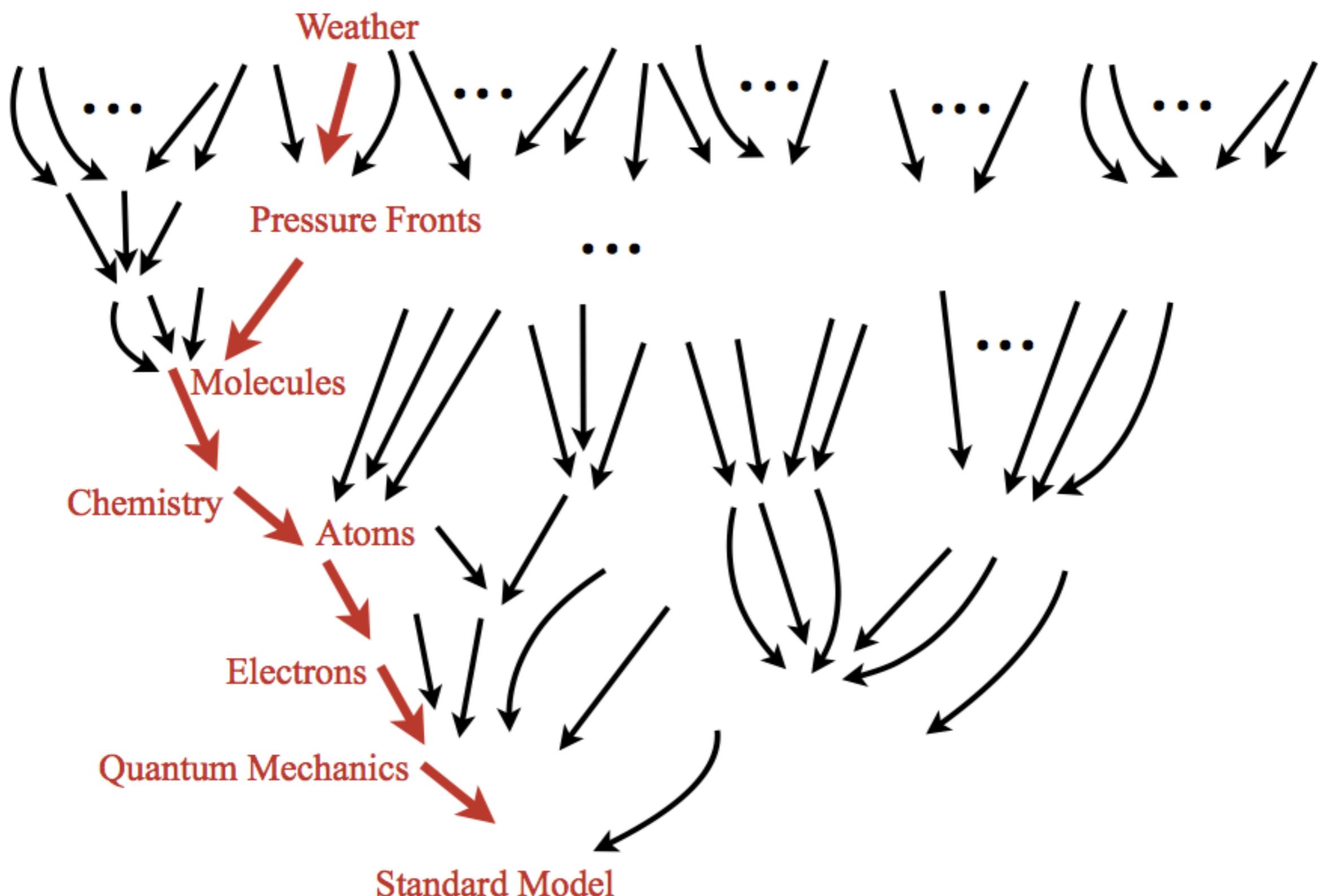


# Standard Model

Consistent theory of strong, weak, and electromagnetic interactions



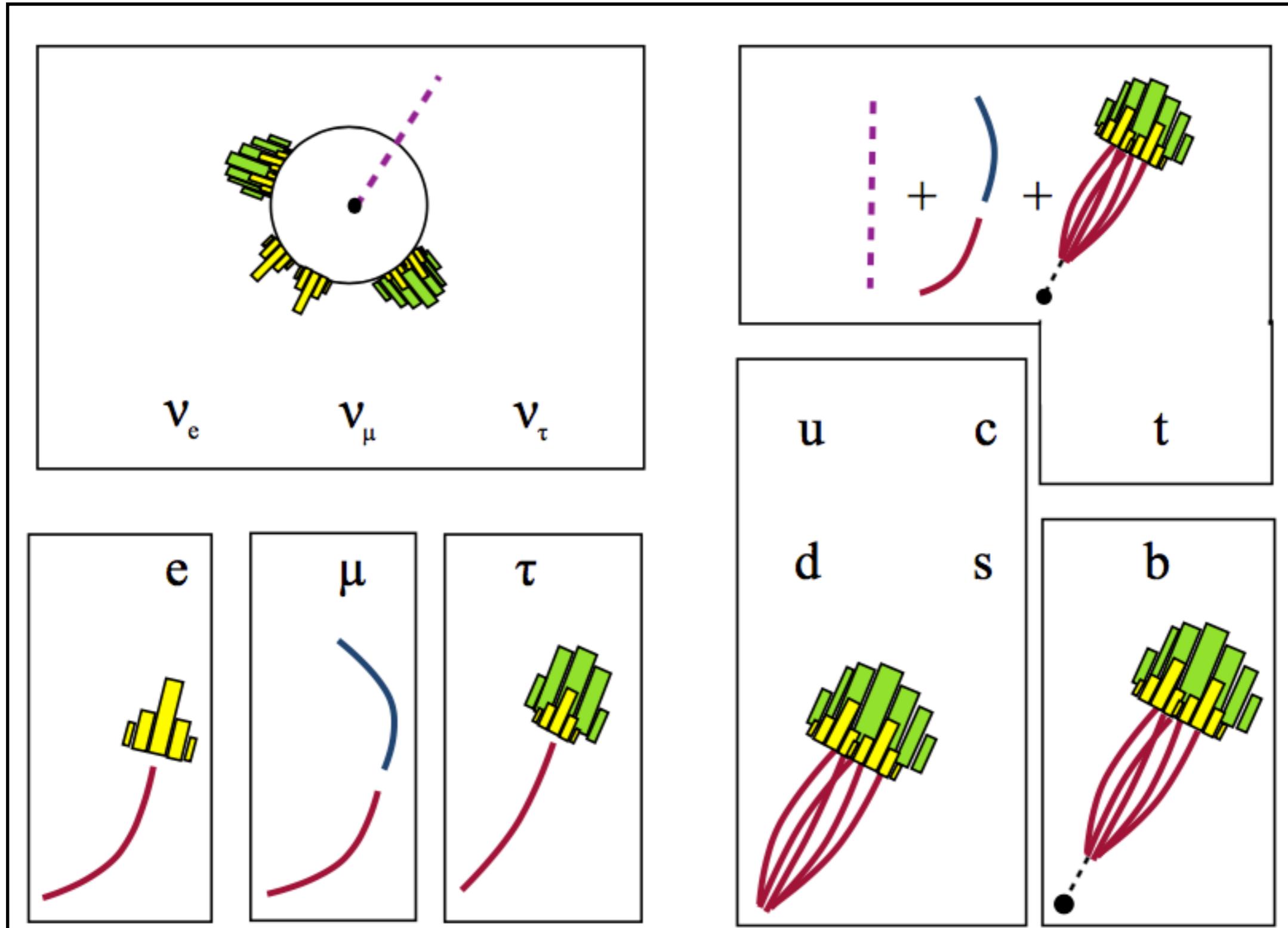
# Scientific description



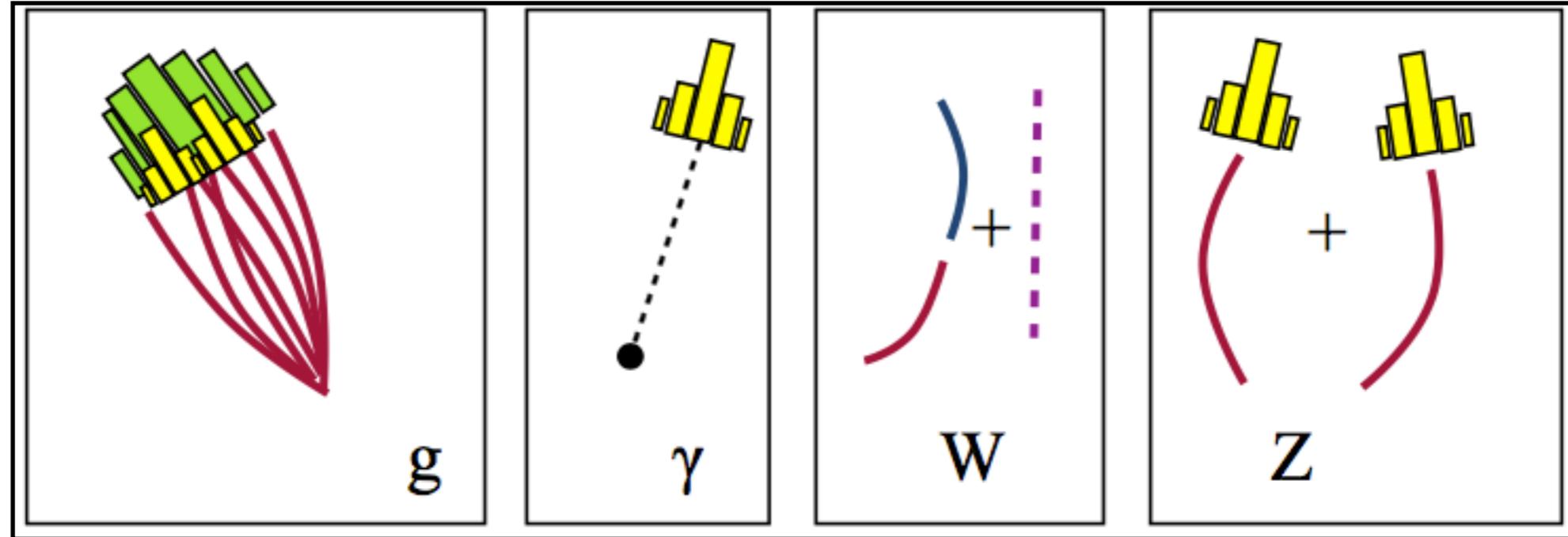
# Identifying Particles

$\nu_e$	$\nu_\mu$	$\nu_\tau$	u	c	t
e	$\mu$	$\tau$	d	s	b

# Identifying Particles



# Identifying Particles

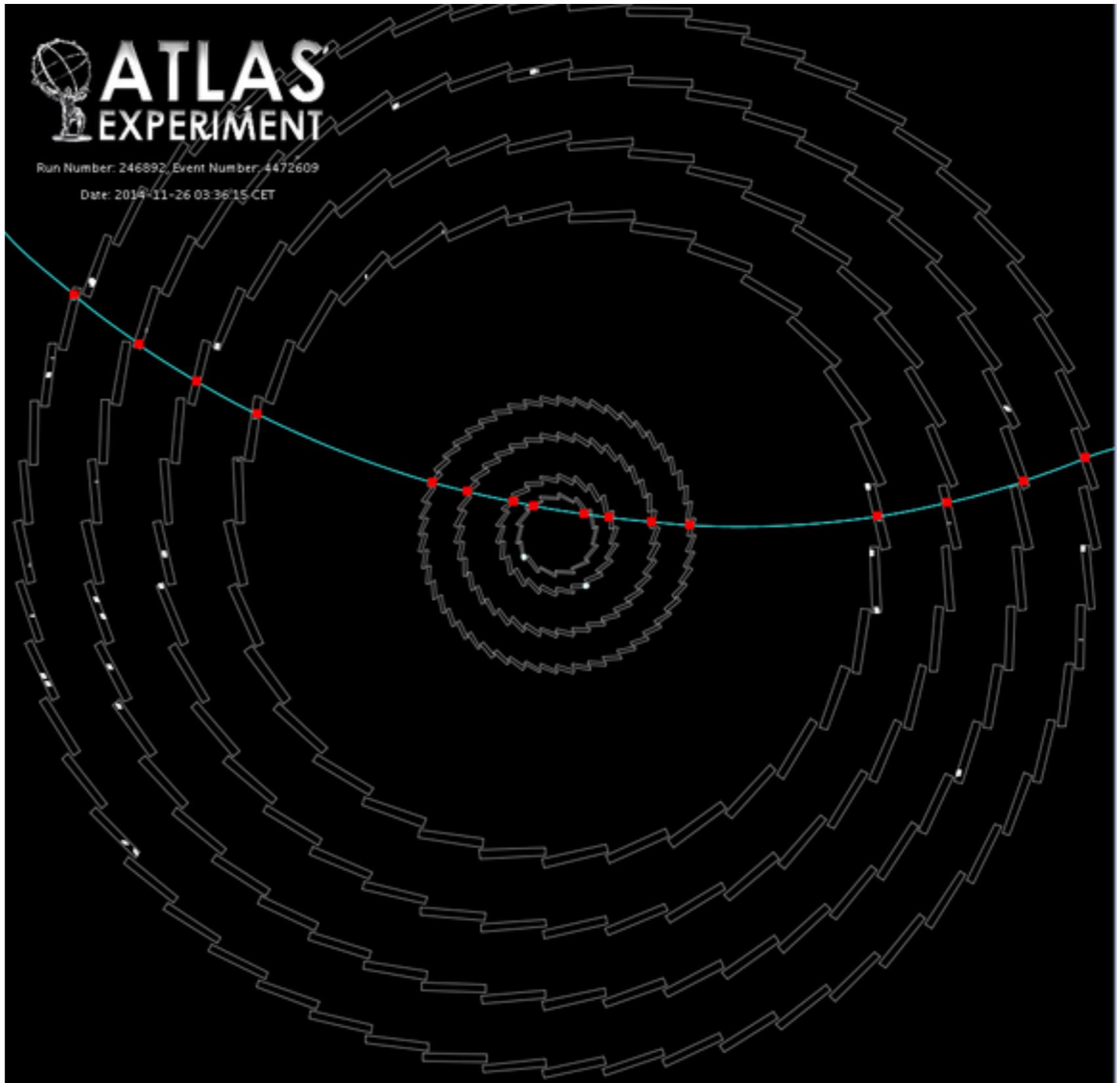


A lot of effort goes in the algorithms that identify these particles based on hits in the inner detectors and energy depositions in the calorimeters

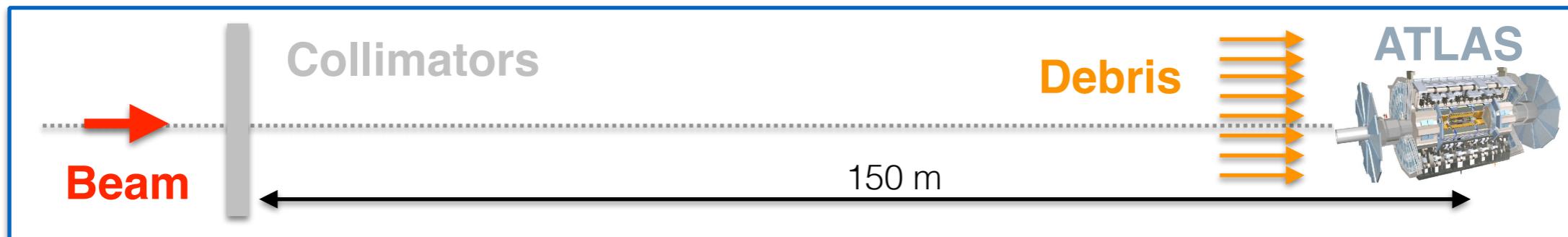
# Cosmic Ray

Pre-data taking:

- ✓ Trigger&DAQ
- ✓ Inner detector
- ✓ Muon system
- ✓ Magnets!

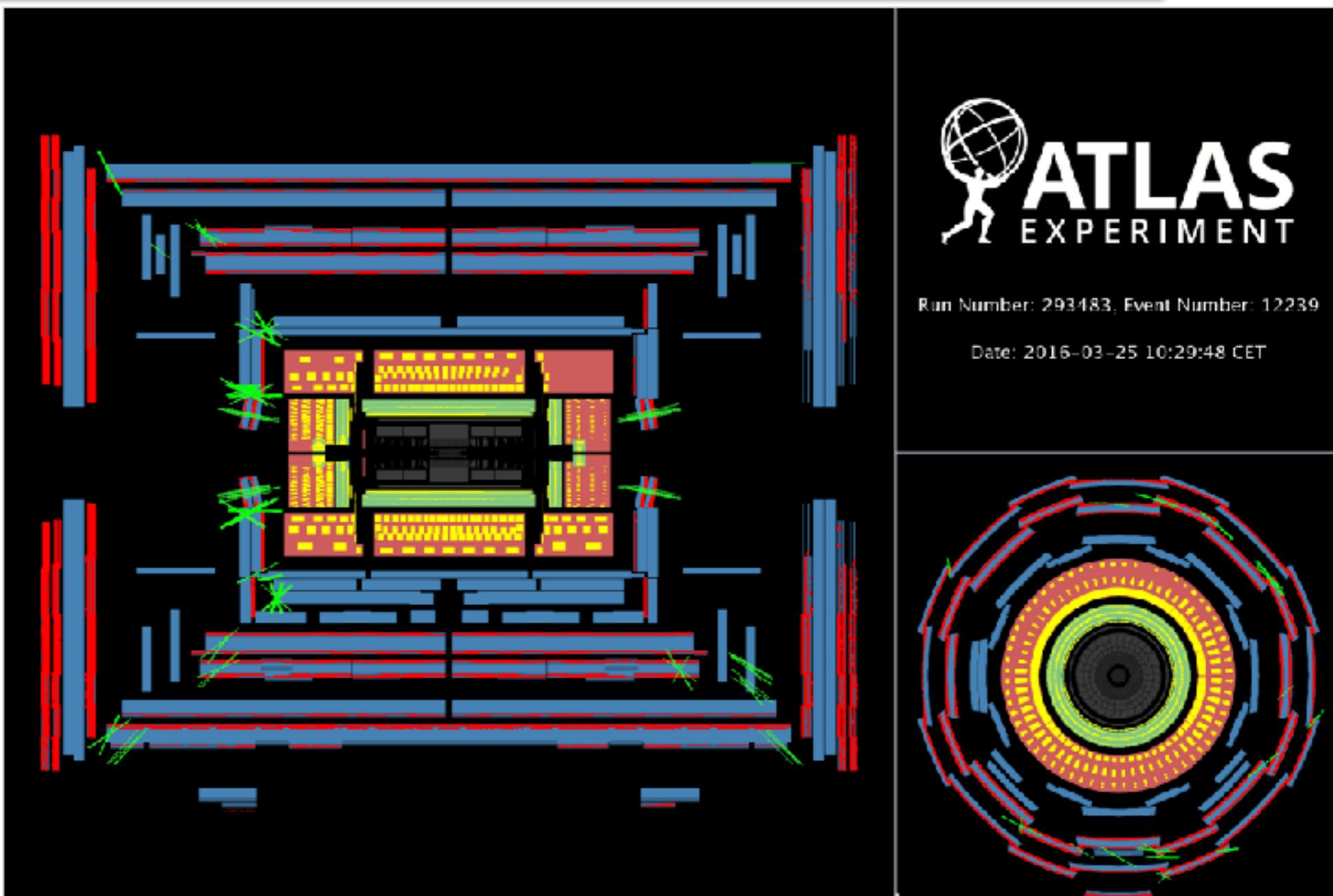


# Beam Splashes



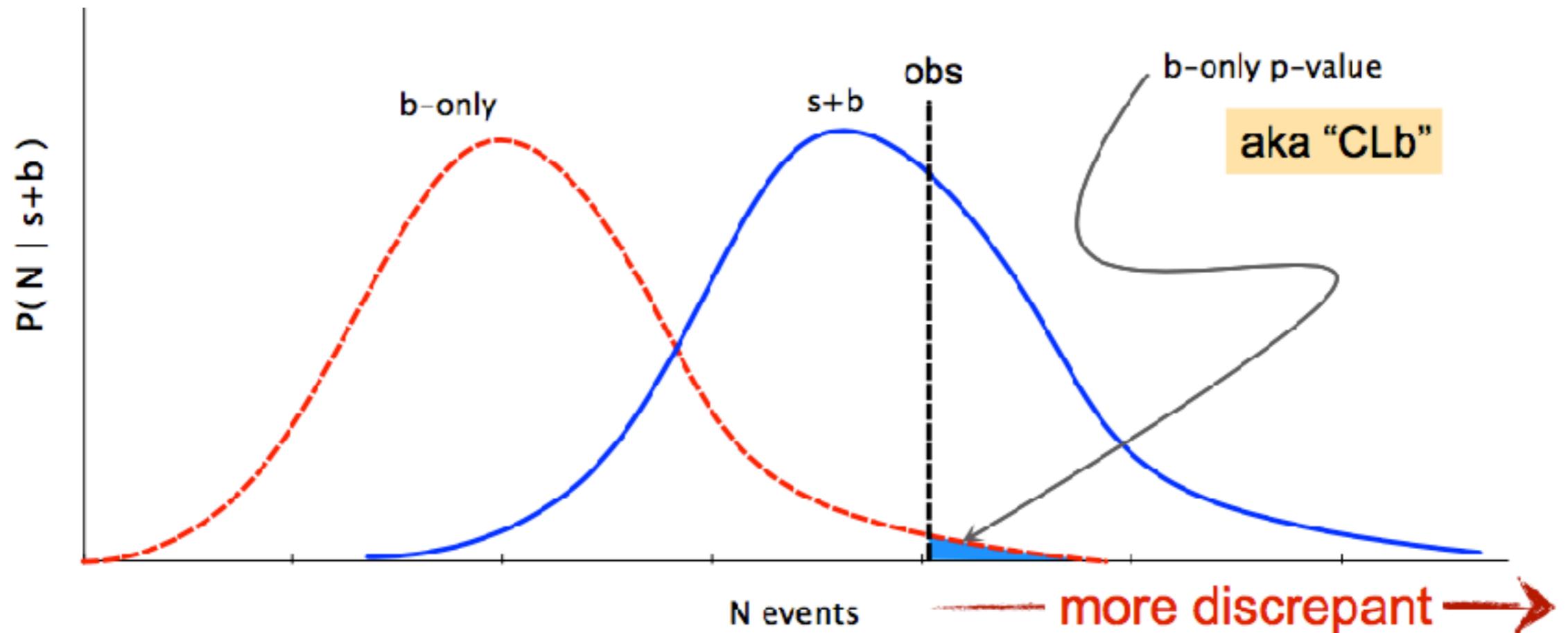
Pre-data taking:

- ✓ Trigger&DAQ
- ✓ Inner detector
- ✓ Muon system
- ✓ Calorimeters



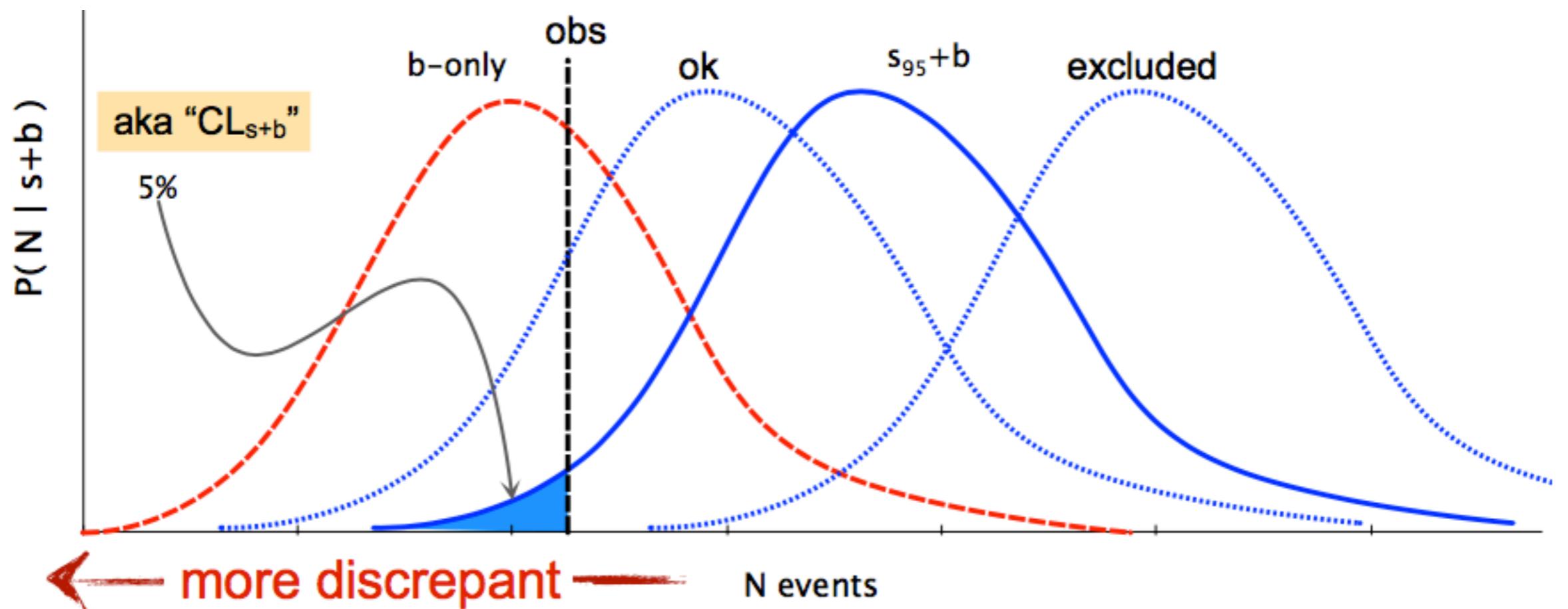
# Statistics in a Nutshell

- p-value is the probability to obtain observed data, or more extreme, given the hypothesis in future experiments
- $p_b$  or p-values of background hypothesis is used to quantify ‘discovery’ excess events over background expectation



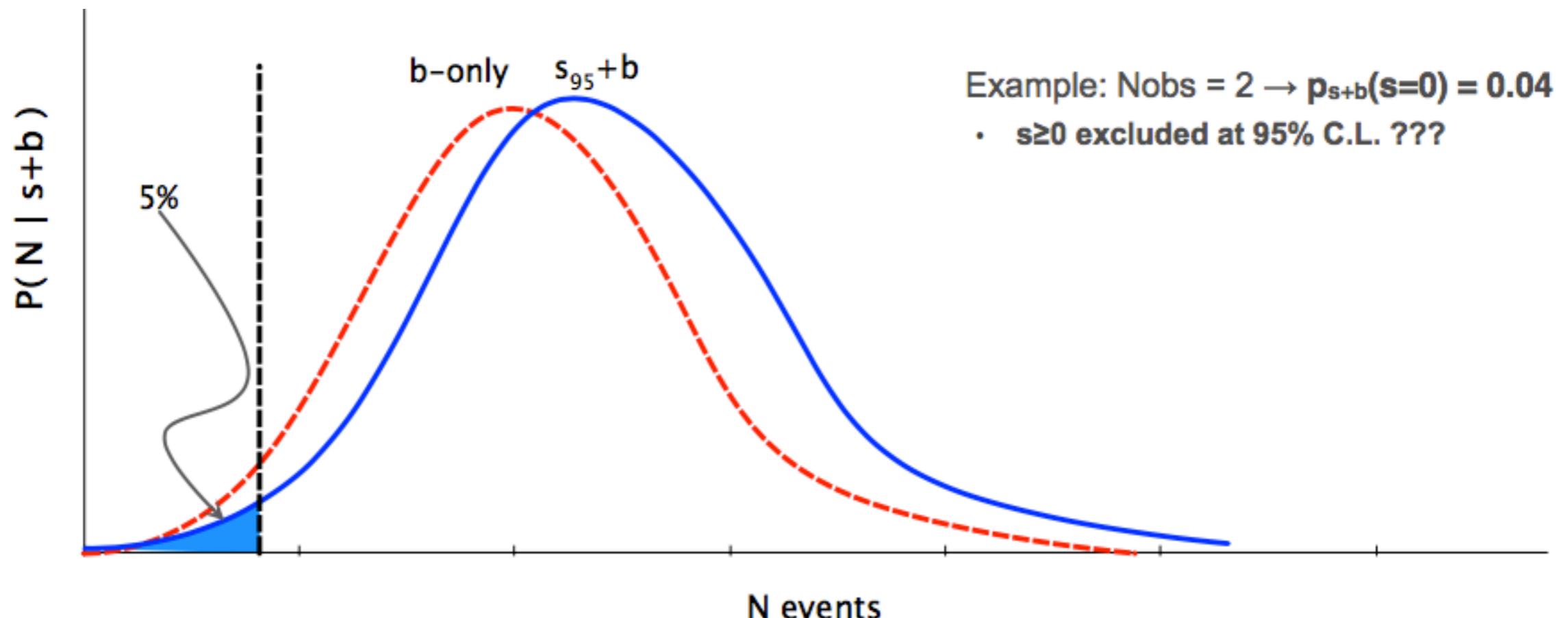
# Statistics in a Nutshell

- p-value for signal+background hypothesis
- Express result as value of  $s$  for which  $p_{s+b} = 5\%$  or exclusion at 95% CL



# Statistics in a Nutshell

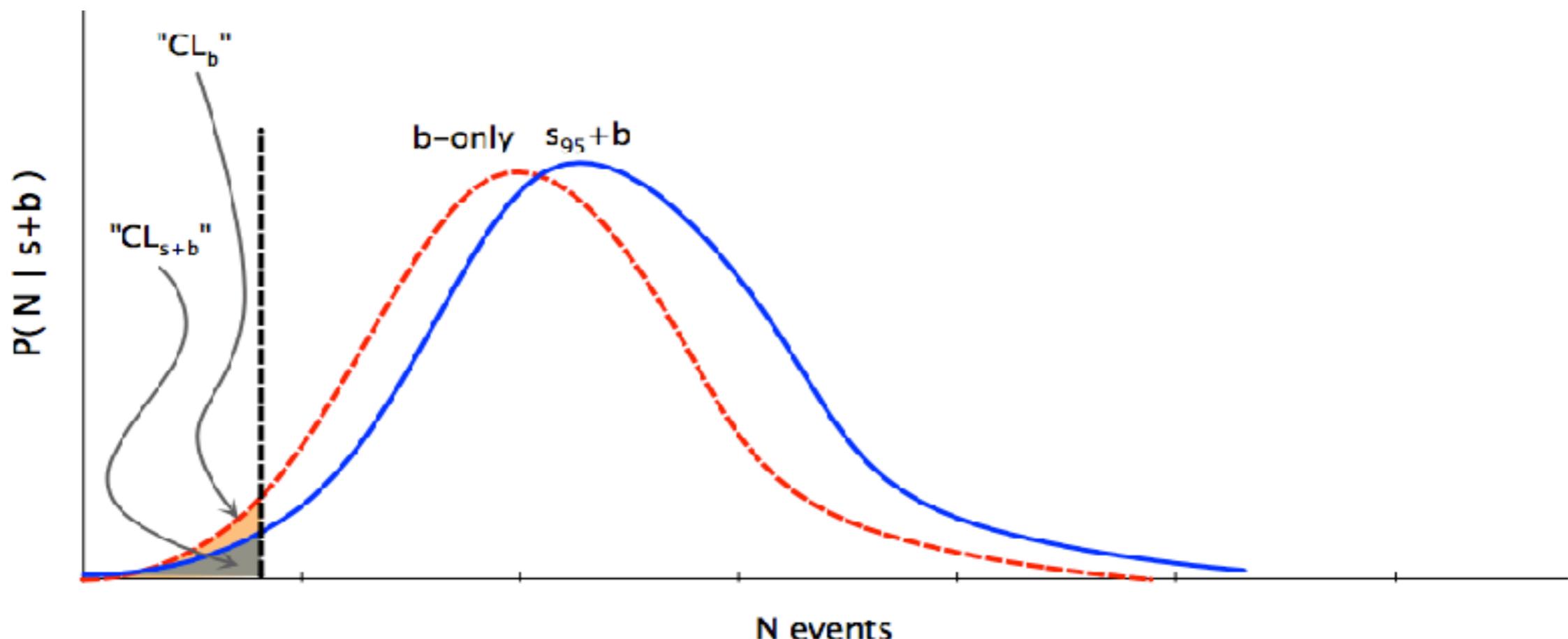
- Interpretation in terms of  $p_{s+b}$  only is problematic:
  - $p_{s+b}$  quantifies consistency with data of signal + background
  - Problem when  $s \ll b$
  - Problem when observed data has a downward fluctuation
- **Exclude arbitrary small values of s**  
5% of the time no matter how small s is!!



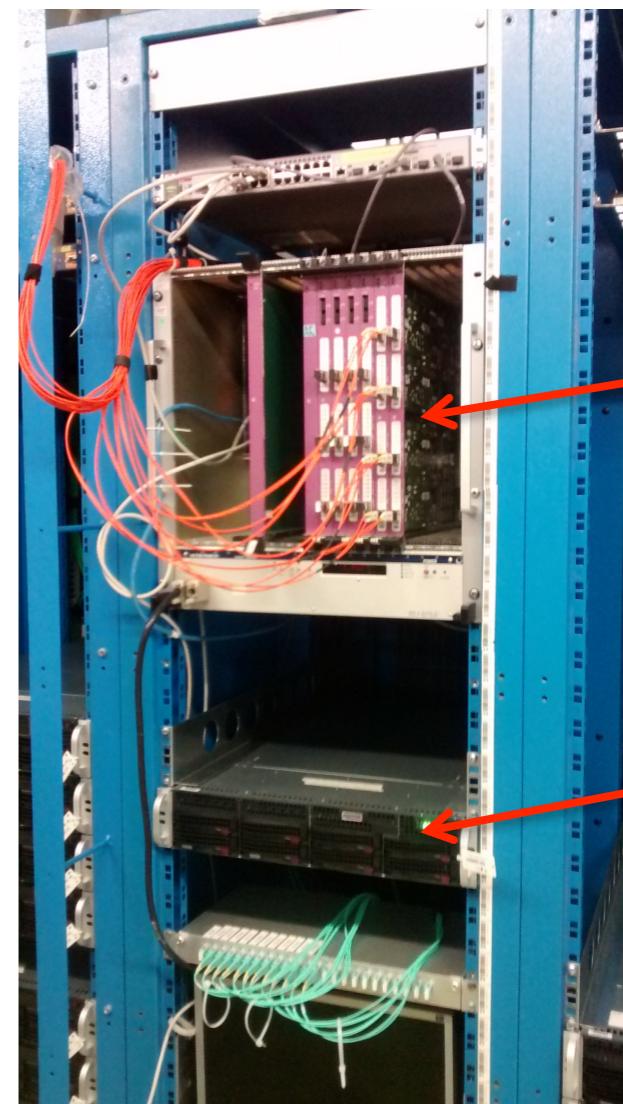
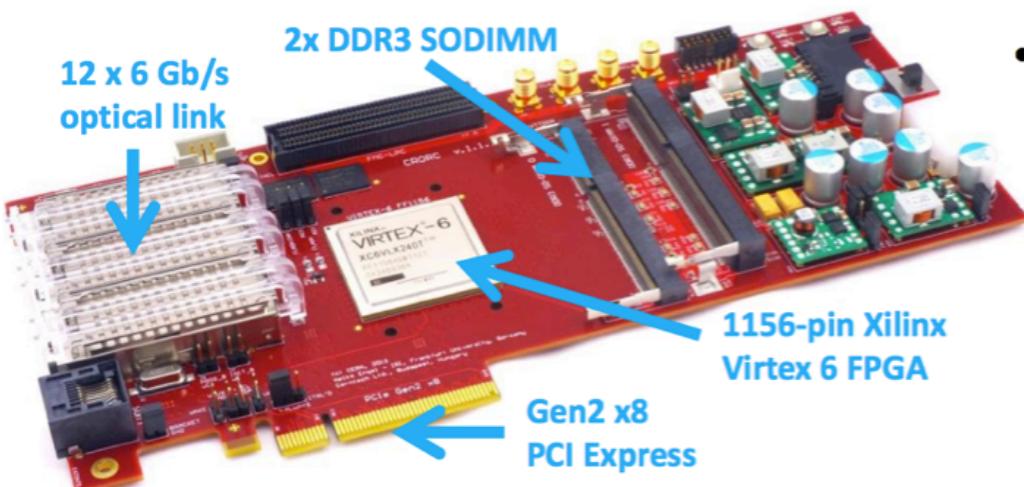
# Statistics in a Nutshell

$$CL_s = CL_{s+b}/CL_b$$

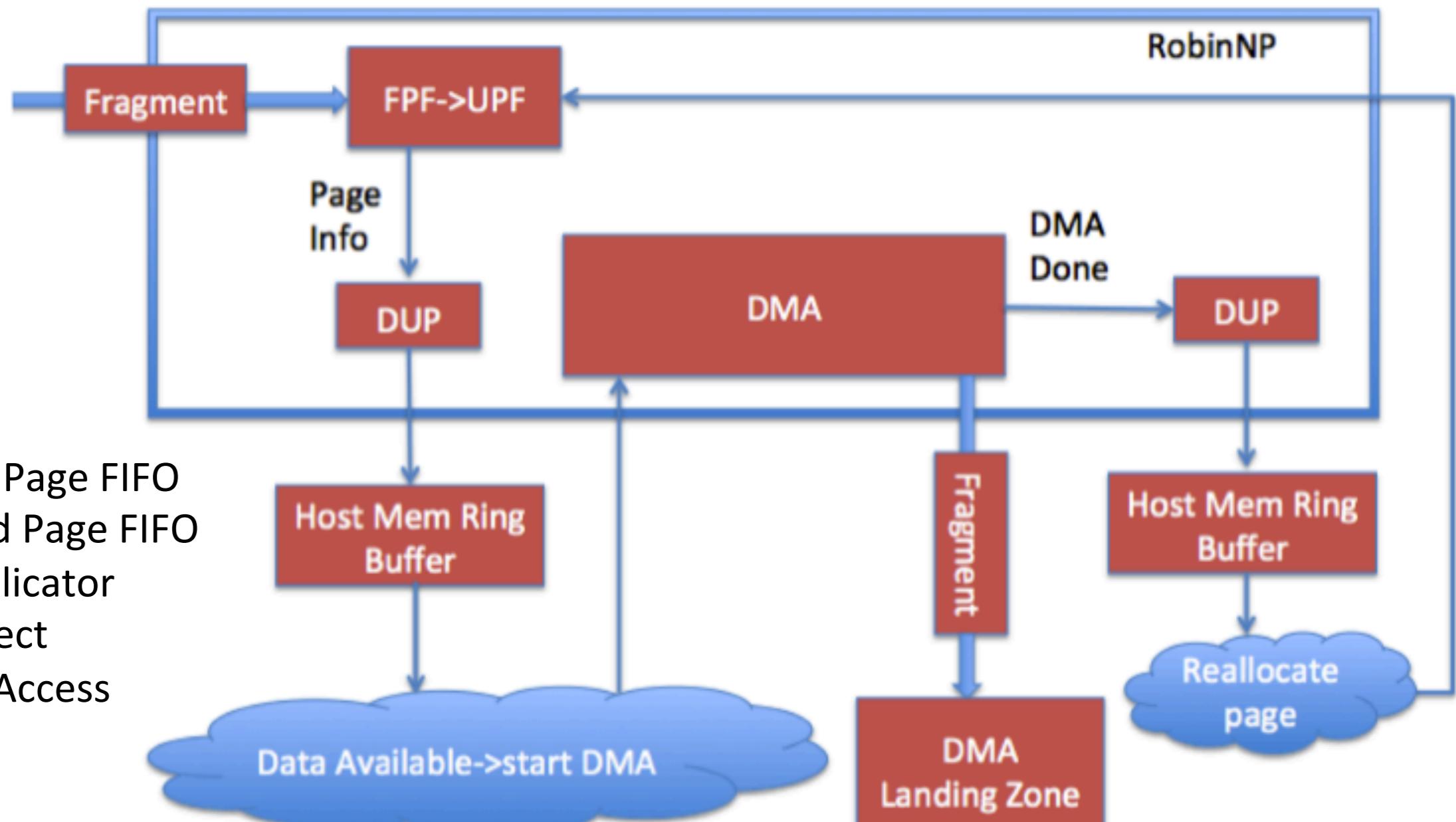
- Only exclude if  $CL_s < 5\%$  (if  $CL_b$  is small,  $CL_s$  gets bigger)
- More conservative



# RoIB



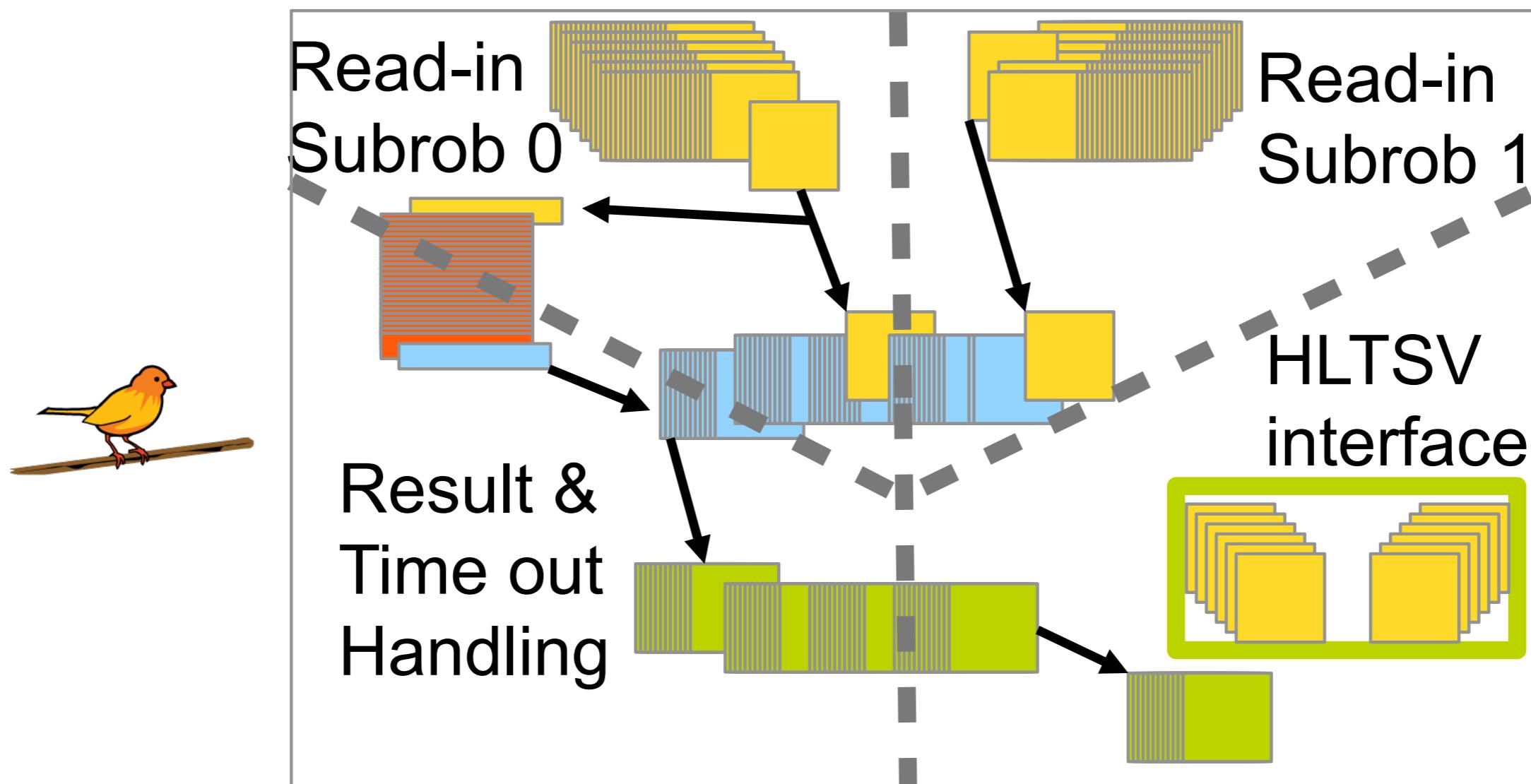
# RoIB



# RoIB

Parallel threads handle data input to the system, event building, event checking, interface to the HLTSV, and publish monitoring information

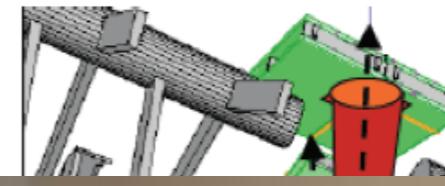
- Intel C++ tbb library used for concurrent data objects to minimize contention



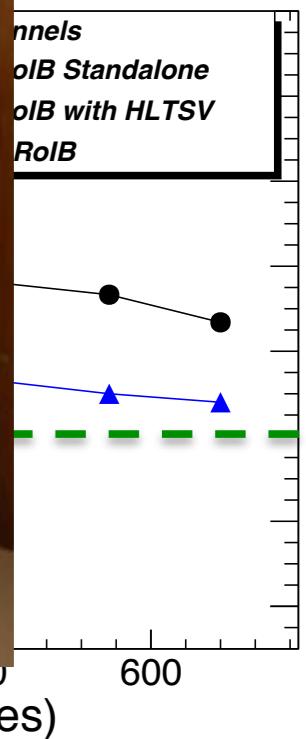
# Region of Interest Builder

Argonne

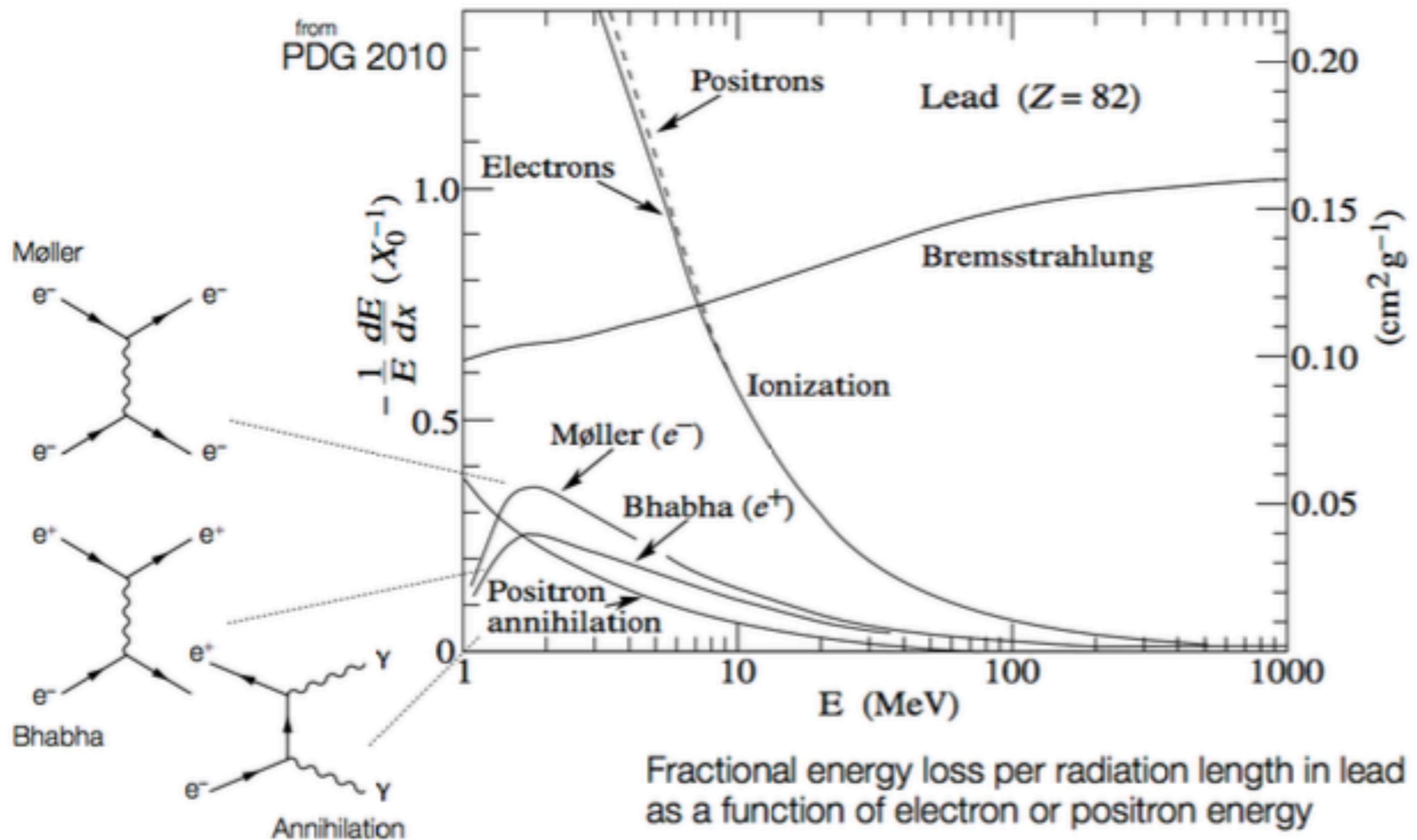
CERN



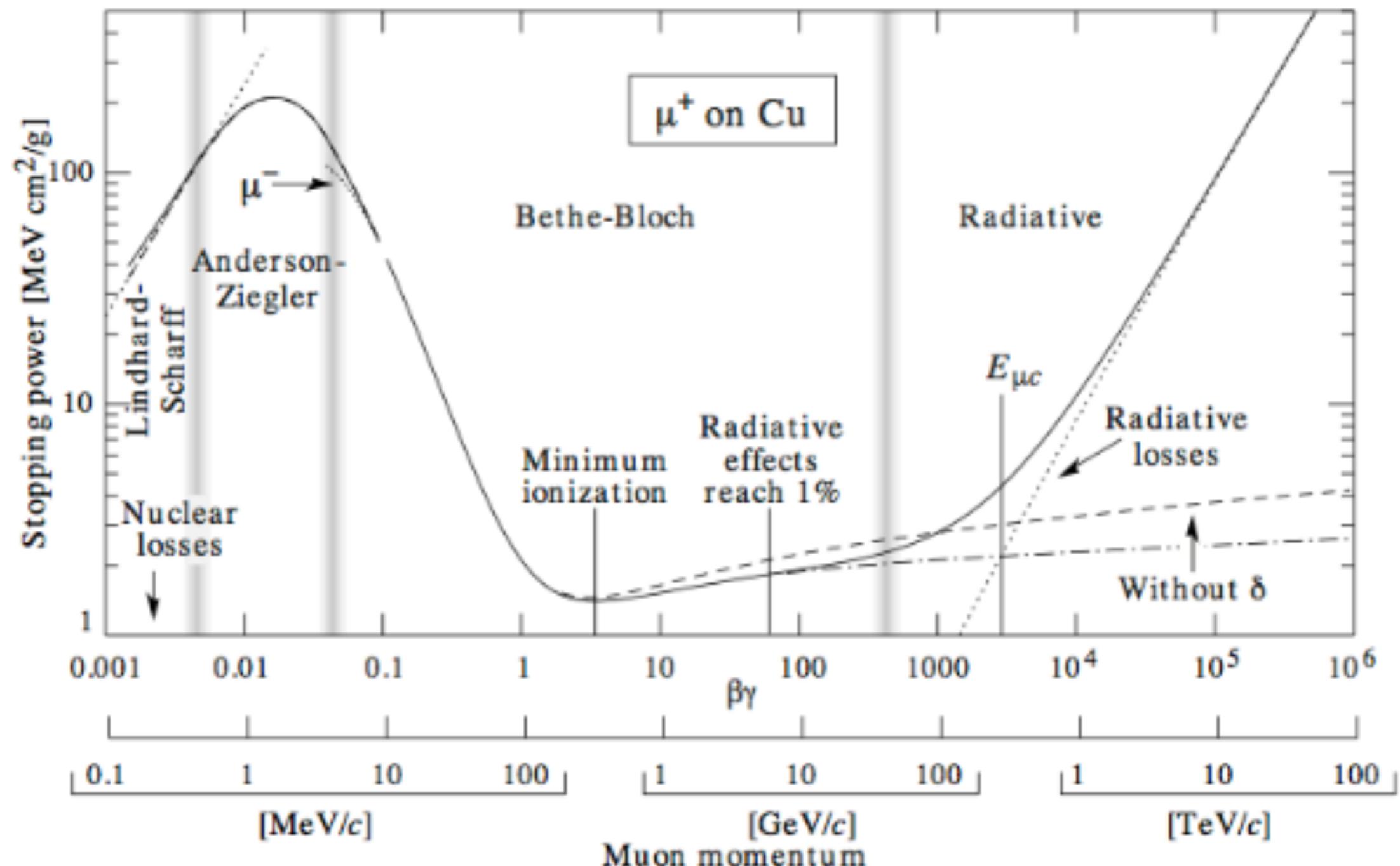
Decommissioned



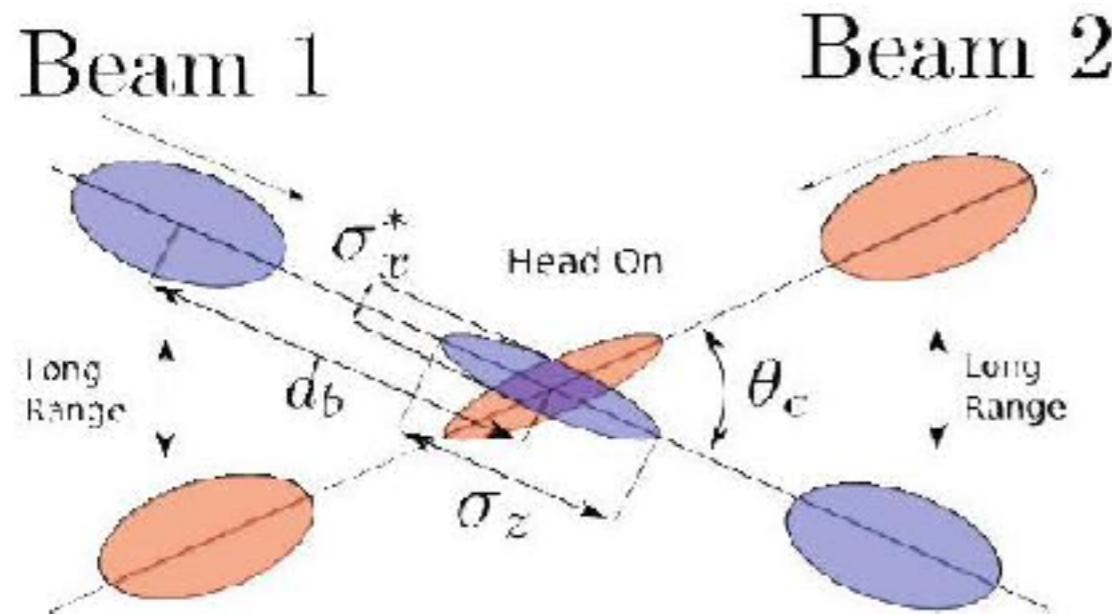
# Total energy loss by e



# Muons in copper



# LHC



$$B = \frac{p}{q \rho}$$

for  $q = e$  numerically

$$B [T] = p [\text{GeV}/c] \cdot 3.336 \text{ m} / \rho$$

high energy,  $v = c$  “ $p = E$ ”

$E < E_H = q B \rho$  Hillas criterion

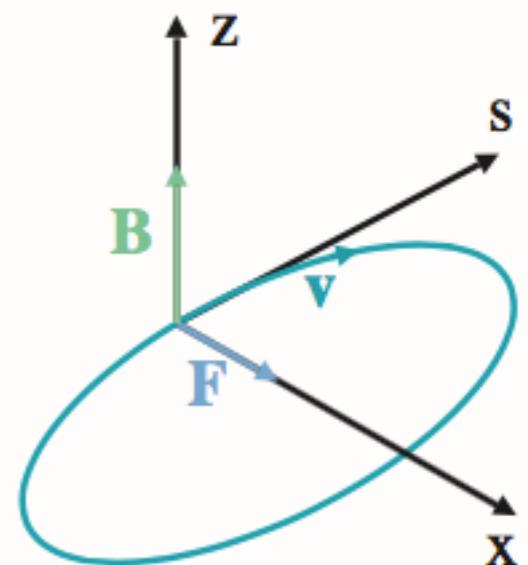
$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi \sigma_x \sigma_y}$$

$$\mathbf{F} = q (\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

## LHC

- Momentum  $p = 7 \text{ TeV}/c$
- LHC bending radius  $\rho = 2804 \text{ m}$
- Bending field  $B = 8.33 \text{ Tesla}$
- magnets at  $1.9 \text{ K}$ , super-fluid He

**Circular motion for**  
 $\mathbf{E} = 0$   
 $\mathbf{v} \perp \mathbf{B}$



# Data-taking 2015/2016

