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

Othmane Rifki

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?

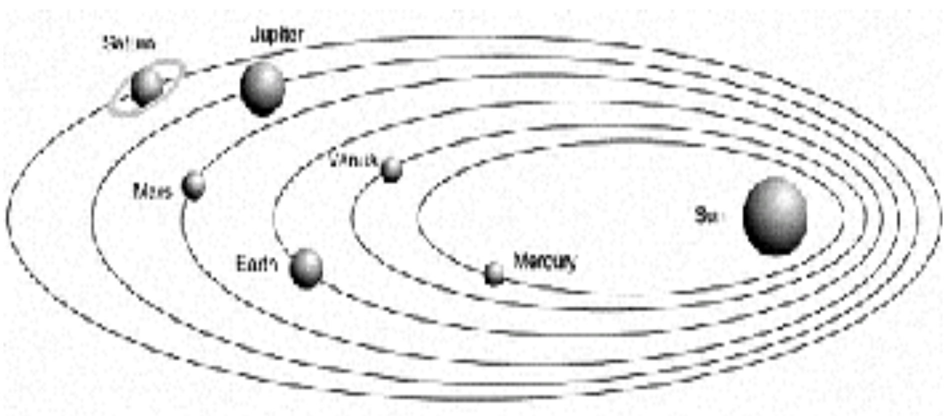
What is our goal?

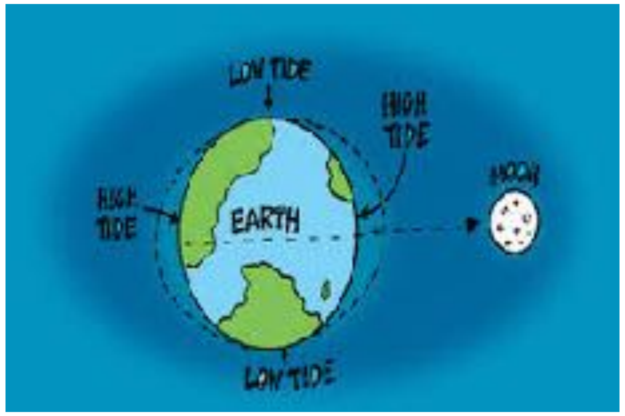
Goal

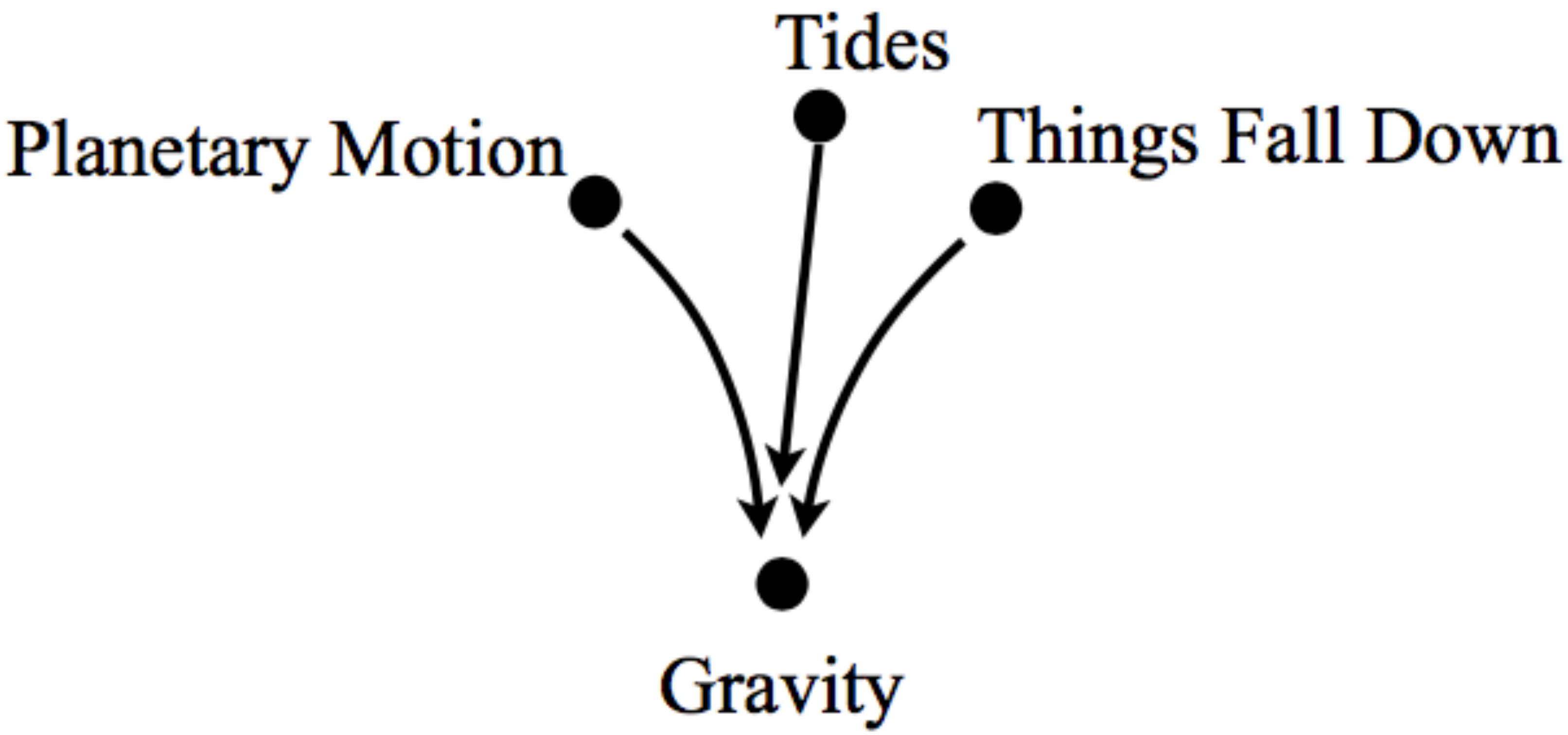
The multitude of phenomena observed around us can be described by fundamental elements obeying simple principles

Why we want to achieve it?

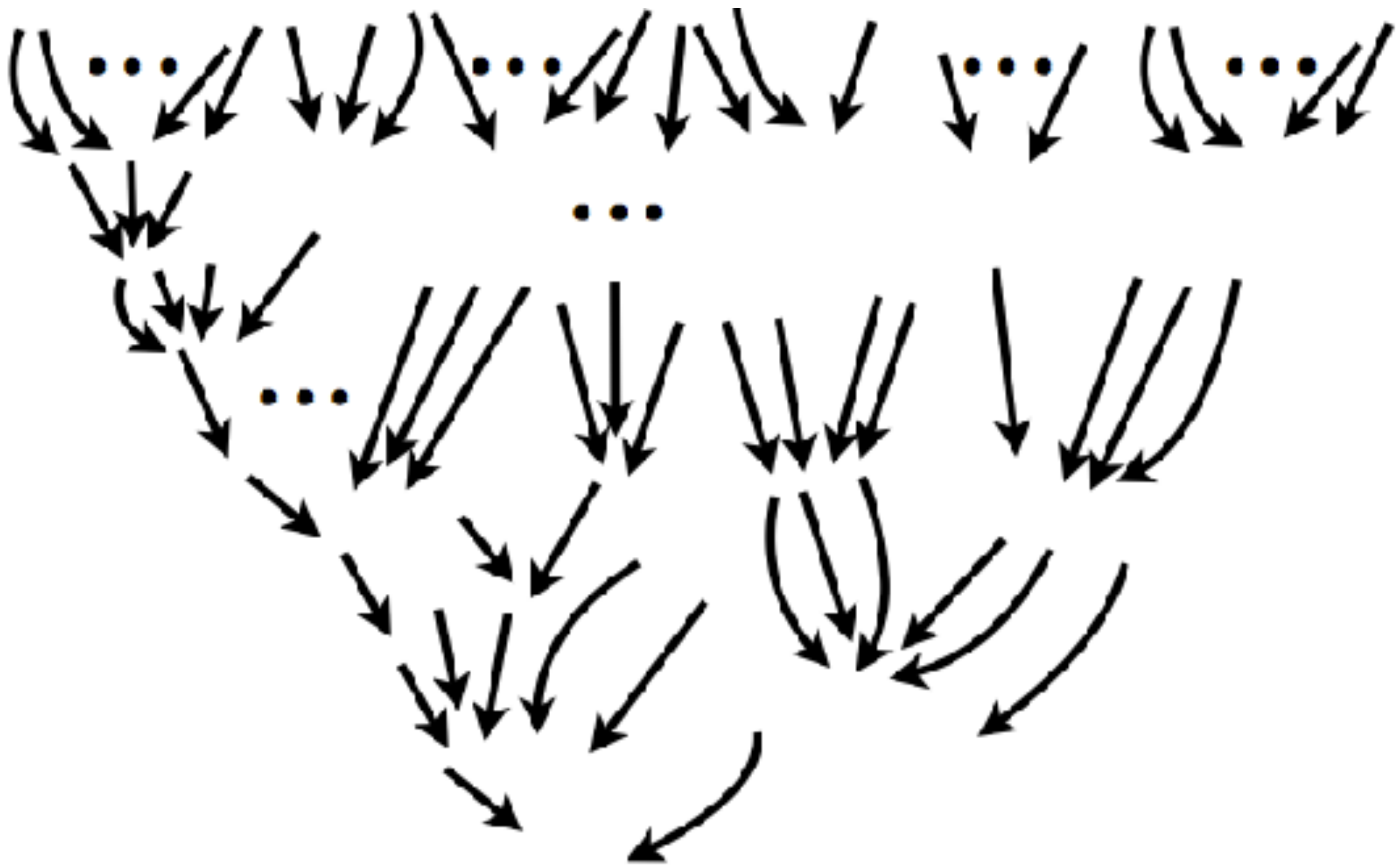
Scientific description







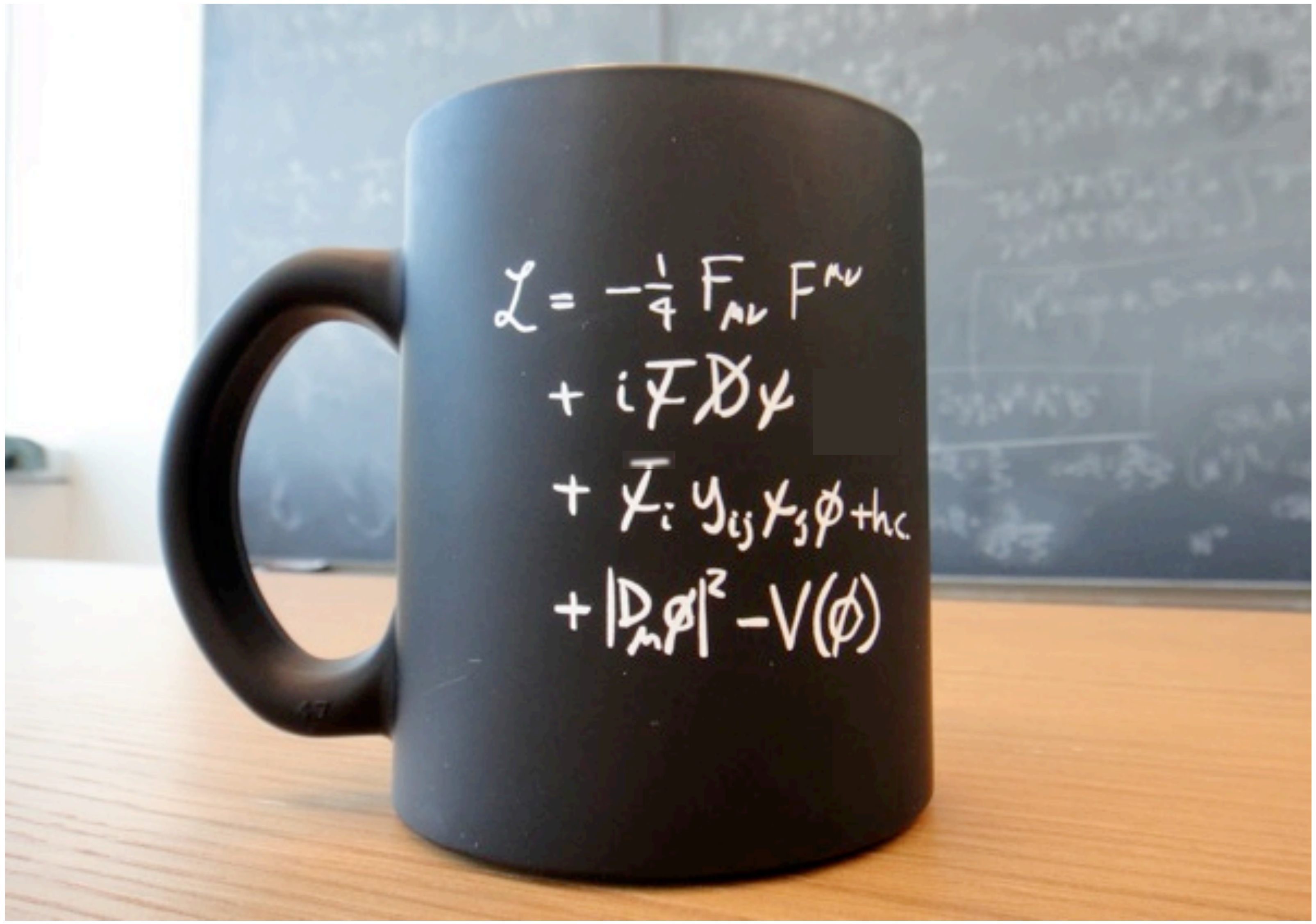
Goal



Standard Model

- **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)



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

Standard Model

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

Gauge invariance *SU(3) x SU(2) x U(1)*

Matter particles:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Gauge bosons:

$$g \qquad W \qquad Z \qquad \gamma$$

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

bas ... etries

Gau

Mat

Gau

Gau ... ge bosons

Hig

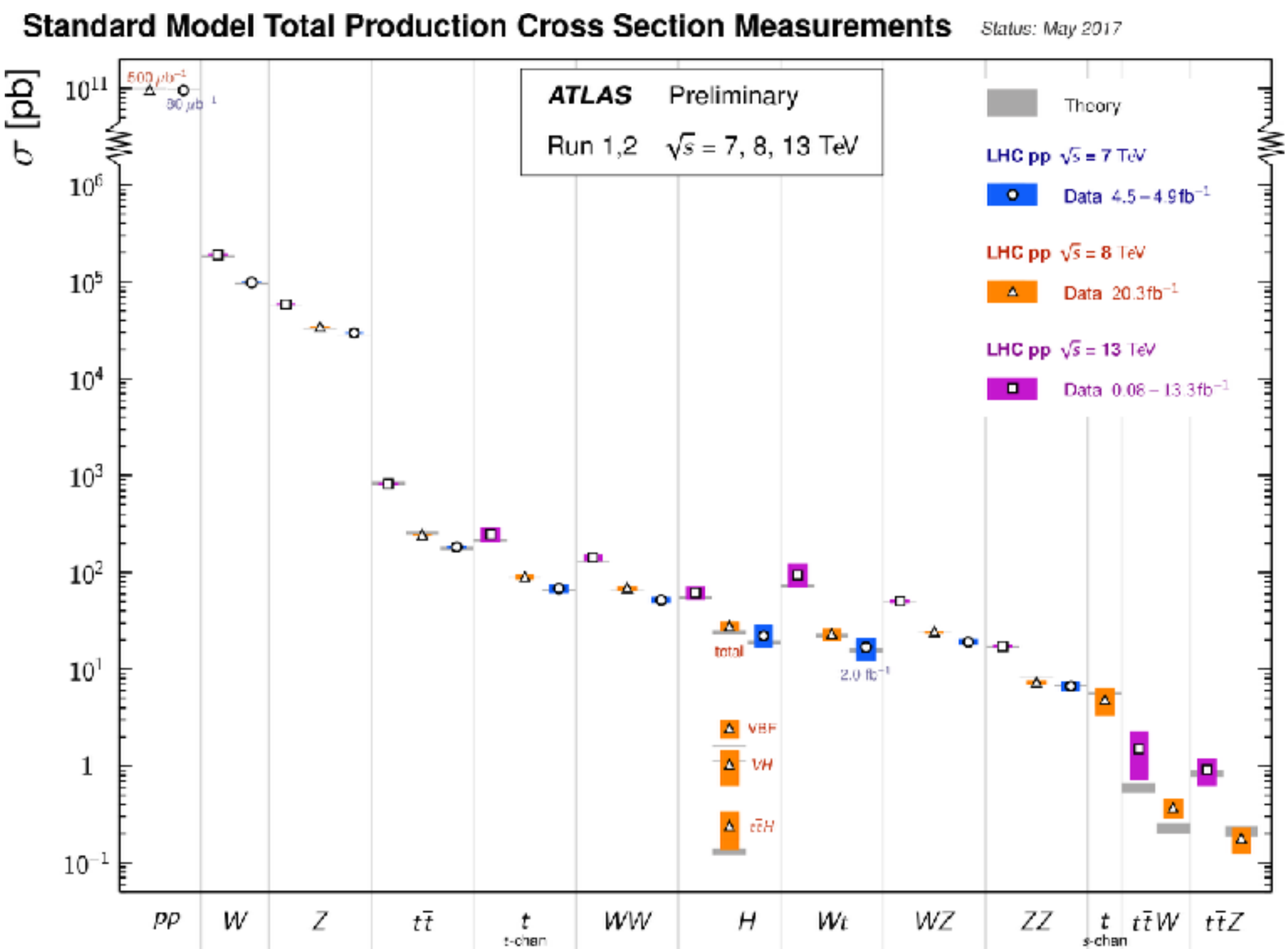
Spo ... ak bosons

while

Prediction of an additional particle: Higgs boson

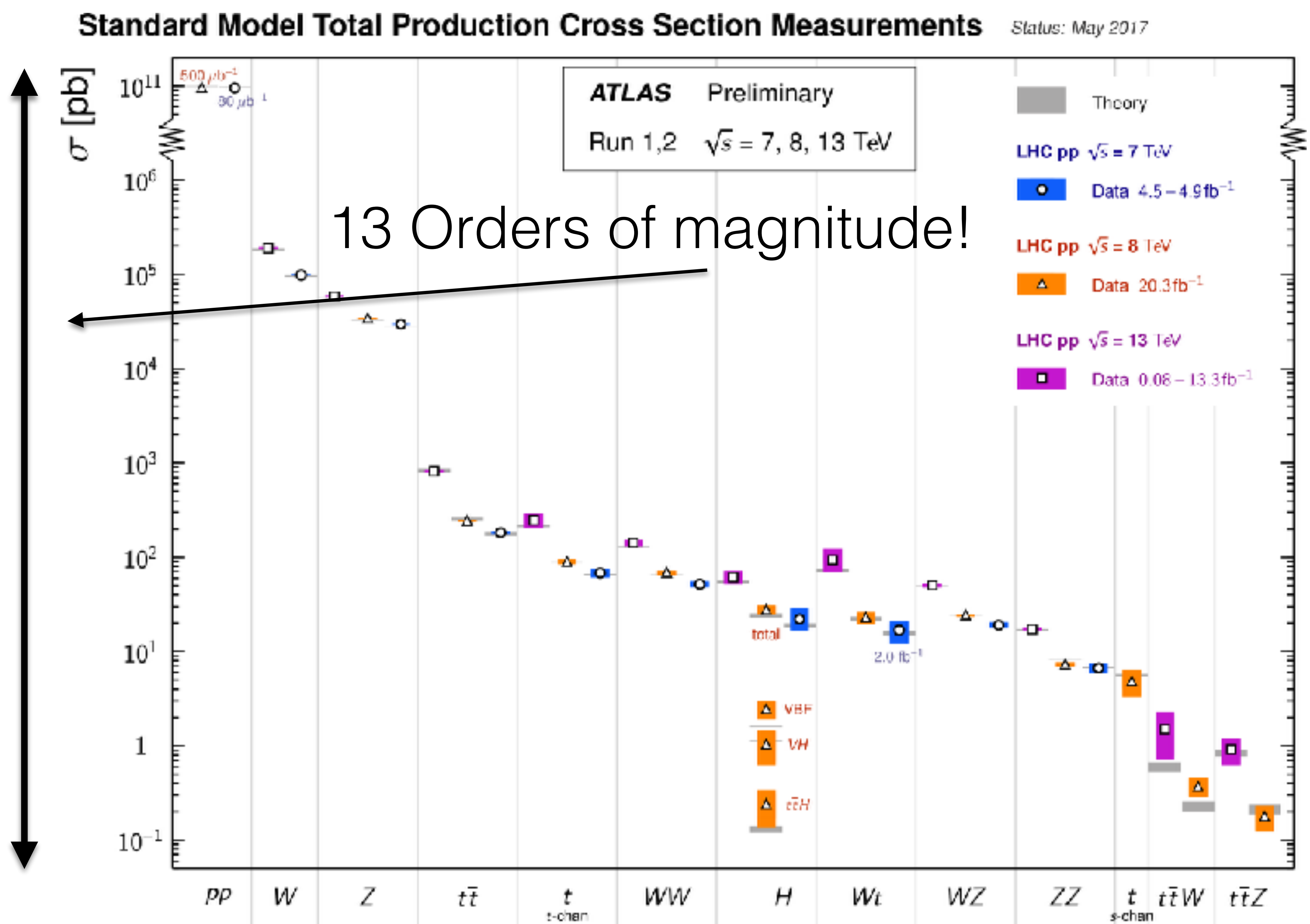
Standard Model

Standard Model works incredibly well!



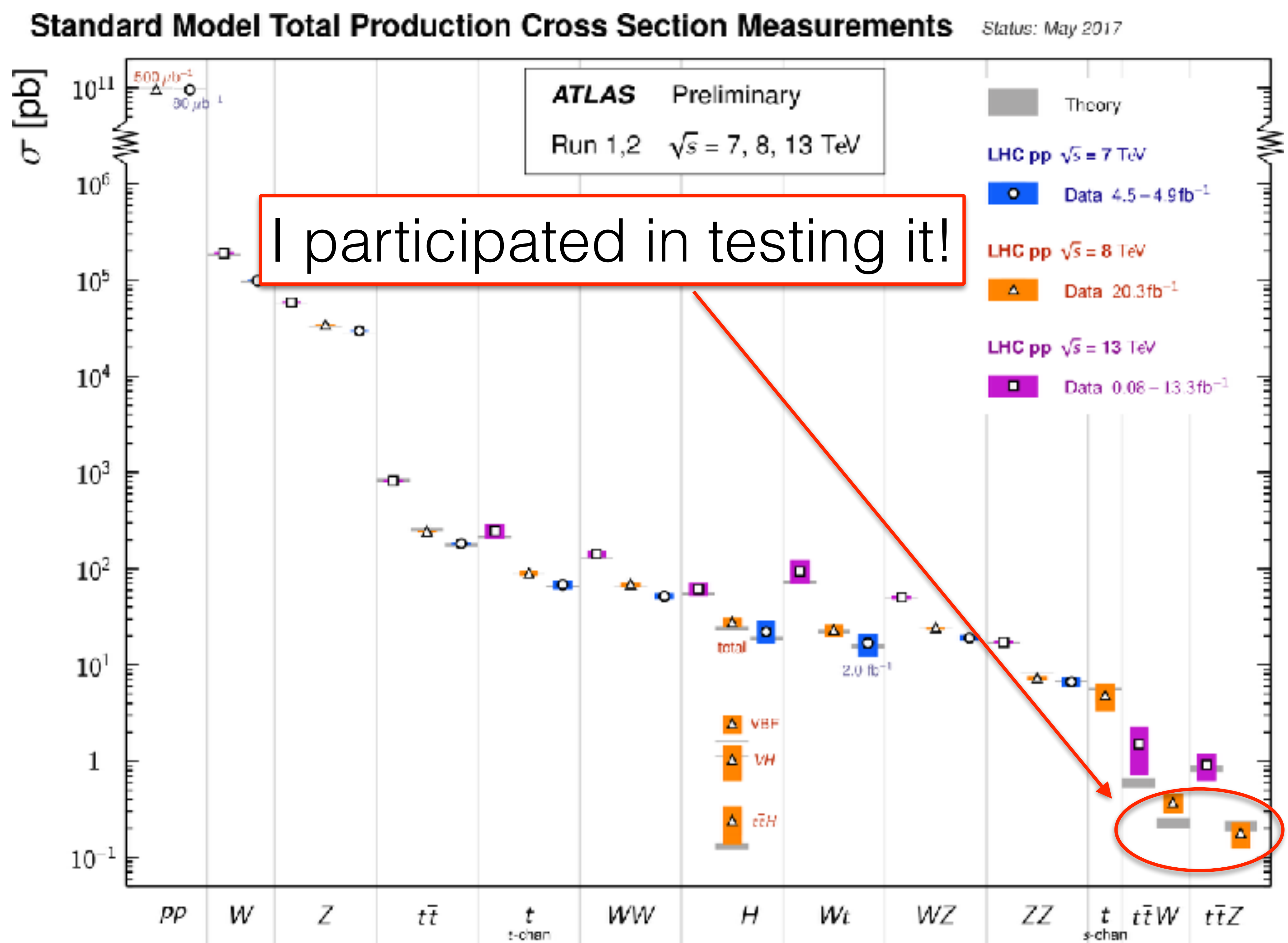
Standard Model

Standard Model works incredibly well!



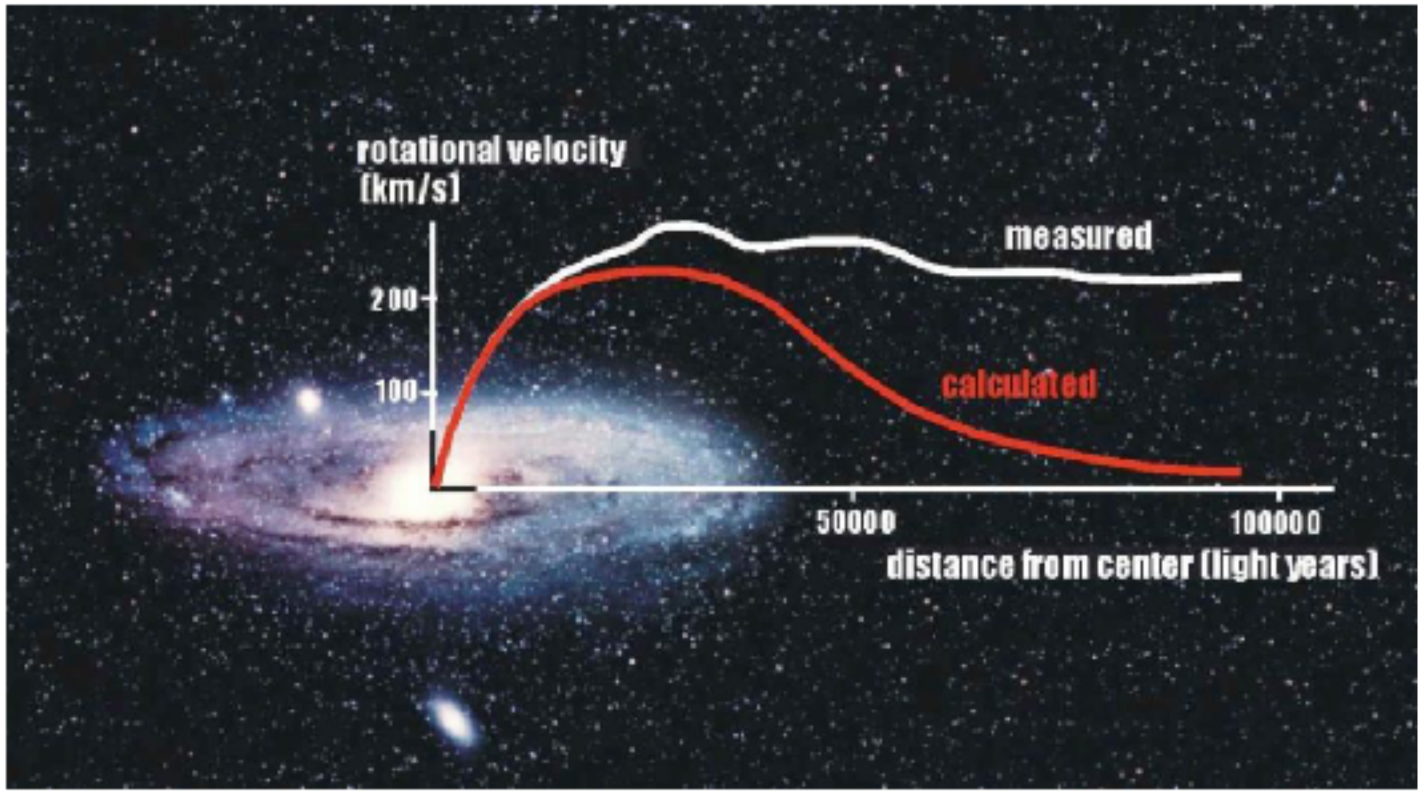
Standard Model

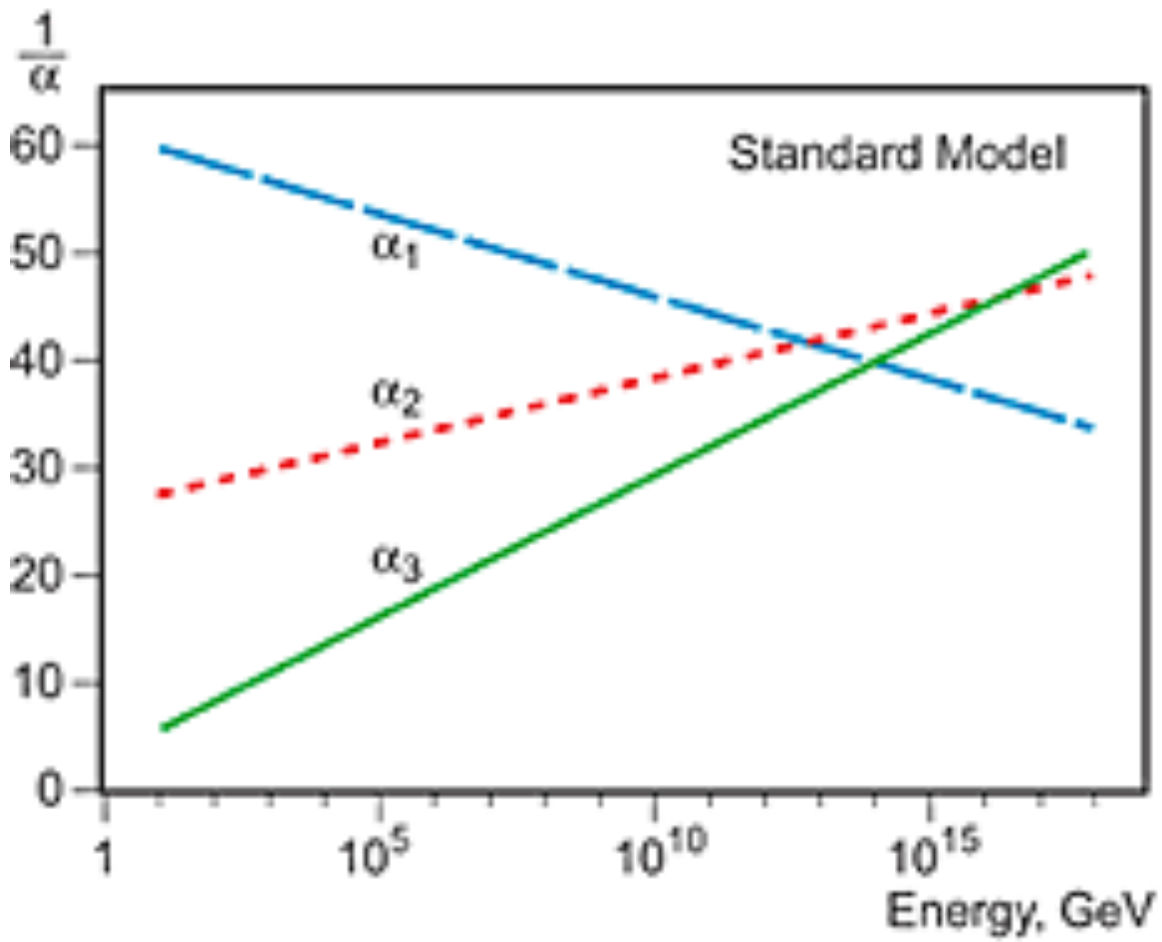
Standard Model works incredibly well!



Open Questions of the SM

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

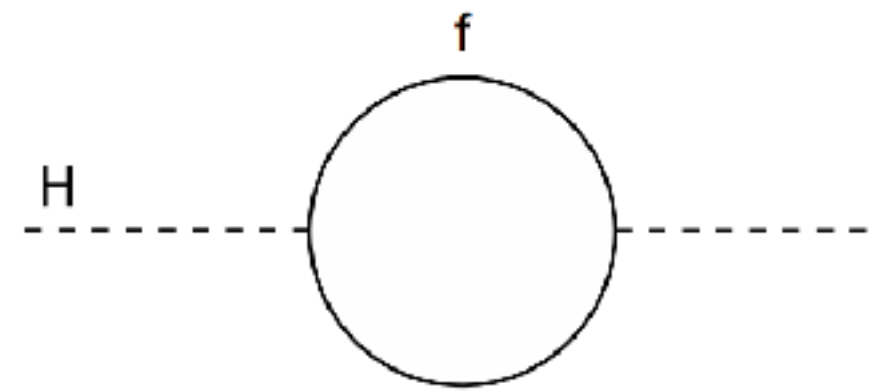




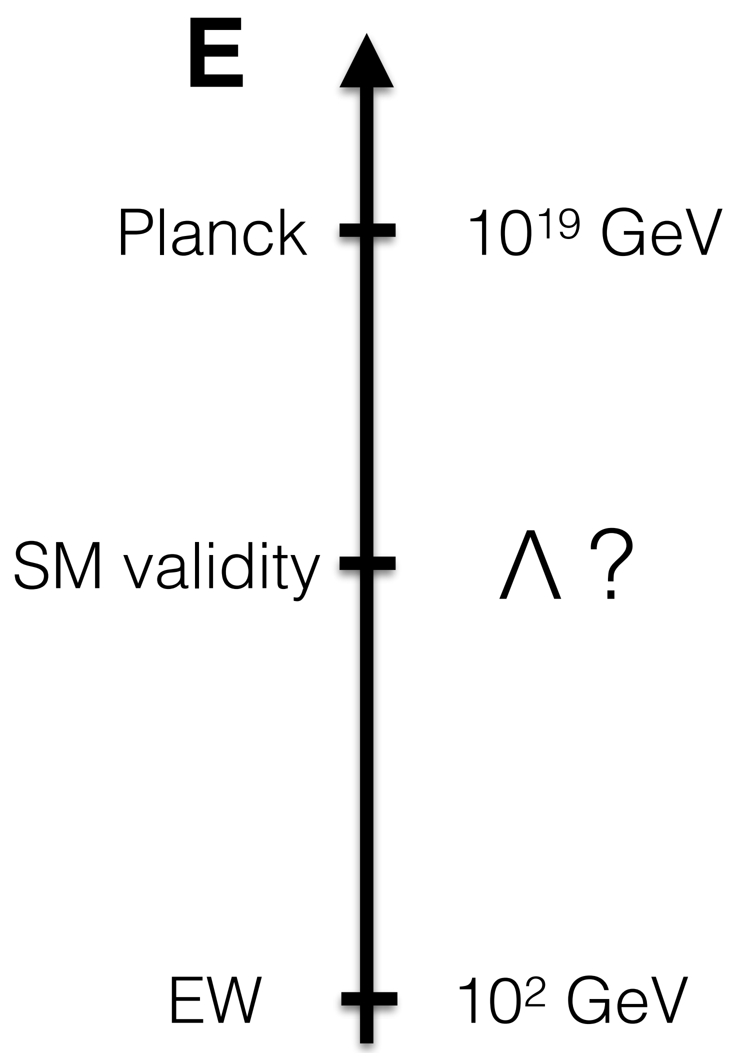
- **Grand unification**: Standard model coupling constants do not unify at high scales ➔ SM does not imply a Grand Unified Theory

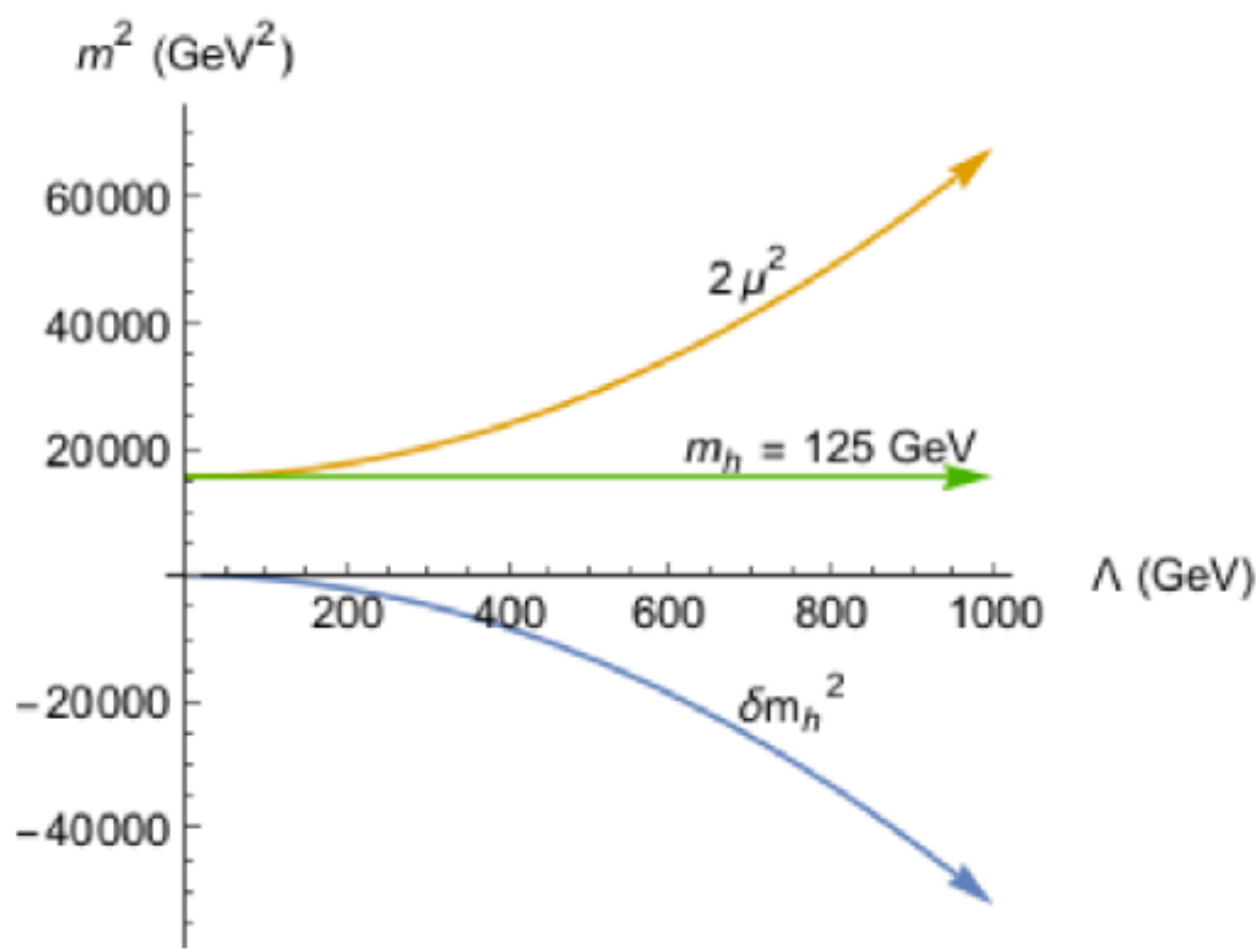
Open Questions of the SM

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



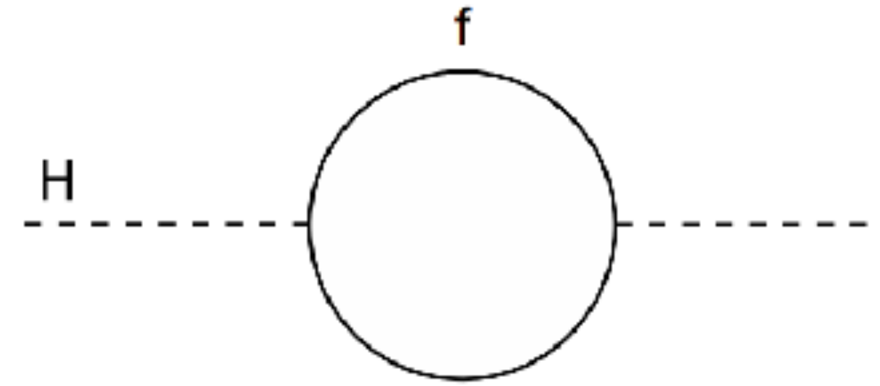
$$m^2_{\mathrm{h,physical}} \simeq m_h^2 + \frac{C}{16\pi^2}\Lambda^2$$



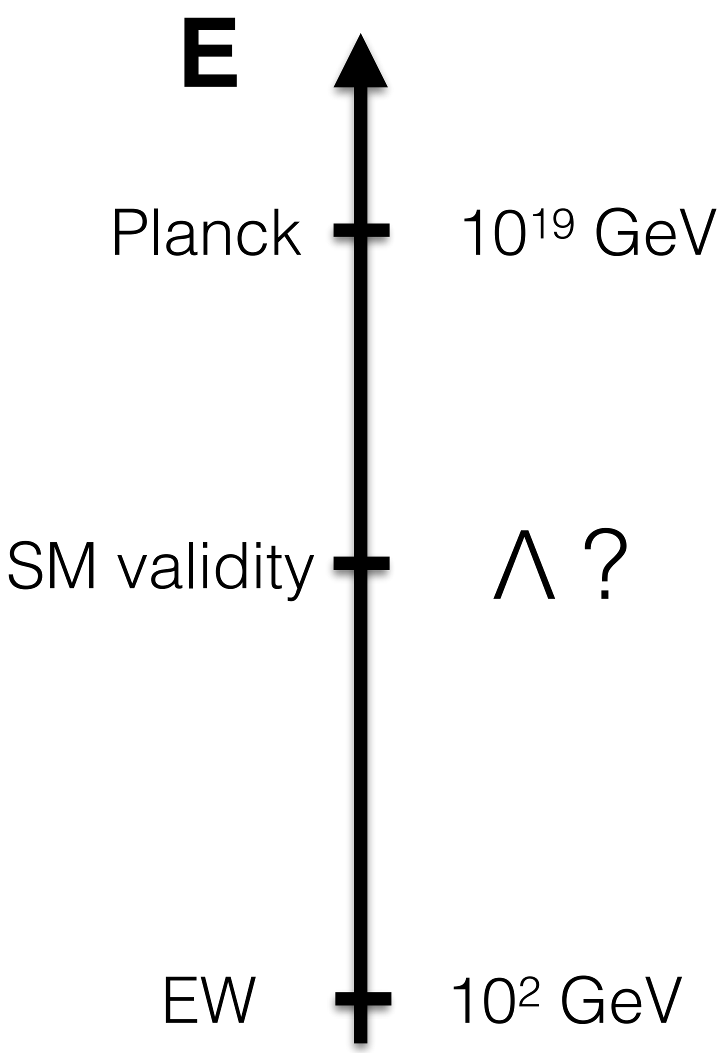


Open Questions of the SM

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

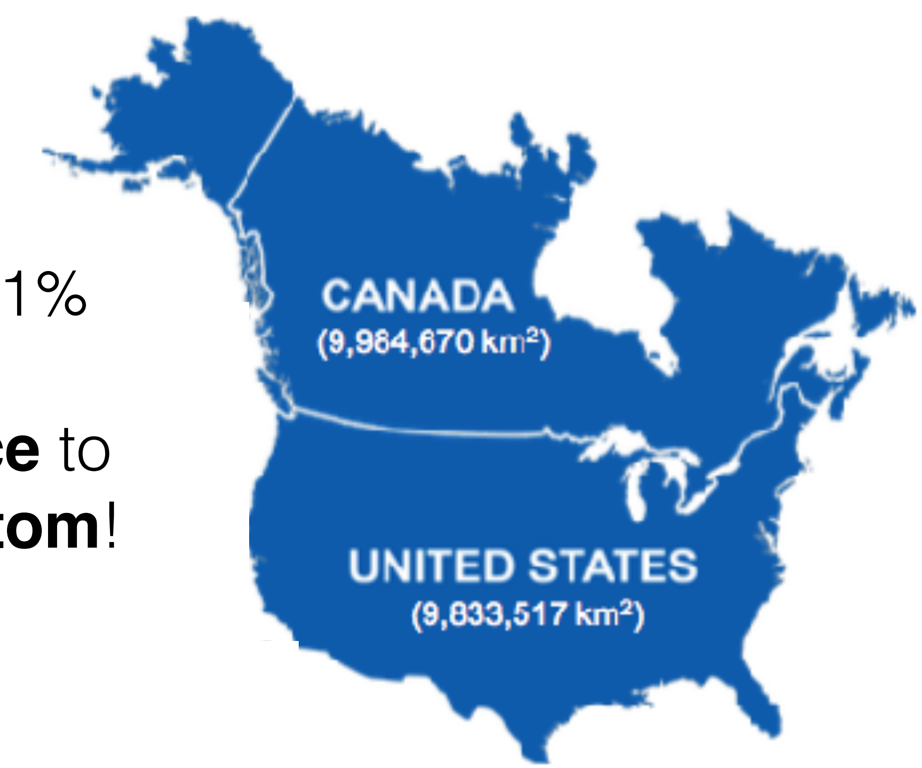


$$m^2_{\text{h,physical}} \simeq m_h^2 + \frac{C}{16\pi^2}\Lambda^2$$



$\Delta m^2/m^2_h \sim 10^{30}$

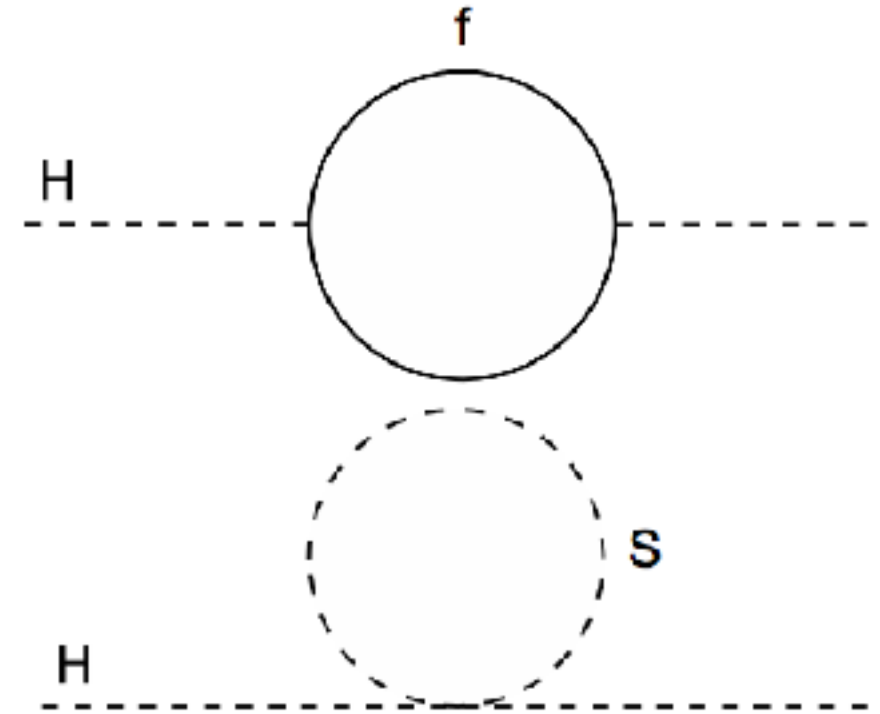
Surface areas within 1%
(151,153 km²)
Imagine the **difference** to be of the **size of an atom**!



Analogy only for illustration!

We need … Supersymmetry (SUSY)!

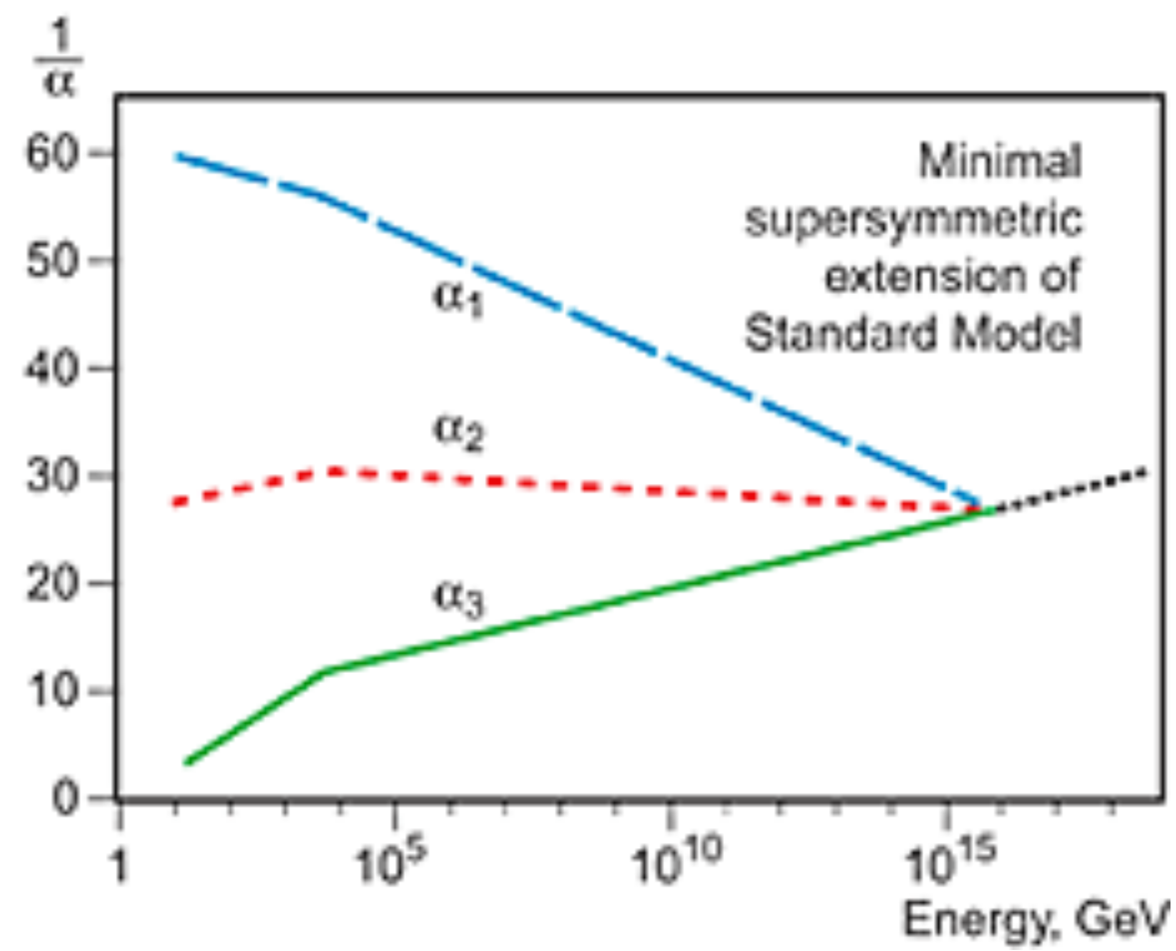
- **Fundamental symmetry** between **fermions** and **bosons** introducing a set of new partner particles to the SM particles with half-spin difference



✓ 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 $M_{GUT} \sim 10^{16}$ GeV

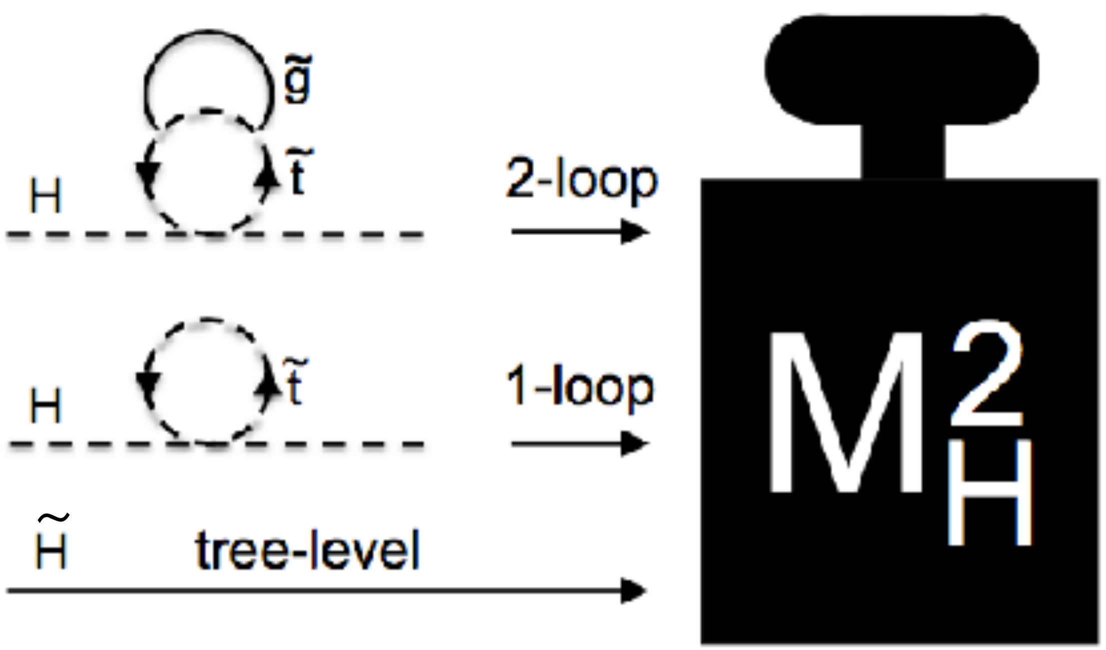


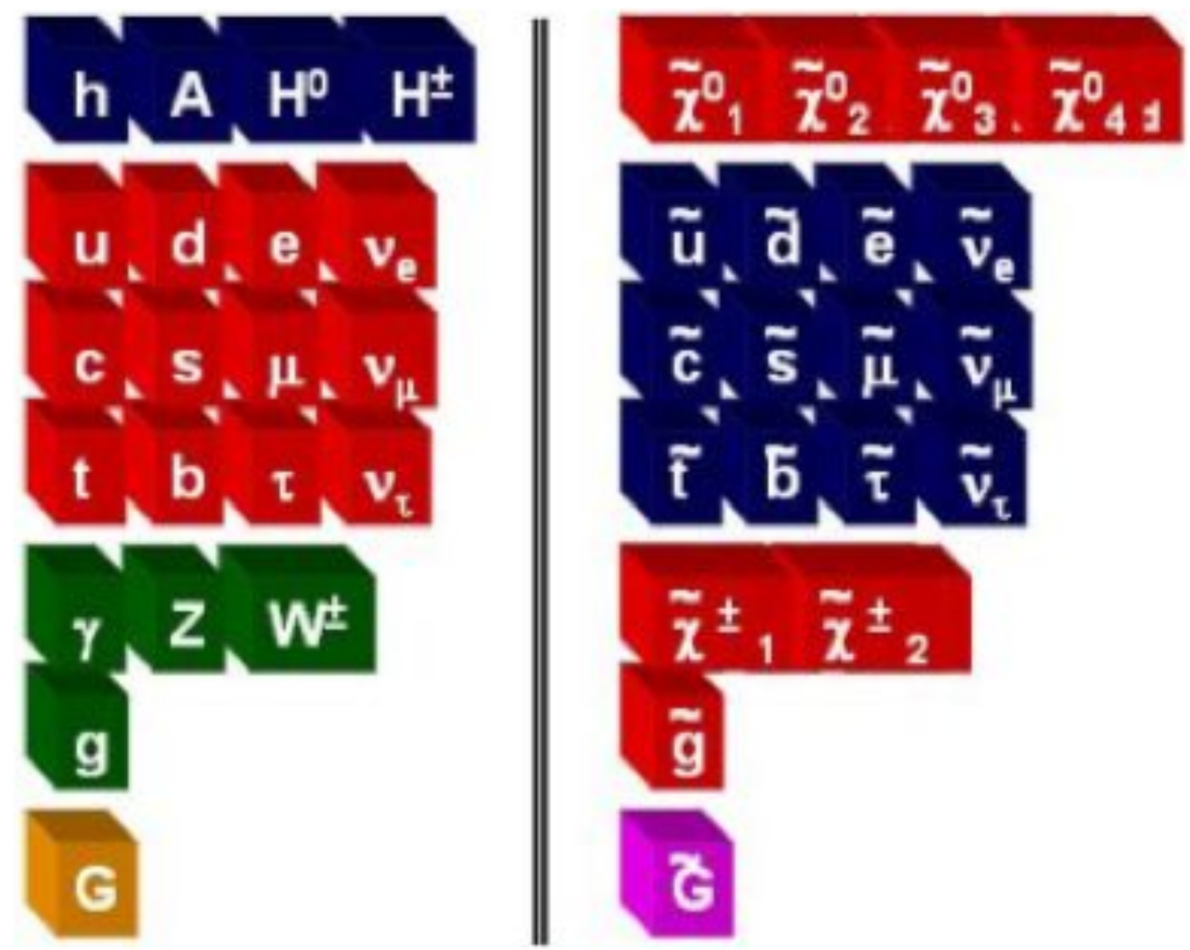
Not any SUSY

- 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





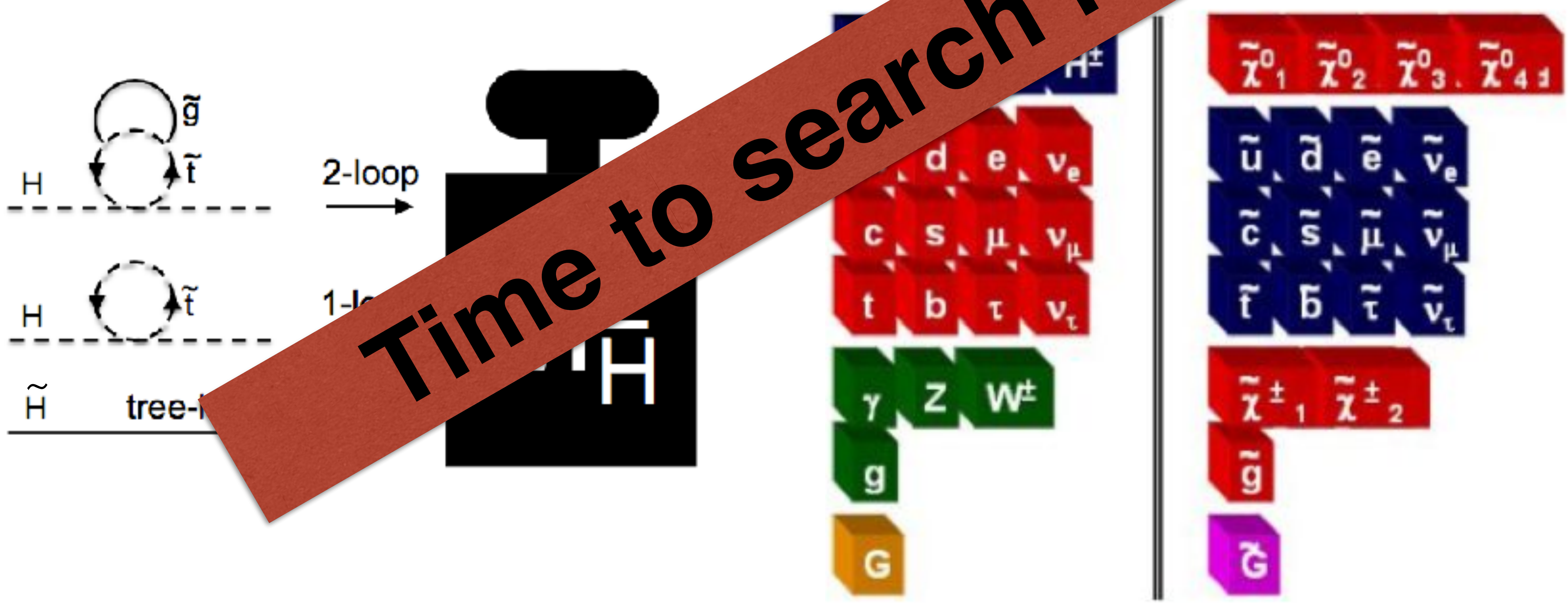
Not any SUSY

- 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 relati **gluinos**, **stops**, and **higgsinos**

➡ Remaining SUSY particles can be decoupled ses

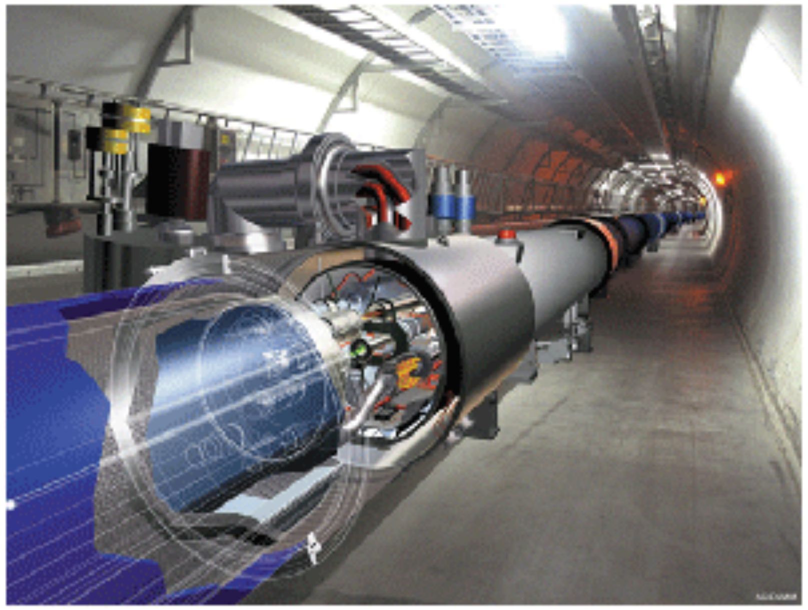
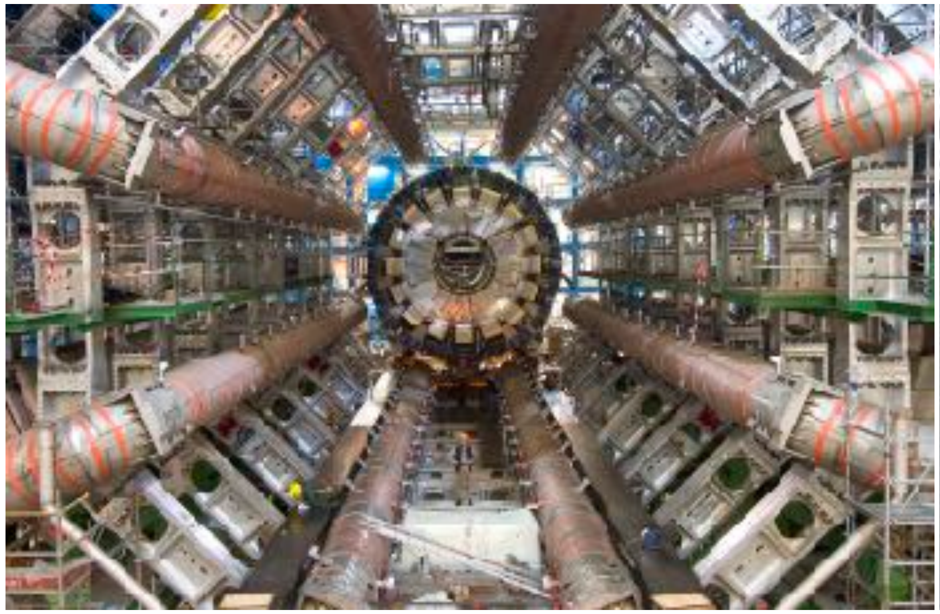
Time to search for it!



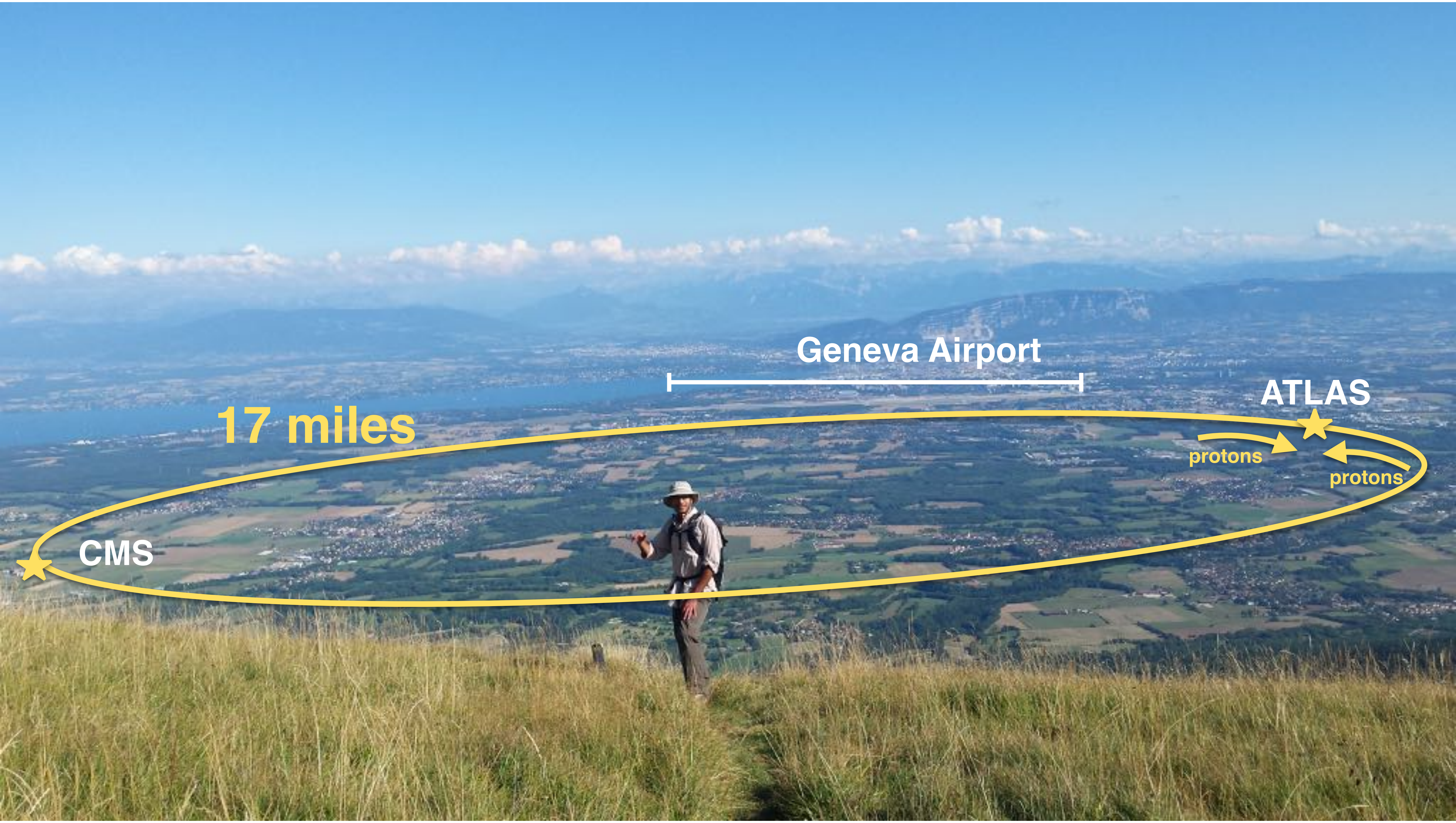
How to do it?

Our Tools

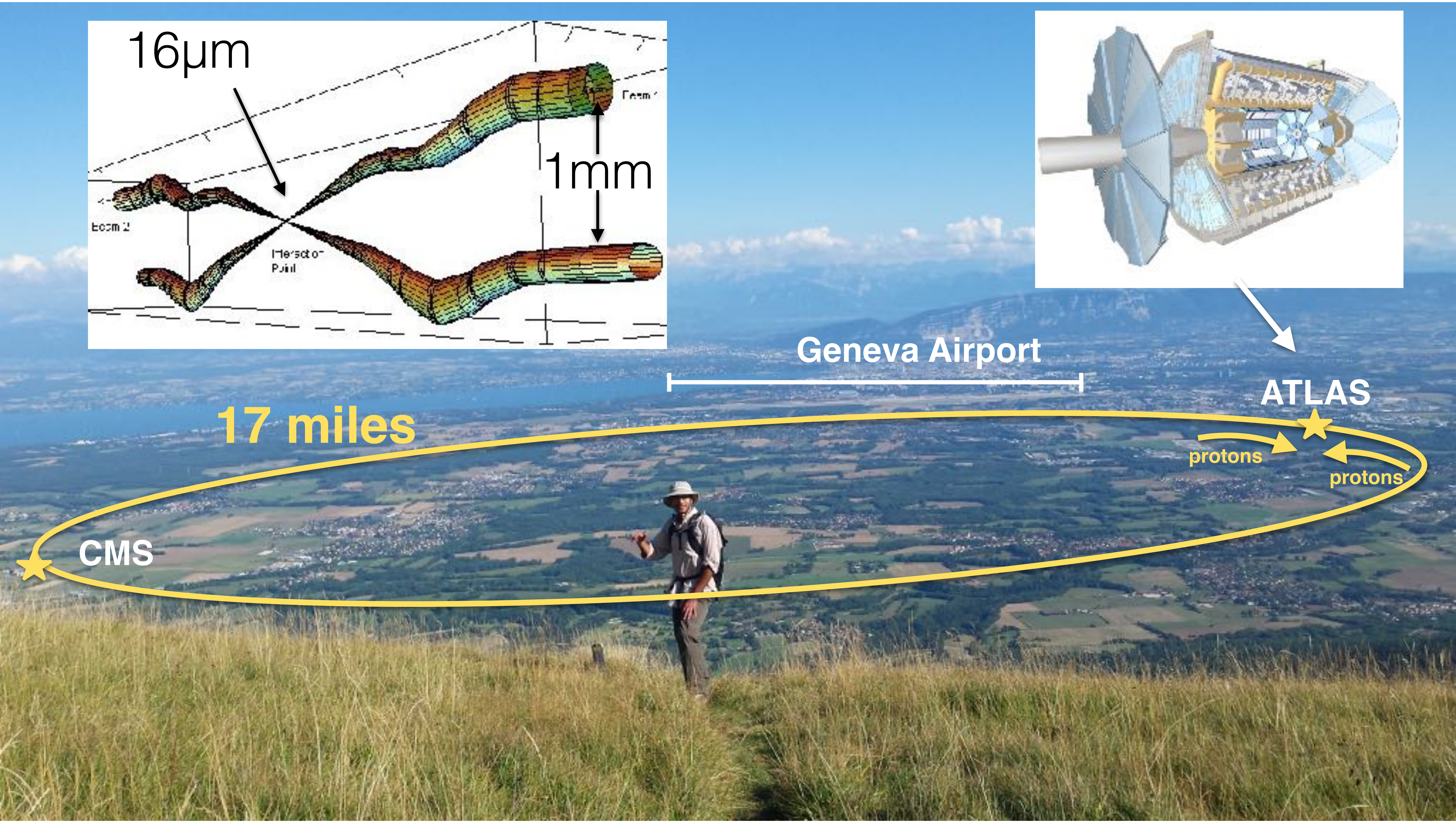
- **L**arge **H**adron **C**ollider (**LHC**)
- **A T**oroidal **L**HC **A**pparatu**S** (**ATLAS**)
- Computing resources (Grid)

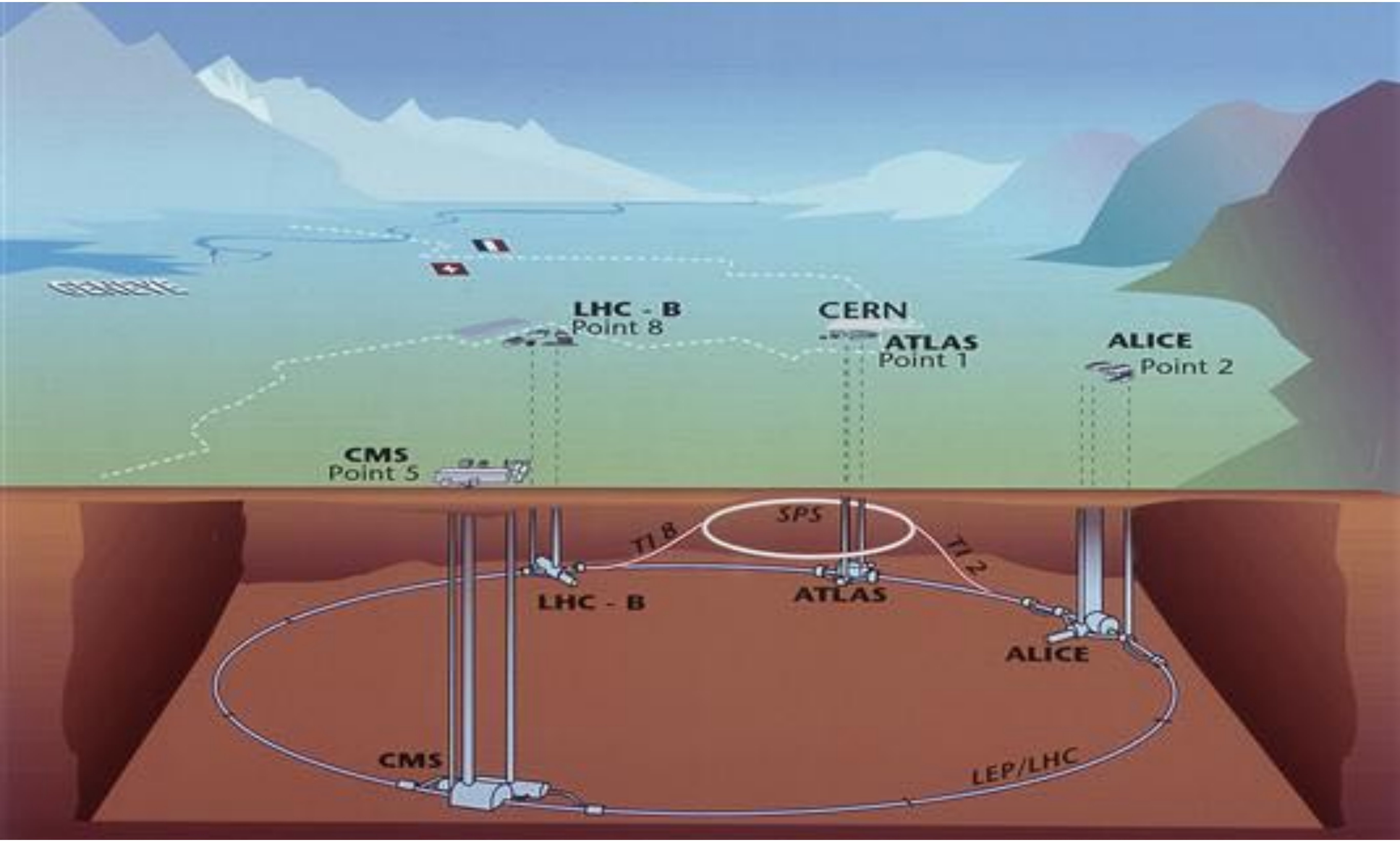

The LHC Accelerator



The LHC Accelerator

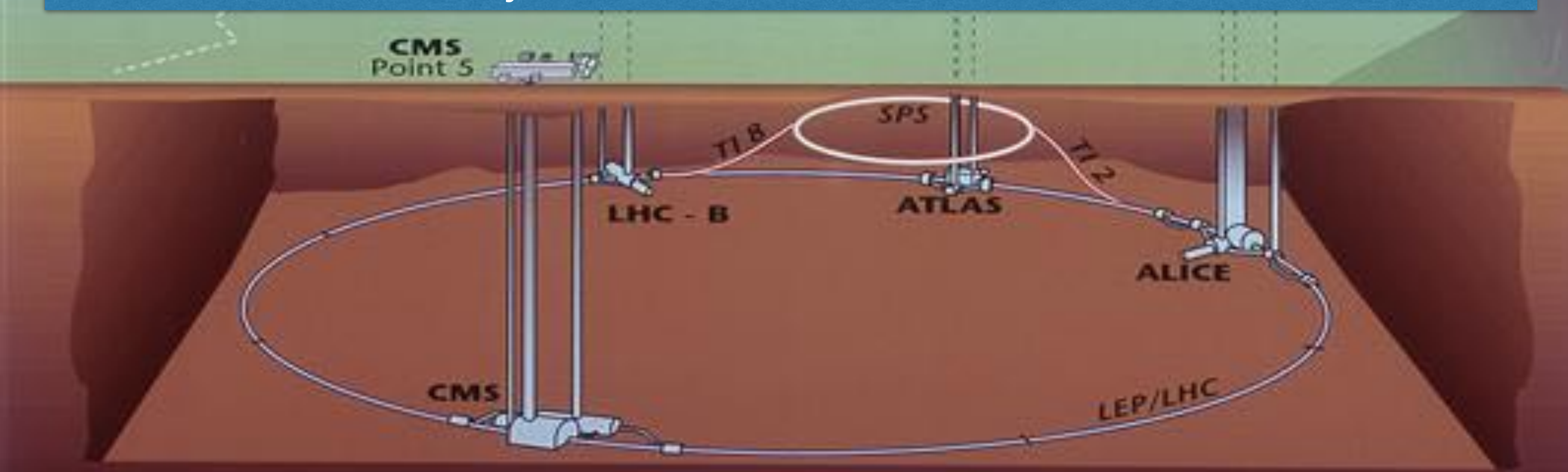


The LHC Accelerator



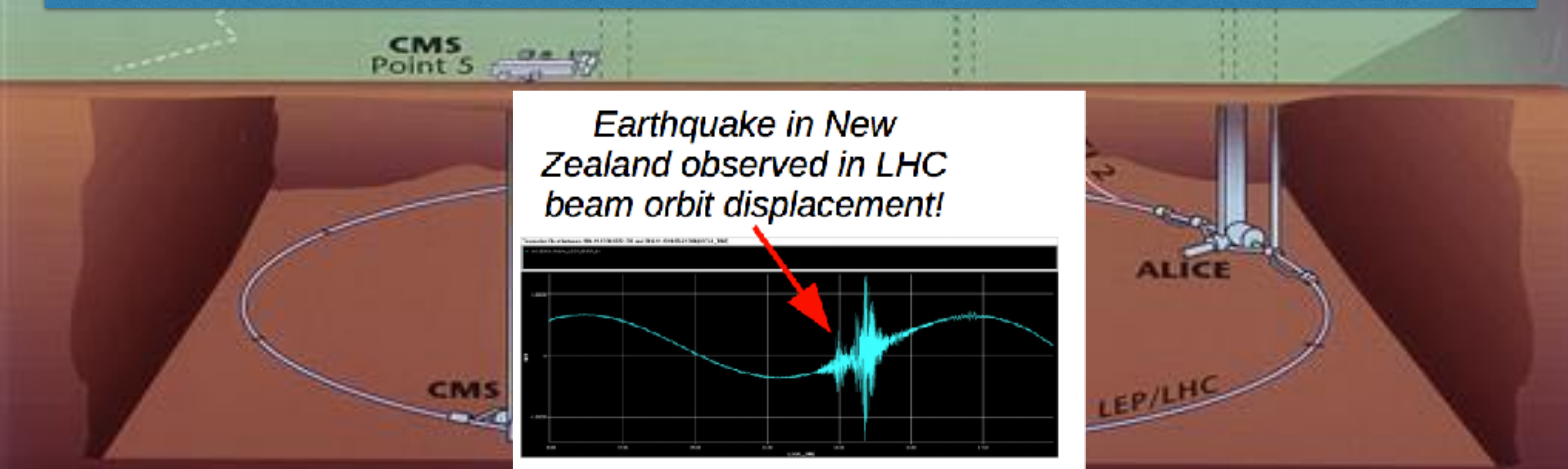
The LHC Accelerator

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



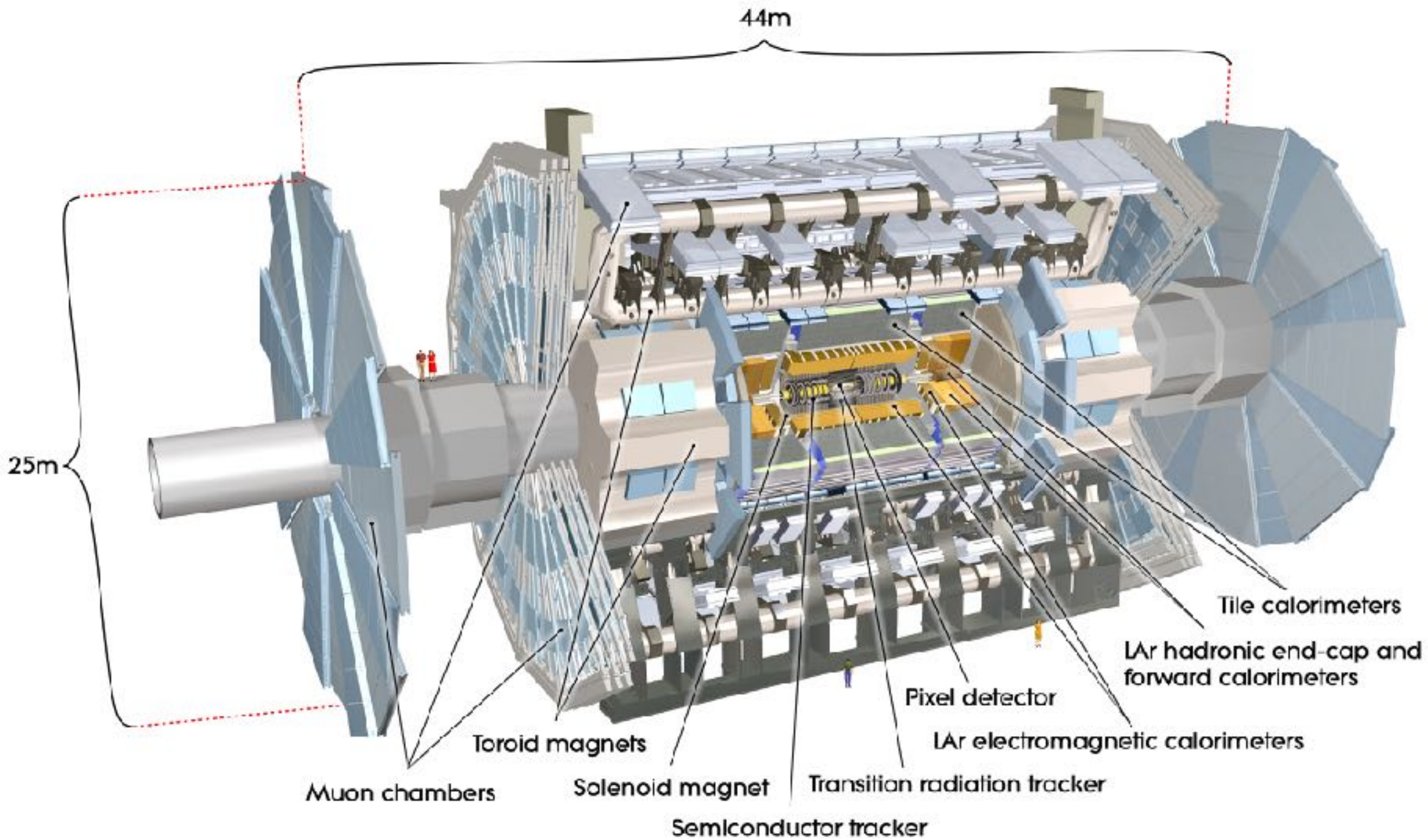
The LHC Accelerator

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



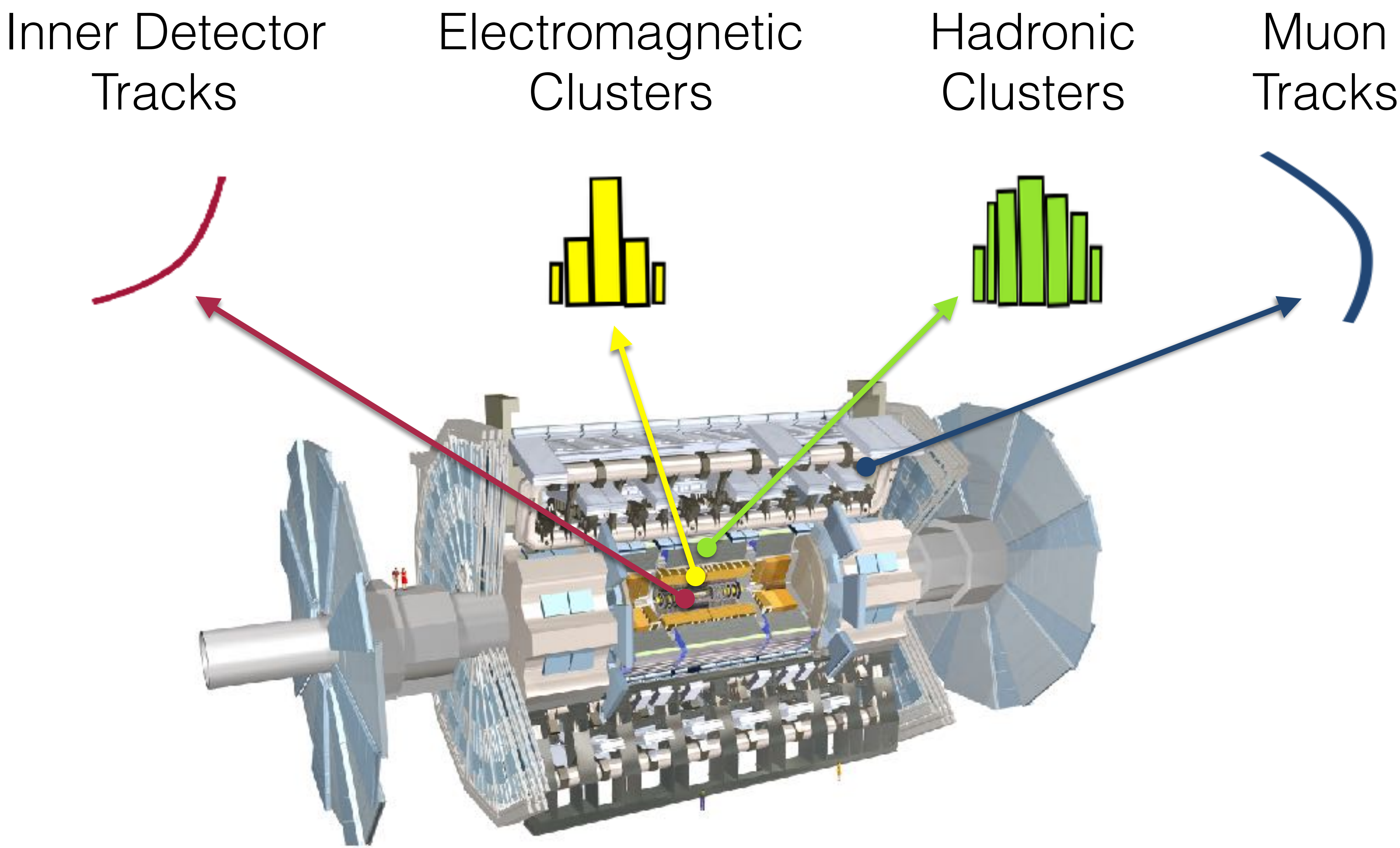
Earthquake in New Zealand observed in LHC beam orbit displacement!

ATLAS

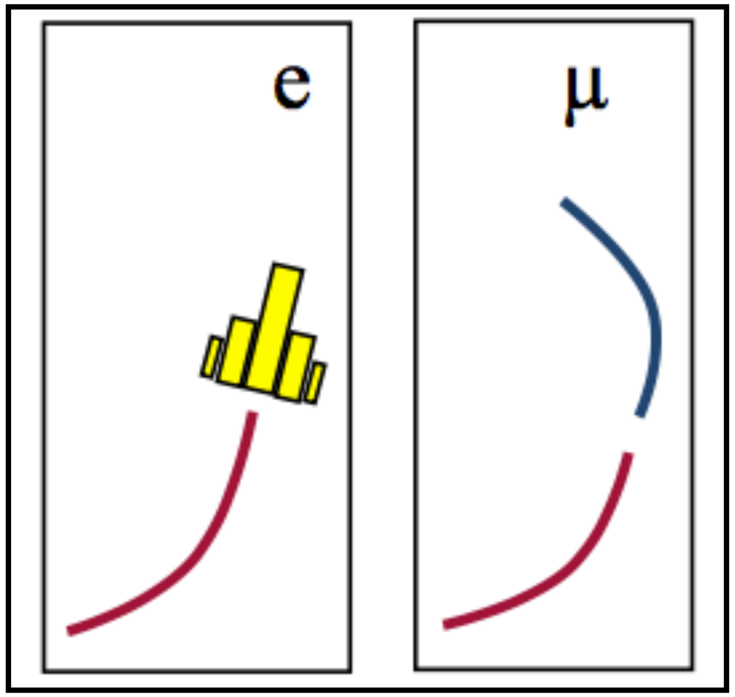


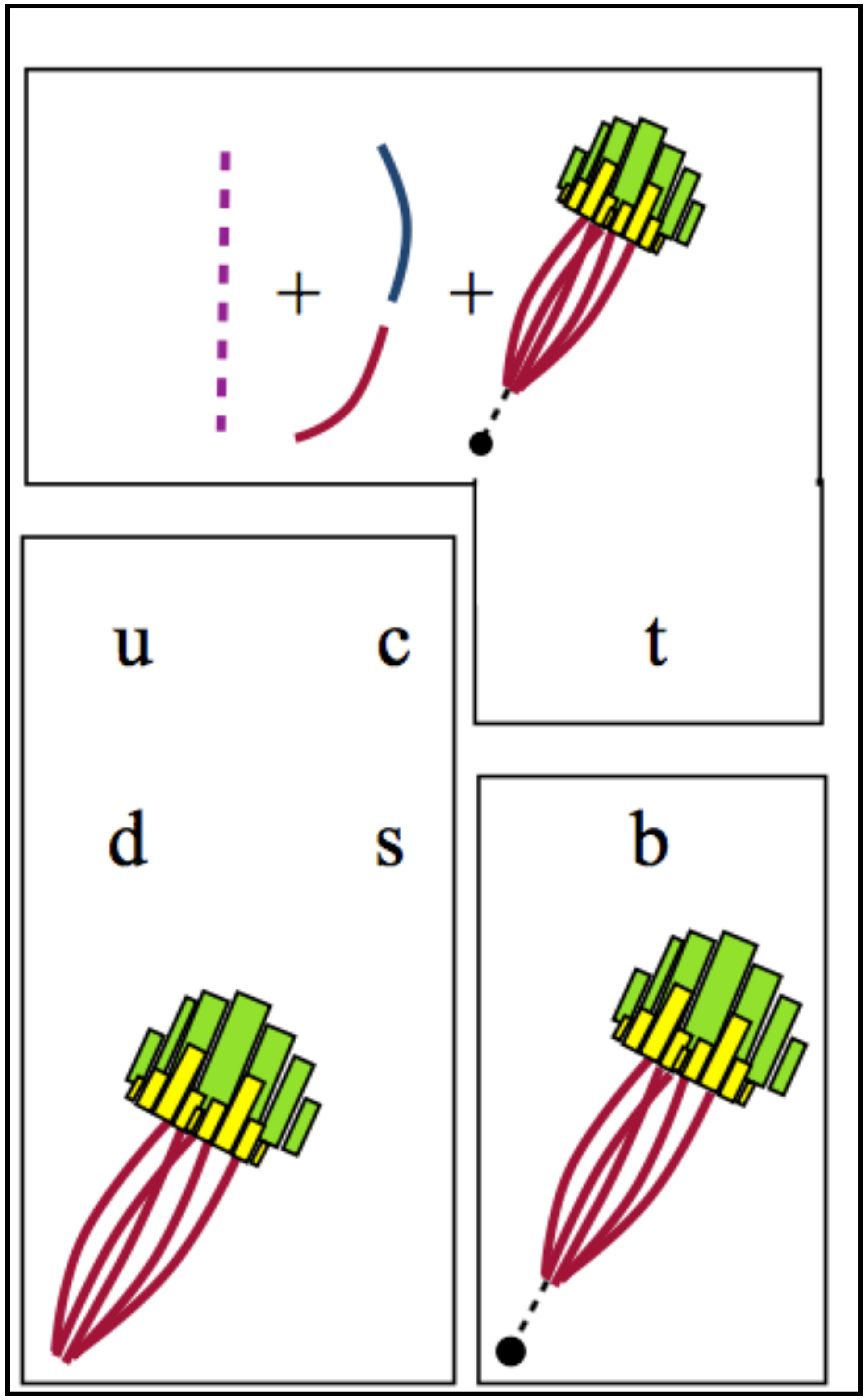
44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

Detector Outputs



Identifying Particles





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

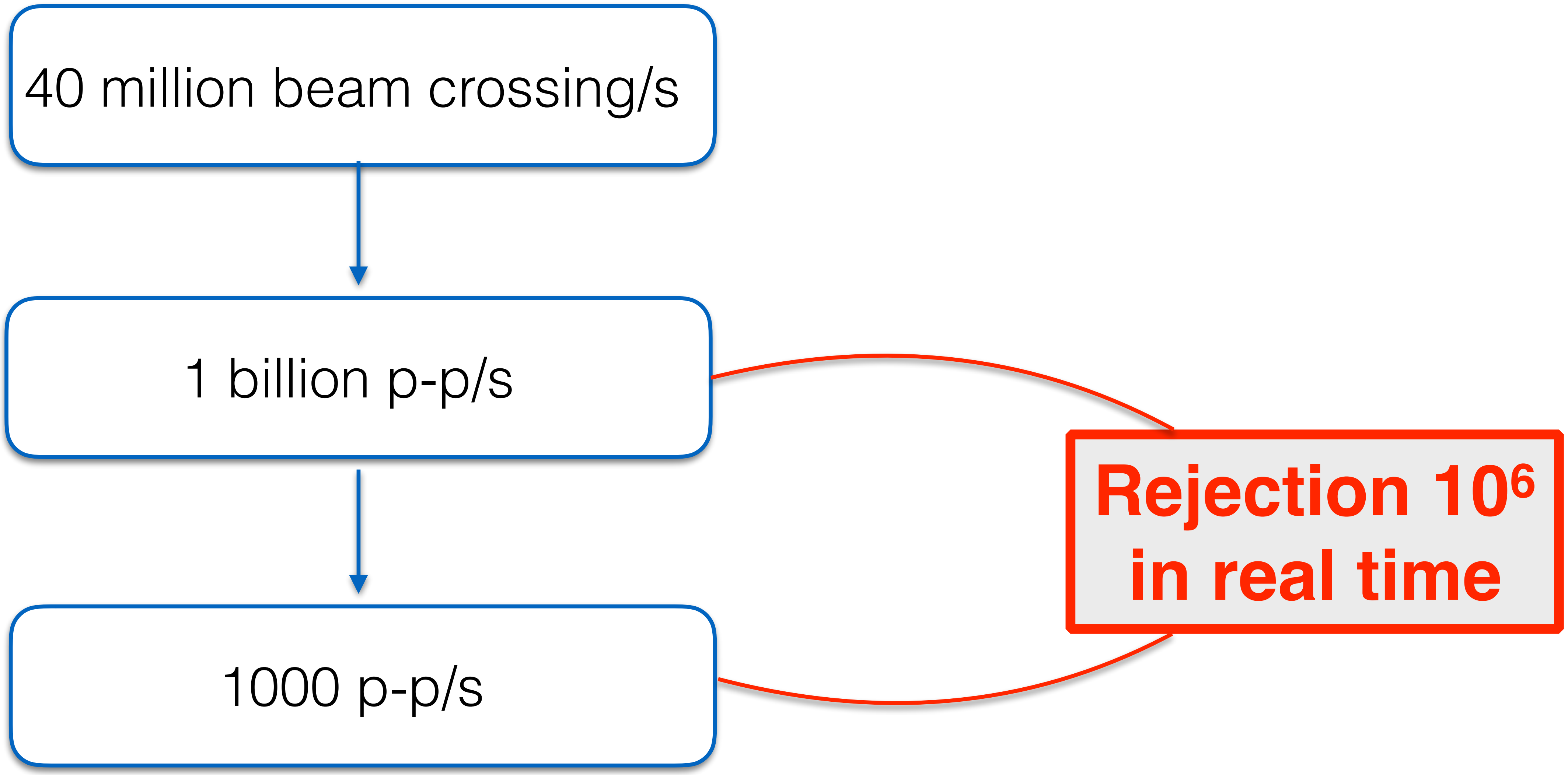
Data Challenge

40 million beam crossing/s

1 billion p-p/s

1000 p-p/s

Data Challenge



Data Challenge

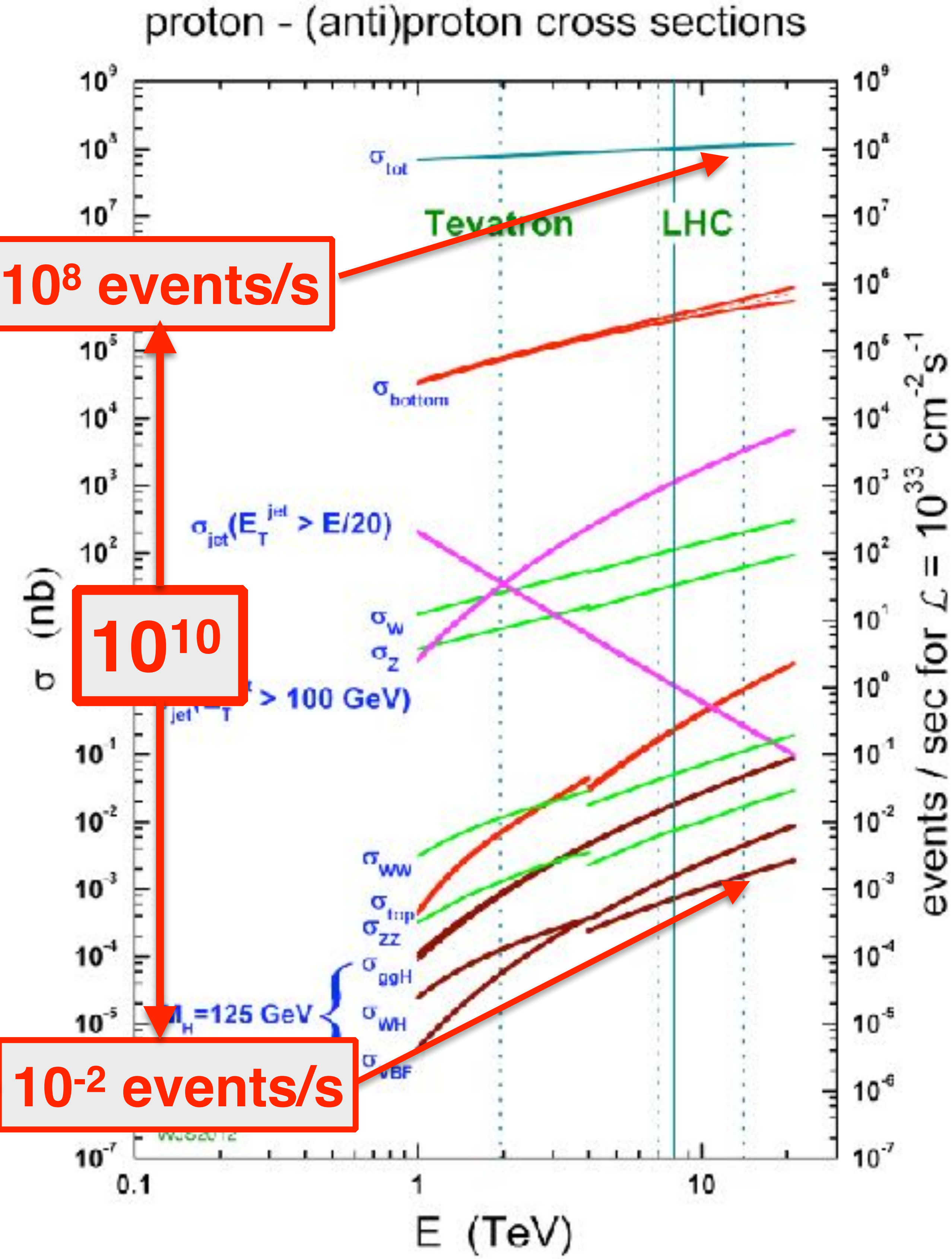
40 million beam crossing/s

[illegible] p/s

Rejection 10^6

1000 p-p/s

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



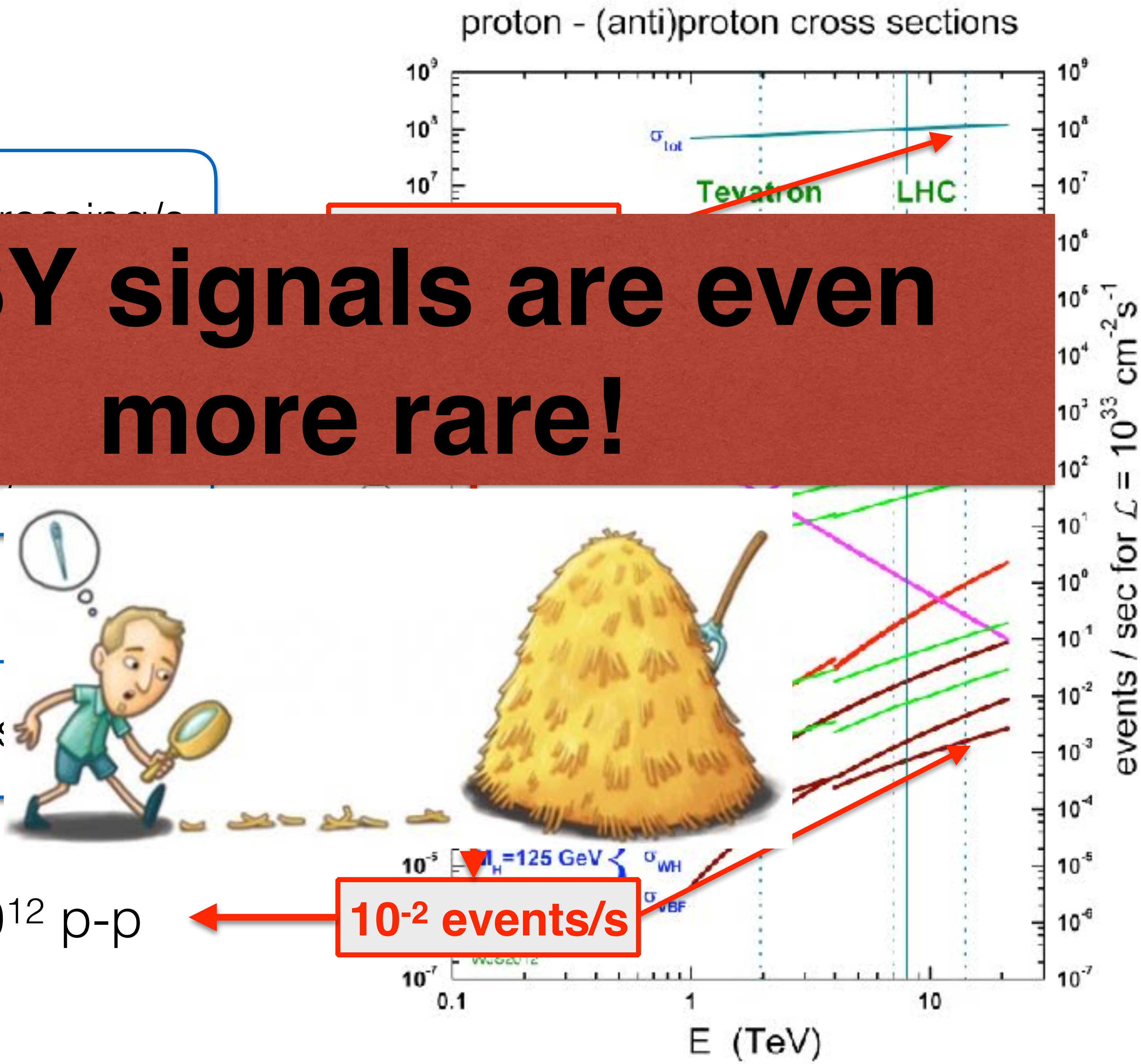
Data Challenge

40 million beam crossing/s

1000 p-p/s

Reject

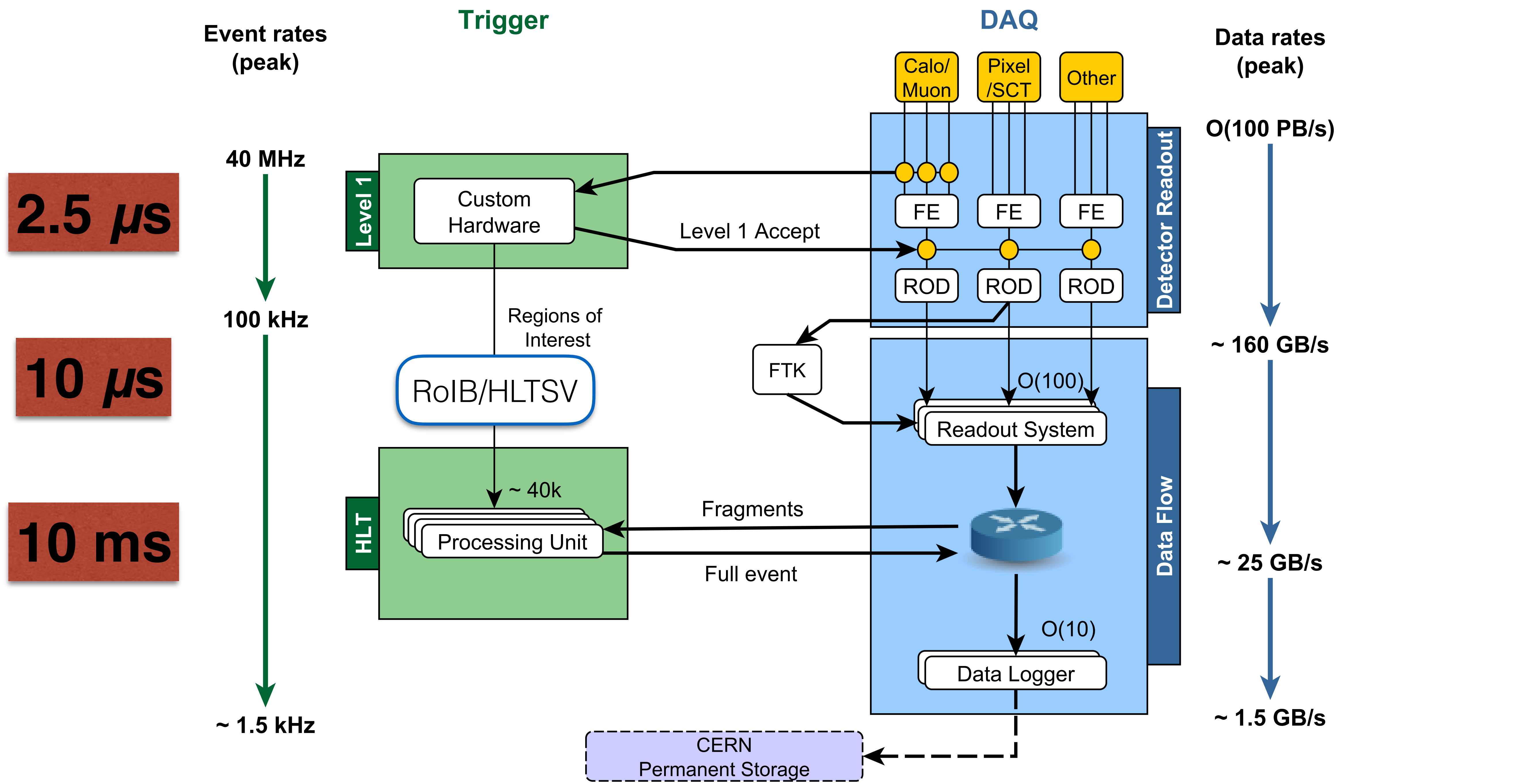
SUSY signals are even more rare!



10^{-2} events/s

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

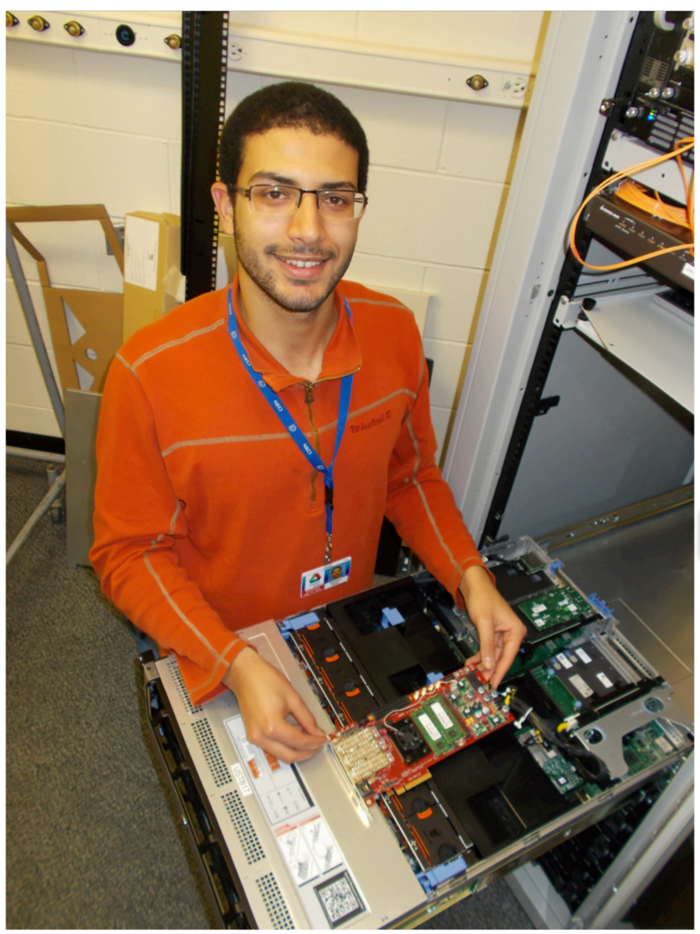
Trigger and Data Acquisition



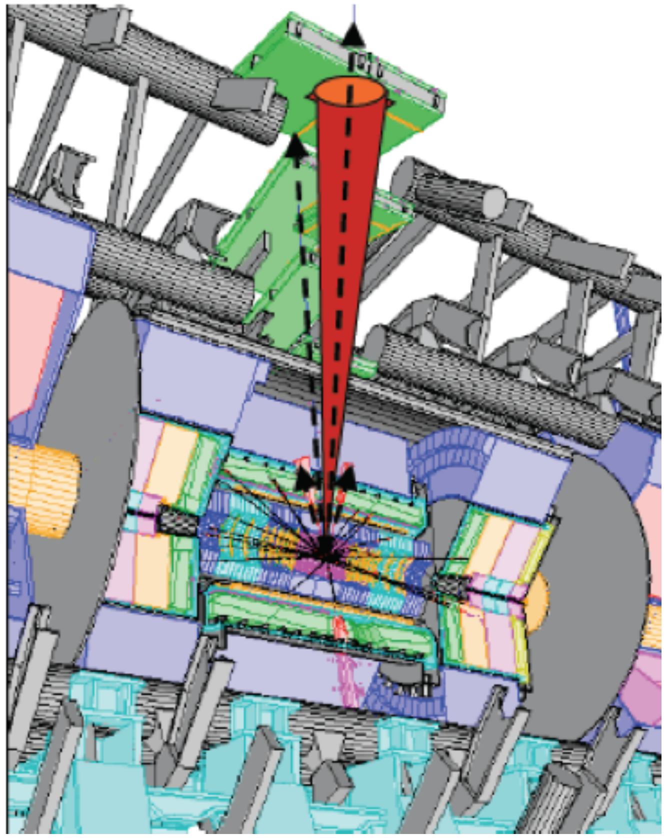
Region of Interest Builder

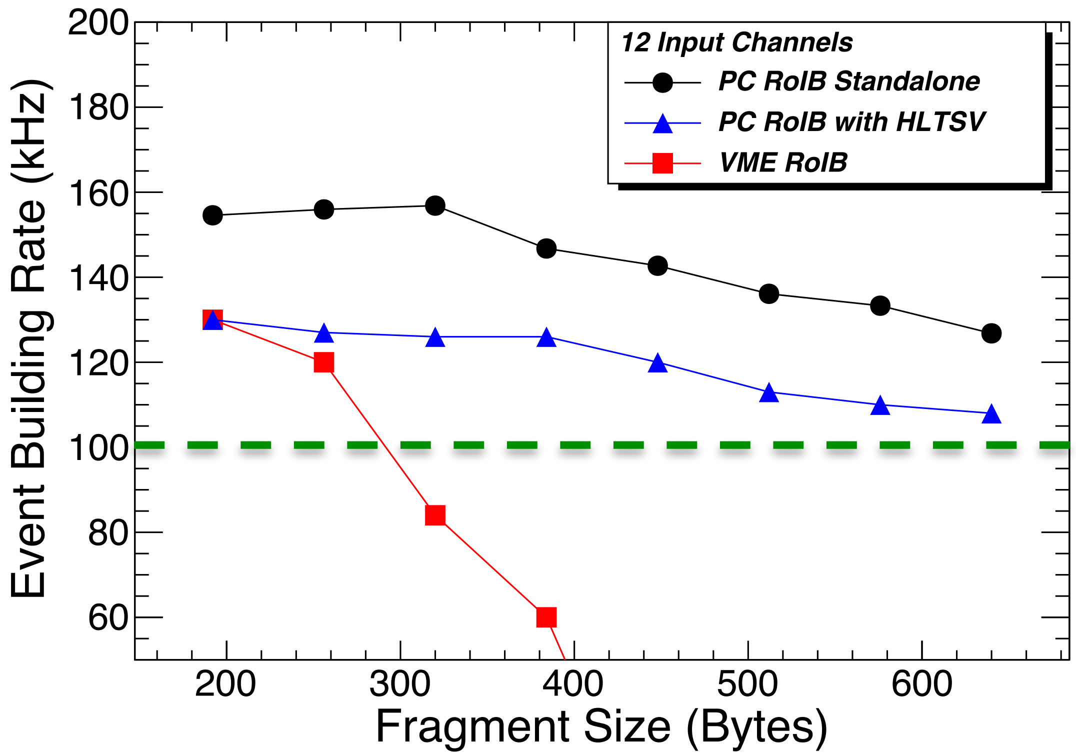
Every event recorded by ATLAS is processed by the RoIB

Argonne



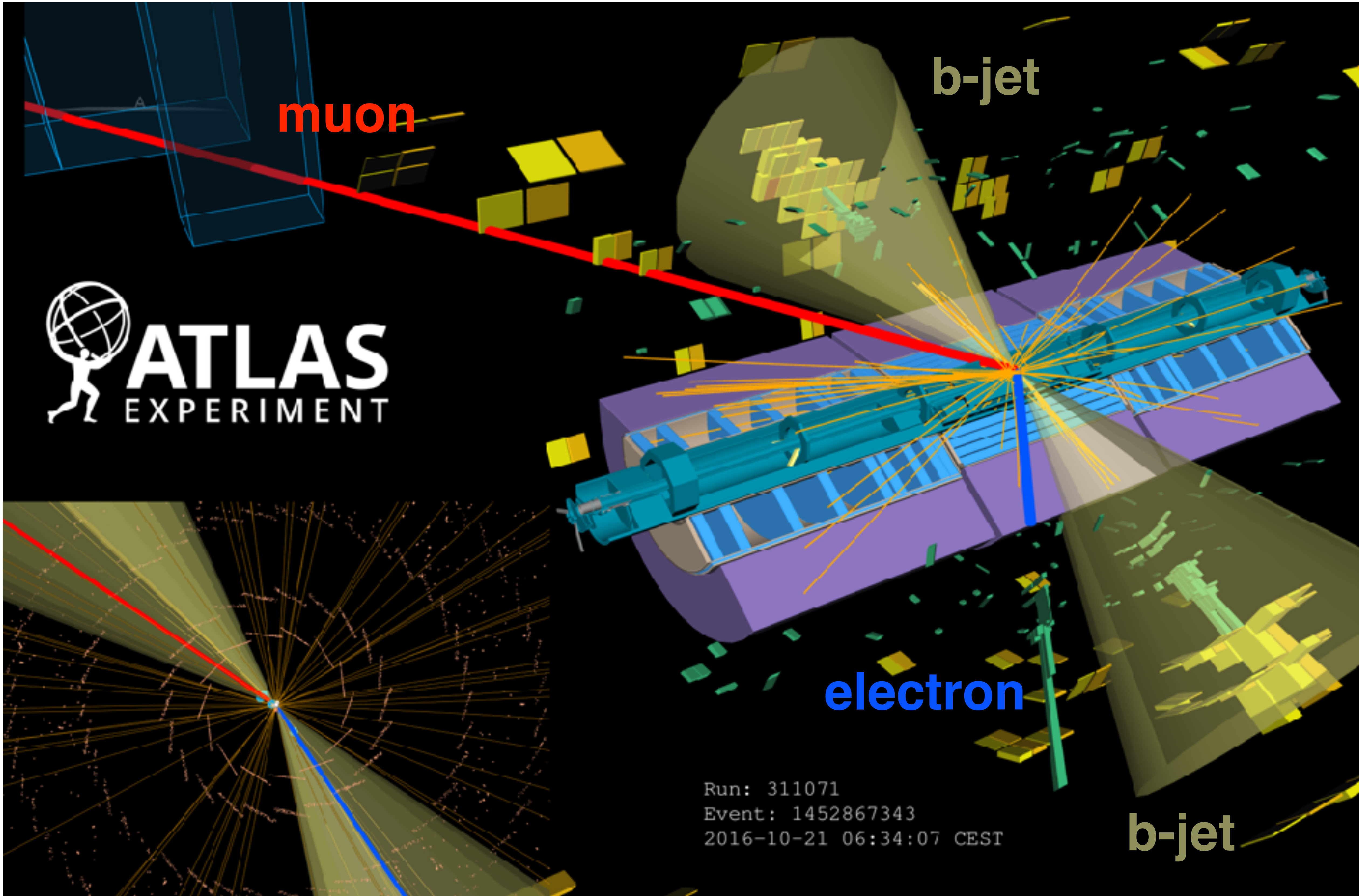
CERN



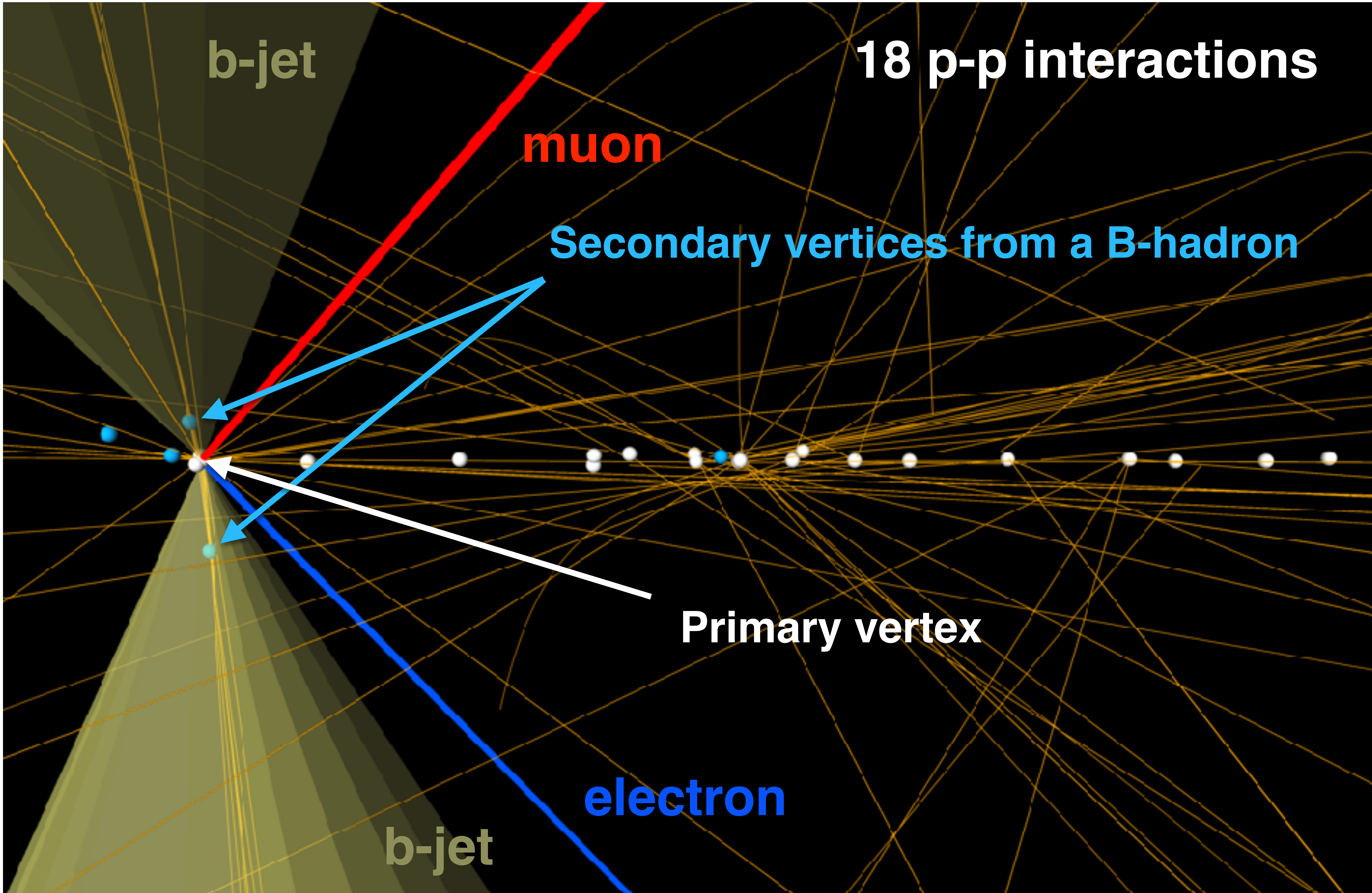


ATLAS Control Room

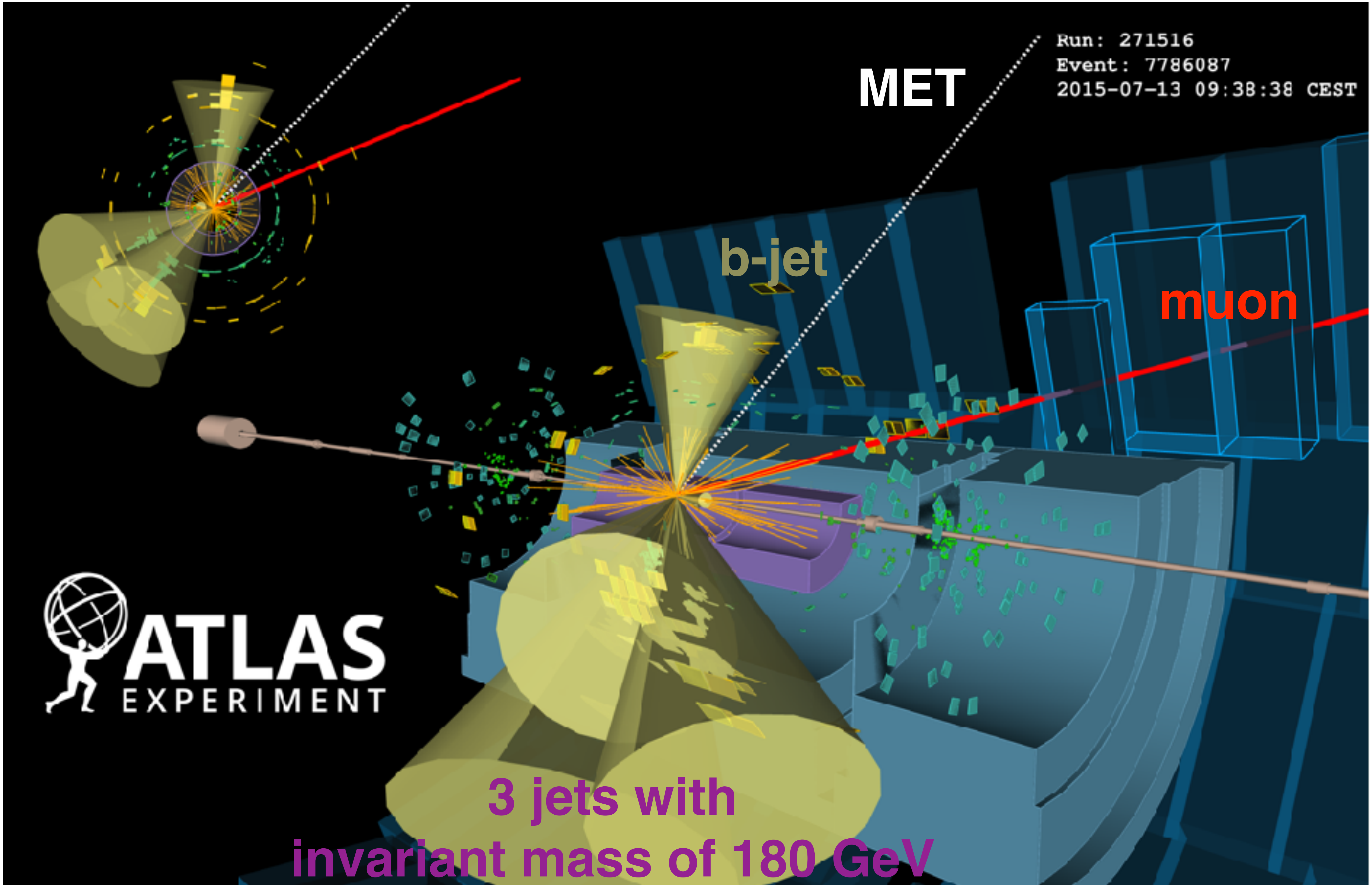
Top anti-top candidate 1



Top anti-top candidate 1

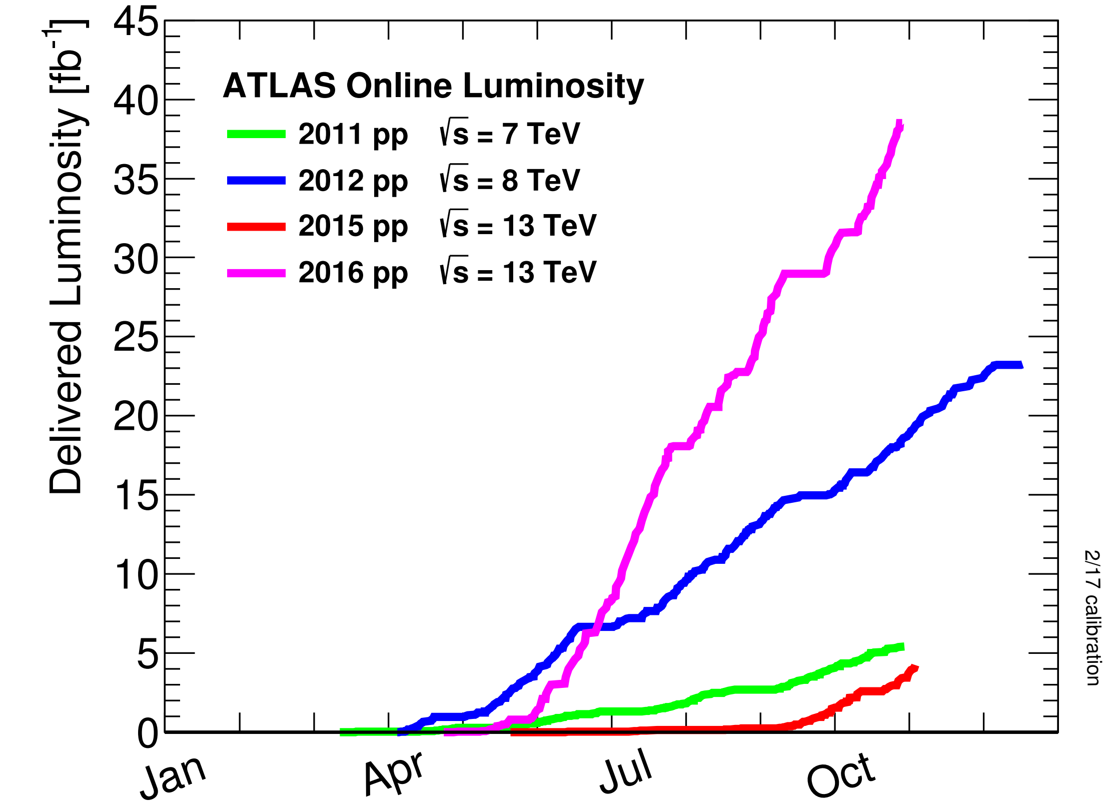


Top anti-top candidate 2

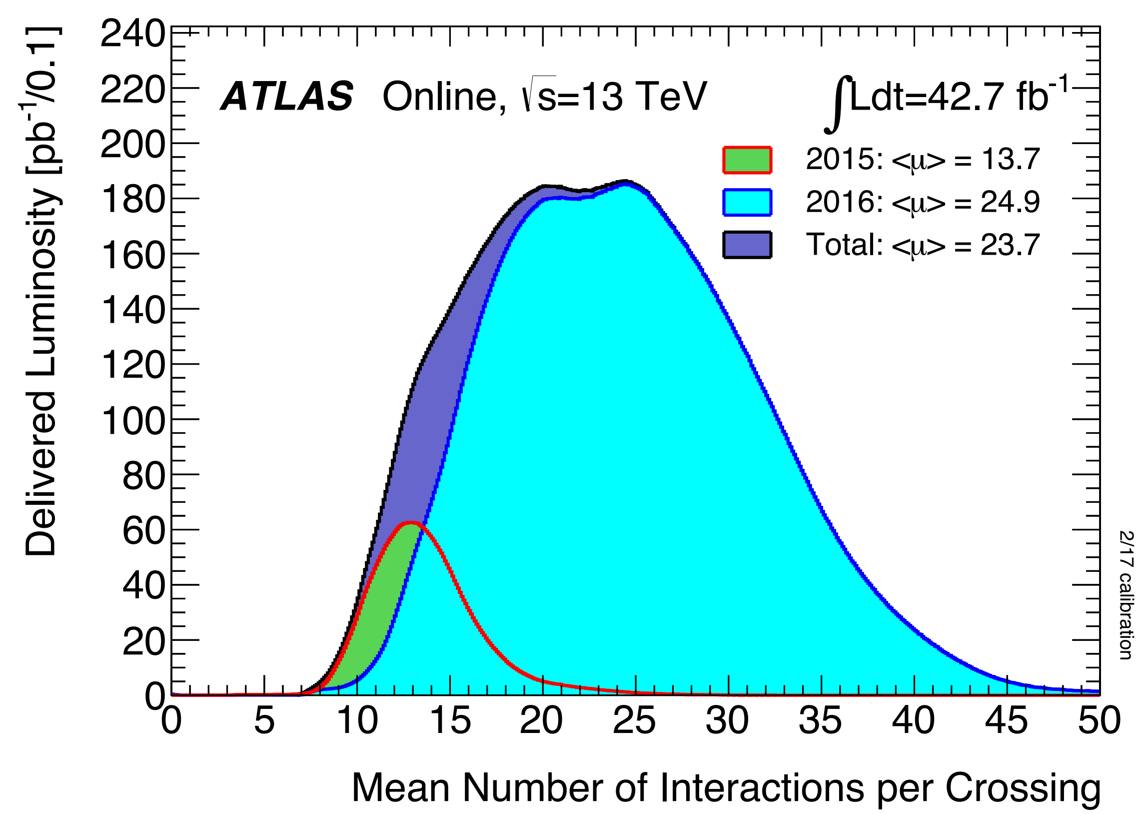


Data-taking 2015/2016

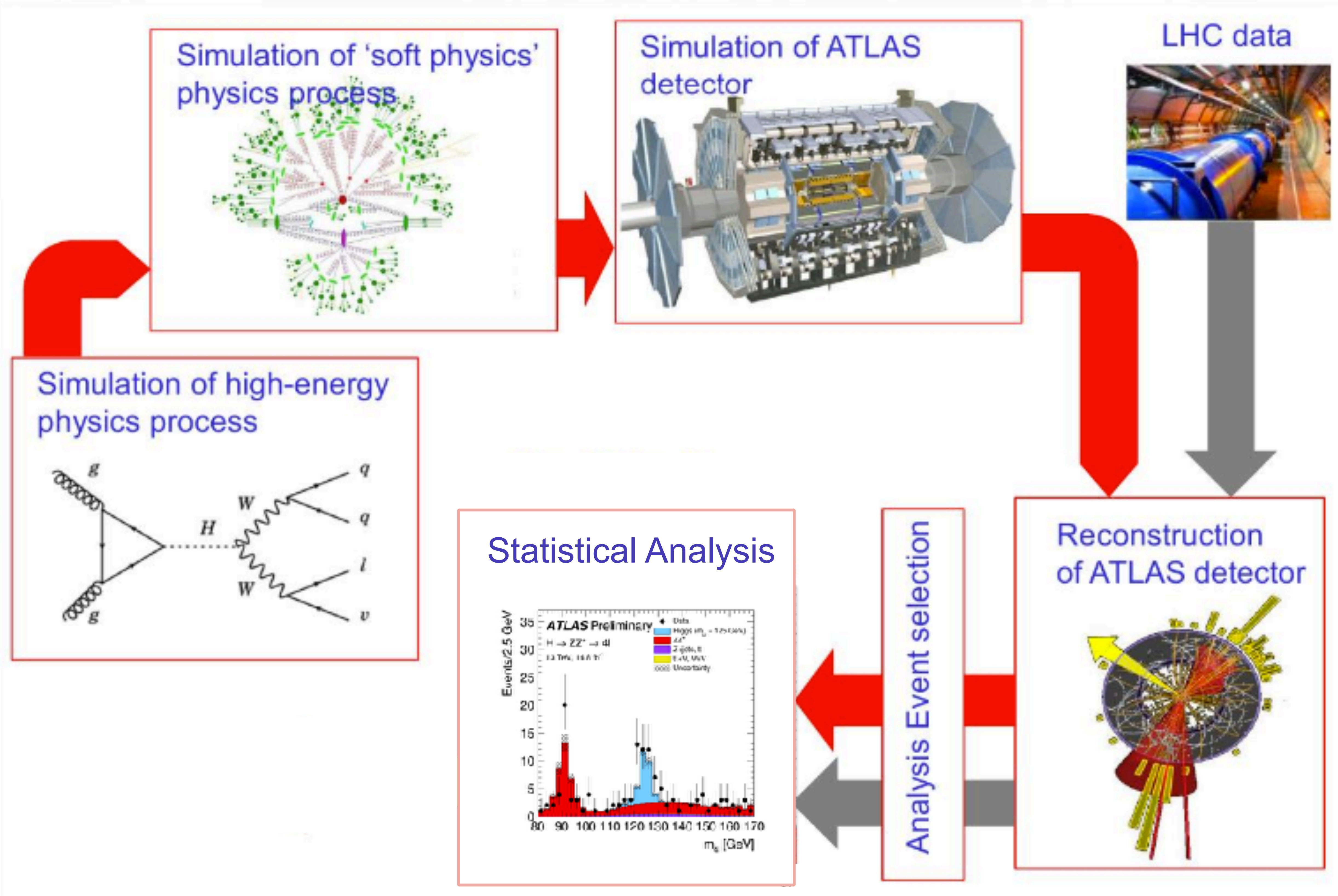
- Record performance of the LHC in 2016:
  - **1680 hours** of **13 TeV** stable beams data-taking
  - Peak luminosity of **1.4 x 10^{34} cm^{-2}s^{-1}** 40% higher than design
  - Pile-up of **50** interactions per crossing



- Excellent Run-2 data-taking campaign for ATLAS:
  - **3.9 fb^{-1} + 35.6 fb^{-1}** recorded in 2015 + 2016
  - In total **36.1 fb^{-1}** (i.e. 91.4%) good for **SUSY searches**!

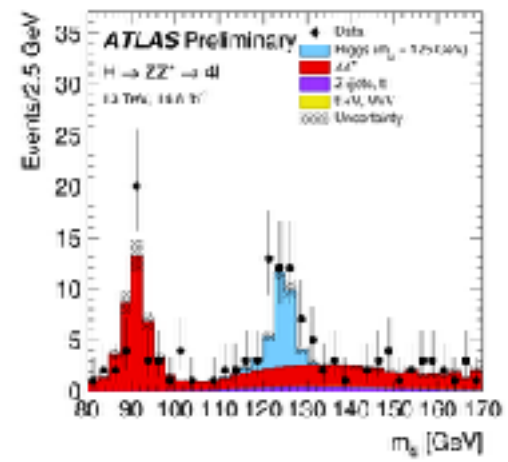


Workflow

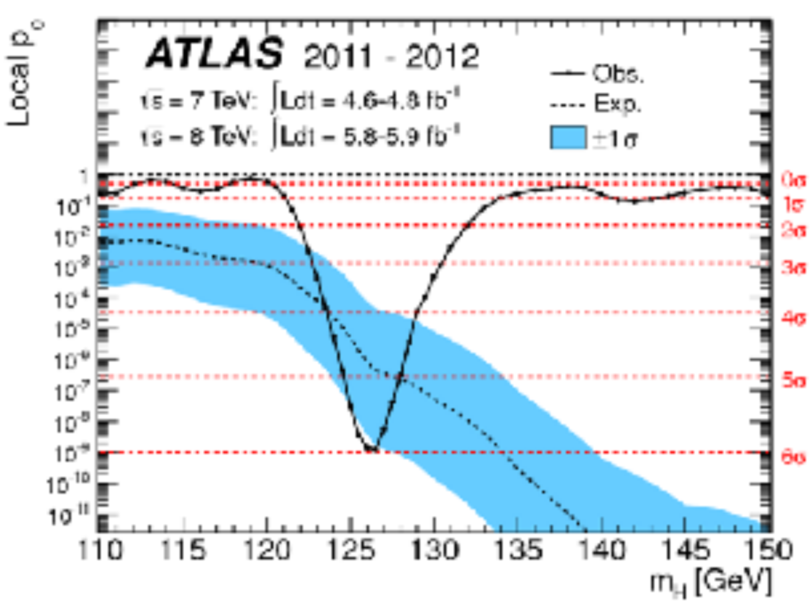

Simulation of 'soft physics' physics process
Simulation of ATLAS detector
LHC data
Simulation of high-energy physics process
g
g
H
W
W
q
q
l
ν
Statistical Analysis
ATLAS Preliminary
H → ZZ* → 4l
Events/2.5 GeV
m4l [GeV]
Data
Uncertainty
Analysis Event selection
Reconstruction of ATLAS detector

Workflow

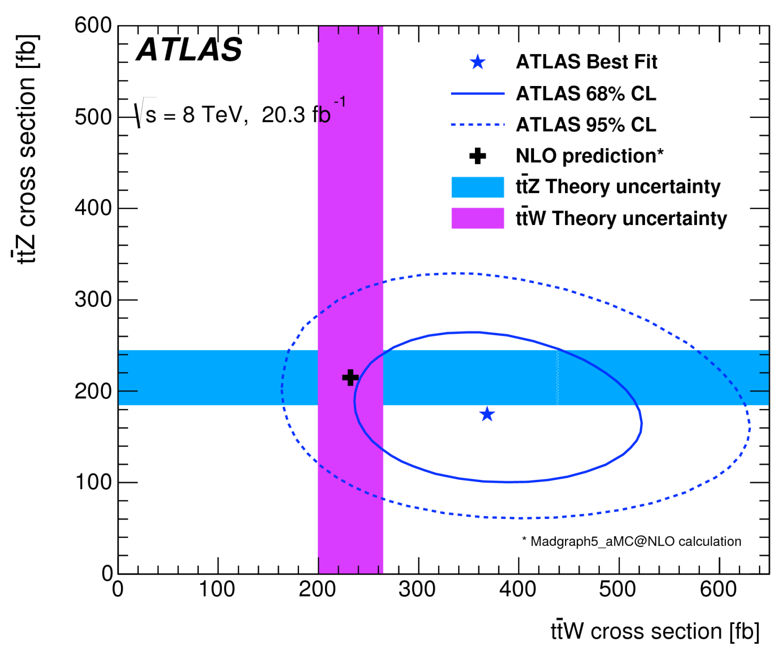
Statistical Analysis



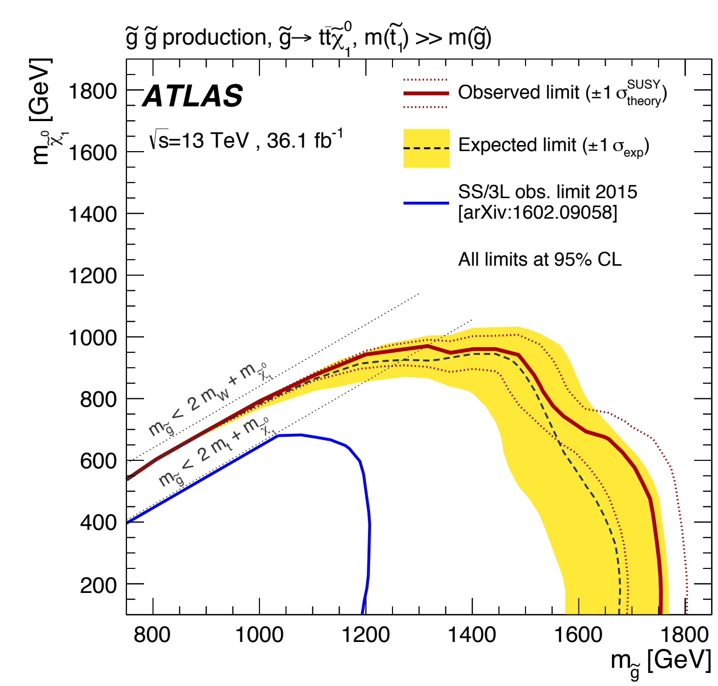
Discovery



Measurement



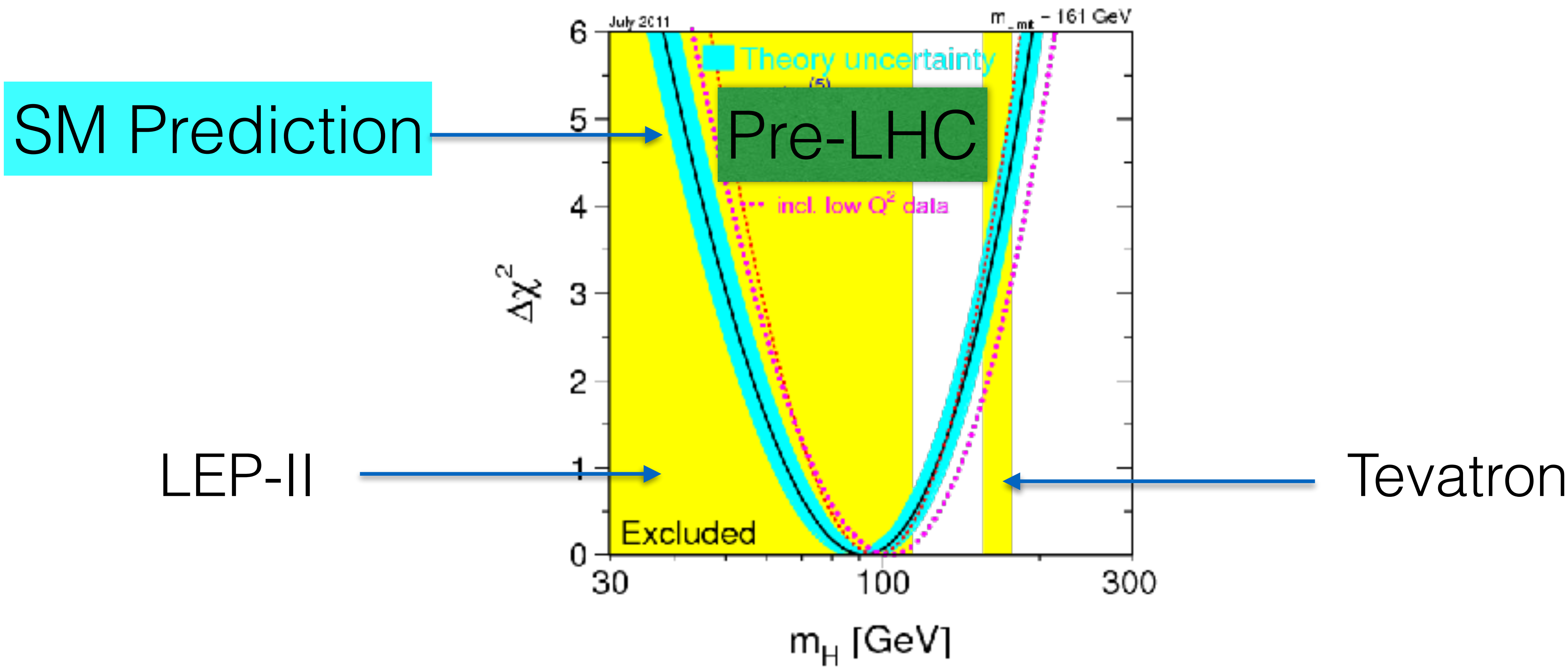
Limit



Where are we at?

Signals of Discovery

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

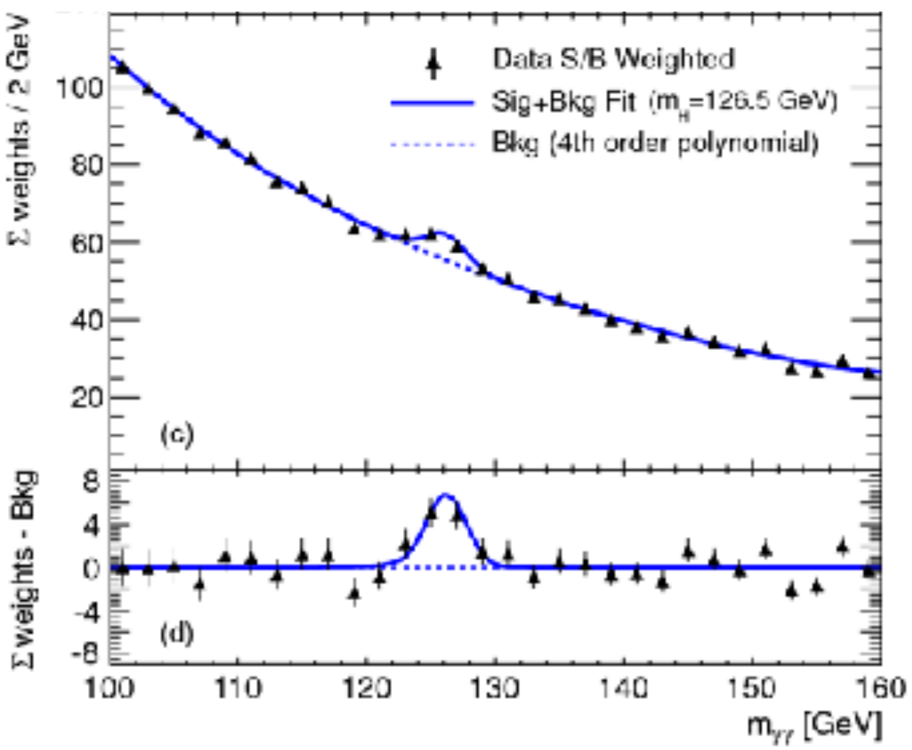


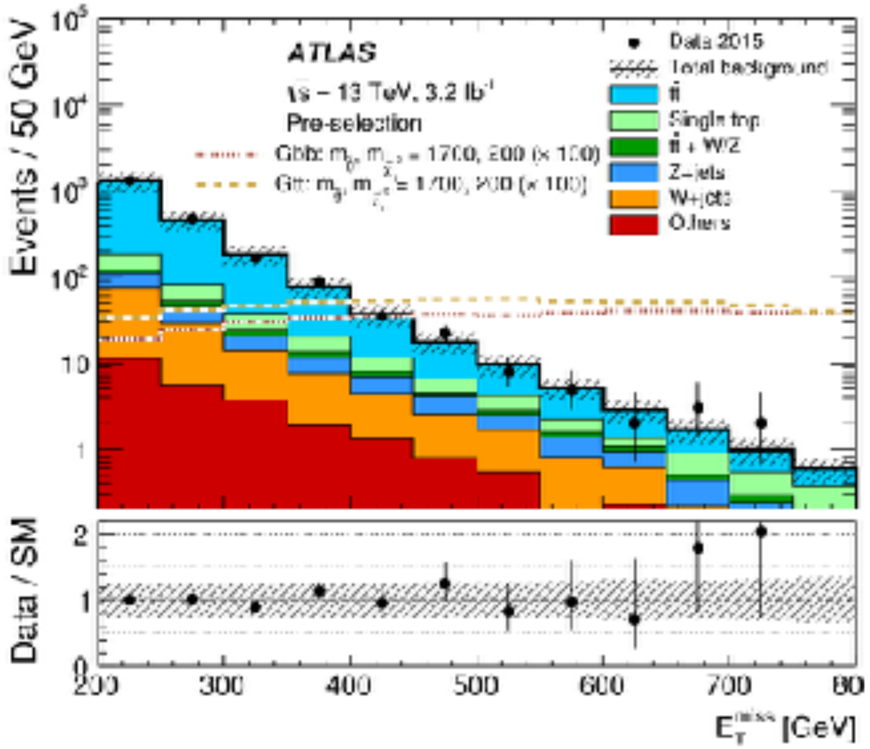
- Today, **we don't know what/where the unknown physics is**
- Discovery will most likely follow two steps:
  1. Establish a deviation from the SM
  2. Understand what this deviation corresponds to

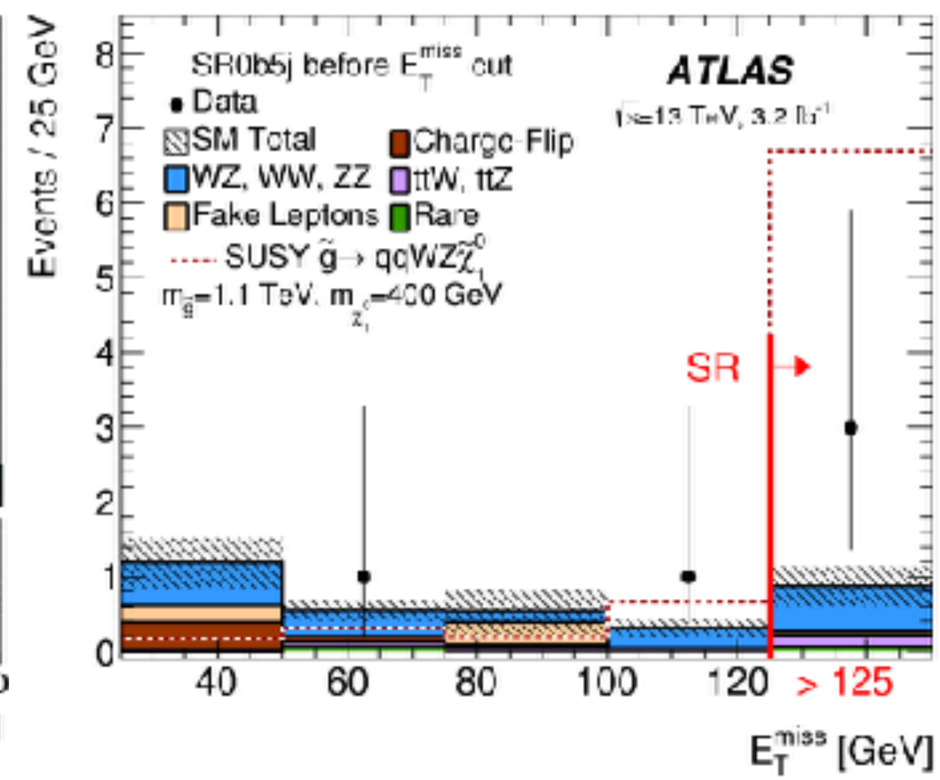
Signals of Discovery

In hadron colliders, deviations in roughly three categories:

Mass Peak	Shape Discrepancies	Counting experiment







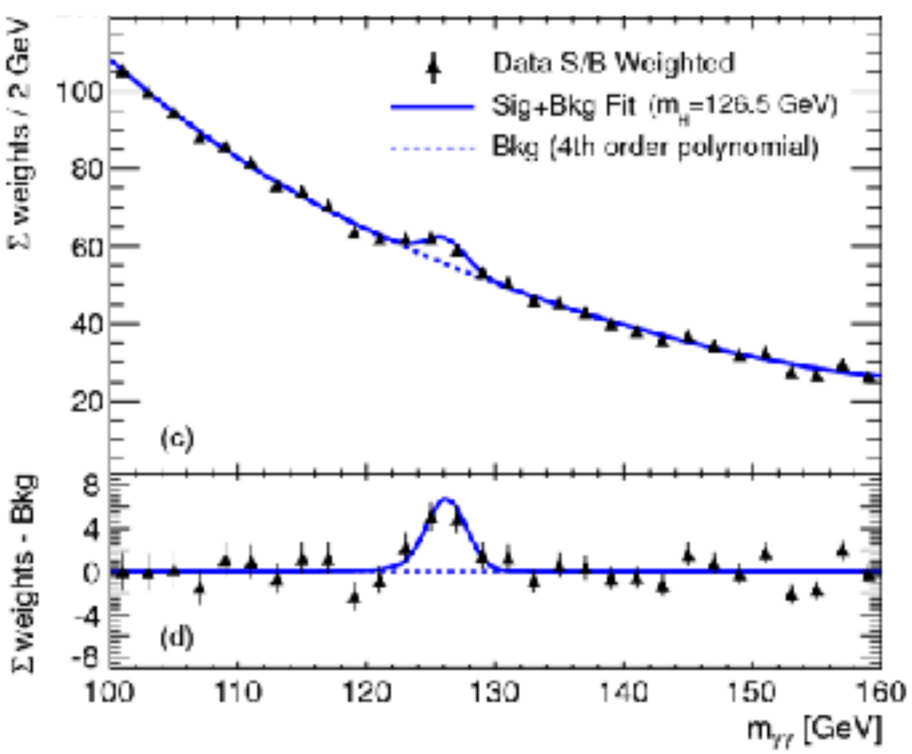
Most robust signature

Requires careful background estimation

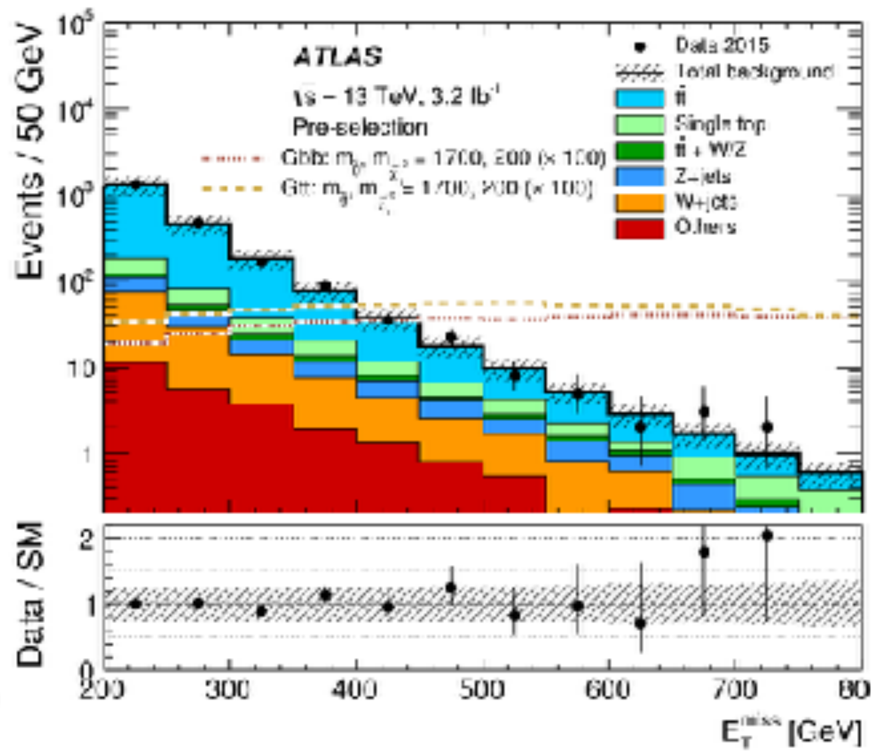
Signals of Discovery

In hadron colliders, possible deviations in roughly three categories:

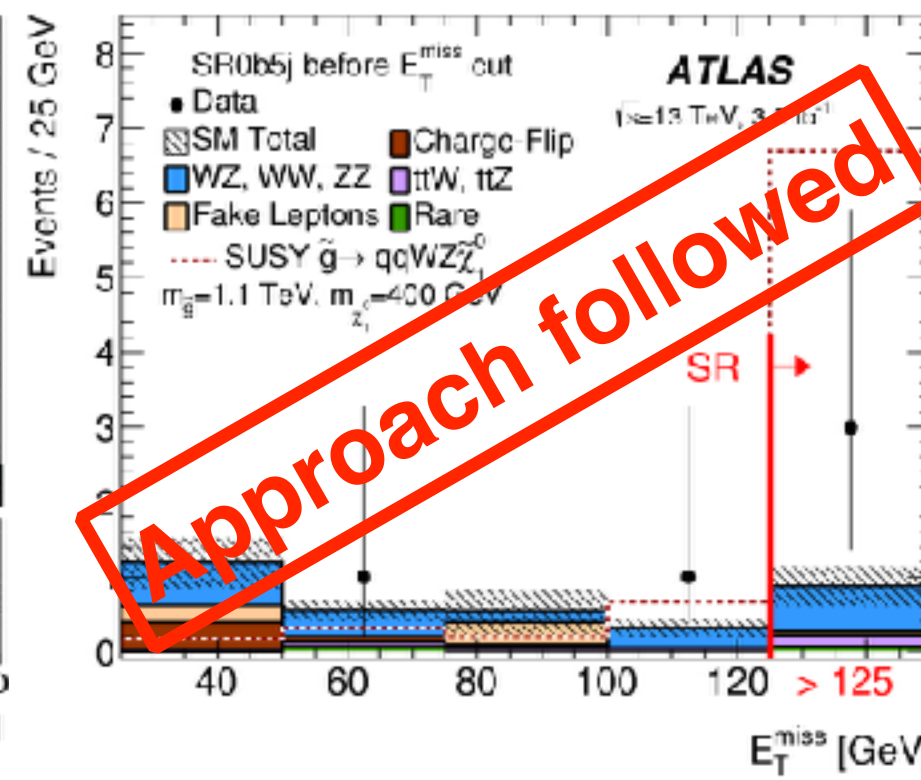
Mass Peak



Shape Discrepancies



Counting experiment



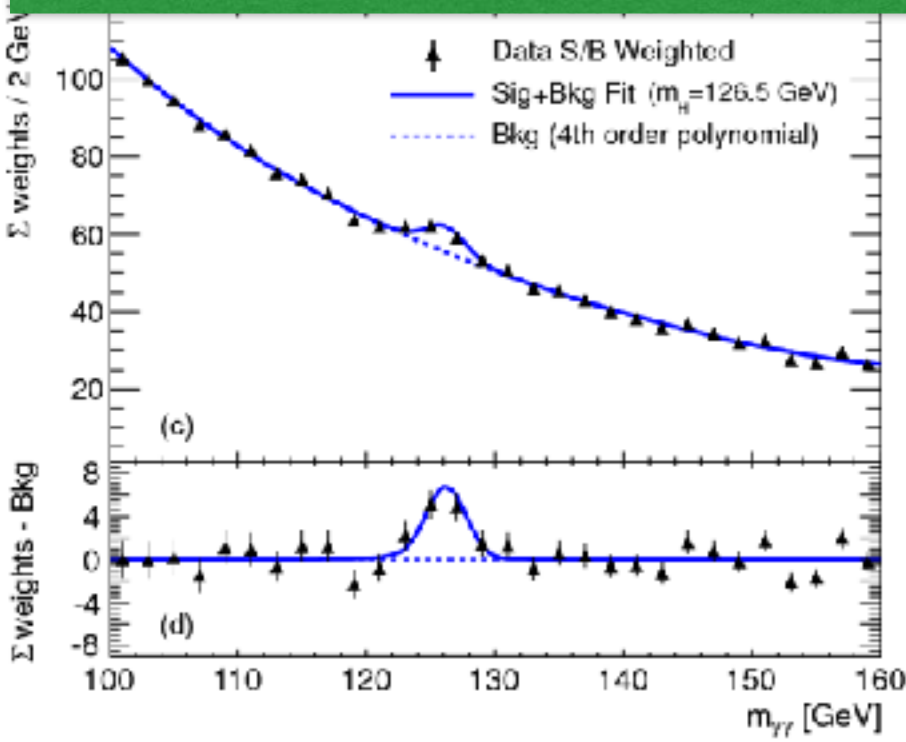
Most robust signature

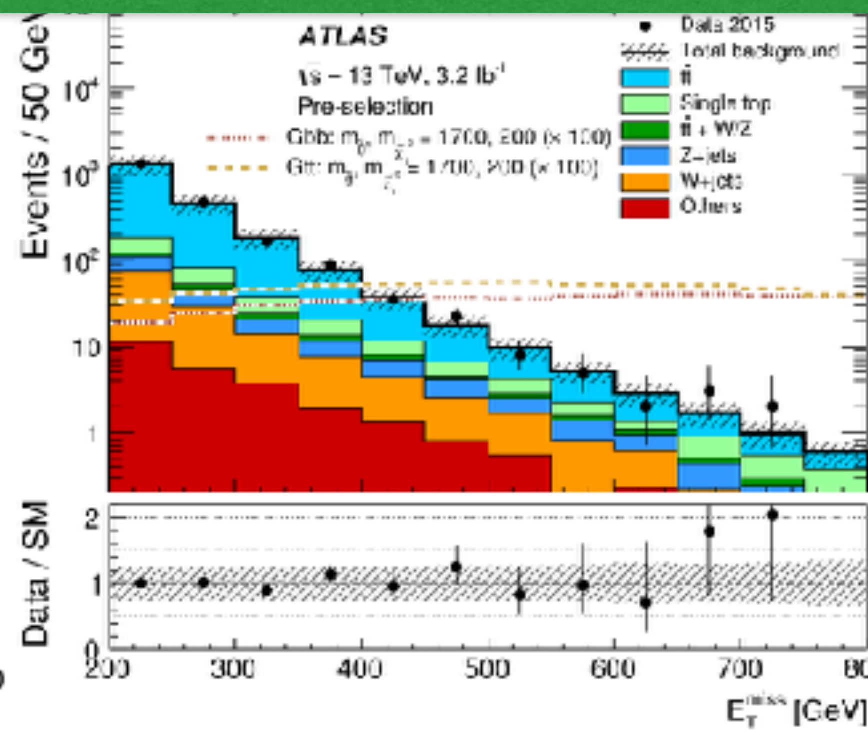
Requires careful background estimation

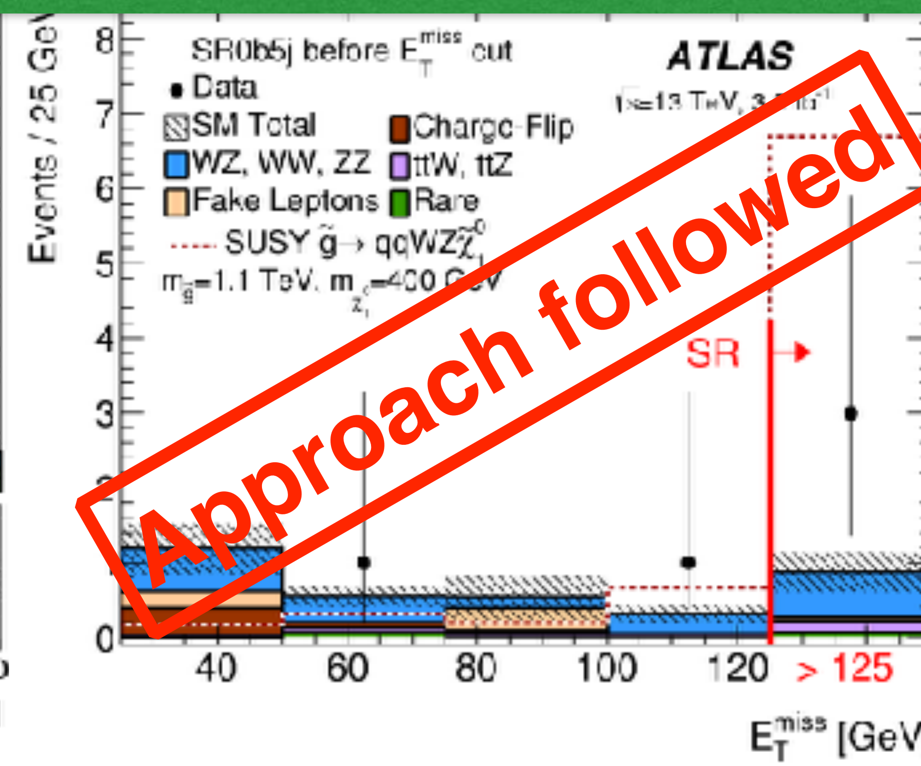
Signals of Discovery

In hadron colliders, possible deviations in roughly three categories:

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



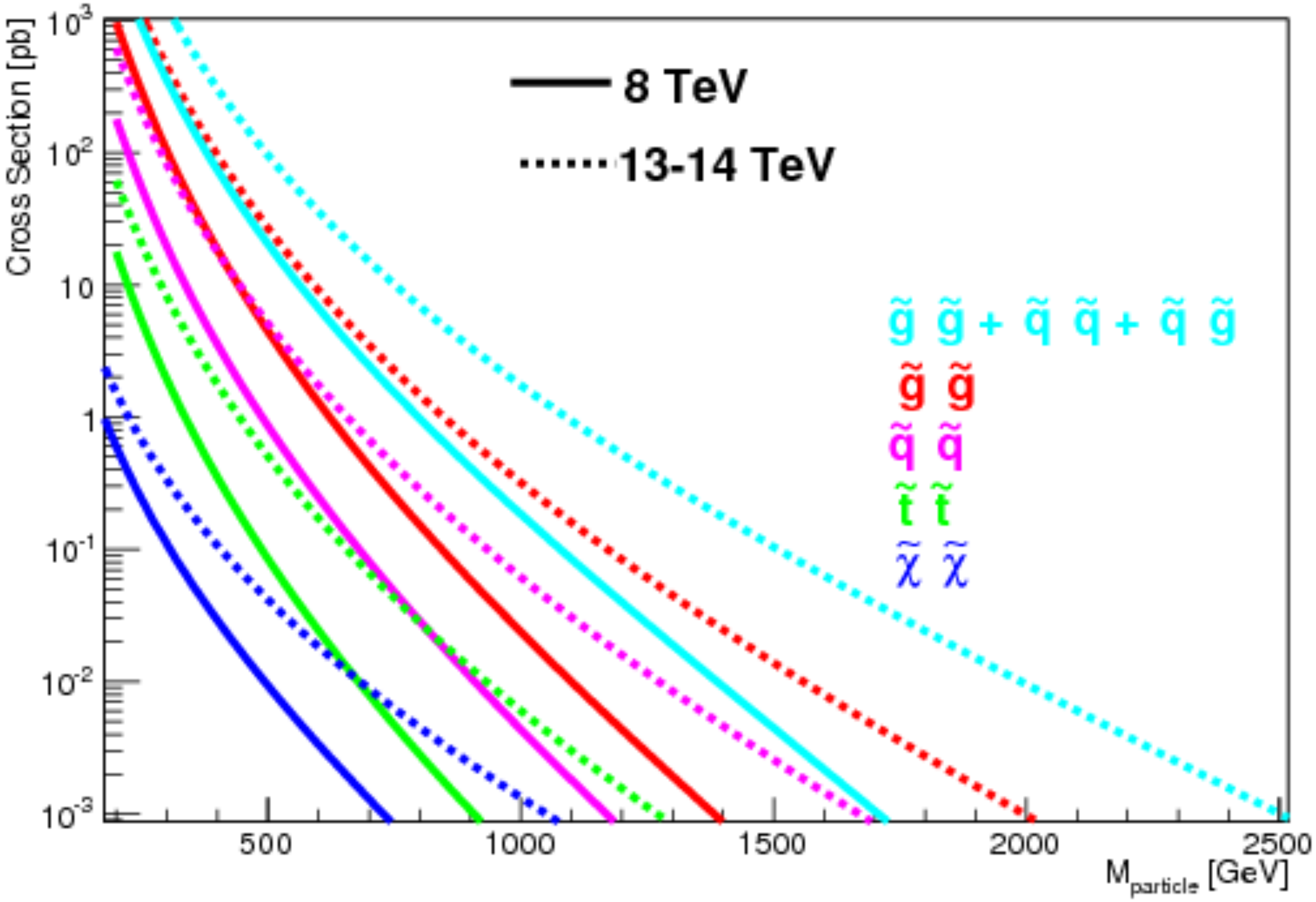


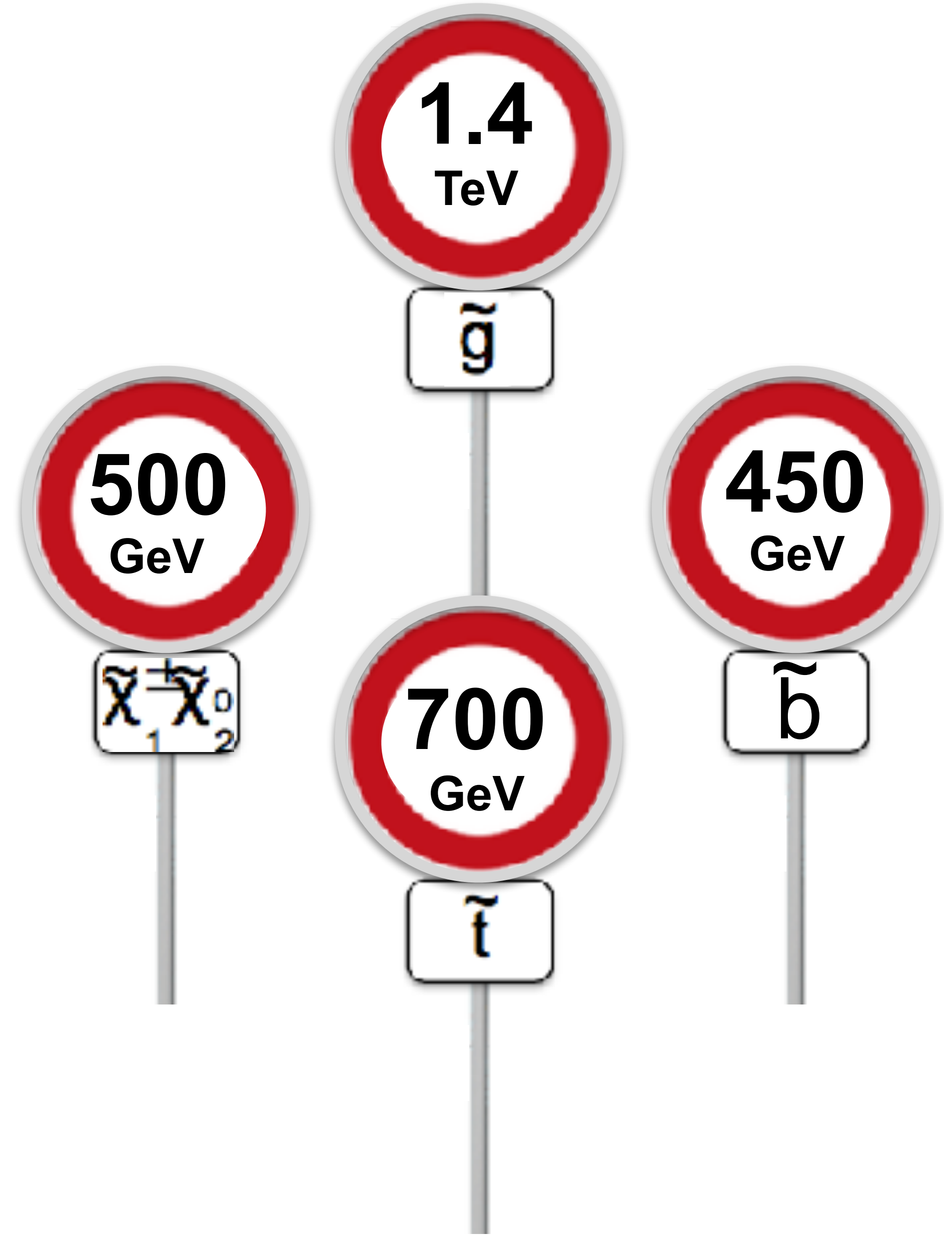


Most robust signature

Requires careful background estimation

Run-1 at 8 TeV status





Run-2 at 13 TeV starts…

Search for Supersymmetry

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

Submitted to: JHEP

CERN-EP-2017-108
14th June 2017

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

Search for supersymmetry in final states with two same-sign or three leptons and jets using 36 fb^{-1} of $\sqrt{s} = 13$ 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 μ), 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 $\sqrt{s} = 13$ TeV recorded with the ATLAS detector at the Large Hadron Collider in 2015 and 2016, corresponding to a total integrated luminosity of 36.1 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 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 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

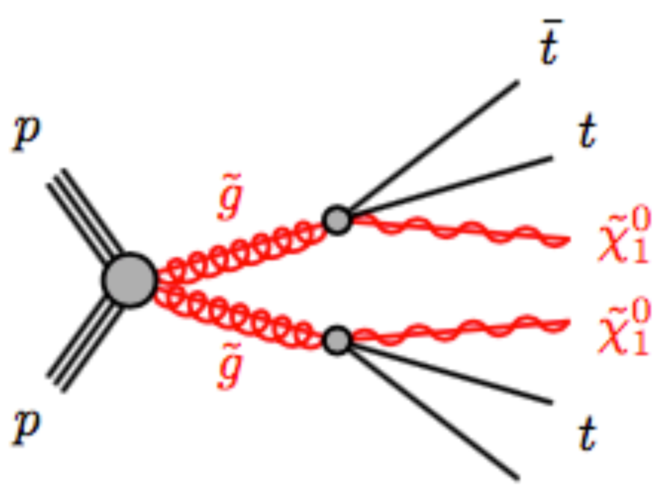
1. Determine SUSY scenarios
   - Simplified models
   - Realistic models
2. Design search regions
   - Optimize for discovery
3. Estimate the background
   - SM background
   - Detector background
4. Evaluate the uncertainties
   - Statistical uncertainties
   - Experimental uncertainties
   - Theoretical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

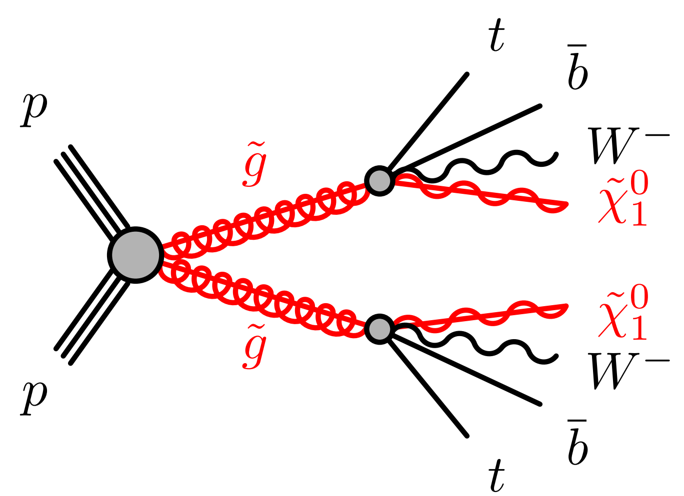
Gluinos

Many b-jets



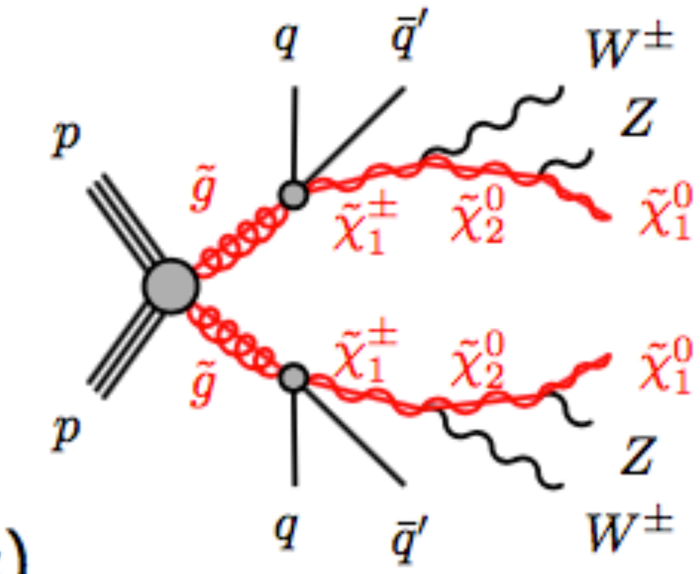
a)

Off-shell tops



b)

High N_{jets}

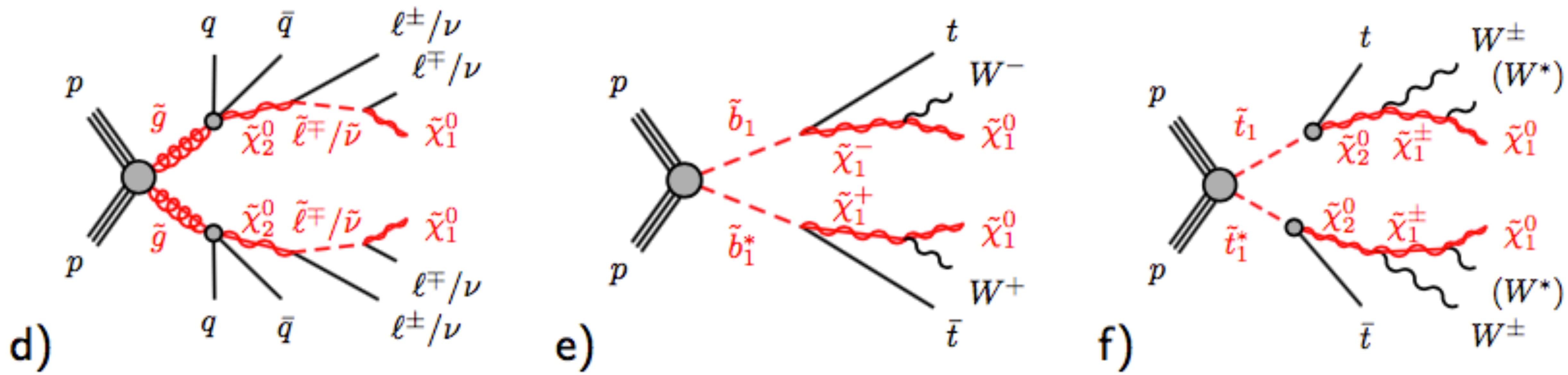


c)

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

Simplified Models

Gluinos	3rd Gen Squarks	
highest BR to leptons	**Completes** $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	**Novel 3LSS**



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

Realistic Model

Non-Universal Higgs Model with 2 parameters (NUHM2)

- $m^2_{H_d} \neq m^2_{H_u} \neq m^2_0$ at the GUT scale
- All parameters set to respect m_h = 125 GeV
  $m_{1/2}$ = 300 - 800 GeV, $m_{\tilde{g}}$ ~ 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
$t\bar{t}\chi^0_1$	0.13	$tb\chi^{\pm}_1$	0.45
$t\bar{t}\chi^0_2$	0.21	$tb\chi^{\pm}_2$	0.04
$t\bar{t}\chi^0_3$	0.13	-	-
$t\bar{t}\chi^0_4$	0.02	-	-
$t\bar{t}\chi^0_i$	0.49	$tb\chi^{\pm}_i$	0.49

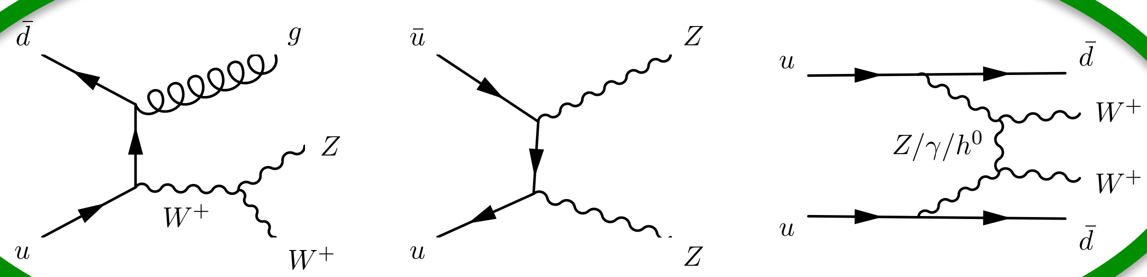
Data and Simulation

- **Data** collected during 2015 and 2016 at **13 TeV**: **36.1 fb^{-1} ± 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

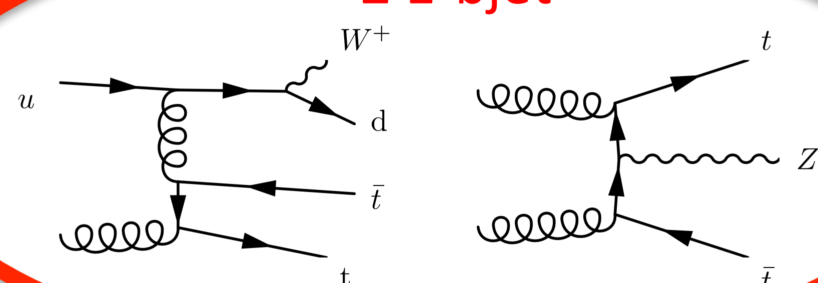
SM Background

Determine all the SM processes with SS/3L

0-bjet



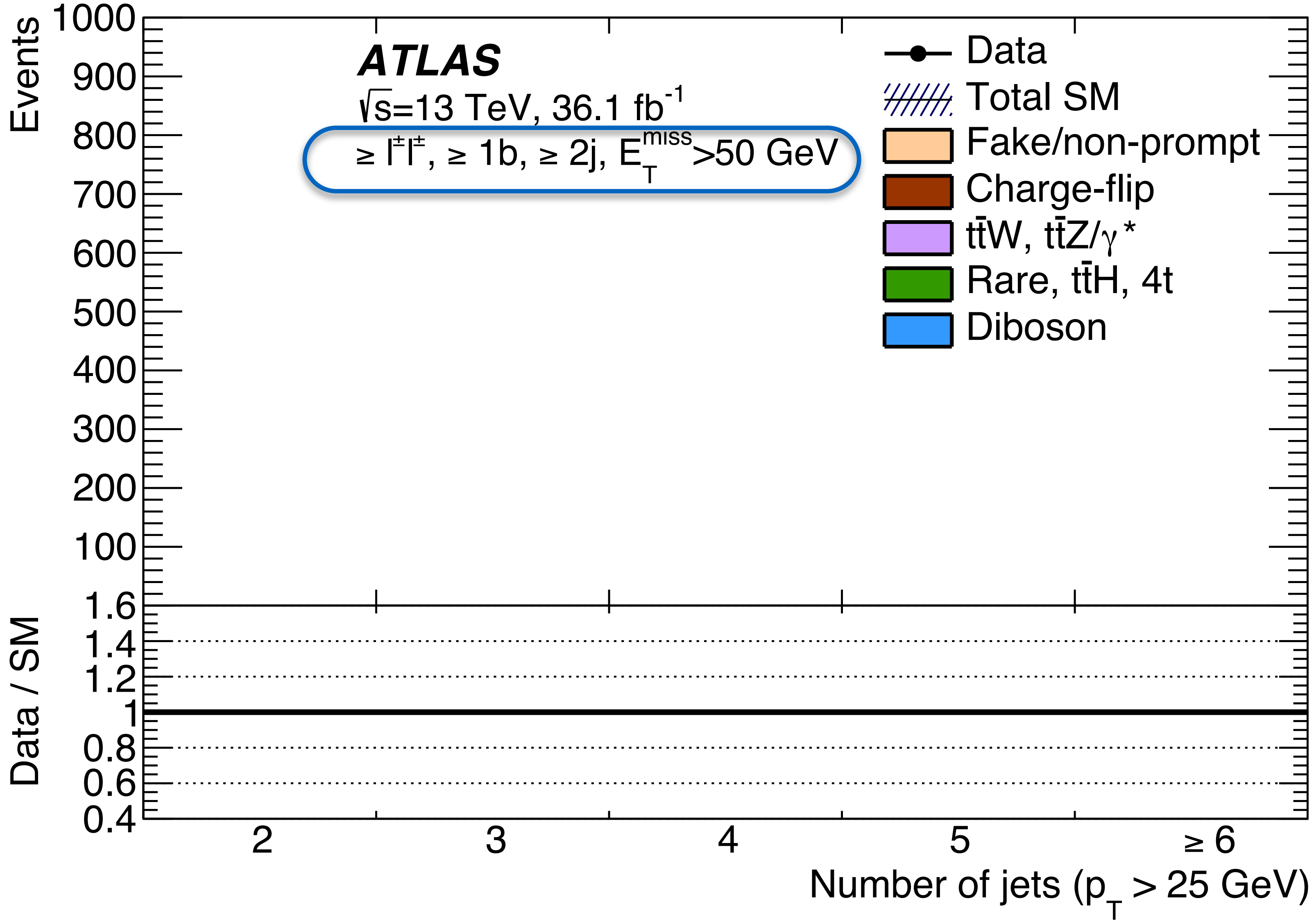
≥ 1-bjet



Process	Cross Section (pb)
$\tilde{g}\tilde{g}$, $m_{\tilde{g}} = 1000$ GeV	0.163
$\tilde{g}\tilde{g}$, $m_{\tilde{g}} = 1400$ GeV	0.025
$\tilde{b}\tilde{\bar{b}}$, $m_{\tilde{b}} = 550$ GeV	0.296
$\tilde{b}\tilde{\bar{b}}$, $m_{\tilde{b}} = 700$ 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

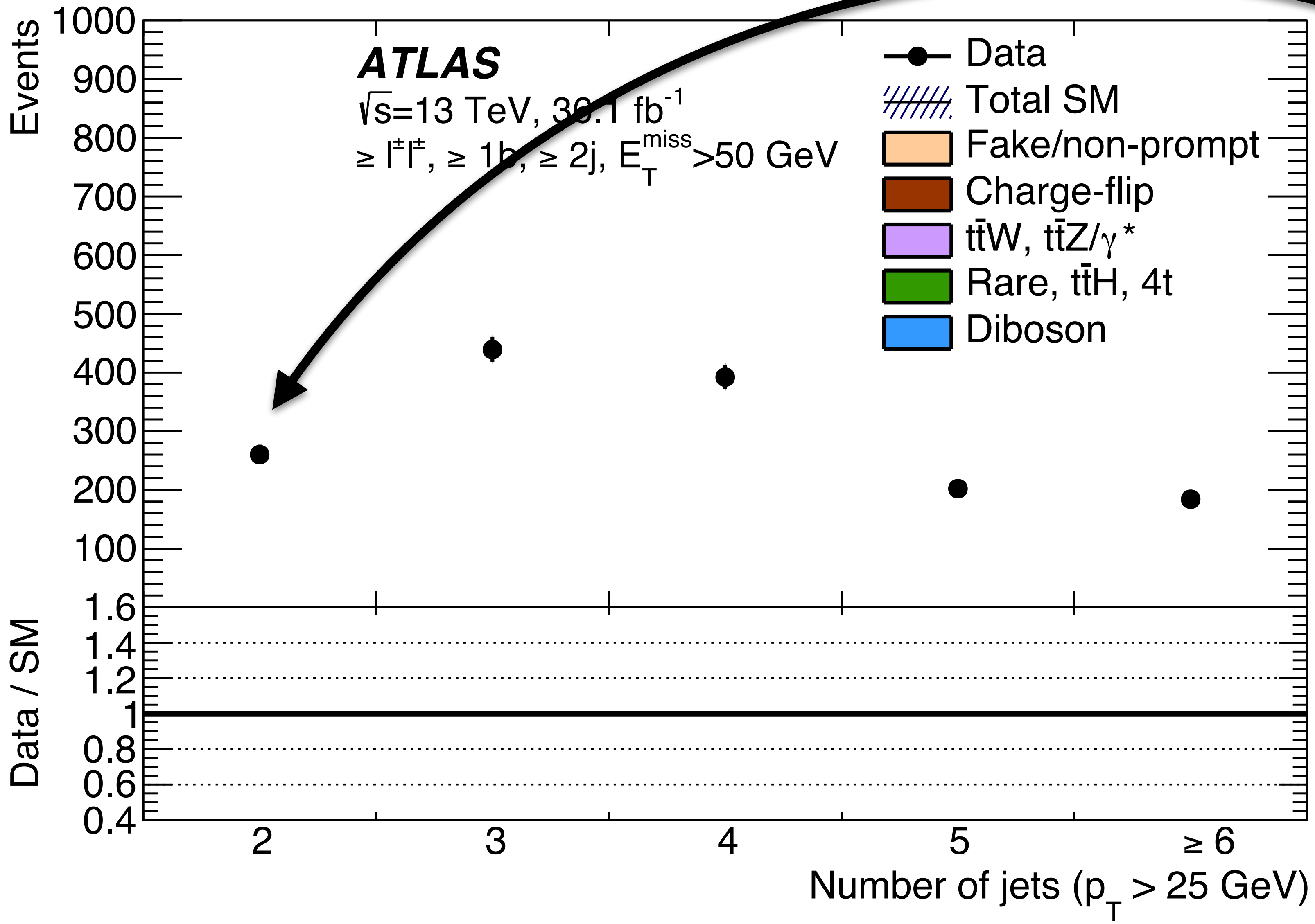
Data vs. Expectation

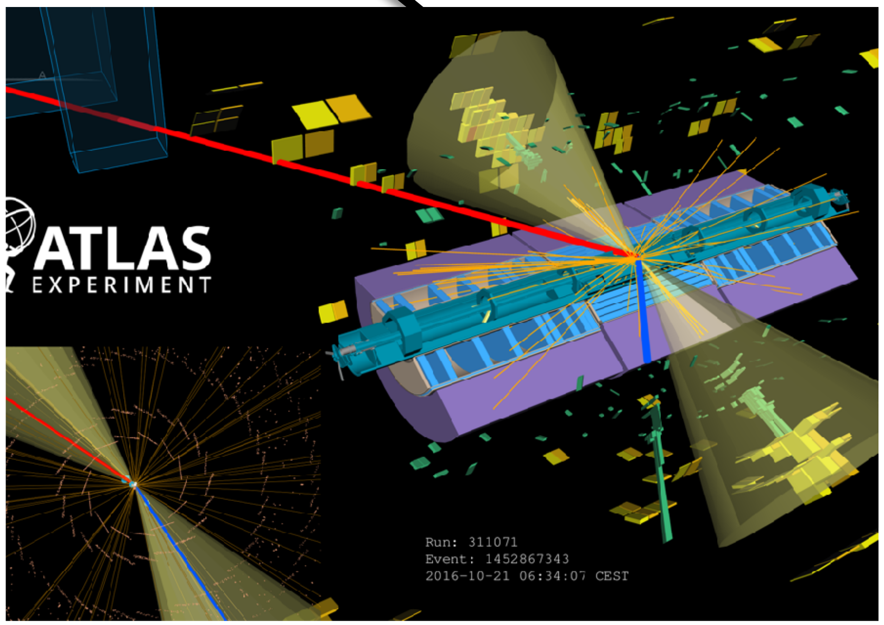
Selection close to the search regions



Data vs. Expectation

Observed events in this selection

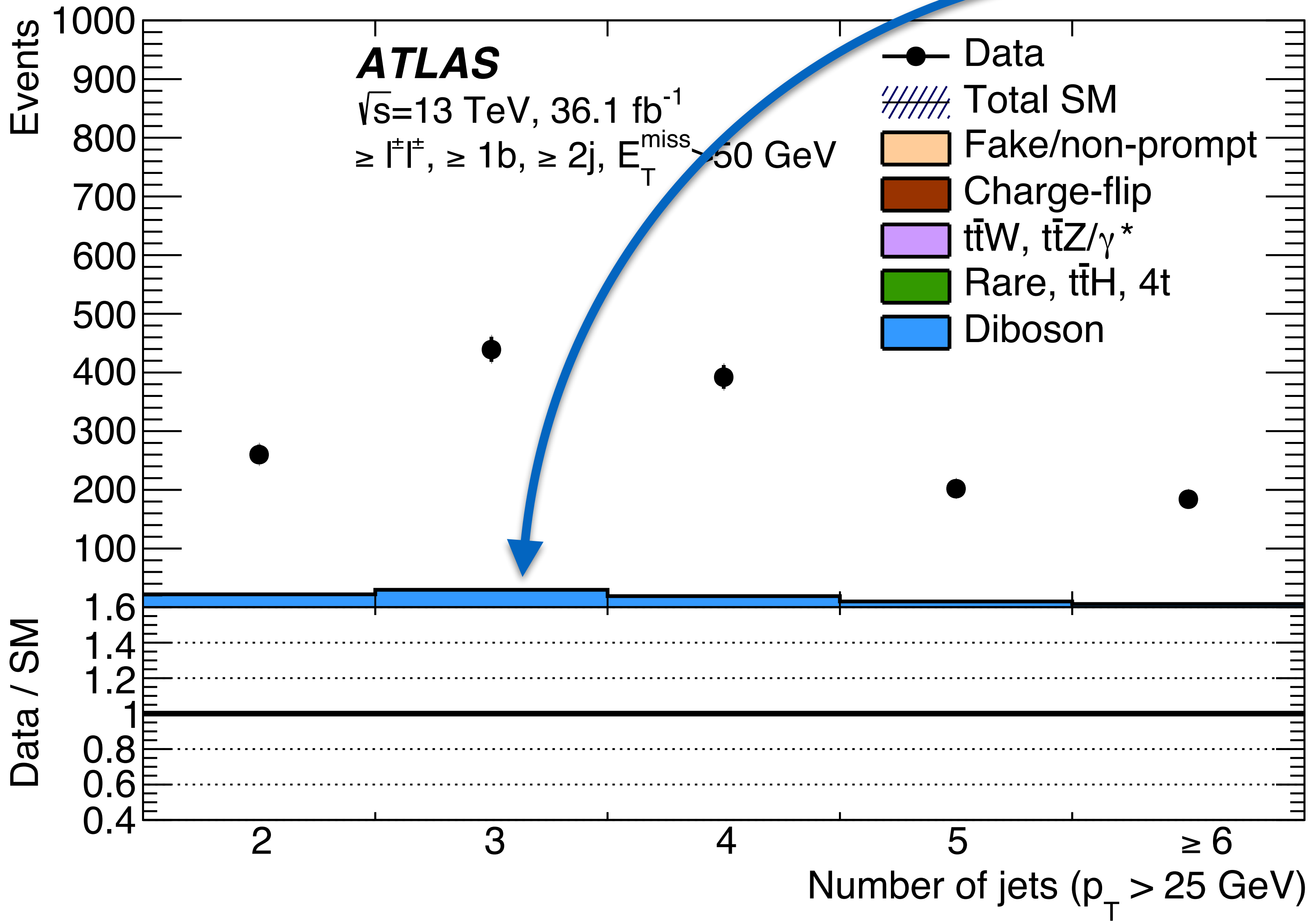


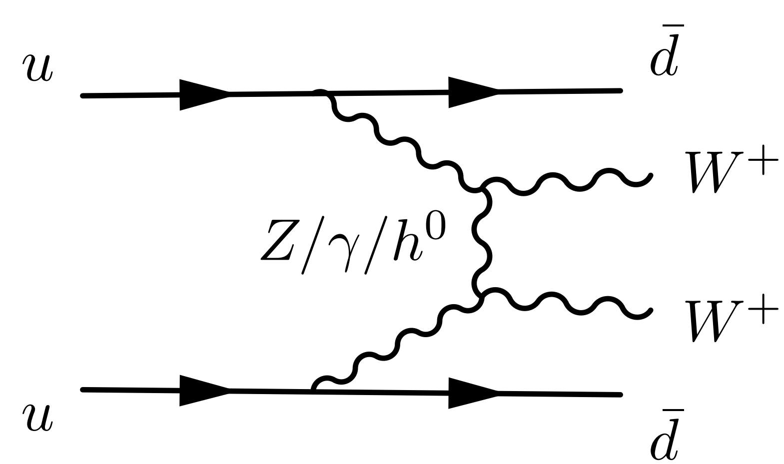


Data

Data vs. Expectation

SM background from MC:

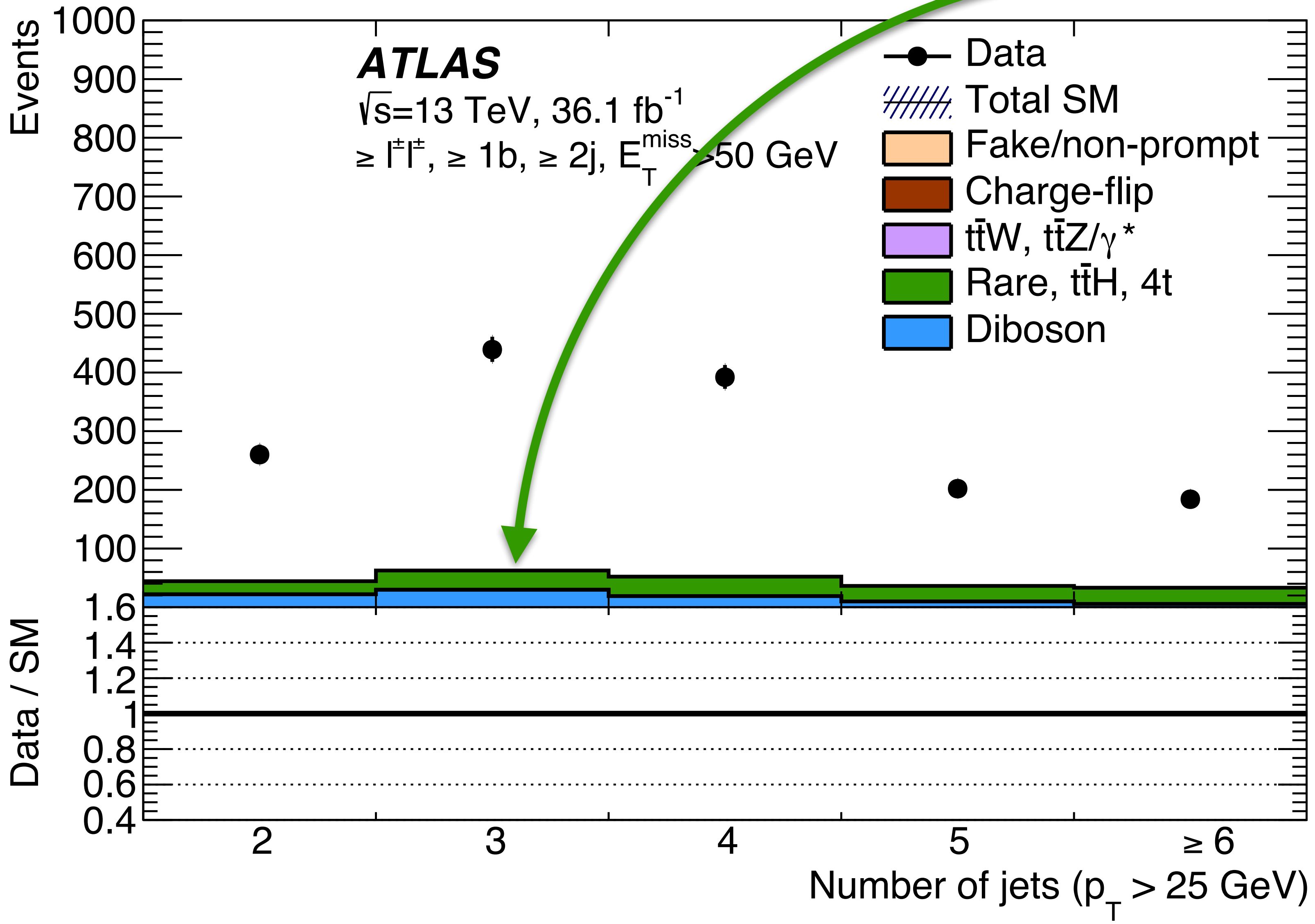


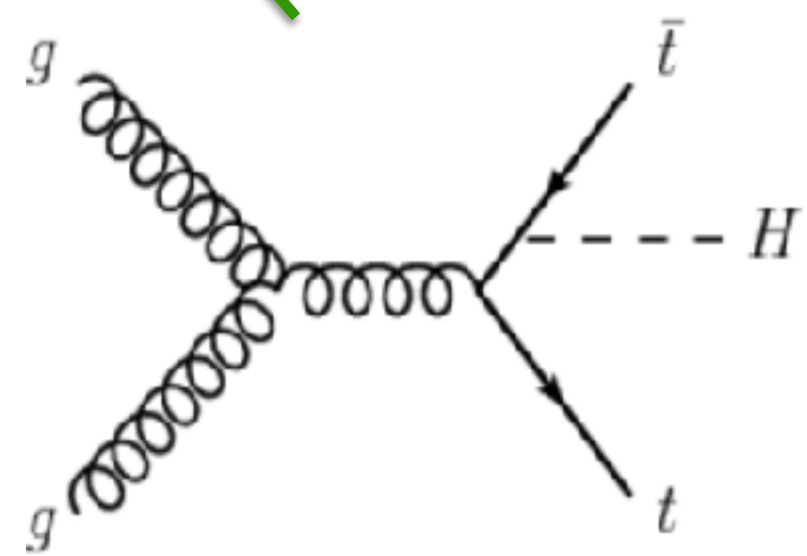


WW,WZ,ZZ

Data vs. Expectation

SM background from MC:

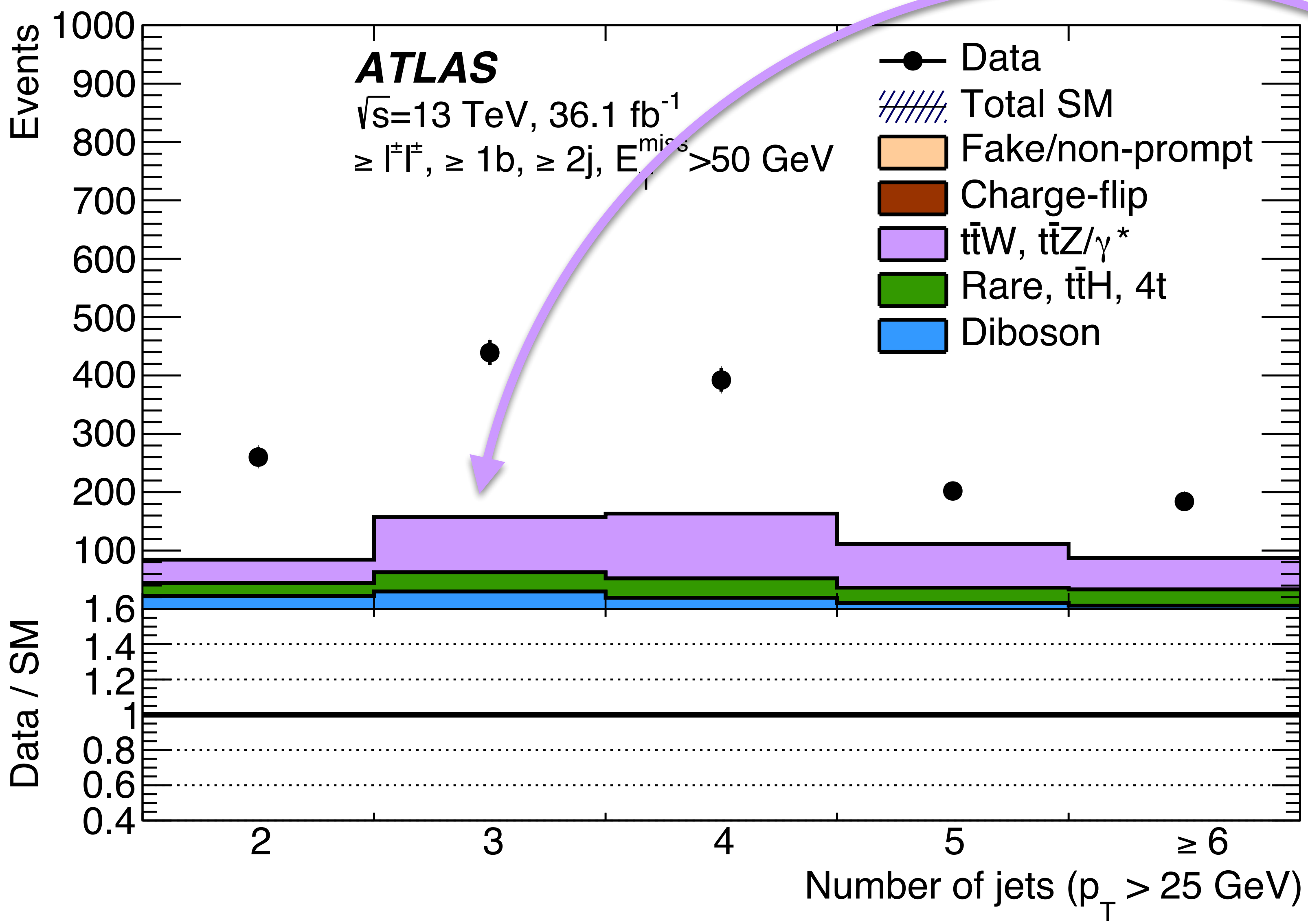


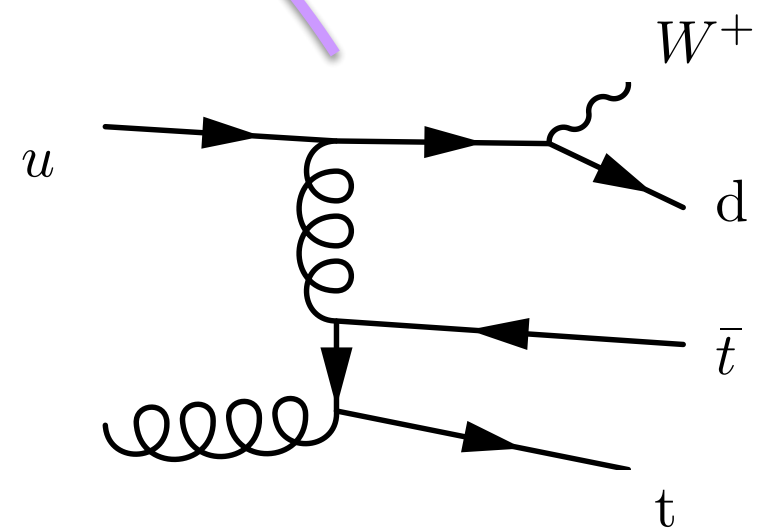


ttH, 4t, 3t, VVV, tWZ, ttWW, VH

Data vs. Expectation

SM background from MC:



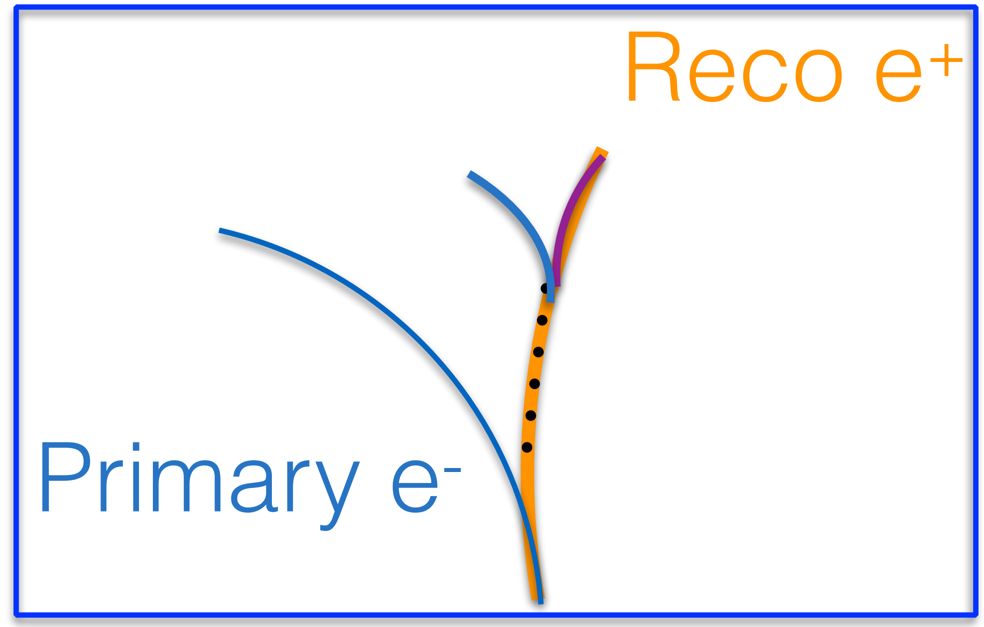


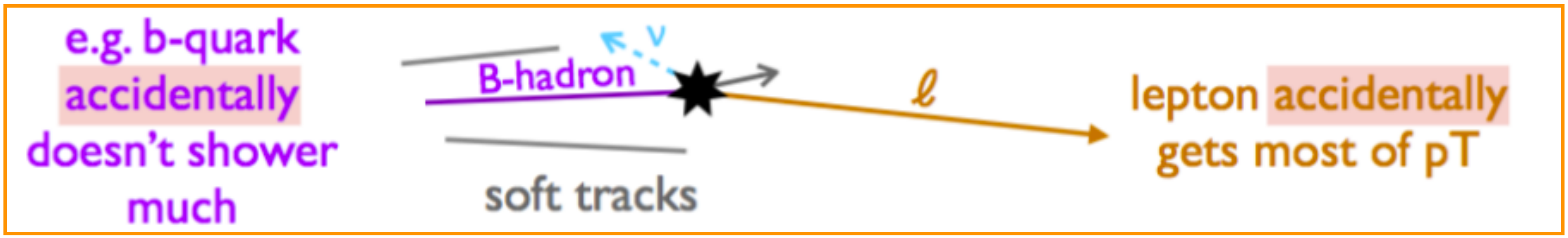
ttW, ttZ

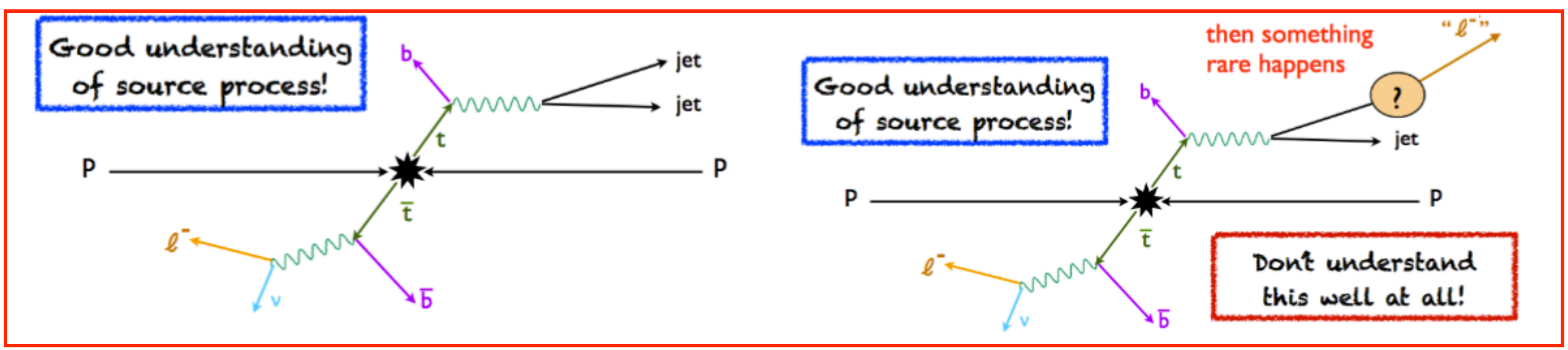
Clearly not done yet!

Detector background

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





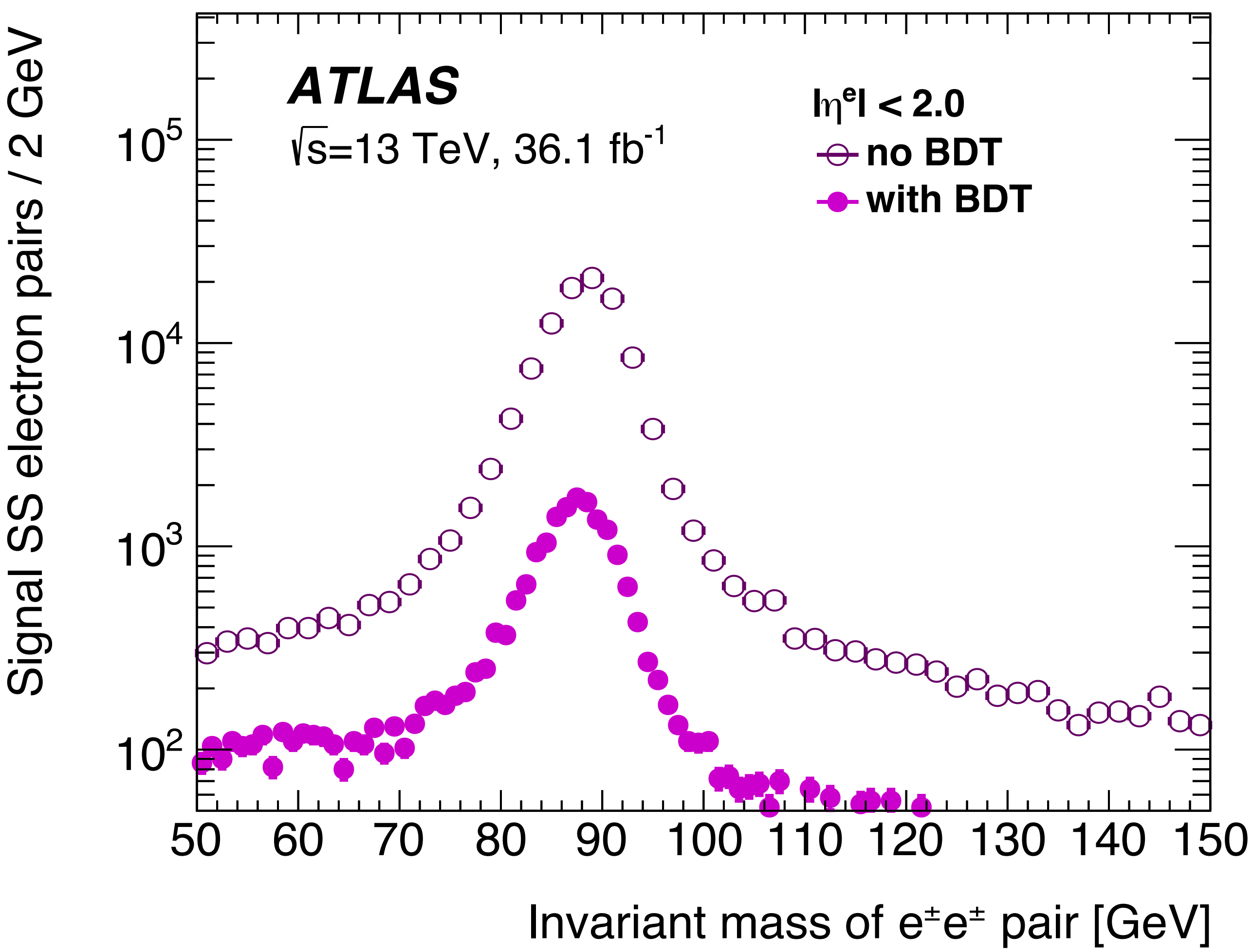


Charge flip

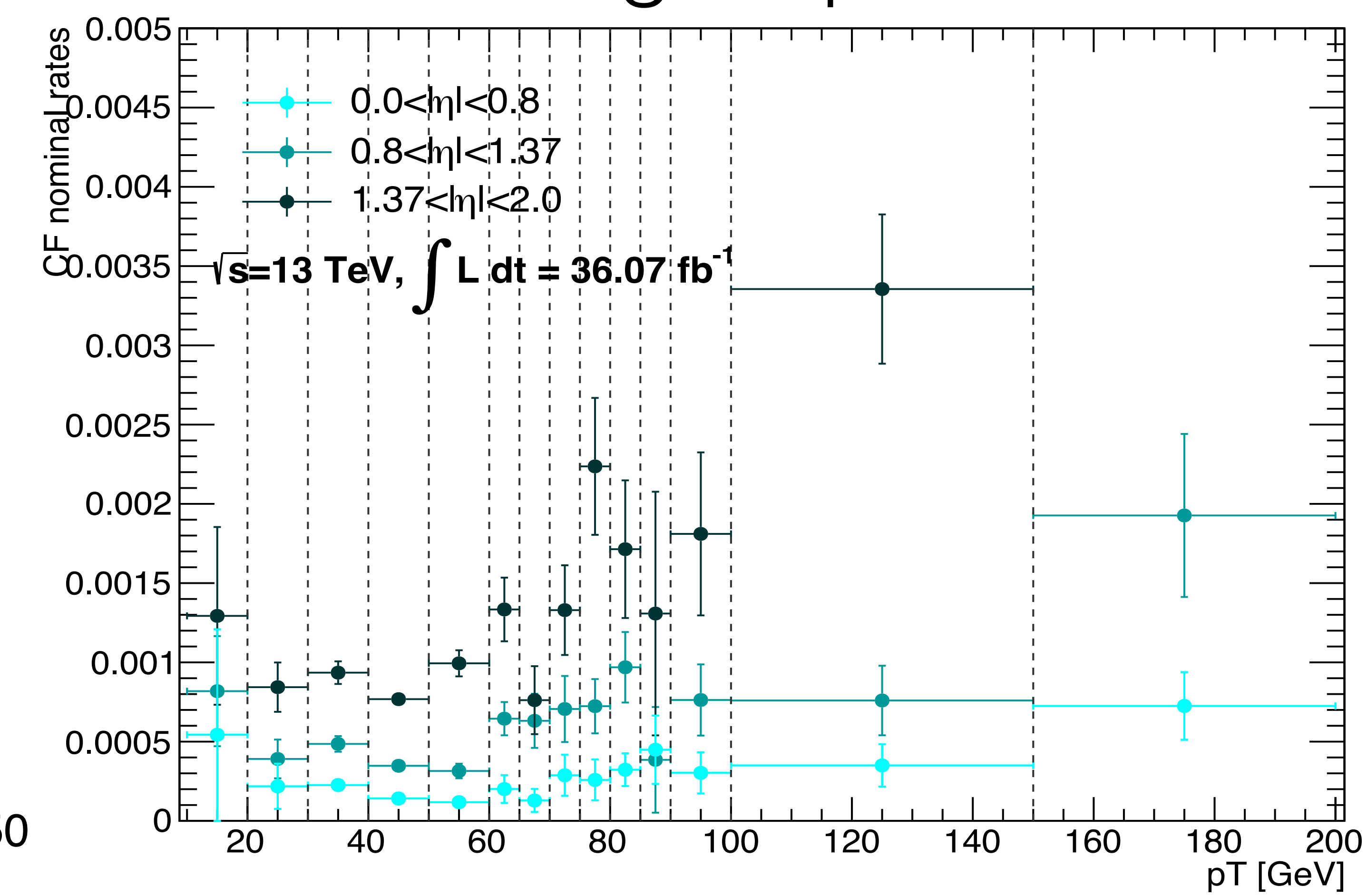
Electron charge mis-identification is relevant for same-sign lepton analyses

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

Charge-flip reduction

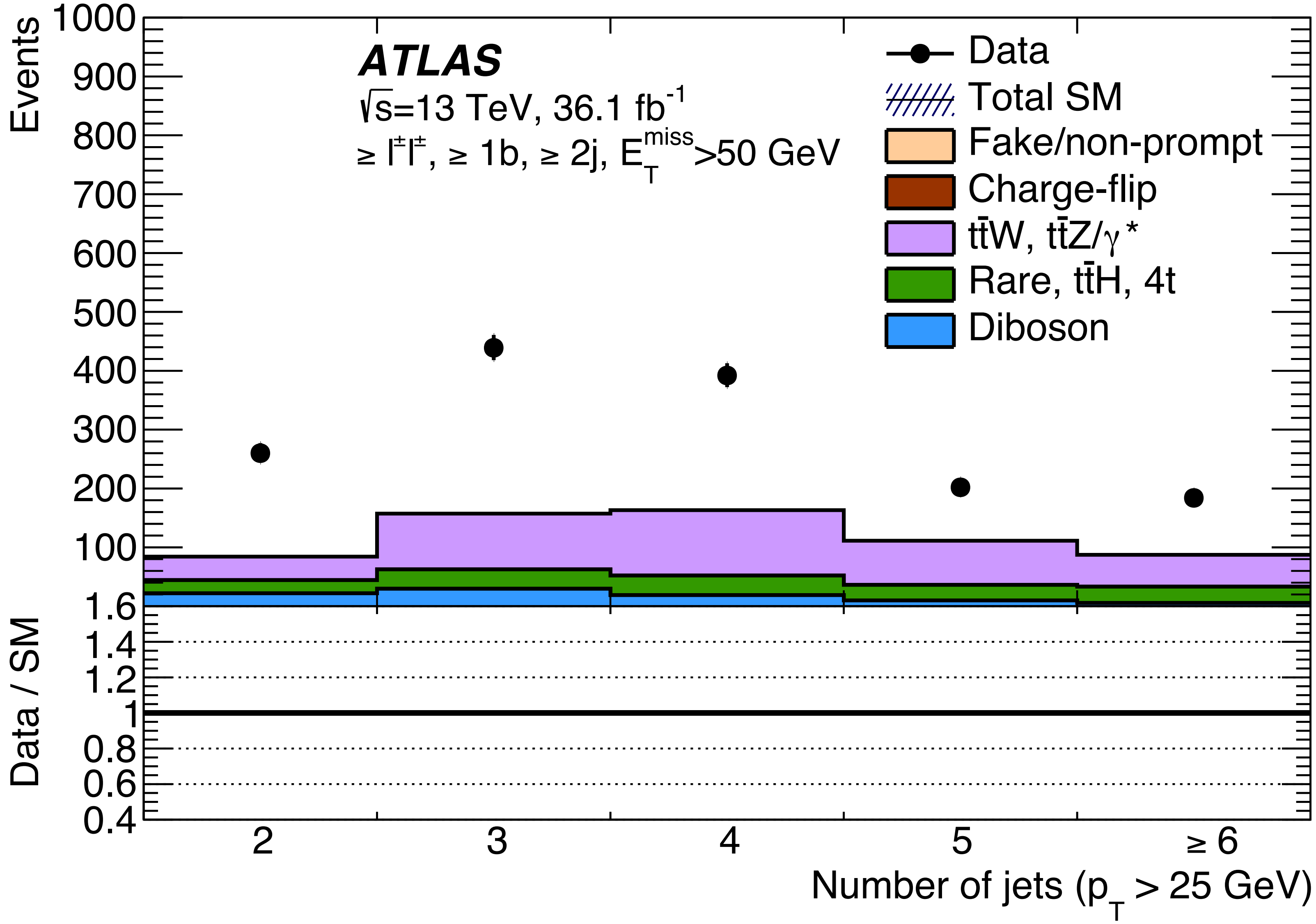


Charge-flip rates



Data vs. Expectation

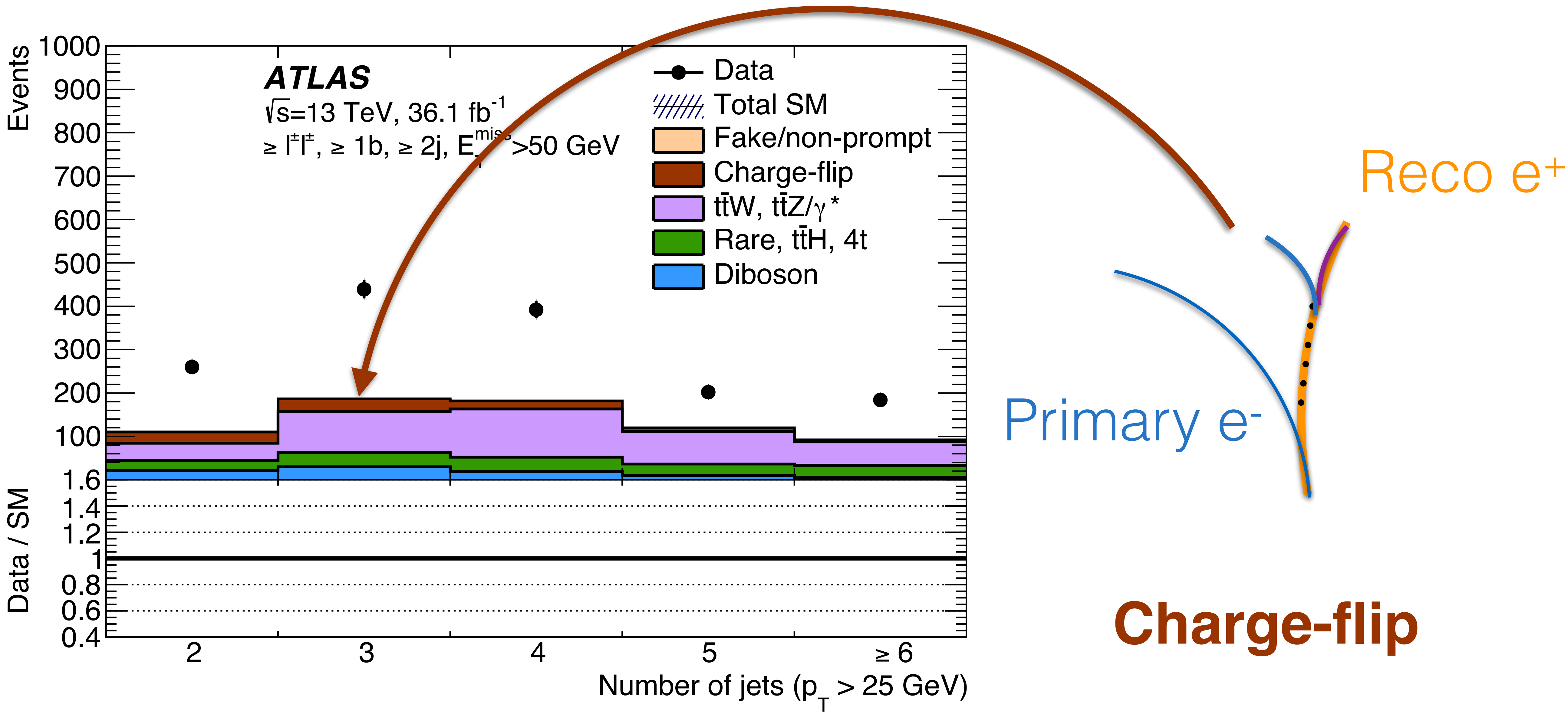
SM background from MC:



Remember!

Data vs. Expectation

Detector background from data-driven:

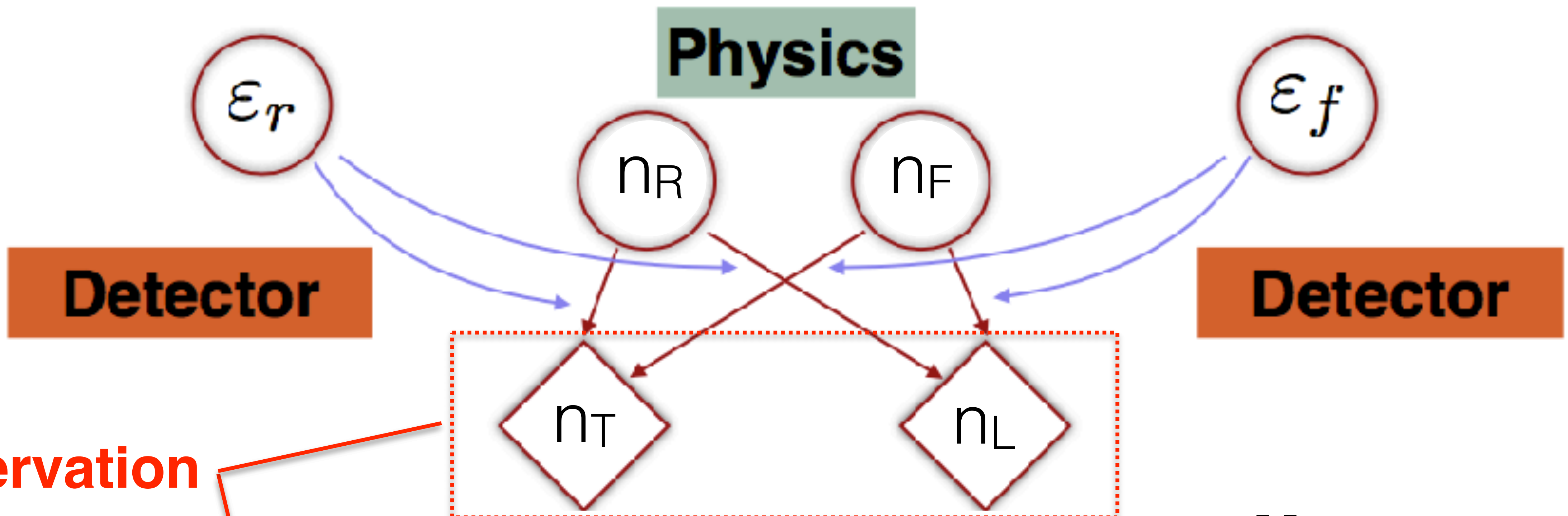


Fake/Non-prompt background

- 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:



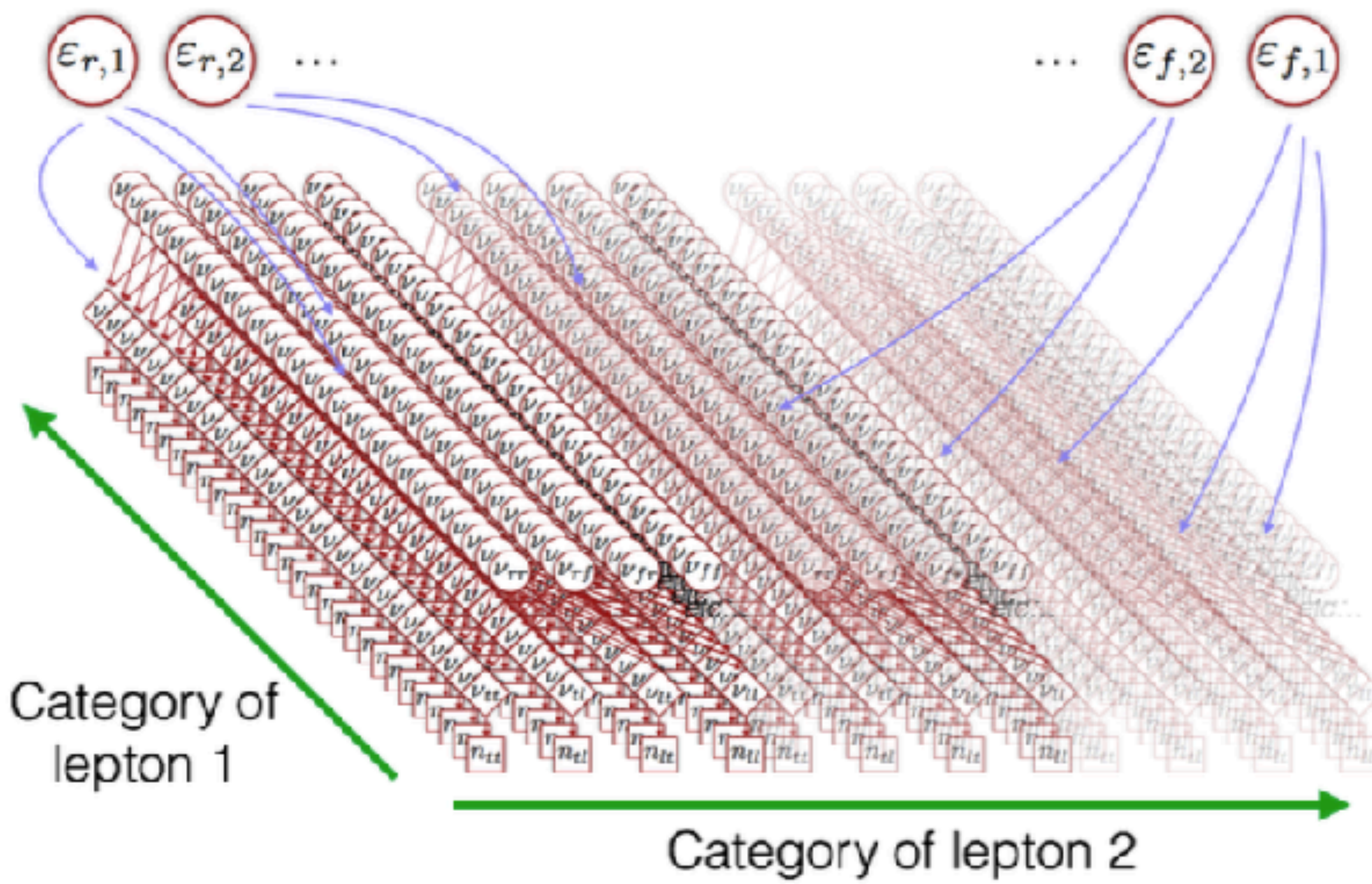
Observation

Measure

$$\begin{pmatrix} n_{\mathrm{T}} \\ n_{\mathrm{L}} \end{pmatrix} = \begin{pmatrix} \varepsilon_r & \varepsilon_f \\ 1-\varepsilon_r & 1-\varepsilon_f \end{pmatrix} \begin{pmatrix} n_{\mathrm{R}} \\ n_{\mathrm{F}} \end{pmatrix}$$

Matrix Method

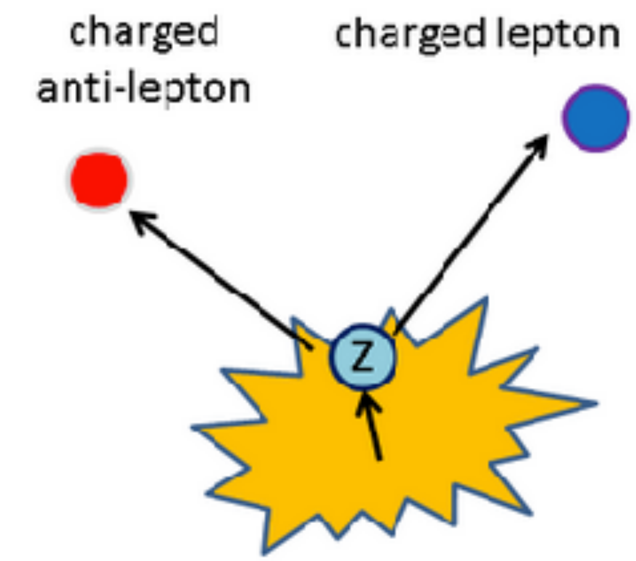
2-leptons case in multiple categories (~100):



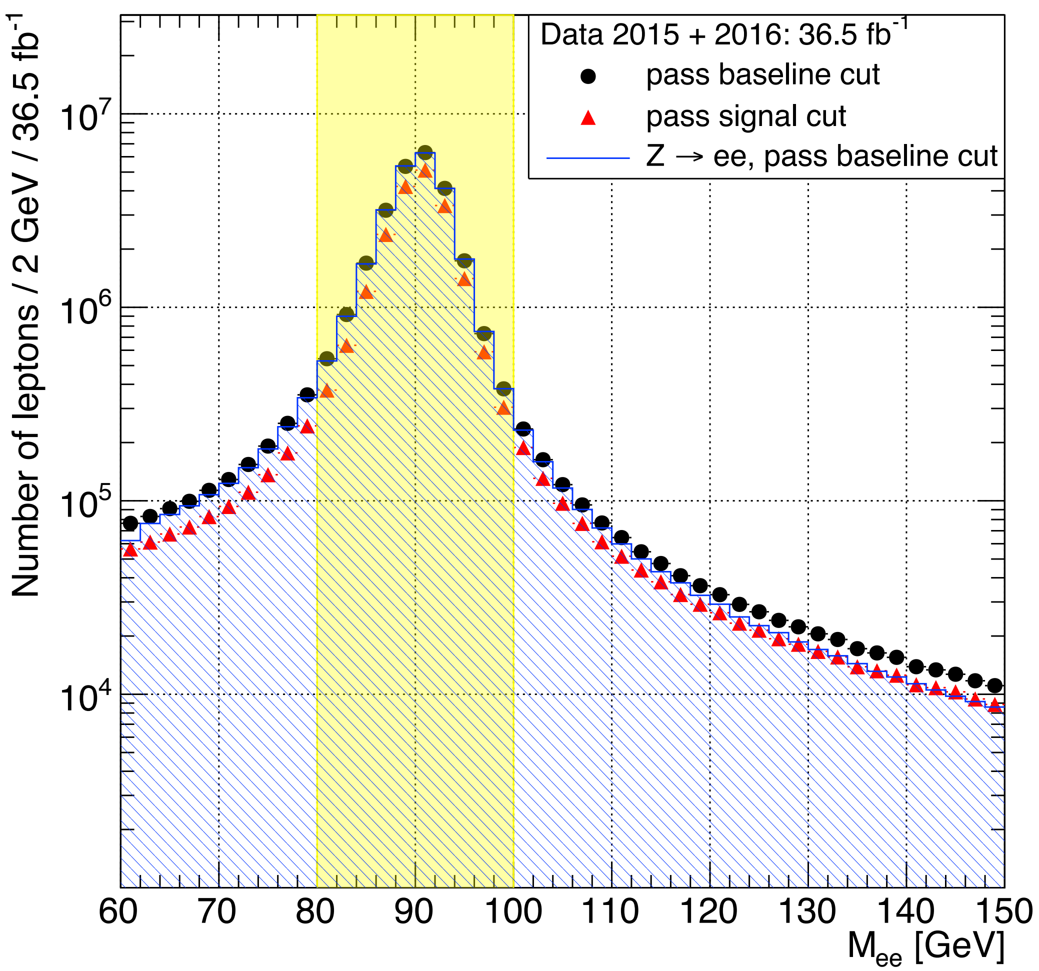
We have to deal with an arbitrary number of leptons with multiple categories, not trivial!

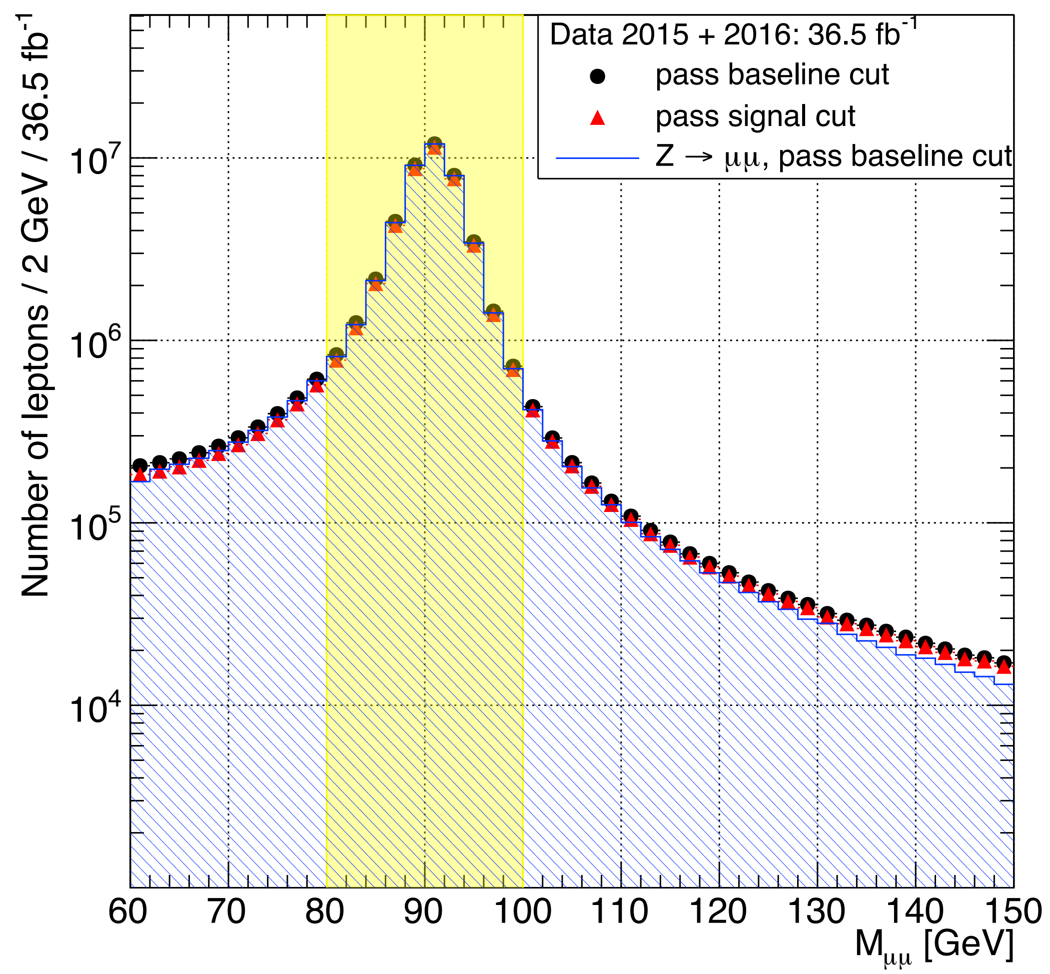
Real efficiency

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



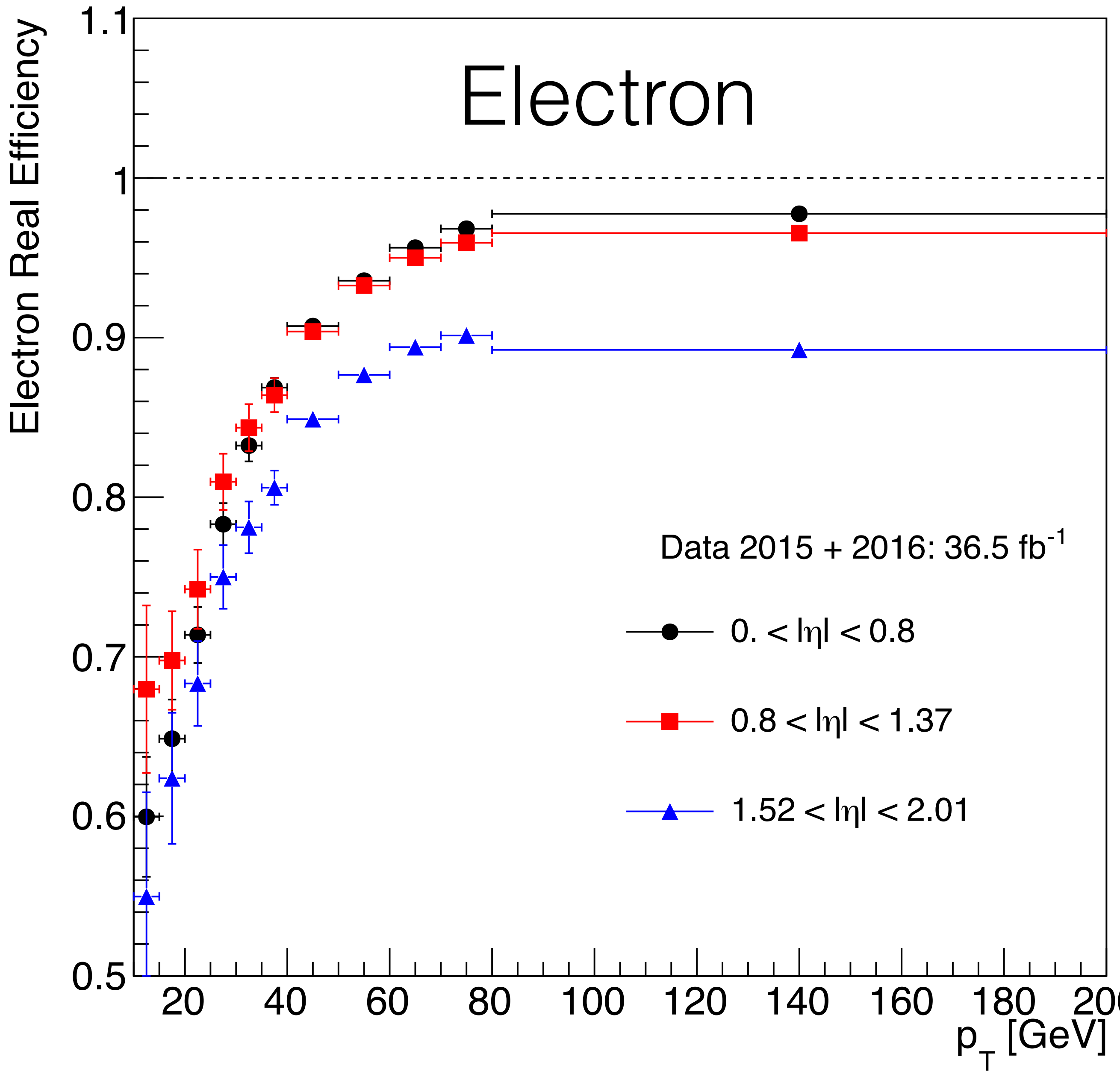
$$\varepsilon_r = \frac{n^{\text{data}}_{\text{signal}}}{n^{\text{data}}_{\text{baseline}} - n^{\text{BKG}}_{\text{baseline}}}$$

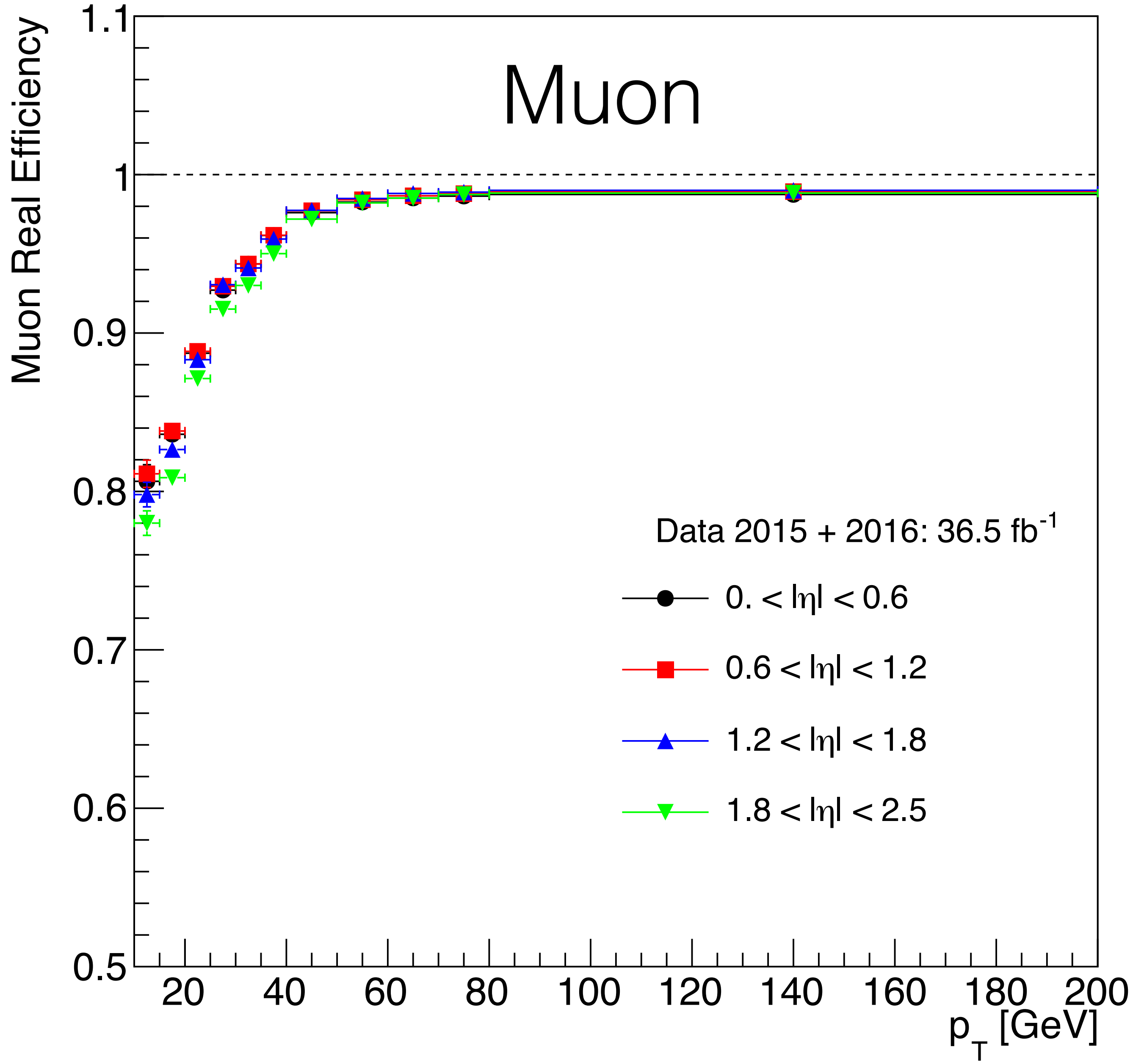




Real efficiency

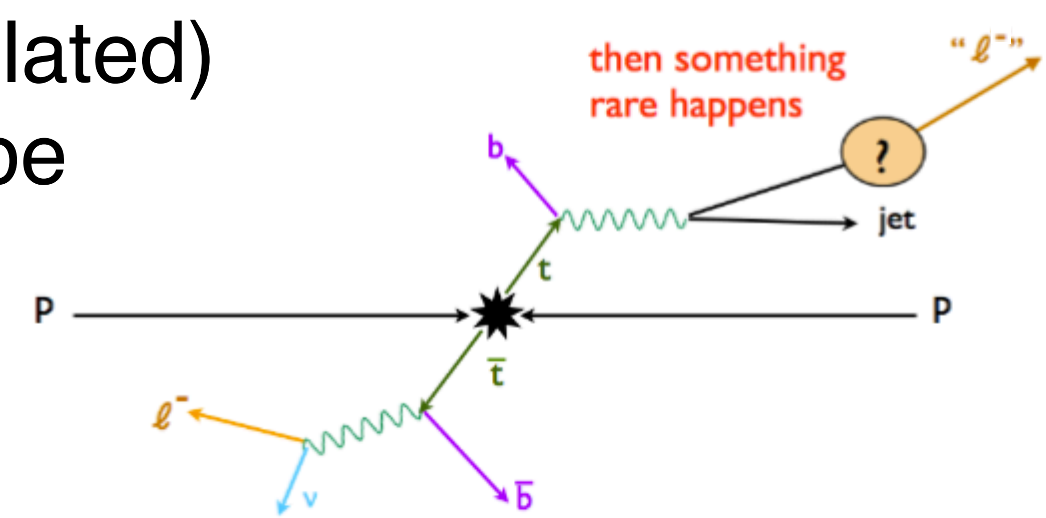
- Real efficiency in data (33 for *e*, 44 for *μ*):



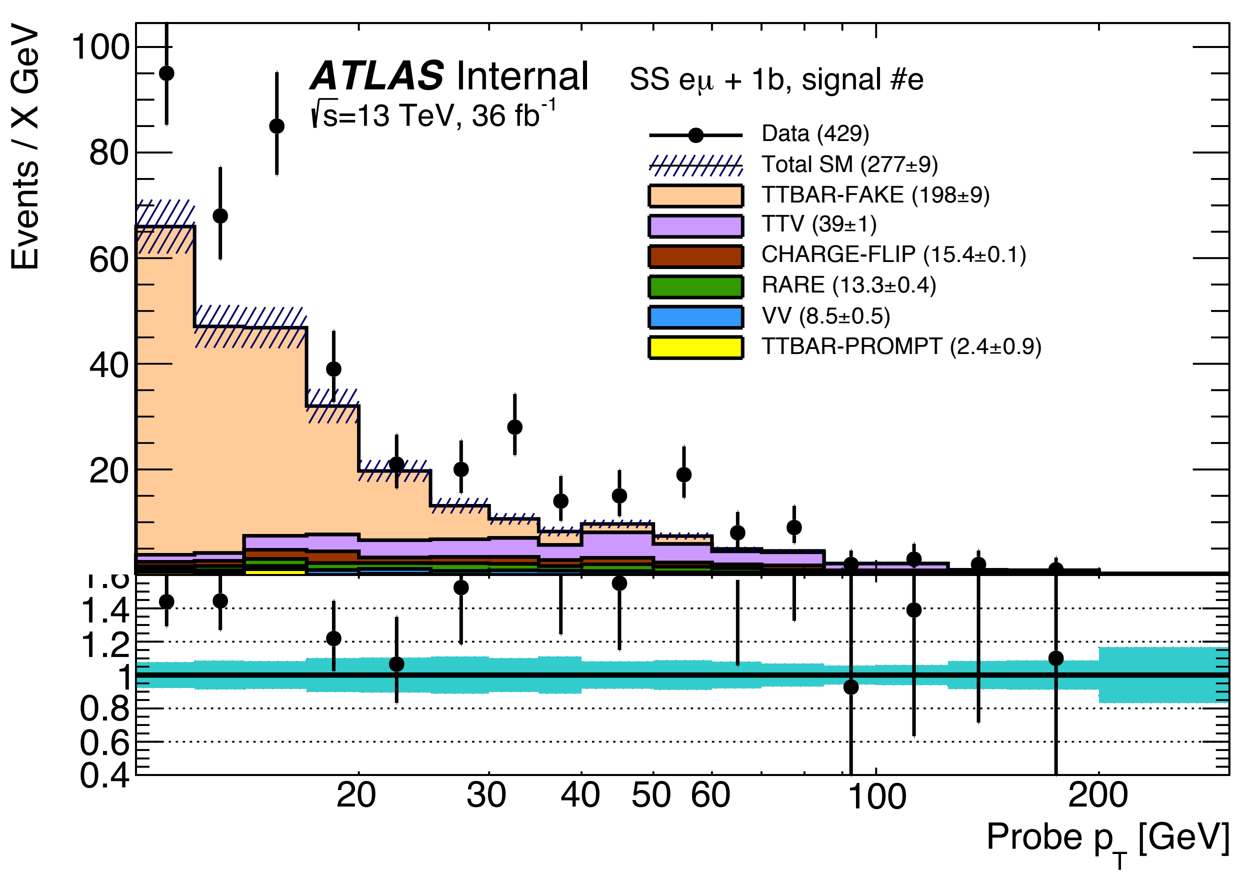


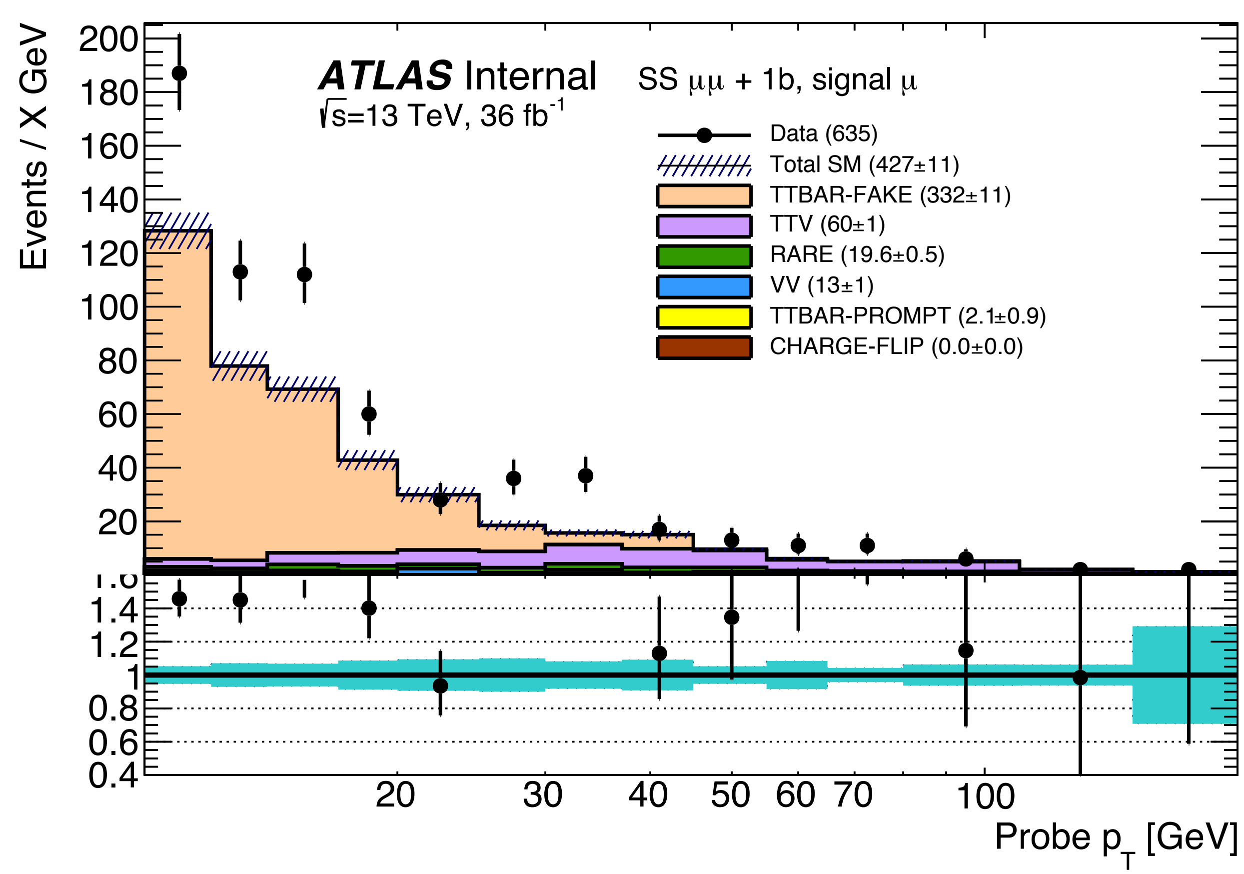
Fake rate

- tt-enriched region: >= 1 b-jet, and >= 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



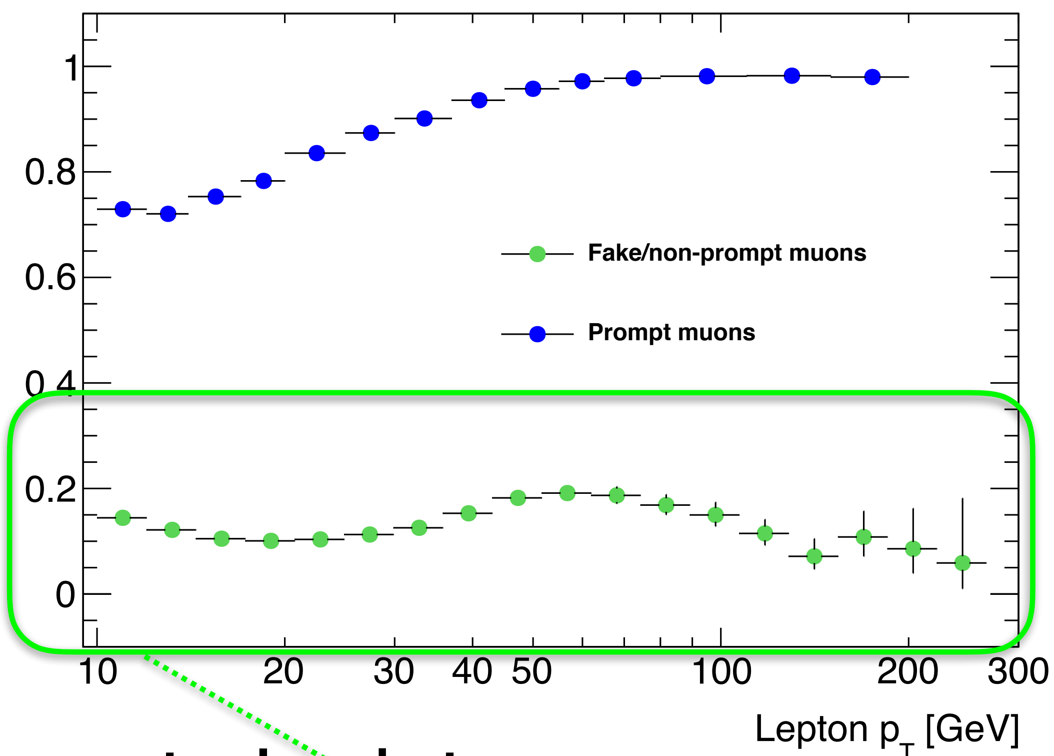
$$\varepsilon_f = \frac{n_{\text{signal}}^{\text{data}} - n_{\text{signal}}^{\text{MC}}}{n_{\text{baseline}}^{\text{data}} - n_{\text{baseline}}^{\text{MC}}}$$

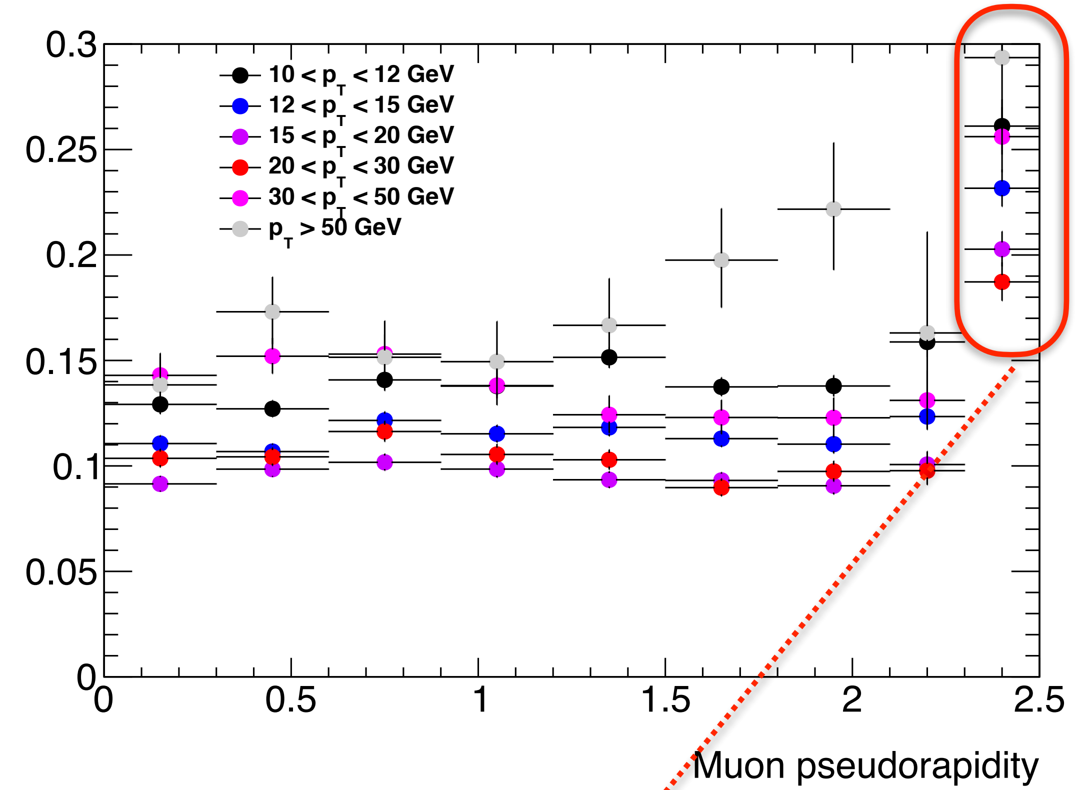




Muon fake rate

- Fake rate in ttbar MC:



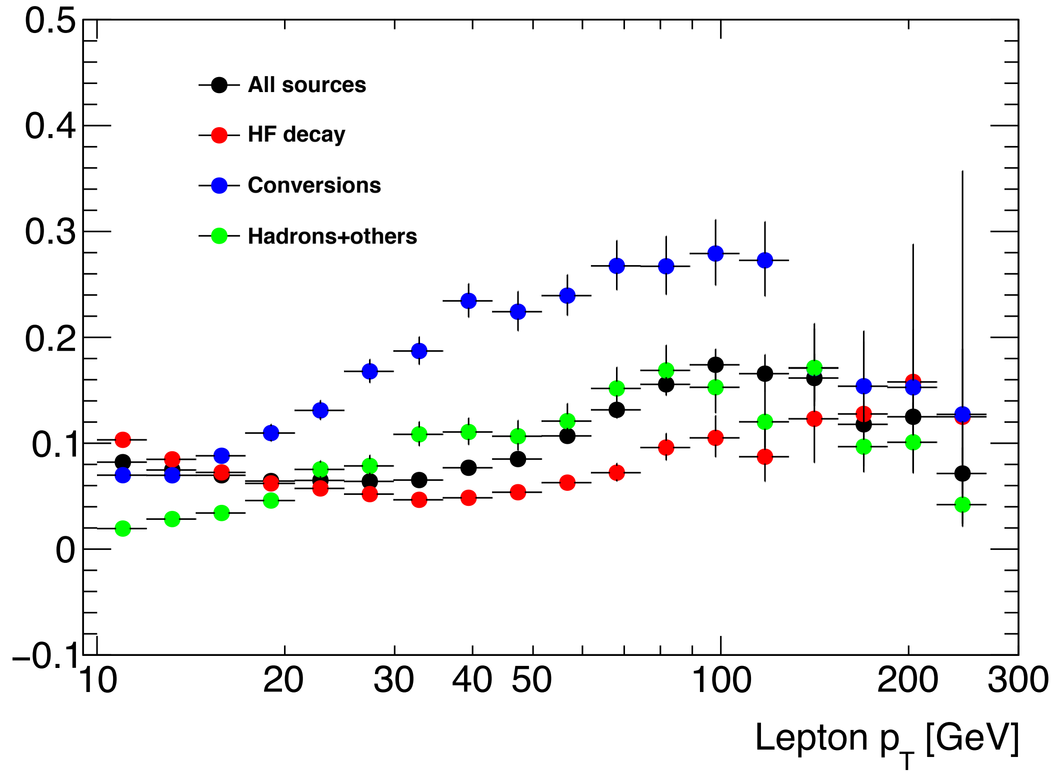


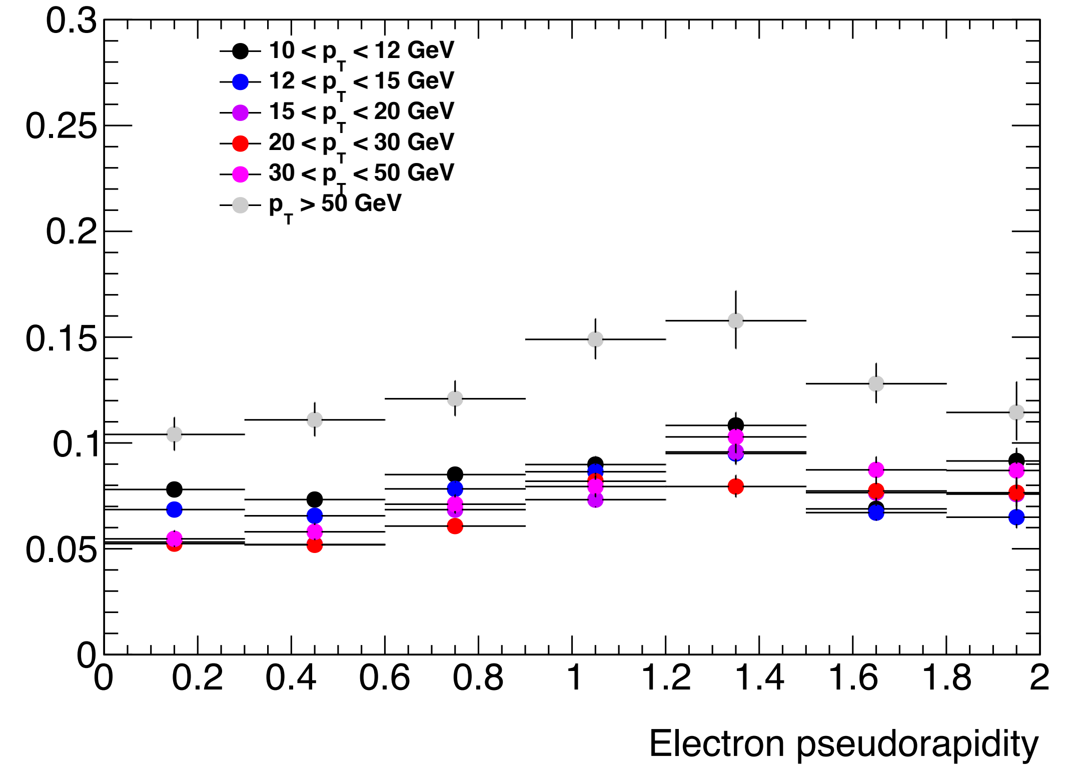
- Fake rate in data:

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

Electron fake rate

- Fake rate in ttbar MC:





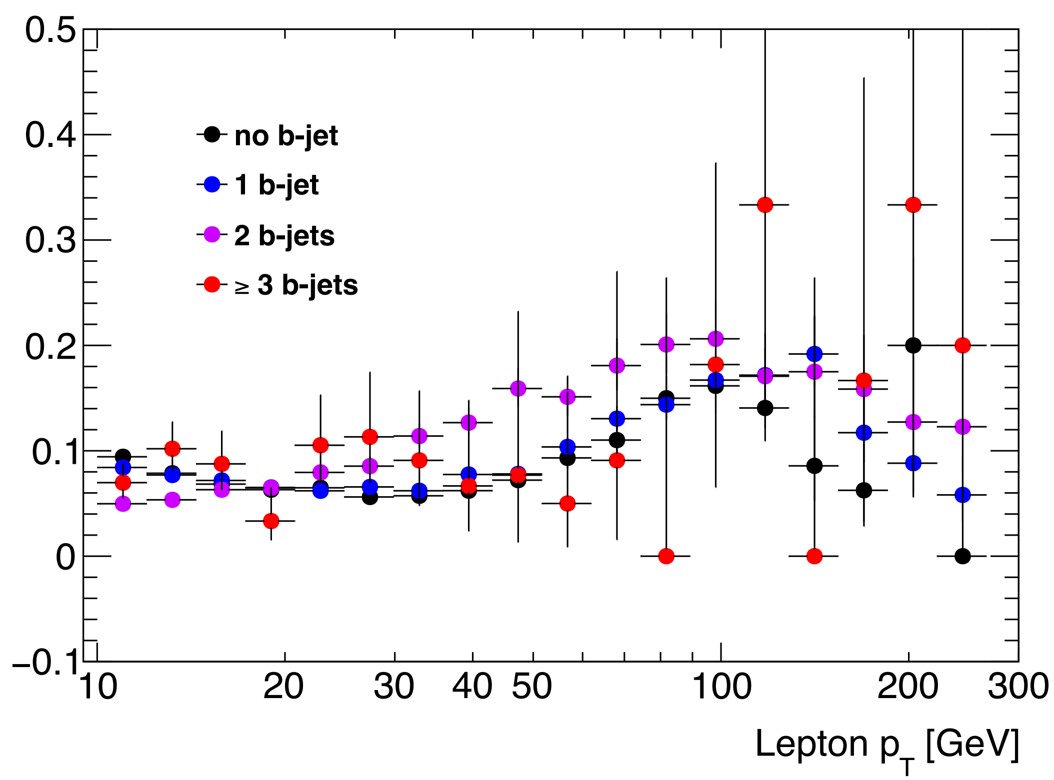
- Fake rate in data electrons:

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

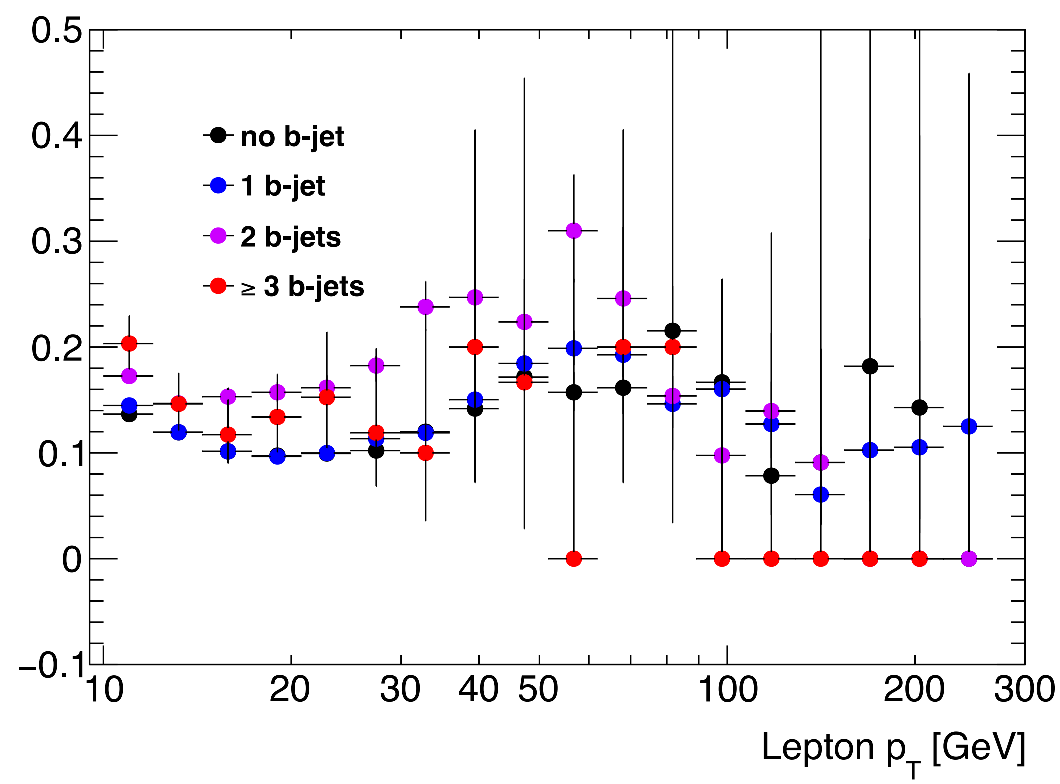
Fake rate and b-jets

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

Electron



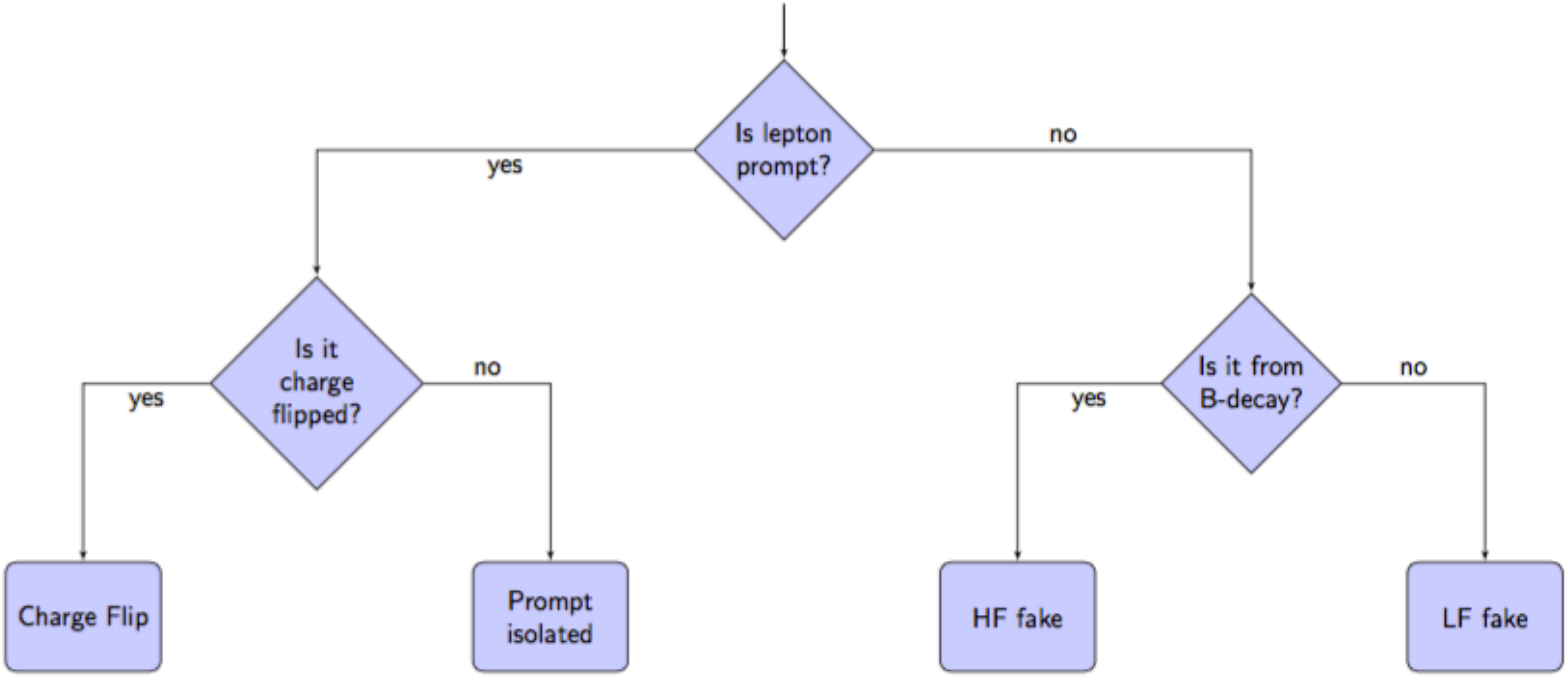
Muon



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

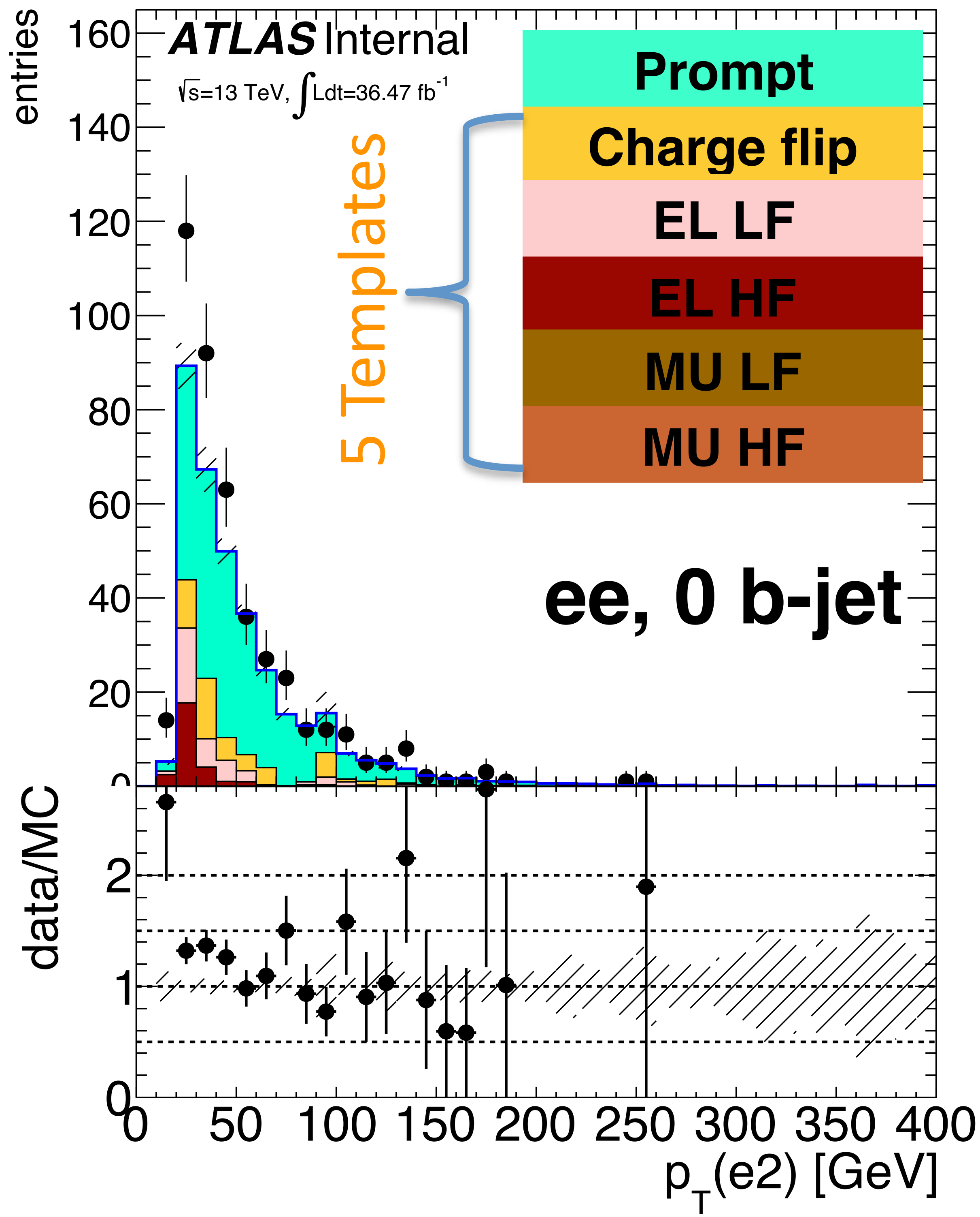
MC Template Method

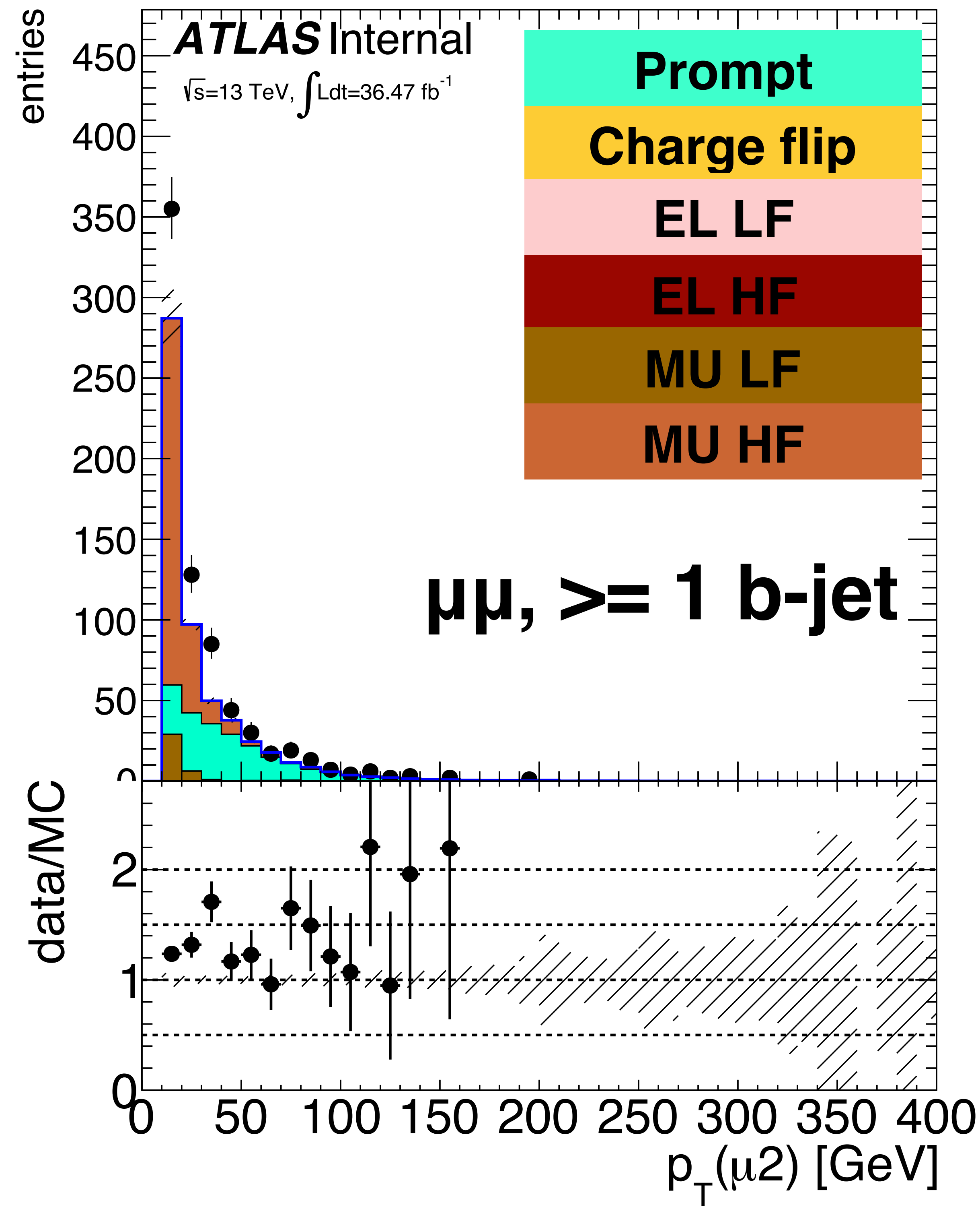
- Assume that the **kinematic distributions are modeled correctly** but the **rate is off** by a constant fraction independent of the selection
- Obtain 5 MC corrections by a simultaneous fit in 6 CRs with 0 b-jet and >=1b-jet to constrain LF and HF, and ee/eμ/μμ to get different handles on charge flip,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



MC Template Method

- Distributions chosen with discrimination power





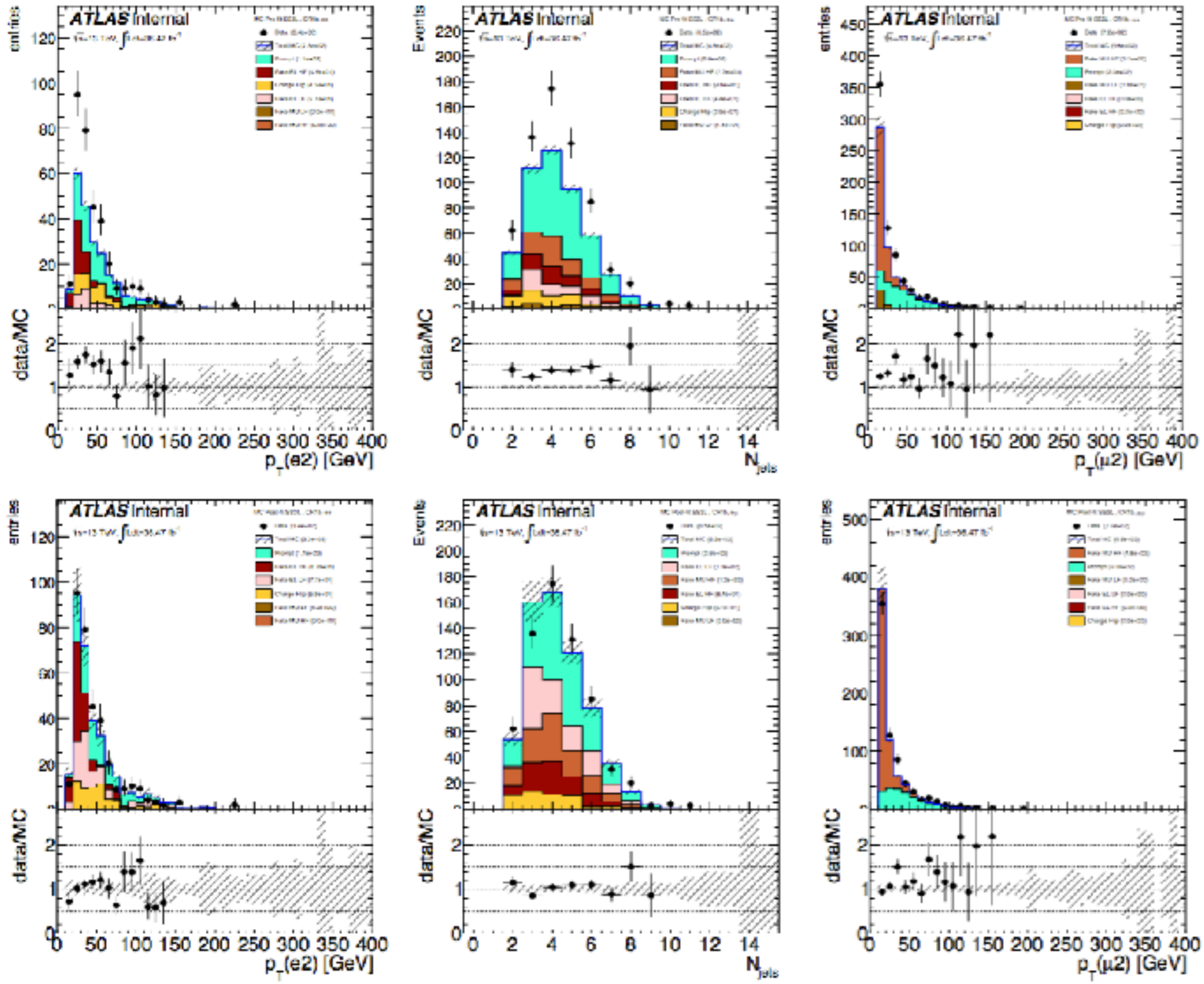
MC Template Method

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

ee eμ μμ

Pre-fit

Post-fit



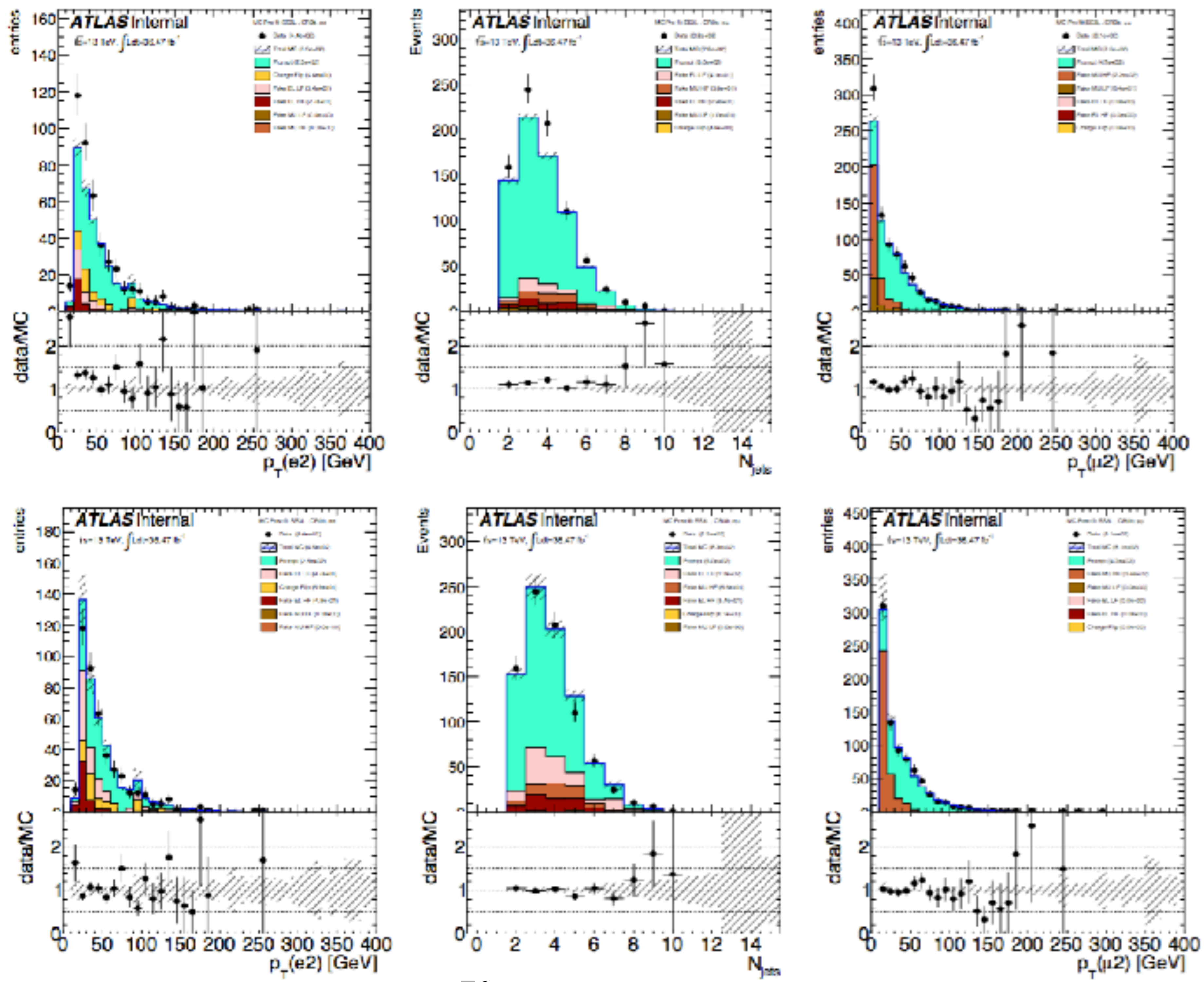
MC Template Method

- Fit recovers MC mis-modeling in CR with >= 1 b-jet

ee eμ μμ

Pre-fit

Post-fit



MC Template Method

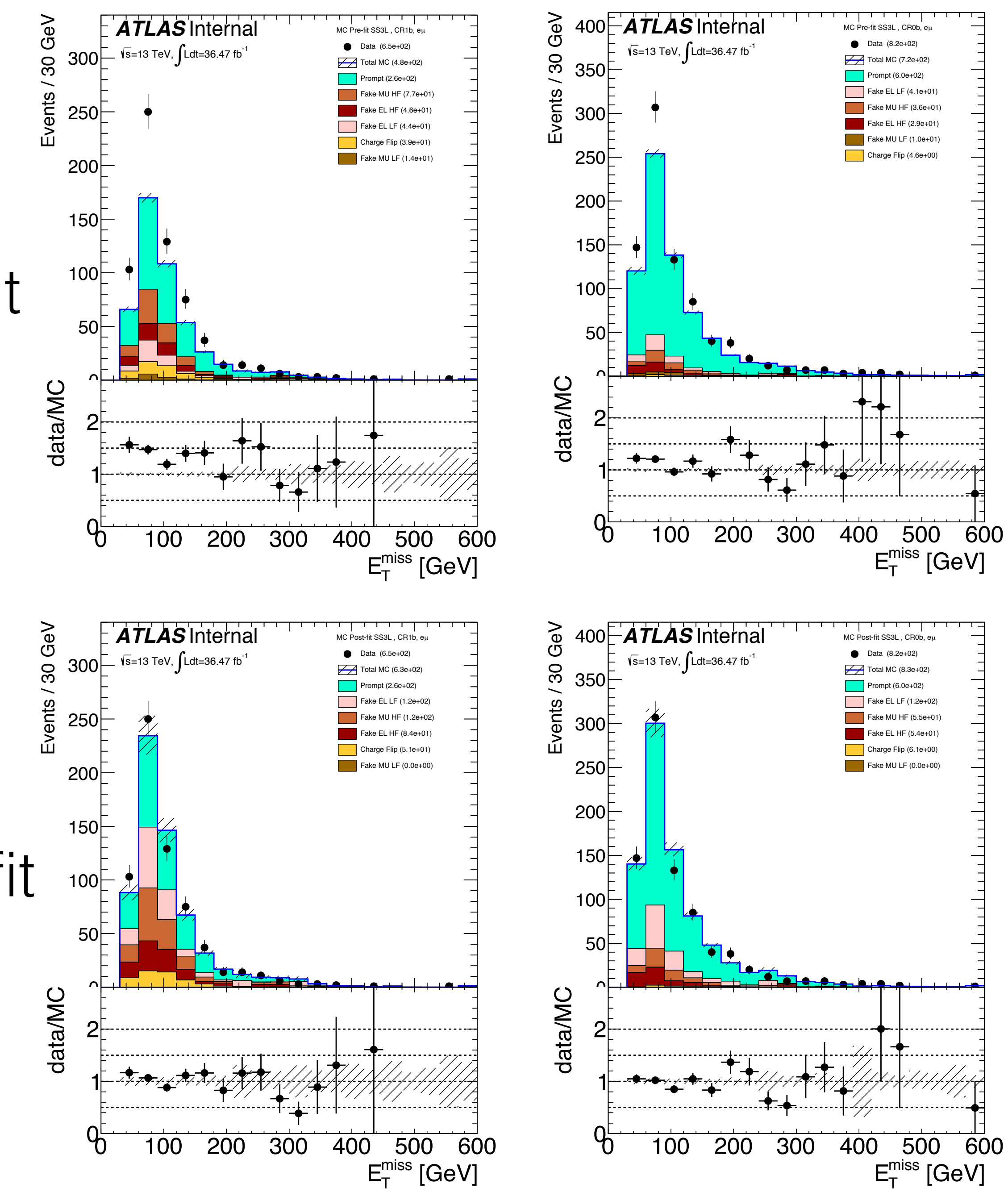
- Distributions other than the ones used in the fit show a reasonable agreement between Data/MC
- The optimization procedure relies on the MC template results

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

CR0b CR1b

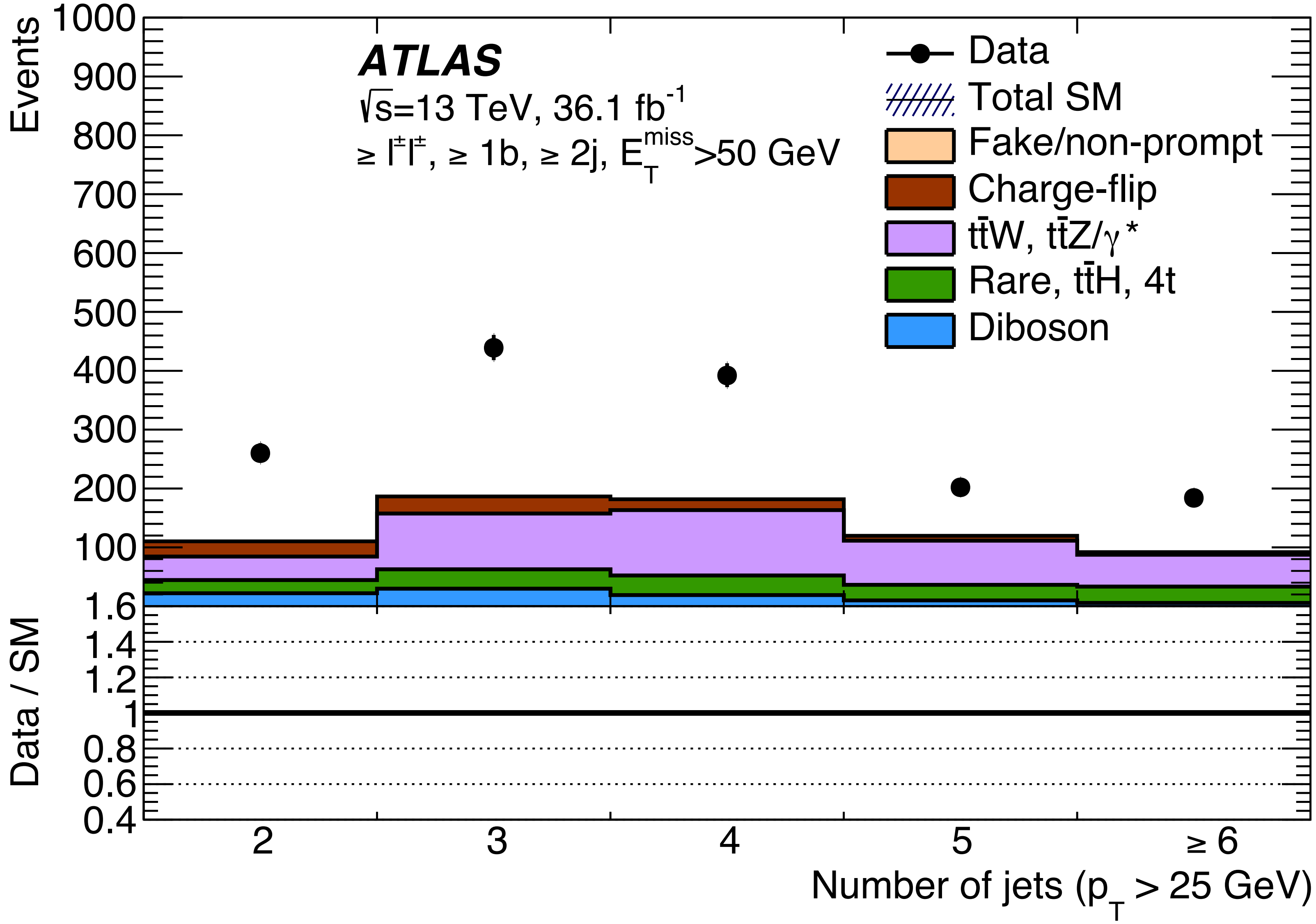
Pre-fit

Post-fit



Data vs. Expectation

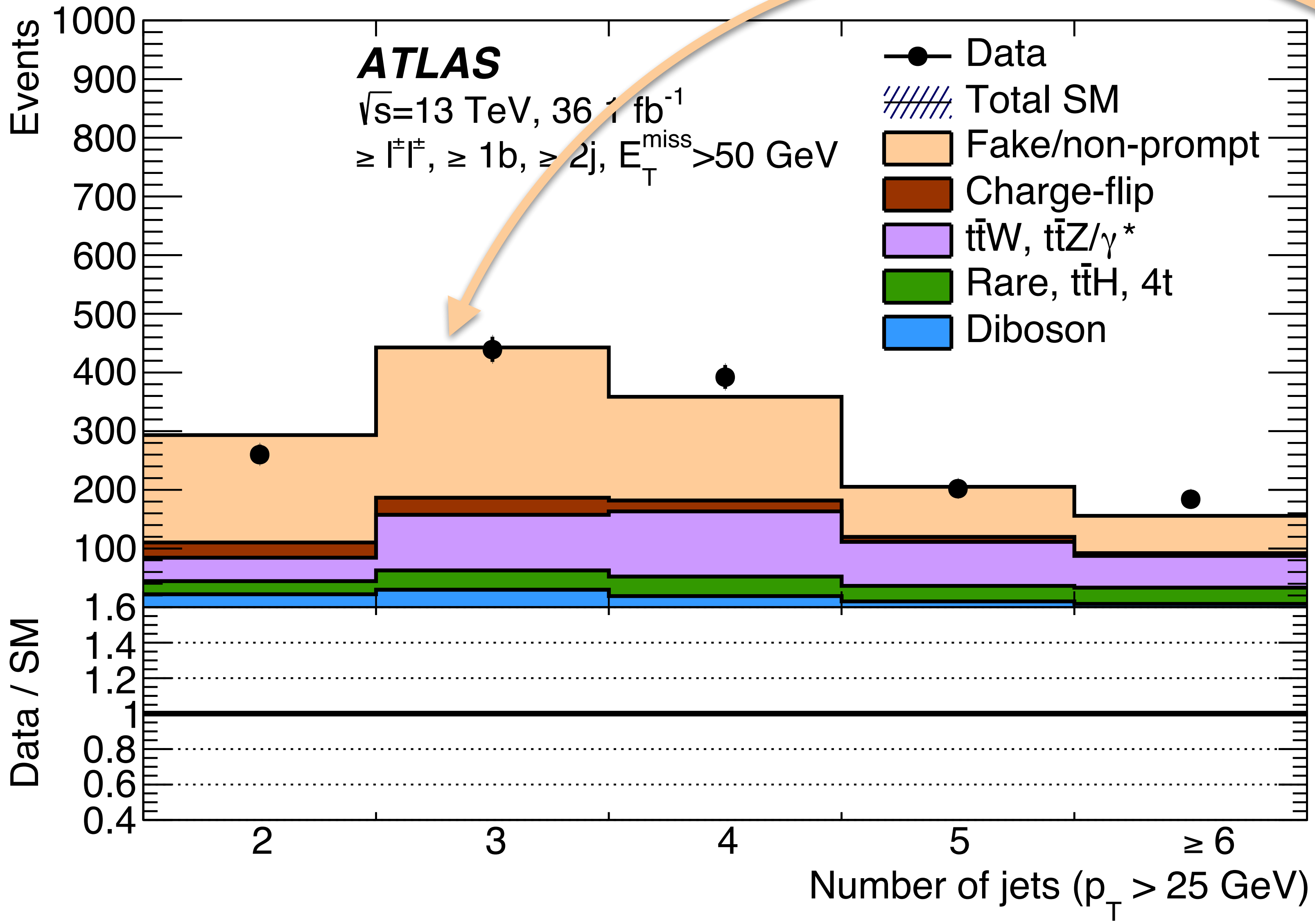
Detector background from data-driven:

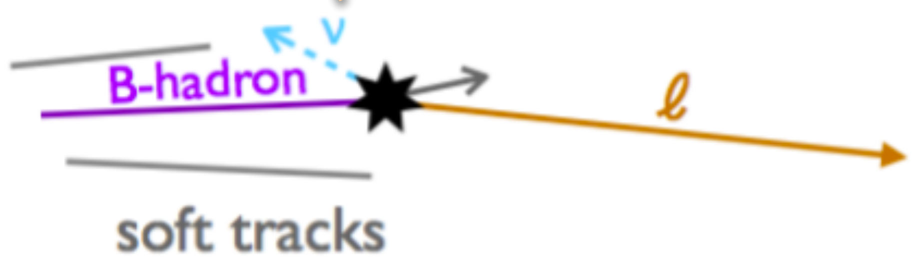


Remember!

Data vs. Expectation

Detector background from data-driven:





Fake/non-prompt

Much better! But need uncertainties

Uncertainties

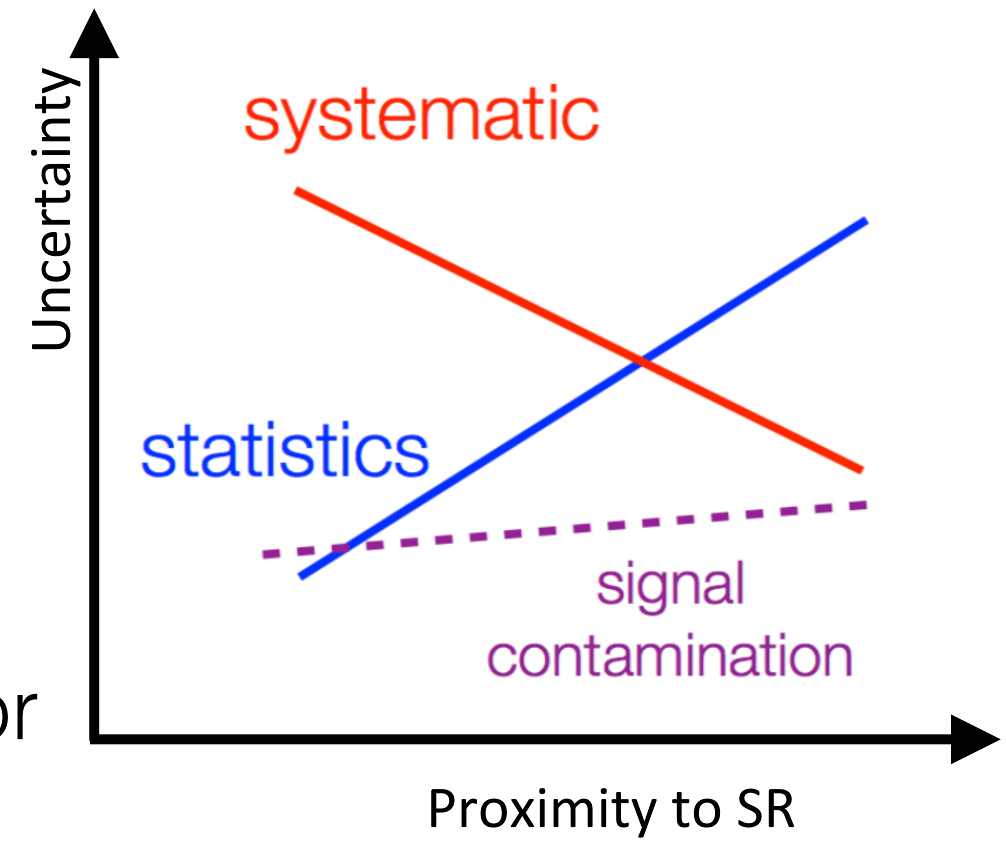
Accuracy of the theoretical and experimental modeling in the MC simulations

- 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:

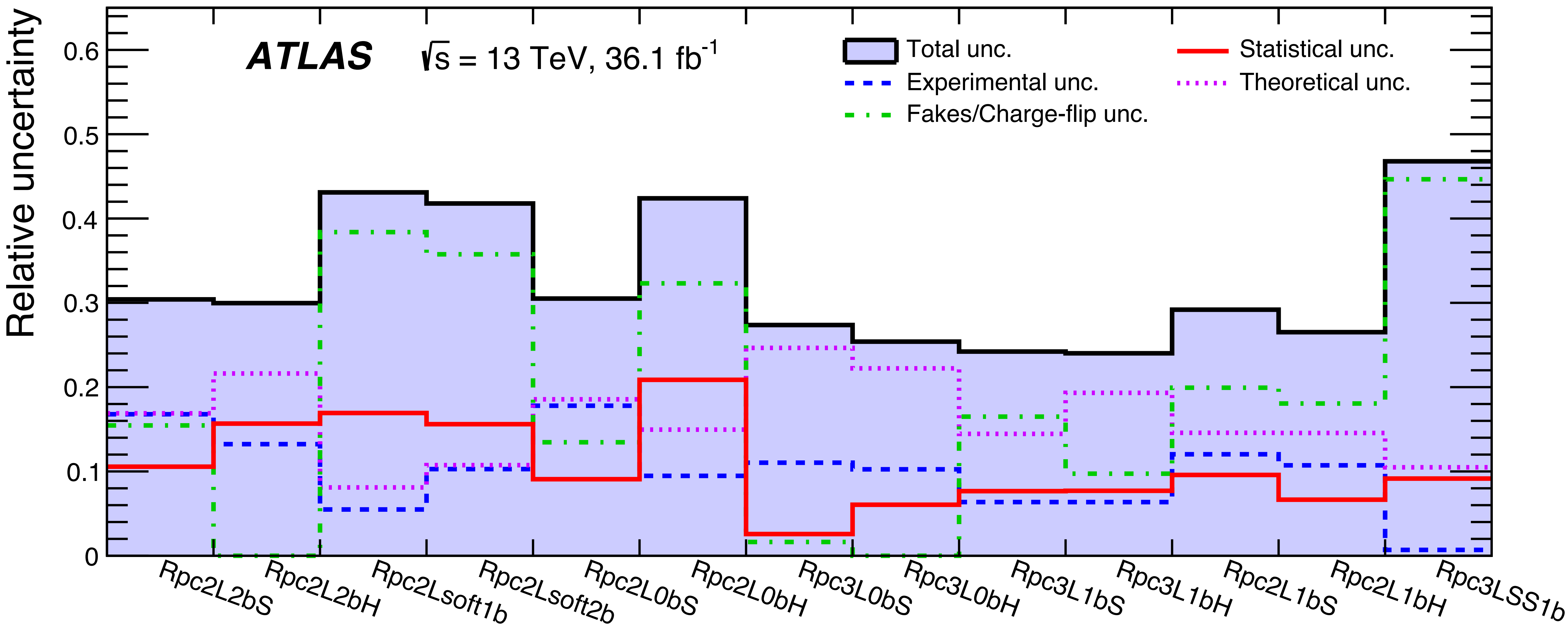
- Electron charge flip:
  - Lack of statistics, background subtraction
    -> **below 20%**
- Fake and non-prompt leptons:
  - MxM: different composition of fake leptons between the CR and SR
    -> **30%-85% for muons**
    -> **50% for electrons**
  - MC template: variation of the generator
    ->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



  - Final sys. unc. are propagated assuming a full correlation

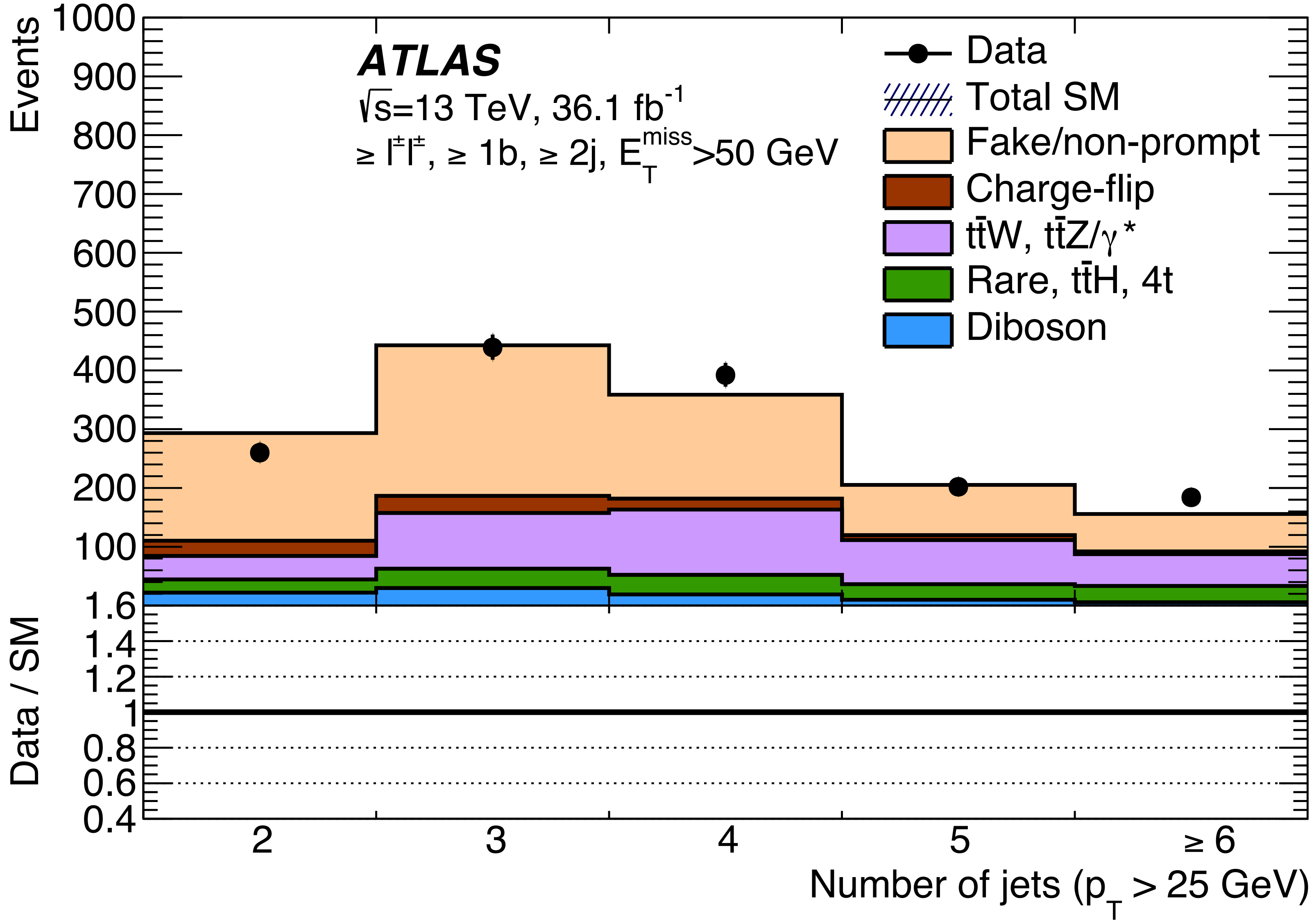
Uncertainties

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



Data vs. Expectation

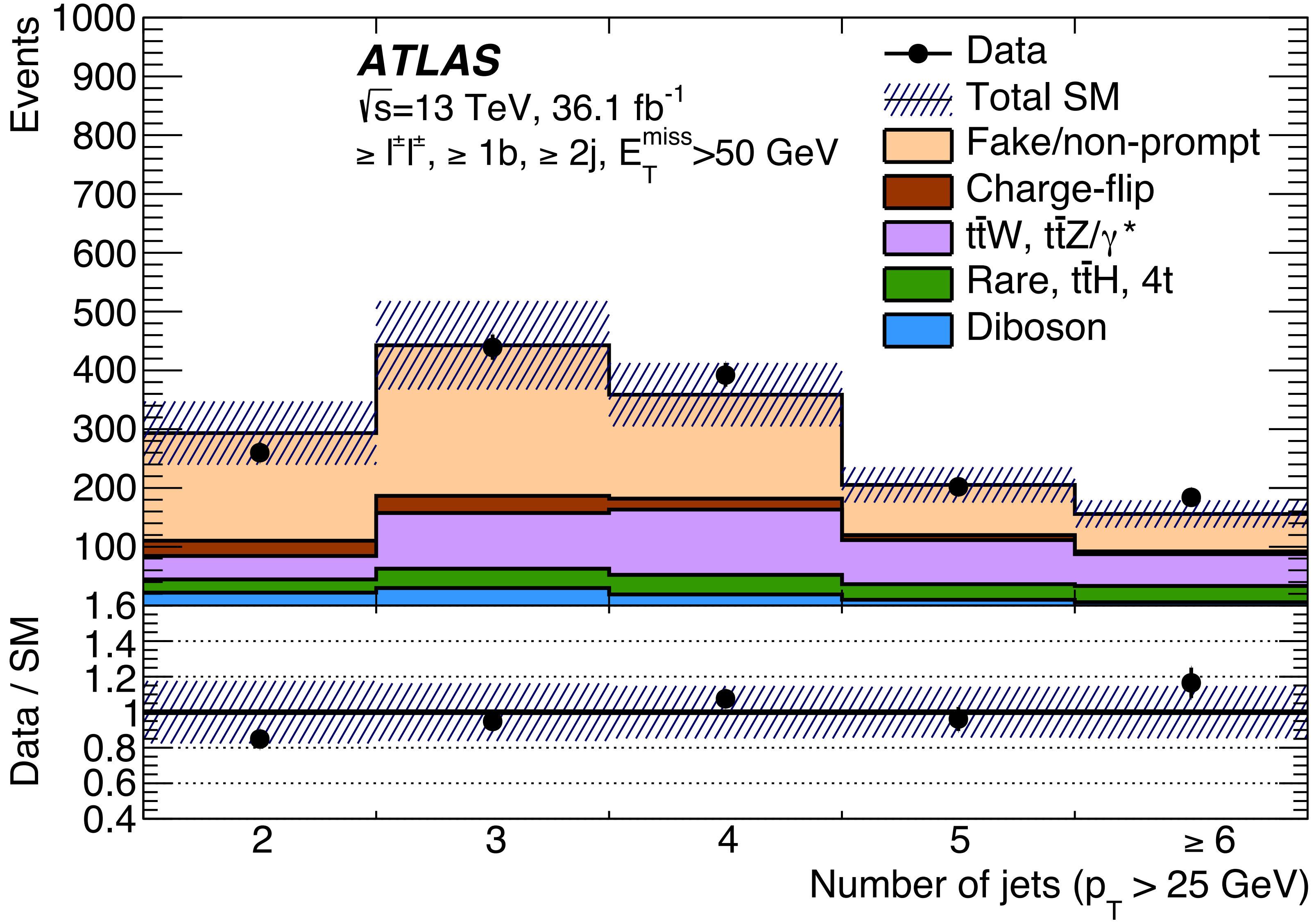
Detector background from data-driven:



Remember!

Data vs. Expectation

Final estimate:

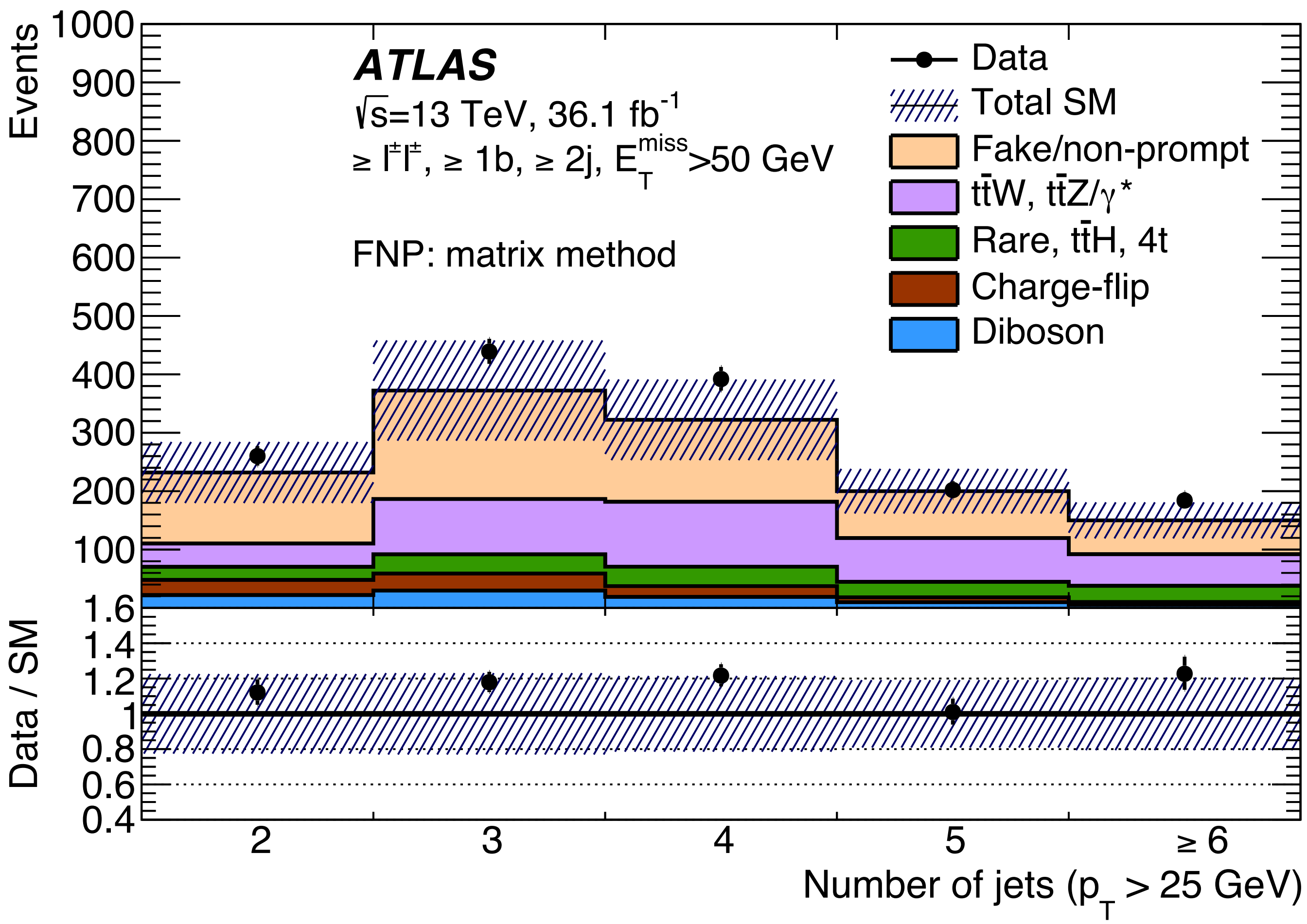


- Add ratio plot and uncertainties
- Good agreement!

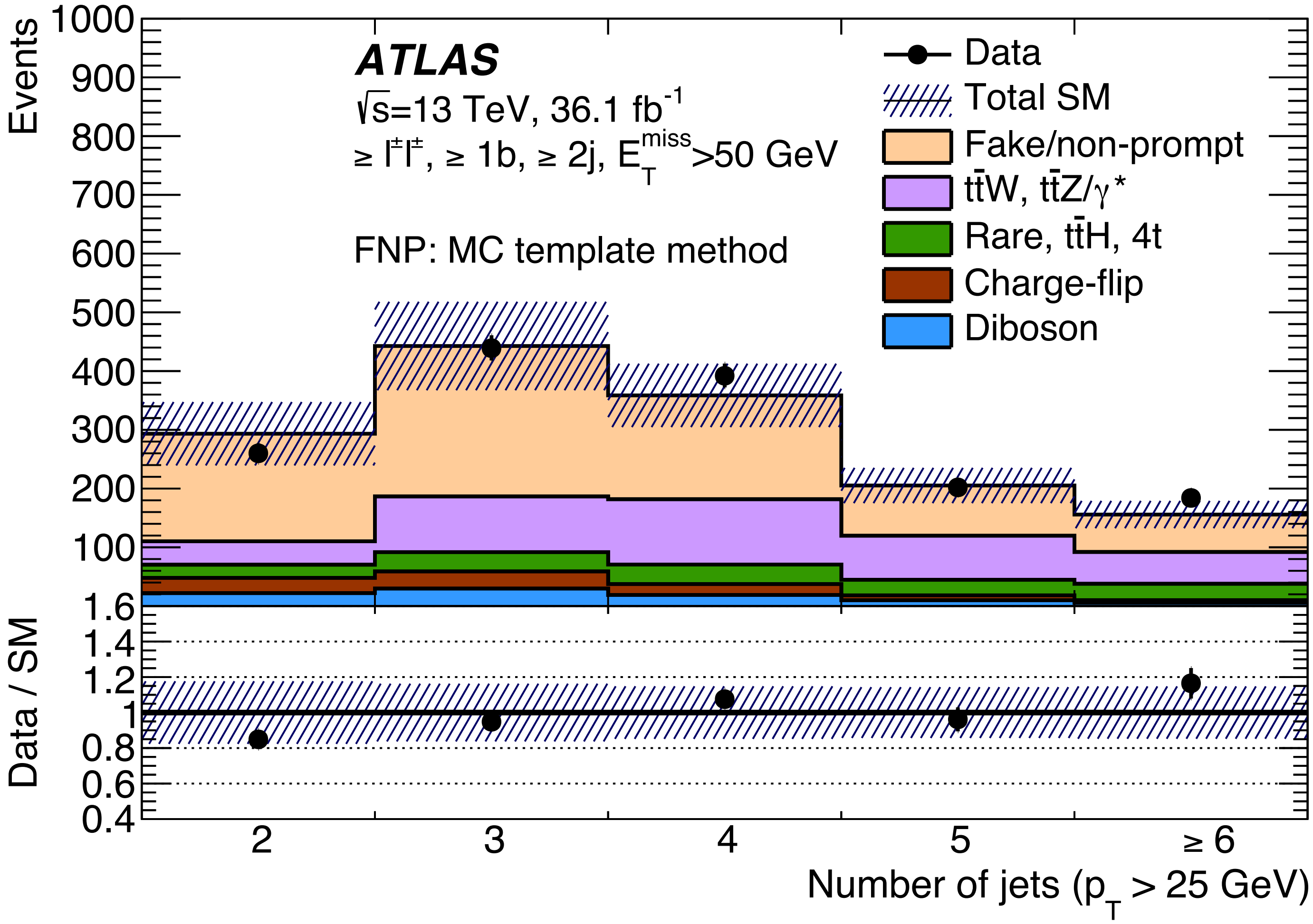
MxM vs. MC tempalte

Excellent agreement in fake enriched regions for both:

Matrix method



MC template

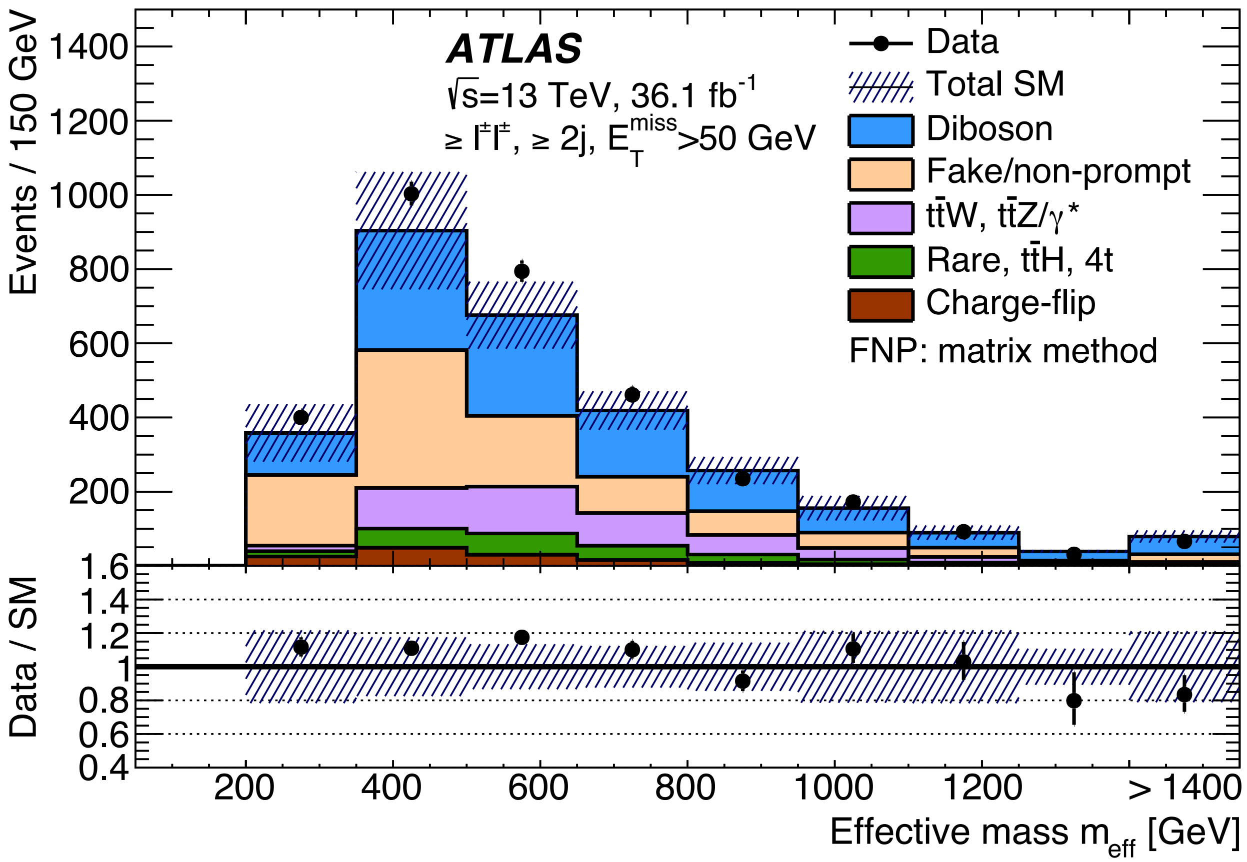


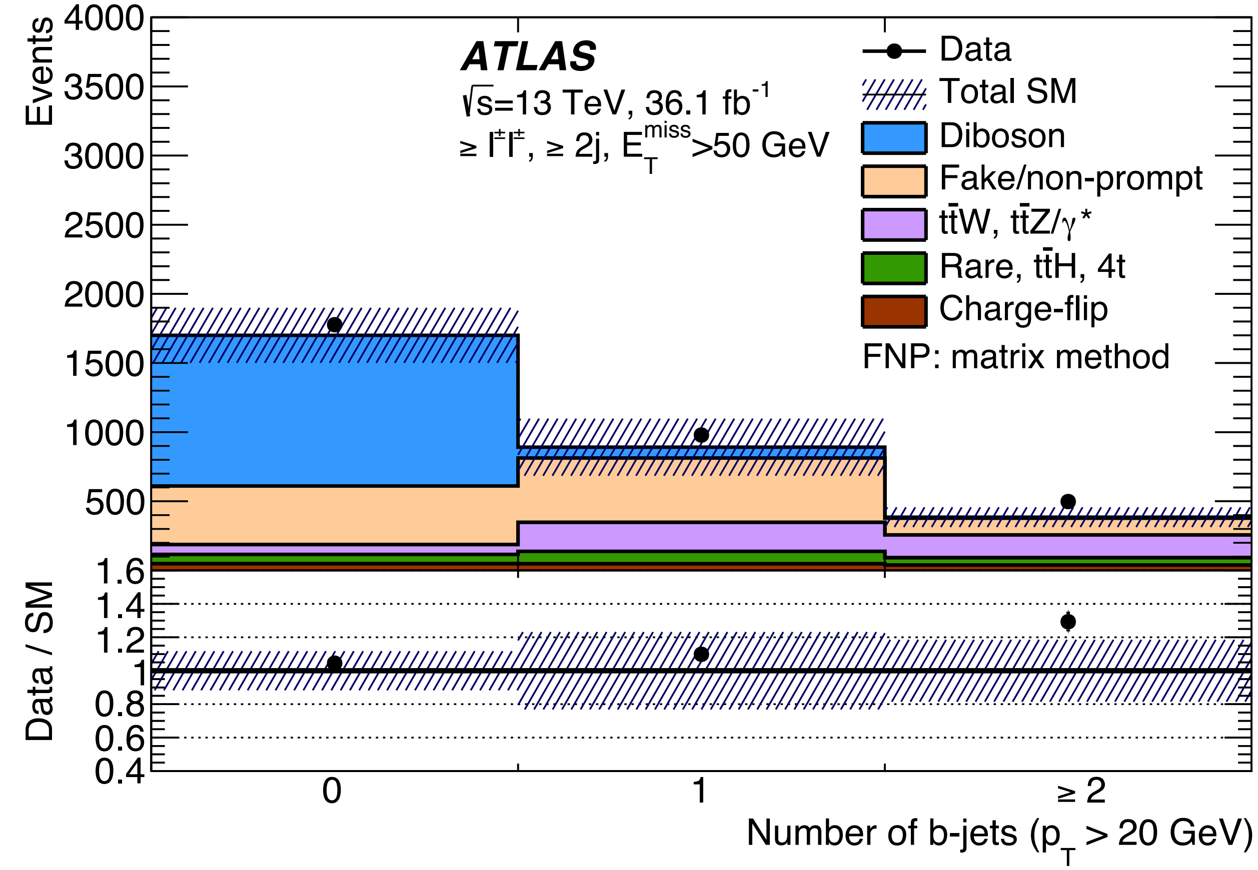
Background validation

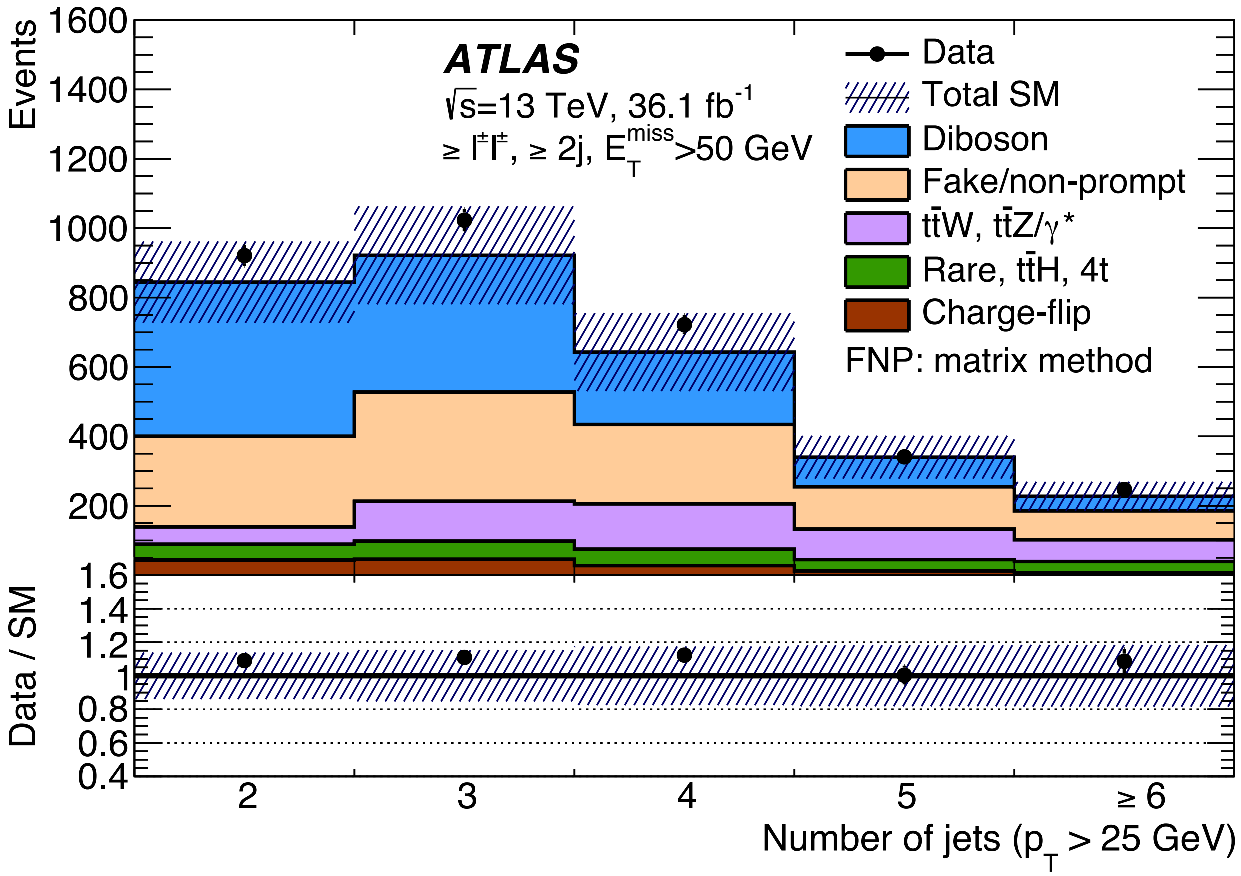
- Regions designed to verify the estimates of the dominant SM processes: ttW, ttZ, WZ, and $W^{\pm}W^{\pm}$
- Overall good agreement between data and estimated SM background

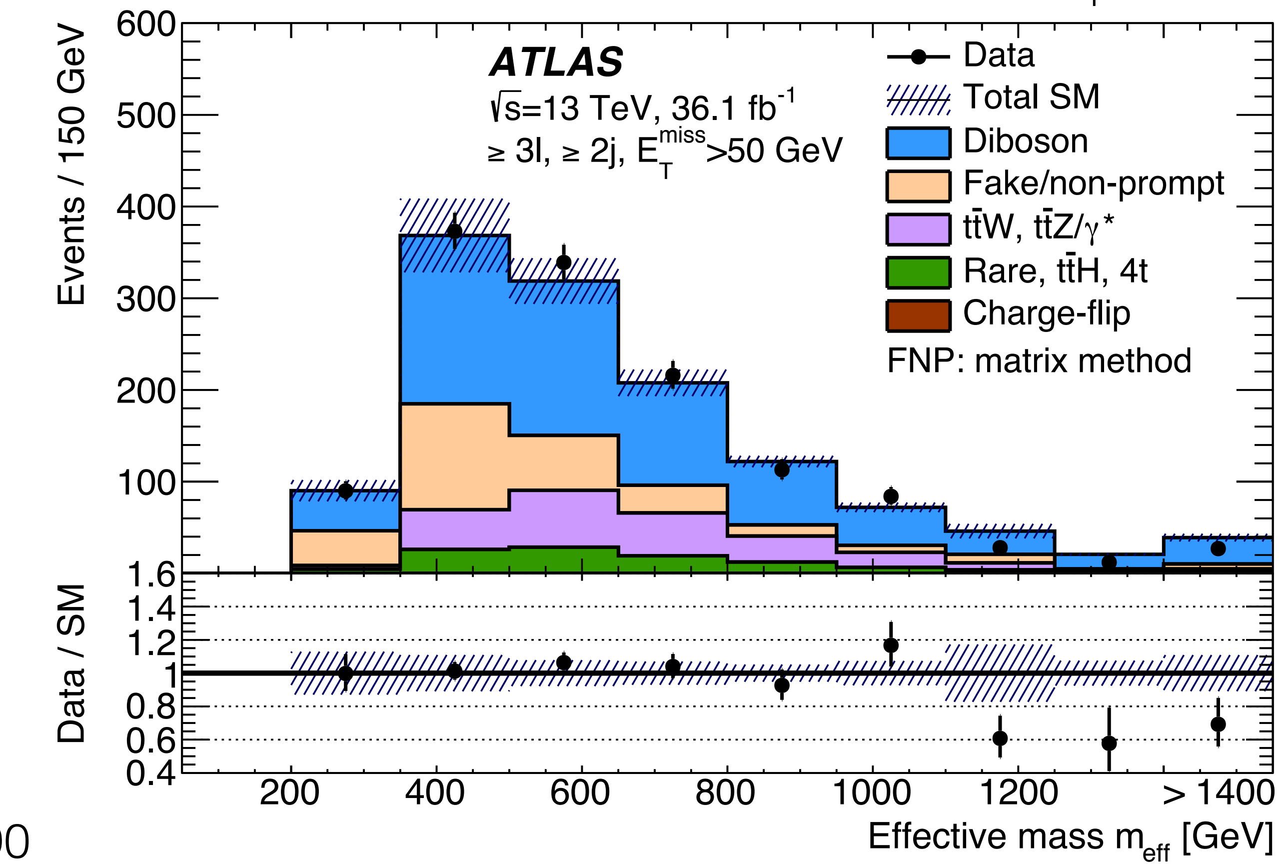
Validation Regions	$t\bar{t}W$	$t\bar{t}Z$	$WZ4j$	$WZ5j$	$W^{\pm}W^{\pm}jj$
$t\bar{t}Z/\gamma^*$	6.2 ± 0.9	123 ± 17	17.8 ± 3.5	10.1 ± 2.3	1.06 ± 0.22
$t\bar{t}W$	19.0 ± 2.9	1.71 ± 0.27	1.30 ± 0.32	0.45 ± 0.14	4.1 ± 0.8
$t\bar{t}H$	5.8 ± 1.2	3.6 ± 1.8	1.8 ± 0.6	0.96 ± 0.34	0.69 ± 0.14
$t\bar{t}t\bar{t}$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

Background validation



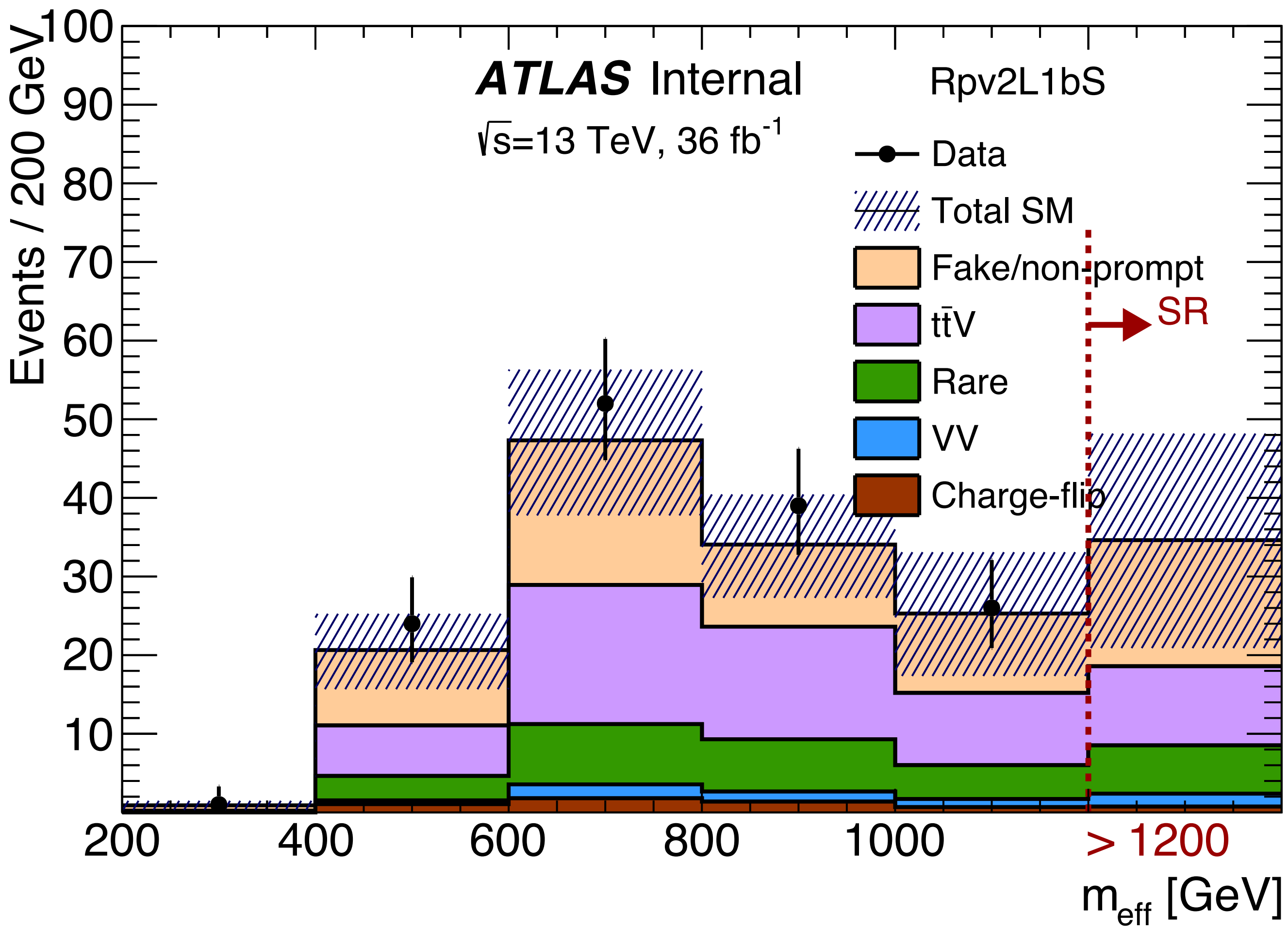


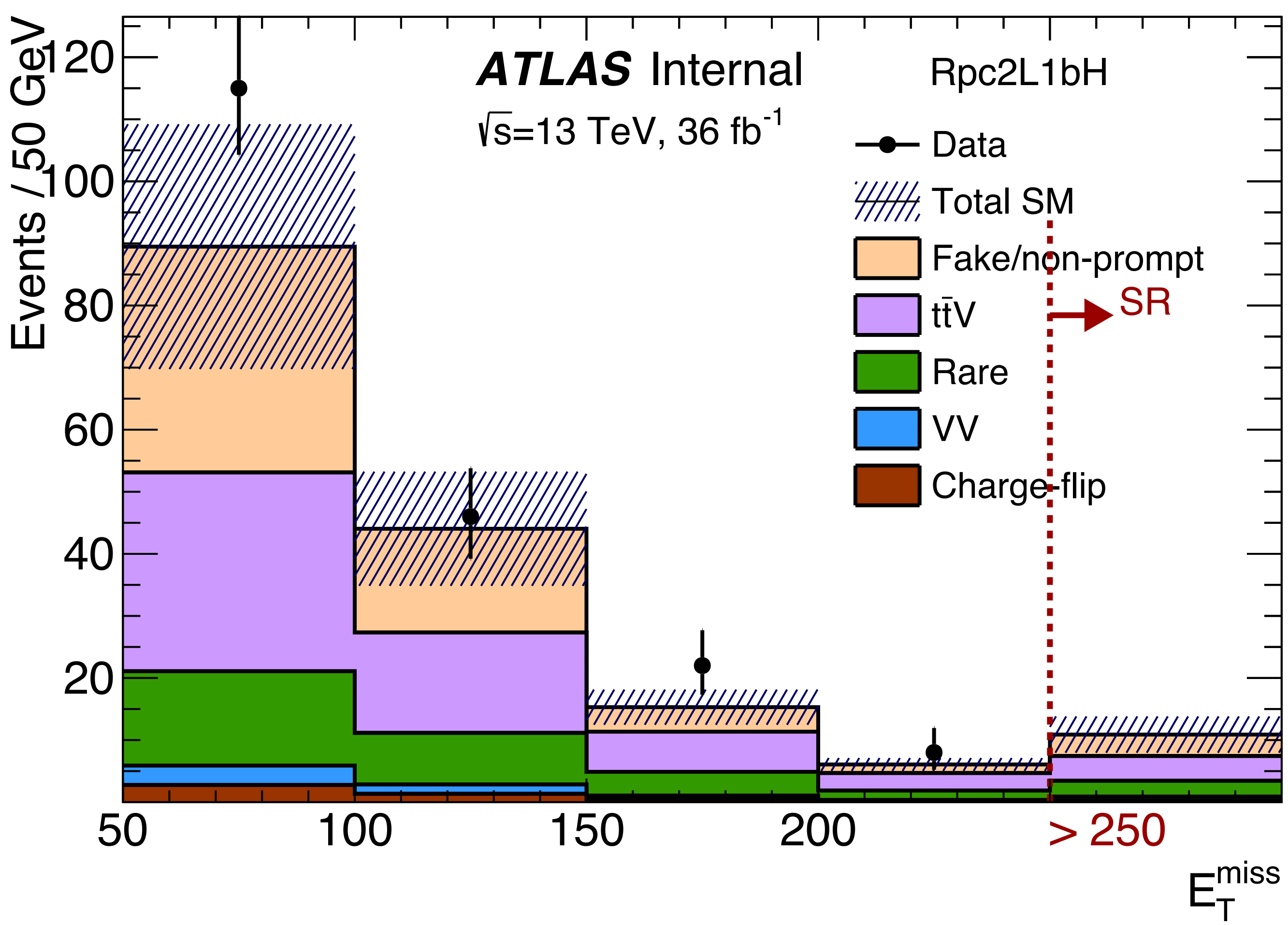




Background validation

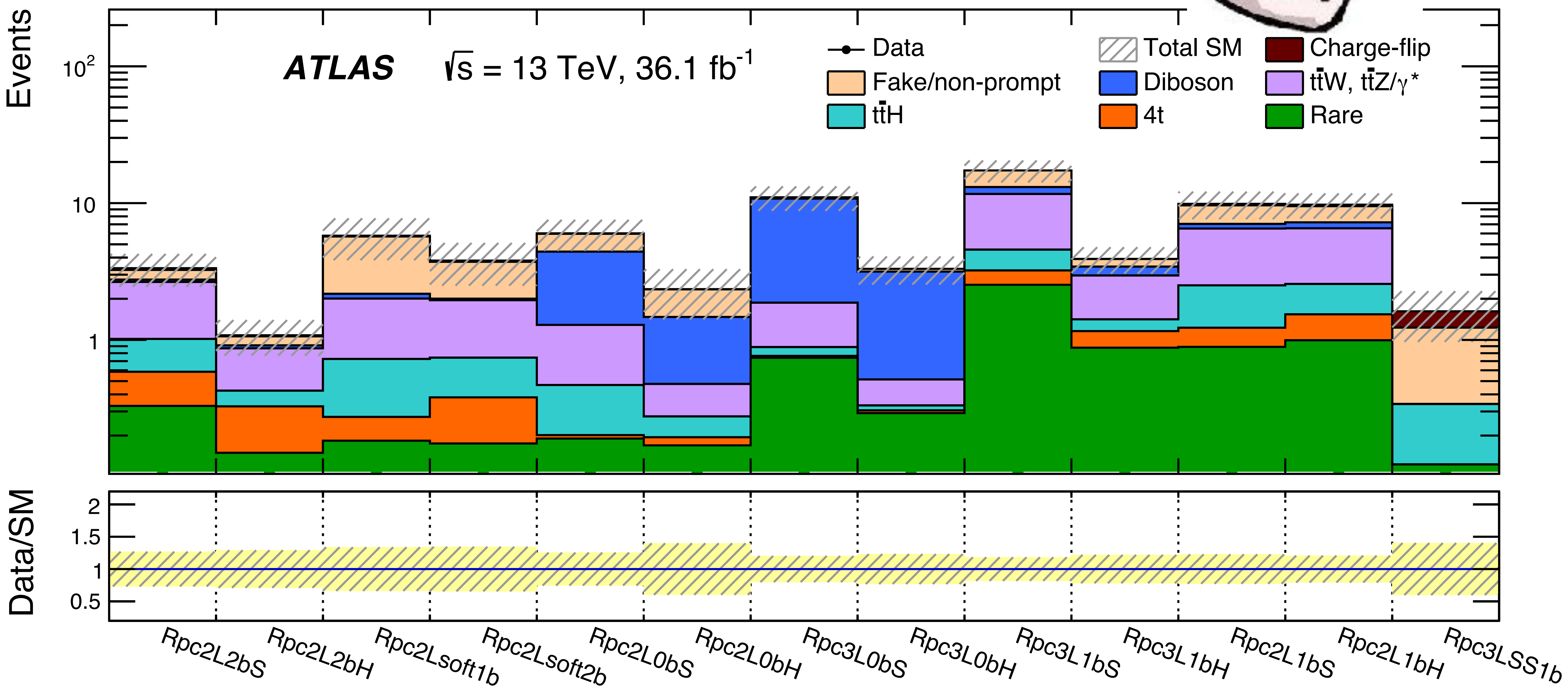
Very good agreement near the search regions (blinded)





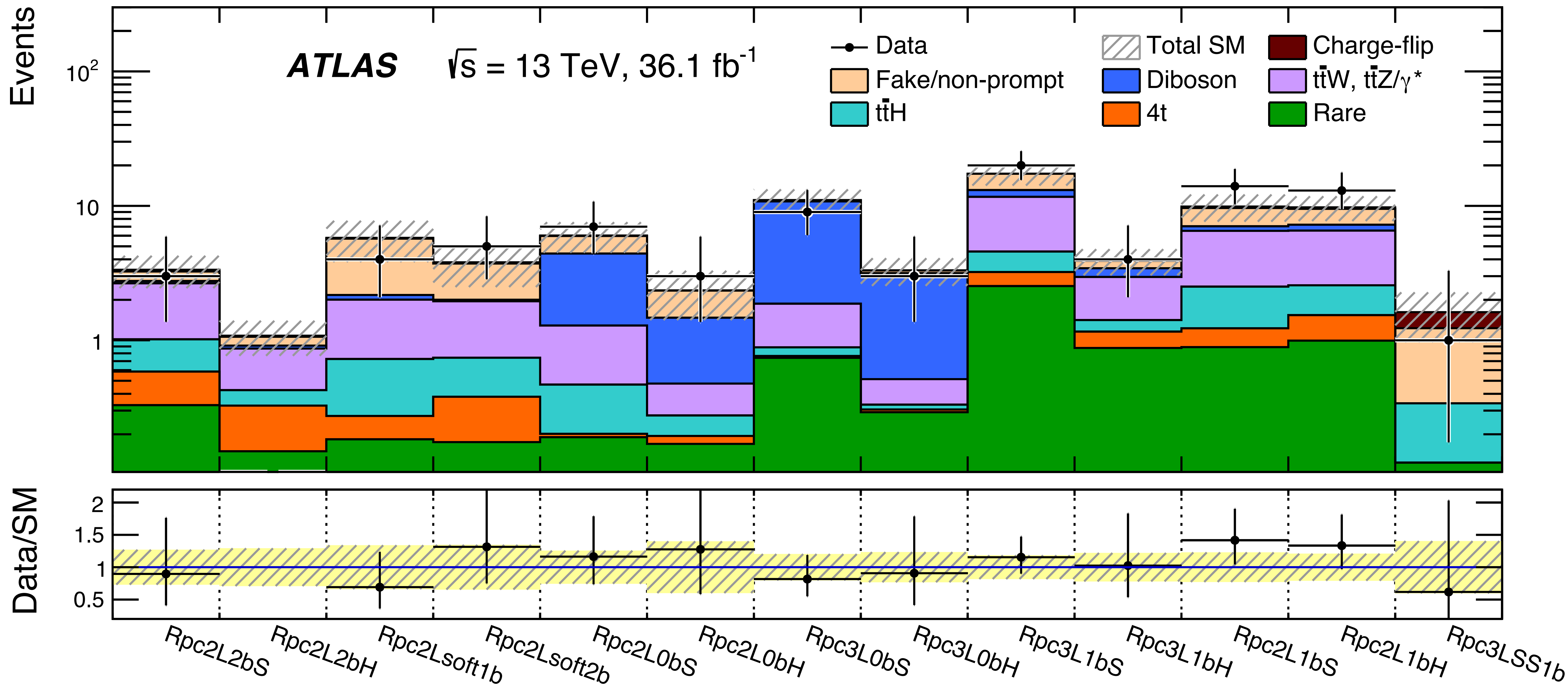
Background Estimation

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)

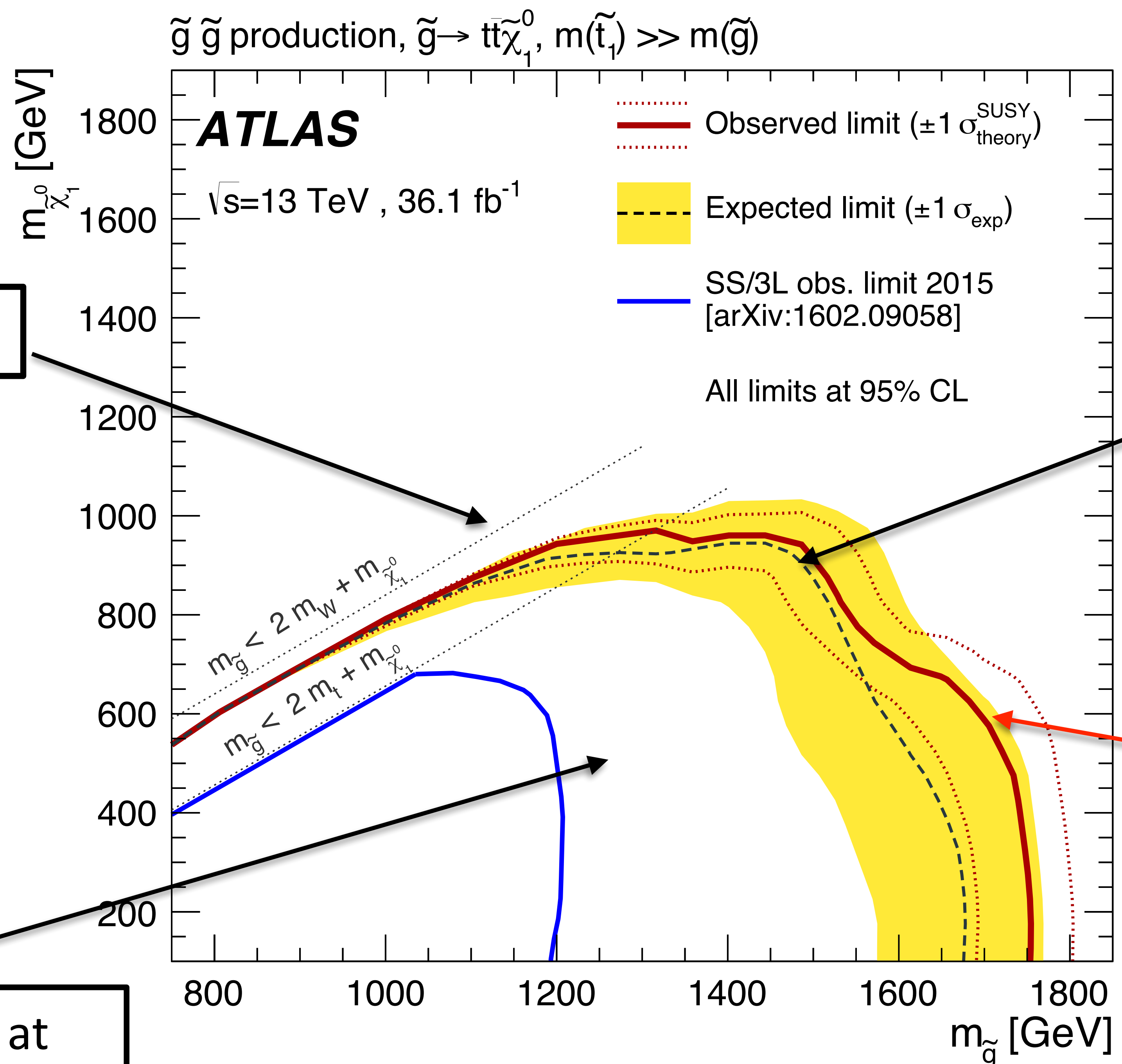
Model Independent Limits

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

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

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

Model dependent



Expected mass limit

- At nominal production cross section
- 1σ variations due to stat+syst

Kinematic limit

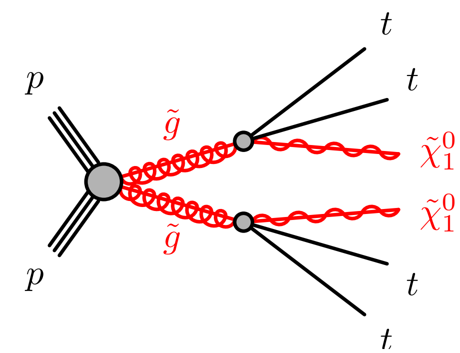
Excluded region at 95% confidence level

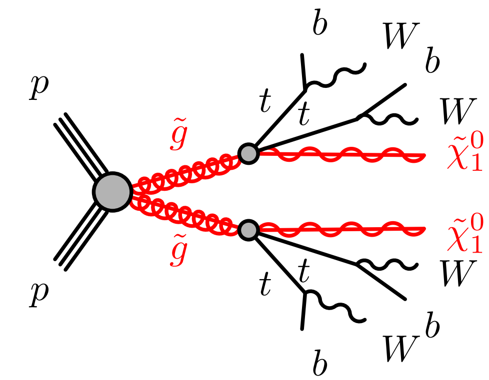
Observed mass limit

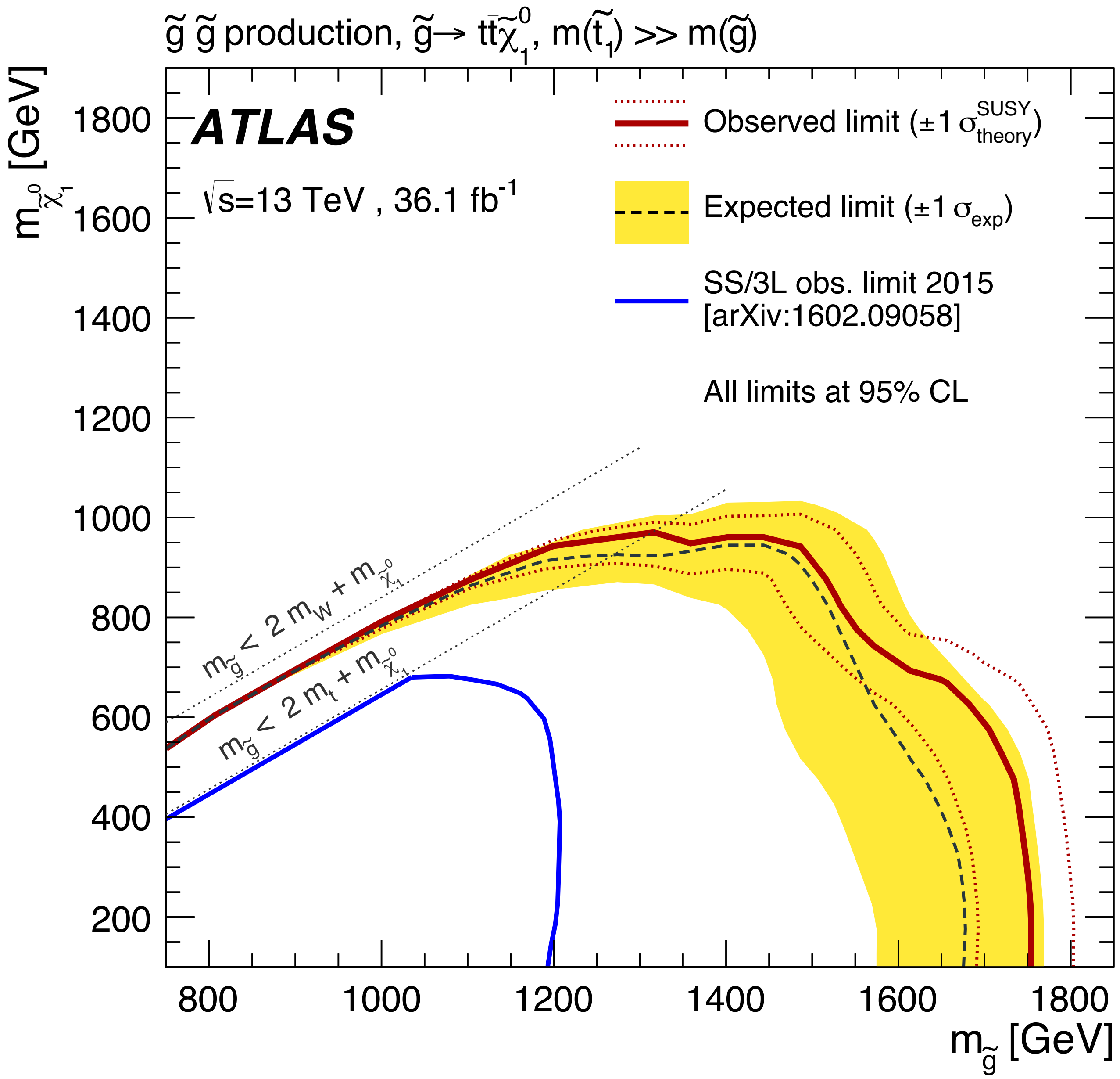
- variations correspond to ±1σ uncertainty on total production cross section

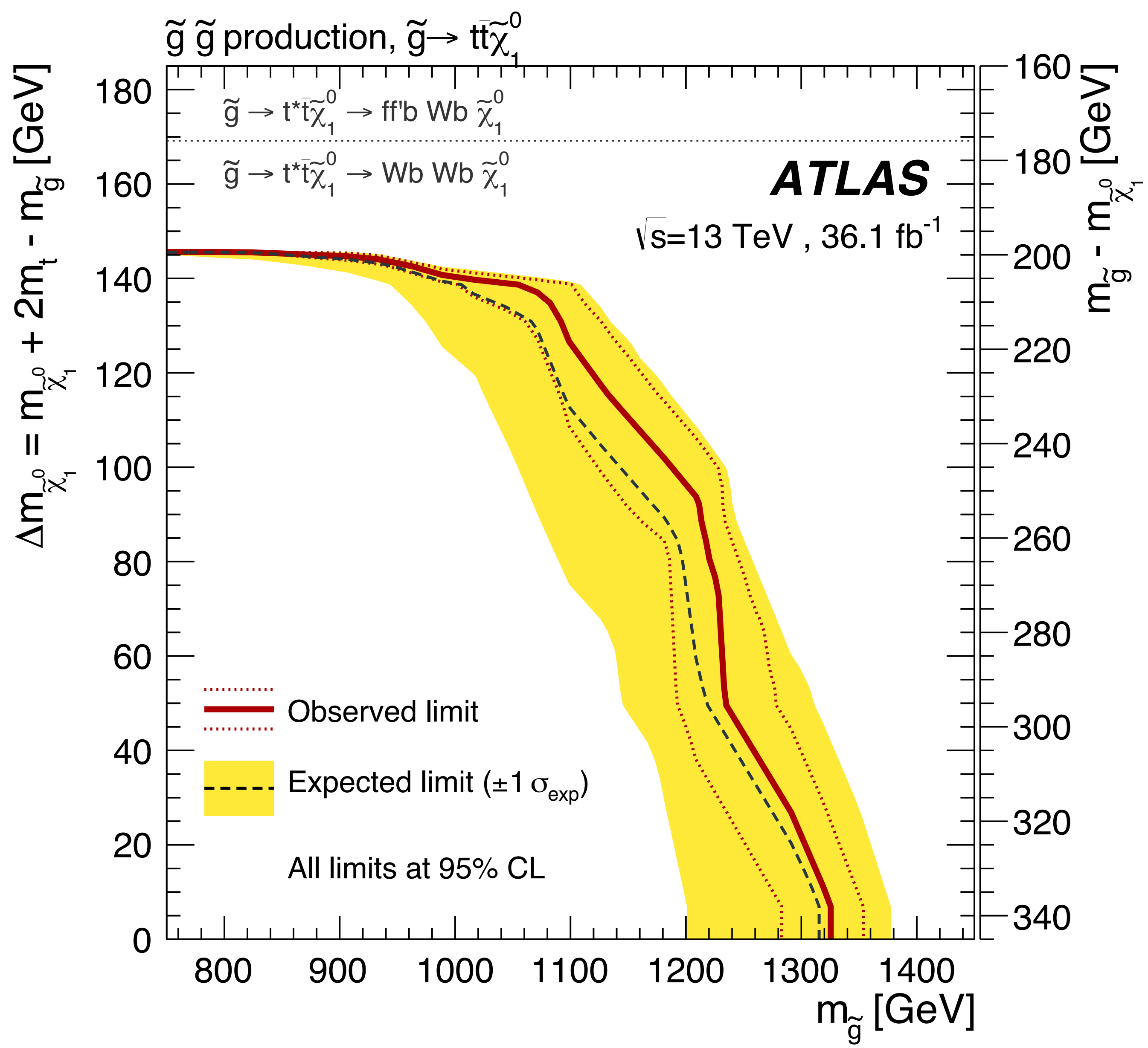
Model dependent

- SRs: Rpc2L2bS, Rpc2L2bH, Rpc2Lsoft1b, Rpc2Lsoft2b



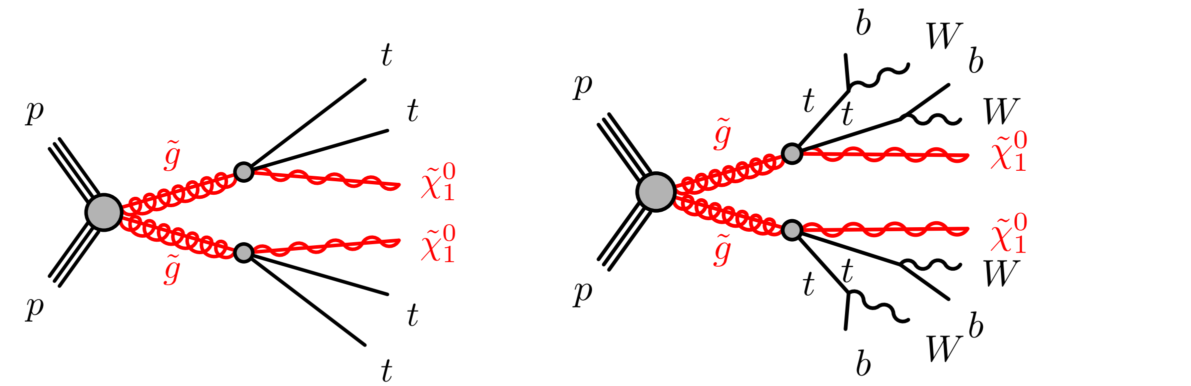


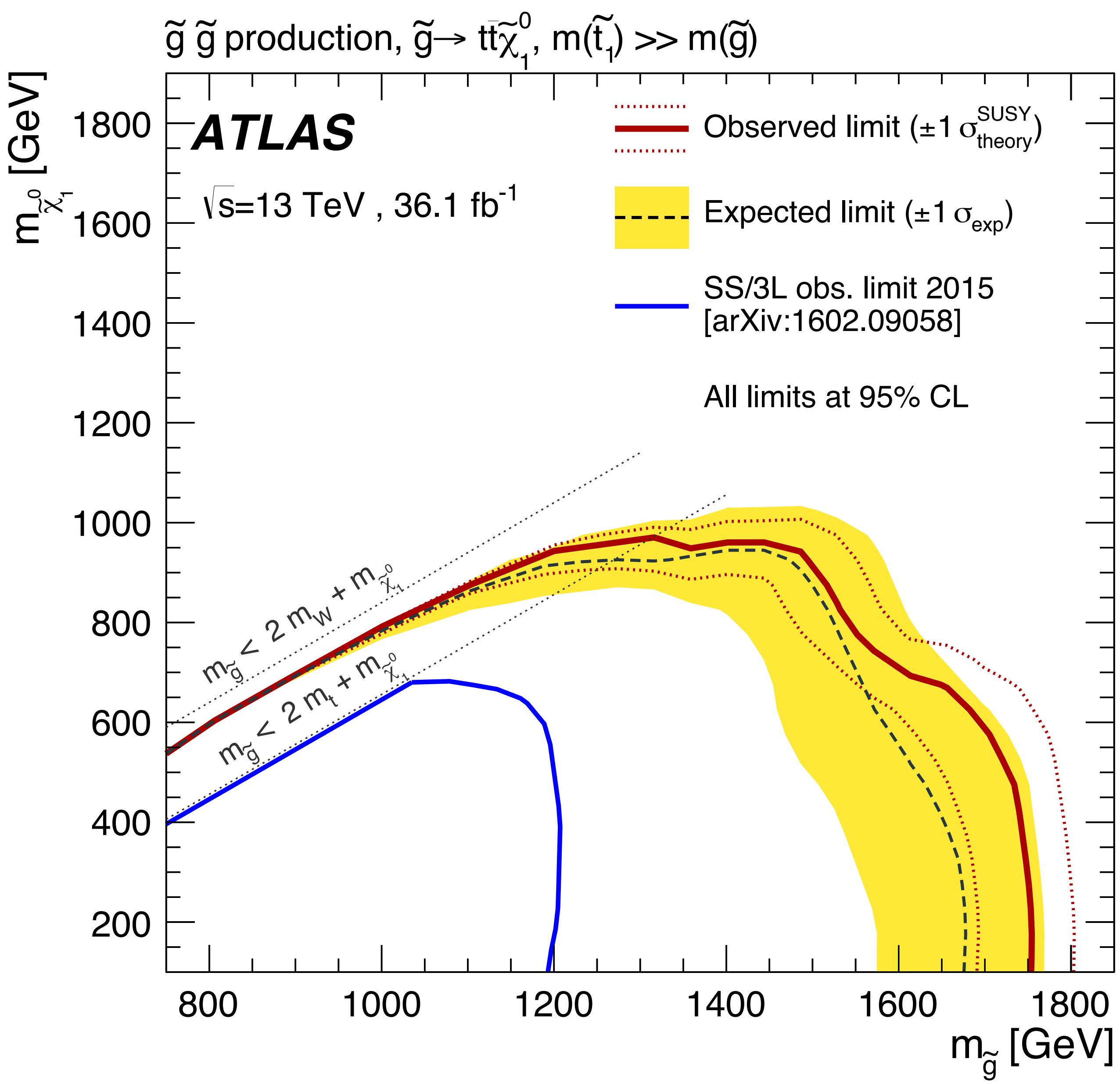


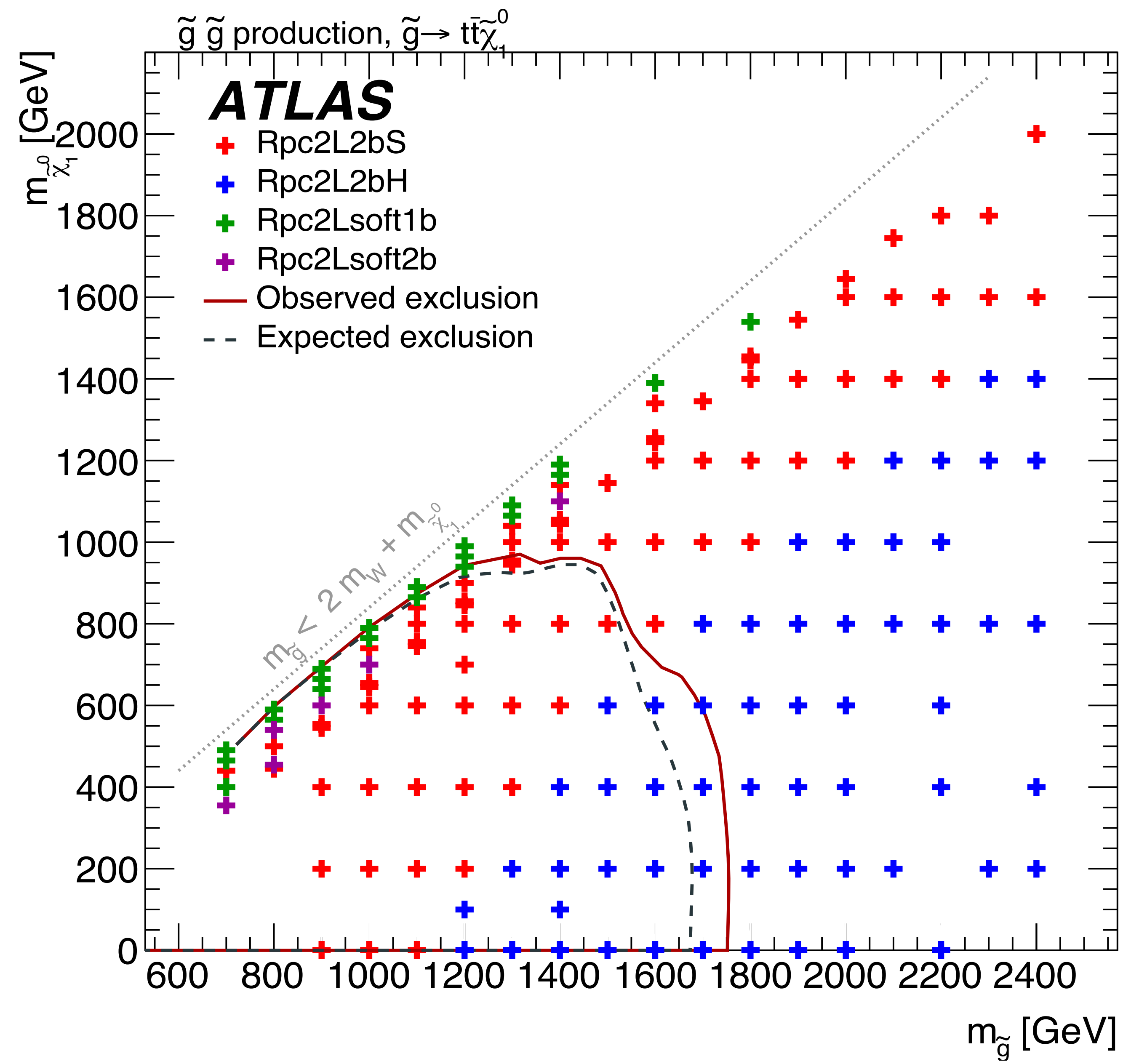


Model dependent

- SRs: Rpc2L2bS, Rpc2L2bH, Rpc2Lsoft1b, Rpc2Lsoft2b

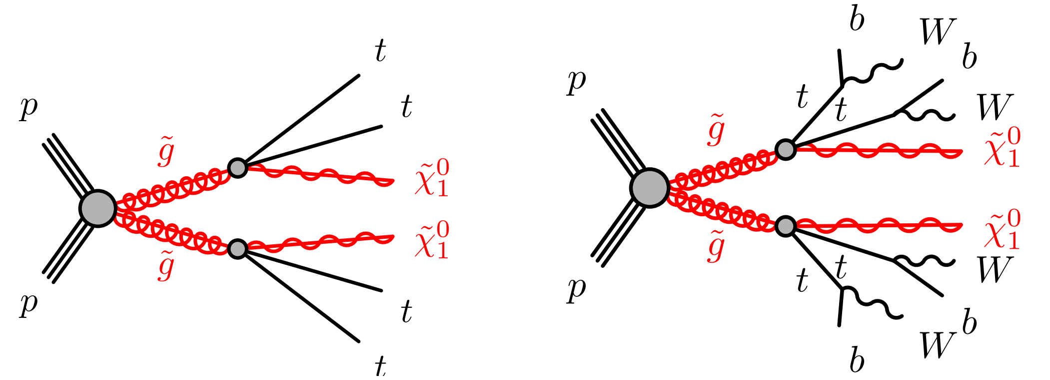


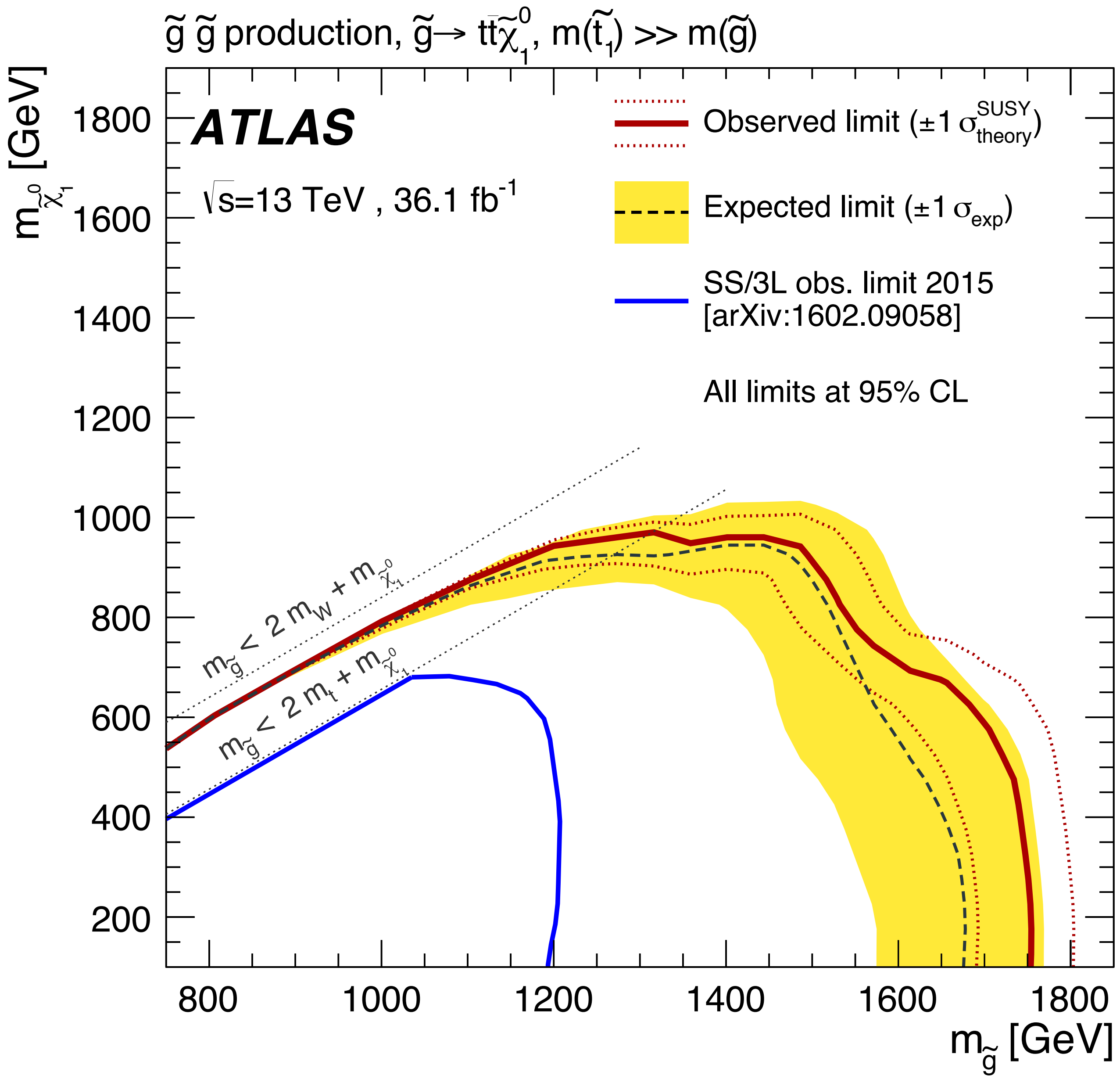


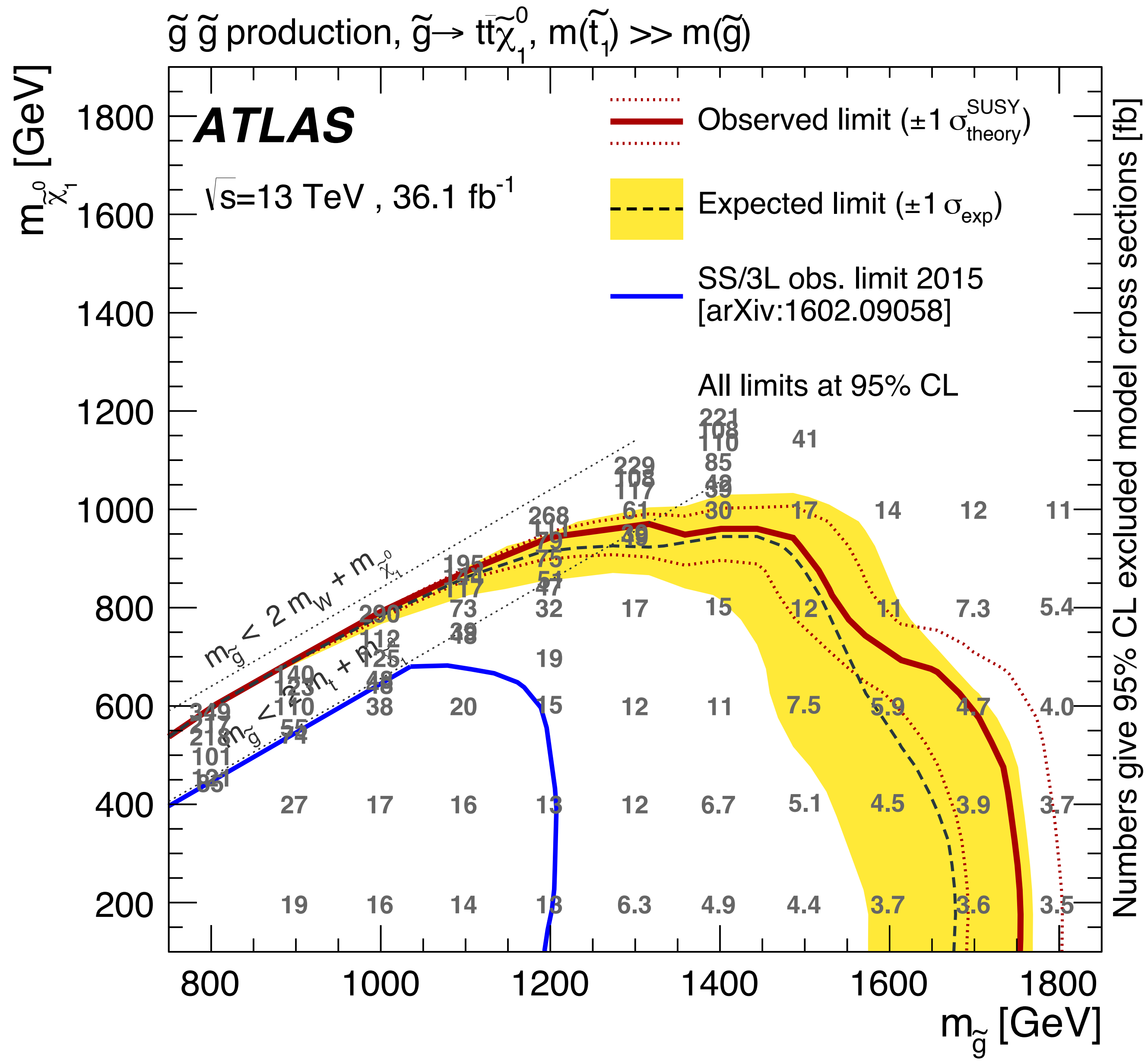


Model dependent

- SRs: Rpc2L2bS, Rpc2L2bH, Rpc2Lsoft1b, Rpc2Lsoft2b

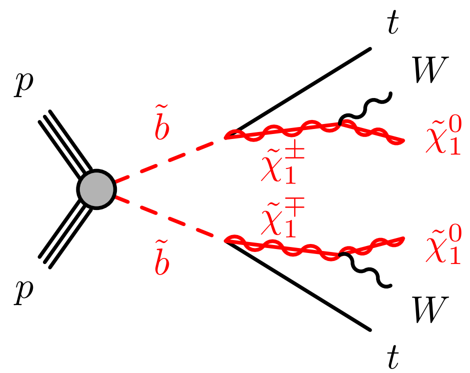


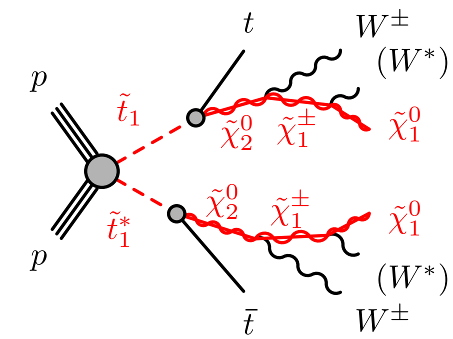


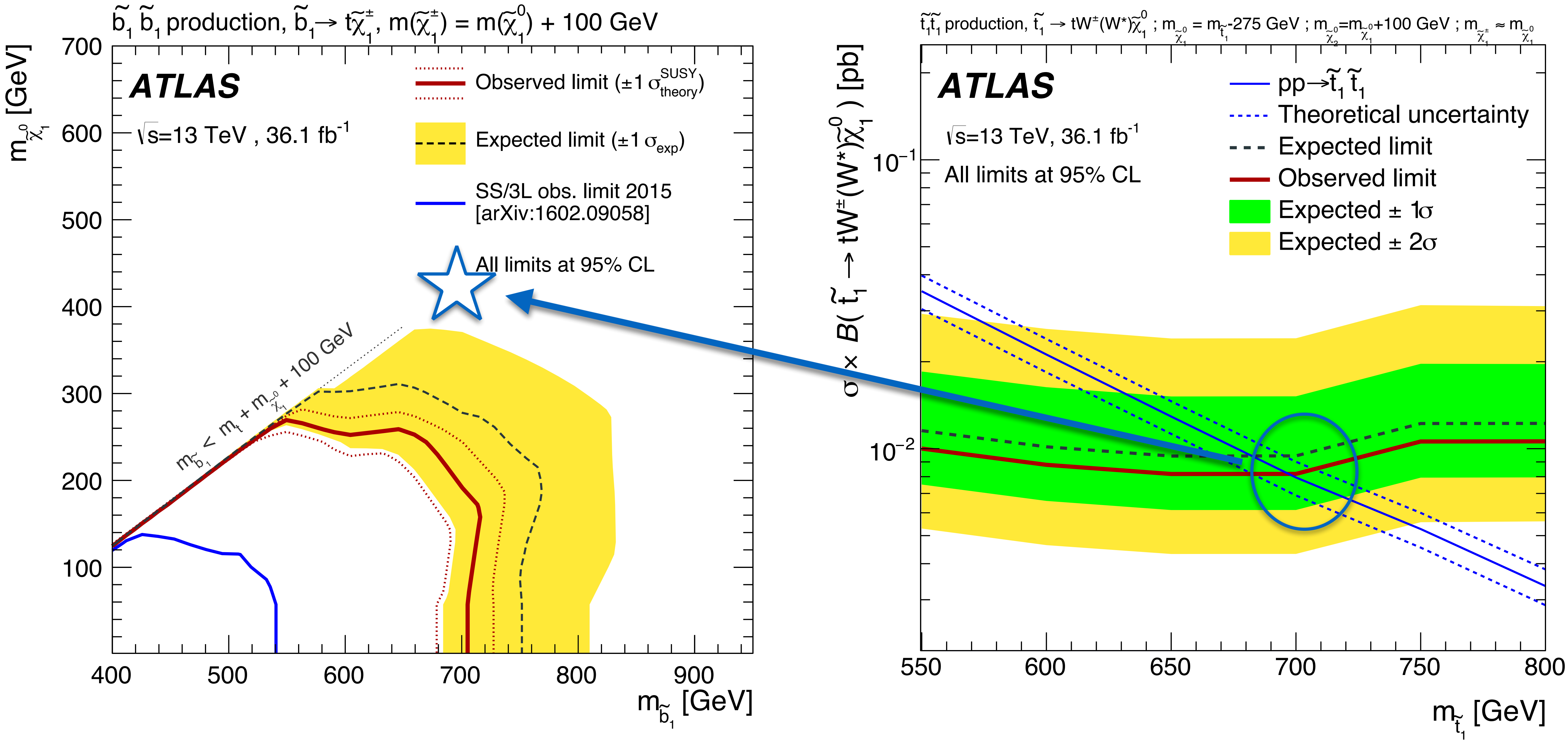


RPC Interpretation: 3rd Gen

- SRs: Rpc2L1bS, Rpc2L1bH, Rpc3LSS1b

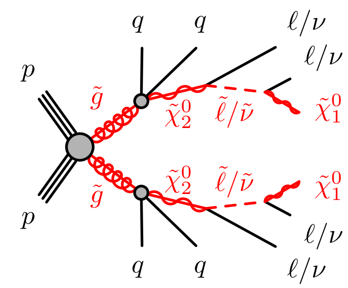


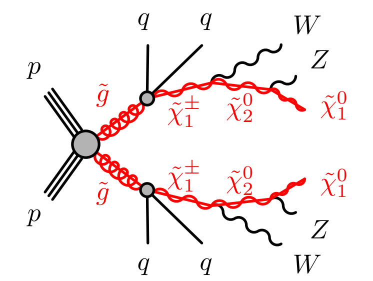


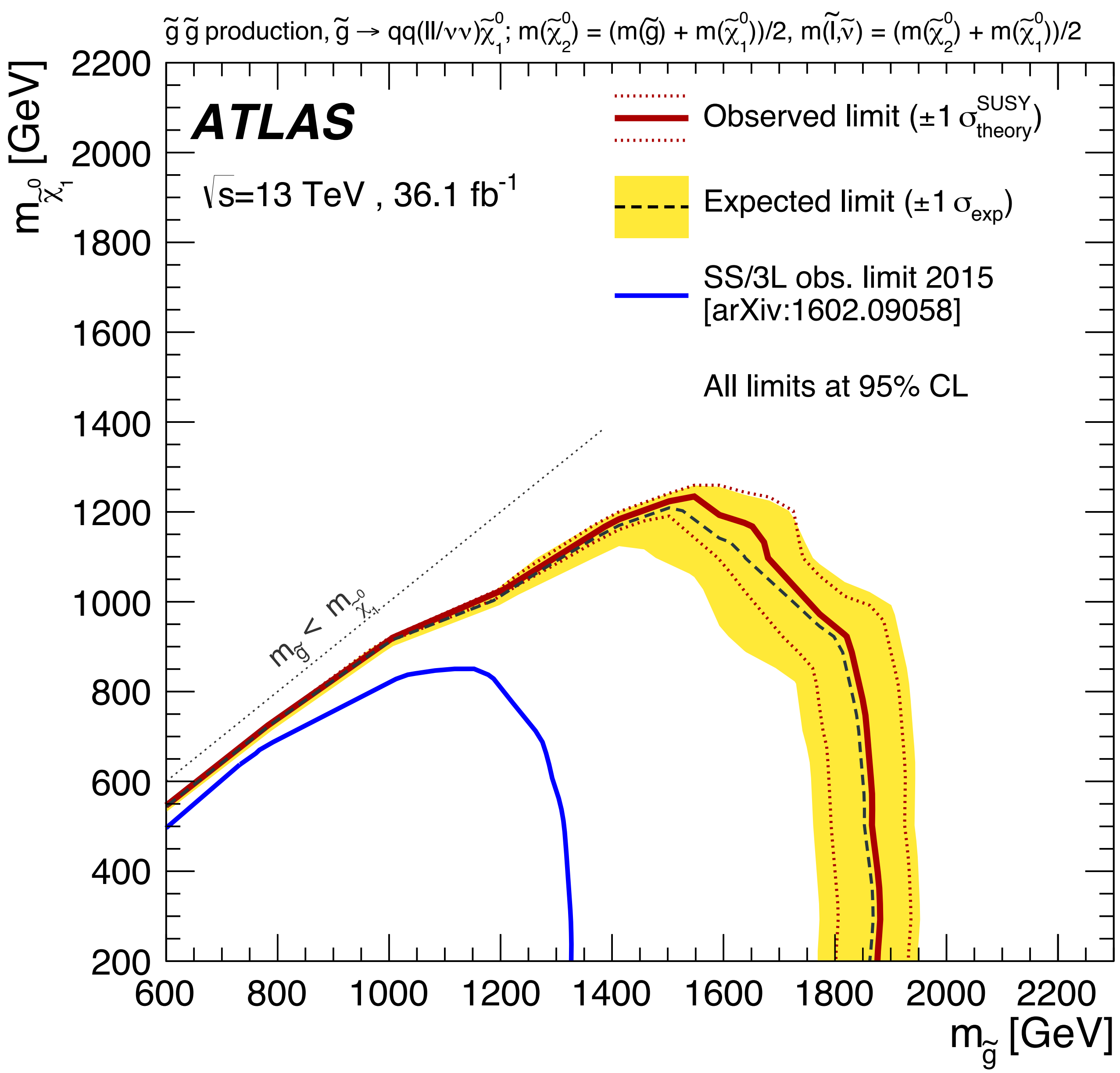


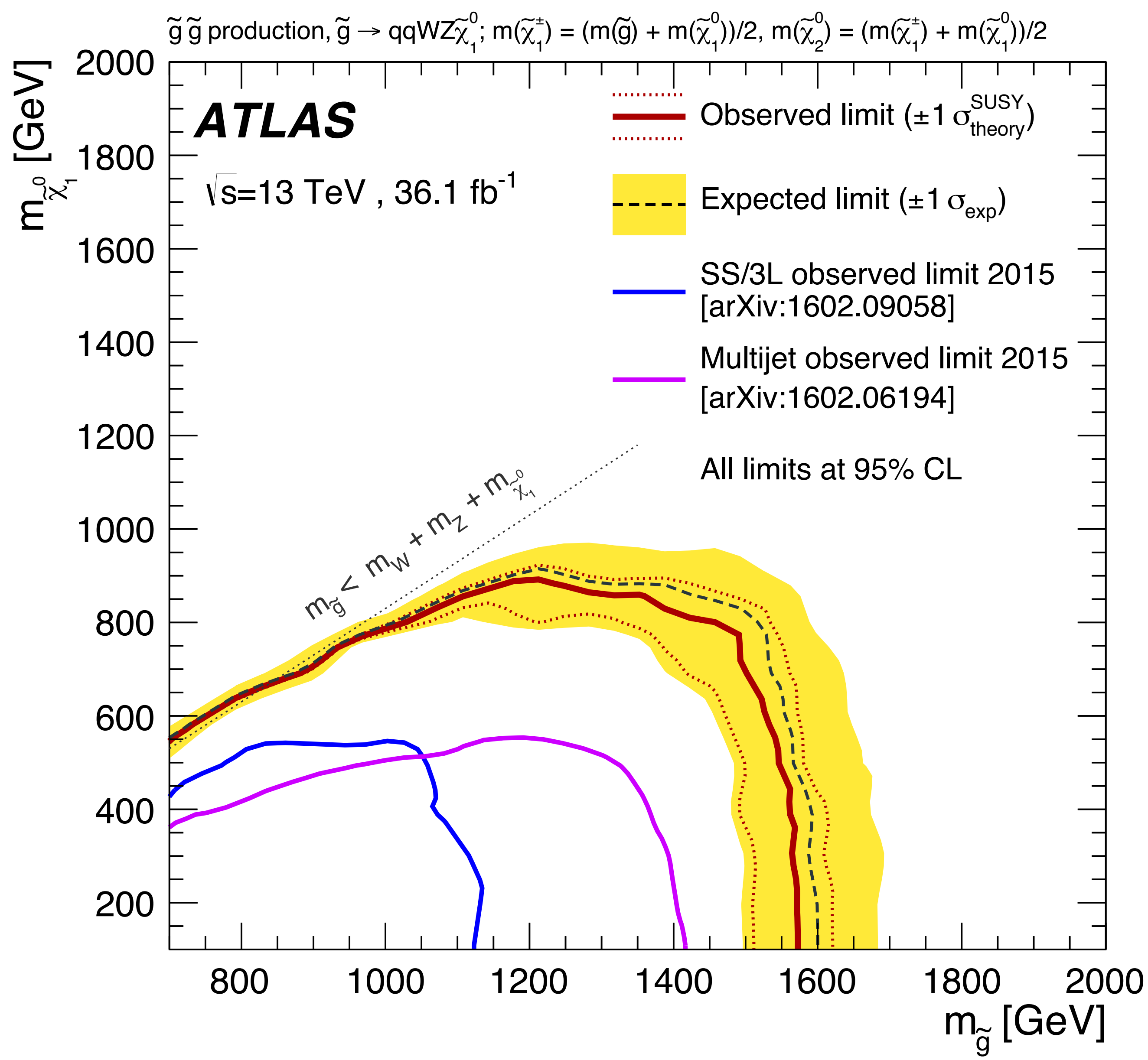
RPC Interpretation: GSL and 2setp-WZ

- SRs: Rpc3L0bS and Rpc3L0bH , Rpc2L0bS and Rpc2L0bH



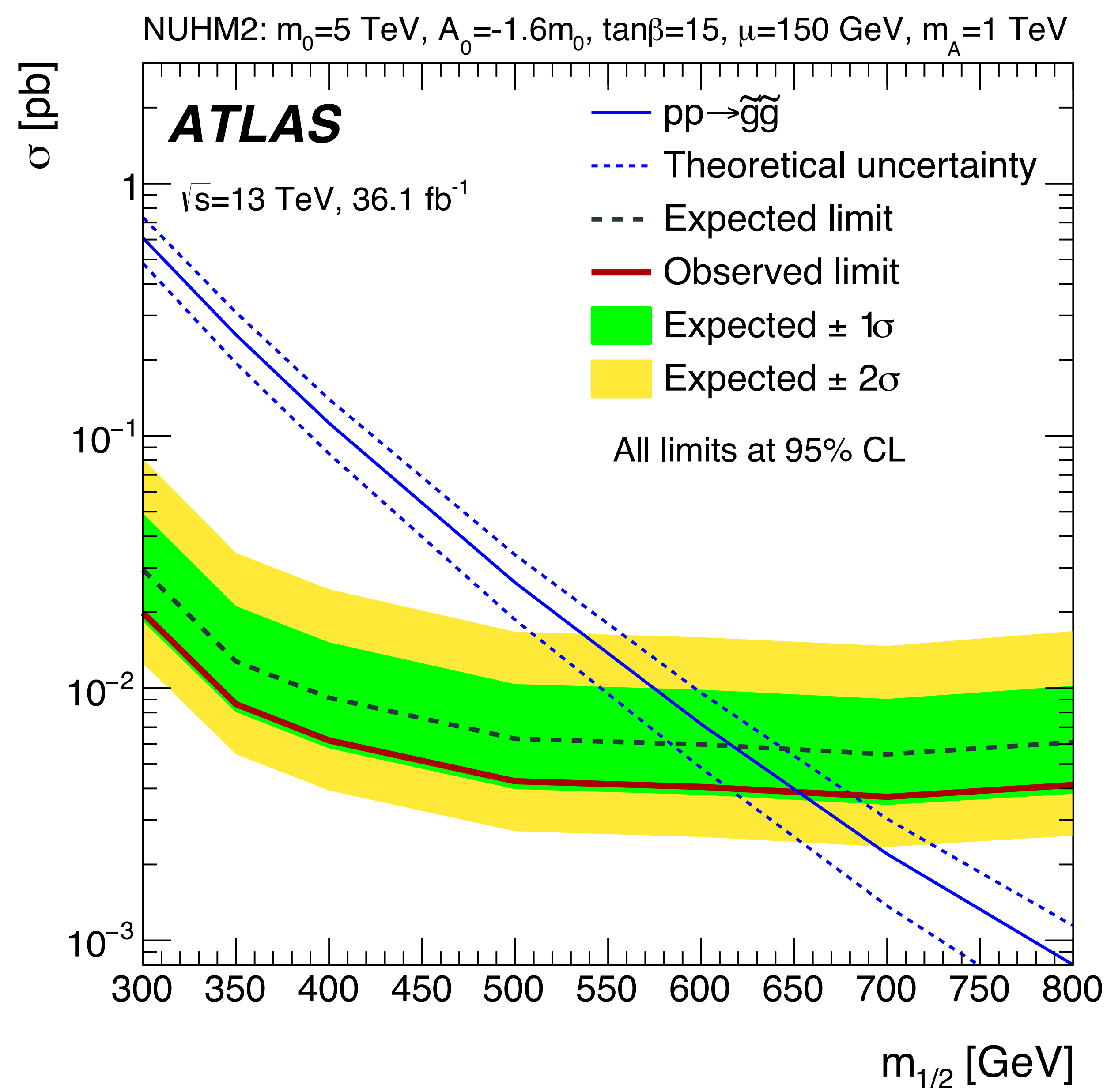






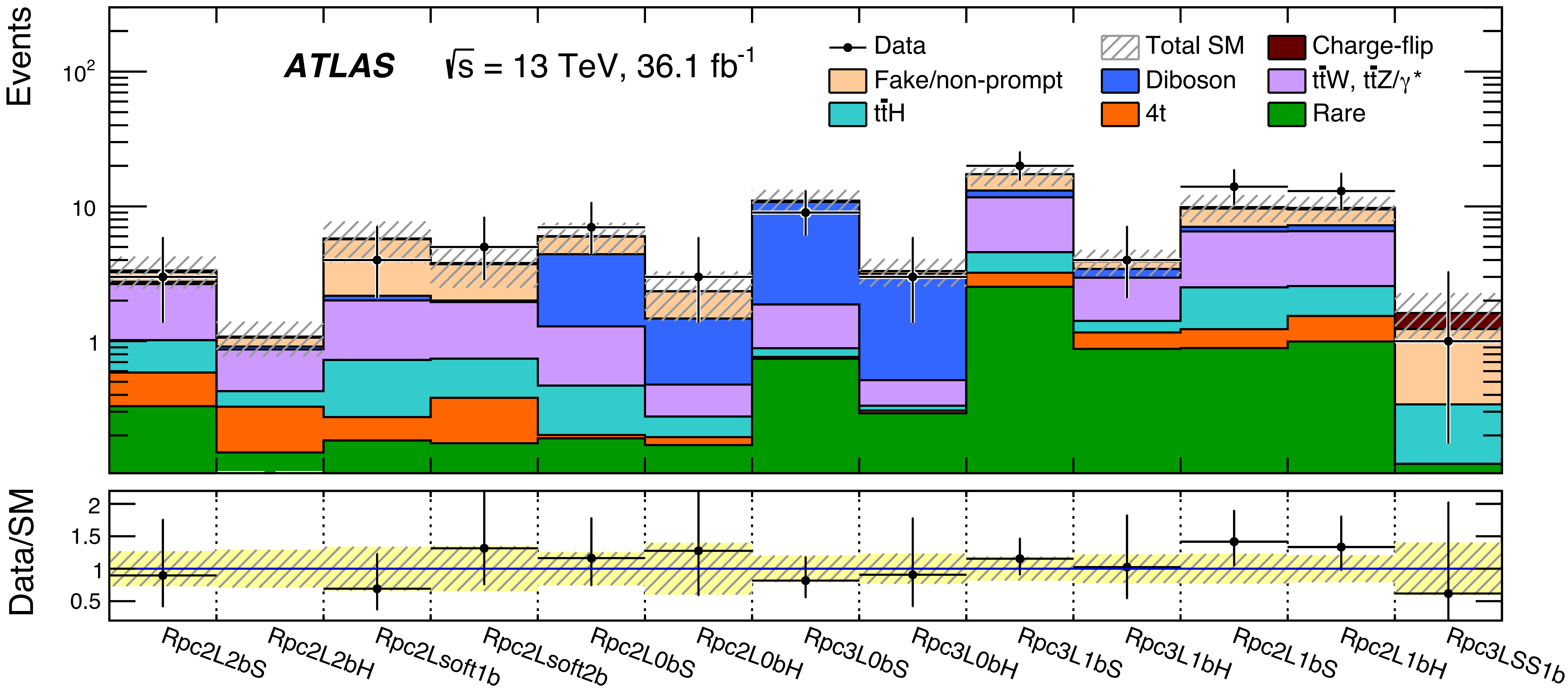
RPC Interpretation: NUHM2

- SR: Rpc2L2bH



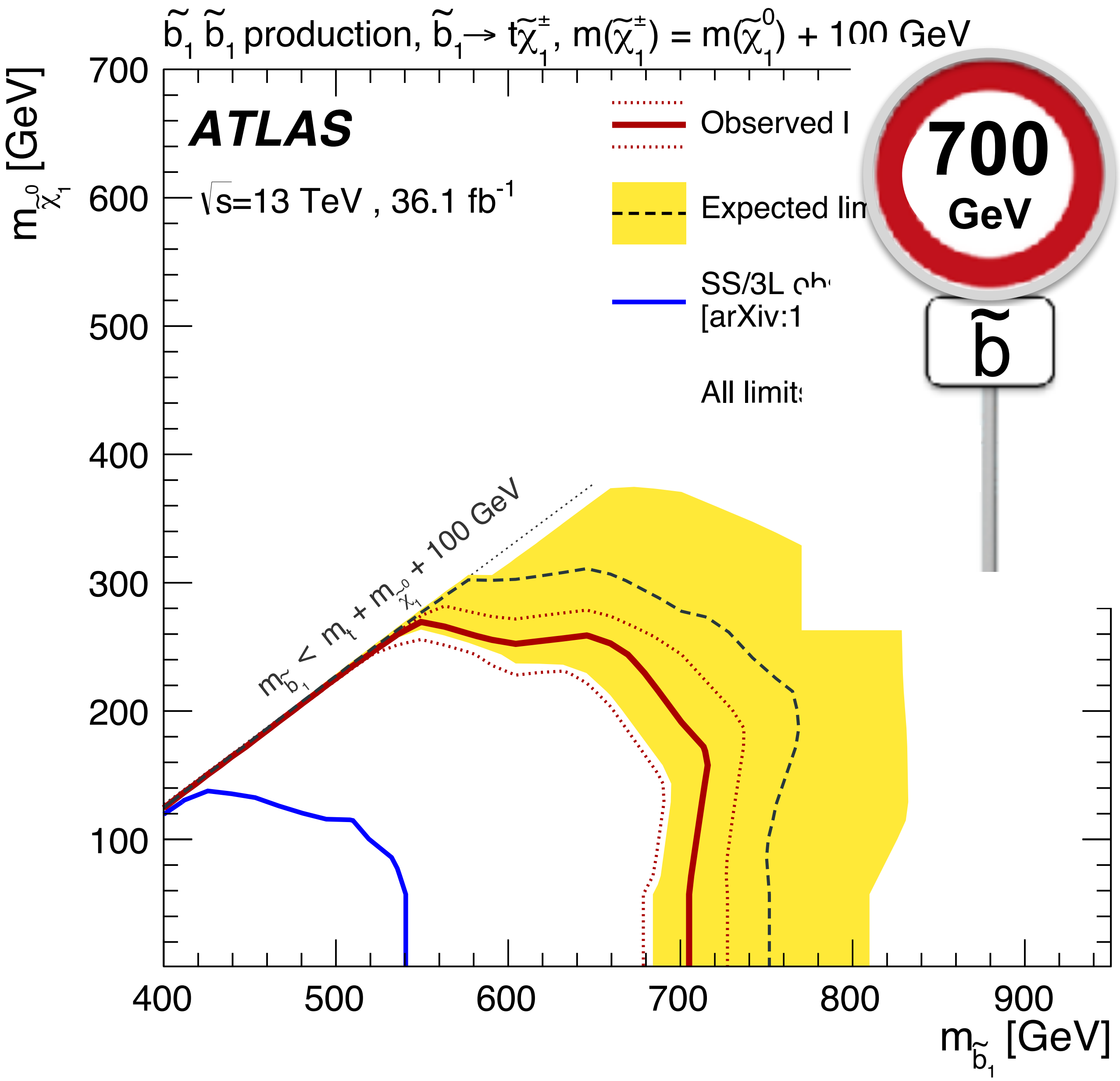
Closing remarks...

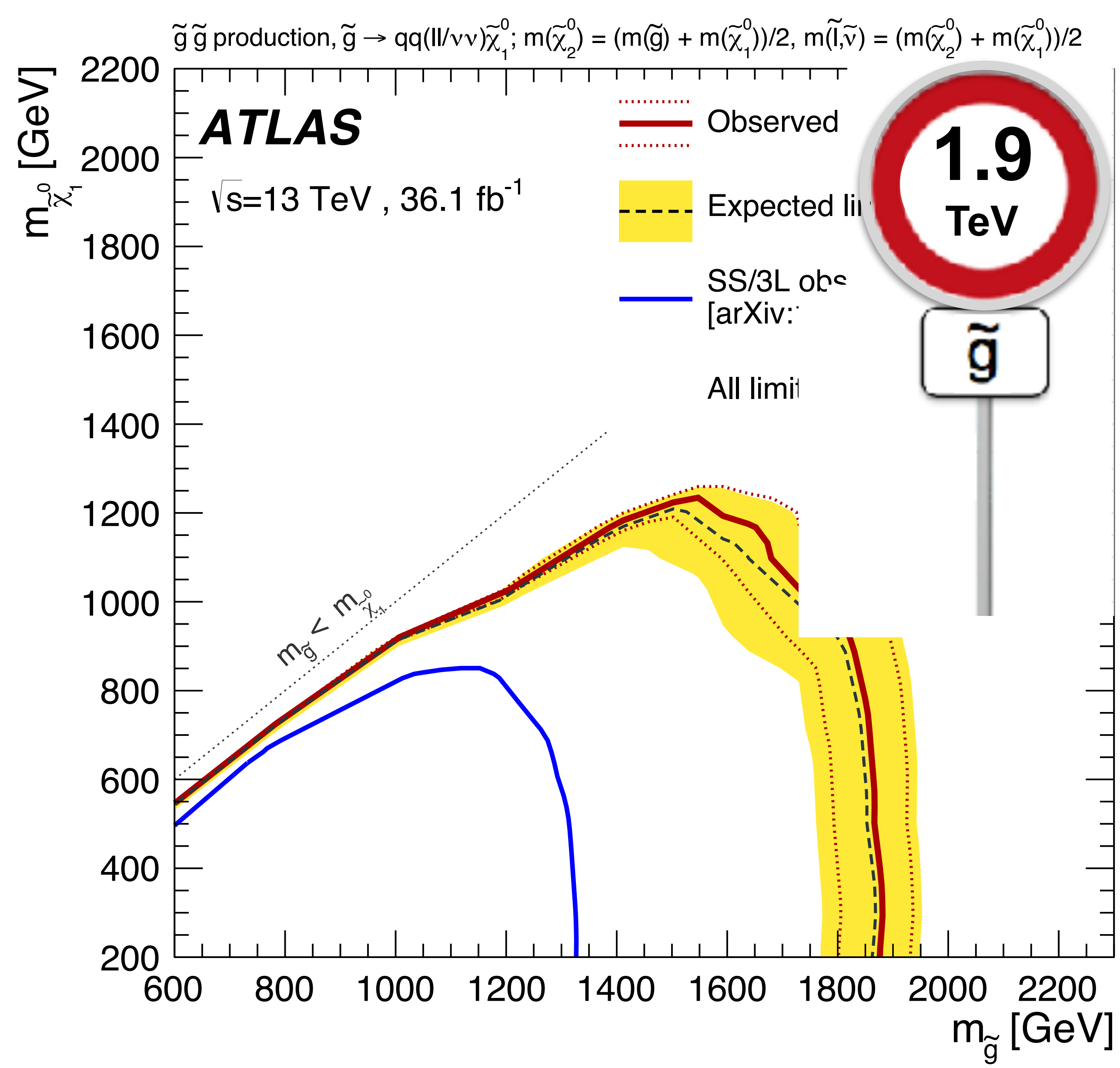
I didn't find any evidence for supersymmetry in all the search regions:



Closing remarks...

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

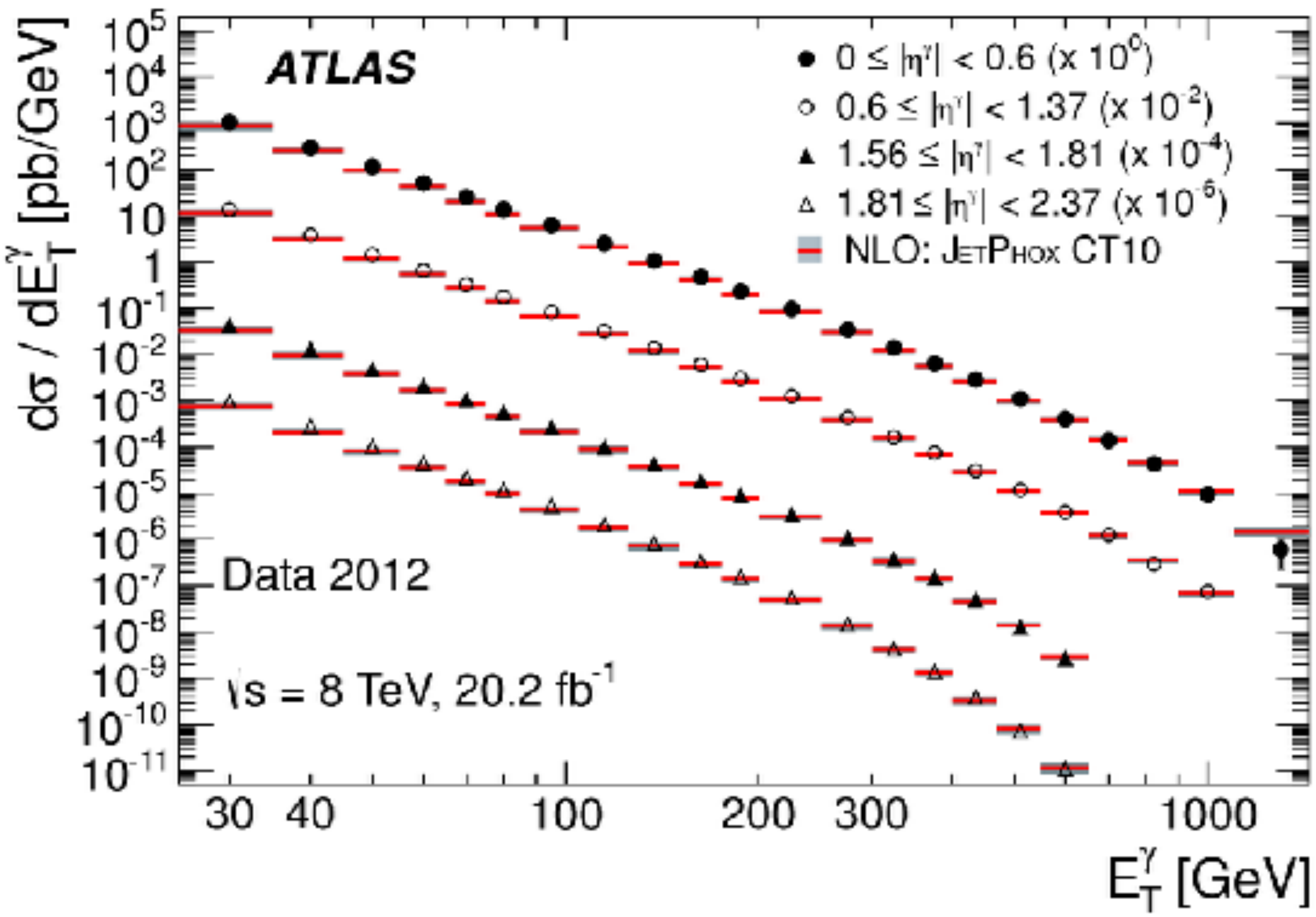




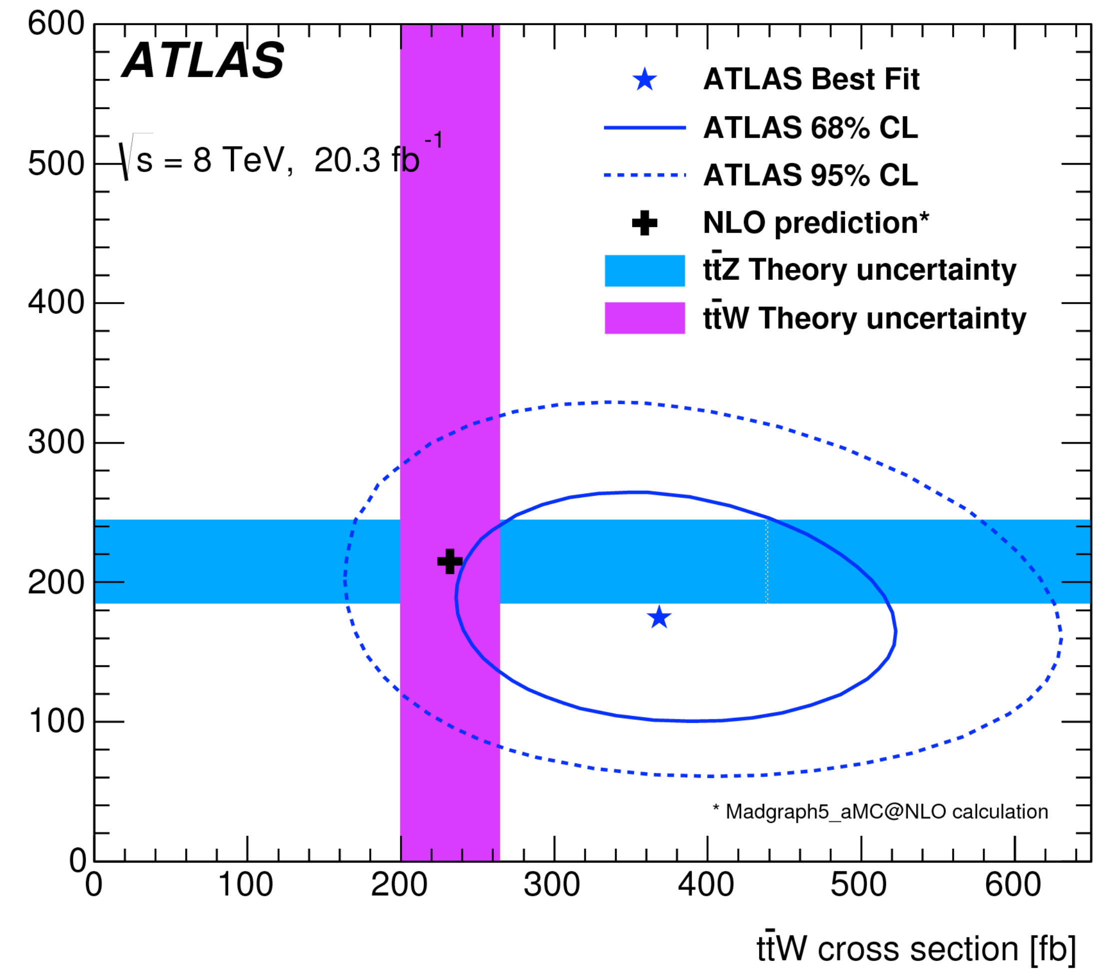
Closing remarks...

I performed two standard model measurements

Photon cross-section

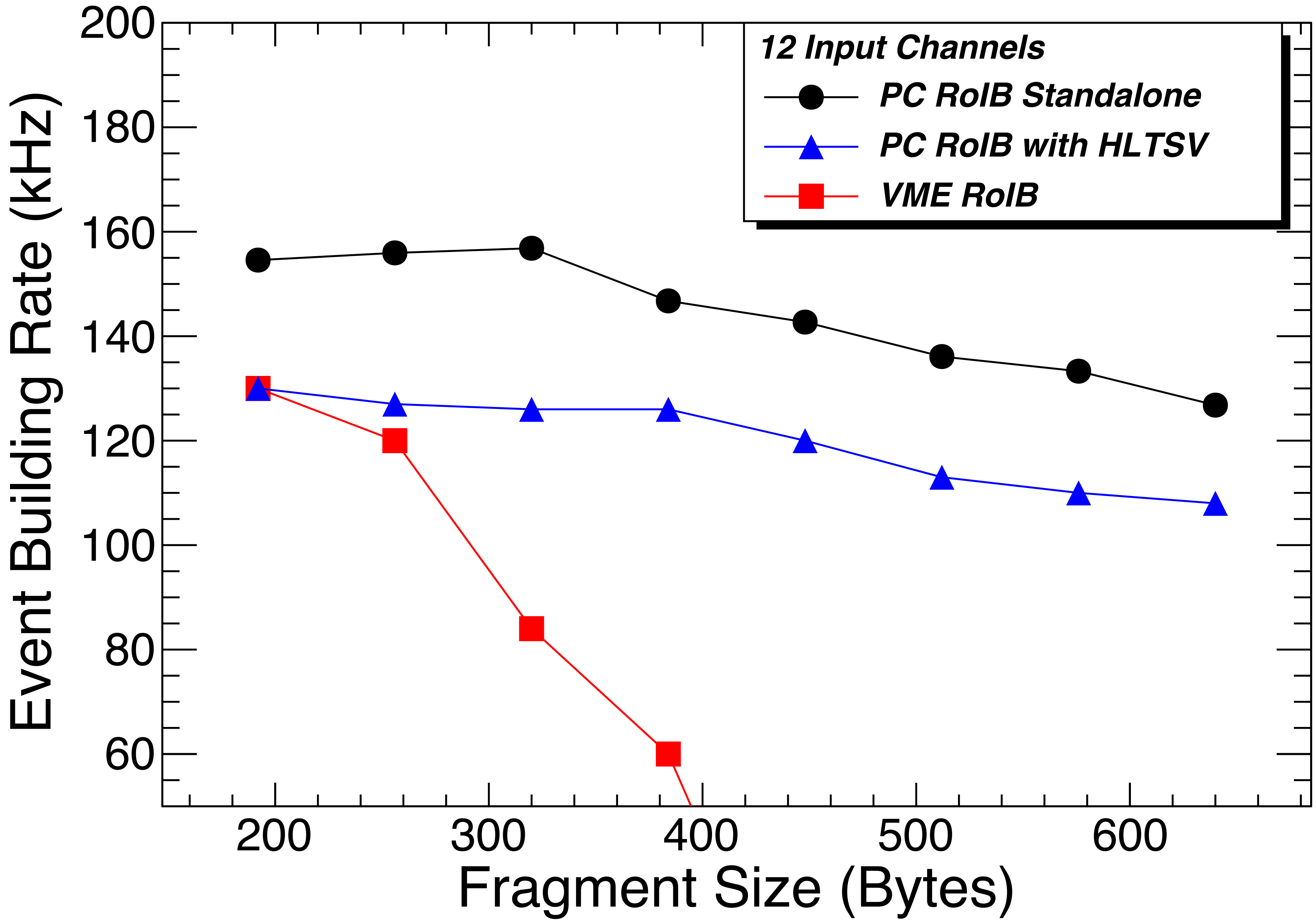


ttW, ttZ cross-section



Closing remarks...

I enabled a simplified readout architecture of ATLAS



Closing remarks…

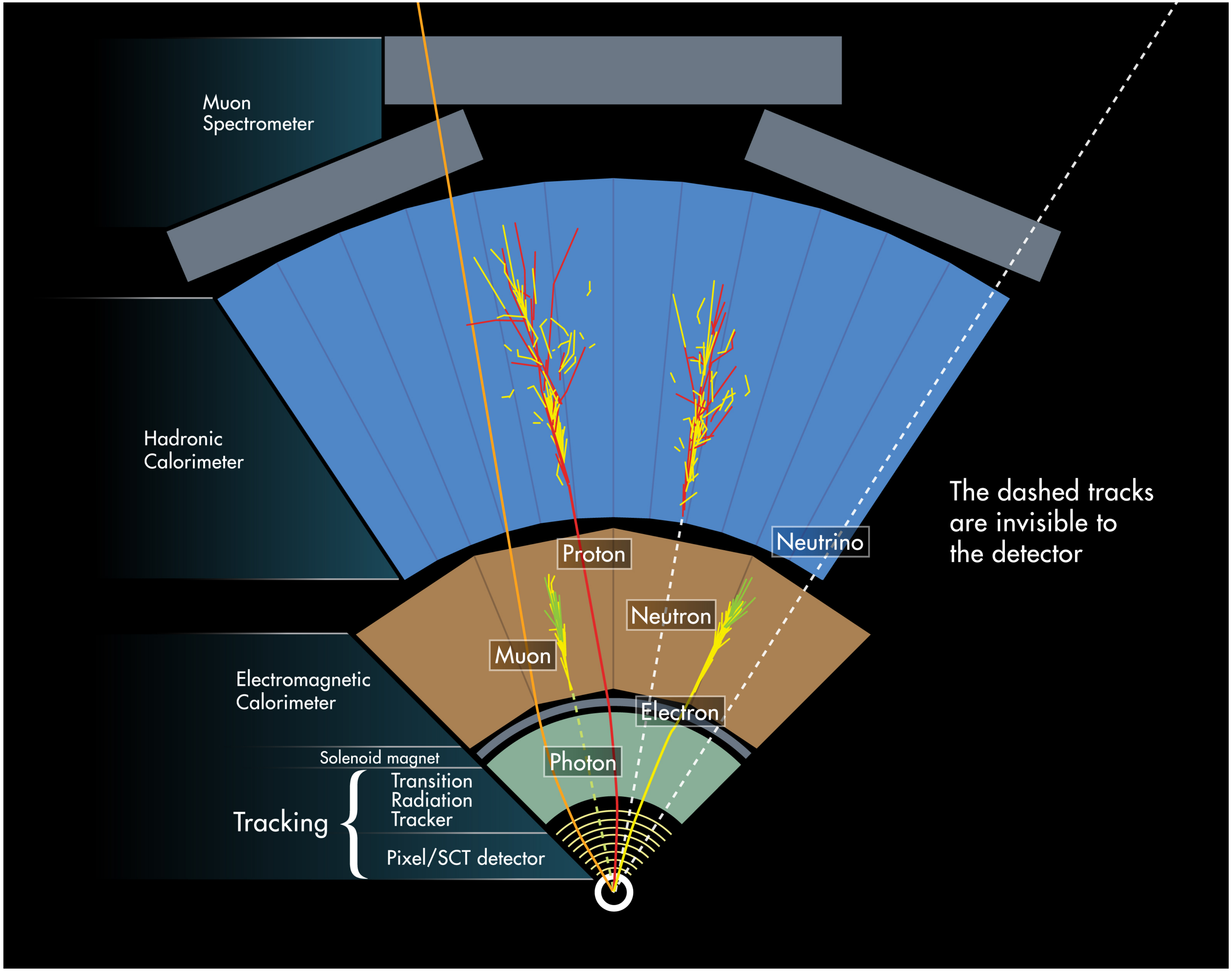
and I had a great time at CERN while analyzing the LHC data

Closing remarks…

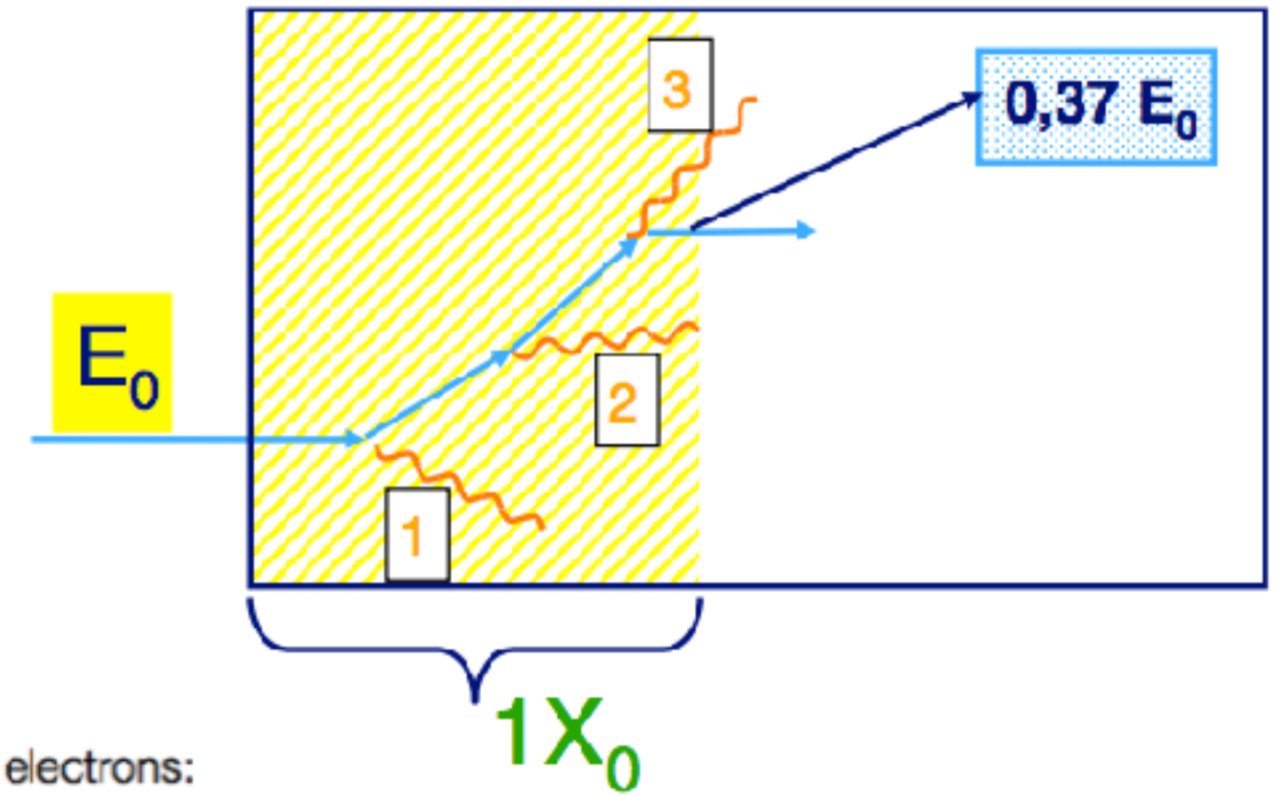
Thank you for your attention!

Backup

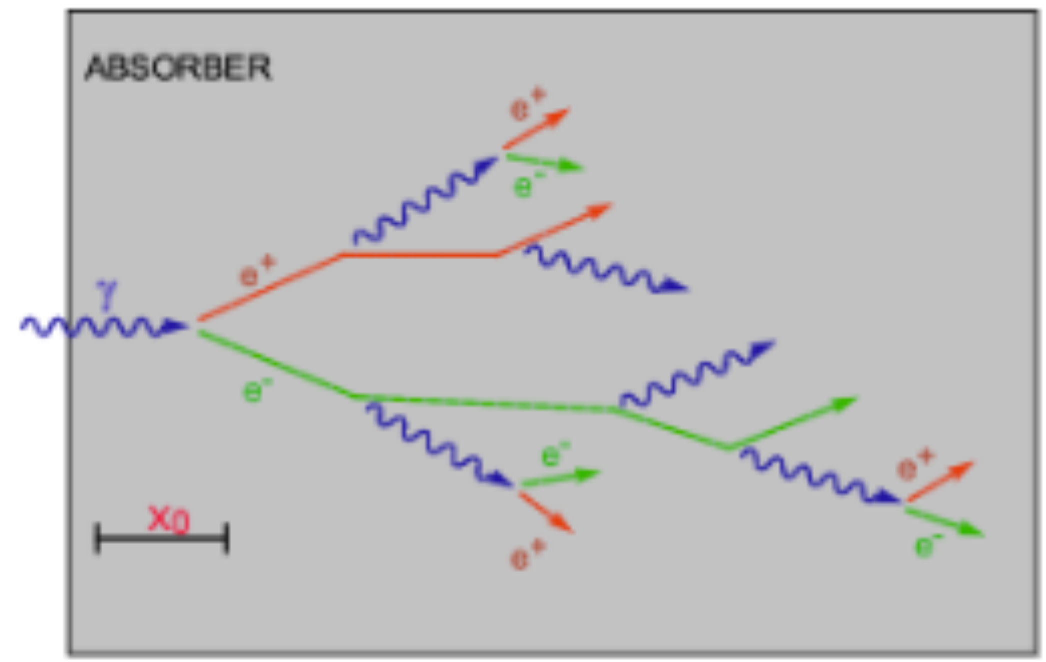
Particle Identification



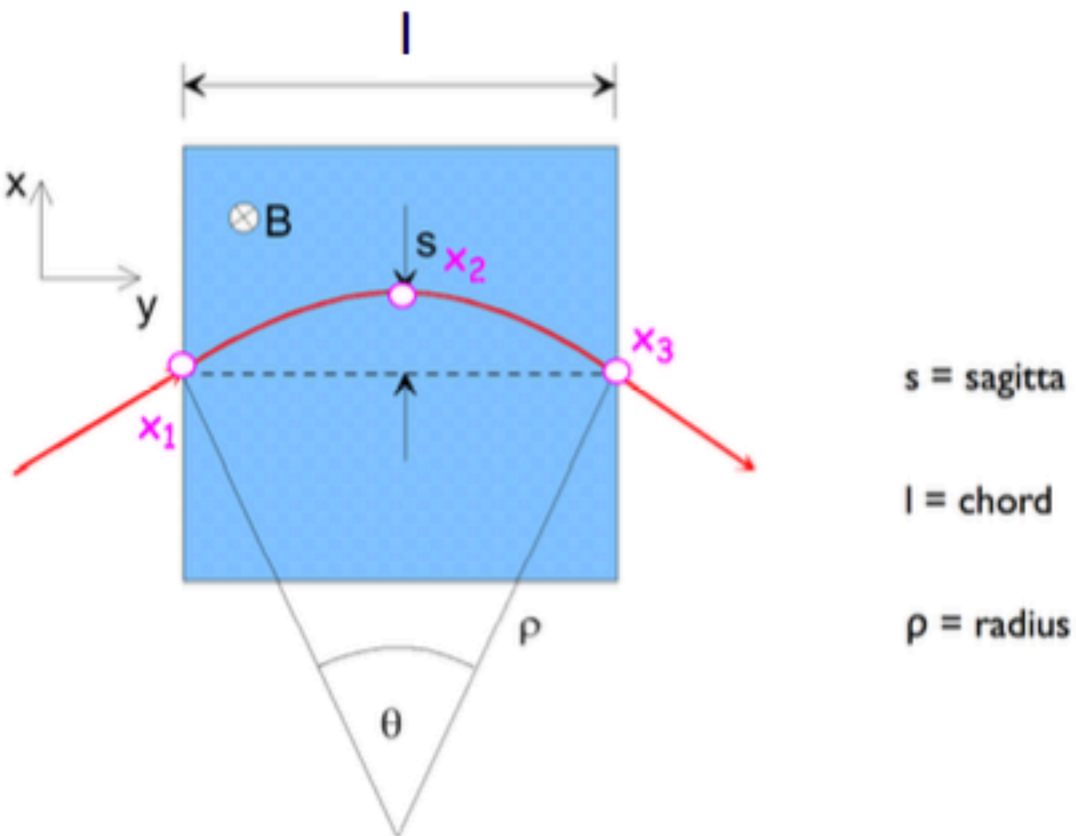
Radiation Length



r electrons:



Magnetic Analysis



$$\rho \simeq \frac{l^2}{8s} \qquad p = 0.3\frac{Bl^2}{8s} \qquad \left|\frac{\delta p}{p}\right| = \left|\frac{\delta s}{s}\right|$$

Charged particle of momentum p in a magnetic field B

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

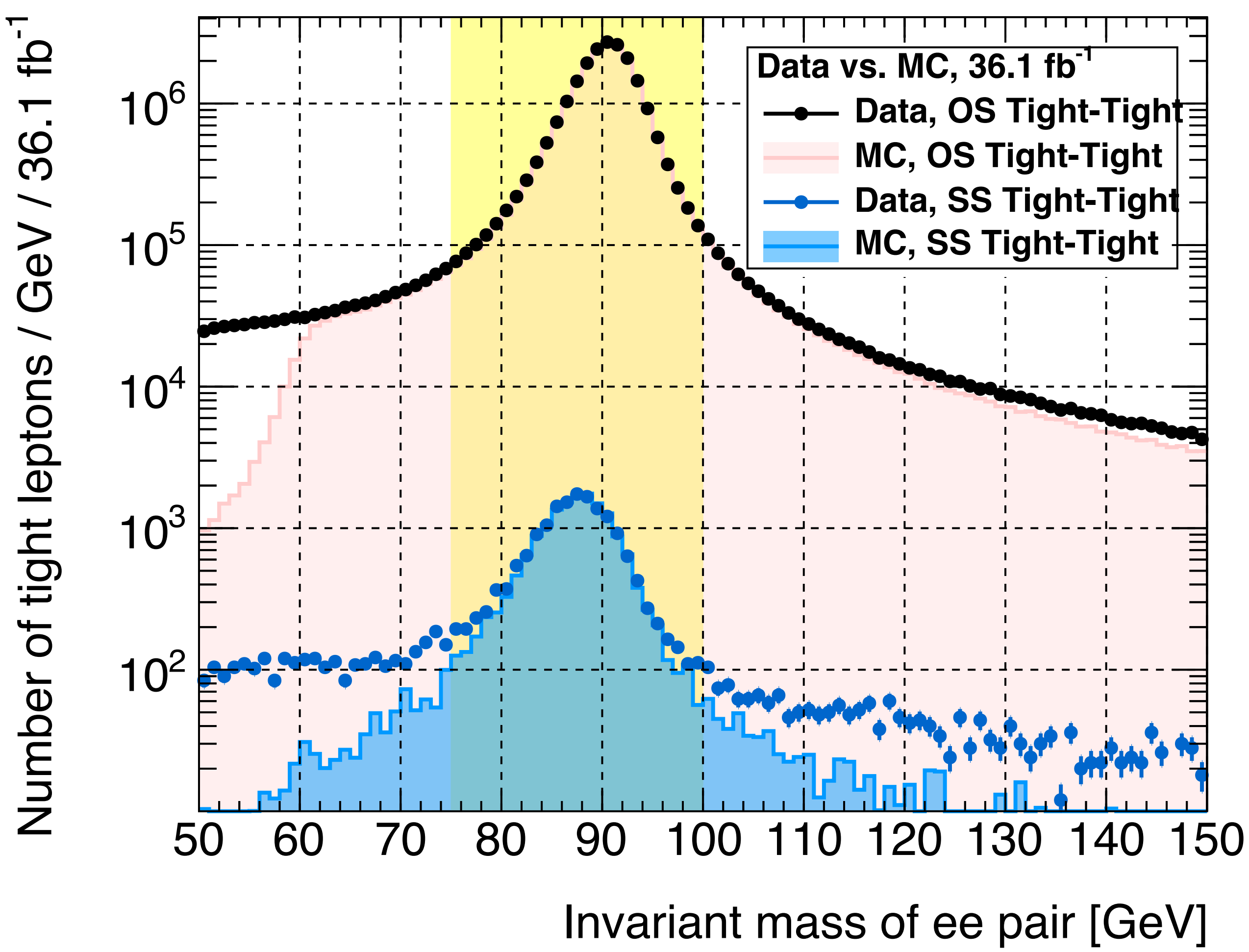
MC Samples

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

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

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



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:

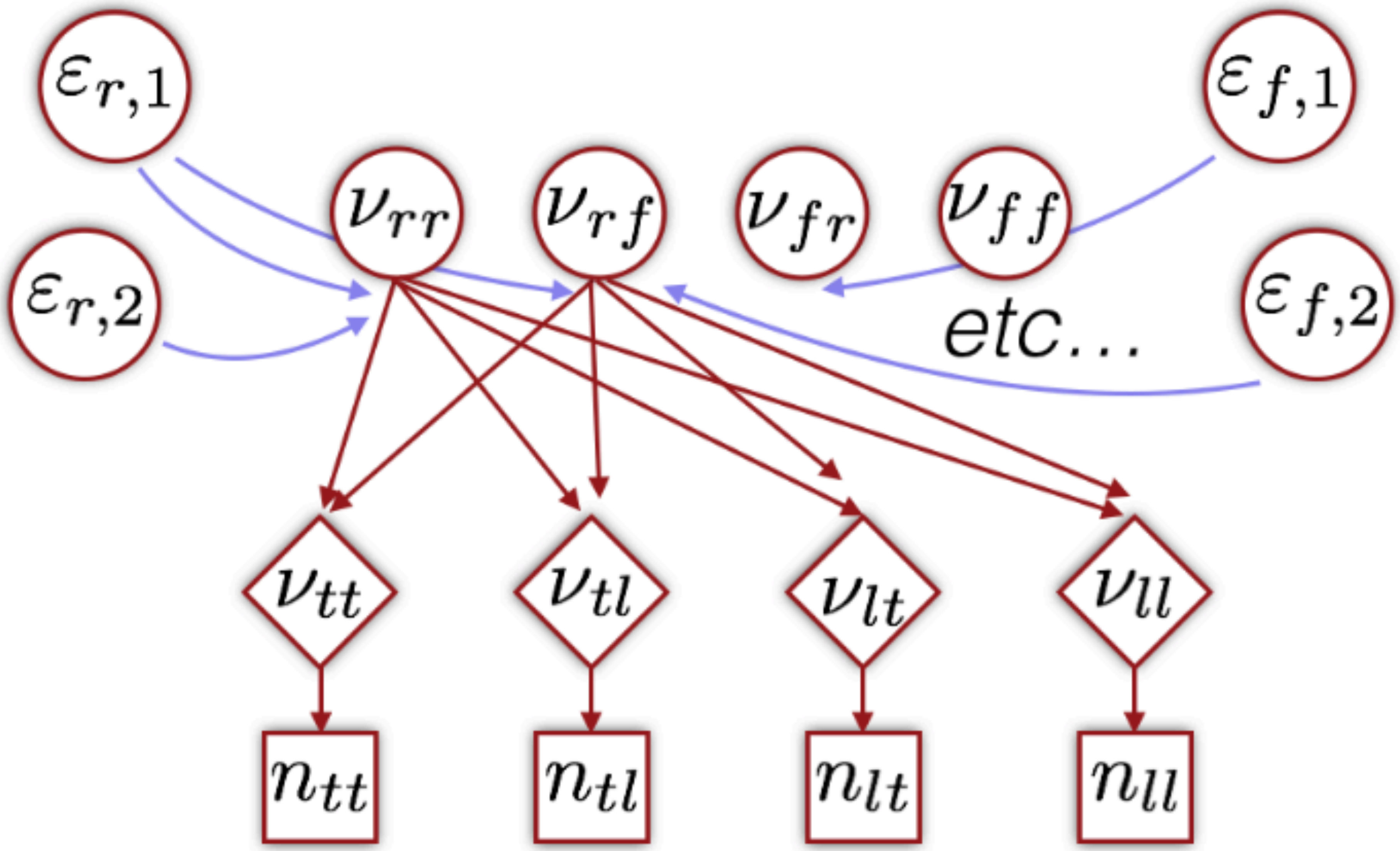
$$(w\zeta_1 + (1-w)\zeta_2) \pm \sqrt{w^2\left(\Delta\zeta_1^{(\mathrm{stat})}\right)^2 + (1-w)^2\left(\Delta\zeta_2^{(\mathrm{stat})}\right)^2} \pm \left(w\Delta\zeta_1^{(\mathrm{syst})} + (1-w)\Delta\zeta_2^{(\mathrm{syst})}\right)$$

$$\text{with } w = \frac{\left(\Delta\zeta_2^{(\mathrm{stat})}\right)^2}{\left(\Delta\zeta_1^{(\mathrm{stat})}\right)^2 + \left(\Delta\zeta_2^{(\mathrm{stat})}\right)^2}$$

ξ1: estimate from MxM
ξ2: estimate from MC template

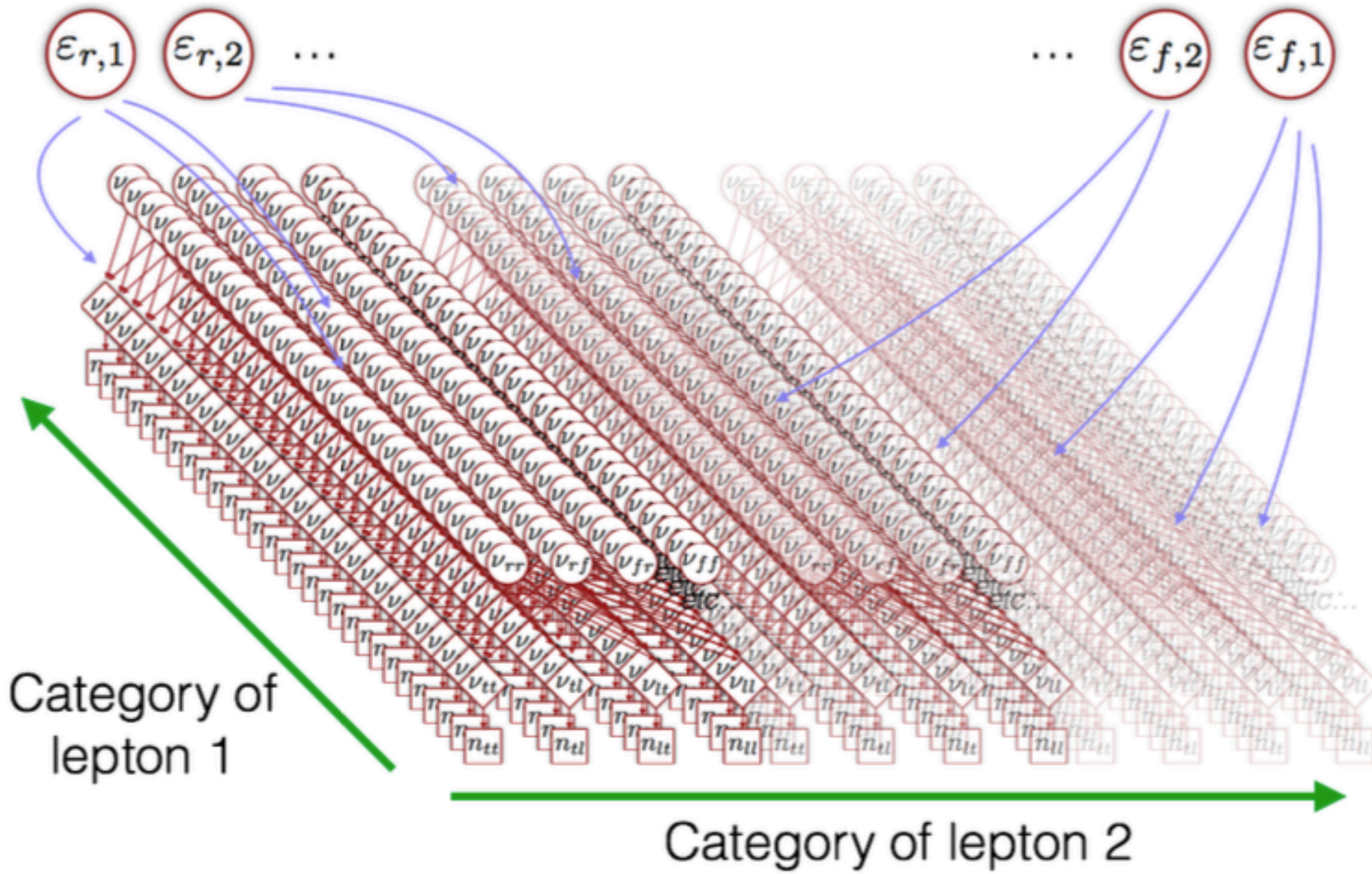
Matrix Method

2-leptons case in one category:



Matrix Method

2-leptons case in multiple categories:



Real efficiency uncert.

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

efficiency loss (electrons)								
$\Delta R(e, jet)$	[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%

efficiency loss (muons)								
$\Delta R(\mu, jet)$	[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

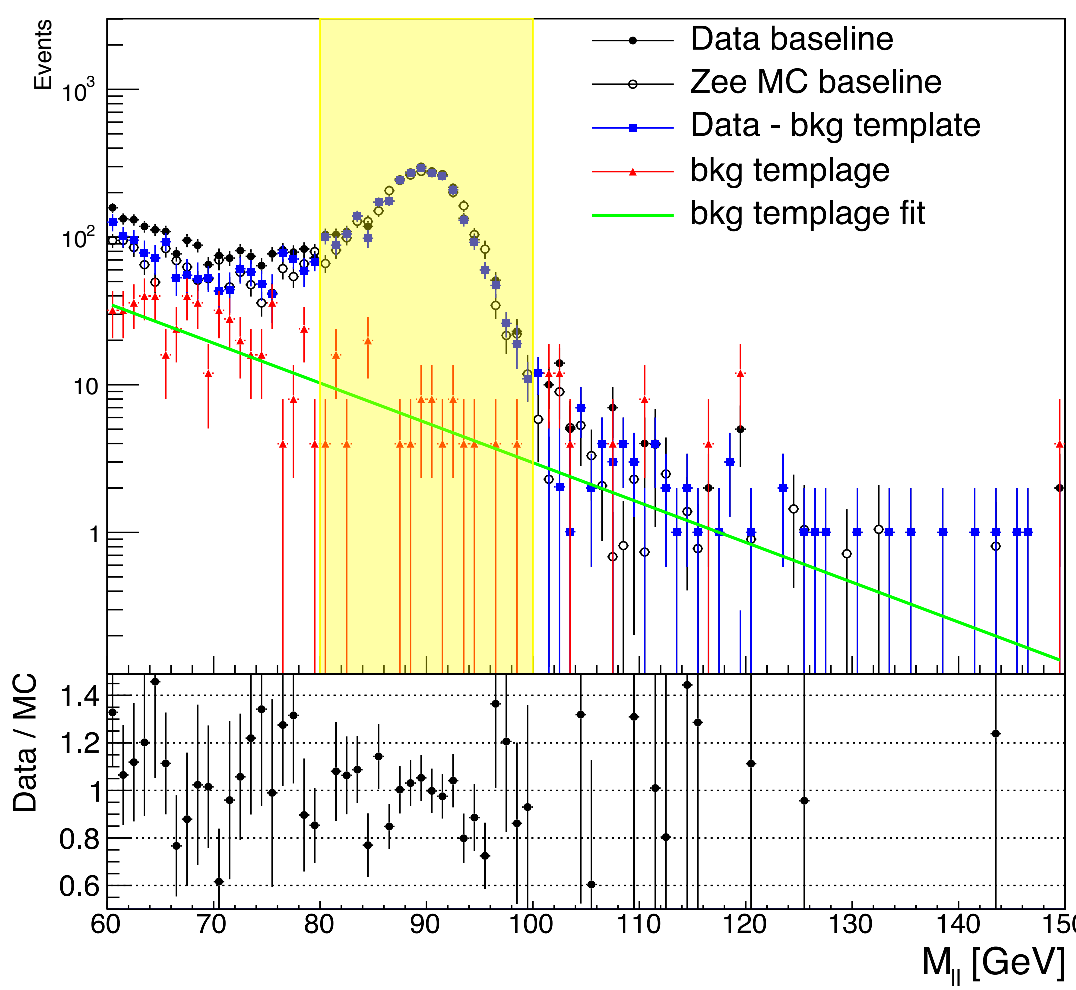
$$N^{BKG}_{baseline} = \int_{80}^{100} dM_{\ell\ell} N_{Template}\left[\frac{N^{Tail}_{baseline} - N^{MC,Tail}_{signal}/\epsilon^{MC}_{real}}{N^{Tail}_{Template}}\right]$$

$N^{Tail}_{baseline} = N^{Tail}_{BKG} + N^{Tail}_{contamination}$

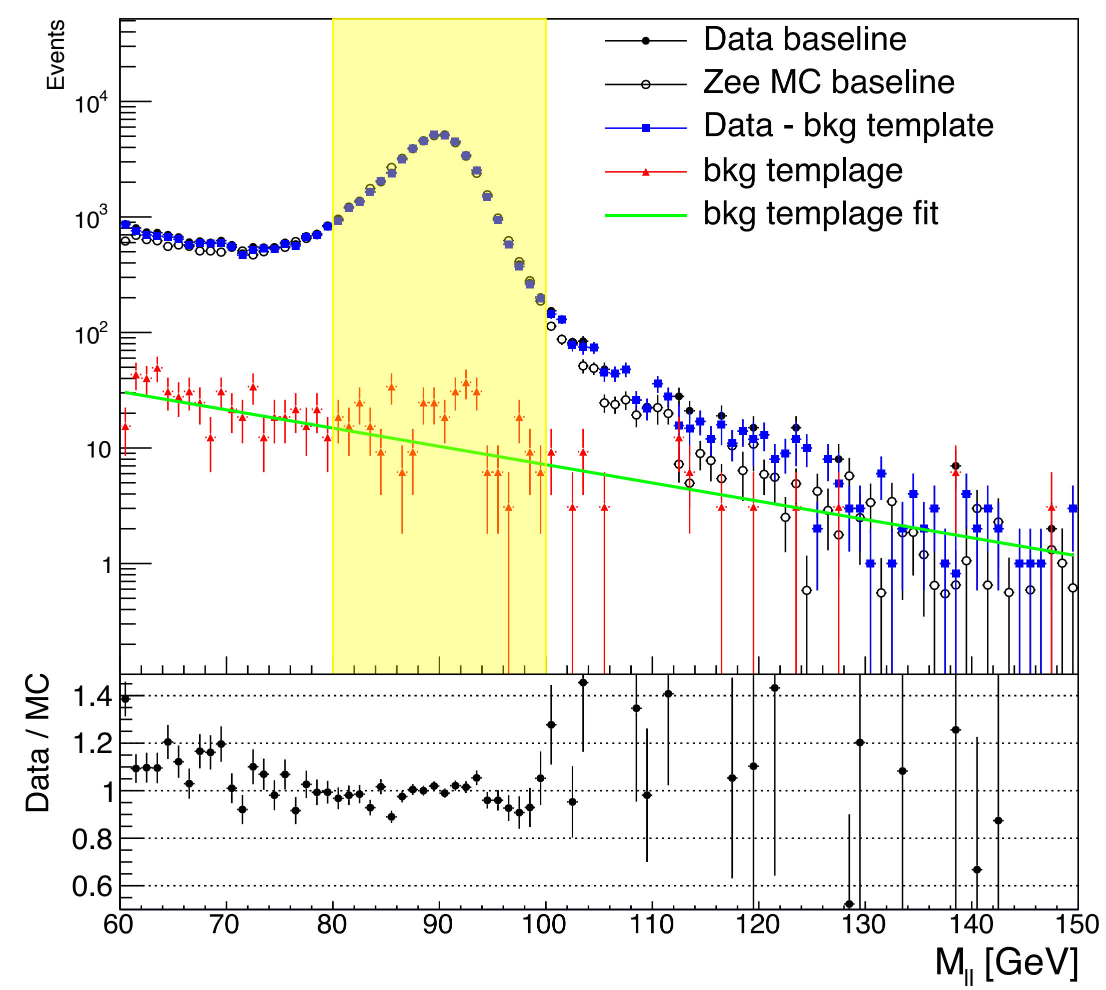
The signal contamination in the tail region are estimated using MC:

$N^{Tail}_{contamination} = N^{MC,Tail}_{signal}/\epsilon^{MC}_{real}$

10<pT<15GeV

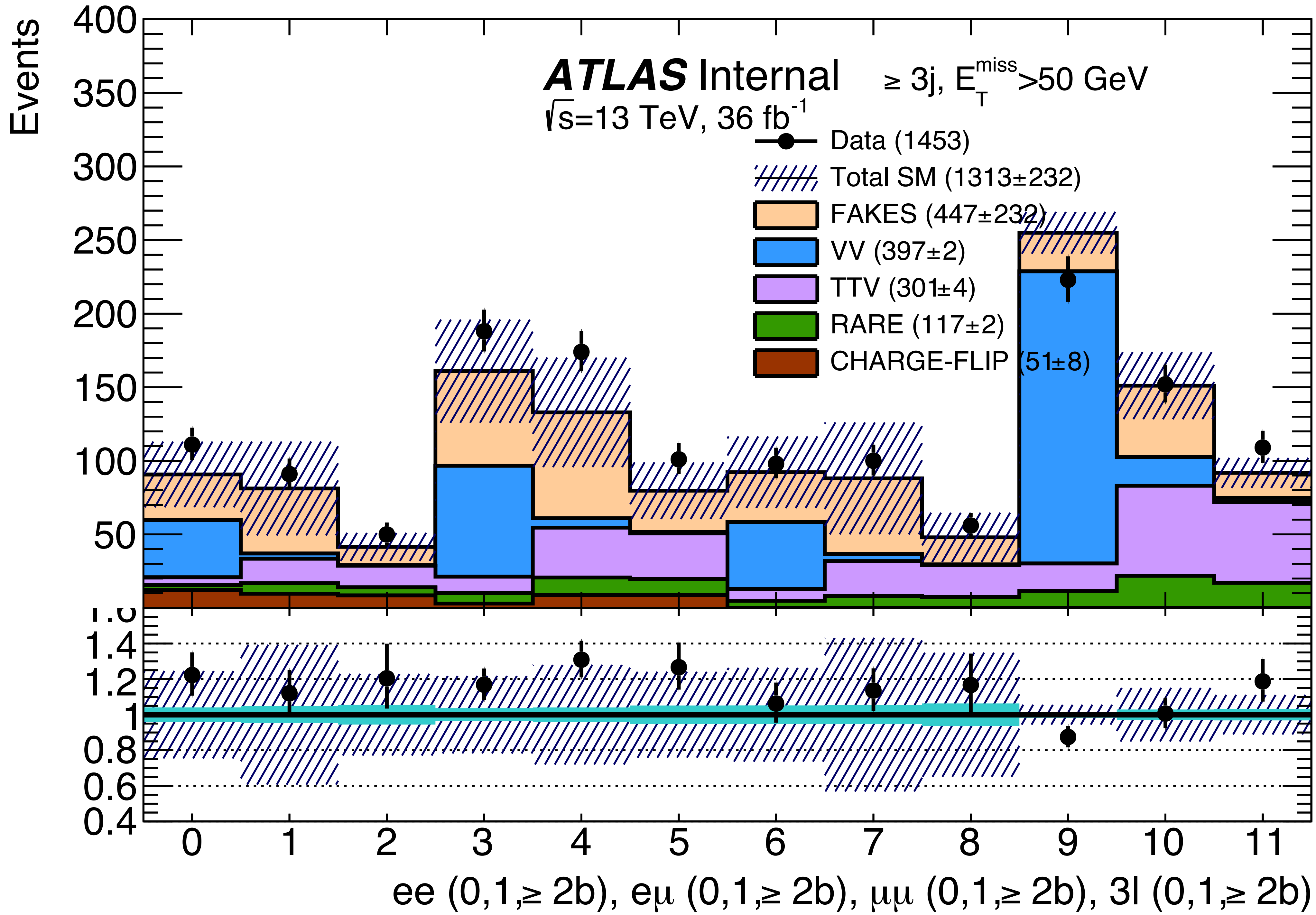


15<pT<20GeV



Validation of fake estimates

- Good agreement in inclusive SS/3L selection with MET>50GeV, >=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

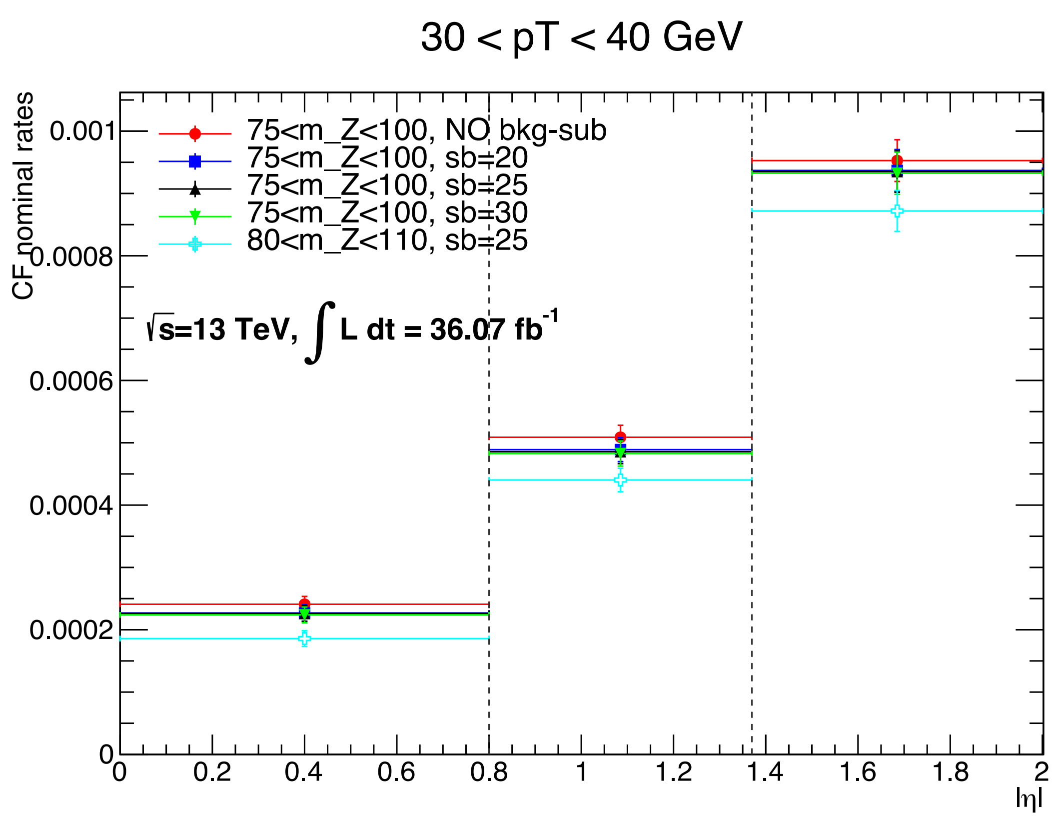
	$N_{\text{lept}}^{\text{signal}}$ ($N_{\text{lept}}^{\text{base}}$)	$N_{b-\text{jets}}$	N_{jets}	jet p_{T} [GeV]	$E_{\text{T}}^{\text{miss}}$ [GeV]	m_{eff} [GeV]	Other
$W^{\pm}W^{\pm}$-VR	=2 (=2) =1 SS pair	==0	≥ 2	> 50	> 55	> 650	veto $81 < m_{ee} < 101$ GeV $p_{\text{T}}(\ell_2) > 30$ GeV $\min\{\Delta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

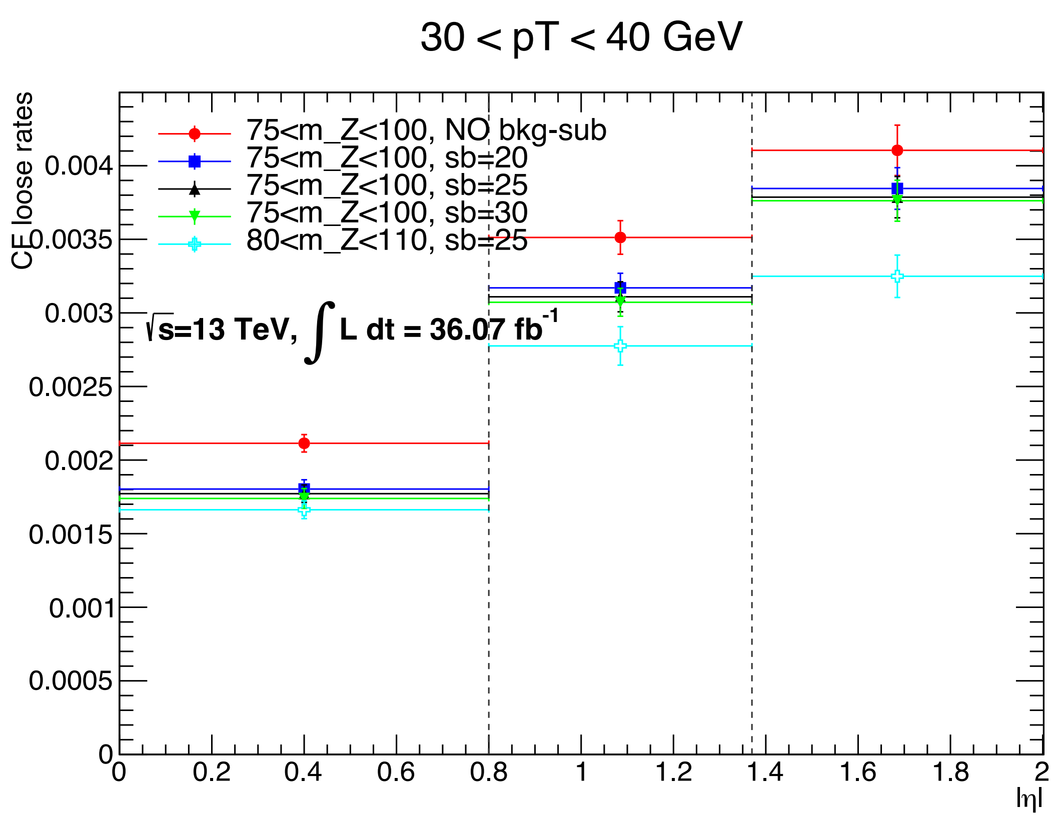
separate estimates from the matrix and MC template methods:

	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





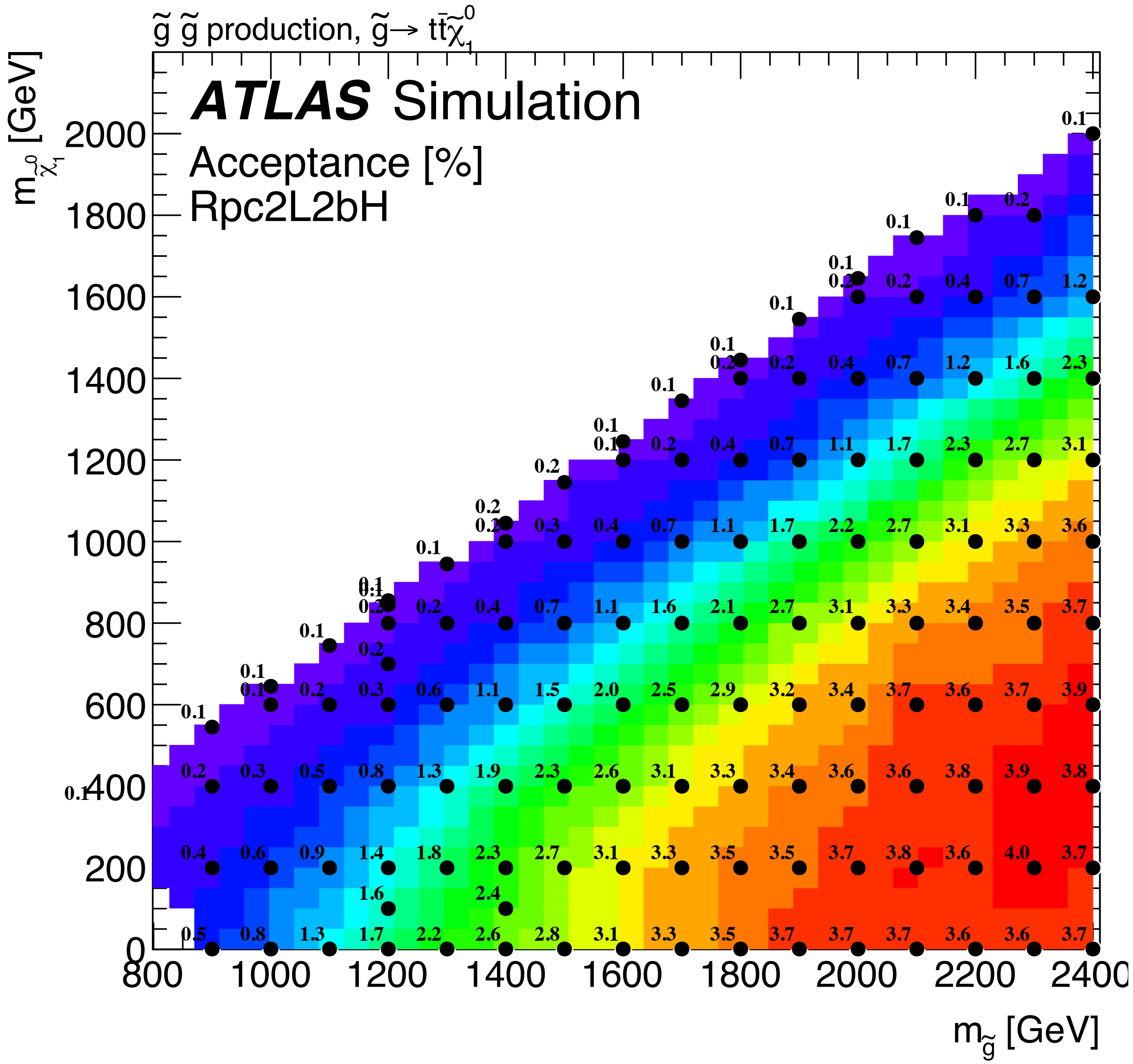
Uncertainties

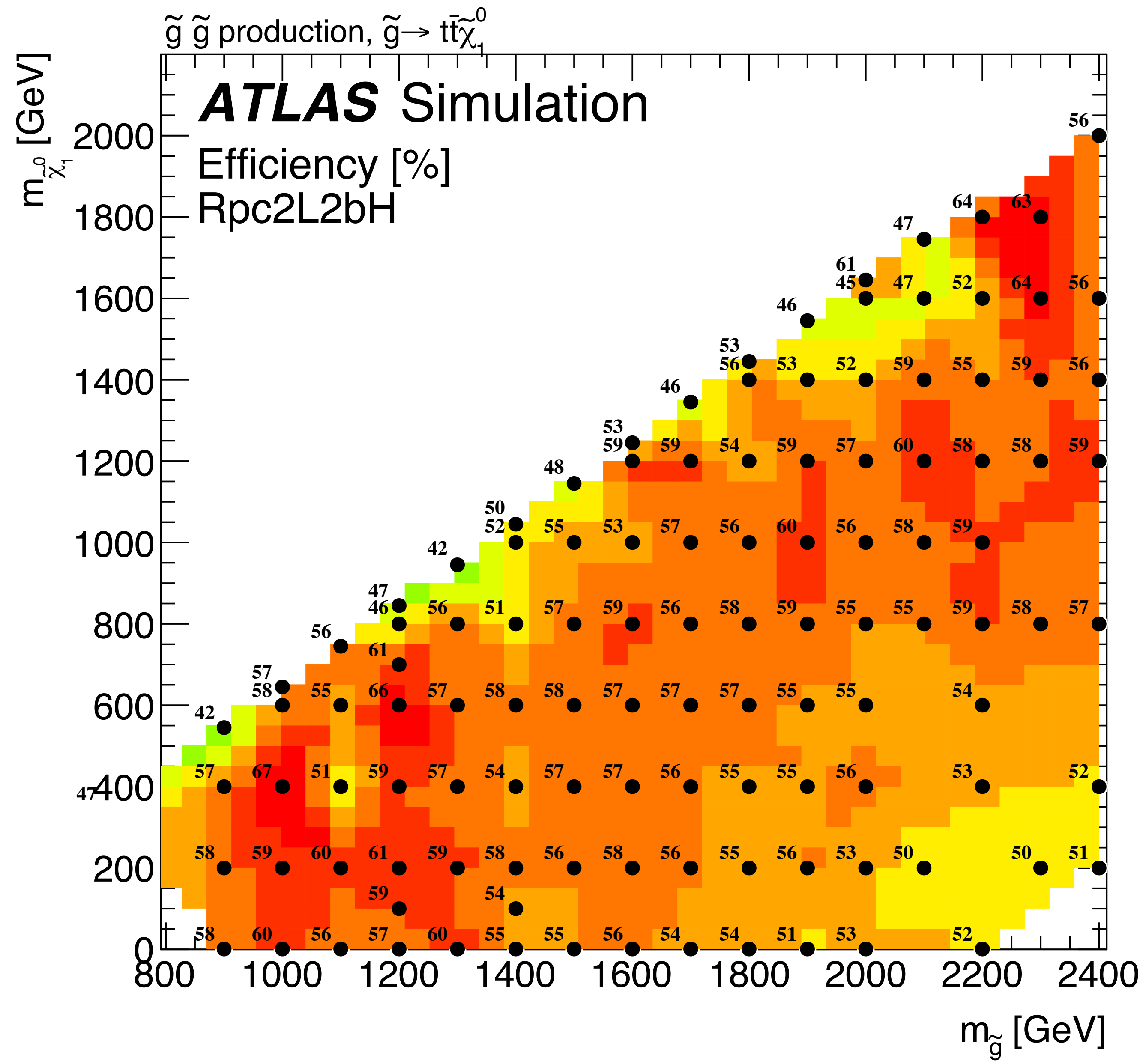
Signal Region	Rpc2L2bS	Rpc2L2bH	Rpc2Lsoft1b	Rpc2Lsoft2b	Rpc2L0bS	Rpc2L0bH
Total background expectation	3.35	1.08	5.78	3.80	6.02	2.35
Total statistical	10.56%	15.67%	16.93%	15.61%	9.08%	20.87%
Total background systematic	30.41%	29.97%	43.10%	41.79%	30.51%	42.39%
Fake/non-prompt	15.46%	0.00%	38.39%	35.75%	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

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





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.
- μ (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 μ 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.
- $m^2_{H_d}$ and $m^2_{H_u}$ are no longer set equal to m_0 at the GUT scale.

$$m^2_{H_d} \neq m^2_{H_u} \neq m^2_0$$

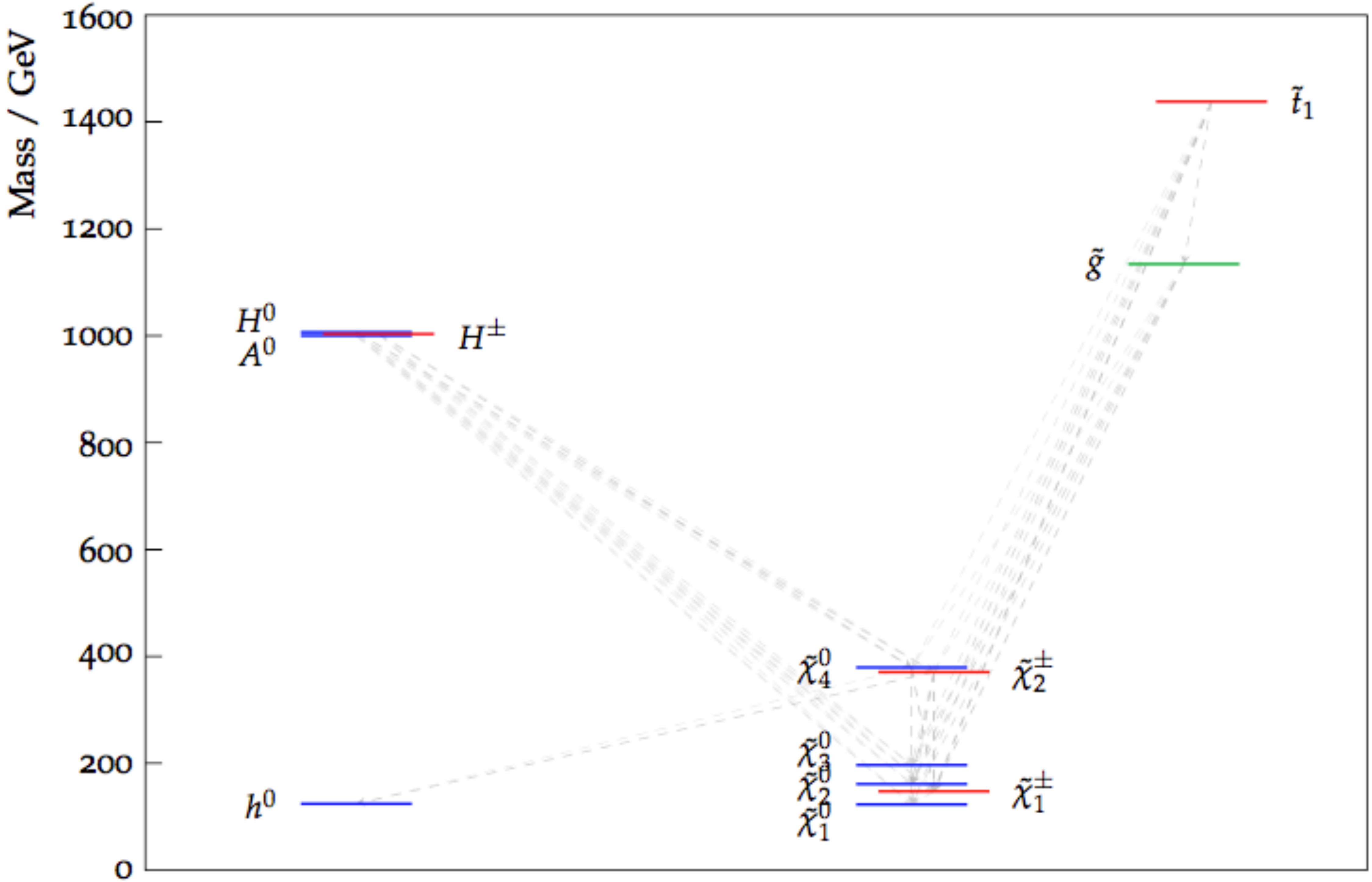
- Six free parameters: $m_0, m_{1/2}, A_0, \tan\beta, \mu, m_A$.

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

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

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

NUHM2



Mass / GeV
1600
1400
1200
1000
800
600
400
200
0
$\tilde{t}_1$
$\tilde{g}$
H^0
A^0
$H^\pm$
$\tilde{\chi}_4^0$
$\tilde{\chi}_2^\pm$
$\tilde{\chi}_3^0$
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^\pm$
h^0

Standard Model

interaction particles

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \bar{\psi}_i y_{ij}\psi_j\phi + \text{h.c.} + \left|D_\mu\phi\right|^2 - V(\phi)$$

interactions between matter particles

mass for antimatter particles

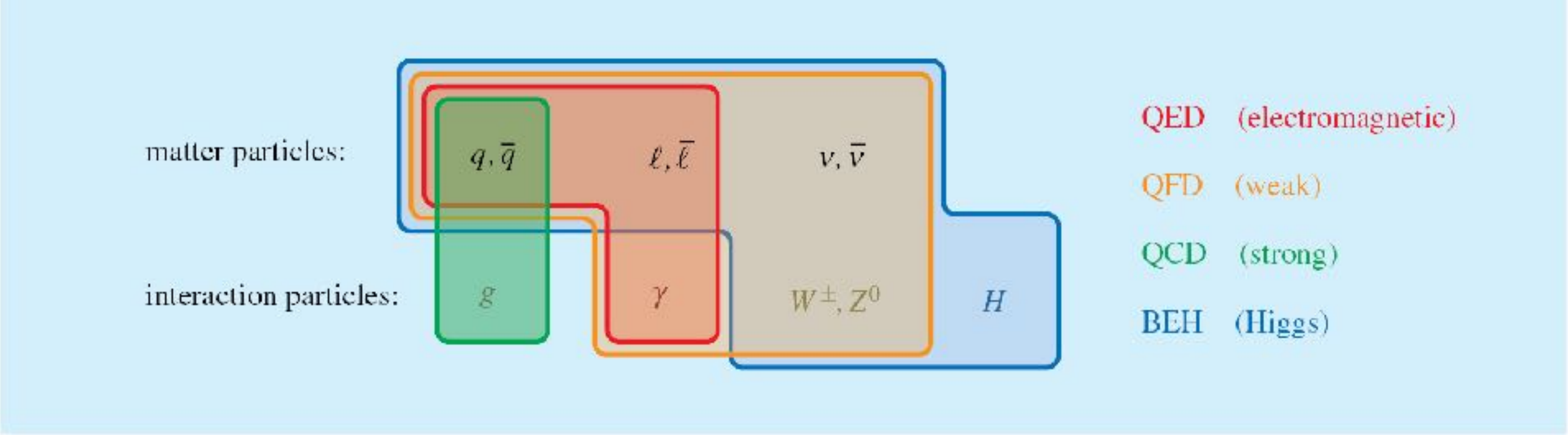
mass for matter particles

mass for interaction particles

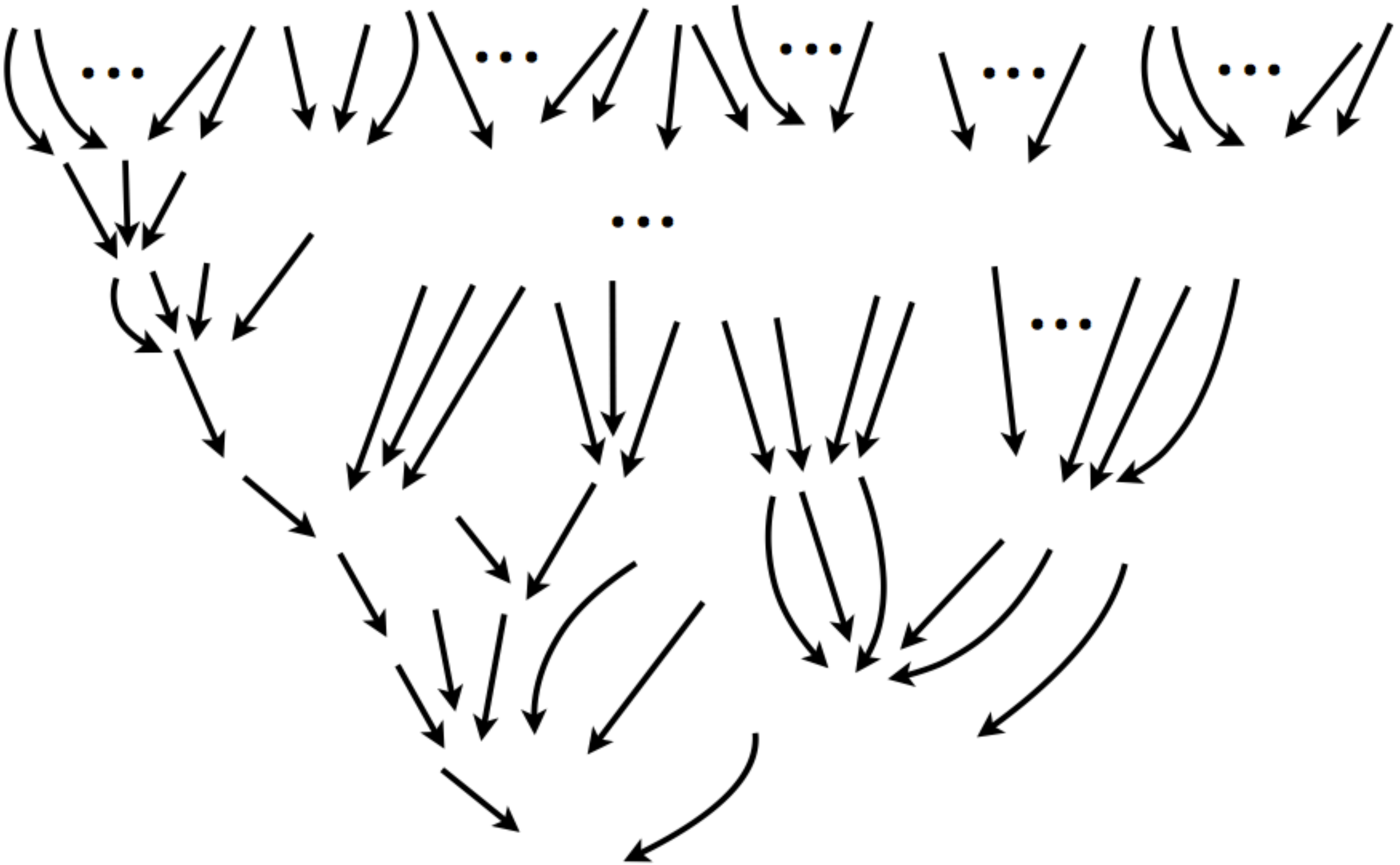
Higgs self-interactions

Standard Model

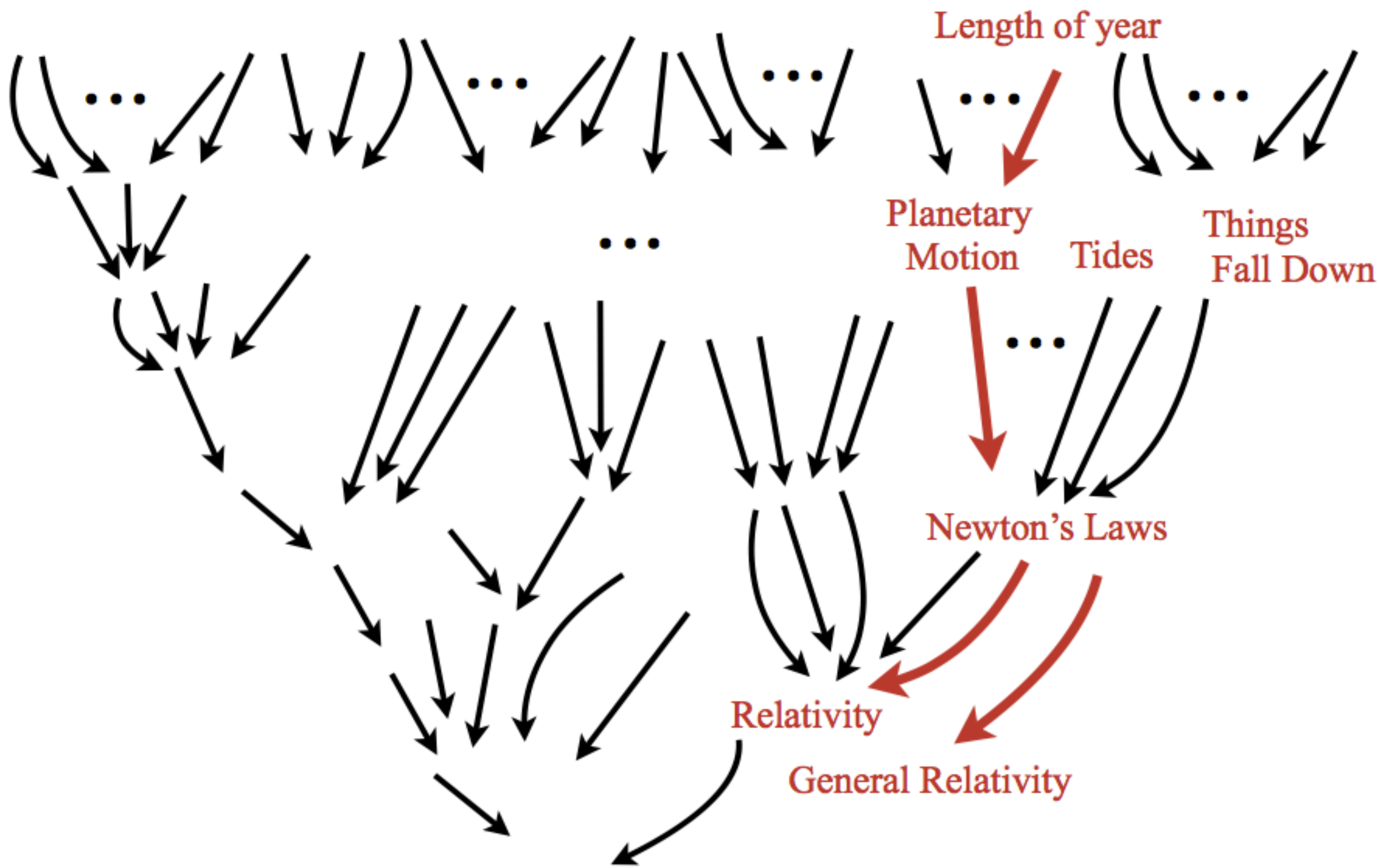
Consistent theory of strong, weak, and electromagnetic interactions



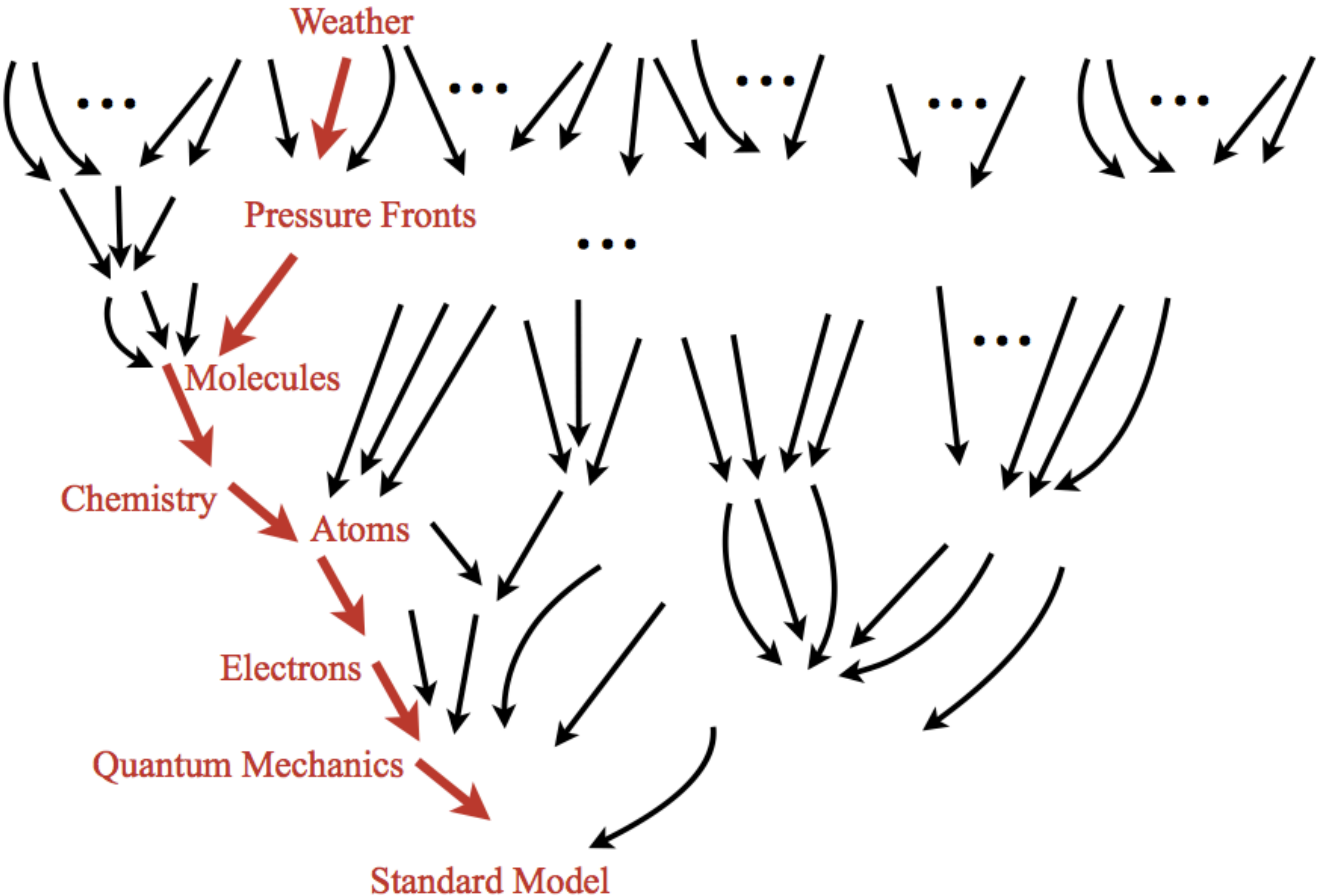
Scientific description



Scientific description



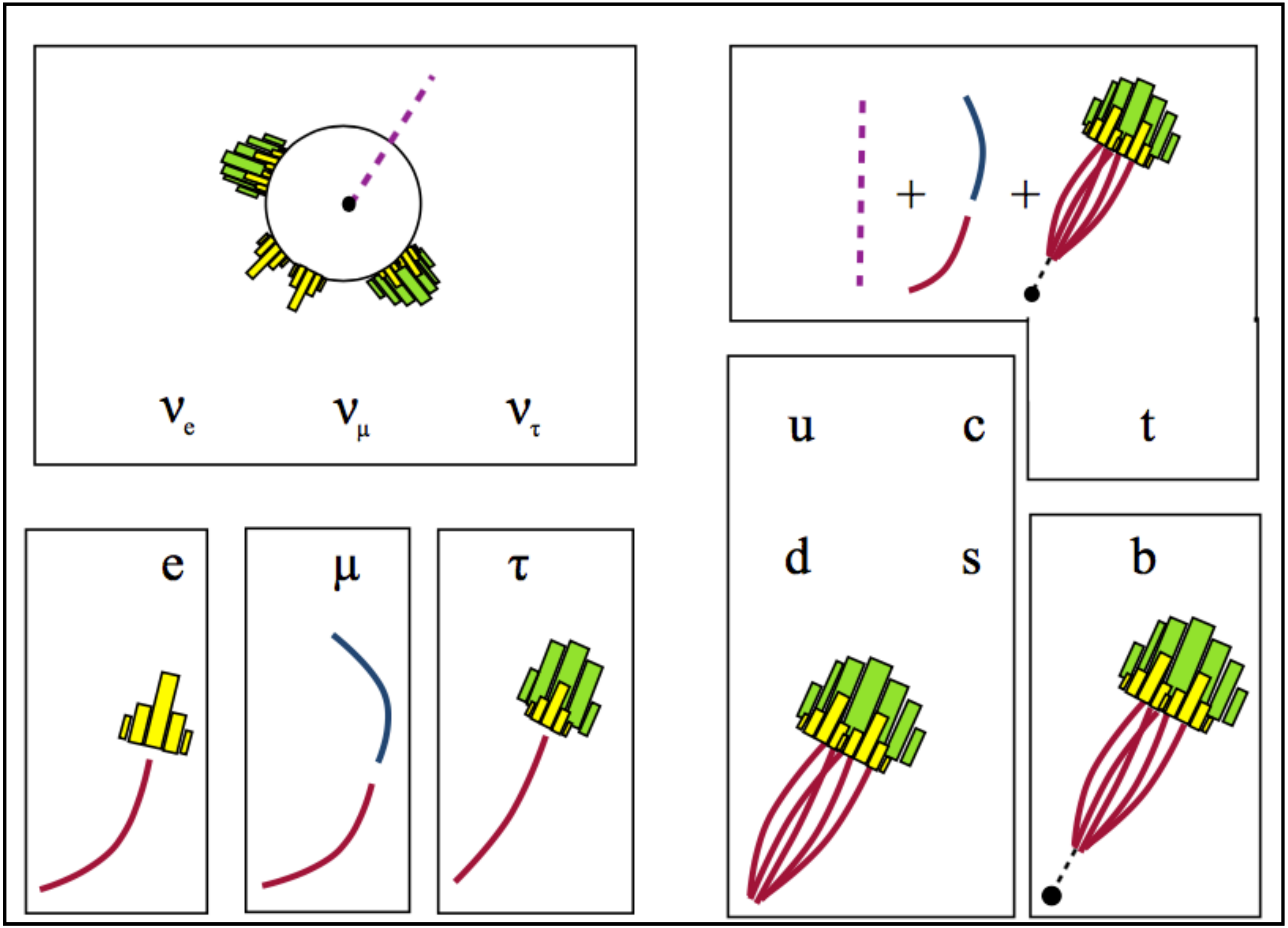
Scientific description



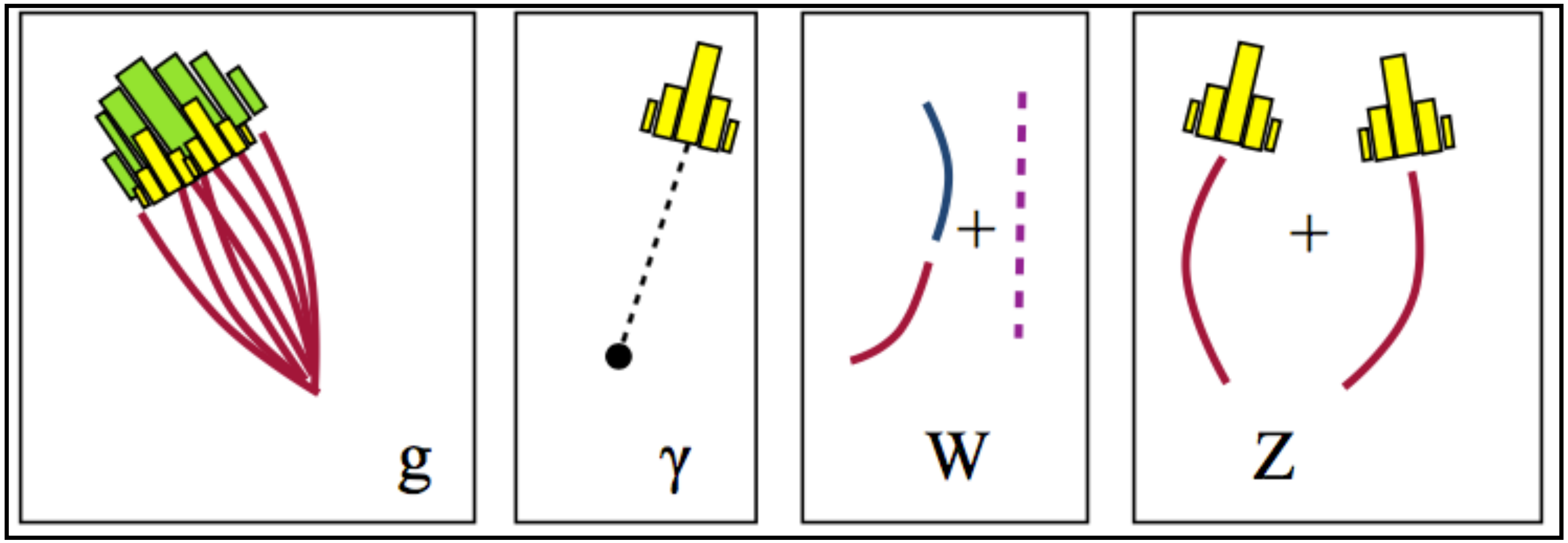
Identifying Particles

ν_e	ν_μ	ν_τ	u	c	t
e	μ	τ	d	s	b

Identifying Particles



Identifying Particles

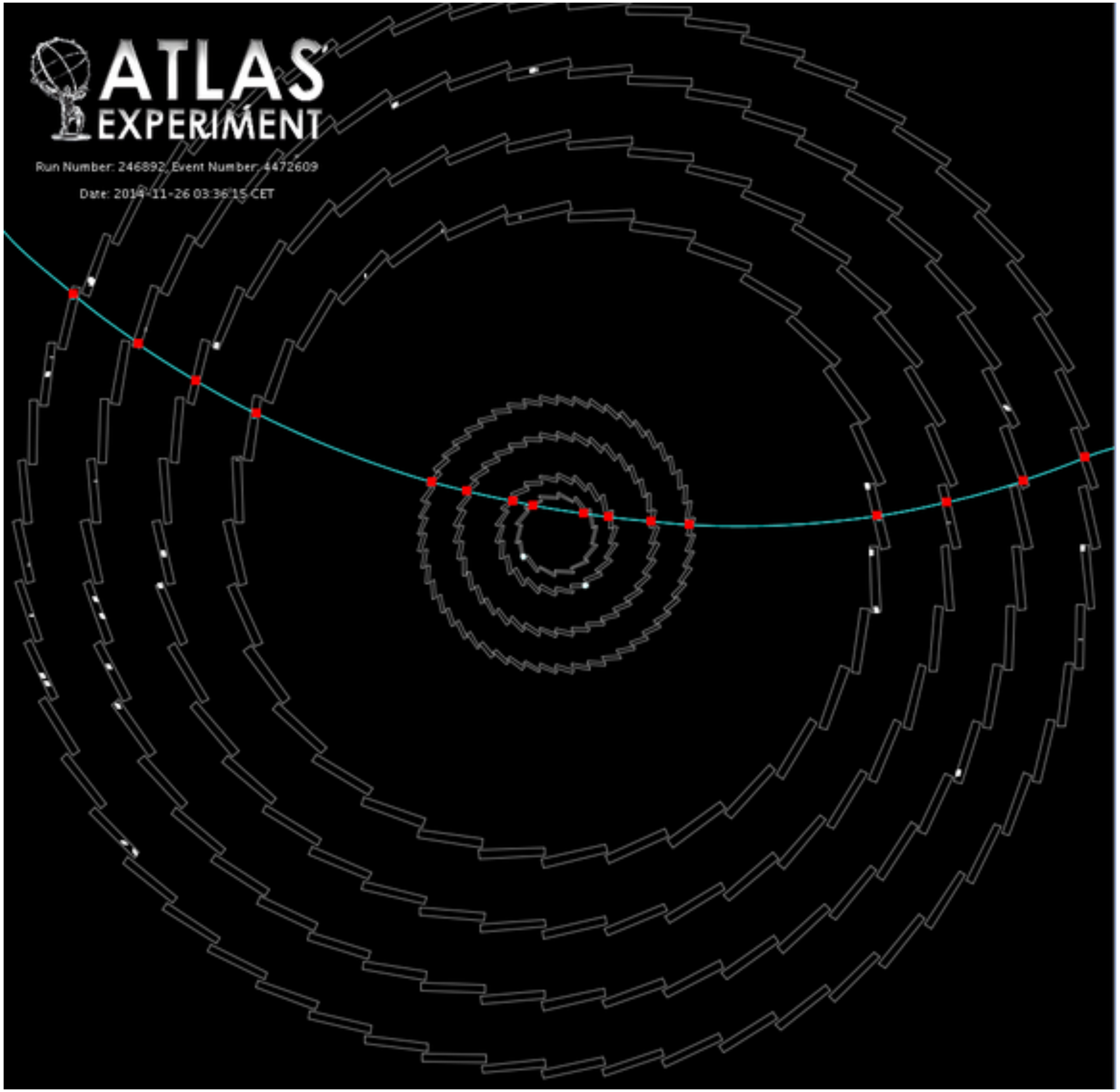


A lot of effort goes in the algorithms that identify these particles based on hits in the inner detectors and energy depositions in the calorimeters

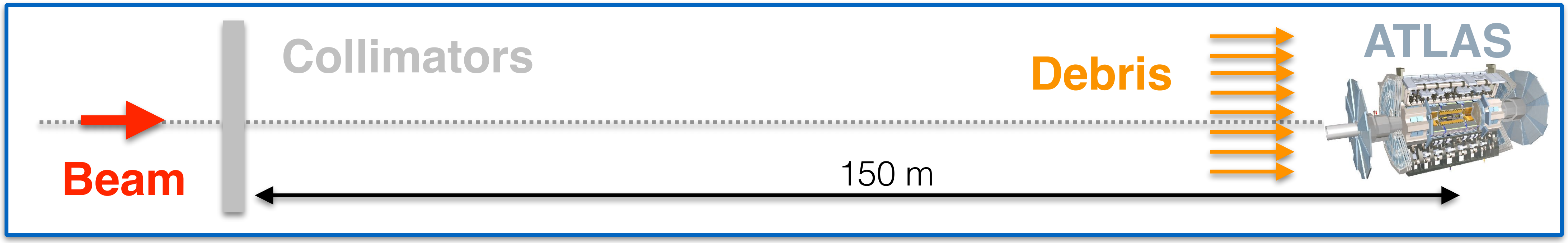
Cosmic Ray

Pre-data taking:

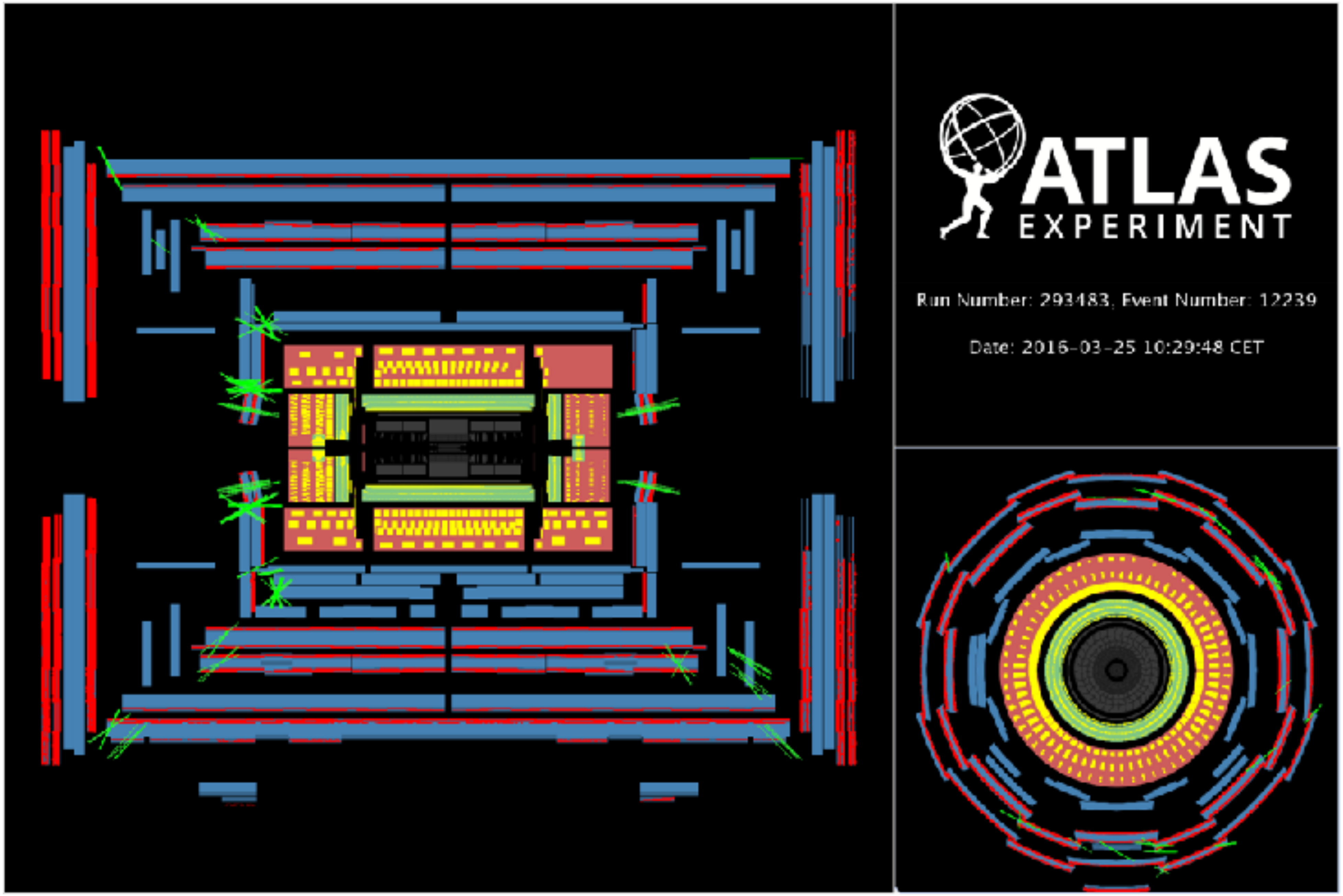
- ✓ Trigger&DAQ
- ✓ Inner detector
- ✓ Muon system
- ✓ Magnets!



Beam Splashes



Pre-data taking:
- ✓ Trigger&DAQ
- ✓ Inner detector
- ✓ Muon system
- ✓ Calorimeters



Statistics in a Nutshell

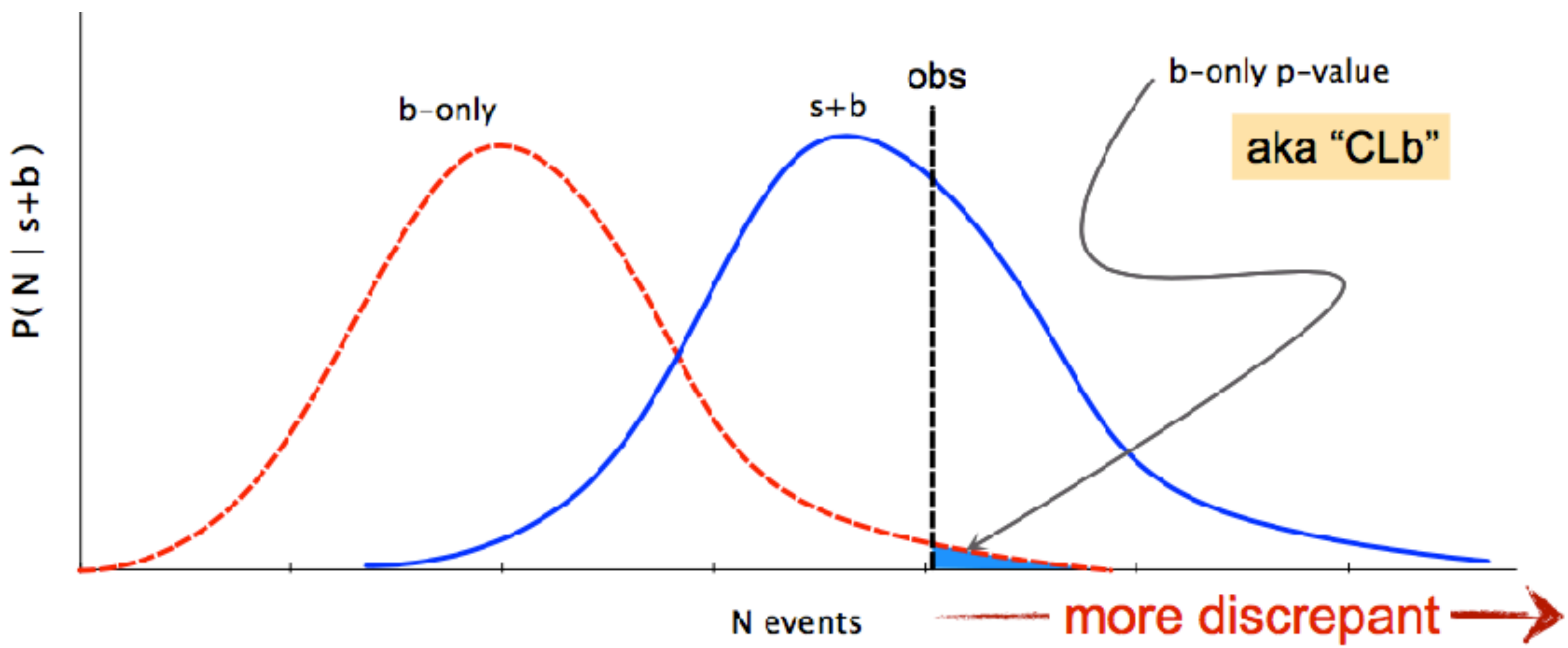
Question: Do we see evidence for SUSY in ATLAS data?

➡ **Yes?**
- What is the strength of the discovery?
- Calculate the significance of the excess

➡ **No?**
- What is the sensitivity of our experiment?
- Set a limit

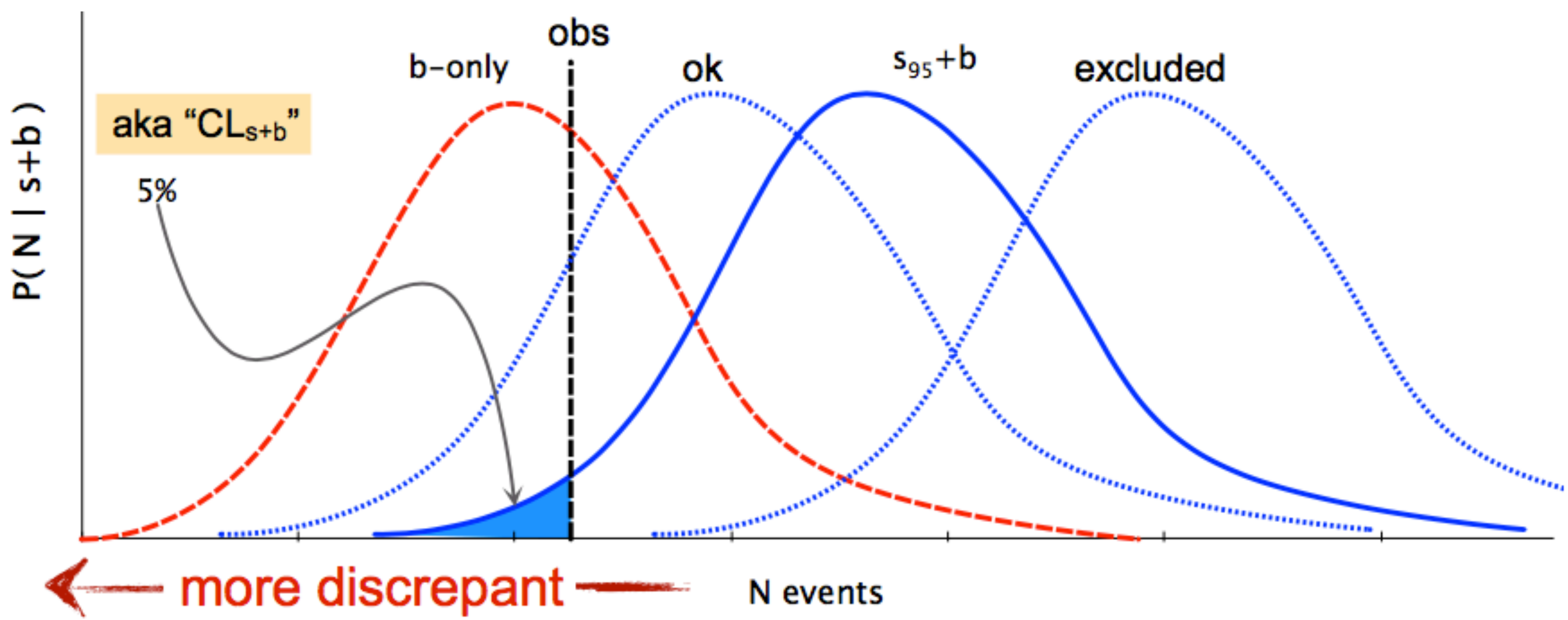
Statistics in a Nutshell

- 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



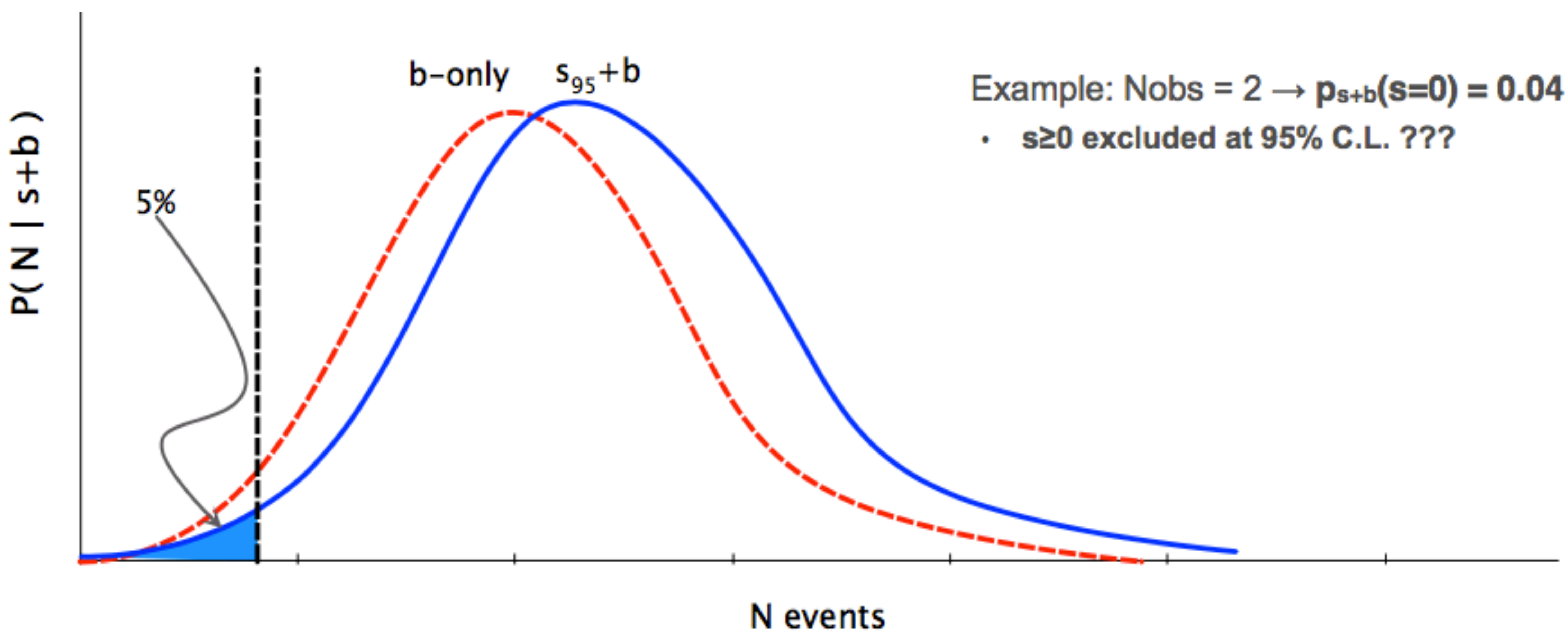
Statistics in a Nutshell

- 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

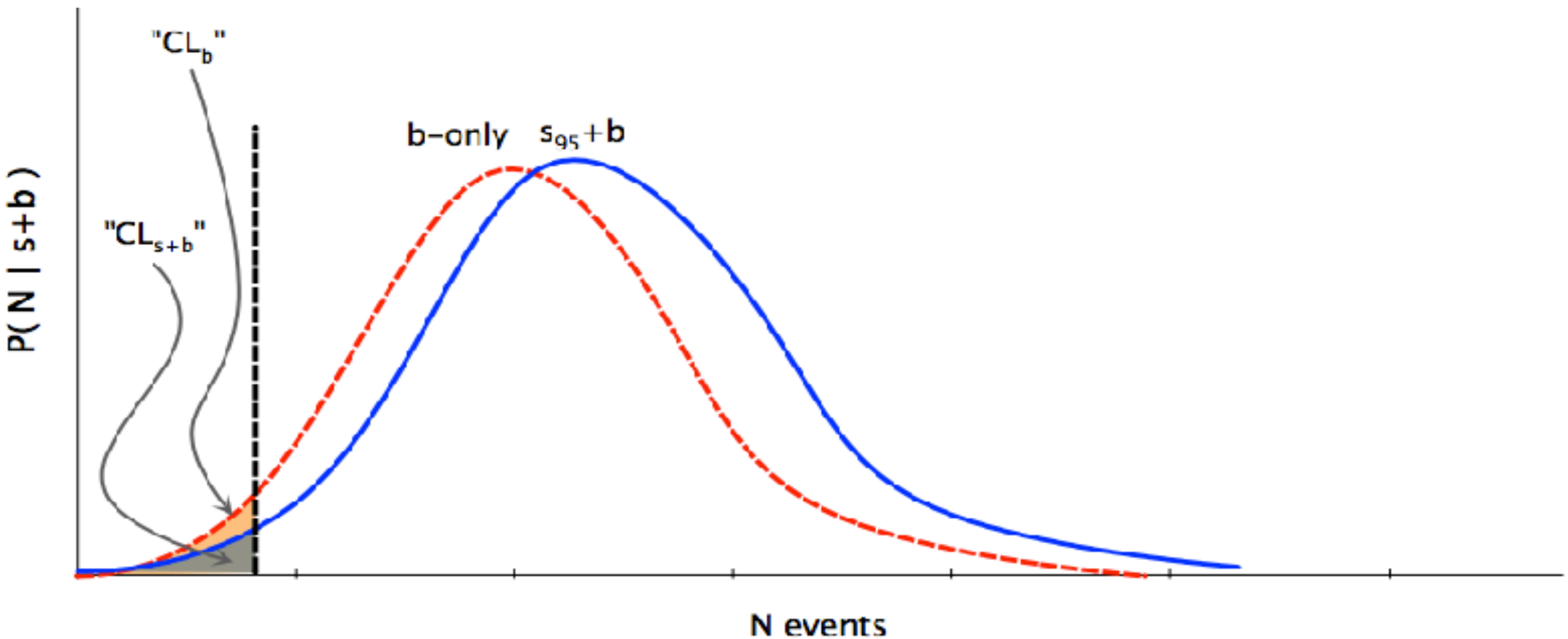
- Interpretation in terms of p_{s+b} only is problematic:
  - p_{s+b} quantifies consistency with data of signal + background
  - Problem when $s << b$
  - Problem when observed data has a downward fluctuation
- **Exclude arbitrary small values of s**
  5% of the time no matter how small s is!!



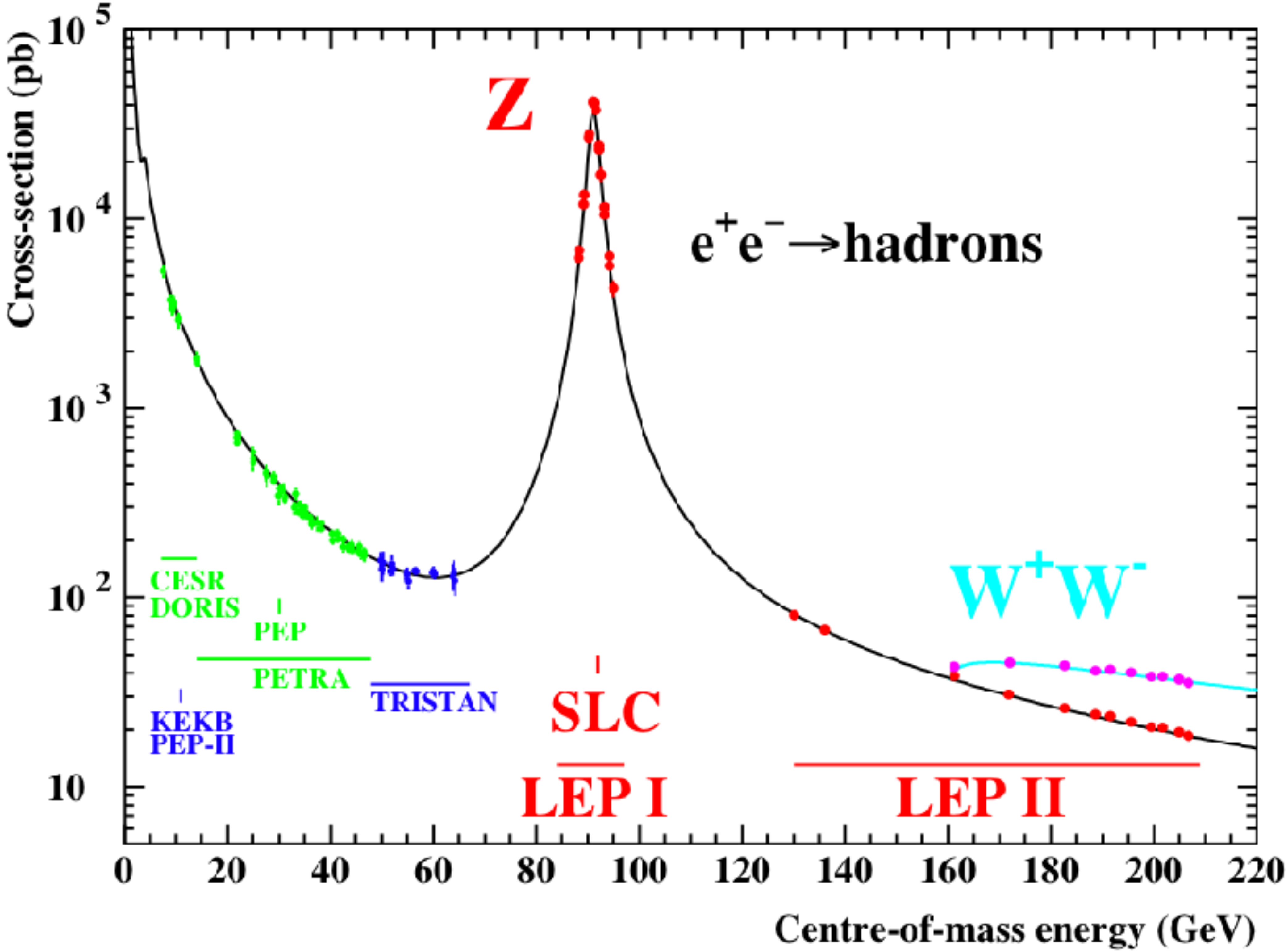
Statistics in a Nutshell

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

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

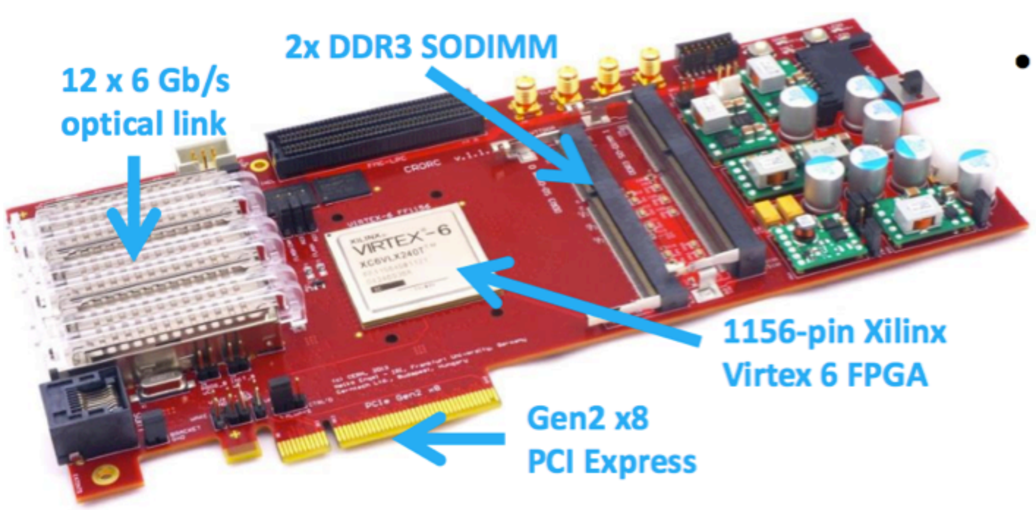


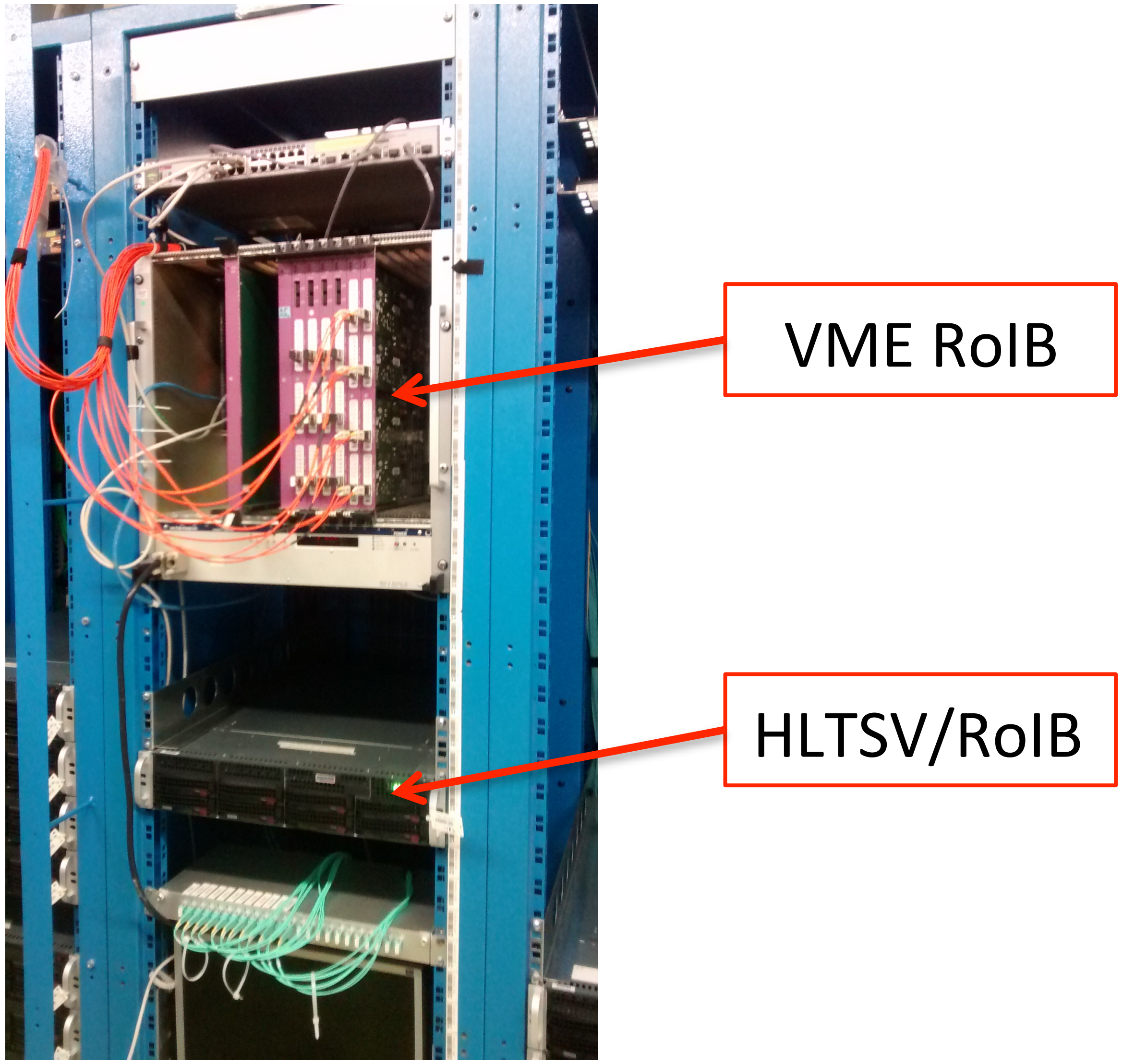
LEP



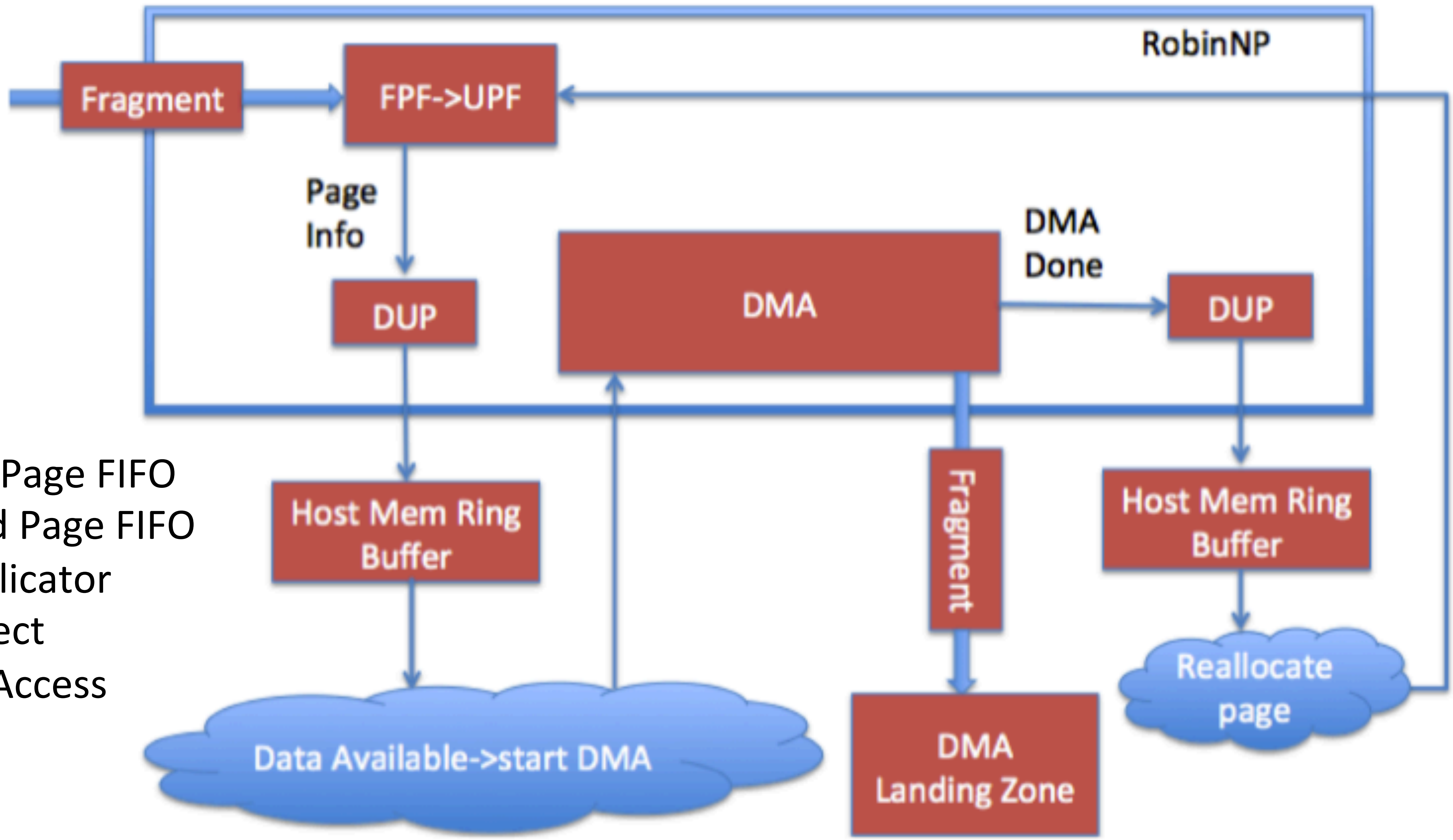
Cross-section (pb)
10^5
10^4
10^3
10^2
10
Z
$e^+e^- \rightarrow$hadrons
W^+W^-
CESR
DORIS
PEP
PETRA
TRISTAN
KEKB
PEP-II
SLC
LEP I
LEP II
0 20 40 60 80 100 120 140 160 180 200 220
Centre-of-mass energy (GeV)

RoIB


2x DDR3 SODIMM
12 x 6 Gb/s
optical link
1156-pin Xilinx
Virtex 6 FPGA
Gen2 x8
PCI Express


VME RoIB
HLTSV/RoIB

RoIB

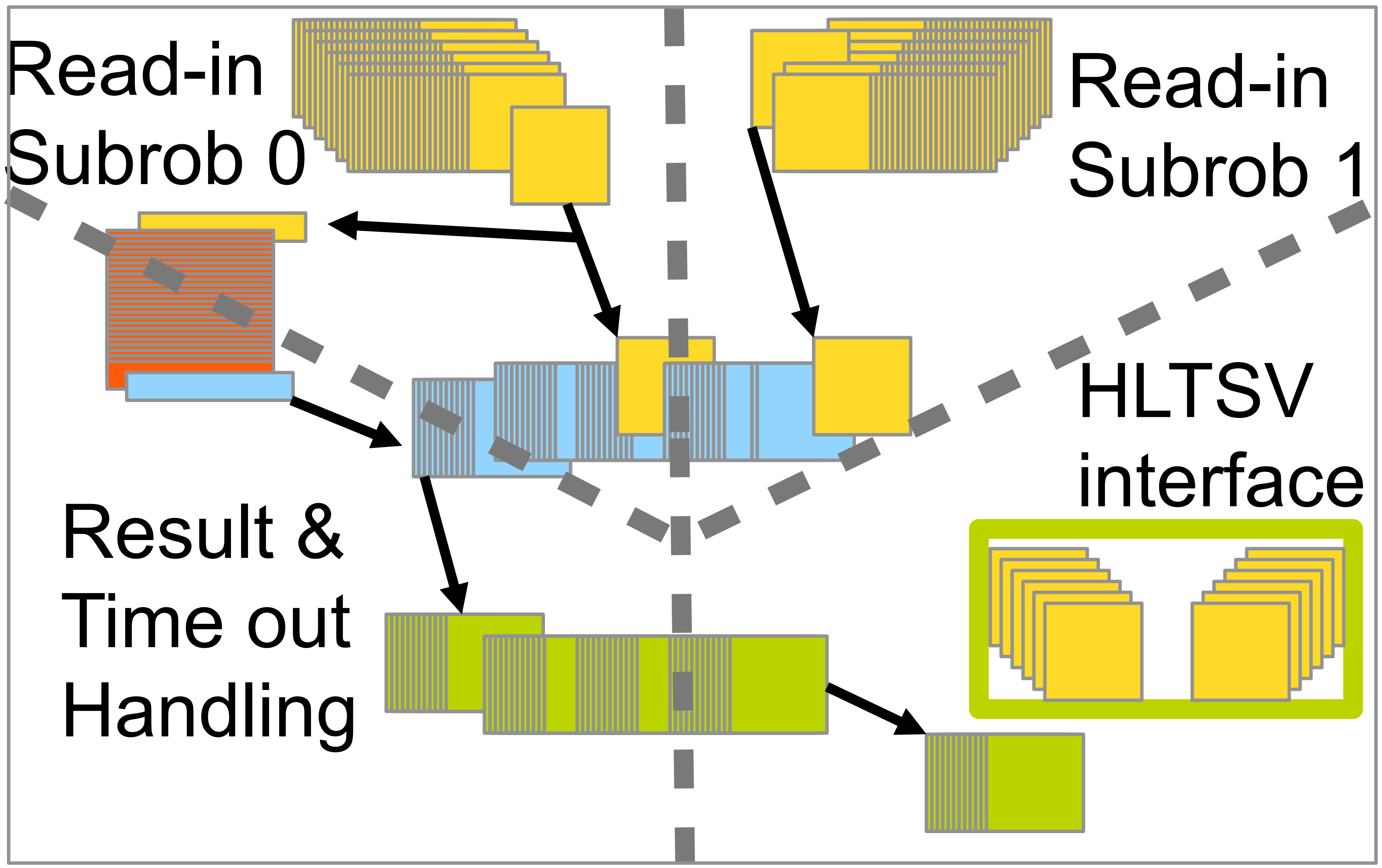


FPF: Free Page FIFO
UPF: Used Page FIFO
DUP: Duplicator
DMA: Direct Memory Access

RoIB

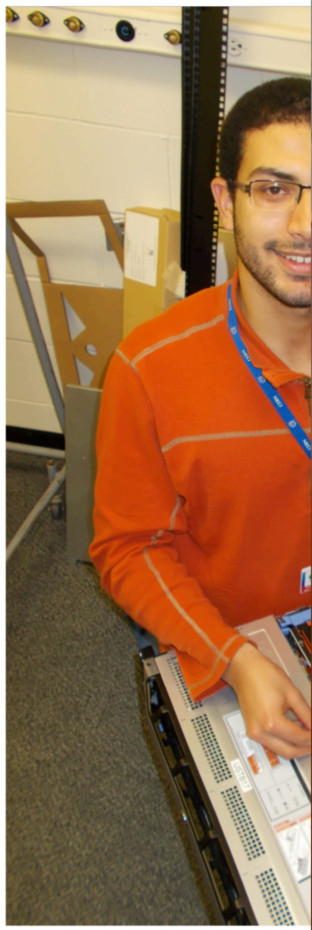
Parallel threads handle data input to the system, event building, event checking, interface to the HLTSV, and publish monitoring information

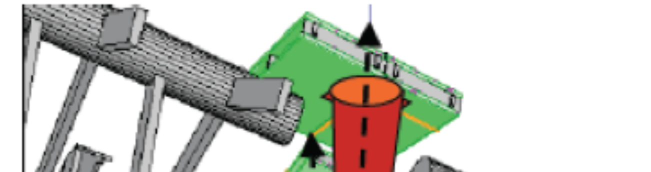
- Intel C++ tbb library used for concurrent data objects to minimize contention

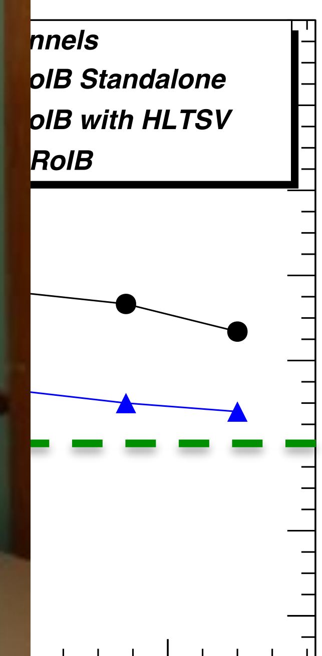


Region of Interest Builder

Arg



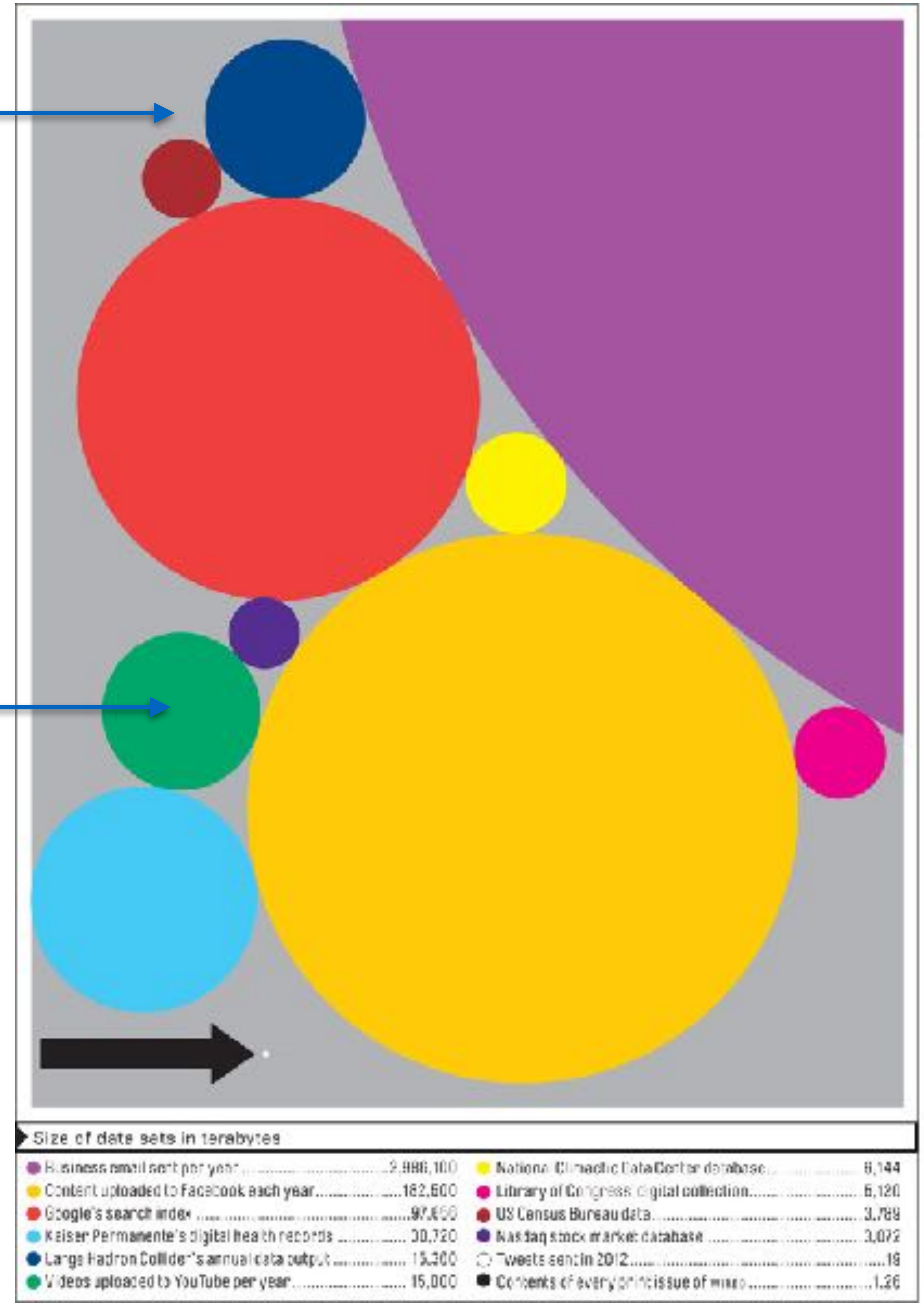




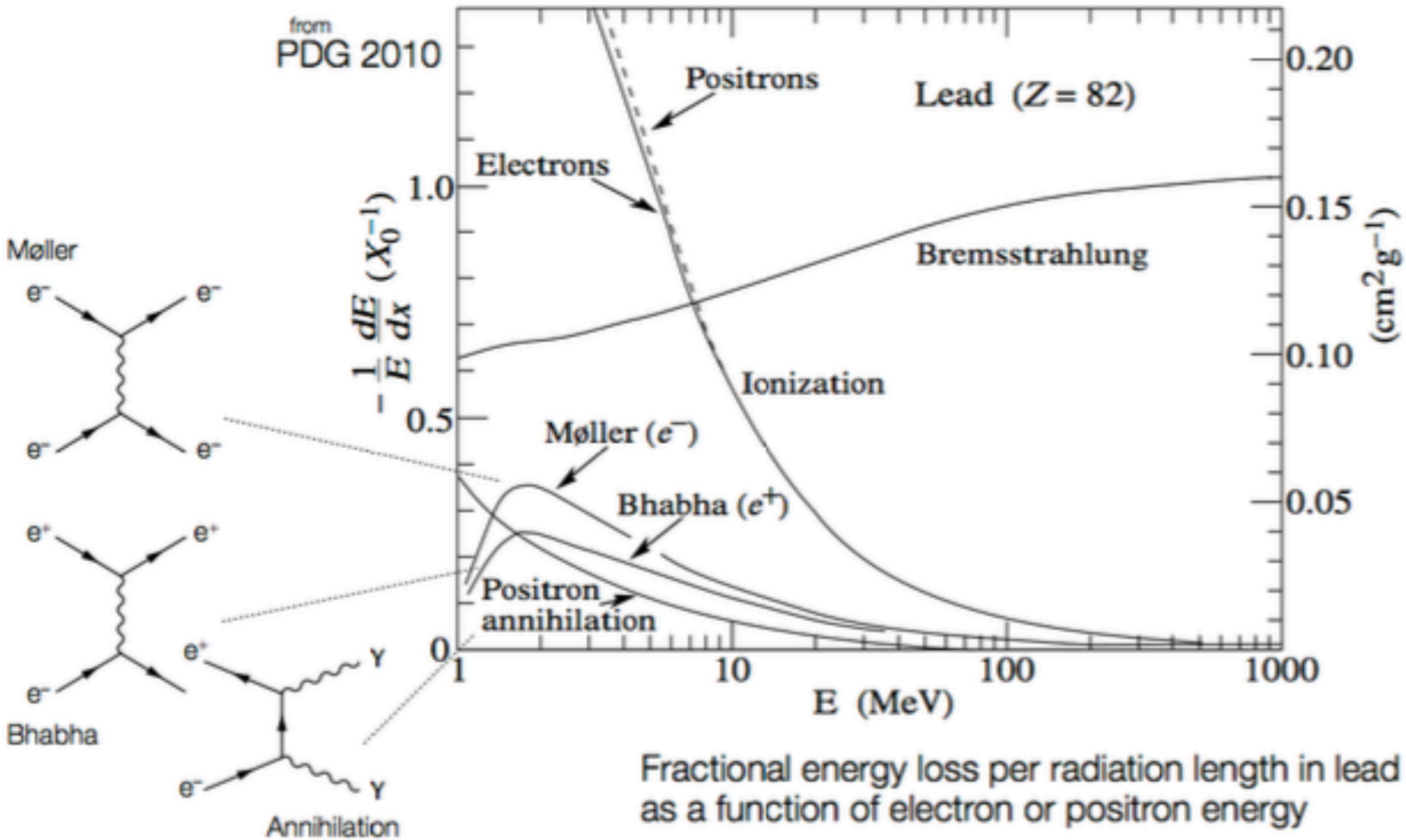
Data, Data, Data

LHC ~ 15 petabytes/2012

Youtube upload /year

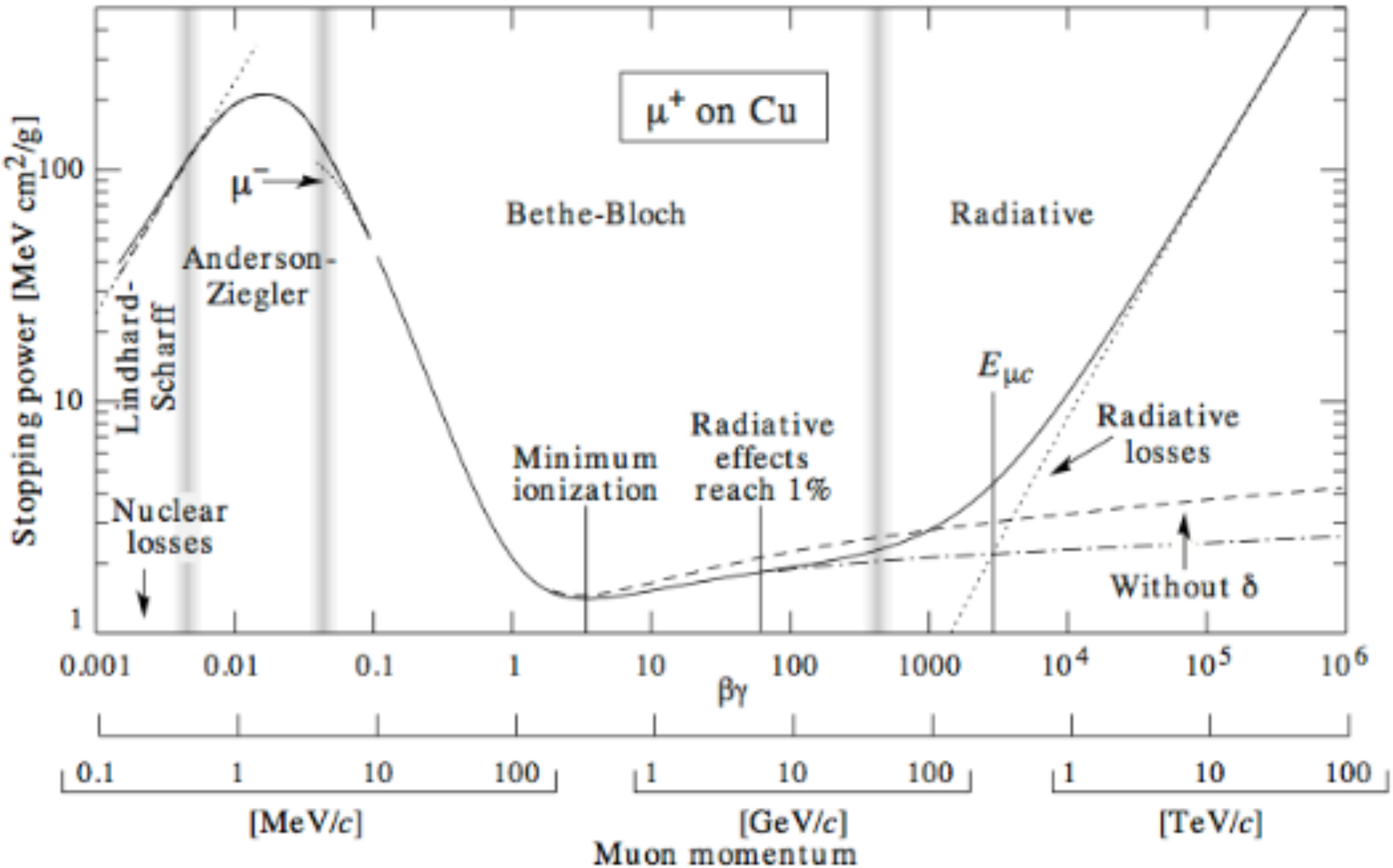


Total energy loss by e

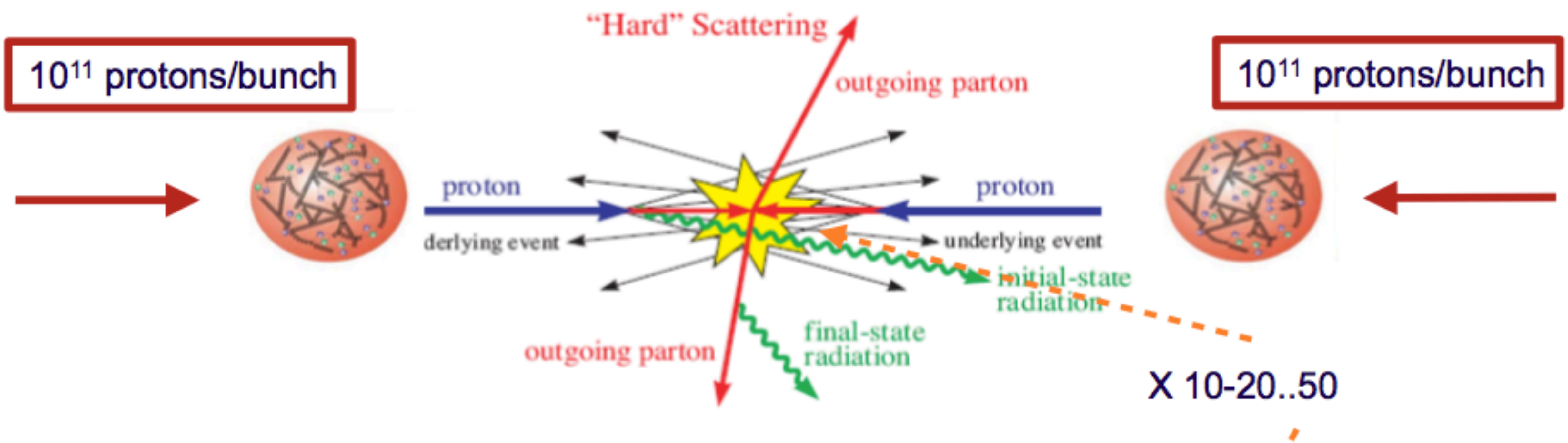


Fractional energy loss per radiation length in lead as a function of electron or positron energy

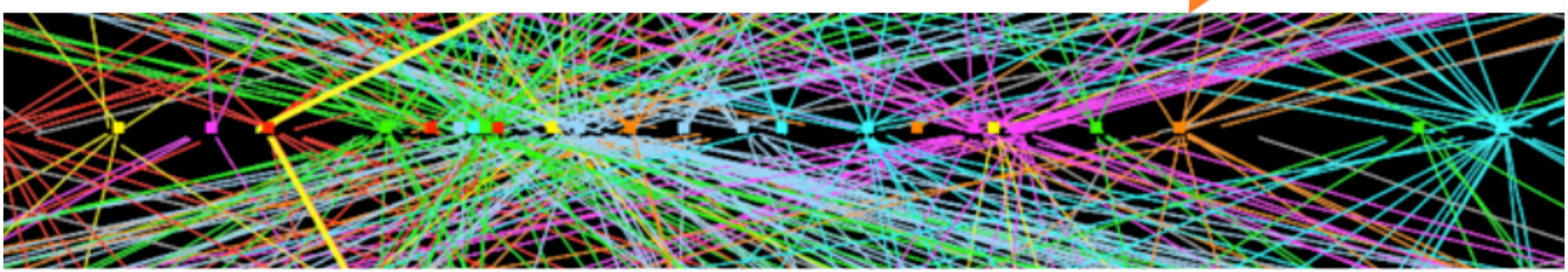
Muons in copper



Pileup

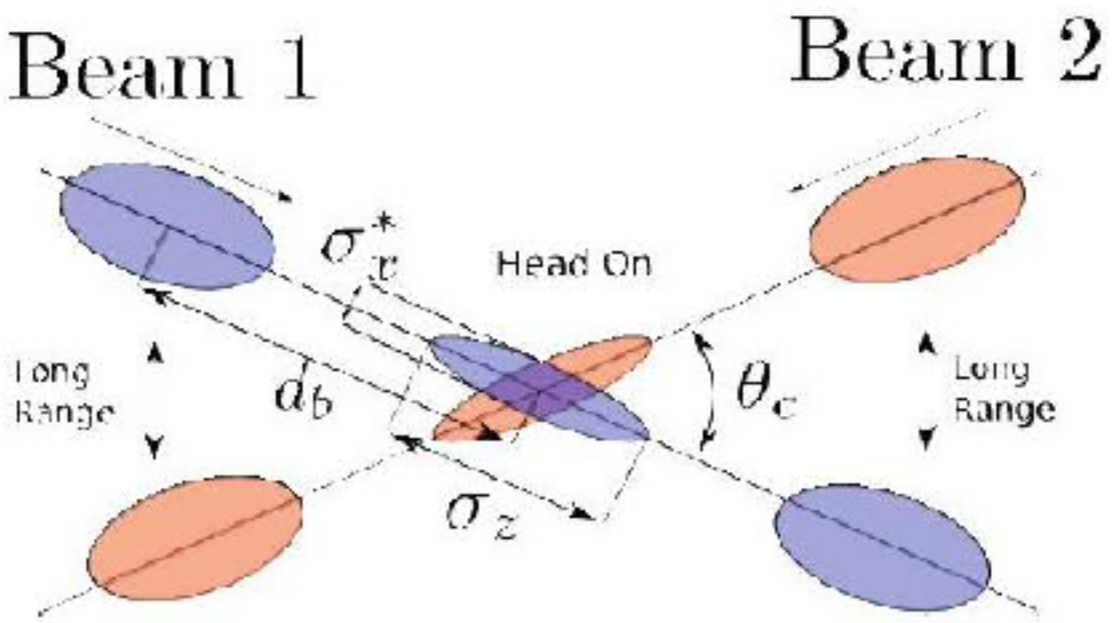


Multi-collisions per beam crossing



Ability to separate individual collisions - 40 MHz

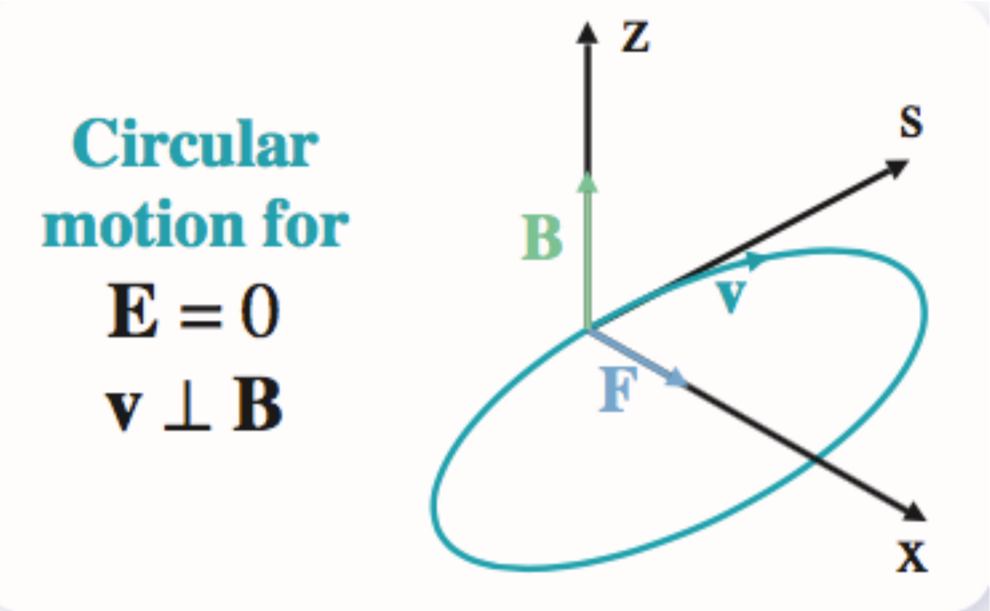
LHC



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

LHC

- Momentum p = 7 TeV/c
- LHC bending radius ρ = 2804 m
- Bending field B = 8.33 Tesla
- magnets at 1.9 K, super-fluid He



Data-taking 2015/2016