Associated production of top quark pairs

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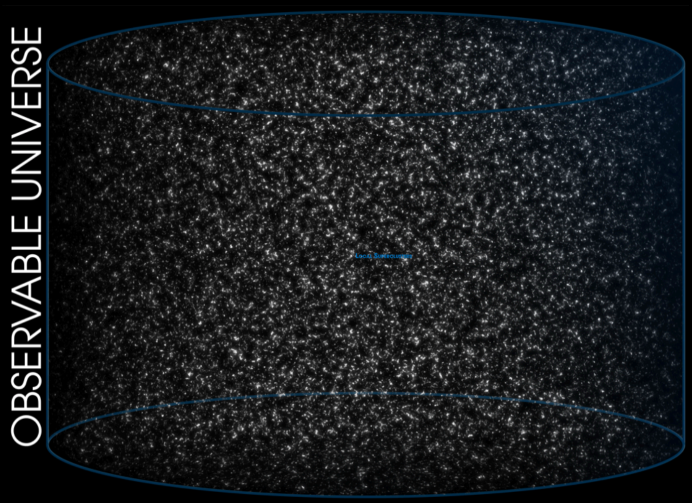
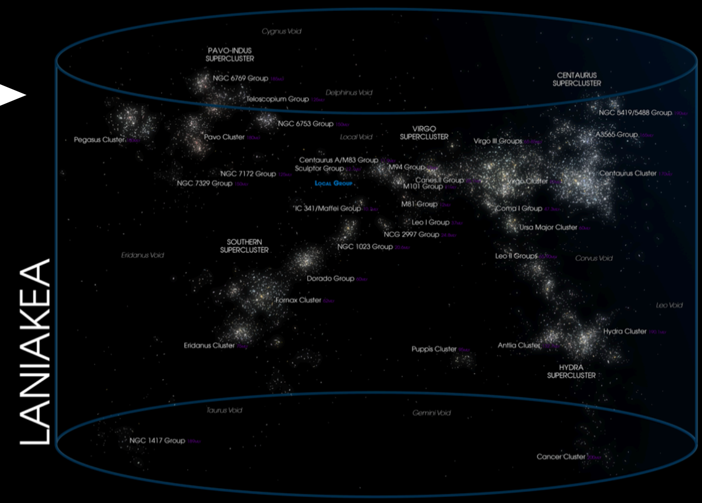
8th October 2020
Seminar, Dept of physics. Oklahoma State University

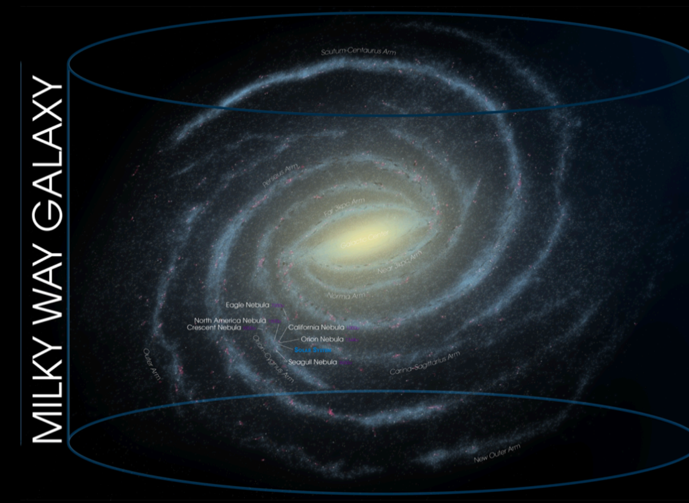
Reductionism at play…



~93B light years

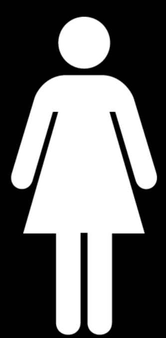


Super cluster
~500M light years



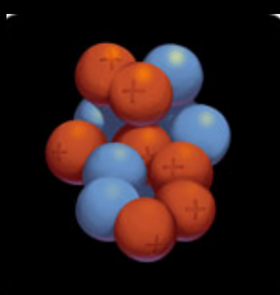
~200k light years

~12,000 km

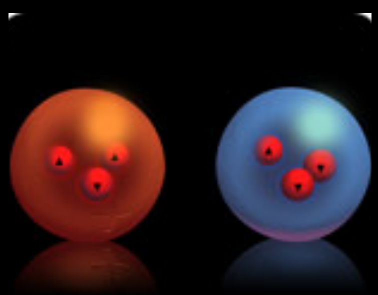


~1 m

Atoms
~1 Å

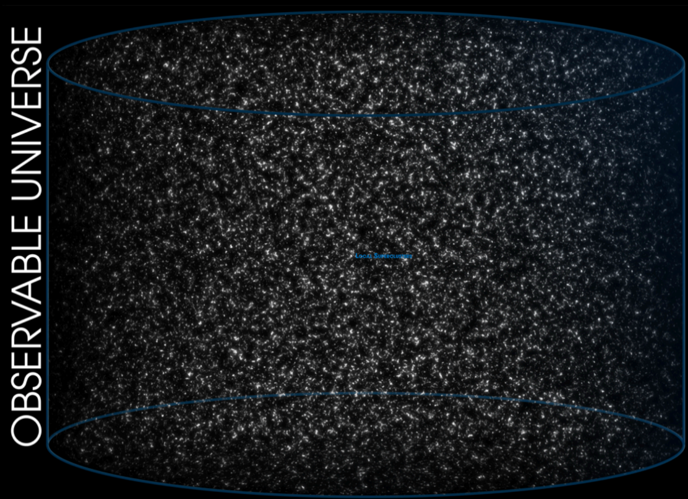


Nuclei
~1fm

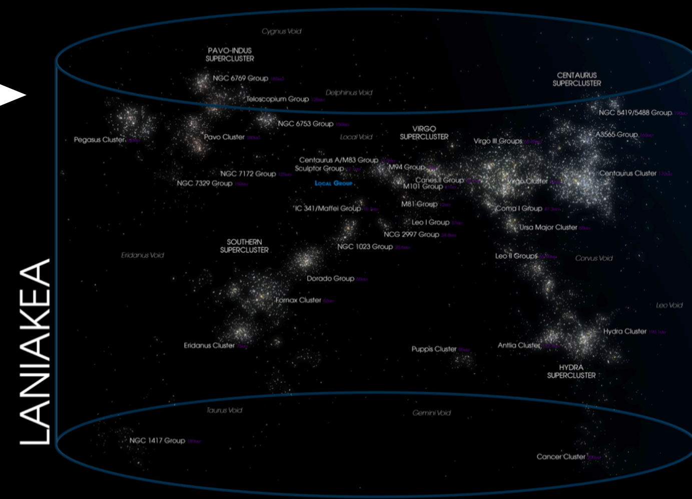


Quarks
< 0.1am

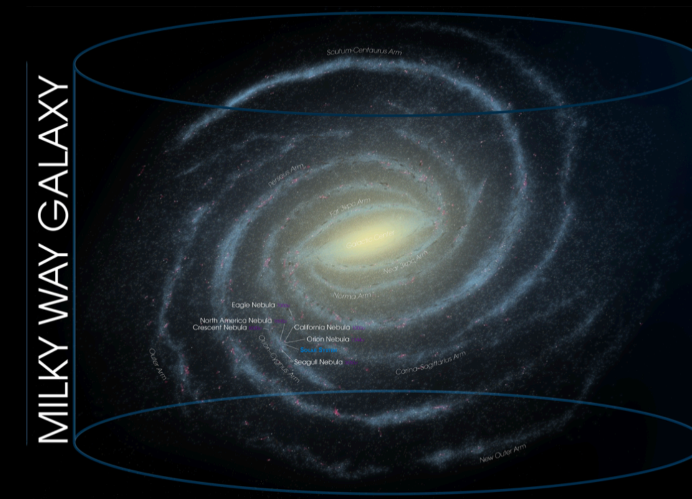
Reductionism at play…



~93B light years

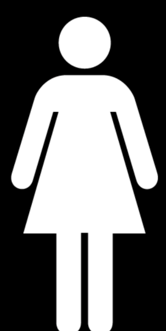


Super cluster
~500M light years

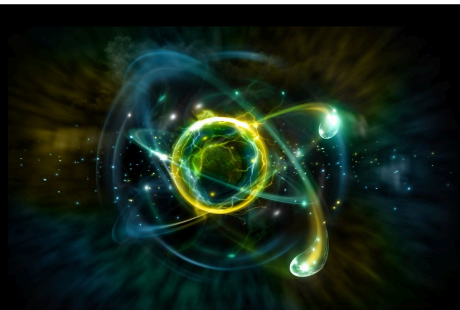


~200k light years

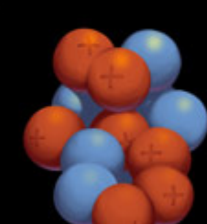
~12,000 km



~1 m



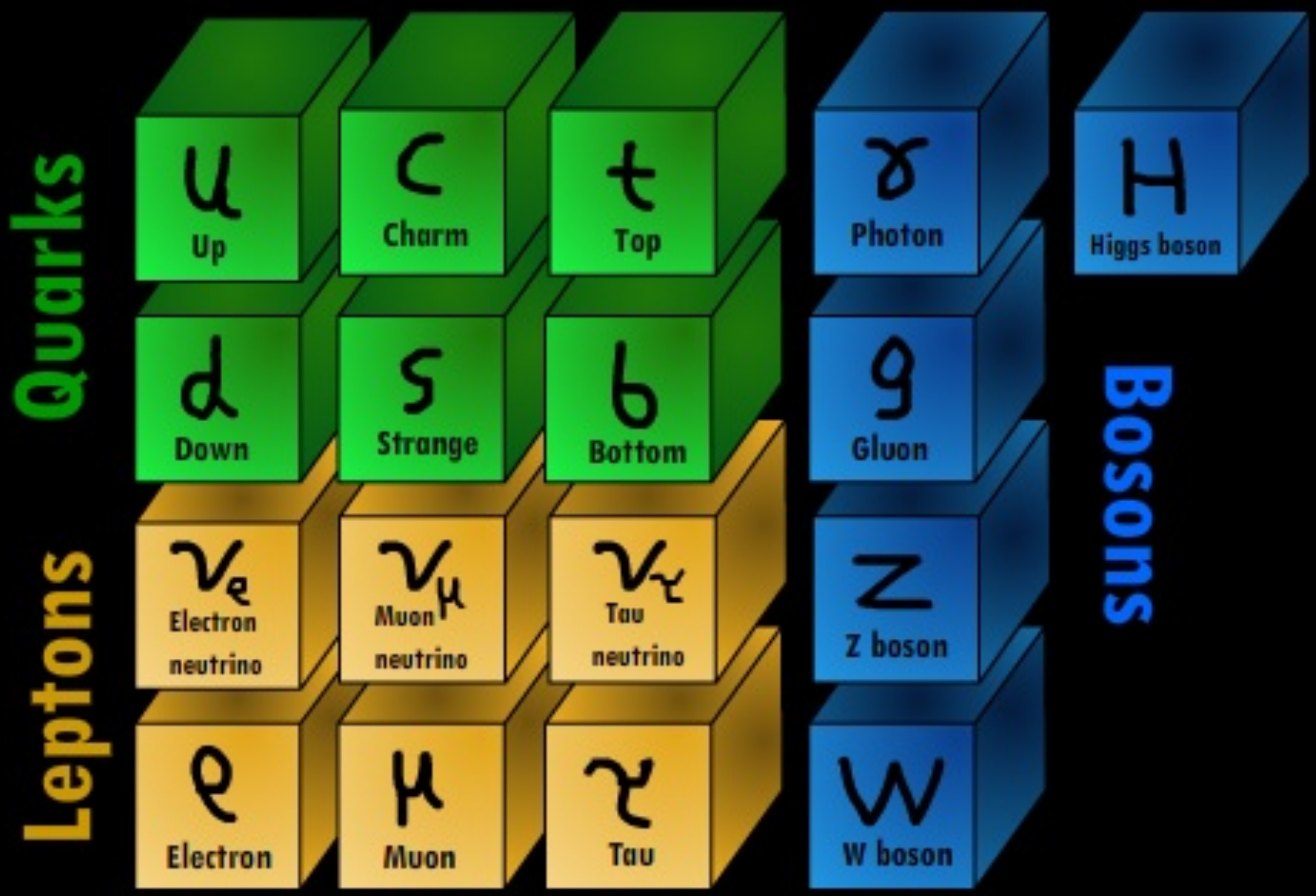
Atoms
~1 Å



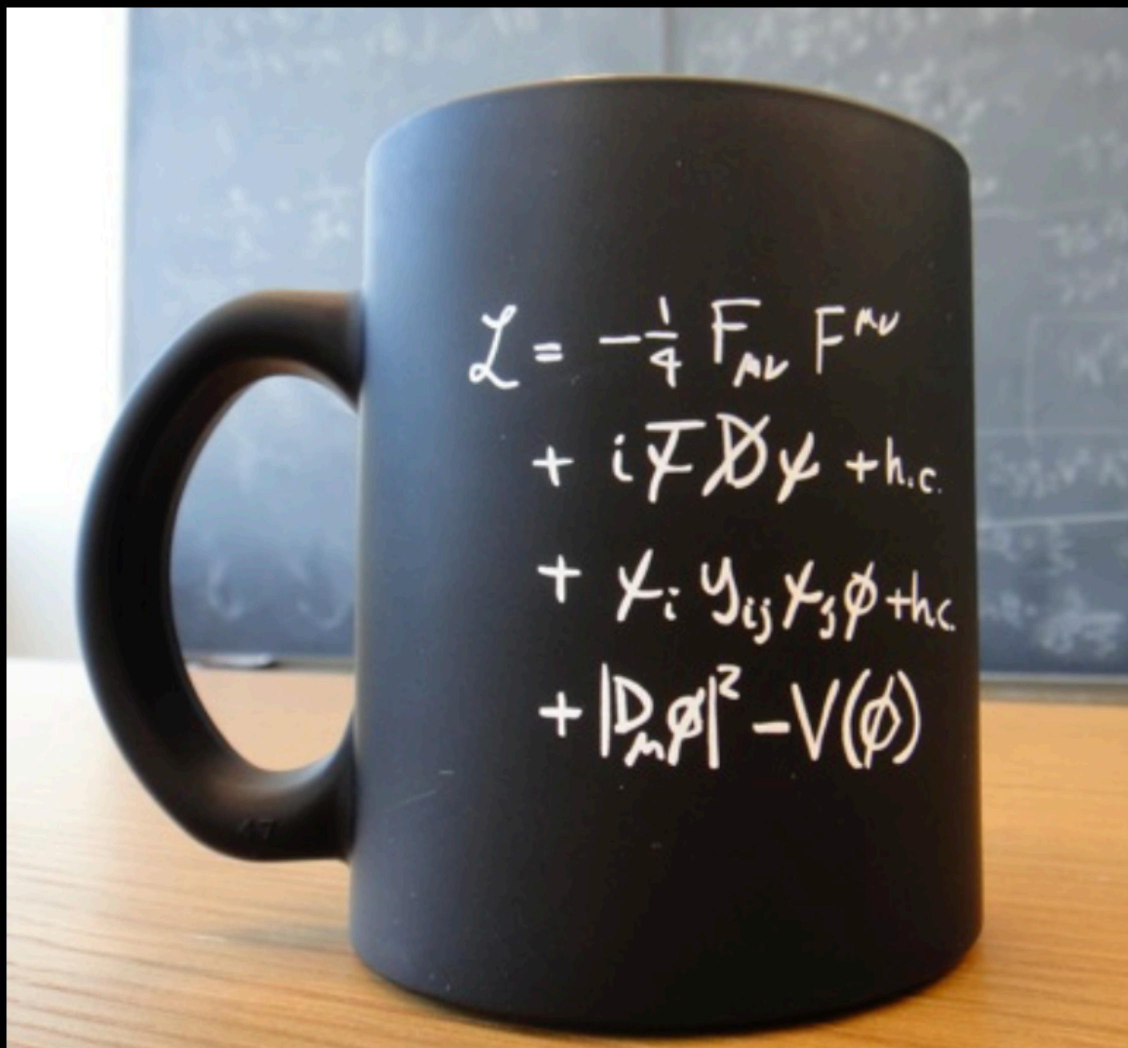
Nuclei
~1fm

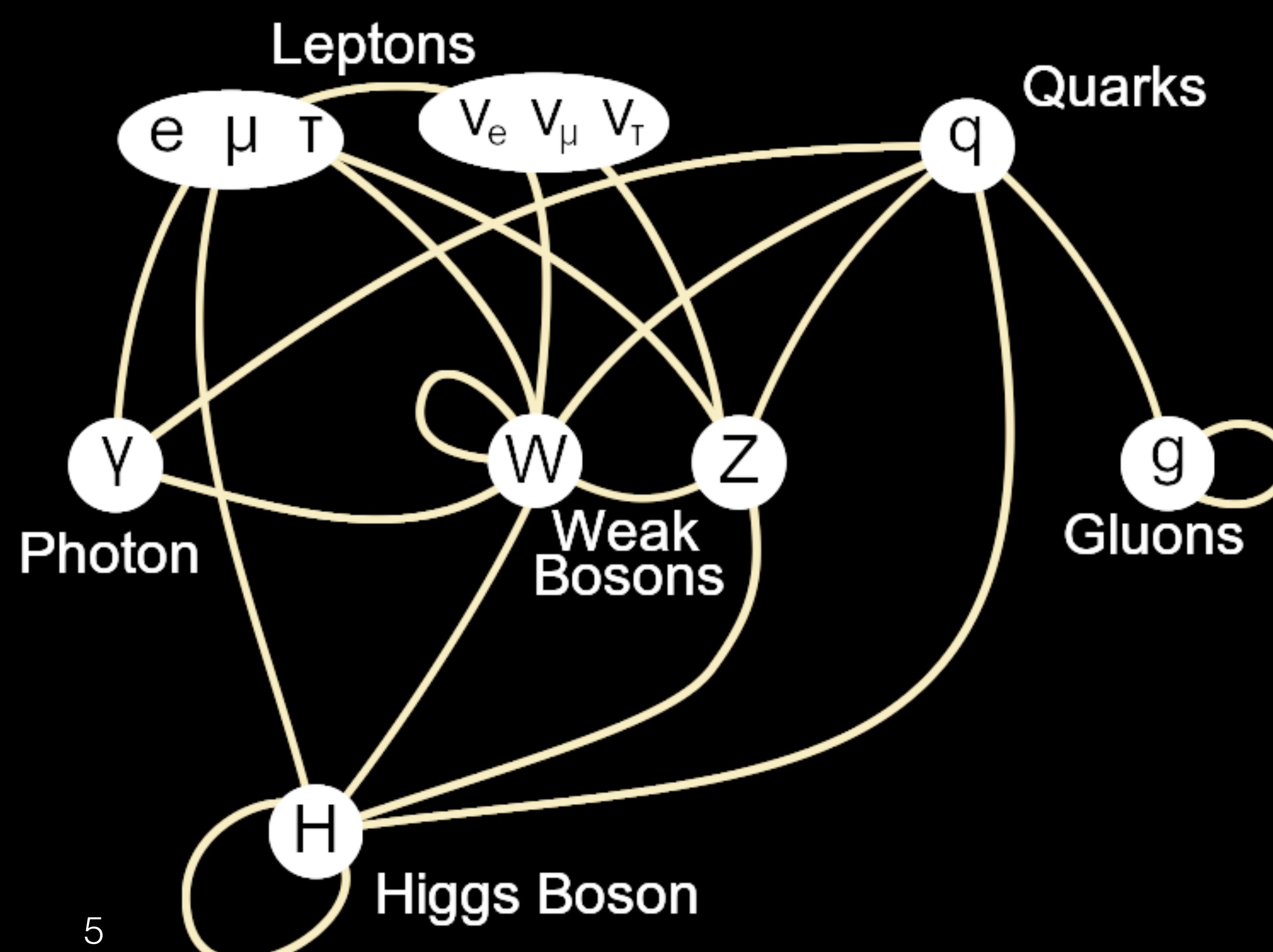
Quarks
< 0.1am

The Standard Model of Particle physics



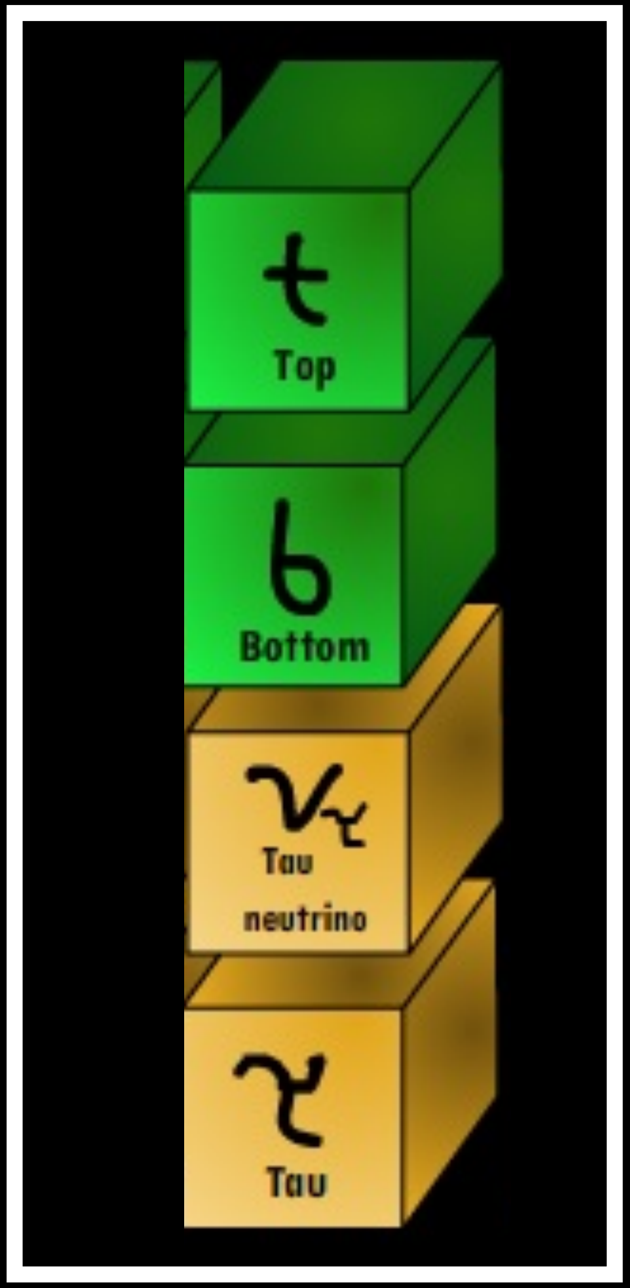
Interactions in the Standard Model





Top Quark

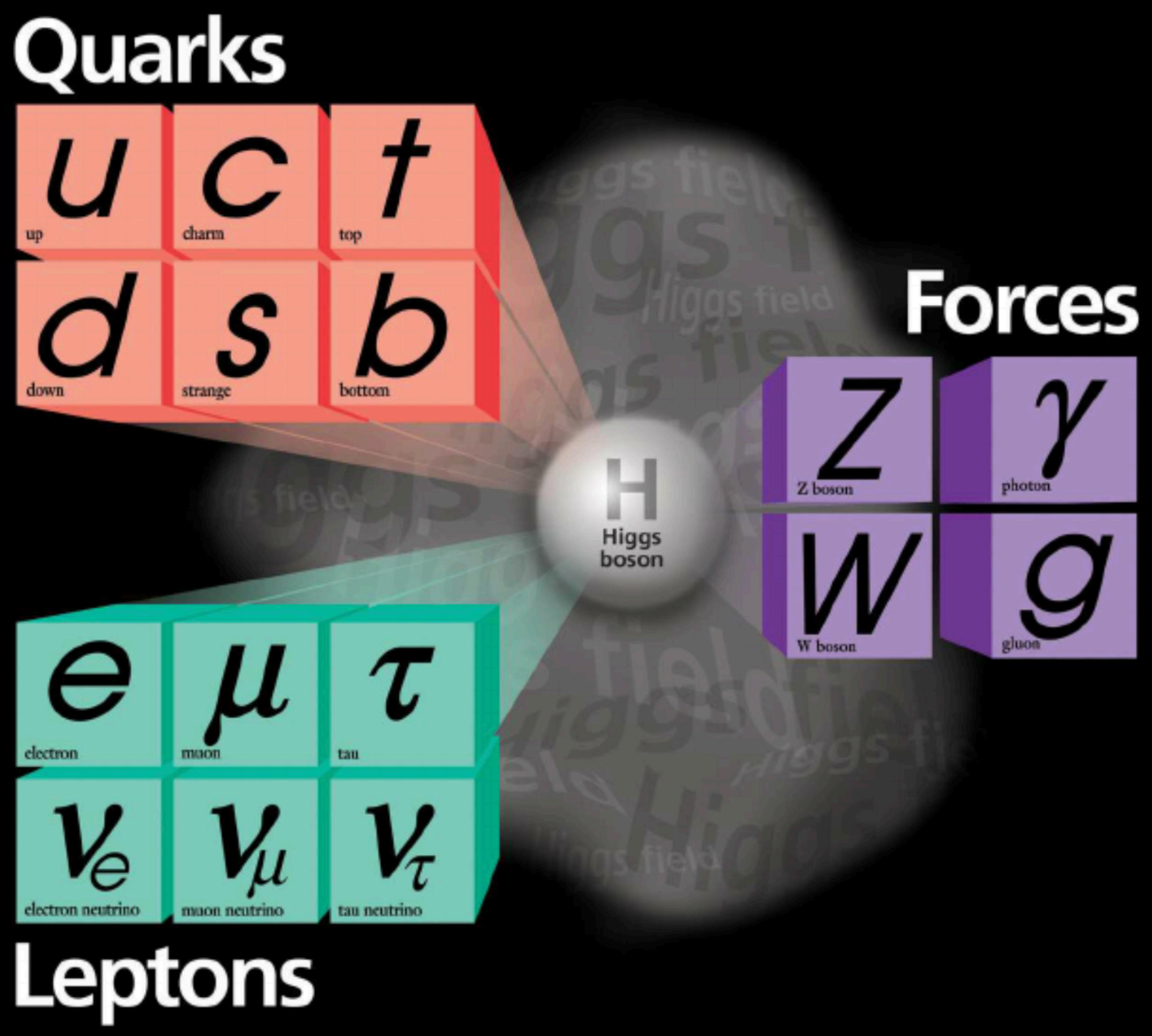
3rd generation



- Top Quark is special

- Heaviest known fundamental particle in the Standard Model (approx 190 times proton mass)
- No top quark bound systems observed
- Decays immediately into lighter quarks

The Higgs Boson



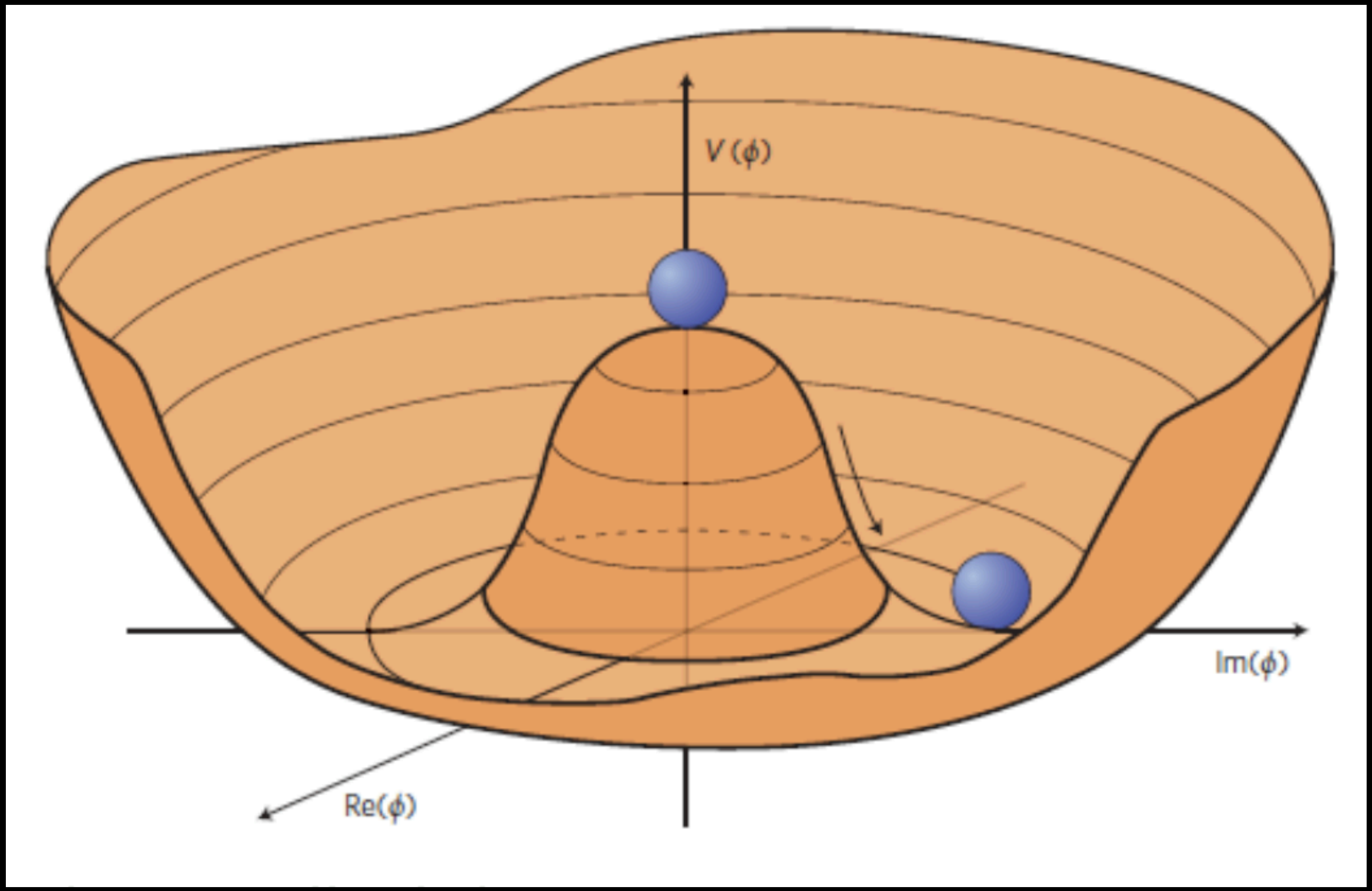
- Its is the quanta of Higgs field which gives mass to fundamental particles
- Higgs field is responsible for EWK gauge boson masses
- Fermions obtain mass via Yukawa interaction with Higgs field.

- Higgs was the last missing piece in the Standard Model
  - Finally discovered in 2012
  - Mass : Approx 125 times proton mass.

Spontaneous symmetry breaking

- Experience tells us that fundamental particles have mass.
    - Adding a mass terms in the Lagrangian violates certain fundamental laws of physics.

$$V = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$



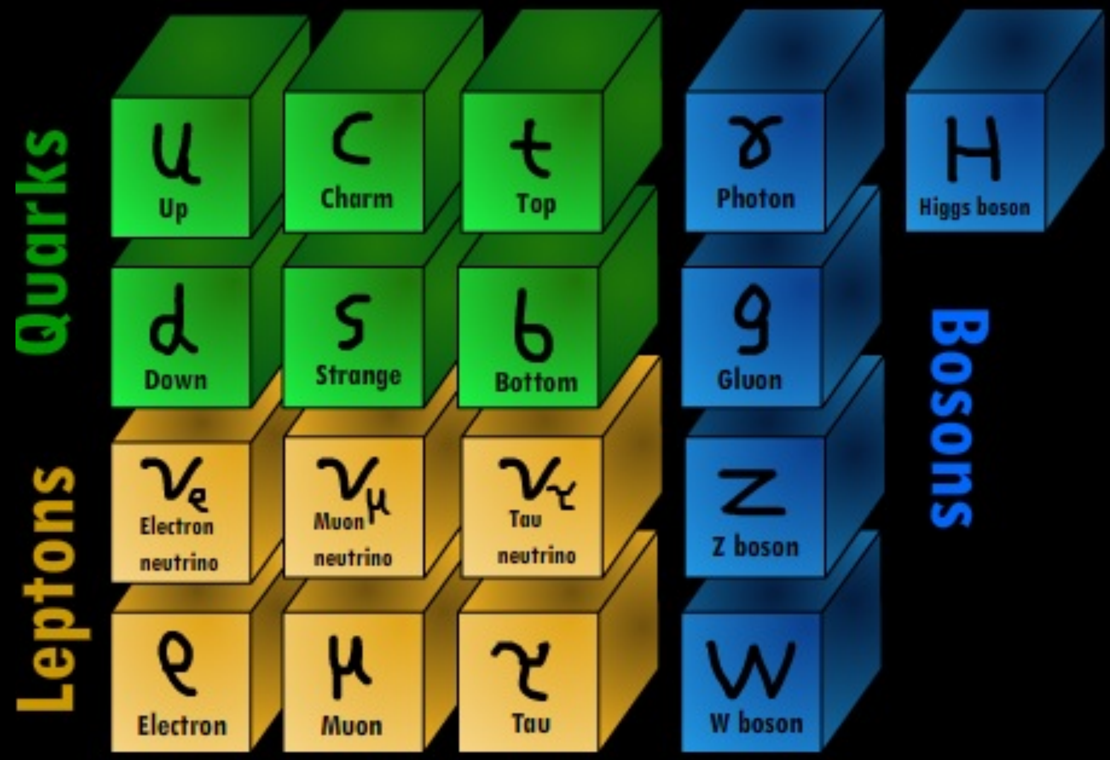
- Fermions get mass through **Yukawa** interaction

$$y\phi\psi^\dagger\psi \rightarrow y(v+h)\psi^\dagger\psi$$

$$= m\psi^\dagger\psi + yh\psi^\dagger\psi$$

Is the Standard Model complete?

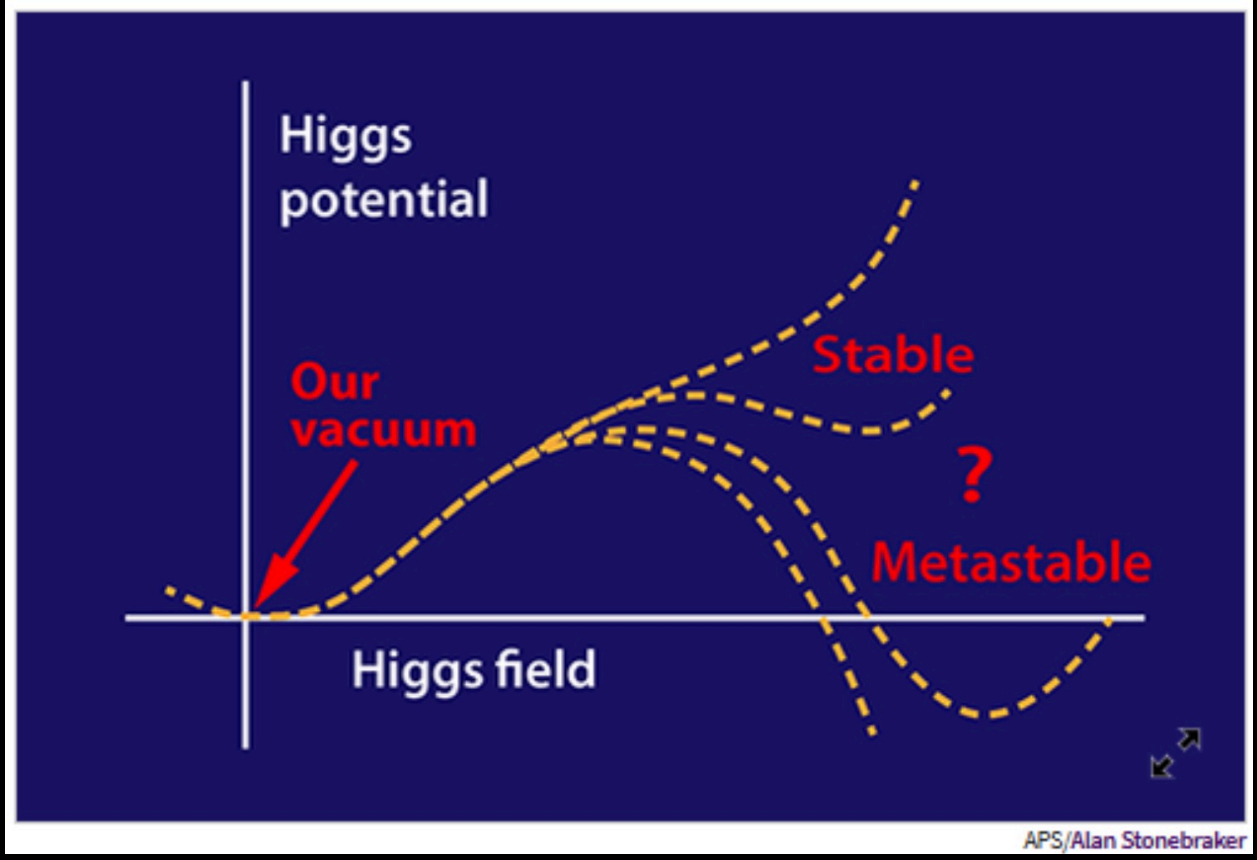
- No Dark matter candidate.

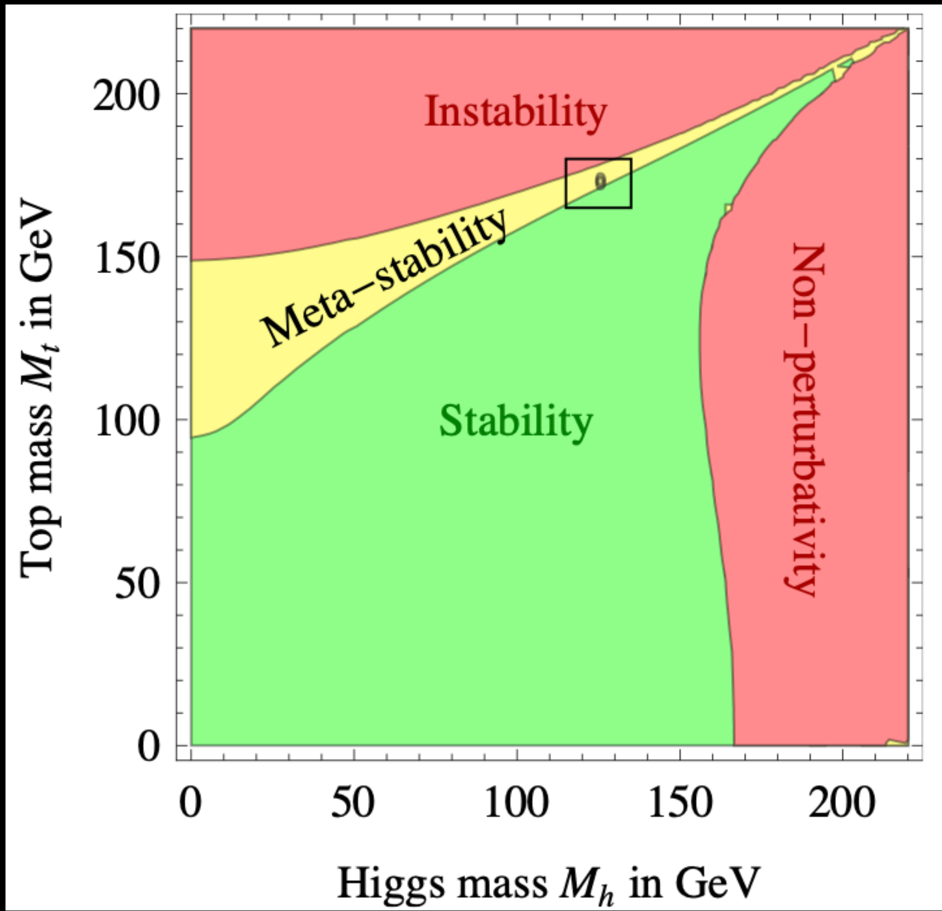


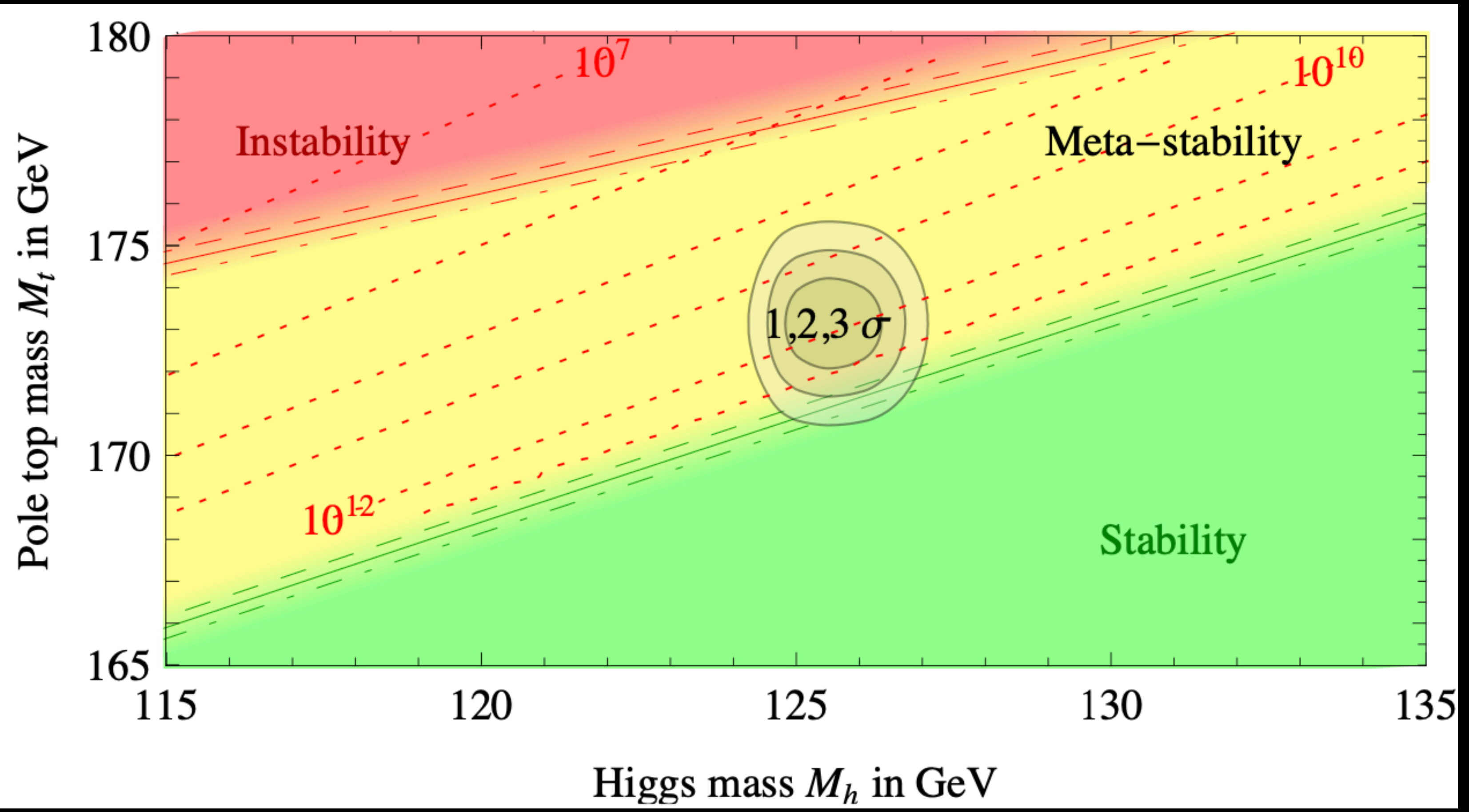
- No Description of Gravity
- No insights on Dark Energy
- No explanation why Neutrinos have mass.
- No explanation for Matter antimatter asymmetry in the Universe.

Are we living in a stable Universe?

- Is the electroweak vacuum stable.
- Assuming Standard Model is true:
  - The observed Higgs Boson mass of 125 GeV means we may be in a false vacuum.

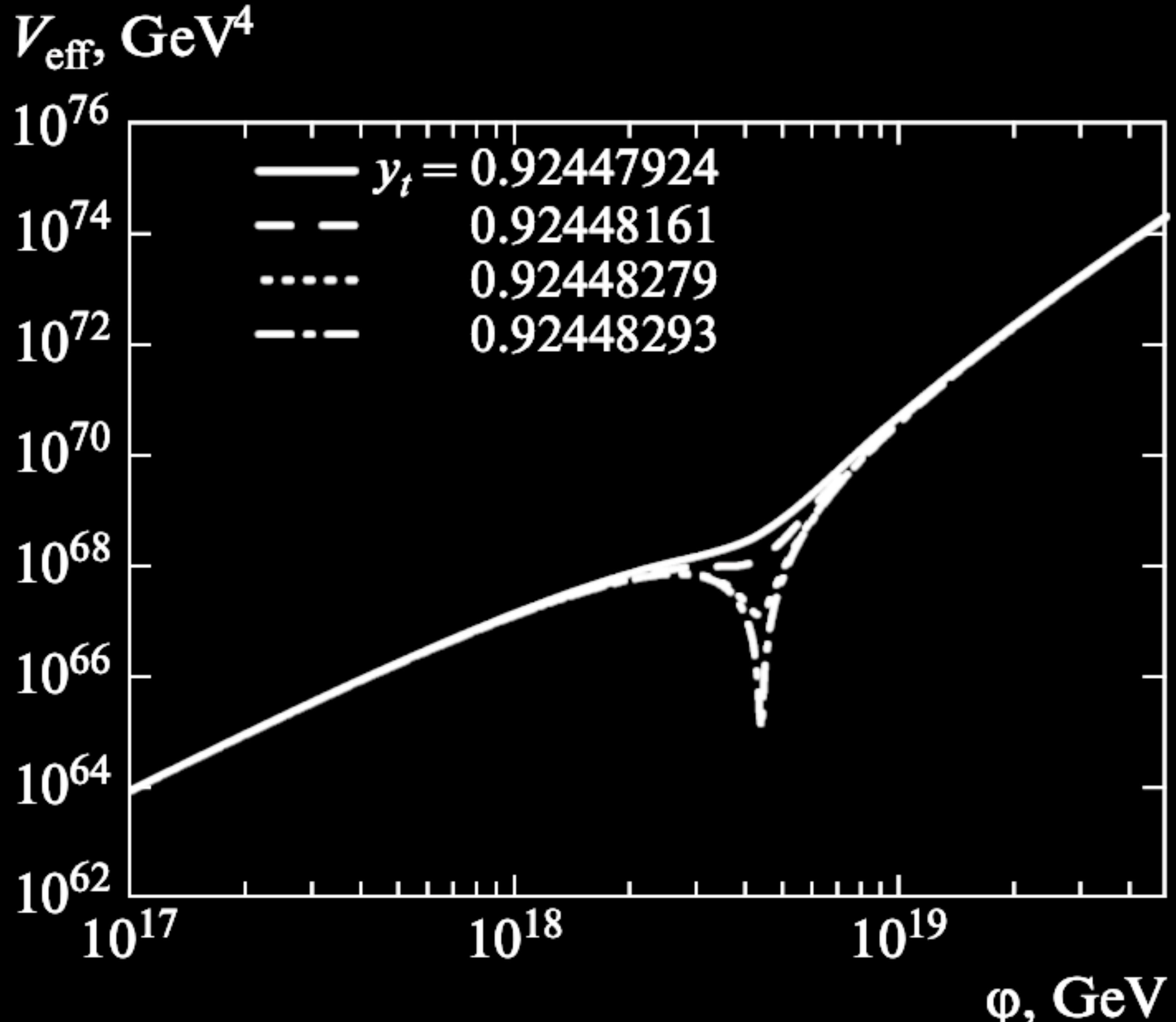






Degrassi et.al

Top quark coupling with Higgs field is critical



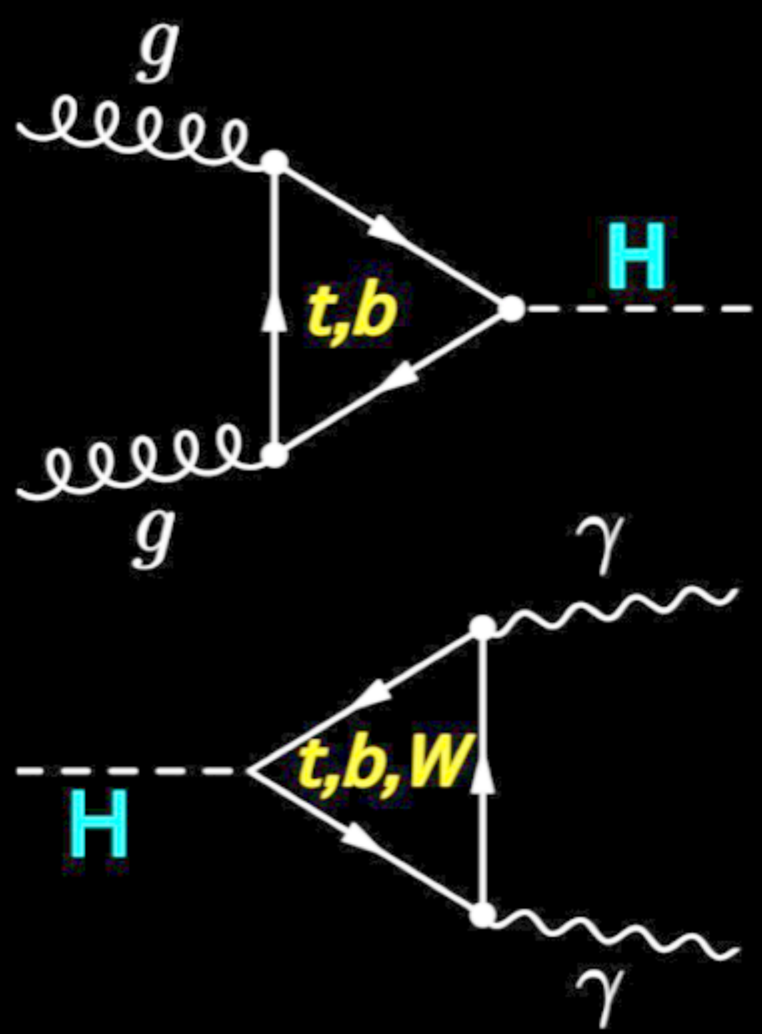
F. Bezrukof & M. Shaposhnikov

- A small change in top-quark coupling with Higgs field (y_t) changes the monotonic behavior of Higgs field potential

How to measure the top-Yukawa

- Being the heaviest SM particle, top-quark is expected to have the largest y_t
- Indirect constraints on top-yukawa coupling are possible through Higgs production through ggH and $H \to \gamma\gamma$ processes
- Current best fit coupling strength modifier (κ_t) (assuming no BSM particles in the loop)
  - $\kappa_t \equiv \frac{y_t}{y_t(\text{SM})} = 1.02^{+0.11}_{-0.10}$

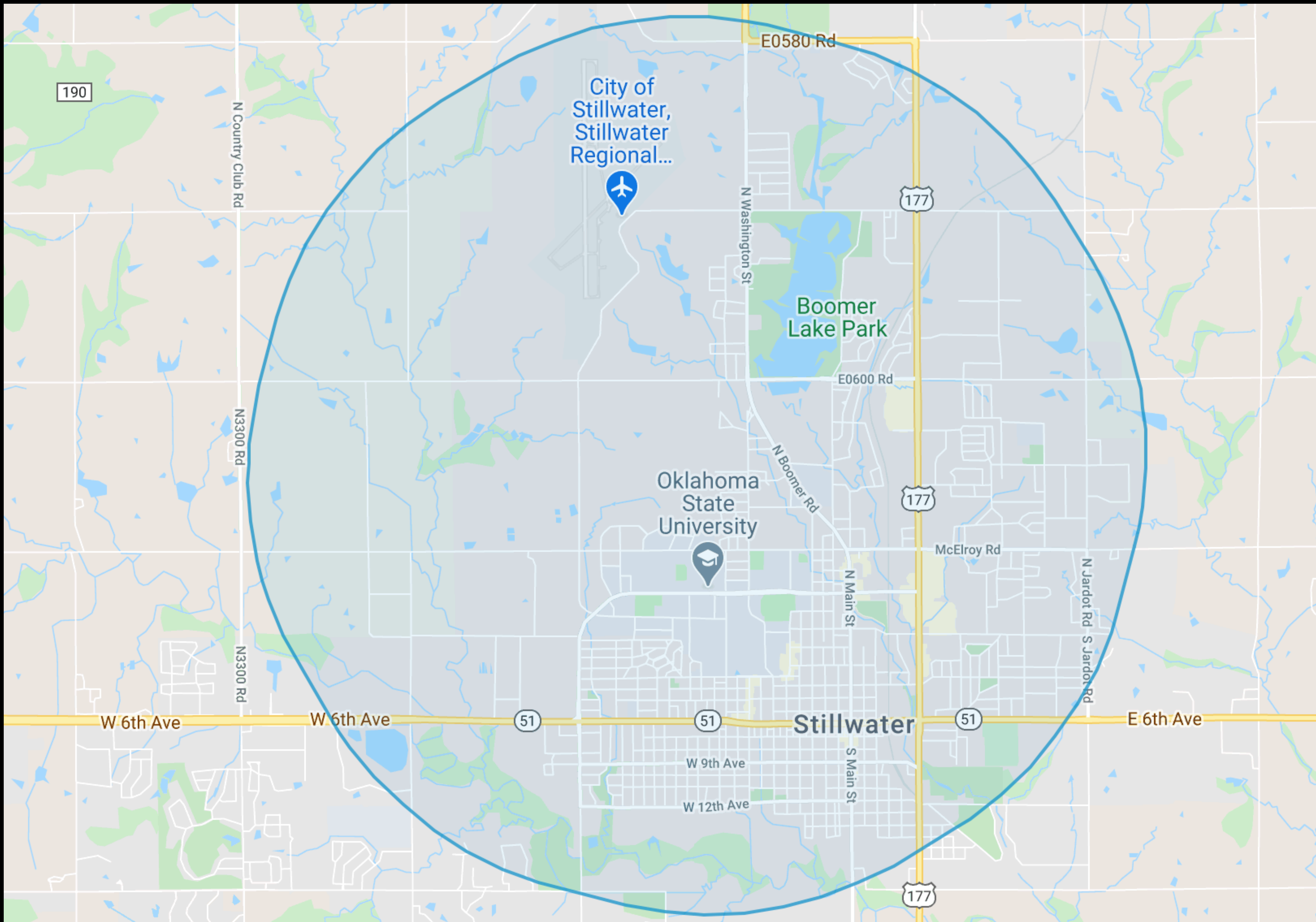
Phys. Rev. D 101, 012002



- $t\bar{t}H$ is one of the direct ways to measure top-yukawa coupling.

The Large Hadron Collider

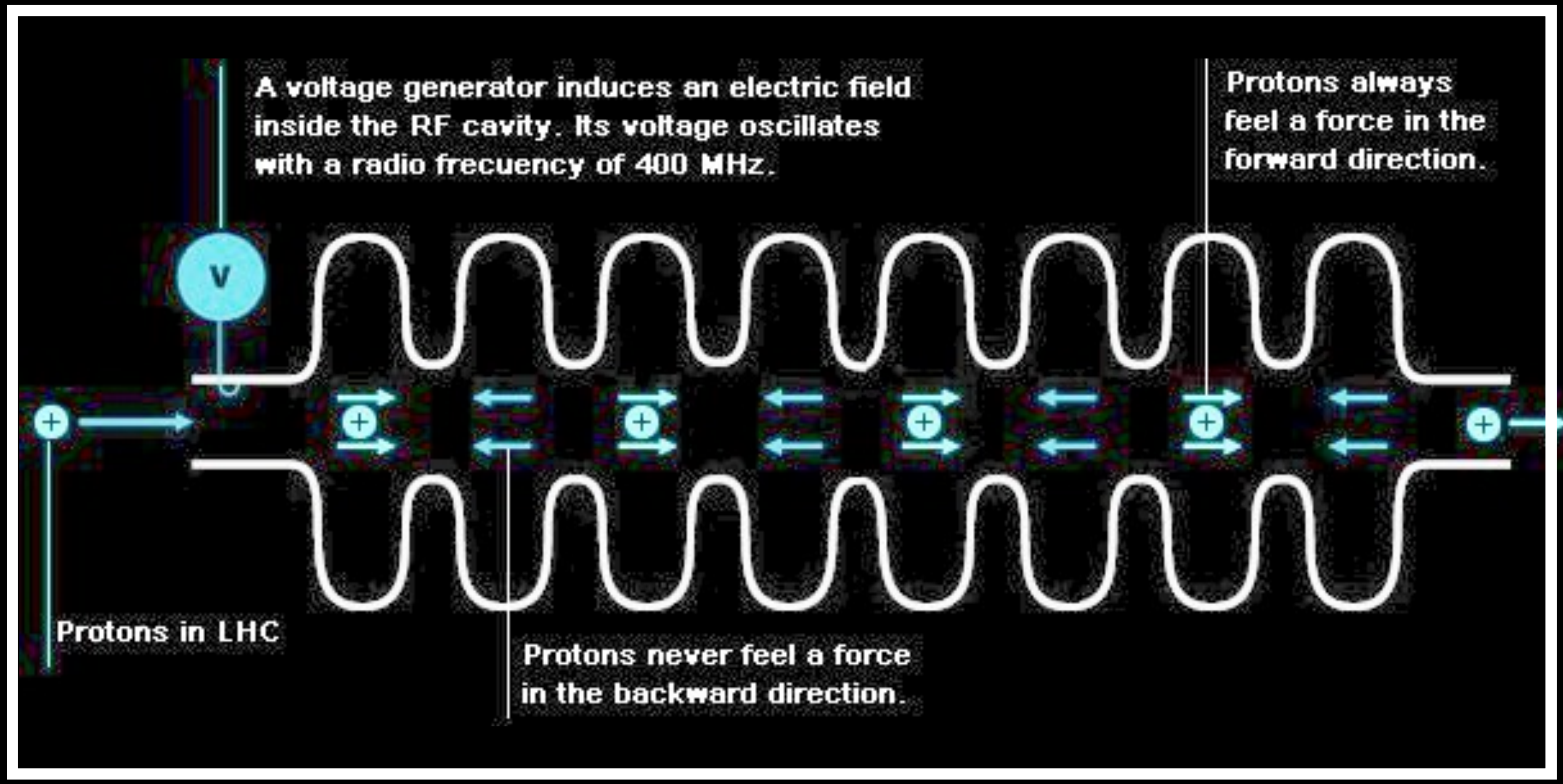
If the LHC were in Stillwater…

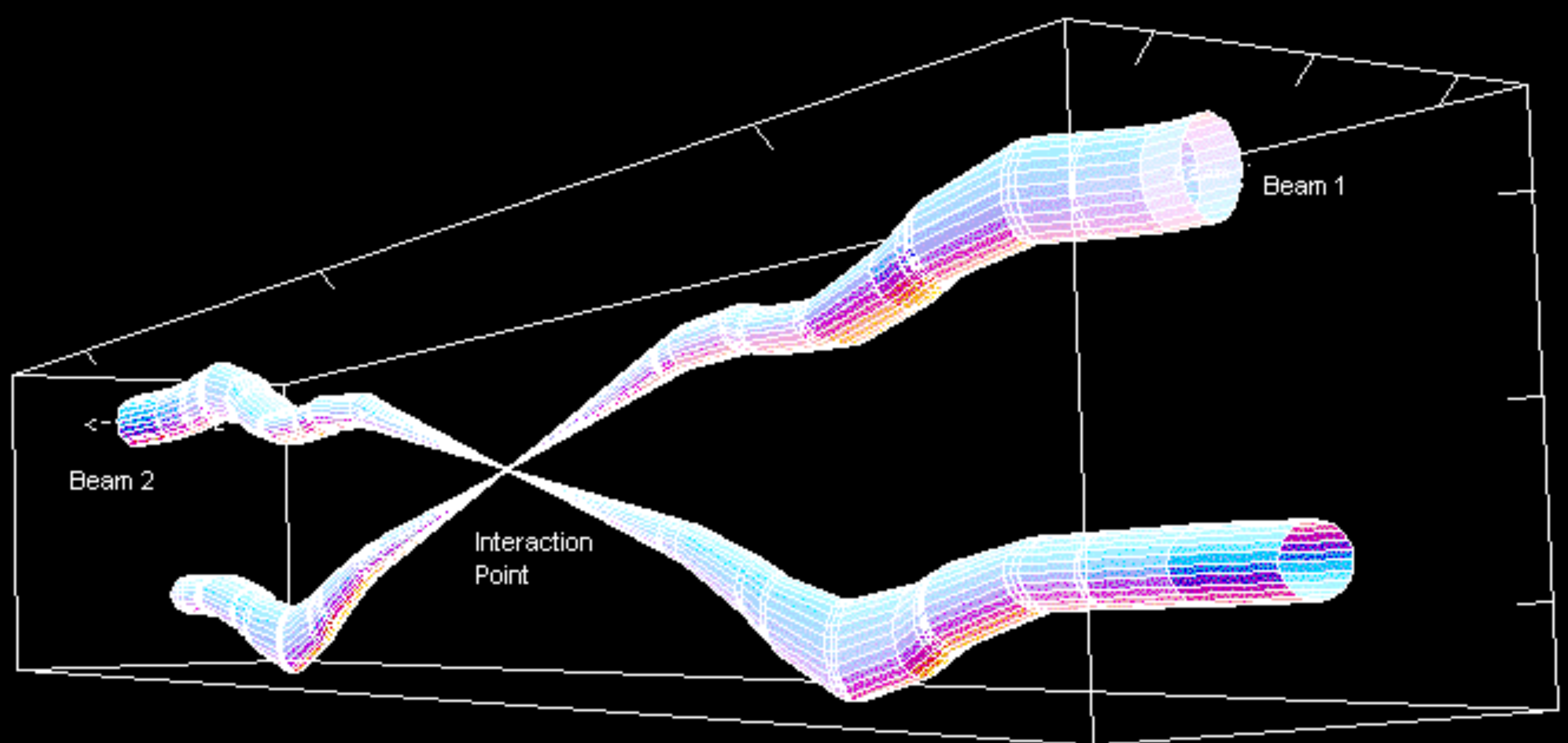


http://howlargeisthelhc.com

Colliding protons

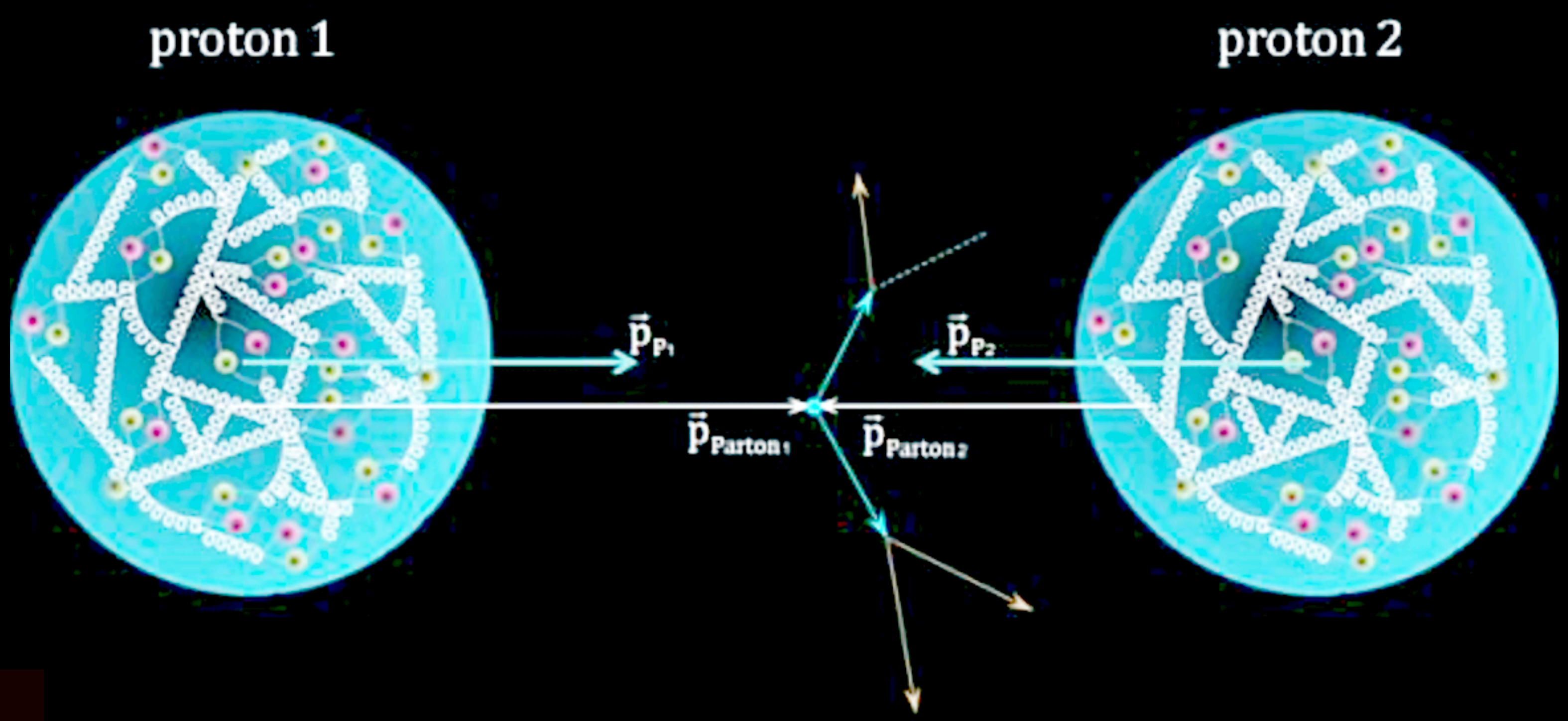
- Protons are circulated as bunches in the LHC
- At interaction points these bunches are squeezed to increase probability of collision.



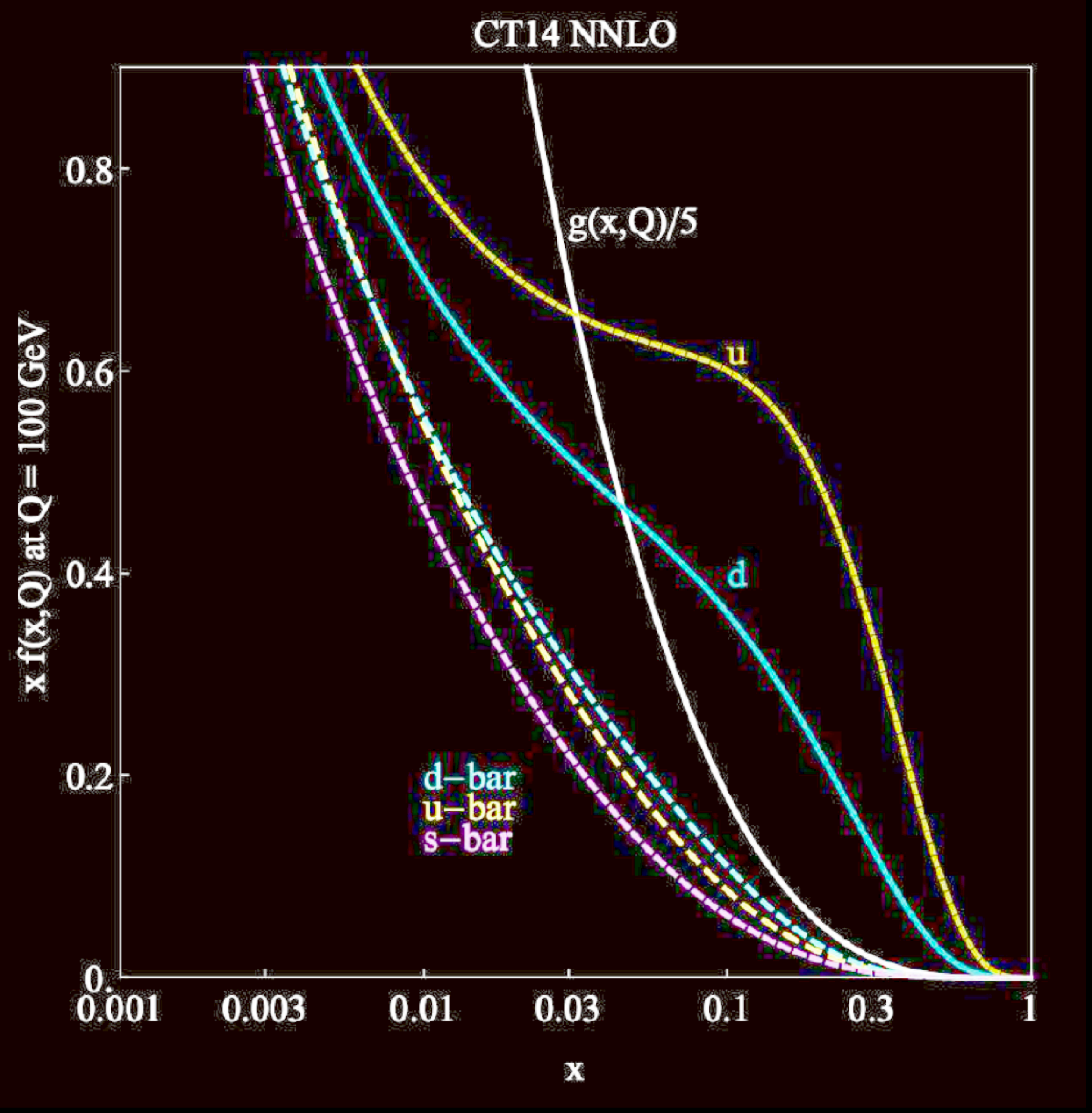


Relative beam sizes around IP1 (Atlas) in collision

Colliding protons



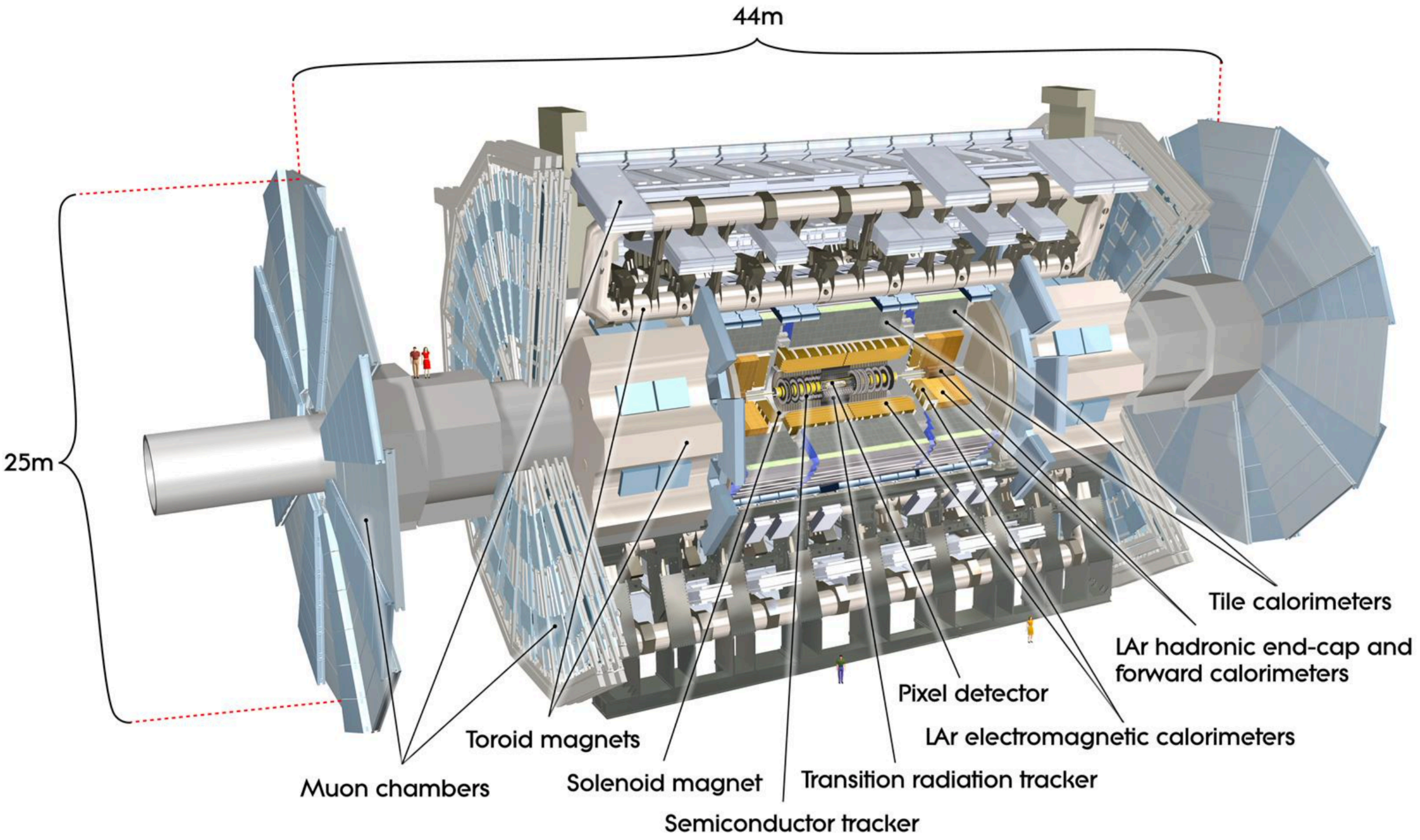
Q=100 GeV

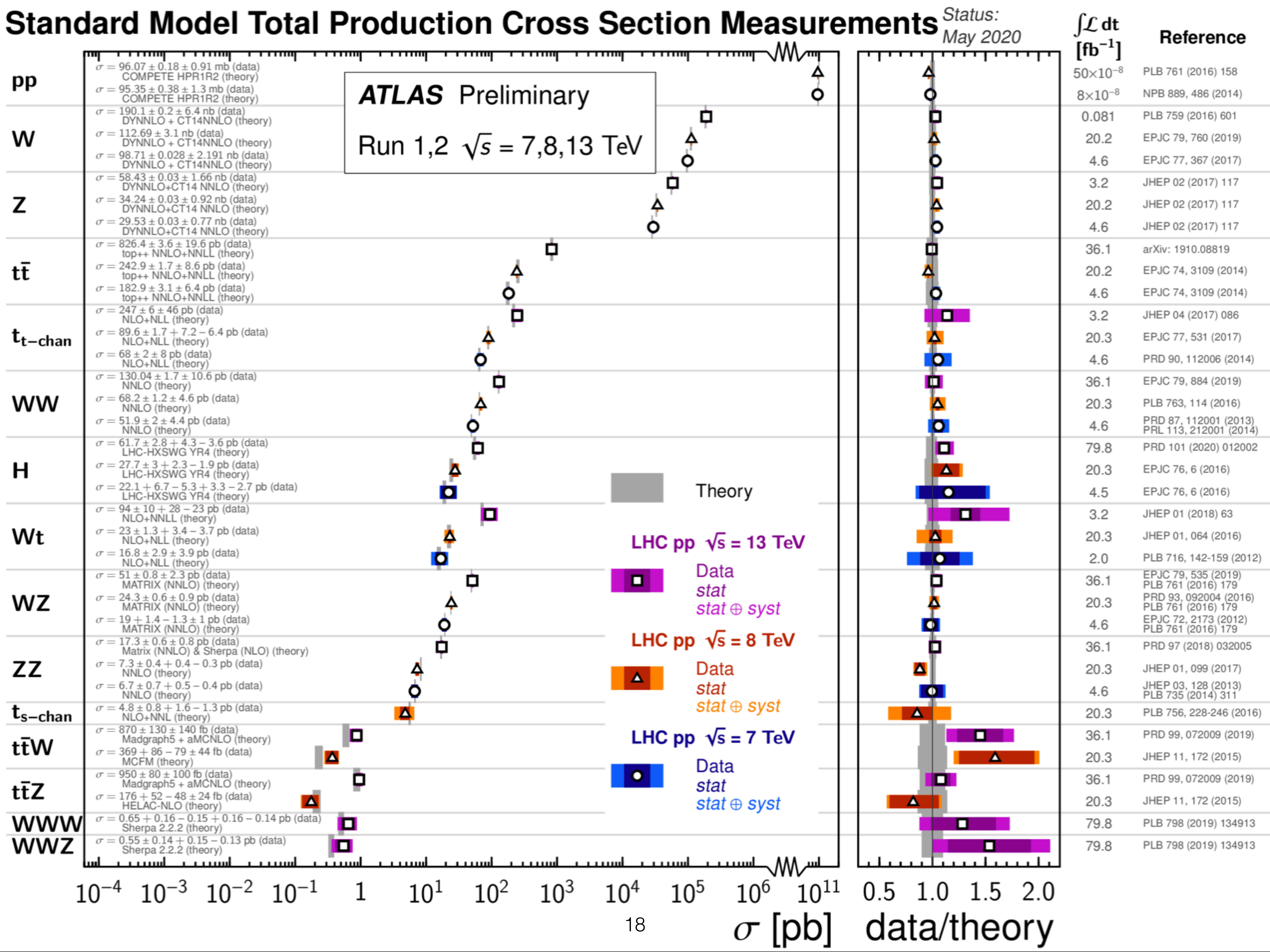


Parton distribution functions

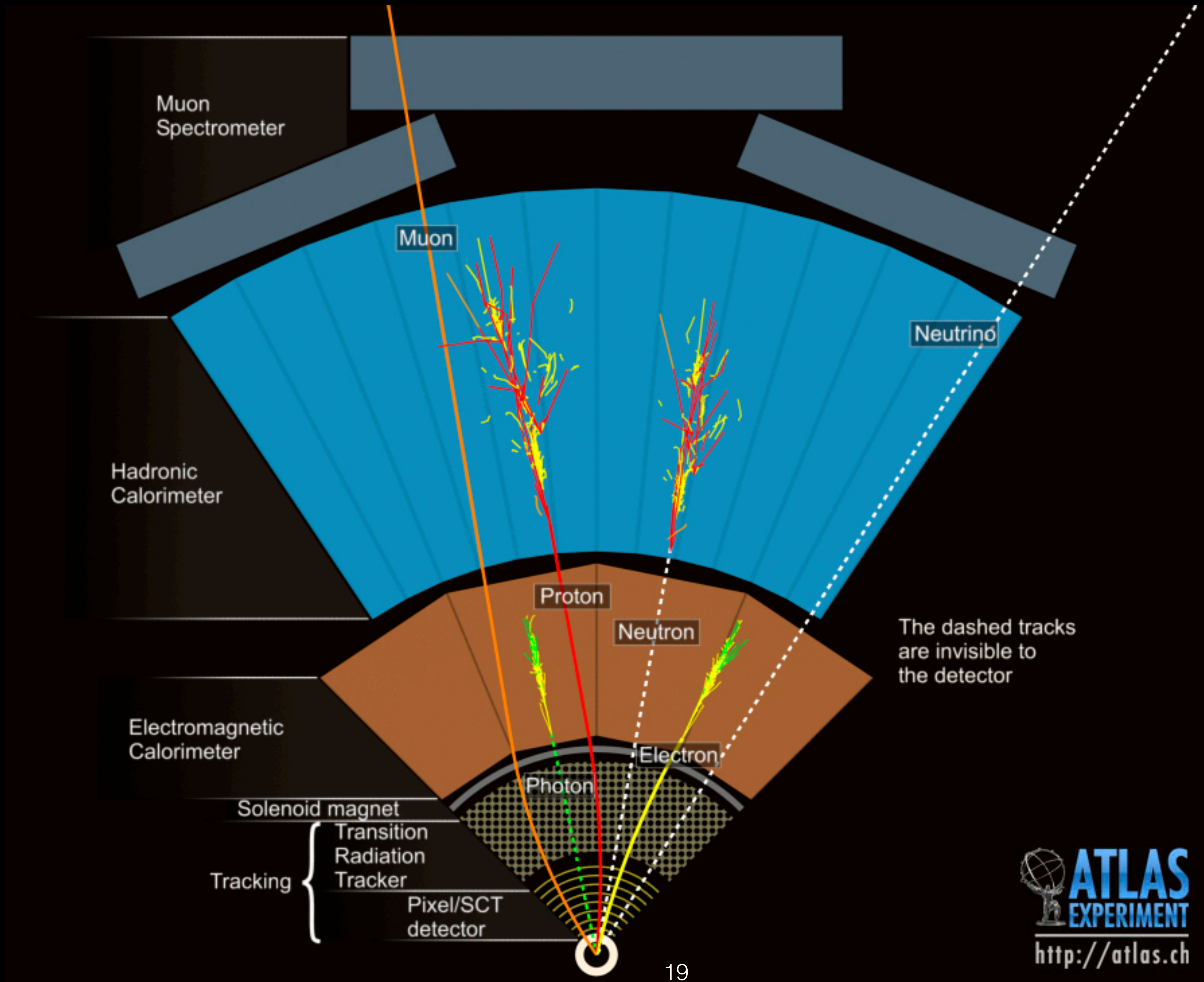
- Proton collisions are effectively collisions between "partons"

ATLAS Detector

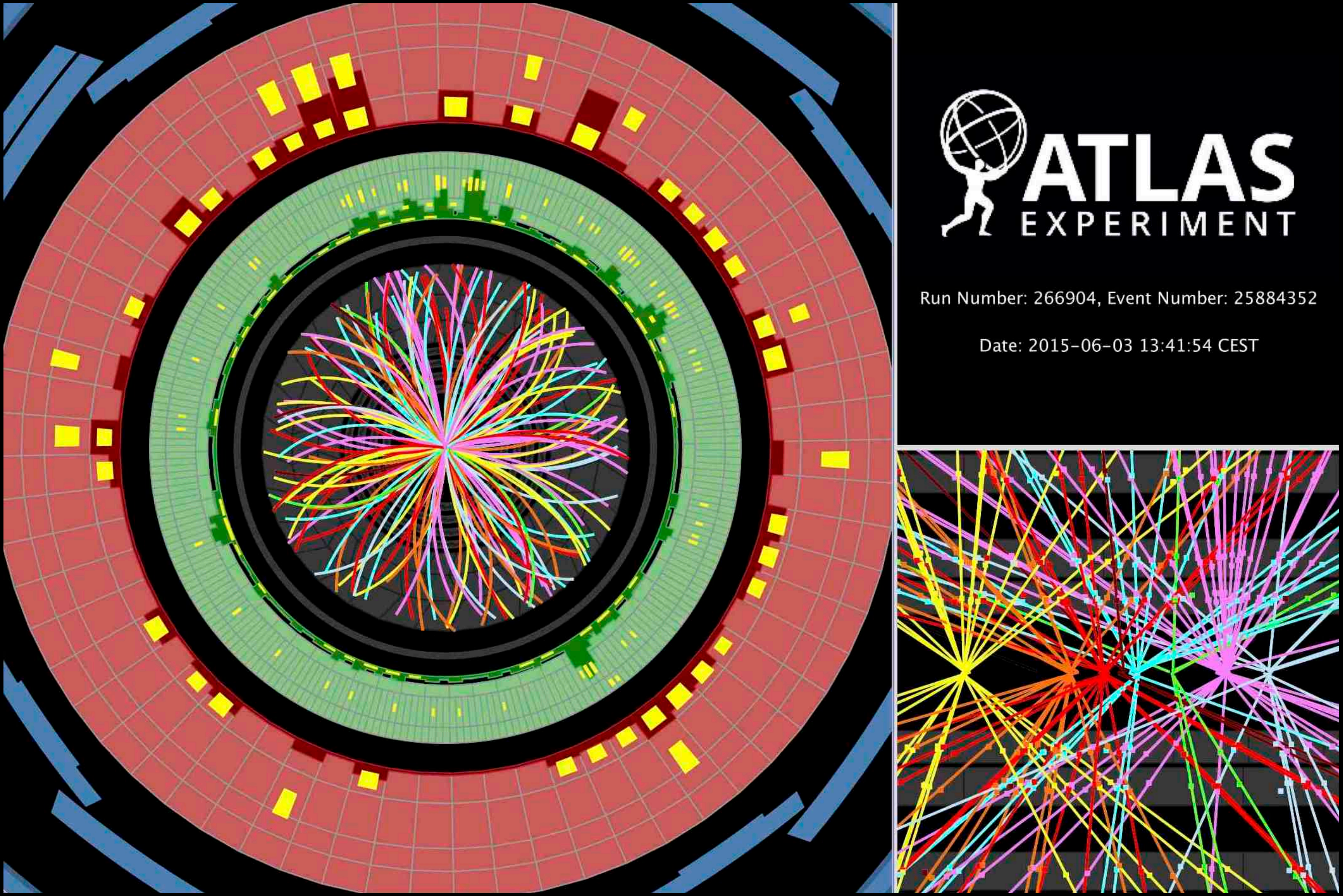



Standard Model Total Production Cross Section Measurements
Status: May 2020
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
∫ℒ dt [fb⁻¹]
Reference
pp
σ = 96.07 ± 0.18 ± 0.91 mb (data) COMPETE HPR1R2 (theory)
σ = 95.35 ± 0.38 ± 1.3 mb (data) COMPETE HPR1R2 (theory)
W
σ = 190.1 ± 0.2 ± 6.4 nb (data) DYNNLO + CT14NNLO (theory)
σ = 112.69 ± 3.1 nb (data) DYNNLO + CT14NNLO (theory)
σ = 98.71 ± 0.028 ± 2.191 nb (data) DYNNLO + CT14NNLO (theory)
Z
σ = 58.43 ± 0.03 ± 1.66 nb (data) DYNNLO+CT14 NNLO (theory)
σ = 34.24 ± 0.03 ± 0.92 nb (data) DYNNLO+CT14 NNLO (theory)
σ = 29.53 ± 0.03 ± 0.77 nb (data) DYNNLO+CT14 NNLO (theory)
tt̄
σ = 826.4 ± 3.6 ± 19.6 pb (data) top++ NNLO+NNLL (theory)
σ = 242.9 ± 1.7 ± 8.6 pb (data) top++ NNLO+NNLL (theory)
σ = 182.9 ± 3.1 ± 6.4 pb (data) top++ NNLO+NNLL (theory)
t t−chan
σ = 247 ± 6 ± 46 pb (data) NLO+NLL (theory)
σ = 89.6 ± 1.7 + 7.2 − 6.4 pb (data) NLO+NLL (theory)
σ = 68 ± 2 ± 8 pb (data) NLO+NLL (theory)
WW
σ = 130.04 ± 1.7 ± 10.6 pb (data) NNLO (theory)
σ = 68.2 ± 1.2 ± 4.6 pb (data) NNLO (theory)
σ = 51.9 ± 2 ± 4.4 pb (data) NNLO (theory)
H
σ = 61.7 ± 2.8 + 4.3 − 3.6 pb (data) LHC-HXSWG YR4 (theory)
σ = 27.7 ± 3 + 2.3 − 1.9 pb (data) LHC-HXSWG YR4 (theory)
σ = 22.1 + 6.7 − 5.3 + 3.3 − 2.7 pb (data) LHC-HXSWG YR4 (theory)
Wt
σ = 94 ± 10 + 28 − 23 pb (data) NLO+NNLL (theory)
σ = 23 ± 1.3 + 3.4 − 3.7 pb (data) NLO+NLL (theory)
σ = 16.8 ± 2.9 ± 3.9 pb (data) NLO+NLL (theory)
WZ
σ = 51 ± 0.8 ± 2.3 pb (data) MATRIX (NNLO) (theory)
σ = 24.3 ± 0.6 ± 0.9 pb (data) MATRIX (NNLO) (theory)
σ = 19 + 1.4 − 1.3 ± 1 pb (data) MATRIX (NNLO) (theory)
ZZ
σ = 17.3 ± 0.6 ± 0.8 pb (data) Matrix (NNLO) & Sherpa (NLO) (theory)
σ = 7.3 ± 0.4 + 0.4 − 0.3 pb (data) NNLO (theory)
σ = 6.7 ± 0.7 + 0.5 − 0.4 pb (data) NNLO (theory)
t s−chan
σ = 4.8 ± 0.8 + 1.6 − 1.3 pb (data) NLO+NNL (theory)
tt̄W
σ = 870 ± 130 ± 140 fb (data) Madgraph5 + aMCNLO (theory)
σ = 369 + 86 − 79 ± 44 fb (data) MCFM (theory)
tt̄Z
σ = 950 ± 80 ± 100 fb (data) Madgraph5 + aMCNLO (theory)
σ = 176 + 52 − 48 ± 24 fb (data) HELAC-NLO (theory)
WWW
σ = 0.65 + 0.16 − 0.15 + 0.16 − 0.14 pb (data) Sherpa 2.2.2 (theory)
WWZ
σ = 0.55 ± 0.14 + 0.15 − 0.13 pb (data) Sherpa 2.2.2 (theory)
Theory
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
50×10⁻⁸ PLB 761 (2016) 158
8×10⁻⁸ NPB 889, 486 (2014)
0.081 PLB 759 (2016) 601
20.2 EPJC 79, 760 (2019)
4.6 EPJC 77, 367 (2017)
3.2 JHEP 02 (2017) 117
20.2 JHEP 02 (2017) 117
4.6 JHEP 02 (2017) 117
36.1 arXiv: 1910.08819
20.2 EPJC 74, 3109 (2014)
4.6 EPJC 74, 3109 (2014)
3.2 JHEP 04 (2017) 086
20.3 EPJC 77, 531 (2017)
4.6 PRD 90, 112006 (2014)
36.1 EPJC 79, 884 (2019)
20.3 PLB 763, 114 (2016)
4.6 PRD 87, 112001 (2013) PRL 113, 212001 (2014)
79.8 PRD 101 (2020) 012002
20.3 EPJC 76, 6 (2016)
4.5 EPJC 76, 6 (2016)
3.2 JHEP 01 (2018) 63
20.3 JHEP 01, 064 (2016)
2.0 PLB 716, 142-159 (2012)
36.1 EPJC 79, 535 (2019) PLB 761 (2016) 179
20.3 PRD 93, 092004 (2016) PLB 761 (2016) 179
4.6 EPJC 72, 2173 (2012) PLB 761 (2016) 179
36.1 PRD 97 (2018) 032005
20.3 JHEP 01, 099 (2017)
4.6 JHEP 03, 128 (2013) PLB 735 (2014) 311
20.3 PLB 756, 228-246 (2016)
36.1 PRD 99, 072009 (2019)
20.3 JHEP 11, 172 (2015)
36.1 PRD 99, 072009 (2019)
20.3 JHEP 11, 172 (2015)
79.8 PLB 798 (2019) 134913
79.8 PLB 798 (2019) 134913
10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10¹¹
σ [pb]
0.5 1.0 1.5 2.0
data/theory

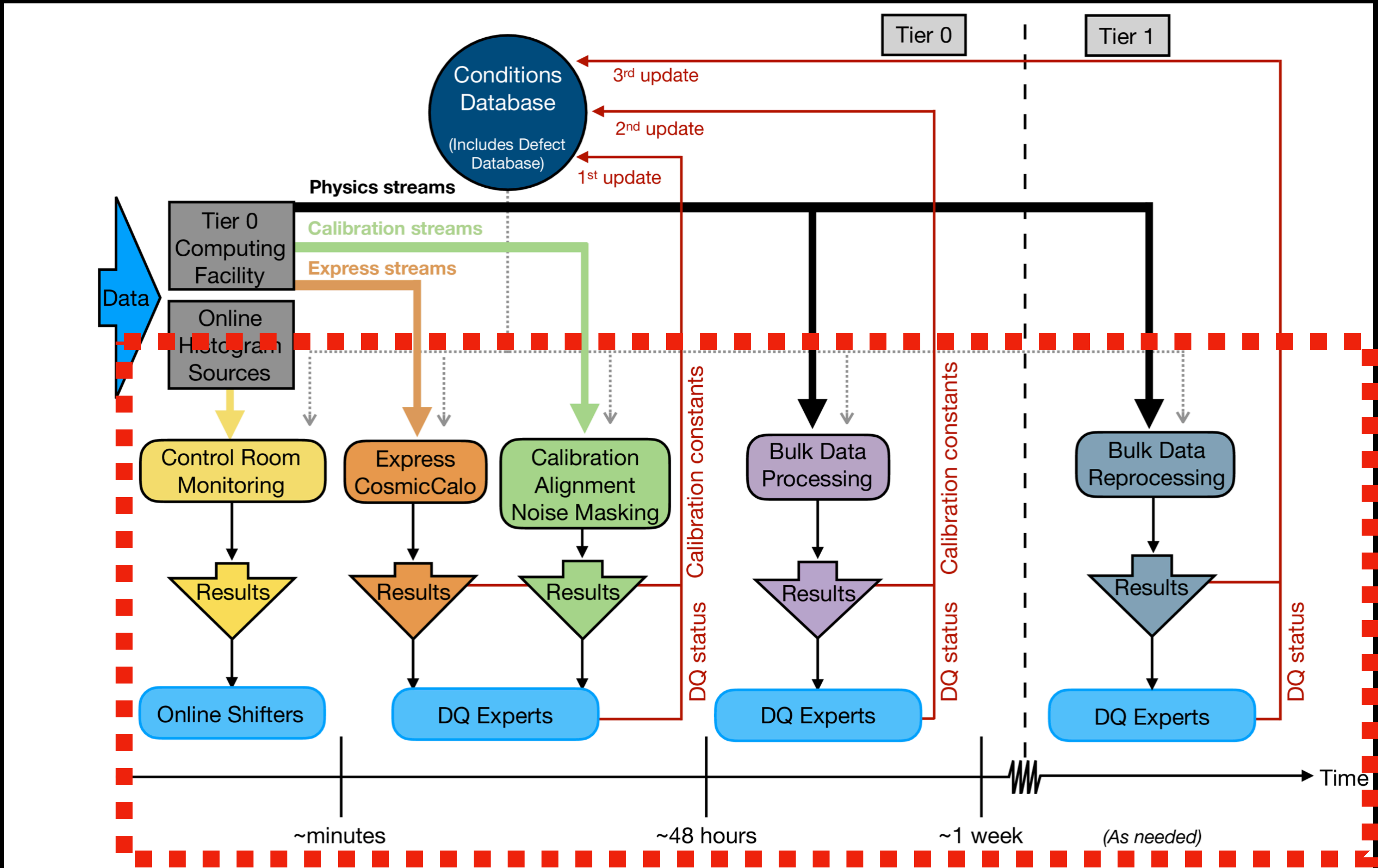
Detector subsystems and particle identification



Multiple collisions: “Pileup”

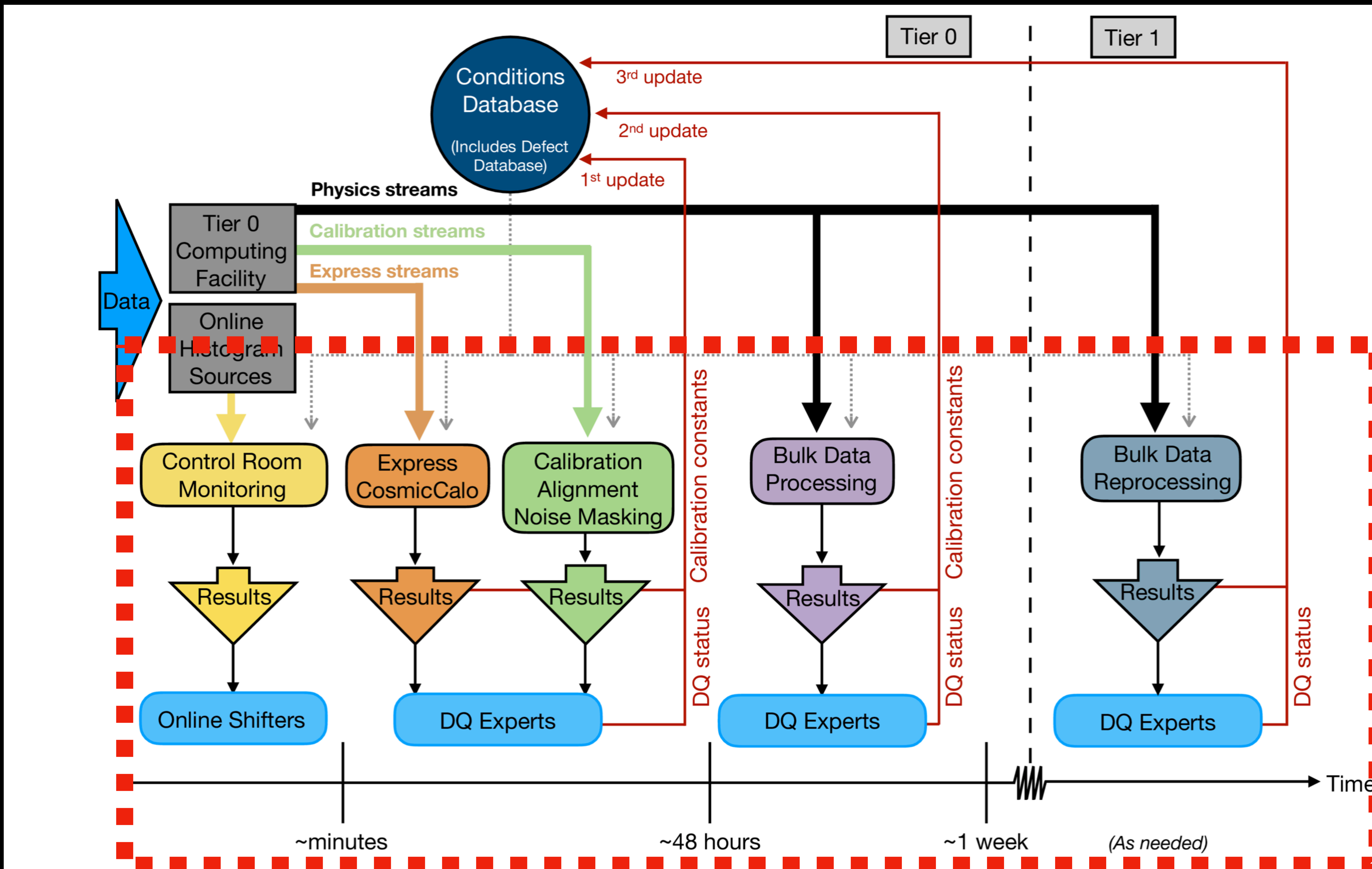


ATLAS data taking and computing

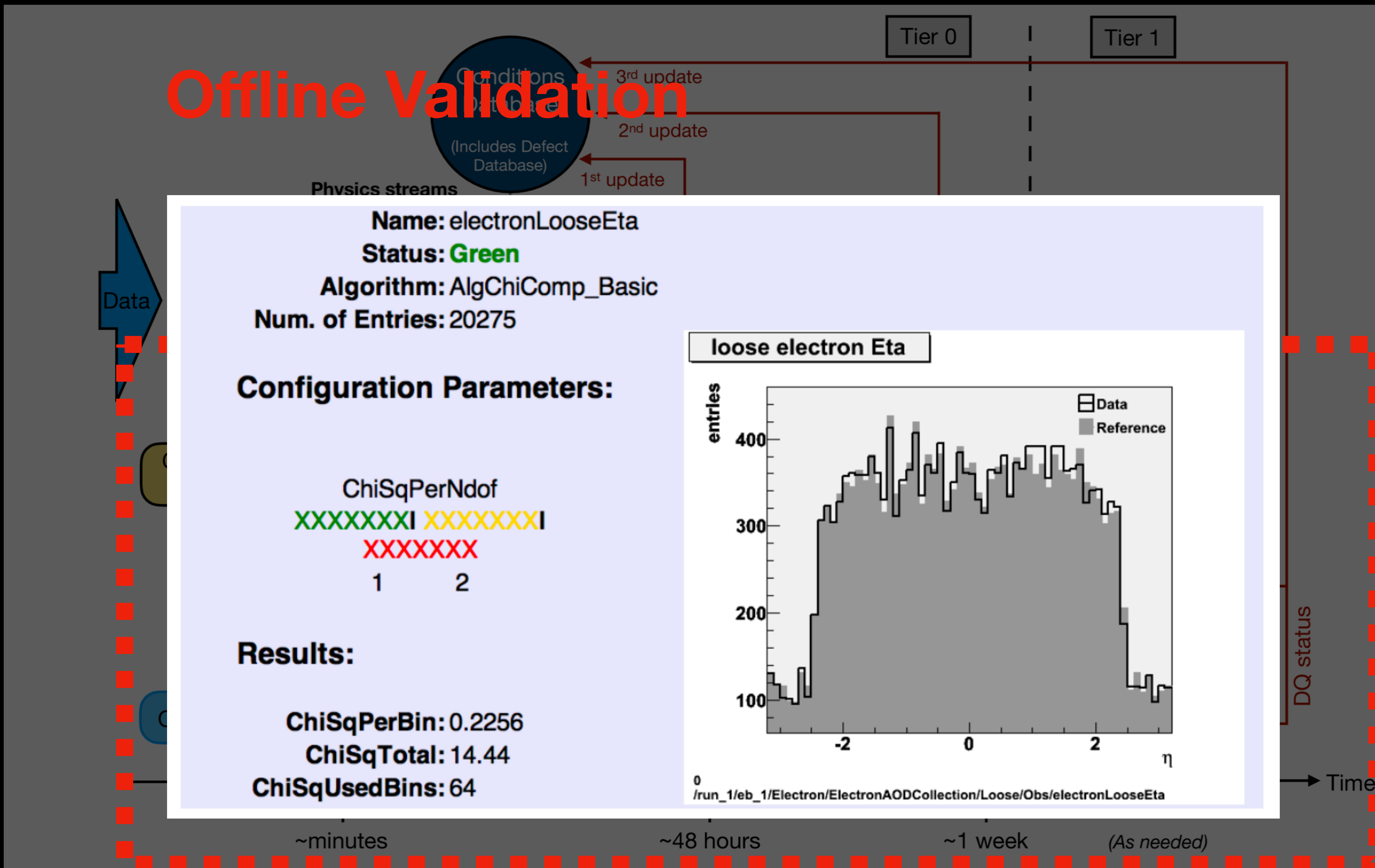


ATLAS data taking and computing

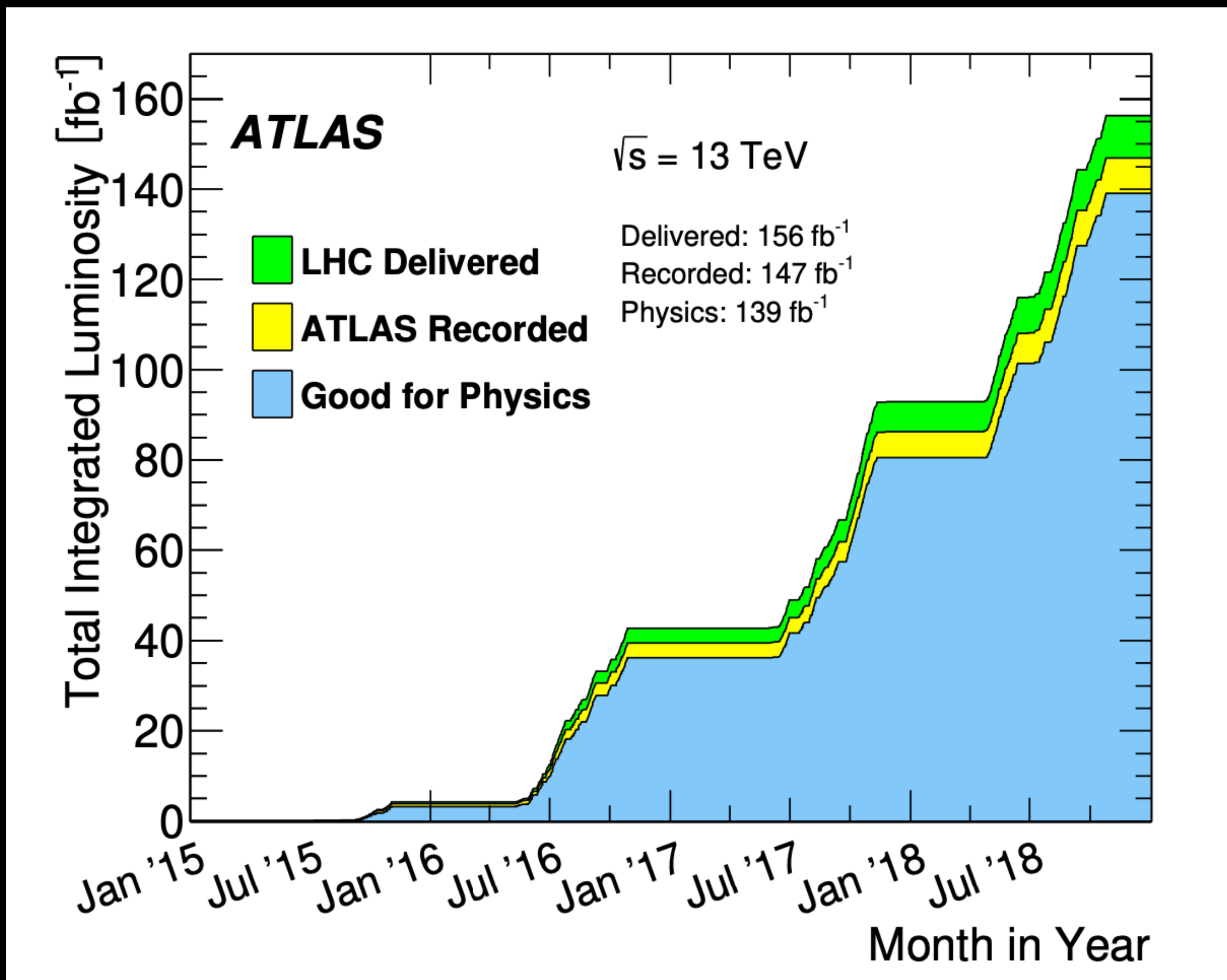
ATLAS data taking and computing

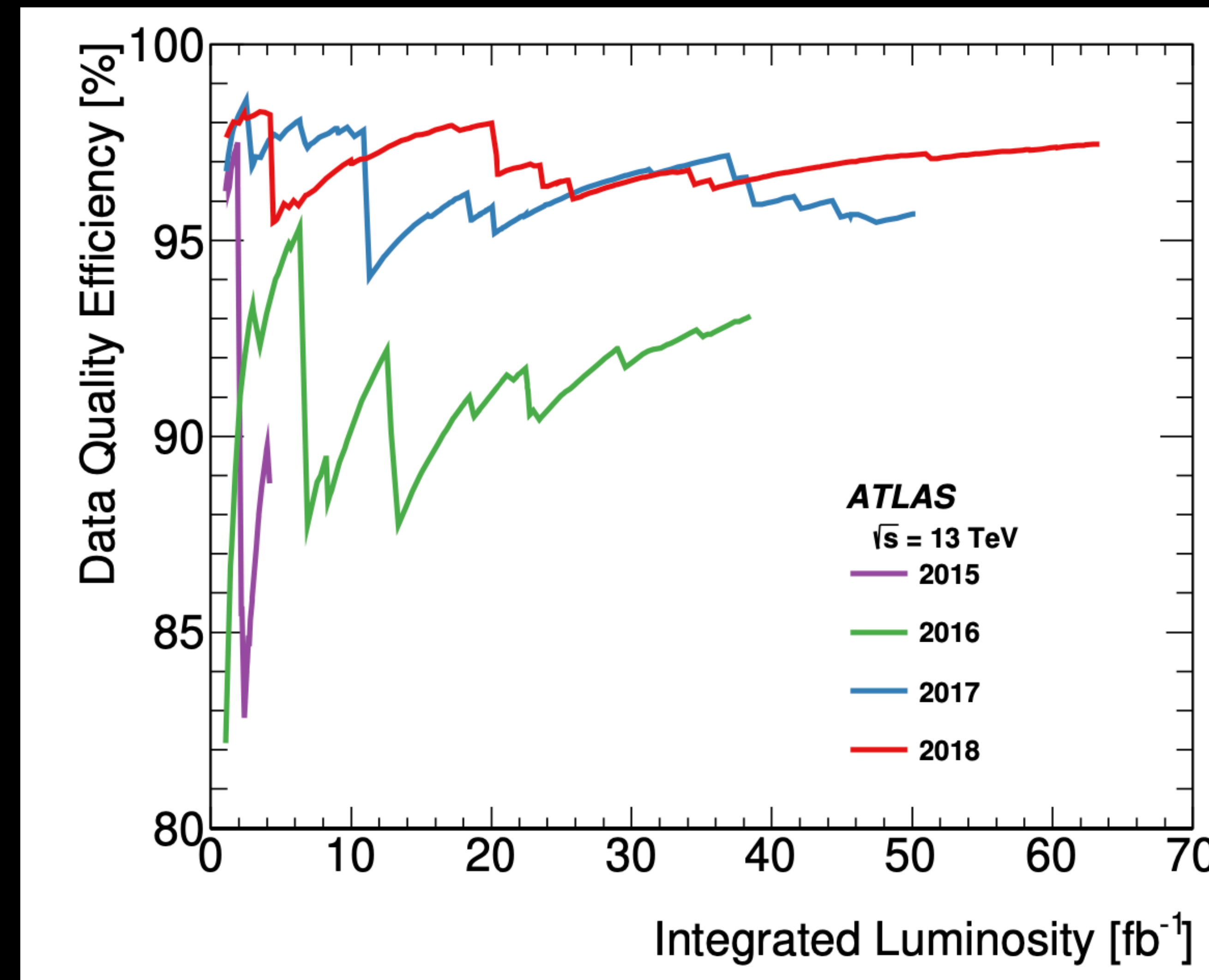


ATLAS data taking and computing



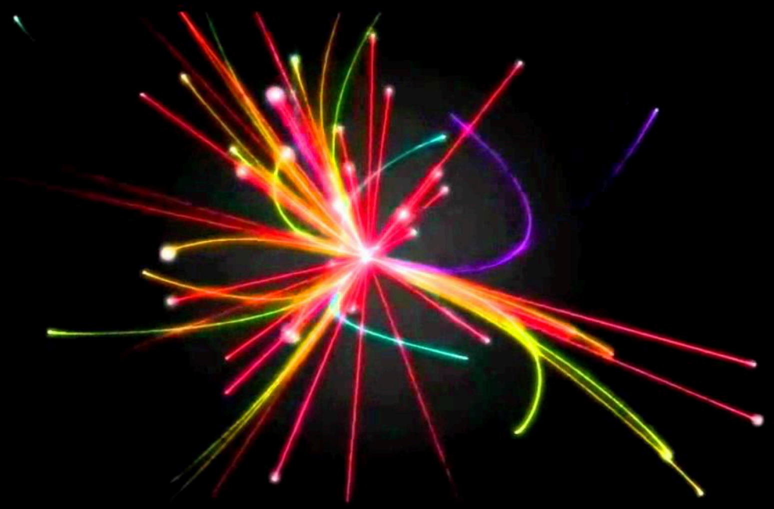
ATLAS data taking and computing



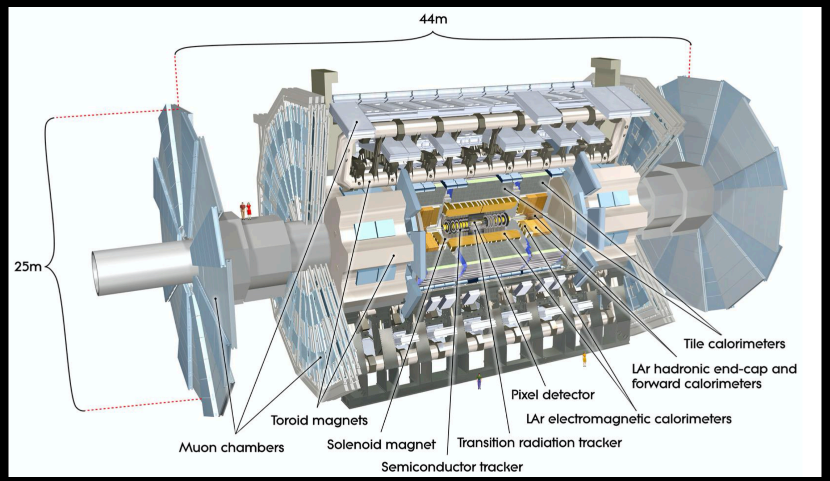


- High data taking efficiency
- Successive improvement in efficiency in every passing year.

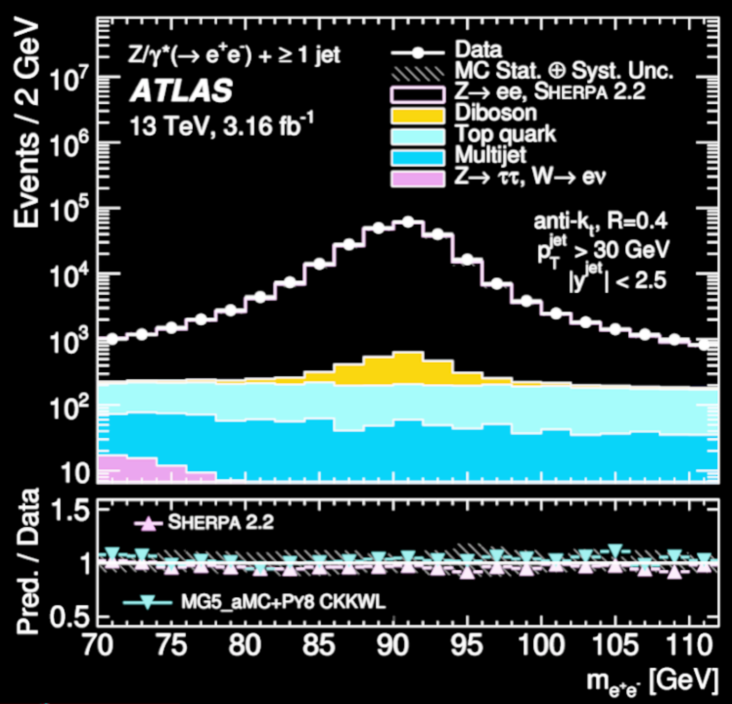
General principle of analysis



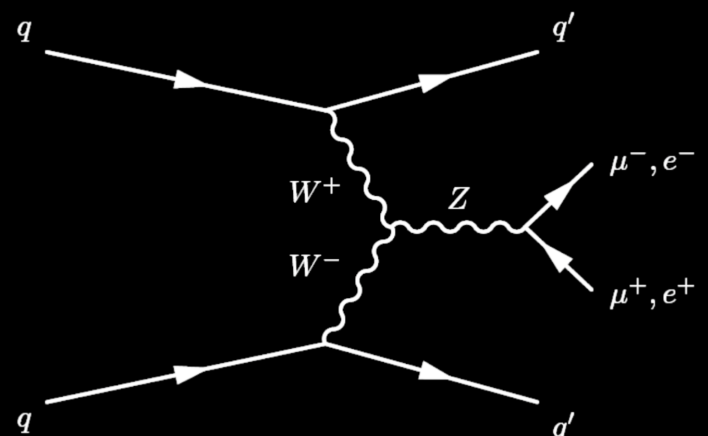
P-P collision



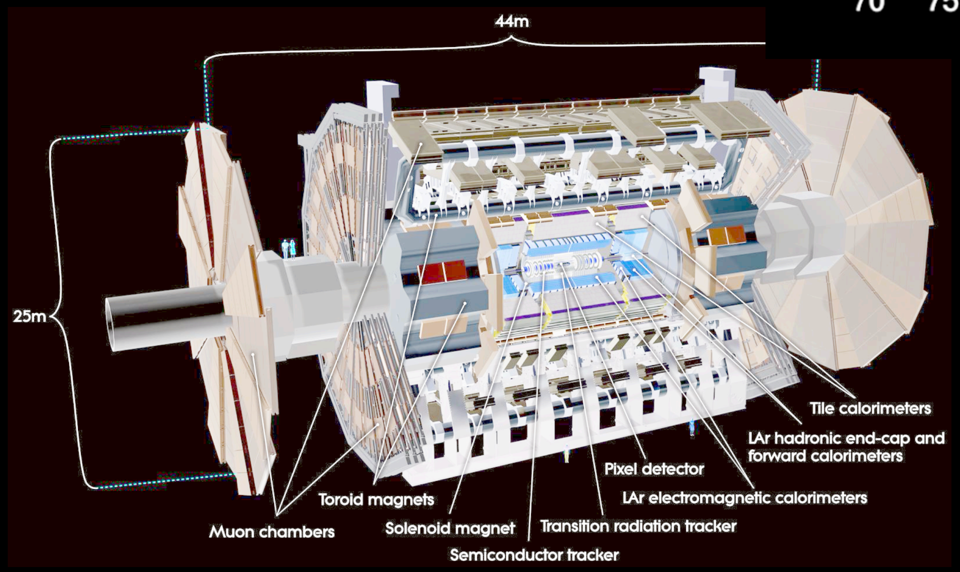
Real Detector



Simulated Detector

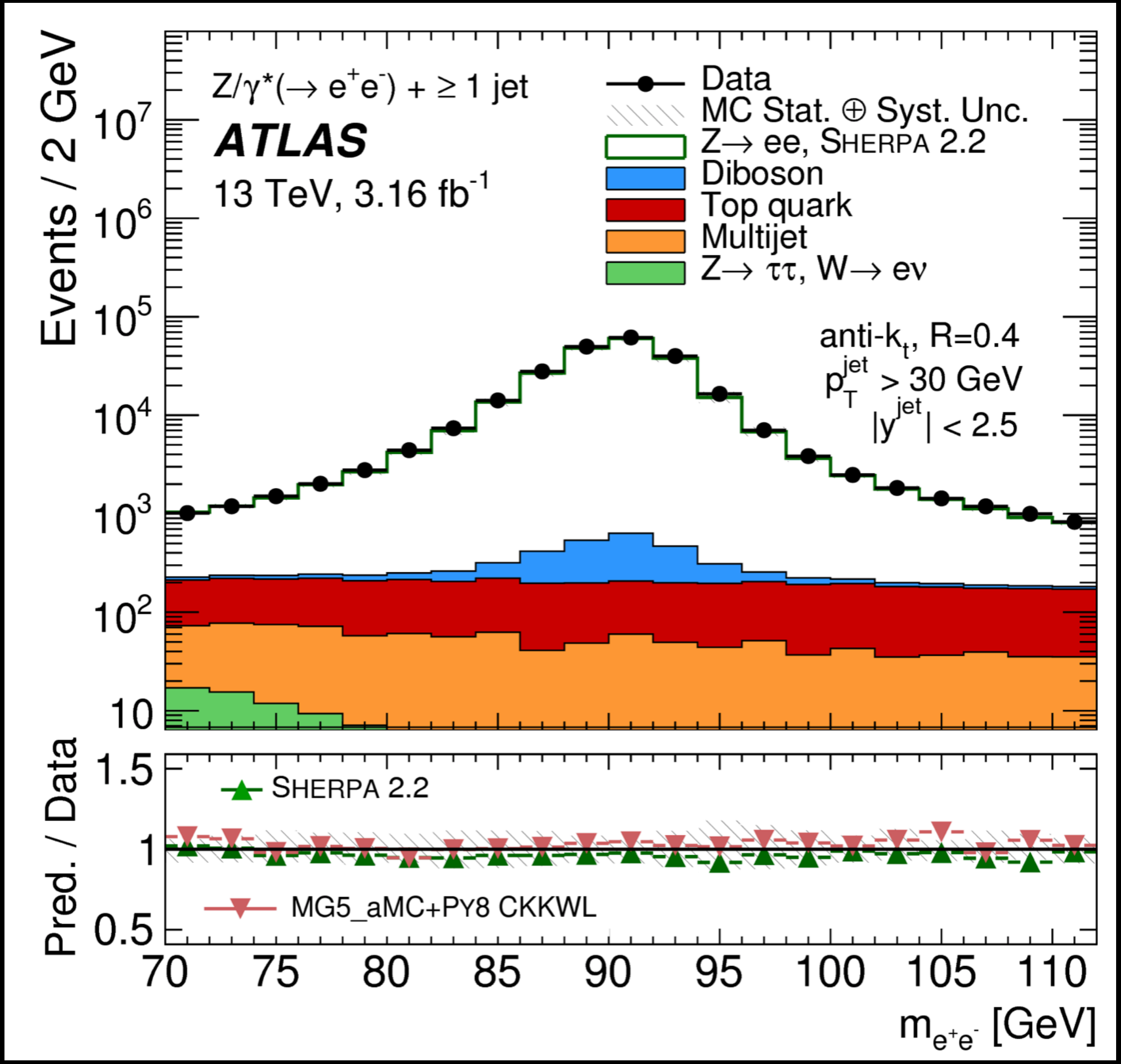


Theory prediction



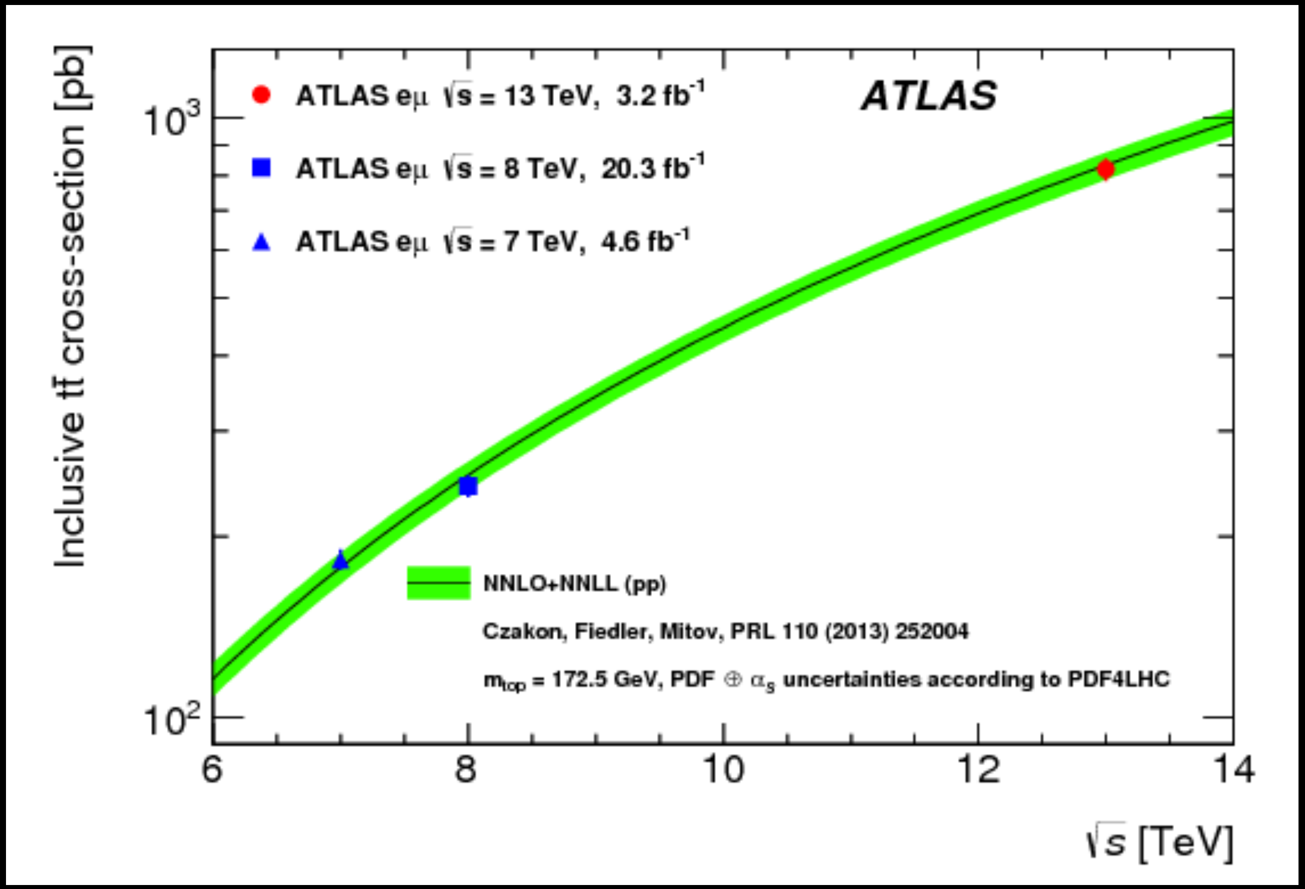
General principle of analysis

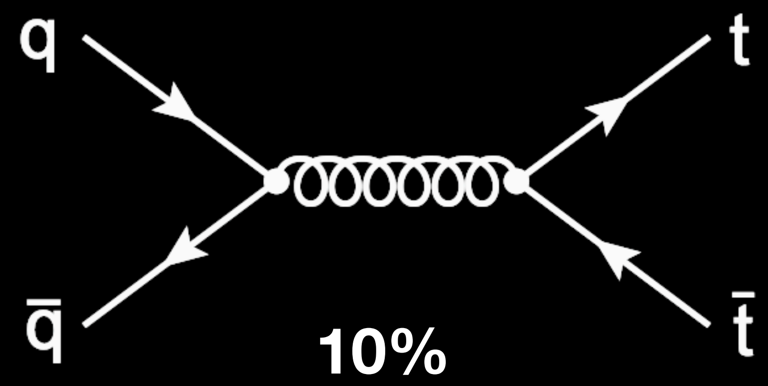
- Out of all the data collected select a sub sample of events of interest.
- Compare the selected events with a simulated theory model.

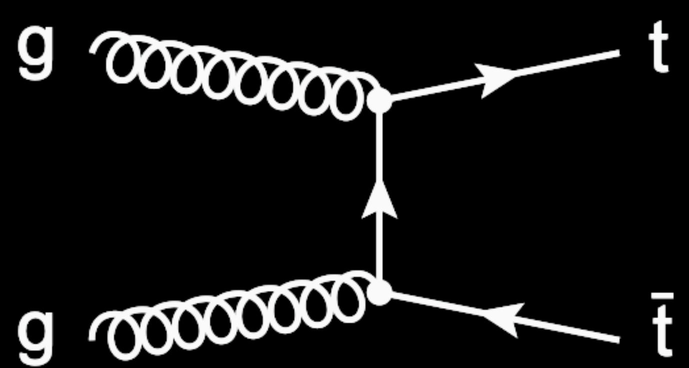


- Sometimes in case where the rate of production has to be measured we fit the simulated theory to the observed data.
- The fit parameters can be
  - simple normalization factors, or.
  - $\mu \equiv \frac{\text{Measured}}{\text{SM predicted}}$

Top Quark pair production at LHC

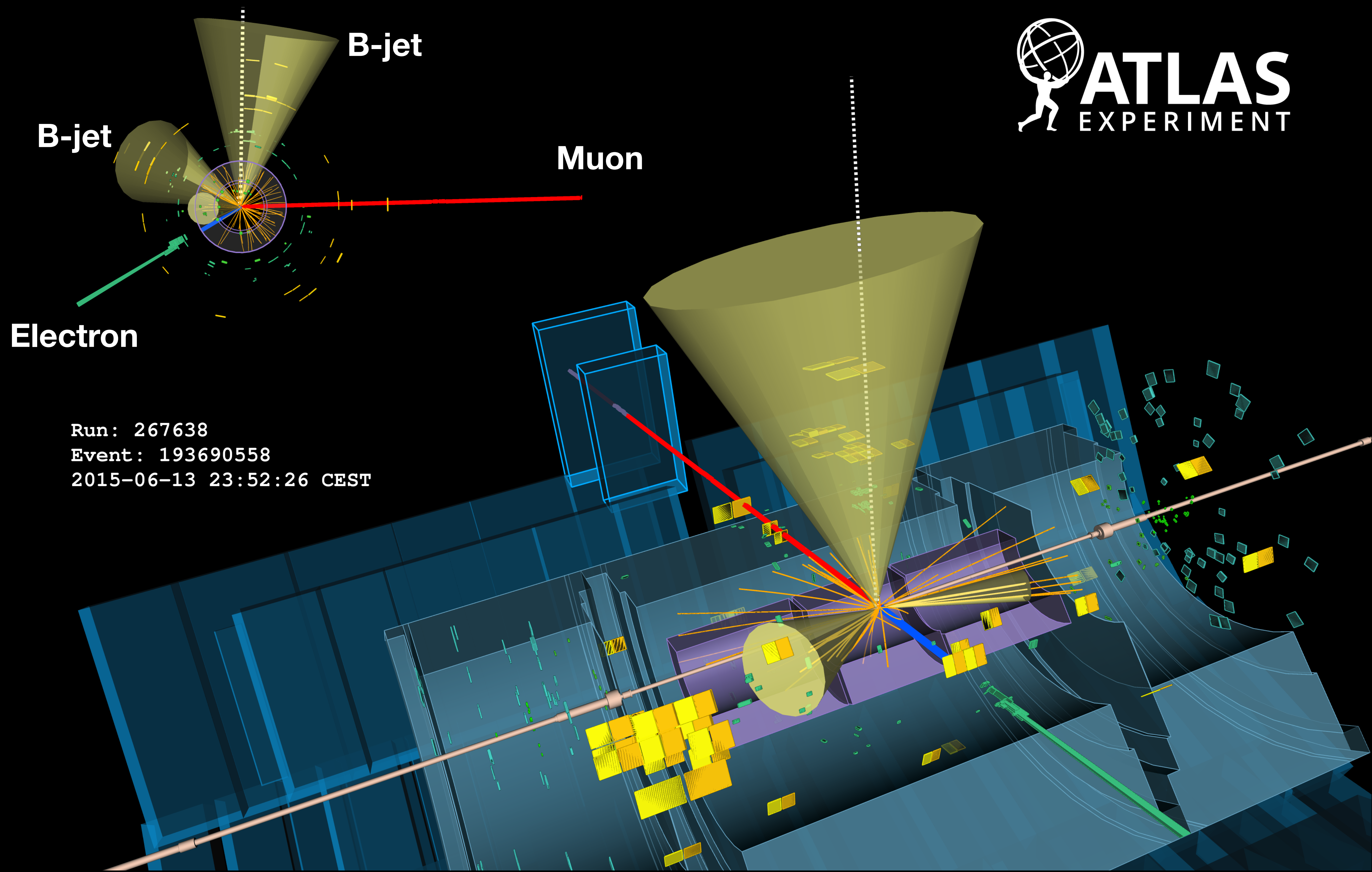






- Between 2015 and 2018 ATLAS several Millions of ttbar events.
- Rare top processes like $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$ and even processes like $t\bar{t}t\bar{t}$ are now becoming accessible at the LHC.

Top Quark pair production at LHC



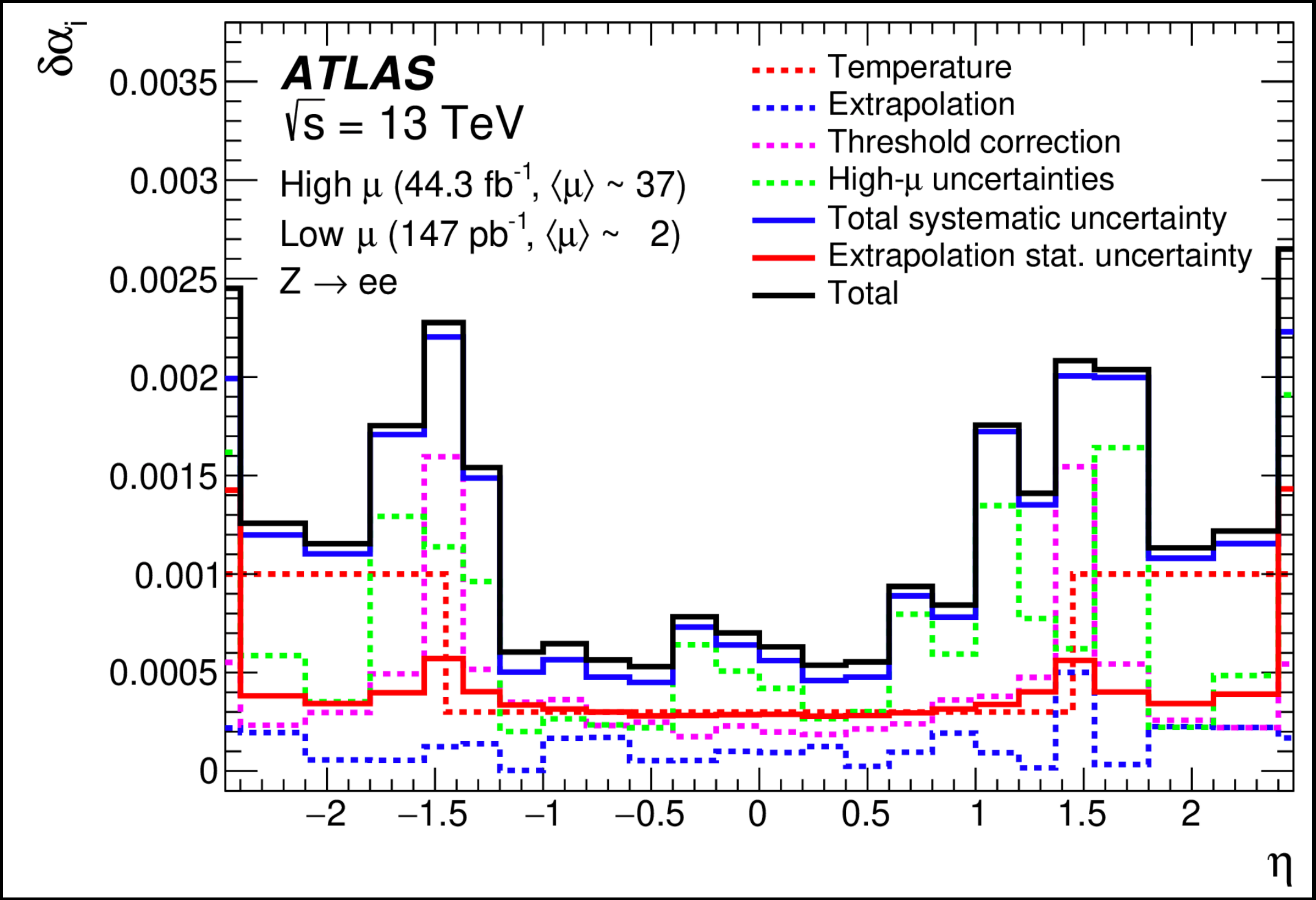
The Challenges

- Though ~10 top quarks are produced every second, all of them may not be seen in the detector due to efficiencies and acceptances.

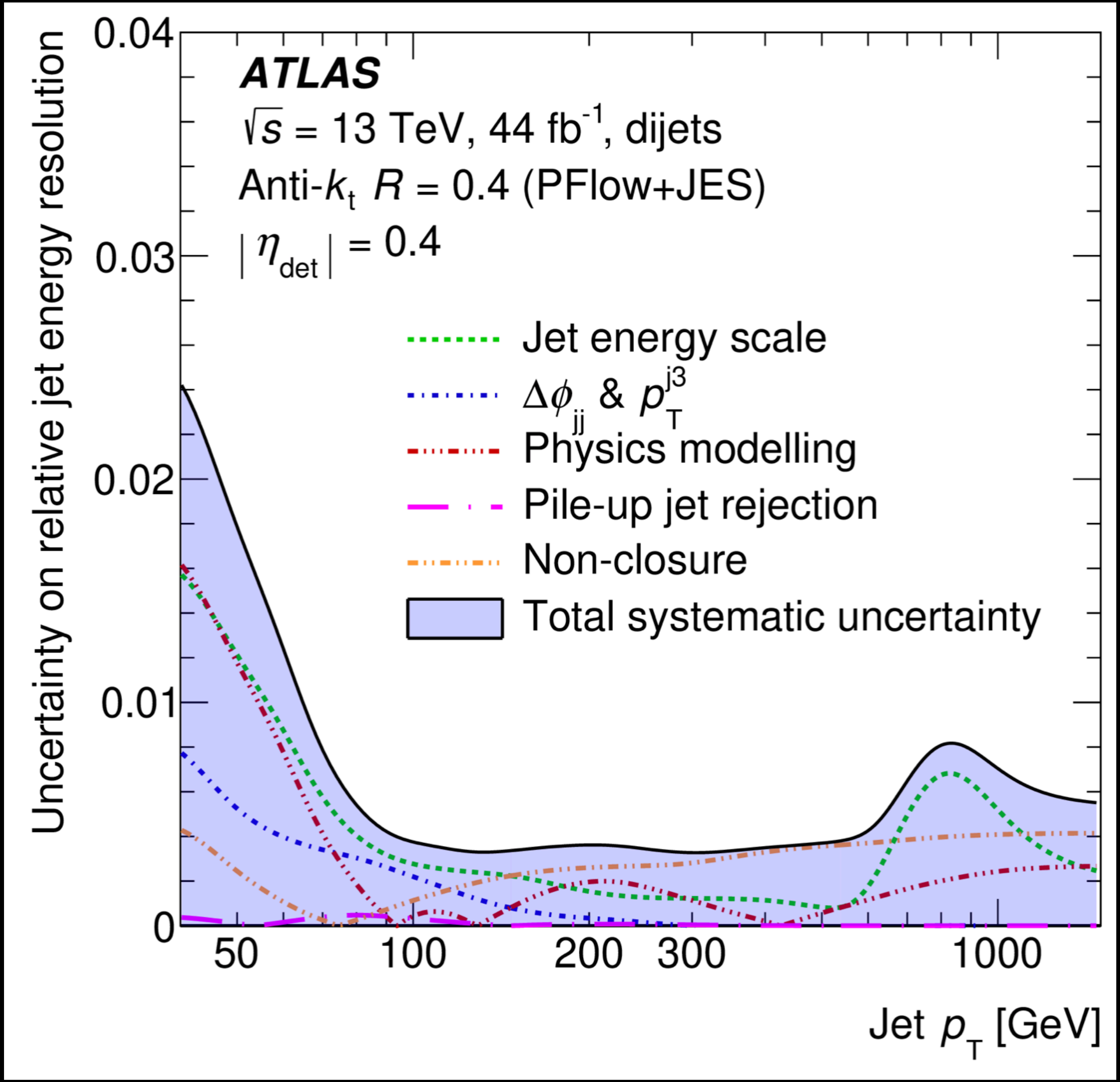
- Calibration of the detector. Understanding the difference between simulation and real data

- Theory uncertainties: Limited by available technologies for calculations.

Understanding electrons in the detector



Understanding Jets

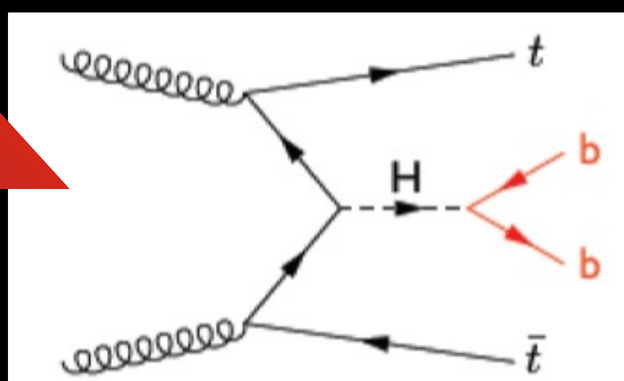


Experimental challenges in measuring $t\bar{t}H$

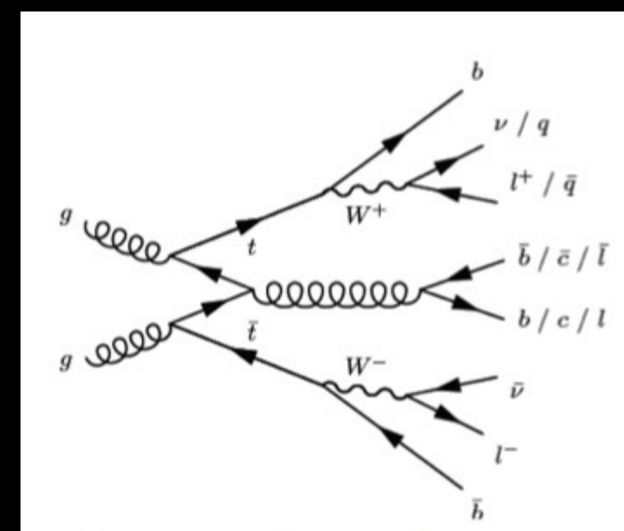
- Standard Model expectation: ~507 fb: About 1% of total Higgs cross-section.
  - Many final states
  - Tiny signal and large backgrounds

Signal | **Background**

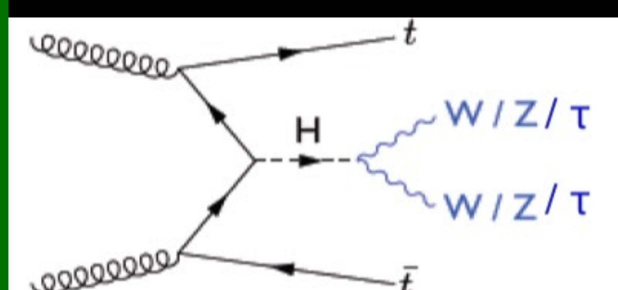
Higgs Branching ratio



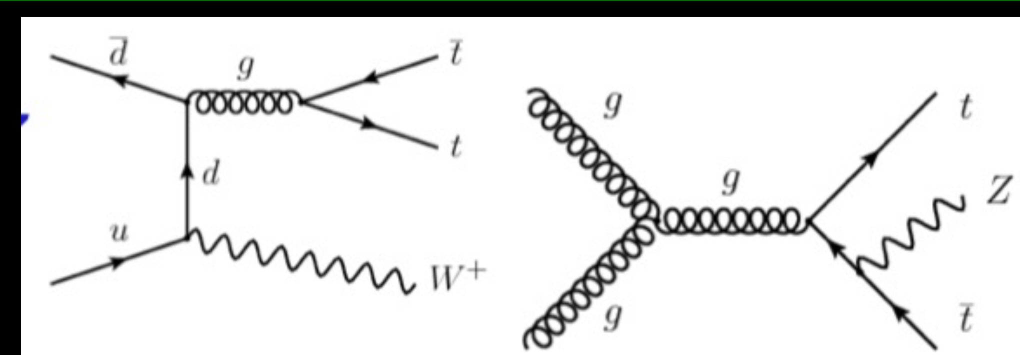
ttH(bb)



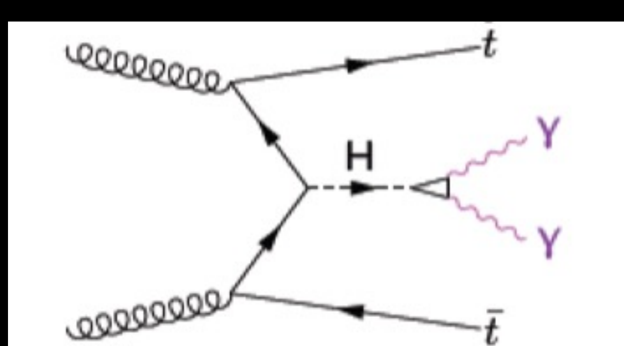
tt+jets



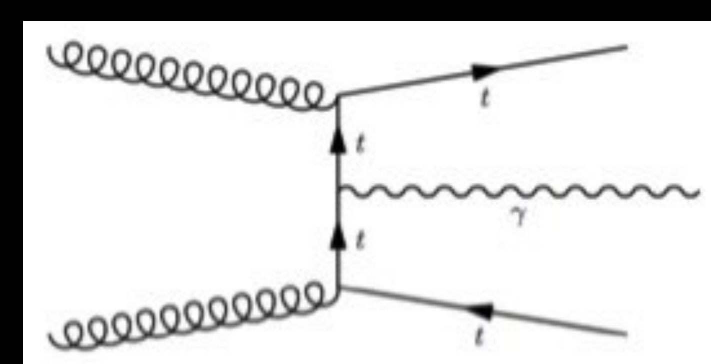
ttH-multileptons



ttV

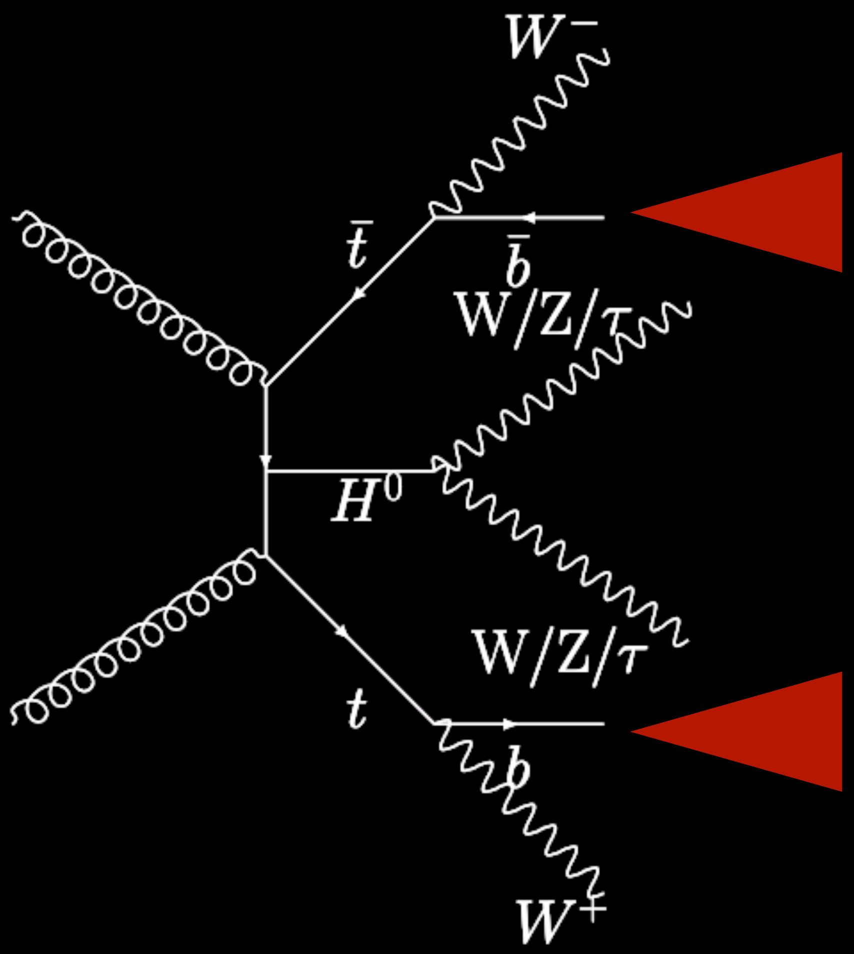


ttH(γγ)



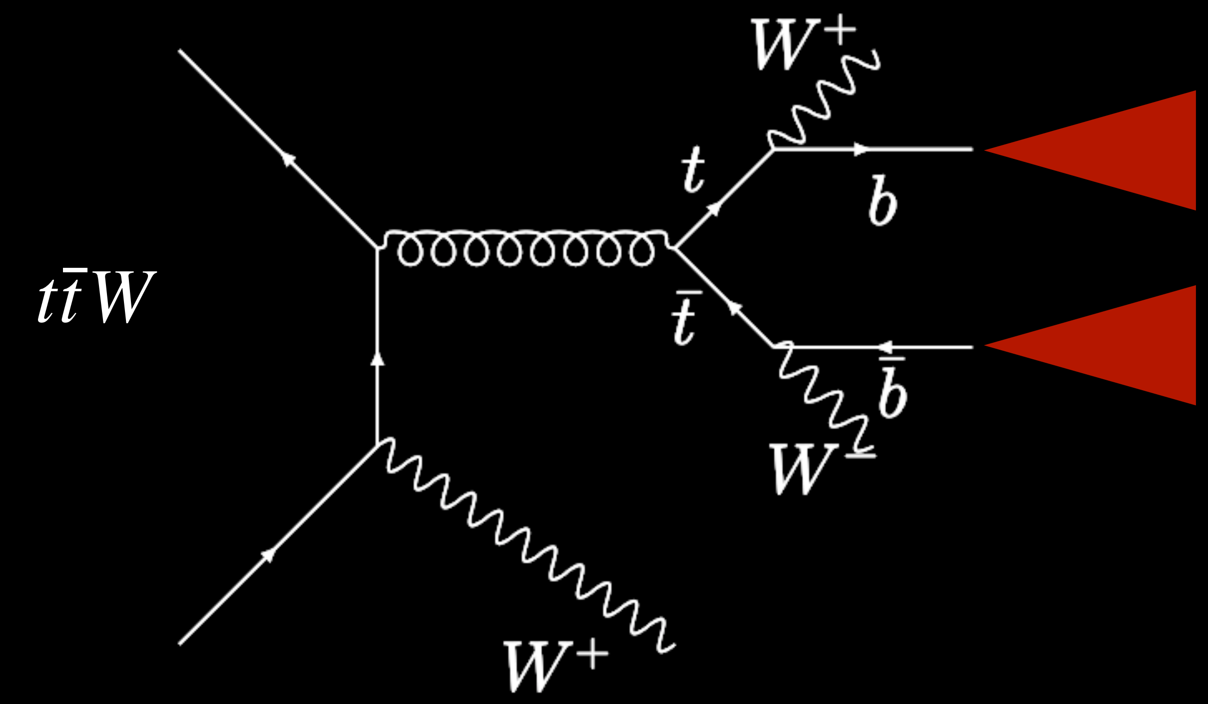
ttγ

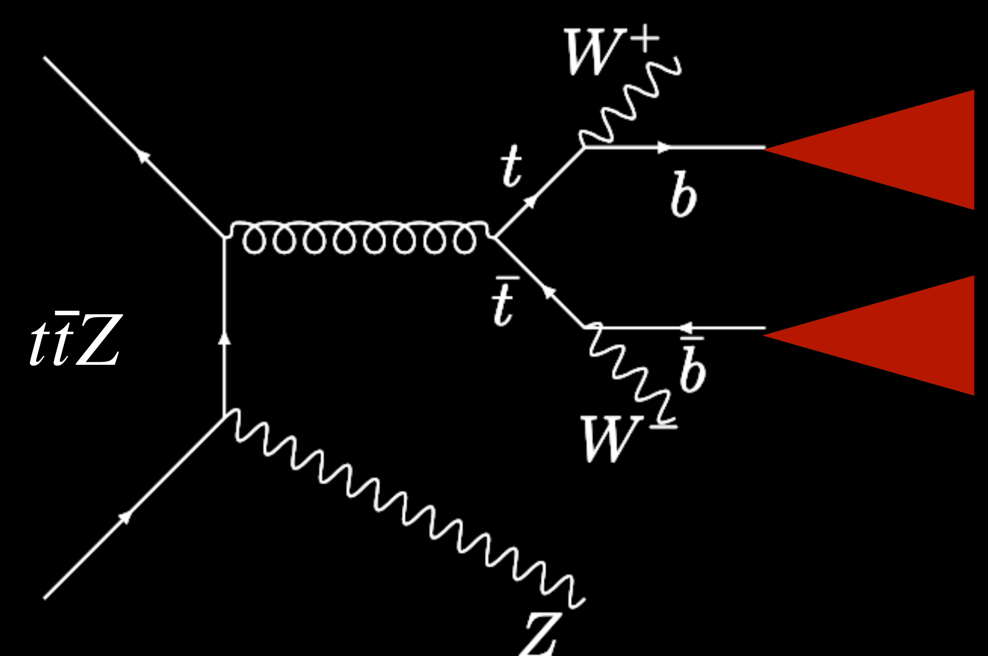
$t\bar{t}H$ multileptons



$t\bar{t}H$ **(Signal)**

Major Irreducible backgrounds





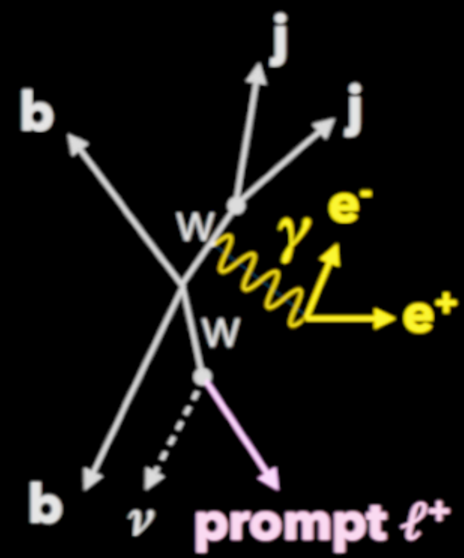
…and many other

$t\bar{t}H$ multileptons

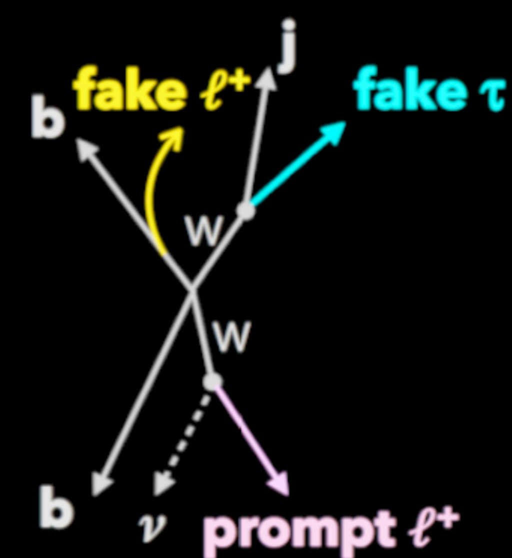
Reducible backgrounds

Semileptonic b-decay

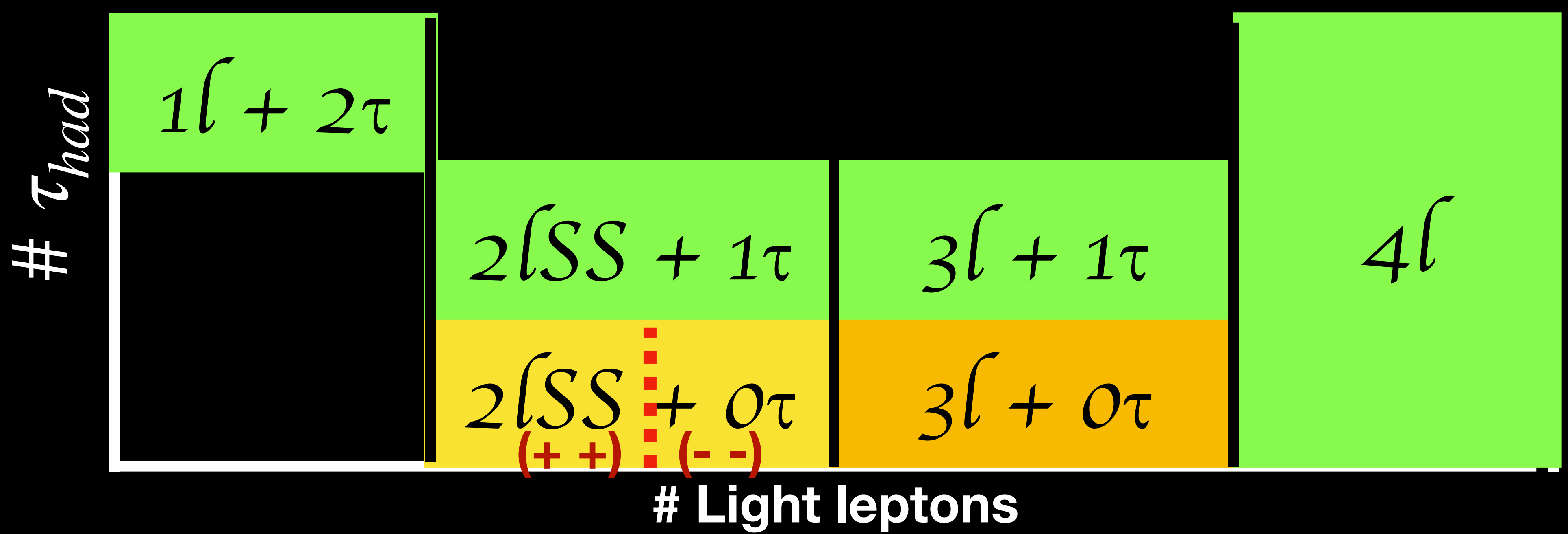
Photon conversions

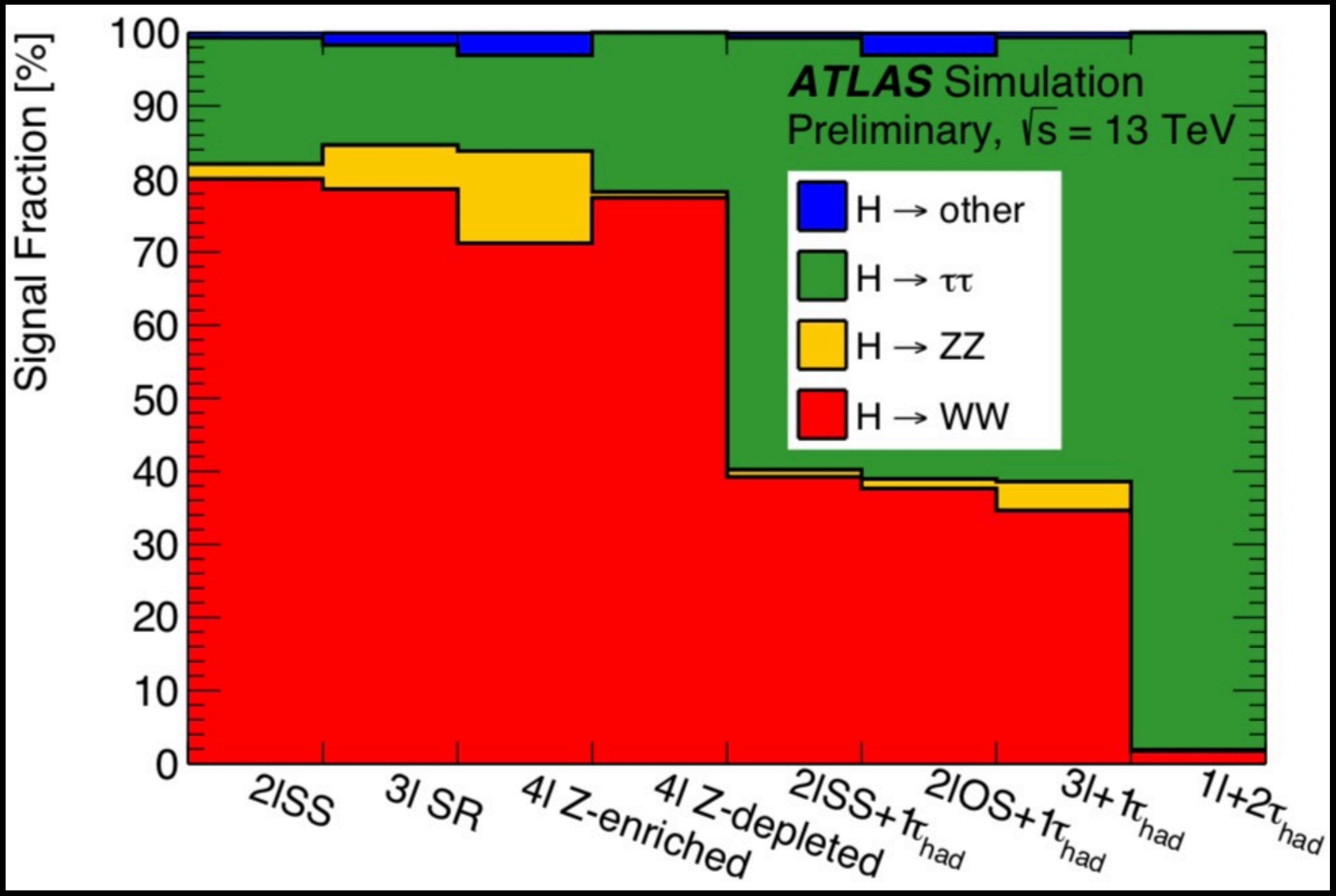


Non-prompt lepton & fake τ



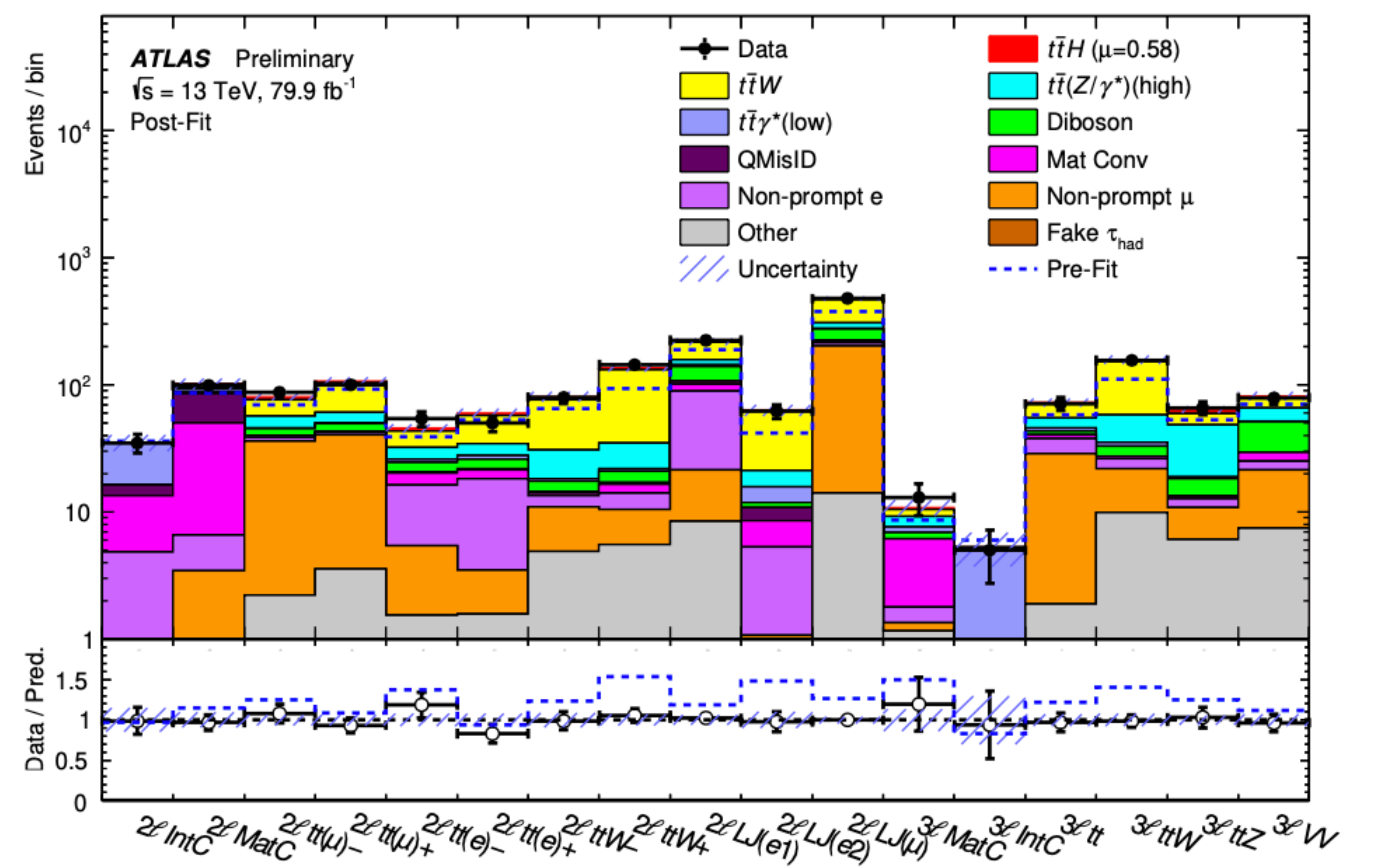
Multilepton signatures



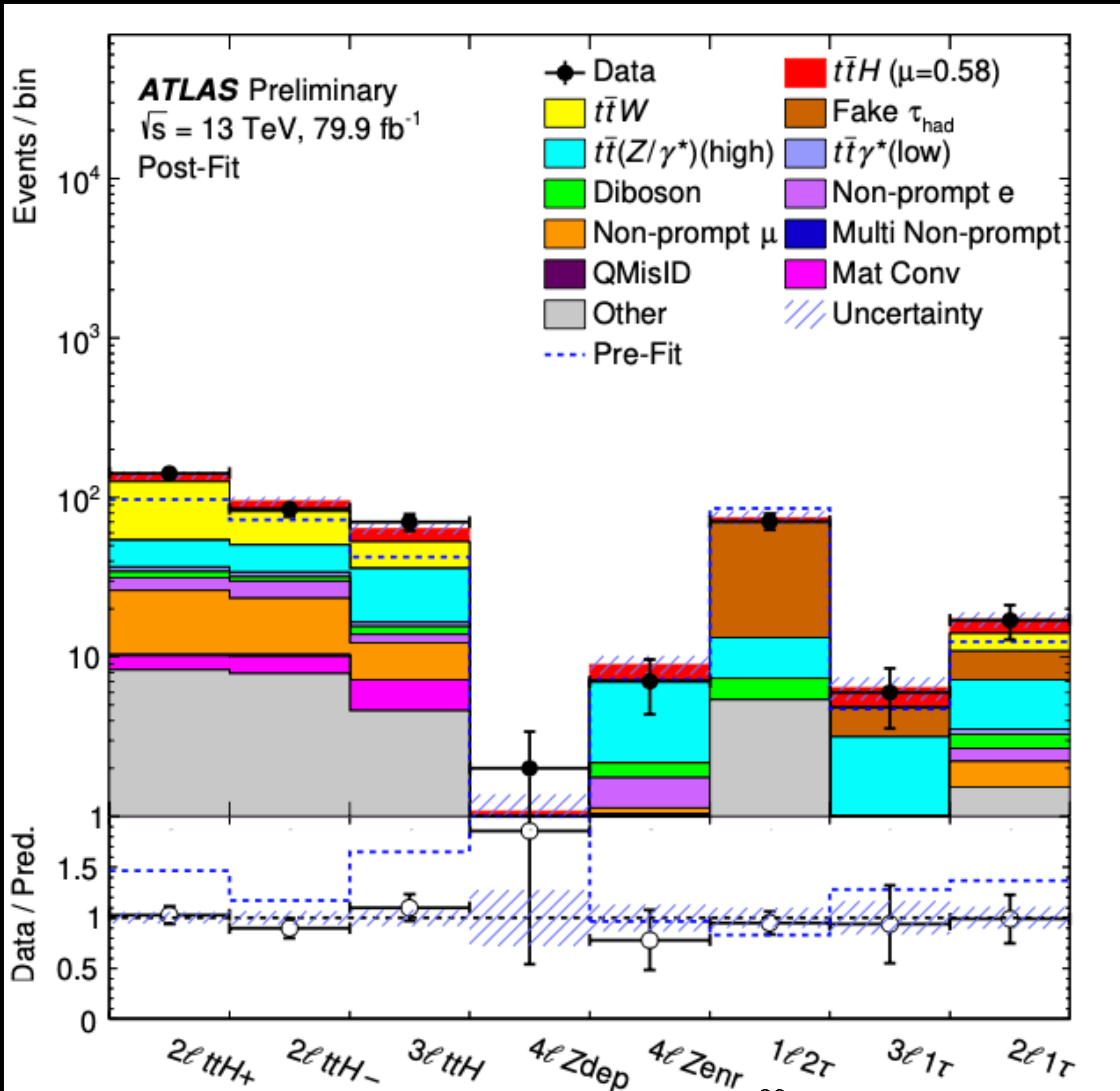


- Events are classified into several different categories to optimize signal selection
- Machine learning algorithms (boosted decision trees) are used to separate signal from background

Modeling agreement in data: Control regions

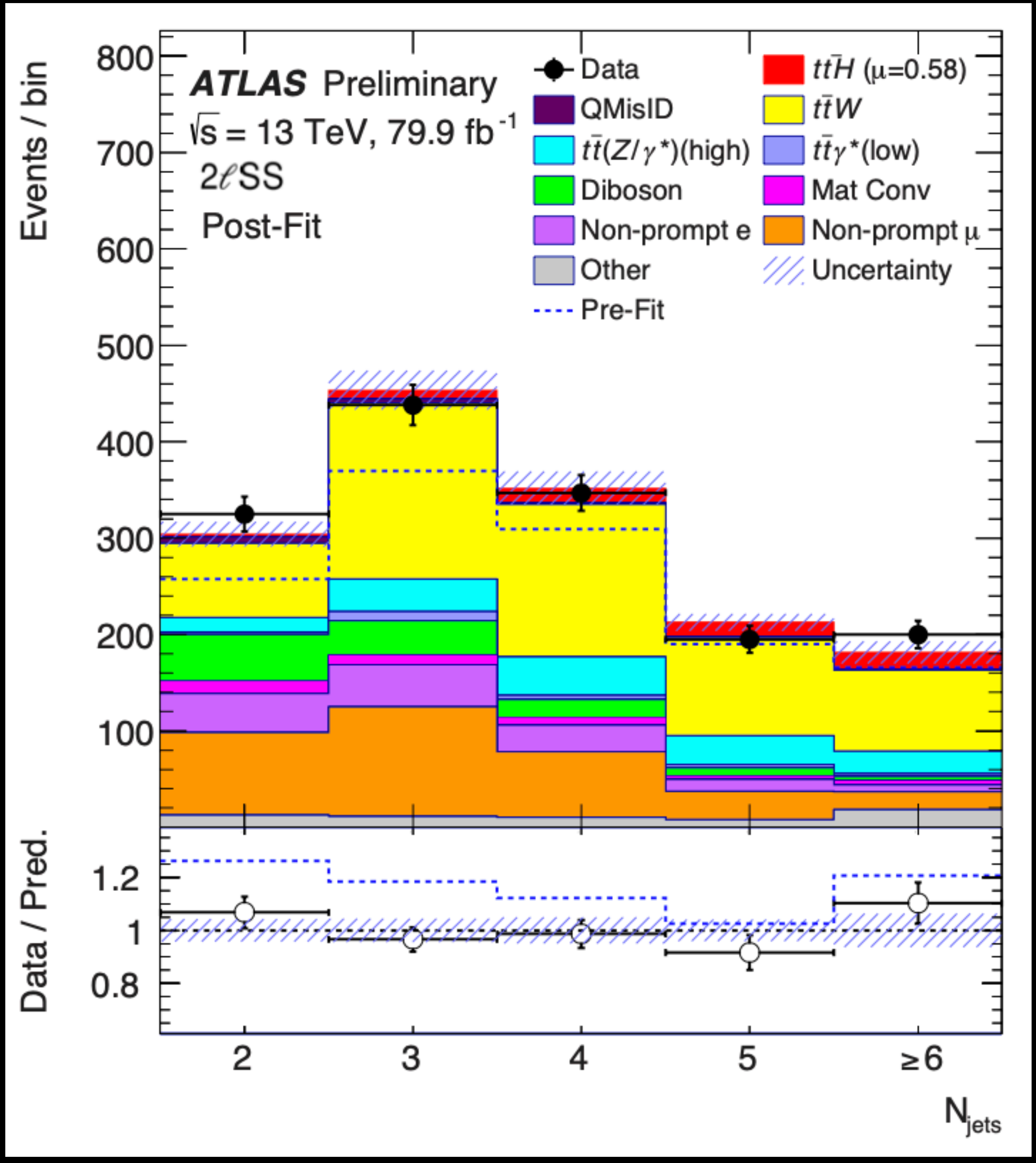


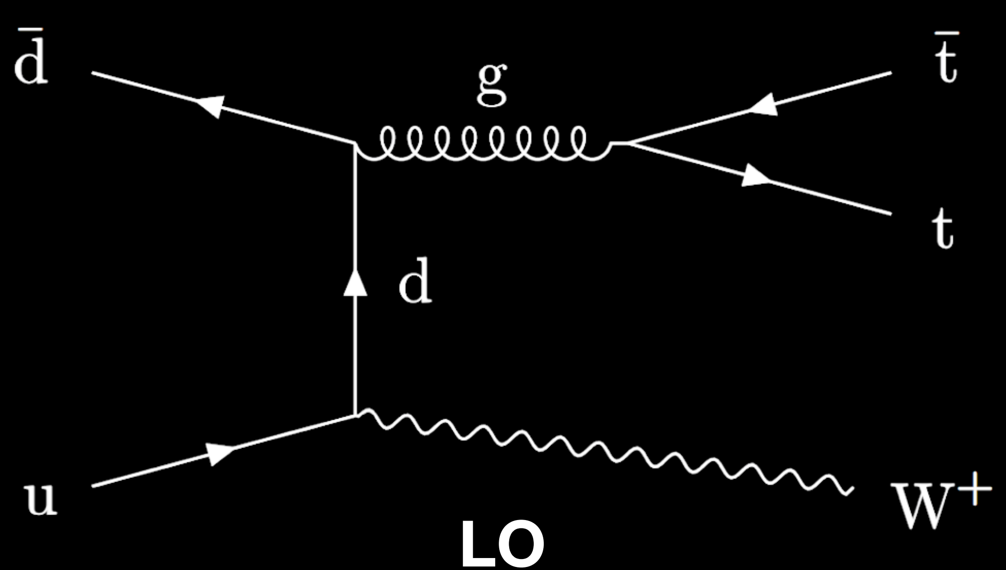
Modeling agreement in data: Signal regions

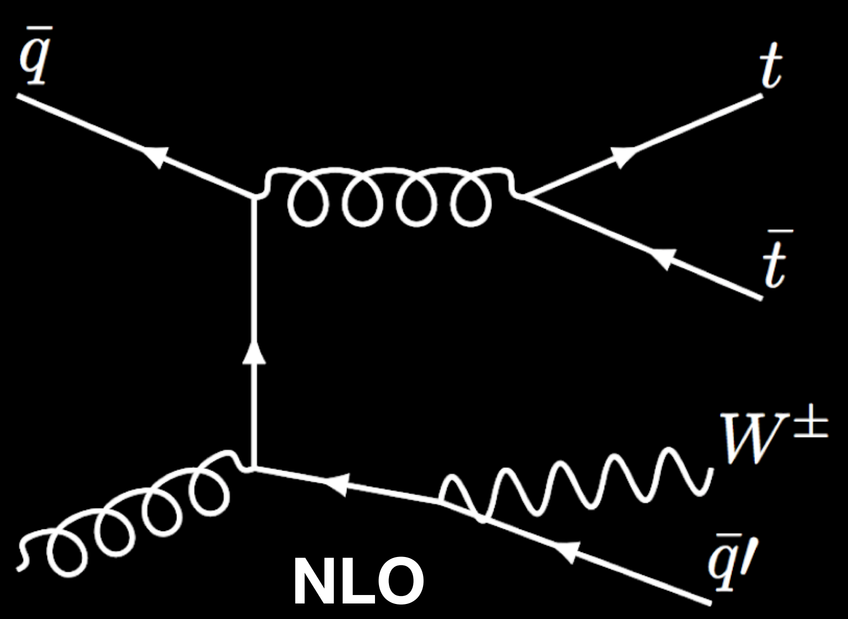


Problem with $t\bar{t}W$ Modeling

- A large mis-modeling in $t\bar{t}W$ process was observed.
- At NLO $t\bar{t}W$ is a quark gluon initiated process.
- Gluon initial states become important at higher orders.







The $t\bar{t}W$ case

Anatomy of inclusive $t\bar{t}W$ production at hadron colliders

Stefan von Buddenbrock[a], Richard Ruiz[b], Bruce Mellado[a,c]

[a]*School of Physics and Institute for Collider Particle Physics, University of the Witwatersrand, Wits, Johannesburg 2050, South Africa*
[b]*Centre for Cosmology, Particle Physics and Phenomenology* (CP3), *Université catholique de Louvain, Chemin du Cyclotron, Louvain-la-Neuve, B-1348, Belgium*
[c]*iThemba LABS, National Research Foundation, PO Box 722, Somerset West 7129, South Africa*

Stimulated discussions among the theory community

The simplest of them all: $t\bar{t}W^{\pm}$ at NLO accuracy in QCD

Giuseppe Bevilacqua,[a] Huan-Yu Bi,[b] Heribertus Bayu Hartanto,[c] Manfred Kraus[d] and Malgorzata Worek[b]

[a]*MTA-DE Particle Physics Research Group, University of Debrecen, H-4010 Debrecen, PBox 105, Hungary*
[b]*Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, D-52056 Aachen, Germany*
[c]*Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham, DH1 3LE, UK*
[d]*Physics Department, Florida State University, Tallahassee, FL 32306-4350, USA*

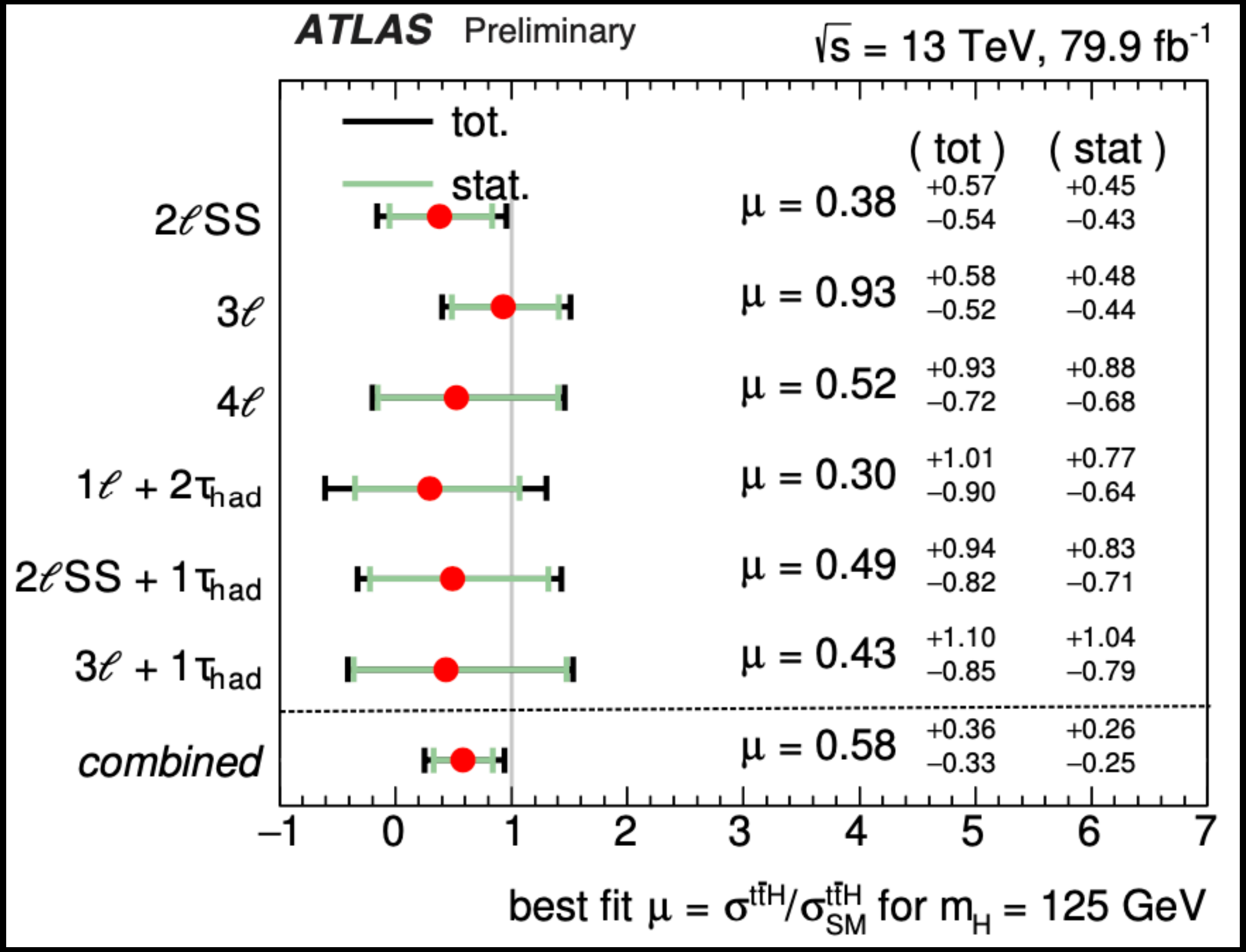
Subleading EW corrections and spin-correlation effects in $t\bar{t}W$ multi-lepton signatures

Rikkert Frederix*[1] and Ioannis Tsinikos†[2]

[1,2]Theoretical Particle Physics, Department of Astronomy and Theoretical Physics, Lund University, Sölvegatan 14A, SE-223 62 Lund, Sweden

April 22, 2020

$t\bar{t}H$ multileptons results



- Cross-section (Measured: 294^{+182}_{-162} fb Standard Model expected: 507^{+35}_{-50} fb)
  - Consistent with Standard Model (within uncertainties)
- $t\bar{t}W$ contributions scaled between 1.2 and 1.7 than Standard Model expectation

Measurement uncertainties

Uncertainty source	$\Delta\hat{\mu}$	
Jet energy scale and resolution	+0.13	−0.13
$t\bar{t}(Z/\gamma^*)$ (high mass) modelling	+0.09	−0.09
$t\bar{t}W$ modelling (radiation, generator, PDF)	+0.08	−0.08
Fake τ_{had} background estimate	+0.07	−0.07
$t\bar{t}W$ modelling (extrapolation)	+0.05	−0.05
$t\bar{t}H$ cross section	+0.05	−0.05
Simulation sample size	+0.05	−0.05
$t\bar{t}H$ modelling	+0.04	−0.04
Other background modelling	+0.04	−0.04
Jet flavour tagging and τ_{had} identification	+0.04	−0.04
Other experimental uncertainties	+0.03	−0.03
Luminosity	+0.03	−0.03
Diboson modelling	+0.01	−0.01
$t\bar{t}\gamma^*$ (low mass) modelling	+0.01	−0.01
Charge misassignment	+0.01	−0.01
Template fit (non-prompt leptons)	+0.01	−0.01
Total systematic uncertainty	+0.25	−0.22
Intrinsic statistical uncertainty	+0.23	−0.22
$t\bar{t}W$ normalisation factors	+0.10	−0.10
Non-prompt leptons normalisation factors (HF, material conversions)	+0.05	−0.05
Total statistical uncertainty	+0.26	−0.25
Total uncertainty	+0.36	−0.33

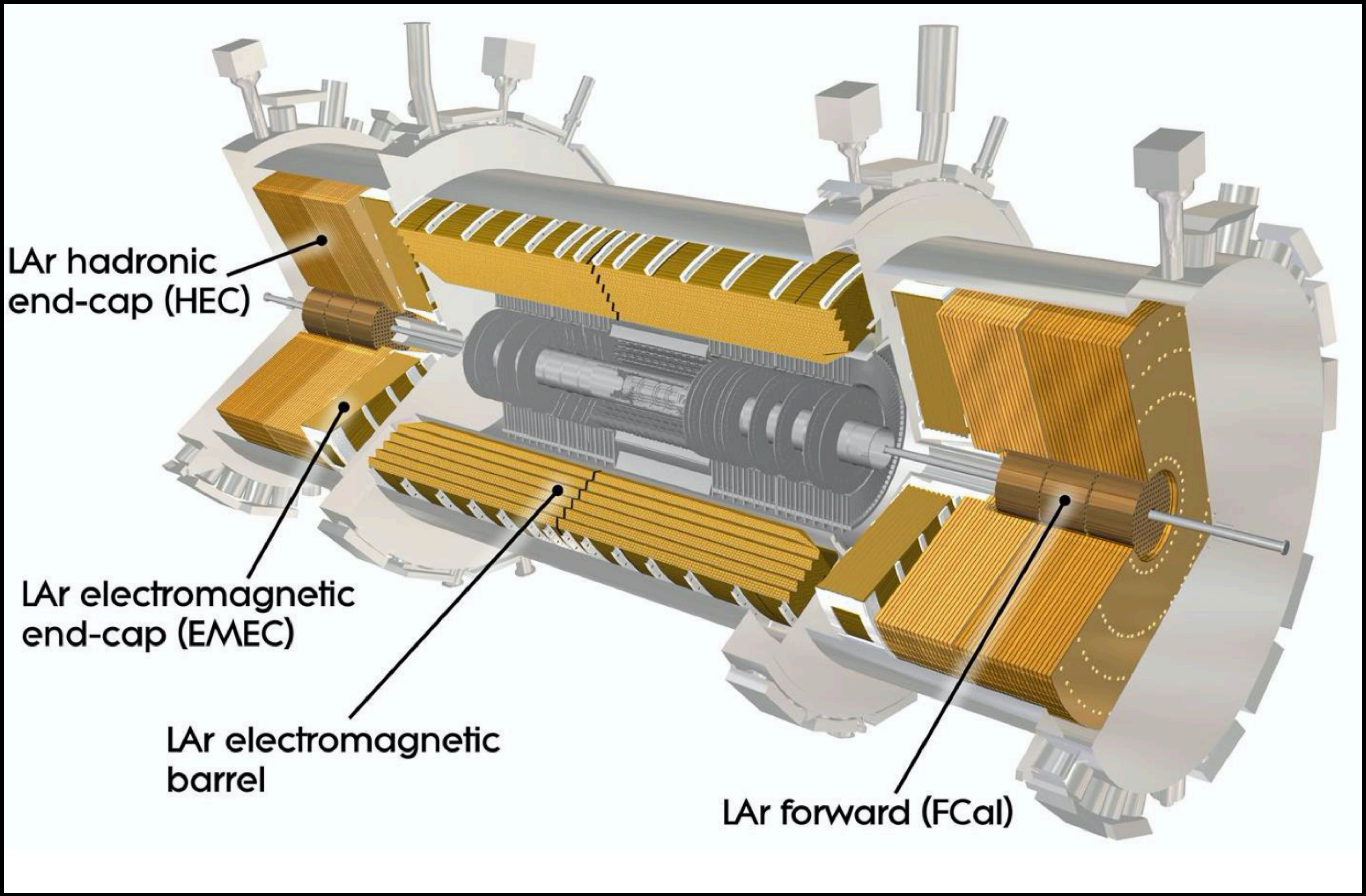
The future

The LHC Schedule

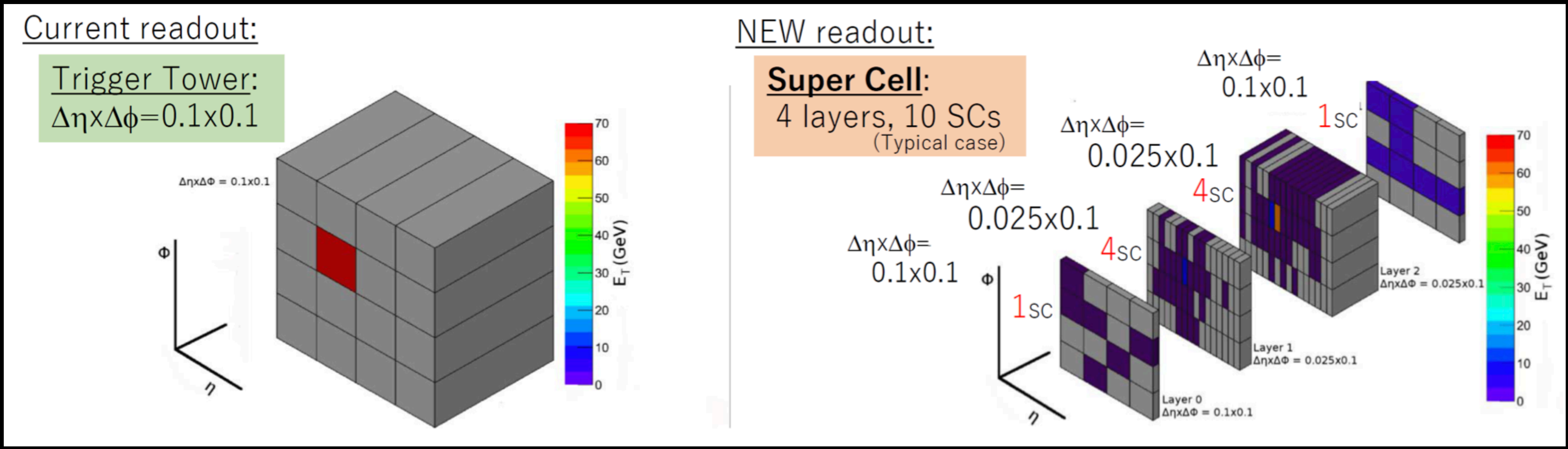
- LHC will increase its instantaneous luminosity over several phases.
- ATLAS will also upgrade its detector components to cope up with this increased luminosity.

LS2: ATLAS Calorimeter upgrade

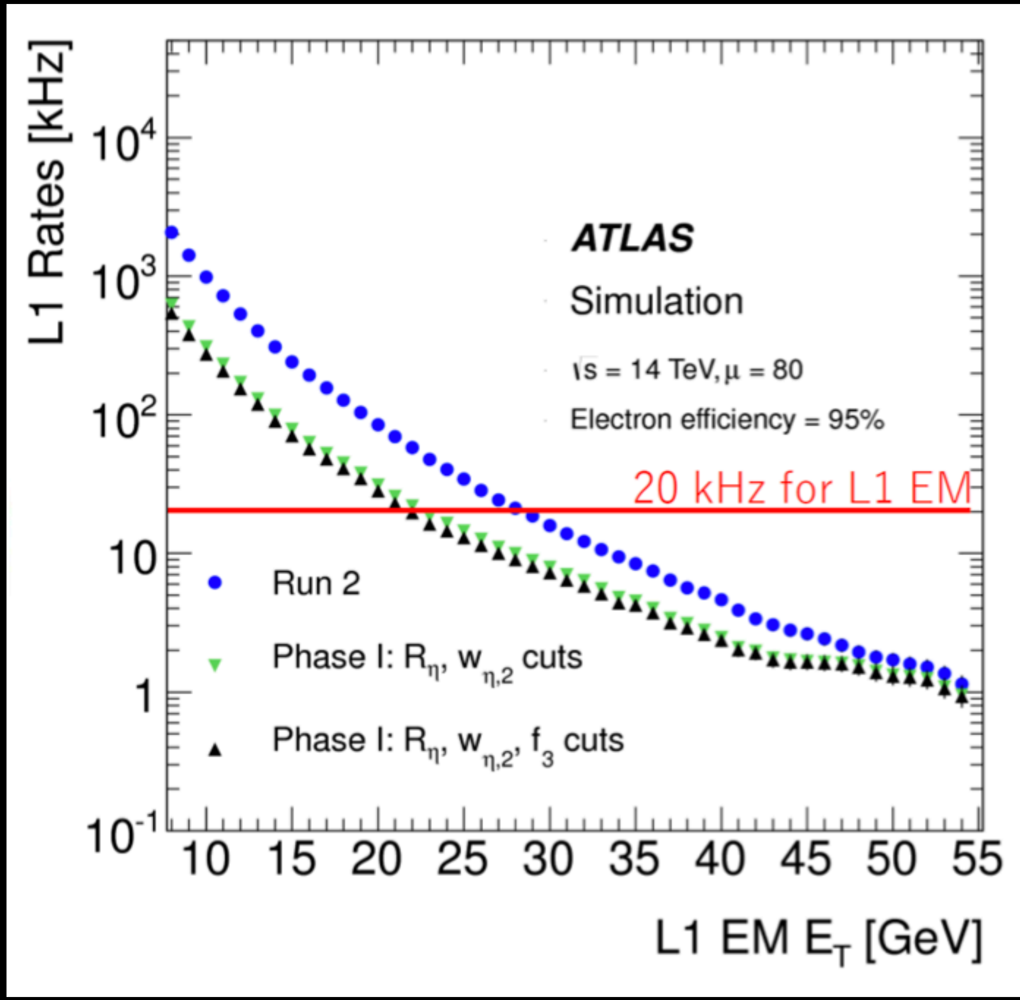
- In Run-3 LHC will deliver up to 1.5 times Run-2 instantaneous collisions.
- This will increase the pileup



ATLAS Calorimeter upgrade



- Information granularity for the trigger system will be increased
- This will enable a lower threshold for triggers.
  - Meaning better signal acceptance.

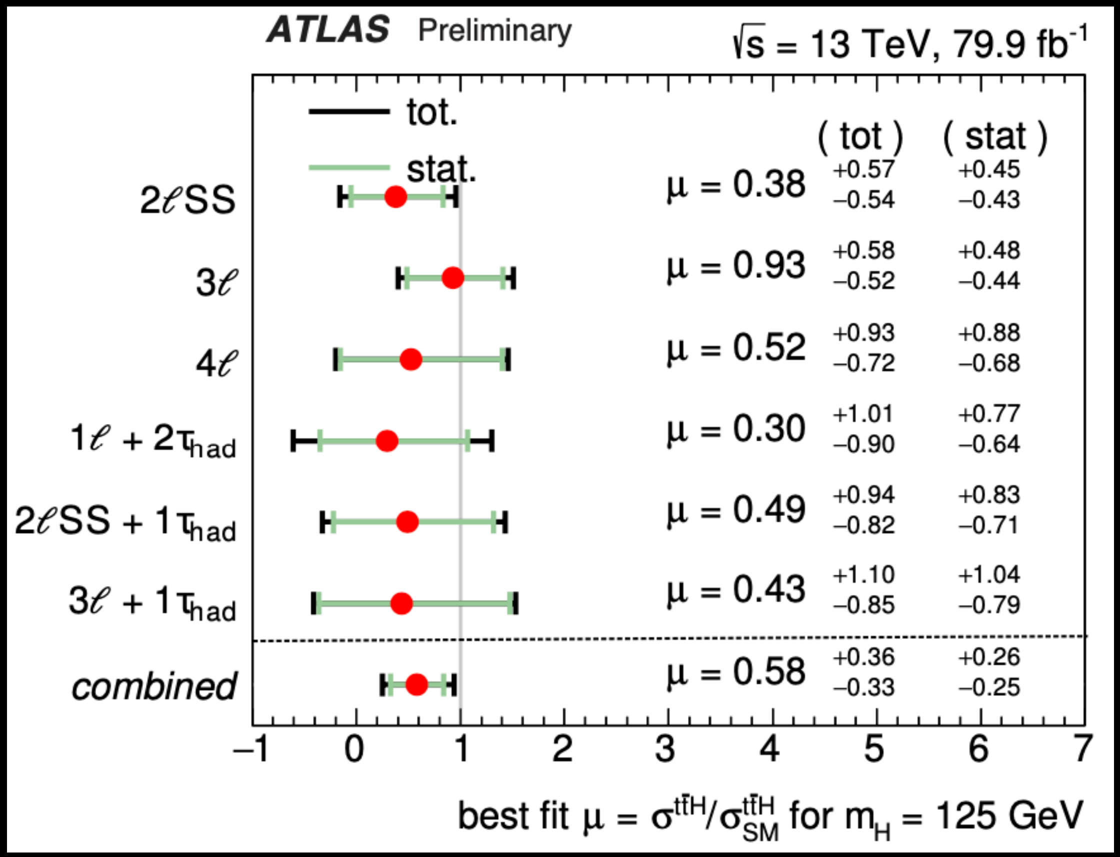


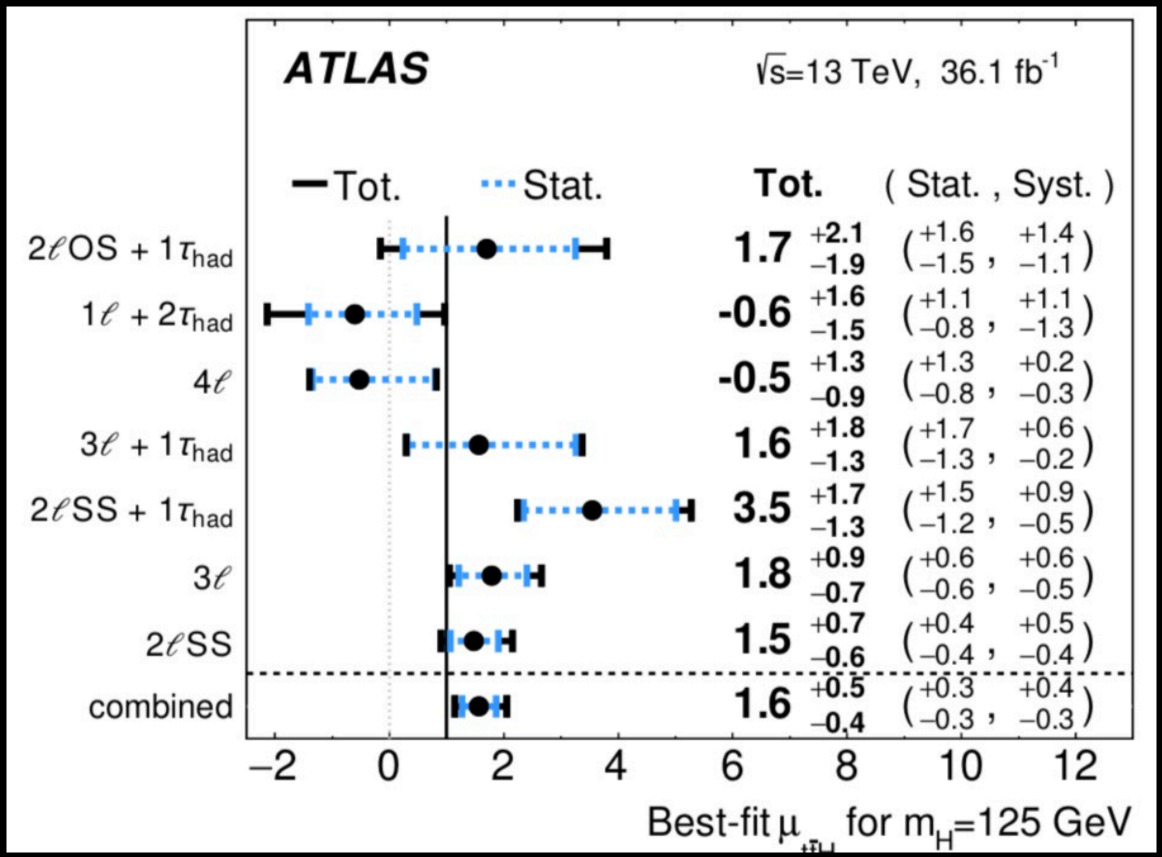
Conclusion

- Associated production of top-quark pairs with Higgs bosons is an important process to probe top-Higgs interaction in the Standard Model.
- With more data coming from the LHC, a very good understanding of low rate processes like $t\bar{t}W$ is becoming crucial for precise determination of rate of processes like $t\bar{t}H$
- Future detector developments will help in improving the ability to perform measurements with multi leptonic signatures at ATLAS.

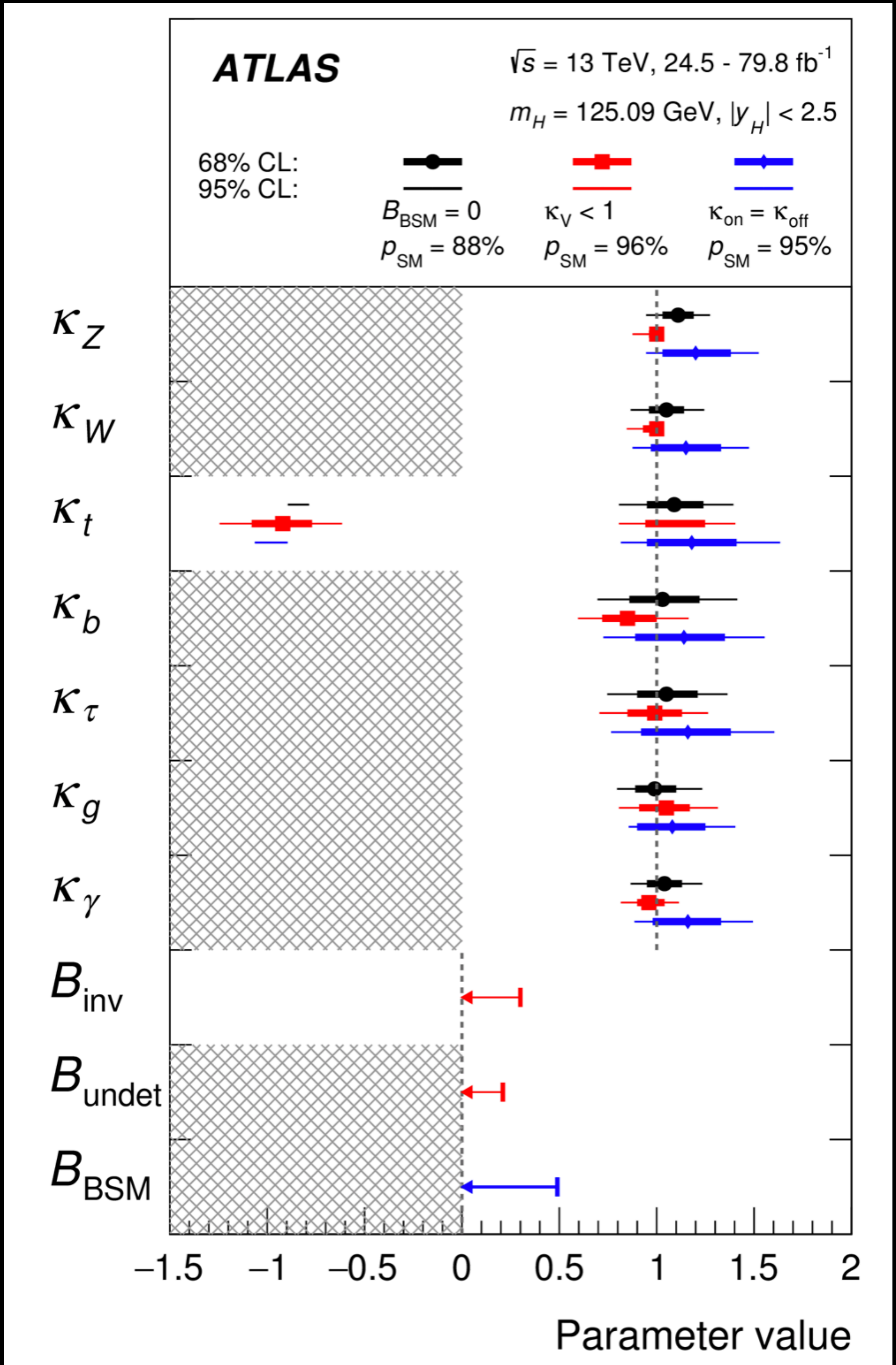
Backup

Previous $t\bar{t}H$-multileptons result





Higgs Couplings



ATLAS ttH combinations