

Top Quark physics

HASCO Summer School

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July 21st 2023

HARVARD
UNIVERSITY

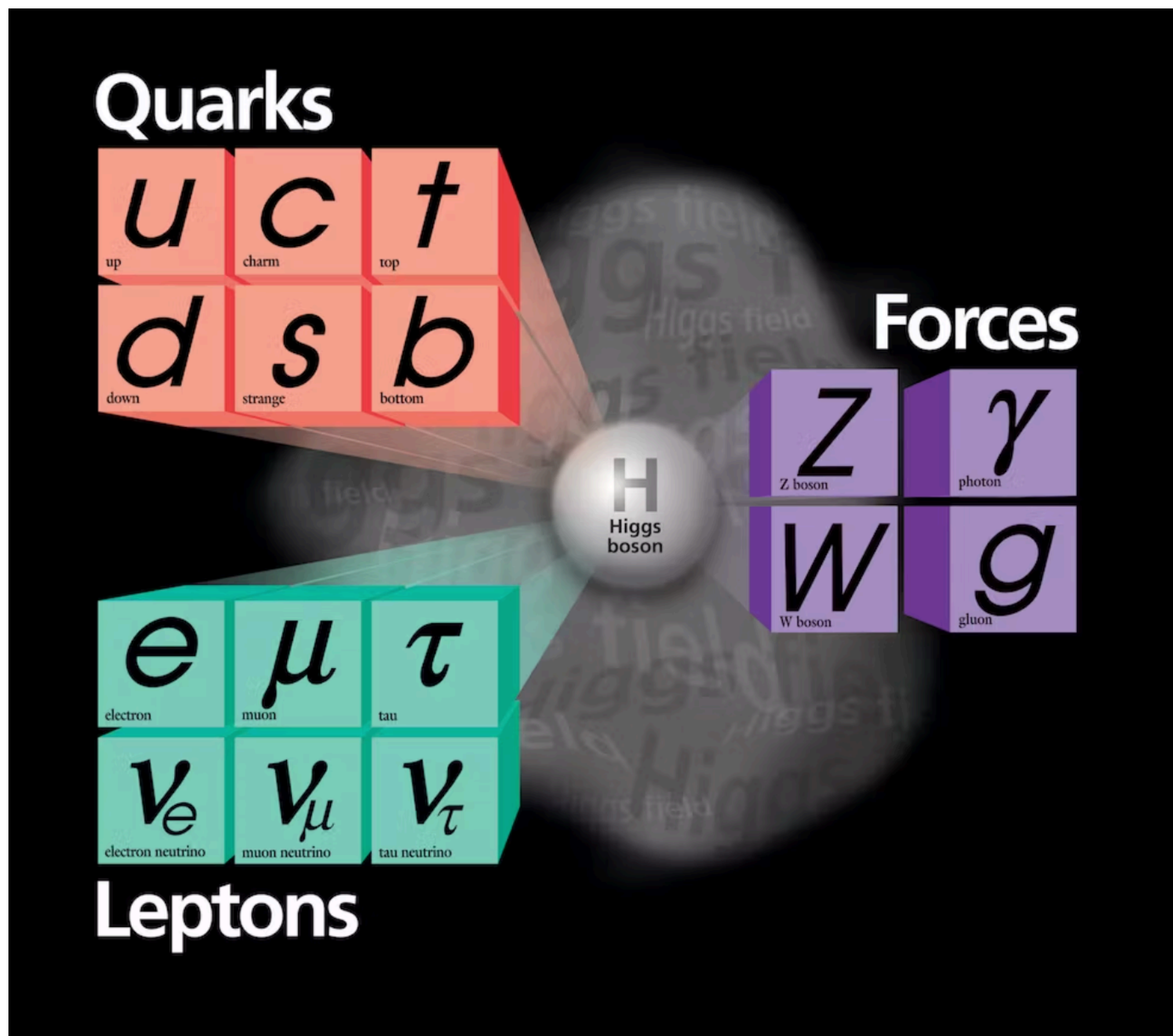


What to expect from my lecture

- Learn how the top was discovered
- What the most important properties are
- Why the top quark is exciting
- Get a general idea how to measure the top quark properties
 - Few examples are given; leaving out a lot of the analysis because we need to have lunch!
- **But the most important point is to convince you to work on top physics!**



The Standard Model of Particle Physics



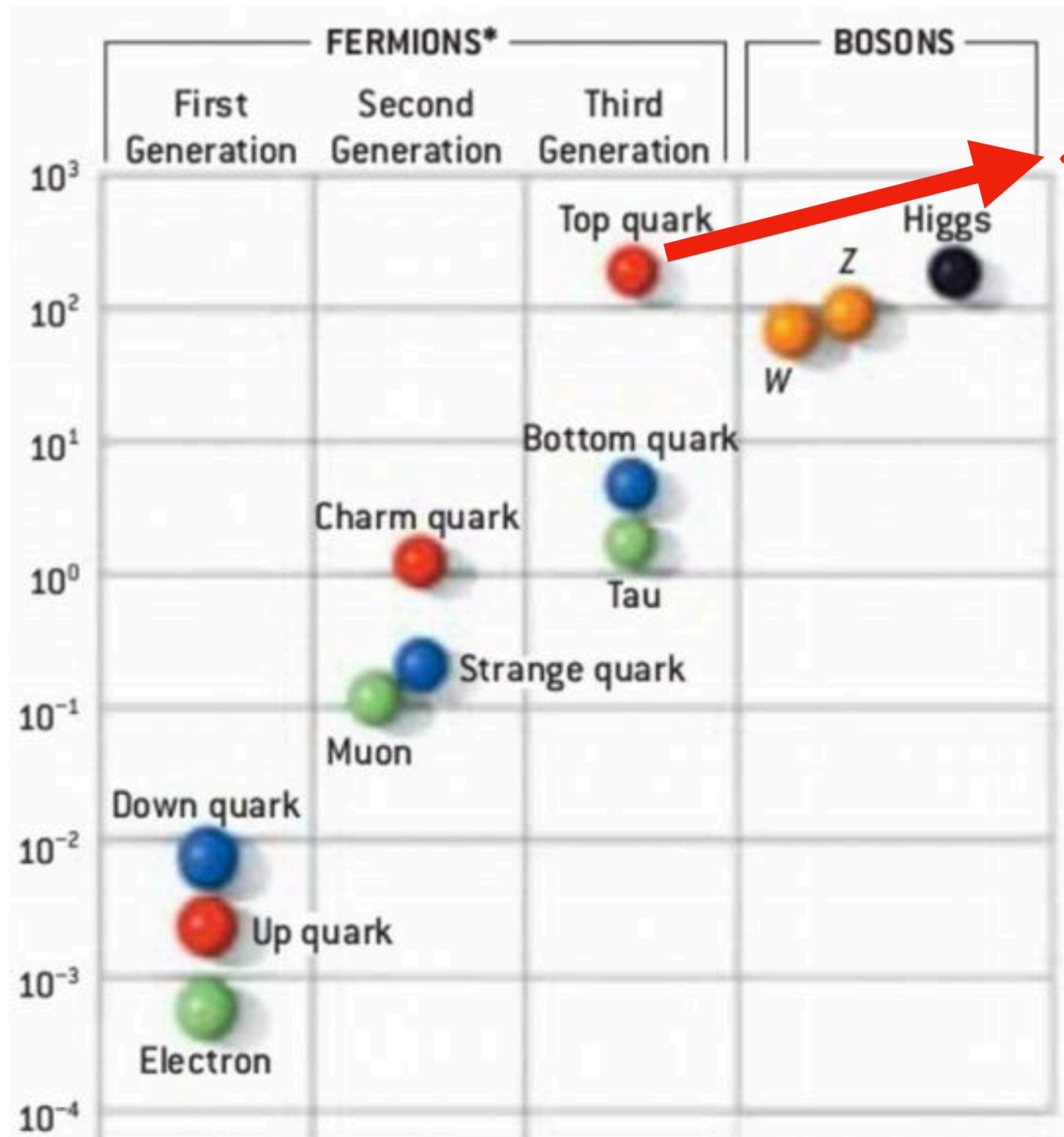
Mystery of Mass

Mass [GeV]



Mystery of Mass

Mass [GeV]



~170 GeV

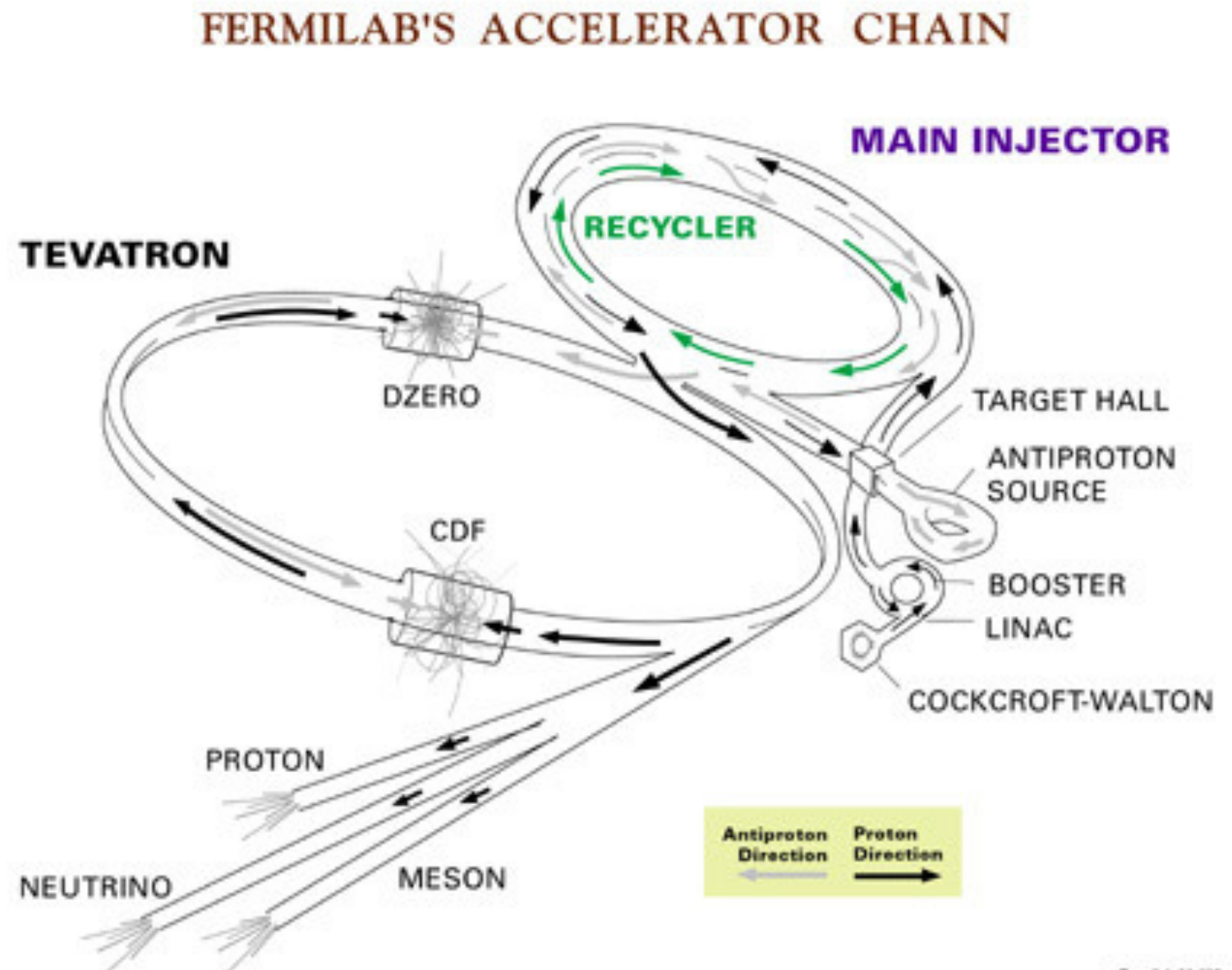
Discovery of the Top Quark

- CDF and D-zero detectors at the Tevatron (Fermilab in Chicago)



The Tevatron collider at Fermilab (Chicago)

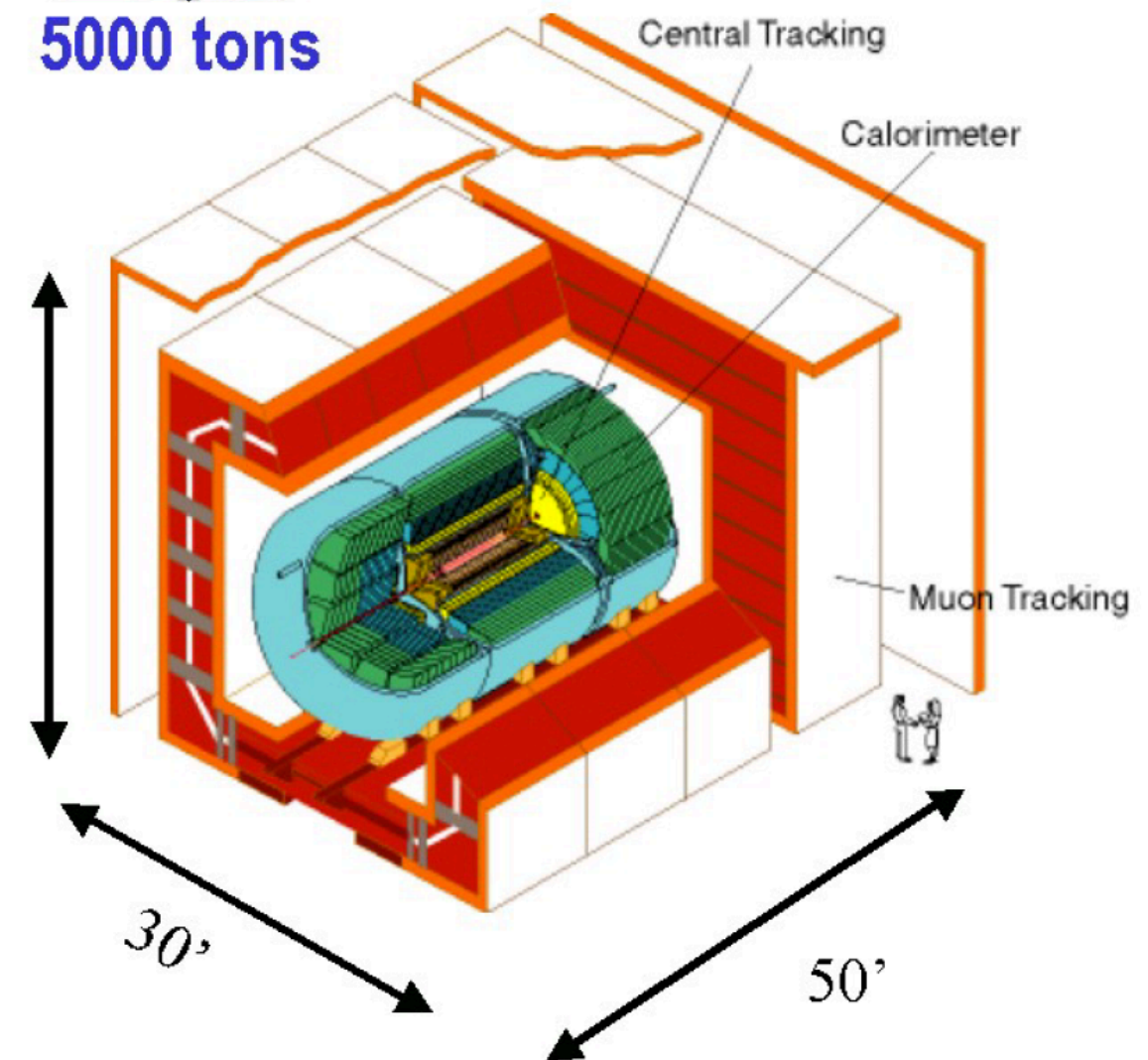
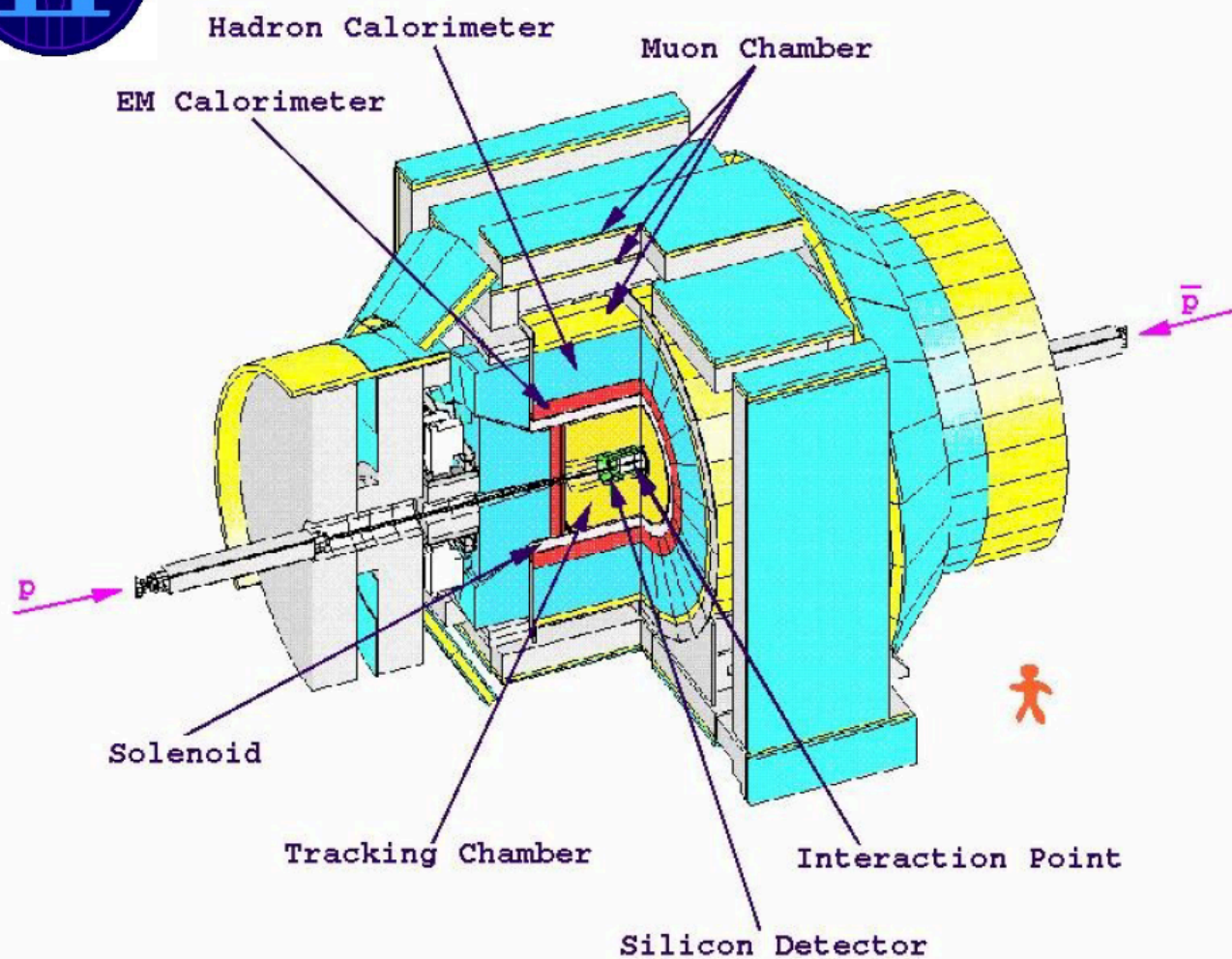
- colliding protons with antiprotons
- from 1986 - 2001: $\sqrt{s} = 1.8$ TeV
- after 2001: upgrade to 1.96 TeV
- decommissioned in 2011
- 2 main experiments: CDF and D0
 - multipurpose detectors



Fermilab 00-635

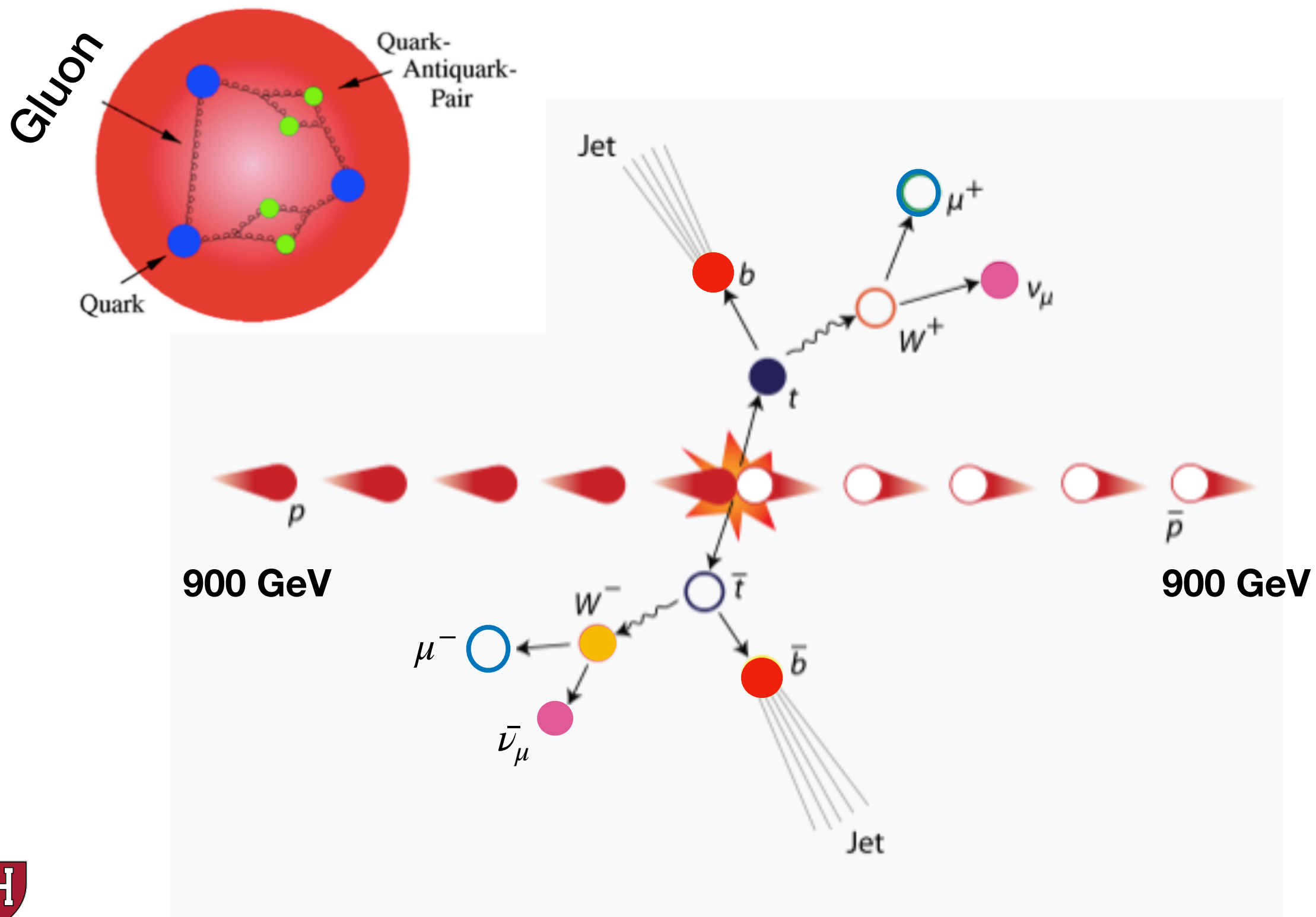
Discovery of the Top Quark

- CDF and D-zero detectors at the Tevatron (Fermilab in Chicago)



Discovery of the Top Quark

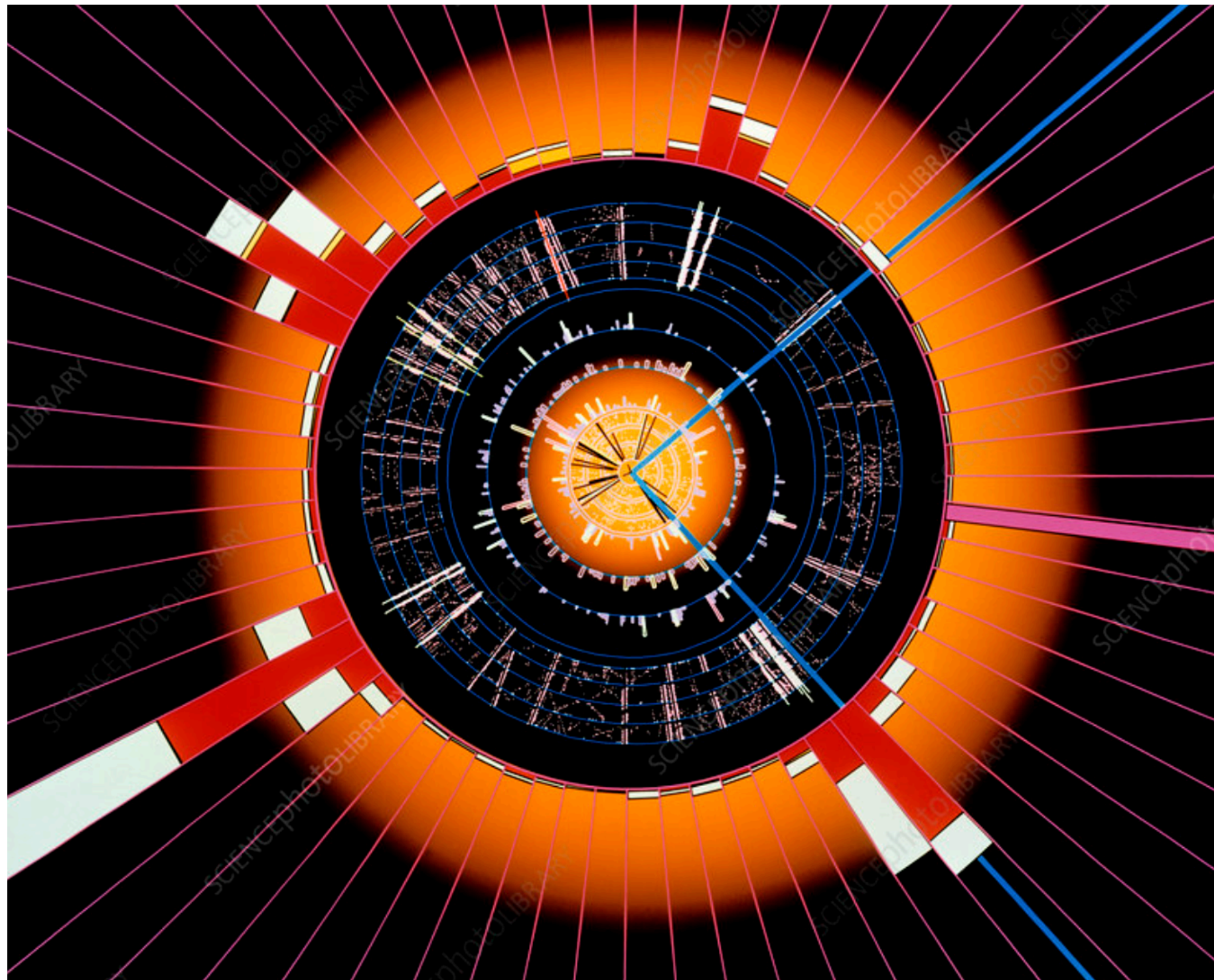
- CDF and D-zero detectors at the Tevatron (Fermilab in Chicago)



Top-quark discovered in 1995

One of the first top-quark pairs

muon



Invisible
neutrinos

Jets

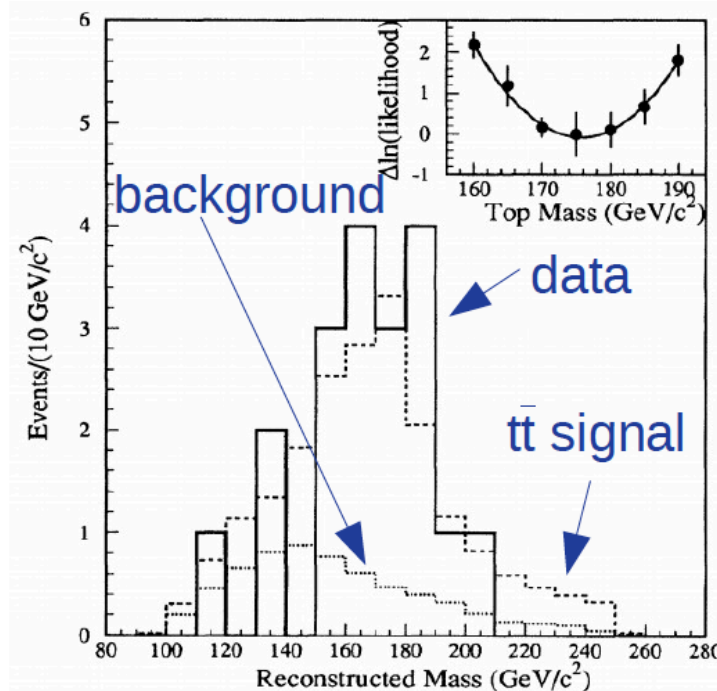
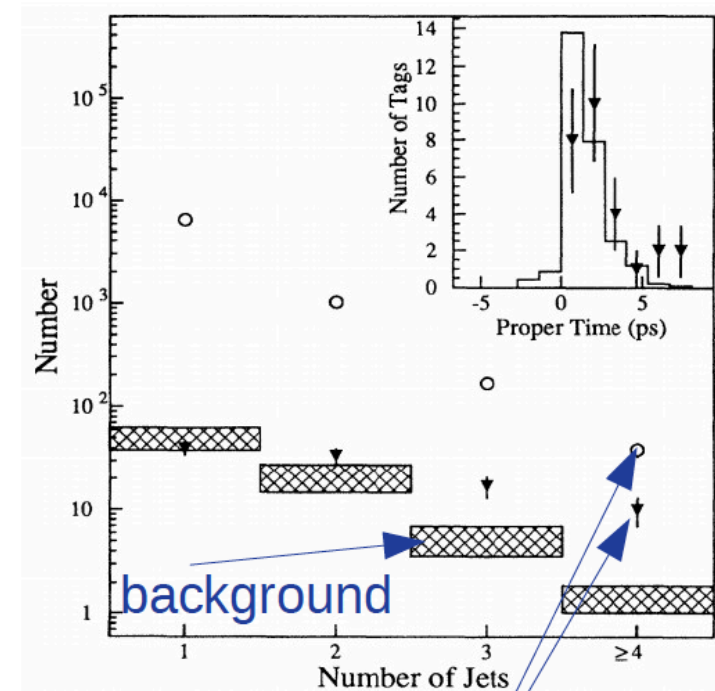
muon

28 years old!

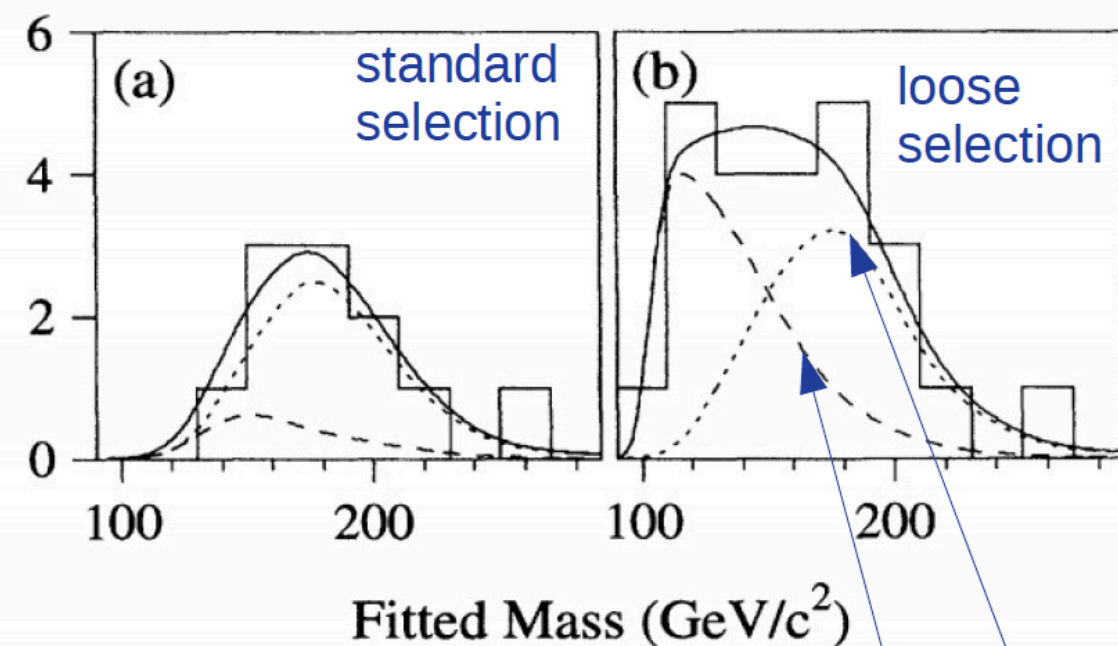


Top-quark discovered in 1995

Evidence of top quark by **CDF** and **D0** with $\sim 70 \text{ pb}^{-1}$ of Run1 data



Events / 20 GeV/c²



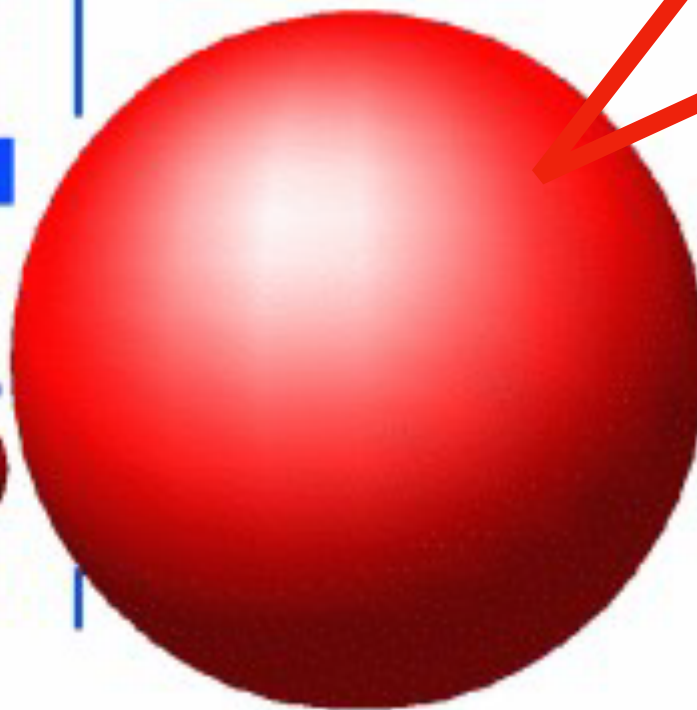
Number of events before and
after secondary vertex tagging
Excess for $N_{\text{jets}} > 2$

$$m_{\text{top}} = 176 \pm 8 \pm 10 \text{ GeV}$$

Top-quark ID card!

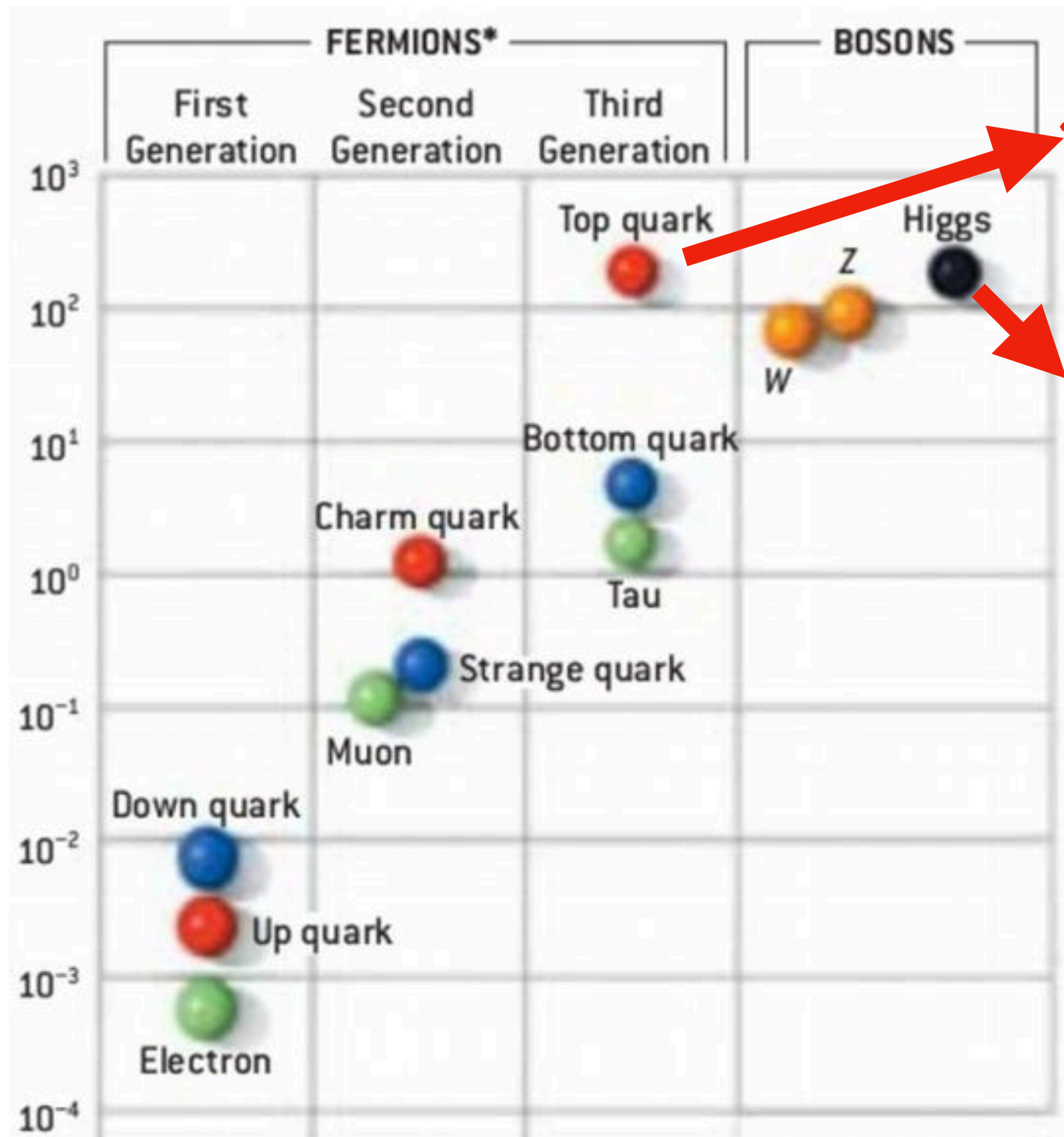
LEPTONS		
Electron Neutrino Mass ~0	Muon Neutrino ~0	Tau Neutrino ~0
Electron .511	Muon 105.7	Tau 1 777
QUARKS		
Up Mass: 5	Charm 1 500	Top ~180 000
Down 8	Strange 160	Bottom 4 250

Birth: 1995, Fermilab
Mass: 172.5 GeV
Charge: $+2/3 |e|$
Spin: $1/2$
Width: 1.3 GeV



Mystery of Mass

Mass [GeV]

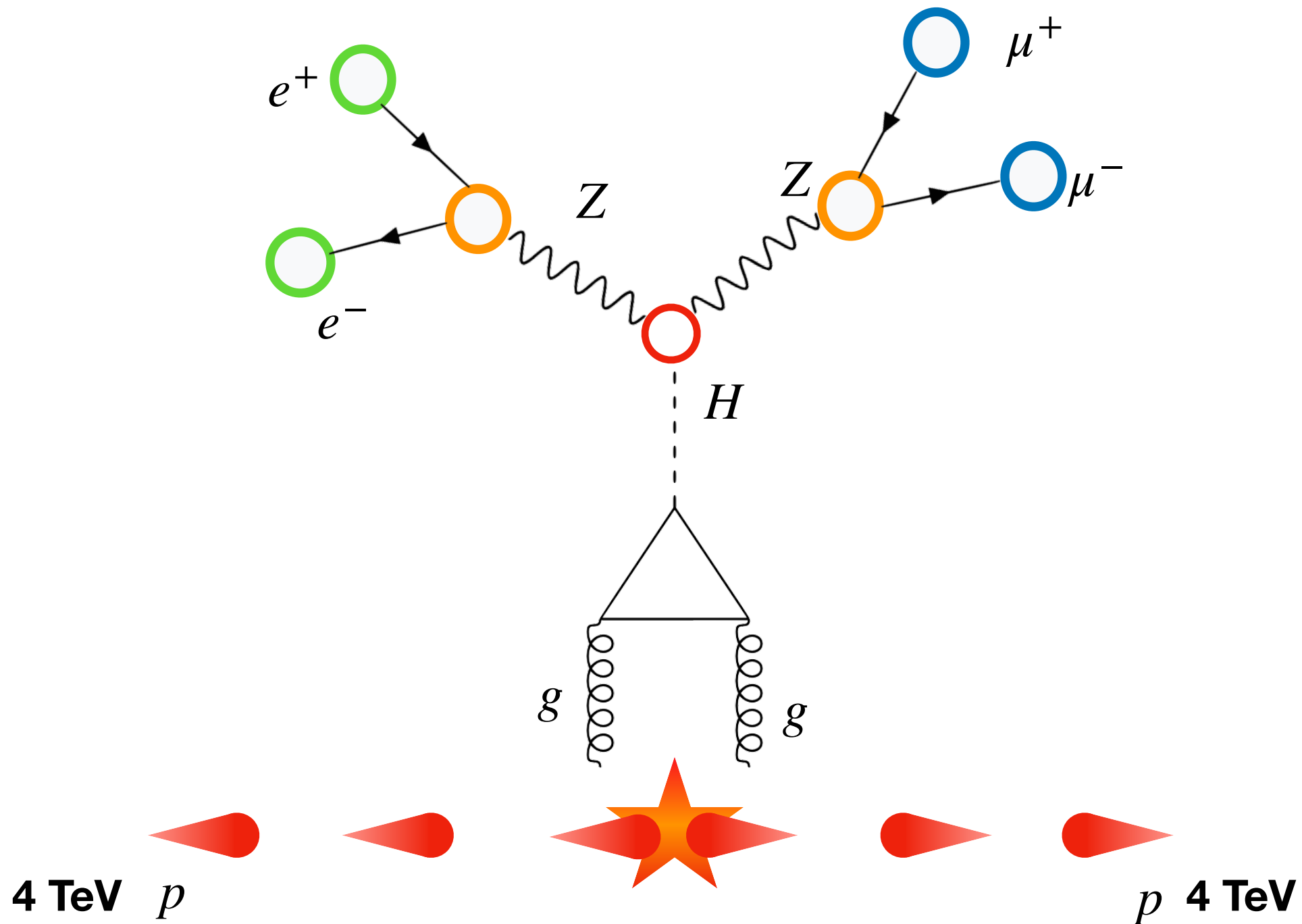


~170 GeV

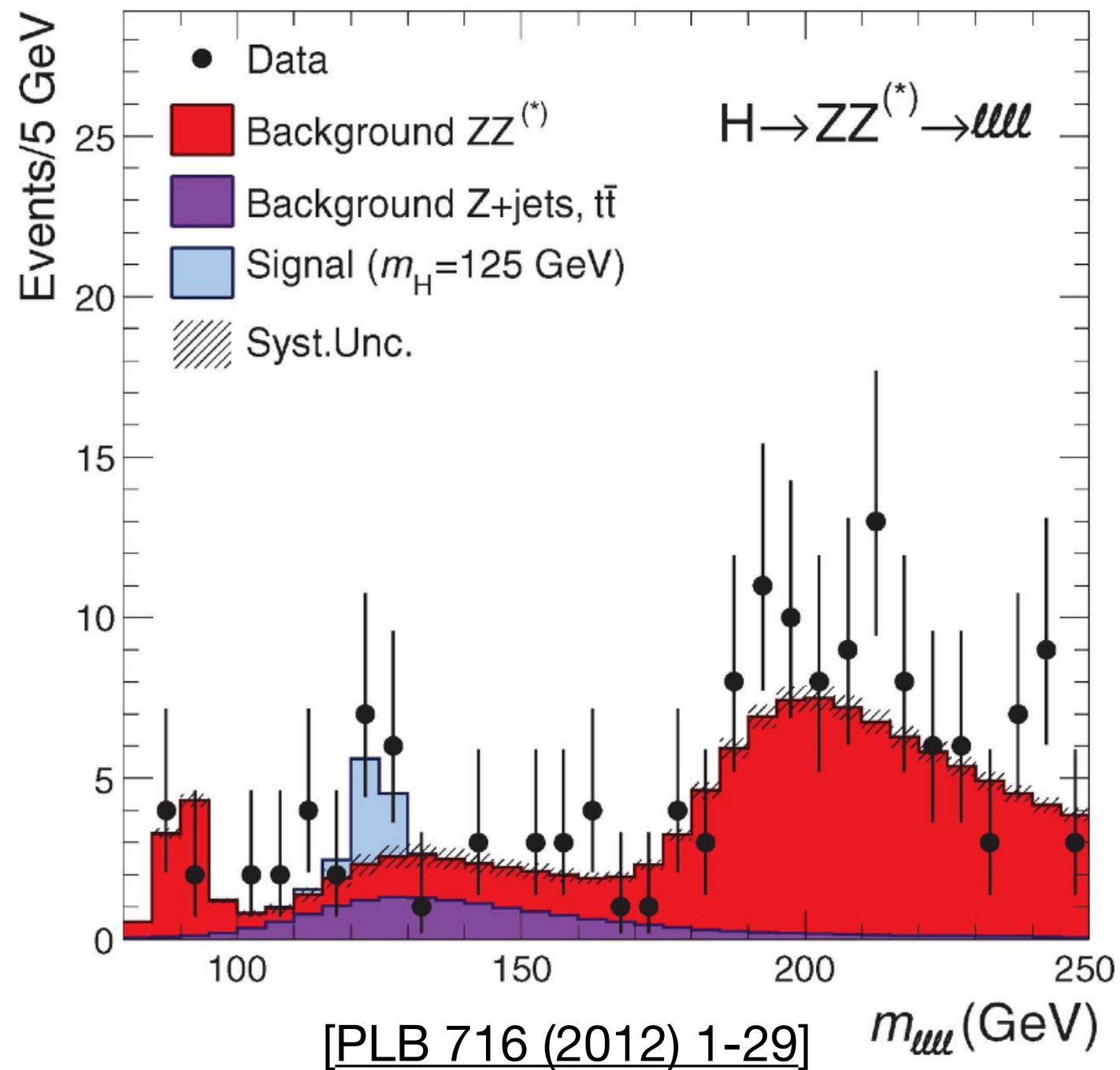
~125 GeV

Discovery of the Higgs Boson

- At the Large Hadron Collider by the ATLAS and CMS detectors

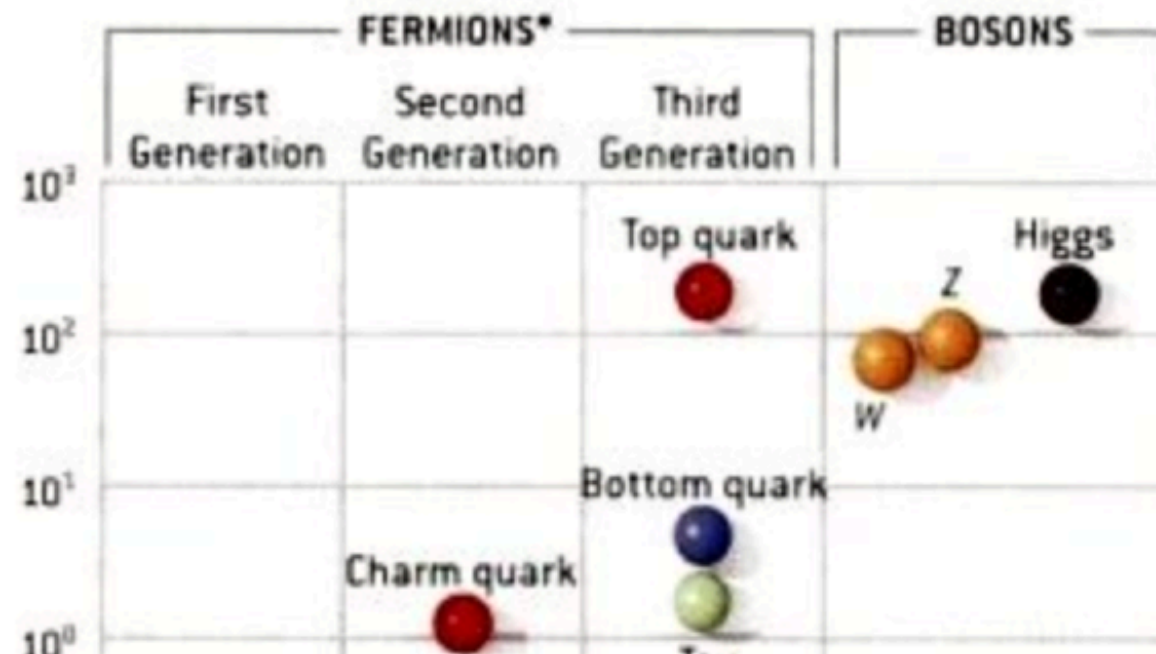


First Higgs observation at ATLAS in 4 lepton

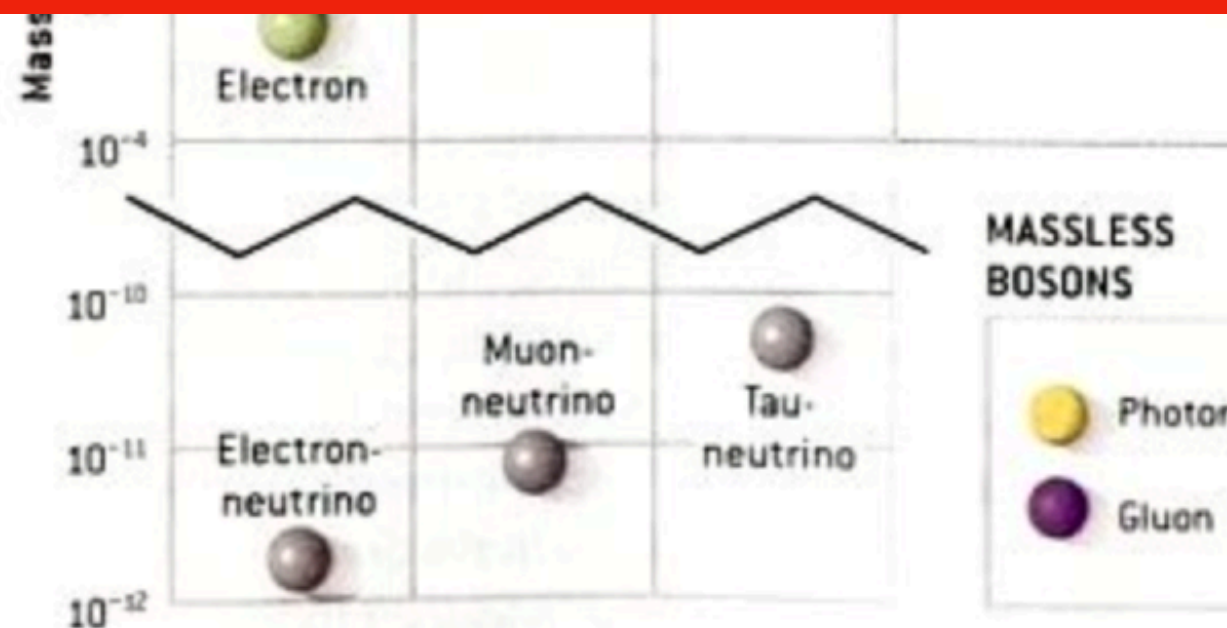


11 years old!

Mystery of Mass

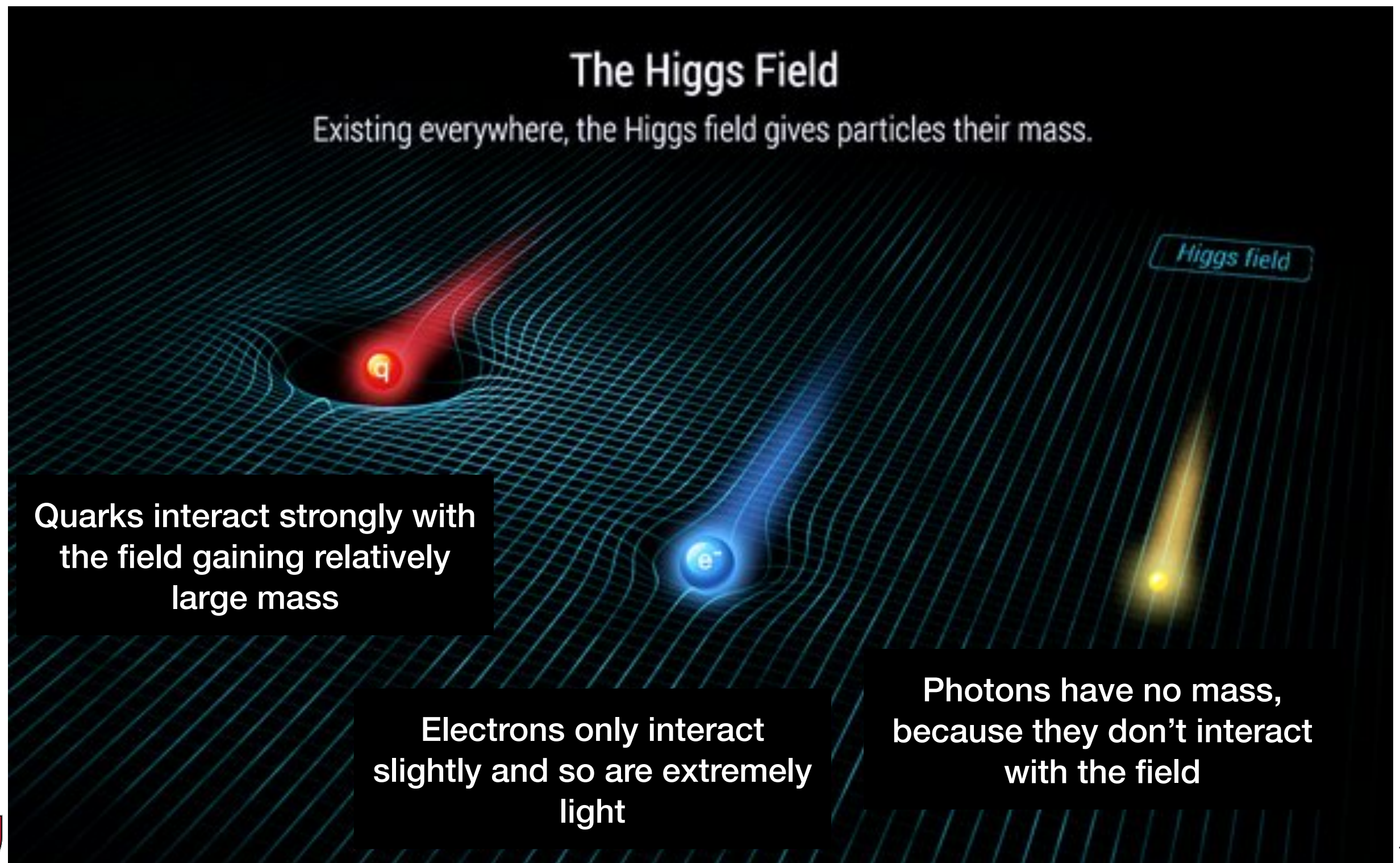


Why do particles have these masses ???



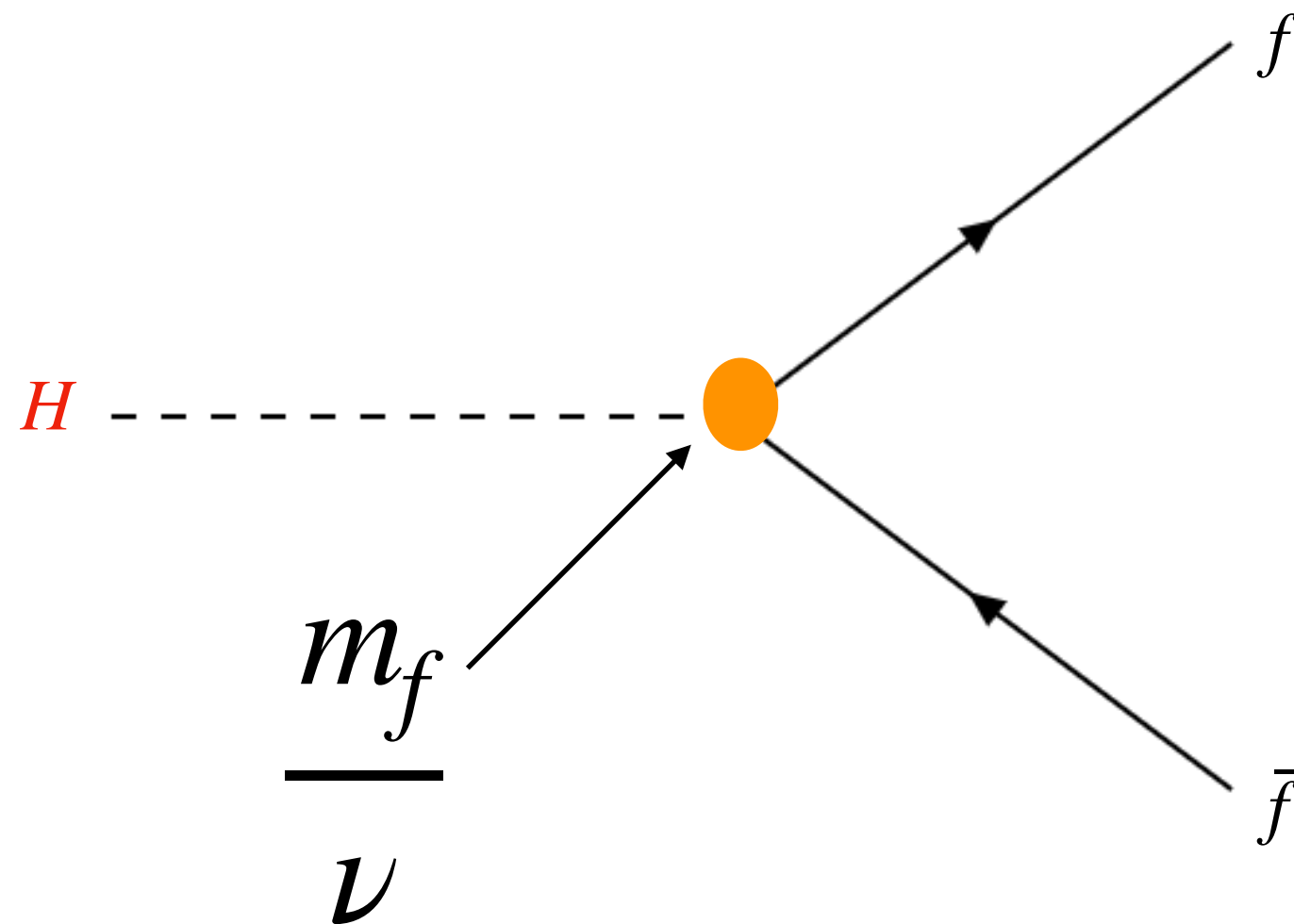
Higgs Mechanism

- Particles gain mass through interactions with the Higgs field



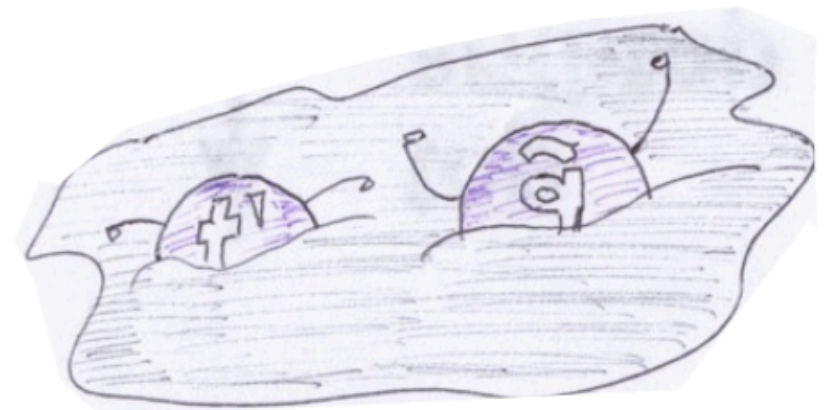
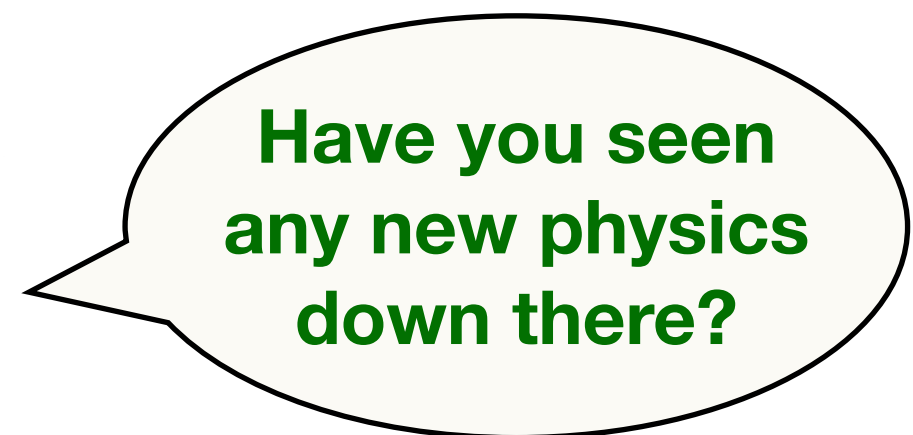
Higgs Mechanism

- In the SM the coupling between the Higgs field and the fermions (except for neutrinos) is described by the **Yukawa coupling**



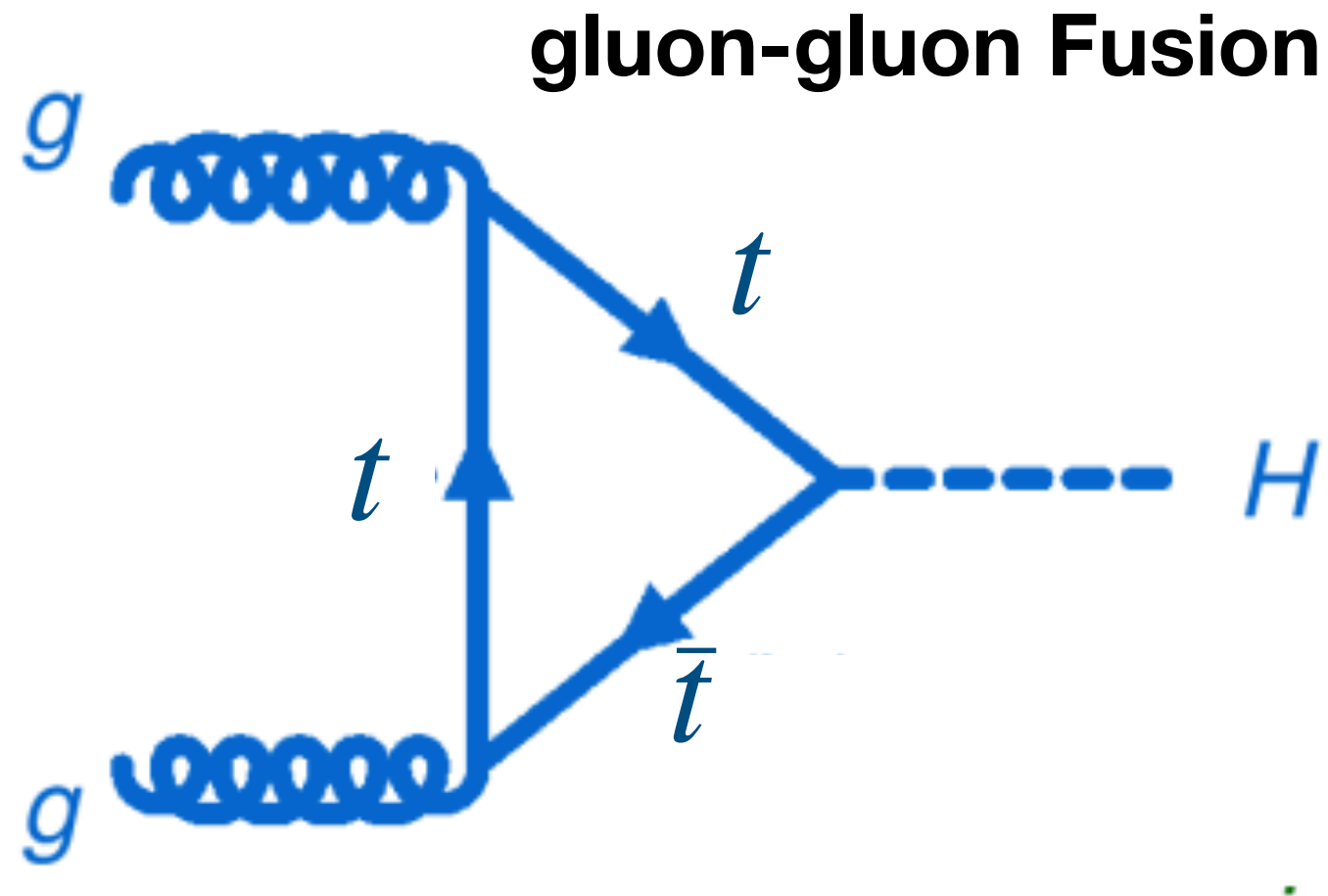
Top and Higgs: a dynamic duo!

- Top-quark strongly interacts with the Higgs sector
 - top yukawa coupling $y_t \sim 1$
- Why do top quarks interact so much more with the Higgs than with any other (known) particle?

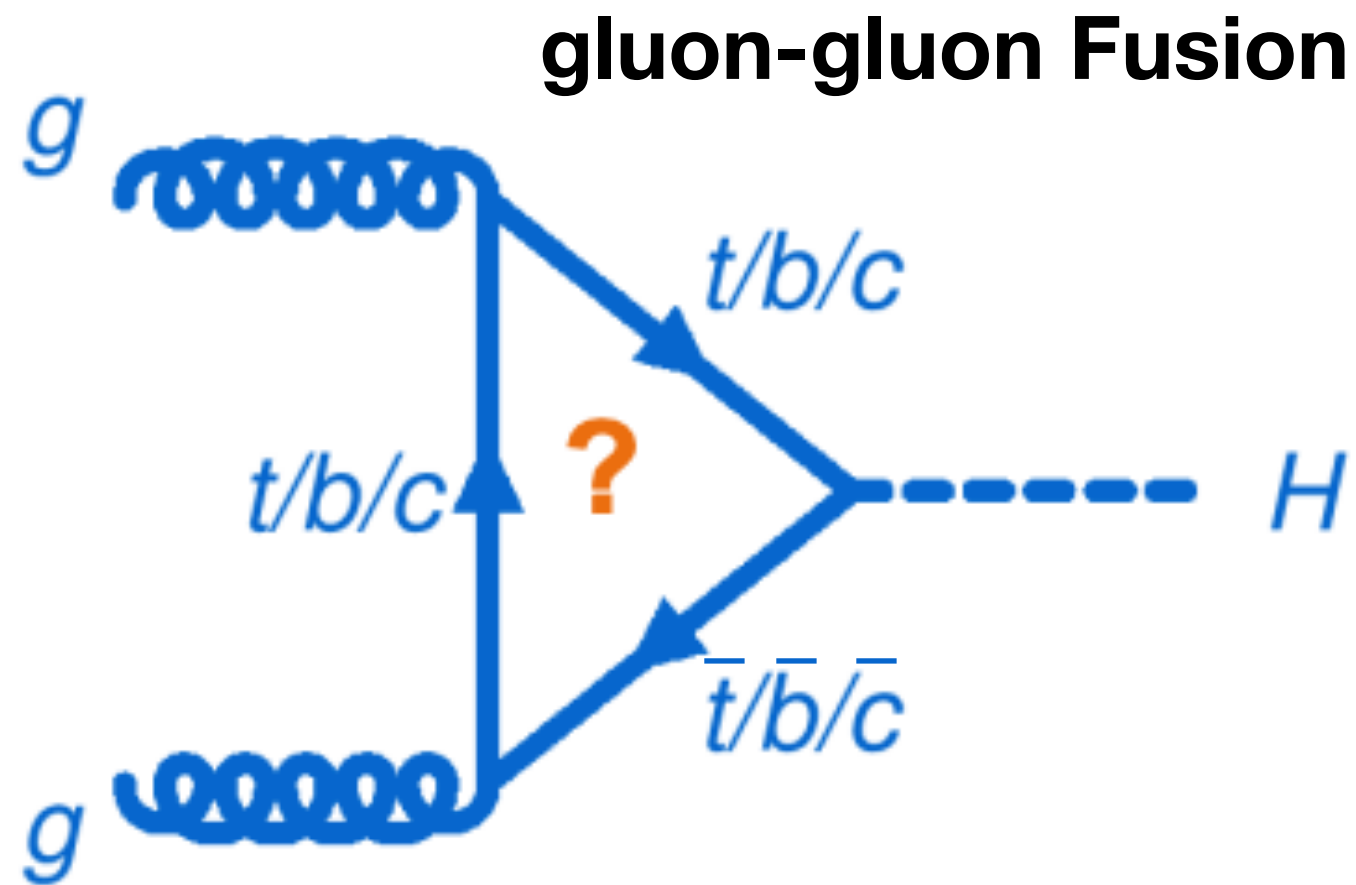


Two ways to measure top-Higgs Coupling

- Dominant production mode of the Higgs boson at the LHC
- Proceeds primarily through a top quark loop

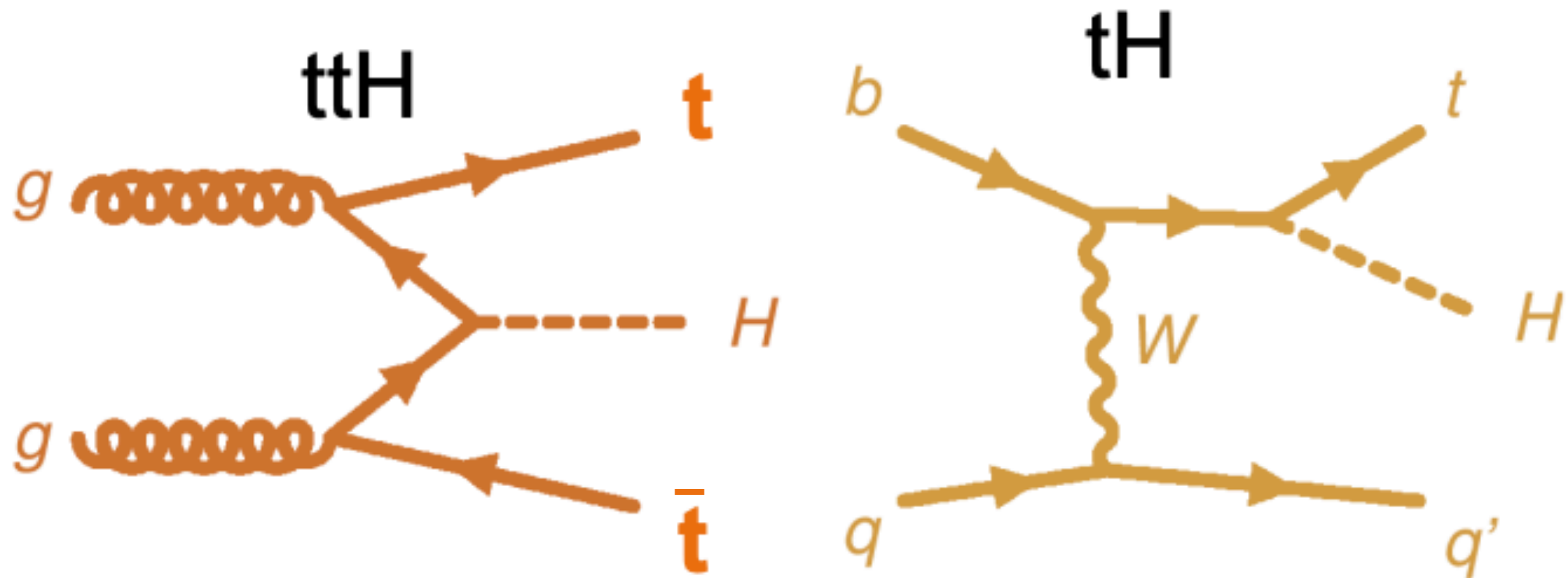


Two ways to measure top-Higgs Coupling



Two ways to measure top-Higgs Coupling

$t\bar{t}H+tH$:
probe of top-Higgs coupling



Only 1% of Higgs at LHC

Only 0.1%!!!

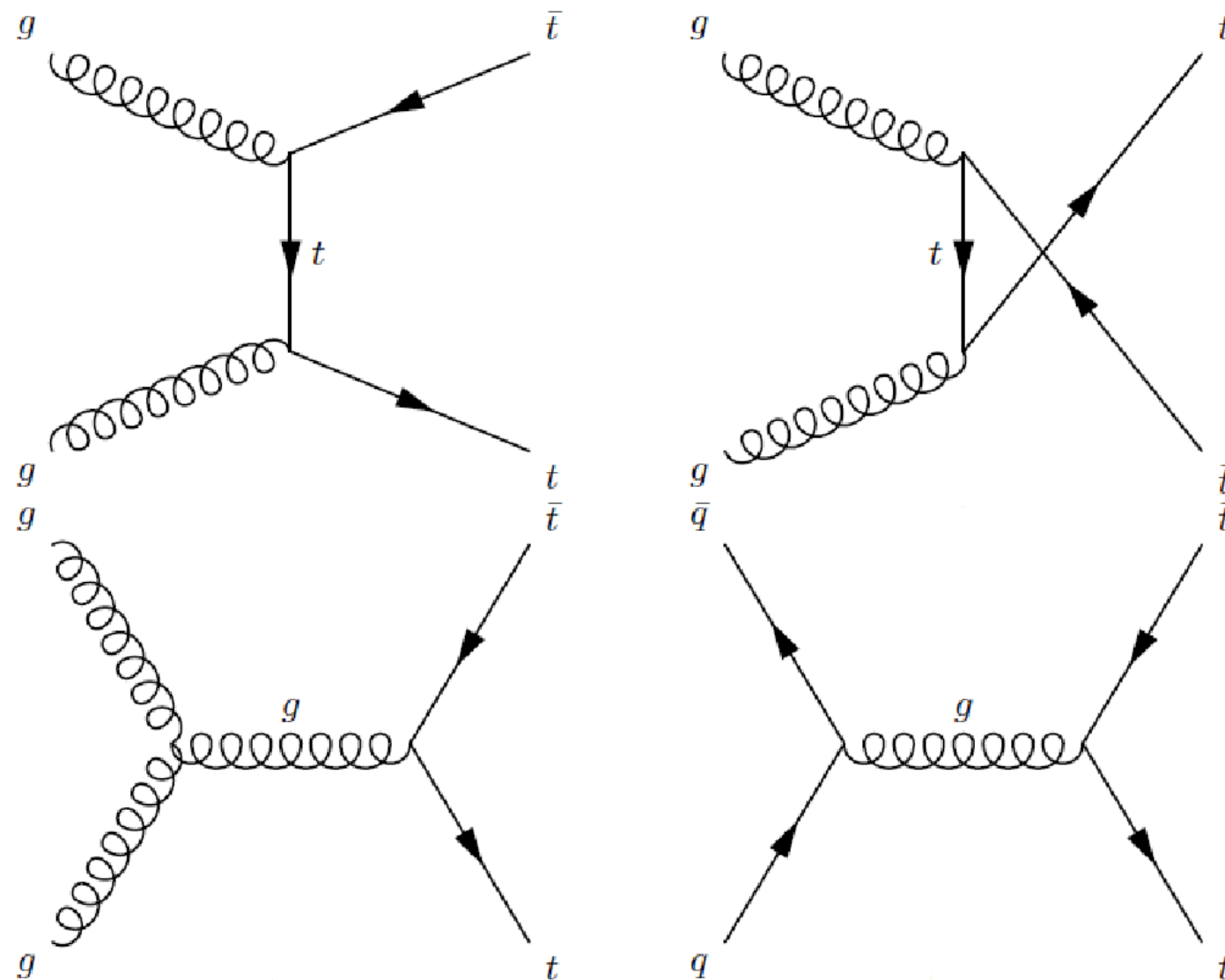
Why do we care to measure the top properties precisely?

- need to test theoretical predictions (top as signal)
 - enhanced cross-section possible if we have production of new physics
- many BSM searches have similar final states (top as background)
 - top production has to be well understood to increase discovery potential
- top quark plays a role in many standard model extensions
 - mass close to the scale of electroweak symmetry breaking
- top quark special: very heavy, has a very short lifetime:
 - decays before it can form any bound states!
 - only "bare" quark we can study



Top-Quark pair production via the strong force

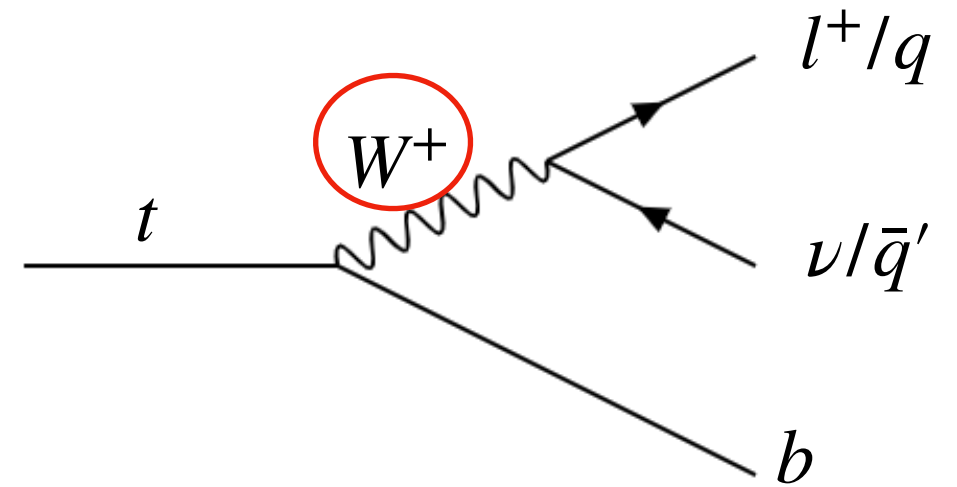
- production mainly via $q\bar{q}$ annihilation or gg -fusion
- $gg/q\bar{q}$ ratio changes with centre-of-mass energy
- dominant top-quark pair production channel at the **Tevatron** is **$q\bar{q}$ annihilation**
- dominant top-quark pair production channel at the **LHC** is **gg -fusion**
- top-pair production has largest cross-section (see in later slides)



Experimental signatures of $t\bar{t}$ events

- How can we identify Top-Quark pairs?

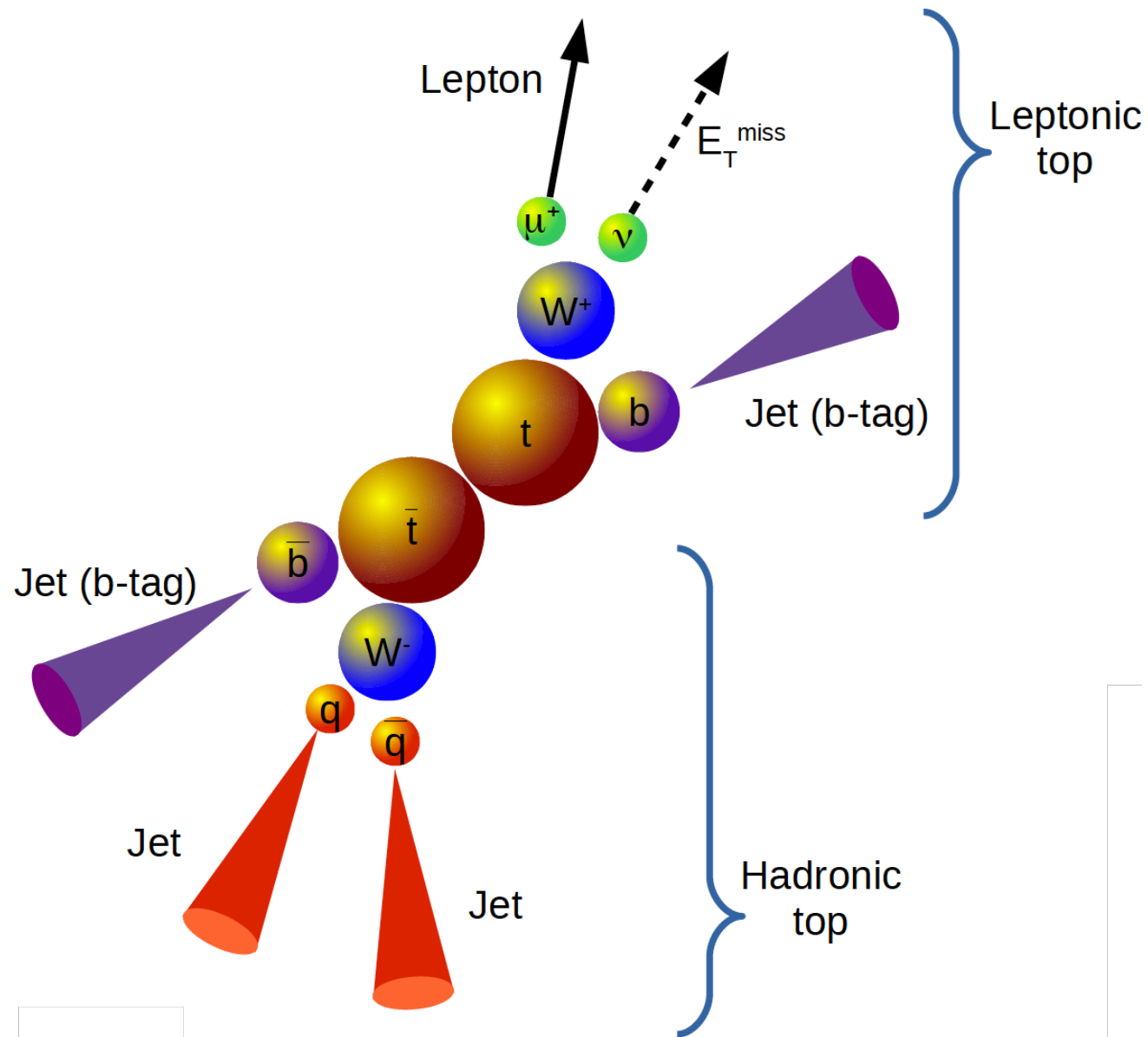
- $\text{BR}(t \rightarrow bW) \sim 1$
- final state defined by W decay
- W decays to $l\nu_l$ or $q\bar{q}$
- **b-jet identification is crucial!**



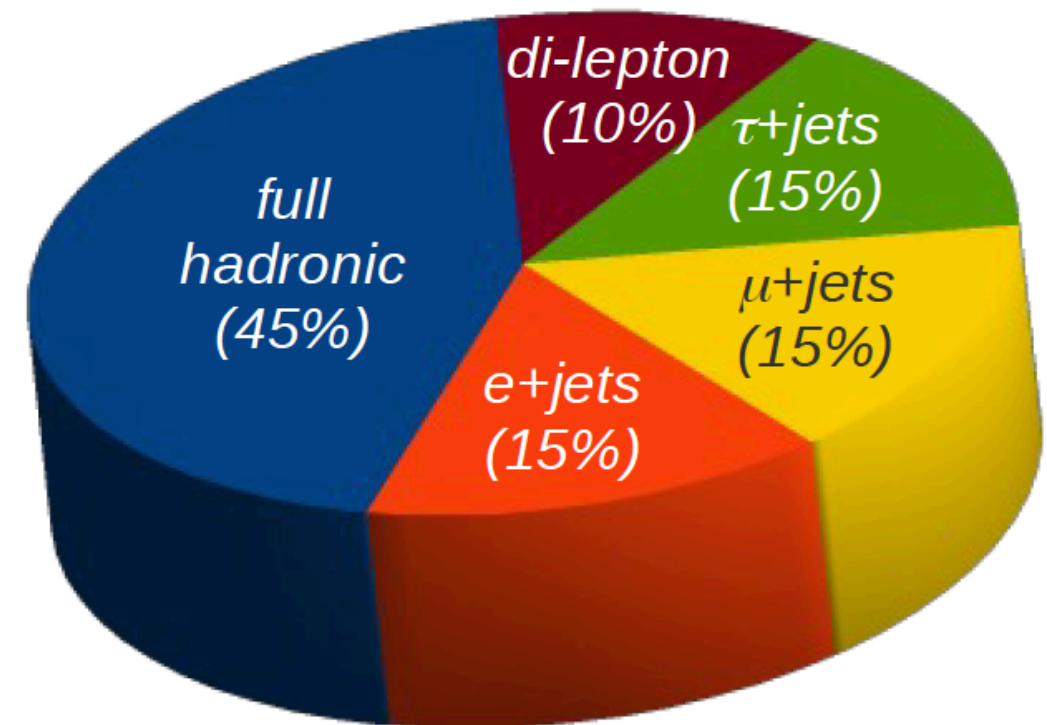
- | | | |
|--------------------------------|-------------------------------------|---------------------|
| • $W \rightarrow q\bar{q}$ 2/3 | | } ~75% hadronically |
| • $W \rightarrow \tau\nu$ 1/9 | | |
| <hr/> | | |
| • $W \rightarrow e\nu$ 1/9 | • $\tau \rightarrow q\bar{q}$ (65%) | } ~25% e or μ |
| • $W \rightarrow \mu\nu$ 1/9 | • $\tau \rightarrow \mu\nu$ (17.5%) | |
| | • $\tau \rightarrow e\nu$ (17.5%) | |

Experimental signatures of $t\bar{t}$ events

Example of μ +jets

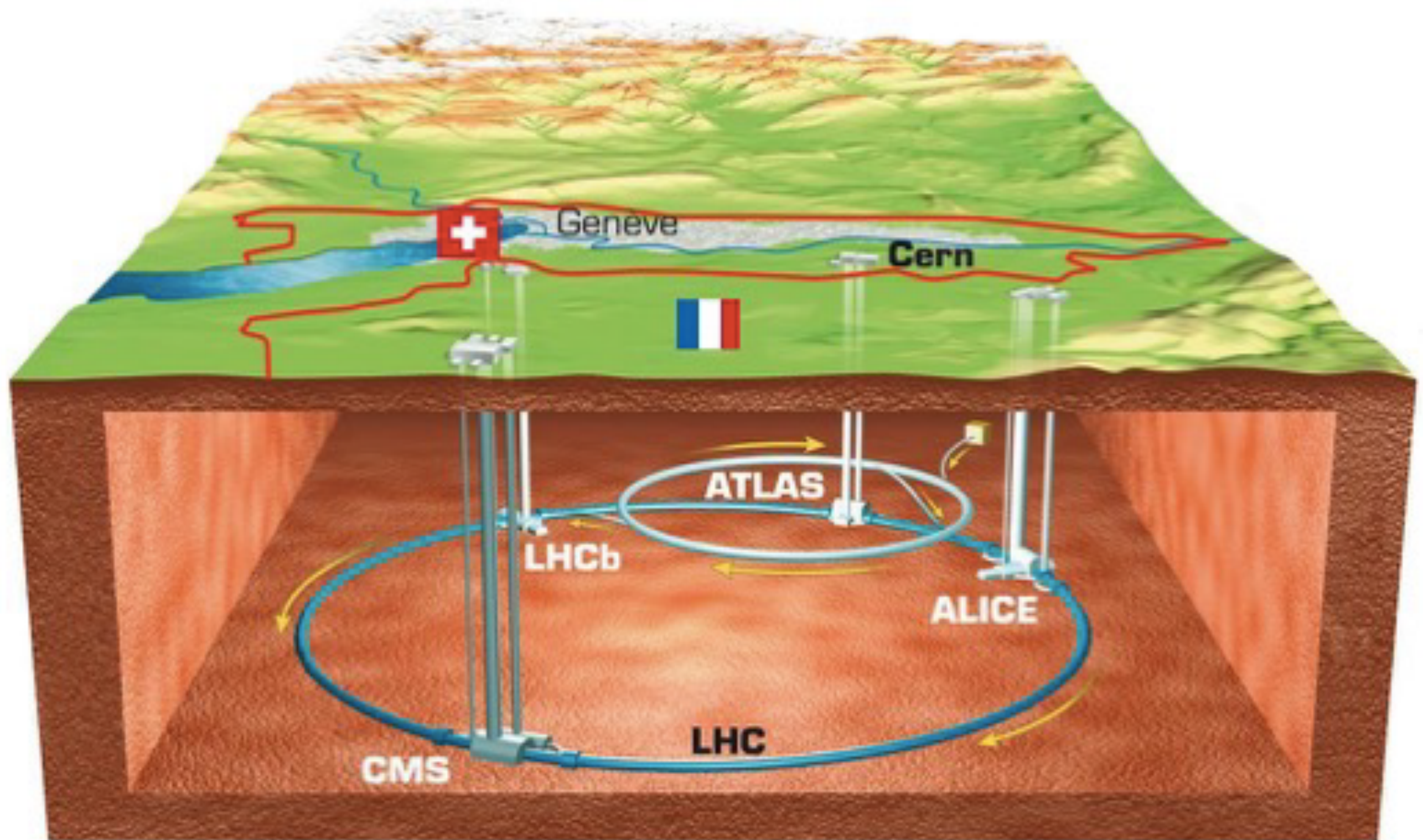


Branching fractions for $t\bar{t}$ events



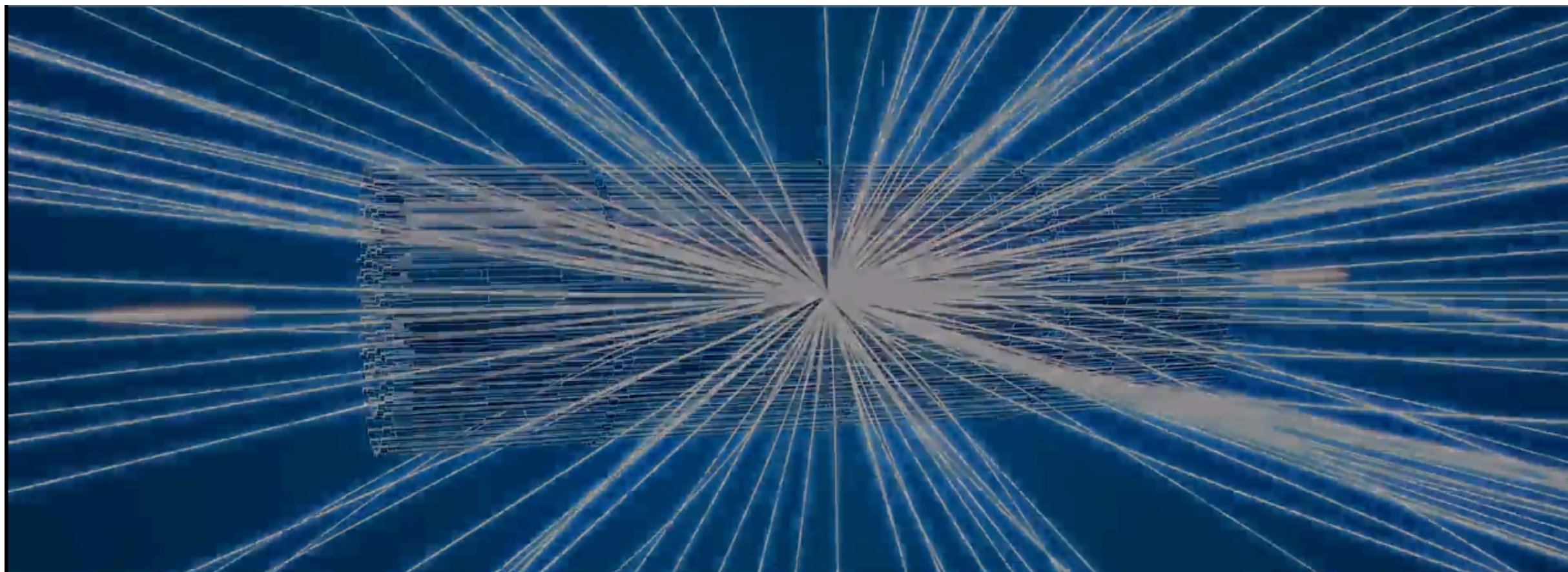
The Large Hadron Collider (LHC)

- The LHC is the largest physics accelerator in the world



The Large Hadron Collider (LHC)

- ~1 billion p-p collisions per second that can produce interesting & new physics



The LHC is a Top Factory
~25,000 $t\bar{t}$ events are produced every hour

- The number of collisions that can be produced in a detector per cross-section and per second is referred to as the **Luminosity**
- A huge amount of data!
 - $140 \text{ fb}^{-1} \Rightarrow$ millions and millions of interesting events

How to detect top quarks

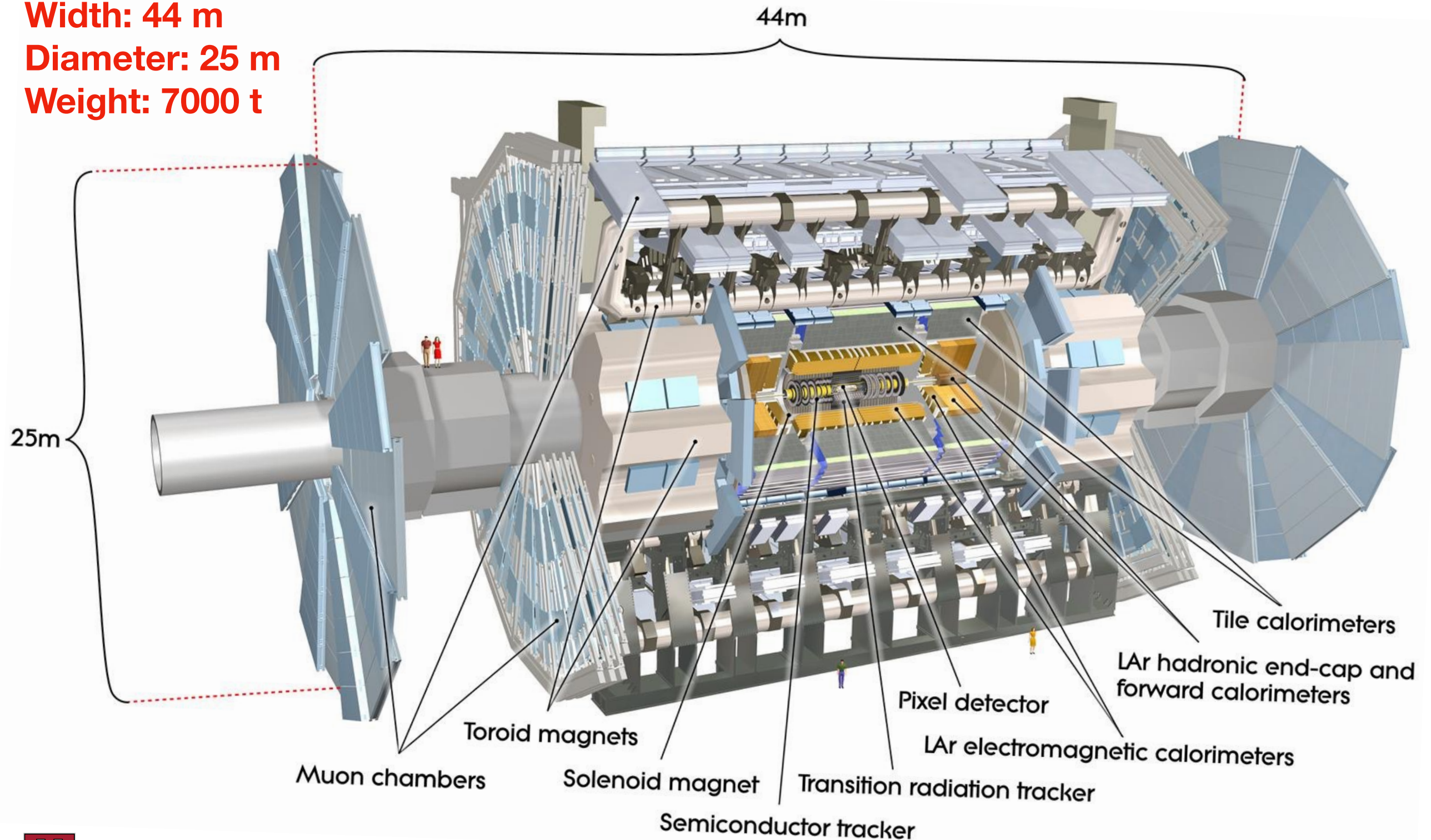
A Toroidal LHC ApparatuS (ATLAS)

- Several sub-detectors \Rightarrow particle tracking and energy measurement

Width: 44 m

Diameter: 25 m

Weight: 7000 t



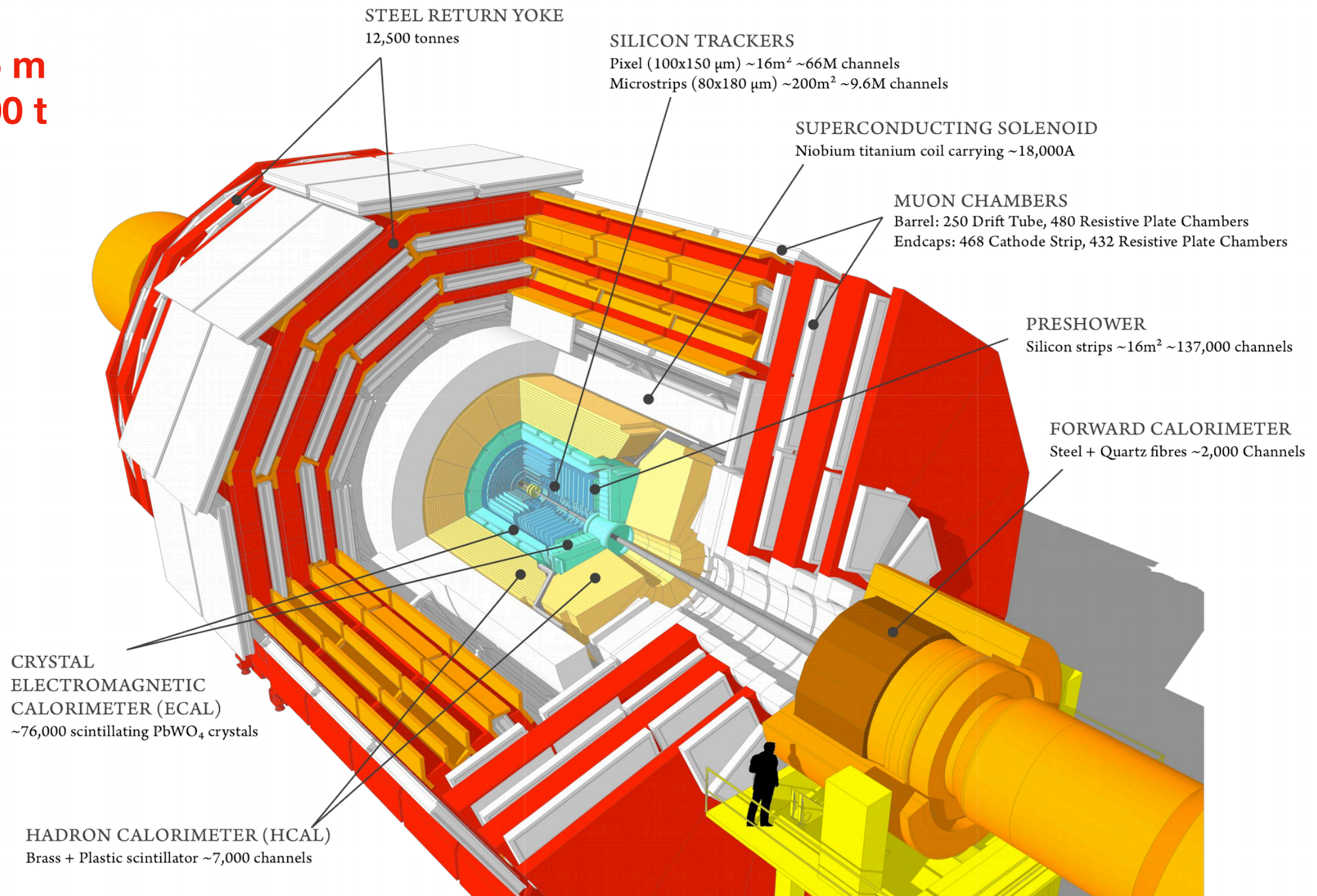
Compact Muon Solenoid (CMS)

- Several sub-detectors \Rightarrow particle tracking and energy measurement

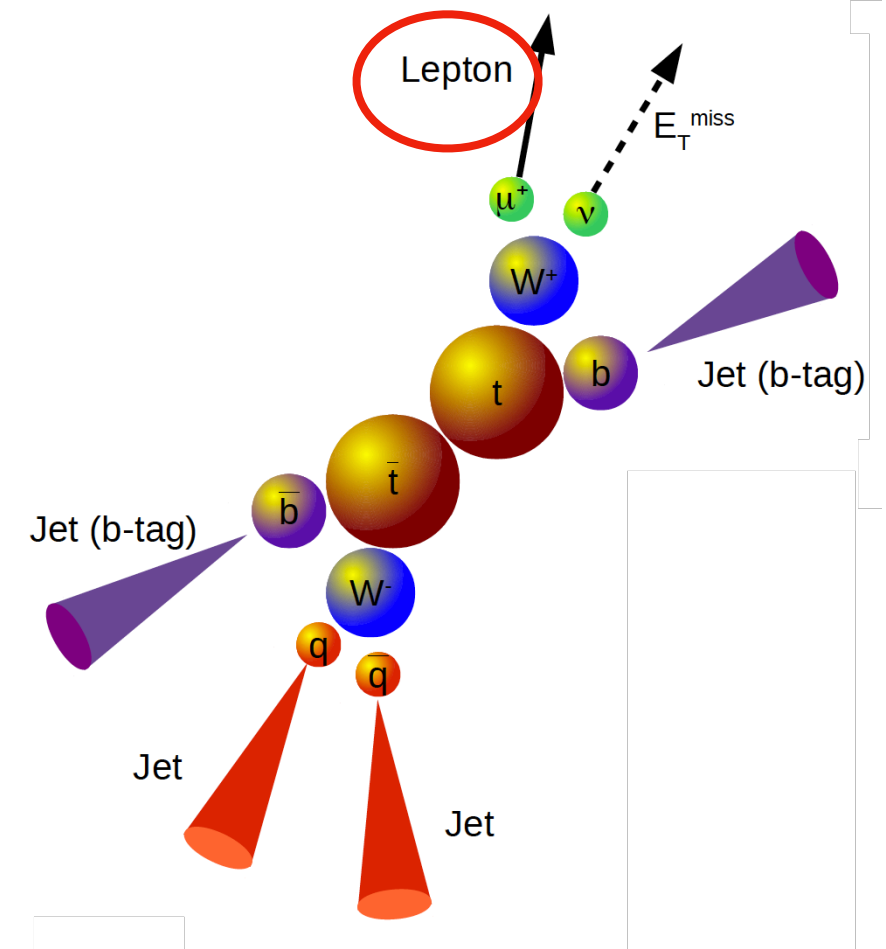
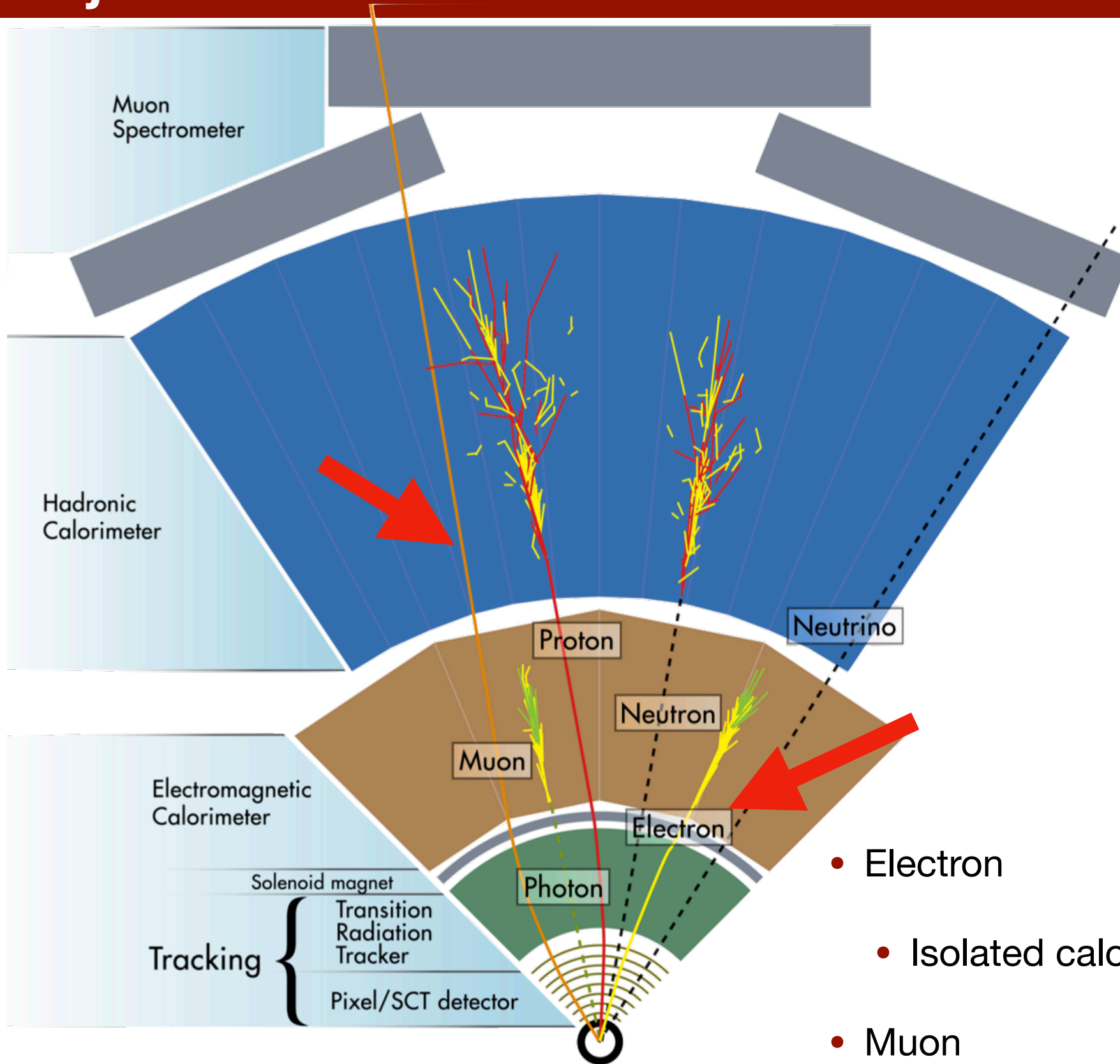
Width: 22 m

Diameter: 15 m

Weight: 12500 t

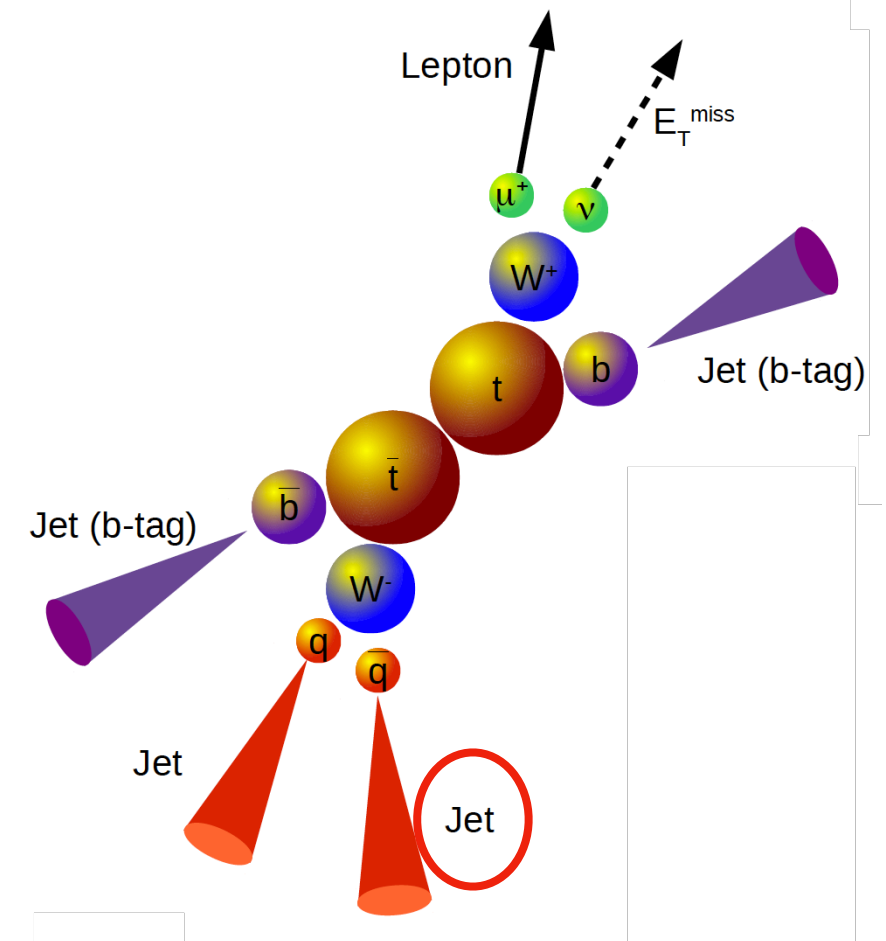
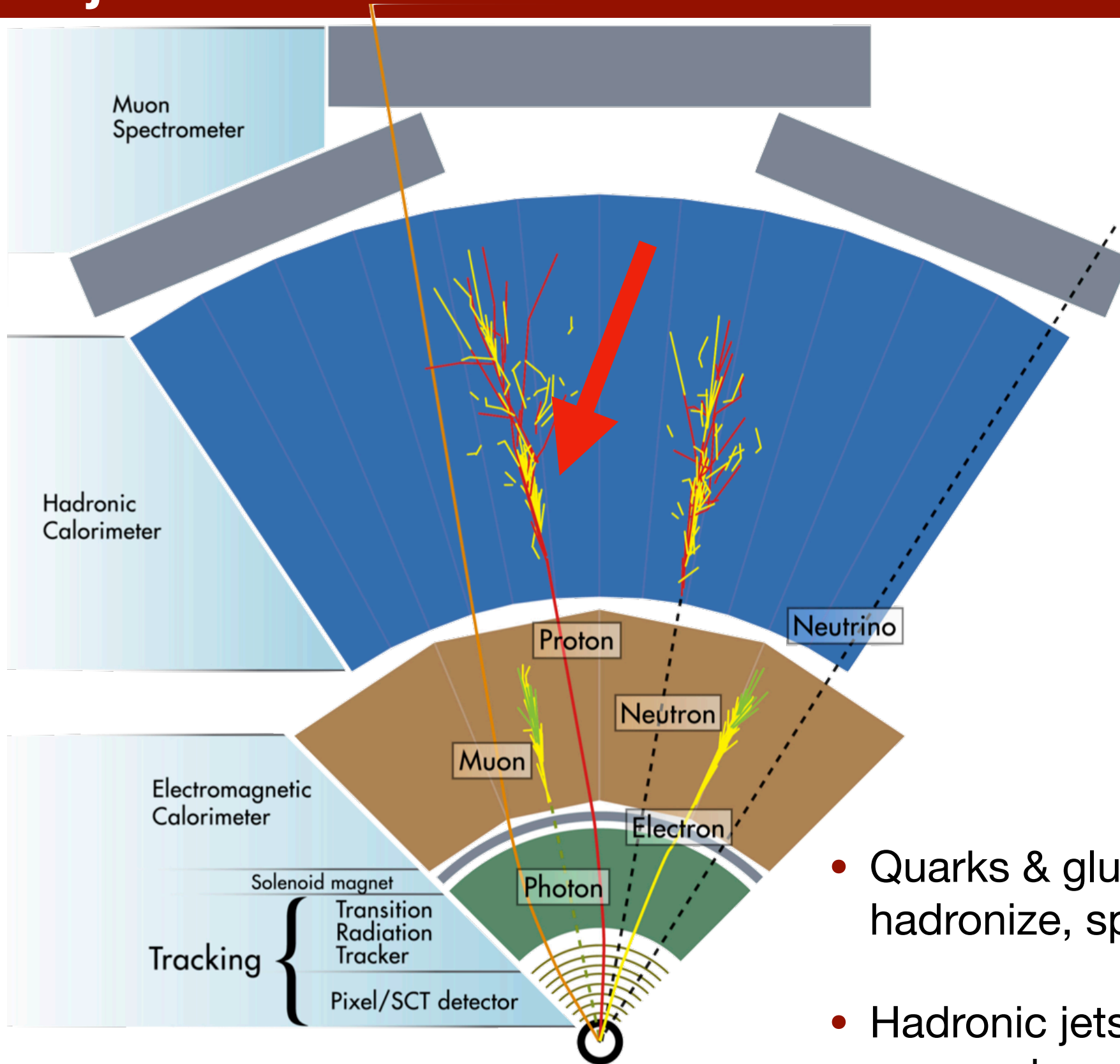


Object Reconstruction and Identification



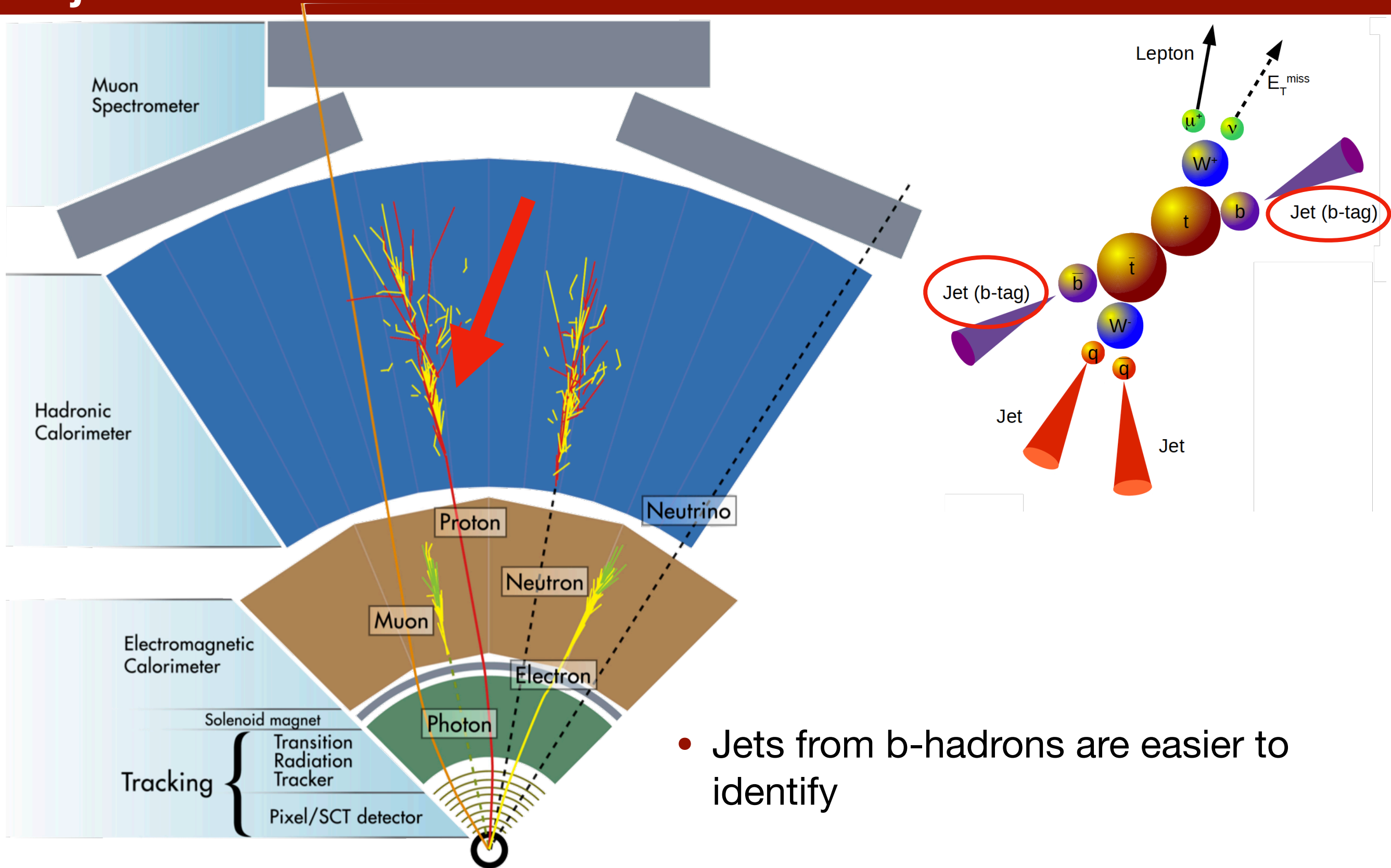
- Electron
- Isolated calorimeter deposit matched to track
- Muon
- Segment in muon detector matched to track

Object Reconstruction and Identification



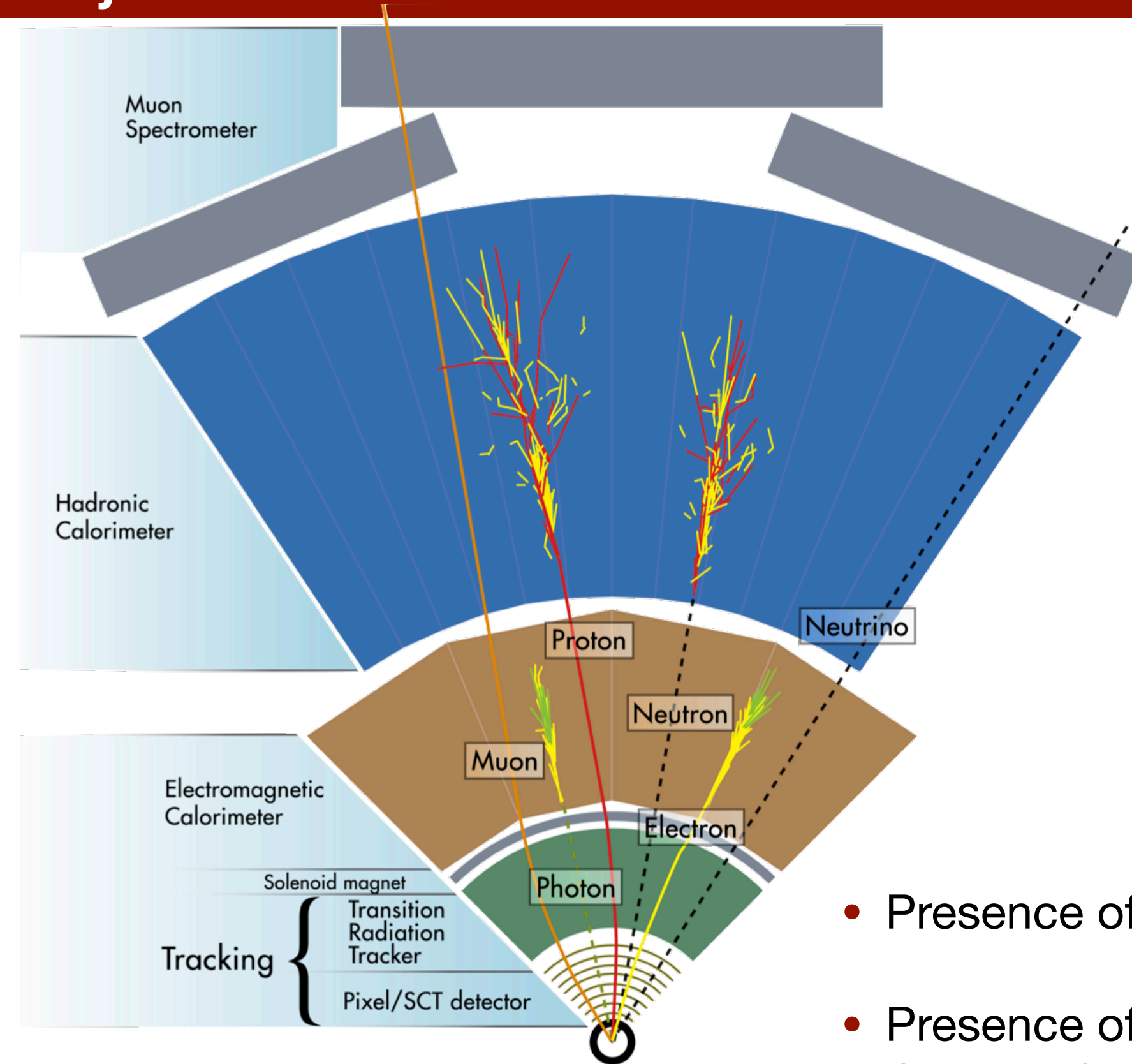
- Quarks & gluons quickly shower and hadronize, spraying hundreds of particles
- Hadronic jets are reconstructed from energy deposits in EM and hadronic calorimeters

Object Reconstruction and Identification

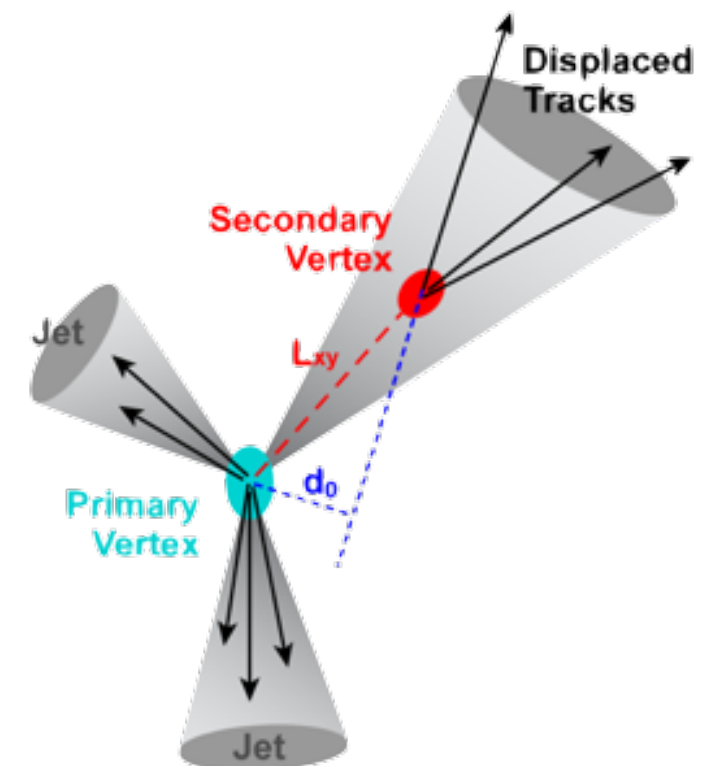


- Jets from b-hadrons are easier to identify
- B-hadron's long-lifetime & large mass

Object Reconstruction and Identification

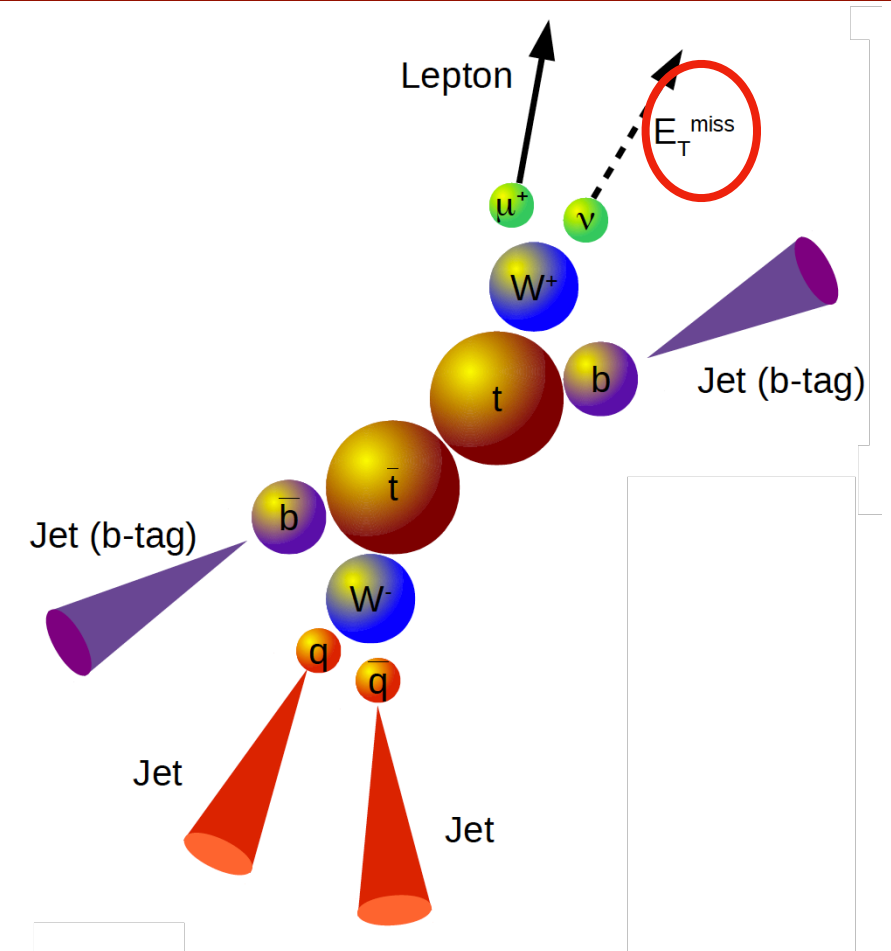
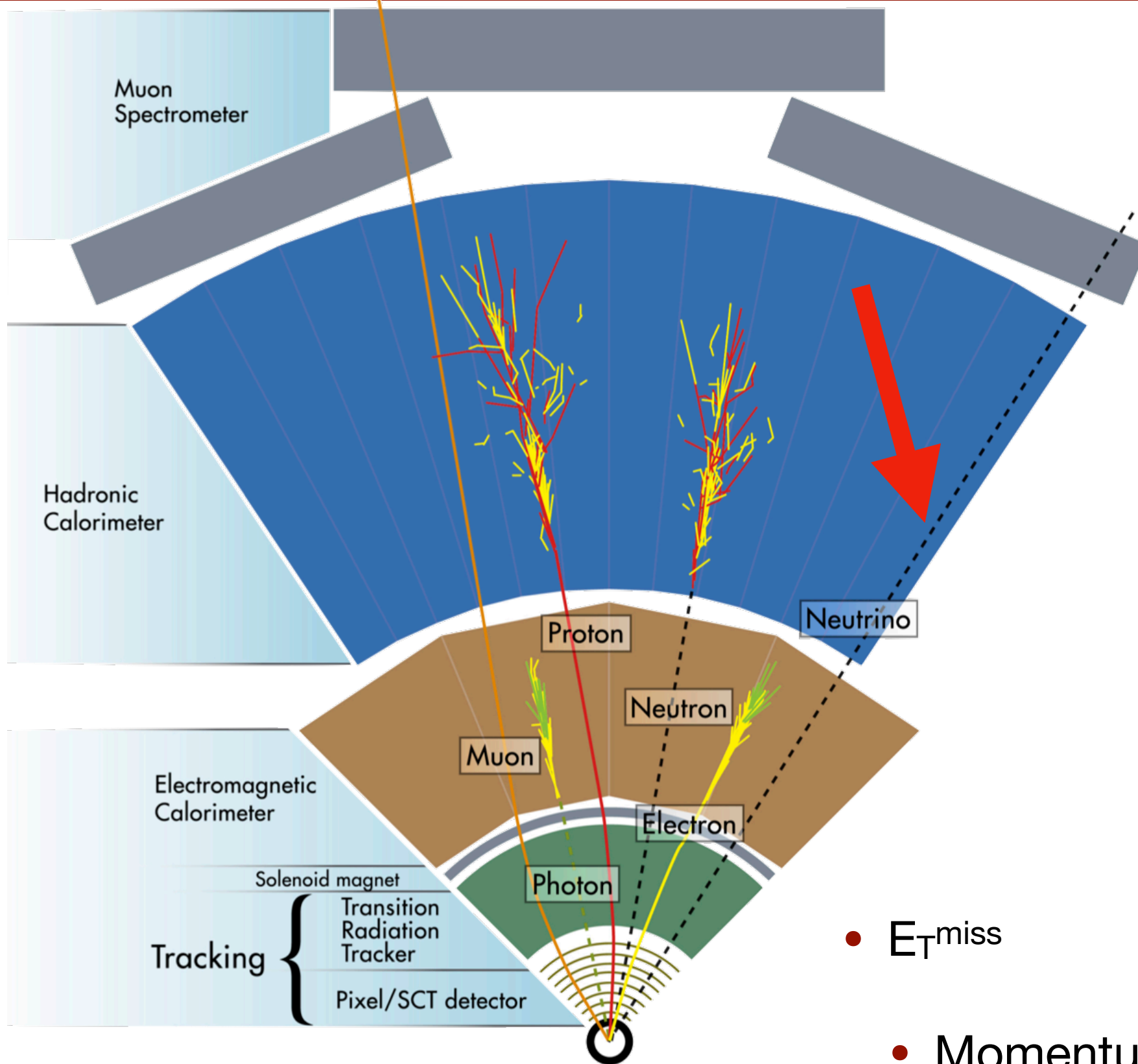


b-tagged jet



- Presence of displaced tracks
- Presence of secondary vertices ($B \rightarrow C \rightarrow \text{light}$)

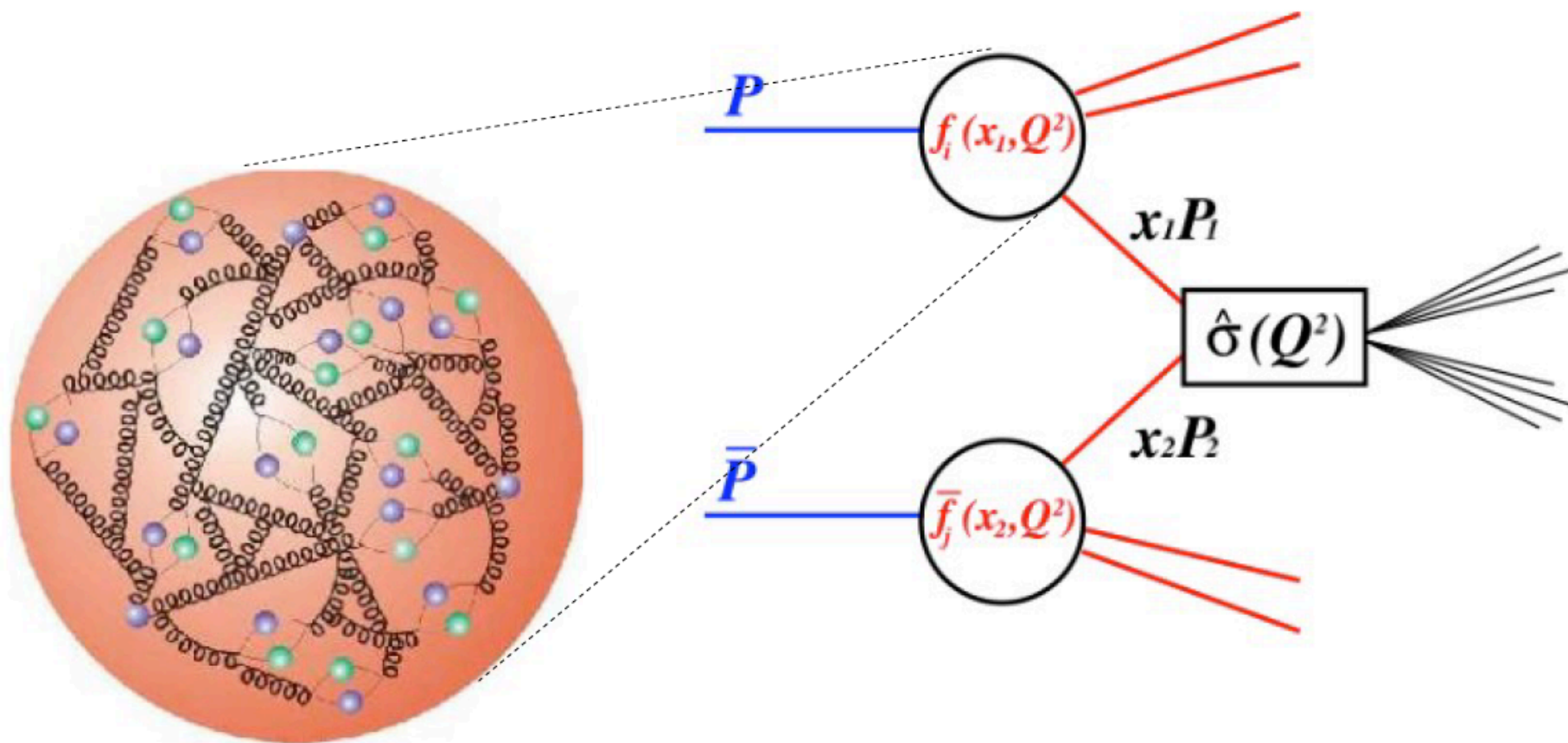
Object Reconstruction and Identification



- E_T^{miss}
- Momentum unbalance

Cross section calculation

- LHC is pp collider. Top quarks are produced by the interaction of partons composing the protons



$$\underbrace{\sigma^{t\bar{t}}(\sqrt{s}, m_t)}_{\text{Cross section}} = \underbrace{\sum_{i,j=q,\bar{q},g} \int dx_i dx_j}_{\text{Sum over all parton type and momenta}} \underbrace{f_i(x_i, \mu^2) \cdot \bar{f}_j(x_j, \mu^2)}_{\text{PDF}} \cdot \underbrace{\hat{\sigma}^{ij \rightarrow t\bar{t}}(\rho, m_t^2, \alpha_s(\mu^2), \mu^2)}_{\text{Partonic cross section}}$$

How can we measure the cross-section?

- Example: lepton+jets
- select events: exactly one electron or muon, $E_T^{\text{miss}}, \geq 4\text{jets}$
- estimate the amount background processes (from Monte Carlo simulation or from data)

$$\sigma = \frac{N_{\text{sel}} - N_{\text{bkg}}}{\epsilon_{\text{sel}} A \mathcal{L}}$$

- N_{sel} : number of selected events
- N_{bkg} : number of expected background events
- ϵ_{sel} : selection efficiency
- A : acceptance
- \mathcal{L} : luminosity \rightarrow precise knowledge important!



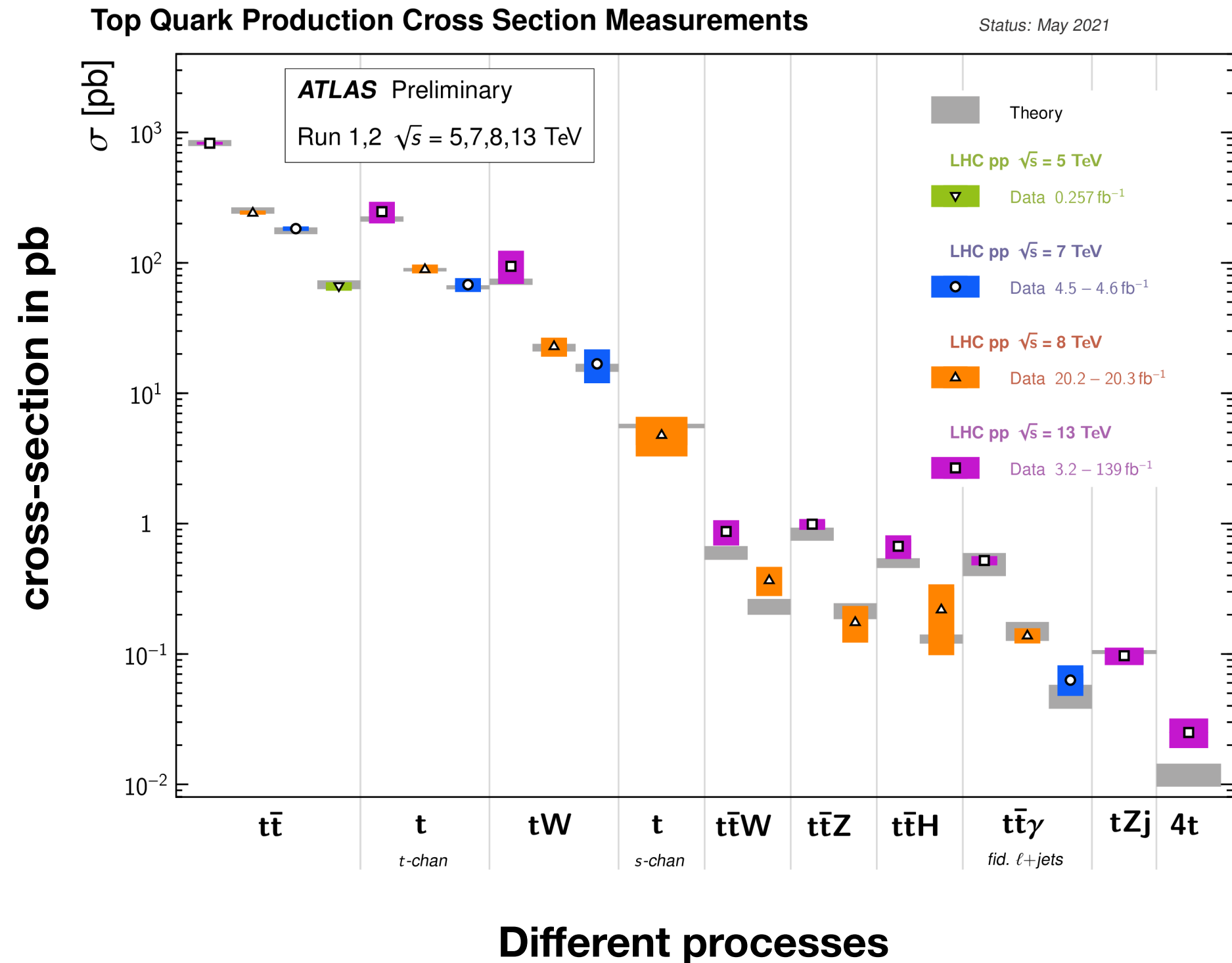
Top-quark Production Cross-section Measurements

Run 1 @ 7 TeV

Run 1 @ 8 TeV

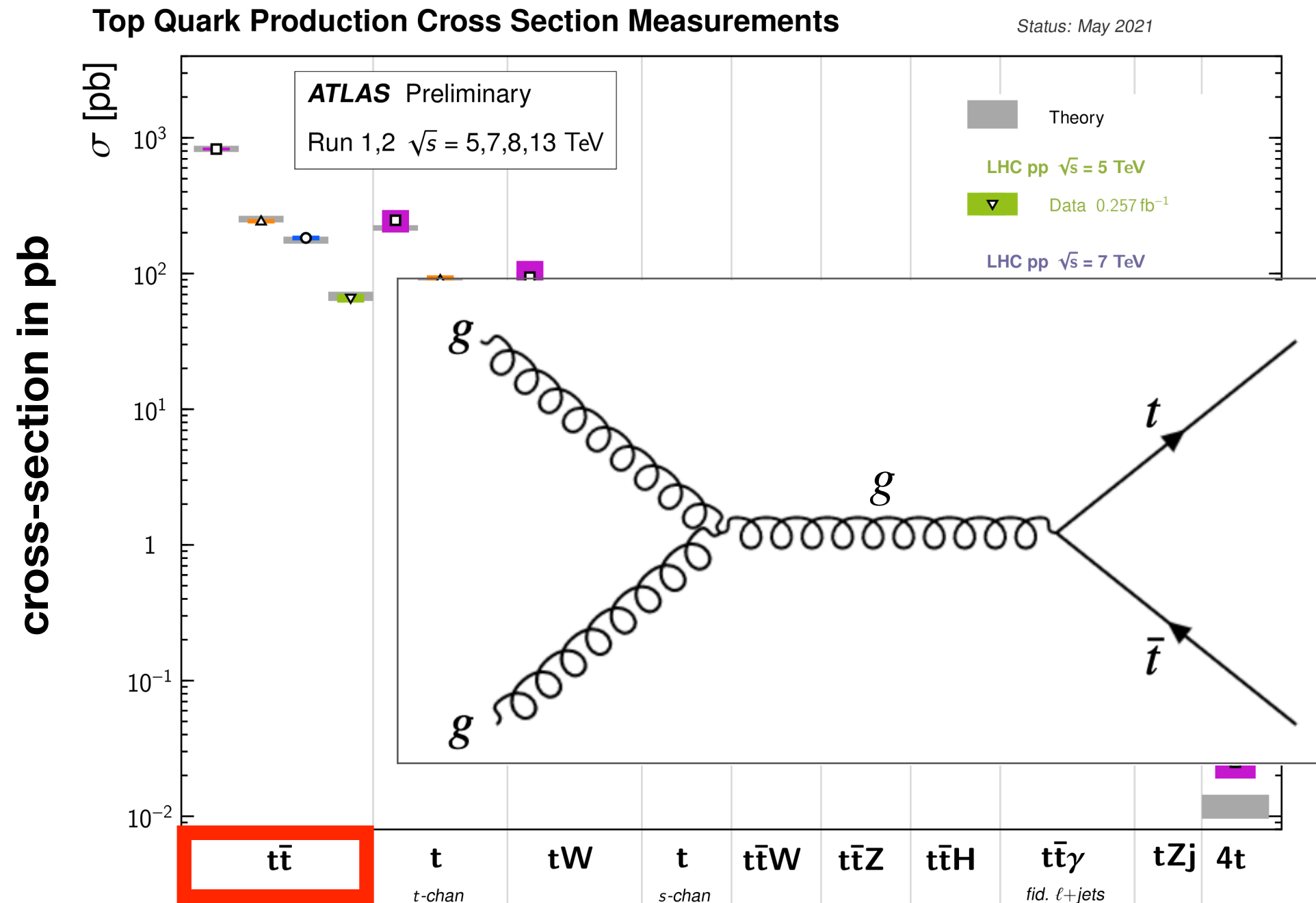
Run 2 @ 13 TeV

Theory



Top-quark Production Cross-section Measurements

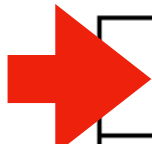
- $t\bar{t}$ production is produced abundantly at the LHC and extremely well studied (total and differential cross sections)



Different processes

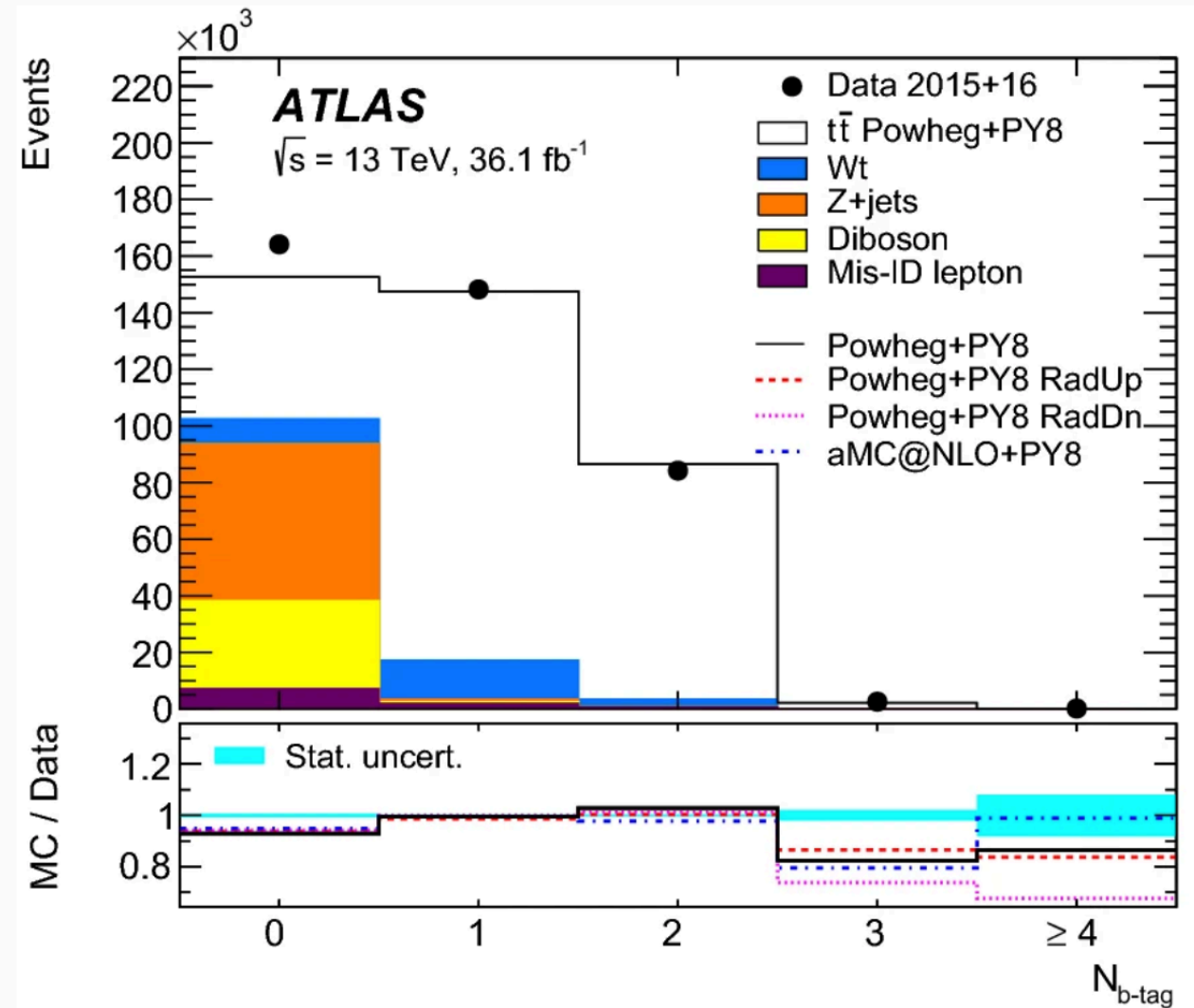
How many of those events do we have available for measurements?

LHC (ATLAS experiment) $\sqrt{s} = 13$ TeV; 139 fb⁻¹ data in 2015-2018

Process	Cross-section [pb]	Events before selection
 $t\bar{t}$	832	115,648,000
t channel	217	30,163,000
tW -channel	71.7	9,966,300
s -channel	10.32	1,434,480
$t\bar{t} + Z$	0.88	122,320
$t\bar{t} + W$	0.60	83,400
$t\bar{t} + \gamma$	0.77	107,030
$t\bar{t} + H$	0.51	70,890
$t\bar{t}t\bar{t}$	0.012	1,668

$t\bar{t}$ channels: the “clean channel”

- Dilepton
 - The cleanest channel (largest S/B) because of 2 leptons in the final state
- But
 - smallest branching fraction
 - need kinematical assumptions to fully reconstruct the event because of 2 neutrinos
- Main backgrounds
 - Z/γ +jets
 - diboson
 - single top

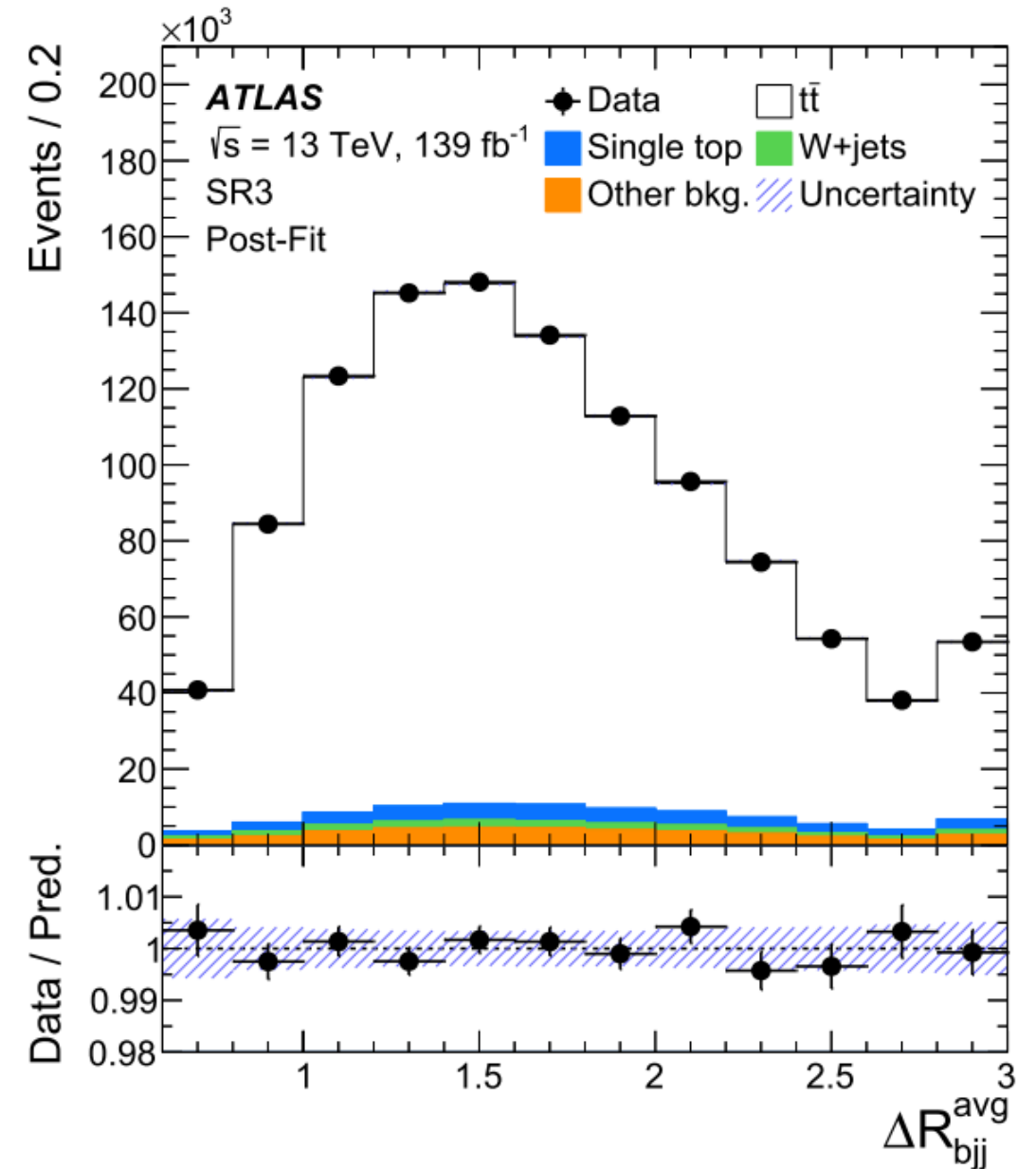


$$\sigma_{t\bar{t}} = 826.4 \pm 3.6(\text{stat}) \pm 11.5(\text{syst}) \pm 15.7(\text{lumi}) \pm 1.9(\text{beam})\text{pb}$$

Total uncertainty of 2.4%

$t\bar{t}$ channels: the “fair channel”

- lepton + jets
 - Clean channel because of the presence of the lepton
 - “fair” branching ratio
- But
 - kinematical fit to reconstruct the leptonic top because of the neutrino
- Main backgrounds
 - W +jets
 - multi-jet QCD
 - single top

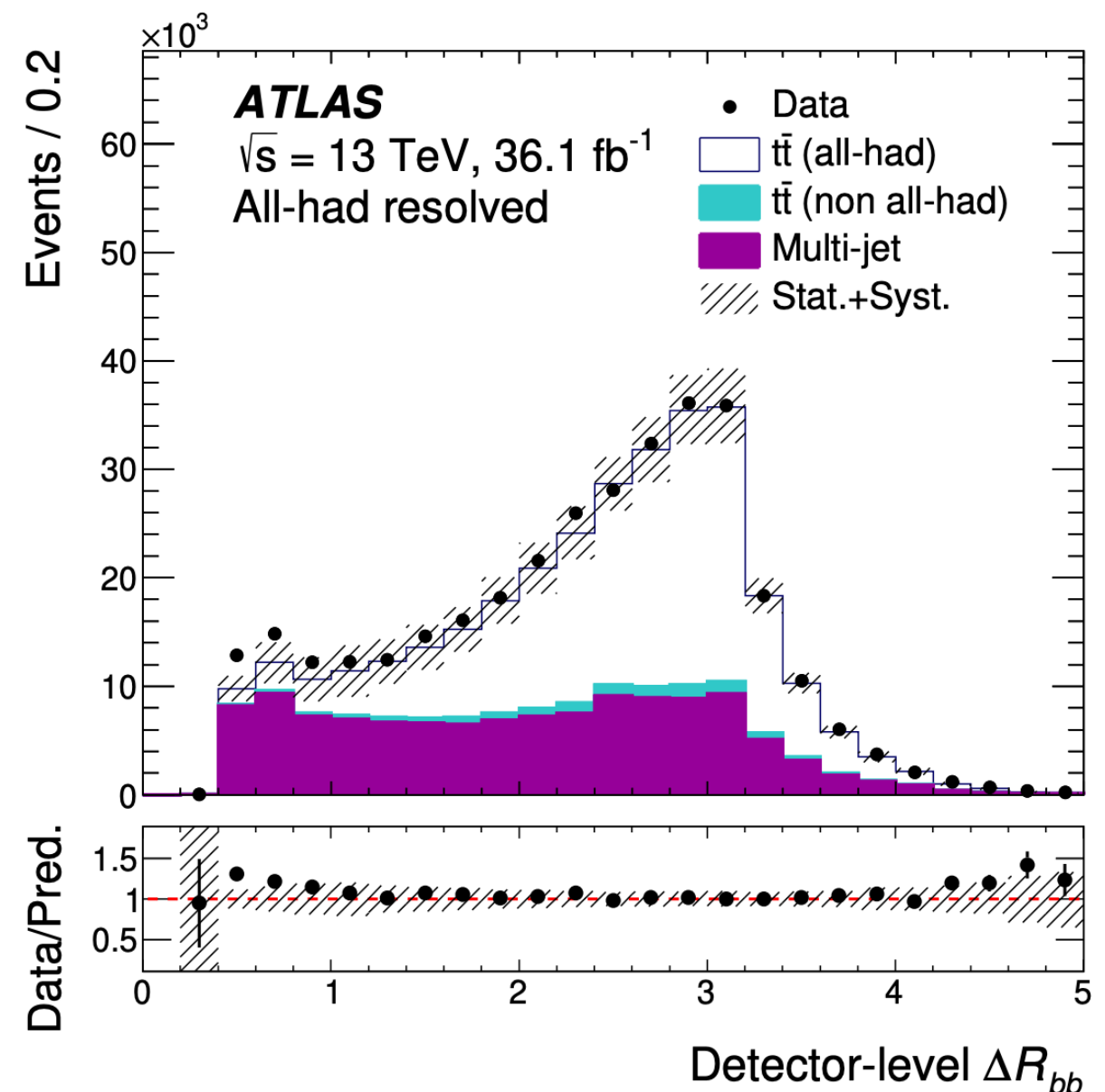


$$\sigma_{inc} = 830 \pm 0.4(\text{stat}) \pm 36(\text{syst}) \pm 14(\text{lumi})\text{pb}$$

Total uncertainty of 4.6%

$t\bar{t}$ channels: the “dirty channel”

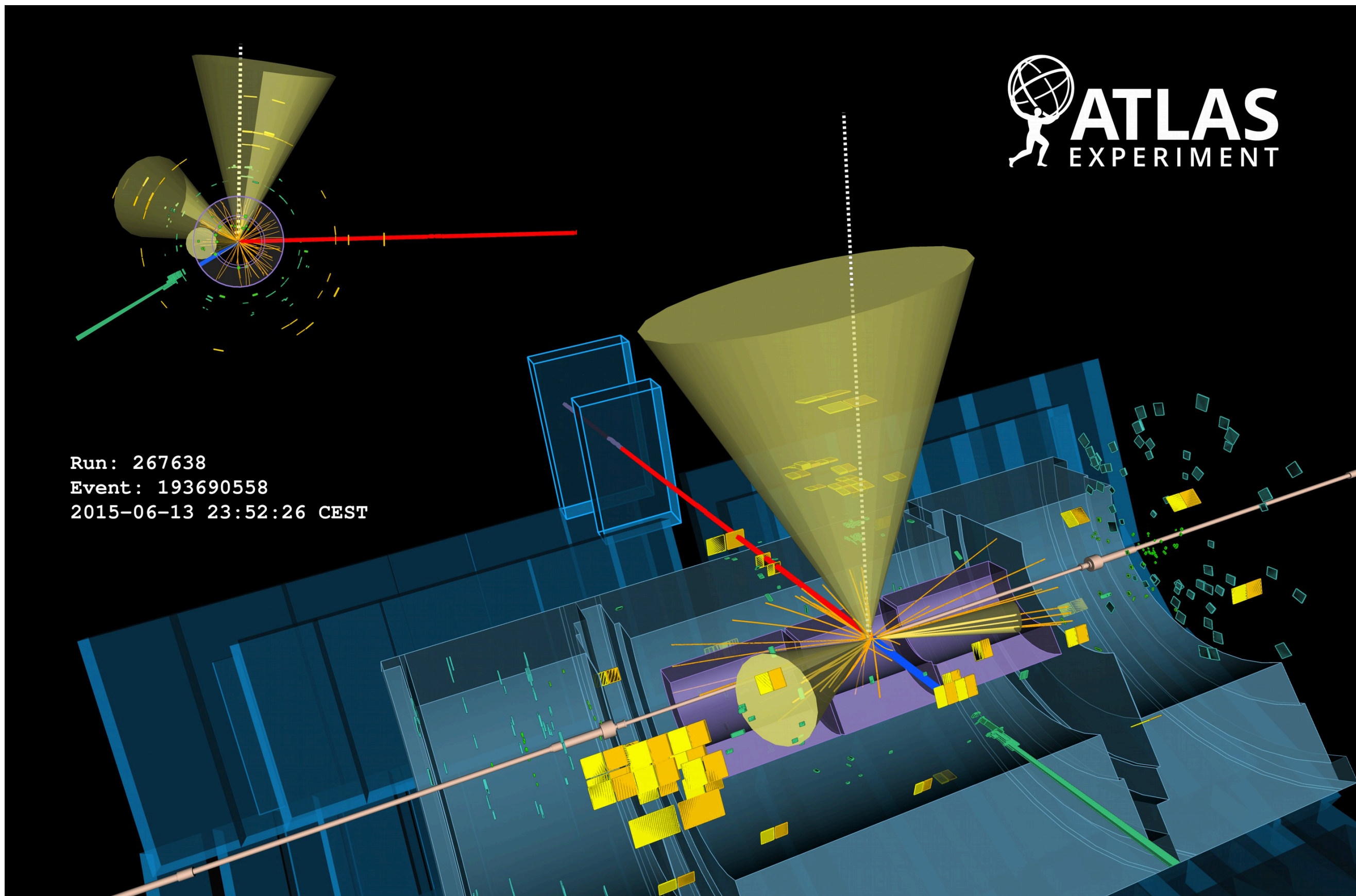
- all-hadronic
 - The largest branching ratio
- But
 - large hadronic background
 - Combinatorial effect in $t\bar{t}$ event reconstruction
- Main backgrounds
 - multi-jet QCD



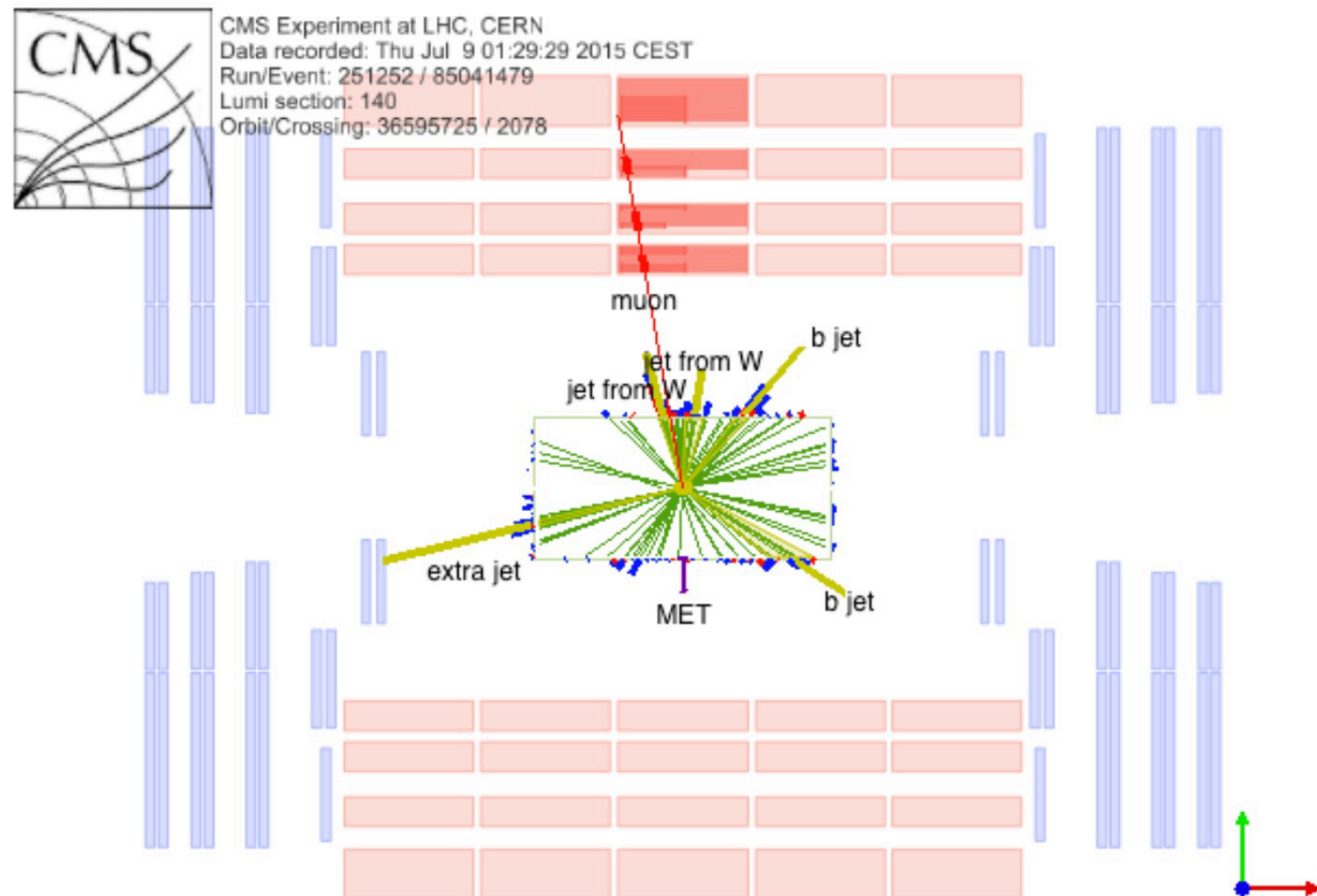
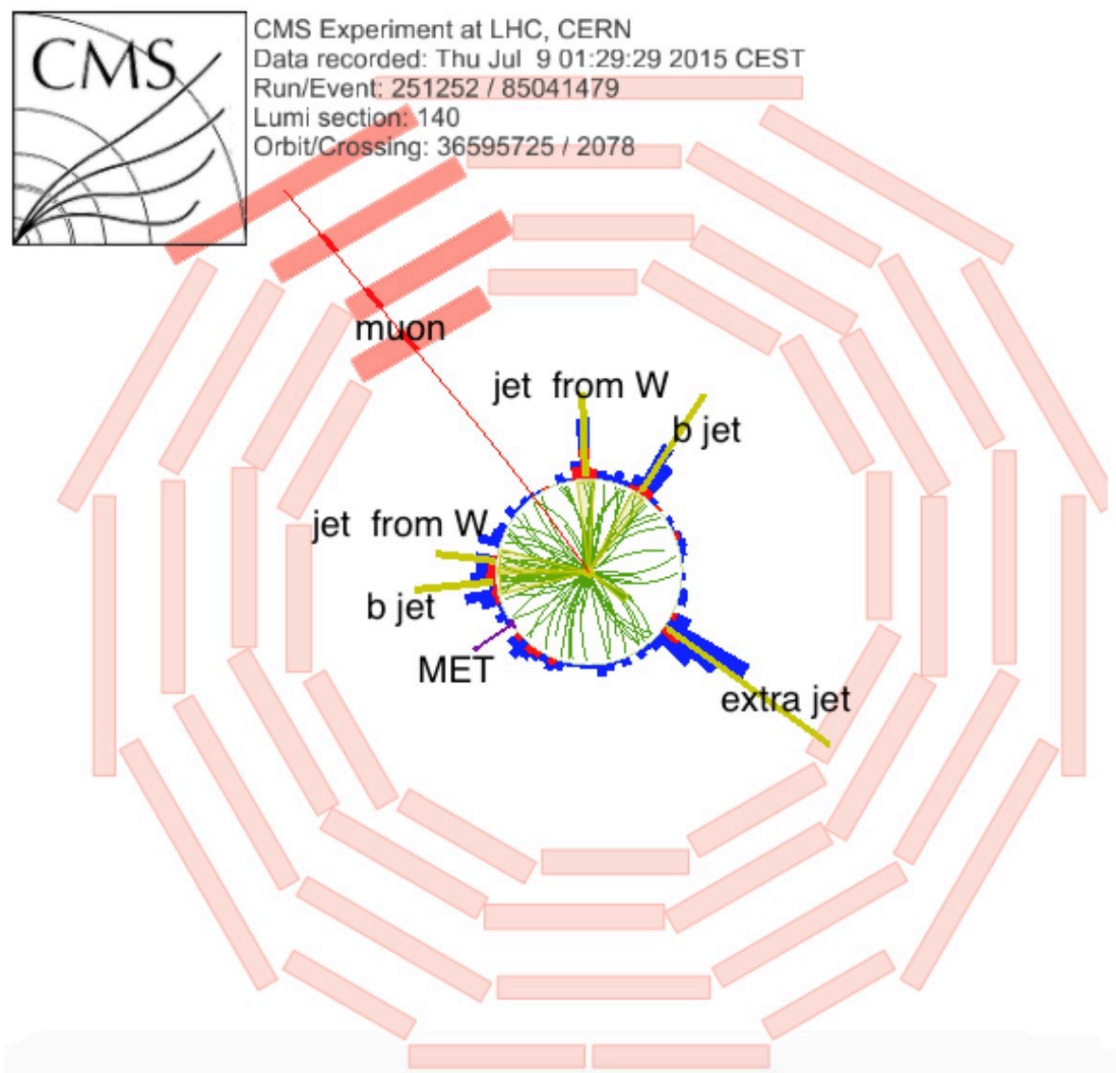
$$\sigma_{t\bar{t}} = 864 \pm 127(\text{stat} + \text{syst})\text{pb}$$

Total uncertainty of 15% and the statistical uncertainty is 0.5%

Dilepton $t\bar{t}$ event display

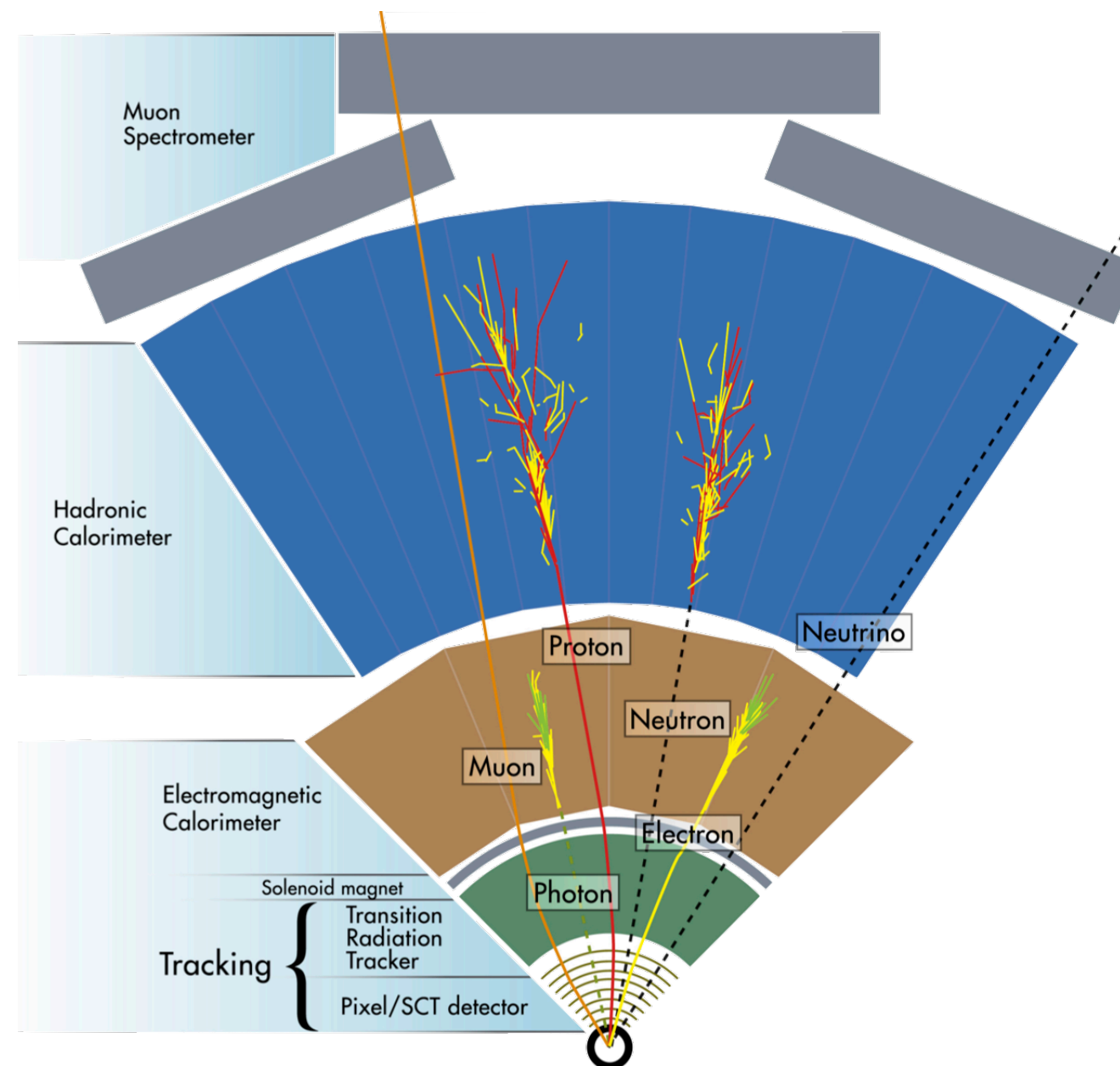


lepton+jets $t\bar{t}$ event display



Recap

- What are the advantages and disadvantages of the three $t\bar{t}$ reconstruction channels (dilepton, lepton+jets, all-hadronic)?
- What are the detector components used in top quark physics?



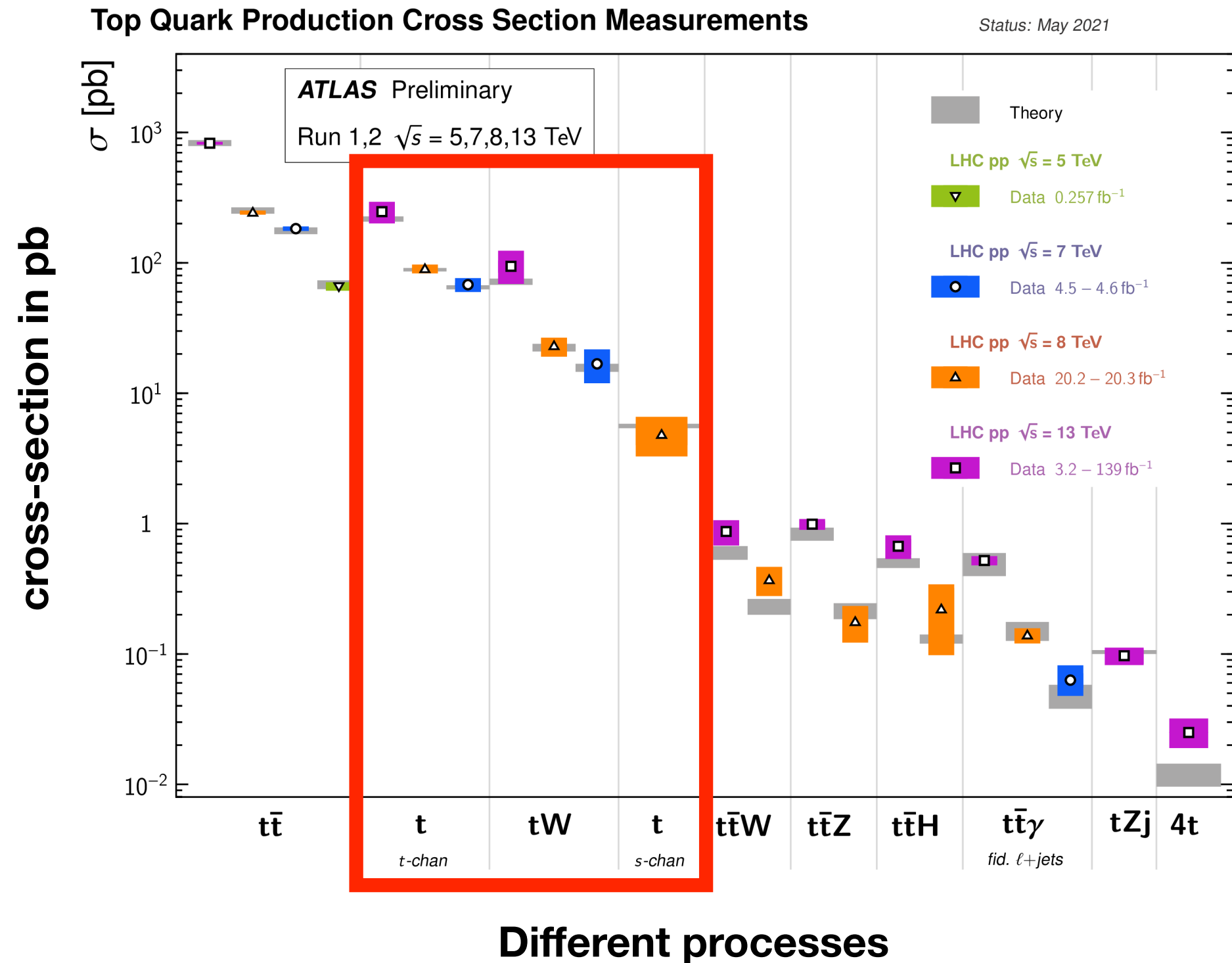
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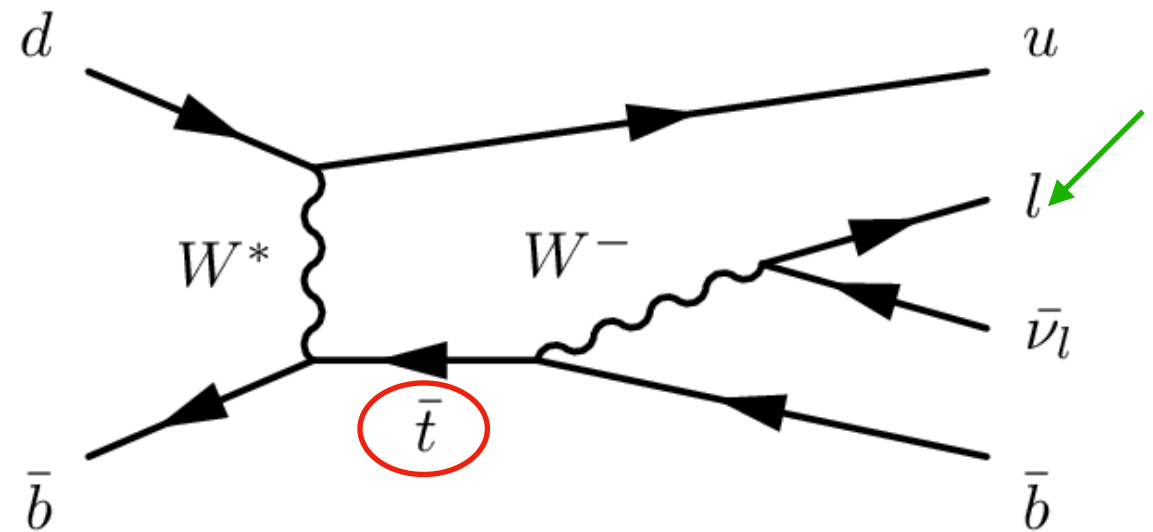
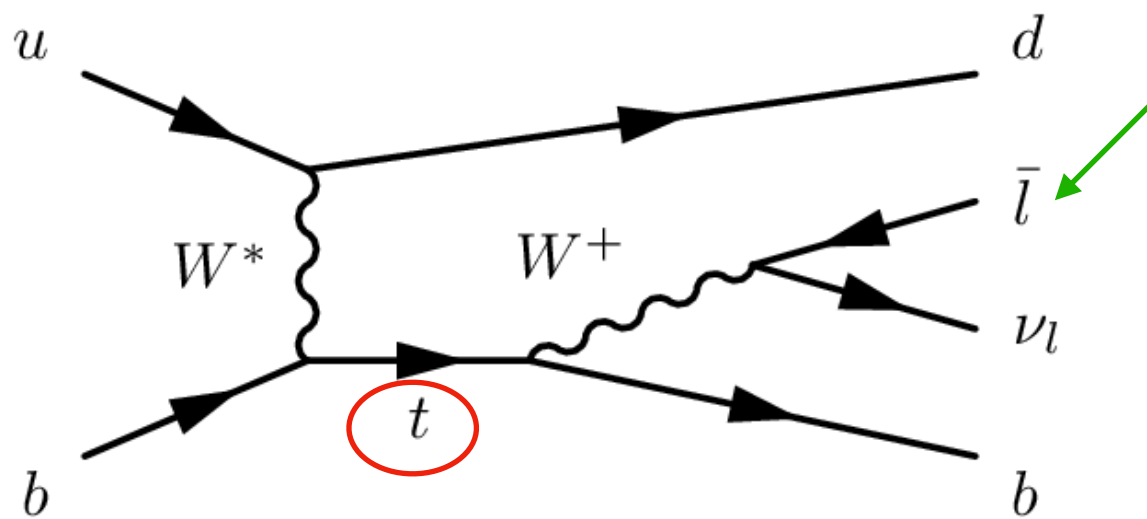
Run 1 @ 8 TeV

Run 2 @ 13 TeV

Theory

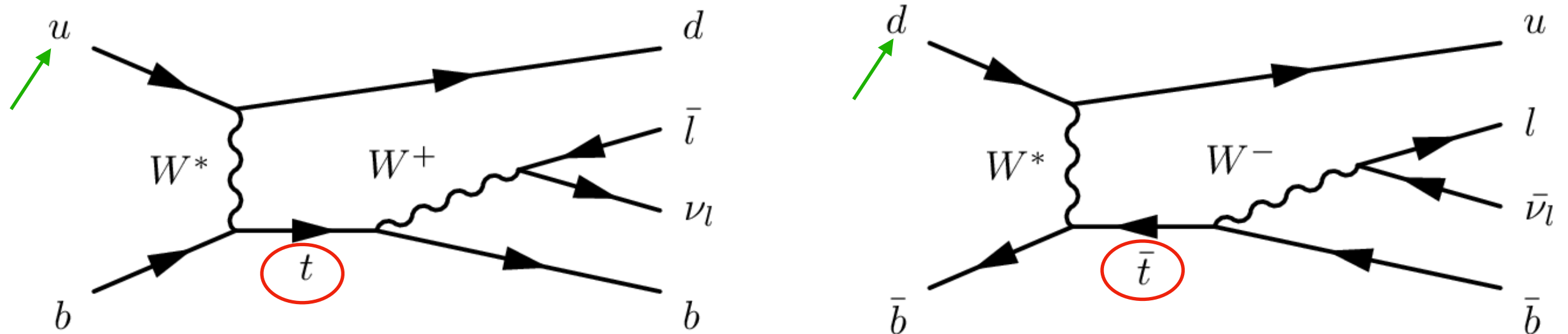


Inclusive t-channel cross-section



- Goal is to measure t - and \bar{t} - channel cross-sections in lepton+jets channel
- $\sigma_t > \sigma_{\bar{t}}$ due to different initial state
- Can you guess why?

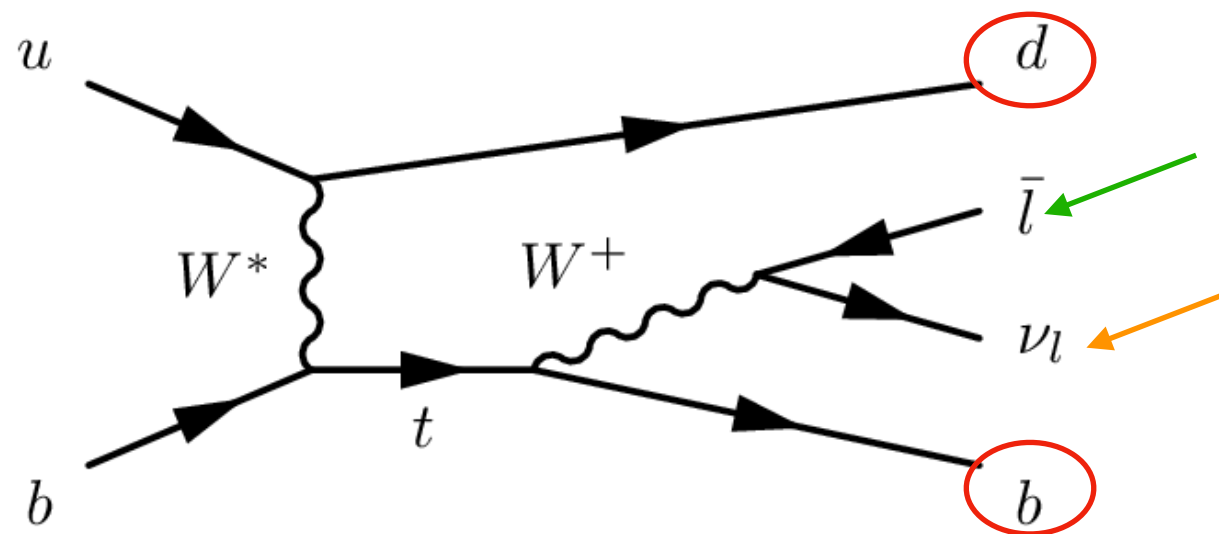
Inclusive t-channel cross-section



- Goal is to measure t - and \bar{t} - channel cross-sections in lepton+jets channel
- $\sigma_t > \sigma_{\bar{t}}$ due to different initial state
 - Can you guess why?
 - valence u -quark density of the proton is about twice as high as the valence d -quark density
- measure the cross-section ratio: $R_t = \sigma(tq)/\sigma(\bar{t}q)$

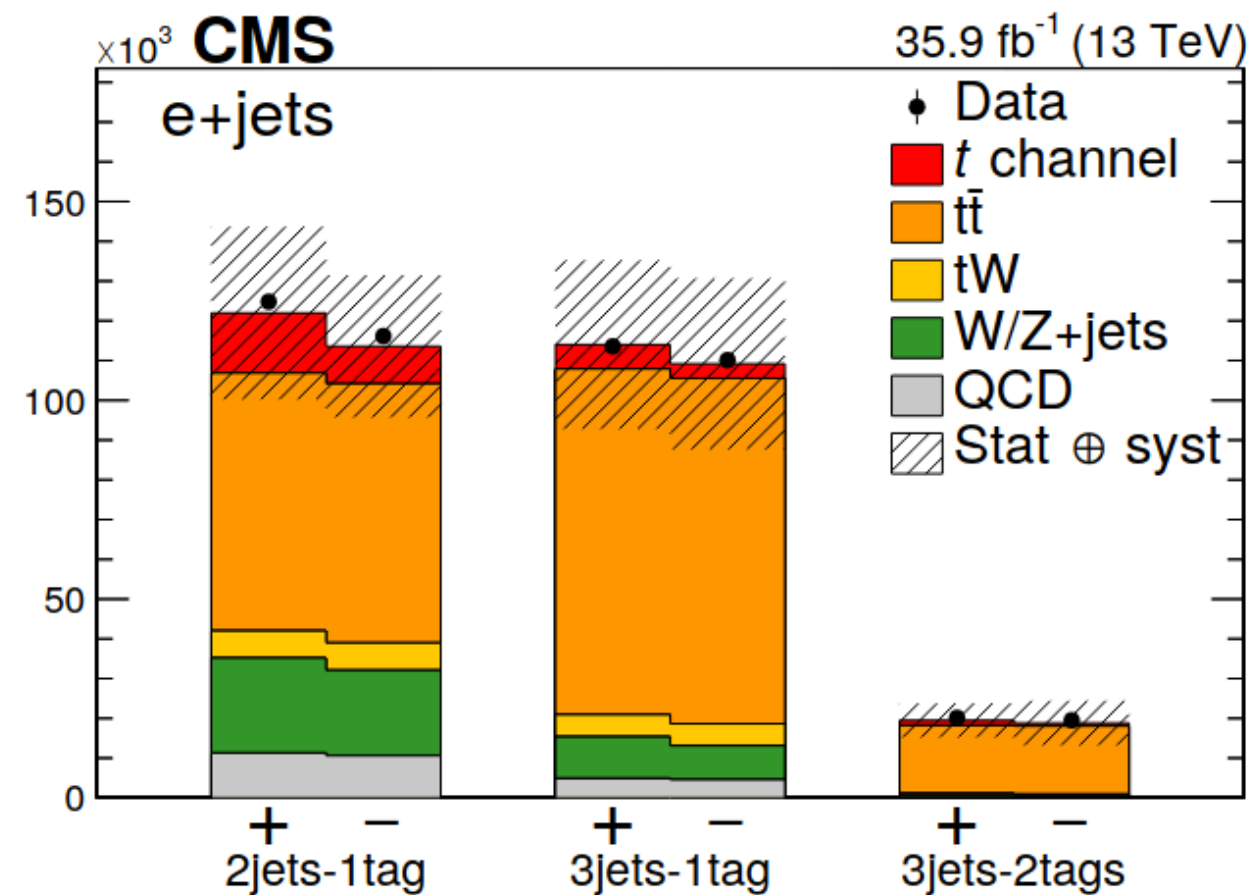
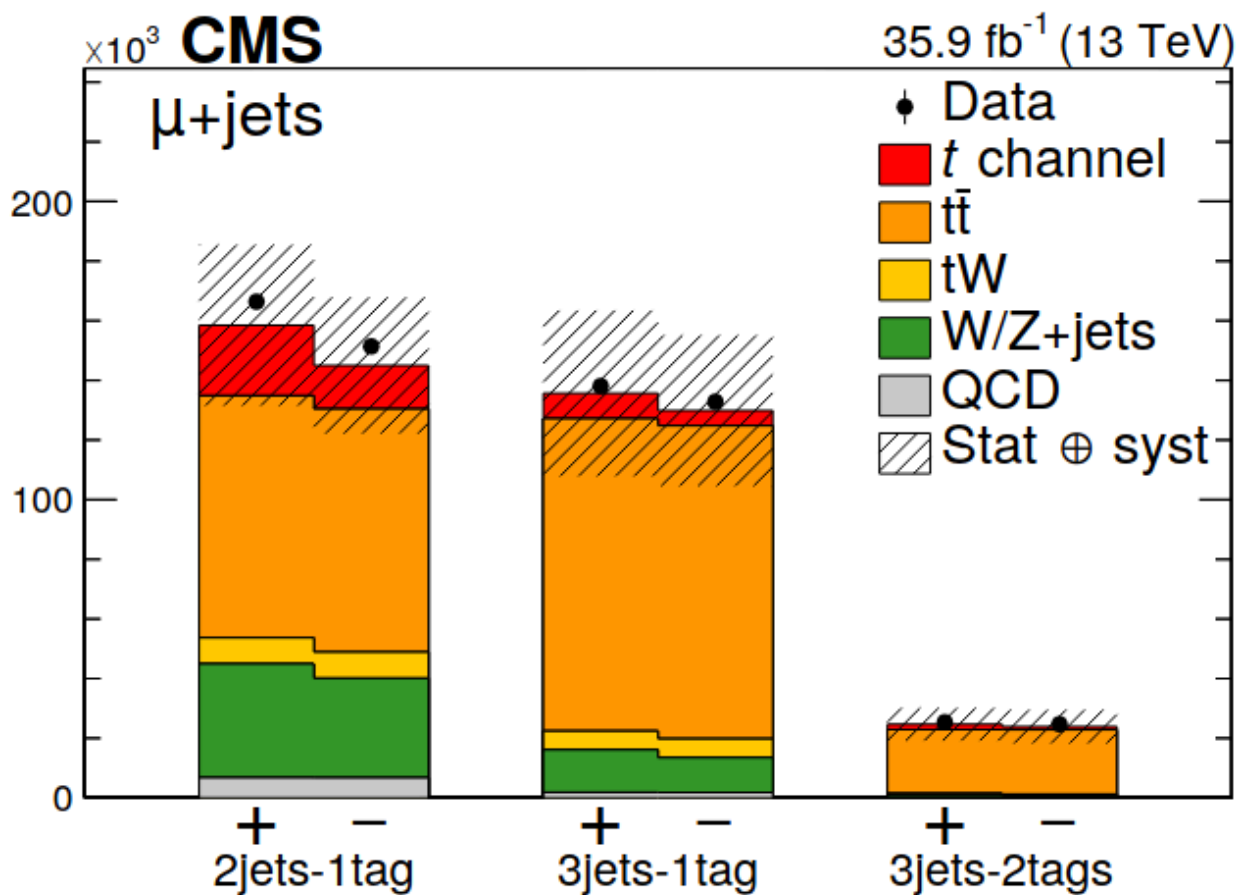
Inclusive t-channel cross-section

Example from CMS



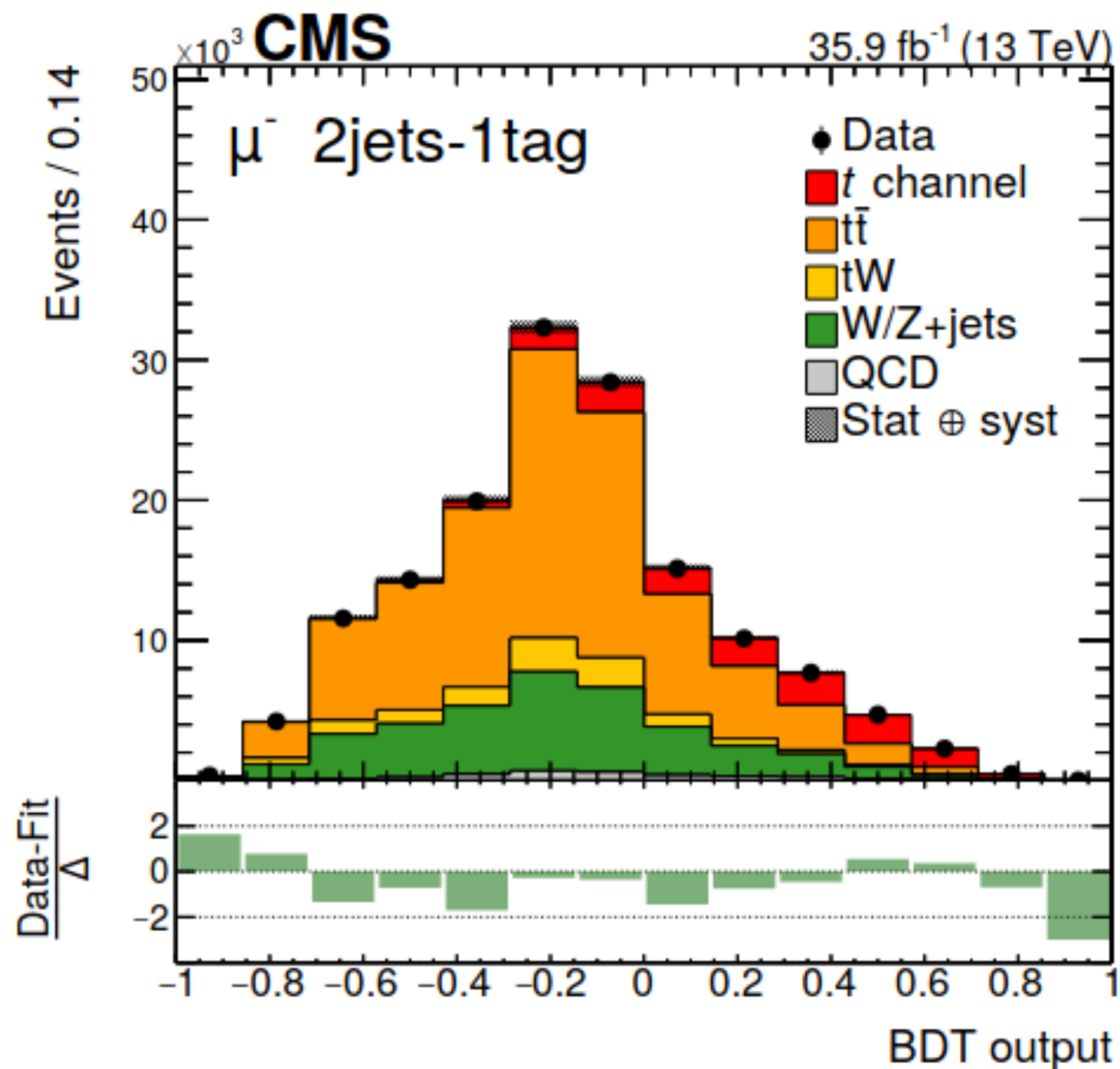
- First step: define an event selection
 - exactly **one lepton** (electron or muon)
 - E_T^{miss}
 - ≥ 2 **jets**; ≥ 0 b-tagged jets (must be identified as originating from a b -quark)
- Second step: define different regions depending on the number of jets (N_{jets}) and number of b-tagged jet ($N_{\text{b-tag}}$)
 - define regions dominant by backgrounds (background coming from $t\bar{t}$ and fake leptons)
 - define regions dominant by signal

Inclusive t-channel cross-section



Inclusive t-channel cross-section

- Use of Machine learning (like Boosted Decision Tree - BDT) to obtain a better separation between signal and background
- Who used Machine learning techniques? In what context?
- Choose variables that show clear difference between the signal and the background
- variables like jet/lepton p_T and η , top-quark mass, ΔR (lepton, b jet)...

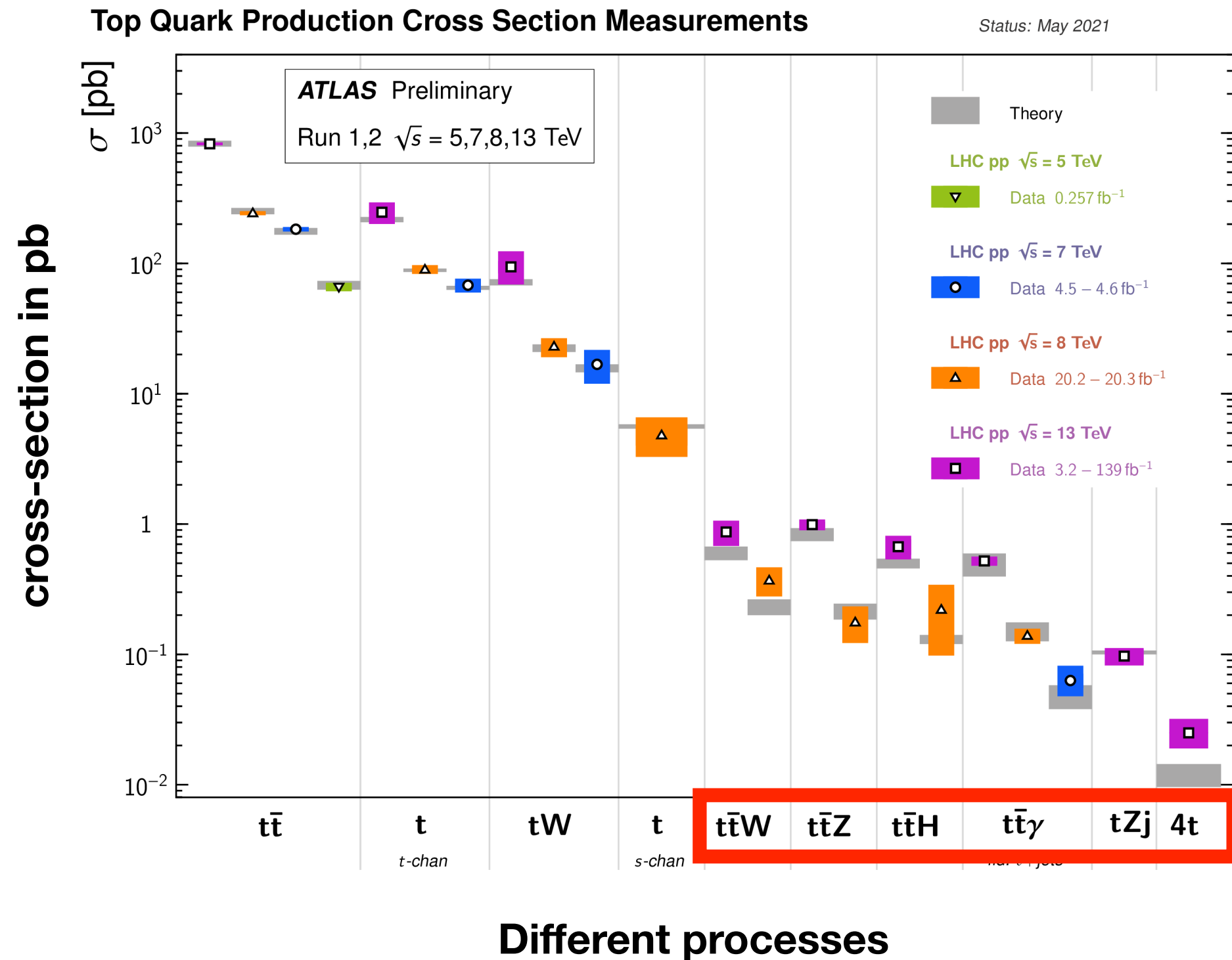


$$\sigma_t = 130 \pm 19 \text{ pb}; \sigma_{\bar{t}} = 77 \pm 12 \text{ pb}$$

$$\sigma_{\text{total}} = 207 \pm 31 \text{ pb}, R = 1.68 \pm 0.06$$

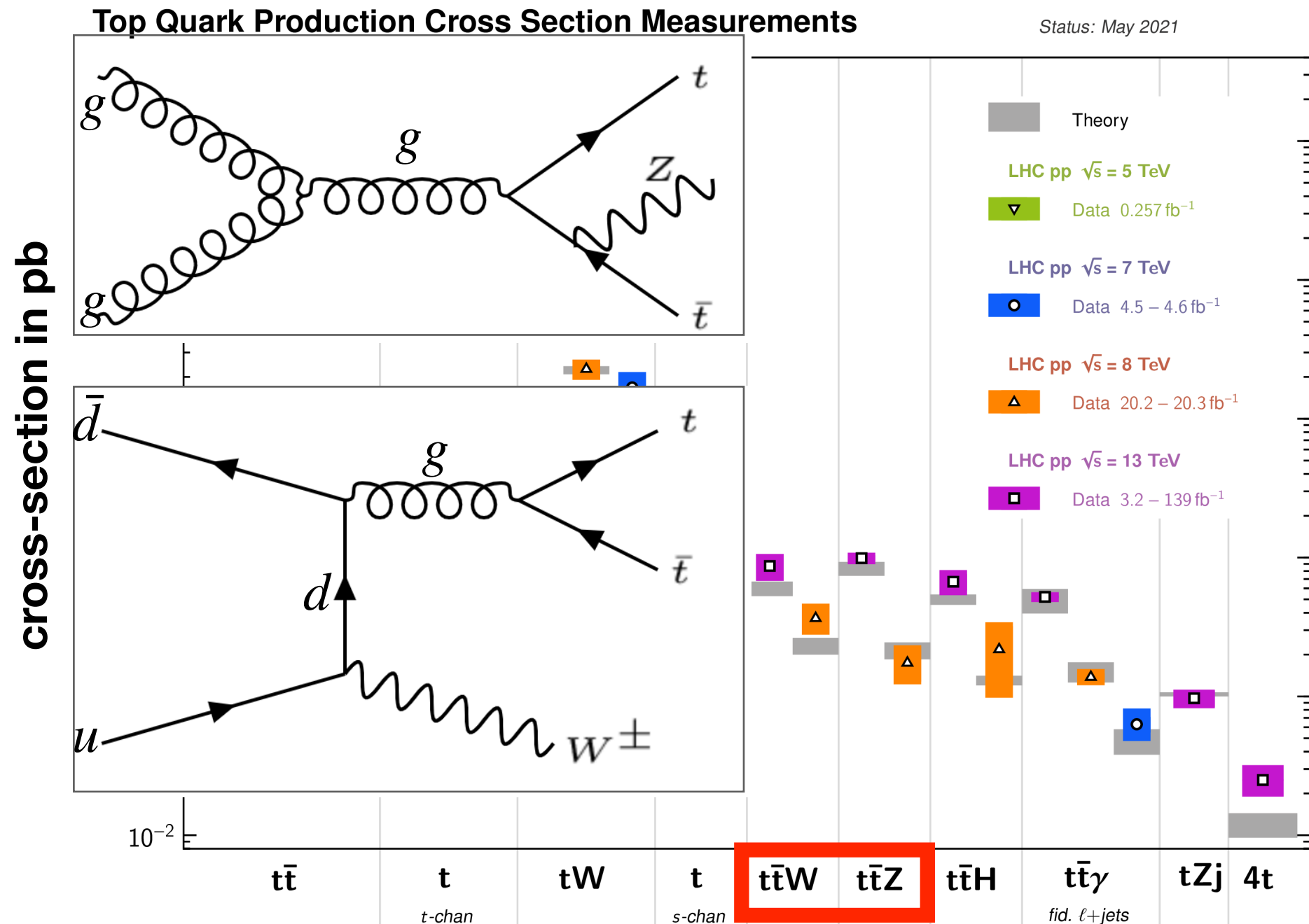
Top-quark Production Cross-section Measurements

- Rare top production modes become fully accessible with Run 2 data



Top-quark Production Cross-section Measurements

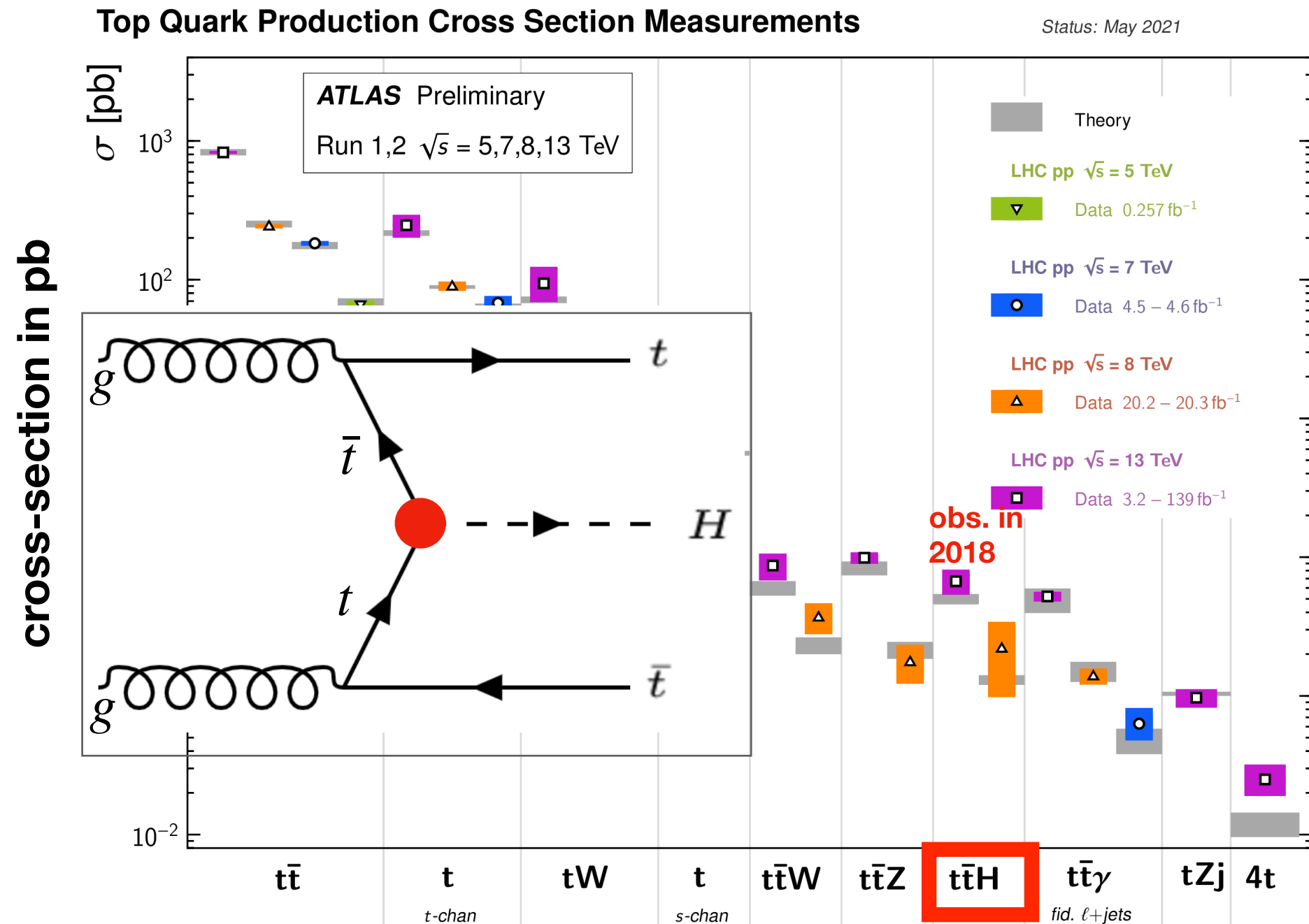
- $t\bar{t}Z/t\bar{t}W$ are among the most massive signatures that can be studied at the LHC with high precision
- **Important backgrounds** for searches and measurements



Different processes

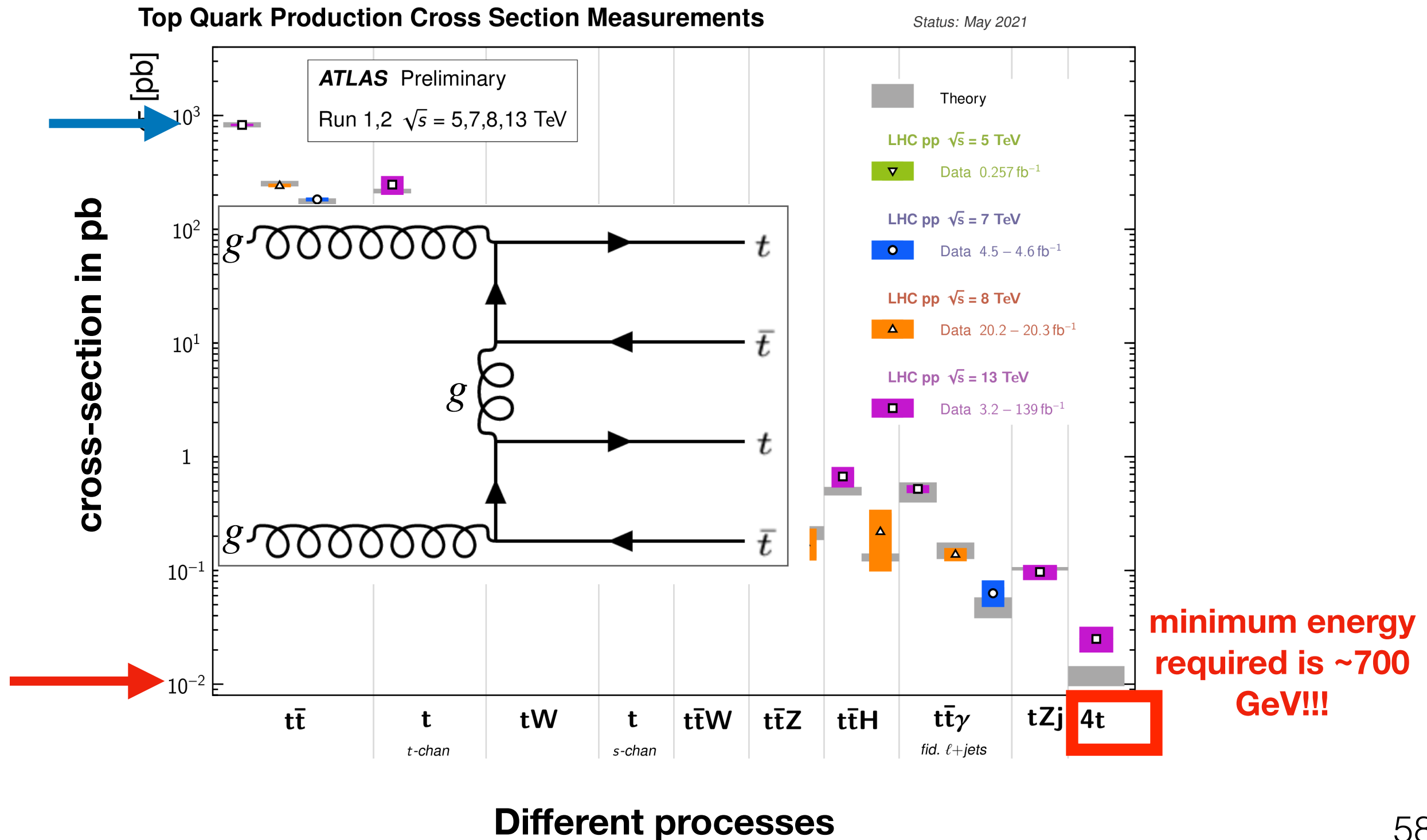
Top-quark Production Cross-section Measurements

- Both ATLAS and CMS confirmed the top-quark Yukawa coupling at the 5σ C.L.



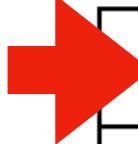
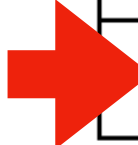
Top-quark Production Cross-section Measurements

- four-top-quark has a **very tiny cross section in the SM**
- $\sigma_{SM}(t\bar{t}t\bar{t}) \sim 12 \text{ fb}$



How many of those events do we have available for measurements?

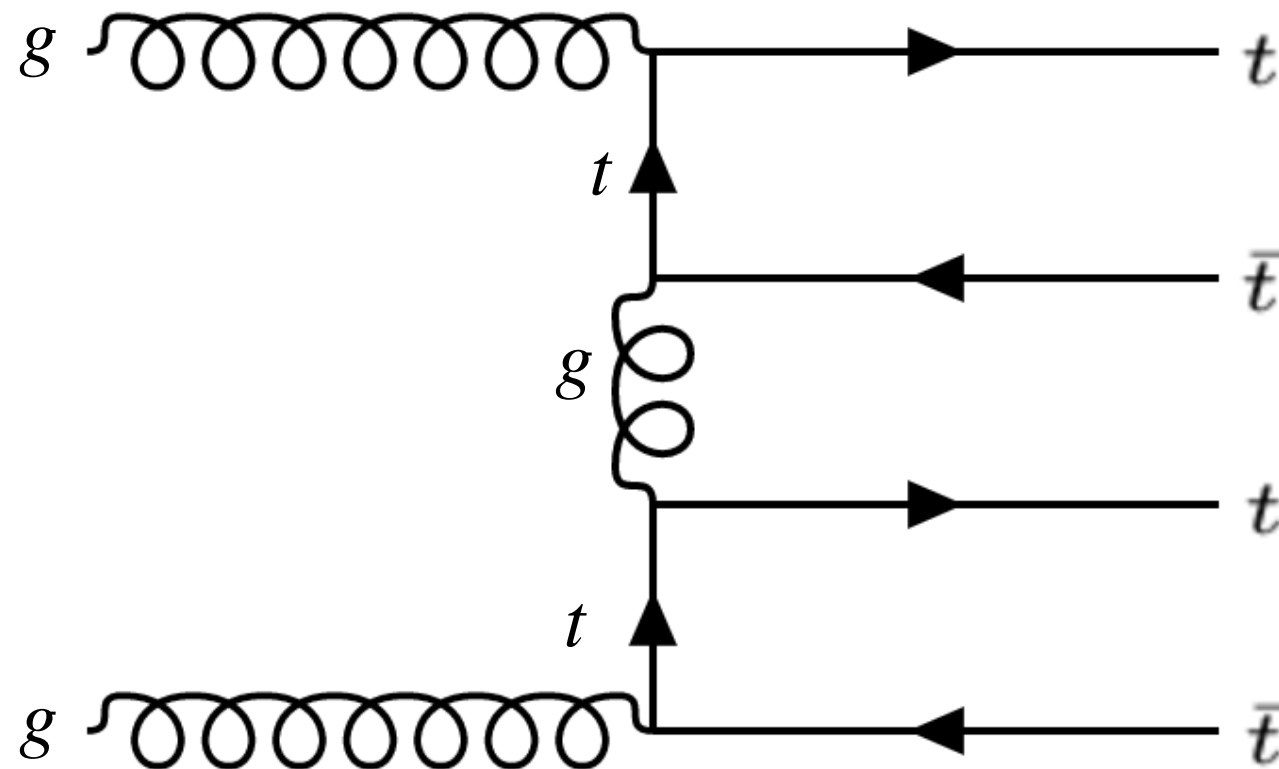
LHC (ATLAS experiment) $\sqrt{s} = 13$ TeV; 139 fb⁻¹ data in 2015-2018

Process	Cross-section [pb]	Events before selection
 $t\bar{t}$	832	115,648,000
t channel	217	30,163,000
tW -channel	71.7	9,966,300
s -channel	10.32	1,434,480
$t\bar{t} + Z$	0.88	122,320
$t\bar{t} + W$	0.60	83,400
$t\bar{t} + \gamma$	0.77	107,030
$t\bar{t} + H$	0.51	70,890
 $t\bar{t}t\bar{t}$	0.012	1,668

Predictions for four tops

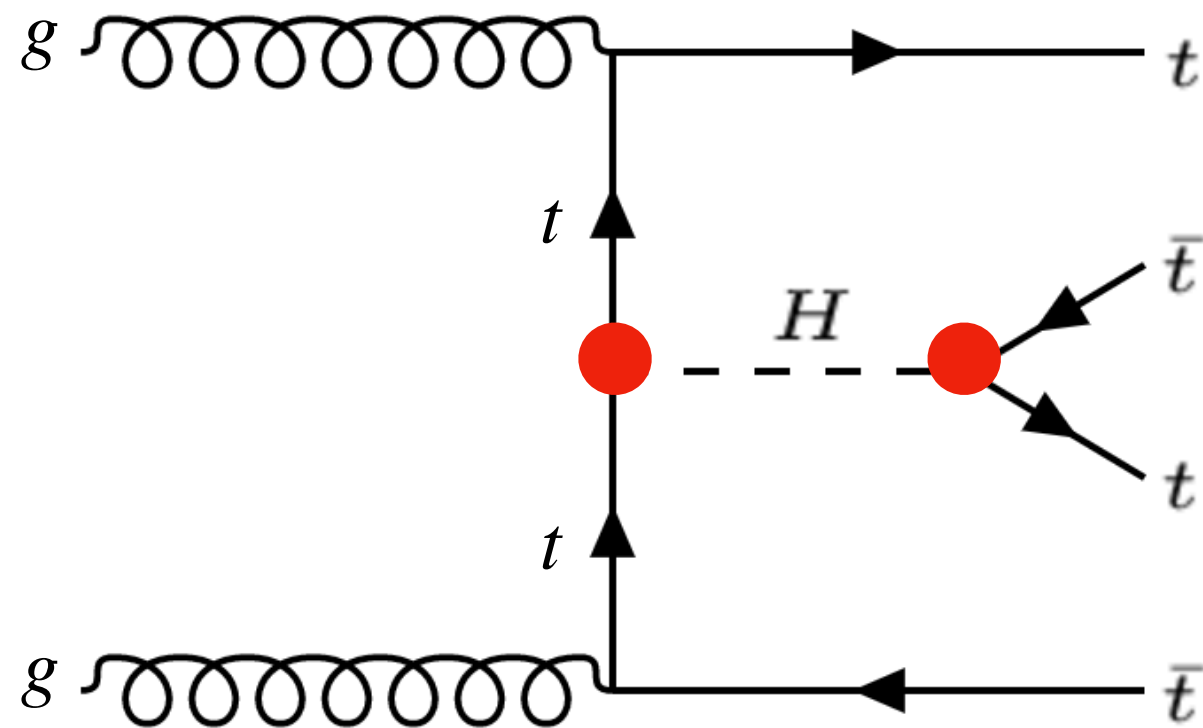
- **Rare** process predicted by the SM

Dominant production of $t\bar{t}t\bar{t}$

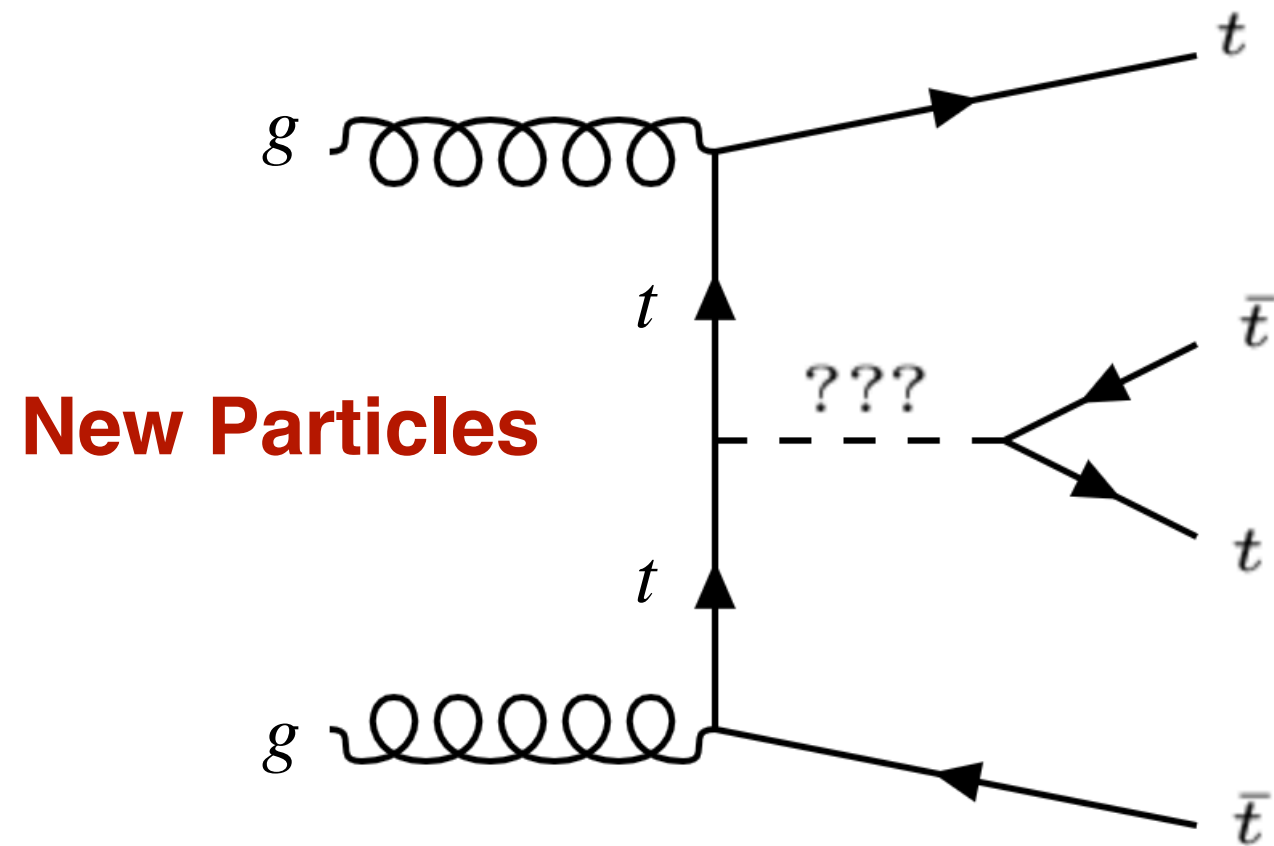


Predictions for four tops

- Four top quarks can be produced via an **offshell SM Higgs boson**
- **Sensitive to the magnitude and CP properties of the Yukawa coupling of the top quark to the Higgs boson**

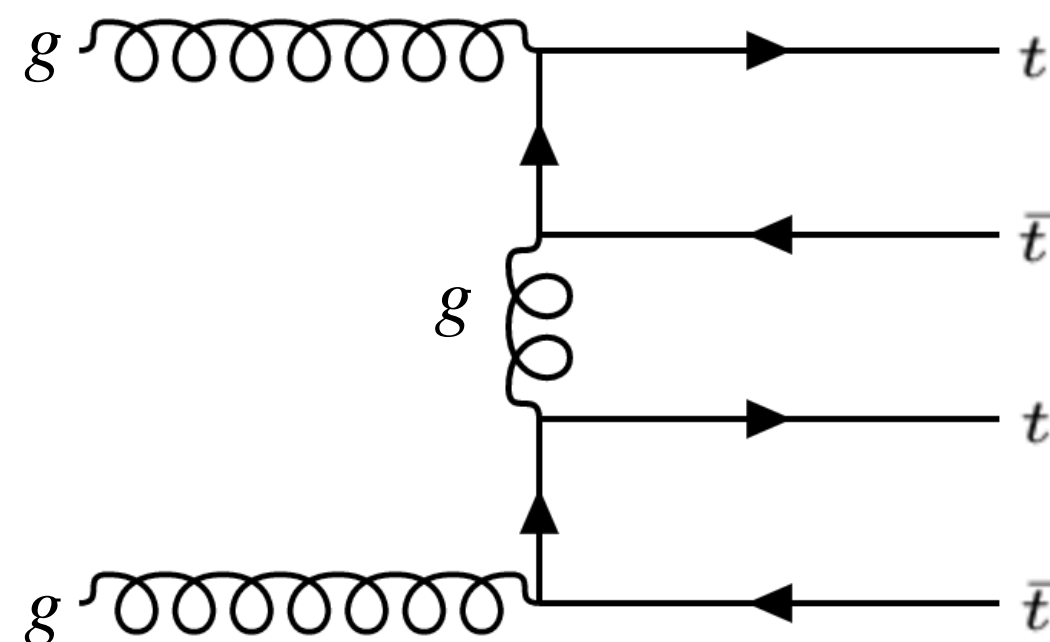


Four top quarks can be sensitive to BSM scenarios



Signatures

- We have **four tops** in our final state
- Each **top** decays to **Wb** and the detector signature is defined by:
 - The presence of four b-quarks
 - The decays of the W bosons



Branching ratio $t\bar{t}t\bar{t}$:

0l: $(75\%)^4 \sim 32\%$

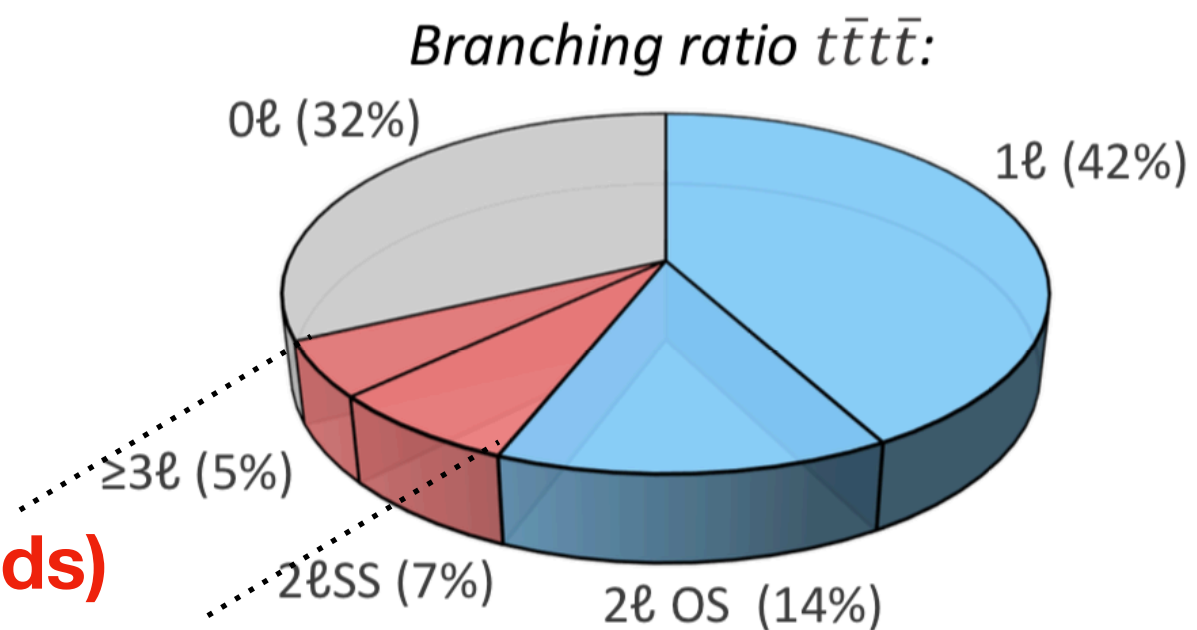
1l: $(25\%) \times (75\%)^3 \times 4 \sim 42\%$

$\geq 3l$: 5 %

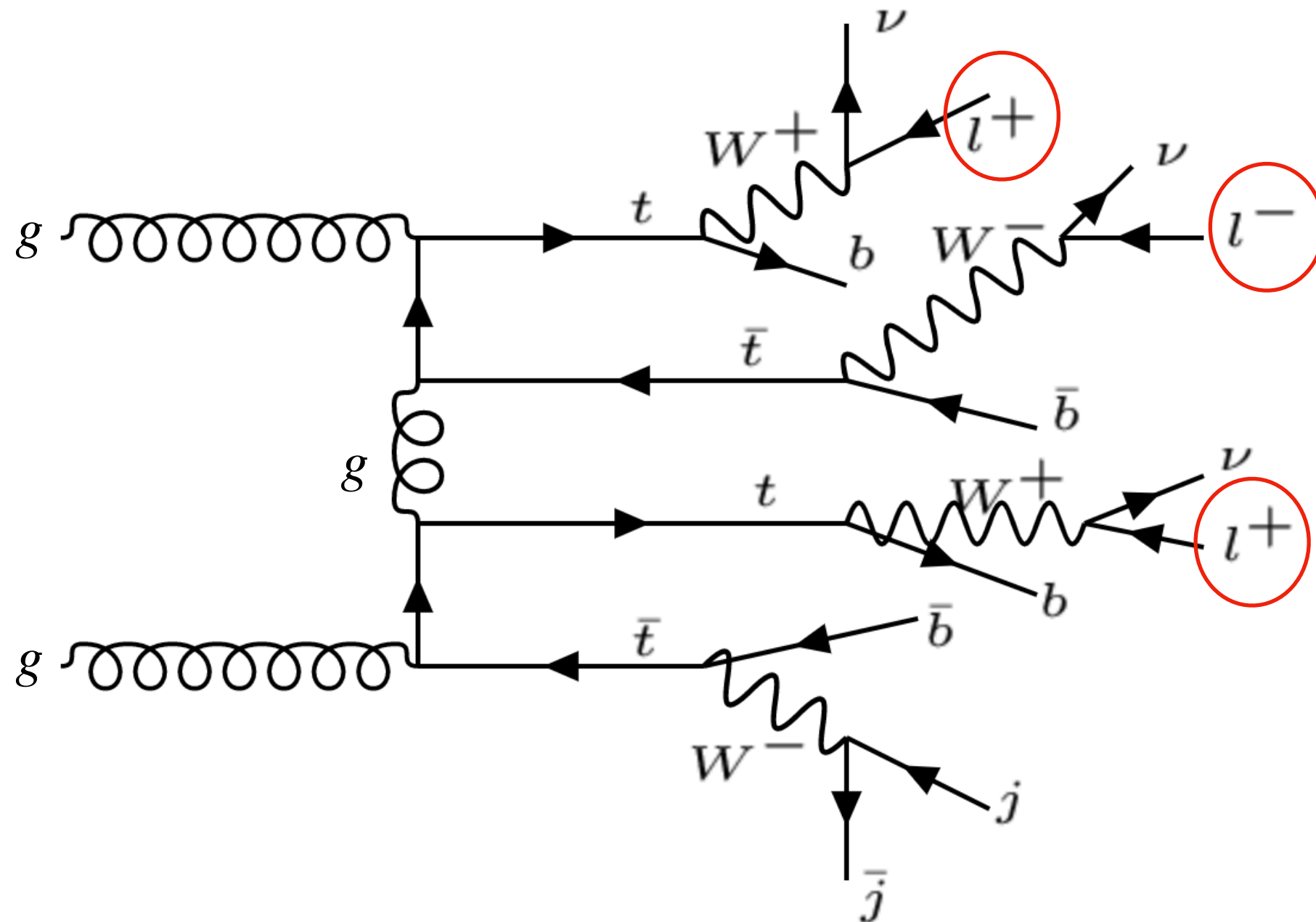
2ISS: $(25\%)^2 \times (75\%)^2 \times 2 \sim 7\%$

2IOS: $(25\%)^2 \times (75\%)^2 \times 4 \sim 14\%$

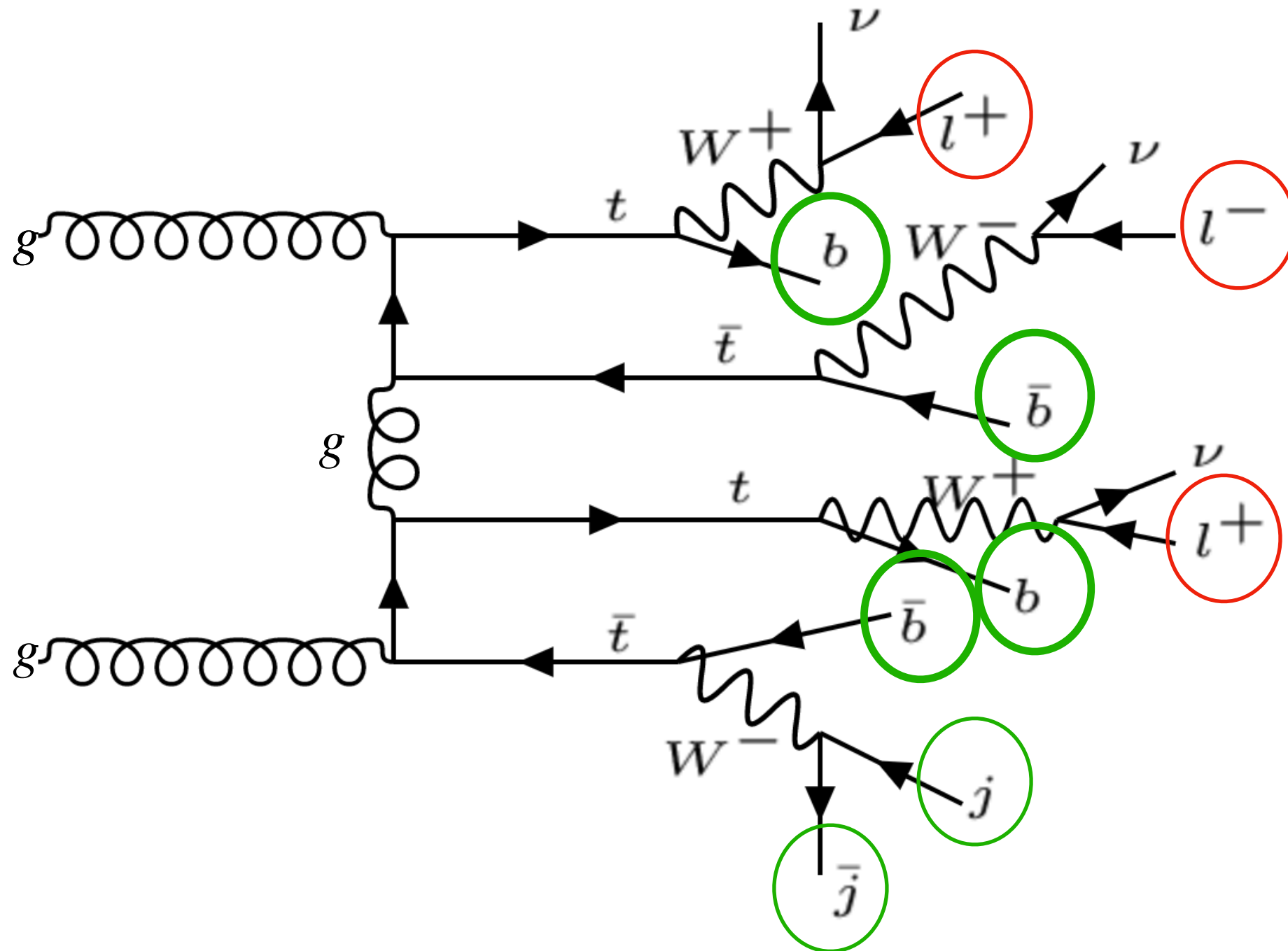
**Smallest branching ratio
but very clean (low backgrounds)
Most sensitive channel**



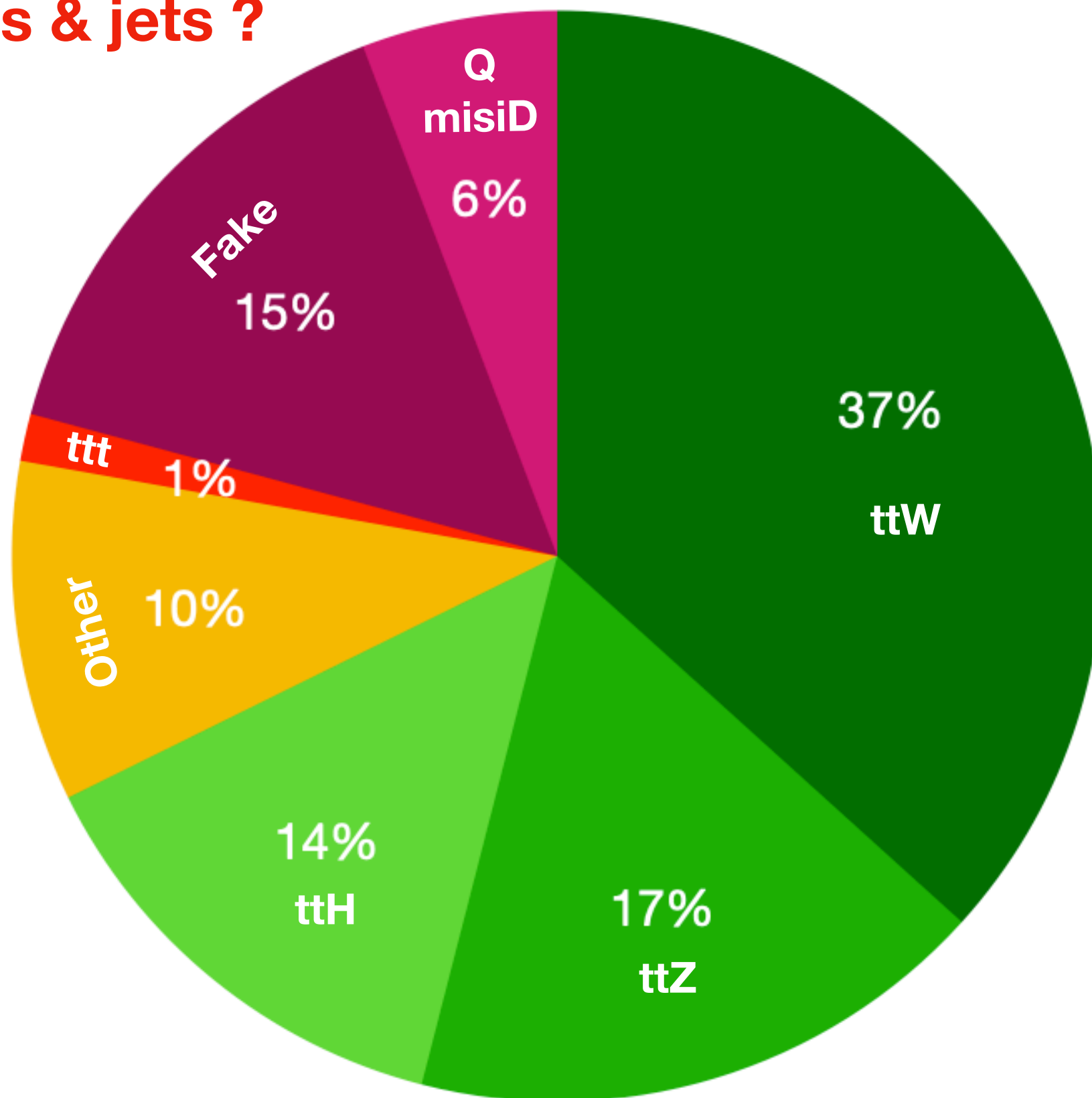
Example from the 3ℓ channel



Example from the 3ℓ channel

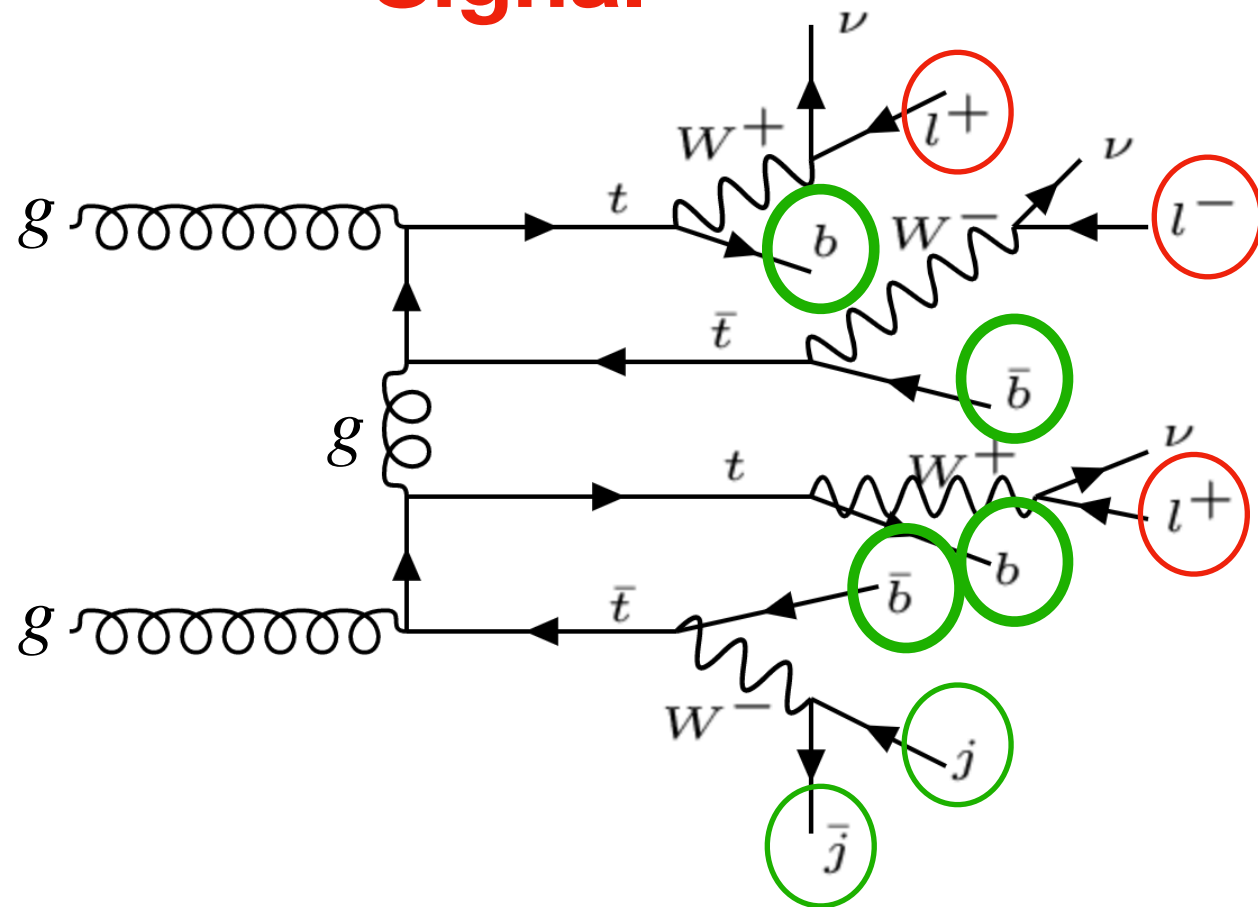


What else can produce
many leptons & jets ?

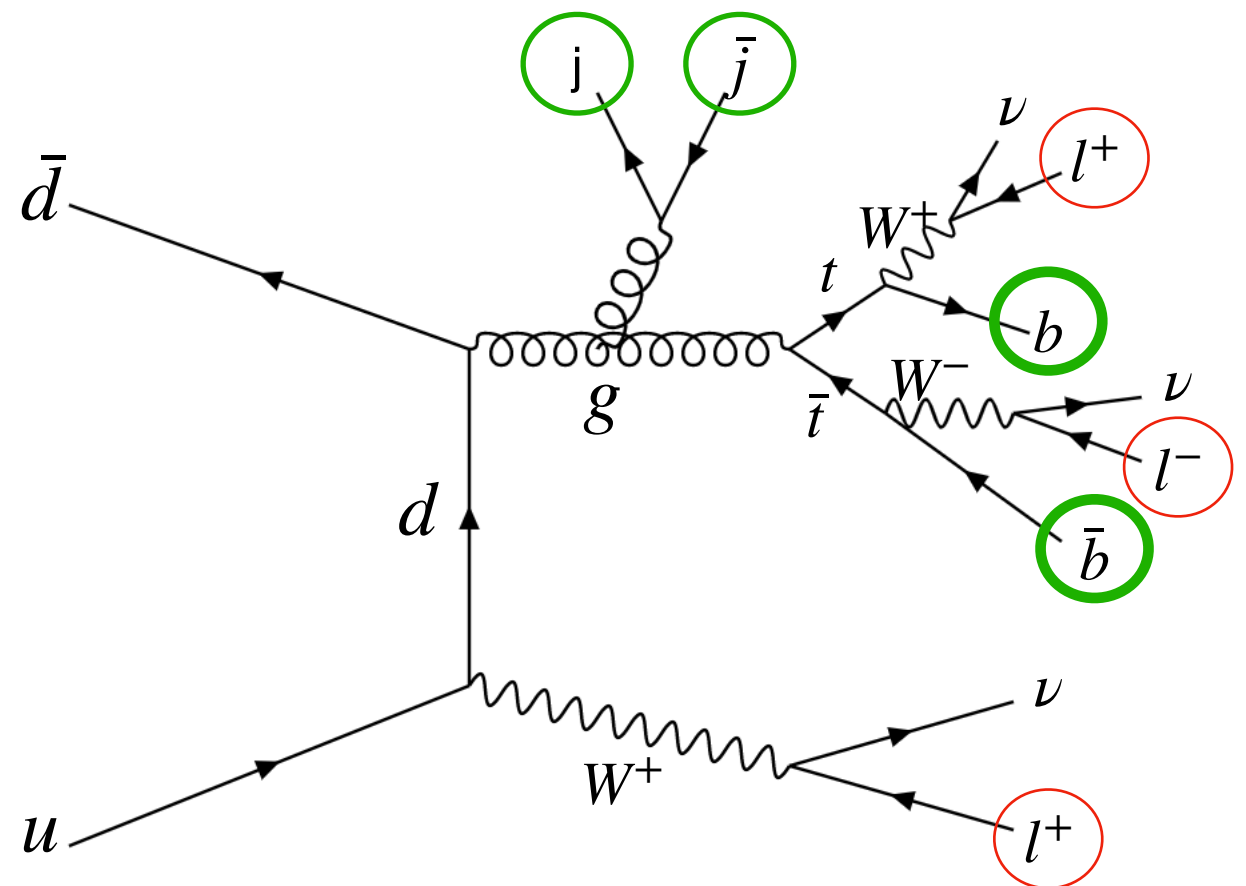


Disentangling Signal from Background

Signal

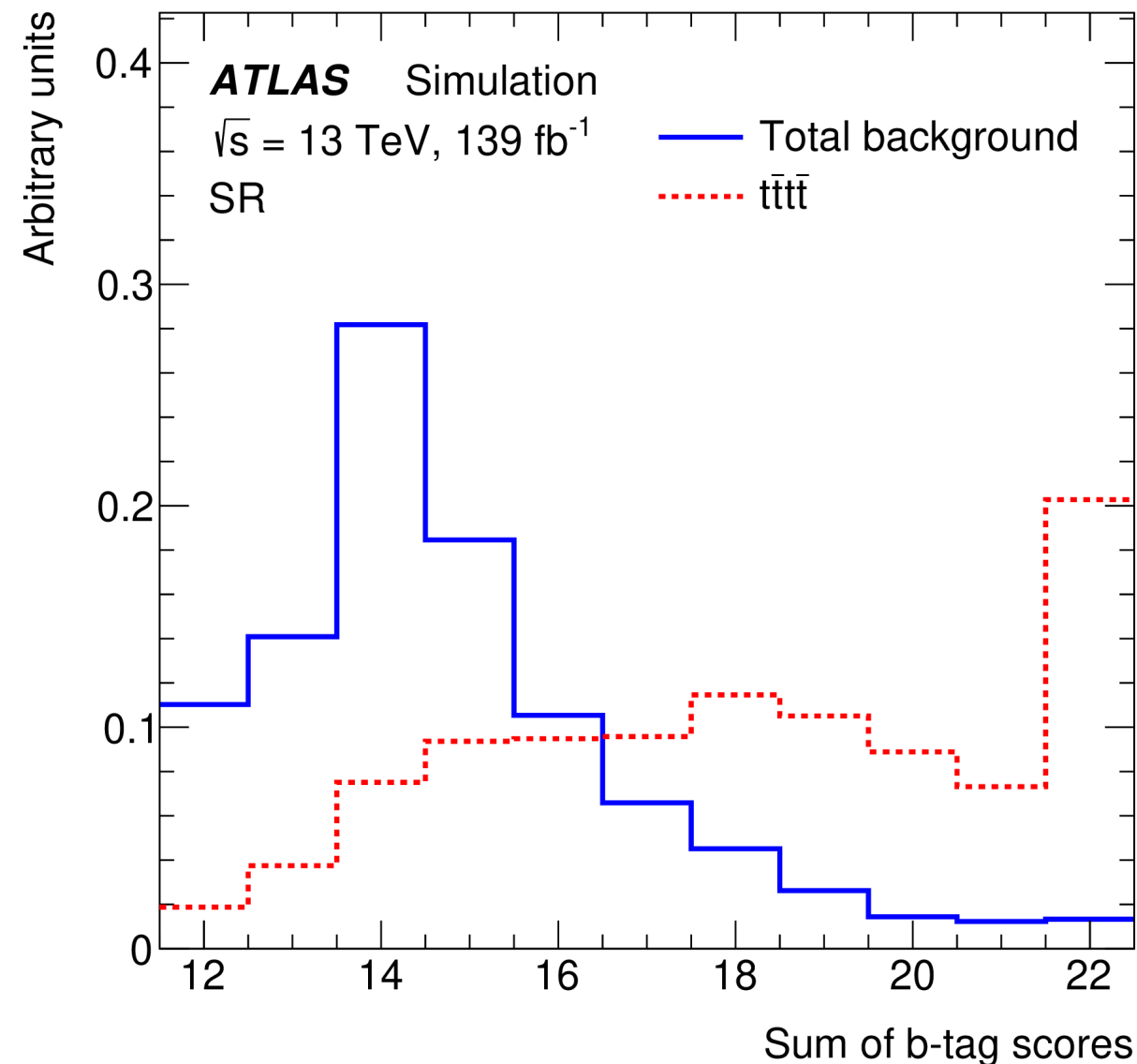


Background



- Look for variables showing kinematic differences between signal and background
- Many jets, b-jets, leptons (identified 12 optimal variables)
- Example: use b-jet “tagging” variable *continuously* and *across all jets*

Kinematic differences between signal and background

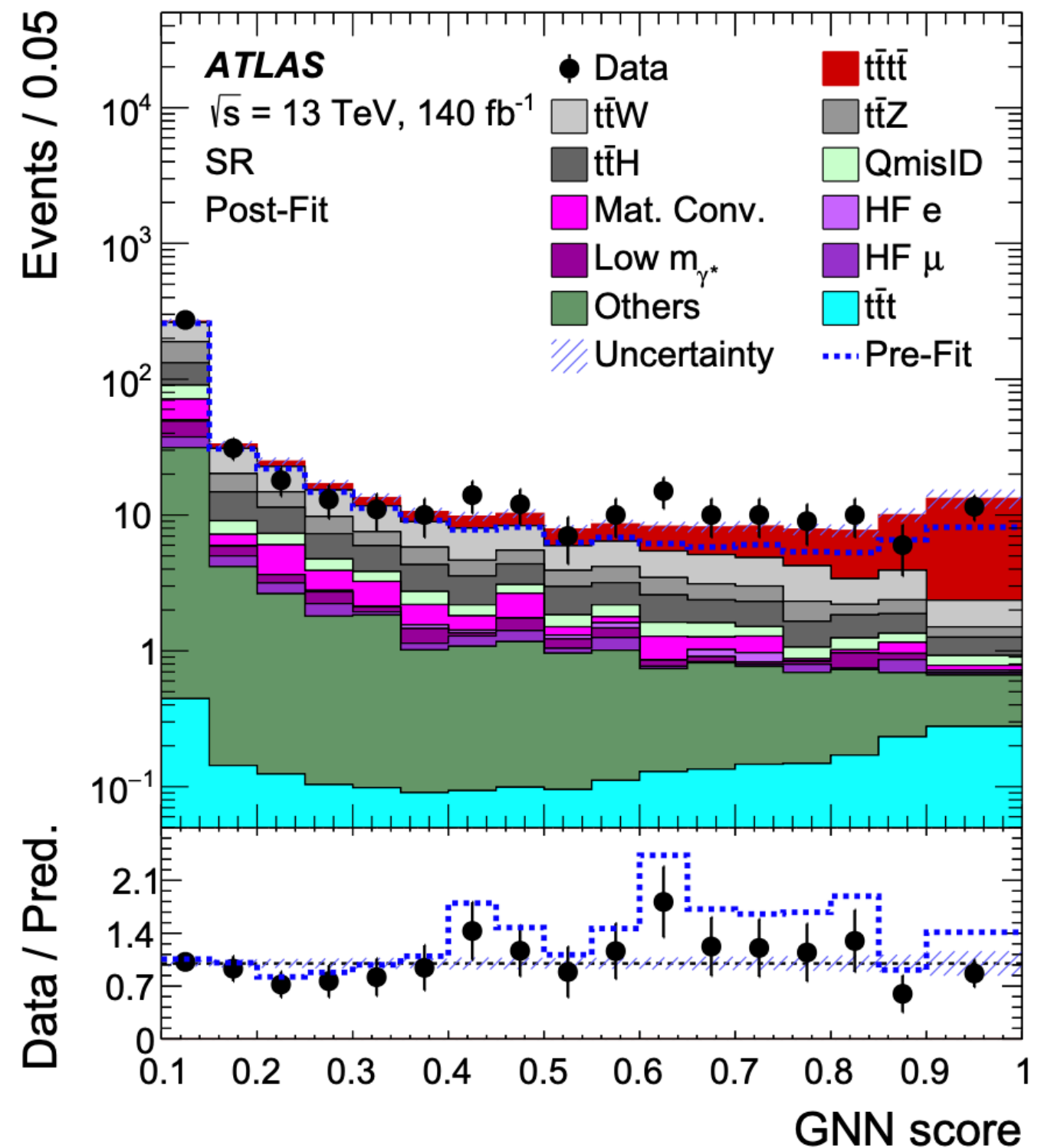


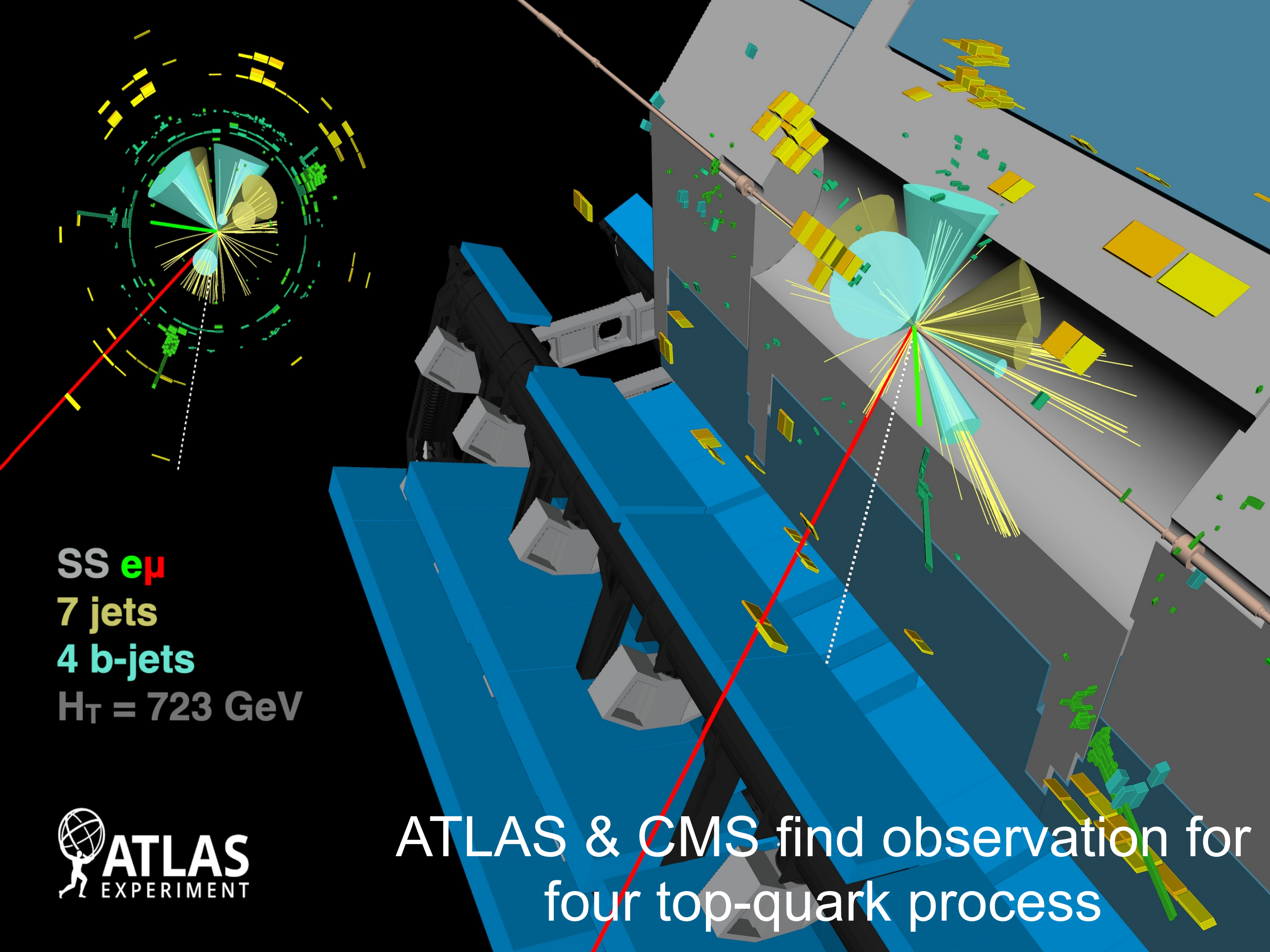
Sum of b-tag scores

- Use Machine learning to learn the differences between the signal and background

Observation of four-top-quark process

- Measured four-top cross-section:
 $\sigma(t\bar{t}t\bar{t}) = 22.5^{+6.6}_{-5.5} \text{ fb}$
- Predicted four-top cross-section:
 $\sigma(t\bar{t}t\bar{t})_{\text{SM}} = 12 \pm 2.4 \text{ fb}$
- 6.1 (4.3) σ observed (expected) significance
- Consistent with SM prediction at 1.8/1.7 σ





SS $e\mu$

7 jets

4 b-jets

$H_T = 723 \text{ GeV}$



ATLAS & CMS find observation for
four top-quark process

Recap

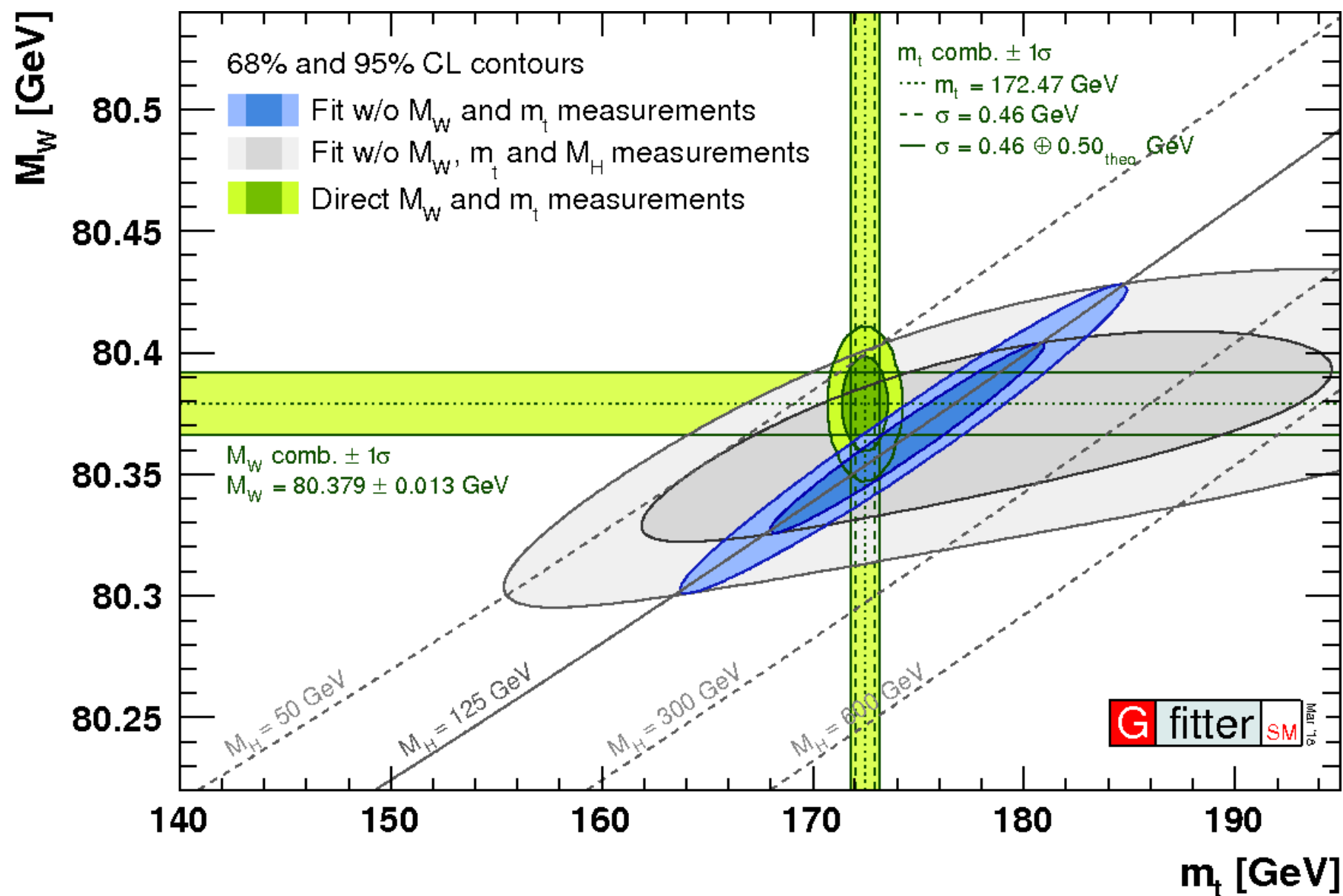
- which is the dominant single top production mode at the LHC?
- Why is the four-top-quark process interesting?



Top quark mass

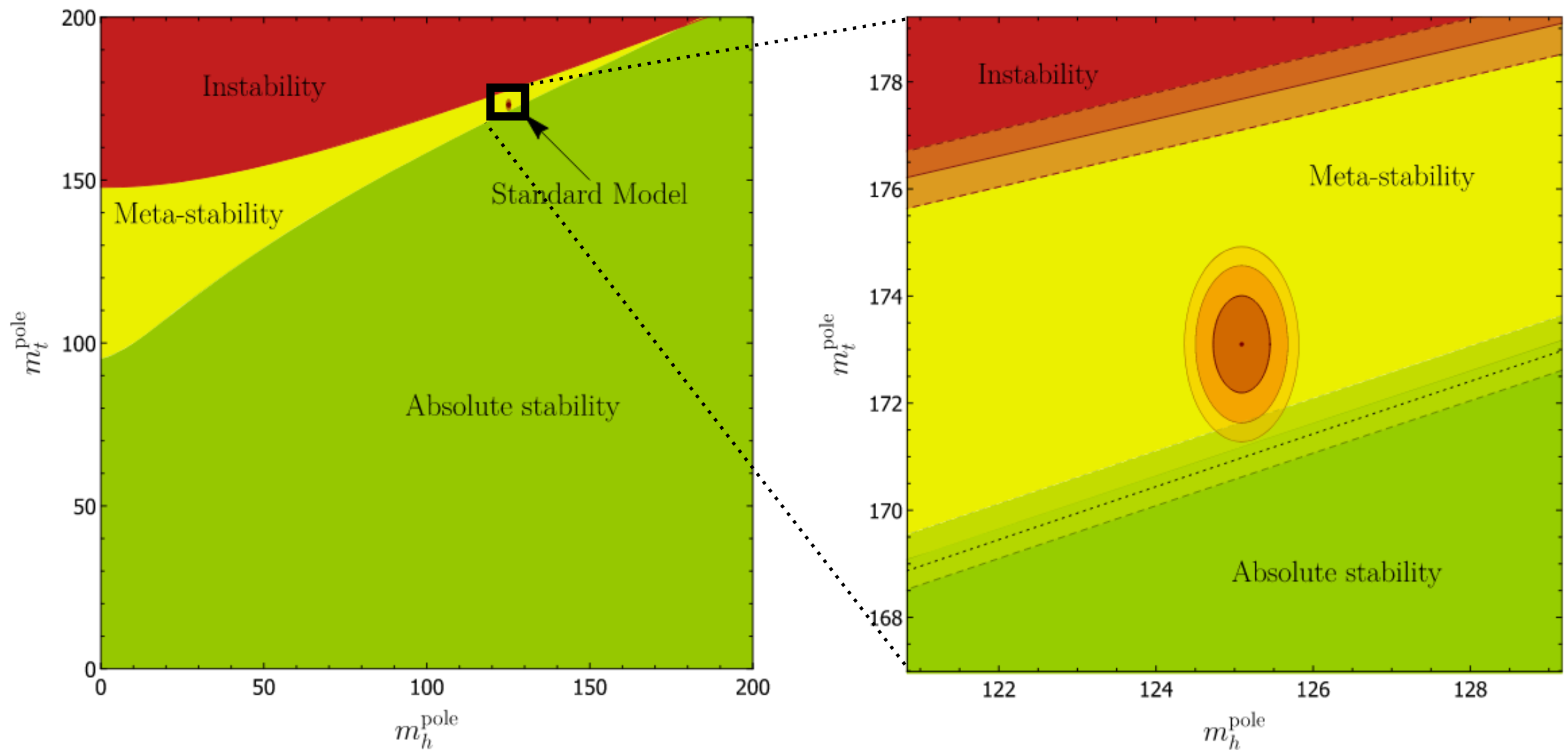
The top quark mass

- m_{top} is a fundamental parameter of the SM
- linked to the m_W and m_H through EW observables
- New physics may imply inconsistencies in the fit

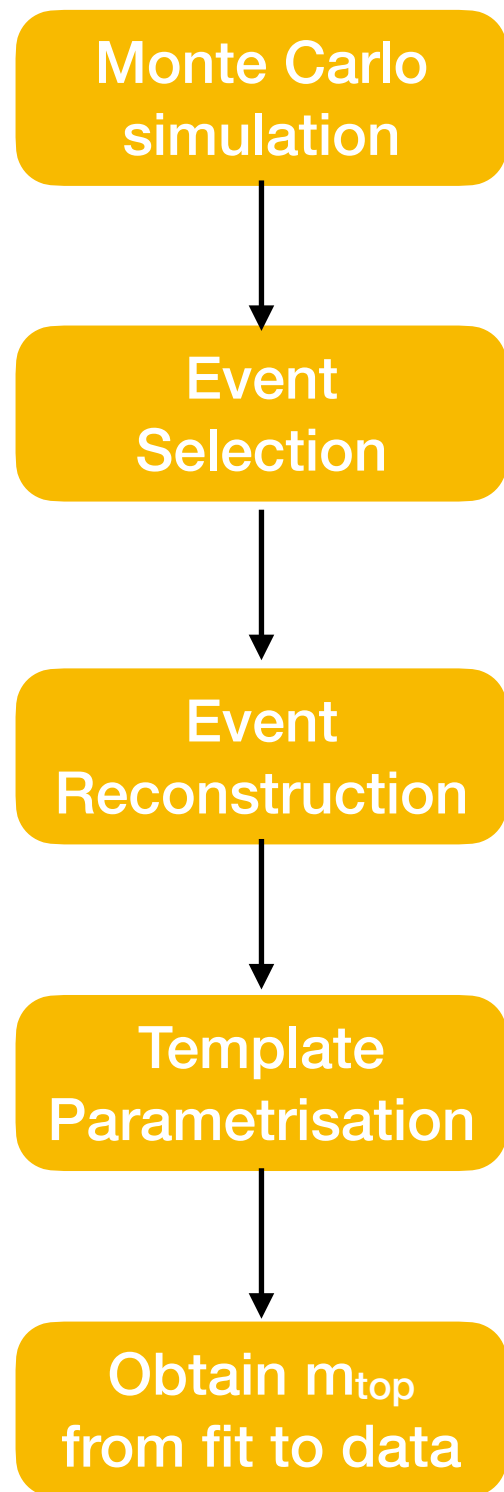


Why do we need to precisely measure the Top mass

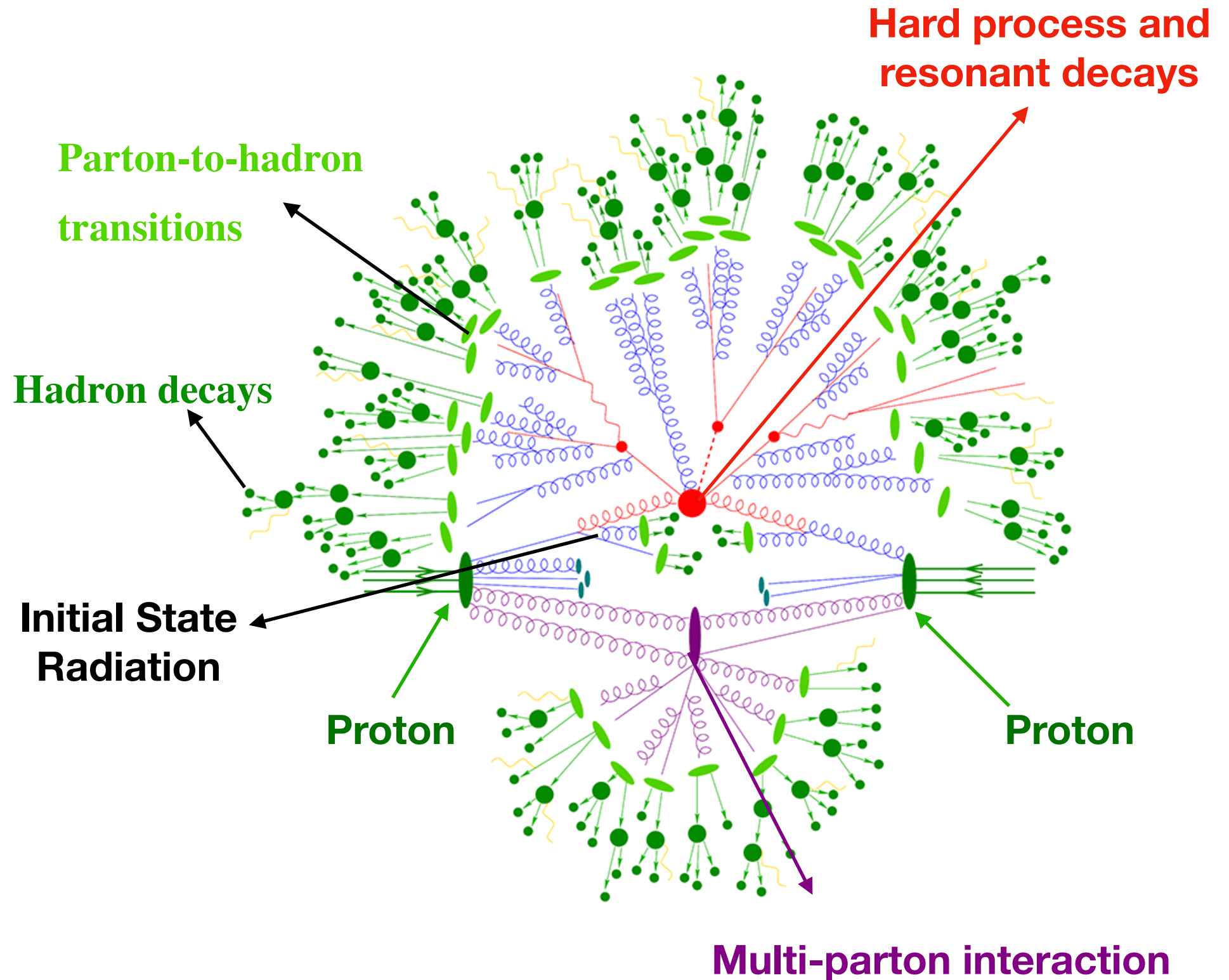
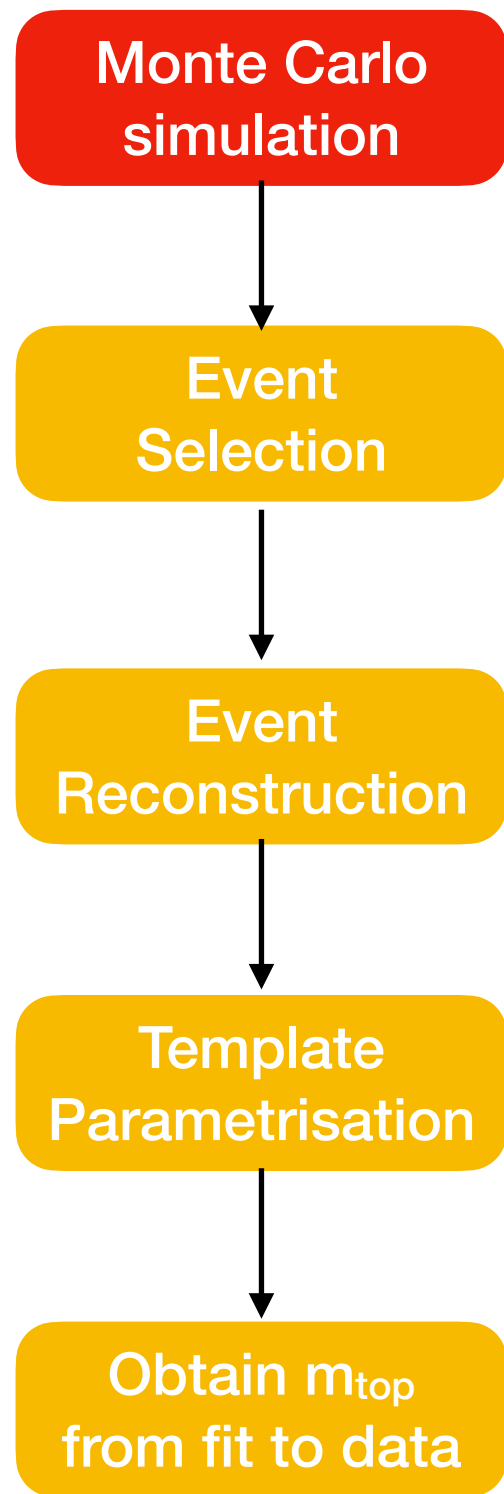
- m_H , m_{top} and the stability of the universe
- Is the higgs potential stable/meta-stable?
 - assuming no new physics up to Planck scale: stability depends strongly on m_H and m_{top}



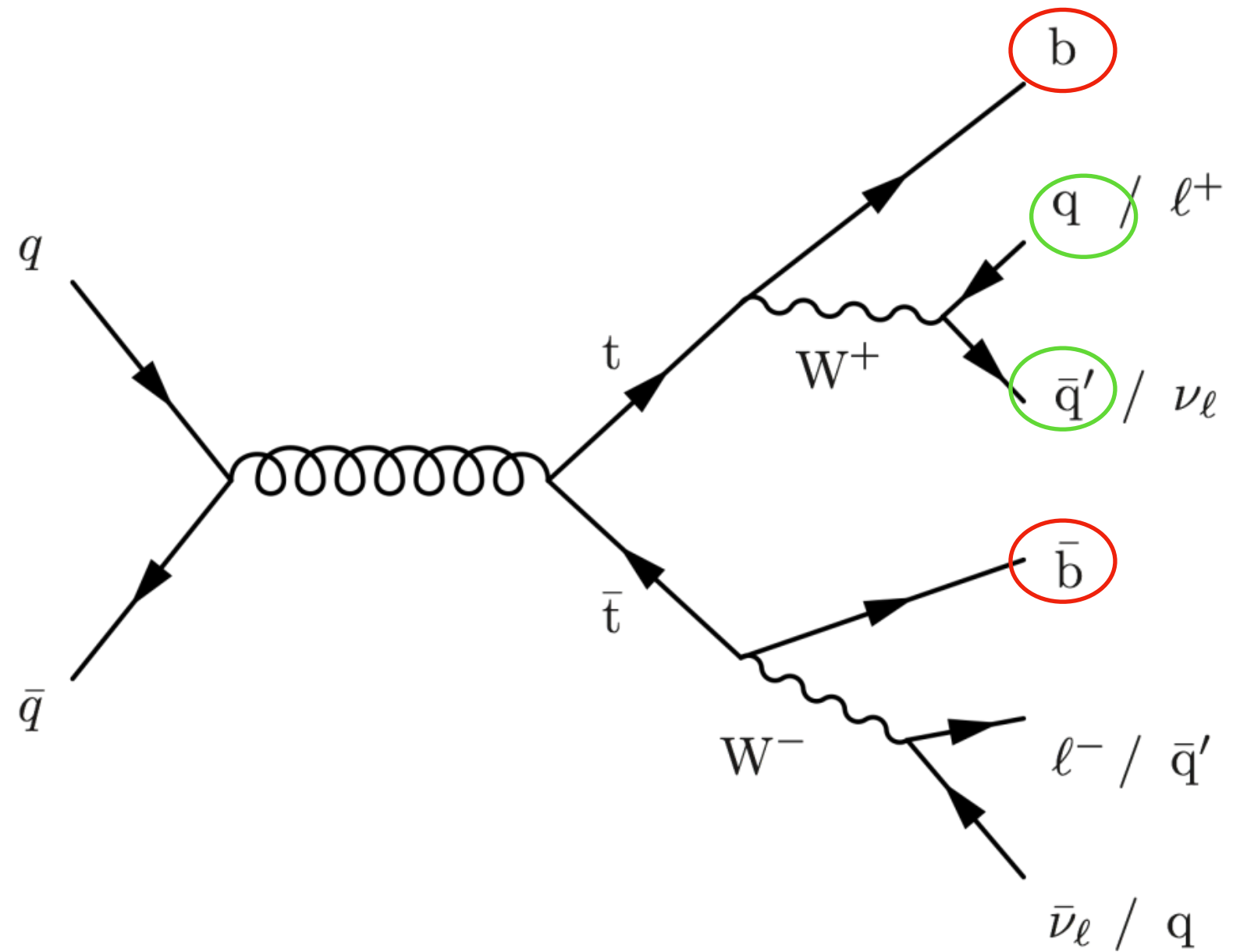
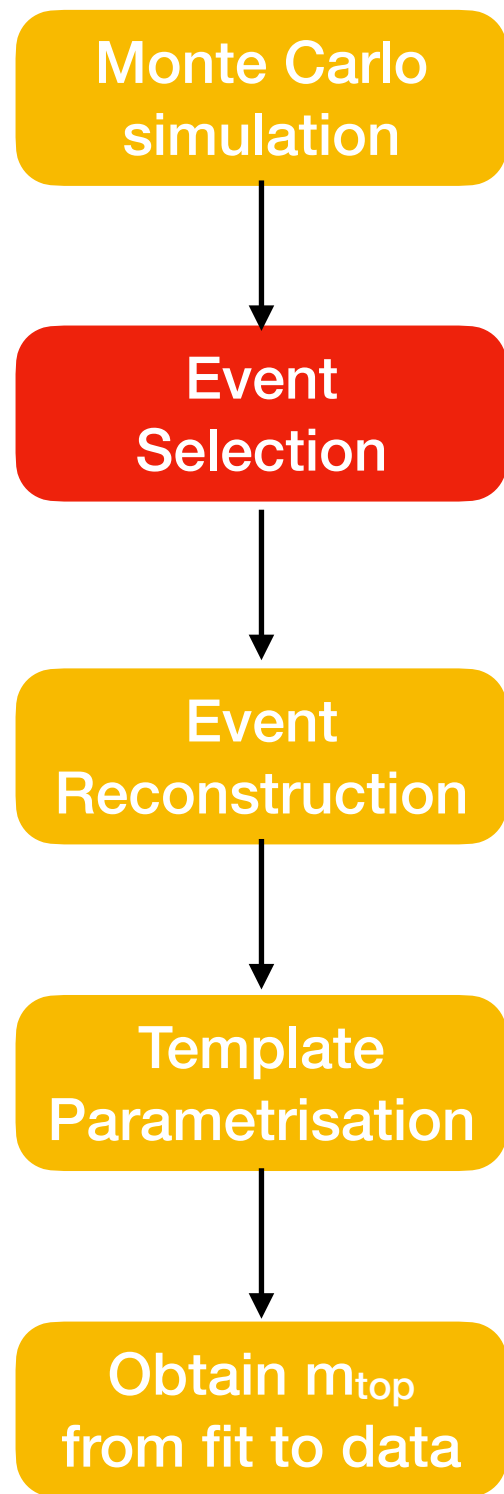
How to measure m_{top}



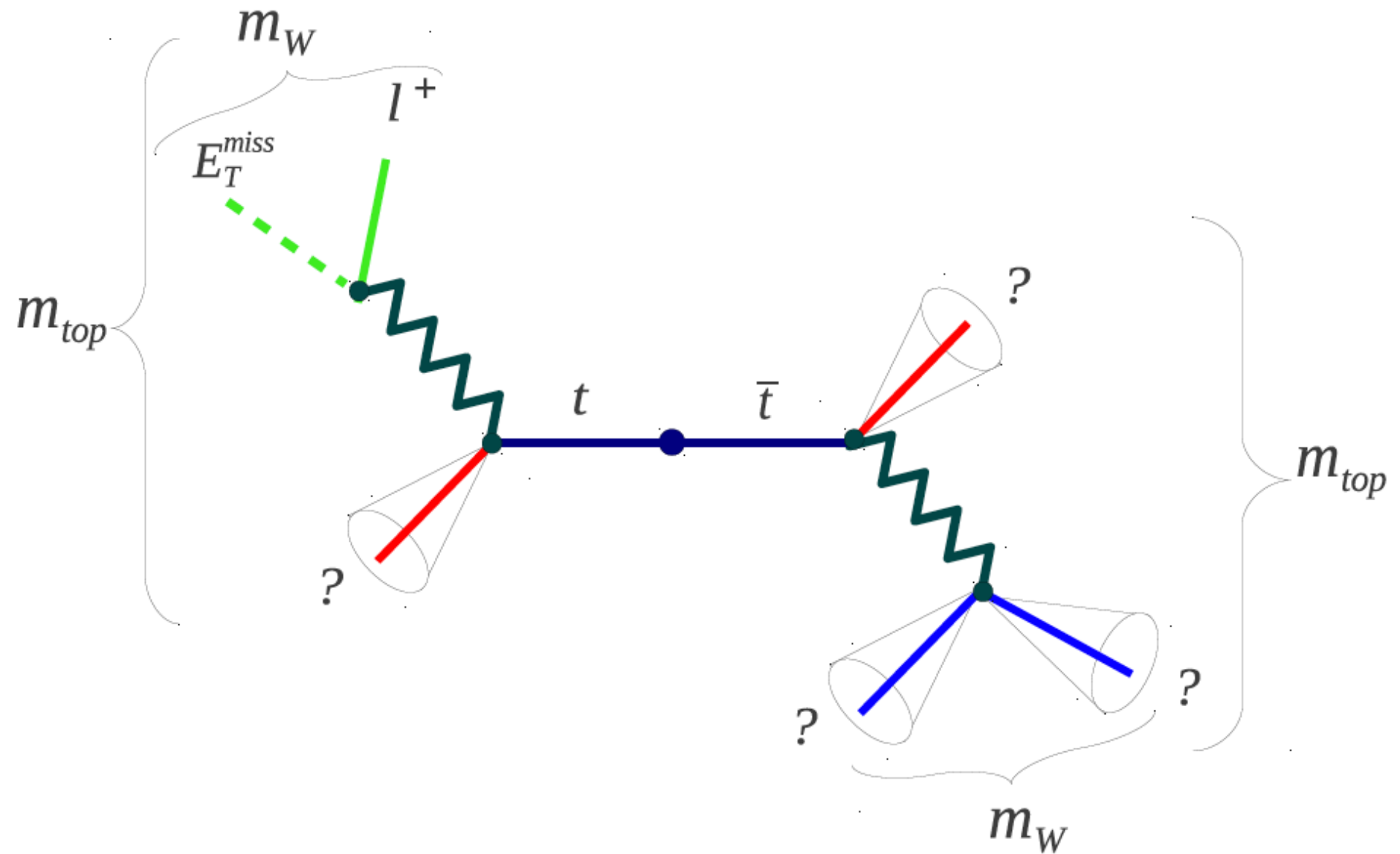
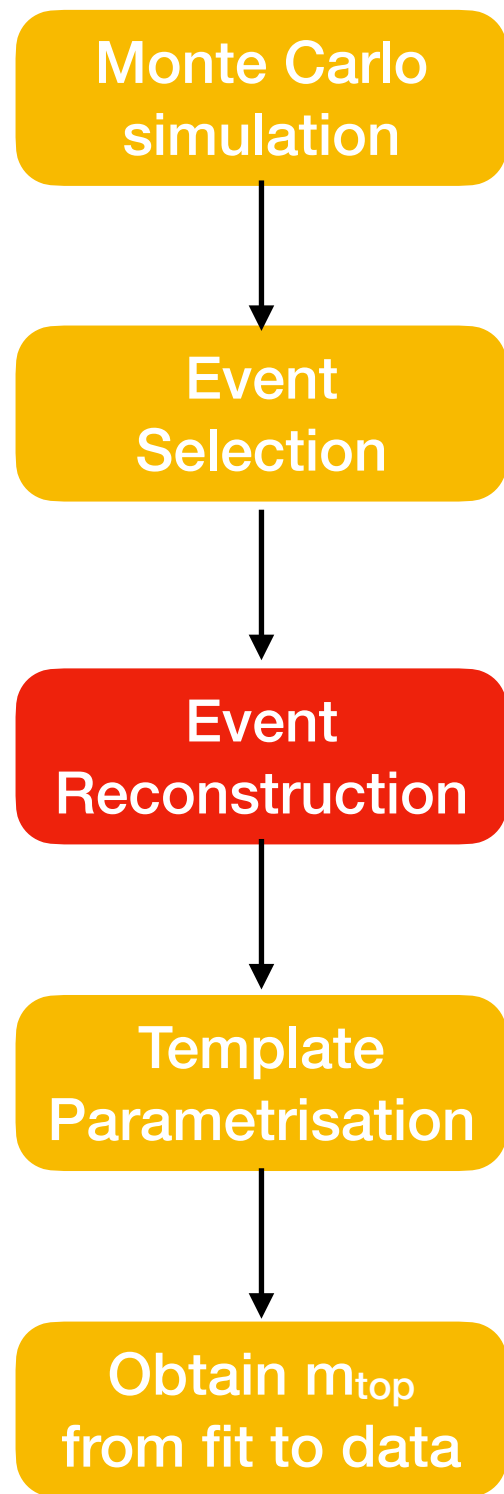
How to measure m_{top}



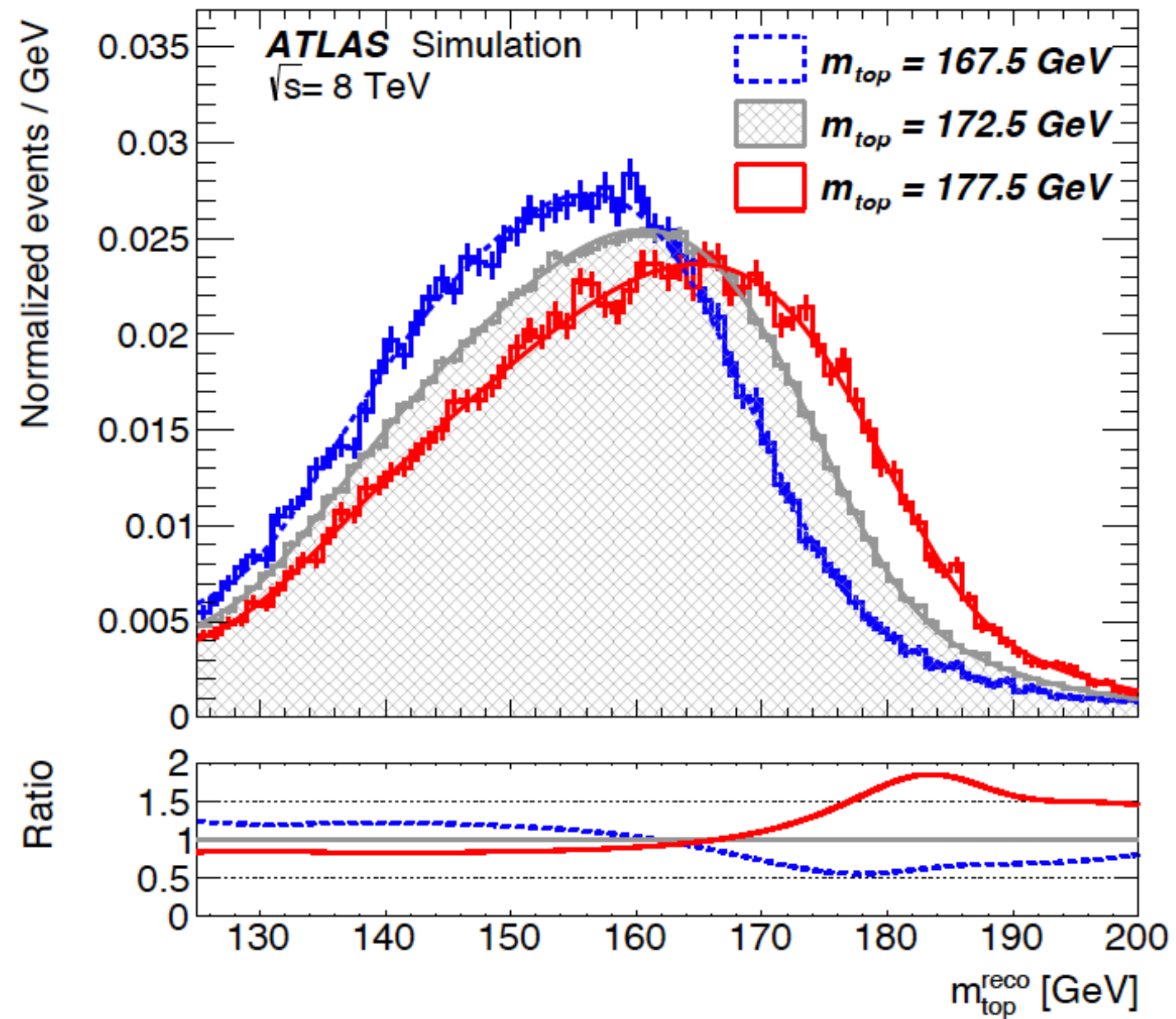
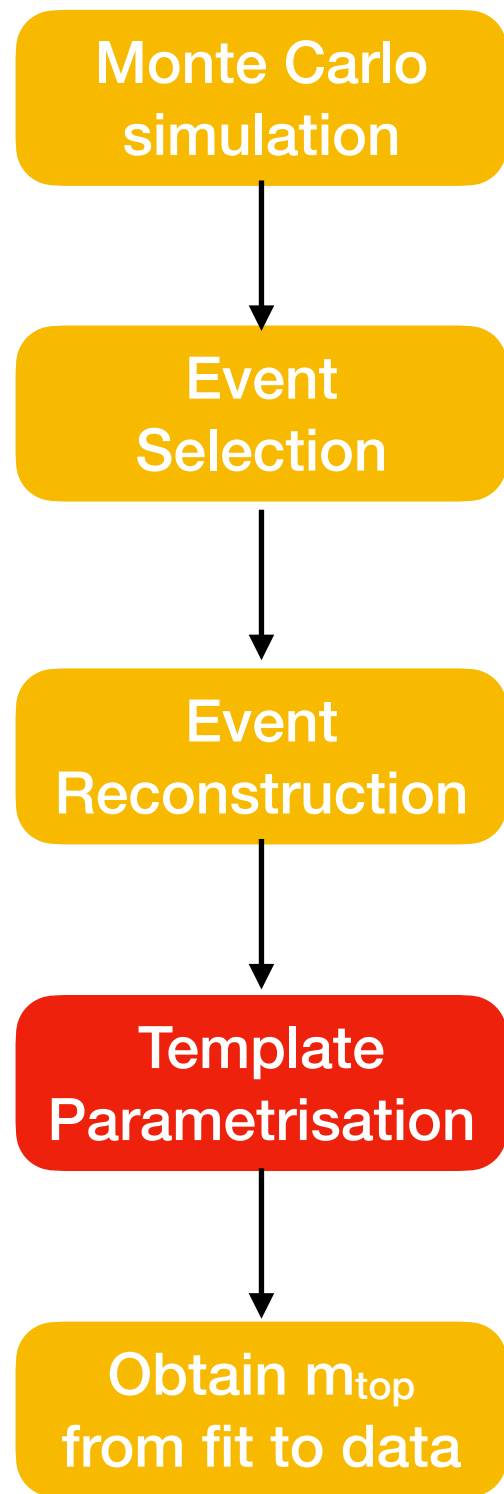
How to measure m_{top}



How to measure m_{top}

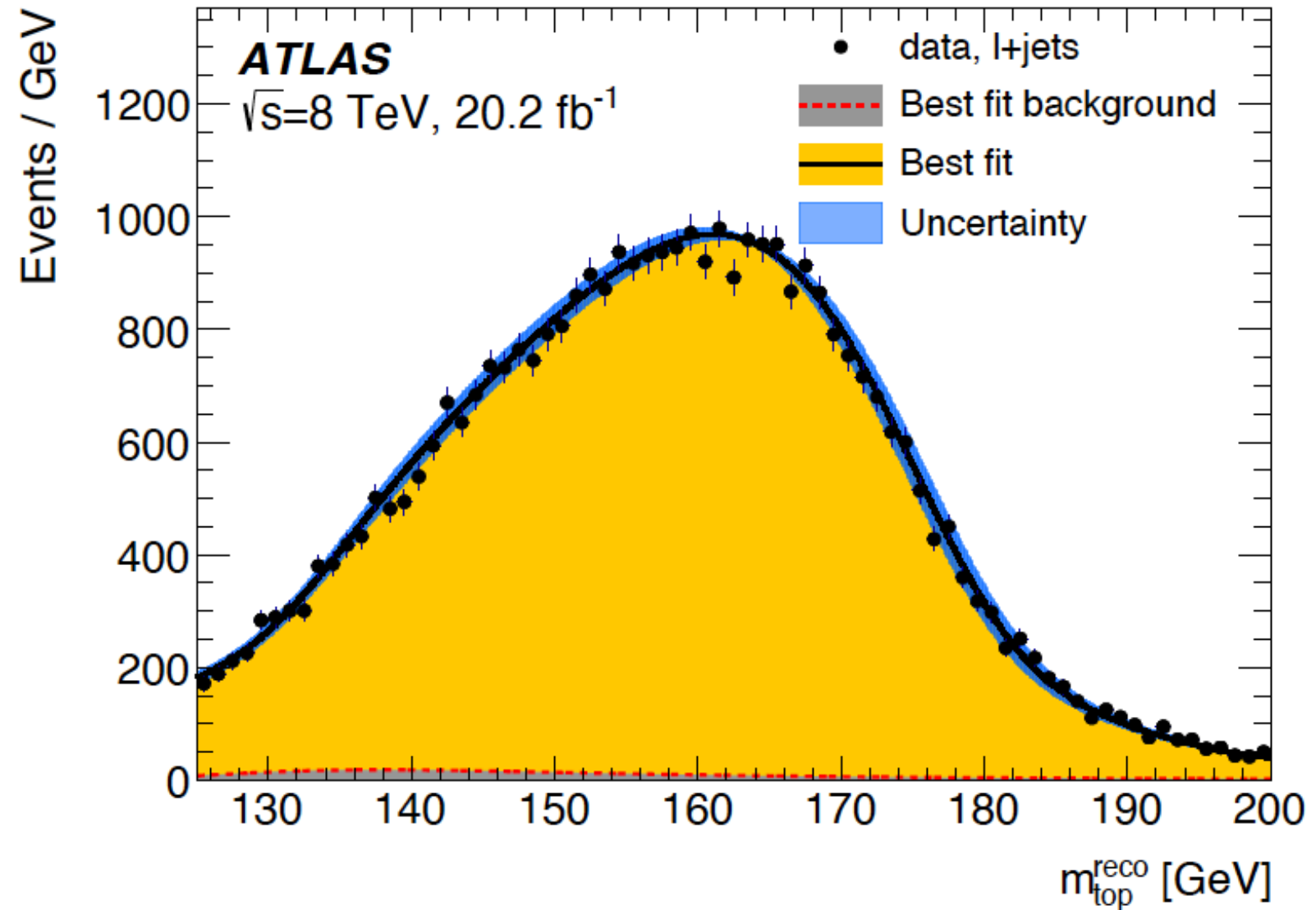
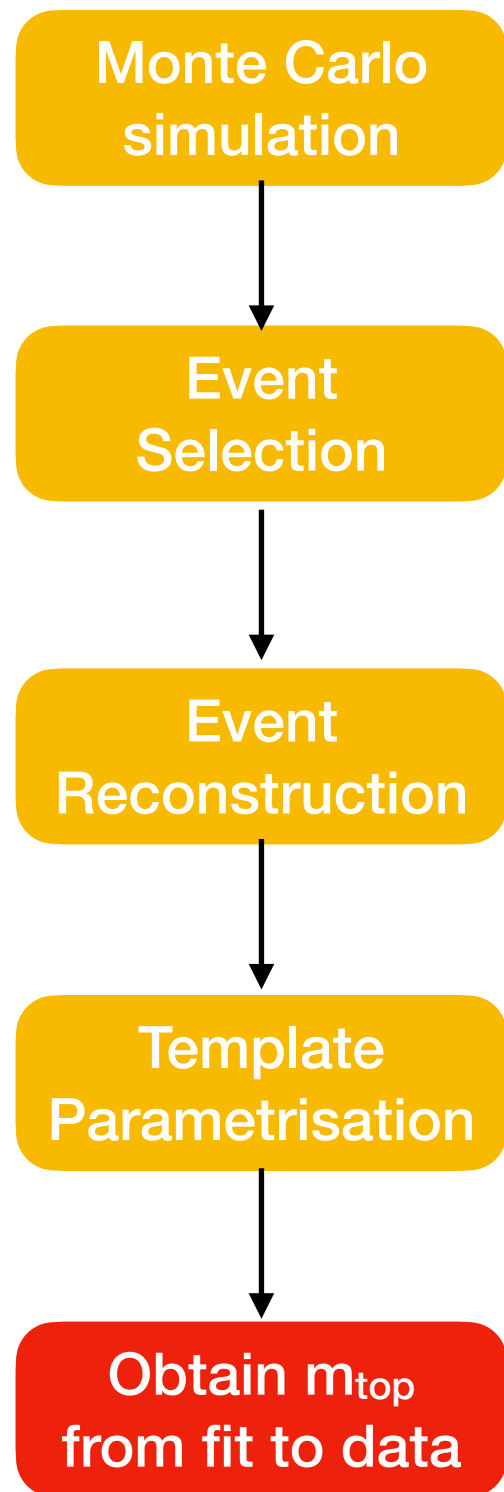


How to measure m_{top}



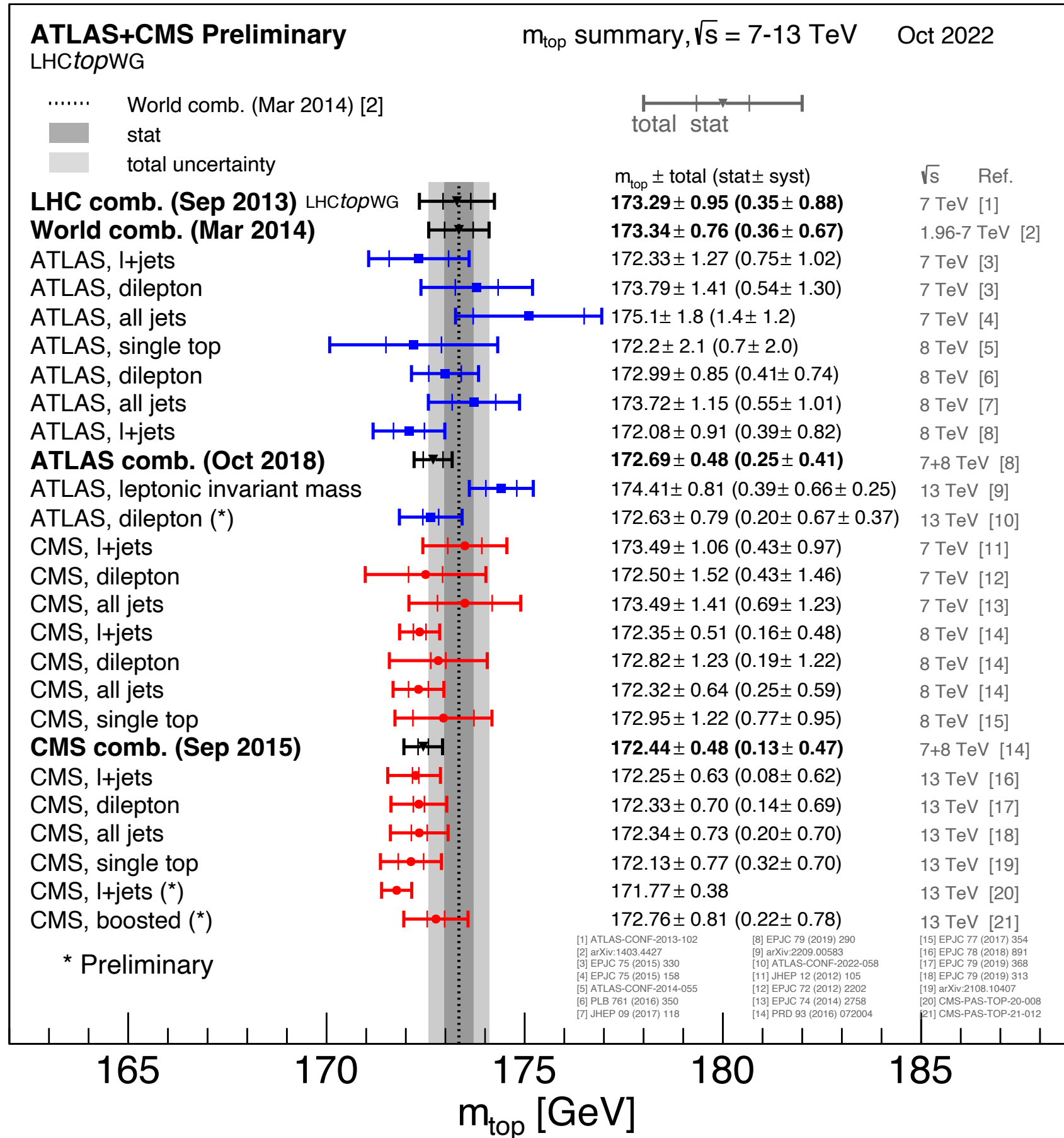
Fit function to histogram: templates for unbinned likelihood fit

How to measure m_{top}

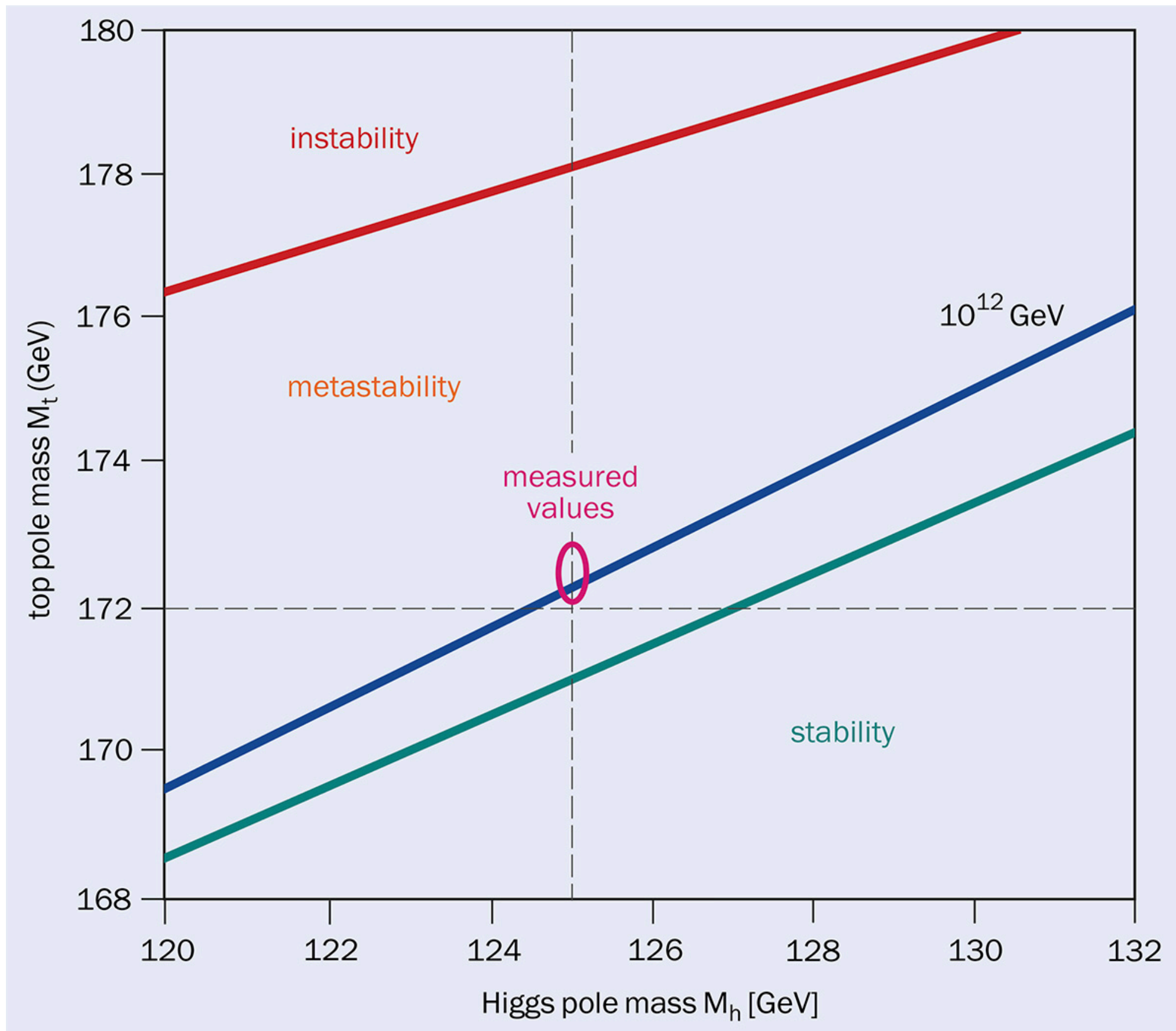


Extract top-quark mass from fit of templates to data

Summary of the ATLAS and CMS measurements



How much do we know now?



Other top quark properties

Top quark has a short lifetime ... but how short?

- b -hadron lifetime $\mathcal{O} = 10^{-12}$ s
- top-quark lifetime $\approx 5 \times 10^{-25}$ s
- hadronisation time: $\frac{1}{\Lambda_{\text{QCD}}} \approx 3.3 \times 10^{-24}$ s
- spin decorrelation time: $\frac{m_{\text{top}}}{\Lambda_{\text{QCD}}^2} \approx 3 \times 10^{-21}$ s

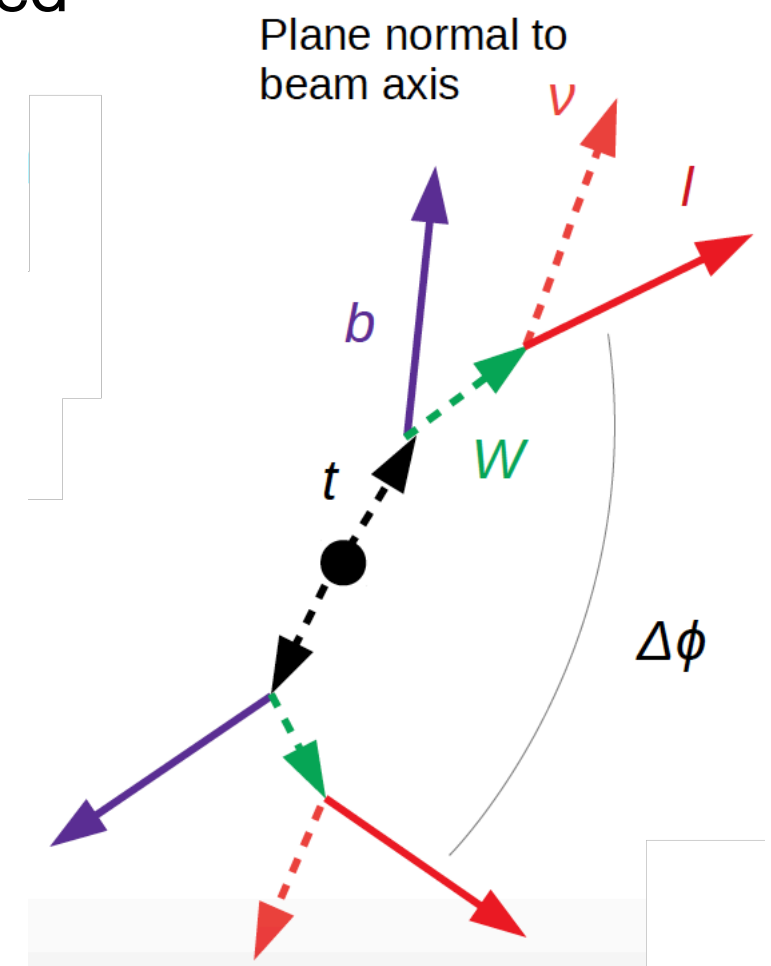
Tops decay before the spins of the two top-quarks can decorrelate!

Top spin correlation

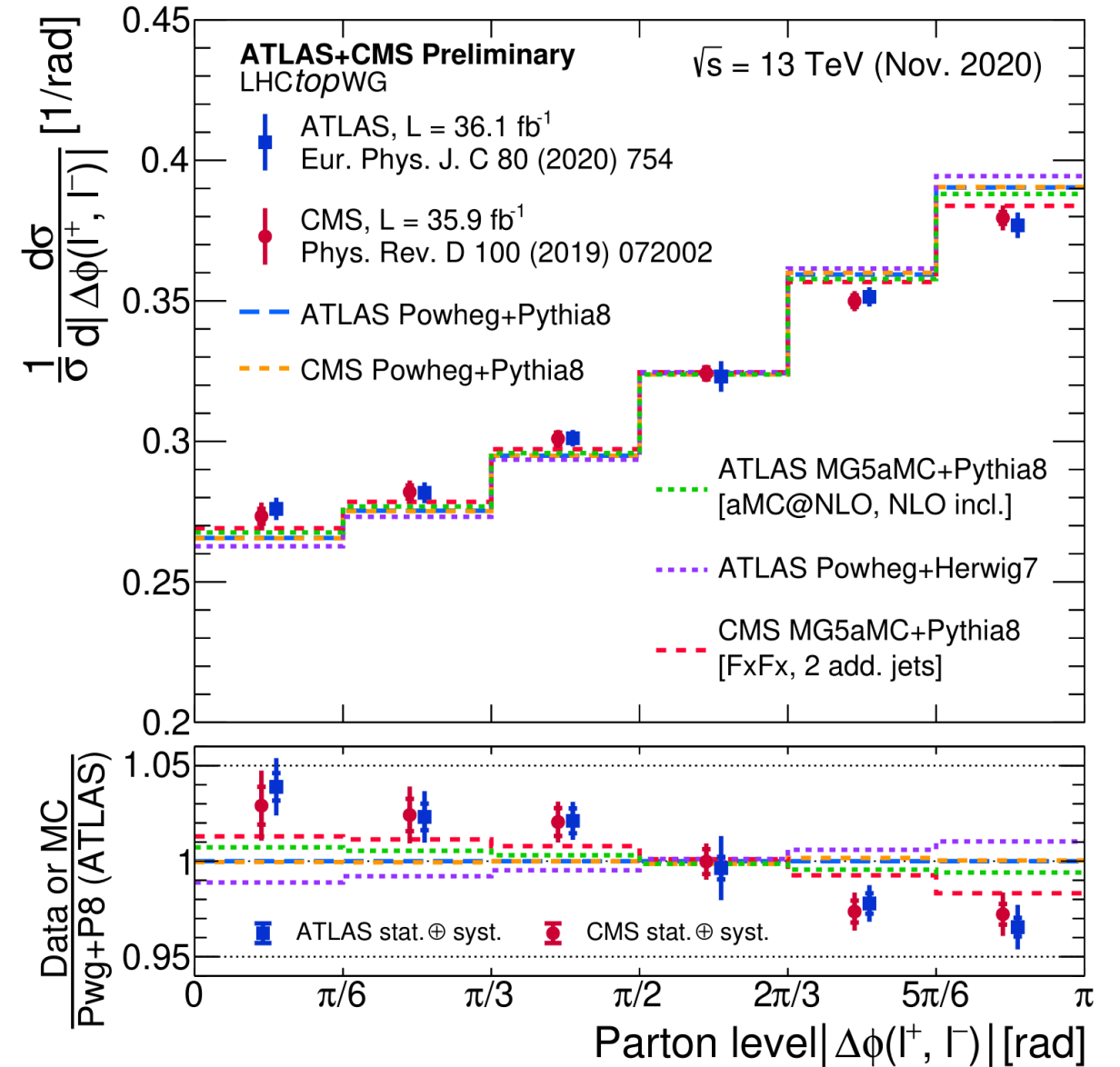
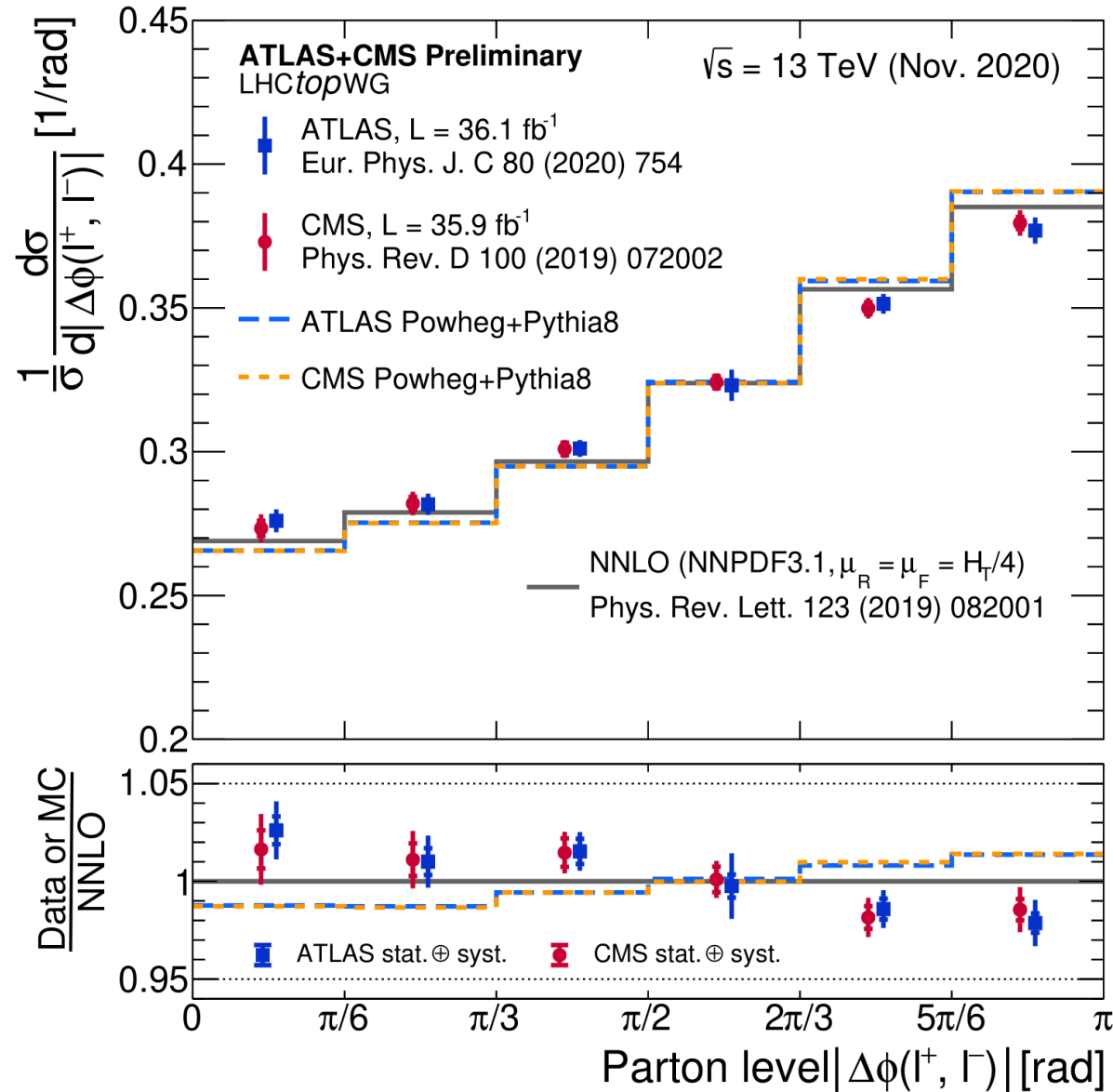
- Top quarks decay very rapidly, before spin decorrelation effects occur
 - Information on the spin can be obtained from the decay products
- Top quarks are not expected to be polarized in the SM
 - however, the spins of t and \bar{t} are predicted to be correlated
 - Spin correlation depends on the production mechanism
 - New physics can affect spin correlation
- $\Delta\phi$: azimuthal opening angle between the 2 leptons

What do we expect to see ?

- the two top quarks decay mainly in opposite direction
- leptons fly in direction of top quarks: also opposite direction
 - opening angle between leptons: around 180 degrees
 - spin correlation: increases fraction of leptons with same direction

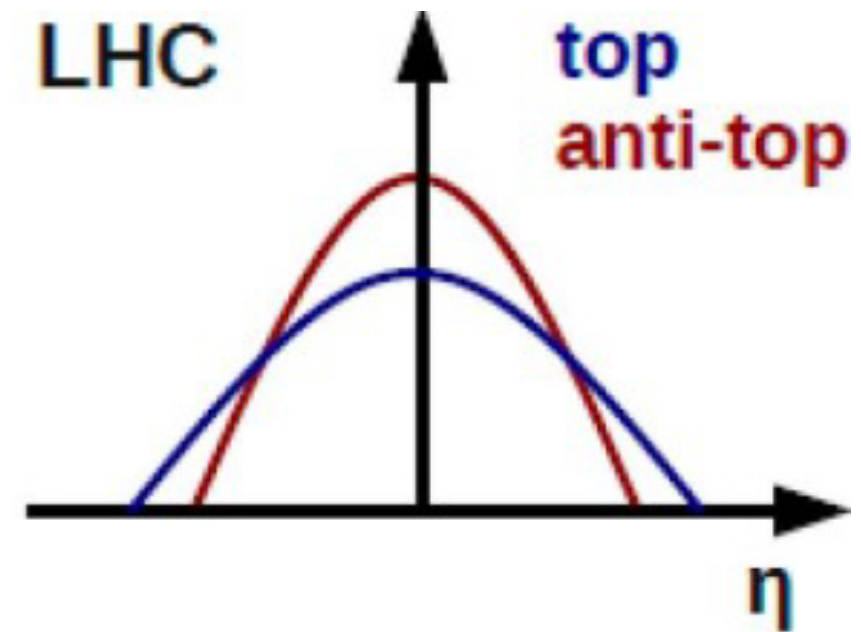
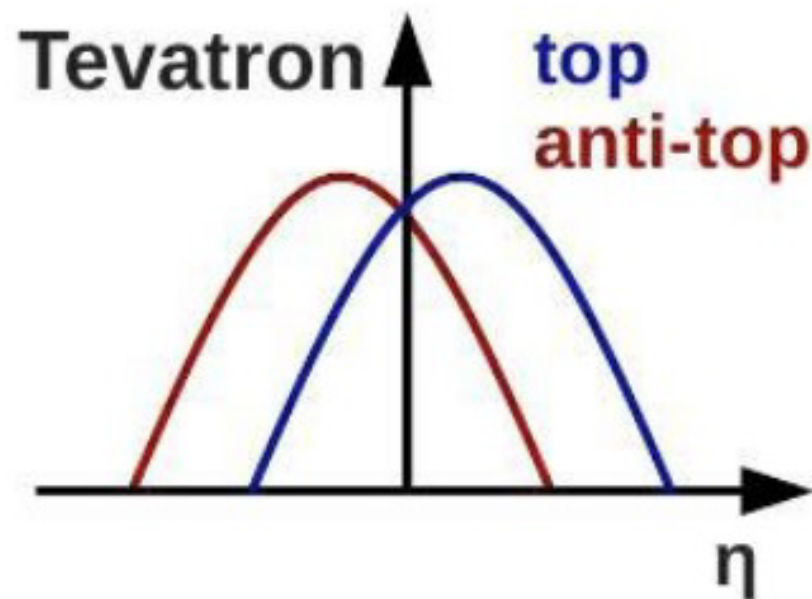


Top spin correlation measurement at 13 TeV



- Some deviations with respect to the MC prediction (similar for ATLAS and CMS)
- Ongoing discussion with theorists to further understand this

Asymmetries at hadron colliders



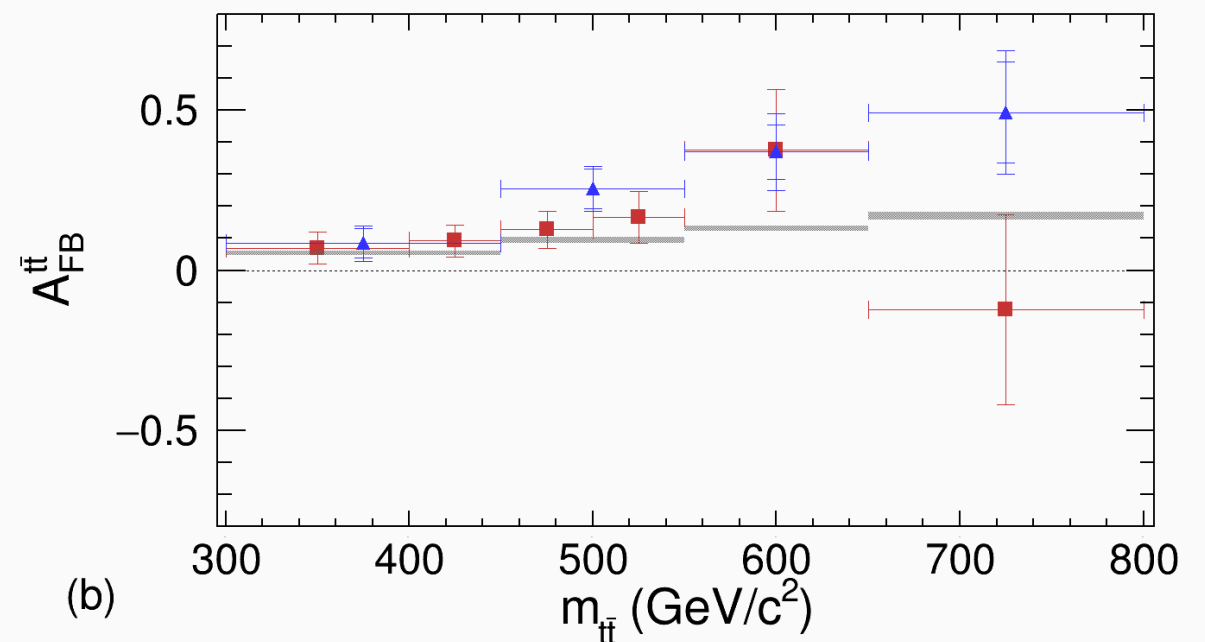
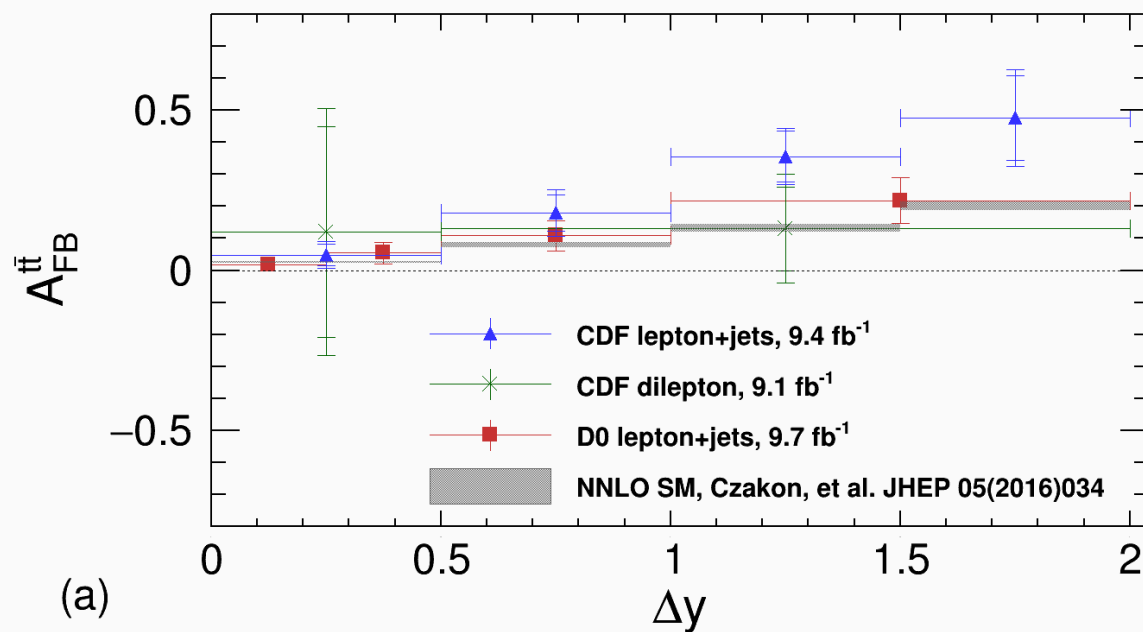
- NLO calculations predict a small asymmetry for $t\bar{t}$ produced in $q\bar{q}$ annihilation
 - interference between tree and box diagrams (no asymmetry at LO); No asymmetry in gg fusion
- **Tevatron**
 - possible to define “forward” and “backward” directions
 - $t\bar{t}$ production dominated by $q\bar{q}$
- **LHC**
 - impossible to define “forward” and “backward” directions
 - $t\bar{t}$ production dominated by gg

Forward-Backward asymmetry - Tevatron

- Measure asymmetry in Forward-Backward $t\bar{t}$ production

$$A_{\text{FB}}^{t\bar{t}} = \frac{N(\Delta y_{t\bar{t}} > 0) - N(\Delta y_{t\bar{t}} < 0)}{N(\Delta y_{t\bar{t}} > 0) + N(\Delta y_{t\bar{t}} < 0)} \quad \Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$$

- Compare with SM expectation
 - small but not null asymmetry

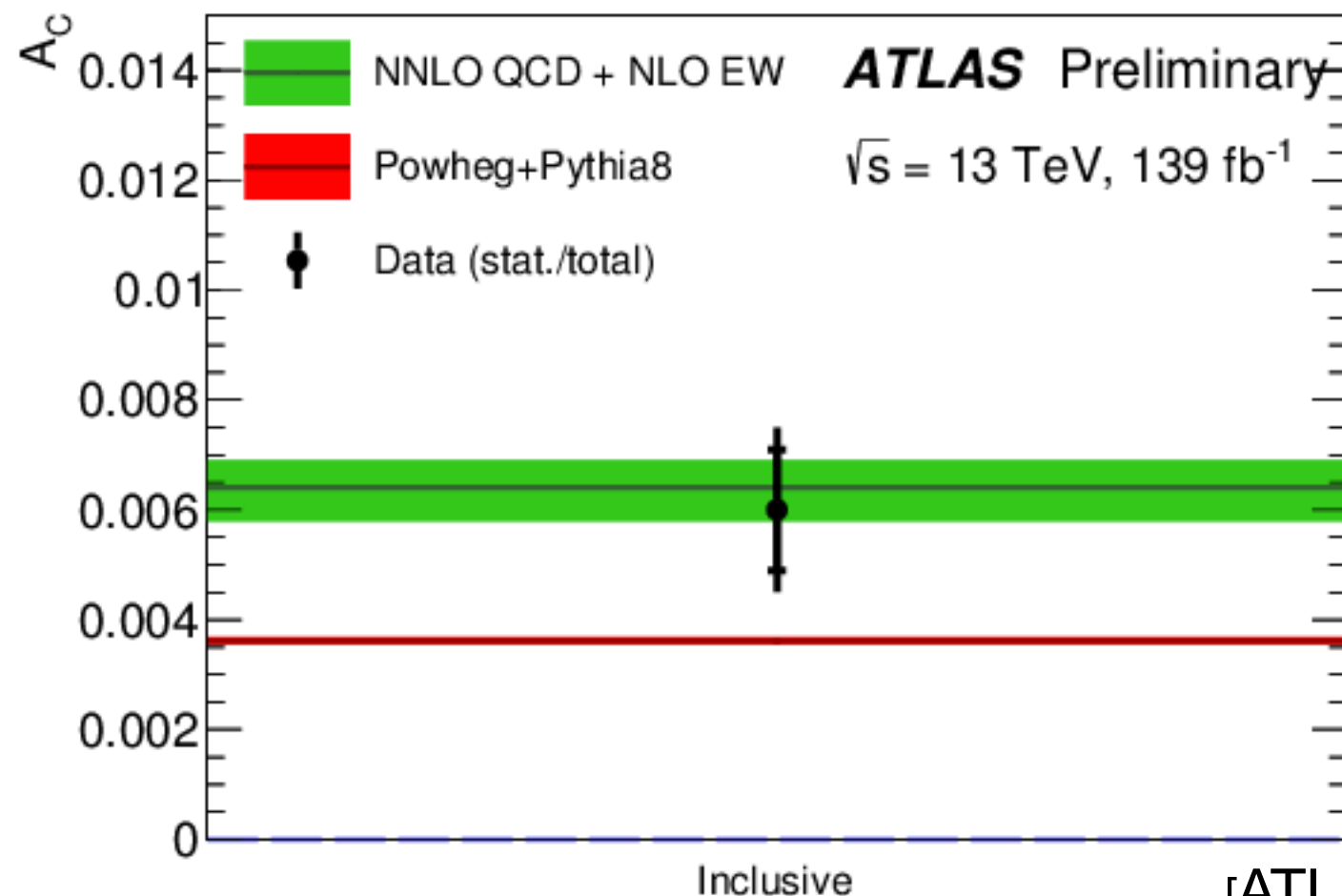


Charge asymmetry - LHC

- Select events in the lepton+jets channel - large statistics

$$\text{Calculate } A_C = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)} \quad \Delta |y| = |y_t| - |y_{\bar{t}}|$$

- Inclusive measurement: $A_C = 0.0060 \pm 0.0015$: 4 standard deviations away from zero \Rightarrow **first evidence!**

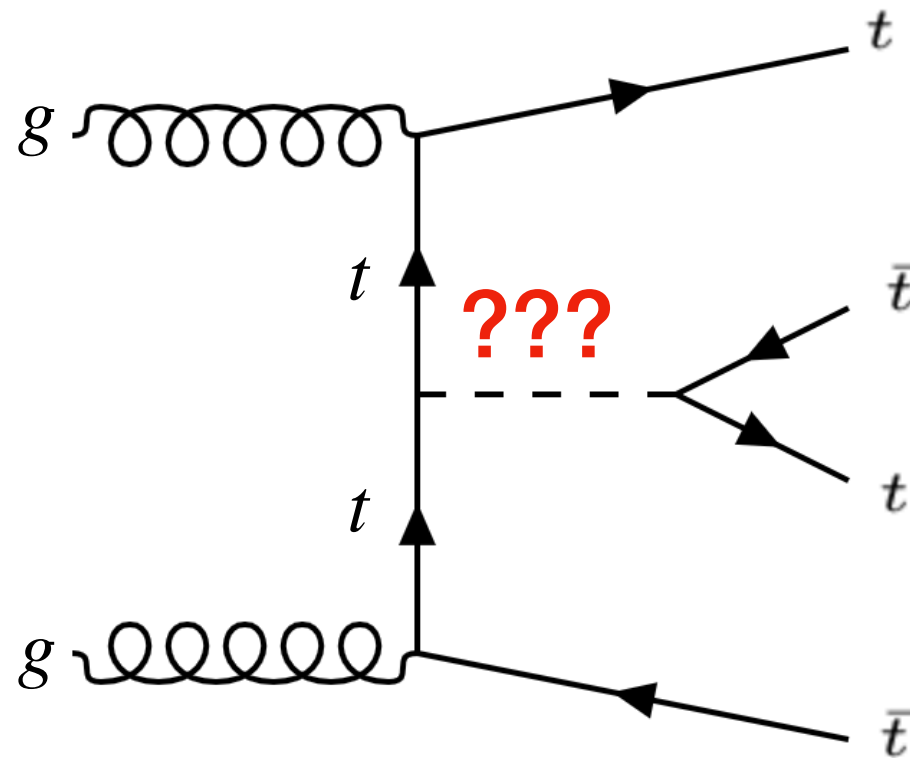


looking for new physics effects

- Standard Model does not explain everything (Dark Matter, neutrino masses, hierarchy problem ...)
- Many BSM involve top-quarks
- One example today!

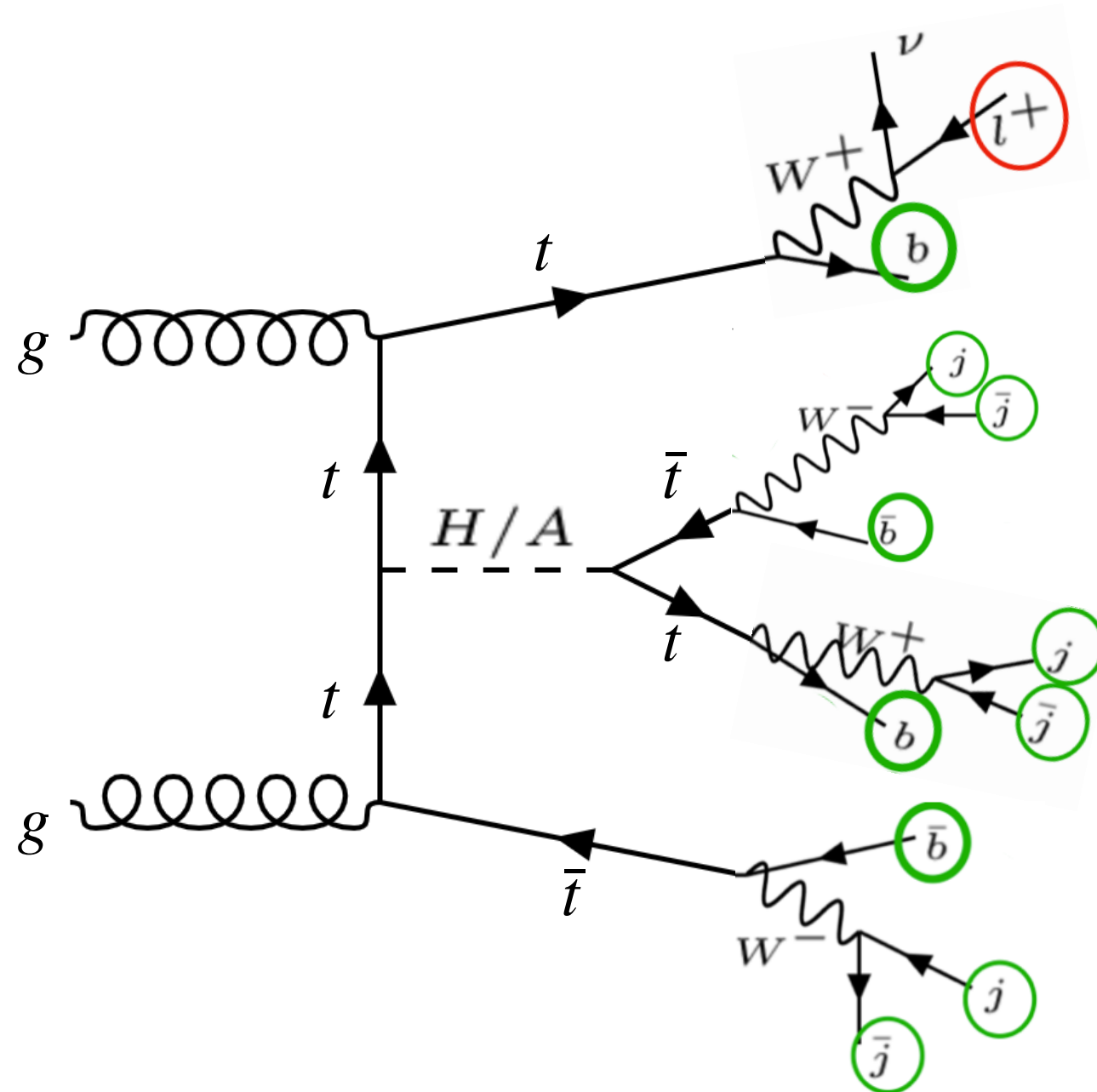
Searches using Four-top-quarks

Searches for heavy resonances



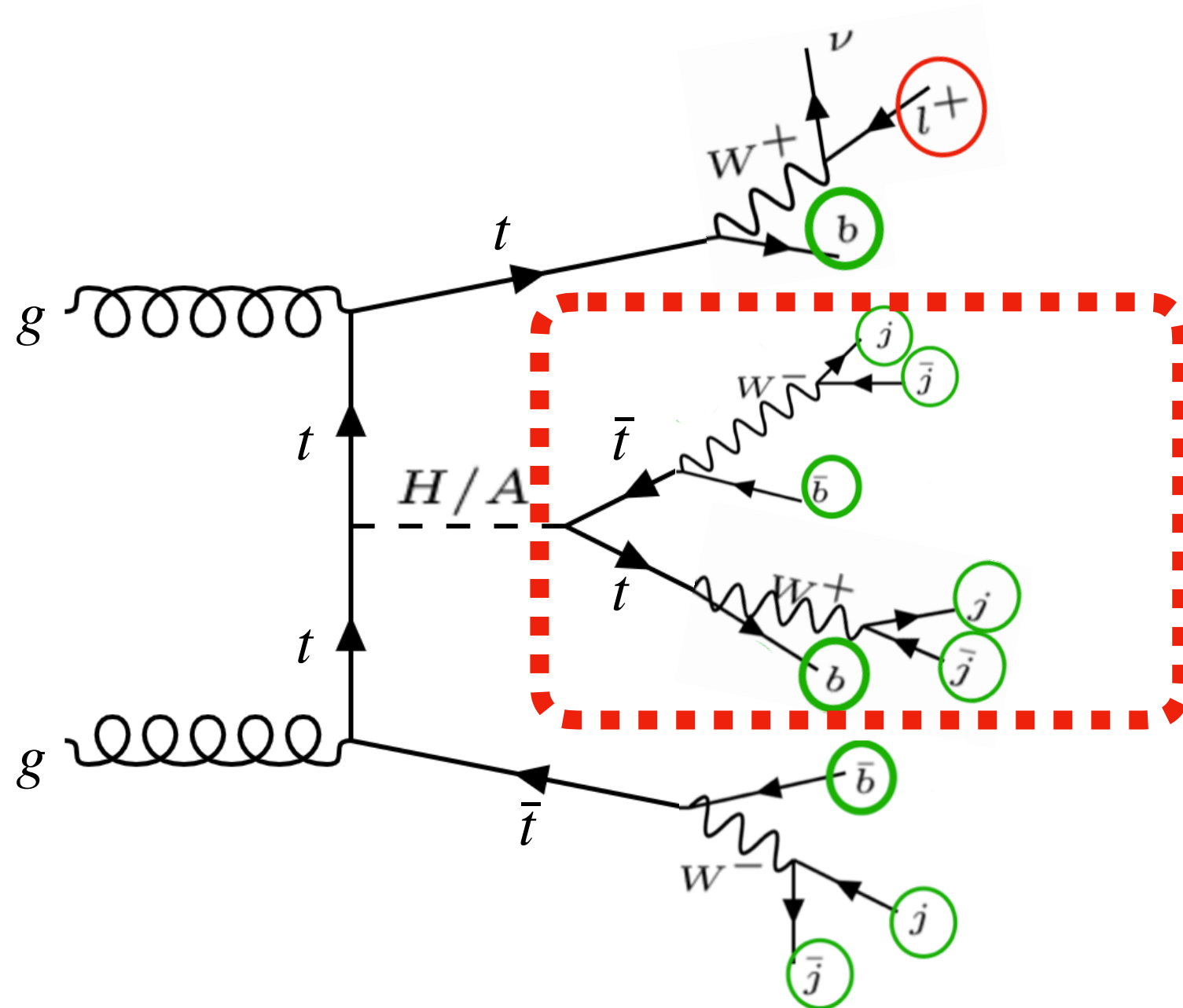
BSM Searches with four-top-quarks

- Benefit from more data but new strategies are needed
- Very busy final state, previous result did not match objects to top quarks



BSM Searches with four-top-quarks

- Heavy mass resonance search benefits from matching & reconstructing $t\bar{t}$ decays
 - Two top-quarks will be boosted - decay products close together (collimated)
- Attempt to identify and reconstruct top-quarks \rightarrow reconstruct H/A resonance



Conclusions

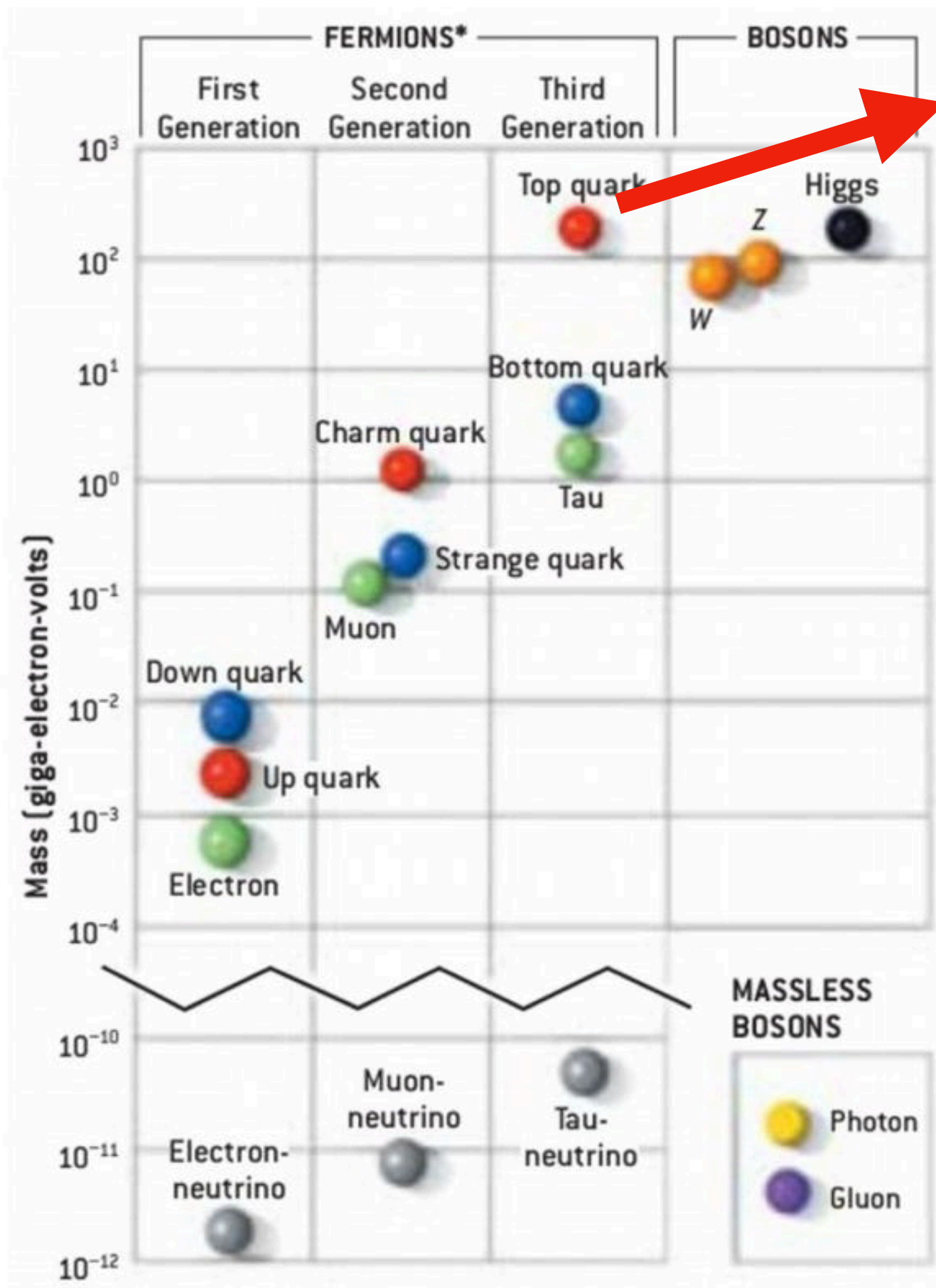
- Higgs boson discovery gave the last piece of the SM, what else can we learn from it?
 - Why three generations of fermions with radically different masses?
 - Why is the Higgs mass at 125 GeV and lighter than the top quark?
 - Evidence of new physics beyond the Standard Model, such as massive amount of Dark Matter?
- Studies of the most massive particles (**top-quark, Higgs boson**) are key for finding answers!

Feel free to contact me with your questions at
nedaa-alexandra.asbah@cern.ch



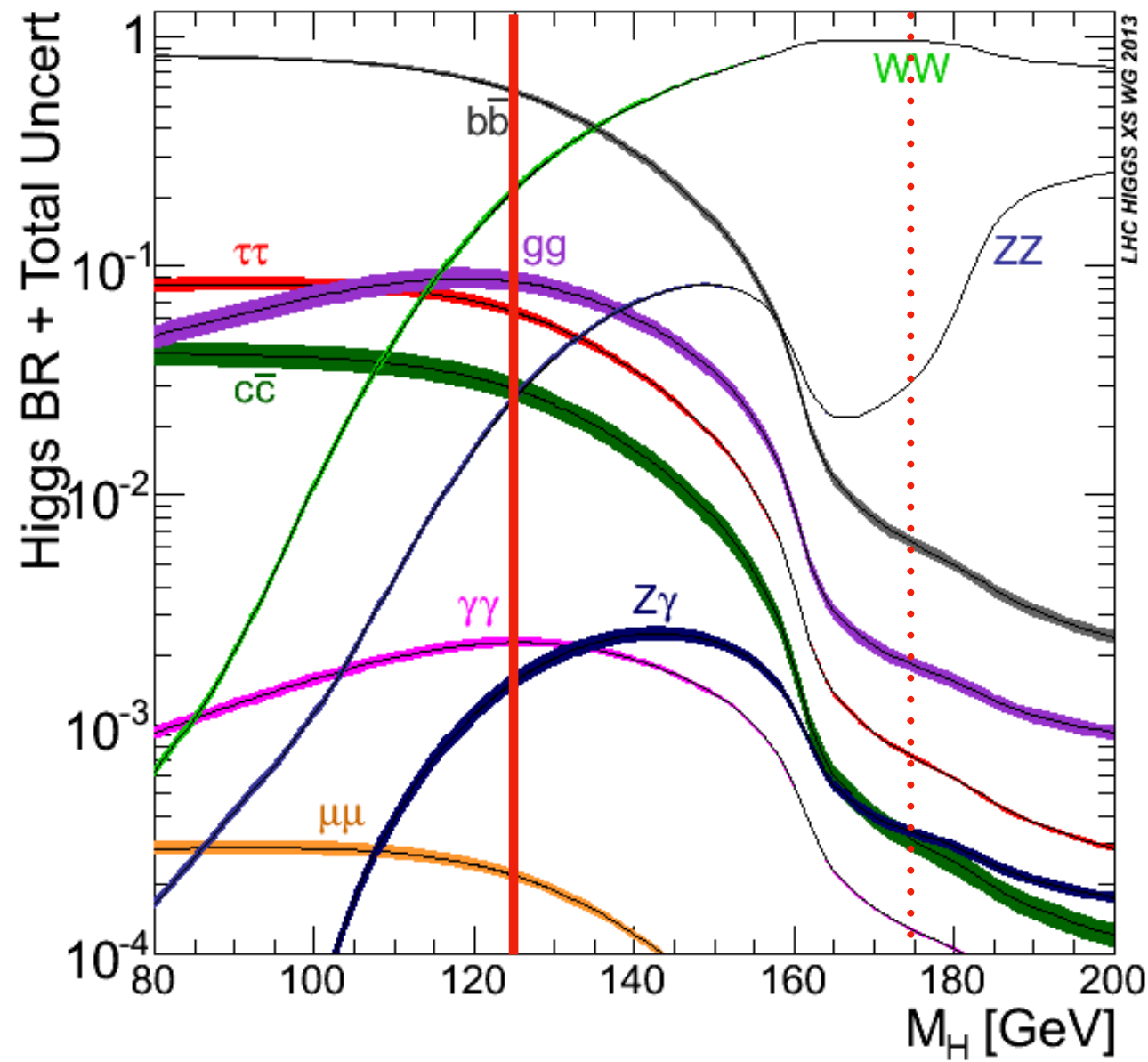
Back-up

Mystery of Mass

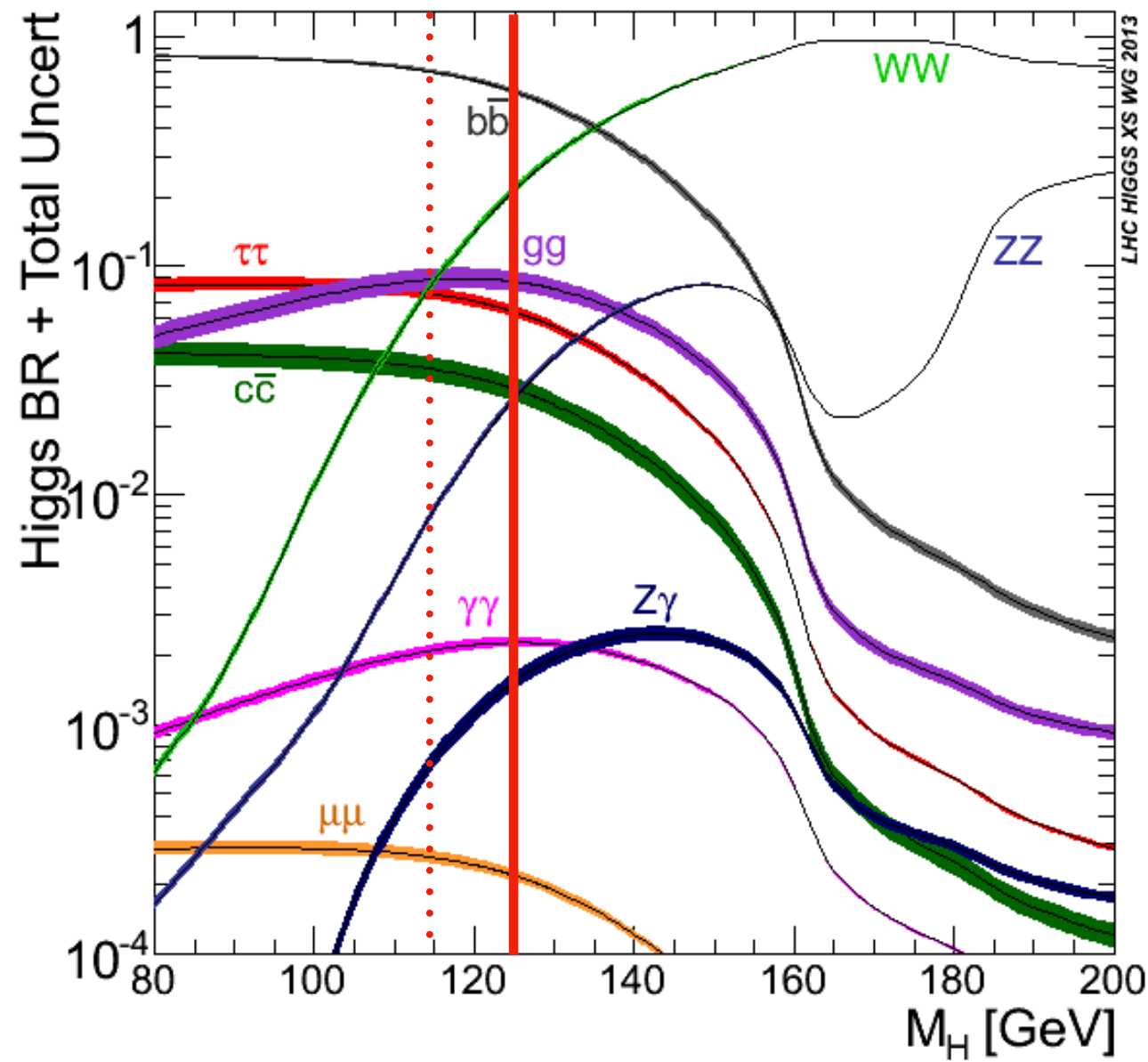


~170 GeV

Higgs mass lies in a lucky spot



Higgs mass lies in a lucky spot



Top-quark

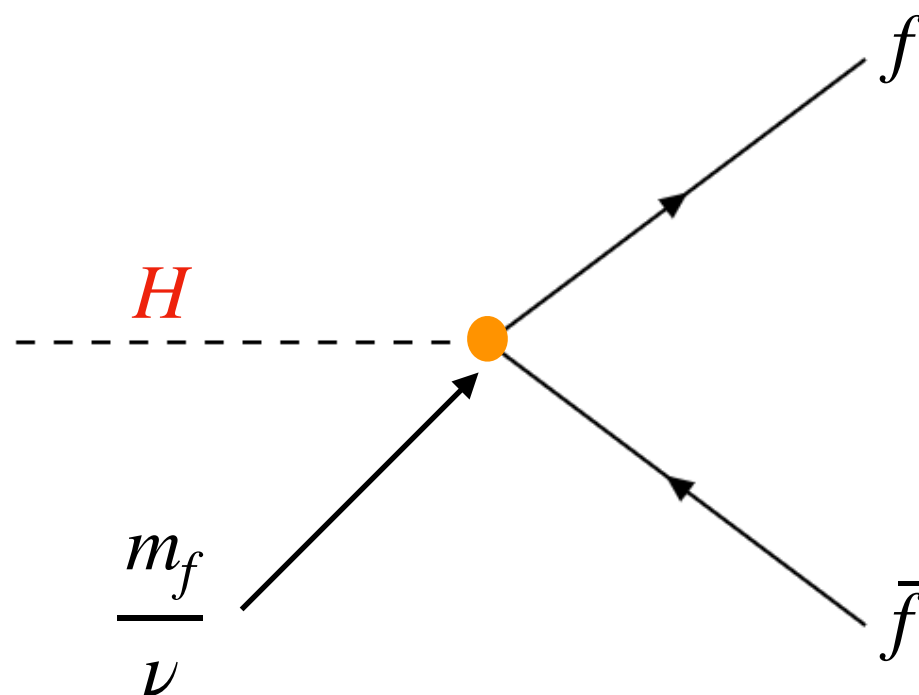
- Short-lived, it decays before hadronizing
 - $\tau_{had} \approx 2 \times 10^{-24} s$
 - $\tau_{top} \approx 0.5 \times 10^{-24} s$
 - Possible to study the properties of a bare quark
- LHC is a top factory & many top-quarks are produced
 - About 25,000 $t\bar{t}$ events are produced every hour
- Gateway to **New Physics**
 - Precision SM top-quark properties measurements
 - Search for non-SM top-quark interactions
 - Searches of top-quark partners and other states



Higgs Mechanism

- Particles gain mass through interactions with the Higgs field
- In the SM the coupling between the Higgs field and the fermions (except for neutrinos) is described by the **Yukawa coupling**

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi + |D_{\mu}\phi|^2 - V(\phi) + \boxed{\bar{\psi}_i y_{ij} \psi_j \phi} + h.c.$$



The Higgs Boson in the SM

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi + |D_{\mu}\phi|^2 - V(\phi) + \bar{\psi}_iy_{ij}\psi_j\phi + h.c.$$

1

The scalar product of the field strength tensor $F_{\mu\nu}$ containing the mathematical encoding of all interaction particles except the Higgs boson where μ and ν are Lorentz indices representing the spacetime components

2

Describes how interaction particles interact with matter particles. The fields ψ and $\bar{\psi}$ describe (anti)quarks and (anti)leptons (bar: corresponding vector must be transposed and complex-conjugated; a technical trick to ensure that the Lagrangian density remains scalar and real)

D is the so-called covariant derivative

3

Describes how the interaction particles couple to the BEH field. This applies only to the interaction particles of the weak interaction, which thereby obtain their mass

4

Describes the potential of the BEH field. Contrary to the other quantum fields, this potential does not have a single minimum at zero but has an infinite set of different minima.

5

Describes how matter particles couple to the Brout–Englert–Higgs field ϕ and thereby obtain mass. The entries of the Yukawa matrix y_{ij} represent the coupling parameters to the Brout–Englert–Higgs field, and hence are directly related to the mass of the particle in question. These parameters are not predicted by theory, but have been determined experimentally.

6

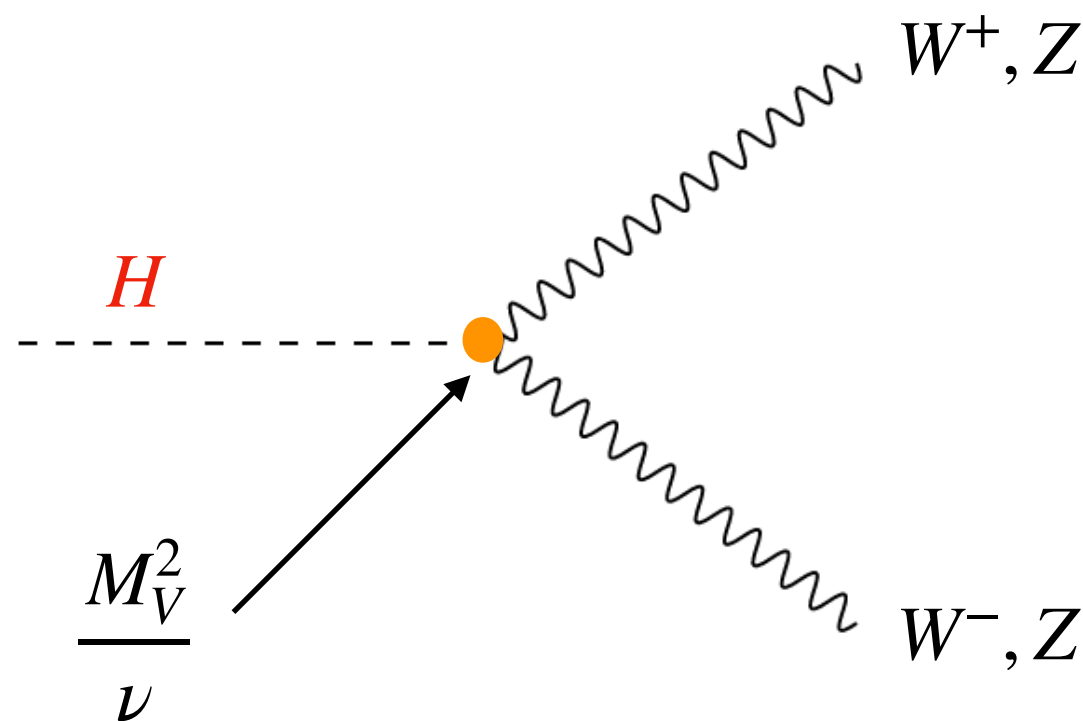
Represents the ‘hermitian conjugate’. The hermitian conjugate is necessary if arithmetic operations on matrices produce complex-valued ‘disturbances’. By adding h.c., such disturbances cancel each other out, thus the Lagrangian remains a real-valued function.



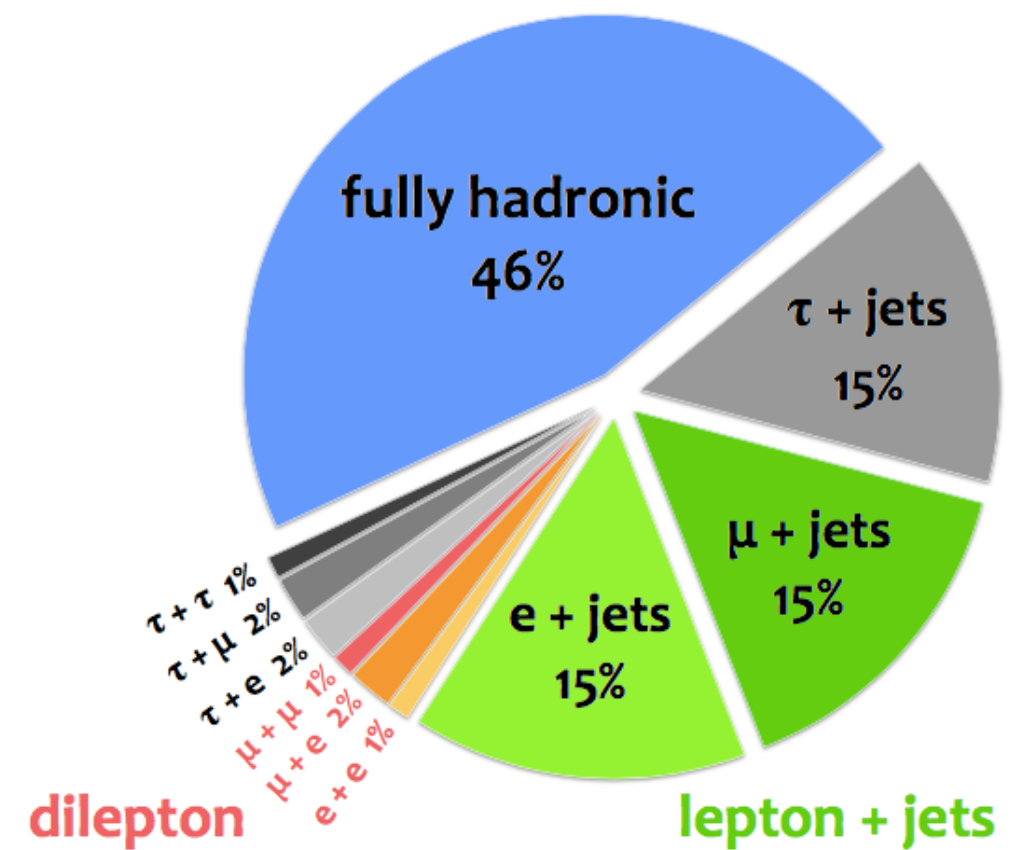
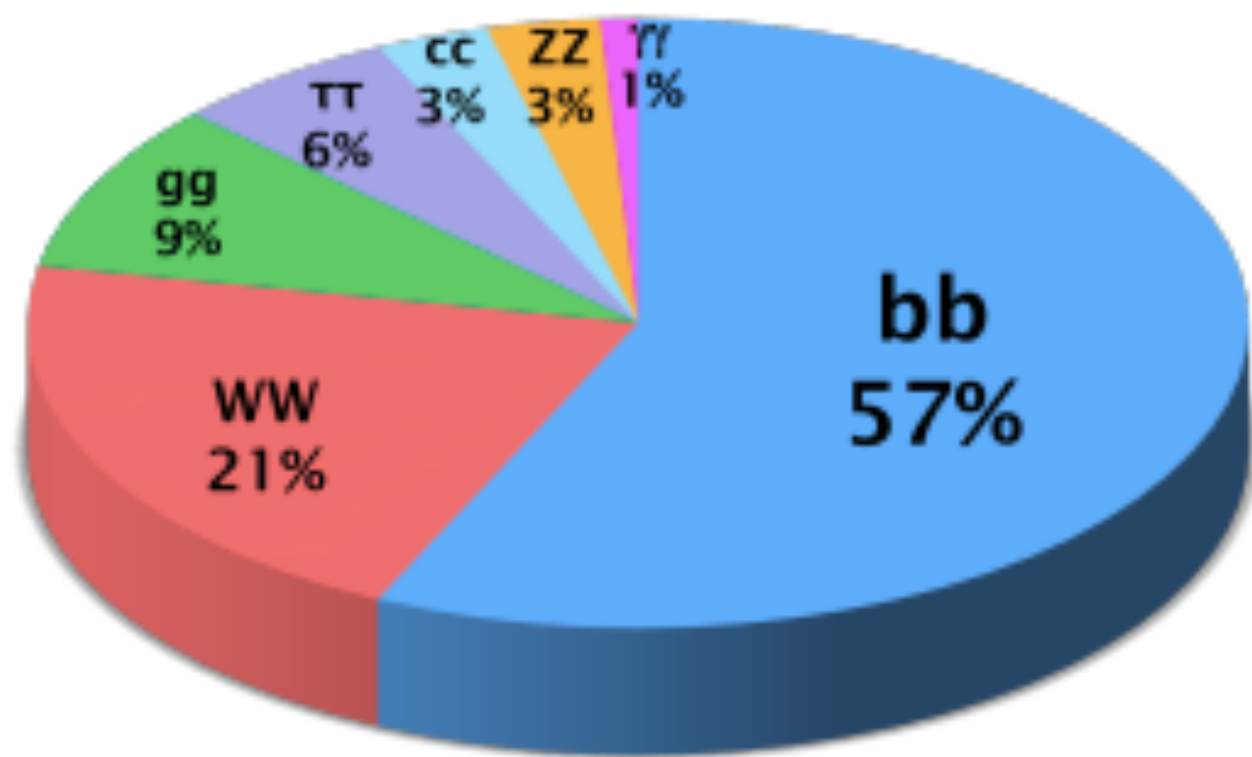
Higgs Mechanism

- Particles gain mass through interactions with the Higgs field

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi + \boxed{|D_{\mu}\phi|^2} - V(\phi) + \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$



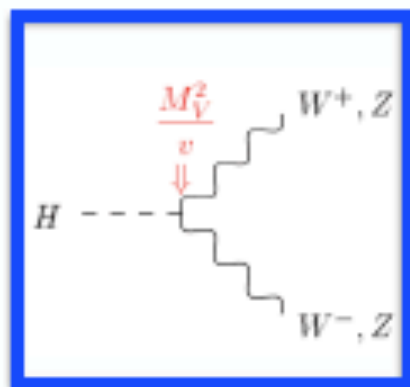
Higgs decay modes



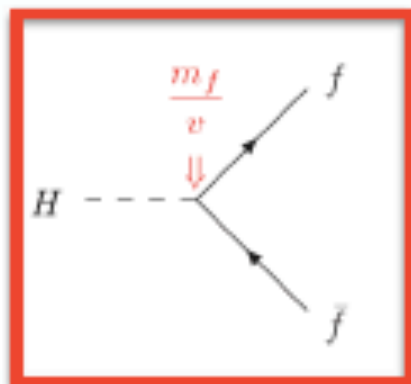
$$N_{events} = L \cdot \sigma_{ttH} \cdot B(H) \cdot B(tt) \cdot \varepsilon \cdot A$$

Higgs Boson Coupling : Production Mode

to Bosons

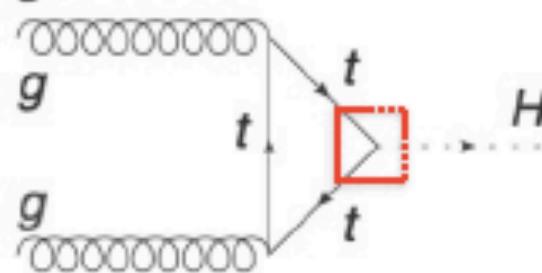


to Fermions



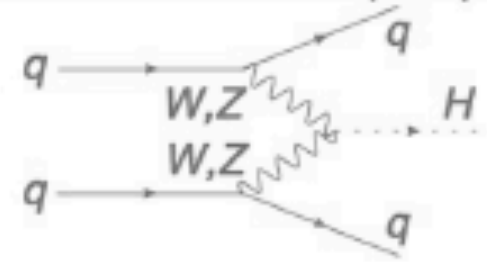
Loop induced

gluon fusion



σ (13 TeV) **Nevt**
(36 fb⁻¹)
48.5pb ~1.8M

vector boson fusion (VBF)



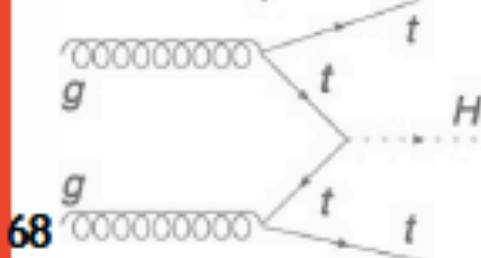
3.8pb ~140K

associated prod. with W/Z



2.25pb ~80K

associated prod. with tt

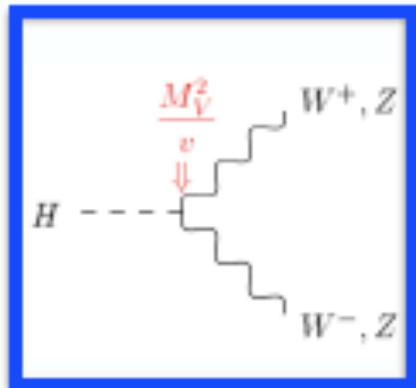


0.5pb ~20K

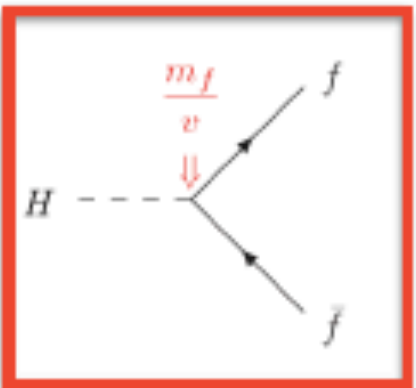
Tree level coupling to bosons
Tree level coupling to fermions

Higgs Boson Coupling : Decay Mode

to Bosons



to Fermions



Tree level coupling
to bosons

$$H \rightarrow WW^*$$

$$H \rightarrow ZZ^*$$

Tree level coupling
to fermions

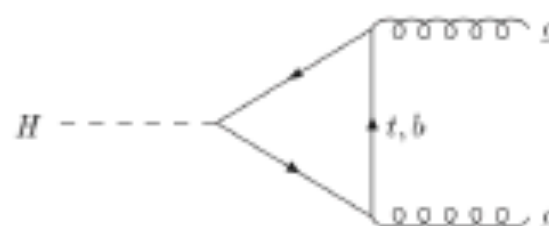
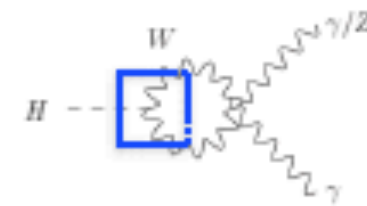
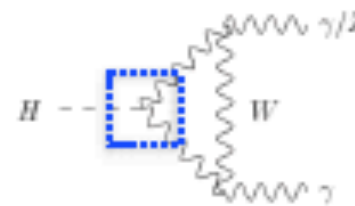
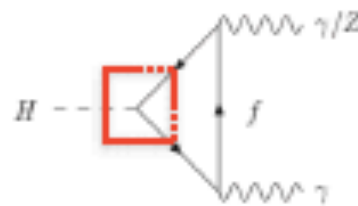
$$H \rightarrow \tau\tau$$

$$H \rightarrow \mu\mu$$

$$H \rightarrow b\bar{b}$$

$$H \rightarrow c\bar{c}$$

Loop induced



$$H \rightarrow \gamma\gamma/Z\gamma$$

$$H \rightarrow gg$$

- The production and decay of the Higgs boson can be factorised
- The cross section times branching fraction of an individual channel $\sigma(i \rightarrow H \rightarrow f)$ contributing to a measured signal yield can be parameterised as

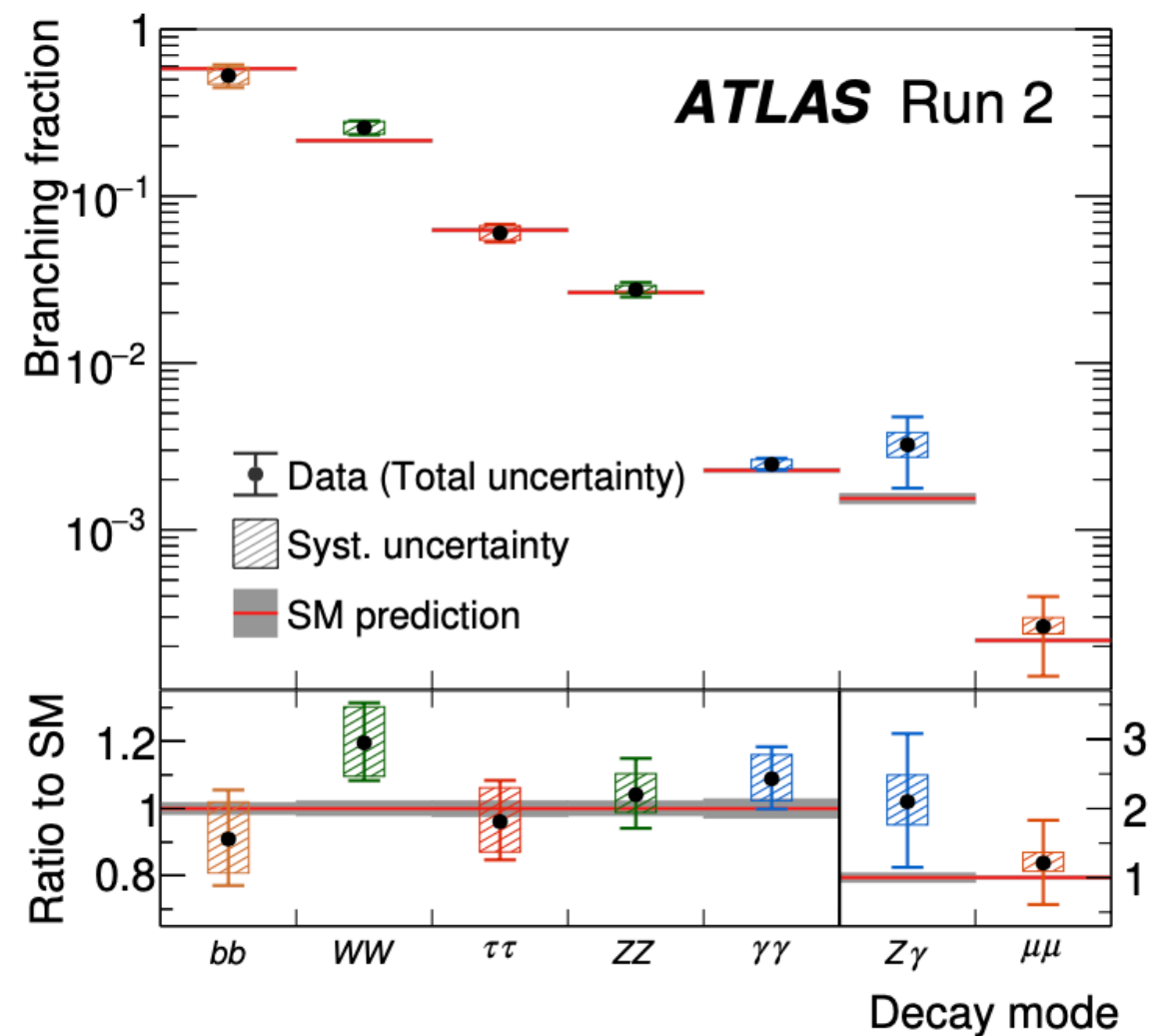
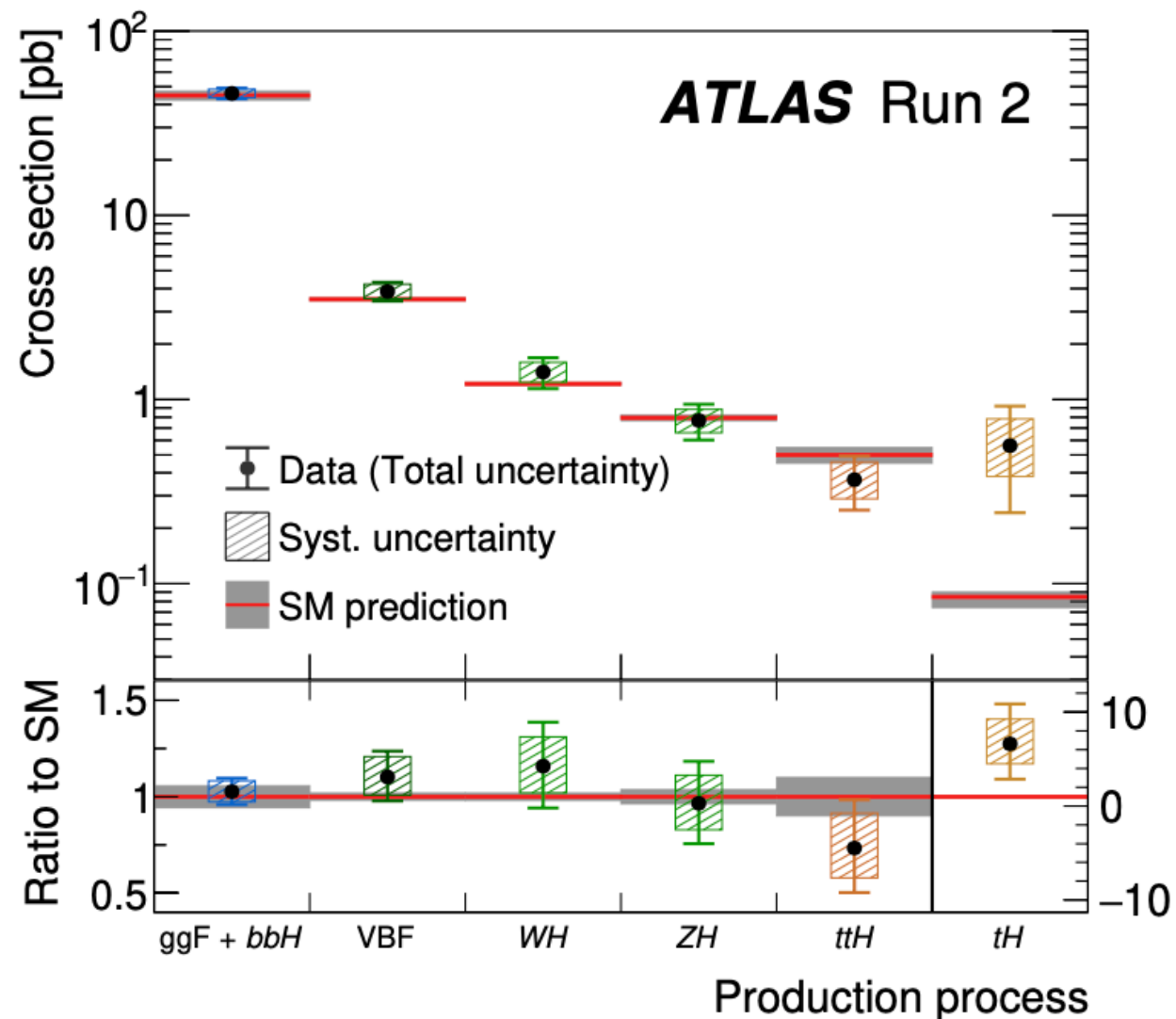
$$\sigma_i \cdot B^f = \frac{\sigma_i(\vec{k}) \cdot \Gamma^f(\vec{k})}{\Gamma_H},$$

Partial width for Higgs boson decay to the final state f
Total width of the Higgs boson

- A set of coupling modifiers, κ , is introduced to parameterise possible deviations from the SM predictions of the Higgs boson couplings to SM bosons and fermions

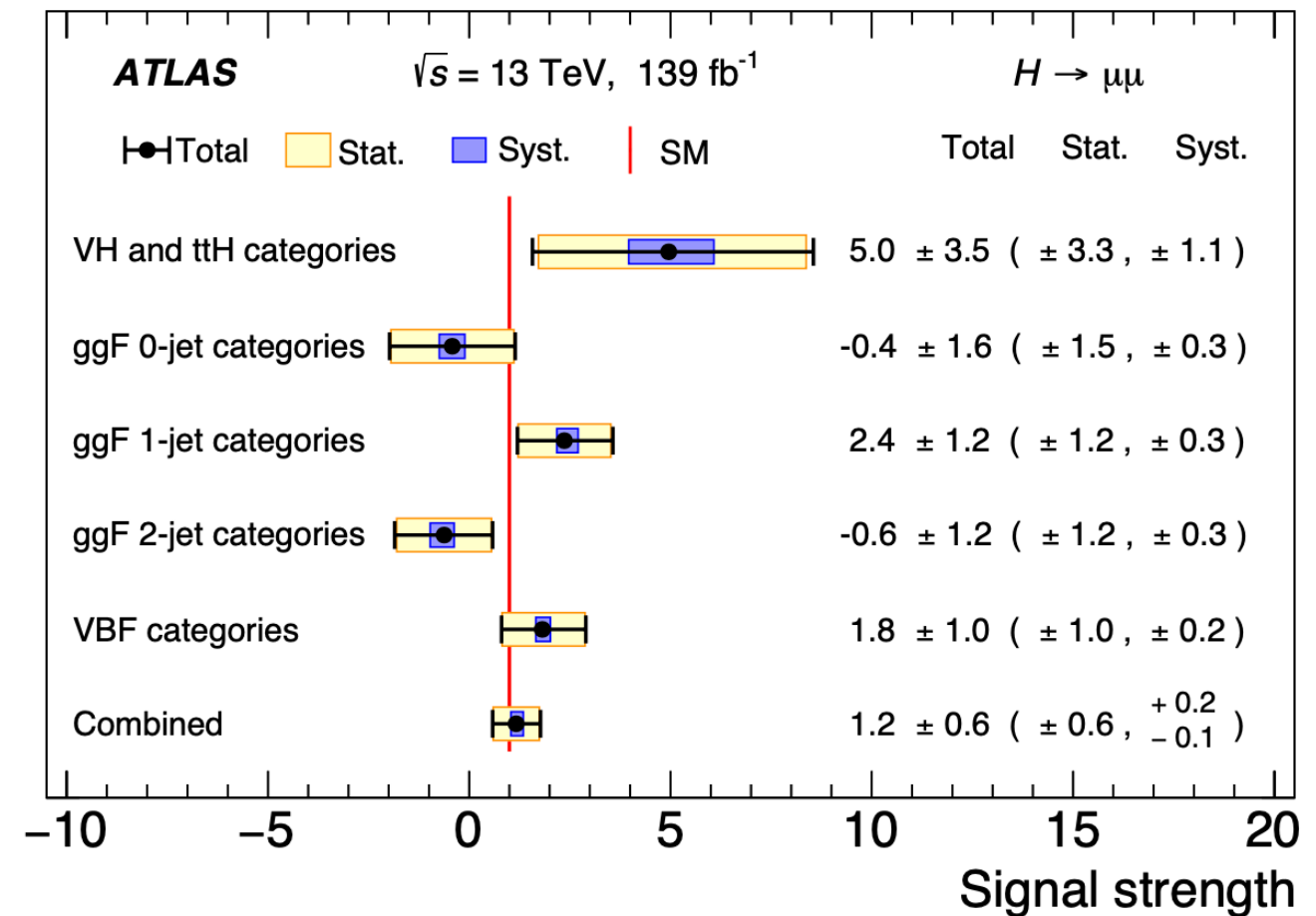
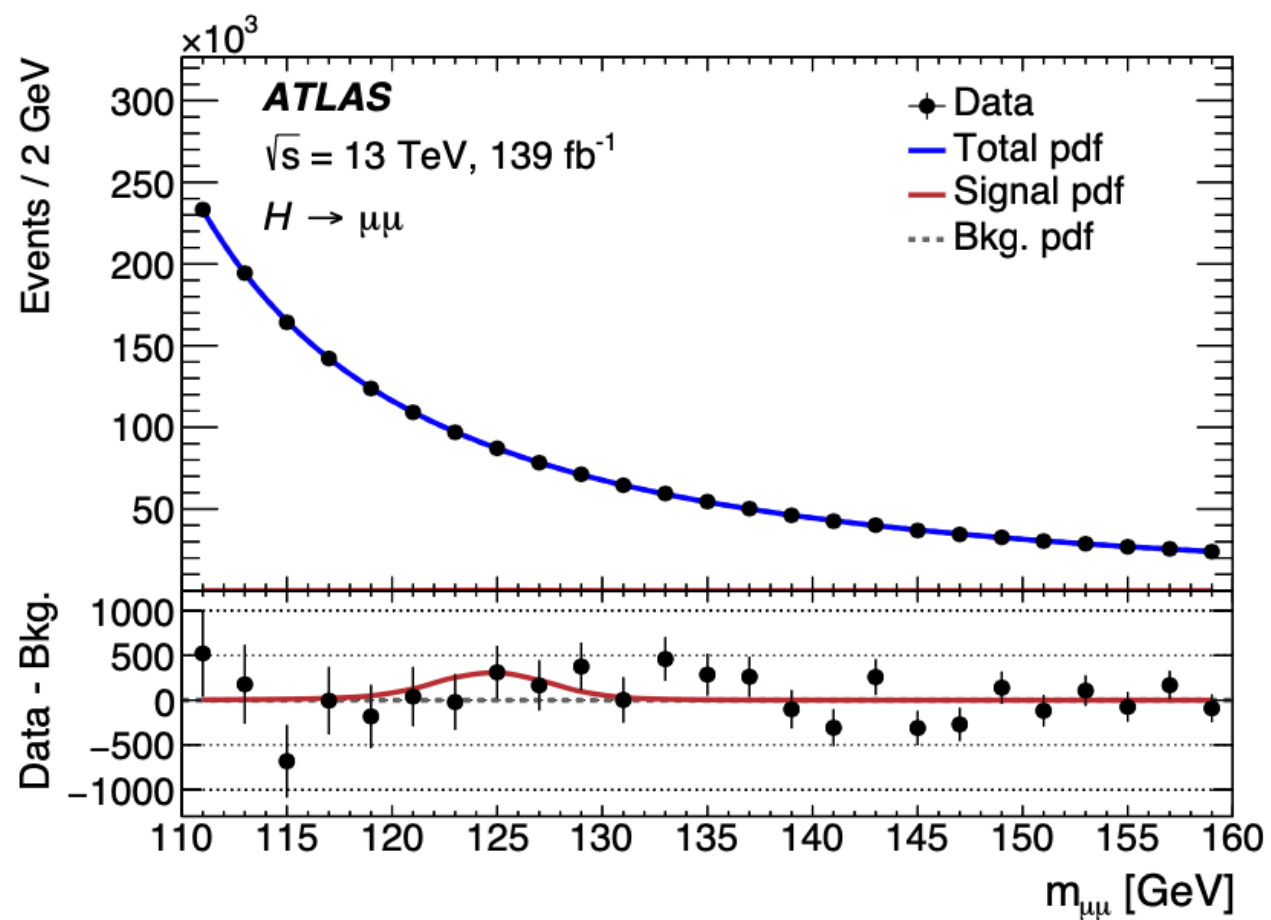
$$\kappa_j^2 = \sigma_j / \sigma_j^{\text{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma_j / \Gamma_{\text{SM}}^j,$$

Higgs Production & Decay

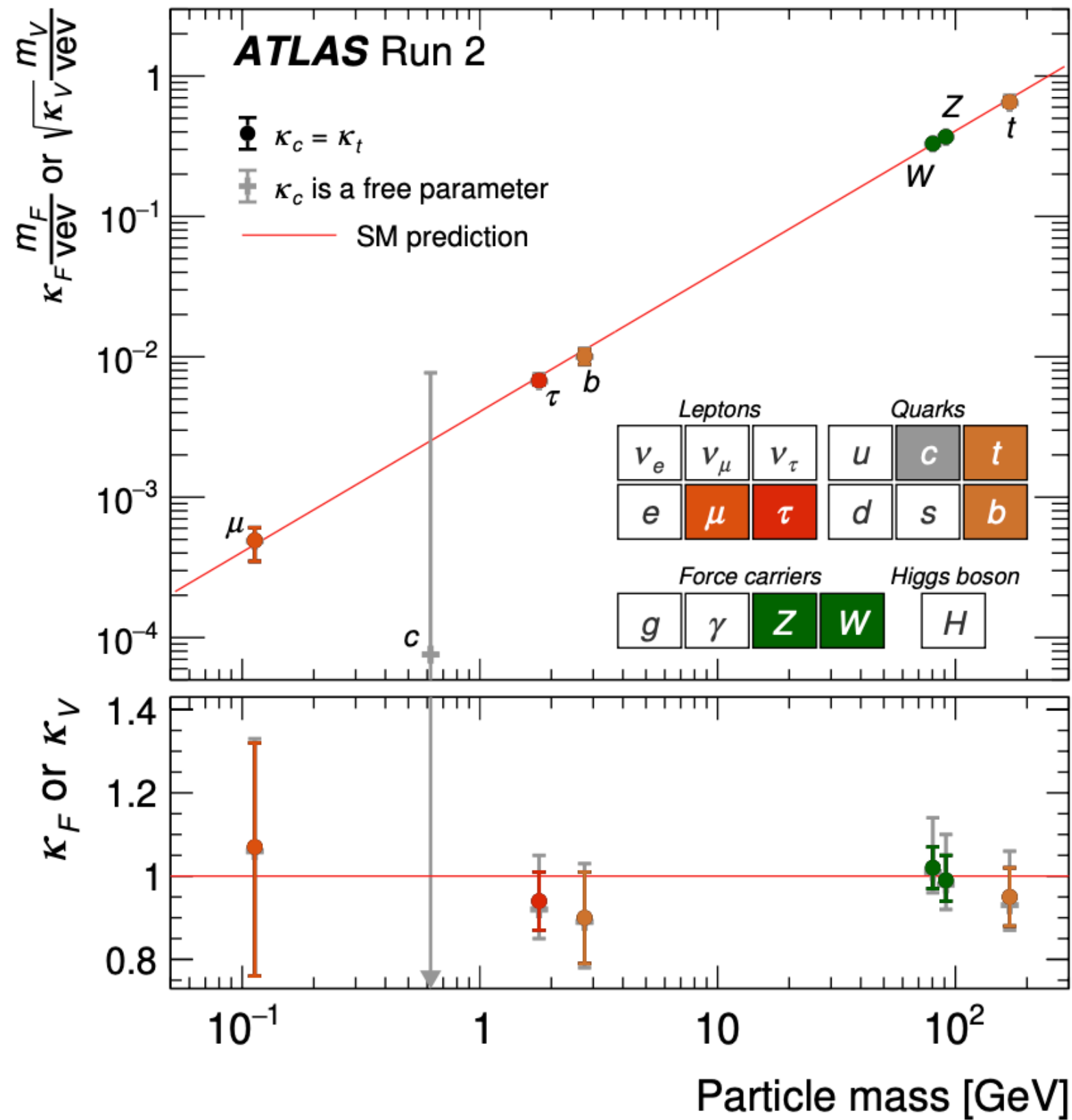


A large number of Higgs production and decay modes have been established
Excellent agreement with theory predictions

Recent highlights

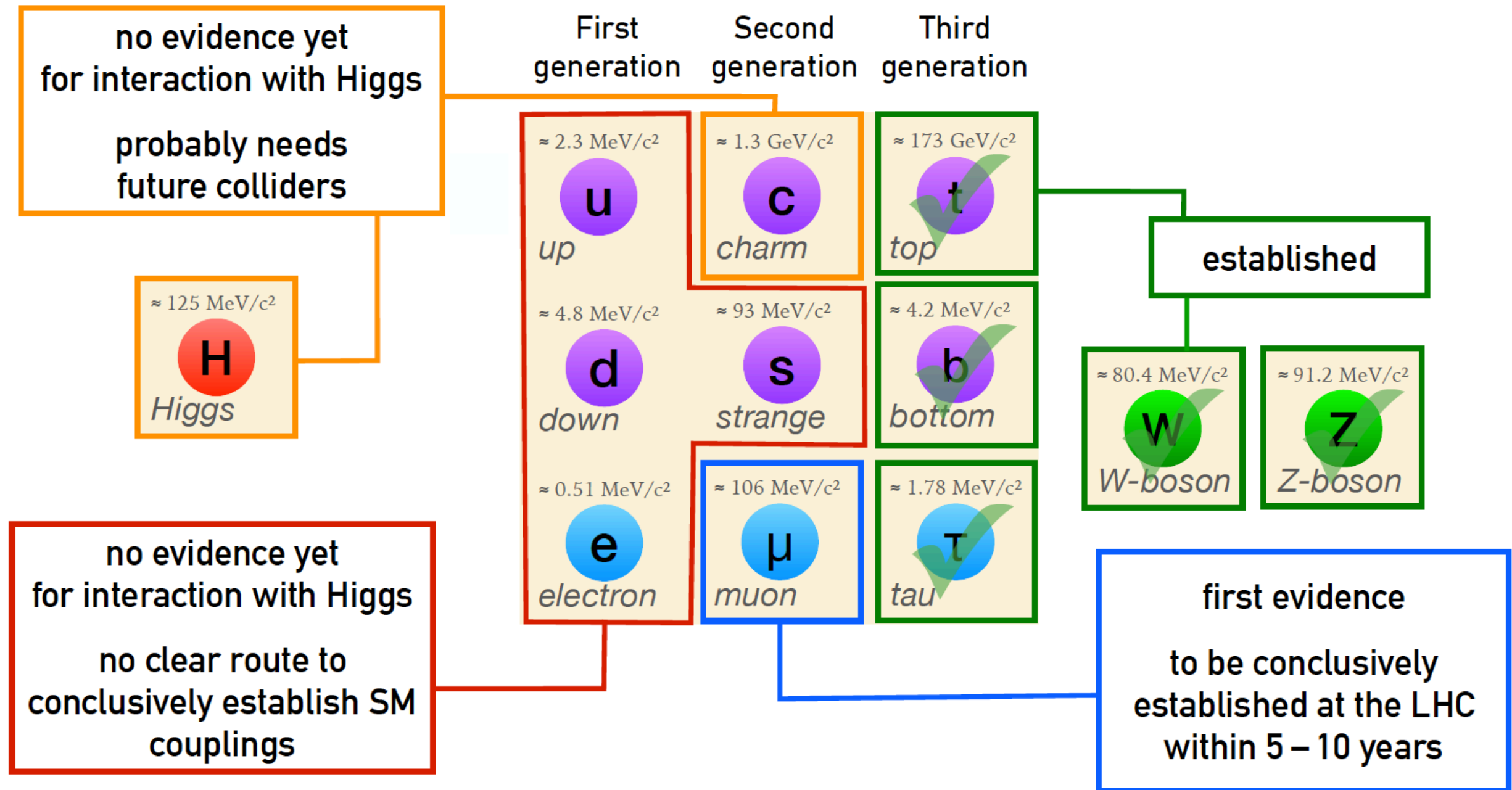


Recent highlights



Higgs interactions

- Status and prospects of our knowledge of Higgs interactions with known particles

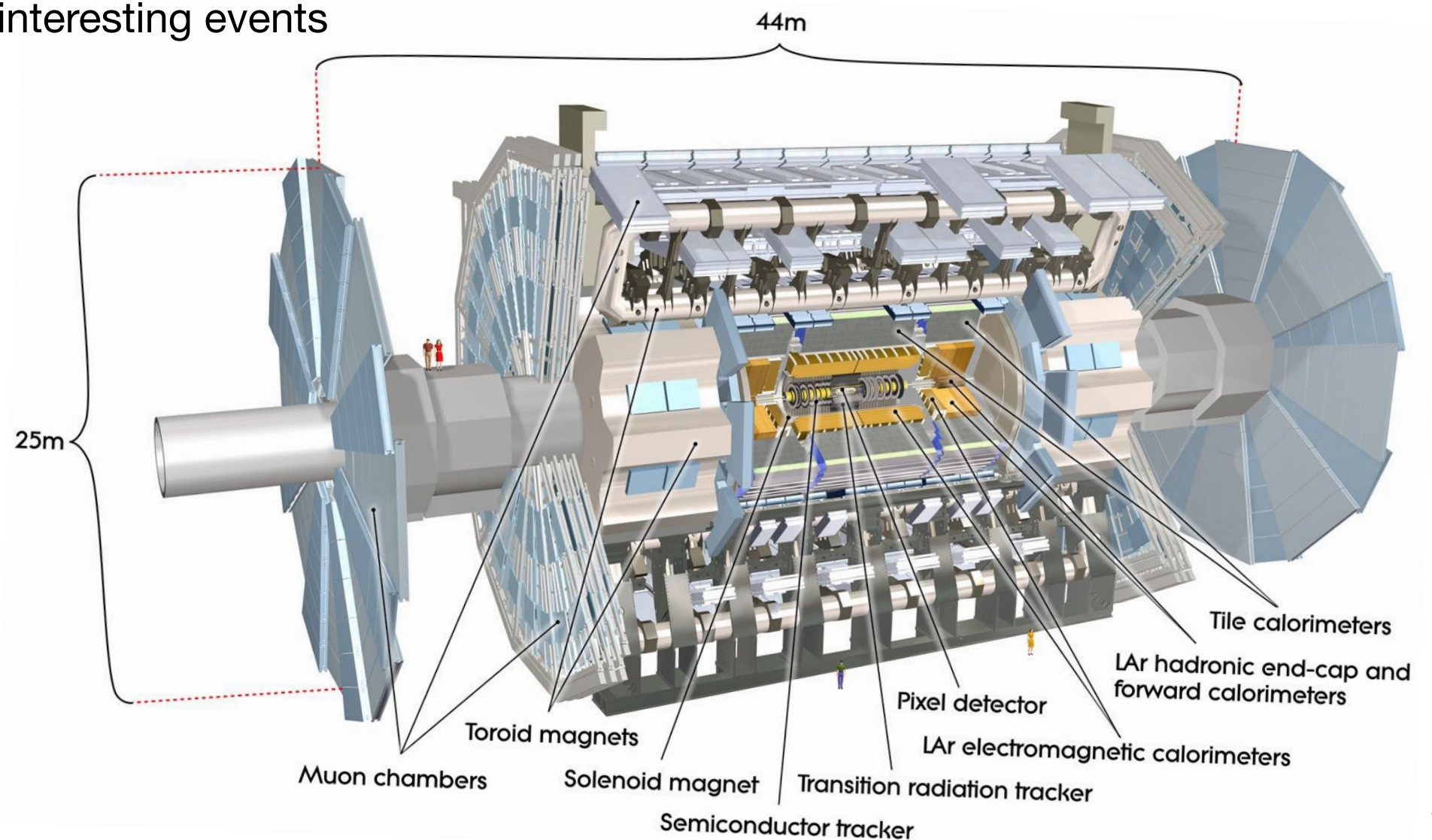


Run3 pre-calibration



A Toroidal LHC Apparatus (ATLAS)

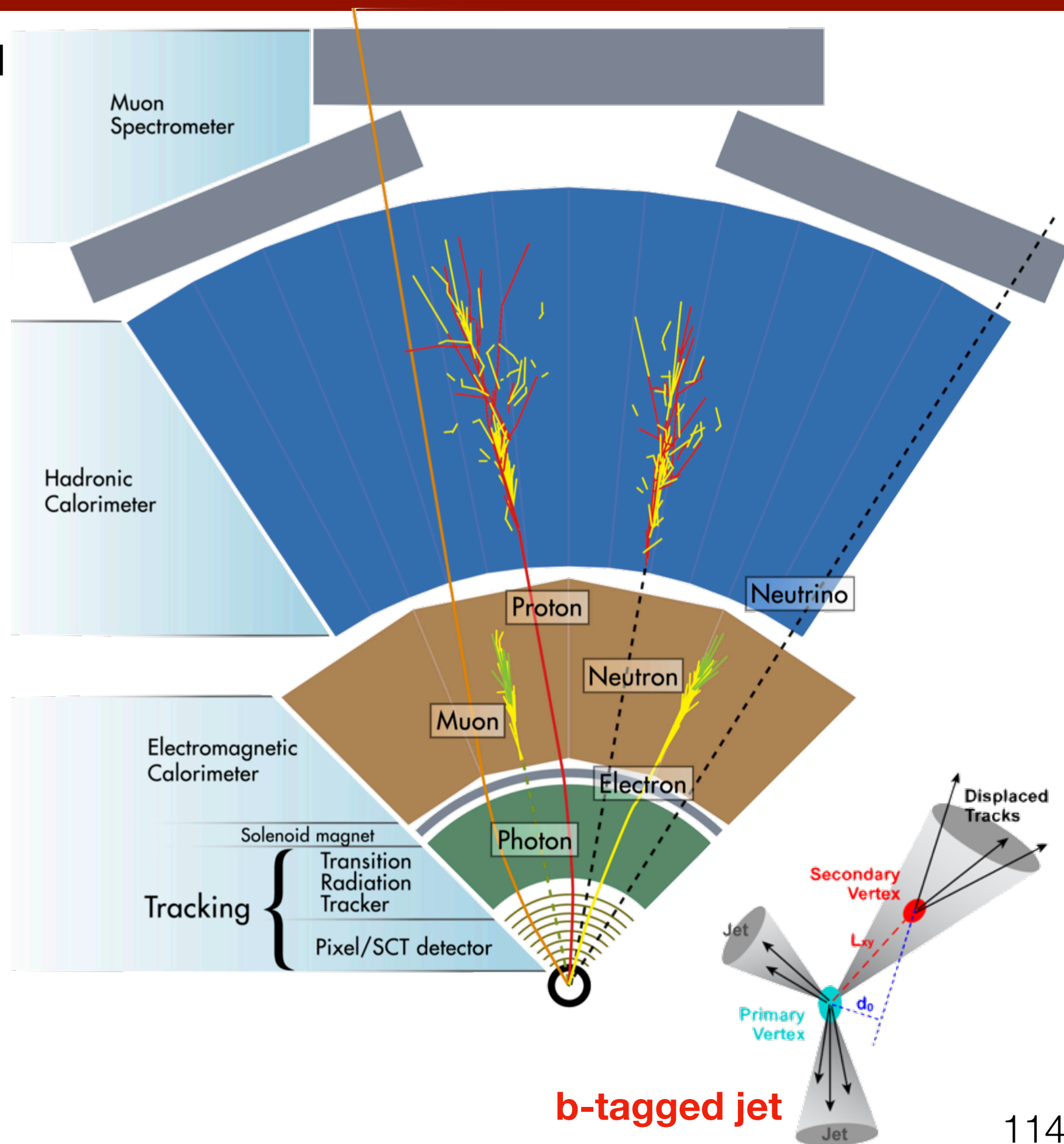
- Several sub-detectors \Rightarrow particle tracking and energy measurement
- Solenoid and Toroid magnets \Rightarrow bend charged particles
 - Particle identification and momentum measurement
- ~ 1 billion p-p collisions are produced per second
- 2 level **Trigger System** reduces the data-flow to a manageable level
 - keeping only the most interesting events



Width: 44 m
Diameter: 25 m
Weight: 7000 t

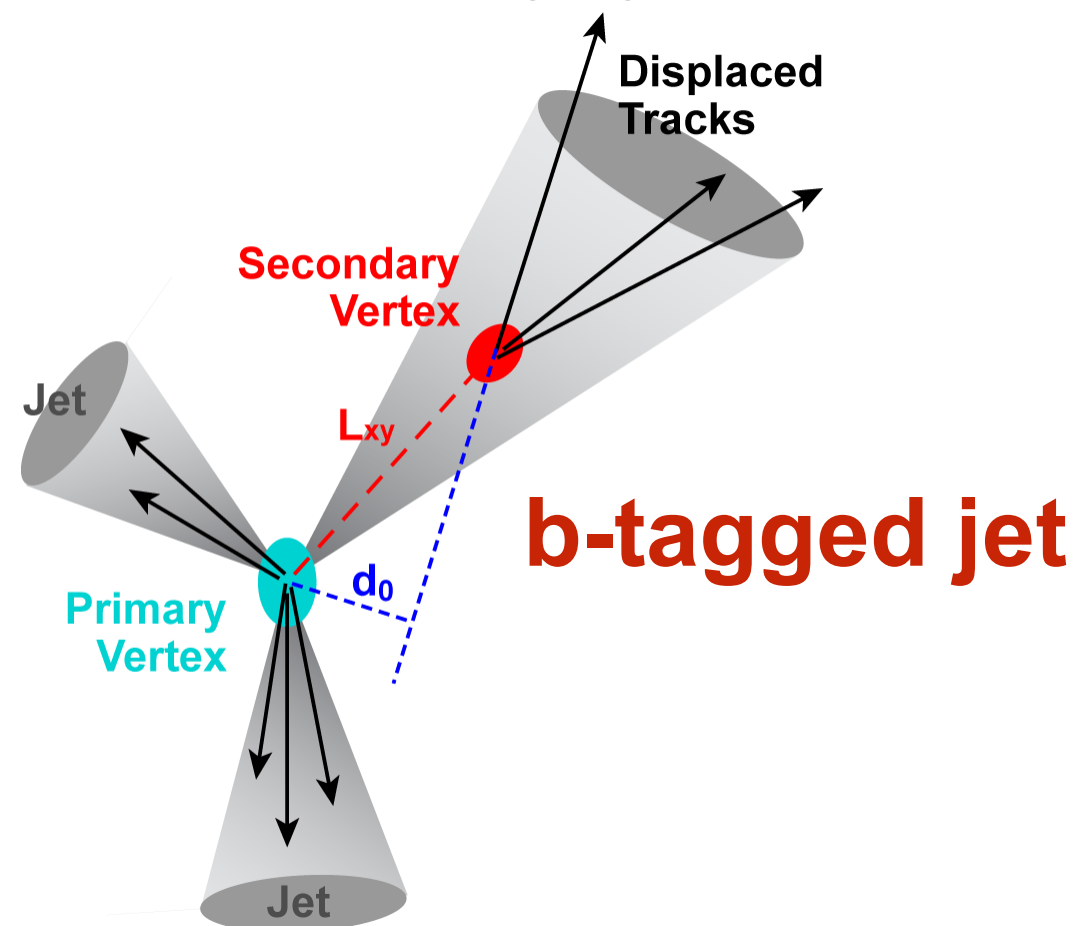
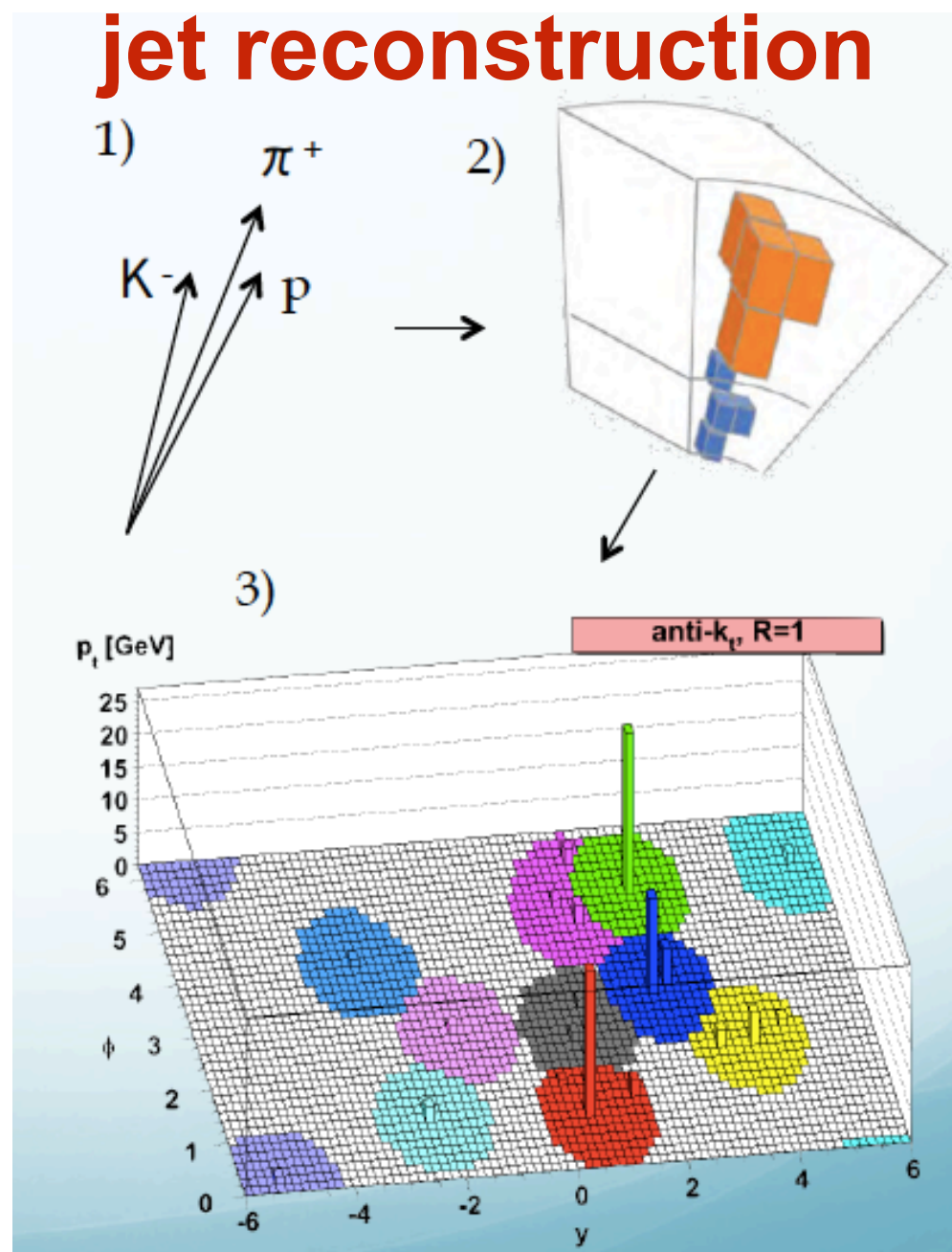
Object Reconstruction and Identification

- Particle momenta measured through tracker and calorimeters
- **Electrons** match tracks in Inner Detector to narrow energy deposits in EM calorimeter
- **Muons** match tracks in Inner Detector to Muon Spectrometer
- Hadronic **jets** formed from energy deposits in EM and hadronic calorimeters
- Jets from b-hadrons can be identified due to their long decay length $\sim 450 \mu\text{m}$



Object reconstruction and Identification

- Charged particles from showers deposit energy in calorimeter cells which are grouped into clusters
- Electrons use rectangular clusters matched to tracks
- Jets group several topological clusters using the anti- k_t jet finding algorithm

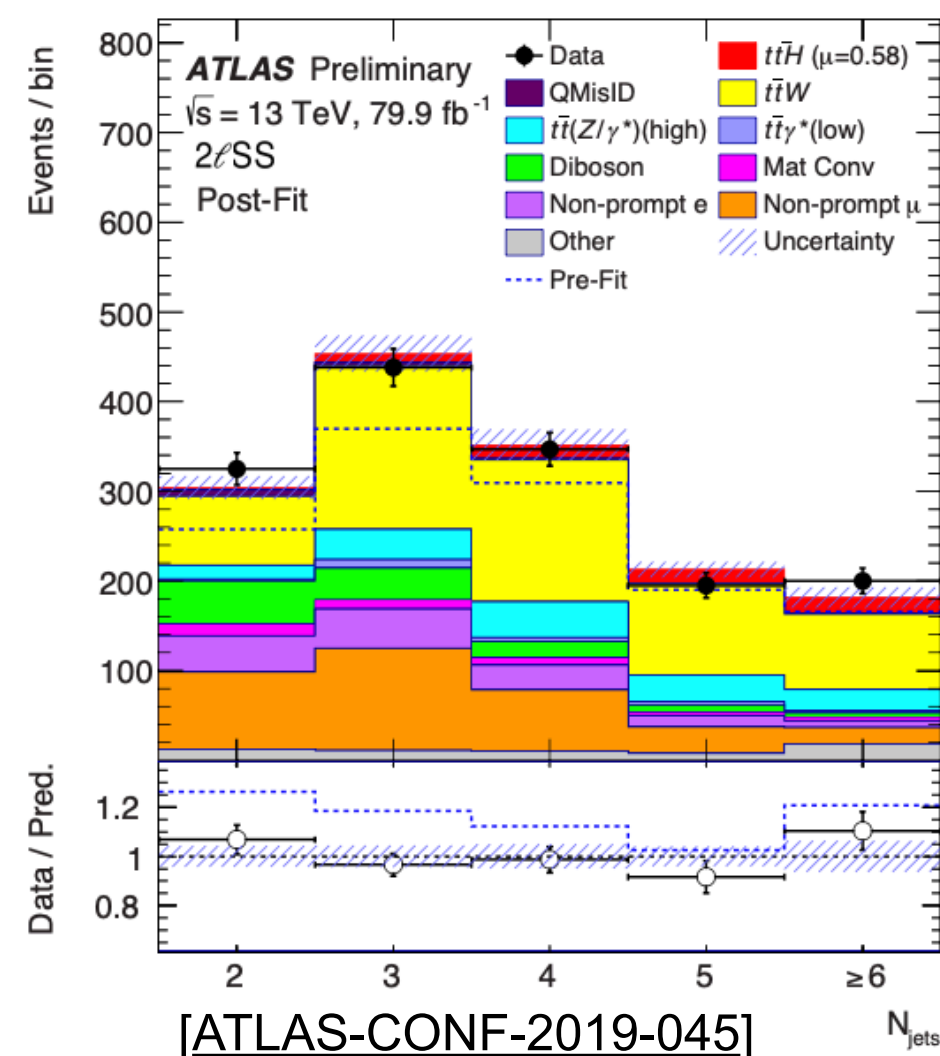
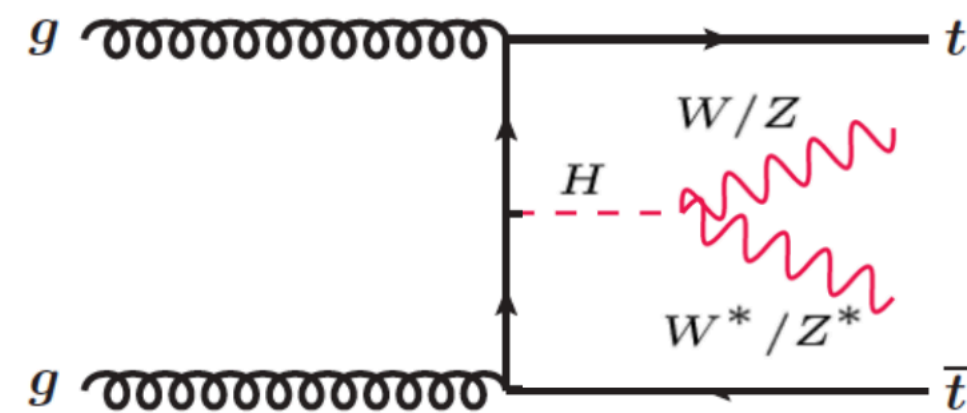
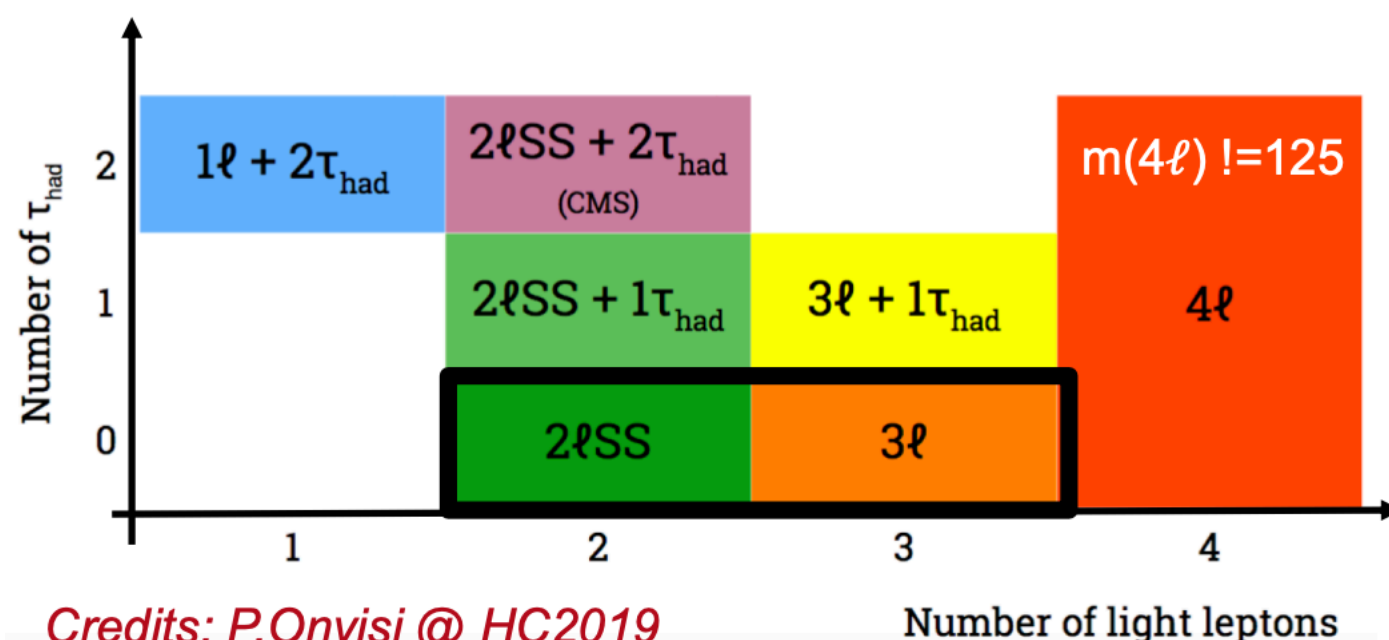


- Jets from b-hadrons are easier to identify
- B-hadron's long-lifetime & large mass
- Presence of displaced tracks
- Presence of secondary vertices ($B \rightarrow C \rightarrow \text{light}$)

ttH

ttH with multi-lepton final state

- Multi-lepton signatures
 - target $H \rightarrow WW^*, \tau\tau, ZZ^*$ decays
($t\bar{t} \rightarrow \geq 1l, H \rightarrow \geq 1l$)
- Rare signature in the SM
 - Small branching ration
- Several categories split based on the number of electrons, muons, hadronic taus
 - Most sensitive channels are the 2lSS and 3l
- Main backgrounds: ttW, ttZ, non-prompt leptons



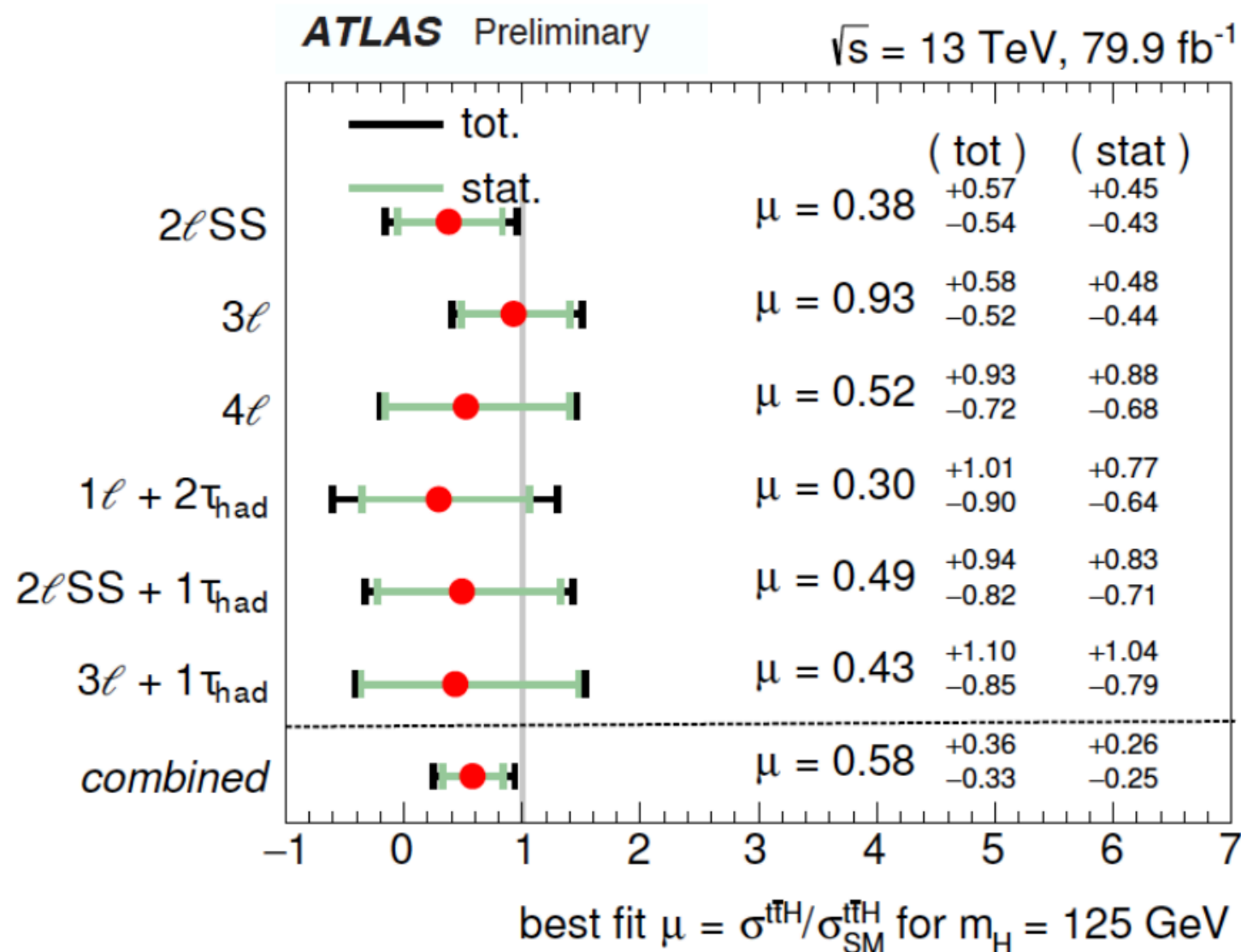
Credits: P.Onyisi @ HC2019

Number of light leptons

ttH with multi-lepton final state

Preliminary results using 80 fb⁻¹

[ATLAS-CONF-2019-045]



$$\hat{\lambda}_{t\bar{t}W}^{2\ell\text{LJ}} = 1.56^{+0.30}_{-0.28}, \hat{\lambda}_{t\bar{t}W}^{2\ell\text{HJ}} = 1.26^{+0.19}_{-0.18}, \text{ and } \hat{\lambda}_{t\bar{t}W}^{3\ell} = 1.68^{+0.30}_{-0.28}$$

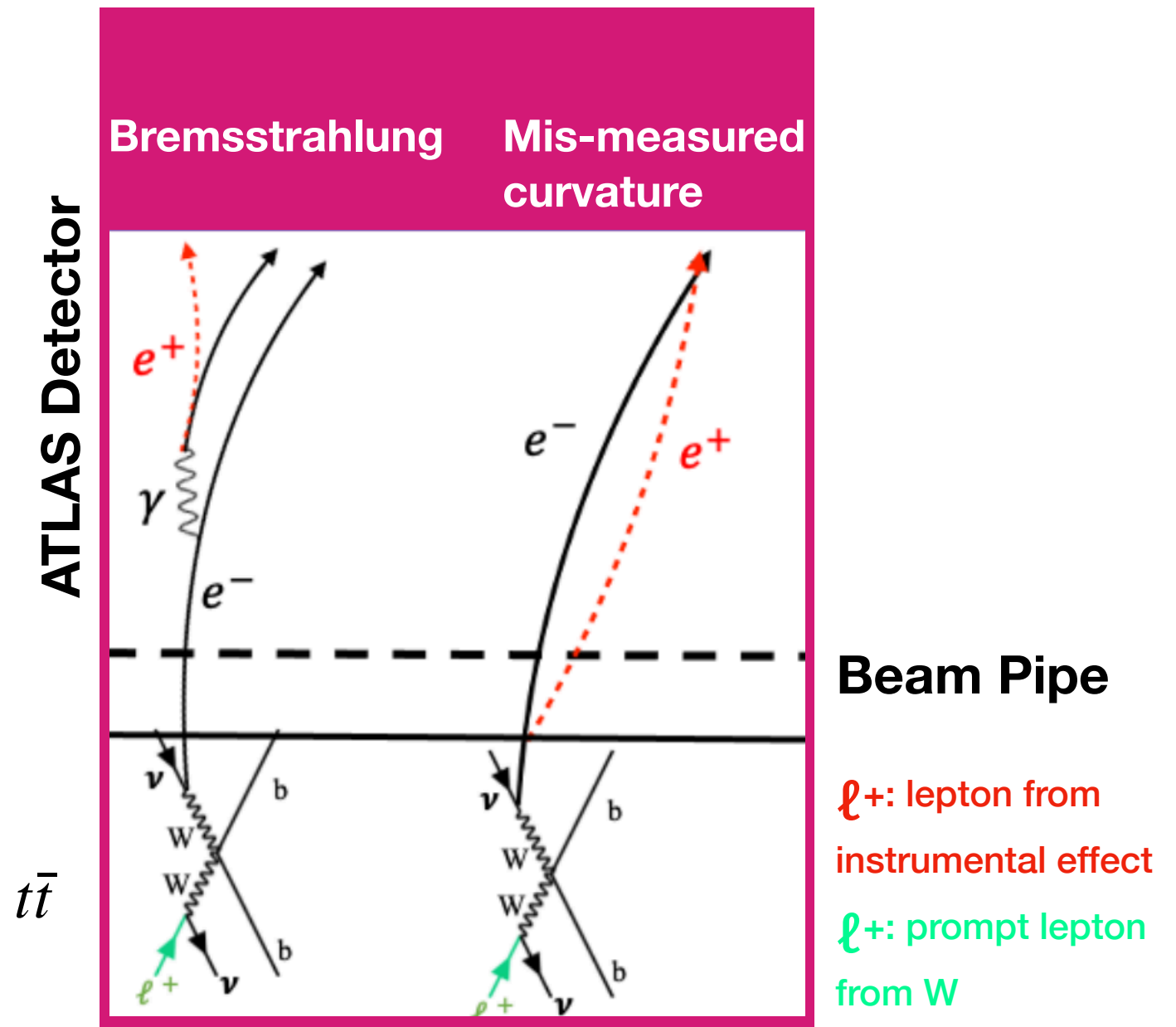
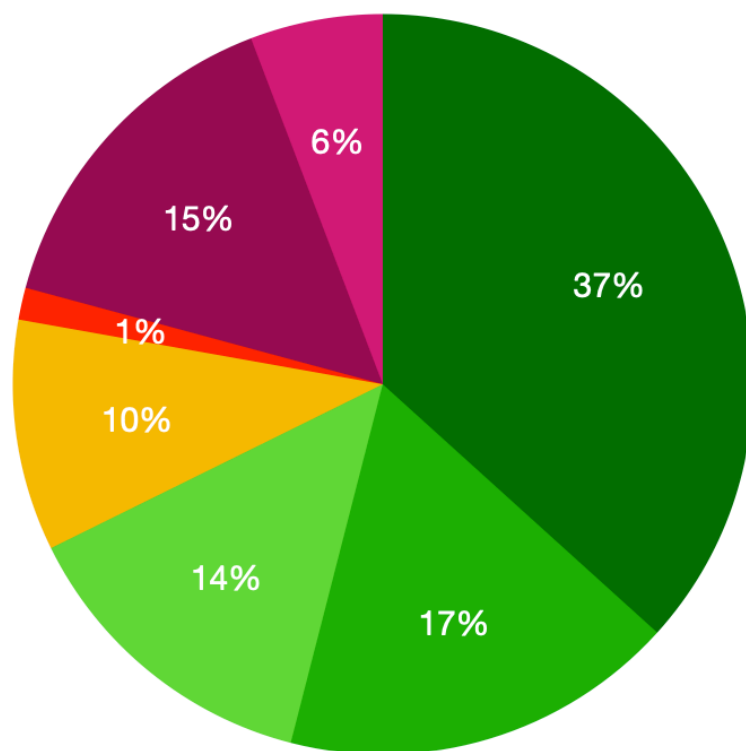
Large $t\bar{t}W$ +jets background normalisation factor!
Leading the ongoing ttH analysis using the full run 2 data-set



Backgrounds in $2\ell\text{SS}/3\ell$ Channel

- **Reducible backgrounds** (3 dedicated control regions):
 - **Charge mis-assignment (6%)** and relevant for the $2\ell\text{SS}$ channel
 - Charge of electron is mis-measured, caused by:
 - Bremsstrahlung photon emission followed by its conversion
 - Mis-measured track curvature

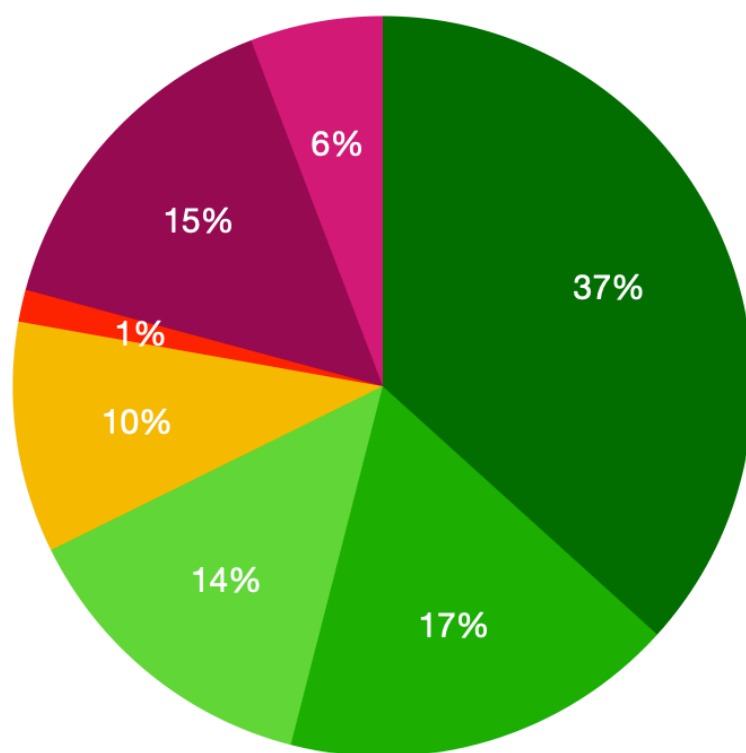
● ttW
 ● ttZ
 ● ttH
 ● Other
 ● ttt
 ● Fake
 ● Q misID



Backgrounds in 2 ℓ SS/3 ℓ Channel

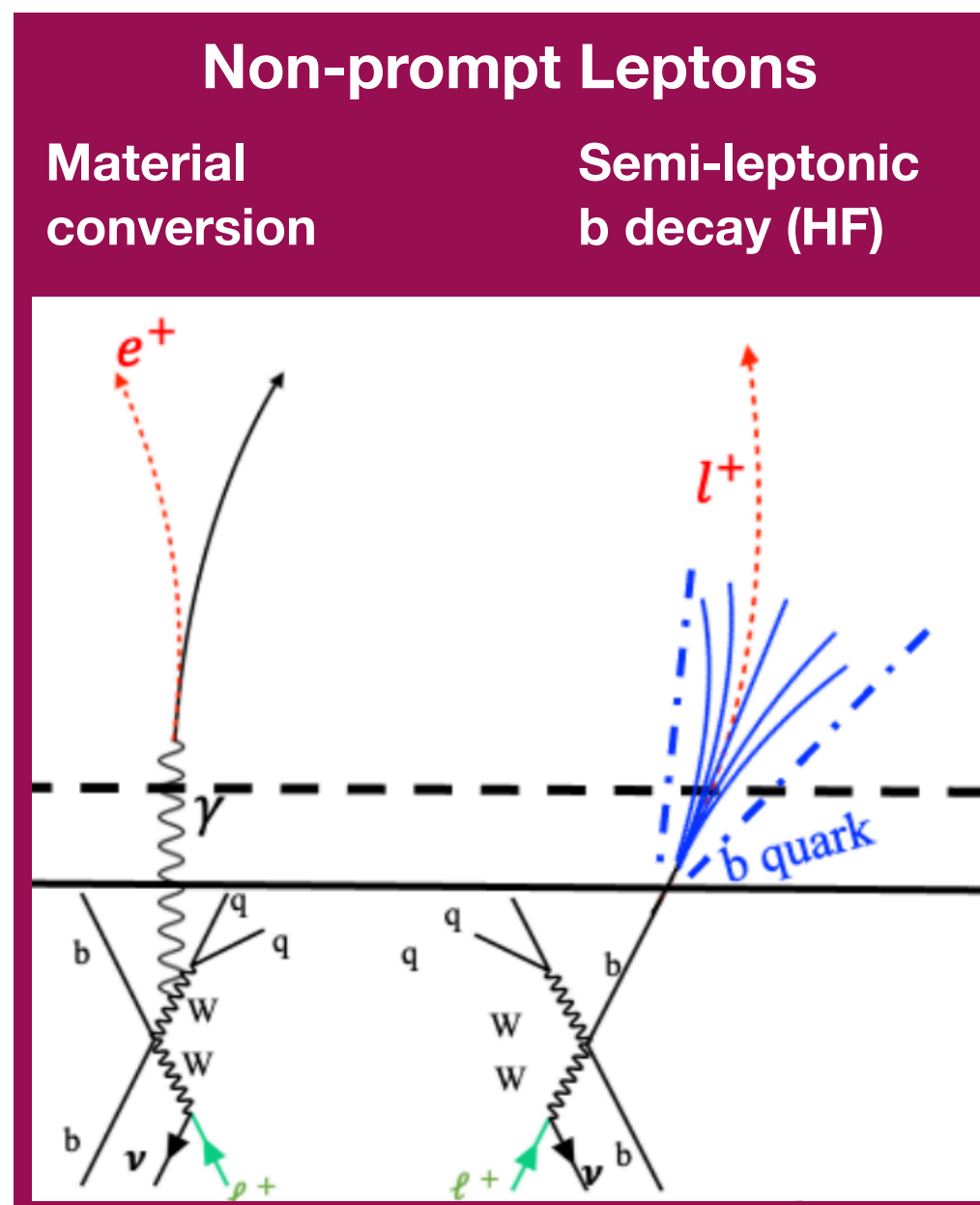
- Fake and non-prompt backgrounds (15%):
 - electrons from γ conversion in detector
 - a virtual photon γ^* leading to an e^+e^- pair (Low M_{ee})
 - electrons (muons) from heavy-flavour (HF) decay

● ttW
 ● ttZ
 ● ttH
 ● Other
 ● ttt
 ● Fake
 ● Q misID



ATLAS Detector

$t\bar{t}$



Beam Pipe

ℓ^+ : lepton from instrumental effect
 ℓ^+ : prompt lepton from W