The Thrilling World of Top Quark Physics
Dive into the Heaviest Known Particle

HASCO Summer School

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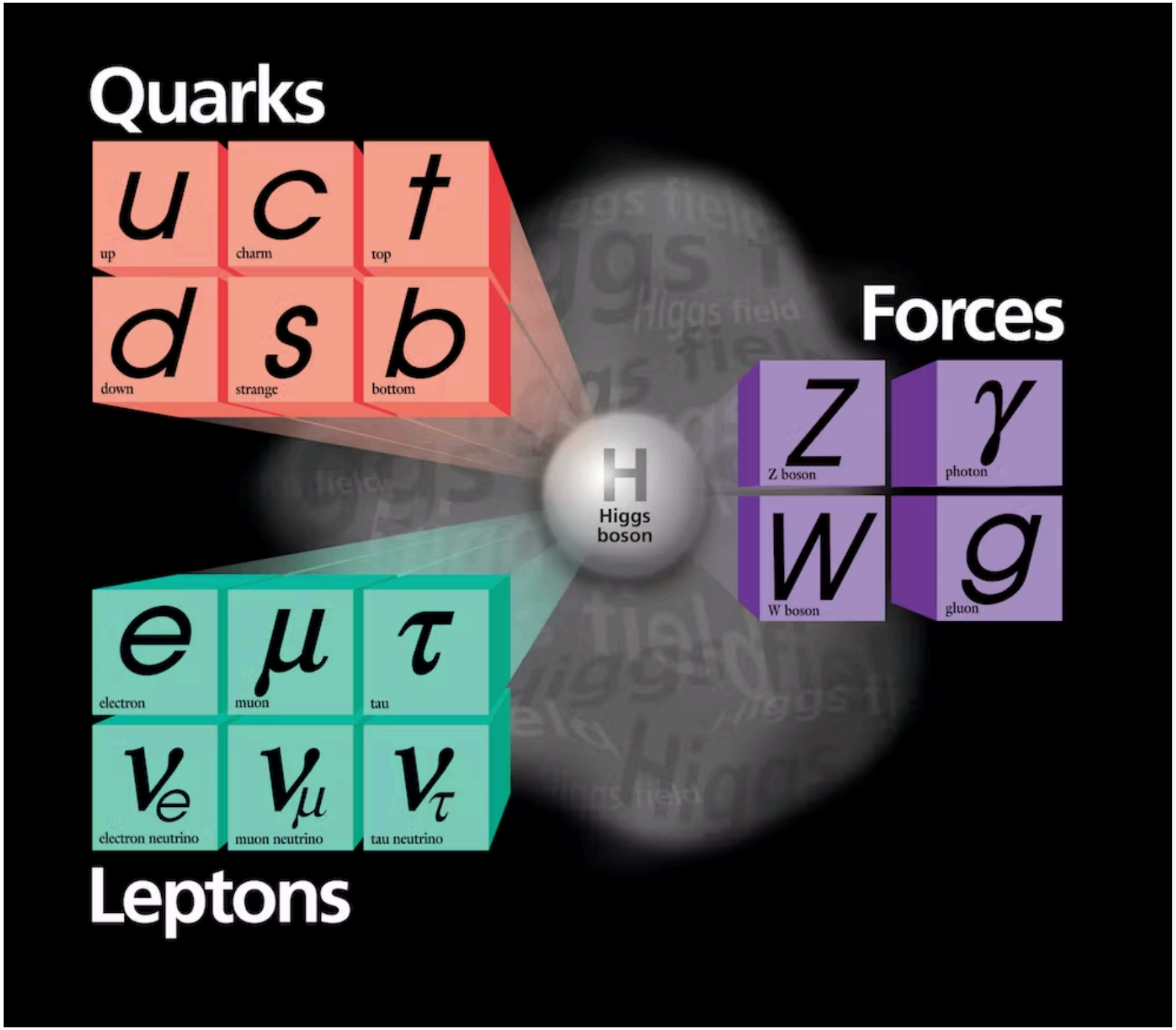
What to expect from My Lecture

- Fundamental Properties of the Top Quark
- Top Quark Production Mechanisms
- Top Quark and the Higgs Mechanism
- Precision Measurements
- Top Quark as a Probe for New Physics

This lecture highlights the rich nature of top quark physics

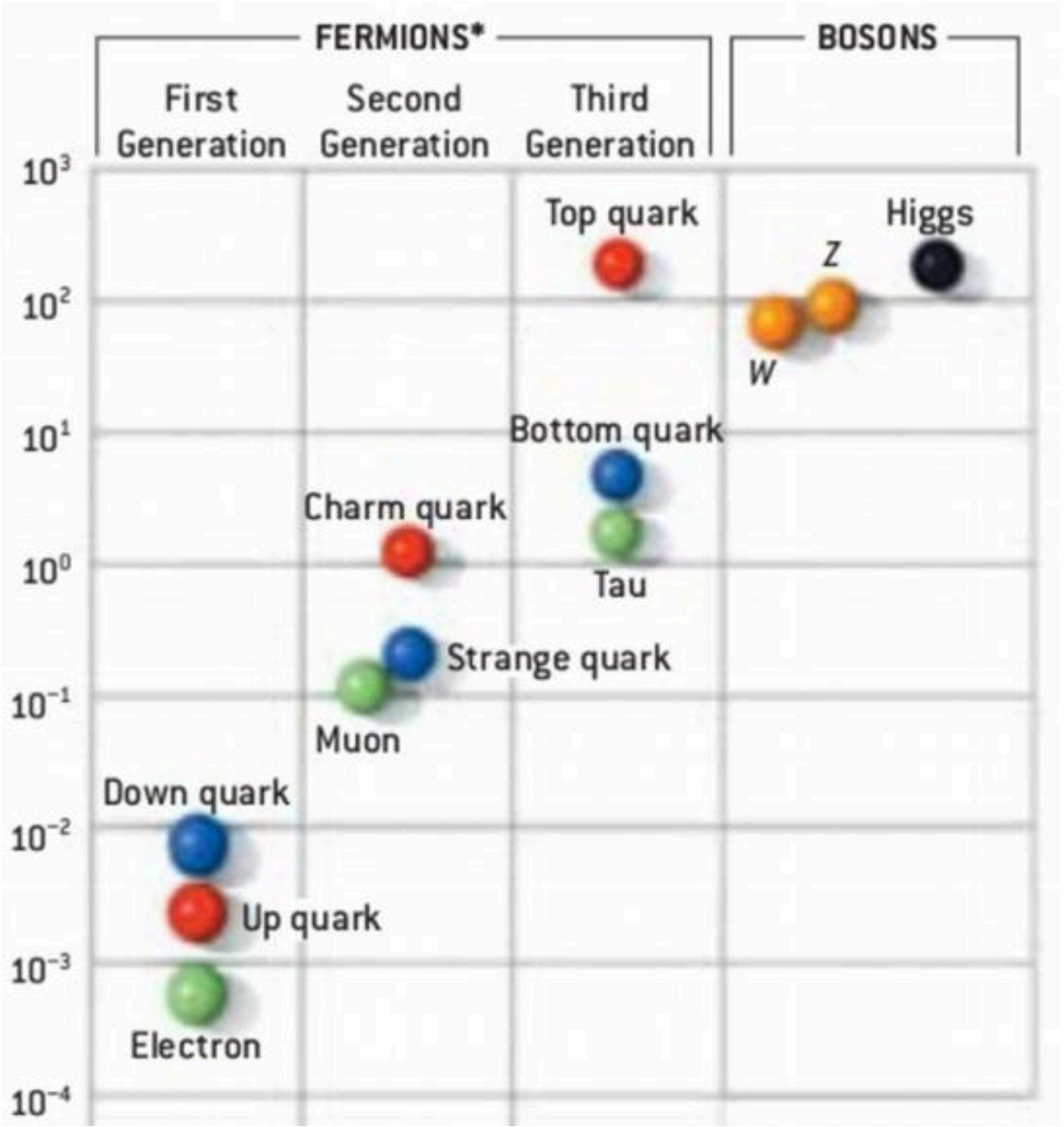
CERN

The Standard Model of Particle Physics

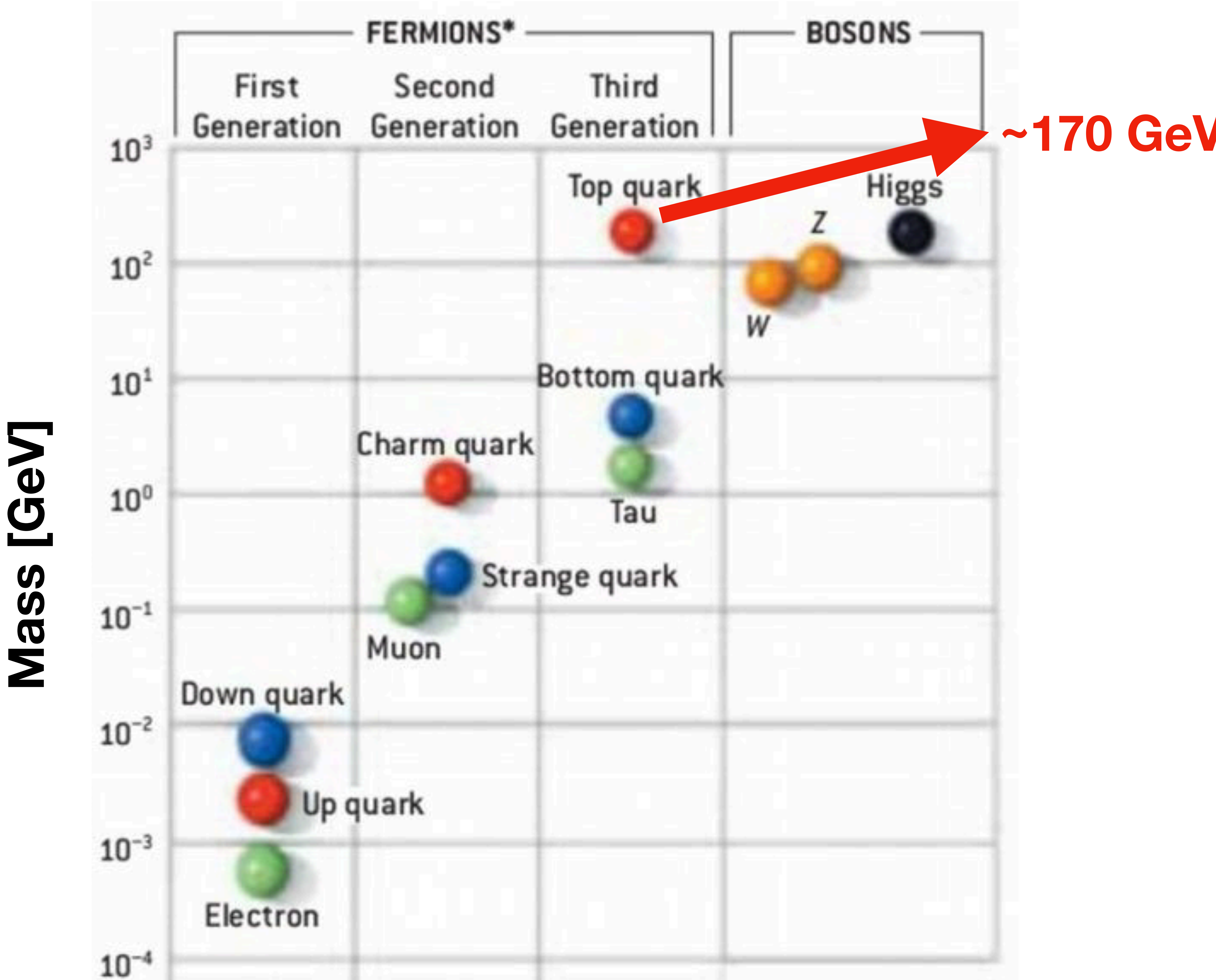


Mystery of Mass

Mass [GeV]



Mystery of Mass

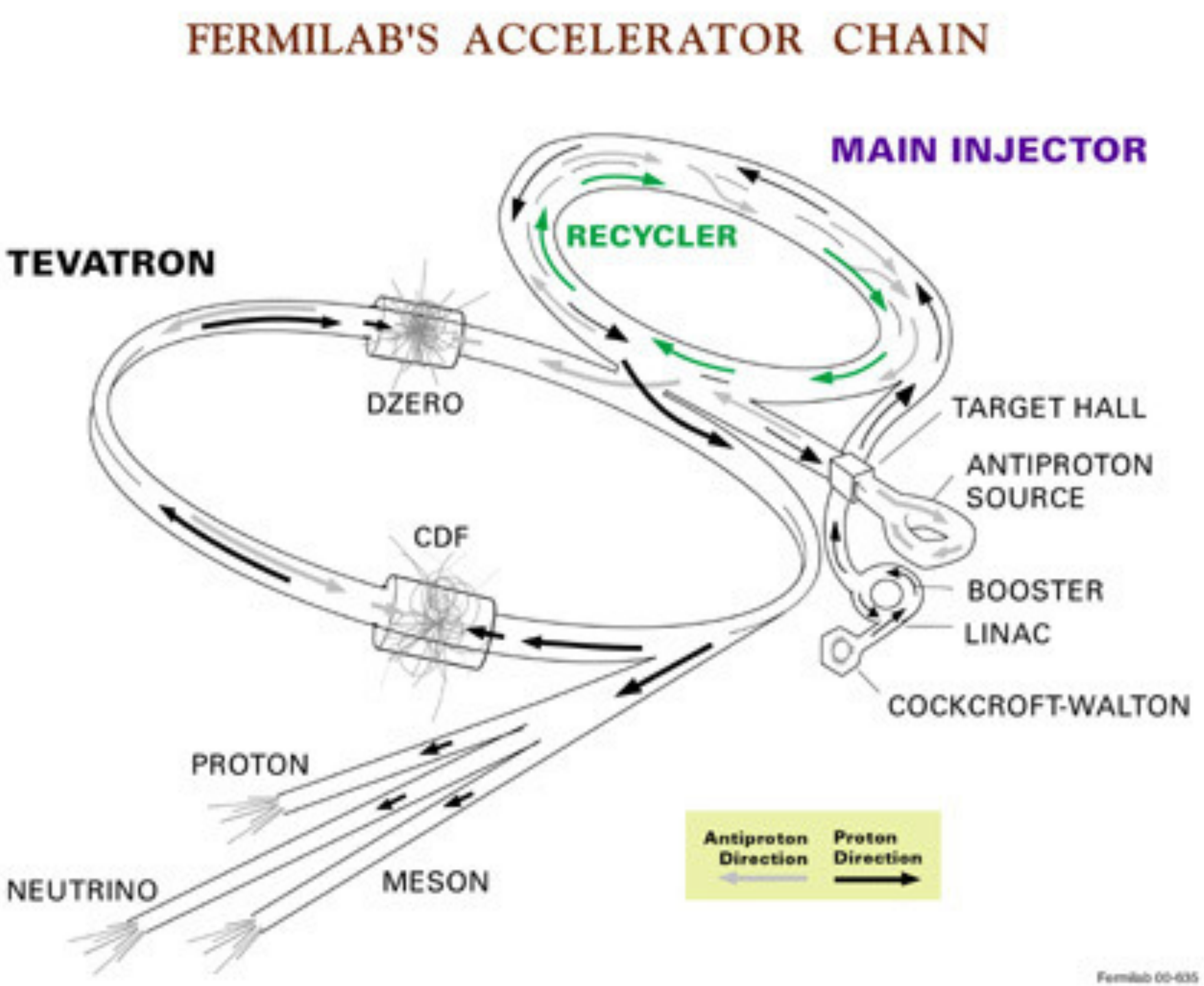


Discovery of the Top Quark

- 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



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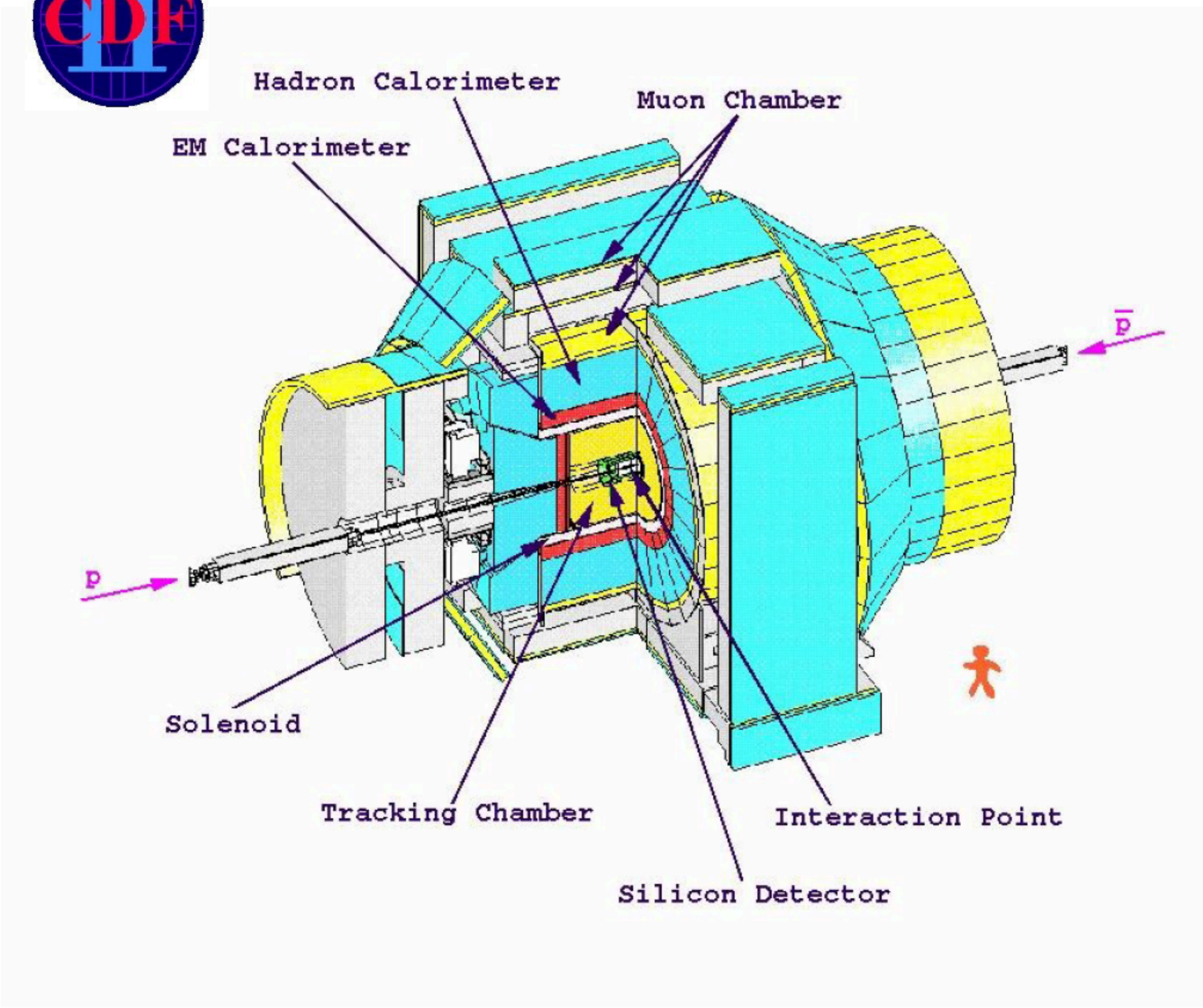

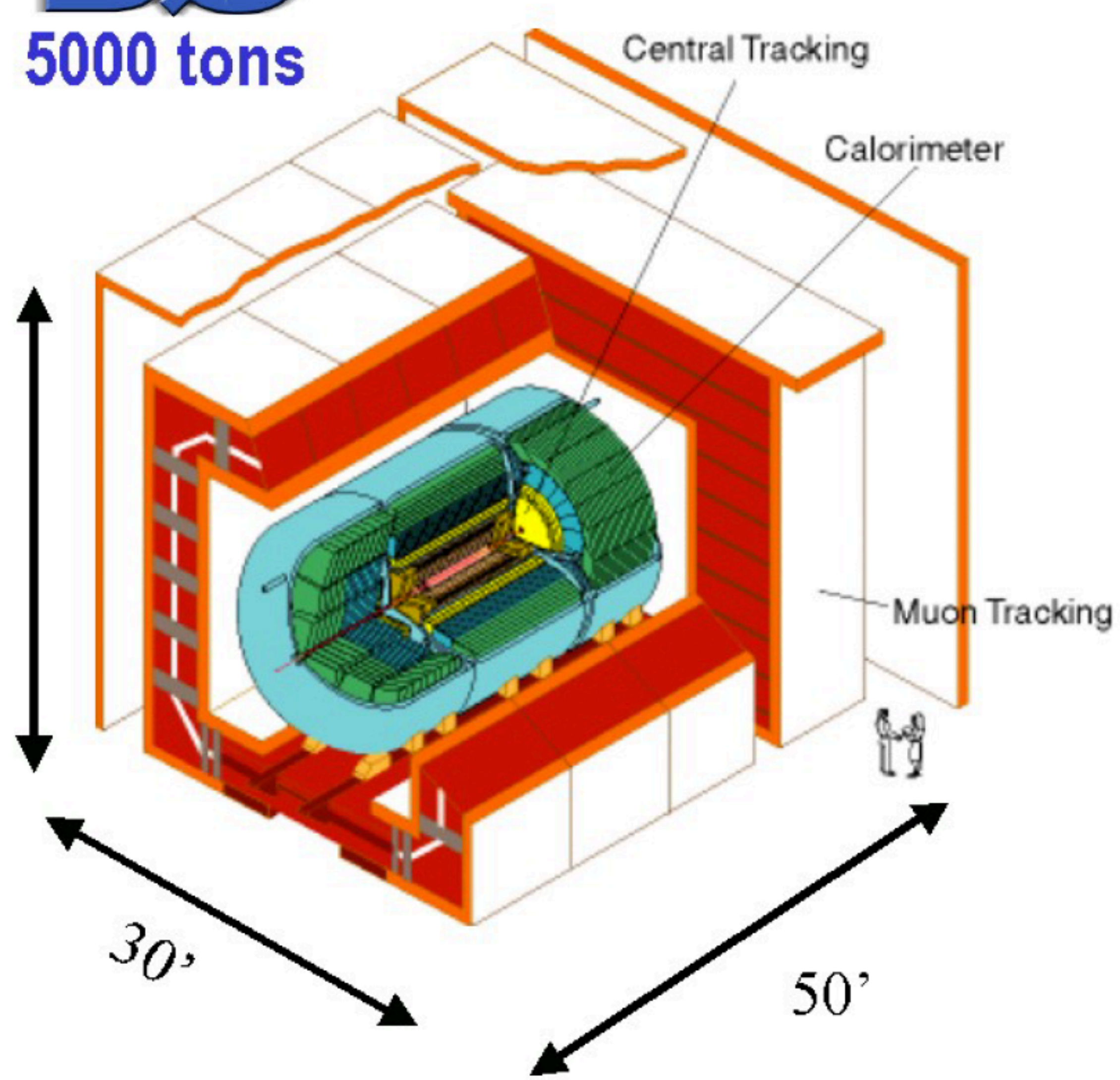

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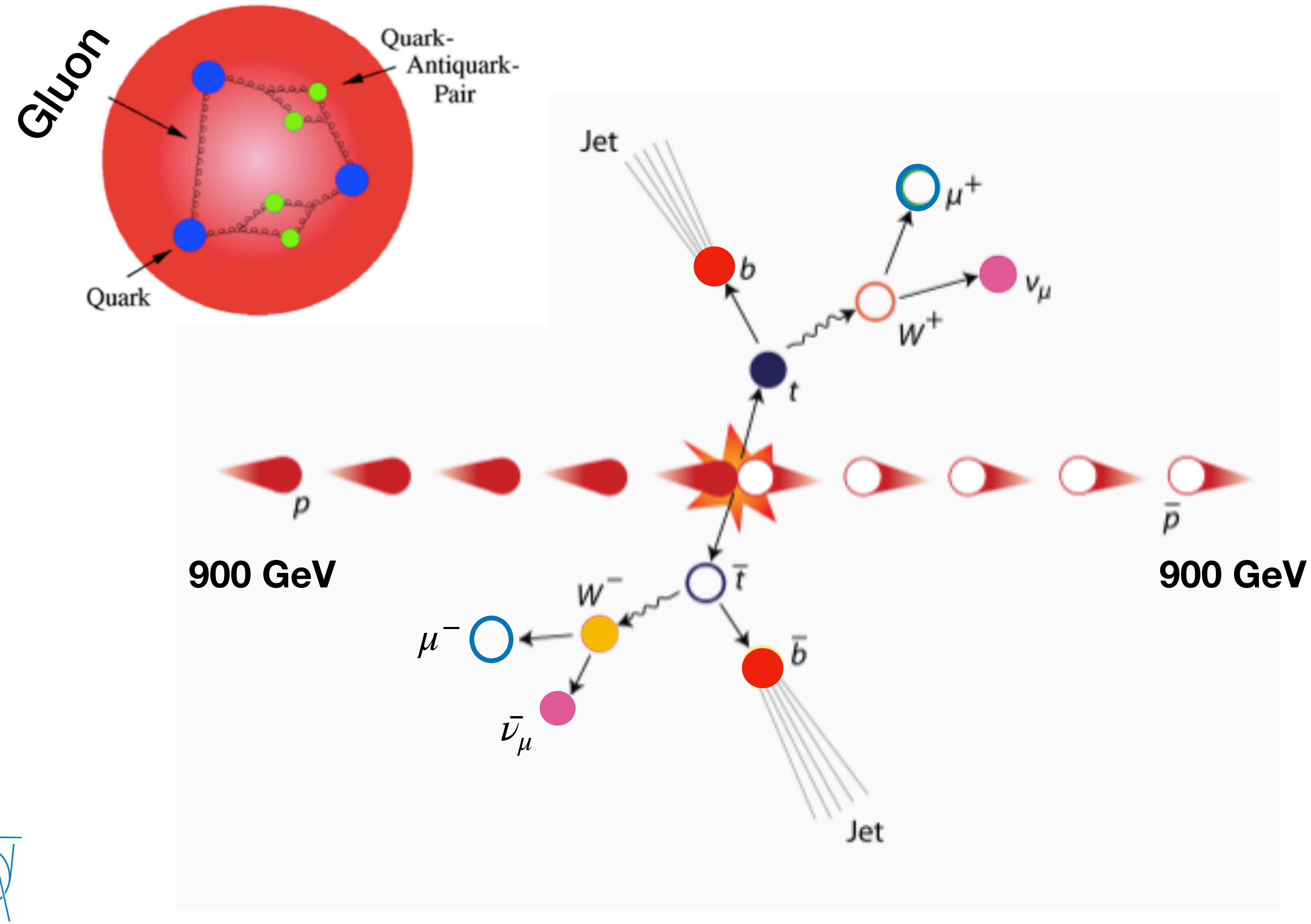
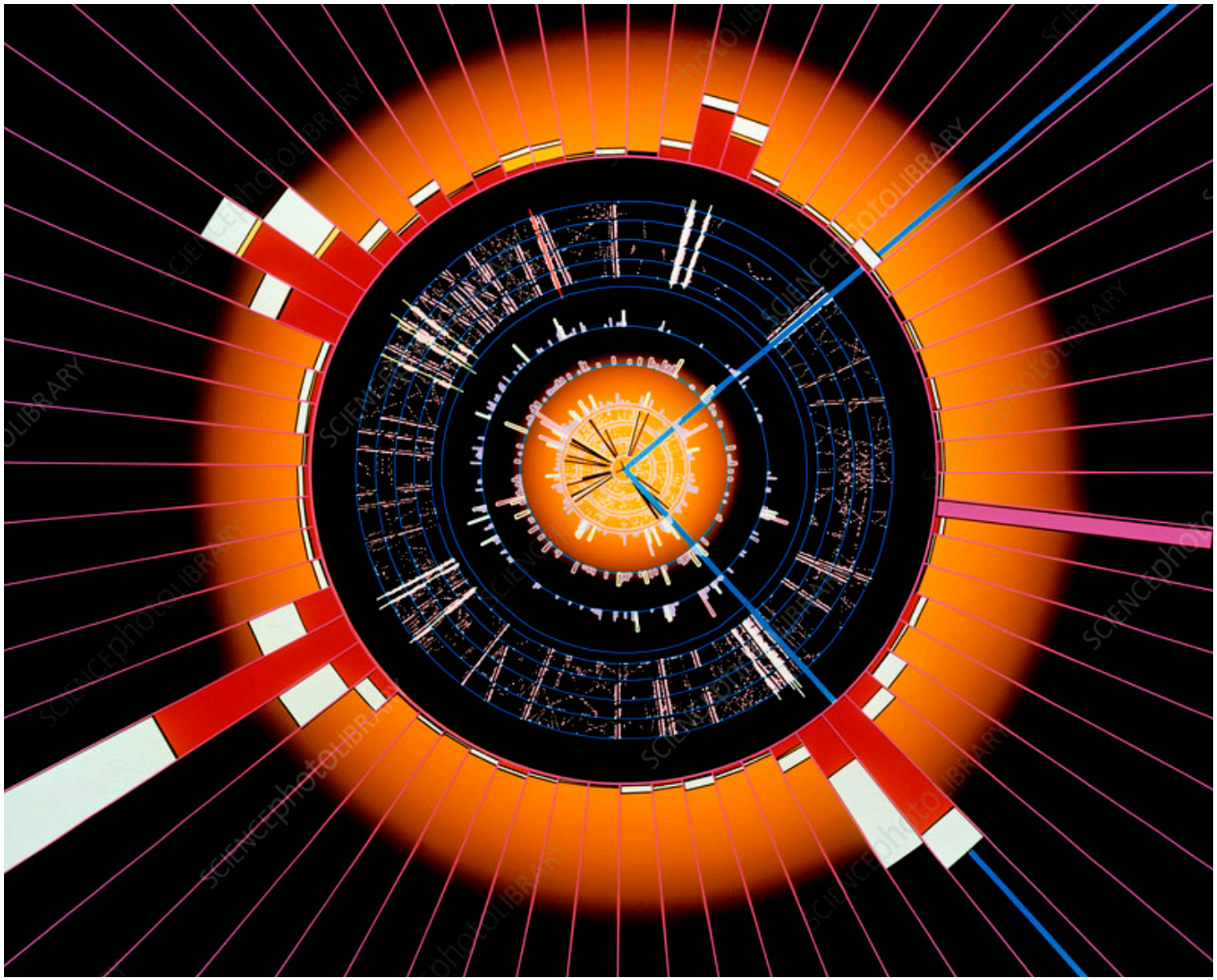


Top-quark discovered in 1995

One of the first top-quark pairs

muon



Invisible neutrinos

Jets

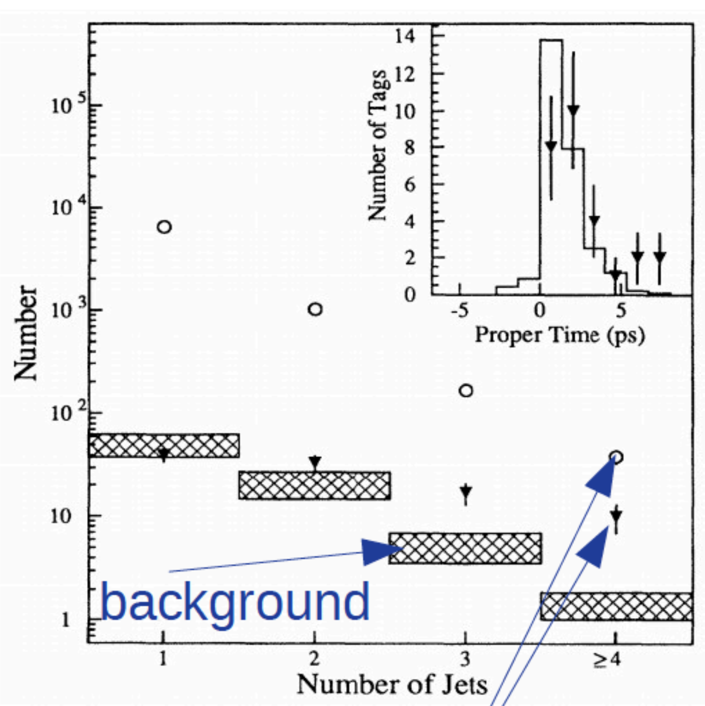
muon

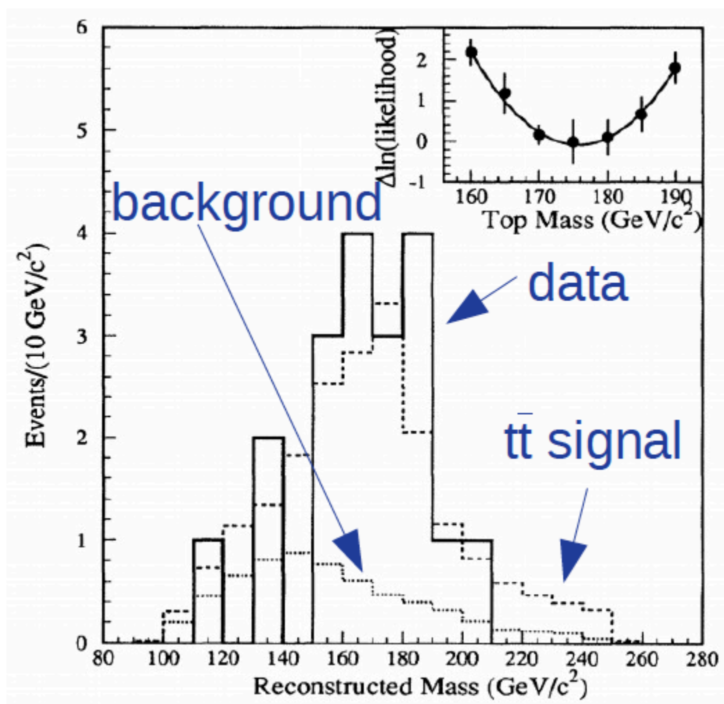
29 years old!

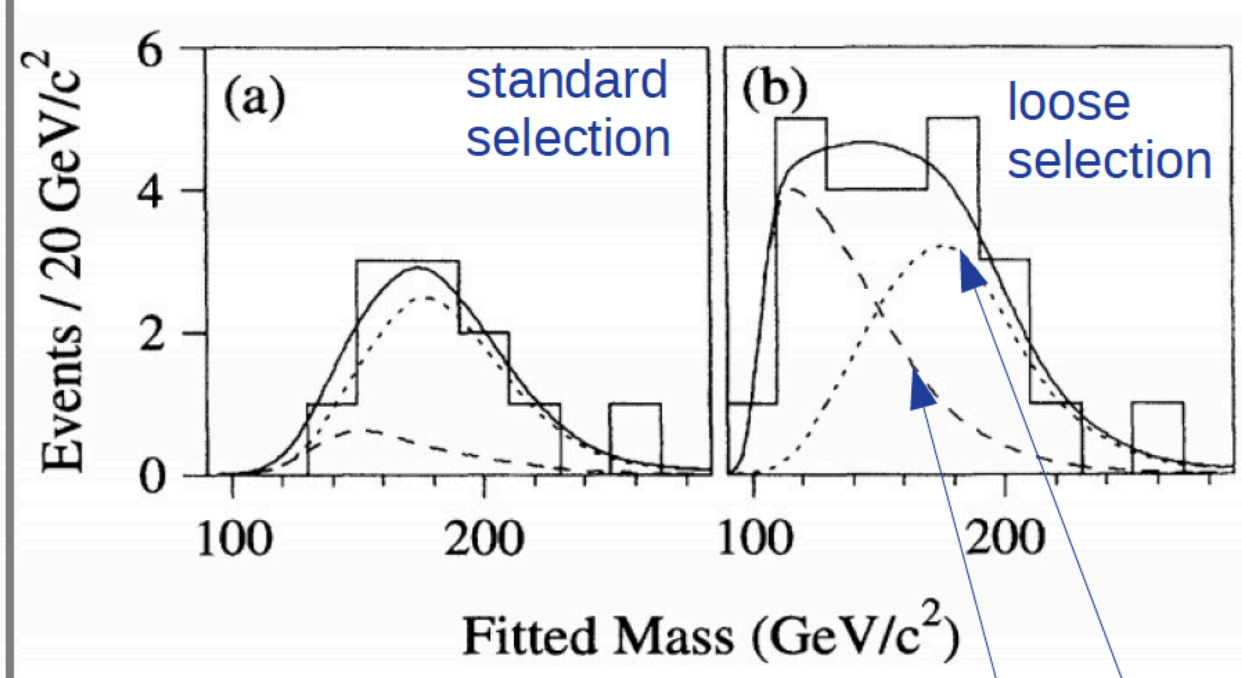
CERN

Top-quark discovered in 1995

Evidence of top quark by CDF and D0 with ~70 pb^{-1} of Run1 data





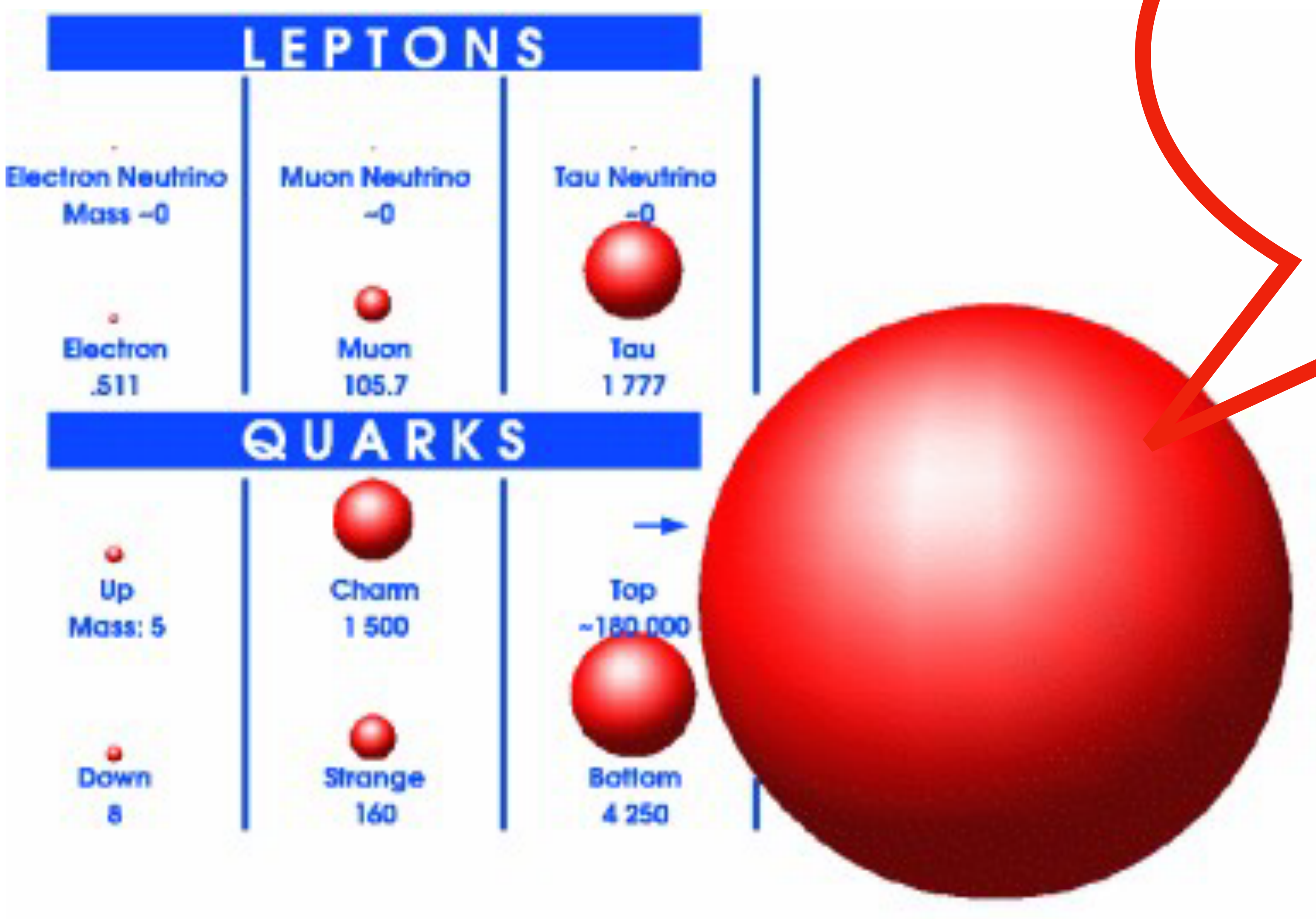


Number of events before and after secondary vertex tagging
Excess for N_{jets}>2

background
tt̄ signal

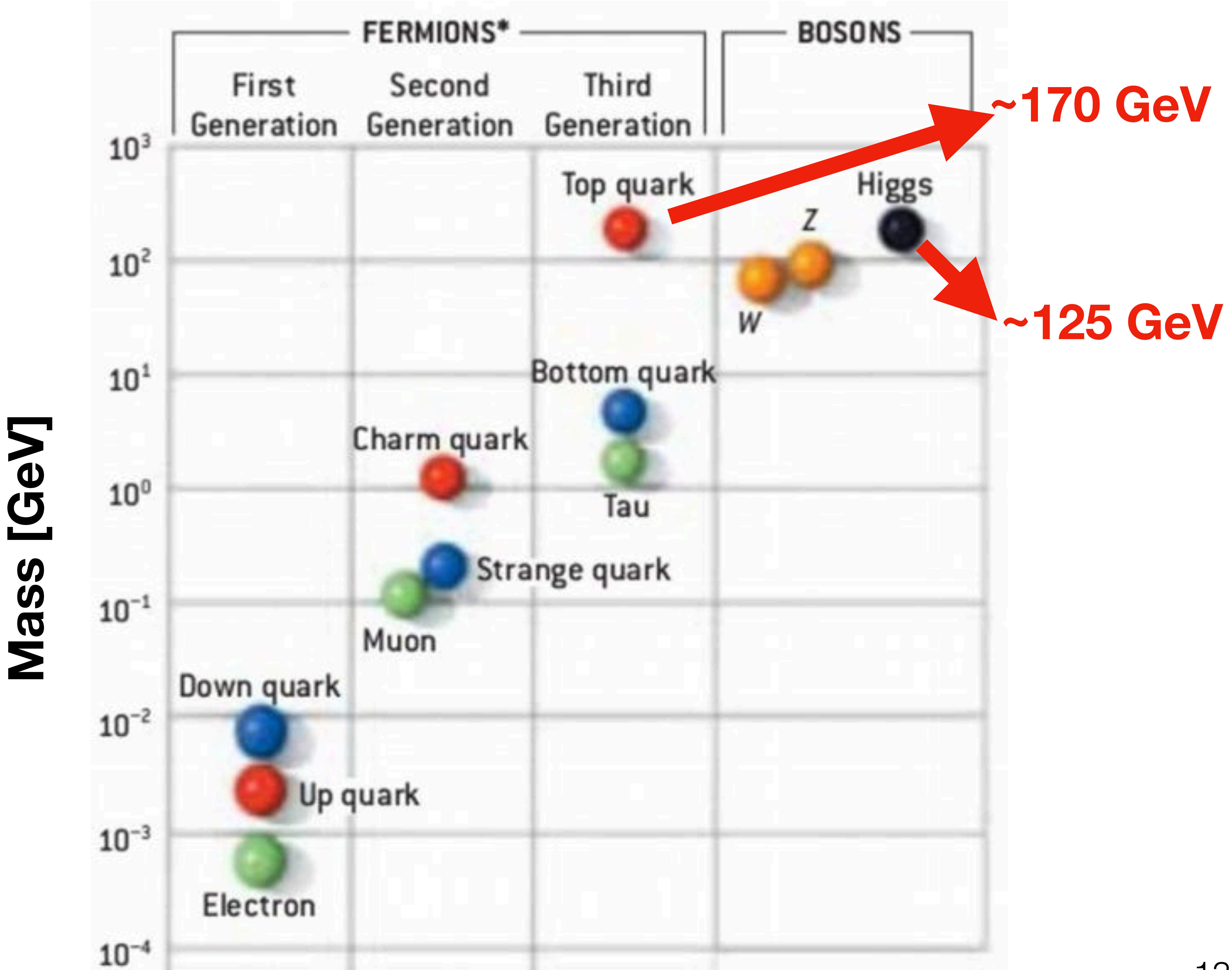
m_{top} = 176 ± 8 ± 10 GeV

Top-quark ID card!



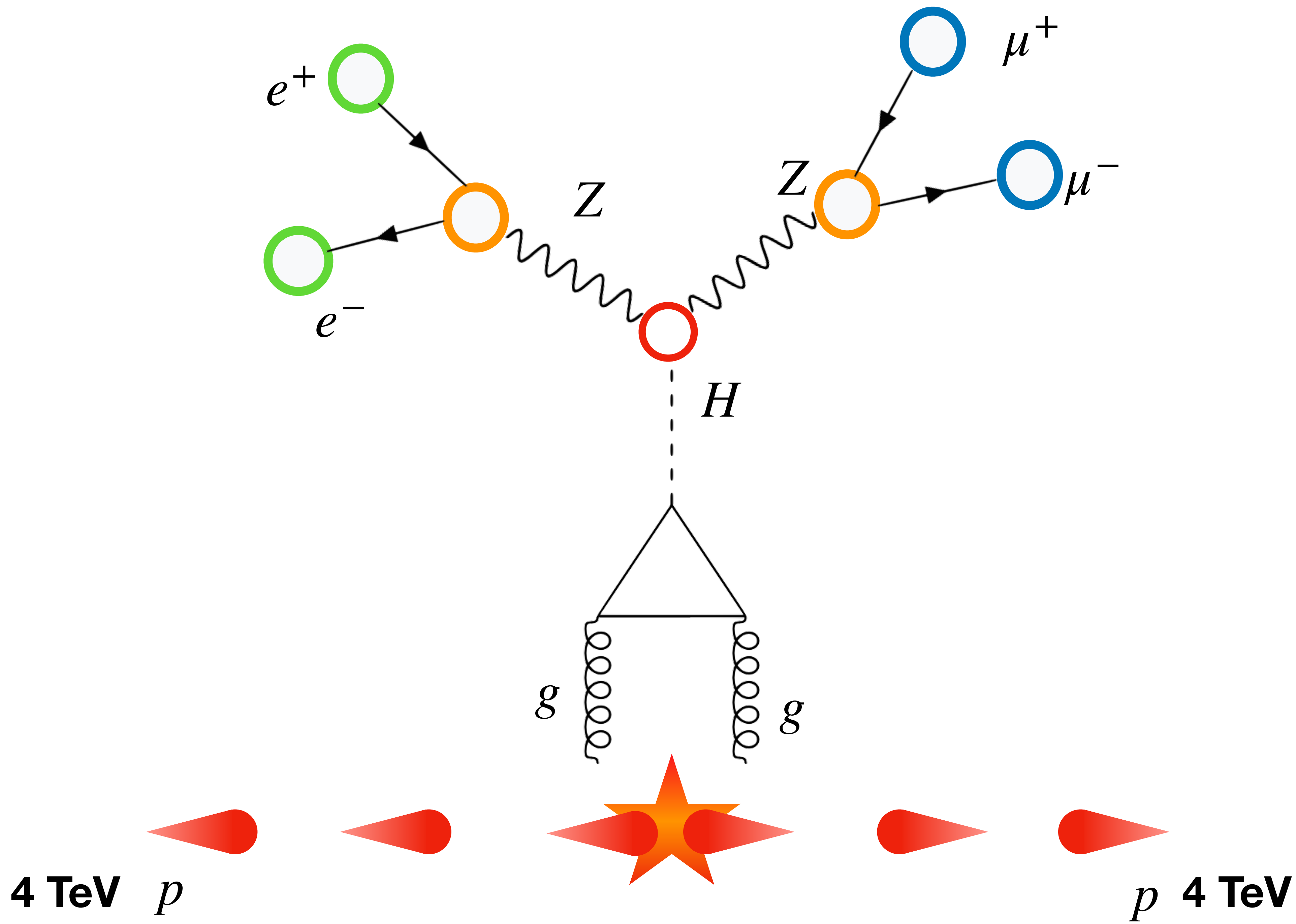
Birth: 1995, Fermilab
Mass: 172.5 GeV
Charge: +2/3 |e|
Spin: 1/2
Width: 1.3 GeV

Mystery of Mass

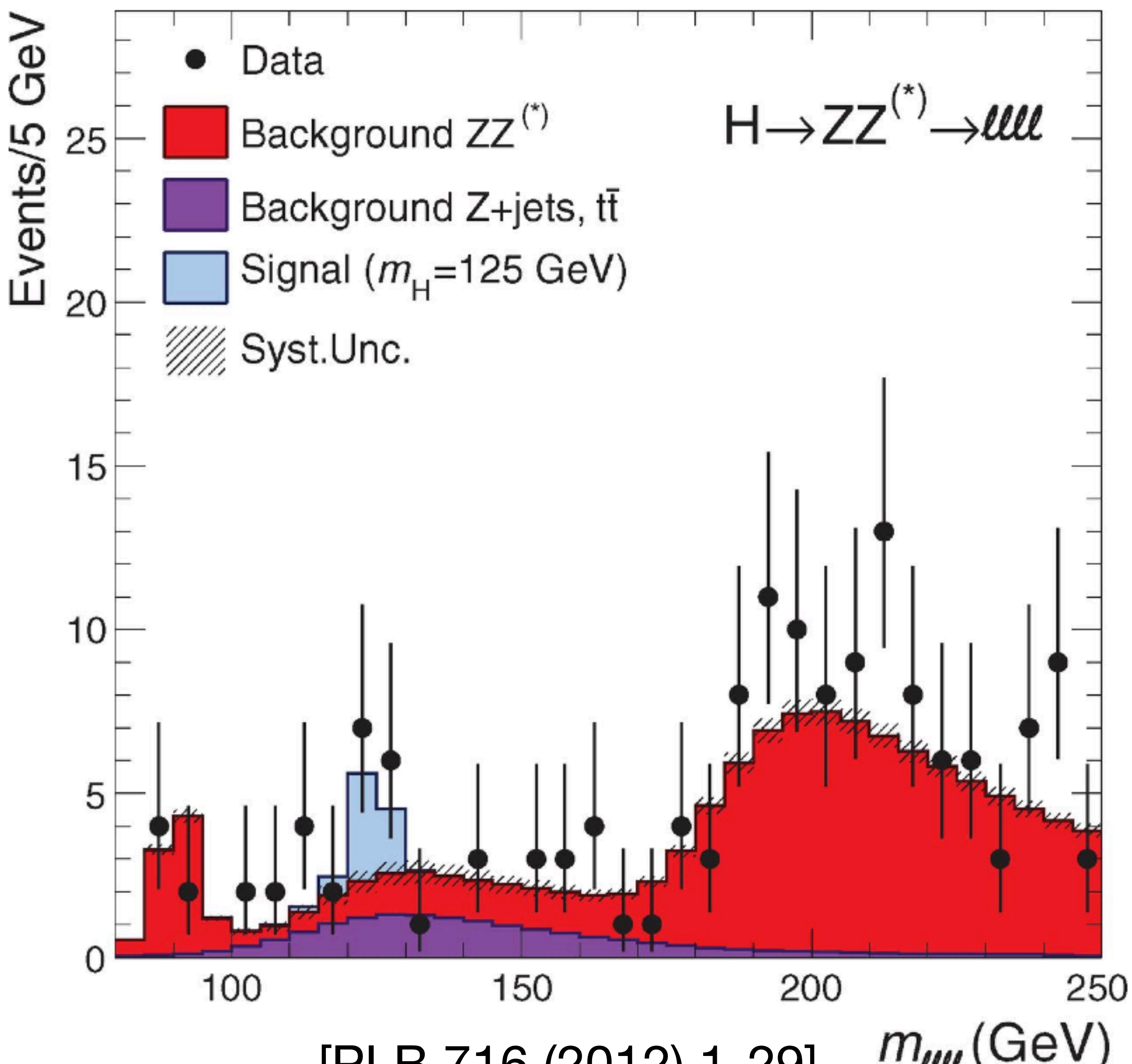


Discovery of the Higgs Boson

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



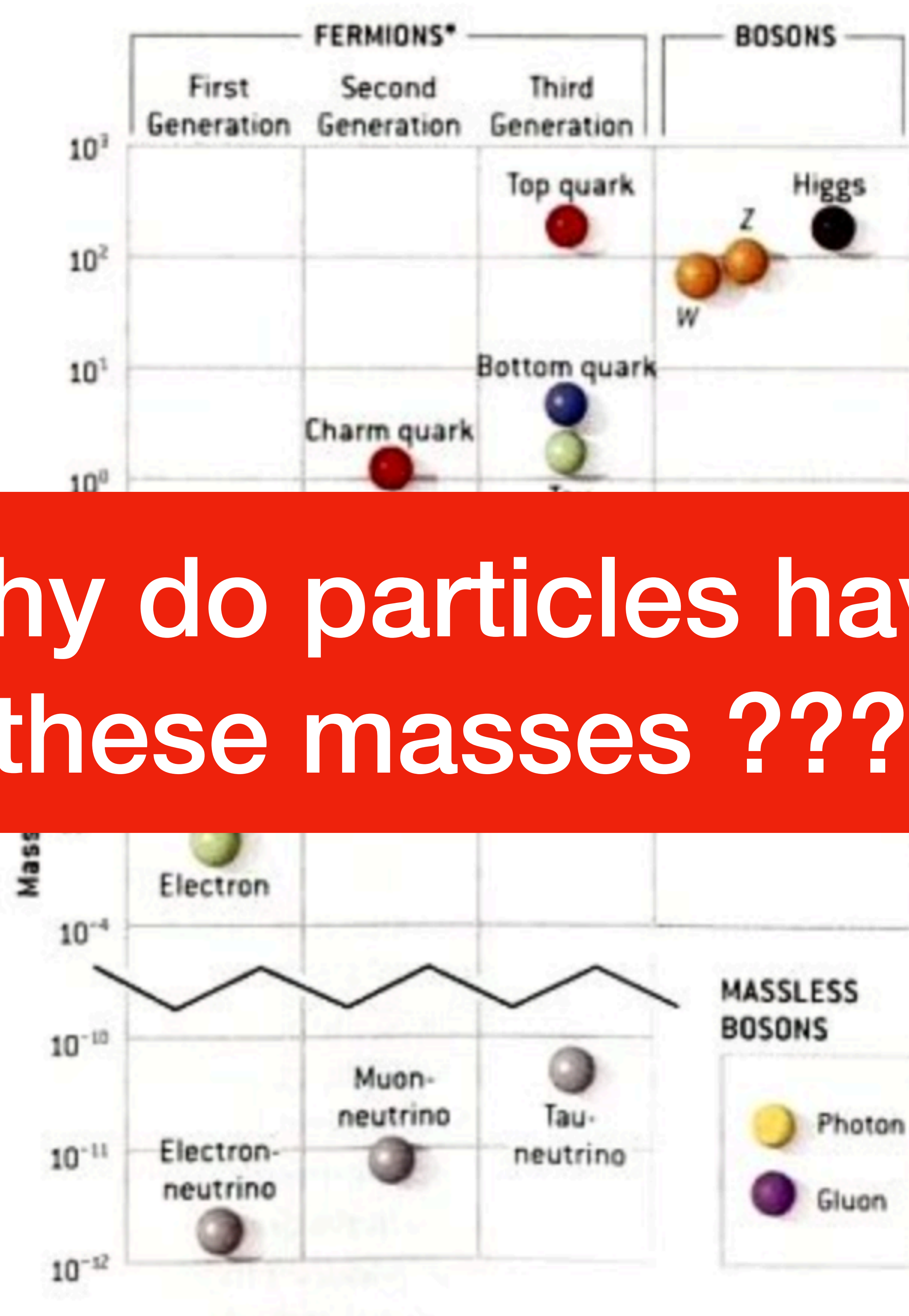
First Higgs observation at ATLAS in 4 lepton



[PLB 716 (2012) 1-29]

12 years old!

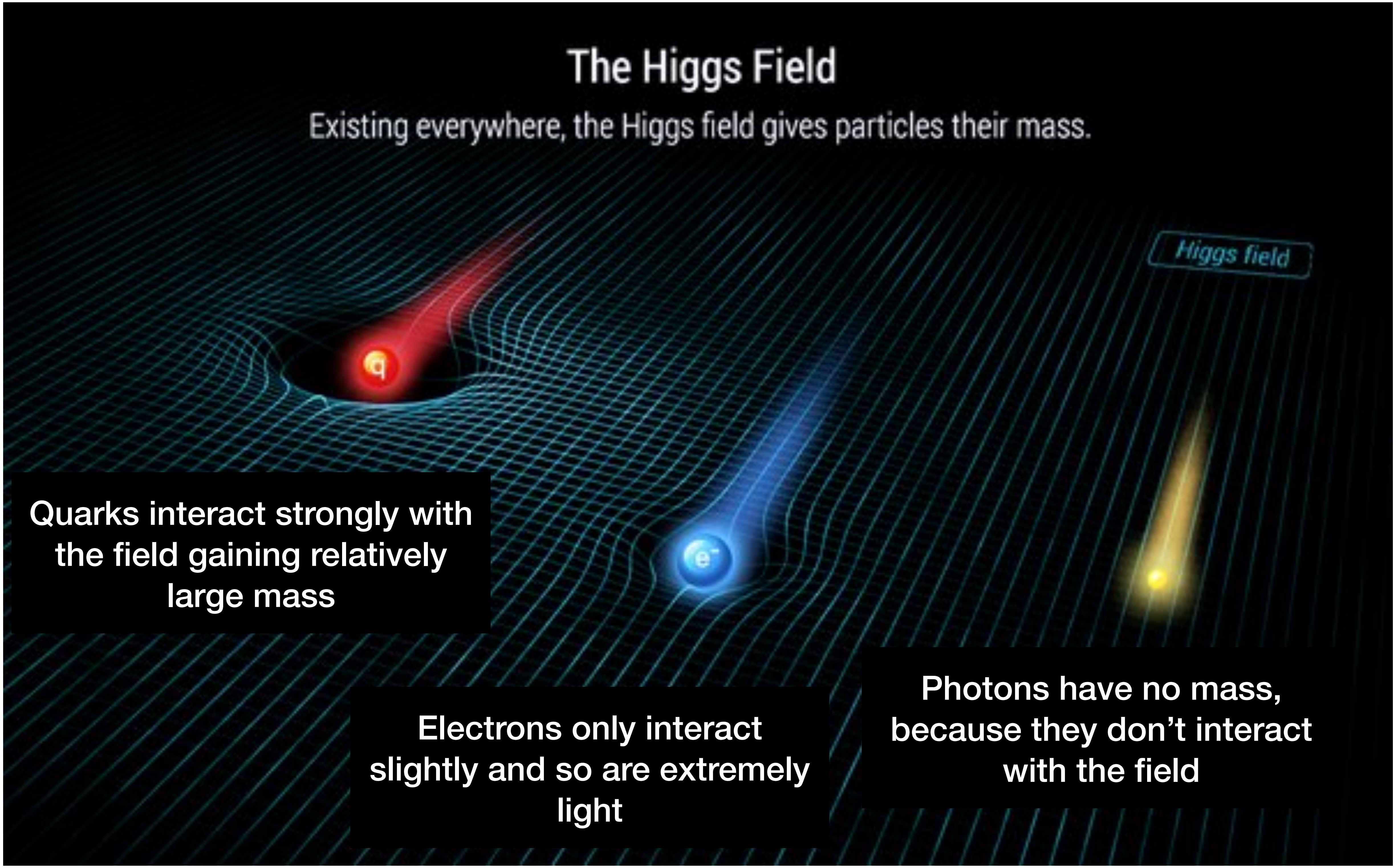
Mystery of Mass



Why do particles have these masses ???

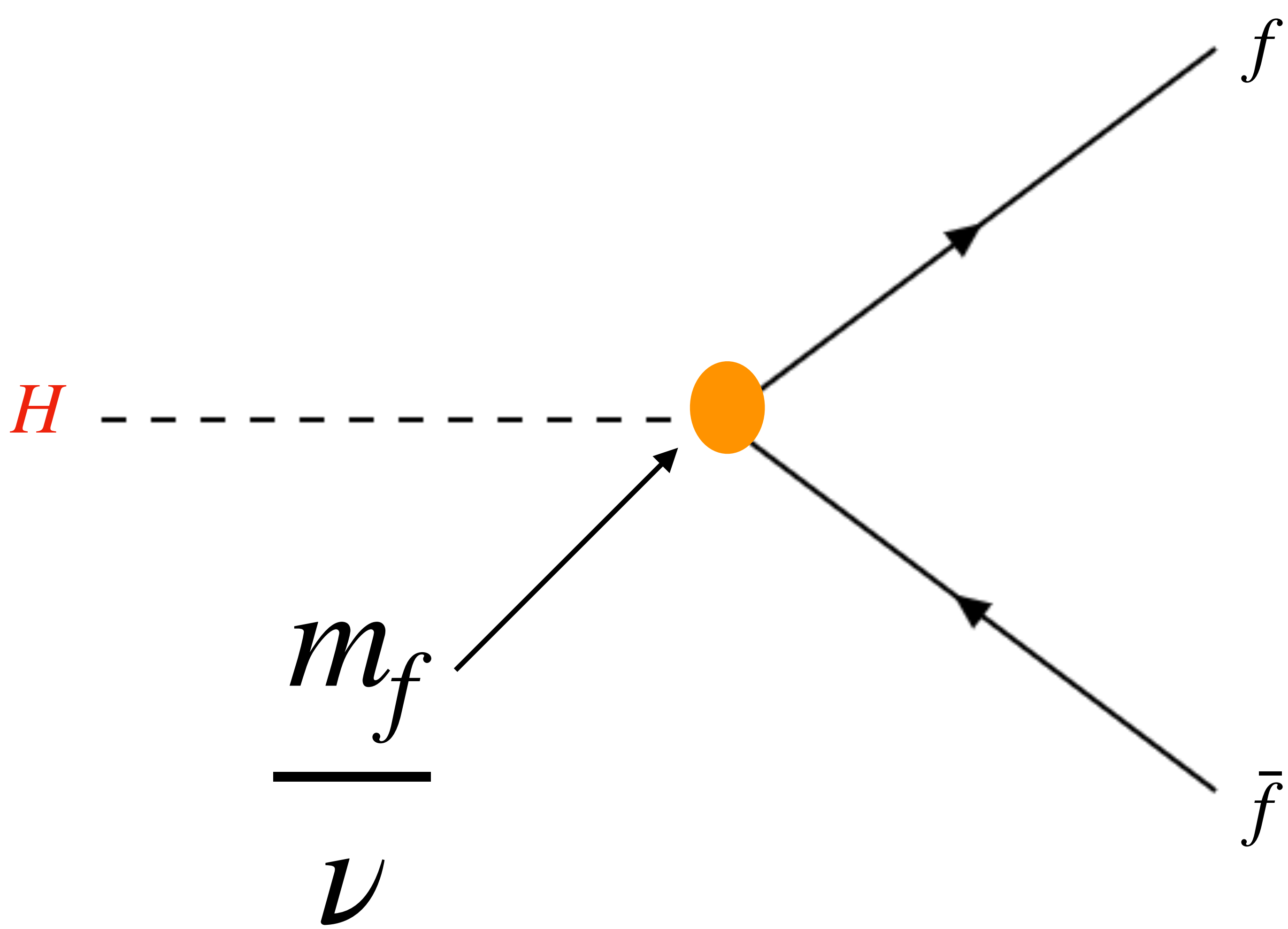
Higgs Mechanism

- Particles gain mass through interactions with the Higgs field



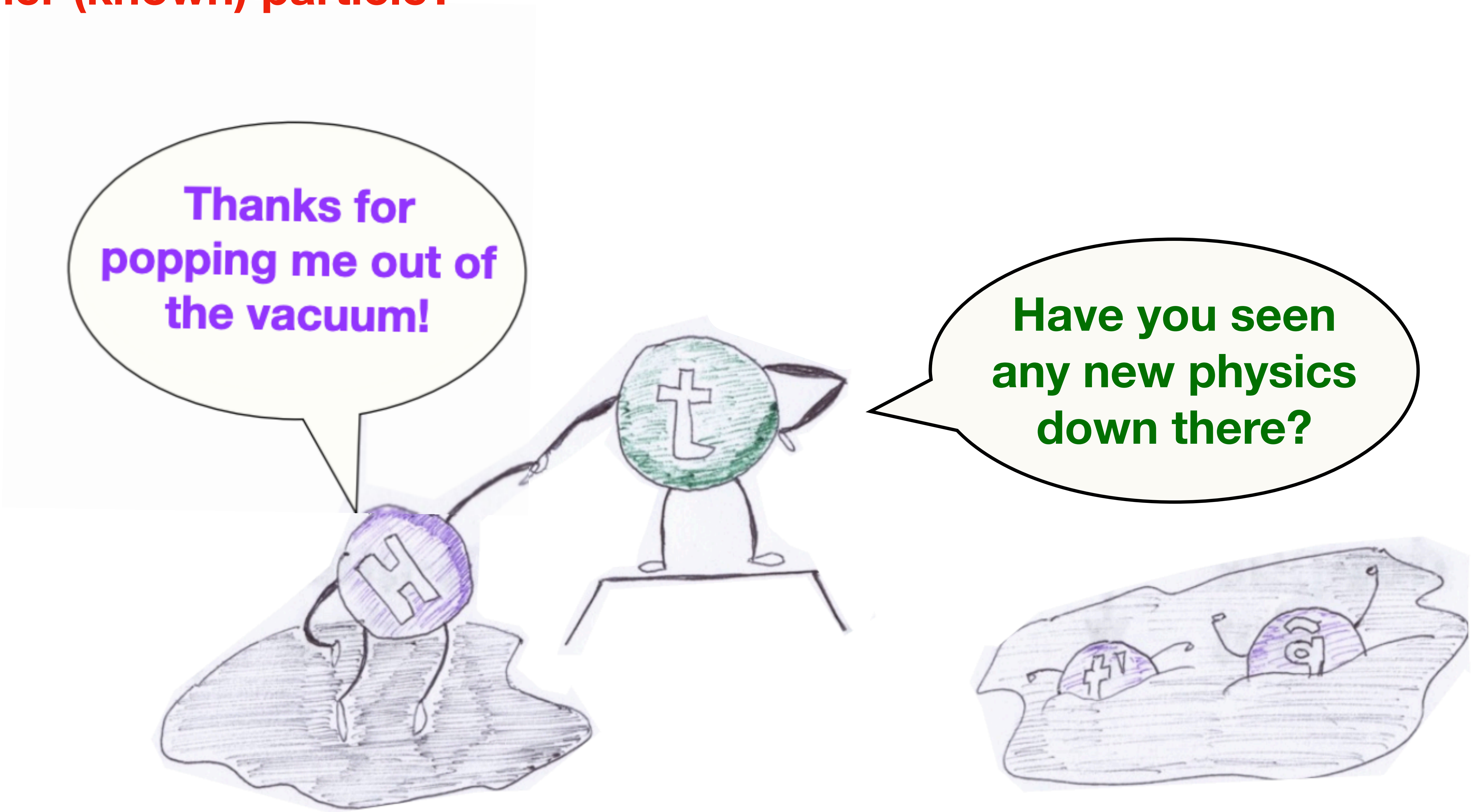
Higgs Mechanism

- 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!

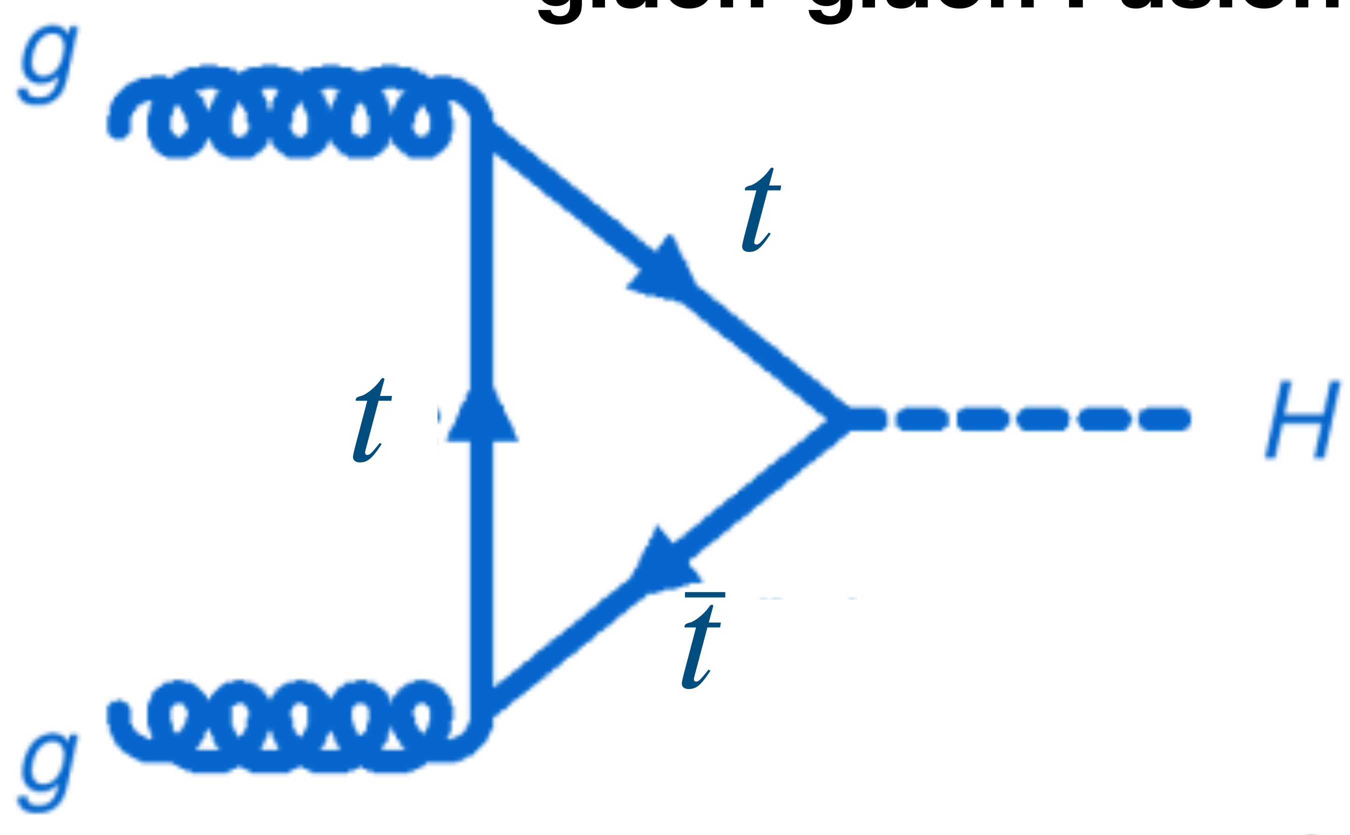
- Top-quark strongly interacts with the Higgs sector
  - top yukawa coupling $\mathbf{y_t \sim 1}$
- **Why do top quarks interact so much more with the Higgs than with any other (known) particle?**



Two ways to measure top-Higgs Coupling

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

gluon-gluon Fusion



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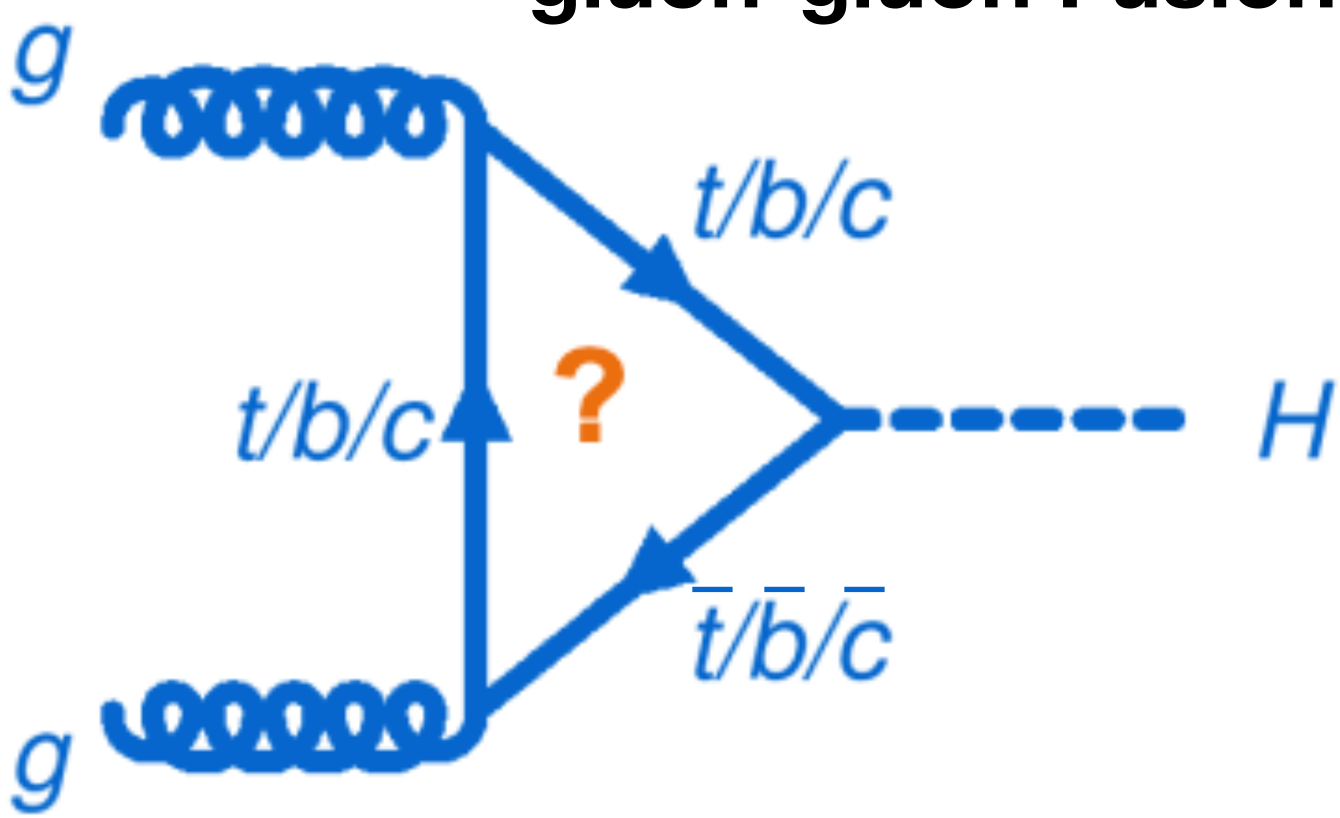
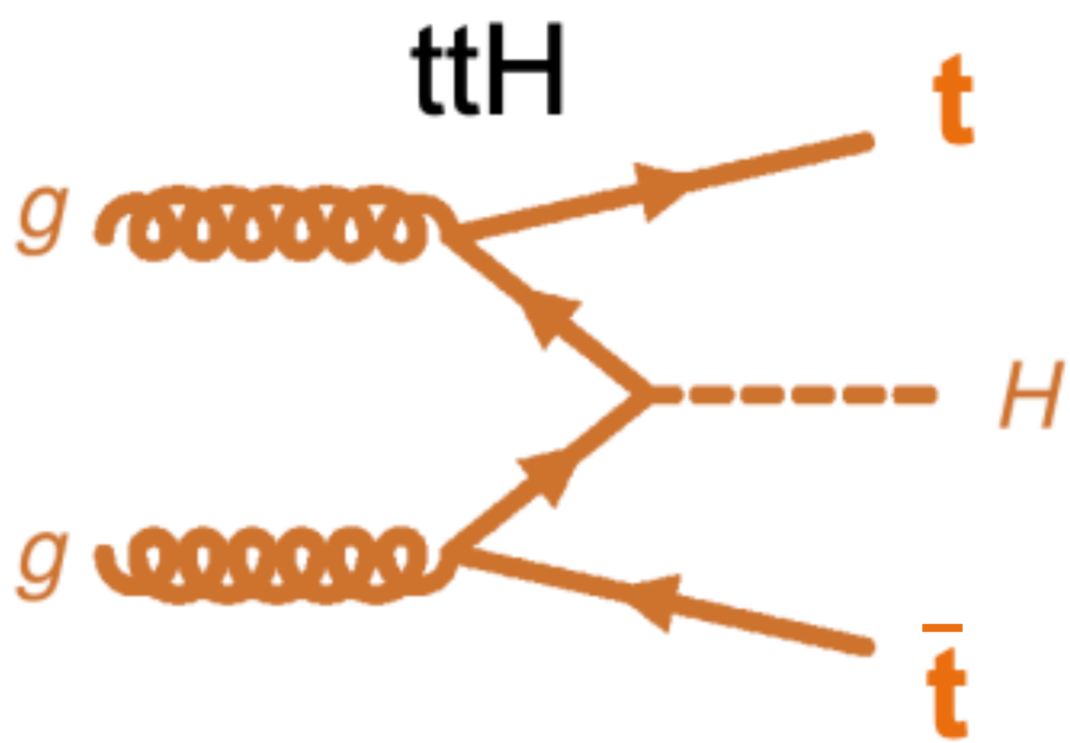
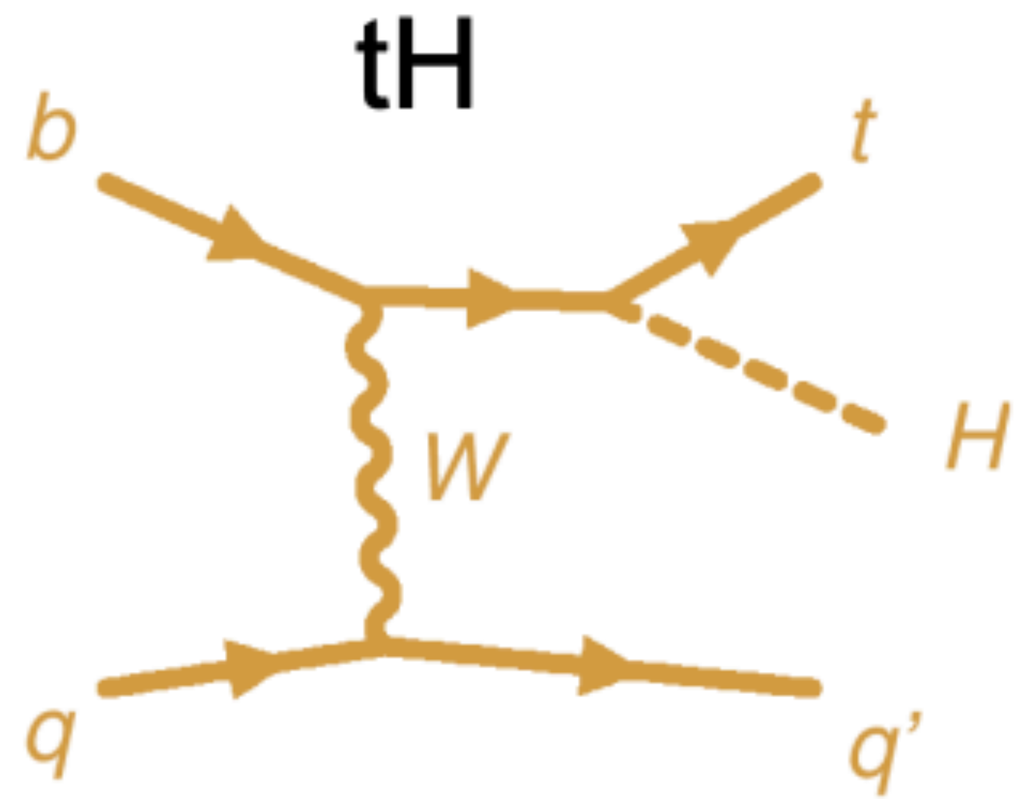


ttH+tH :
probe of top-Higgs coupling





Only 1% of Higgs at LHC

Only 0.1%!!!

Reasons to Measure Top Quark Properties Precisely

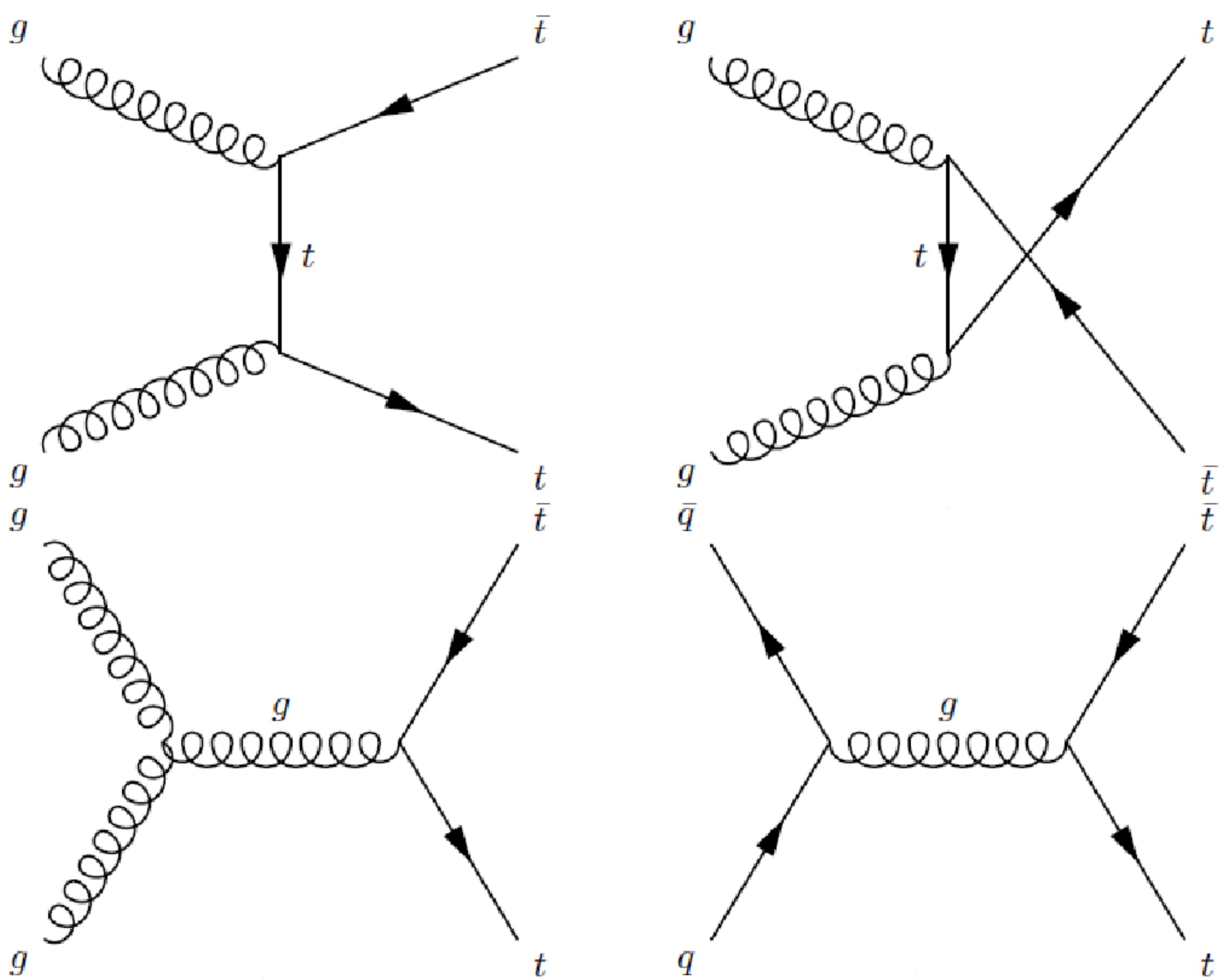
- **Fundamental Parameter of the SM**:
  - The top quark plays a critical role in the SM of particle physics. Its properties, such as **mass**, **charge**, and **spin**, are fundamental parameters that influence predictions and calculations within the SM
- **Electroweak Symmetry Breaking**:
  - The top quark's mass is close to the electroweak scale. It could have a significant role in electroweak symmetry breaking
- **Higgs Boson Interactions:**
  - The top quark **interacts strongly** with the Higgs boson, affecting Higgs production and decay rates. Accurate measurements of top quark properties are essential to refine our understanding of the Higgs boson and its properties
- **Testing Quantum Chromodynamics (QCD):**
  - As the **heaviest quark**, the top quark decays before it hadronizes, providing a unique opportunity to study QCD in a relatively clean environment. This helps in testing and refining QCD predictions

Reasons to Measure Top Quark Properties Precisely

- **Probing for New Physics:**
  - Precise measurements can reveal deviations from SM predictions, hinting at new physics beyond the SM, such as supersymmetry, extra dimensions, or other exotic phenomena
- **Calibrating Detectors and Analyses:**
  - Top quark events are used to calibrate particle detectors and analysis techniques, ensuring the accuracy and reliability of measurements
- **Enhancing Collider Physics:**
  - Understanding top quark production and decay processes enhances the overall physics program at the LHC, enabling more precise searches for rare processes and new phenomena.

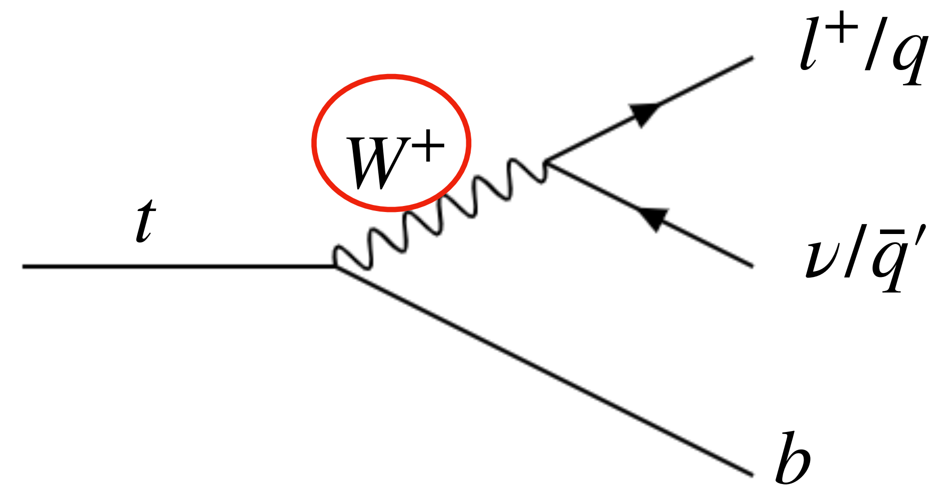
Top-Quark pair production via the strong force

- 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?
  - BR $(t \rightarrow bW)$ ~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
- $W \rightarrow \tau\nu$ 1/9
  - $\tau \rightarrow q\bar{q}$ (65%)

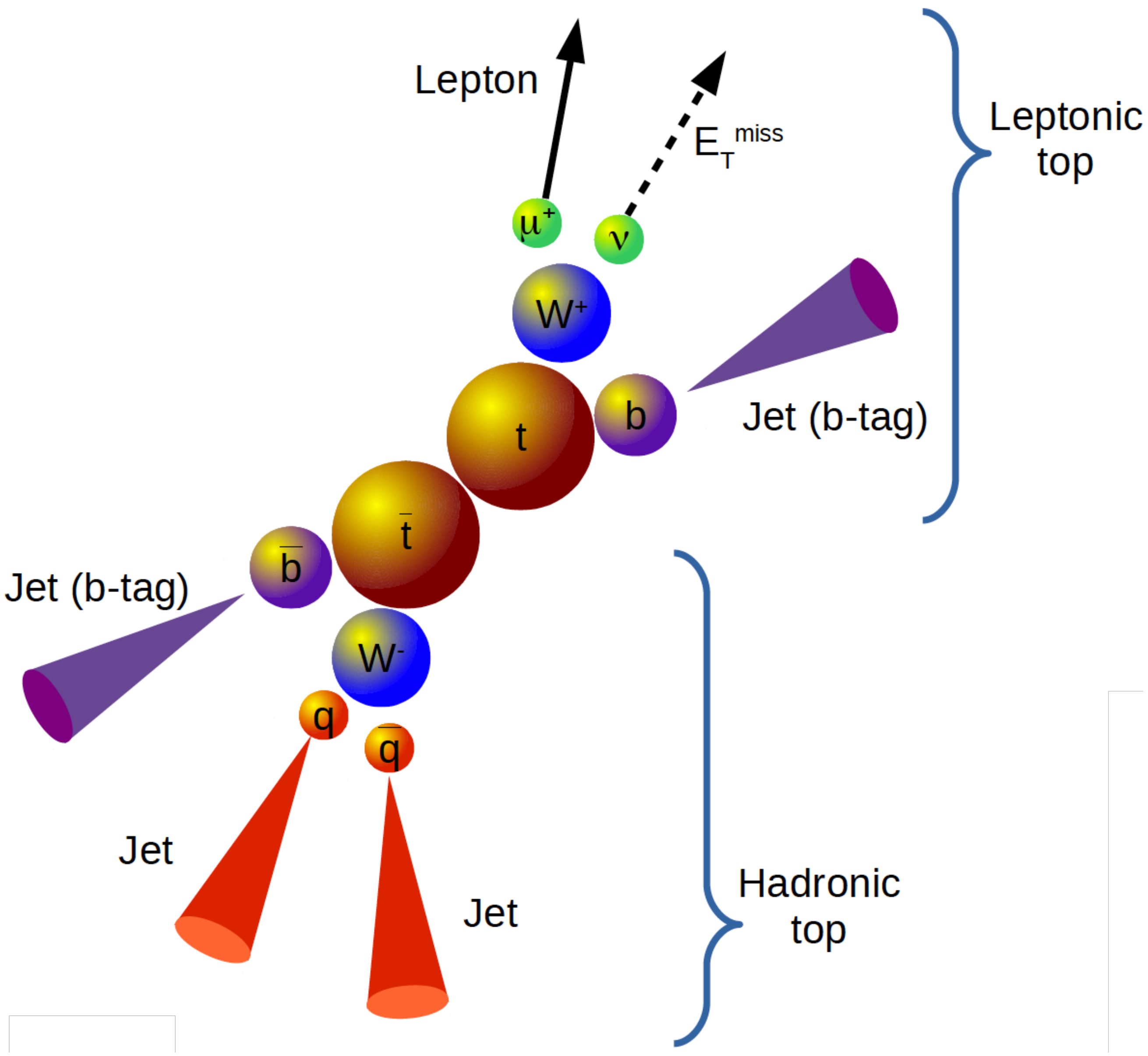
} **~75% hadronically**

- $W \rightarrow e\nu$ 1/9
- $W \rightarrow \mu\nu$ 1/9
  - $\tau \rightarrow \mu\nu$ (17.5%)
  - $\tau \rightarrow e\nu$ (17.5%)

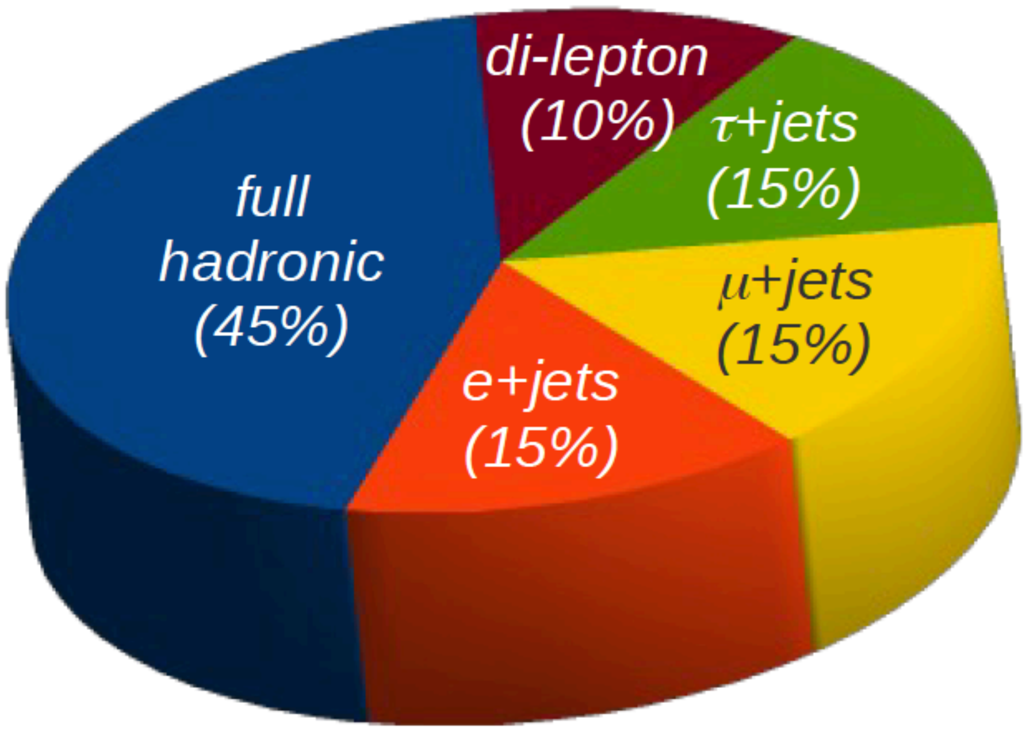
} **~25%** e or μ

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

Example of μ+jets

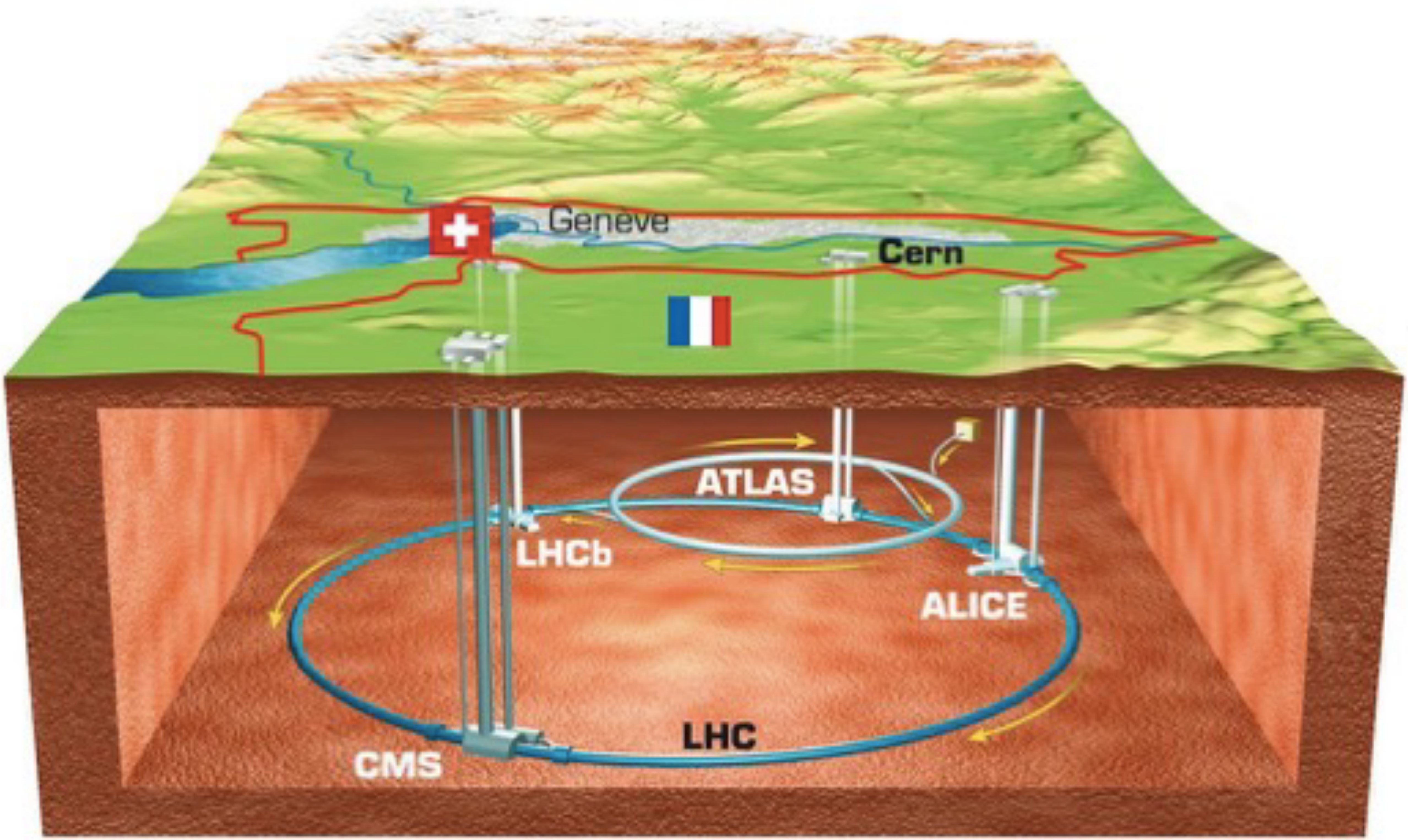


Branching fractions for $t\bar{t}$ events



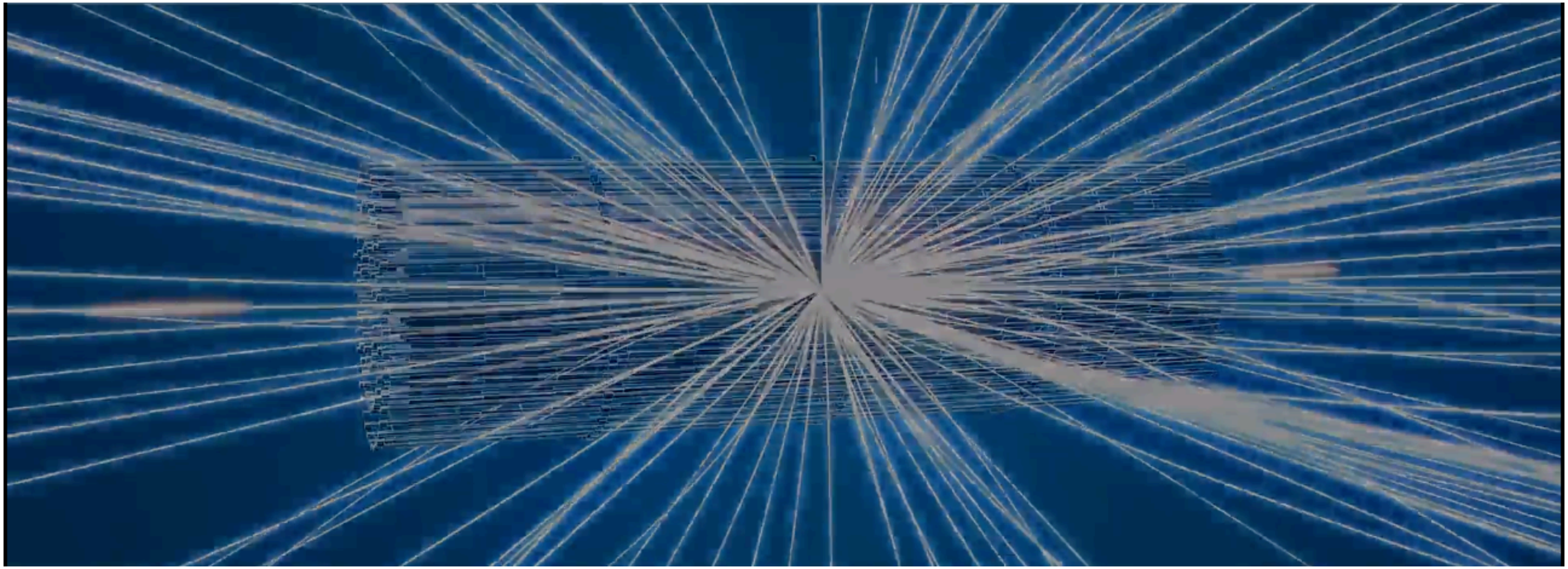
The Large Hadron Collider (LHC)

- 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

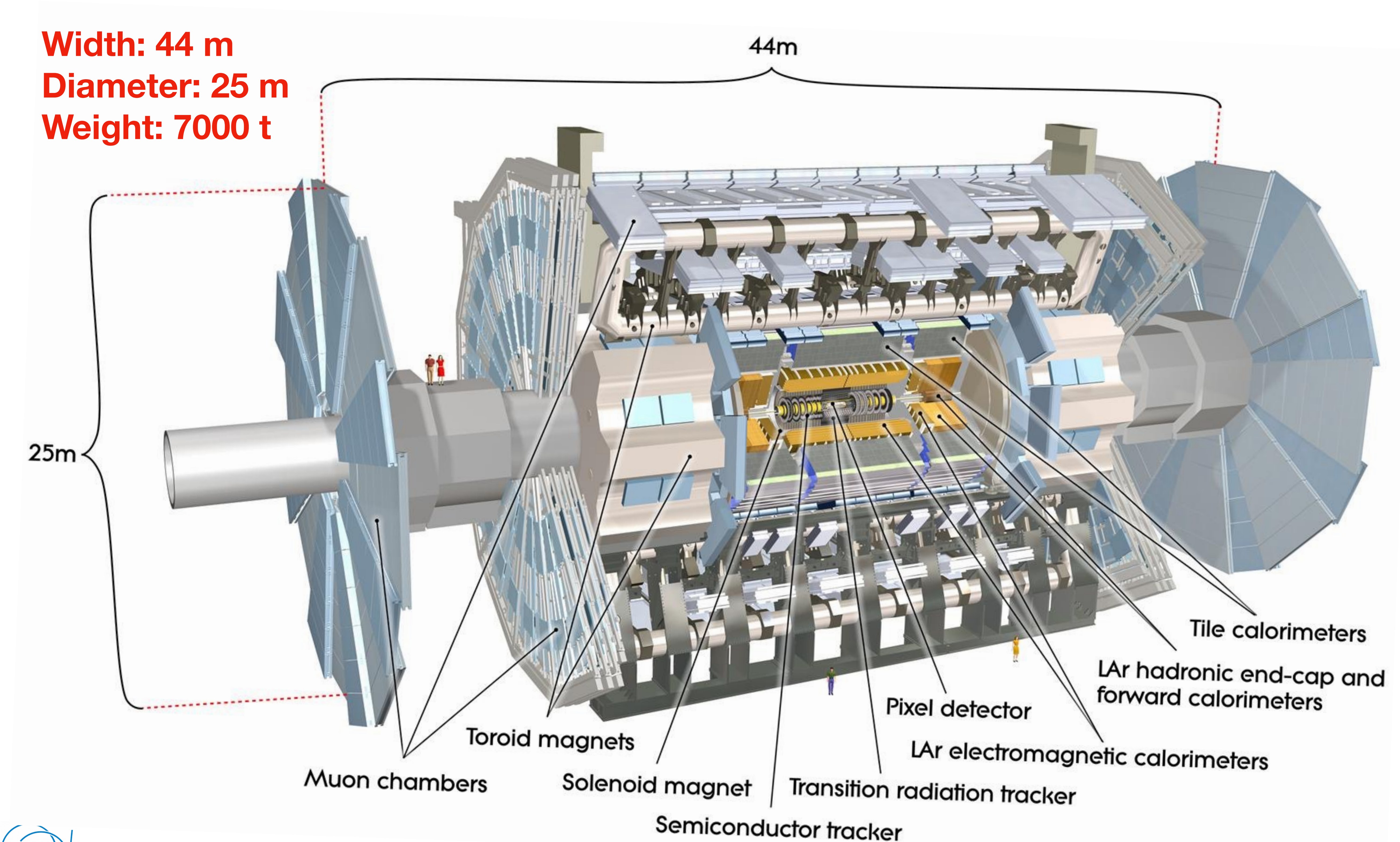
~25,000 $t\bar{t}$ events are produced every hour

How to detect top quarks

A Toroidal LHC ApparatuS (ATLAS)

- Several sub-detectors ⇒ particle tracking and energy measurement

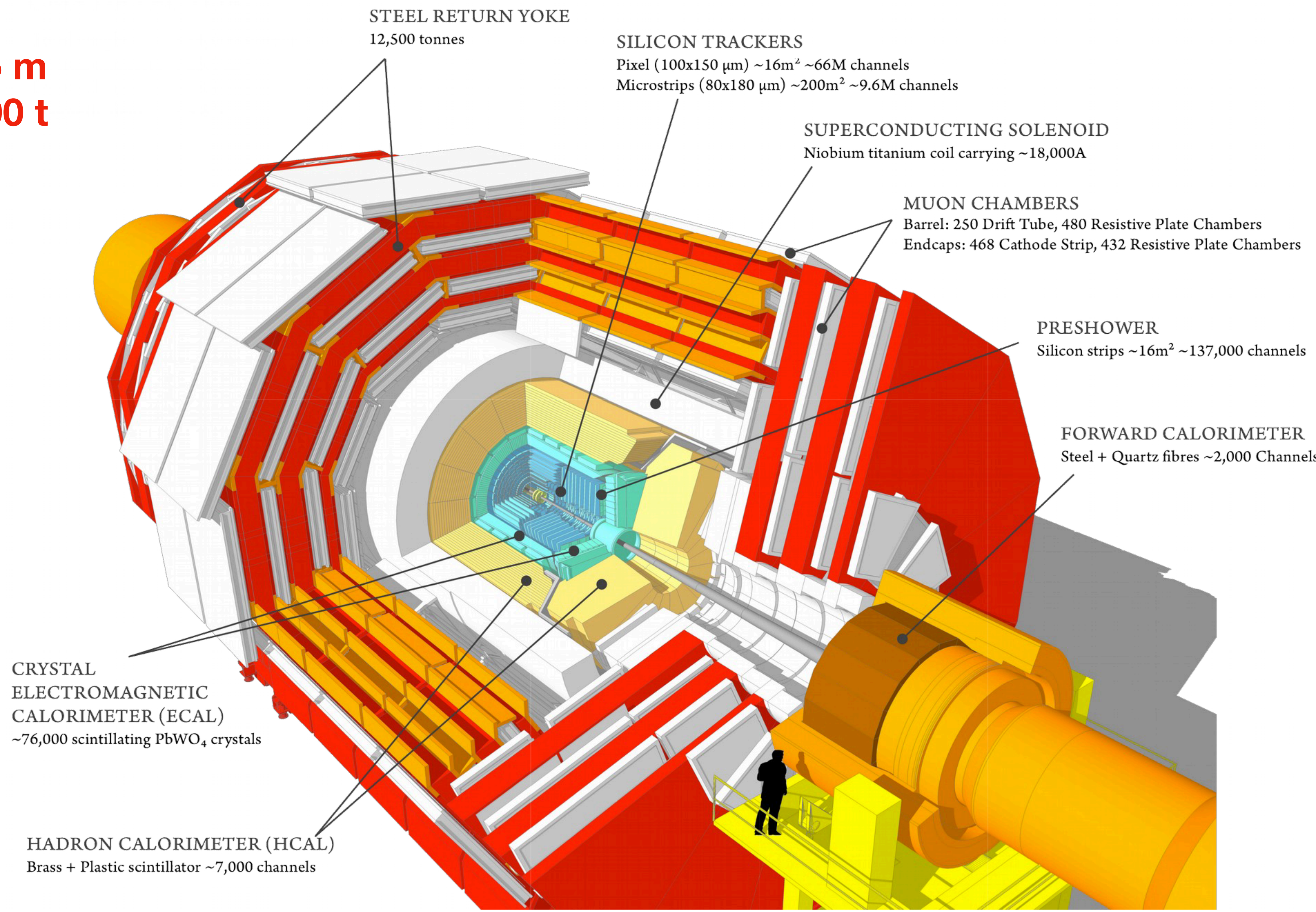
Width: 44 m
Diameter: 25 m
Weight: 7000 t



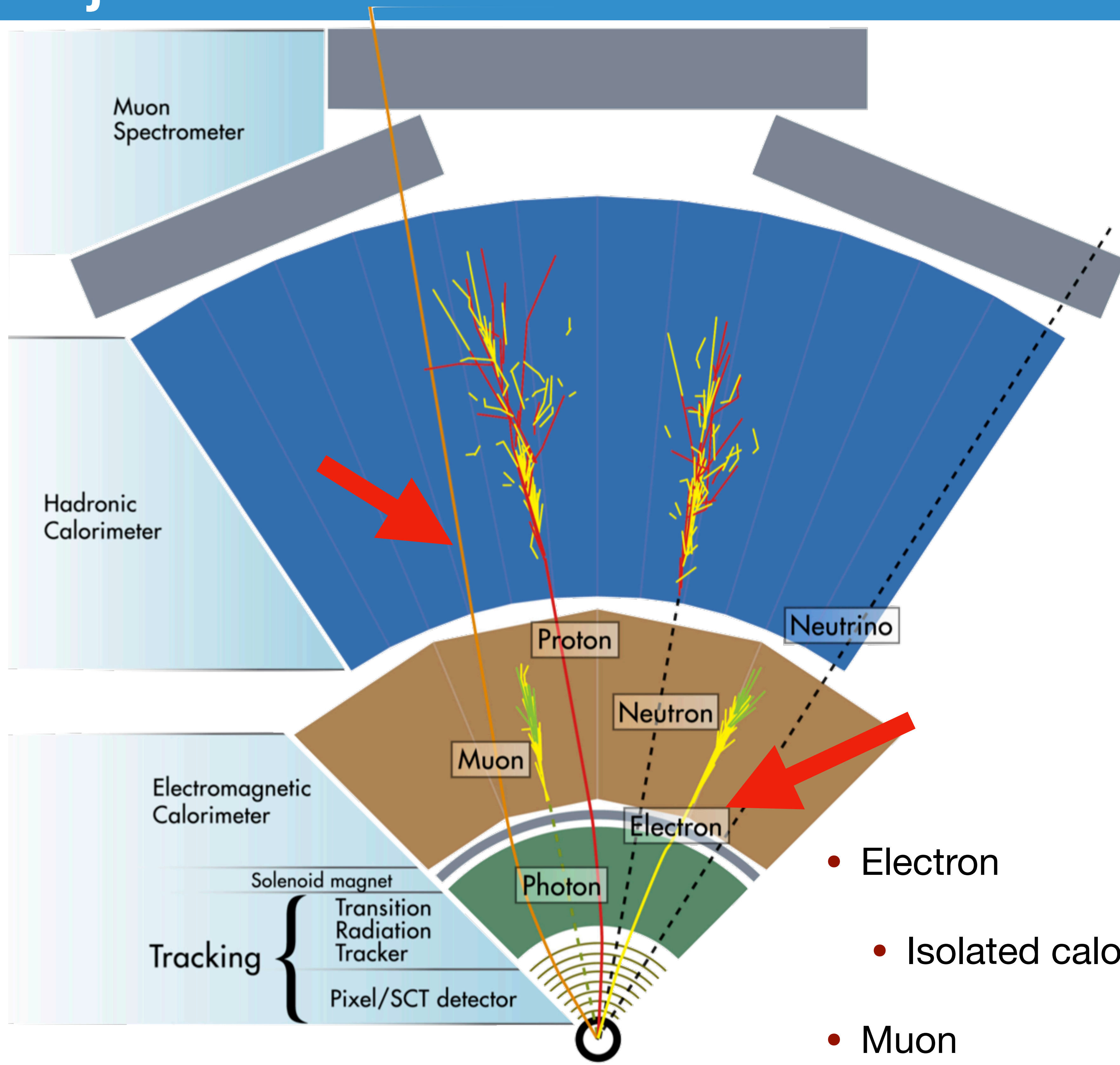
Compact Muon Solenoid (CMS)

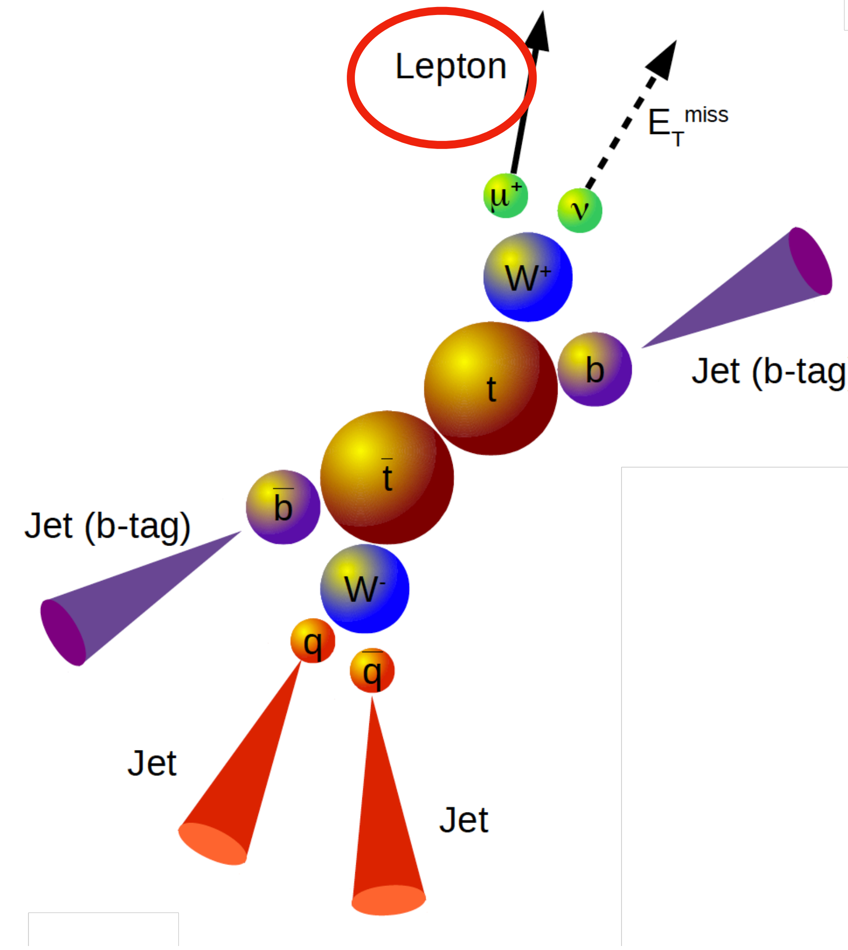
- Several sub-detectors ⇒ particle tracking and energy measurement

Width: 22 m
Diameter: 15 m
Weight: 12500 t



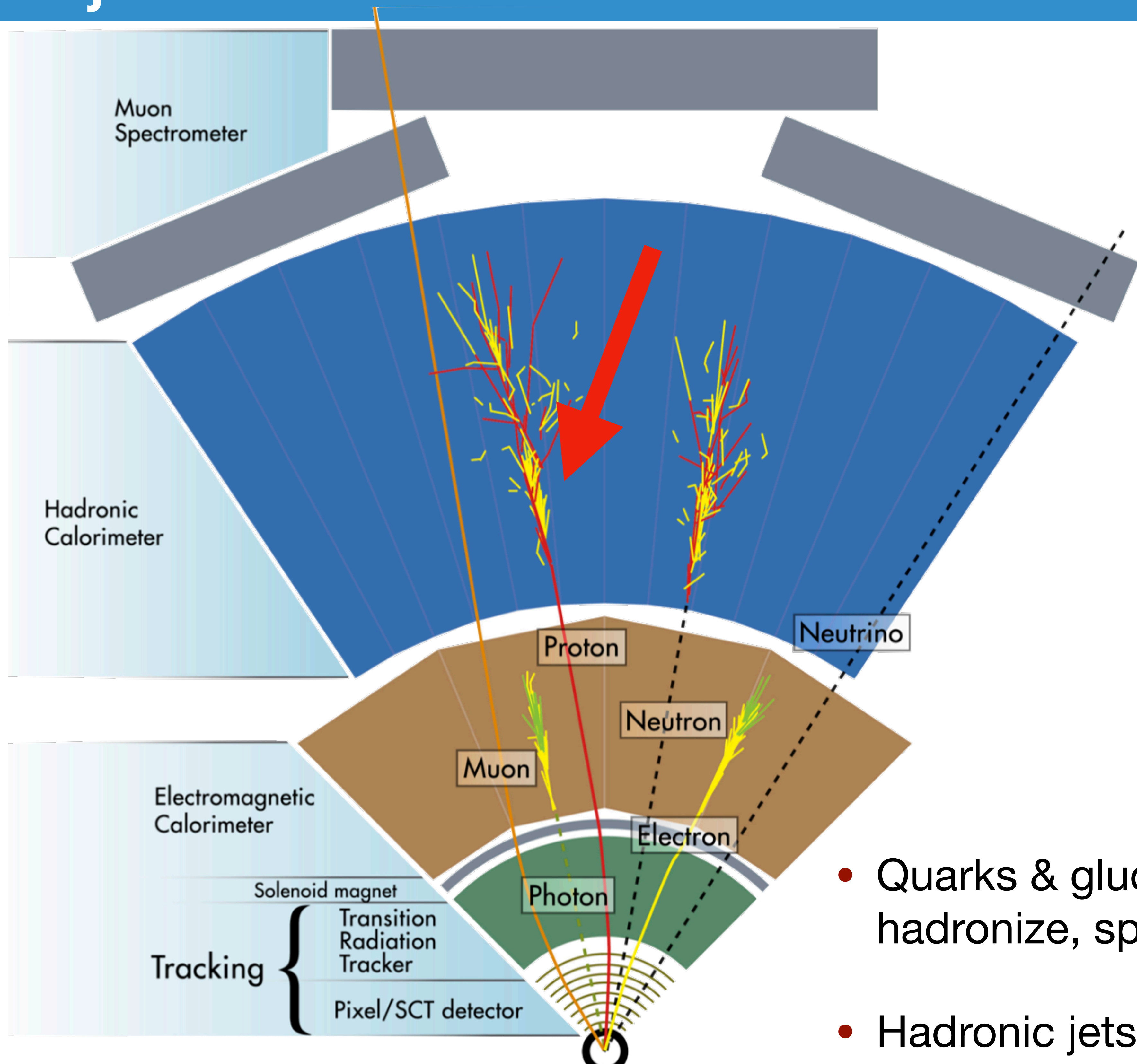
Object Reconstruction and Identification

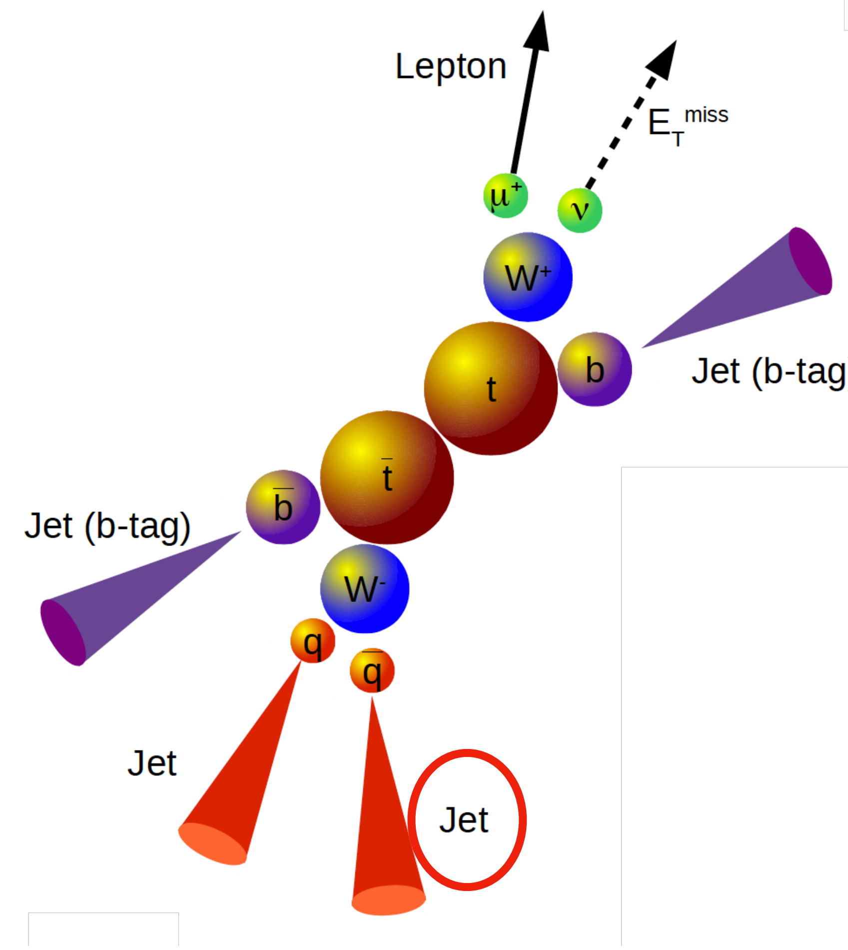




- Electron
    - Isolated calorimeter deposit matched to track
- Muon
    - Segment in muon detector matched to track

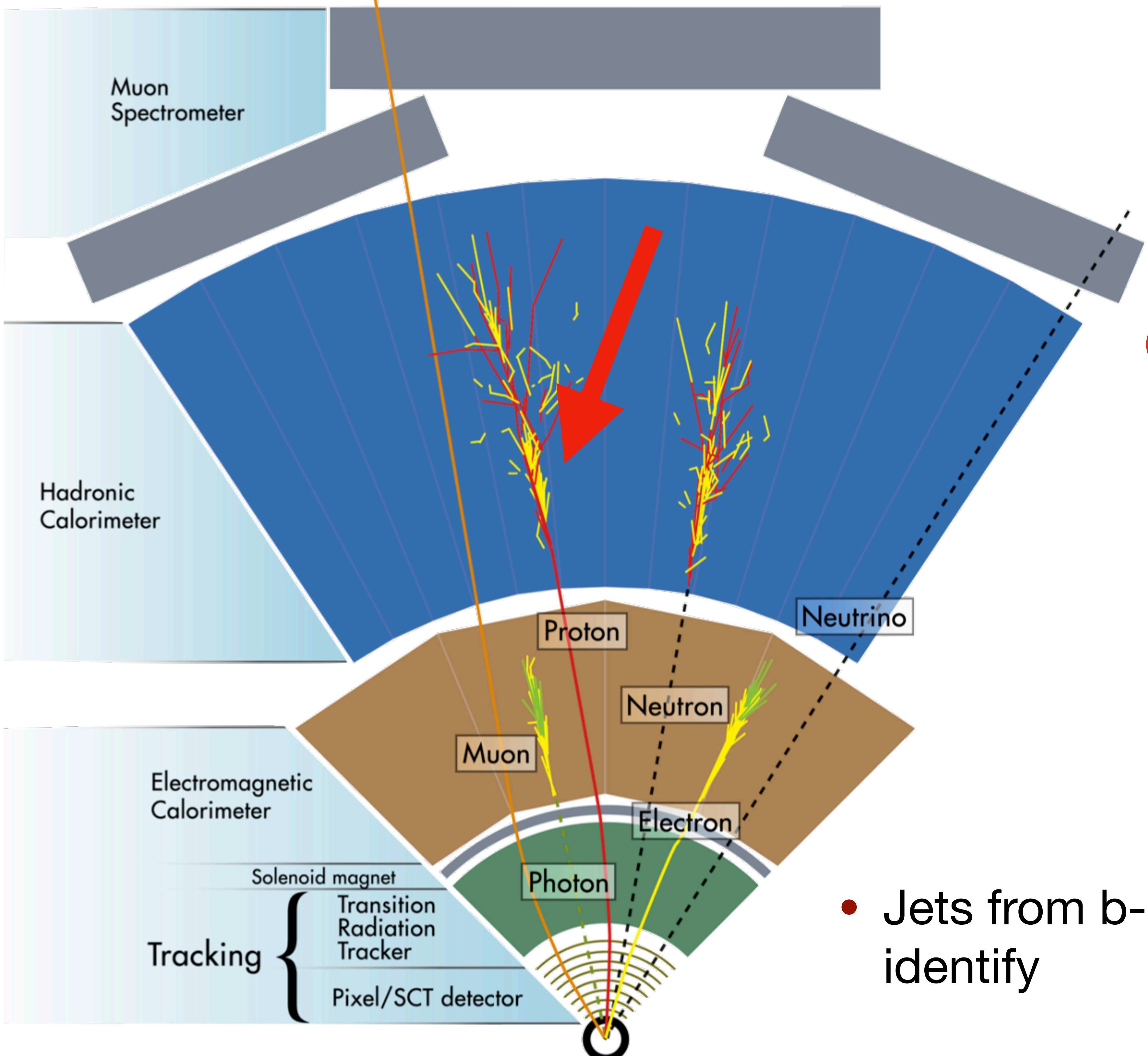
Object Reconstruction and Identification

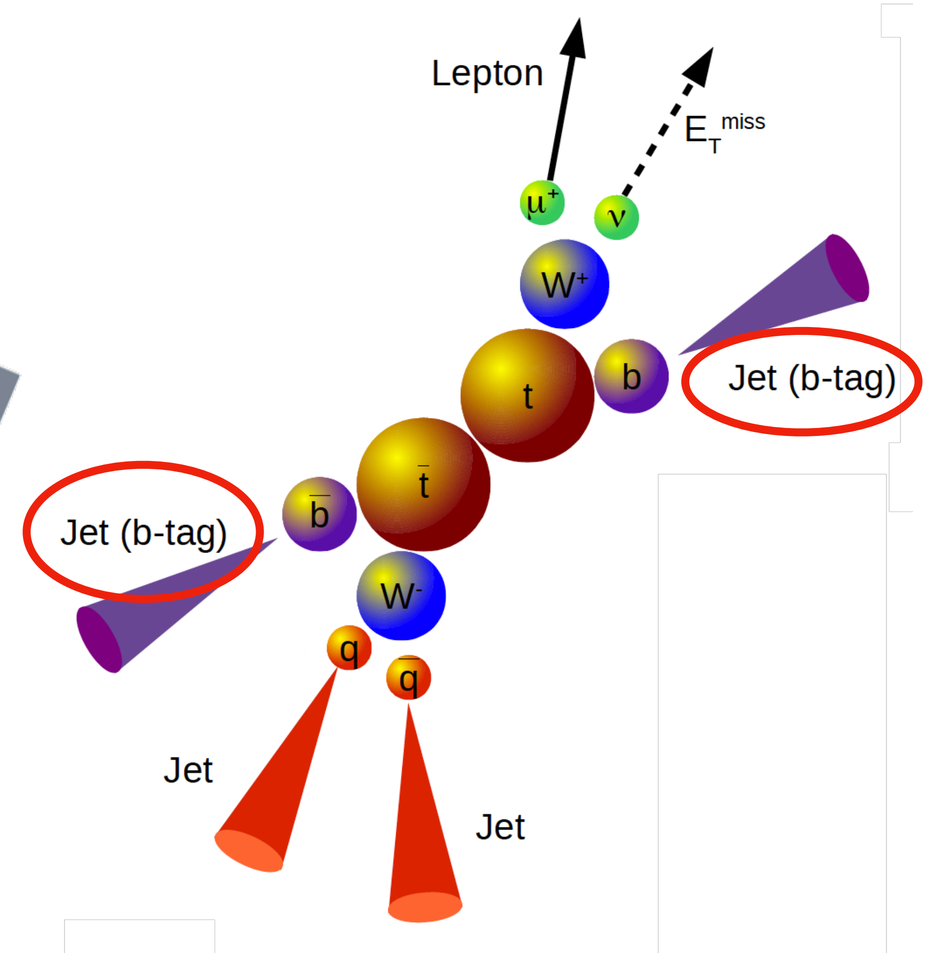




- Quarks & gluons quickly shower and hadronize, spraying hundreds of particles
- Hadronic jets are reconstructed from energy deposits in EM and hadronic calorimeters

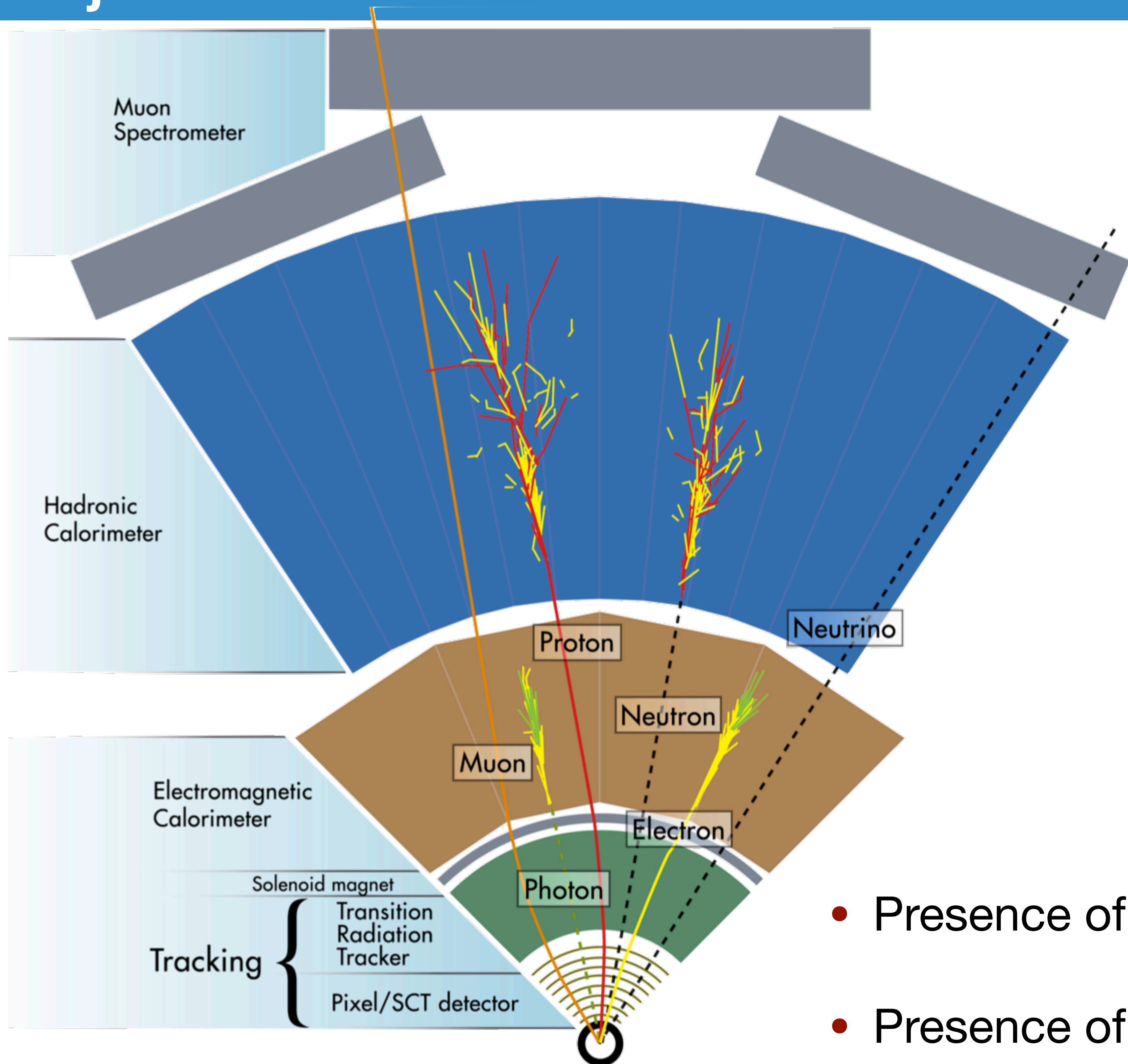
Object Reconstruction and Identification



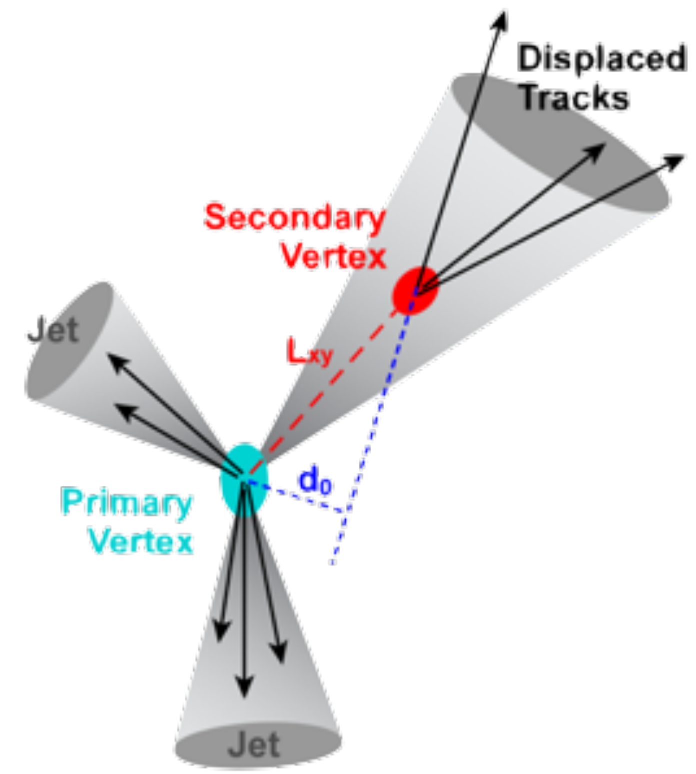


- Jets from b-hadrons are easier to identify
- B-hadron’s long-lifetime & large mass

Object Reconstruction and Identification

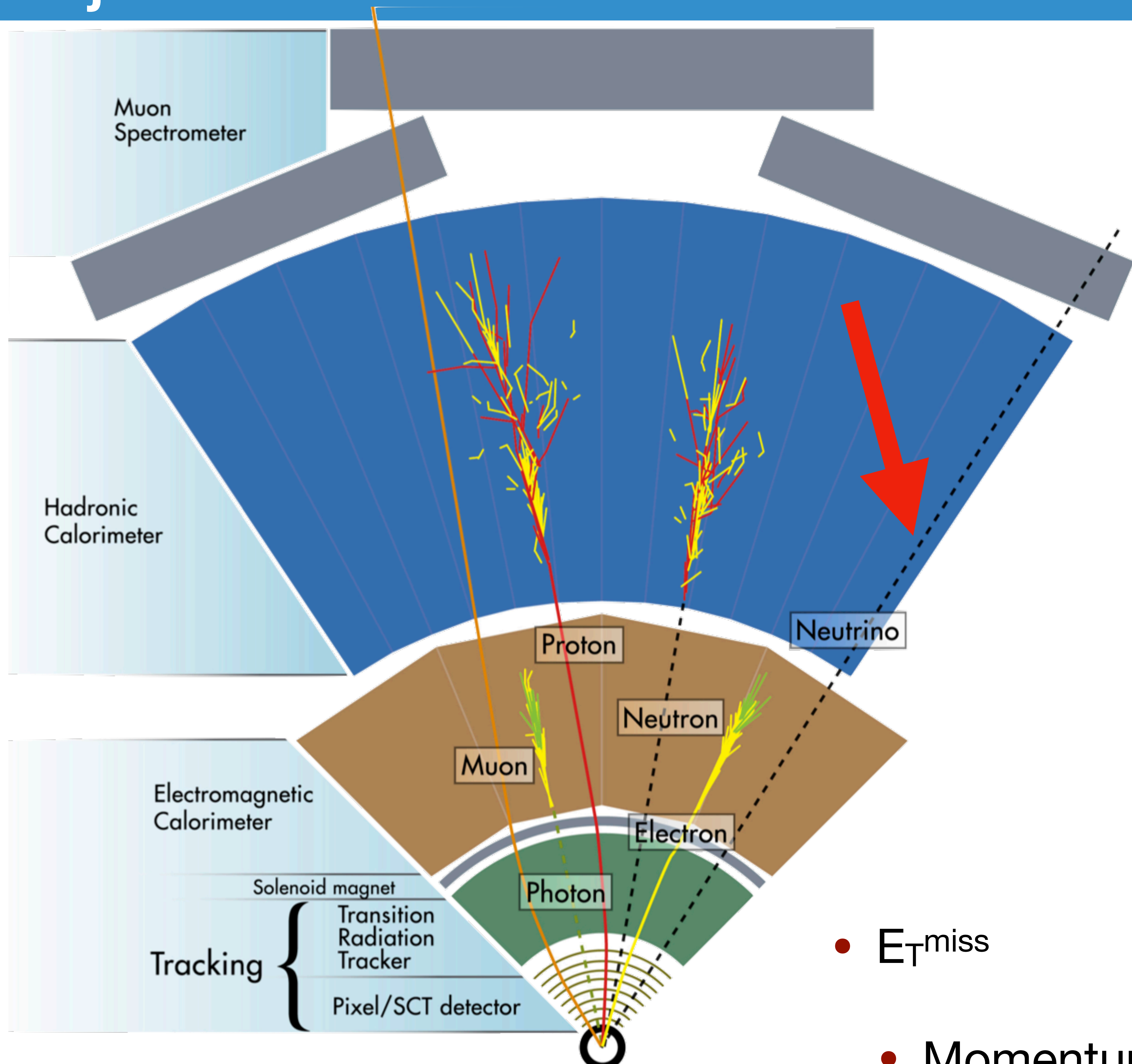


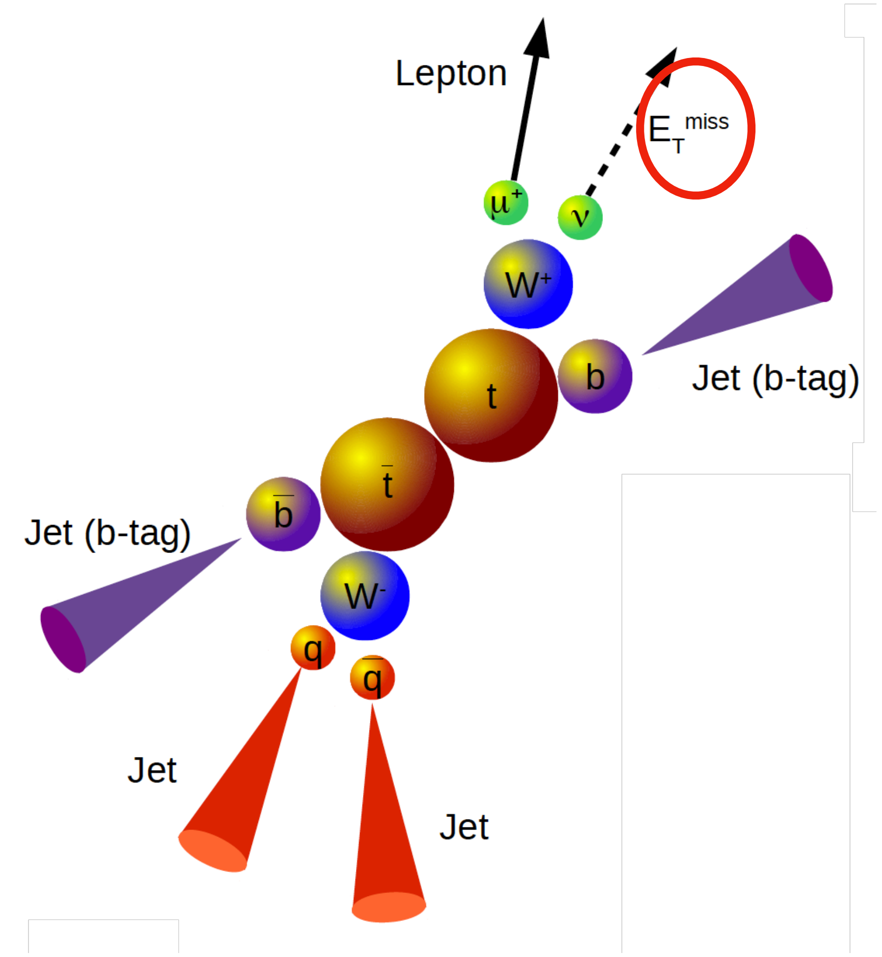
b-tagged jet



- Presence of displaced tracks
- Presence of secondary vertices (B → C → light)

Object Reconstruction and Identification

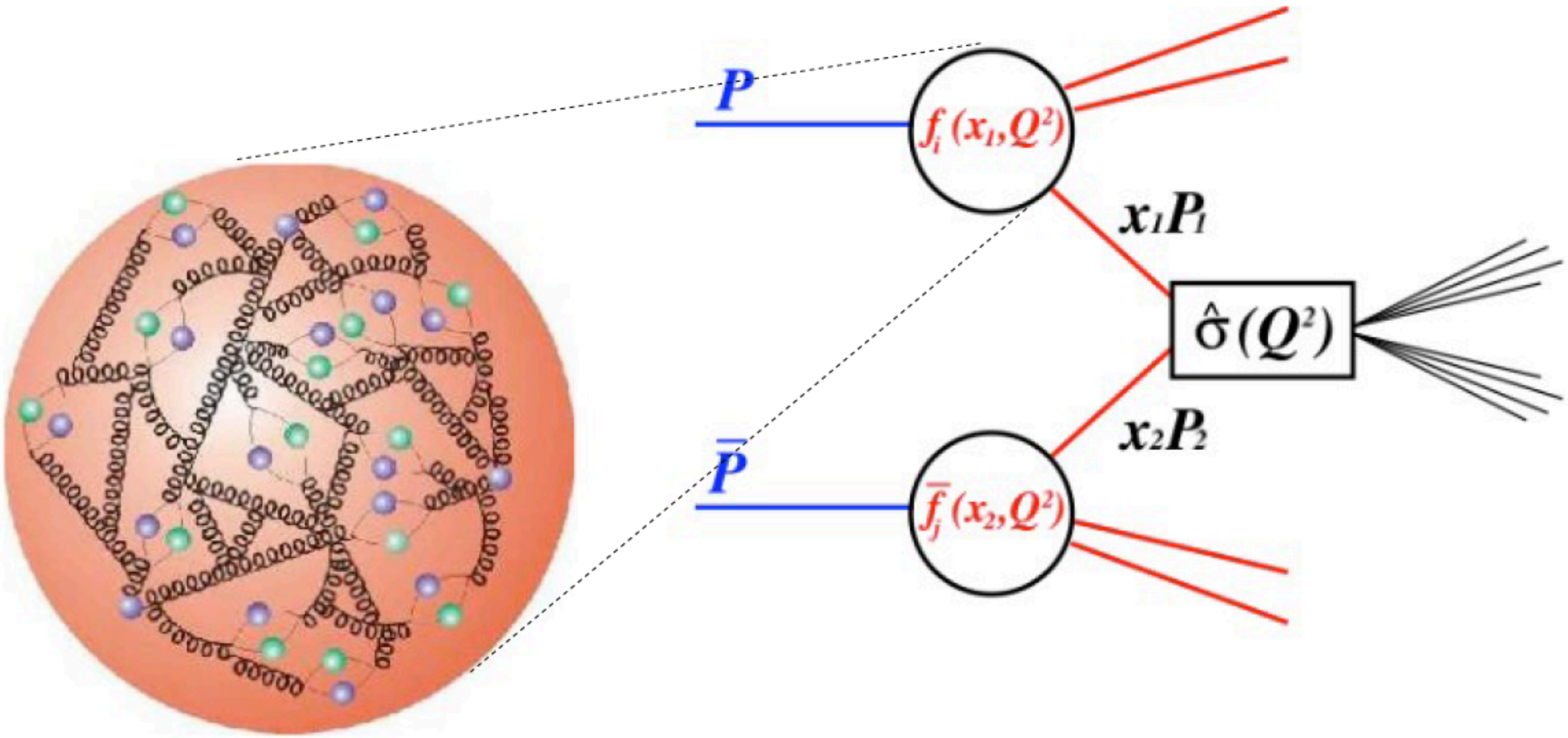




- E_T^{miss}
  - Momentum unbalance

Cross section calculation

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



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

How can we measure the cross-section?

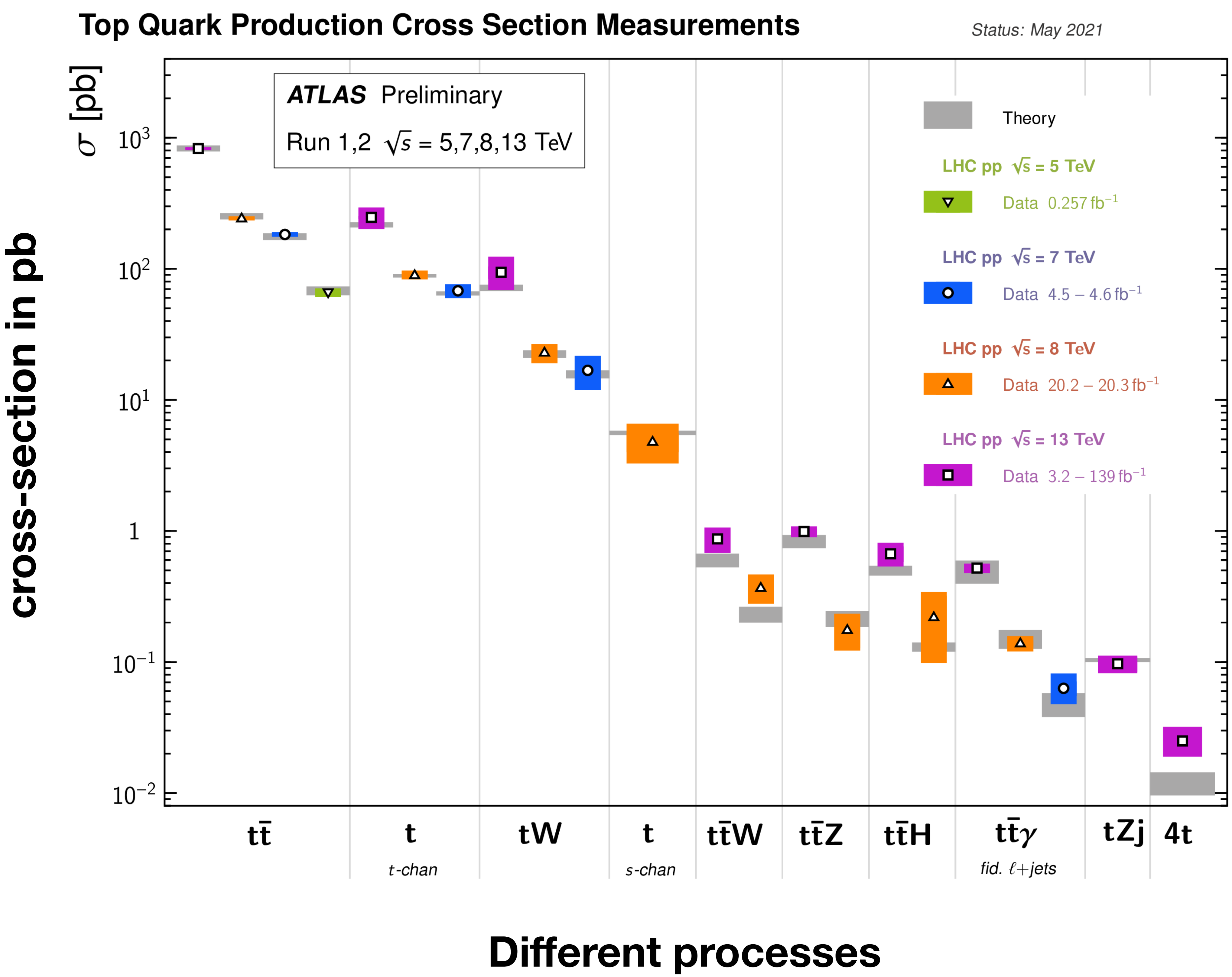
- Example: lepton+jets
- select events: exactly one electron or muon, E_T^{miss}, ≥ 4jets
- estimate the amount background processes (from Monte Carlo simulation or from data)

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

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

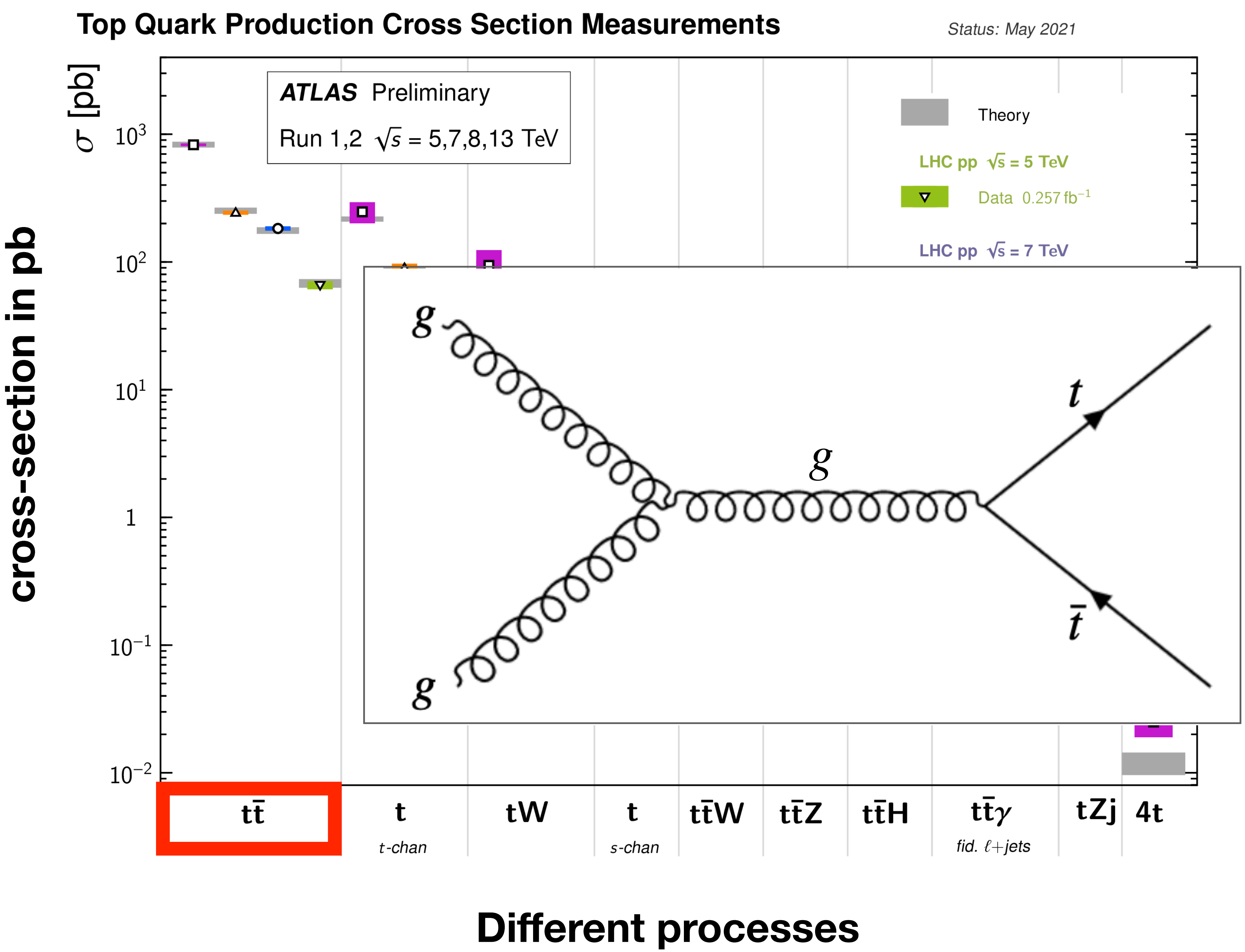
Top-quark Production Cross-section Measurements

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)



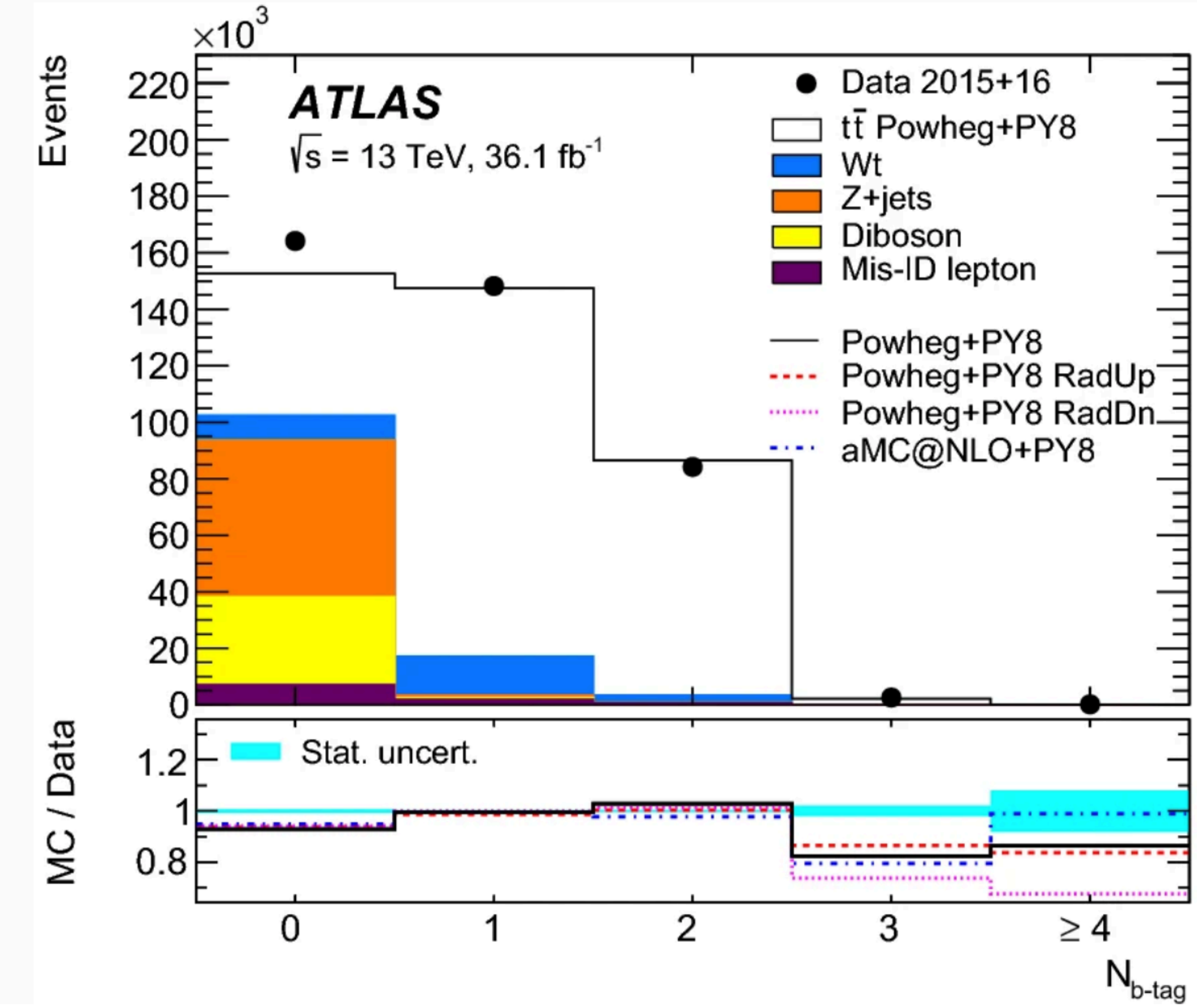
How many of those events do we have available for measurements?

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



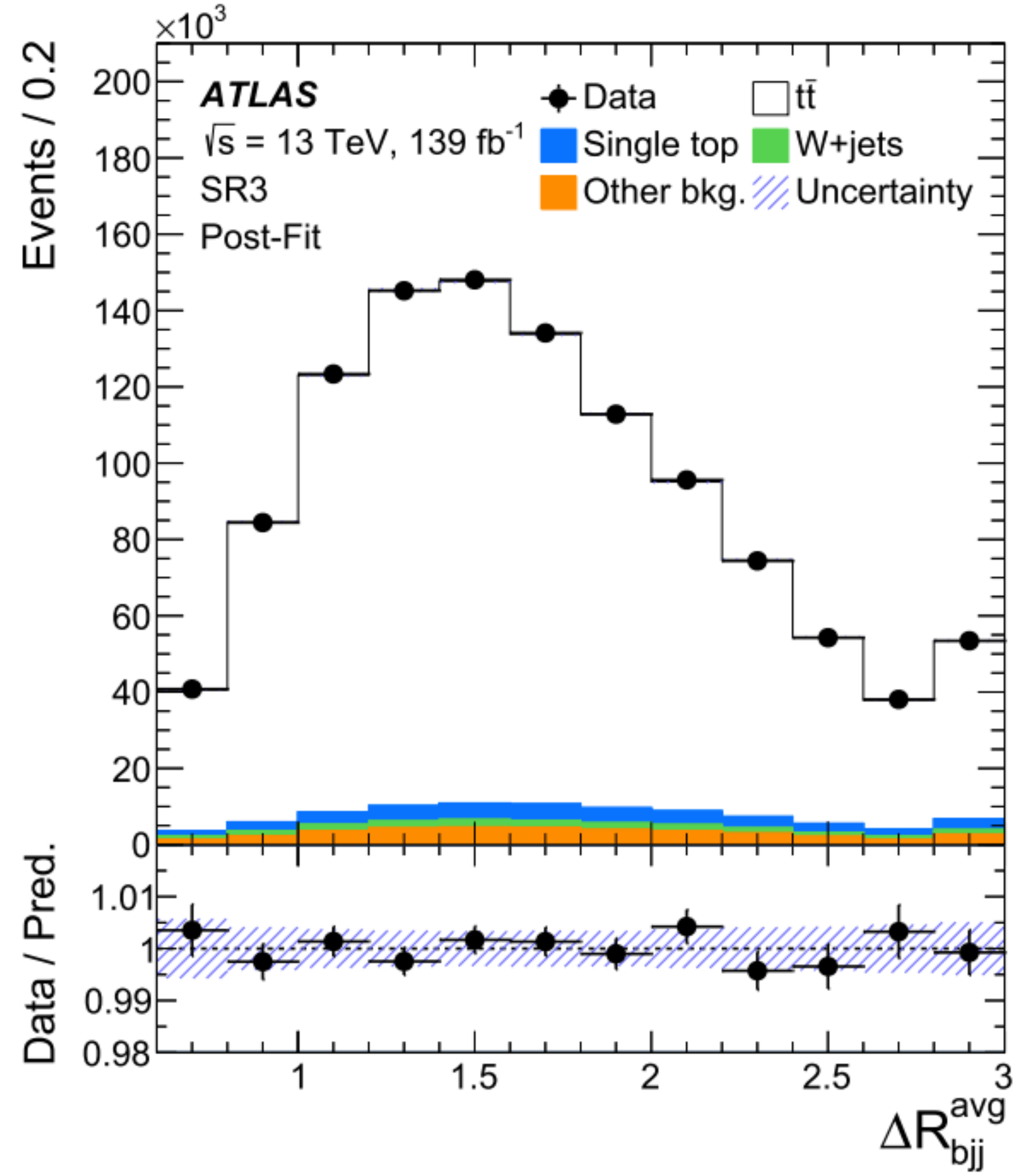
- Main backgrounds
  - Z/γ +jets
  - diboson
  - single top

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

Total uncertainty of 2.4%

[Eur. Phys. J. C 80 (2020) 528]

- 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



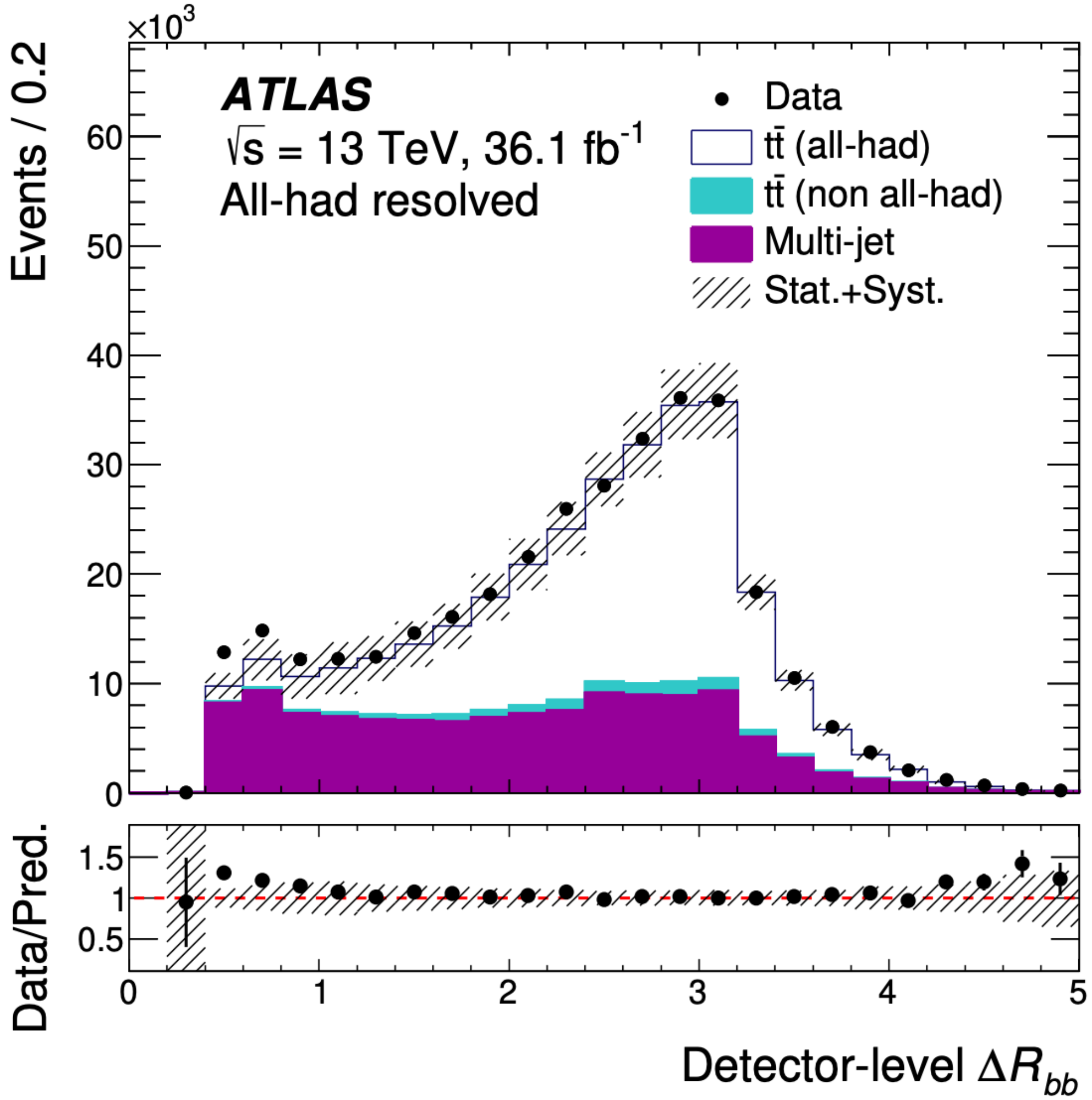
$$\sigma_{inc} = 830 \pm 0.4(\textbf{stat}) \pm 36(\textbf{syst}) \pm 14(\textbf{lumi})\textbf{pb}$$

Total uncertainty of 4.6%

[PLB810(2020)135797]

$t\bar{t}$ 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

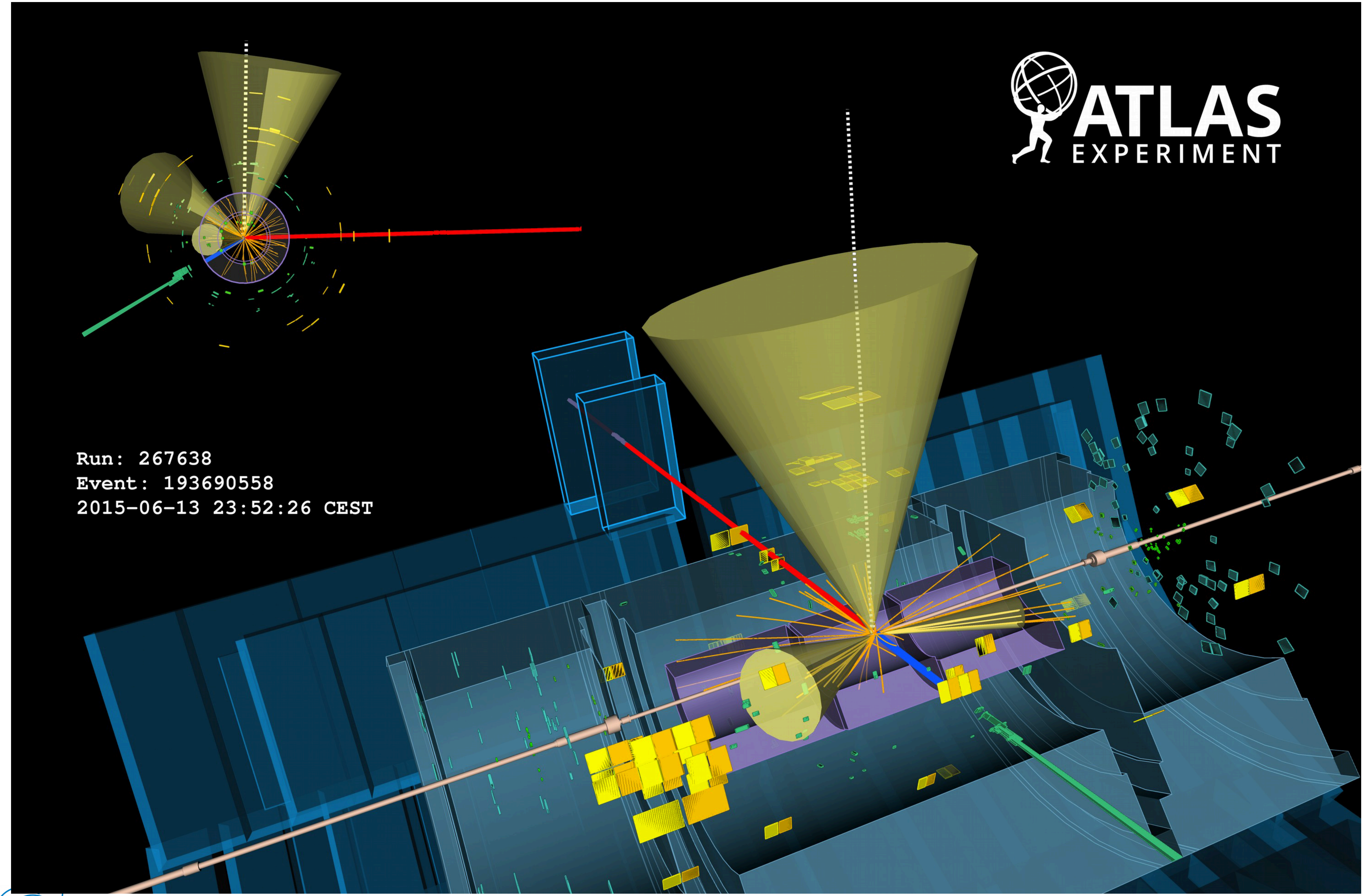


$$\sigma_{t\bar{t}} = 864 \pm 127(\textbf{stat} + \textbf{syst})\textbf{pb}$$

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

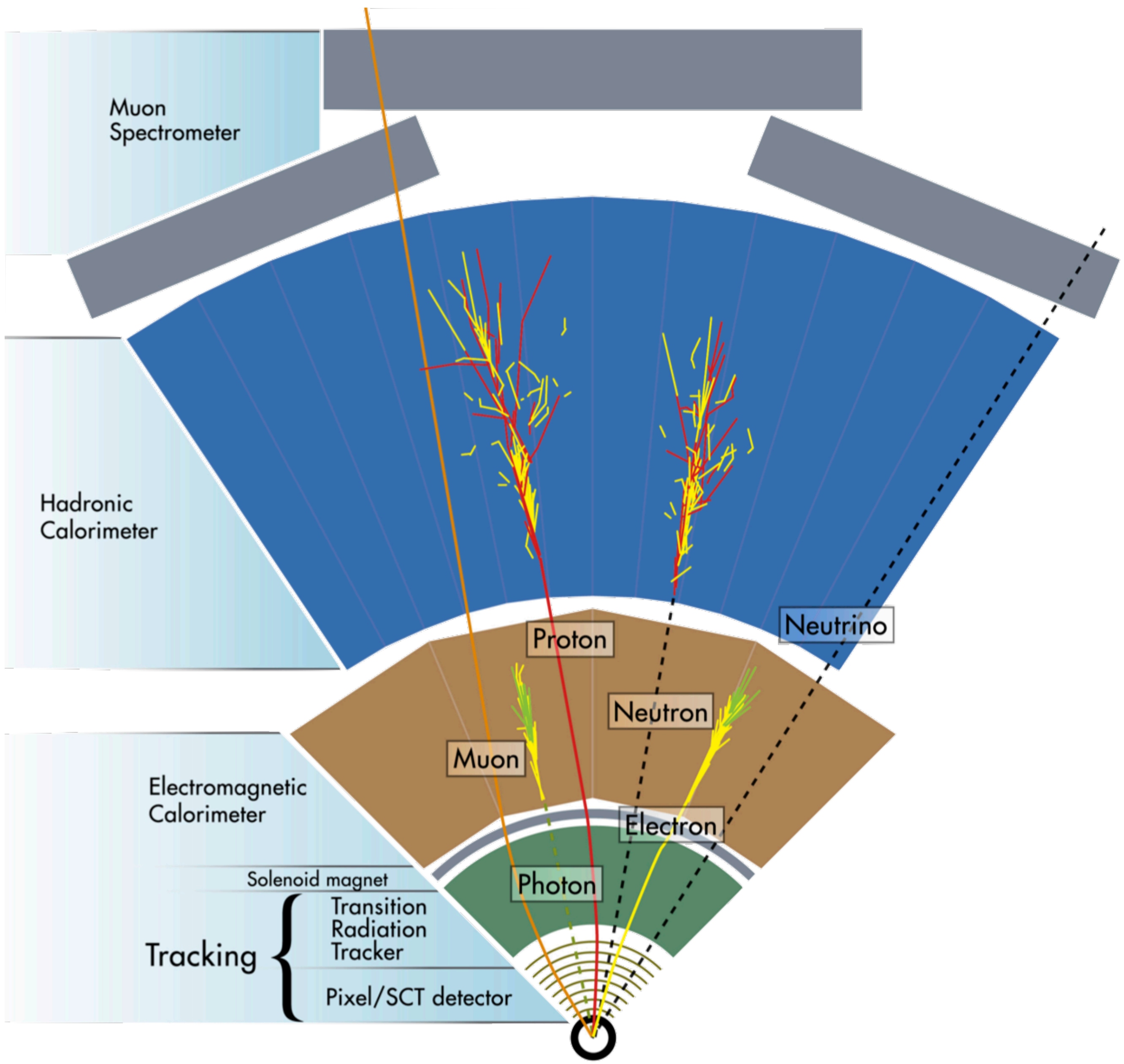
[JHEP 01 (2021) 033]

Dilepton $t\bar{t}$ event display



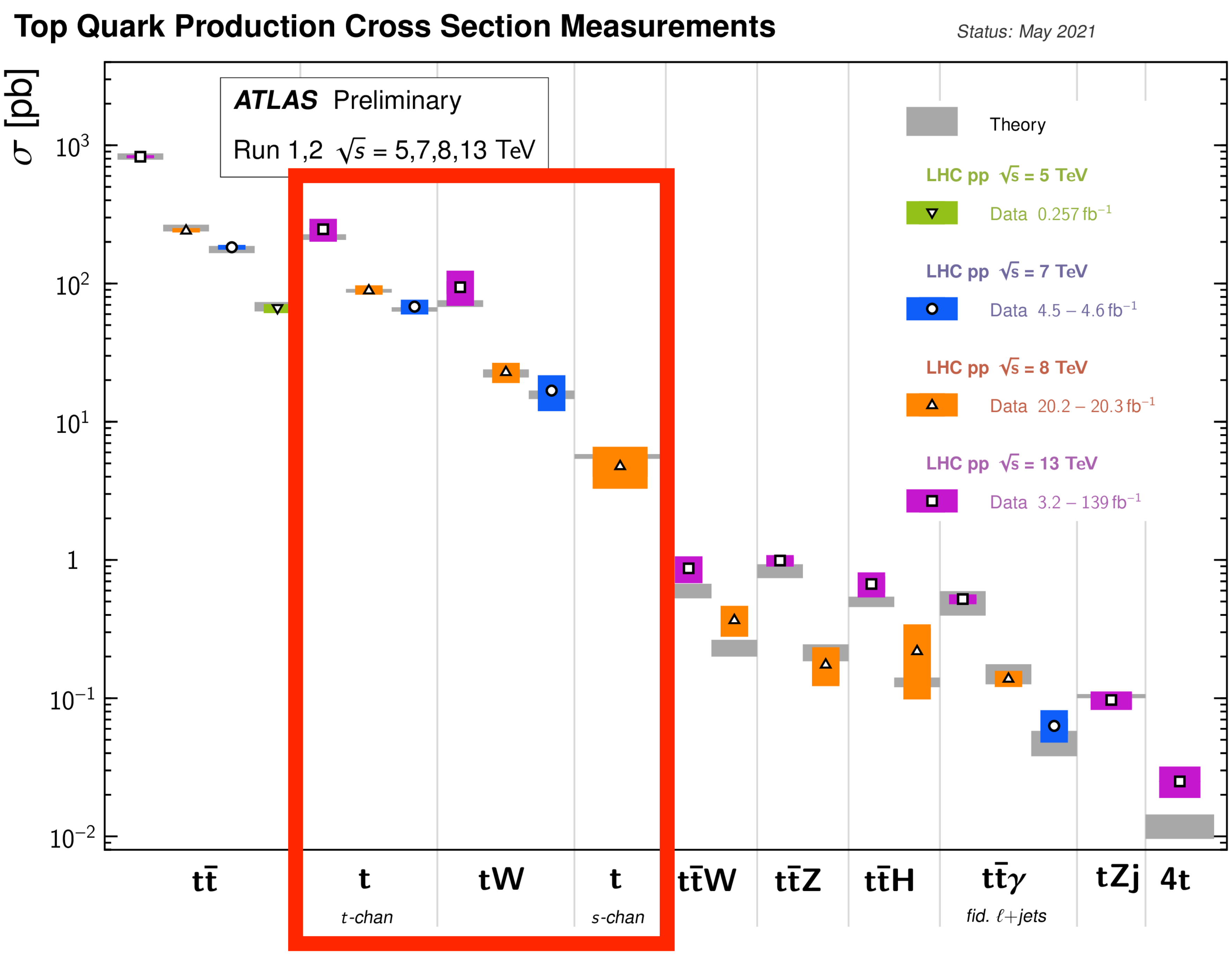
Recap

- 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?



Top-quark Production Cross-section Measurements

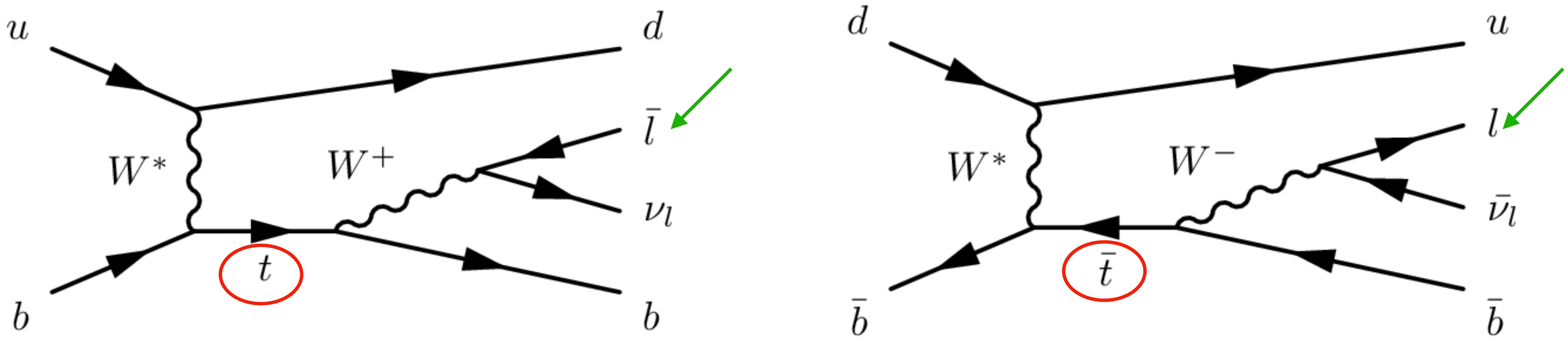
Run 1 @ 7 TeV   Run 1 @ 8 TeV   Run 2 @ 13 TeV   Theory



cross-section in pb

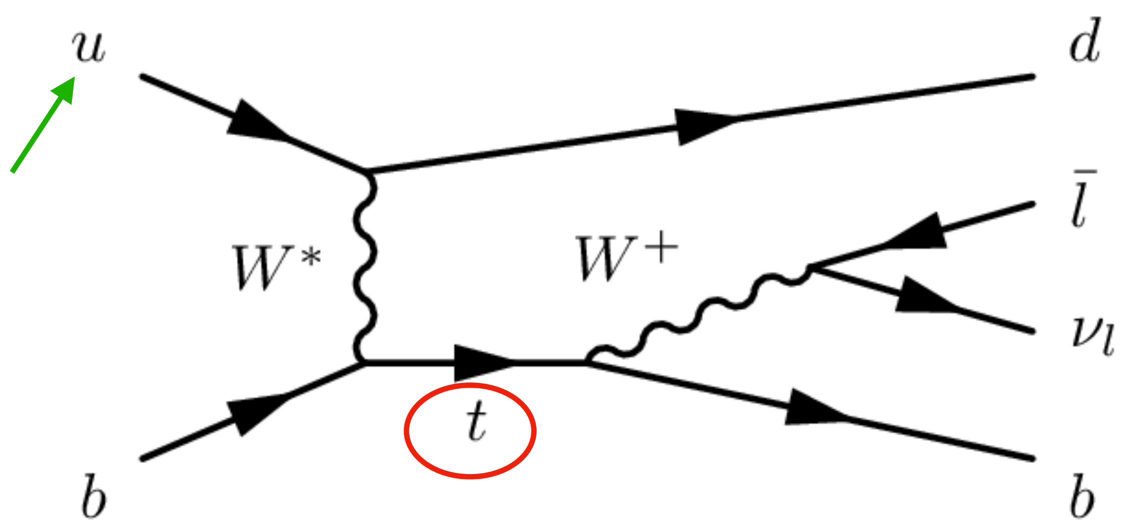
Different processes

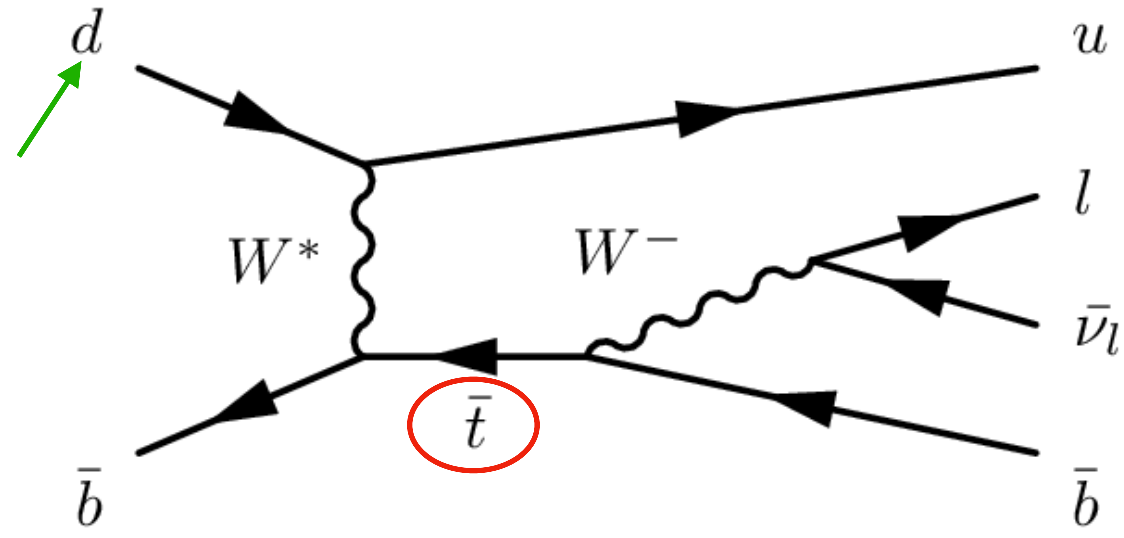
Inclusive t-channel cross-section



- 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



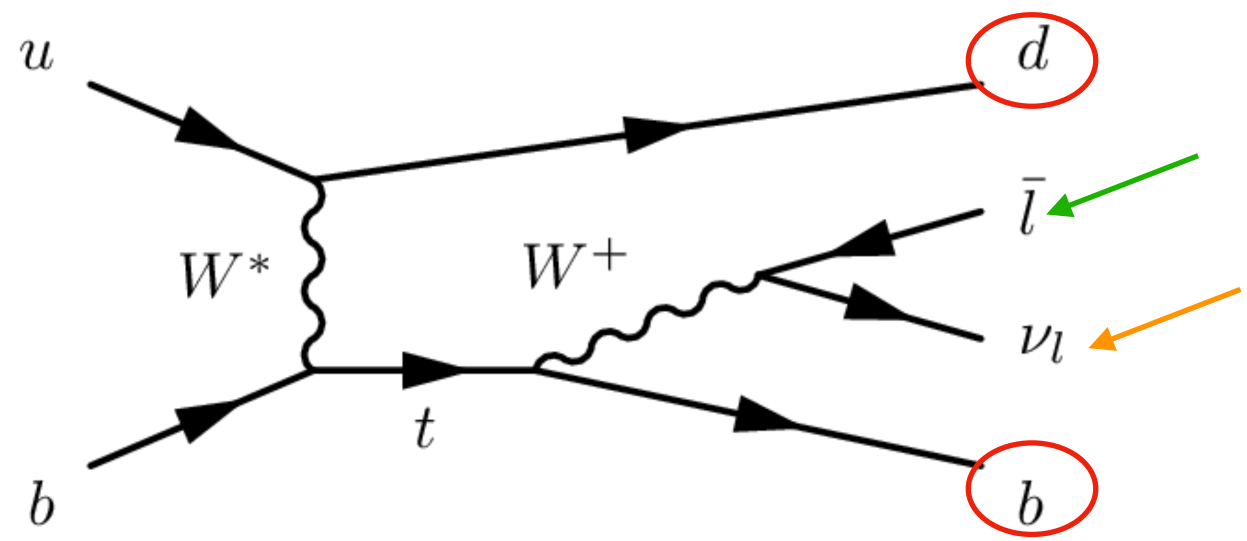


- Goal is to measure t- and $\bar{t}$- channel cross-sections in lepton+jets channel
- $\sigma_t > \sigma_{\bar{t}}$ due to different initial state
  - Can you guess why?
    - valence u-quark density of the proton is about twice as high as the valence d-quark density
- measure the cross-section ratio: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

[PLB 800 (2019) 135042]

Inclusive t-channel cross-section

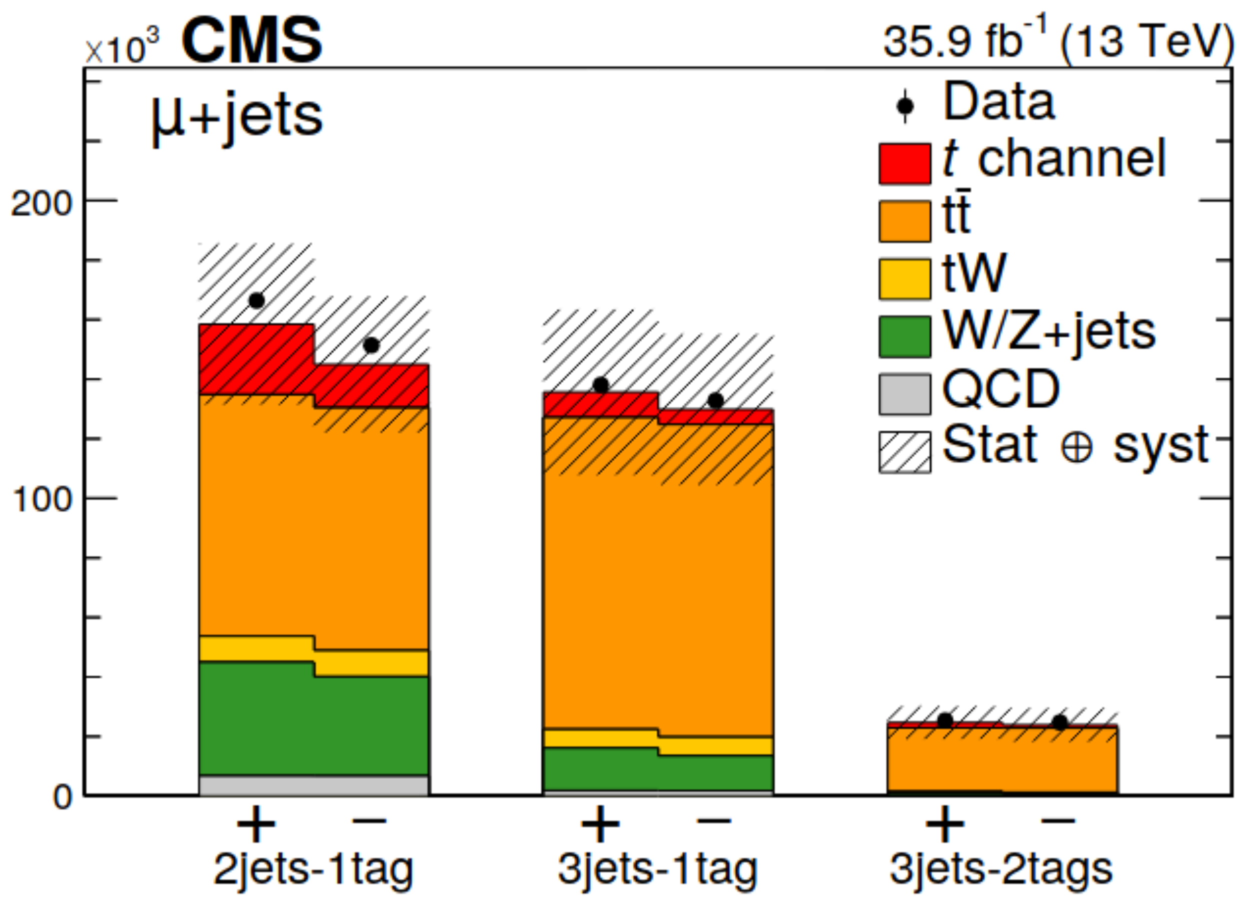
Example from CMS

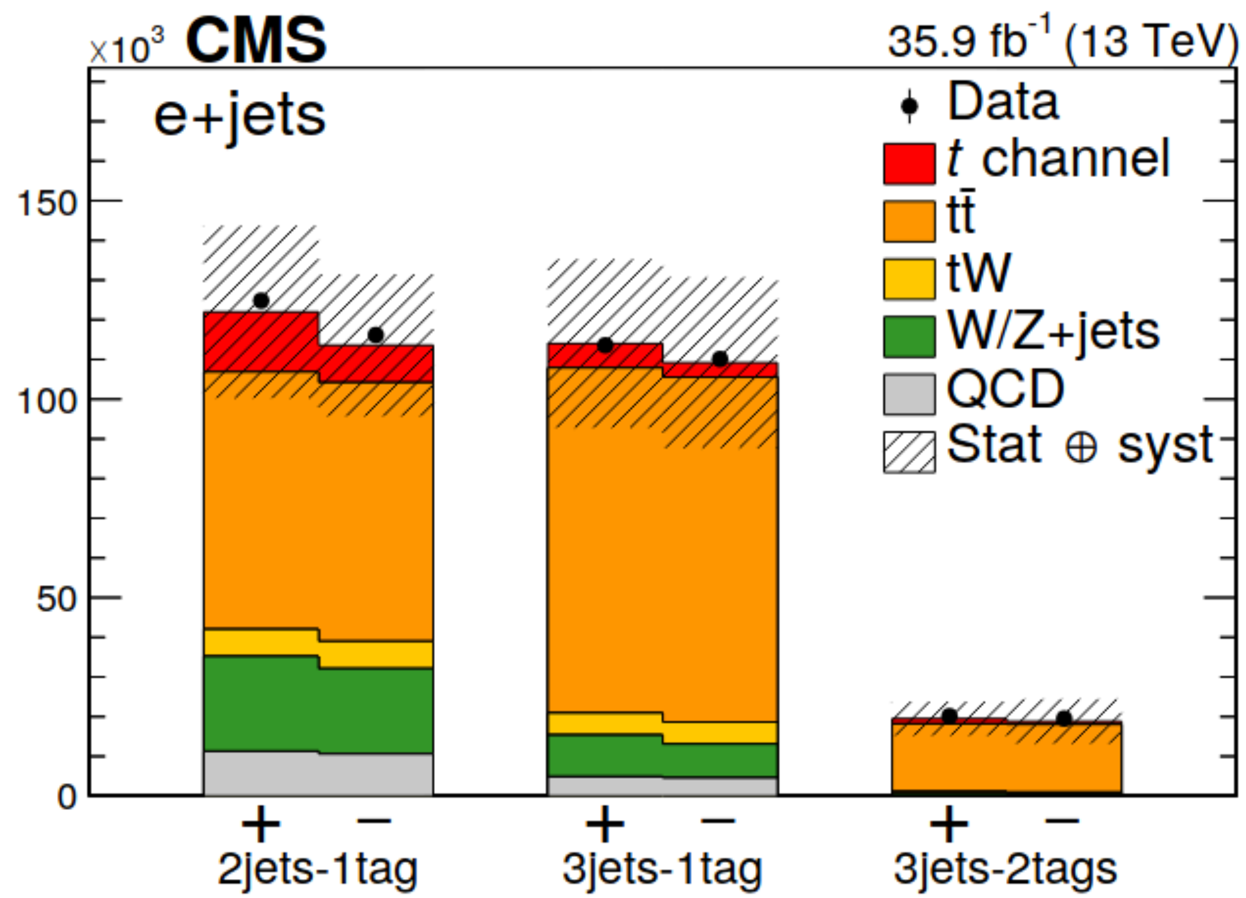


- First step: define an event selection
  - exactly one lepton (electron or muon)
  - E_T^{miss}
  - ⩾ 2 jets; ⩾ 0 b-tagged jets (must be identified as originating from a b-quark)
- Second step: define different regions depending on the number of jets (N_{jets}) and number of b-tagged jet ($N_{b\text{-tag}}$)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

[PLB 800 (2019) 135042]

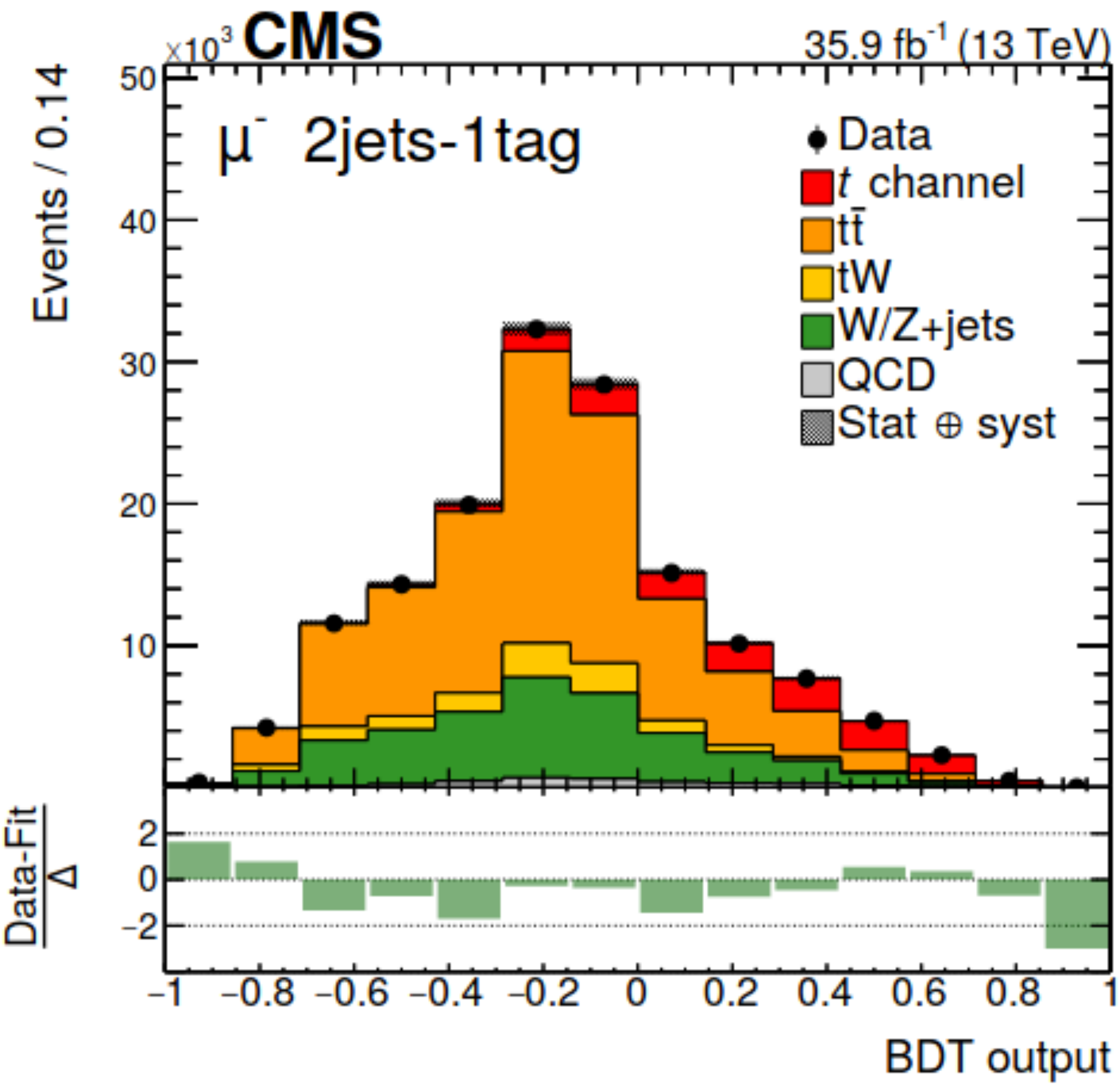
Inclusive t-channel cross-section





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-qaurk mass, ΔR (lepton, b jet)…

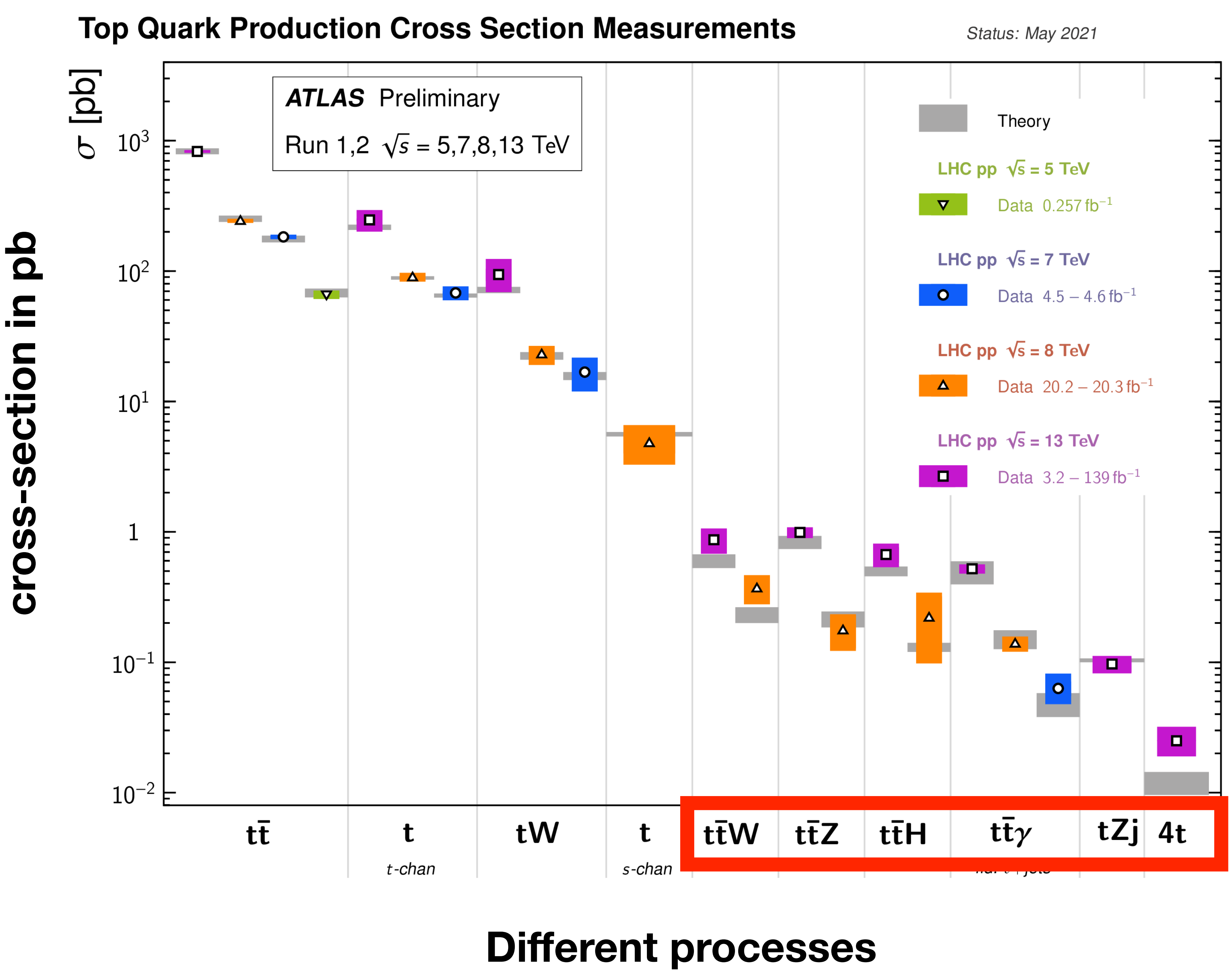


$\sigma_t = 130 \pm 19$ **pb**; $\sigma_{\bar{t}} = 77 \pm 12$ **pb**

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

Top-quark Production Cross-section Measurements

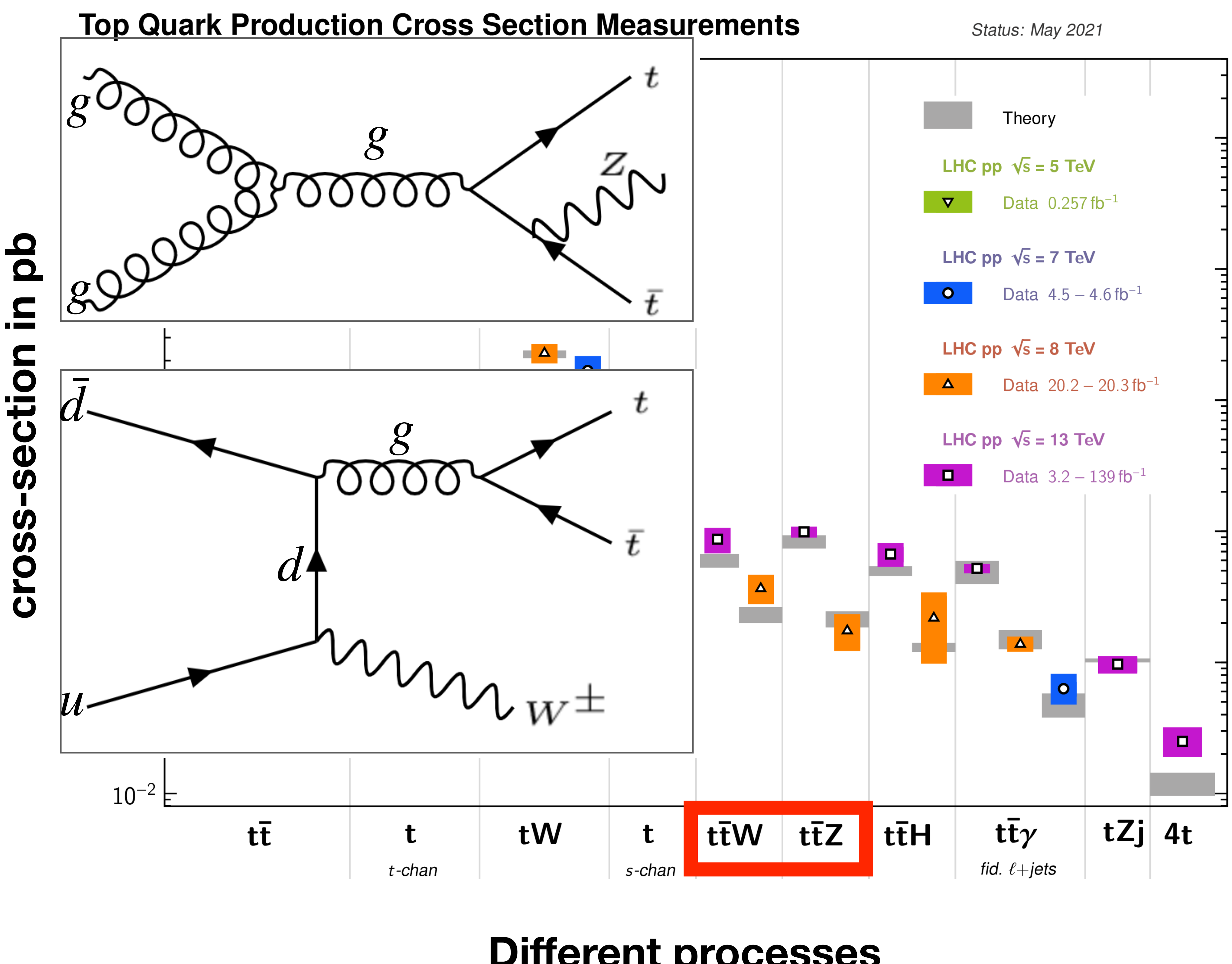
- Rare top production modes become fully accessible with Run 2 data



Top-quark Production Cross-section Measurements

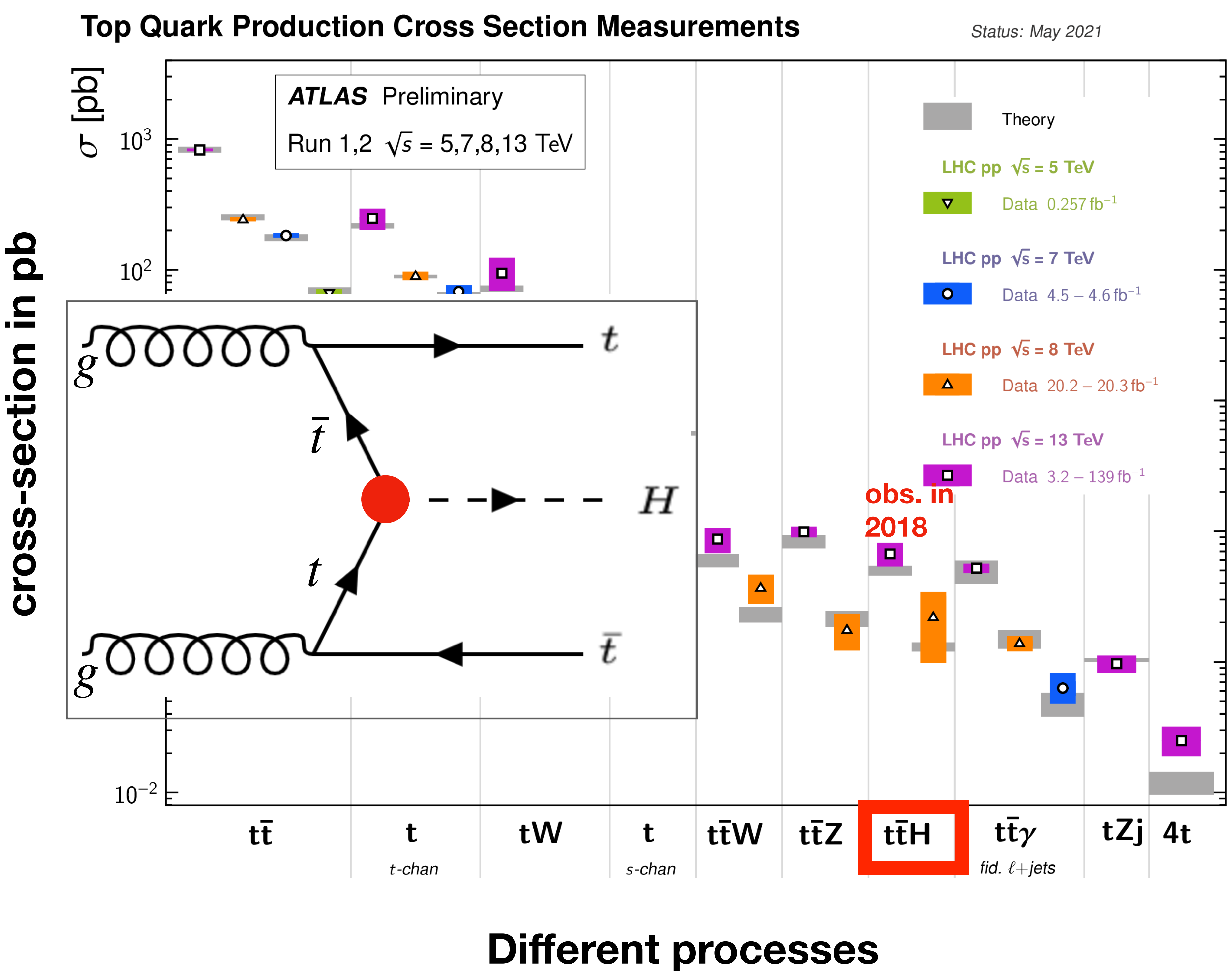
- $t\bar{t}Z/t\bar{t}W$ are among the most massive signatures that can be studied at the LHC with high precision

- **Important backgrounds** for searches and measurements



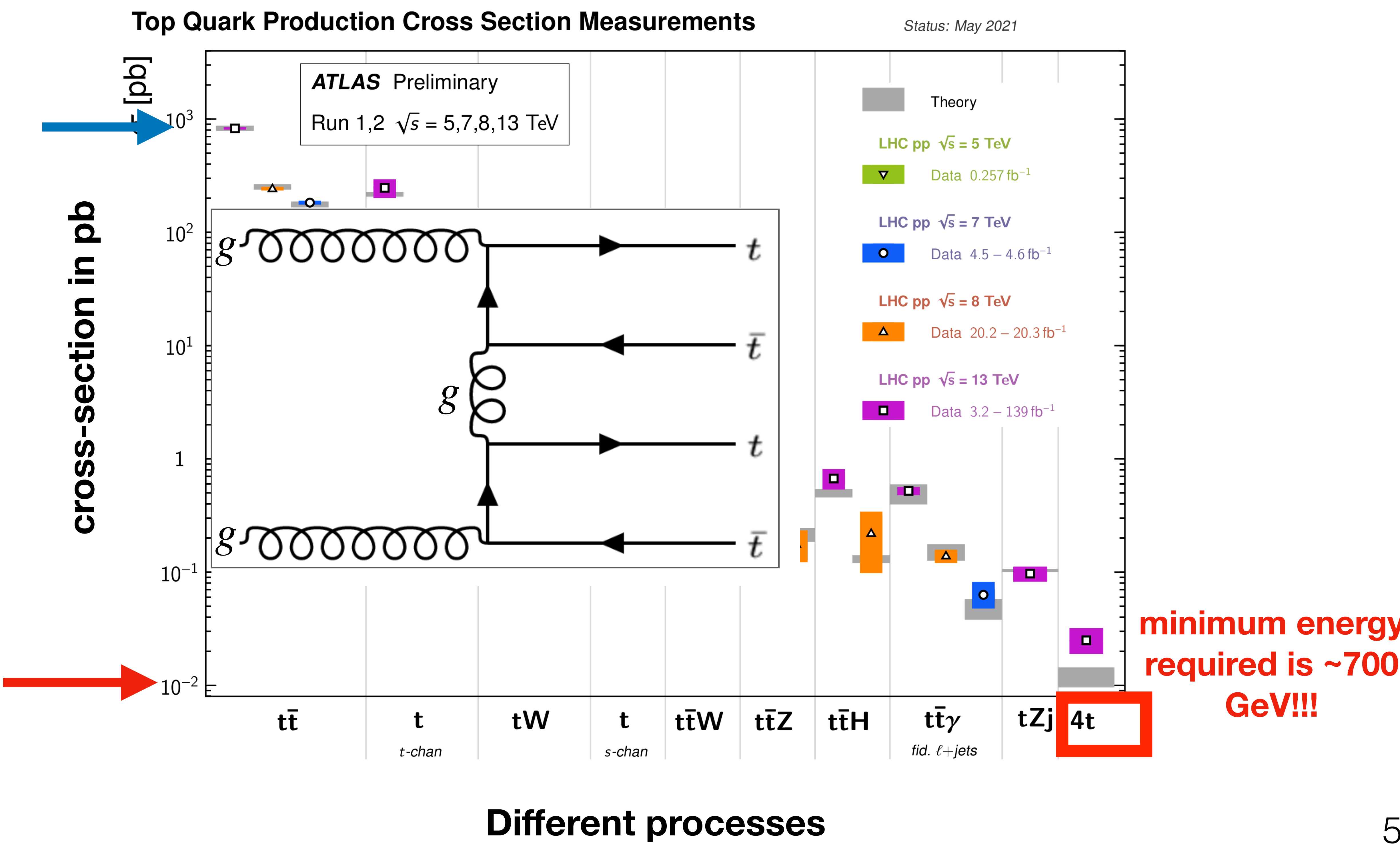
Top-quark Production Cross-section Measurements

- 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**
- $\sigma_{SM}(t\bar{t}t\bar{t})$ ~12 fb



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

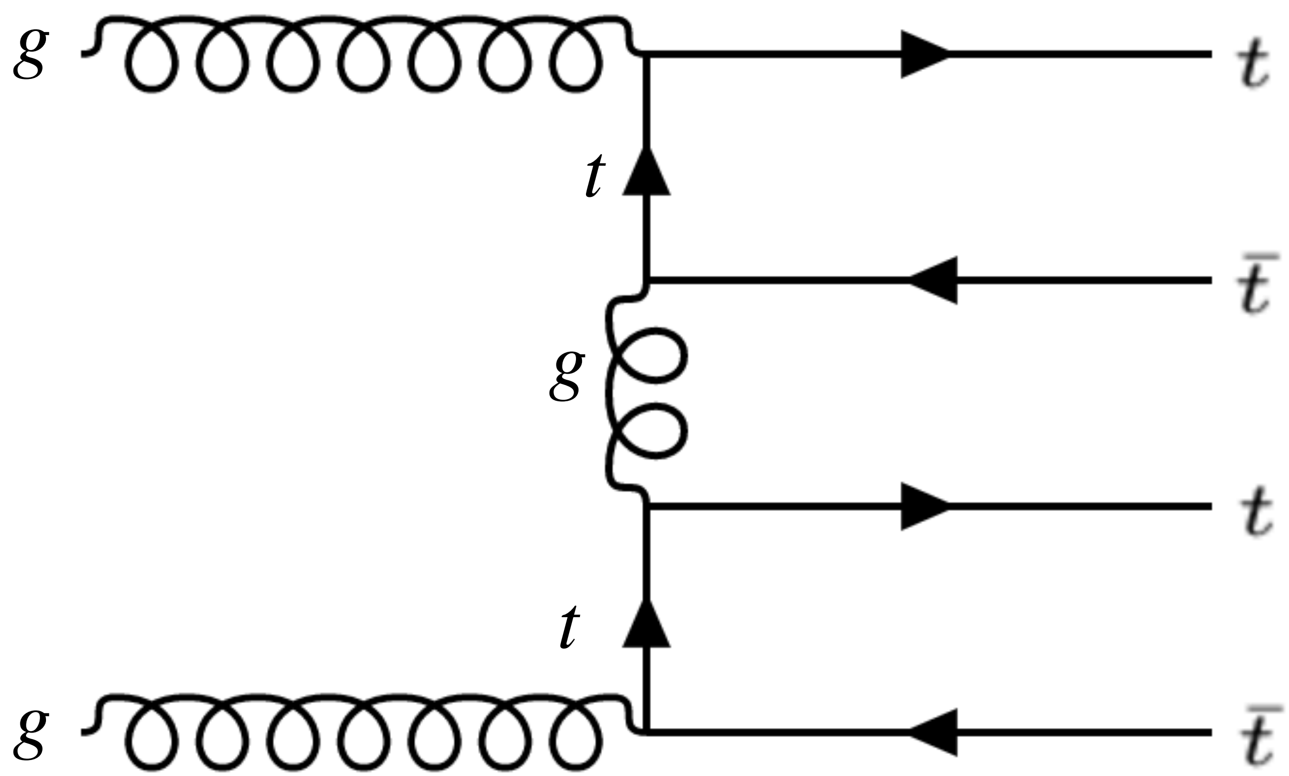
LHC (ATLAS experiment) $\sqrt{s}$ = 13 TeV; 139 fb^{-1} data in 2015-2018

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

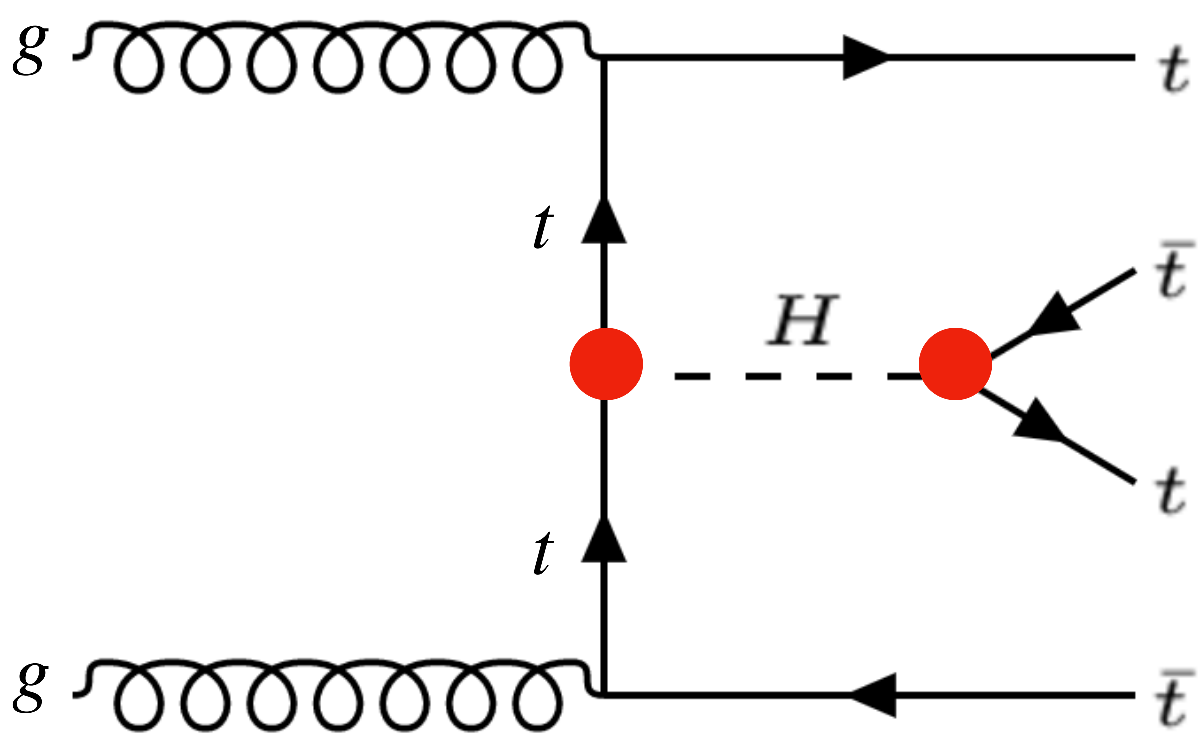
- **Rare** process predicted by the SM

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



Predictions for four tops

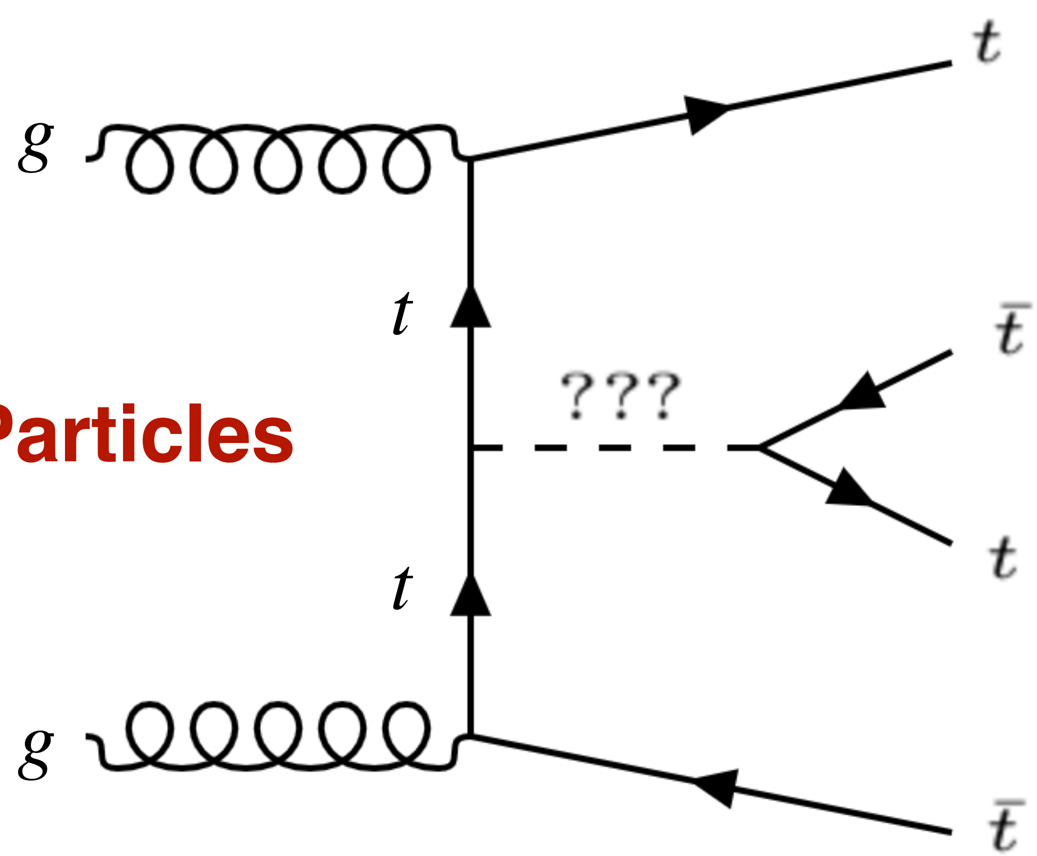
- Four top quarks can be produced via an **offshell SM Higgs boson**
- **Sensitive to the magnitude and CP properties of the Yukawa coupling of the top quark to the Higgs boson**



[arXiv:1611.05032 [hep-ph]]

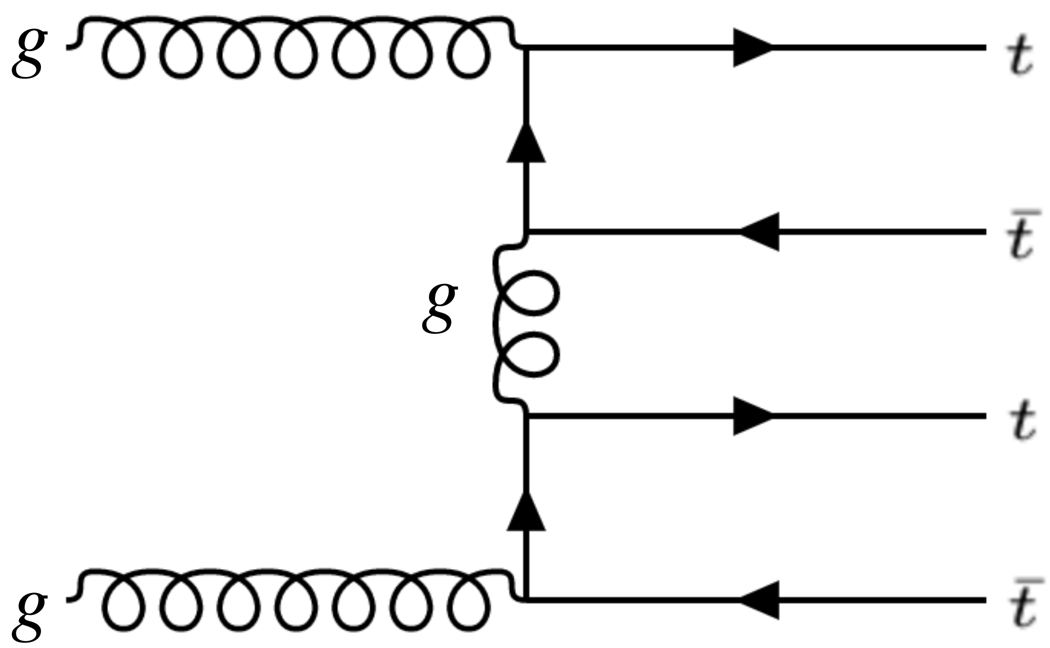
Four top quarks can be sensitive to BSM scenarios

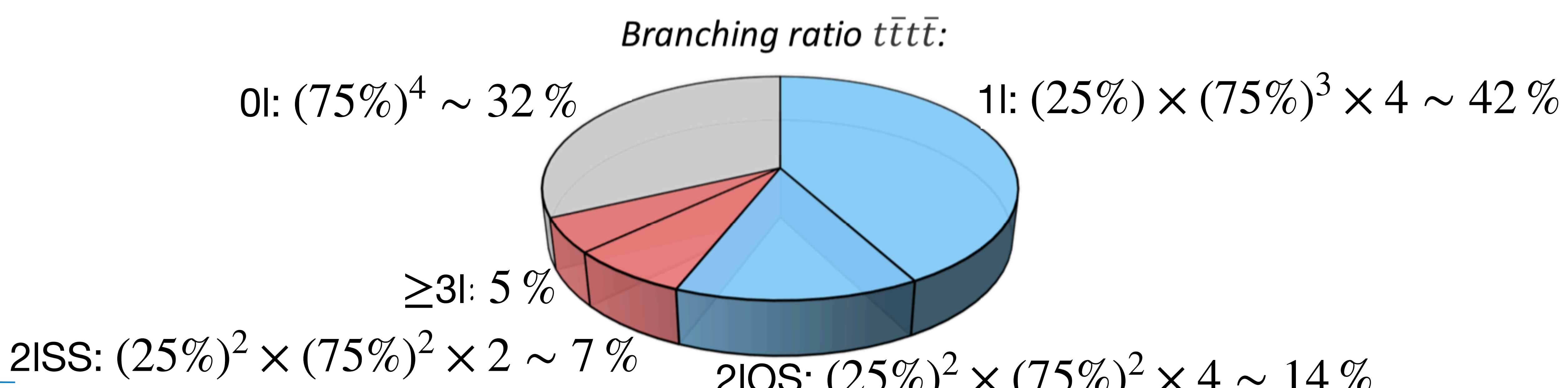
New Particles



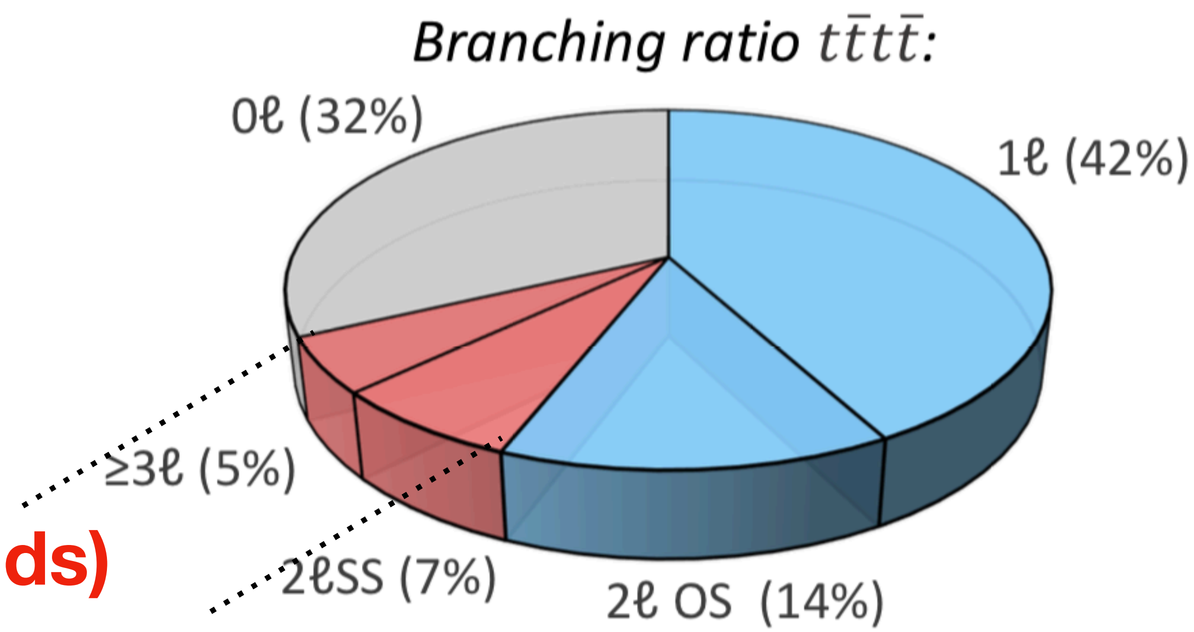
Signatures

- 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



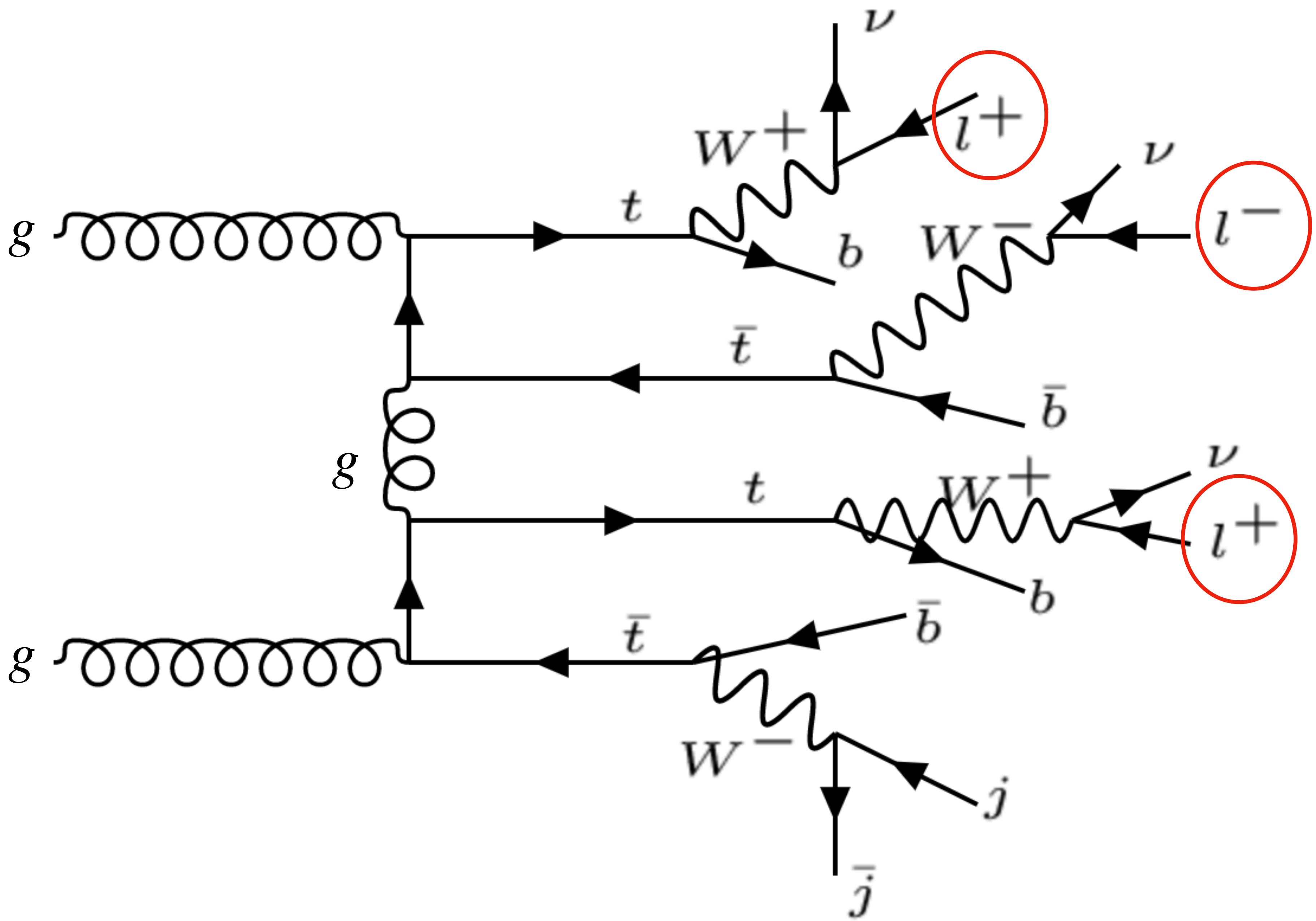


Signatures

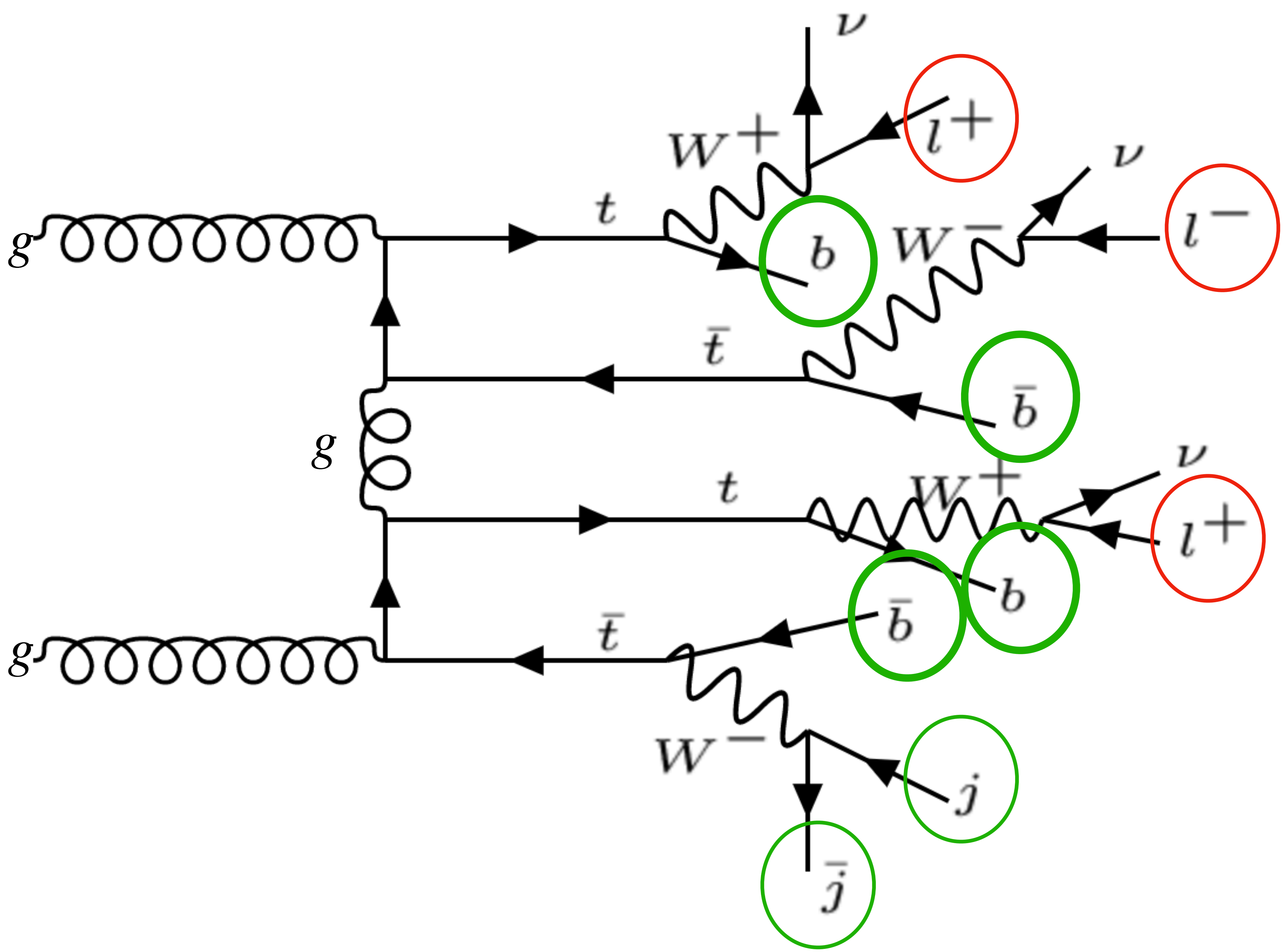


Smallest branching ratio
but very clean (low backgrounds)
Most sensitive channel

Example from the 3l channel

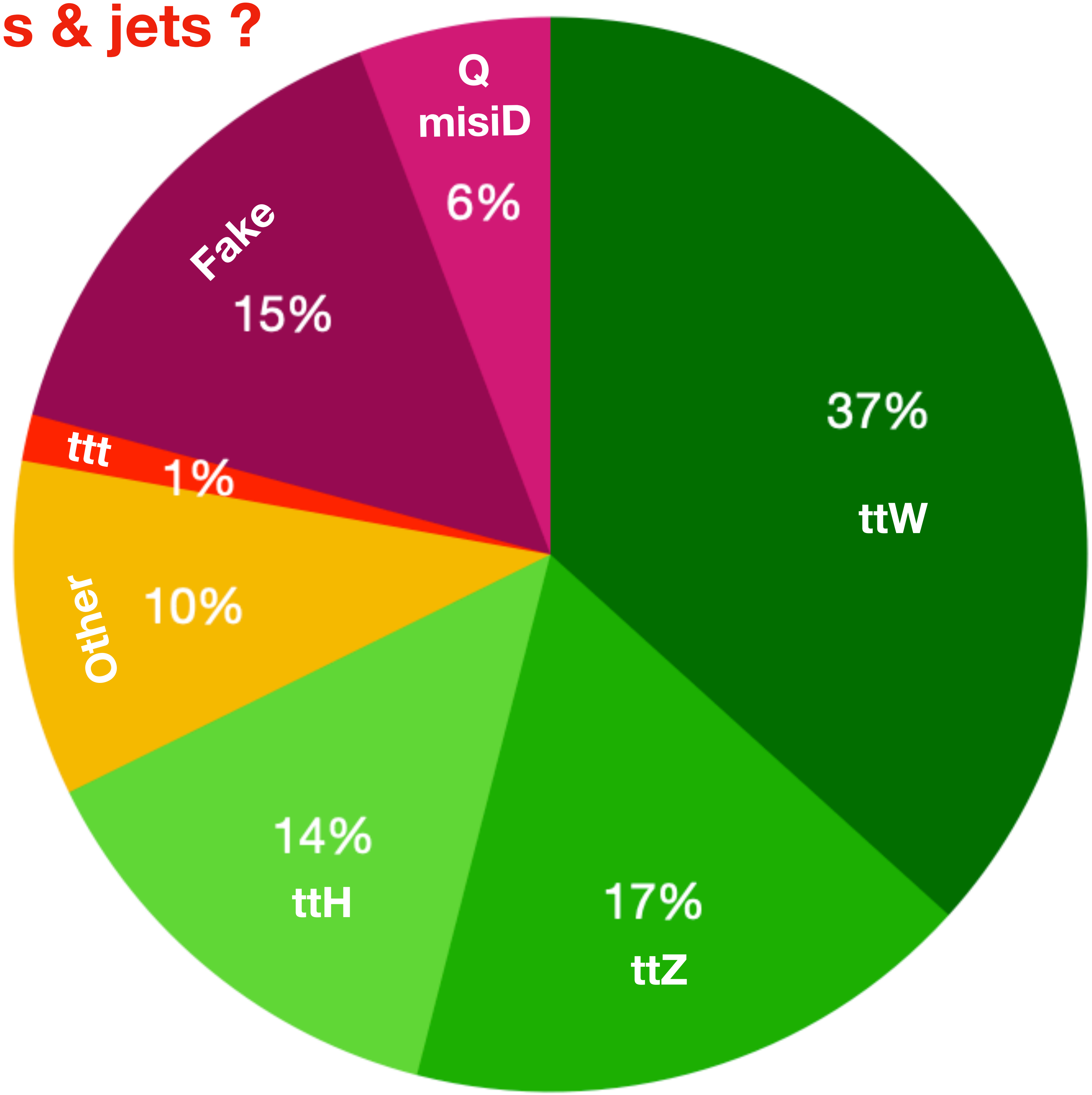


Example from the 3l channel

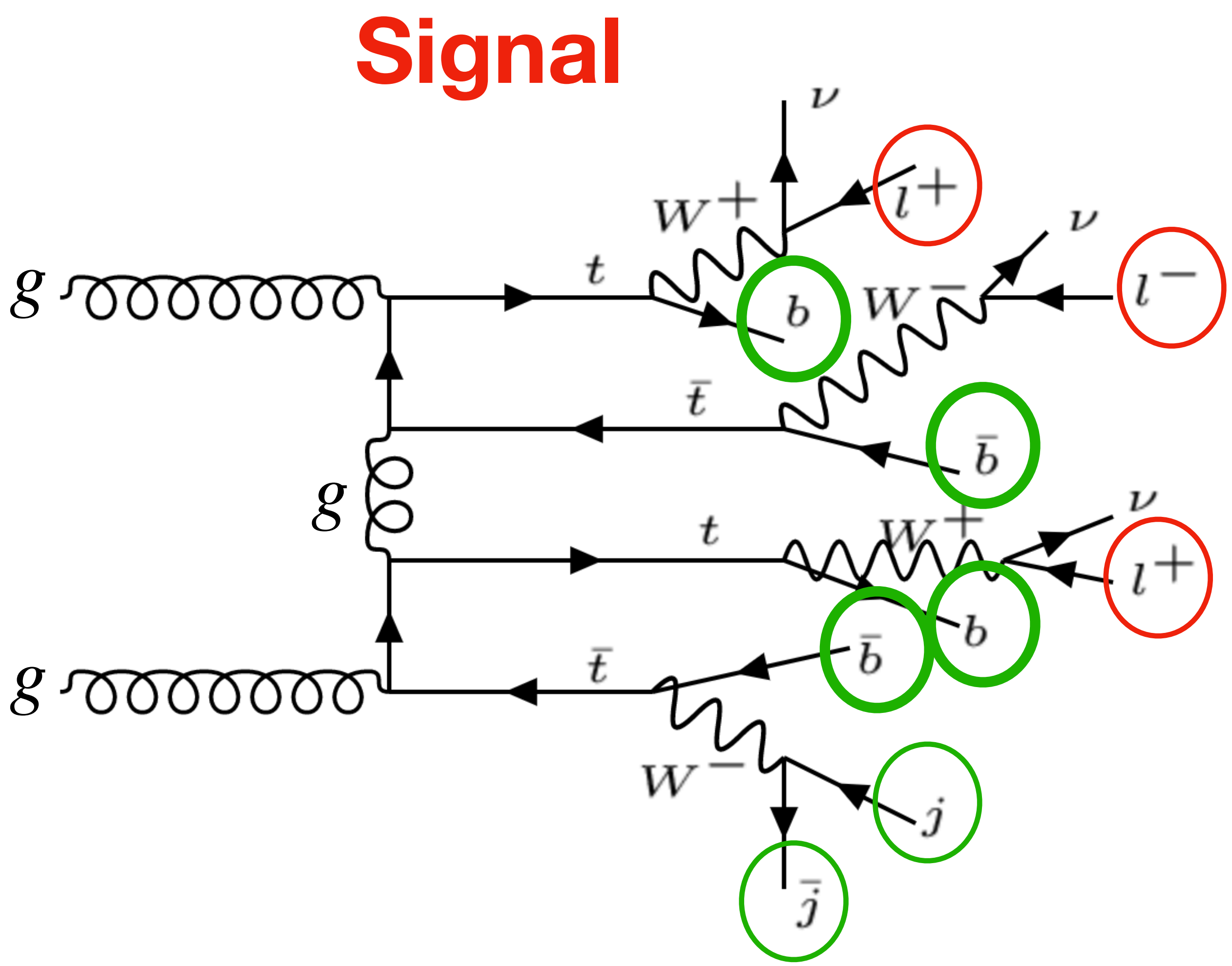


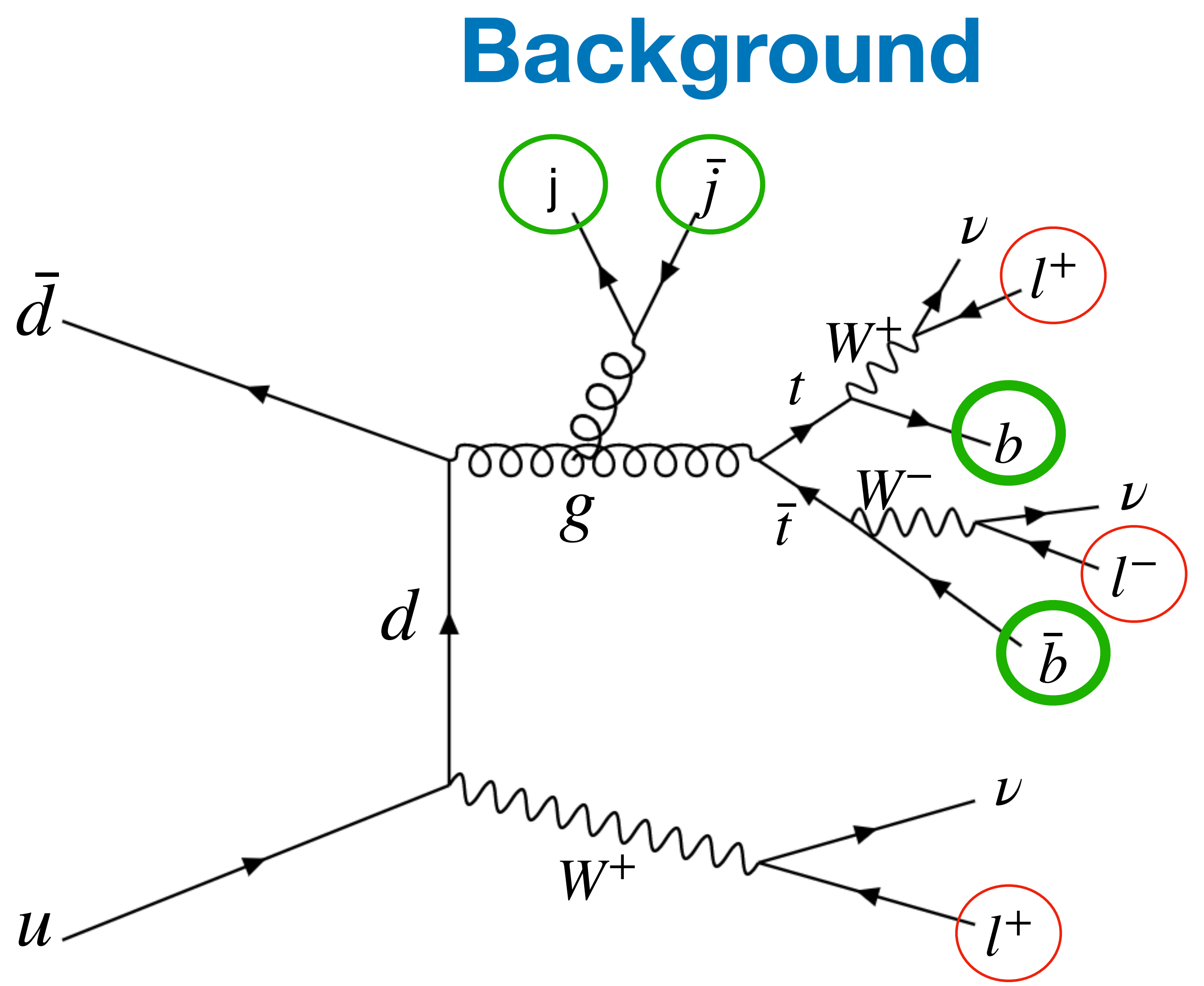
Backgrounds

What else can produce many leptons & jets ?



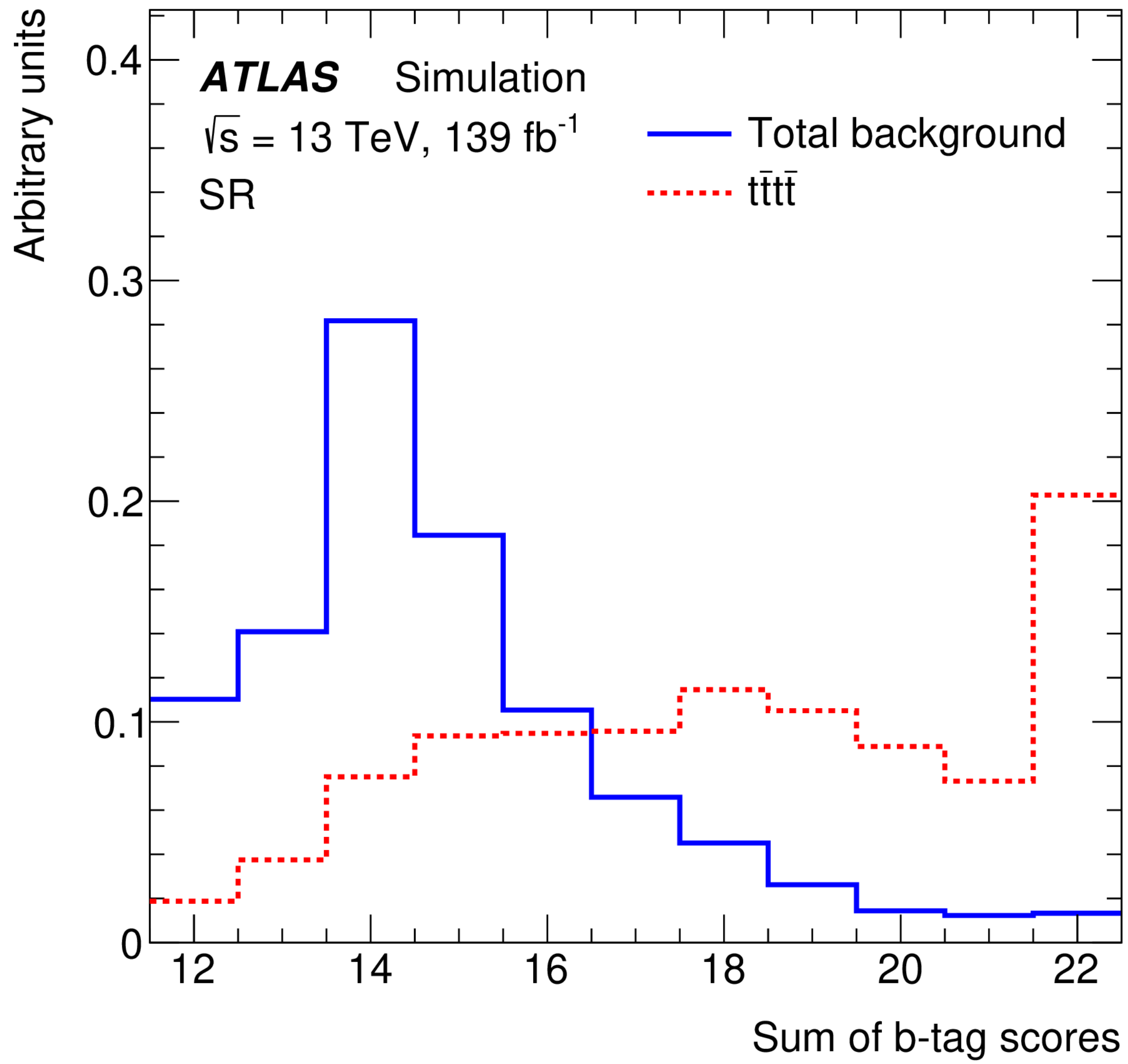
Disentangling Signal from Background





- 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



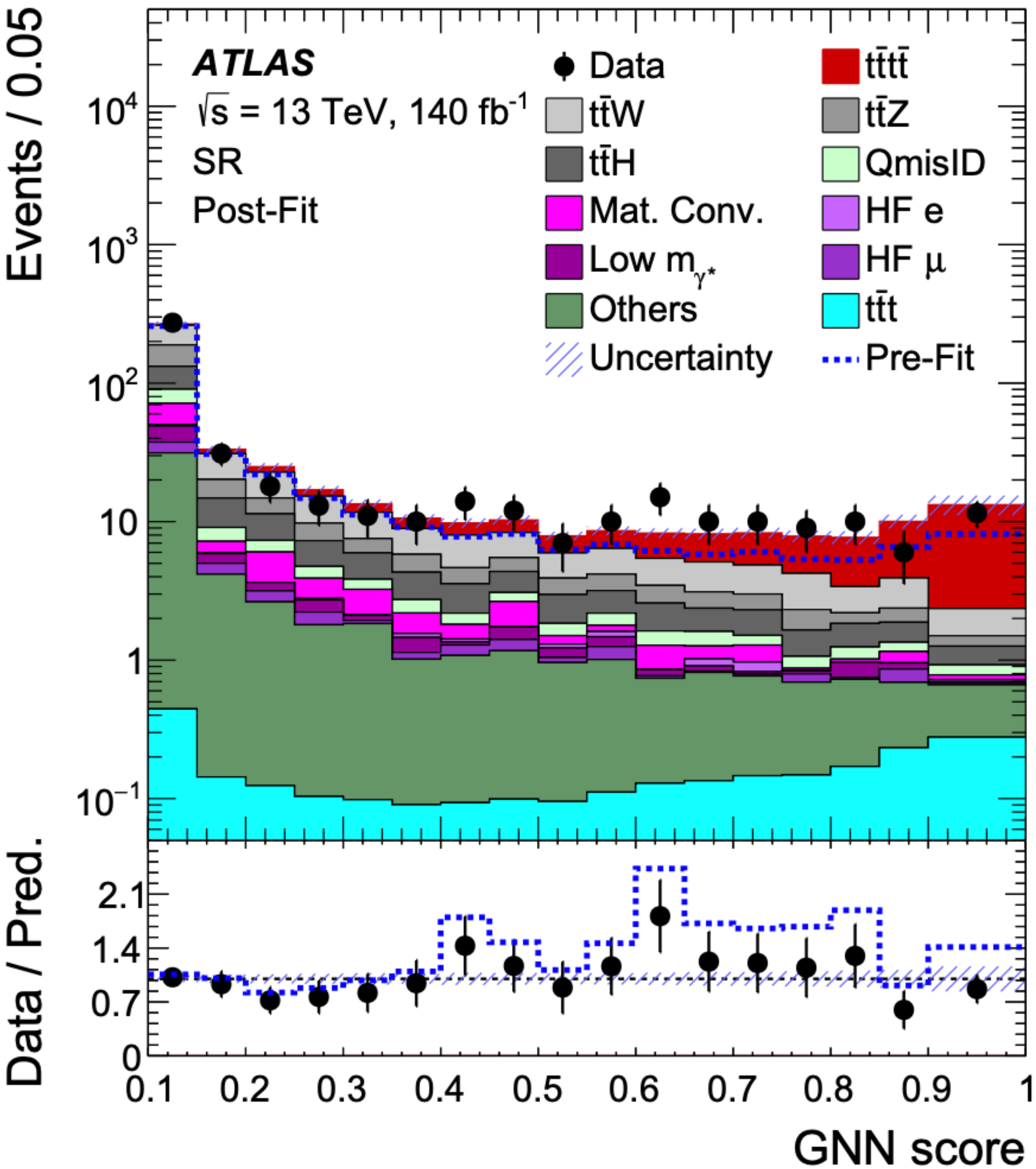
Sum of b-tag scores

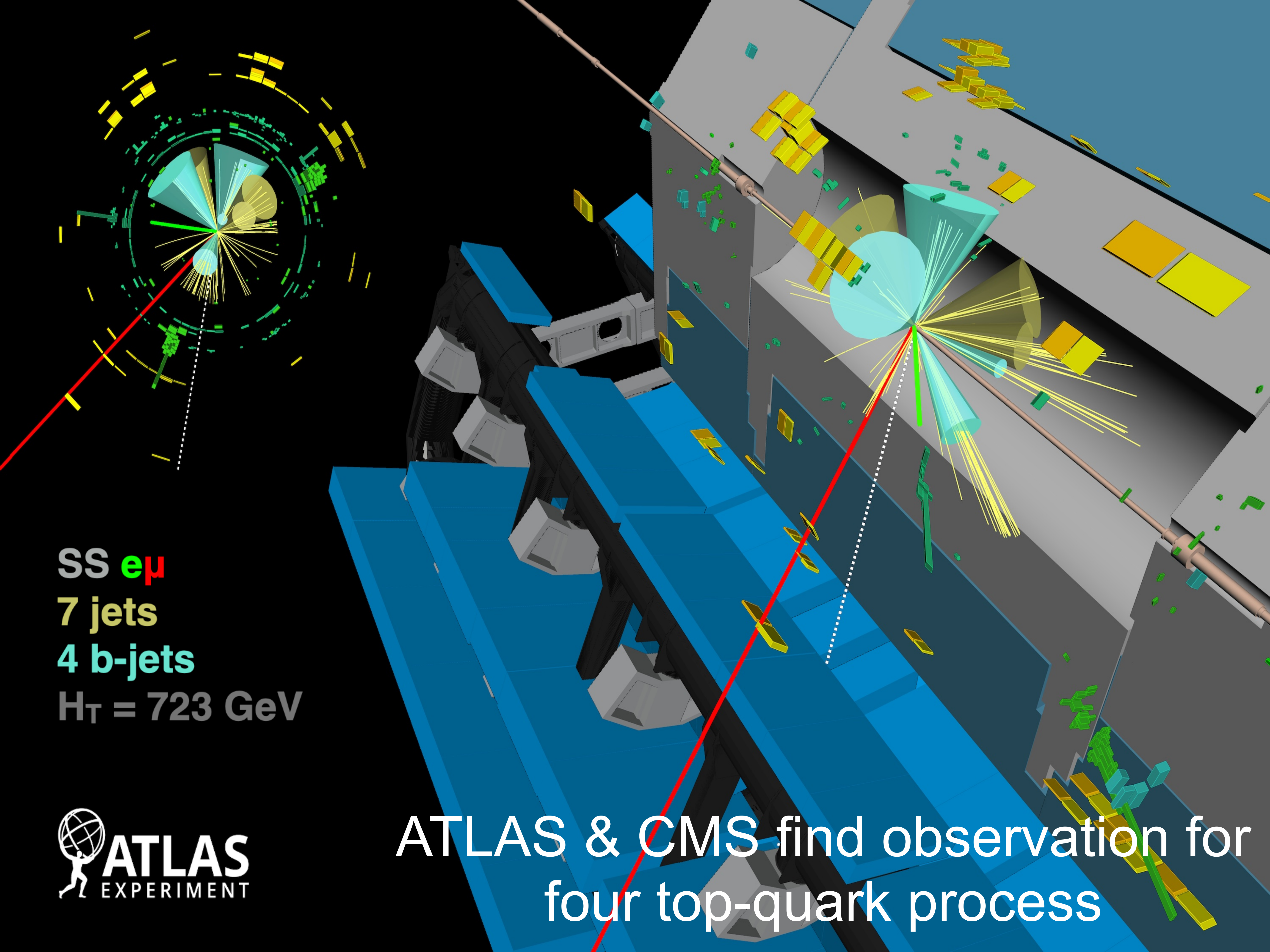
- Use Machine learning to learn the differences between the signal and background

[EPJC 80 (2020) 1085]

Observation of four-top-quark process

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




SS eμ
7 jets
4 b-jets
H_T = 723 GeV
ATLAS EXPERIMENT
ATLAS & CMS find observation for four top-quark process

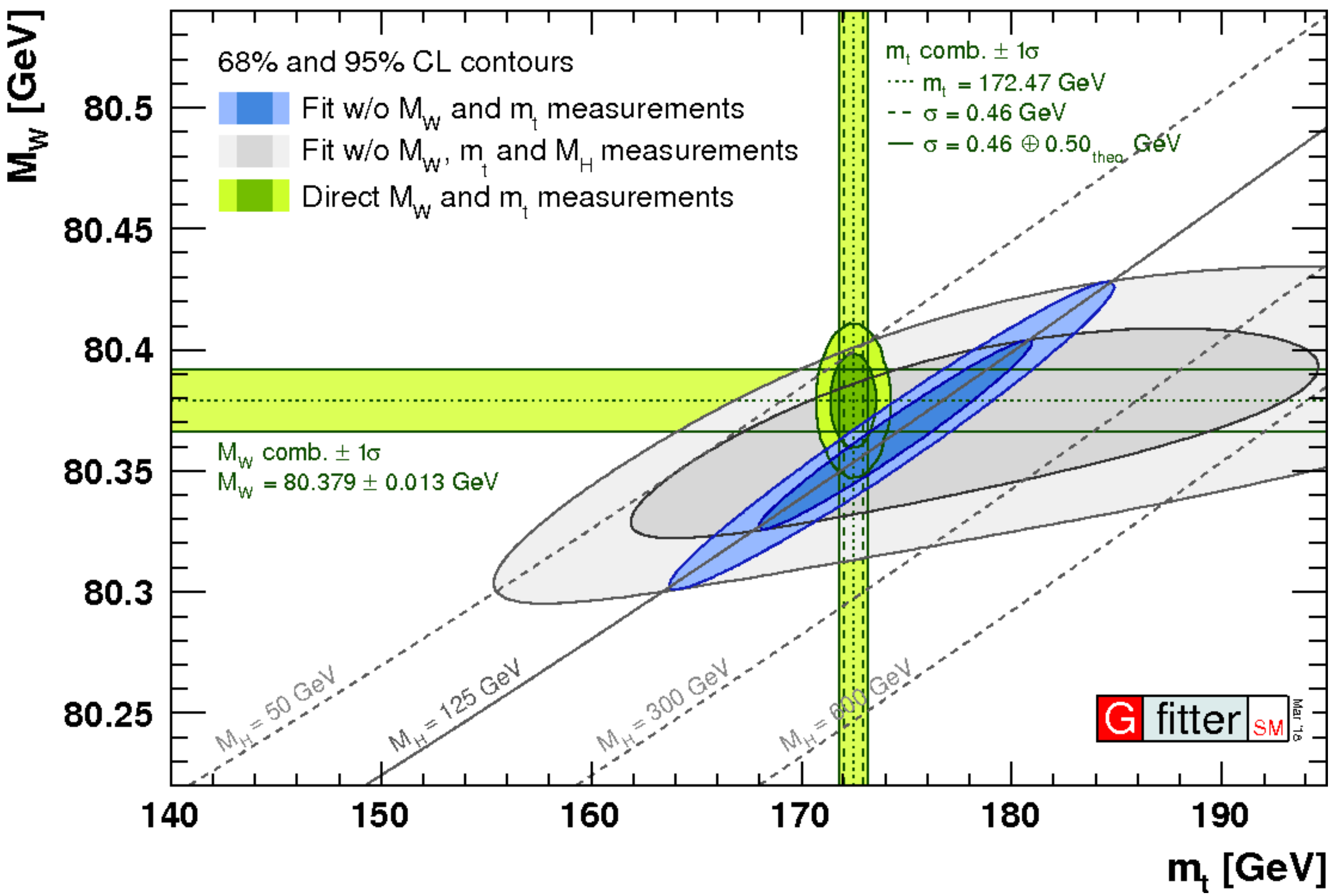
Recap

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

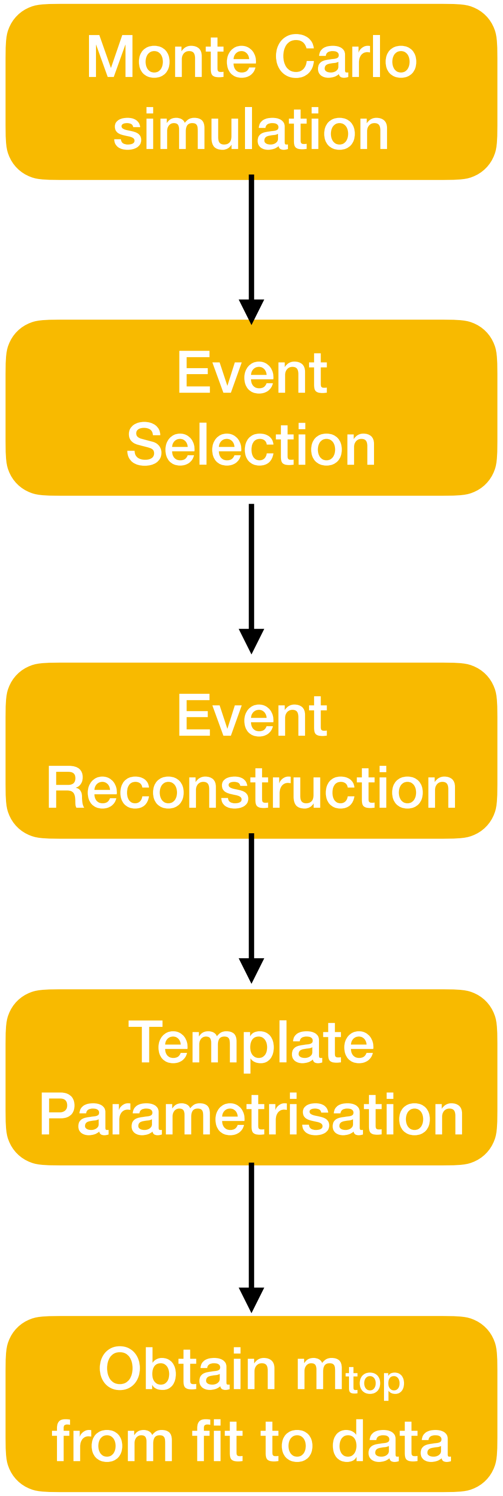
Top quark mass

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

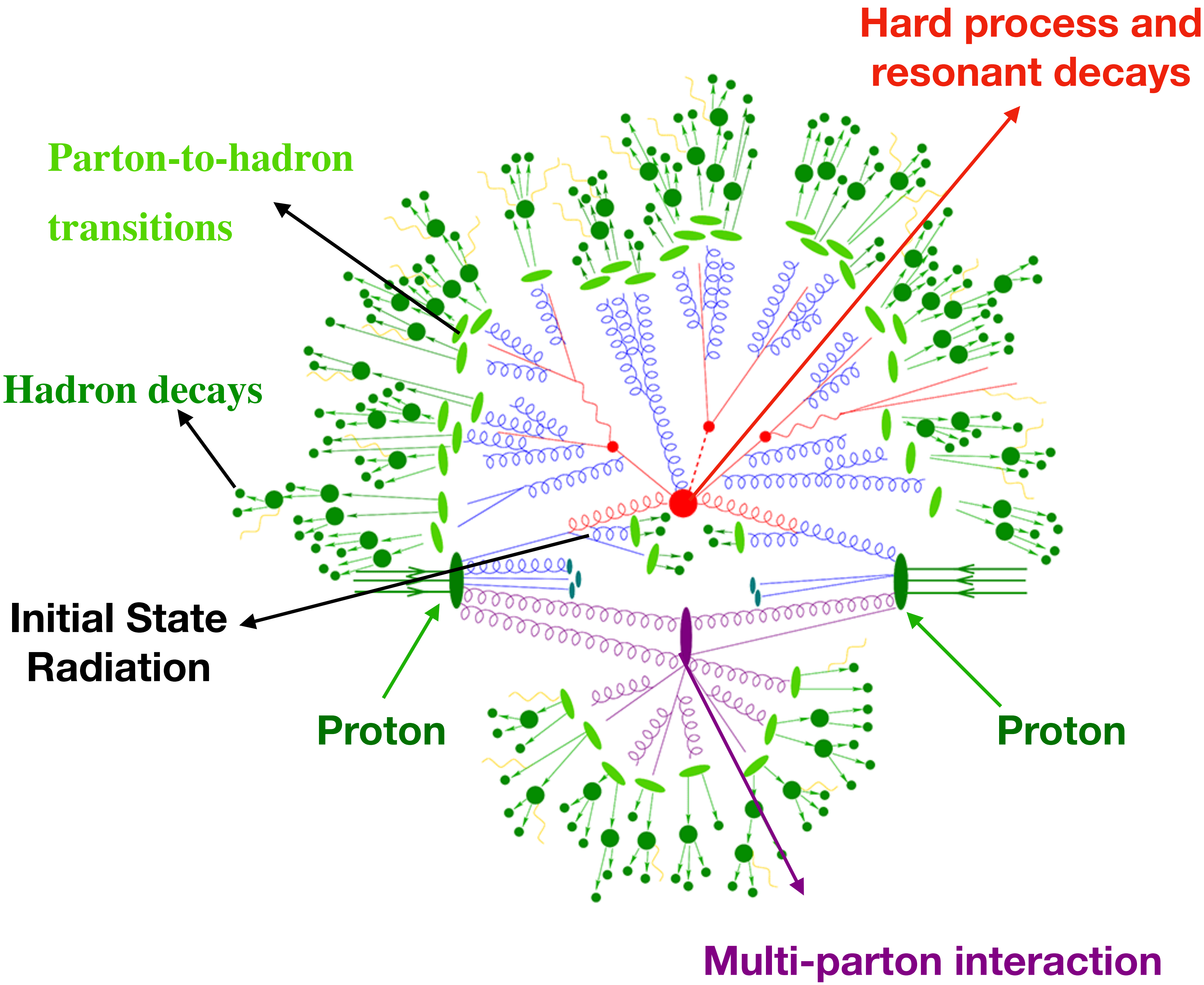


How to measure m_{top}



How to measure m_{top}

Monte Carlo simulation
↓
Event Selection
↓
Event Reconstruction
↓
Template Parametrisation
↓
Obtain m_{top} from fit to data



How to measure m_{top}

Monte Carlo simulation

↓

Event Selection

↓

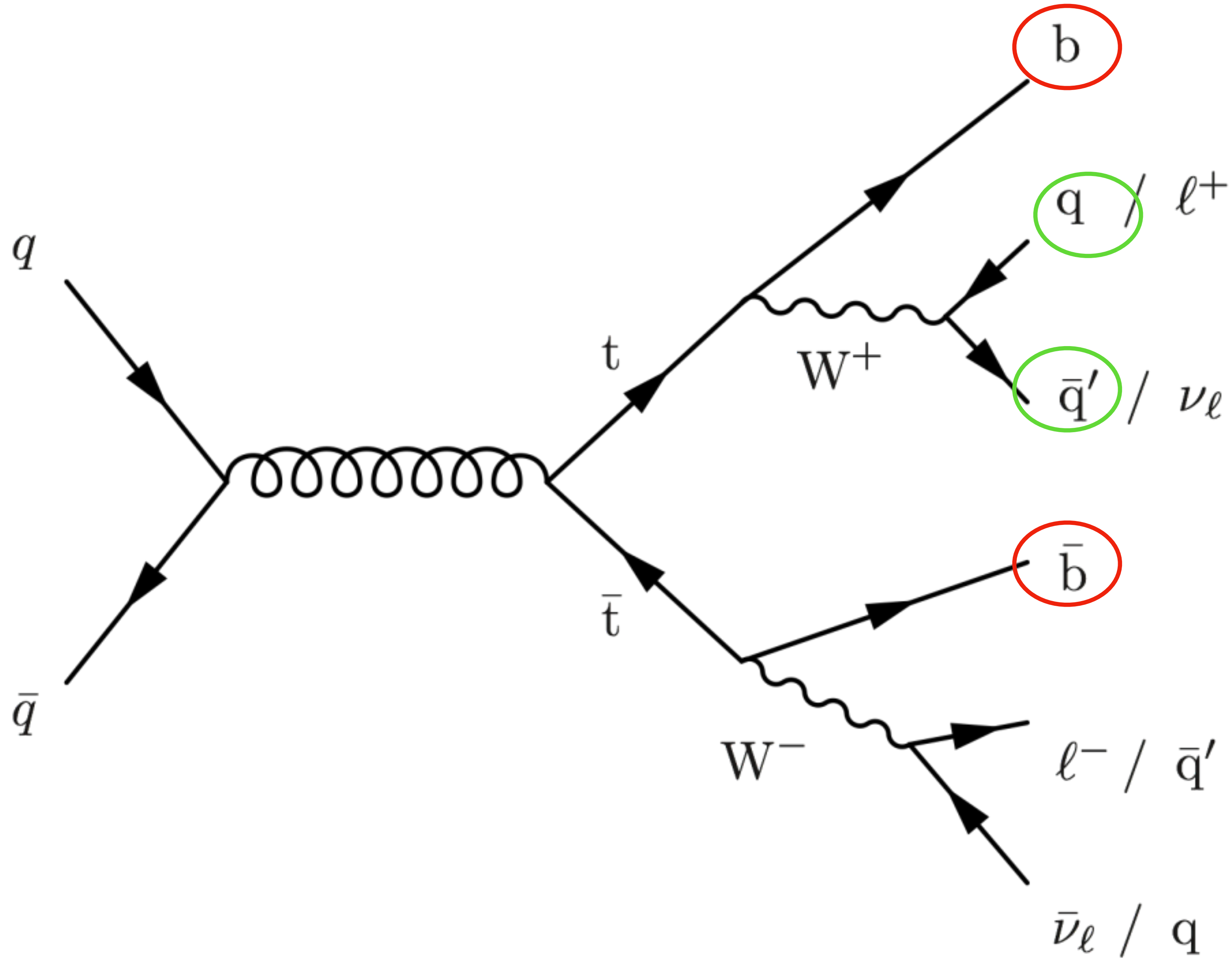
Event Reconstruction

↓

Template Parametrisation

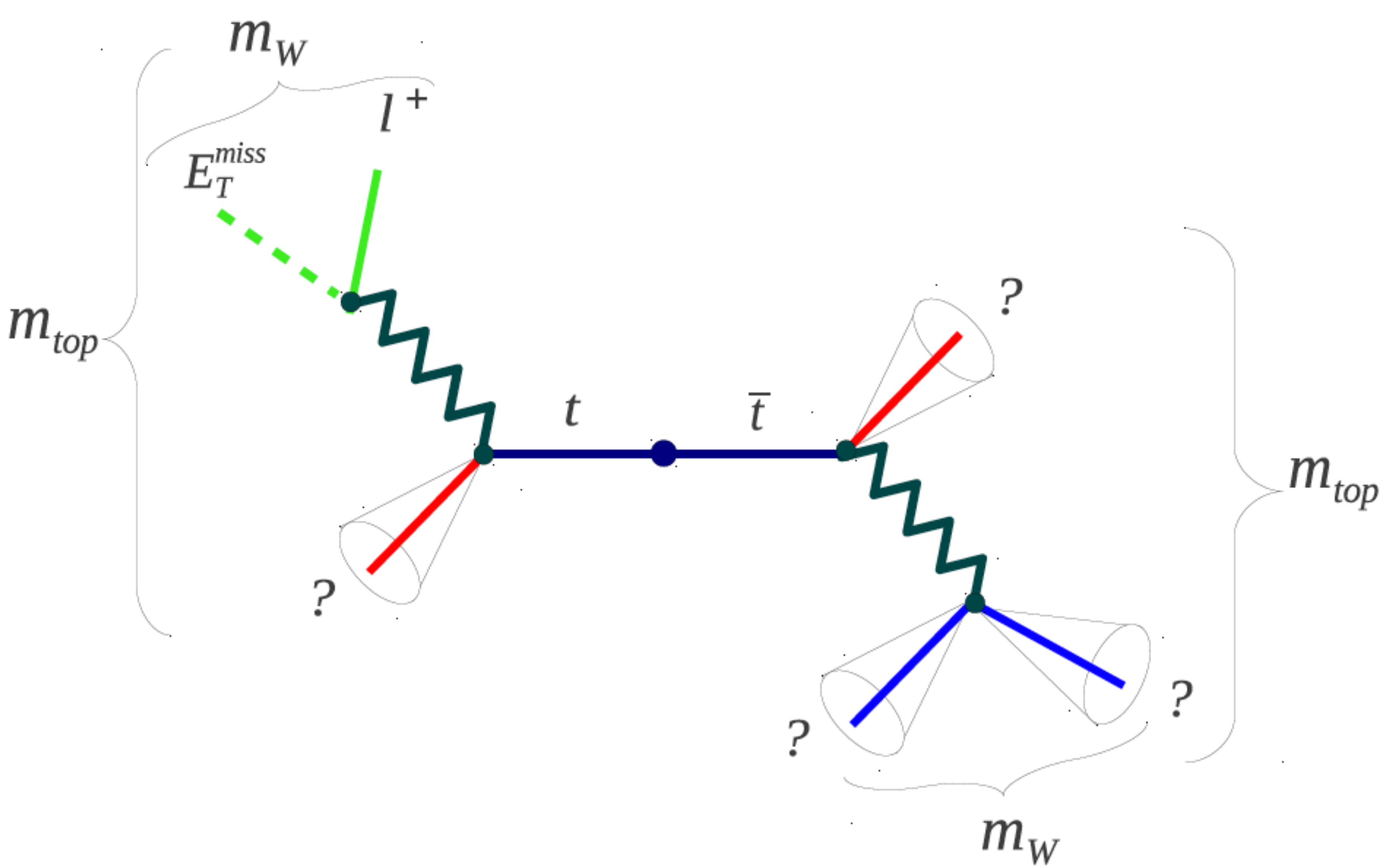
↓

Obtain m_{top} from fit to data



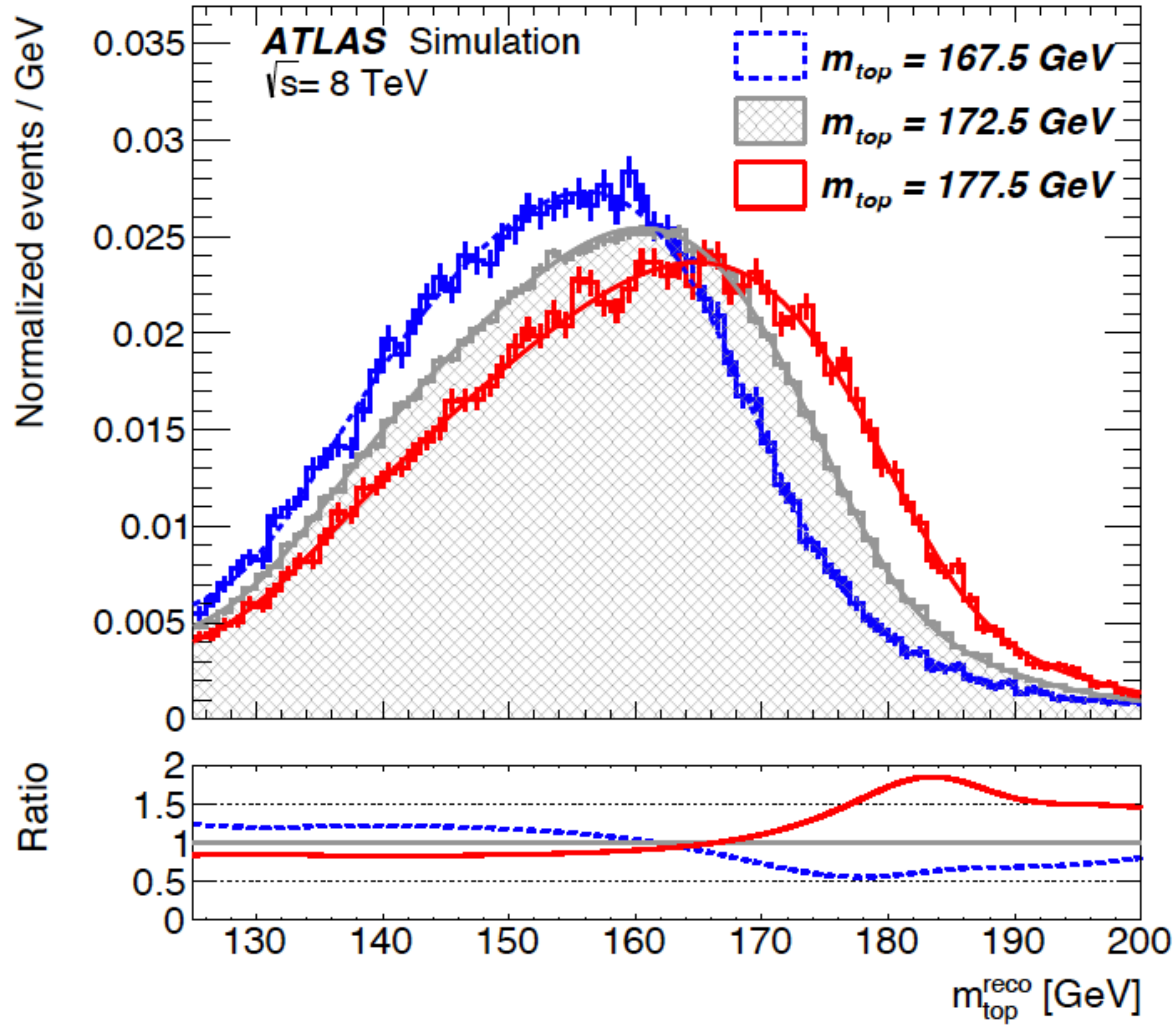
How to measure m_{top}

1. Monte Carlo simulation
2. Event Selection
3. **Event Reconstruction**
4. Template Parametrisation
5. Obtain m_{top} from fit to data



How to measure m_{top}

- Monte Carlo simulation
- Event Selection
- Event Reconstruction
- **Template Parametrisation**
- Obtain m_{top} from fit to data



Fit function to histogram: templates for unbinned likelihood fit

How to measure m_{top}

Monte Carlo simulation

↓

Event Selection

↓

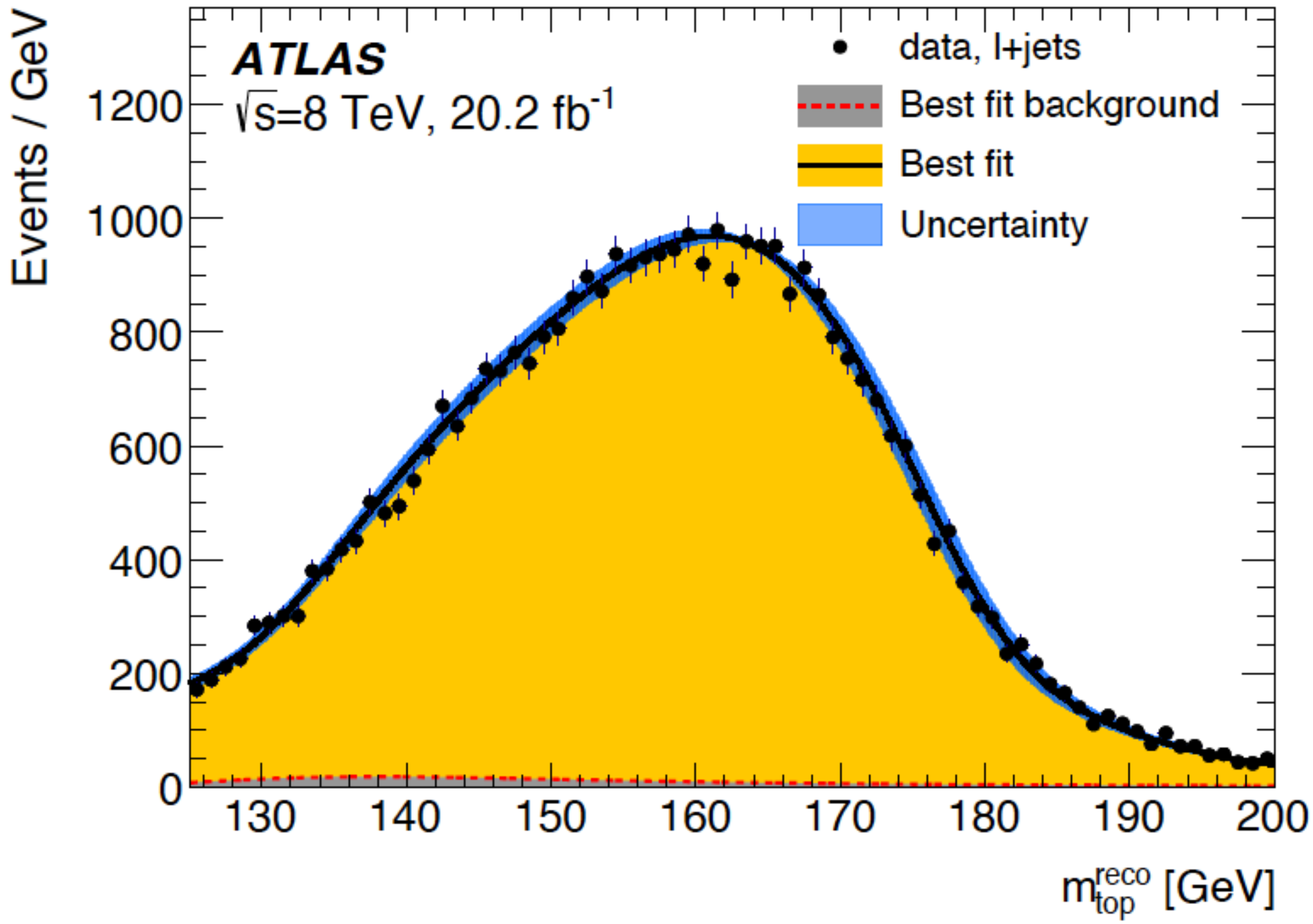
Event Reconstruction

↓

Template Parametrisation

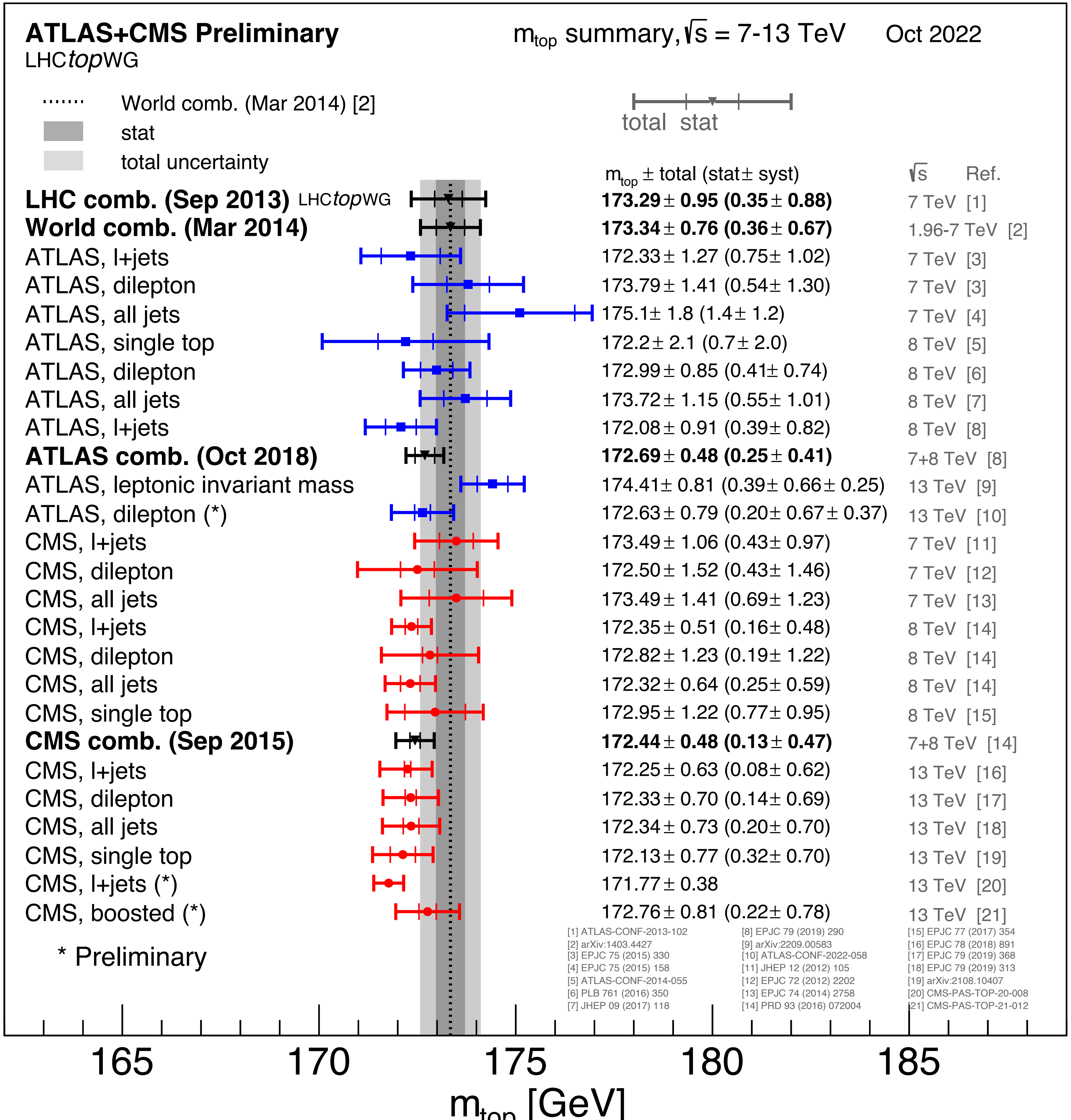
↓

Obtain m_{top} from fit to data



Extract top-quark mass from fit of templates to data

Summary of the ATLAS and CMS measurements



Other top quark properties

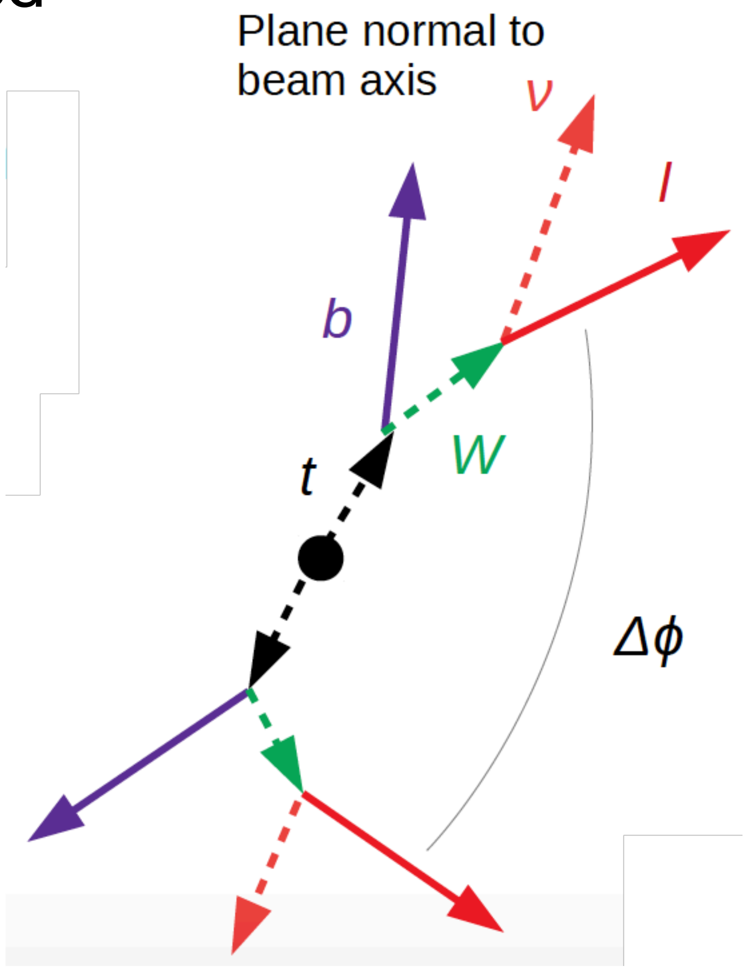
Top quark has a short lifetime … but how short?

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

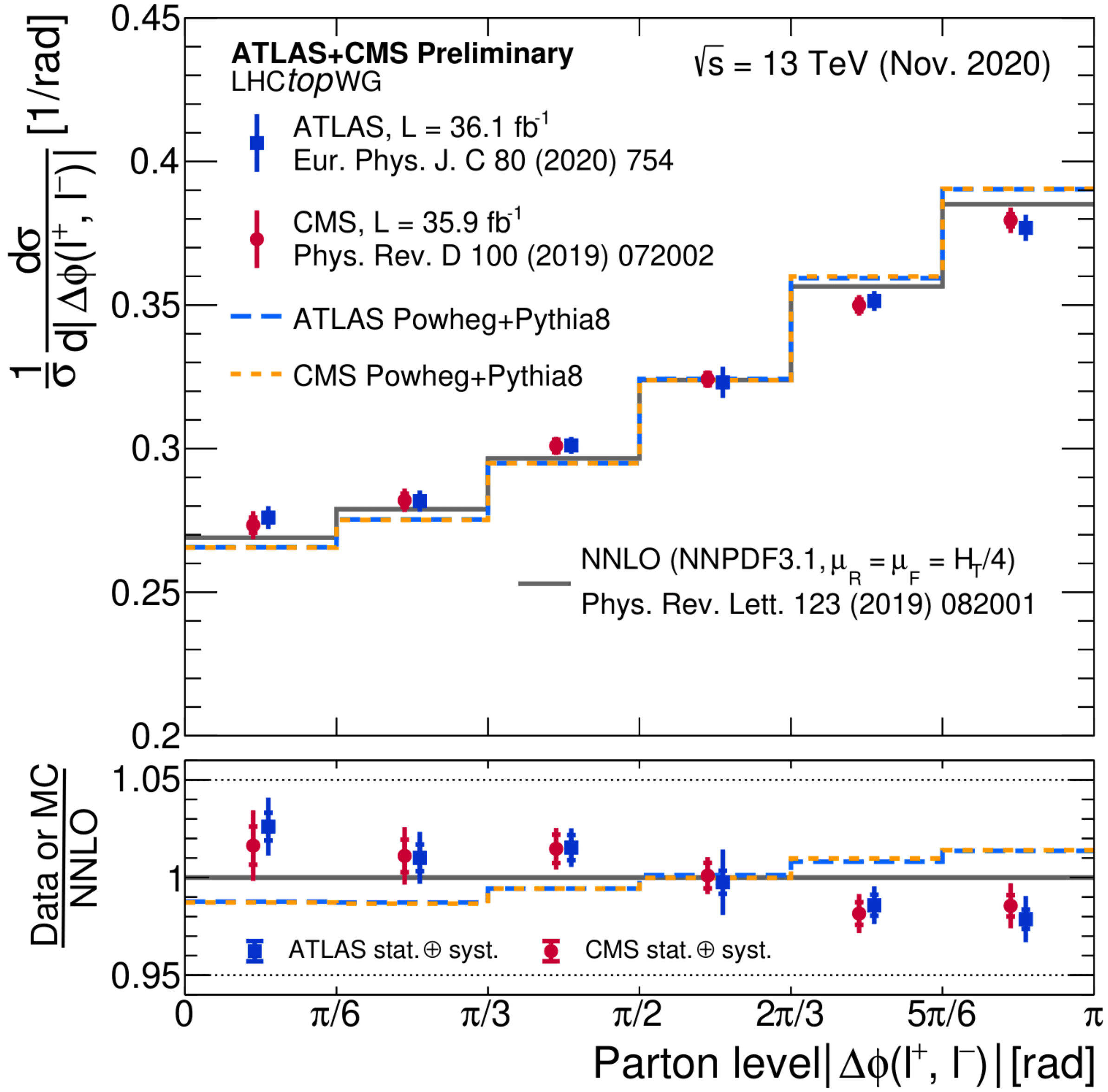


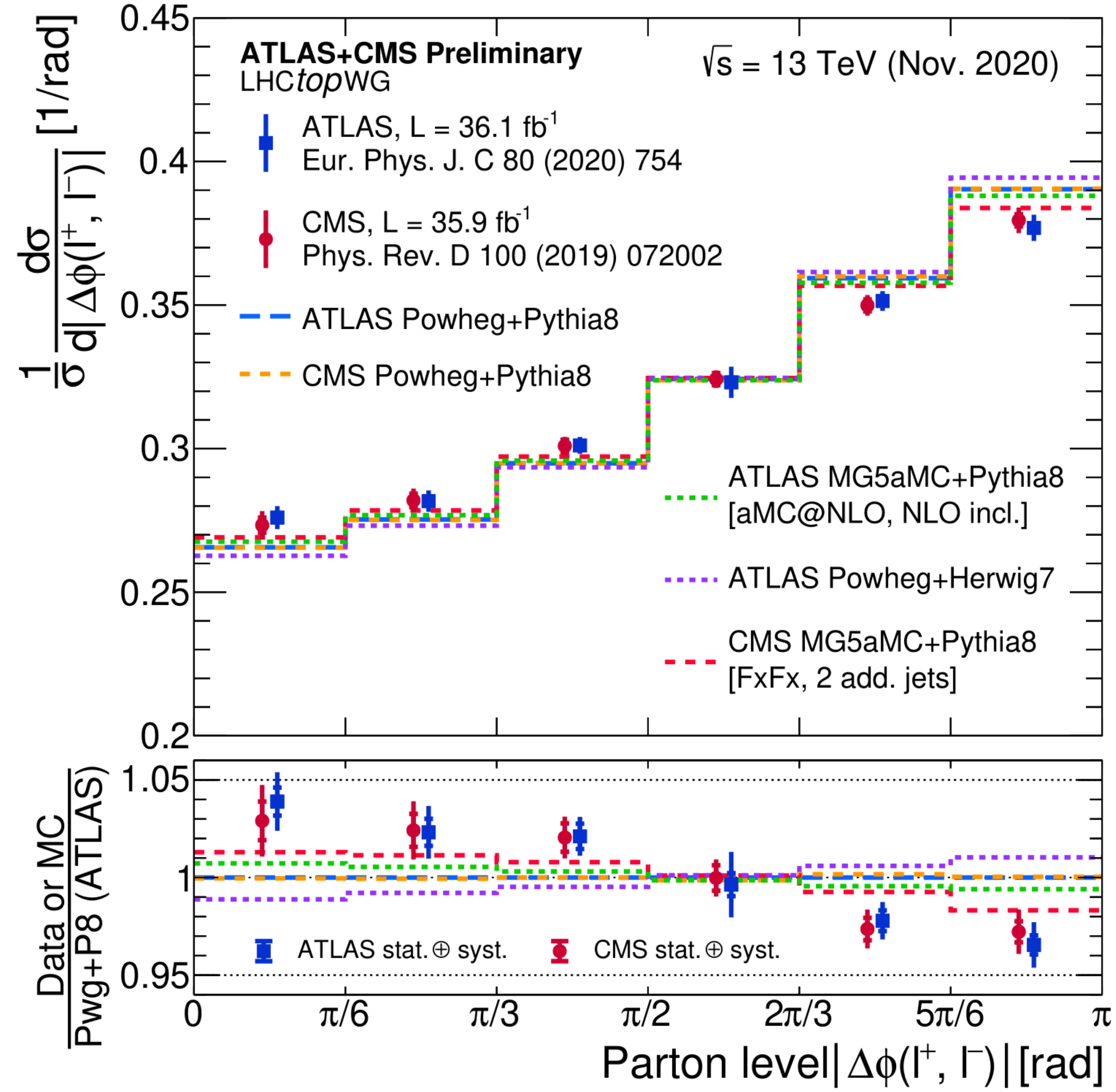
- $\Delta\phi$: azimuthal opening angle between the 2 leptons

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

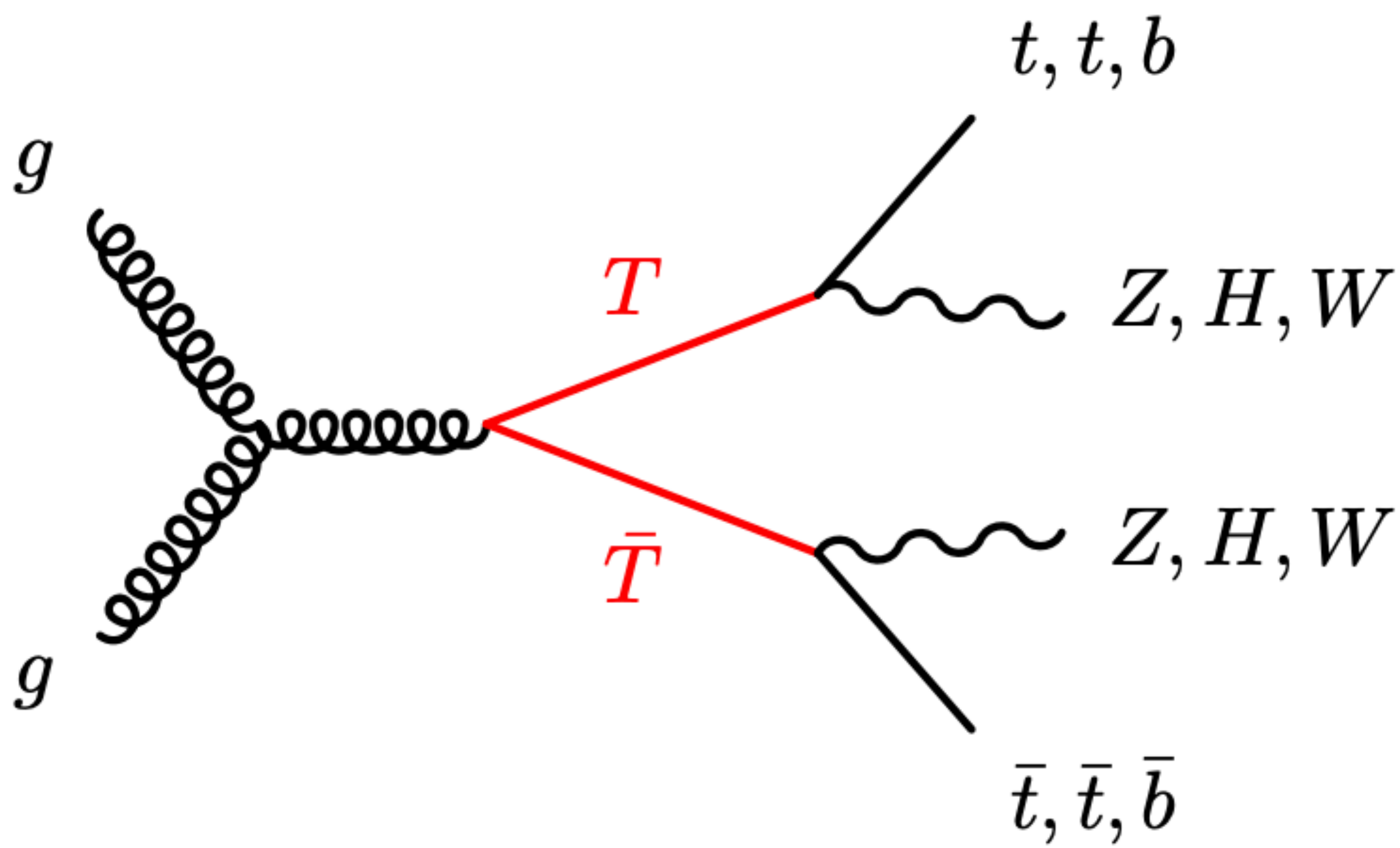
[LHC Top WG]

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!

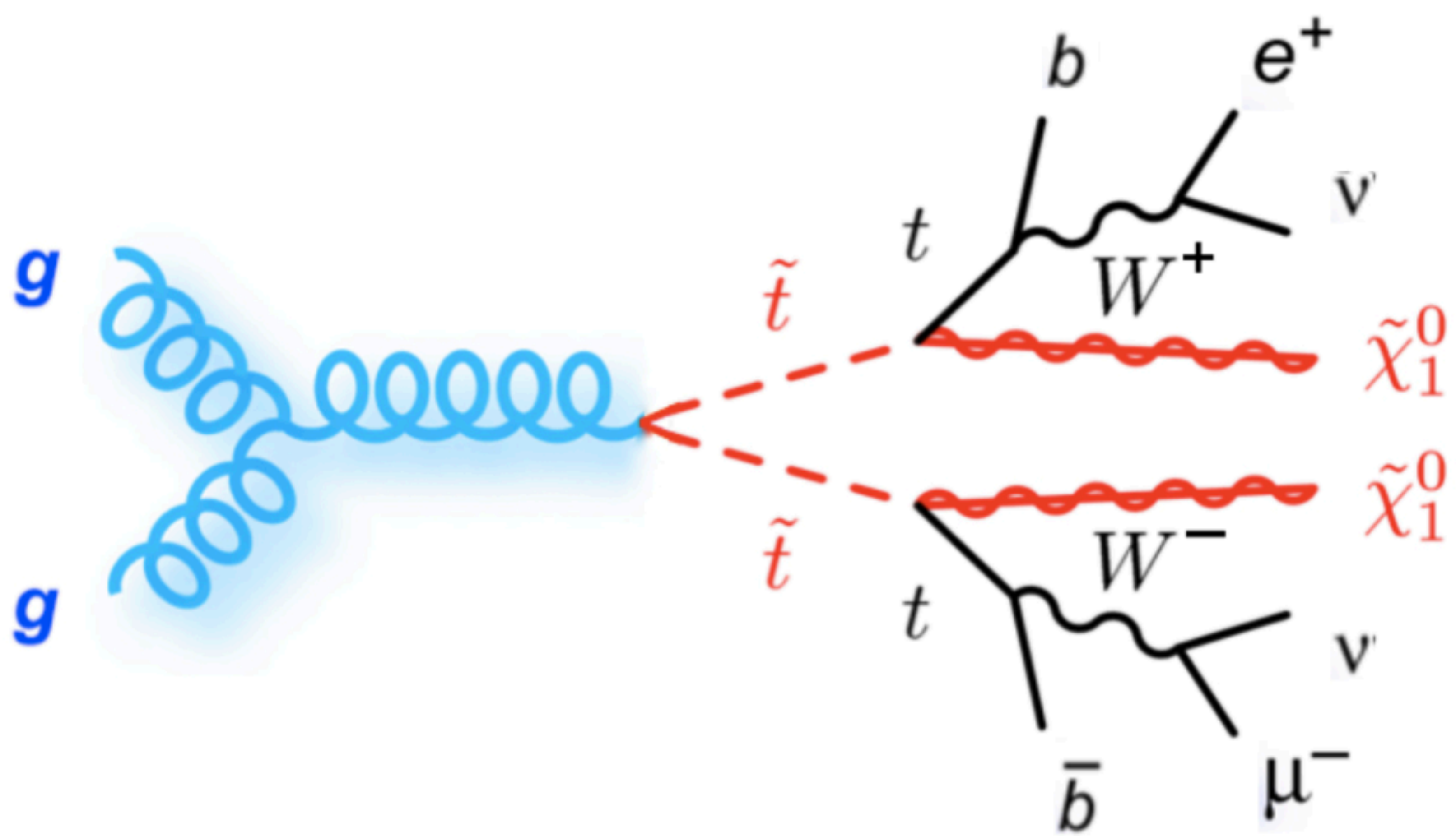
Examples of Searches in Top Physics

- Search for Top Quark Partners (Vector-like Quarks)
  - Look for new heavy quarks, such as vector-like quarks (T), predicted by many extensions of the SM, which can decay into a top quark and a Z boson, Higgs boson, or W boson



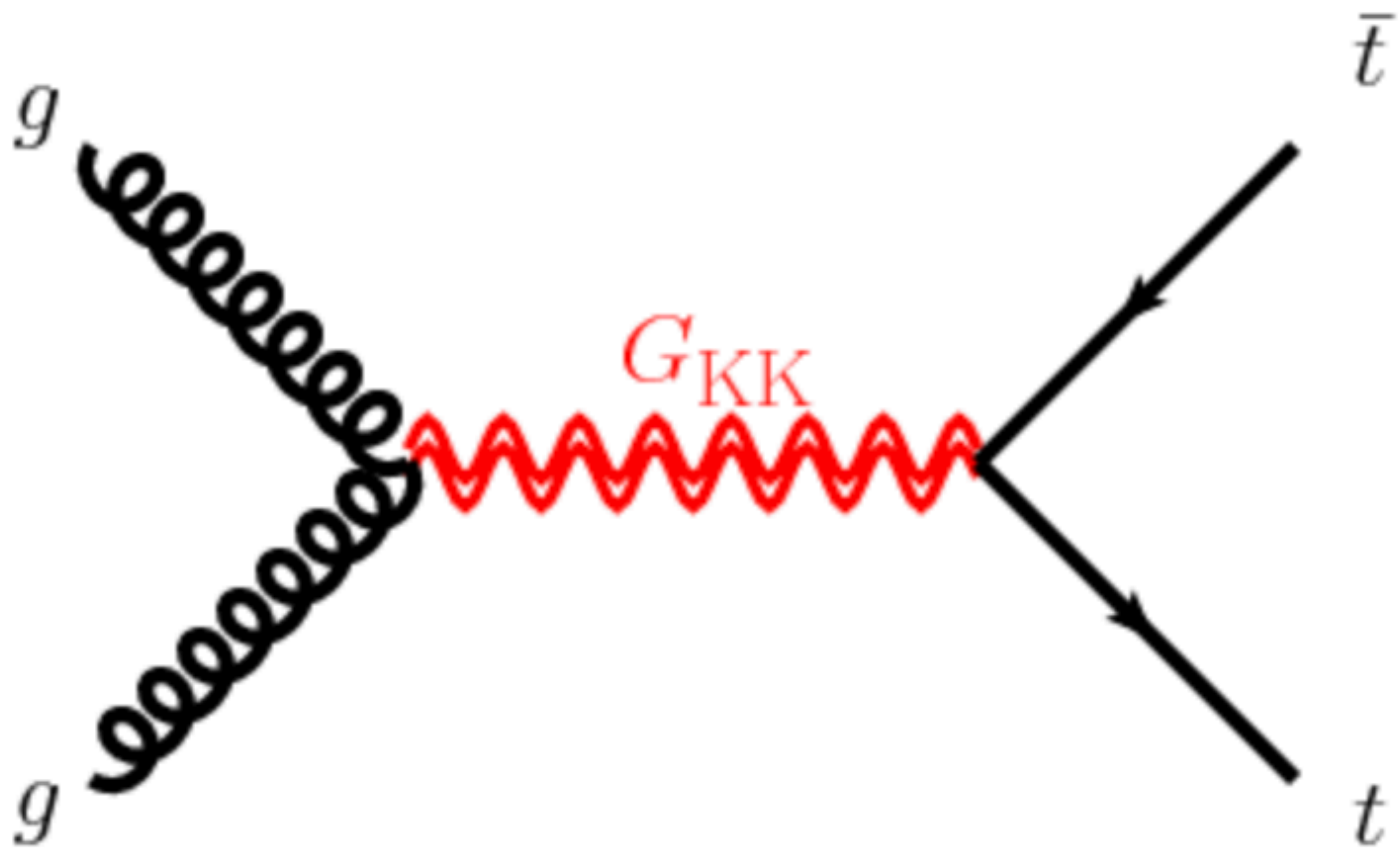
Examples of Searches in Top Physics

- Search for Supersymmetry (SUSY) in Top Quark Decays
  - Search for SUSY particles, where the top quark can decay into a stop quark (the SUSY partner of the top quark) and a neutralino (the lightest SUSY particle).



Examples of Searches in Top Physics

- Search for $t\bar{t}$ Resonances (Heavy Z' or Kaluza-Klein Gluons)
  - Look for new resonances that decay into top quark pairs, such as a heavy Z' boson or Kaluza-Klein gluons, which are predicted by various beyond the Standard Model (BSM) theories.



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Take away points about Top Physics

- Fundamental Properties of the Top Quark
  - **Heaviest Known Elementary Particle**, with a mass of around 173 GeV/c^2
  - **Short Lifetime:** The top quark decays before it can hadronize, allowing physicists to study a "bare" quark. This unique feature enables precise measurements of its properties without the complications introduced by hadronization
- Top Quark Production Mechanisms
  - **Pair Production:** At the Large Hadron Collider, top quarks are primarily produced in pairs via strong interaction processes
  - **Single Top Production:** Single top quark production occurs via electroweak interactions. This process is sensitive to the W-t-b vertex and provides a means to study the properties of the W boson and top quark coupling

Take away points about Top Physics

- **Top Quark and the Higgs Mechanism**
  - **Yukawa Coupling:** The top quark has the largest Yukawa coupling to the Higgs boson, making it a crucial element in studies of the Higgs mechanism. Understanding this coupling helps probe the nature of electroweak symmetry breaking
  - **Higgs Decay Channels:** The top quark plays a significant role in the decay channels of the Higgs boson. Studying these channels can provide insights into new physics beyond the Standard Model
- **Top Quark as a Probe for New Physics**
  - **Beyond the Standard Model (BSM):** The top quark is a potential window to BSM physics. Anomalies in its production rates or properties might indicate new particles or interactions
  - **Effective Field Theory (EFT):** can parametrize possible new physics effects in terms of higher-dimensional operators. Top quark processes are particularly sensitive to these operators, providing a way to test for new physics indirectly

Take away points about Top Physics

- **Precision Measurements**
  - **Top Quark Mass:** Precise measurements of the top quark mass are essential for testing the stability of the SM vacuum. The mass affects calculations related to the Higgs boson and the overall stability of the universe

The Top Quark: A Key Player in the Particle Physics Puzzle

- Precision Matters
  - Accurate measurements of top quark properties are crucial for testing the Standard Model and searching for new physics
- Top quark physics exemplifies the synergy between precision measurement and innovative experimental techniques
  - By refining our measurements and developing new methods, we push the boundaries of what we know about particle physics
- Unlocking New Physics
  - Top quark studies could reveal new particles and forces, potentially transforming our understanding of the universe

Thank you for your attention! I hope you had fun

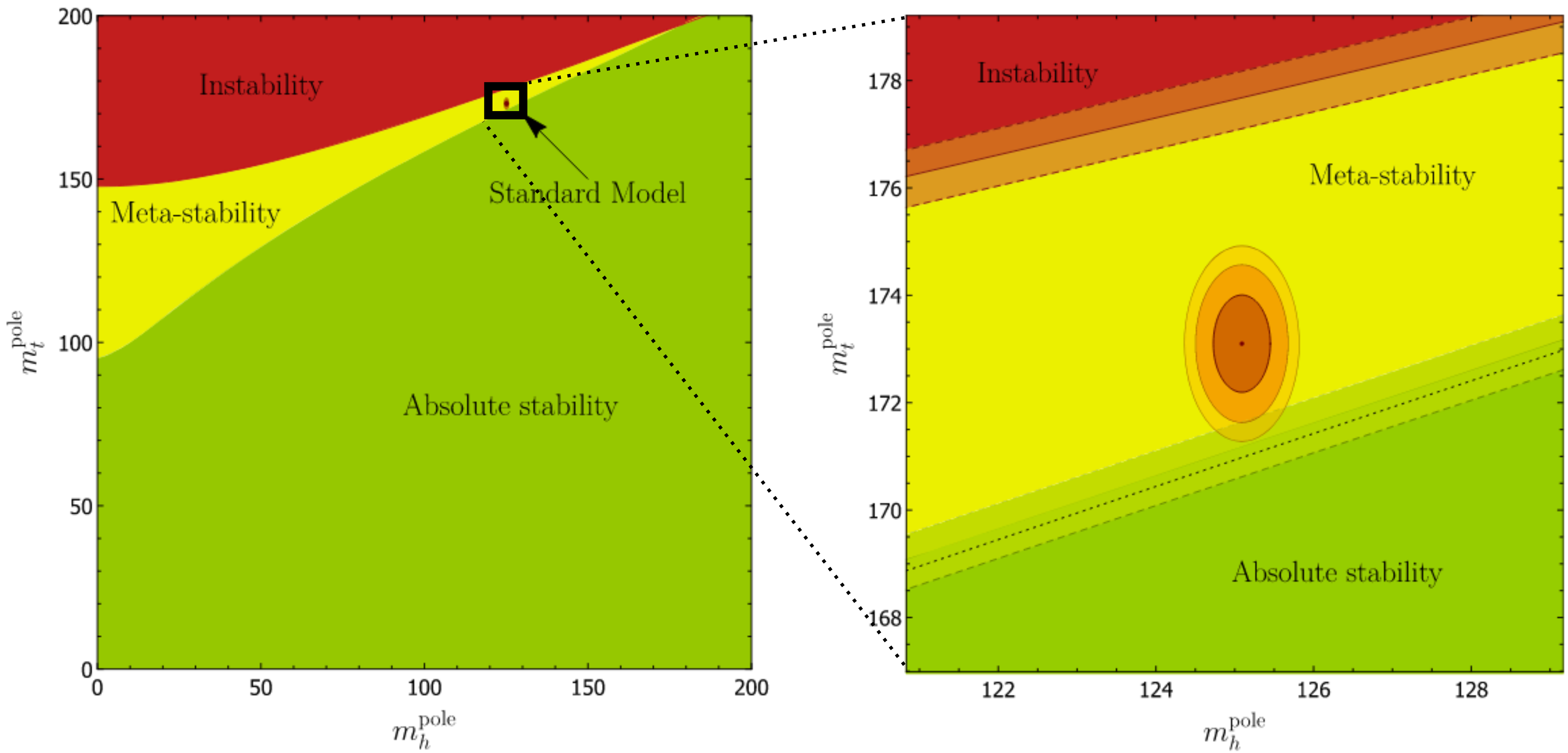
Feel free to contact me with your questions at
nedaa-alexandra.asbah@cern.ch

CERN

Back-up

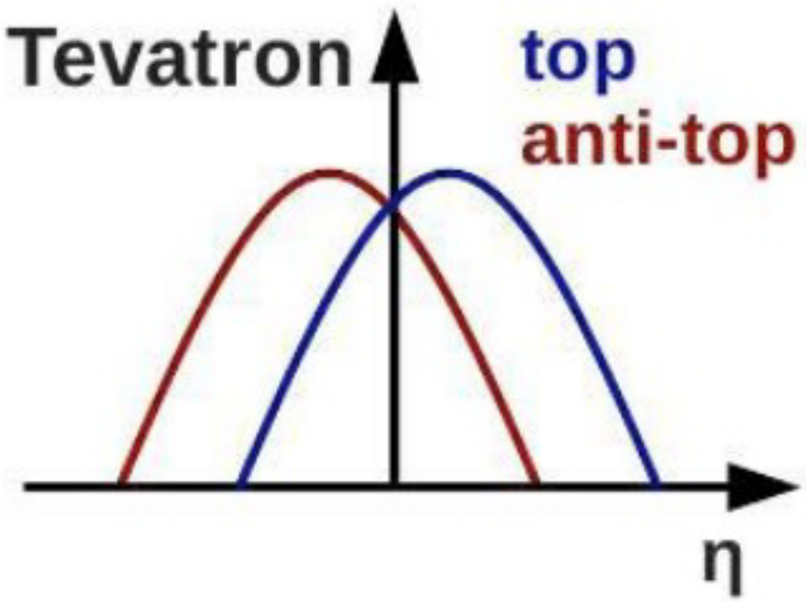
Why do we need to precisely measure the Top mass

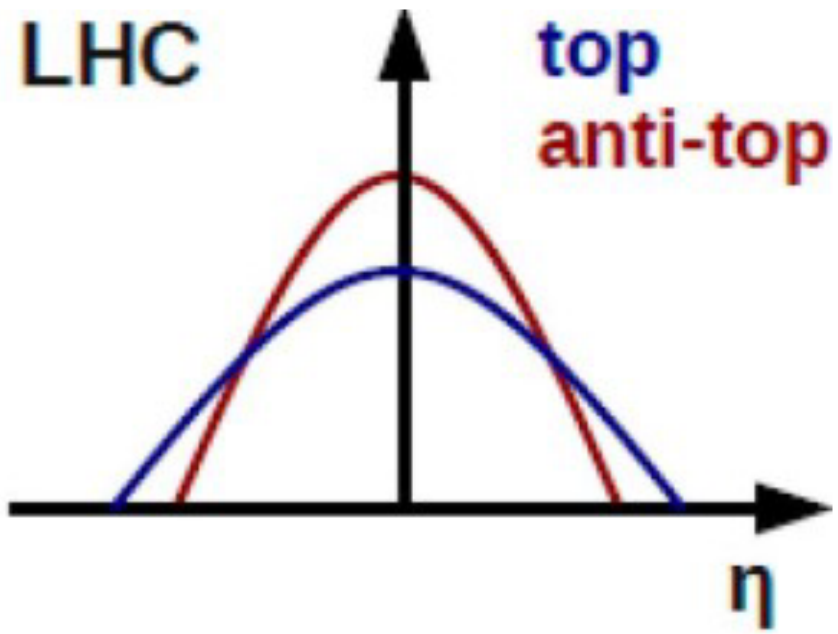
- m_H , m_{top} and the stability of the universe
- Is the higgs potential stable/meta-stable?
  - assuming no new physics up to Planck scale: stability depends strongly on m_H and m_{top}



[PRD 97 056 006]

Asymmetries at hadron colliders





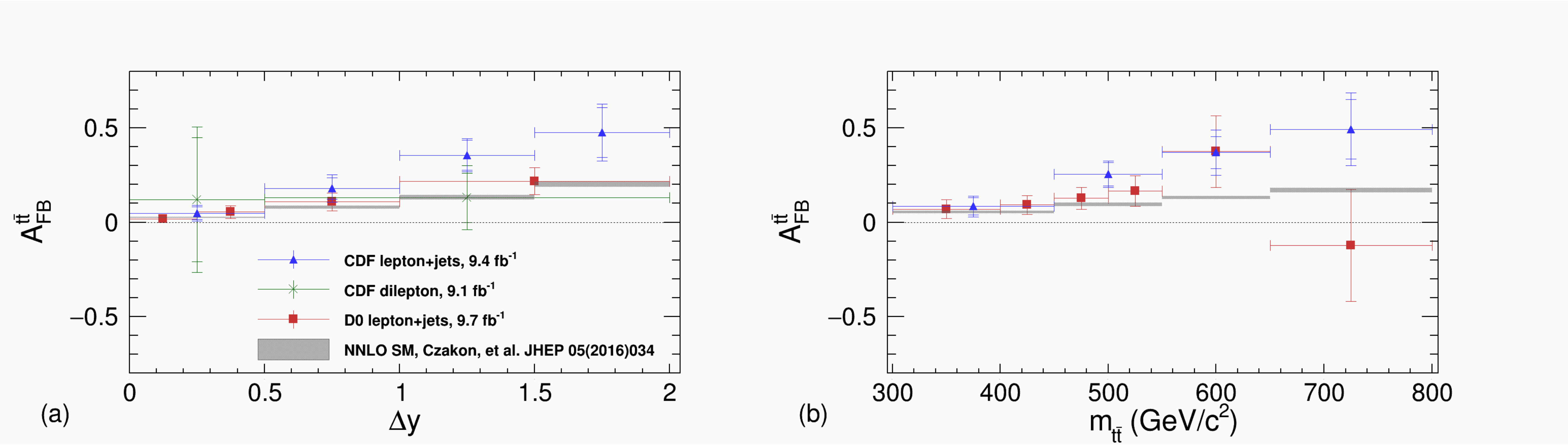
- NLO calculations predict a small asymmetry for $t\bar{t}$ produced in $q\bar{q}$ annihilation
  - interference between tree and box diagrams (no asymmetry at LO); No asymmetry in gg fusion
- **Tevatron**
  - possible to define “forward” and “backward” directions
  - $t\bar{t}$ production dominated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

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

- Compare with SM expectation
  - small but not null asymmetry

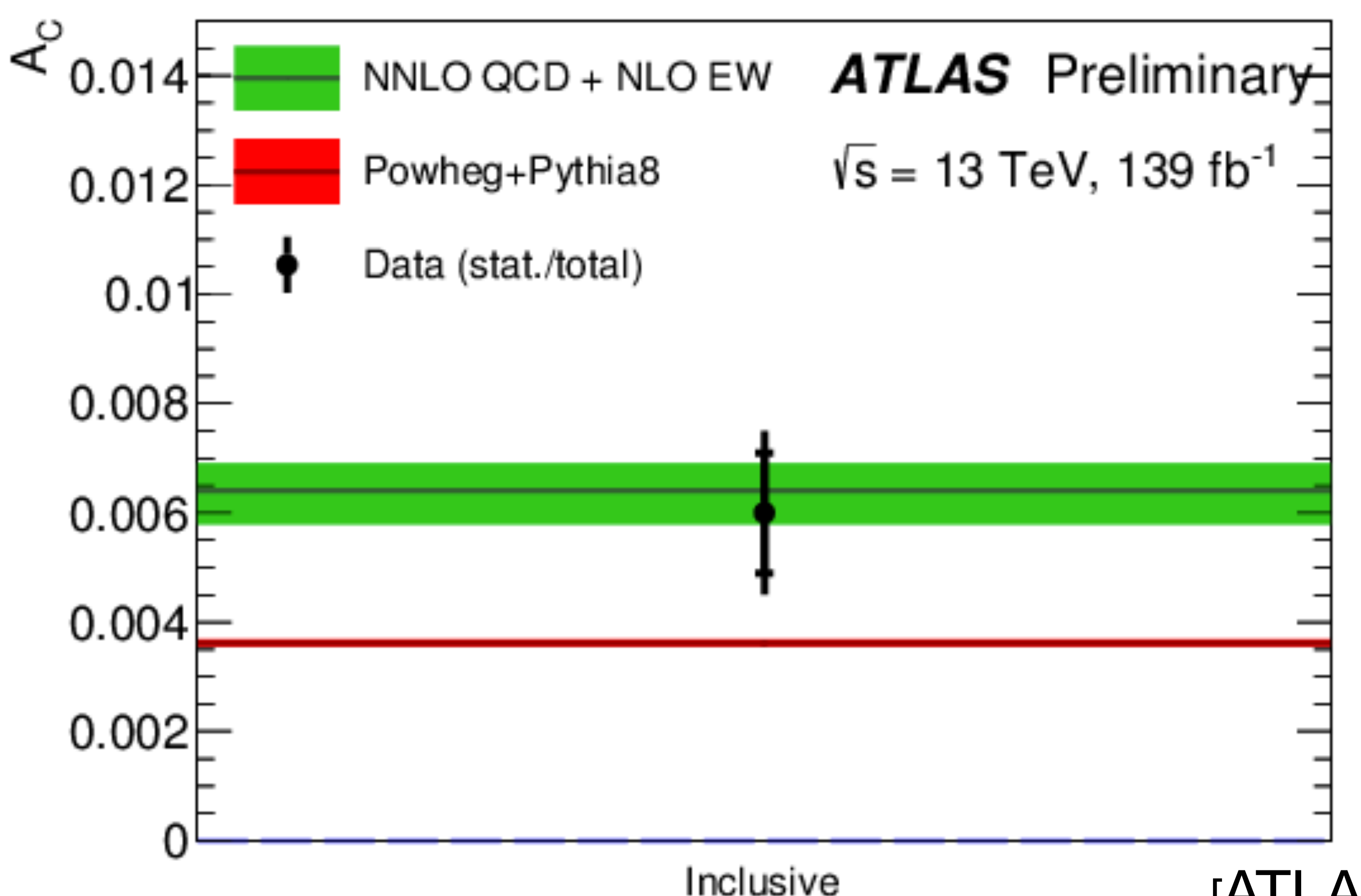


Charge asymmetry - LHC

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

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

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



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