

November 2017

J.R.J.C.



# Search for the associated production of a top quark and a Z boson at 13 TeV with the CMS detector

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Nicolas Tonon - IPHC

# The Standard Model (SM)

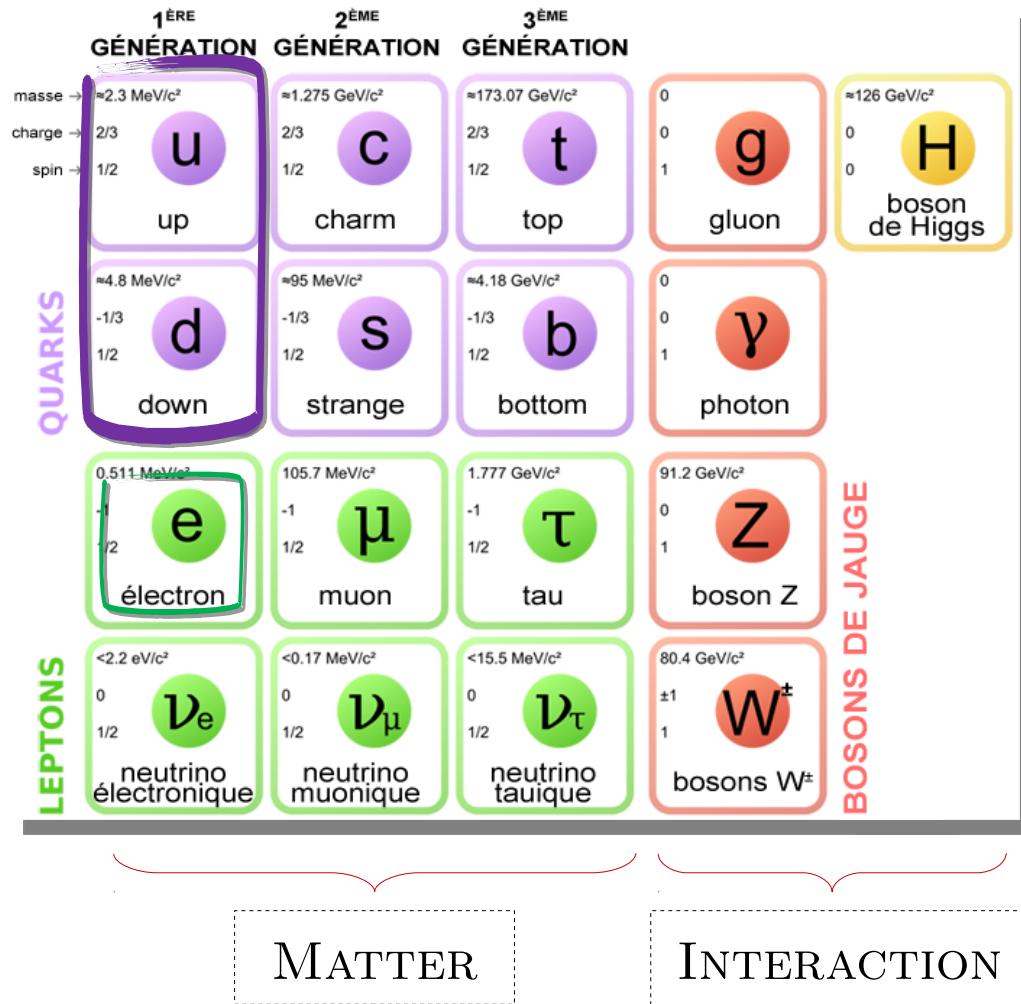
2

- Describes elementary particles & interactions

- ## ✓ Good data/theory agreement

- ✓ 2012 : discovery Higgs Boson

(predicted in 1964 !)



# The Standard Model (SM)

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- Describes elementary particles & interactions
    - ✓ Good data/theory agreement
    - ✓ 2012 : discovery Higgs Boson
  - Several missing pieces :
    - ✗ Dark matter ?
    - ✗ Neutrino oscillations ?
    - ✗ CP violation magnitude ?
    - ✗ Gravity ? Hierarchy ? Fine-tuning ?
  - Many « Beyond-SM » models propose explanations (new particles, mechanisms, etc.)

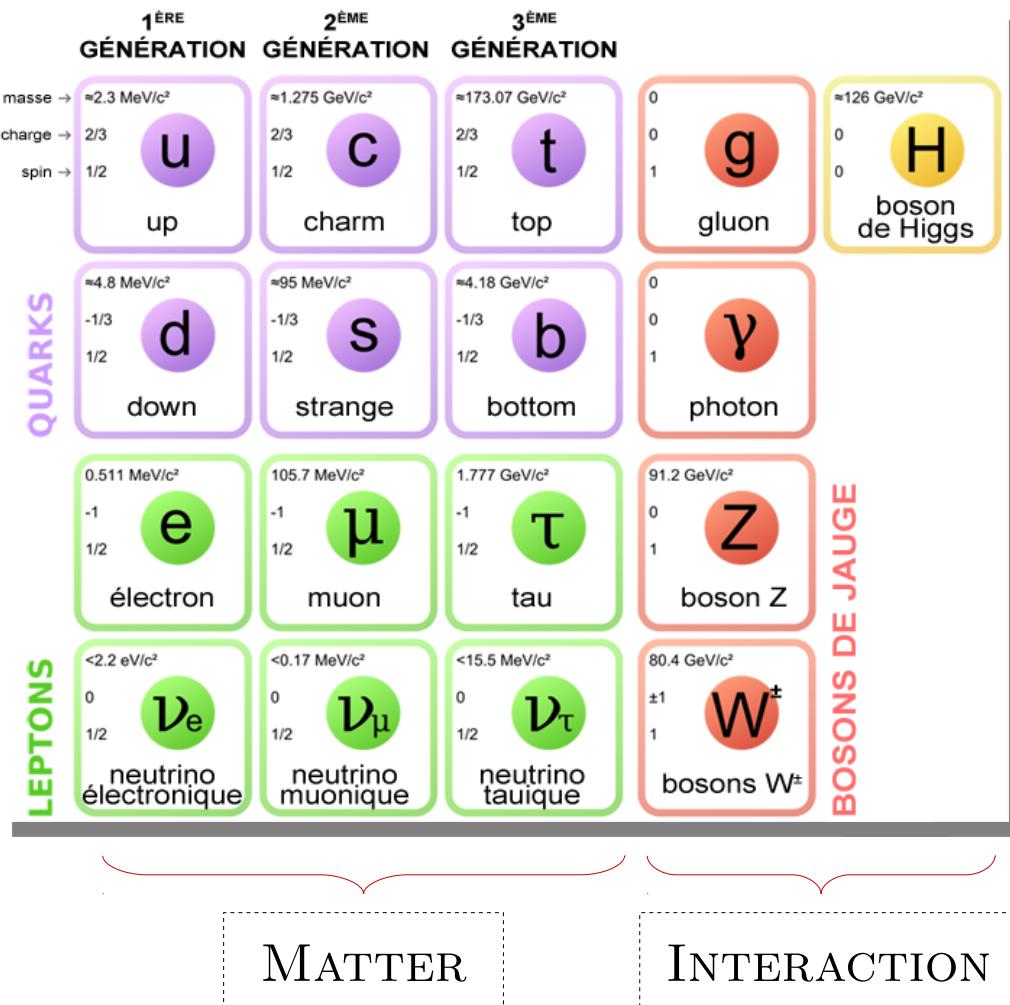
The diagram illustrates the Standard Model particles in two main categories: QUARKS and LEPTONS.

**QUARKS:**

  - Up Quark ( $u$ ):** Mass  $\approx 2.3 \text{ MeV}/c^2$ , Charge  $2/3$ , Spin  $1/2$ . It is labeled "up".
  - Down Quark ( $d$ ):** Mass  $\approx 4.8 \text{ MeV}/c^2$ , Charge  $-1/3$ , Spin  $1/2$ . It is labeled "down".

**LEPTONS:**

  - Electron ( $e$ ):** Mass  $0.511 \text{ MeV}/c^2$ , Charge  $-1$ , Spin  $1/2$ . It is labeled "électron".
  - Neutrino ( $\nu_e$ ):** Mass  $< 2.2 \text{ eV}/c^2$ , Charge  $0$ , Spin  $1/2$ . It is labeled "neutrino électronique".

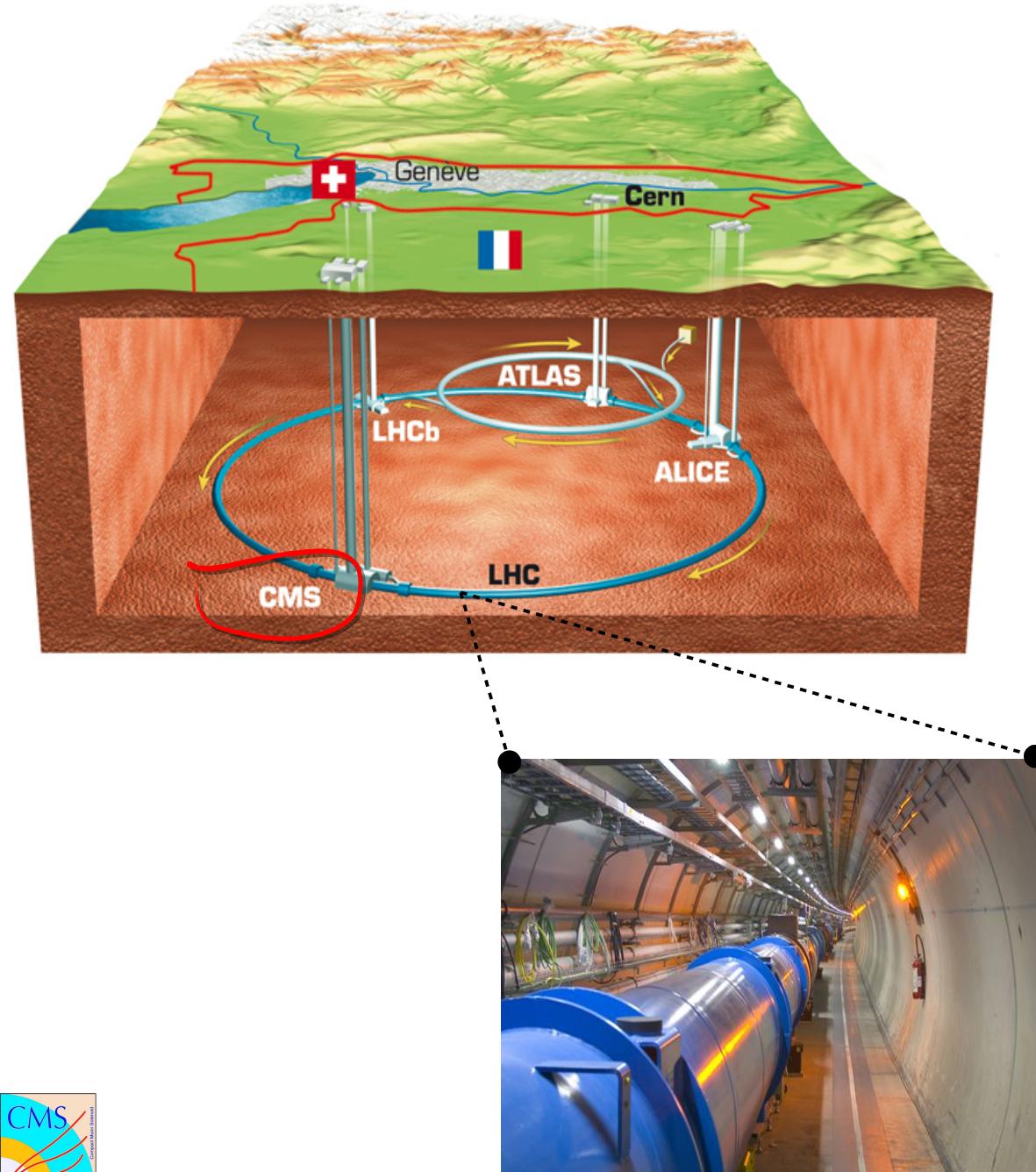


Need to test limits of model to discover « new physics » !



# LHC (Large Hadron Collider)

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- 2010 – 2012 :  $\sqrt{s} = 7\text{-}8 \text{ TeV}$
- Since 2015 :  $\sqrt{s} = 13 \text{ TeV}$   
(nominal energy)



Around 2025 :  
plan to upgrade to  
« High-Lumi LHC »

WHY ?

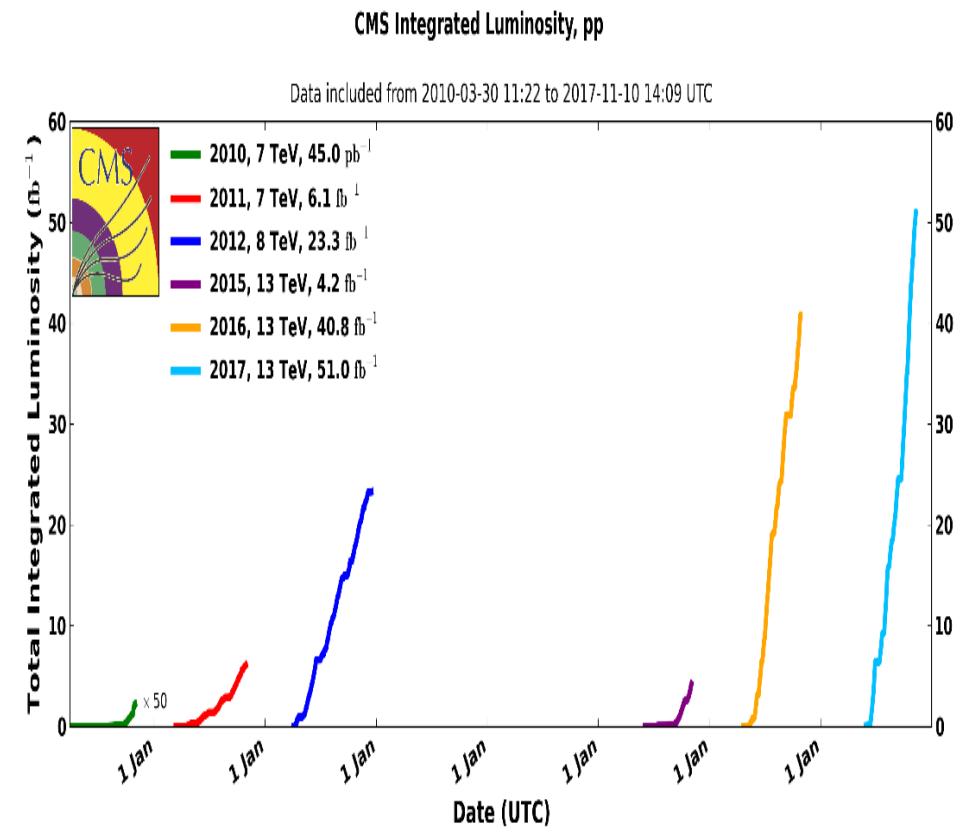
# Luminosity

5

- Key parameter for colliders

- Instant. luminosity :  $L = f \cdot \frac{n_1 \cdot n_2}{4\pi \cdot \sigma_x \cdot \sigma_y}$
- Number of events :  $N = \int L dt \times \sigma$   
(for given process)

- LHC
- $L = 10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$
  - $f = 600M \text{ collisions/second}$
  - $n_1 = n_2 = 10^{11} \text{ protons}$
  - $\sigma_x = \sigma_y \sim 10 \mu\text{m}$

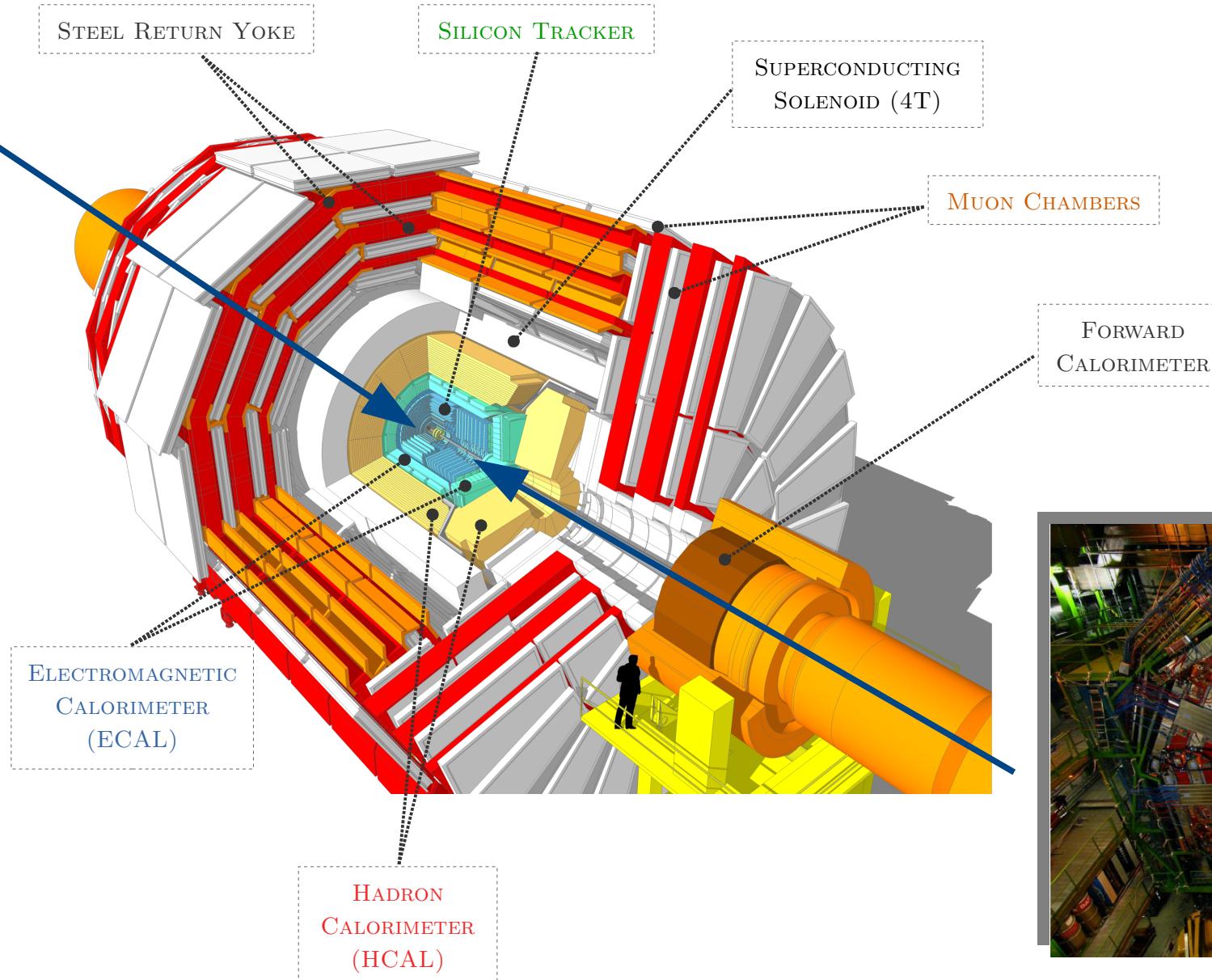


Need to improve these numbers  
to increase luminosity  
=  
more precise measurements

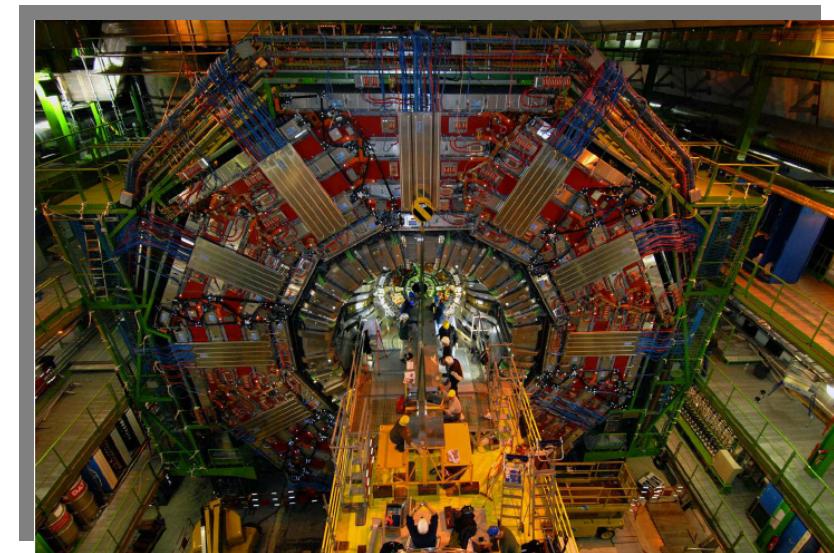


# CMS (Compact Muon Solenoid)

6



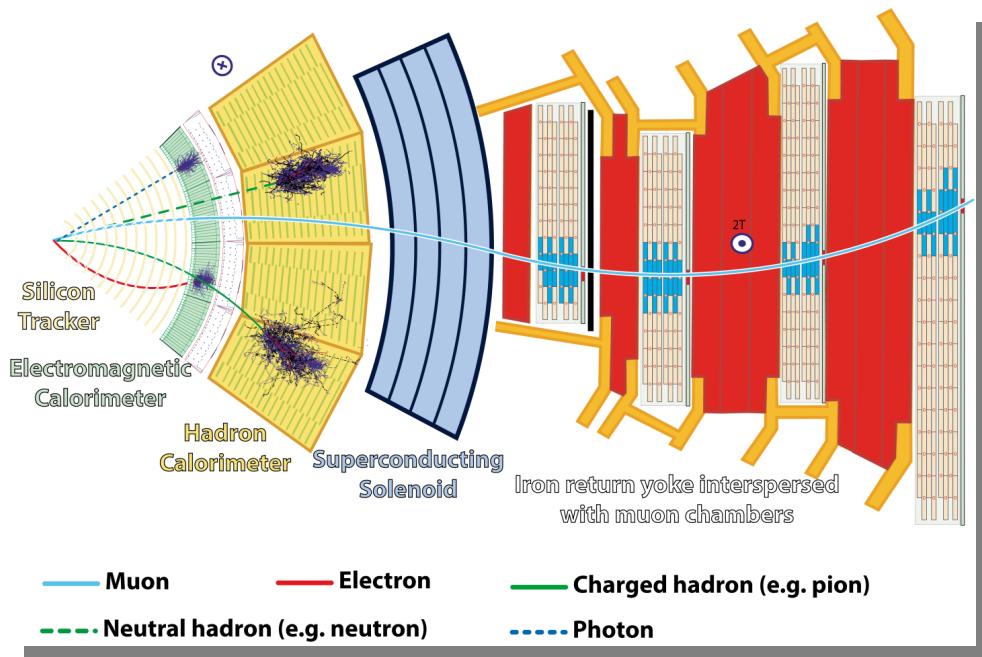
14.000 tons  
30m long  
15m diameter  
~ 4K people



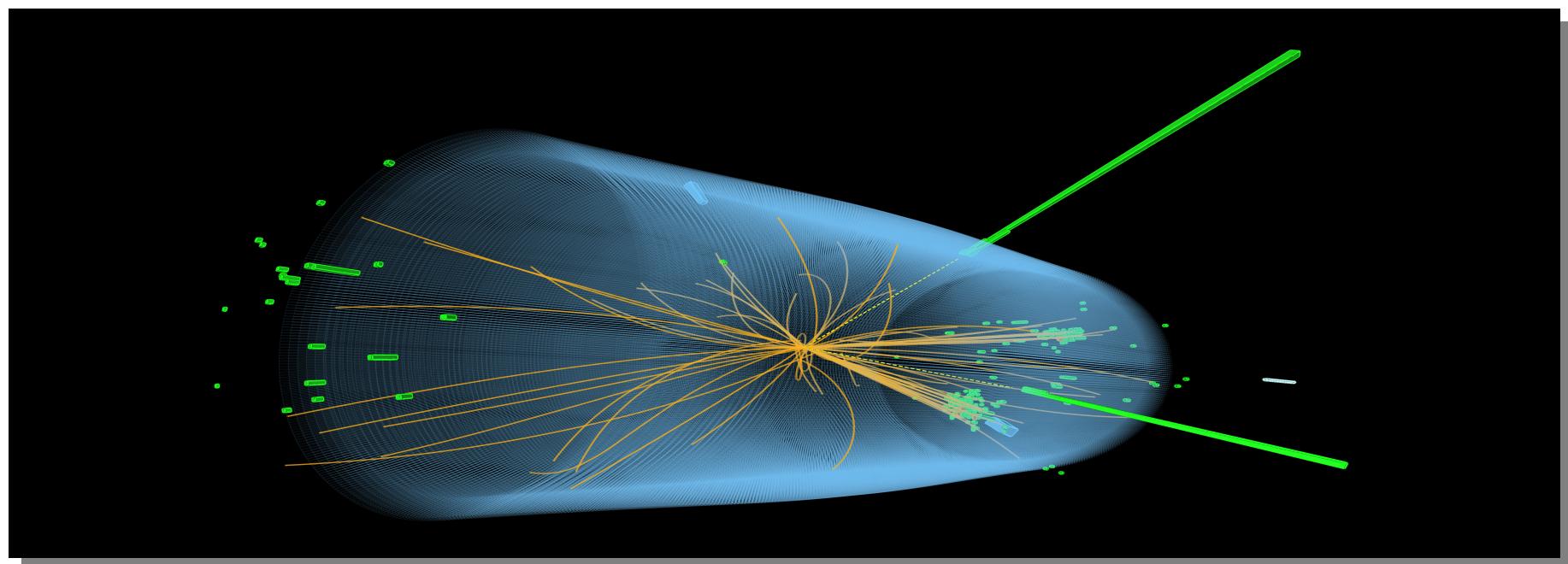
- Many specialized sub-detectors

# CMS (Compact Muon Solenoid)

7



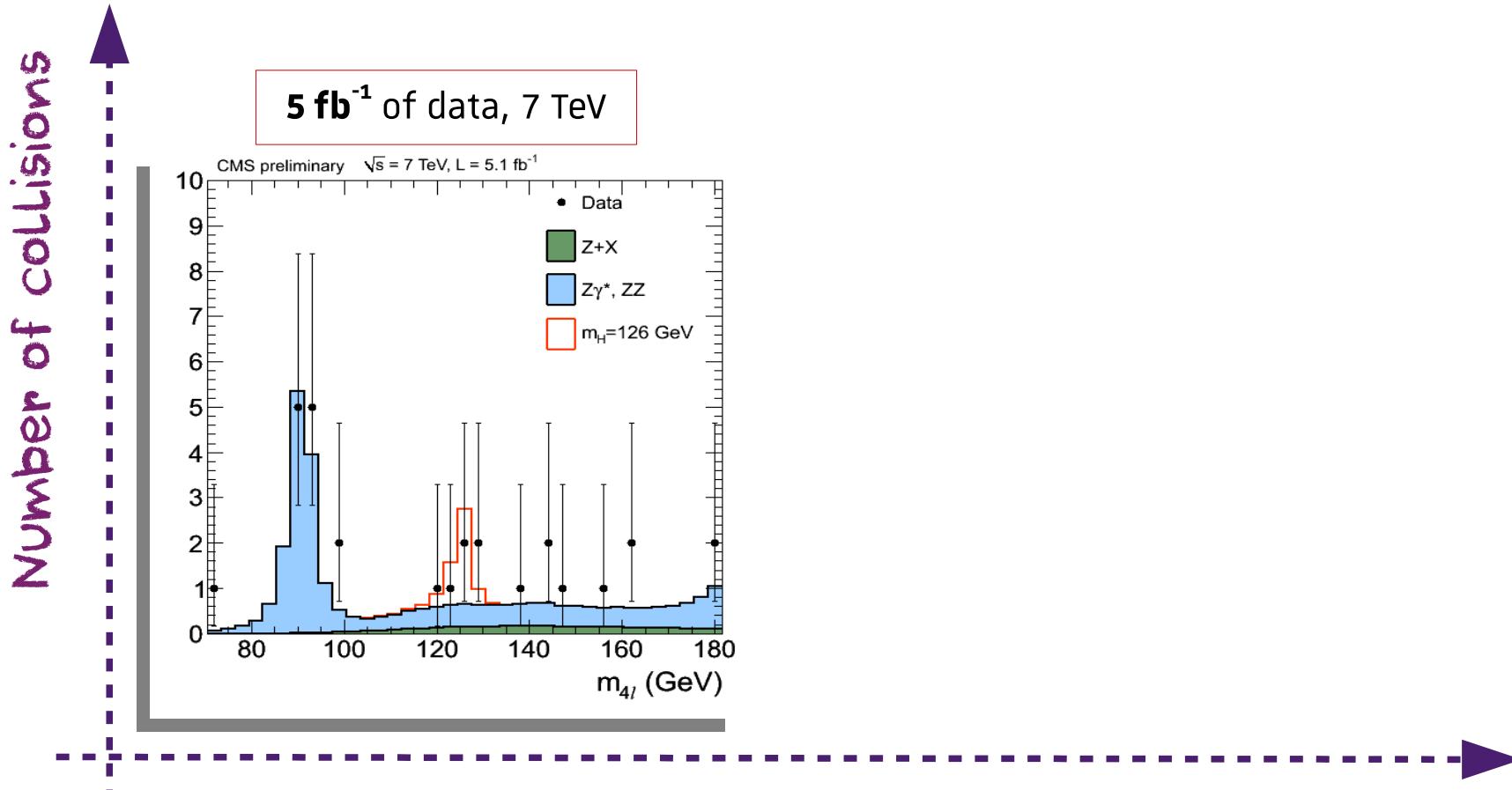
- Combine informations from all sub-detectors
  - **Identify** nature of created particles
  - **Reconstruct full picture of the event**



# << Statistical discovery >> ?

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Example : search for the Higgs boson

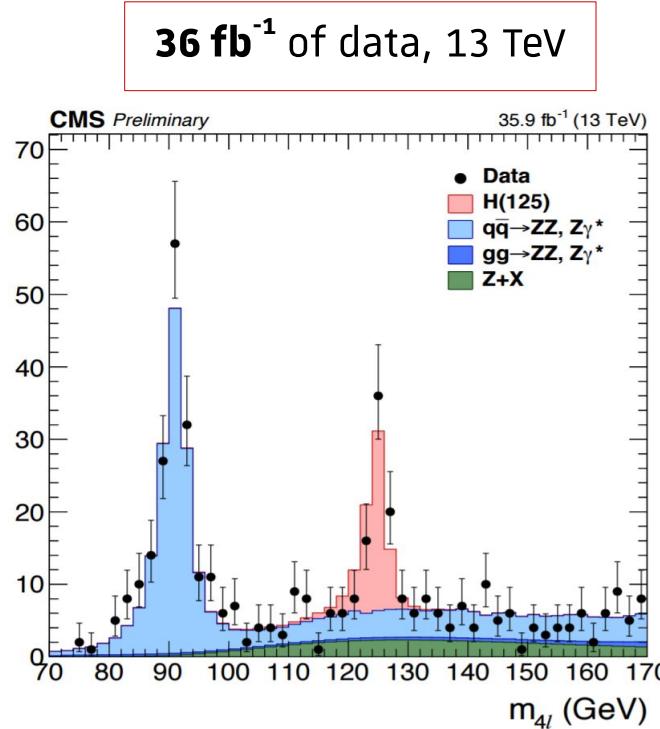
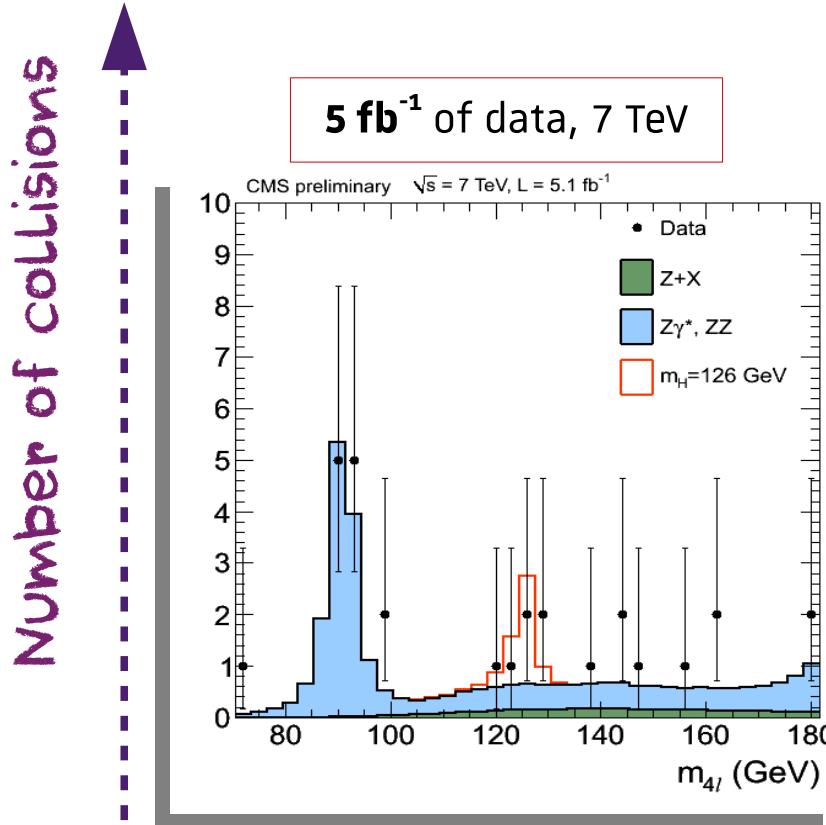


Mass  
(4 leptons)

# « Statistical discovery » ?

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Example : search for the Higgs boson



Mass  
(4 leptons)



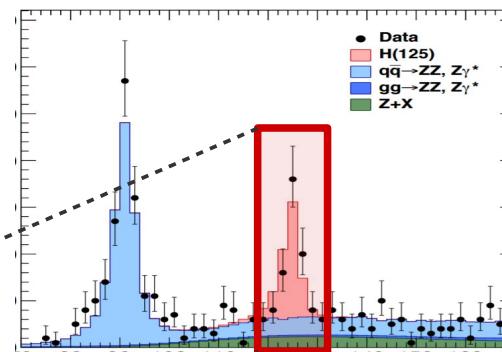
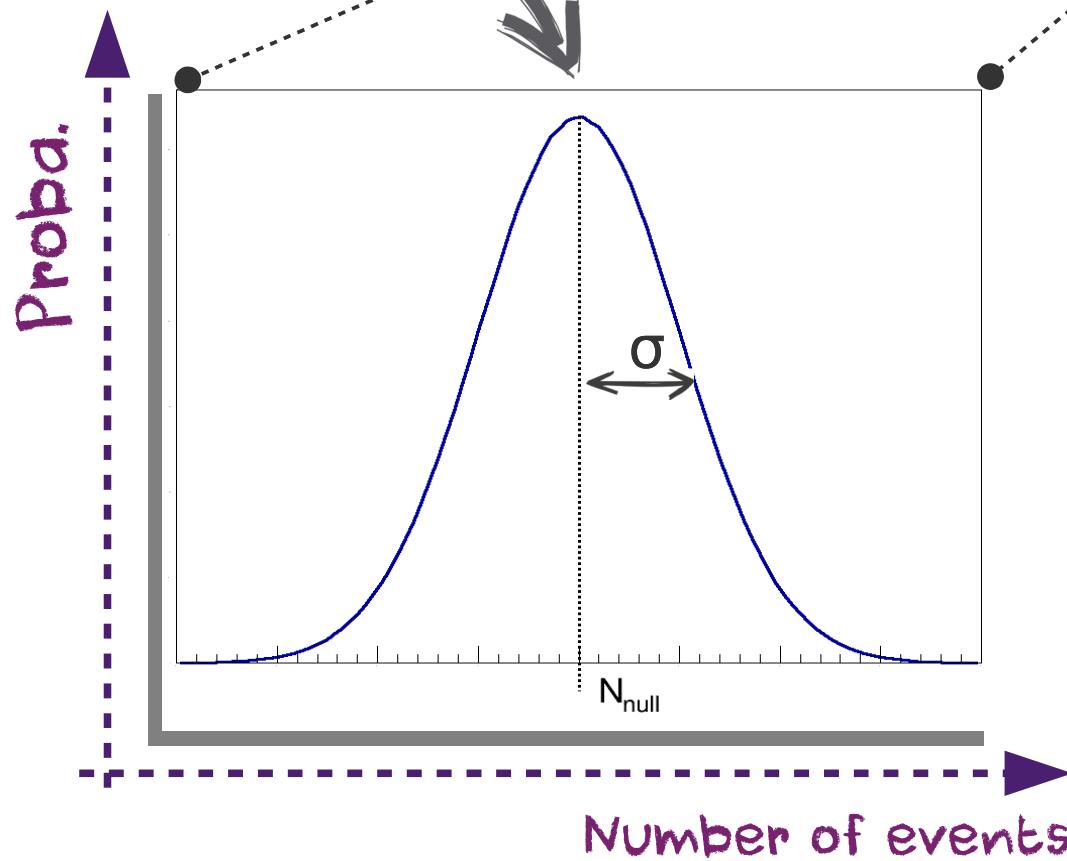
Is the excess of data « statistically significant » ?

# Hypothesis testing (simplified)

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Null hypothesis prediction

=  
SM without Higgs

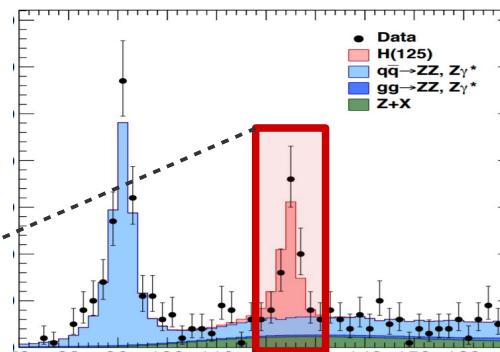
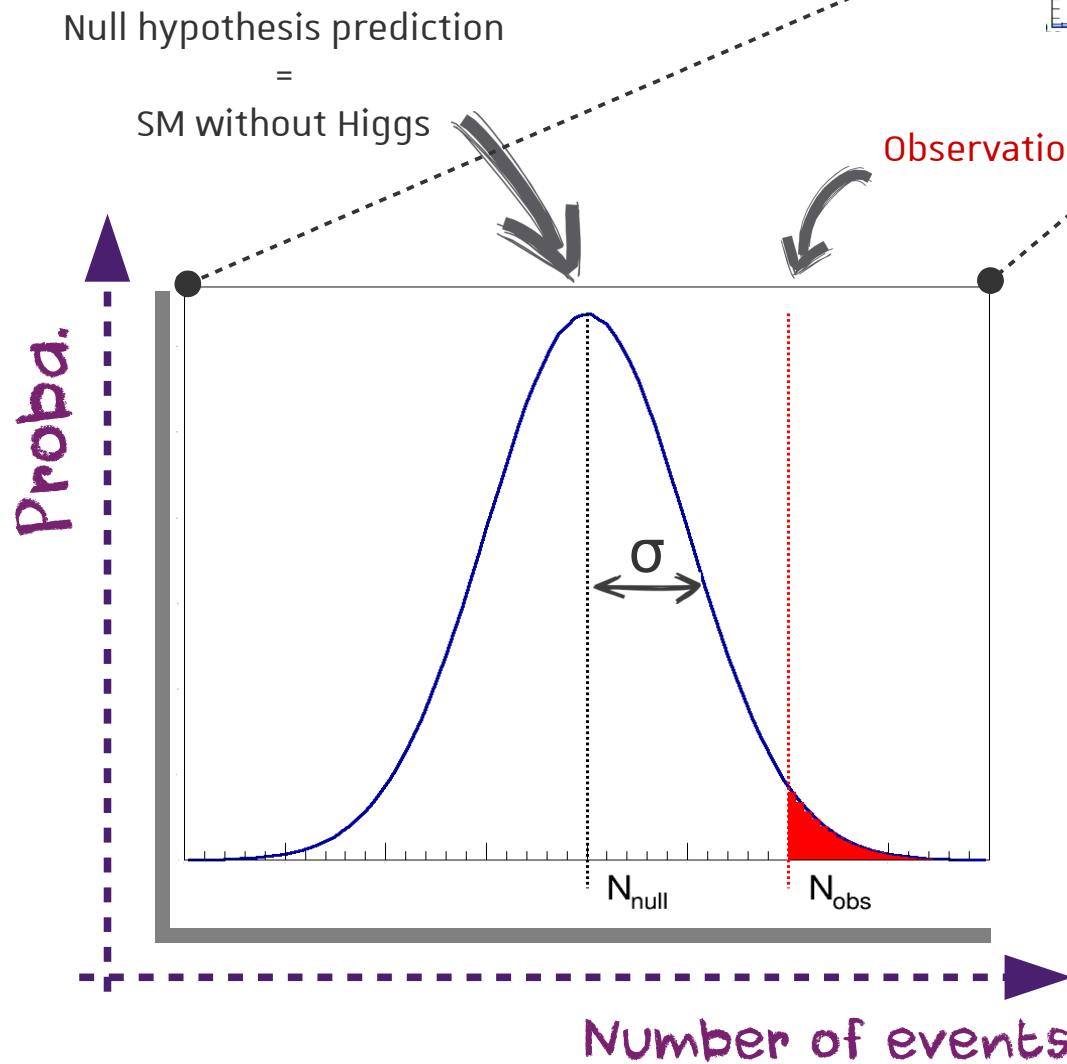


For a given mass bin :

- # of observed events predicted by null hypothesis follows Poissonian  $H_0(\mu_{\text{null}})$

# Hypothesis testing (simplified)

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For a given mass bin :

- # of observed events predicted by null hypothesis follows Poissonian  $H_0(N_{\text{null}})$
- Significance :  $S = (\mu_{\text{obs}} - \mu_{\text{null}})/\sigma$
- P-value :  $p = \int_{\mu_{\text{obs}}}^{+\infty} H_0(x) dx$



$S = 3 \sigma \rightarrow \text{« EVIDENCE »}$   
 $S = 5 \sigma \rightarrow \text{« DISCOVERY »}$

# Top quark

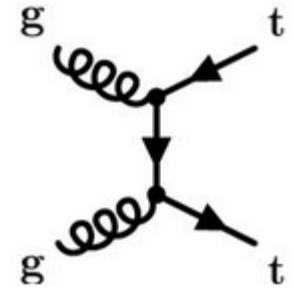
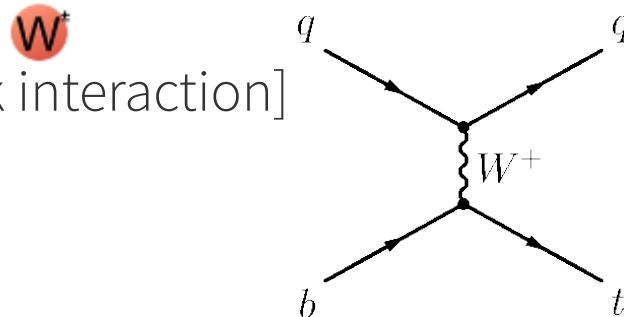
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- Discovered in 1995, **heaviest particle**:  $m_{top} = 173.34 \pm 0.76 \text{ GeV}$

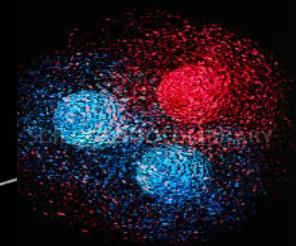
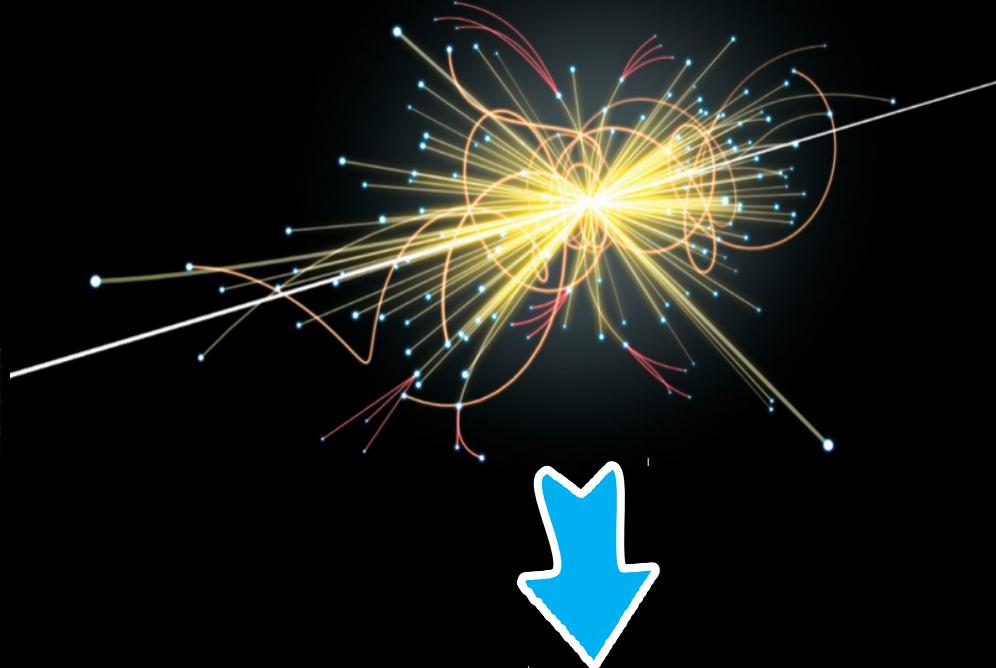
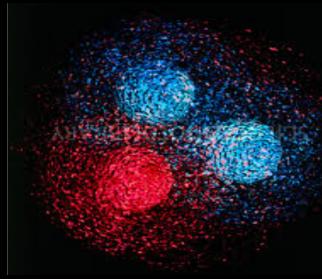
- Mostly produced in  $t\bar{t}$  pair via gluon-fusion [strong interaction]

- Can also produce single-top [weak interaction]

- Decays exclusively via  $\textcolor{red}{t \rightarrow W + b}$  (in SM)

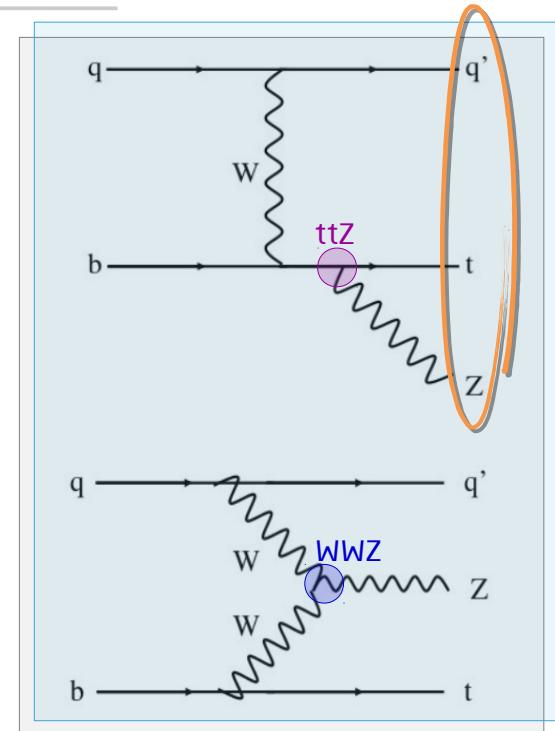


- Only quark decaying before hadronization, properties encoded in decay products
- Enormous mass  $\rightarrow$  **Special role** in symmetry breaking/Higgs mechanism ?



1 <sup>ÈRE</sup> GÉNÉRATION			2 <sup>ÈME</sup> GÉNÉRATION			3 <sup>ÈME</sup> GÉNÉRATION		
masse →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 1.07 \text{ GeV}/c^2$	$\approx 4.4 \text{ GeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 91.2 \text{ GeV}/c^2$	$\approx 126 \text{ GeV}/c^2$	$\approx 2.4 \text{ TeV}/c^2$
charge →	2/3	2/3	-2/3	-1/3	-1/3	0	0	0
spin →	1/2	1/2	1/2	1/2	1/2	0	0	1
	u	c	t	s	b	g	h	photon
	up	charm	top	strange	bottom	gluon	boson de Higgs	photon
QUARKS			LEPTONS			BOSONS DE JARGO		
0.511 MeV/c <sup>2</sup>	105.7 MeV/c <sup>2</sup>	1.777 GeV/c <sup>2</sup>	<2.2 eV/c <sup>2</sup>	<0.17 MeV/c <sup>2</sup>	<15.5 MeV/c <sup>2</sup>	91.2 GeV/c <sup>2</sup>	80.4 GeV/c <sup>2</sup>	
-1	-1	-1	0	0	0	0	±1	
1/2	1/2	1/2	1/2	1/2	1/2	1	1	
	e	$\mu$	$\tau$	$\nu_e$	$\nu_\mu$	$\nu_\tau$	$W^\pm$	$Z$
	électron	muon	tau	neutrino électronique	neutrino muonique	neutrino tauïque	bosons $W^\pm$	boson Z

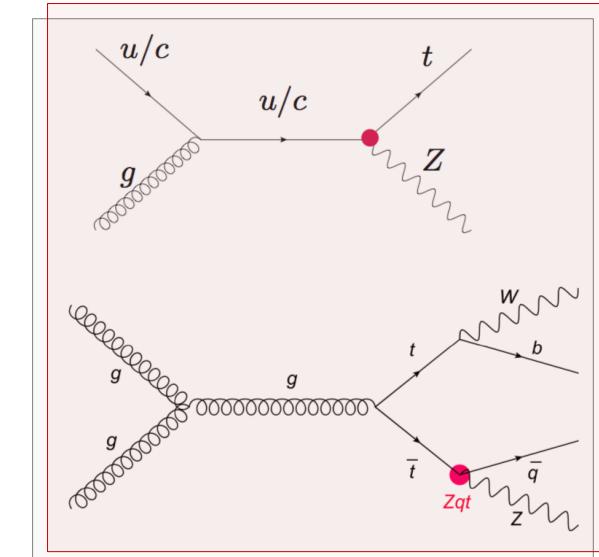
- Yet unobserved process involving single top quark predicted by the SM
- Sensitive to  $t\bar{t}Z$  &  $WWZ$  couplings
- Background for other SM analysis



- Sensitive to Flavour-Changing Neutral Current processes (FCNC)
- FCNC strongly suppressed in SM by GIM mechanism
- Some Beyond-SM models predict large enhancement



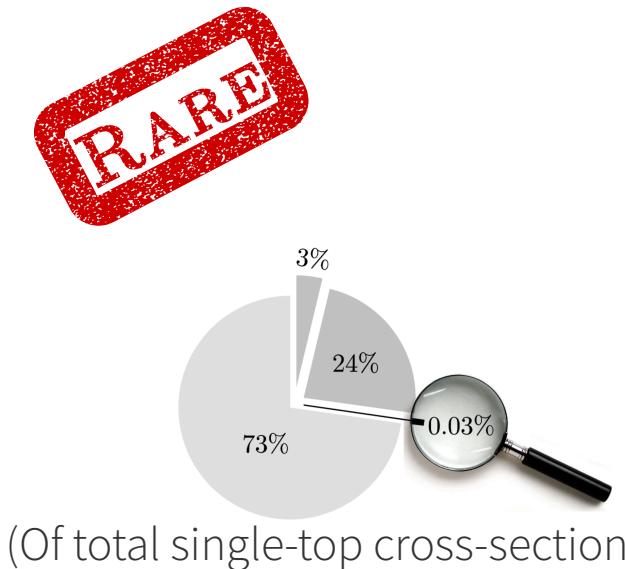
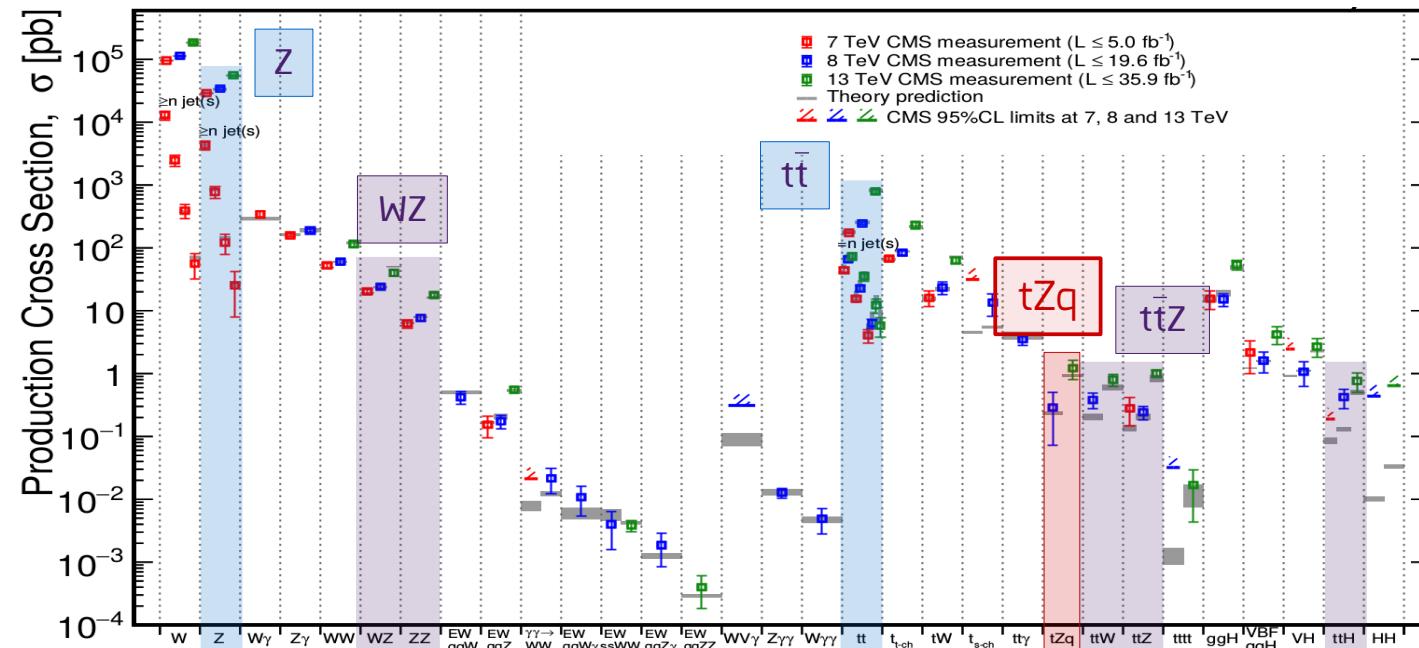
If  $\sigma^{obs}(tZq) \gg \sigma^{SM}(tZq) \rightarrow$  Hint of new physics !



# Rare signal, large backgrounds

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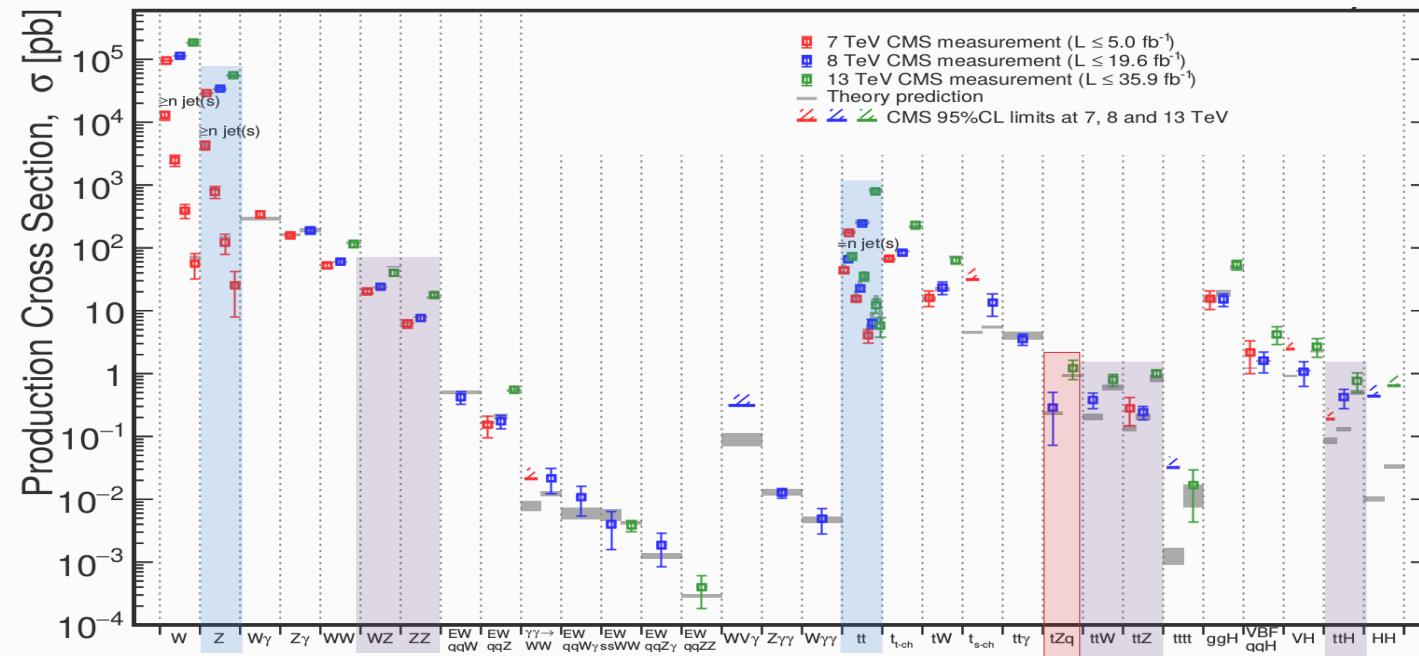
$$\sigma(t\ell^+\ell^-q) = 94.2^{+1.9}_{-1.8} \text{ (scale)} \pm 2.5 \text{ (PDF)} \text{ fb}$$



# Rare signal, large backgrounds

16

$$\sigma(t\ell^+\ell^-q) = 94.2^{+1.9}_{-1.8} \text{ (scale)} \pm 2.5 \text{ (PDF)} \text{ fb}$$

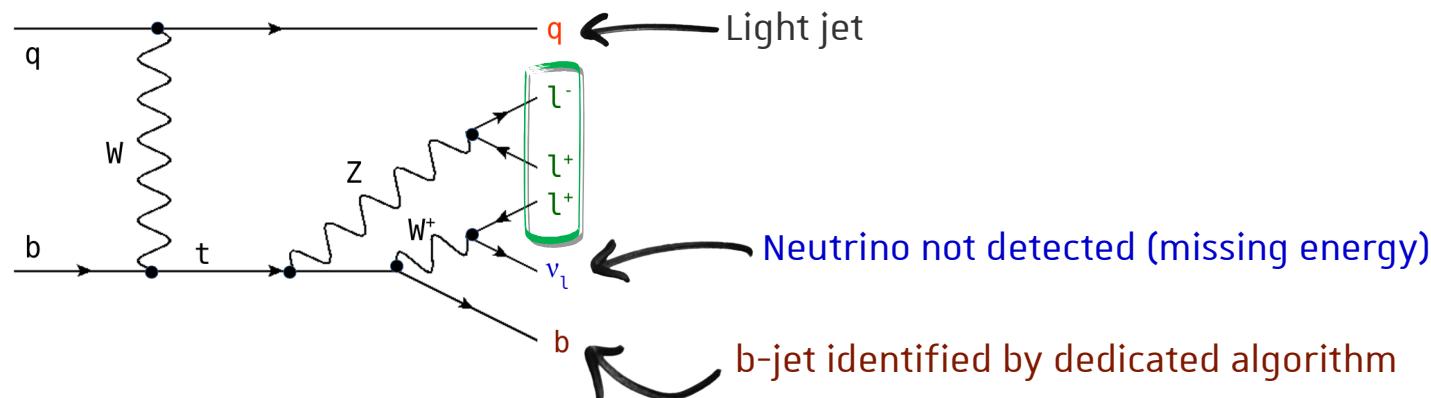


**RARE**



(Of total single-top cross-section)

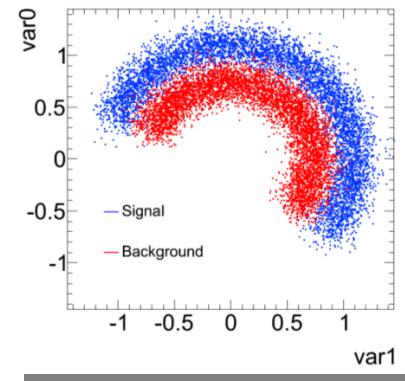
- Consider only final states with **3 leptons** ( best signal/bkg ratio )



- How can we separate signal from backgrounds in our case ? ( $m_{inv}$  plot not very helpful)

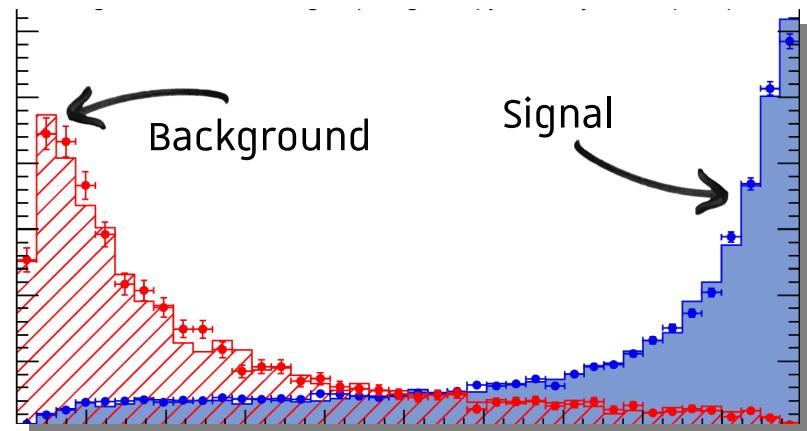
- ✖ No single observable able to do that

→ **Multi-Variate Analysis (MVA) !**



- Check the values of many relevant variables (kinematics of particles, masses, ...)
- Decide if event is more « signal-like » or « background-like »

- Process needs to be automatized
- **Machine-Learning** technique  
(Boosted Decision Tree)



Variable from Machine-Learning

# Matrix Element Method (MEM)

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Principle : for each event, compute a probability related to a given hypothesis

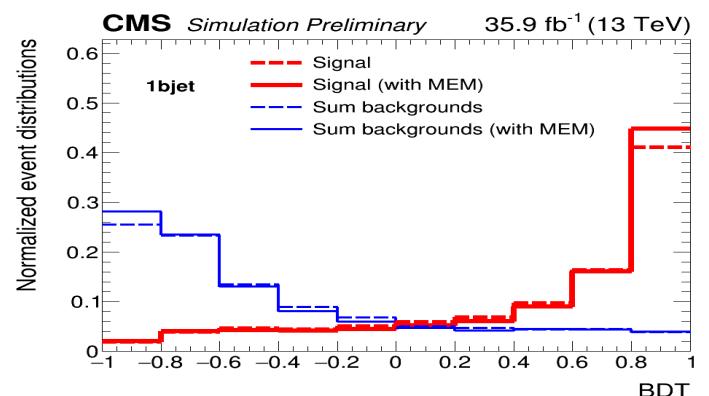
$$P(x|\alpha) = \frac{1}{\sigma_\alpha} \int d\Phi(\mathbf{y}) dq_1 dq_2 \underbrace{f_1(q_1)f_2(q_2)}_{\text{Phase-space}} |M_\alpha|^2(\mathbf{y}) W(x, \mathbf{y})$$

PDF                      Transfer function (parton  $\leftrightarrow$  jet)  
Phase-space              Matrix element  
(diagram)

« How compatible is this event with signal ? With background ? »

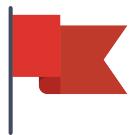


Adding these variables improves discriminating power



— with MEM  
- - no MEM

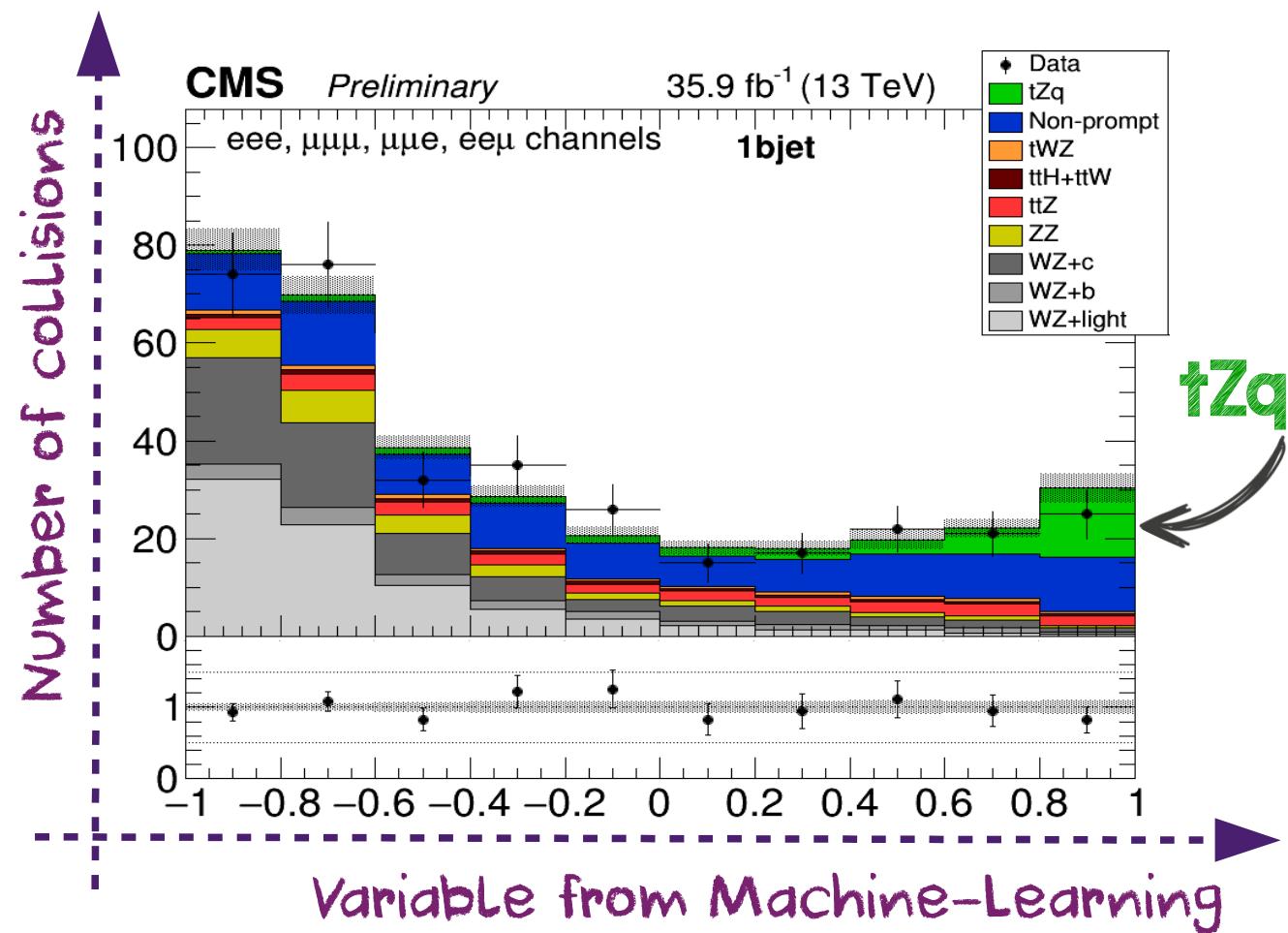
Variable from Machine-Learning



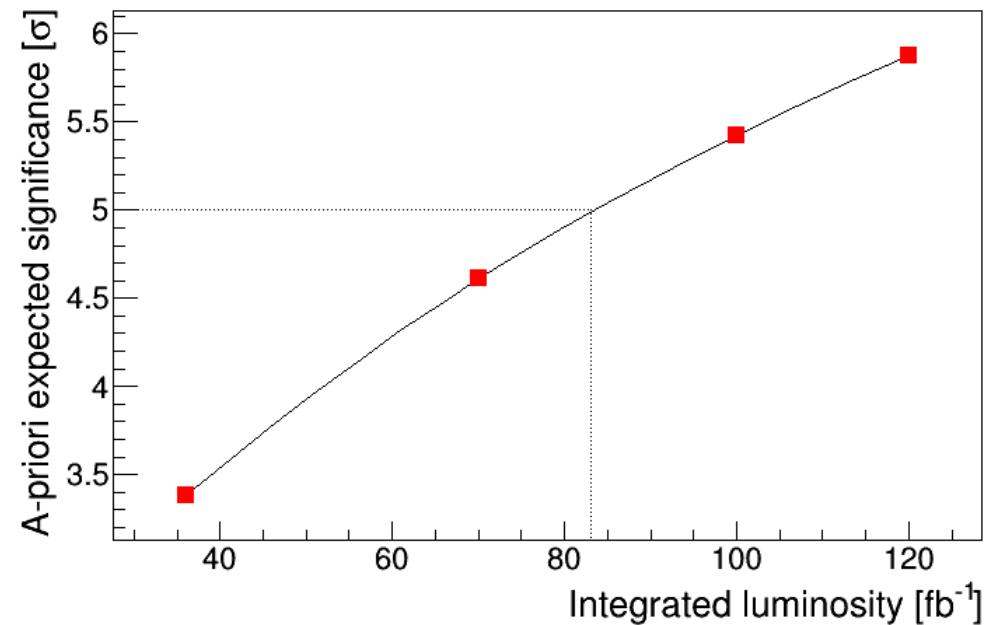
- We found **evidence** that the « tZq process » does exist

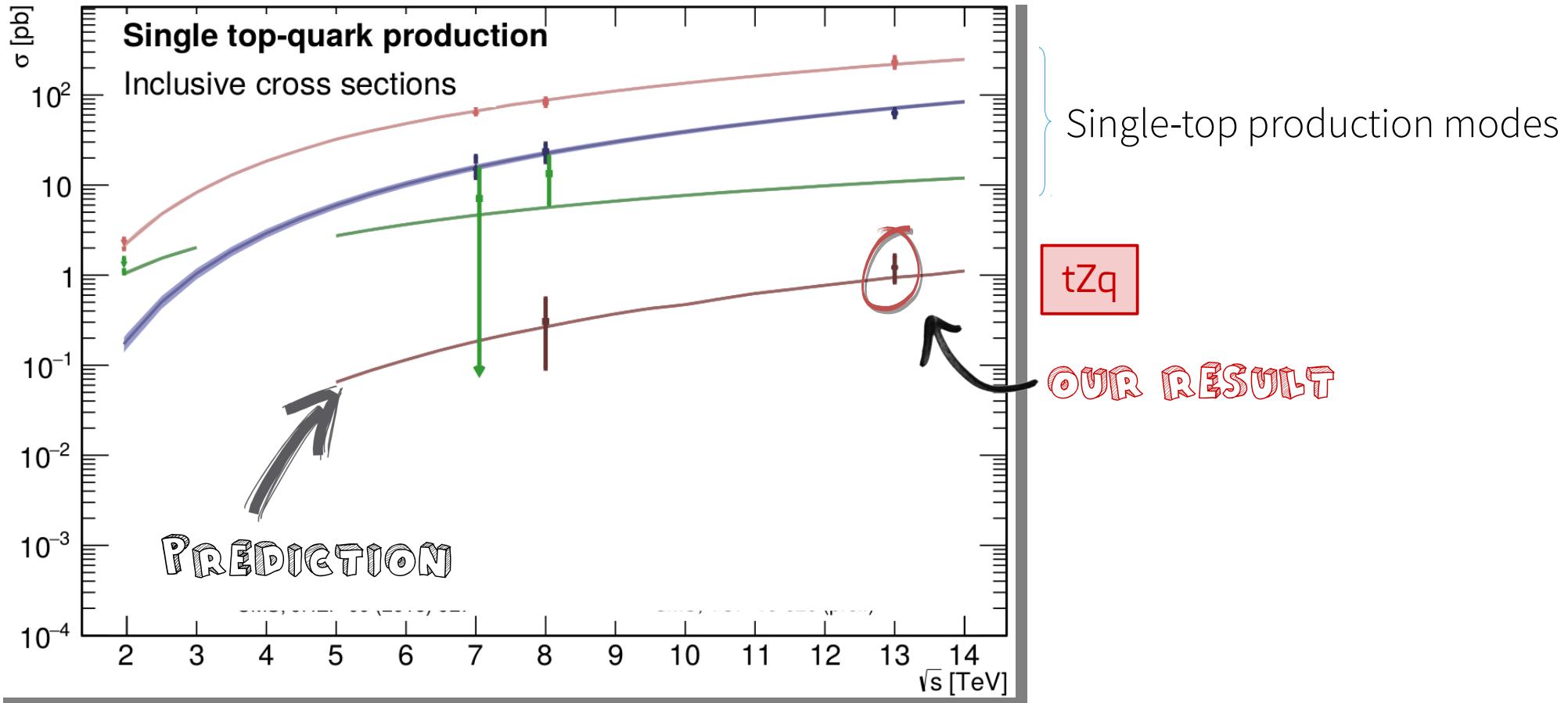
$$\sigma(t\ell^+\ell^-q) = 123^{+33}_{-31} \text{ (stat)}^{+29}_{-23} \text{ (syst) fb}$$

- Observed significance :  **$3.7\sigma$**
- Expected significance :  $3.1\sigma$ 
  - P-value = 0.0001



- Measurement of tZq cross-section provides interesting **test of Standard Model** and is sensitive to possible **new physics** effects
- Found **evidence** for this rare single-top process :  **$3.7\sigma$** 
  - Compatible with SM prediction
- Next step is discovery !
  - Need for more data





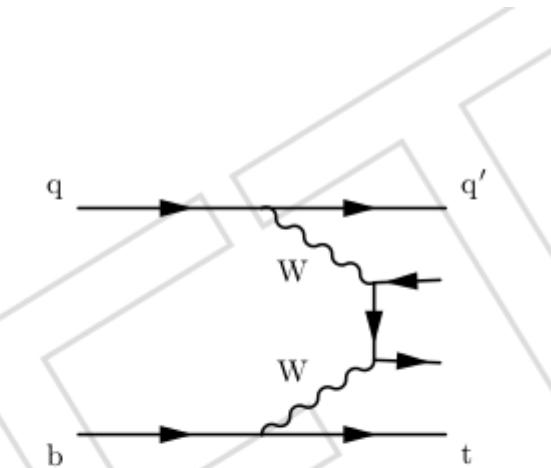
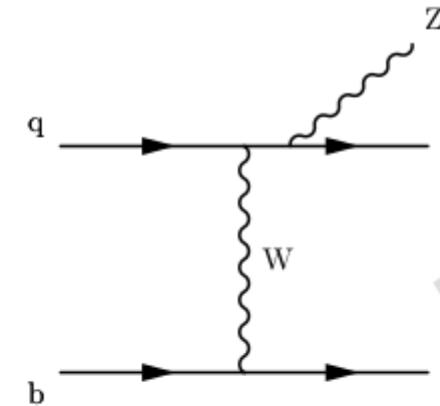
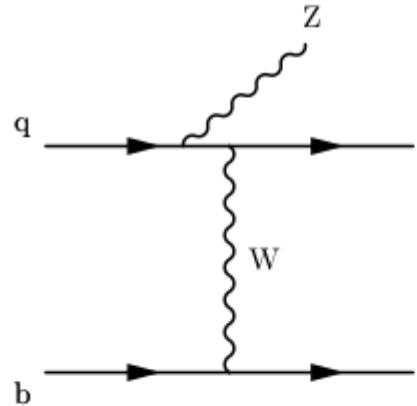
THANK YOU !

# BACKUP

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# More Feynman diagrams

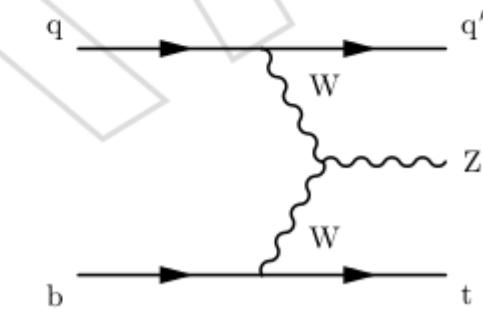
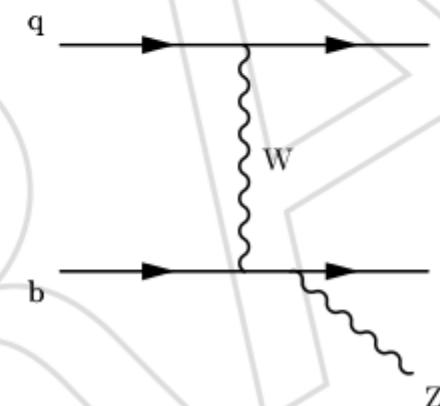
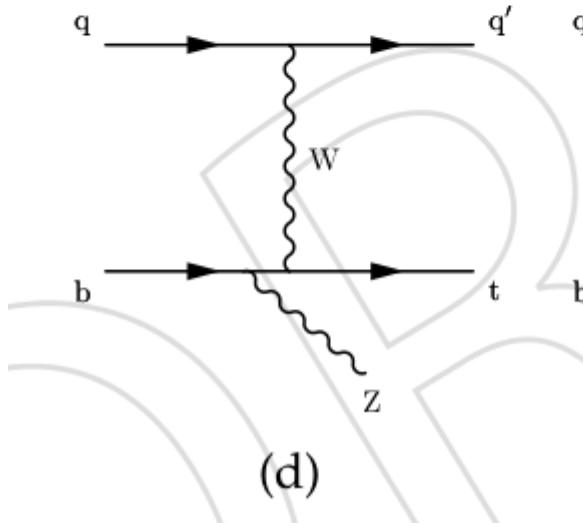
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(a)

(b)

(c)



(d)

(e)

(f)

# Cutflow table (postfit)

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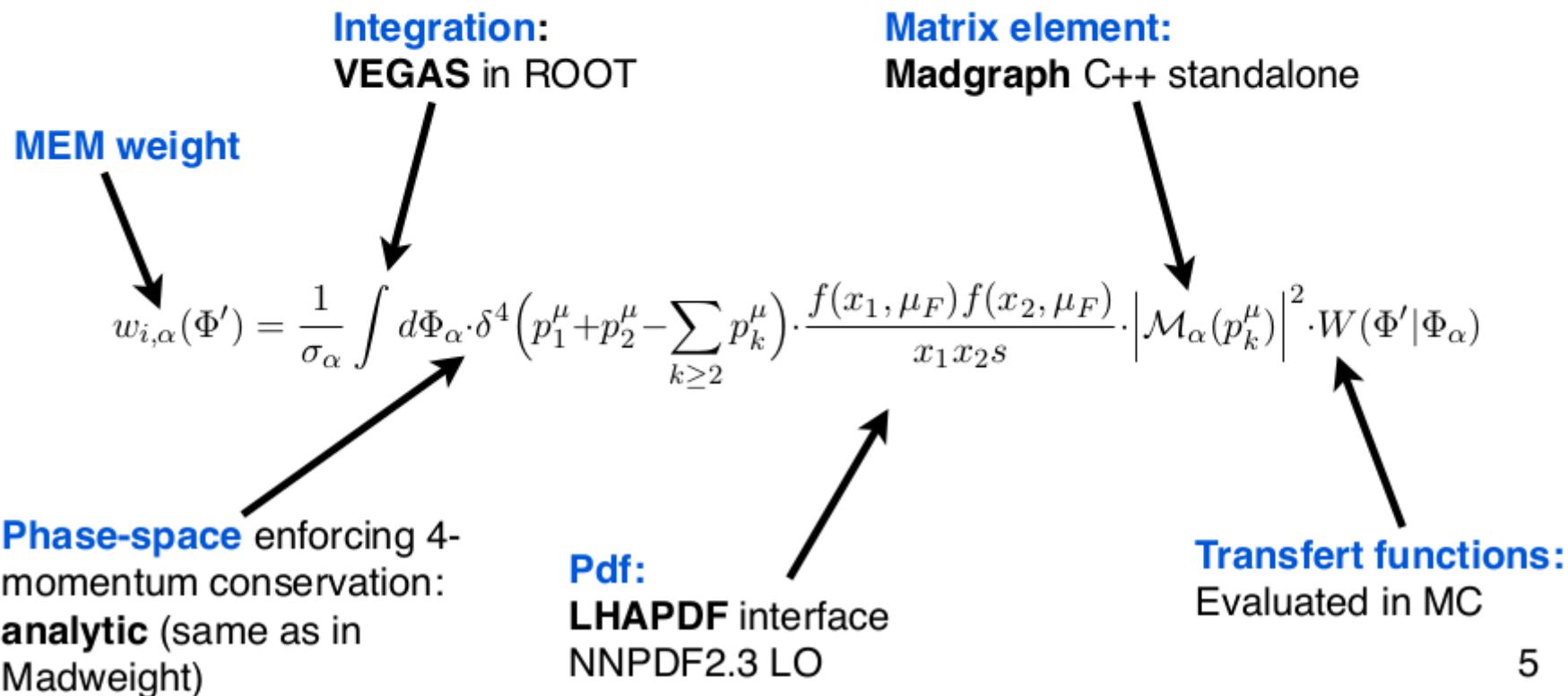
Process	eee	ee $\mu$	$\mu\mu e$	$\mu\mu\mu$	All channels	$\frac{N^{obs}}{N^{pred}}$
tZq	$5.0 \pm 1.5$	$6.6 \pm 1.9$	$8.5 \pm 2.5$	$12.3 \pm 3.6$	$32.3 \pm 5.0$	–
t $\bar{t}$ Z	$3.7 \pm 0.7$	$4.7 \pm 0.9$	$6.1 \pm 1.2$	$8.0 \pm 1.5$	$22.4 \pm 2.2$	$0.9 \pm 0.2$
t $\bar{t}$ W	$0.3 \pm 0.1$	$0.3 \pm 0.1$	$0.7 \pm 0.2$	$0.6 \pm 0.2$	$1.9 \pm 0.3$	$1.0 \pm 0.2$
Z Z	$4.8 \pm 1.3$	$3.2 \pm 0.9$	$9.0 \pm 2.5$	$7.8 \pm 2.2$	$24.7 \pm 3.6$	$1.3 \pm 0.3$
WZ+b	$3.0 \pm 0.9$	$3.4 \pm 1.1$	$4.6 \pm 1.4$	$5.5 \pm 1.7$	$16.6 \pm 2.6$	$1.0 \pm 0.2$
WZ+c	$9.0 \pm 2.4$	$13.7 \pm 3.7$	$18.0 \pm 4.9$	$24.2 \pm 6.5$	$64.8 \pm 9.3$	$1.0 \pm 0.2$
WZ+light	$12.2 \pm 1.6$	$16.6 \pm 2.0$	$22.4 \pm 2.8$	$29.1 \pm 3.4$	$80.3 \pm 5.1$	$0.7 \pm 0.1$
t $\bar{t}$ H	$0.6 \pm 0.2$	$0.9 \pm 0.3$	$1.0 \pm 0.3$	$1.5 \pm 0.4$	$4.0 \pm 0.6$	$1.0 \pm 0.2$
tWZ	$1.0 \pm 0.3$	$1.3 \pm 0.4$	$1.7 \pm 0.5$	$2.4 \pm 0.7$	$6.5 \pm 1.0$	$1.0 \pm 0.2$
NPL: electrons	$19.2 \pm 3.1$	$0.6 \pm 0.1$	$17.9 \pm 2.8$	–	$37.7 \pm 4.2$	–
NPL: muons	–	$7.2 \pm 2.3$	$31.1 \pm 9.9$	$15.3 \pm 4.9$	$53.6 \pm 11.3$	–
Total	$58.8 \pm 4.8$	$58.4 \pm 5.5$	$120.9 \pm 12.4$	$106.6 \pm 10.1$	$344.8 \pm 17.6$	
Data	56	58	104	125	343	

# Matrix Element Method

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## Matrix element method:

- Custom framework in C++
- Categories where 1 or 2 **jets are not reconstructed** are included: integrate over missing jet momenta

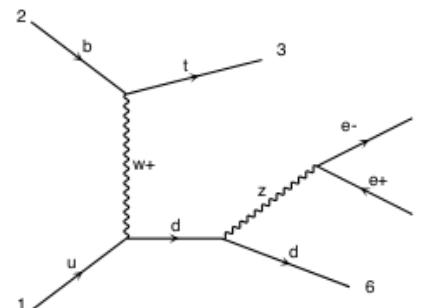


# Matrix Element Method

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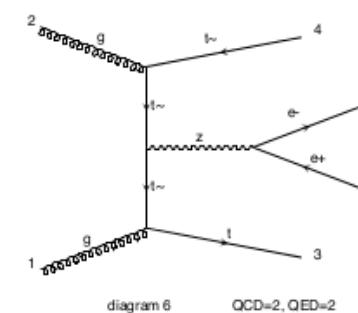
- Assume **narrow-width for top**
- Treat final-state b from top as massive
- Keep **full W and Z propagators** in the top ME: follows a Breit-Wigner
- Dilepton : Z and gamma\* contributions included

**TZQ hypothesis**



Hypothesis

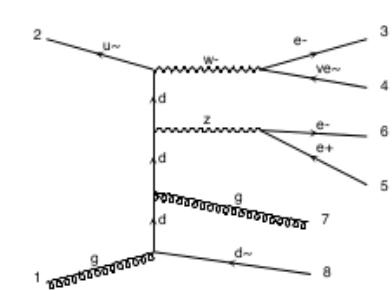
**TTZ hypothesis**



- sm\_no\_b\_mass model in MG5: initial-state b is massless (5FS)
- Top leptonic decay

- Tops : leptonic and hadronic decay

**WZ hypothesis**



- 2 additional jets considered in the ME

**Look for the kinematic configuration having maximum probability:**

**Maximize**

$$w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha} \int d\Phi_\alpha \cdot \delta^4(p_1^\mu + p_2^\mu - \sum_{k \geq 2} p_k^\mu) \cdot \frac{f(x_1, \mu_F) f(x_2, \mu_F)}{x_1 x_2 s} \cdot \left| \mathcal{M}_\alpha(p_k^\mu) \right|^2 \cdot W(\Phi' | \Phi_\alpha)$$

Kin. fit

- The system is fully constrained, by construction: Lorentz momenta of any particles in the hypothesis could be computed
- We will **use solely the maximum of the function** integrated, i.e. the score of the kinematic fit (obtained with the **highest integrand value** tried by **VEGAS** among all iterations of the integration: does not add computing time)

# Triggers & Signal strength/channel

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- Lowest  $p_T$  threshold for tri-lepton triggers : 16/12/8 GeV (electrons) & 12/10/5 GeV (muons)
- Lowest  $p_T$  thresholds for di-lepton triggers : 23/12 GeV (electrons) & 17/8 GeV (muons)
- $p_T$  thresholds for single-lepton triggers : 32 GeV (electrons) & 24 GeV (muons)

→ ~ 100 % trigger efficiency

- 
- Signal strength per channel:

- mmm :  $1.22^{+0.75}_{-0.63}$

Best channel

- eee :  $1.32^{+1.14}_{-0.99}$

- eem :  $0.66^{+0.78}_{-0.63}$

- mme :  $0.01^{+0.97}_{-0.01}$

tZq → MADGRAPH5\_aMC@NLO

WZ+jets & ttV → MADGRAPH5\_aMC@NLO, up to 1 add. jet at NLO

ZZ → MADGRAPH5\_aMC@NLO

ttH → POWHEG

tWZ → MADGRAPH (LO)

- PDF set → NNPDF3.0
- Parton shower & hadronisation → PYTHIA8
- All samples normalised to NLO cross section calculations, but tWZ (LO) and non-prompt (data-driven)

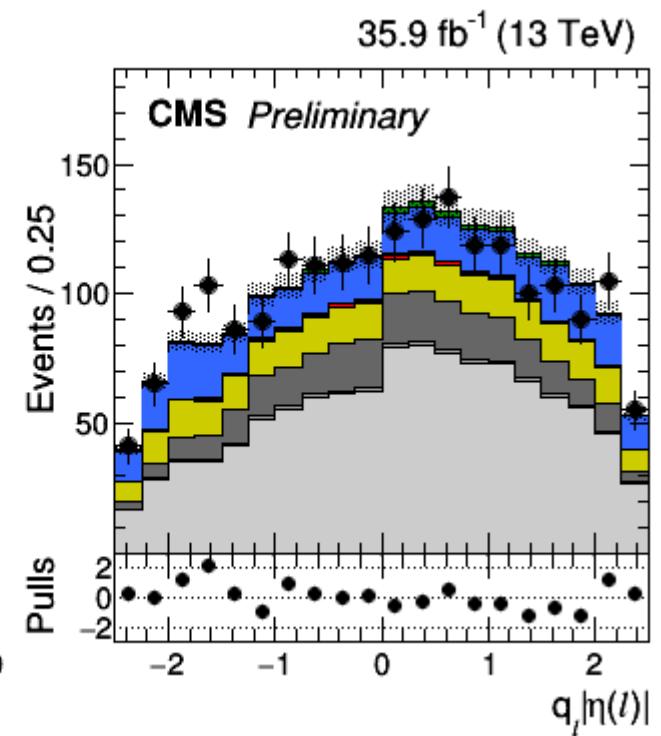
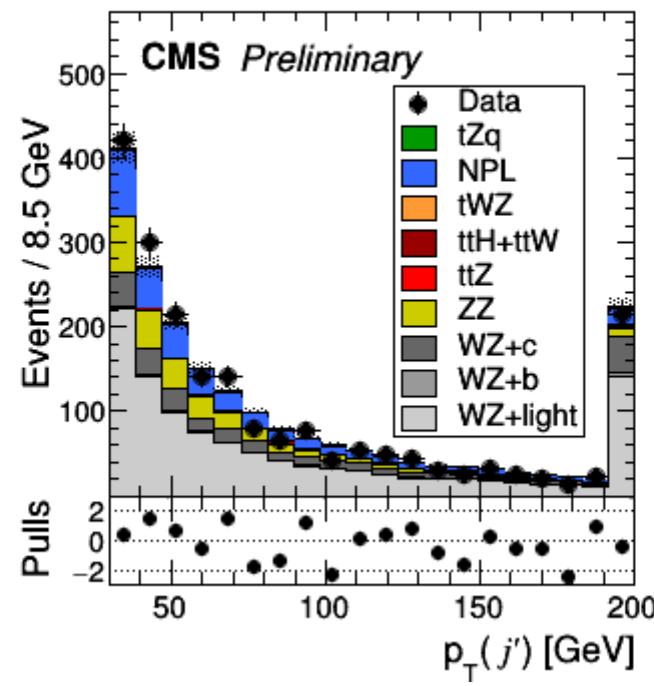
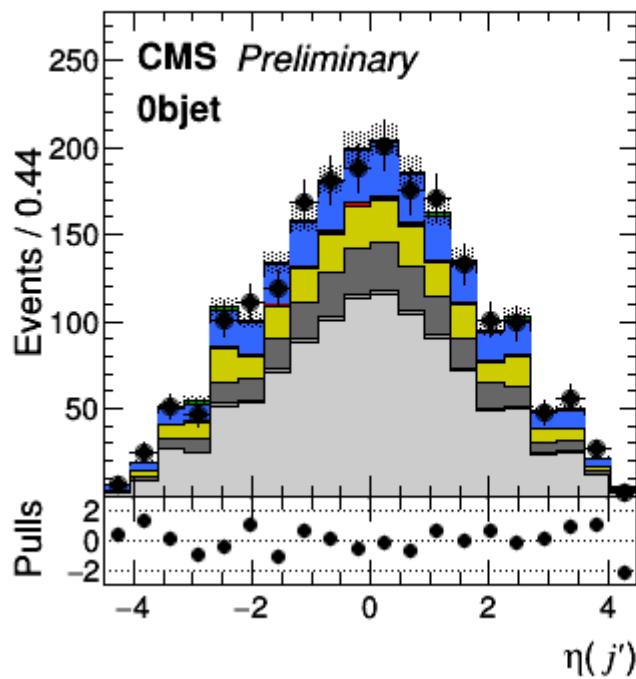
- Luminosity (2.5%, norm.)
  - Trigger (1-2 %, norm.)
  - Pile-up (+- 4.6 %, shape)
  - Lepton selection (SFs +-  $1\sigma$ , shape + norm.)
  - Jet Energy Scale & Resolution (+-  $1\sigma$ , shape + norm.)
  - B-tagging (SFs +-  $1\sigma$ , shape + norm.)
  - Normalisations of MC backgrounds (30 %, norm.)
  - NPL backgrounds shape uncertainties (variation of iso. Criterion)
- 
- - **The scale and PDF uncertainties for simulated signal ( $tZq$ ) and background processes.** These uncertainties affect the shape of the signal as well as the shape and normalisation of the simulated background samples, except for  $tWZ$ , for which only normalisation uncertainties from scale and PDF were considered.
      - The renormalisation and factorisation scales at the matrix element level are varied by factors of 1/2 and 2.
      - The renormalisation and factorisation scales at the parton shower level are varied by factors of 1/2 and 2; this uncertainty is only estimated for the signal sample.
      - The PDF uncertainties are estimated following the PDF4LHC recommendations, as the RMS of the results from 100 variations of the NNPDF.

The dominant systematic uncertainties arise from the normalisation of the NPL background, the scale variations at the parton shower level, the b-tagging efficiency, and the normalisation of the  $t\bar{t}Z$  background.

# Few WZ postfit variables

30

- 4 channels summed



# BDT input variables

31

- Input variables: kinematics of particles, angular distributions, etc.
- Postfit distributions of some of the most discriminating (= best) ones :

