CMS Experiment at LHC, CERN
Data recorded: Tue Jul 26 07:58:48 2016 CEST
Run/Event: 277427 / 669414
Lumi section: 9

LHC machine and Top quark properties

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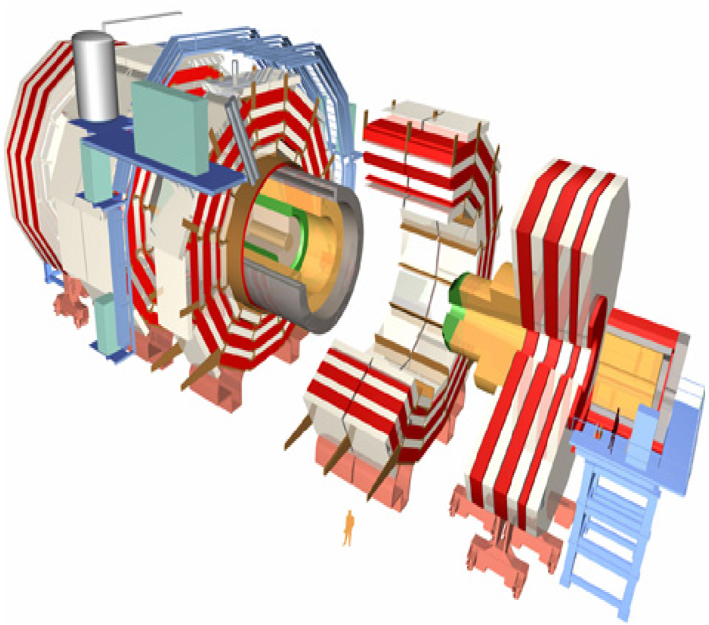
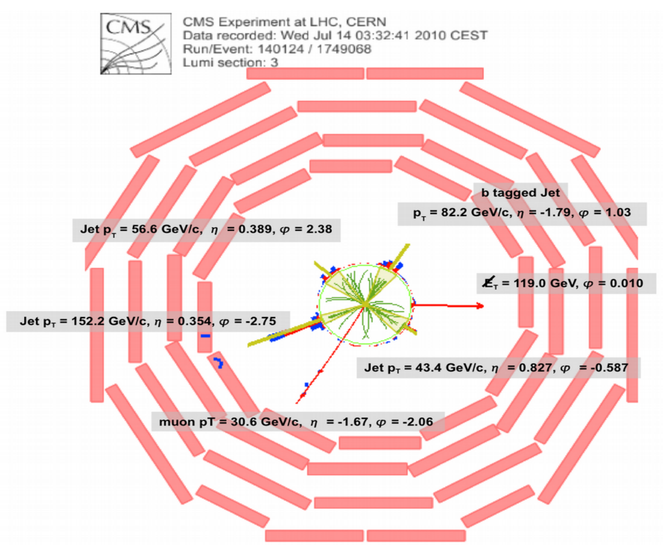
Outline

- LHC Machine
- Experimental tools, TDAQ and triggering
  - Constraints and architectures
  - Why using a trigger
  - Physics requirements
- Analysis strategies
- Top quark physics
- Helicity measurement
- Cross section measurements at 13TeV





LHC machine

CERN

Accélérateur de science

LHC Facts:

- Protons arrived in the LHC, traveled at **0.999997828** times the speed of light.

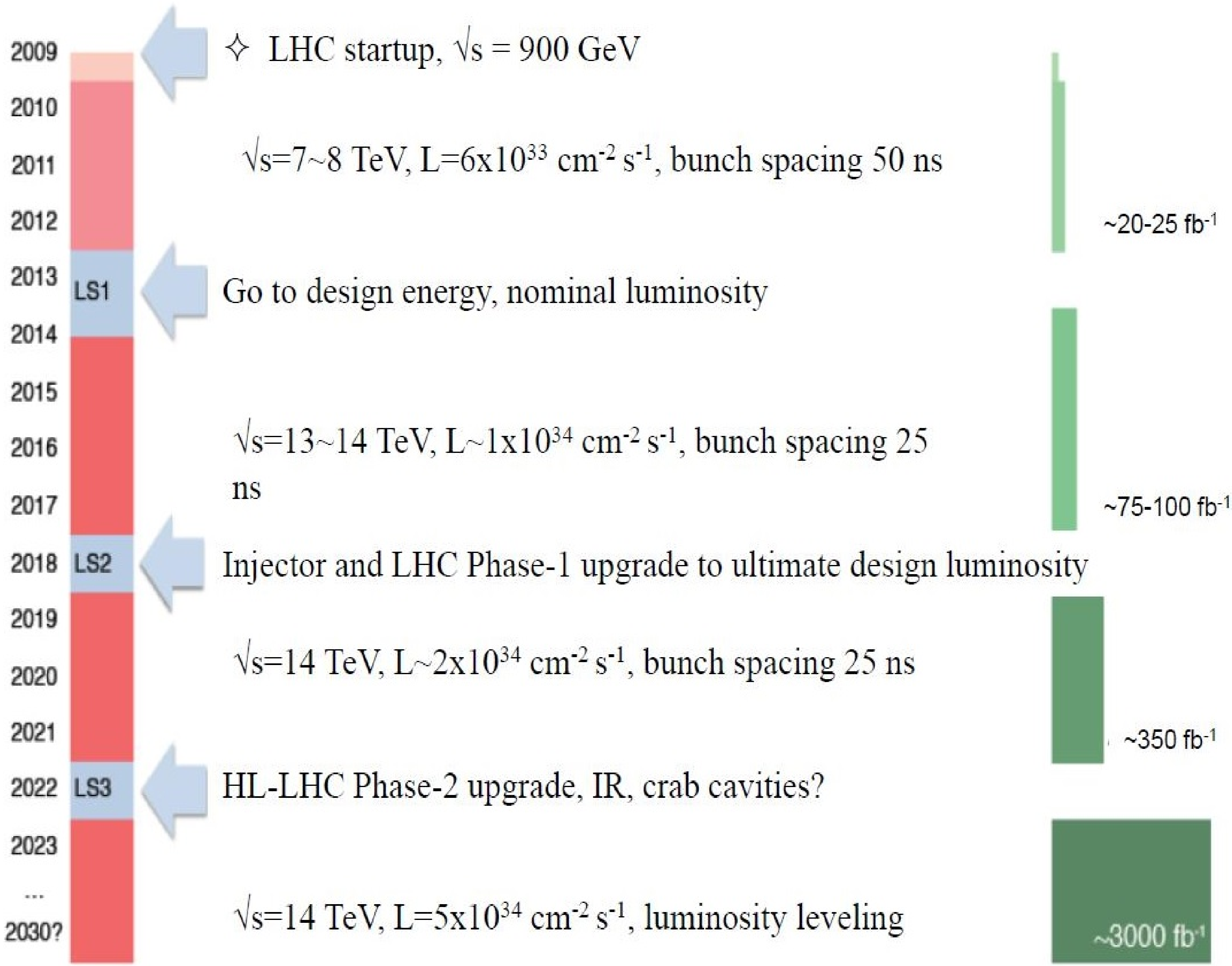
- Between each consecutive bunch there are **7.5 m**
  - time between bunches = $7.5/3*10^8$
  - Bunch spacing = **$2.5*10^{-8}$ s**

- The effective number of bunches is **2808**

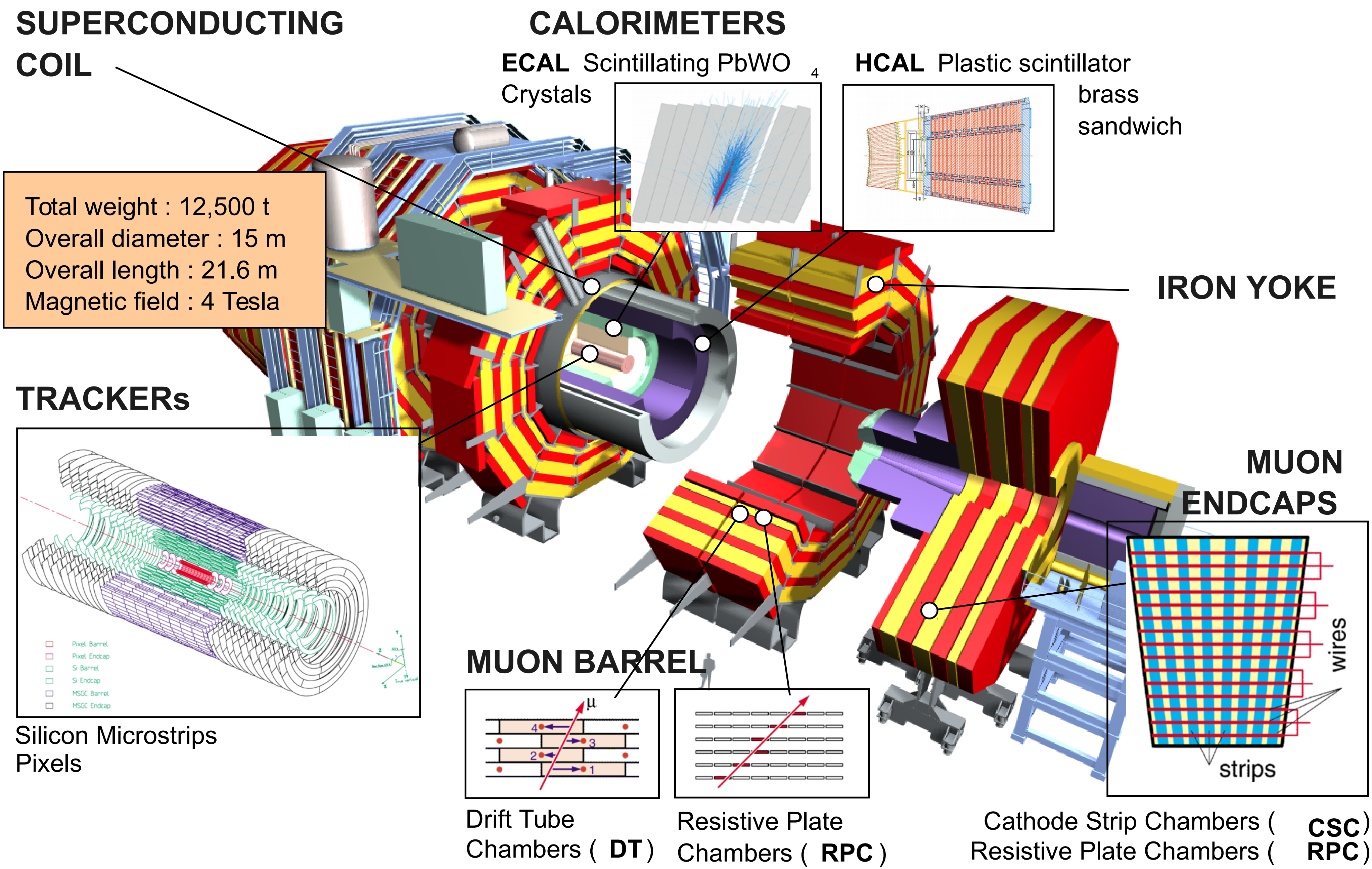
- **11245 * 2808 ~ 32 millions crosses/s** , the "average crossing rate"
  - **20 * 32 millions crosses/s** ~ 600 millions collision/s

- Probability $\approx (d_{proton})^2/(\sigma 2) \Rightarrow$ Probability $\approx$ **$(10^{-15})^2/(16*10^{-6})^2 \approx 4*10^{-21}$**
  - **$(4*10^{-21}) * (1.15*10^{11})^2$** $\Rightarrow$ ~ **50 interactions** every crossing

LHC Road map


2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
...
2030?
LS1
LS2
LS3
✧ LHC startup, $\sqrt{s}$ = 900 GeV
$\sqrt{s}$=7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns
Go to design energy, nominal luminosity
$\sqrt{s}$=13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns
Injector and LHC Phase-1 upgrade to ultimate design luminosity
$\sqrt{s}$=14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns
HL-LHC Phase-2 upgrade, IR, crab cavities?
$\sqrt{s}$=14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity leveling
~20-25 fb^{-1}
~75-100 fb^{-1}
~350 fb^{-1}
~3000 fb^{-1}

CMS


SUPERCONDUCTING COIL
CALORIMETERS
ECAL Scintillating PbWO4 Crystals
HCAL Plastic scintillator brass sandwich
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla
IRON YOKE
TRACKERs
Pixel Barrel
Pixel Endcap
Si Barrel
Si Endcap
MSGC Barrel
MSGC Endcap
Silicon Microstrips
Pixels
MUON ENDCAPS
MUON BARREL
μ
wires
strips
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

Should we read everything?

- A typical collision is “boring”
- The final rate dominated by not interesting physics

$$R = \sigma_{in} \times L$$

LHC: the trigger challenge!

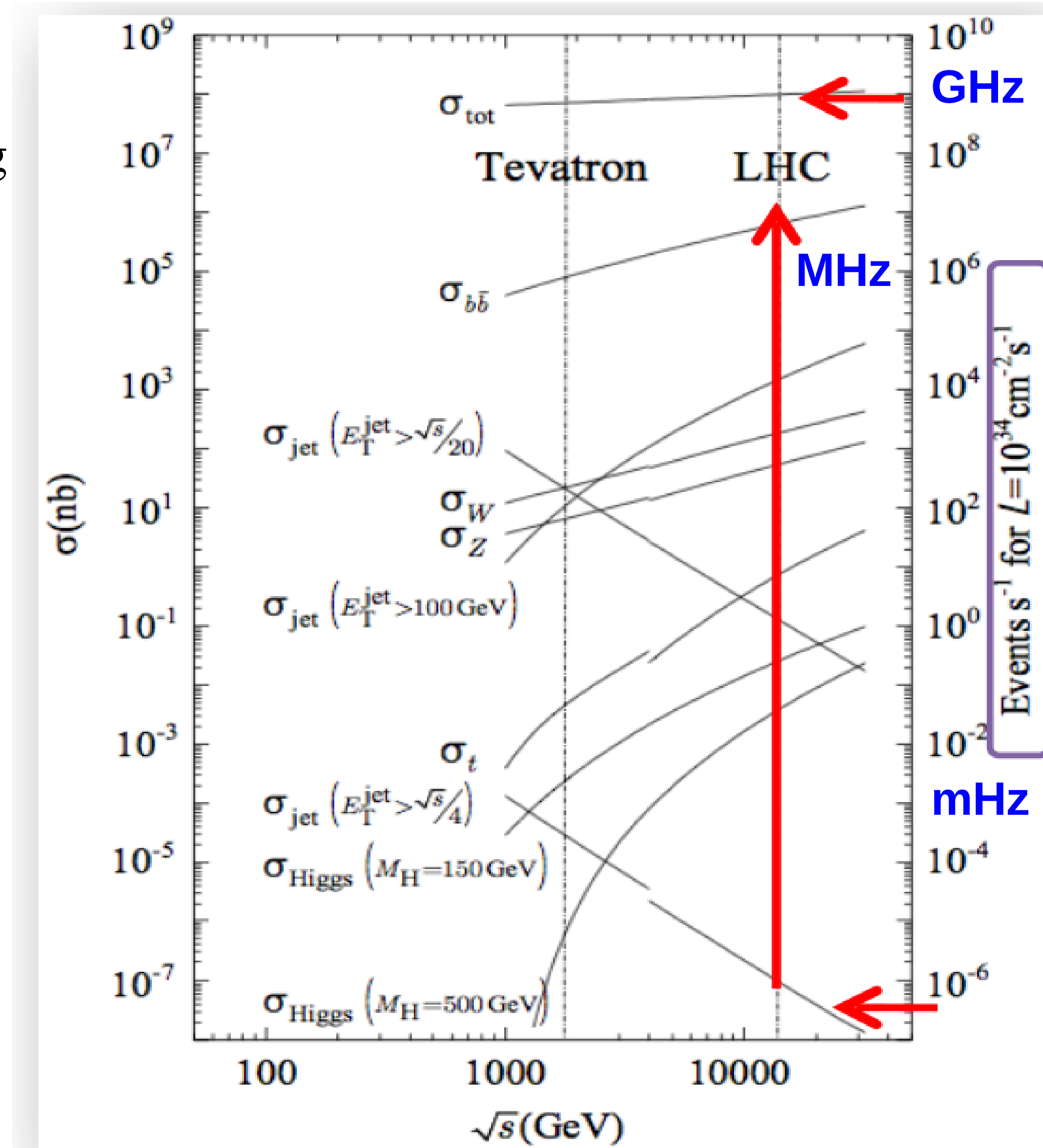
Total non-diffractive p-p cross section is **70 mb**

Total trigger rate is ~ GHz!!!

Huge range of cross-sections and production rates at design:

Beauty (0.7 mb)	– 1000 Hz
W/Z (200/60 nb)	– 100 Hz
Top (0.8 nb)	– 10 Hz
Higgs - 125 GeV (30 pb)	– 0.1 Hz

$$\frac{\sigma_{tot}}{\sigma_{H(500\,\mathrm{GeV})}} \approx \frac{100\,mb}{1\,pb} \approx 10^{11}$$

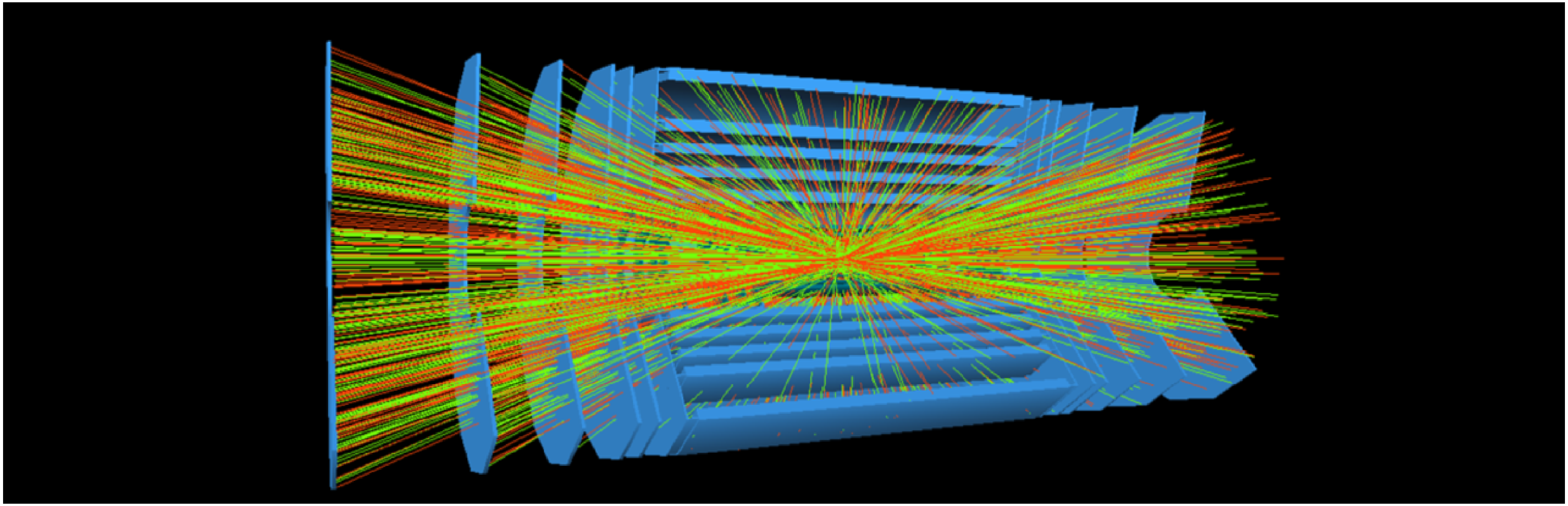


- Efficiently identify the rare processes from the overwhelming background before reading out & storing the whole event
- **Note: this is just the production rate, actual detection is more rare!**

TDAQ Systems at the LHC

A story about how they were designed originally and how they are evolving…

The data deluge



In many systems and experiments, storing all possibly the relevant data provided by sensors are unrealistic.

Three approaches are possible:

-reduce amount of data → **trigger**

-Faster data transmission and processing

-both

What do we need to read out a detector (successfully)?

- A selection mechanism **("trigger")**
- Electronic readout of the sensors of the detectors **("front-end electronics")**
- A system to keep all those things in sync **("clock")**
- A system to collect the selected data **("DAQ")**
- A **Control System** to configure, control and monitor the entire DAQ
- **Time, money, students** (lots of them)

What is a trigger?

Wikipedia:

“A trigger is a system that uses simple criteria to rapidly decide which events in a particle detector to keep when only a small fraction of the total can be recorded. “

- Simple
- Fast decision
- Low dead time
- Flexibility

Basic DAQ: “real” trigger

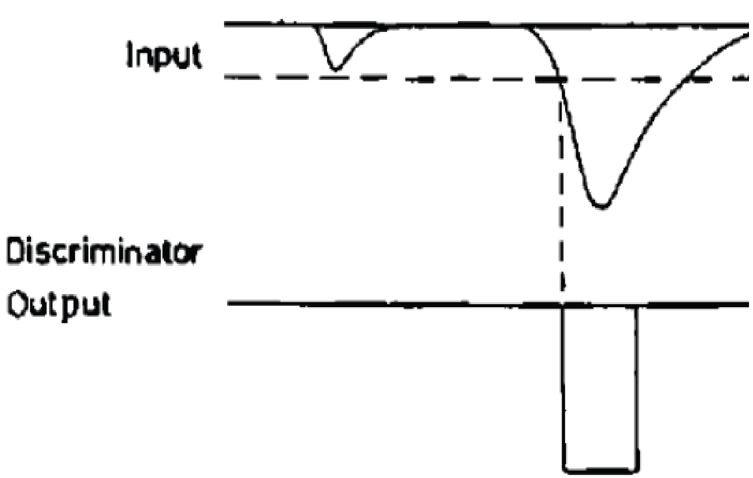
Events asynchronous and unpredictable

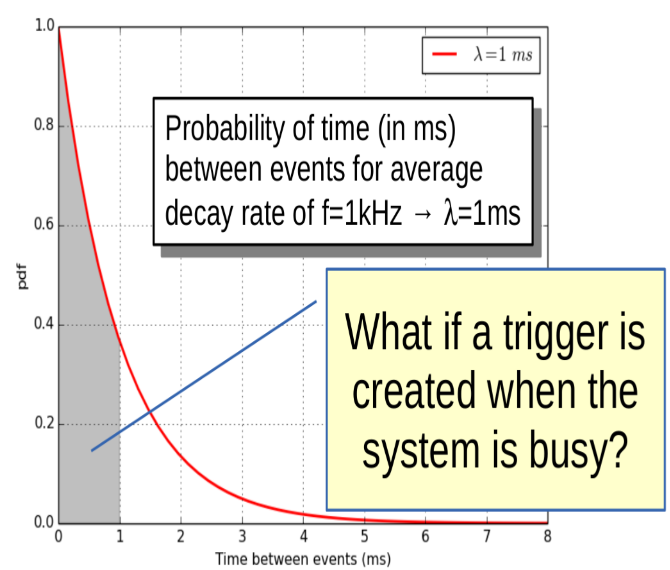
E.g.: beta decay studies

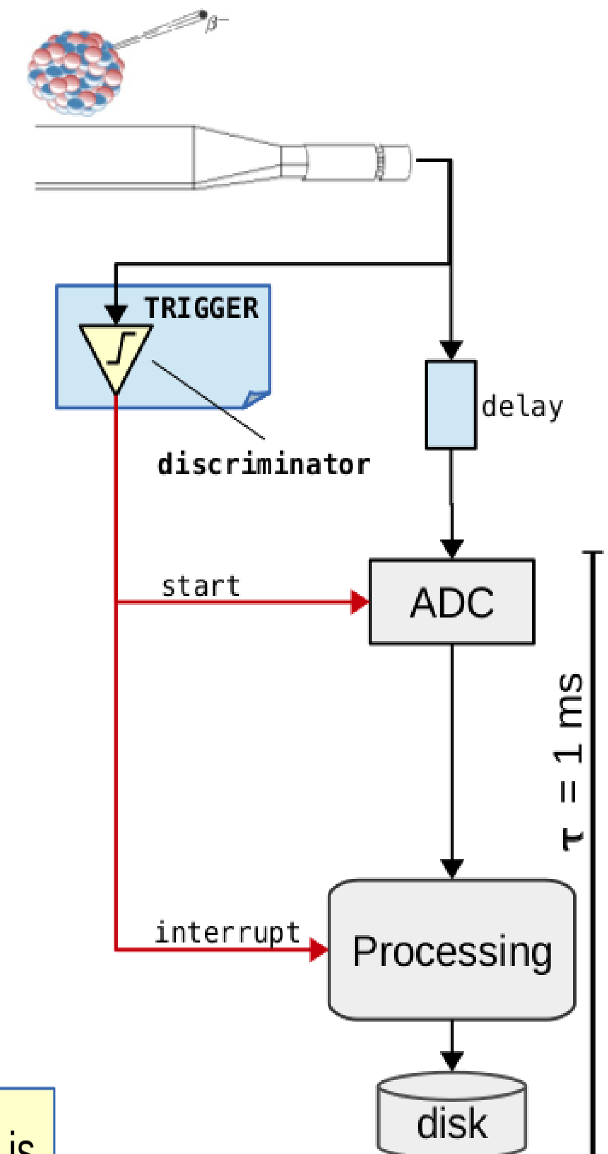
Let's assume for example a process rate f = 1 kHz, i.e.
 λ= 1 ms and τ = 1 ms

A physics trigger is needed.
delay compensate for trigger latency

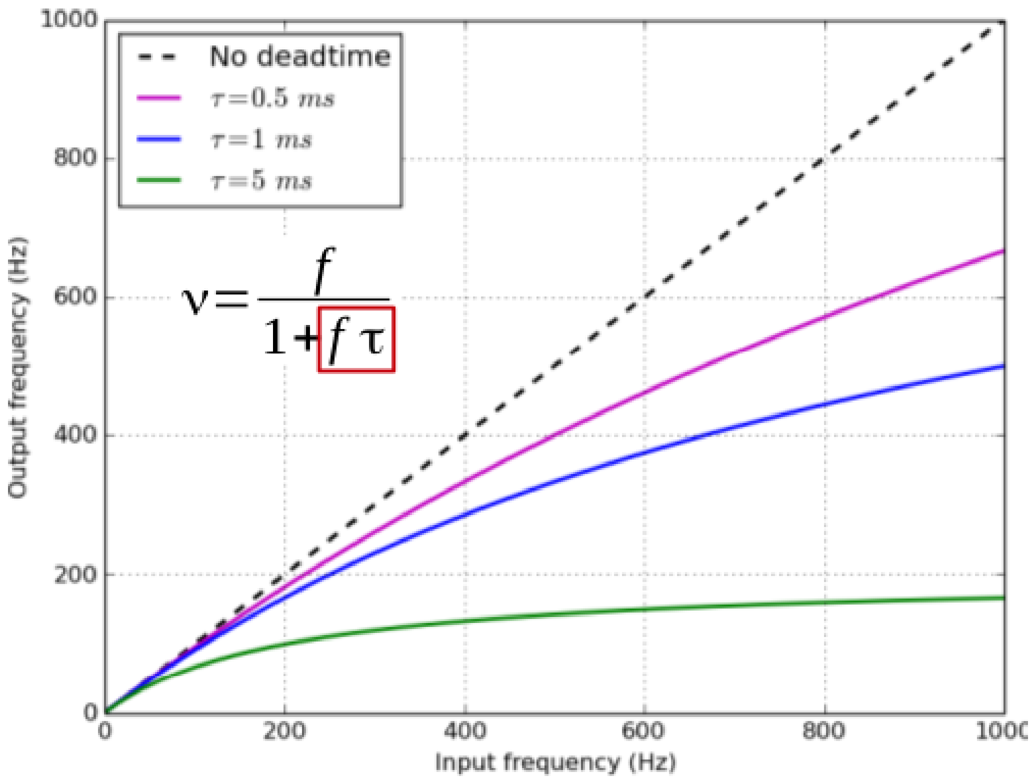
Discriminator: generate an output signal only if amplitude of
 input pulse is grater than a certain threshold



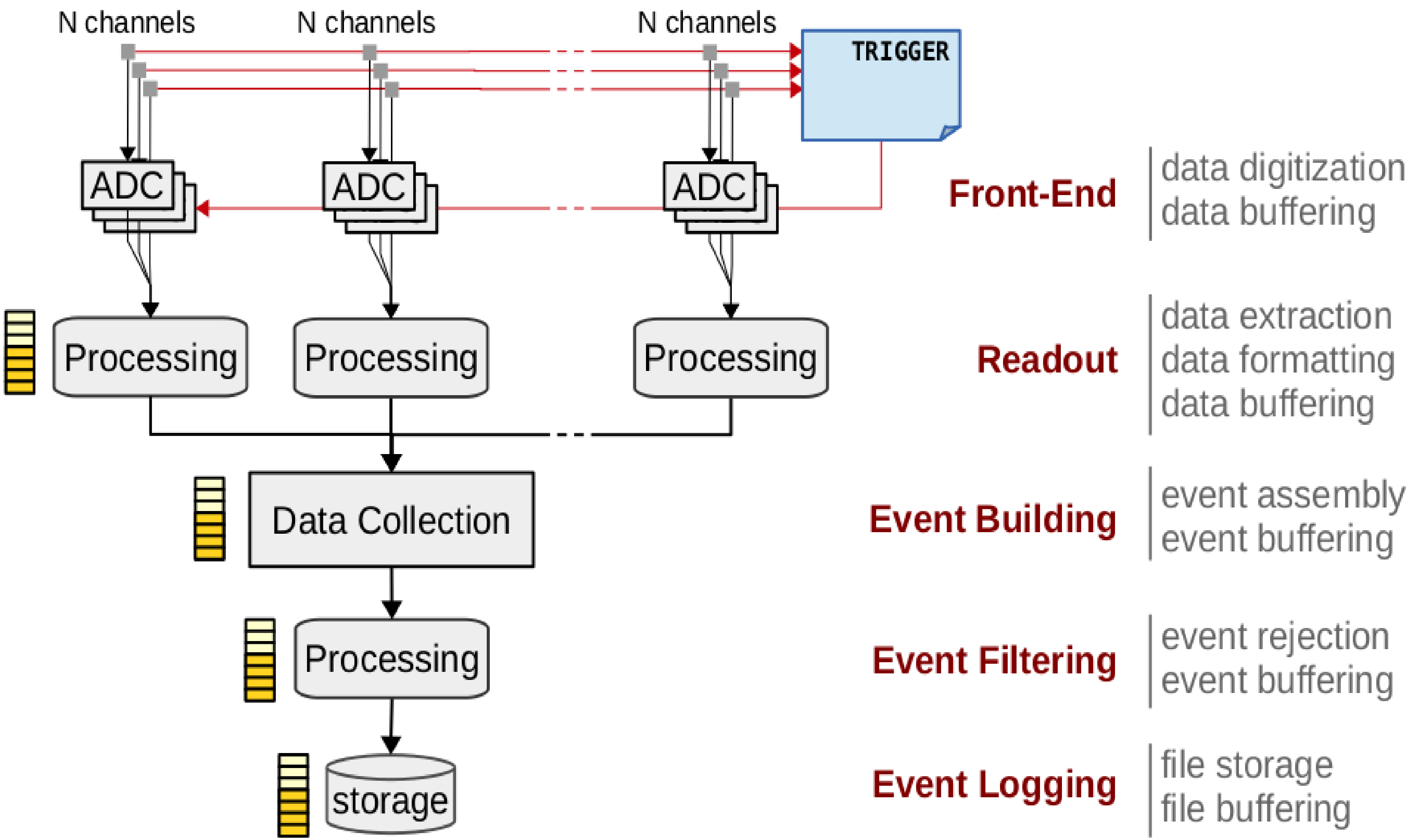




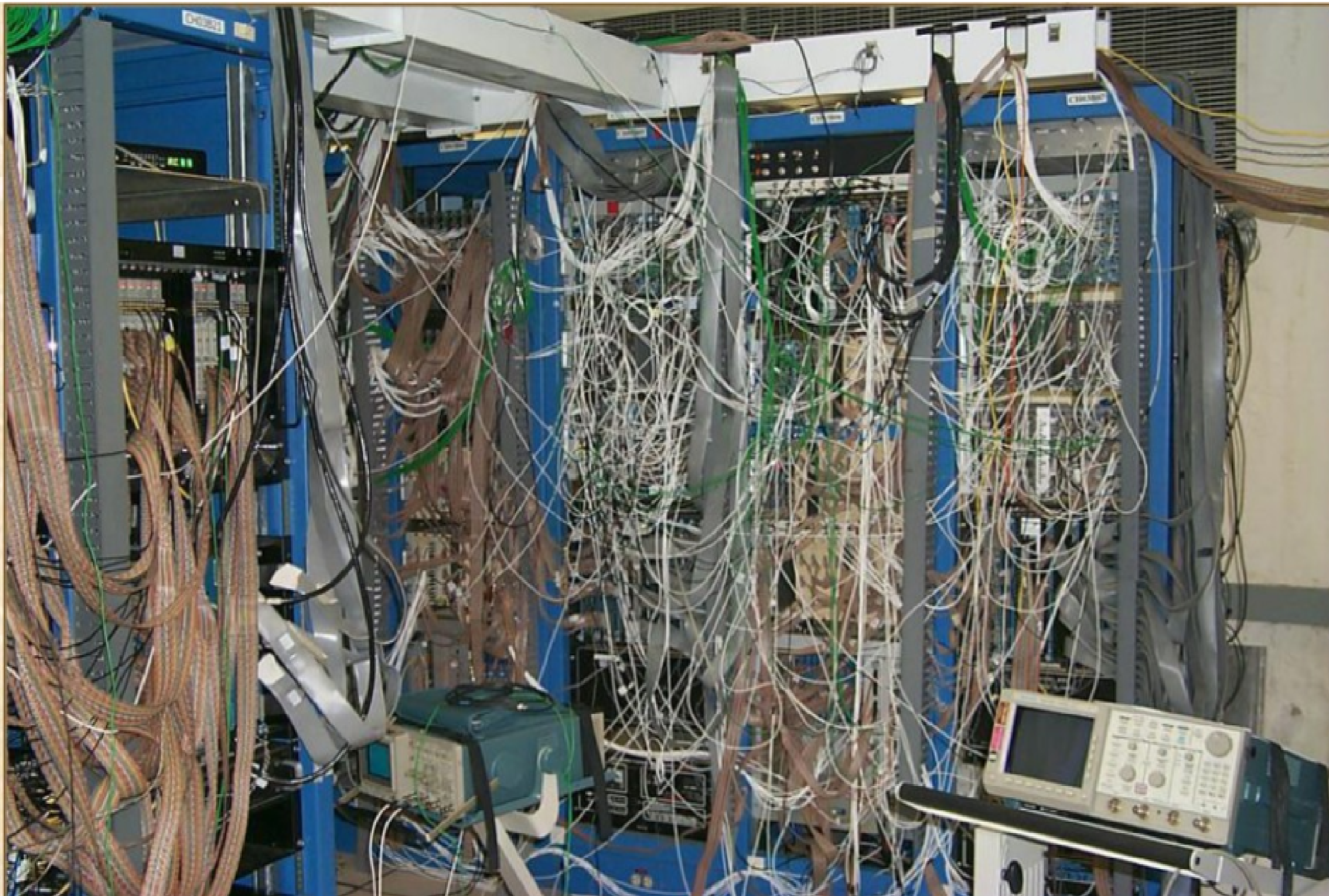
Input frequency v.s. output frequency



- Buffering usually needed at every level



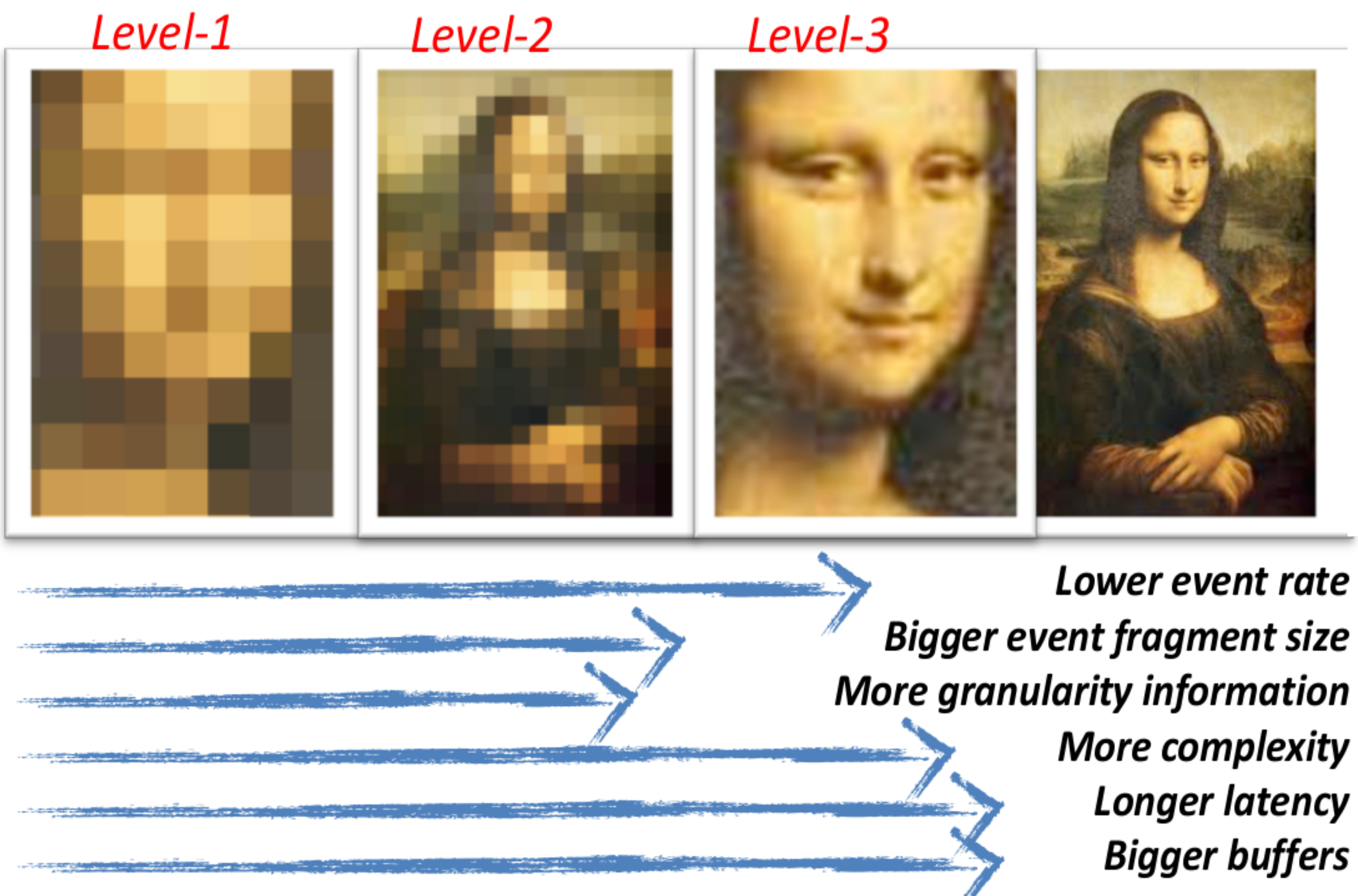
Jungle of experimental tools



In any case:

Multi-level triggers

- Adopted in large experiments
- Successively more complex decisions are made on Successively lower data rates
  - watch out for high transverse momentum electrons, jets or muons
- First level with short latency, working at higher rates
- Higher levels apply further rejection, with longer latency(complexes algorithms)



LHC experiments @ Run1

Exp.	N.of Levels
ATLAS	3
CMS	2
LHCb	3
ALICE	4

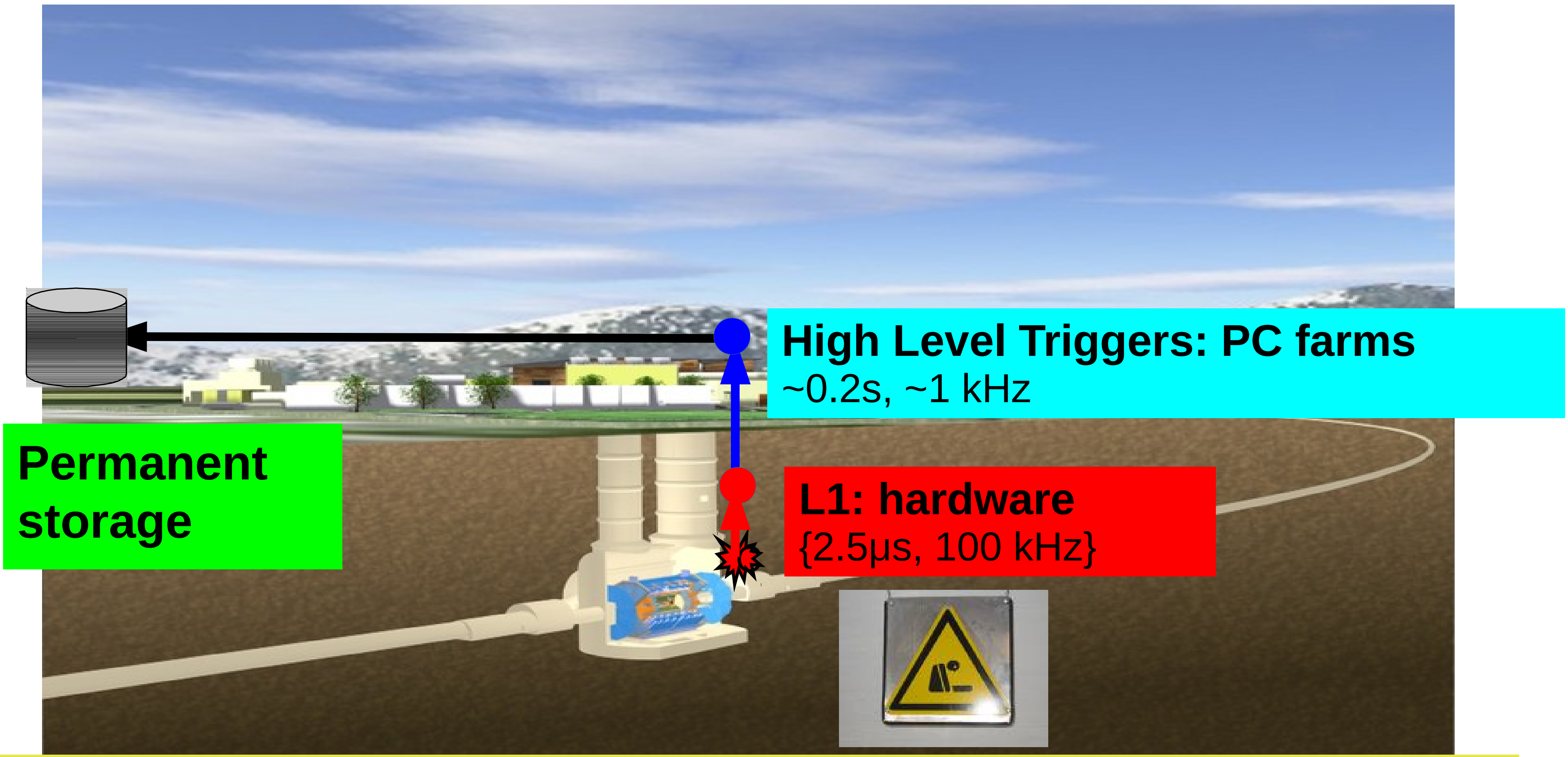
Efficiency for the desired physics must be kept high at all levels, as rejected events are lost for ever

Trigger at 2 stages:

Level1 (L1: fast, no detailed info, Hardwired trigger system, Constant latency buffers in the front-ends)

&

High Level Trigger (HLT: slower, using detailed info)



Trigger & DAQ : Select events and get the data from the detector to the computing center for the first processing.

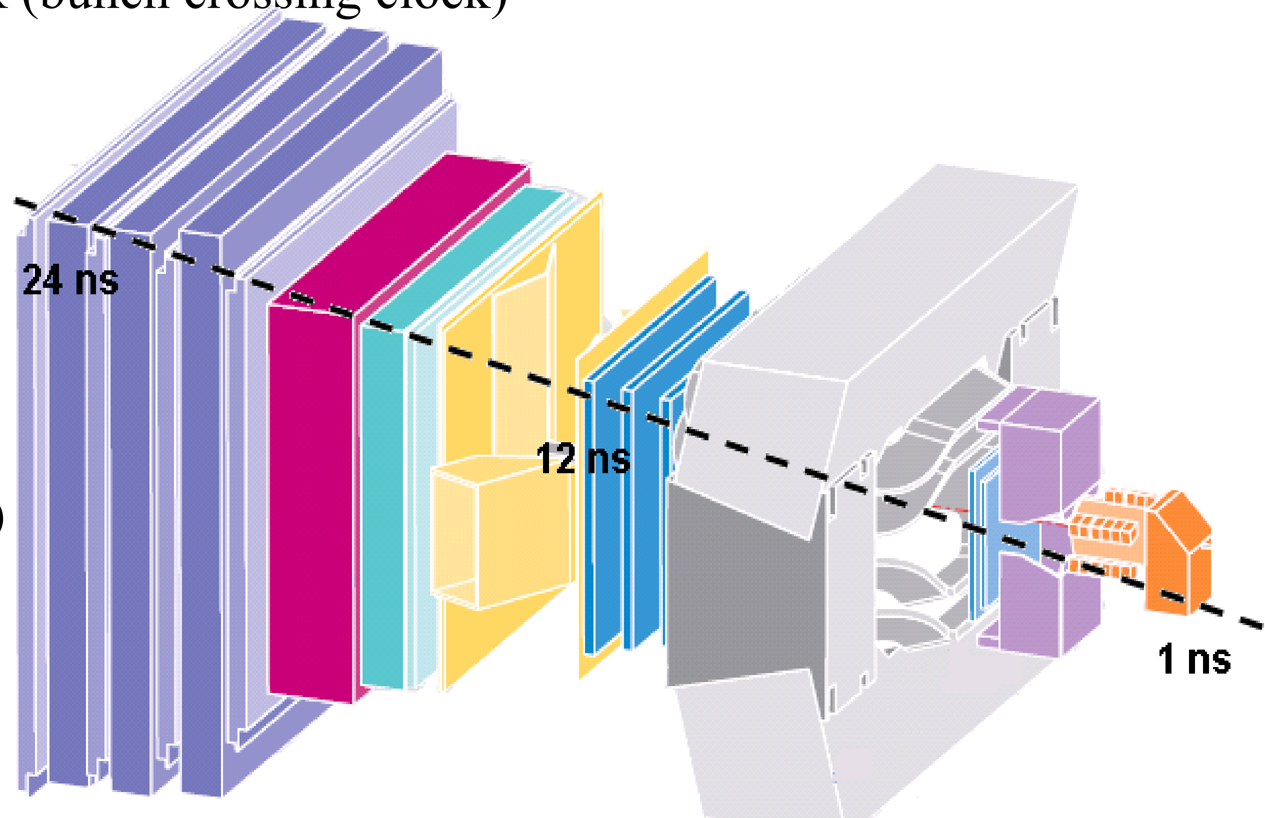
Challenges for the L1 at LHC

- N (channels) ~ O(10^7); ≈20 interactions every 25 ns
  - need huge number of connections
- Detector signal/time of flight can be > 25 ns
  - integrate more than one bunch crossing's worth of information
  - need to identify bunch crossing…
- Need to synchronize detector elements to (better than) 25 ns

  - All channels are doing the same "thing" at the same time

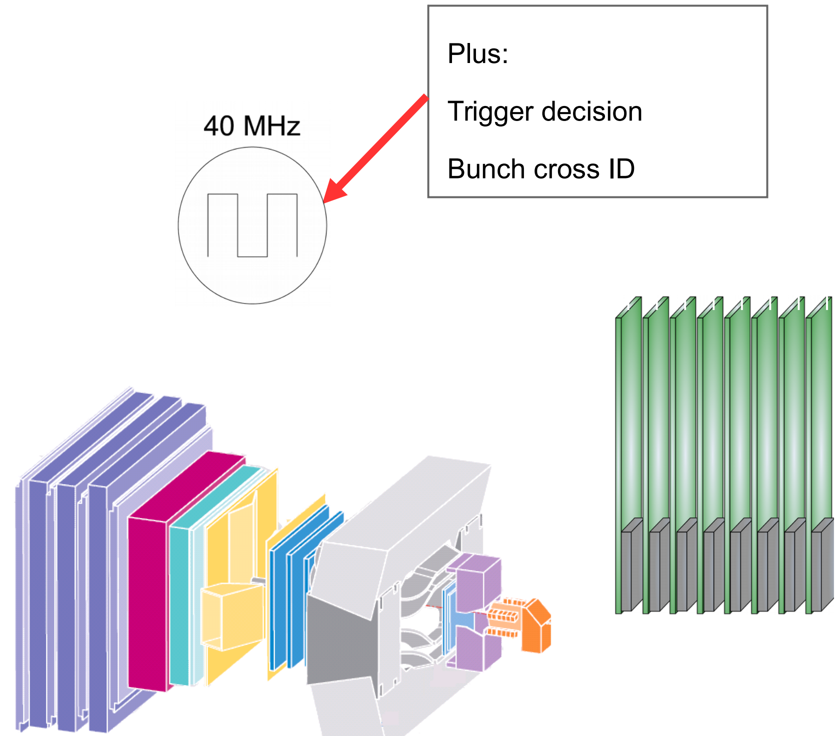
  - Synchronous to a global clock (bunch crossing clock)

<u>But:</u>
Particle TOF >> 25ns
(25 ns ≈ 7.5m)
Cable delay >> 25ns (vsignal ≈ 1/3 c)
Electronic delays



Distributing Synchronous Signals @ the LHC

- **An *event* is a snapshot of the values of all detector front-end electronics elements, which have their value caused by the same collision**
- A common clock signal must be provided to all detector elements
  - Since c is constant, the detectors are large and the electronics are fast, the detector elements must be carefully time-aligned
- Common system for all LHC experiments TTC based on radiation-hard opto-electronics



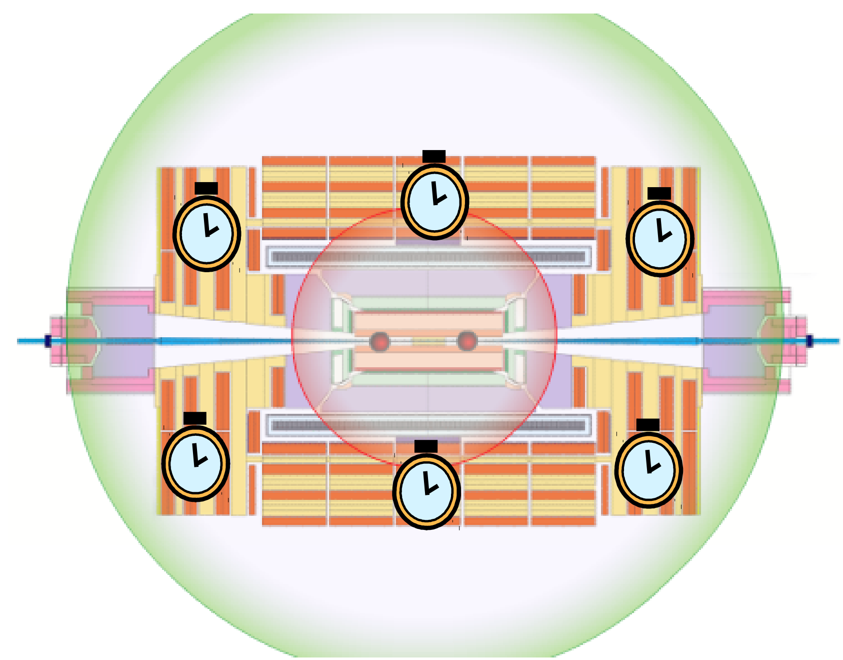
Data corresponding to the same bunch crossing

must be processed together.

Need to:

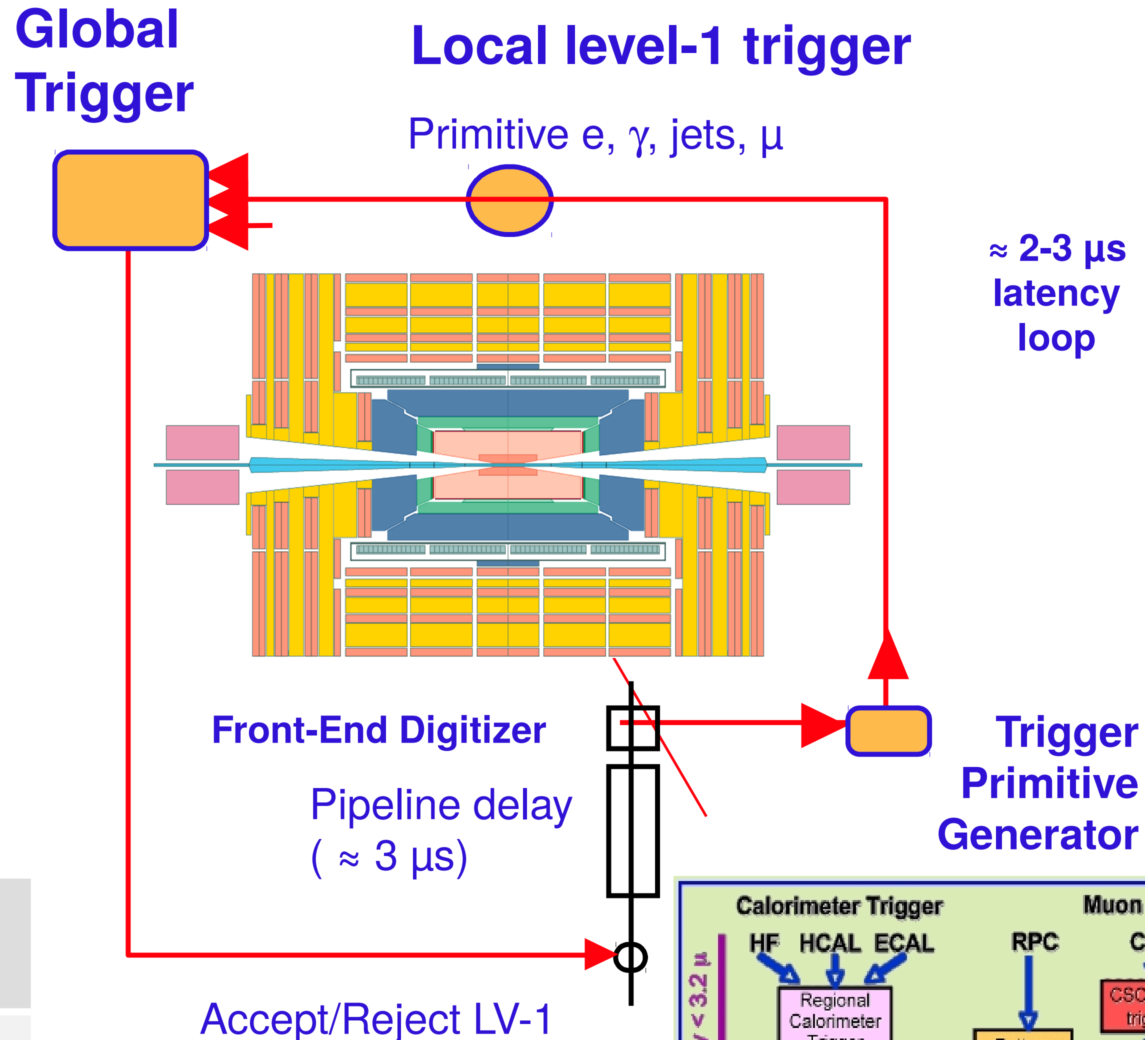
Synchronize signals with programmable delays.

Provide tools to perform synchronization

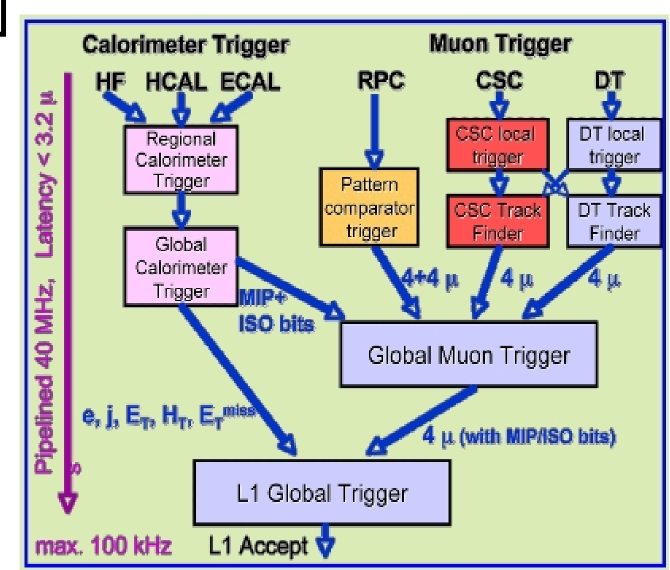


Distributing the L1 Trigger

- Assuming that a magic box tells for each bunch crossing (clock-tick) **yes or no**
- This decision has to be brought for each crossing to all the detector f**ront-end electronics elements** so that they can send of their data or discard it
- LHC use the same **Timing and Trigger Control** (TTC) system as for the clock distribution



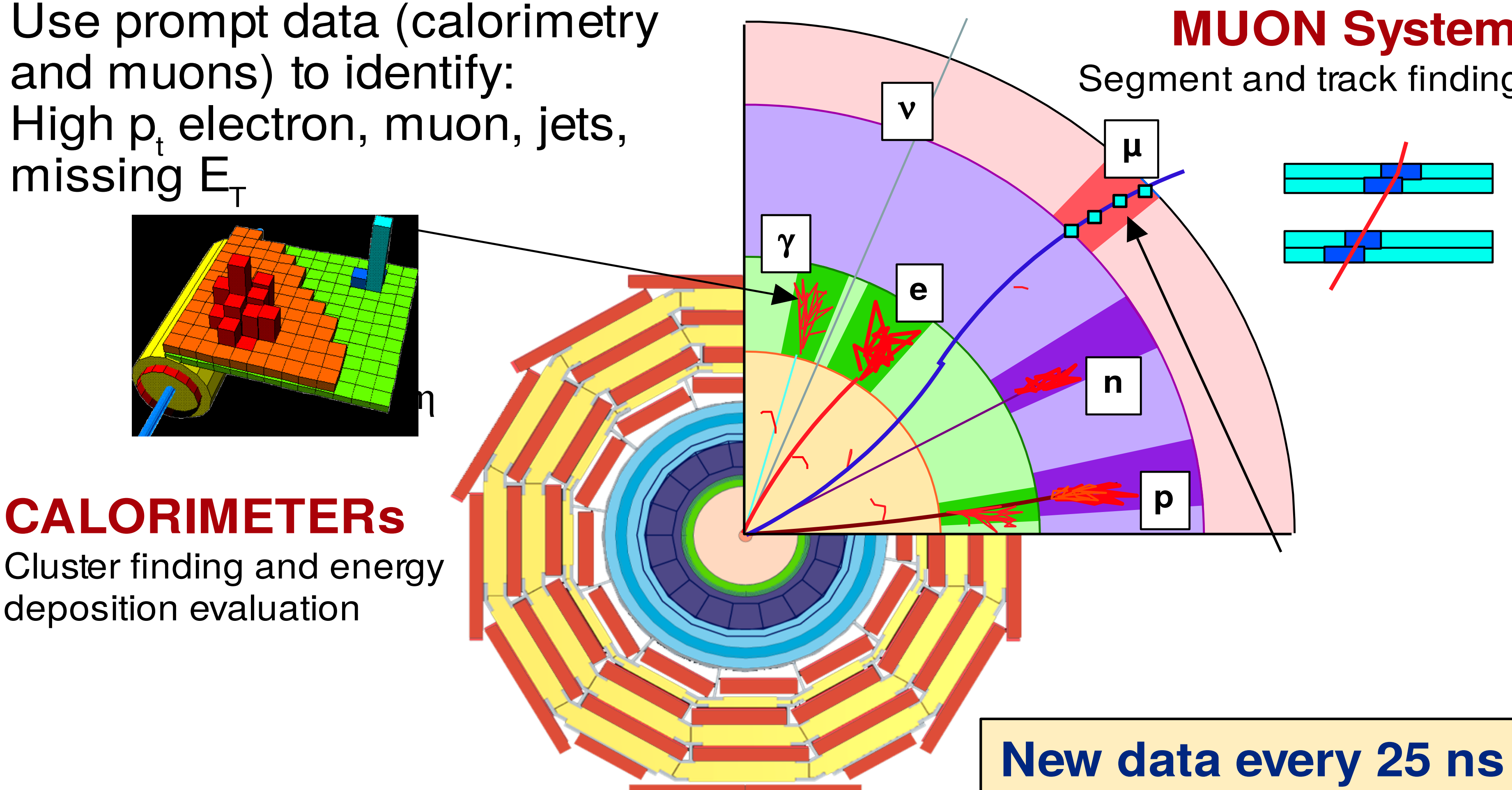
L1 trigger latencies	
ALICE	No pipeline
ATLAS	2.5 us
CMS	3 us
LHCb	4 us



The more you know about the events, the easiest you select the “signal” and reject the “background”

When there is limited time budget (L1 trigger): decide based only on the muon and calorimeter systems

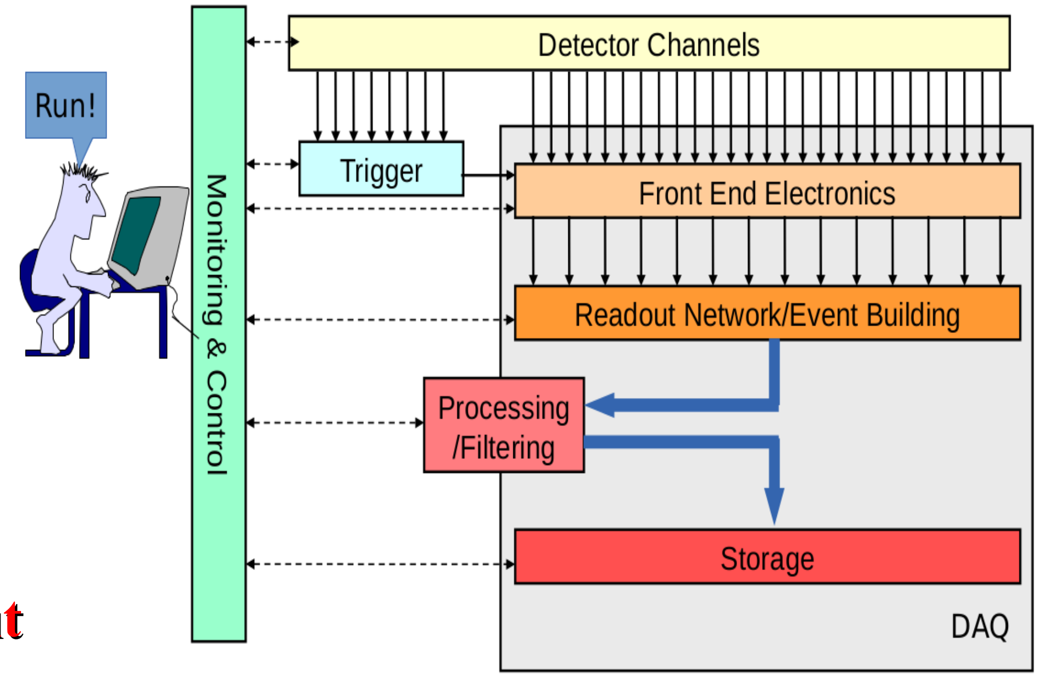
Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T



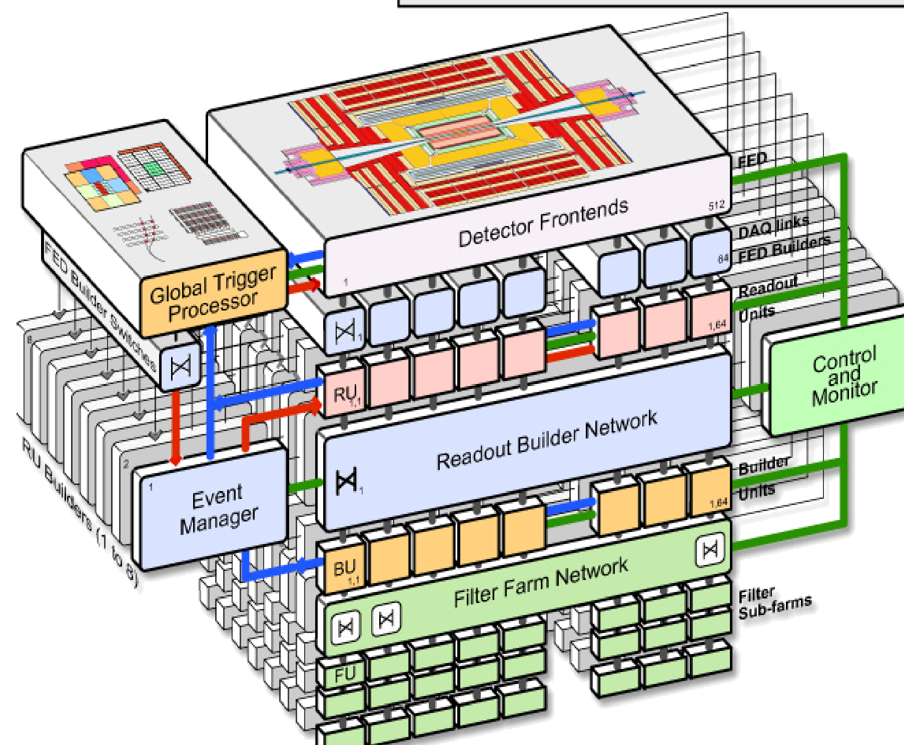
New data every 25 ns
Decision latency ~ µs

Trigger & DAQ

- Trigger
  Either selects interesting events or rejects boring ones, in real time i.e. with minimal controlled latency time it takes to form and distribute its decision



- DAQ
  gathers data produced by detectors: **Readout**
  Possibly feeds several trigger levels: **HLT**
  Forms complete events: **Event Building**
  Stores event data: **Data Logging**
  Provides **Run Control, Configuration and Monitoring**

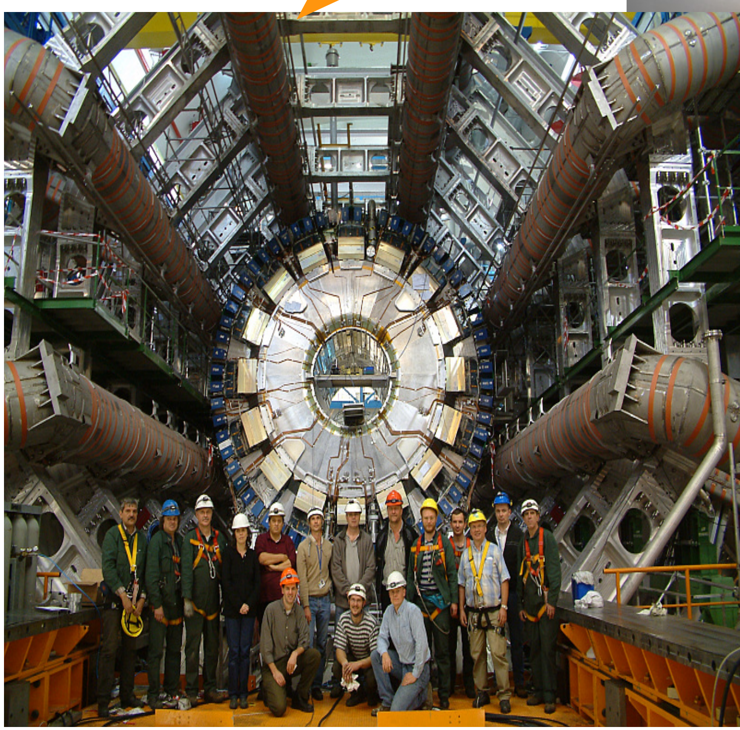


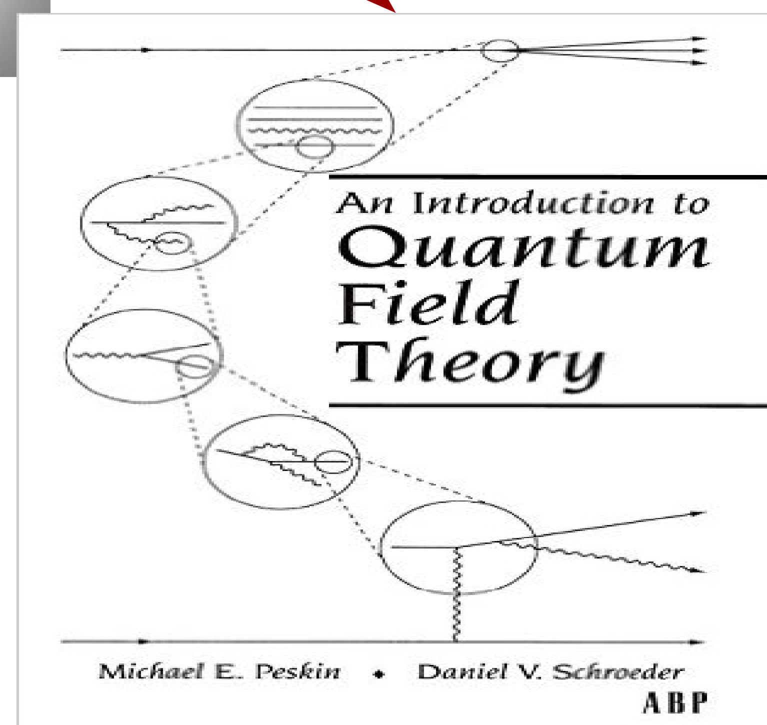
Physics and top quark sector

In which direction an analyzer should be motivated?

Experiment
Soft- or hardware

Phenomenology or theory





Try to get knowledge in both directions as much as possible

Fitting methods

Signal efficiency

uncertainties

Closure tests

Motivation

Real Data

MC simulation

Truth level information

What is signal?

Event reconstruction

What is background?

Bkg estimation

Analysis strategy

Object selection

Control region

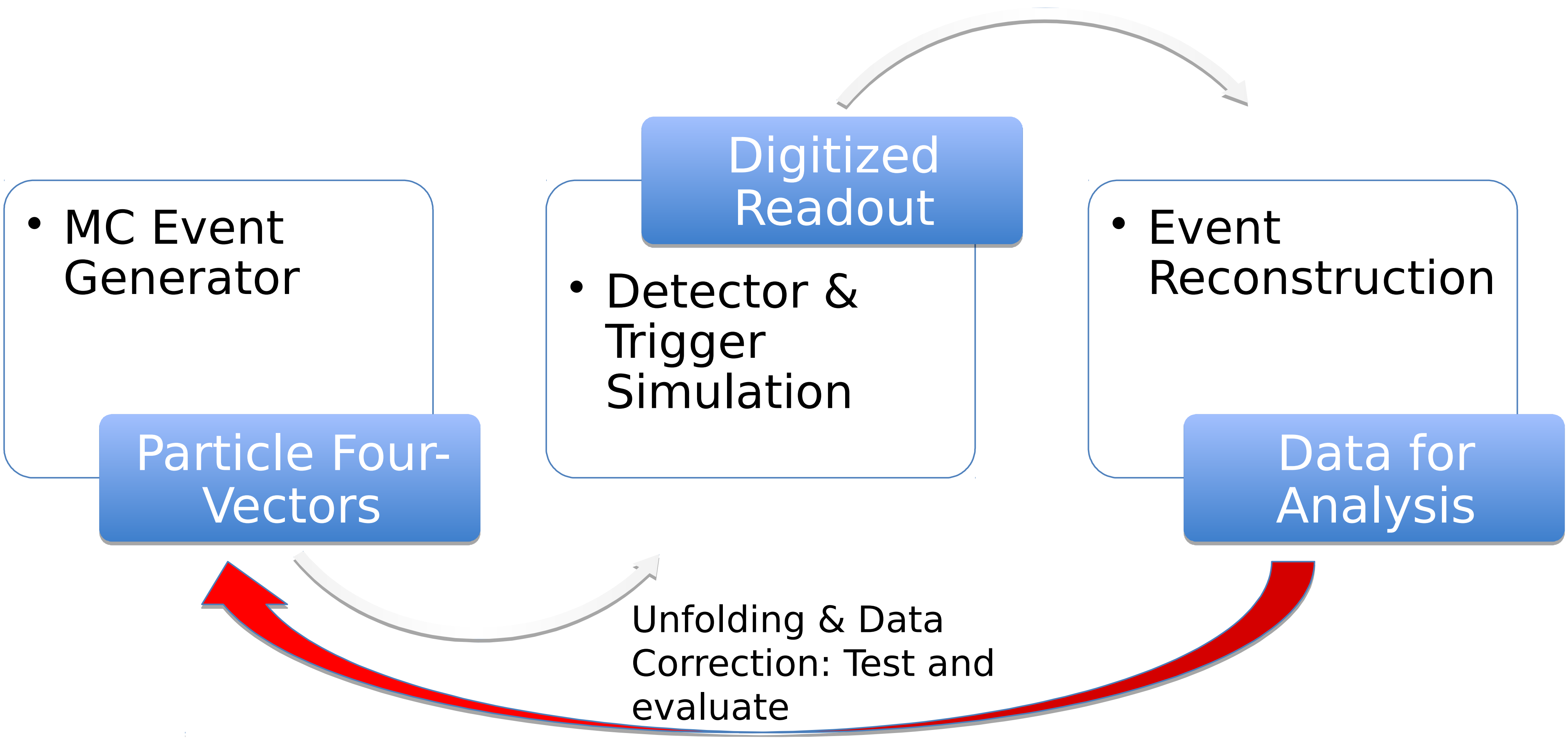
Event selection

Signal region

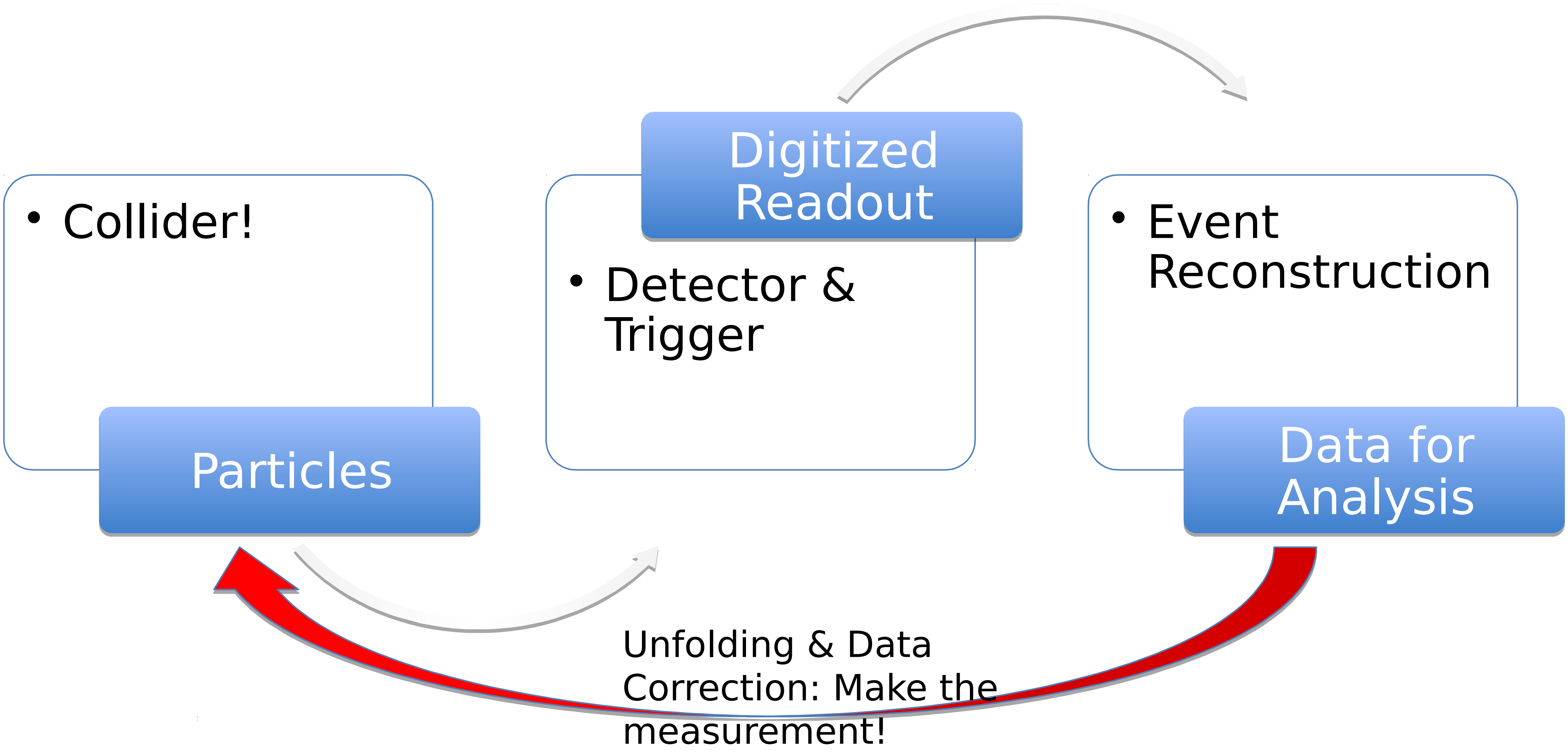
Control plots

What we need to make data based analysis

Simulation and Experiment



Simulation and Experiment



The structure of an event – 1

The structure of an event – 2

The structure of an event – 3

The structure of an event – 4

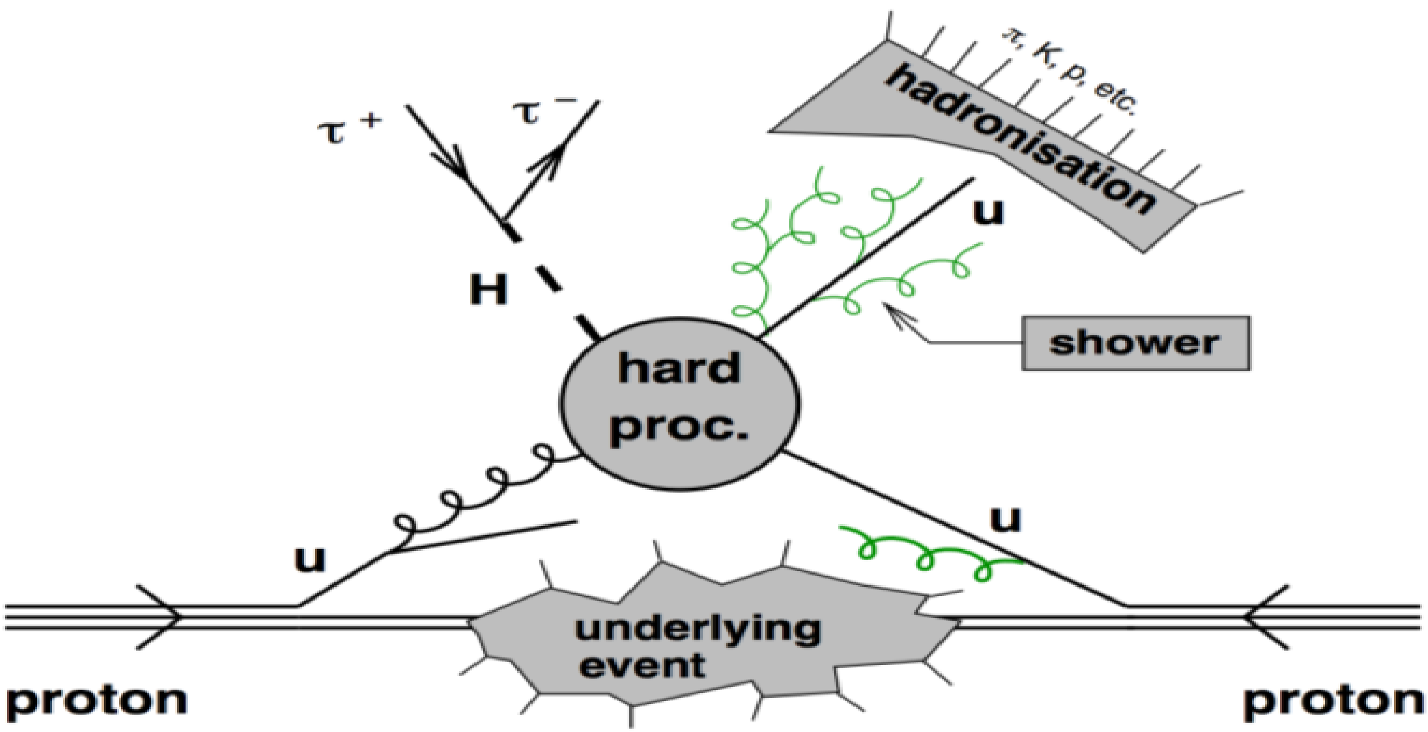
The structure of an event – 5

The structure of an event – 6

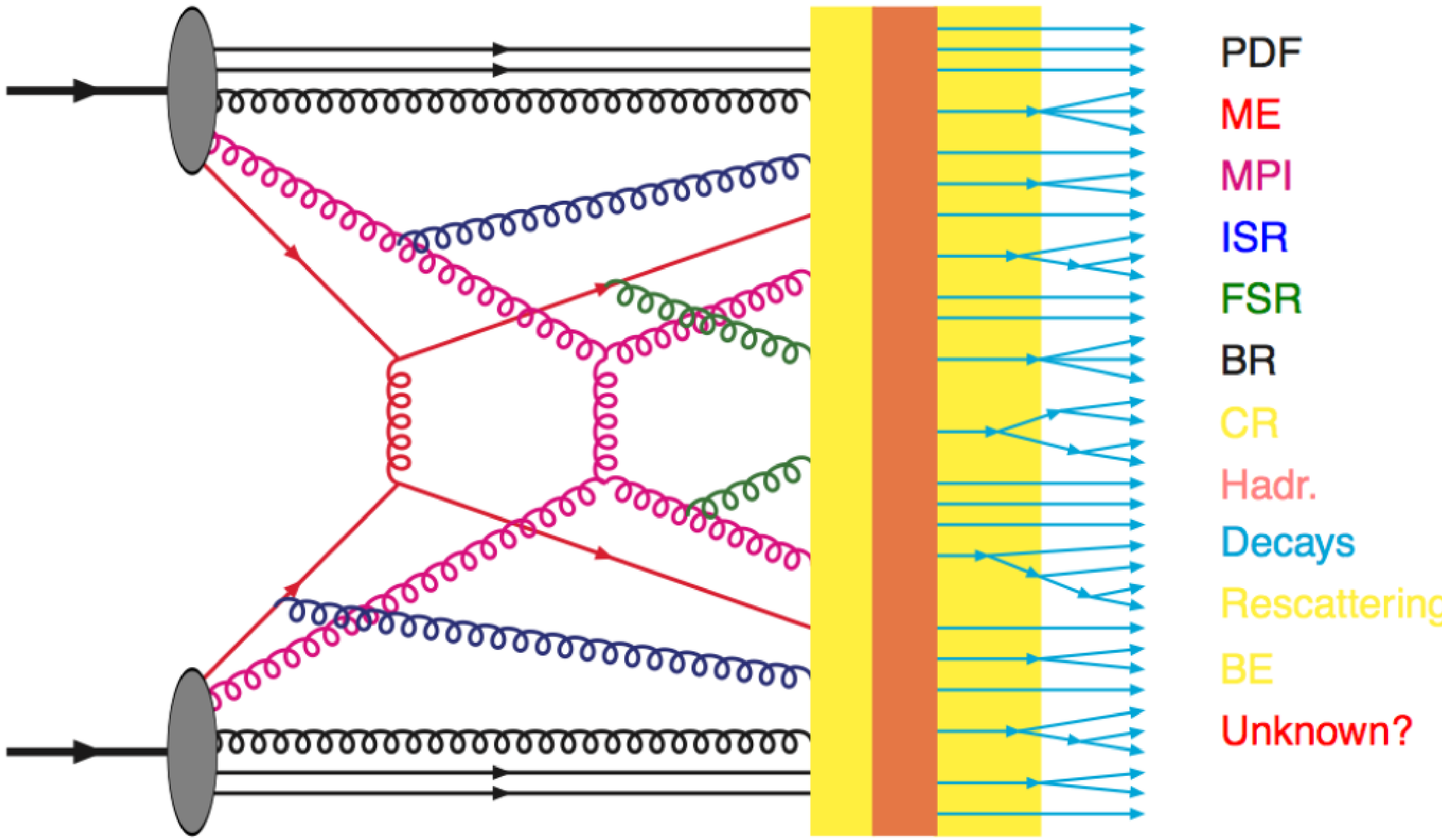
The structure of an event – 7

The structure of an event – 8

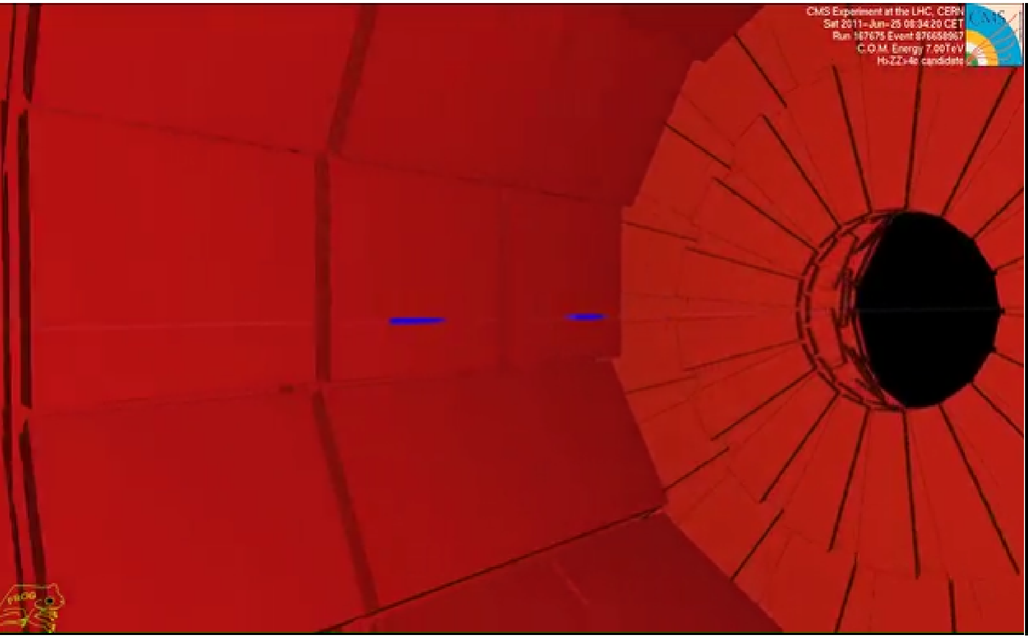
The structure of an event – 11

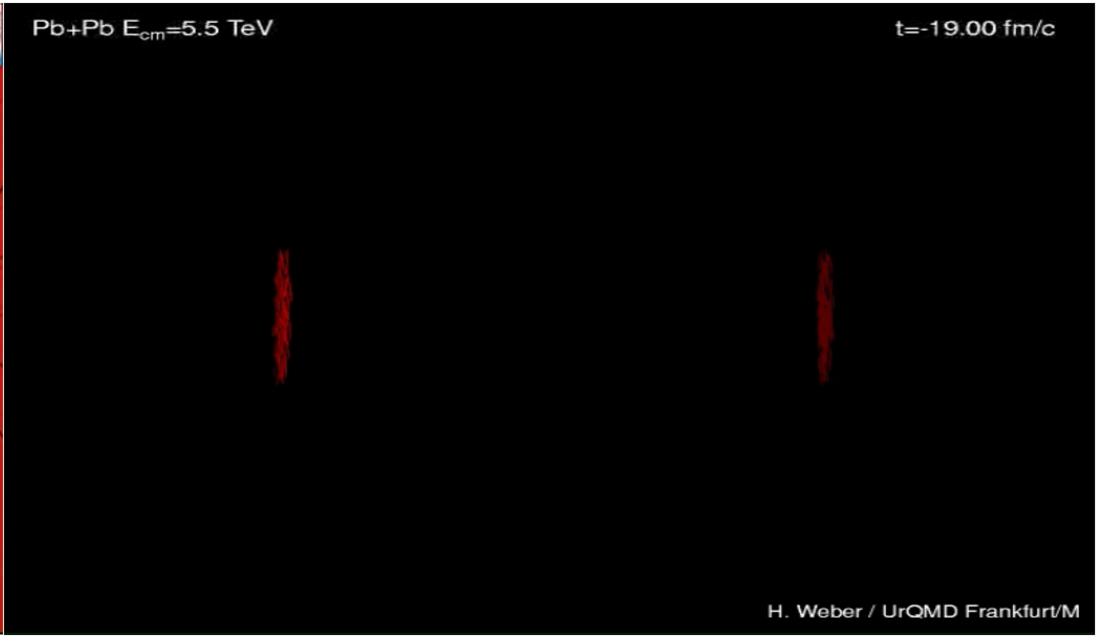


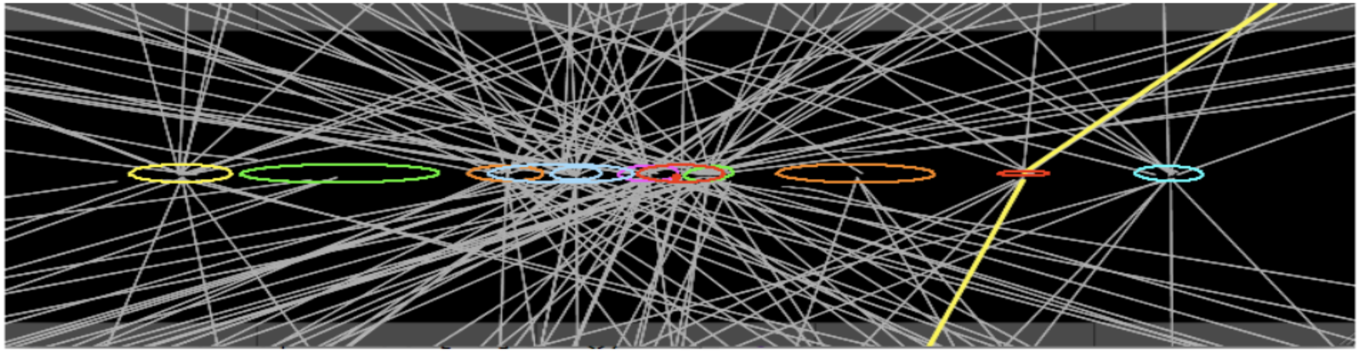
An event consists of many different physics steps, which have to be modeled by event generators.



What happened for real data?



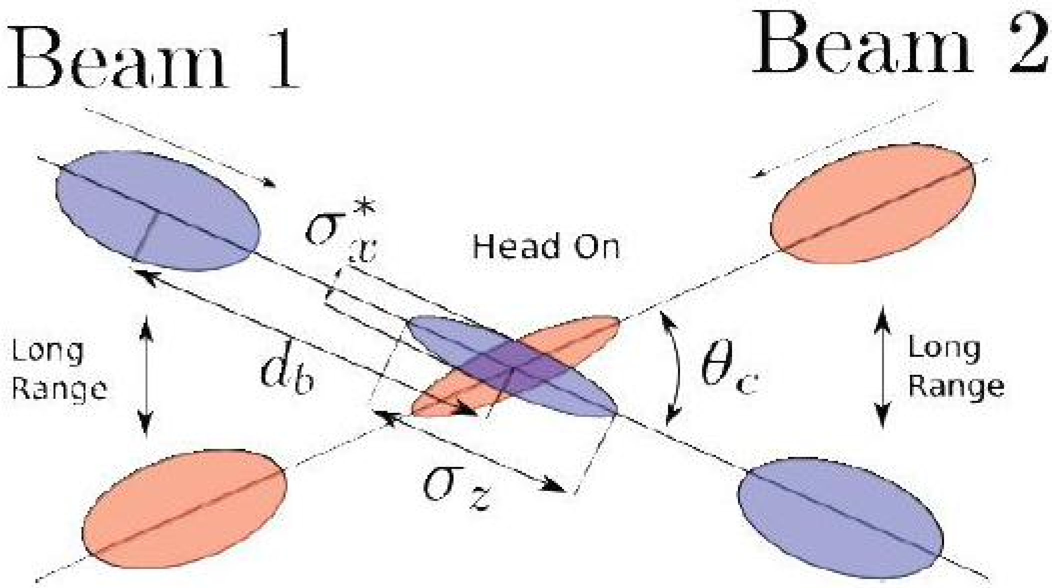


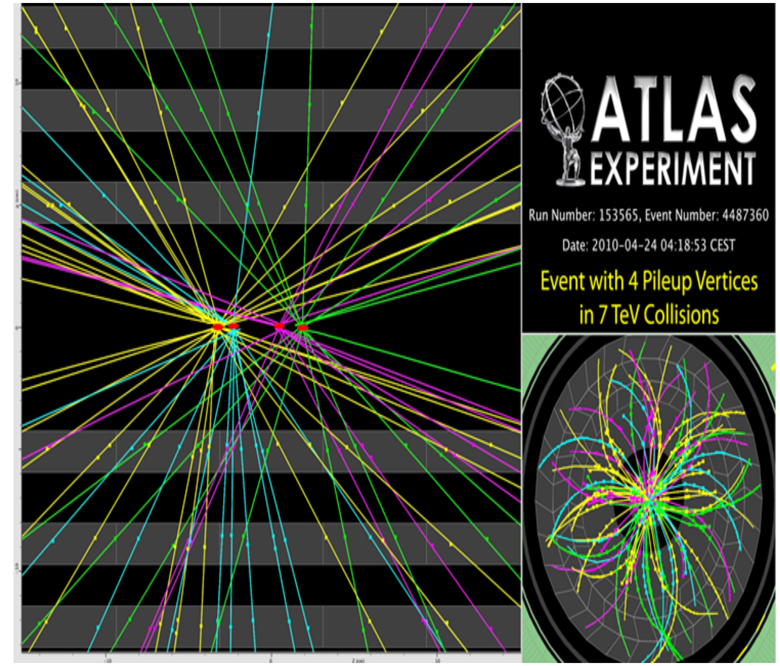


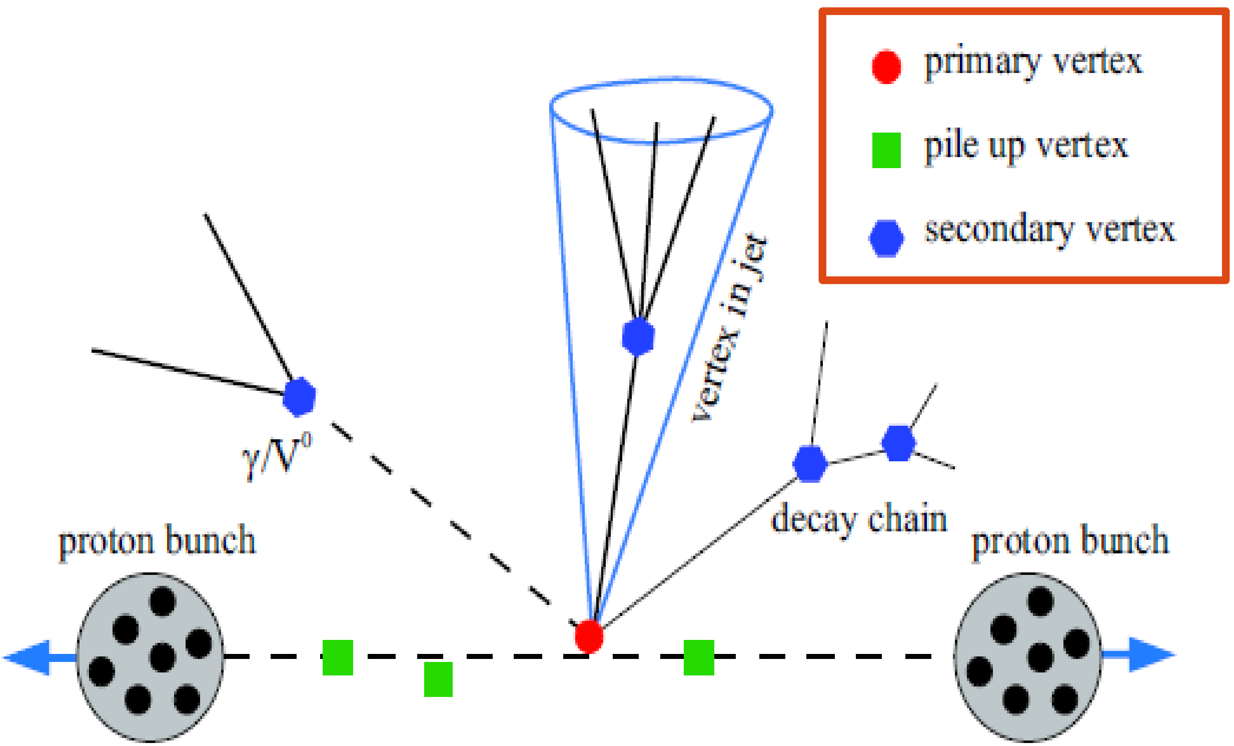
$\langle n \rangle = \overline{\mathcal{L}}\,\sigma$

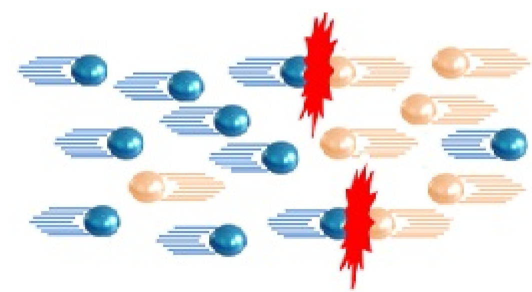
- ➔ The L parameter is machine luminosity per bunch crossing, **$L \sim n_1.n_2 / A$** and $\sigma \sim \sigma_{tot} \approx 100$ mb.
- ➔ Current LHC machine conditions ⇒ n ∼ 10−20.

Pileup introduces no new physics and keep in mind concept of bunches of hadrons leading to multiple collisions.









http://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.lhc_p_collisions

Analysis techniques

-An often faced problem is to predict the answer to a question based on different input variables
- Two different problems:

Classification
■ Predict only a binary response
  Do I need an umbrella today? Yes/No
  What is the measured data?   Signal/Background

Regression
■ Predict an exact value as an answer
● What will be the temperature tomorrow? -19 °C, 7 °C, 38 °C, ...
This session will only cover the classification problem

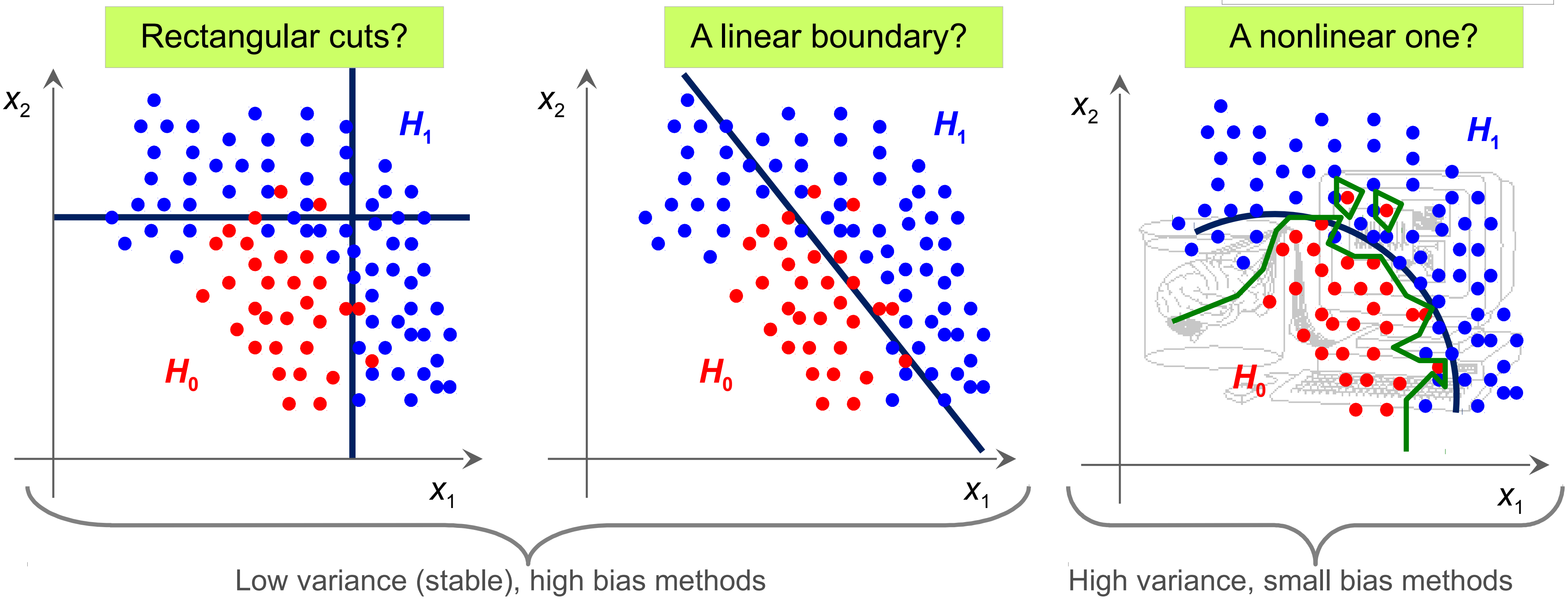
Event Classification

Optimal analysis uses information from all (or in any case many) of the measured quantities → Multivariate Analysis (MVA)

Each event yields a collection of numbers $\vec{x} = (x_1, \ldots, x_n)$

x_1 = number of muons, $x2 = pt$ of jet, ...

- Suppose data sample with two types of events: H_0, $H1$
  - We have found discriminating input variables $x1$, $x2$, …
  - What decision boundary best separates the two classes??



- How can we decide this in an optimal way ? → Let the machine learn it !

Event Classification in High-Energy Physics (HEP)

Allows to combine several discriminating variables into one final discriminator $R^d \rightarrow R$
Better separation than one variable alone Correlations become visible

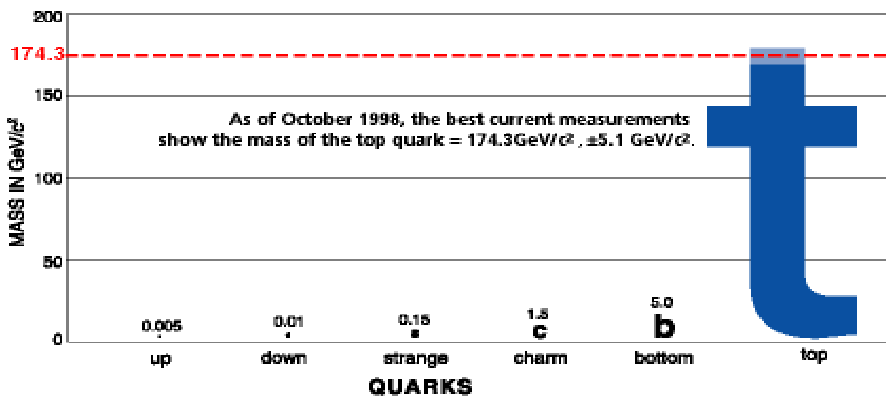
- Most HEP analyses require discrimination of signal from background:
  - Event level (Higgs searches, …)
  - Cone level (Tau-vs-jet reconstruction, …)
  - Track level (particle identification, …)
  - Lifetime and flavour tagging (*b*-tagging, …)
  - etc.
- The multivariate input information used for this has various sources
  - Kinematic variables (masses, momenta, decay angles, …)
  - Event properties (jet/lepton multiplicity, sum of charges, …)
  - Event shape (sphericity, Fox-Wolfram moments, …)
  - Detector response (silicon hits, dE/dx, Cherenkov angle, shower profiles, muon hits, …)
  - etc.

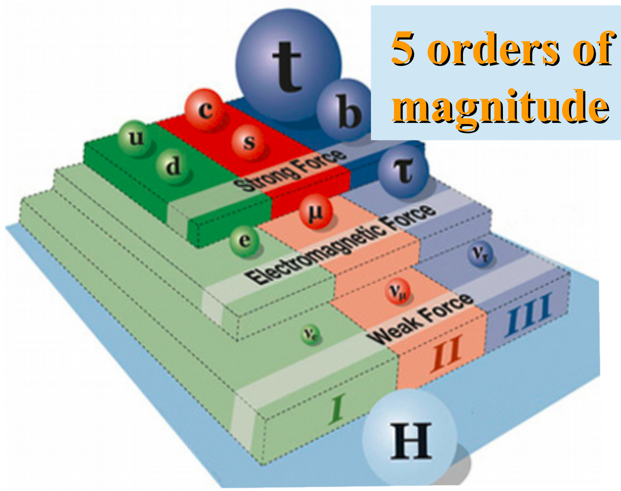
Available methods:

-Boosted Decision Trees
-Neural Networks
-Likelihood Functions
...

Top quark physics

Top quark physics Motivation





5 orders of magnitude

$$\tau_t = \frac{1}{\Gamma_t} \sim 0.5\times 10^{-24} s < \frac{1}{\Lambda_{QCD}} < \frac{m_t}{\Lambda_{QCD}^2} \sim 3\times 10^{-21} s << \tau_b \sim 10^{-12} s$$

$$\tau_t < \tau(hadronization) < \tau(spin - decorrelation) << \tau_b$$

No hadronic bound states

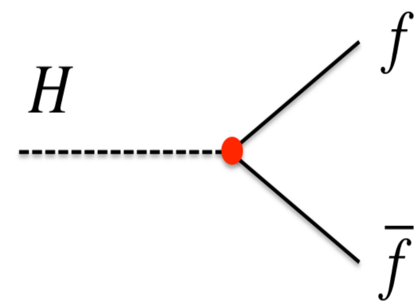
Spin effects propagate to decay products.

→ **bare quark properties accessible via decay products**

Motivations for top quark physics

❑ Special role in the EW sector and in QCD

- Yukawa coupling close to 1.0
- Test of QCD
- Precision on (m_t,m_W) constrains m_H
- Window on properties of bare quark



$$y_t = \frac{\sqrt{2}m_t}{v} \cong 1$$

❑ Top quark as a Window to Physics Beyond the Standard Model

- New physics might be preferentially coupled to top
- Searches for new (heavy) particles flavor/mass dependent couplings
- New particles can produce / decay to tops

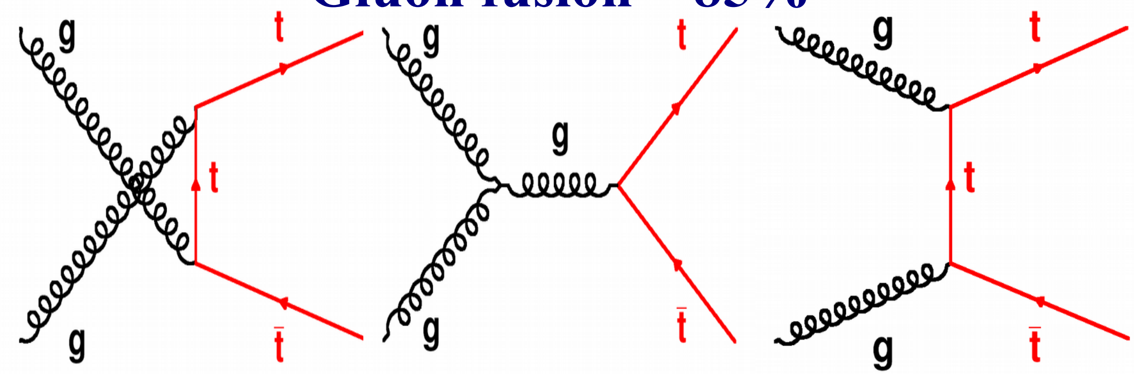
❑ Special interest even if it is just a «standard» quark

➔ **Main backgrounds for many physics searches**

➔ **A tool to understand/calibrate the detector**

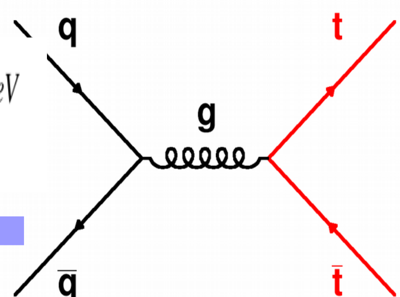
Top quark physics ...

Gluon fusion ~ 85%



$\sigma(t\bar{t}) \sim 830\ pb$ @ 13 TeV $\quad \sigma_{t\bar{t}}^{13TeV} \sim 3\times\sigma_{t\bar{t}}^{8TeV}$

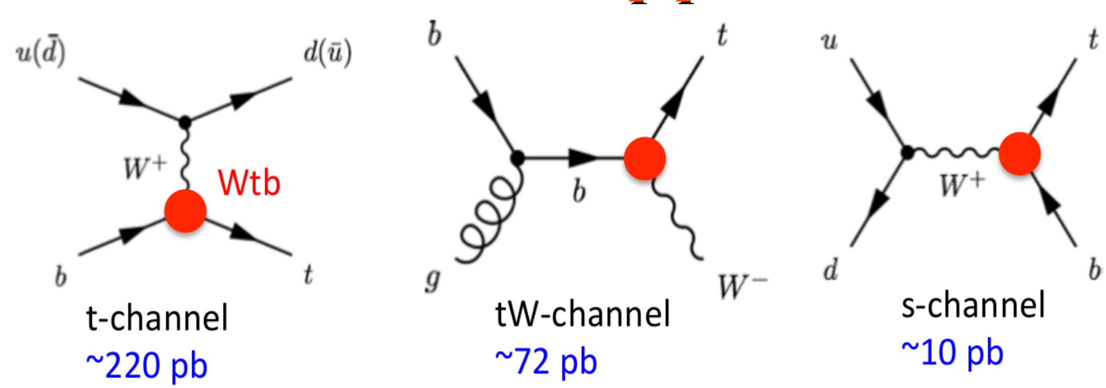
Quark scattering ~ 10%



- At hadron colliders, top quarks are mainly produced as a pair via the strong interaction.
- There are three different sub-processes characterizing the production of the $t\bar{t}$ pairs.
- The LHC will be a Top quark factory, one top pair produced per second

- Top quarks are also produced singly through the electroweak interaction.
- The electroweak production of single top quarks is sensitive to the CKM matrix element $|V_{tb}|$.

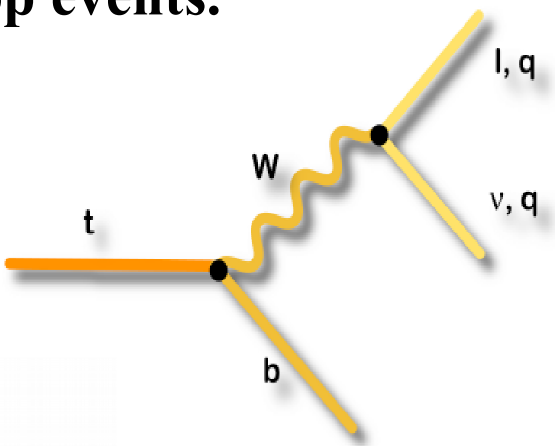
Electroweak top production

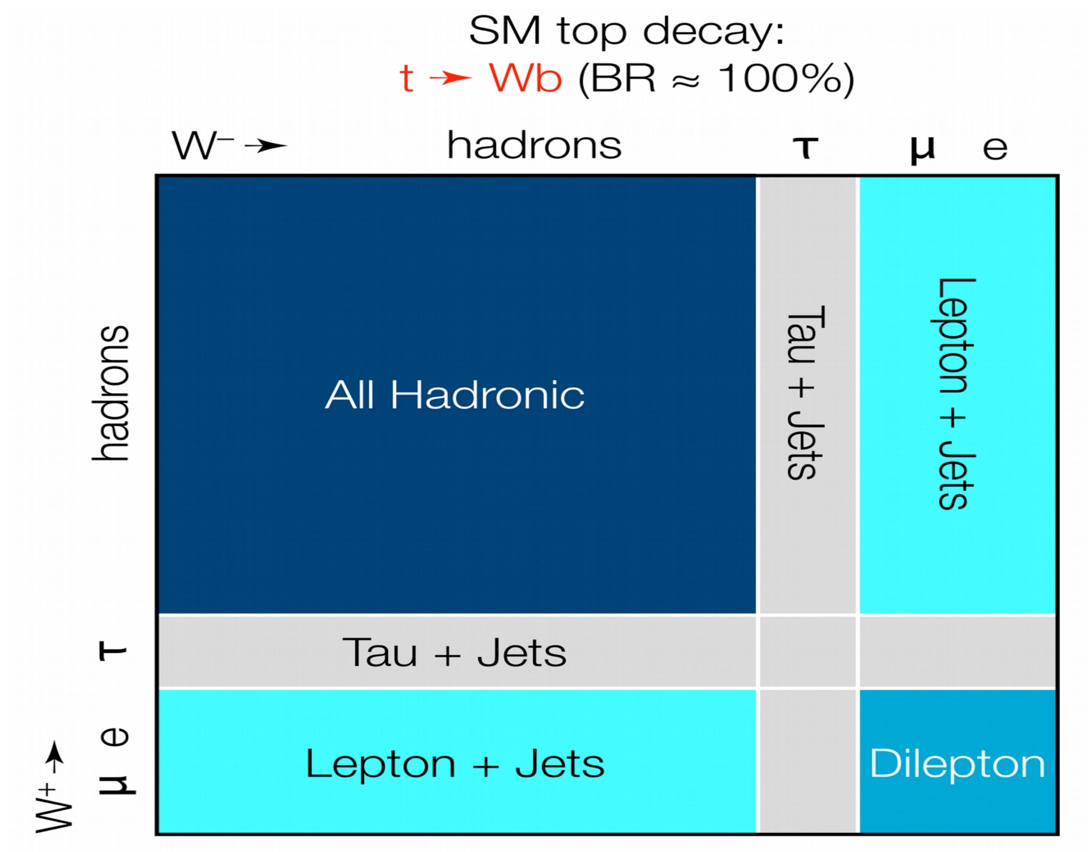


$$\sigma_{t-chan}^{13TeV} \sim 2.5\times\sigma_{t-chan}^{8TeV}$$

Keep one eye in data, one eye in Monte carlo processes

- **Top quark decays almost exclusively into a b-quark and a W boson.**
  - **W boson decays into hadrons ~ 67% and into leptons ~ 33%.**
    - **this allows a simple classification of top - antitop events.**





Top pair classification

Top quark pair signatures by W boson decays:

Dilepton: interesting @ LHC

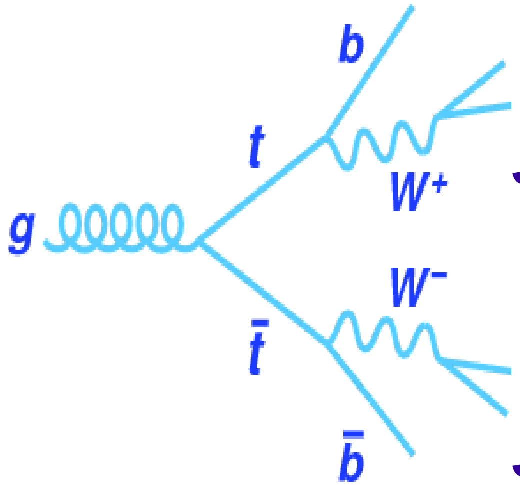
- 2 leptons, 2 neutrino, 2 b-jets
- easy to identify
- Small rate, small backgrounds
- **Main background:** Drell-Yan, tW
- very clean, neutrino ambiguities

Lepton + Jets: golden mode

- Large rate and under control backgrounds
- only one neutrino
- 24 possible jet combinations
- **Main background:** W+jets, QCD

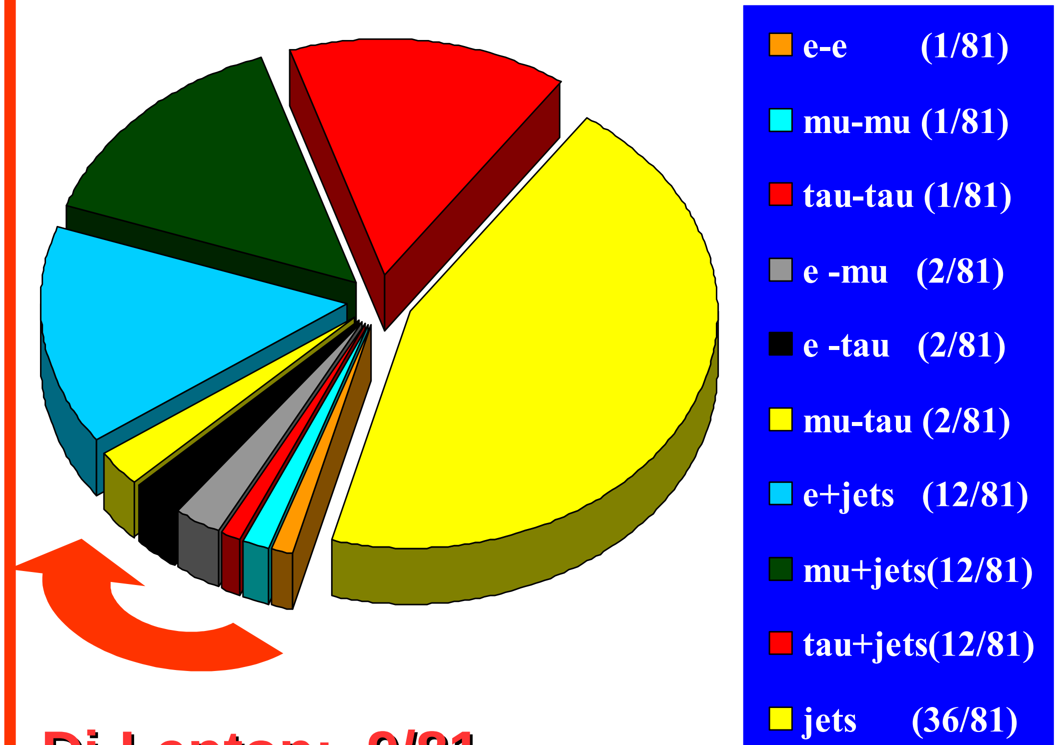
Full-hadronic (all jets): 6 jets

- Decay products are detectable
- Large rate, large QCD background
- Define strategies to enrich and refine clean samples



Jet or Lepton?

Jet or Lepton?

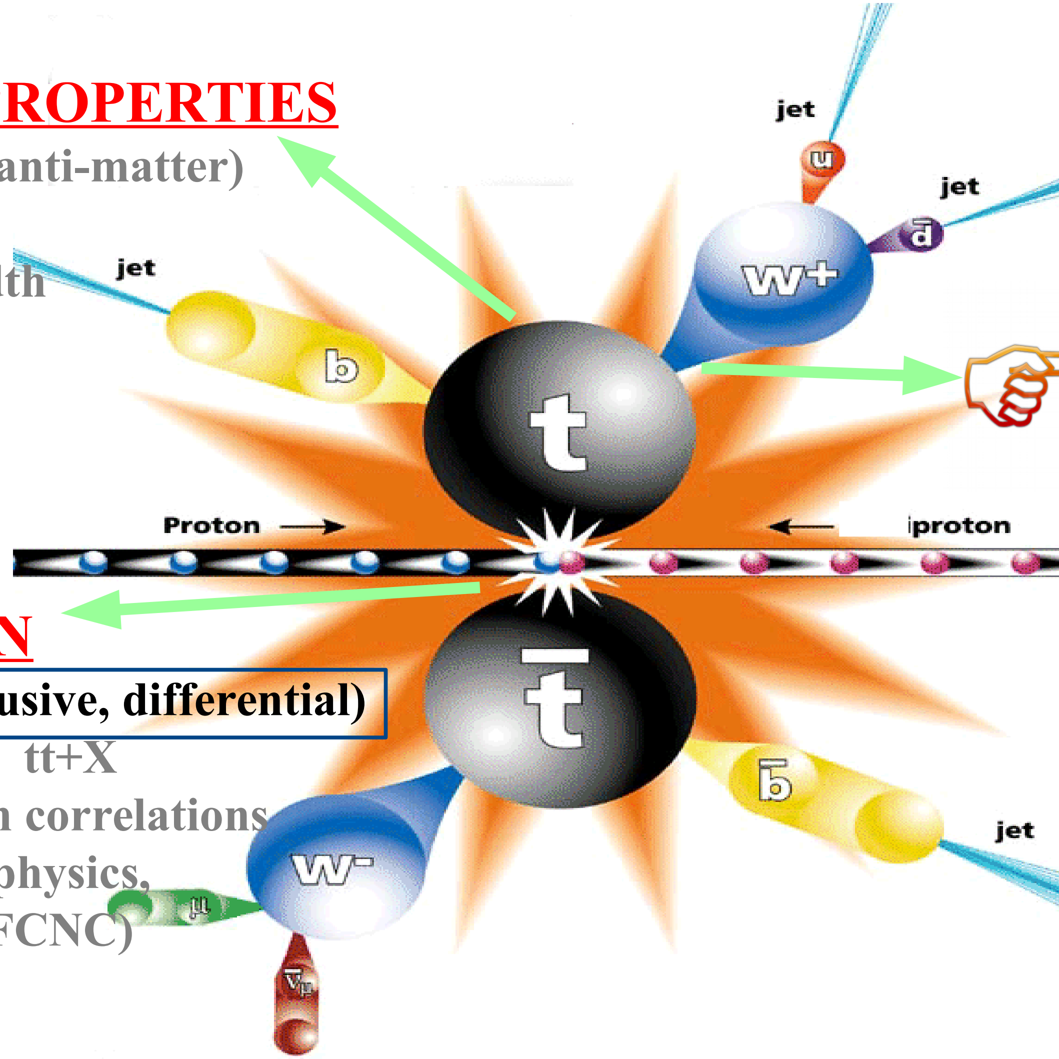


Di-Lepton: 9/81

Top physics Menu

INTRINSIC PROPERTIES

Mass (matter vs. anti-matter)
Charge, spin
Life time and width



DECAY

W helicity
Couplings
Branching ratios
CKM matrix elements
New particles
$B(t \to Wb)$
Rare decays (FCNC)

PRODUCTION

Cross section(inclusive, differential)
QCD parameters, tt+X
Asymmetries, spin correlations
Resonances, new physics,
Flavour physics (FCNC)

only one analysis will be shown in rest of this talk.

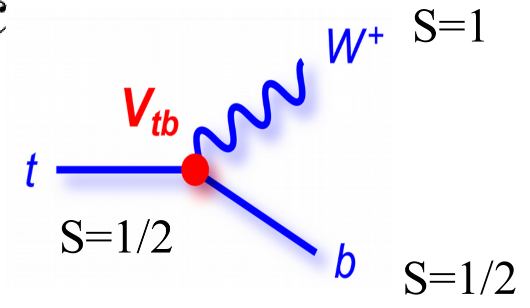
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
http://www-cdf.fnal.gov/physics/new/top/top.html
http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

W boson helicity measurement

W Boson helicity(motivation)

- The **tWb** vertex is written as V-A structure within the SM.

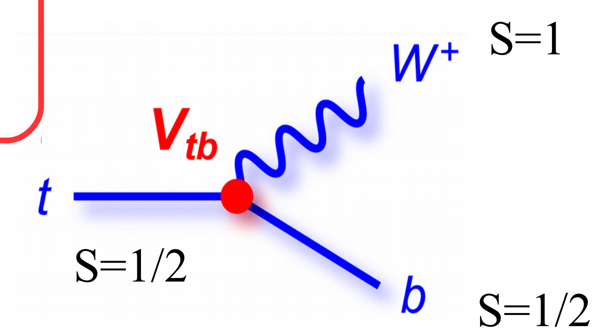
$$\mathcal{L}_{tWb} = \frac{-ig_W}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}P_L t W_{\mu}^{-} + h.c$$



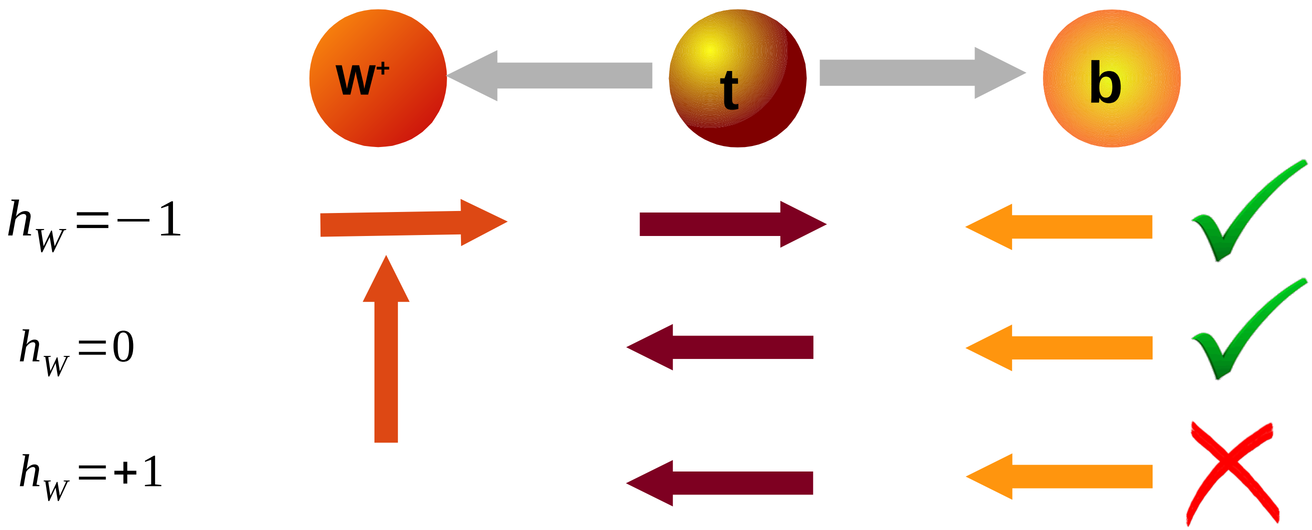
- The W boson helicity is sensitive to non-SM **tWb** couplings.

The W boson is spin 1 ➠ it can be produced with a left-handed(F_L), longitudinal(F_0), or right-handed(F_R) helicity,

$$F_{0/L/R} = \frac{\Gamma_{0/L/R}(t \to Wb)}{\Gamma_{total}}$$



SM prediction[LO, $m_b = 0$] :



$$F_L = \frac{2m_W^2}{2m_W^2 + m_t^2}$$

$$F_0 = \frac{m_t^2}{2m_W^2 + m_t^2}$$

$$F_R = 0$$

☞ Experimentally, the helicity fractions can be deduced from the normalized differential decay rate.

Theory motivation (W Boson helicity)

- The normalized differential decay rate for top quarks in terms of the W boson states:

$$\frac{1}{\Gamma}\frac{d\Gamma}{dcos(\theta^*)} = \sin(\theta^*)^2 F_0 + \frac{3}{8}(1-\cos(\theta^*))^2 F_L + \frac{3}{8}(1+\cos(\theta^*))^2 F_R$$

Longitudinal — Left-Handed — Right-Handed

- SM prediction for helicity fractions [LO, $m_b = 0$] :

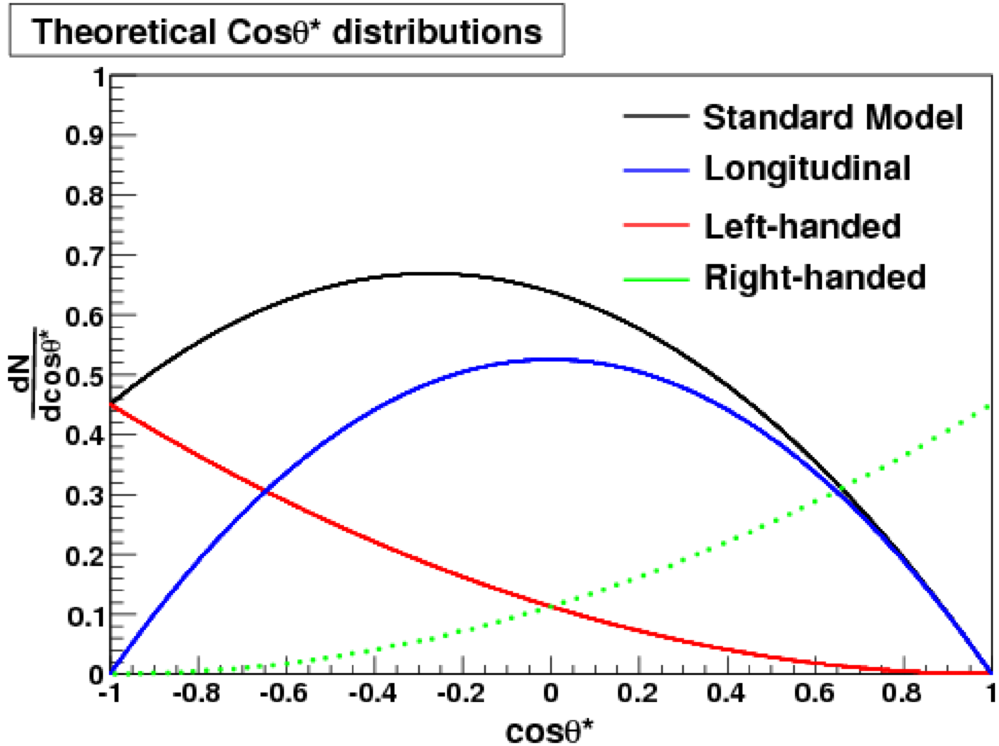
$$F_0 = \frac{m_t^2}{2m_W^2 + m_t^2} \qquad F_L = \frac{2m_W^2}{2m_W^2 + m_t^2} \qquad F_R = 0$$

- The W boson helicity fractions at the NNLO with QCD and electroweak corrections in the limit of non-zero mass b-quark slightly change the right-handed fraction [**Phys. Rev. D 81 (2010) 111503**].

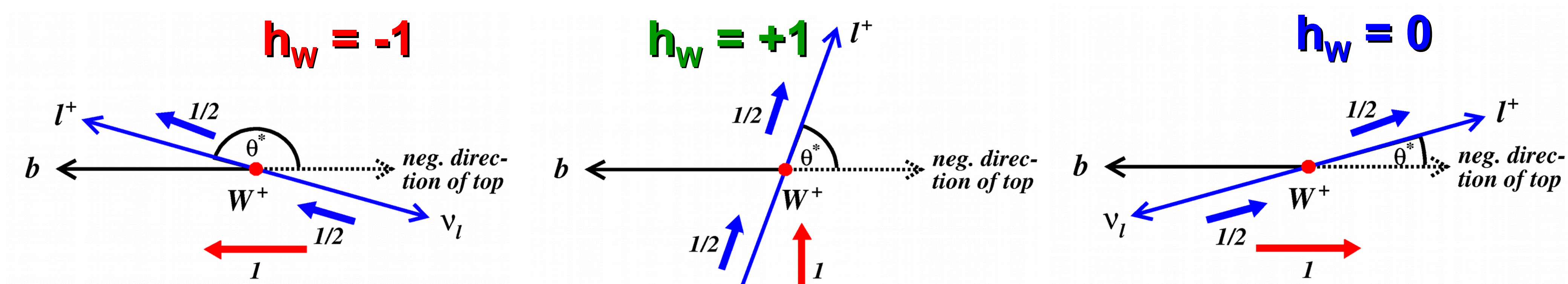
$F_L = 0.3110 \pm 0.0050$, $F_0 = 0.6870 \pm 0.0050$, $F_R = 0.0017 \pm 0.0001$

Observables used to measure the W polarization:

- The transverse spectrum of the leptons
- The matrix element method
- The lepton-b-quark invariant mass
- The helicity angle **θ***



cos* is the angle between the 3-momentum of the charged lepton in the W boson rest frame and the 3-momentum of the W boson in the top quark rest frame.



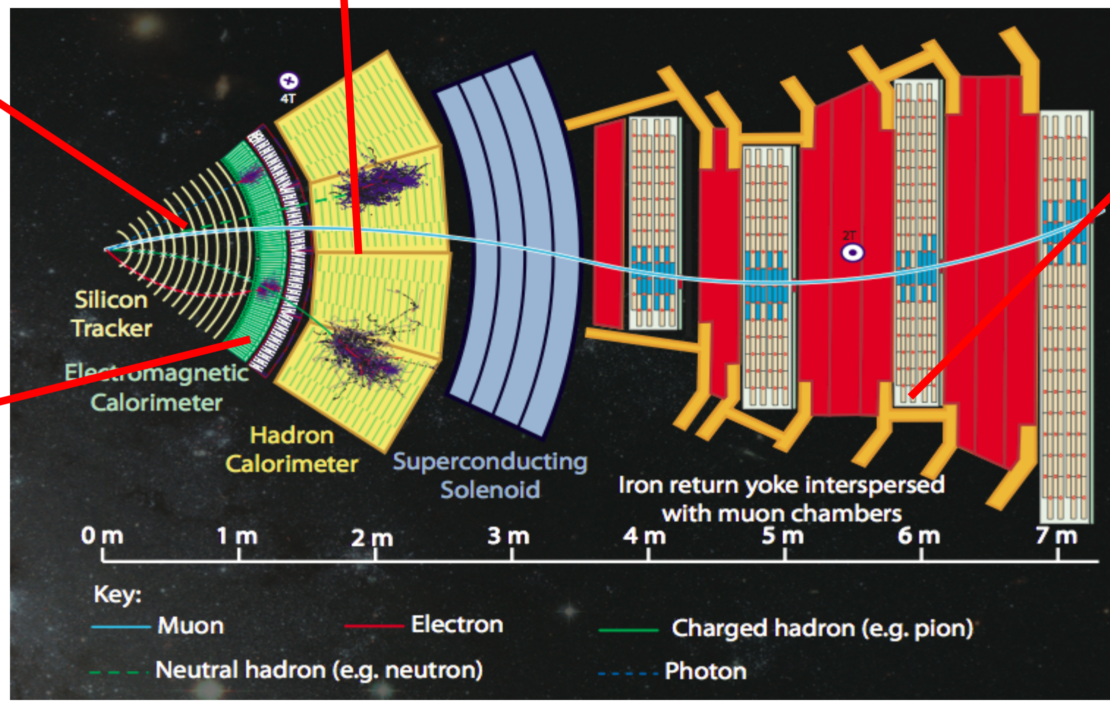
$$\frac{dN}{d\cos\theta^*} \propto \frac{3}{8}(1-\cos\theta^*)^2 \qquad \frac{dN}{d\cos\theta^*} \propto \frac{3}{8}(1+\cos\theta^*)^2 \qquad \frac{dN}{d\cos\theta^*} \propto \frac{3}{4}(1-\cos^2\theta^*)$$

Experimental apparatus ...

Inner detector
measurement of charged particle momentum,vertex reconstruction

Hadronic Calorimeter
Enegy measurement of hadrons

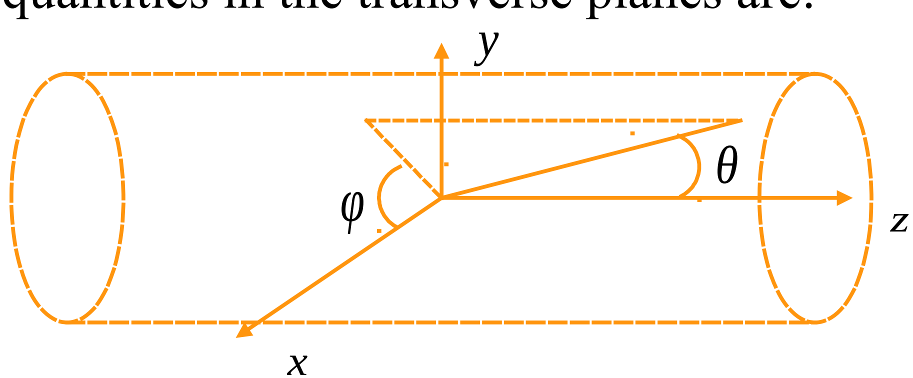
Muon spectrometer
Precise measurement of muon momentum, triggering

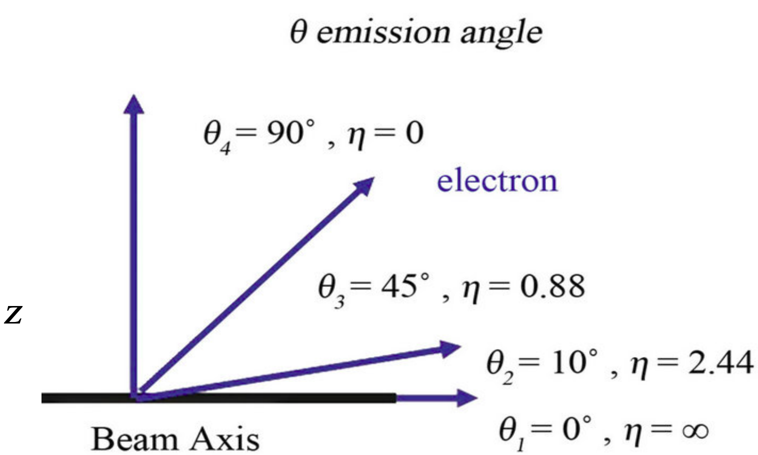


Electromagnetic Calorimeter
Energy measurement of electrons and photons

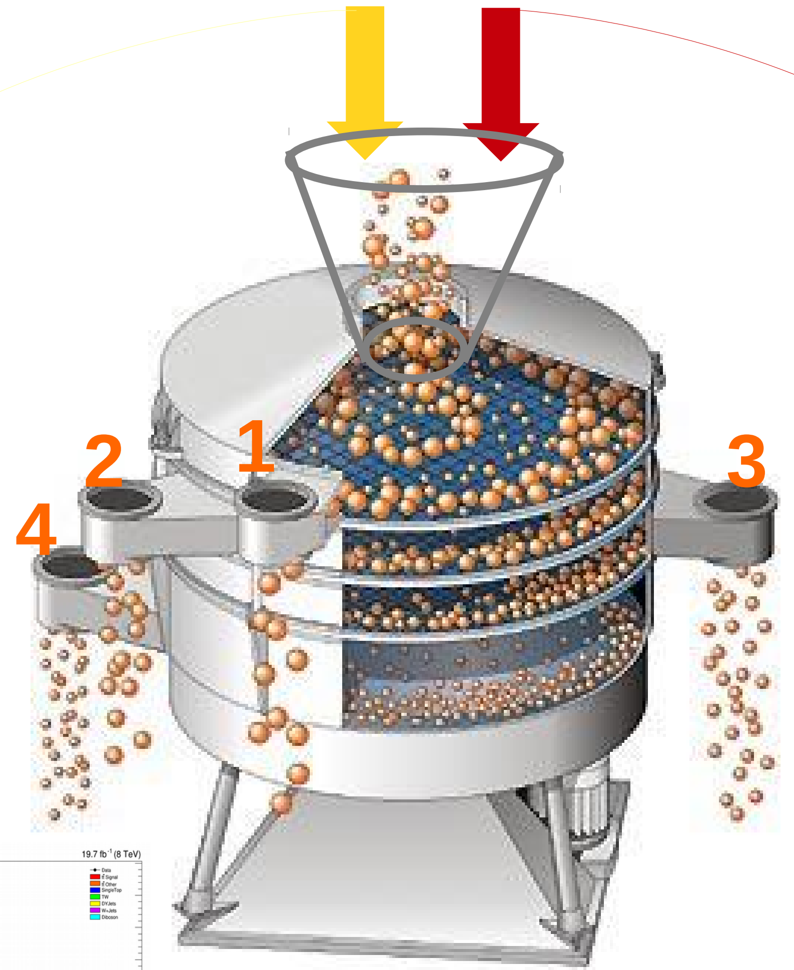
- The kinematic quantities in the transverse planes are:

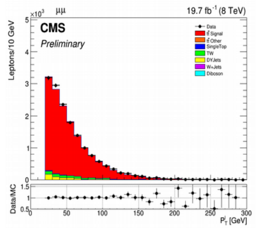
- p_T
- E_T
- $\eta = -\ln\left(\tan\frac{\theta}{2}\right)$





What are inputs of our analysis?





Data

Reconstruction

Detector Passage

Particle decays

Real Collision

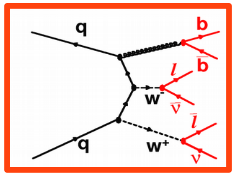
Monte carlo

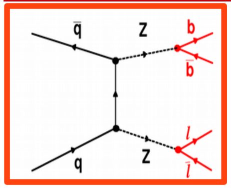
Reconstruction

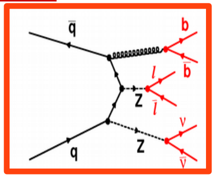
Detector simulation

Particle level

Genaration







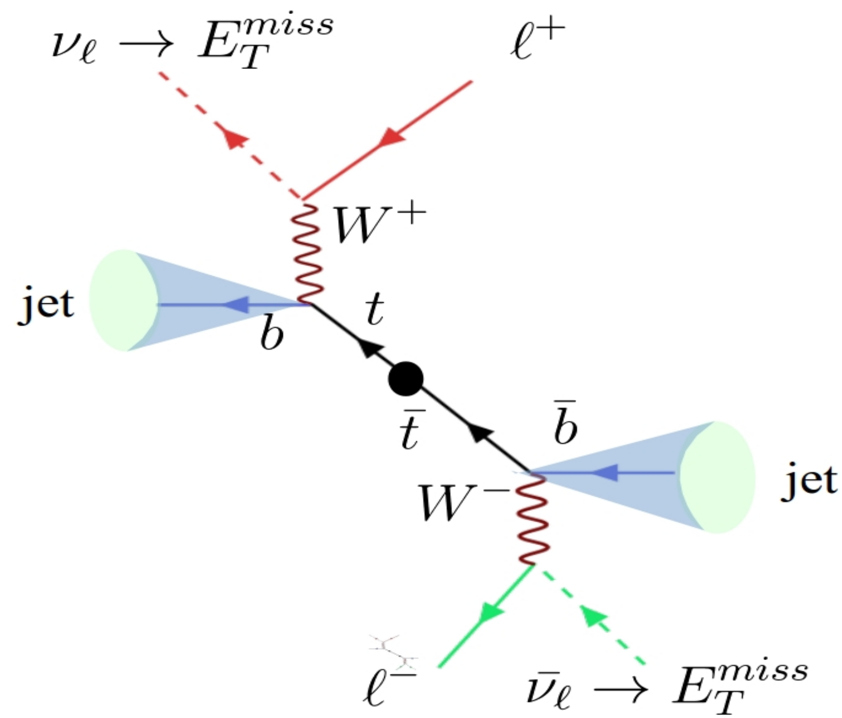
Signal definition

- Studying the di-muon channel, the following final states are considered as signal:

$$pp \to t\bar{t} \to W^+W^-b\bar{b} \to b\bar{b}\mu^+\mu^-\nu_\mu\bar{\nu}_\mu \;1.2\%$$
$$\to b\bar{b}\tau^-\tau^+\nu_\tau\bar{\nu}_\tau \to b\bar{b}\mu^+\mu^- + 6\,neutrinos$$
$$\to b\bar{b}\mu^\mp\tau^\pm\nu_\tau\bar{\nu}_\mu \to b\bar{b}\mu^+\mu^- + 4\,neutrinos.$$

- The di-muon channel is characterized by:

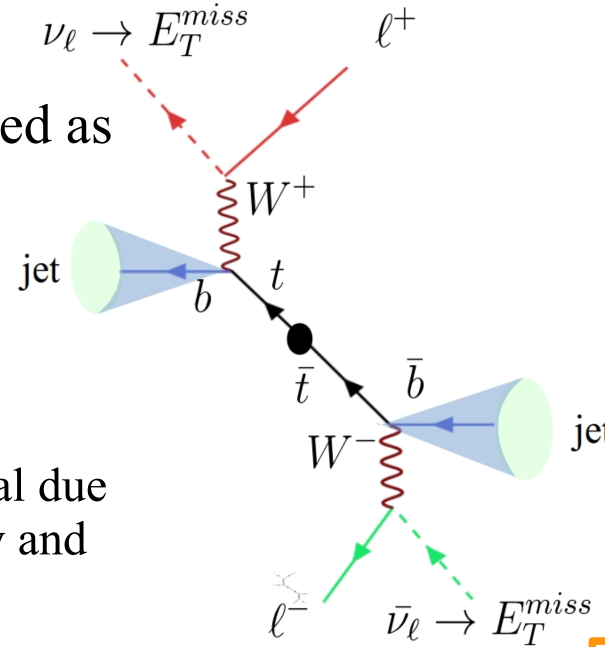
- Two oppositely charged and isolated leptons
- Large missing energy
- Presence of two energetic b-jets, possibly with additional light jets from ISR and FSR



Backgrounds

- In general, background processes can be treated as signal events through two different categories:

- **Physics backgrounds**
- **Instrumental backgrounds**
  - The instrumental backgrounds can mimic the signal due to instrumental effects such as fake missing energy and jet misidentification.



Generation

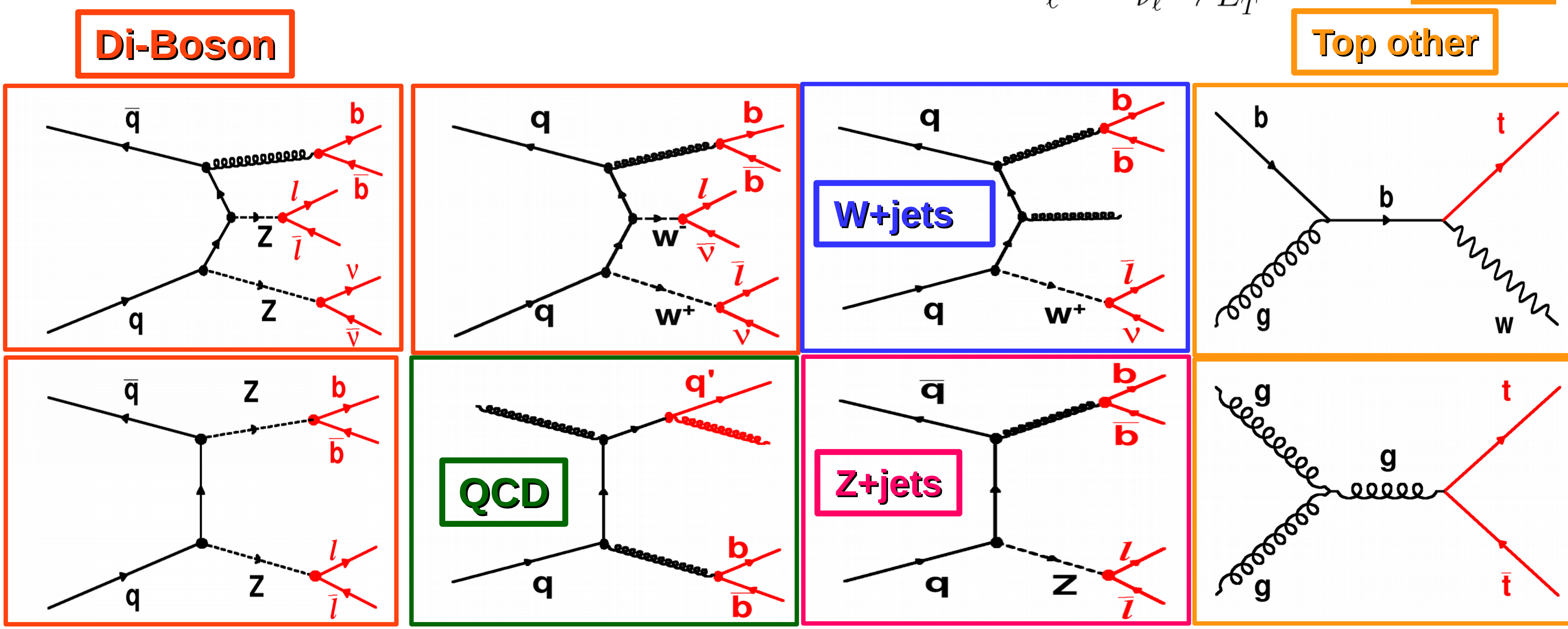
MC Truth

Simulation

Hits in the detector

Reconstruction

Analysis



Data set and triggers

- The measurement in this analysis is based on the data recorded at a center of mass energy of 8 TeV during 2012 corresponding to an integrated luminosity of 19.7 fb^{-1}.

- **Re-reco datasets: Double Muon**

- **Processed with CMSSW 5.3.X GlobalTag: GT STAR53 V7A**

- **The golden JSON file is used to read the full 8 TeV dataset.**

DataSet	DataSet Name	$L_{int}(pb^{-1})$
Run2012A_$\mu\mu$	/DoubleMuon/Run2012A-13Jul2012-v1/AOD	810
Run2012A_$\mu\mu$_EcalRecovery	/DoubleMuon/Run2012A-recover-06Aug2012-v1/AOD	82
Run2012B_$\mu\mu$	/DoubleMuon/Run2012B-13Jul2012-v1/AOD	4404
Run2012C_$\mu\mu$	/DoubleMuon/Run2012C-13Jul2012-v1/AOD	6941
Run2012D_$\mu\mu$	/DoubleMuon/Run2012D-13Jul2012-v1/AOD	7273

Double Muon triggers are applied on the MC a well as the data.

Sample	Channel	Trigger Path
Data	DiMuon	HLT_Mu17_Mu8_v* OR
	DiMuon	HLT_Mu17_TkMu8_v*
MC	DiMuon	HLT_Mu17_Mu8_v17 OR
	DiMuon	HLT_Mu17_TkMu8_v10

- **Golden JSON File:** Cert-190456-208686-8TeV-22Jan2013ReReco-Collisions12-JSON.txt

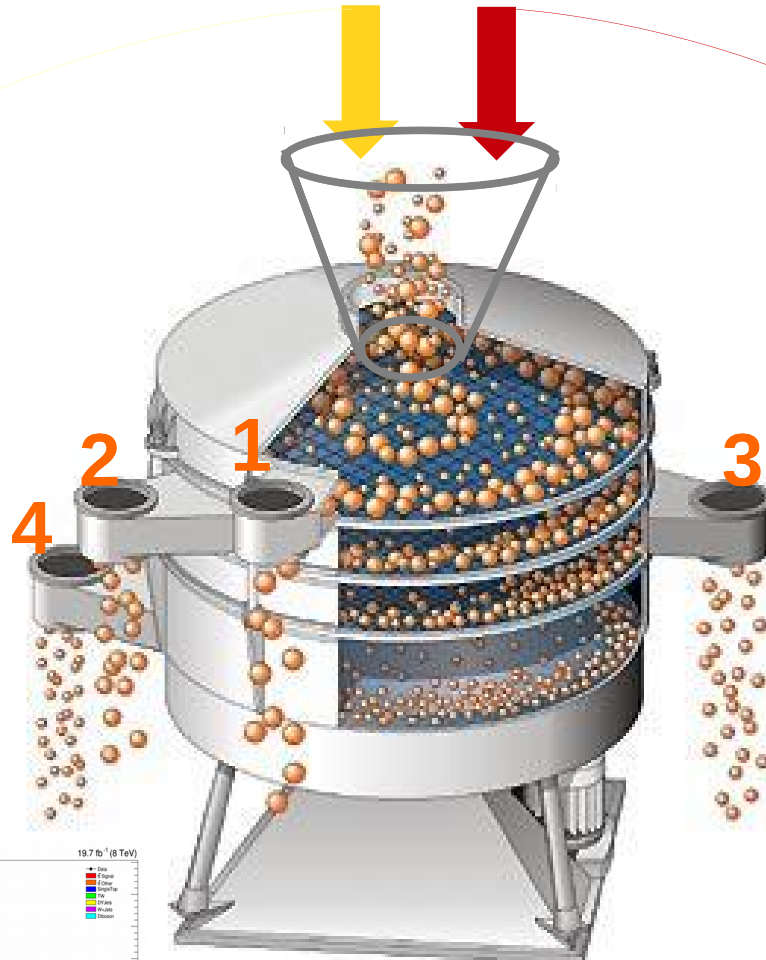
Simulation samples

- All generated events are passed through a detailed **GEANT4** simulation of the CMS detector.

Dataset	Dataset Name	Cross-section (pb)
$t\bar{t}$	/TTJets_FullLeptMGDecays_8TeV-madgraph-tauola/	26.5
	/TTJets_SemiLeptMGDecays_8TeV-madgraph-tauola/	111.1
	/TTJets_HadronicMGDecays_8TeV-madgraph/	115.3
Single t	/T_t-channel_TuneZ2star_8TeV-powheg-tauola/	59.5
	/Tbar_t-channel_TuneZ2star_8TeV-powheg-tauola/	32.1
	/T_s-channel_TuneZ2star_8TeV-powheg-tauola/	4.5
	/Tbar_s-channel_TuneZ2star_8TeV-powheg-tauola/	2.1
tW	/T_tW-channel-DR_TuneZ2star_8TeV-powheg-tauola/	11.2
$\bar{t}$W	/Tbar_tW-channel-DR_TuneZ2star_8TeV-powheg-tauola/	11.2
WW	/WWJetsTo2L2Nu_TuneZ2star_8TeV-madgraph-tauola/	5.8
WZ	/WZ_TuneZ2star_8TeV_pythia6_tauola/	22.4
ZZ	/ZZ_TuneZ2star_8TeV_pythia6_tauola/	9.0
W+ jets	/WJetsToLNu_TuneZ2Star_8TeV-madgraph-tarball/	37509.0
$Z/\gamma^* \to ll$	/DYJetsToLL_M-10To50filter_8TeV-madgraph/	860.5
Z/γ^*+ jets	/DYJetsToLL_M-50_TuneZ2Star_8TeV-madgraph-tarball/	3532.8

- In simulated samples, the **NLO** or **NNLO** cross sections are used to normalize the rate of processes to the integrated luminosity of the data.

Ready to sieve signal candidate events?



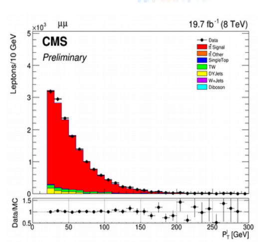
Data

Reconstruction

Detector Passage

Particle decays

Real Collision



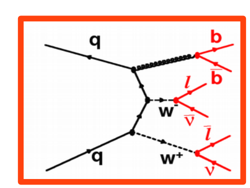
Monte carlo

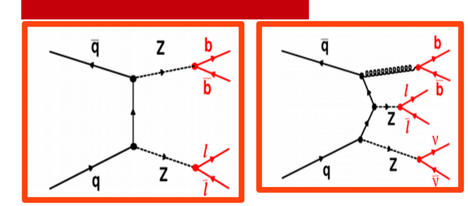
Reconstruction

Detector simulation

Particle level

Genaration



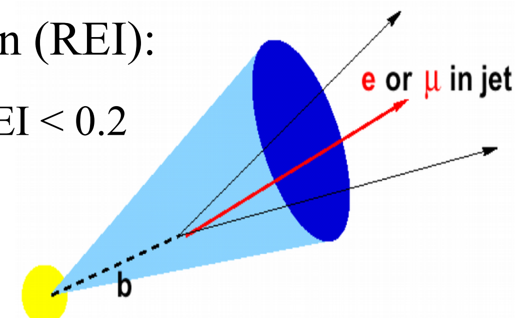


Object selection

Muon Selection

- PF(particle flow) muon reconstruction
- Candidates are GlobalMuon or TrackerMuon
- Corrected Relative Muon Isolation (REI):

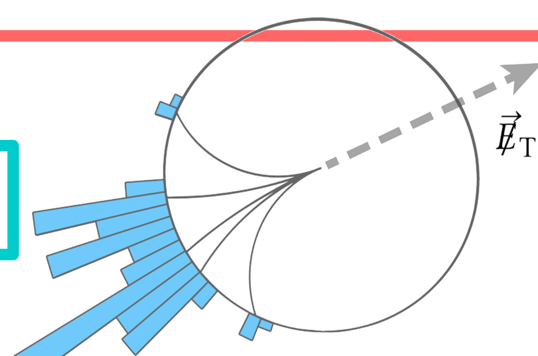
  Cone $\Delta R = 0.4$ around the muon REI < 0.2

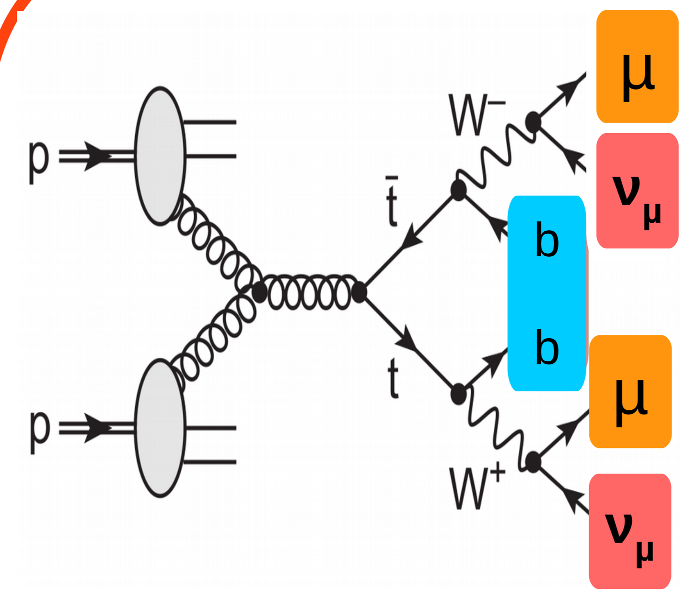


Jets clustered by the anti-k_T algorithm with $R = 0.5$

- PF jets with charge hadron subtraction(CHS)
- Passing the standard Jet ID criteria (loose)
- Jet-lepton cleaning, ΔR (jet, electron) > 0.5

MET calculated from PF objects





Muon: $p_T > 20$ GeV, $|\eta| < 2.4$

Neutrino: MET > 40 GeV

Jets: $p_T > 30$ GeV and $|\eta| < 2.4$

Event selection

Top pair Signature:

- **Two opposite charged muons**

Reduce the contribution of backgrounds with no genuine leptons

- **Invariant mass $M_{\mu\mu} > 20$ GeV and Z-veto: $M_{\mu\mu} < 76$ GeV or $M_{\mu\mu} > 106$ GeV**

Reduce low-mass resonances and Z+jets backgrounds

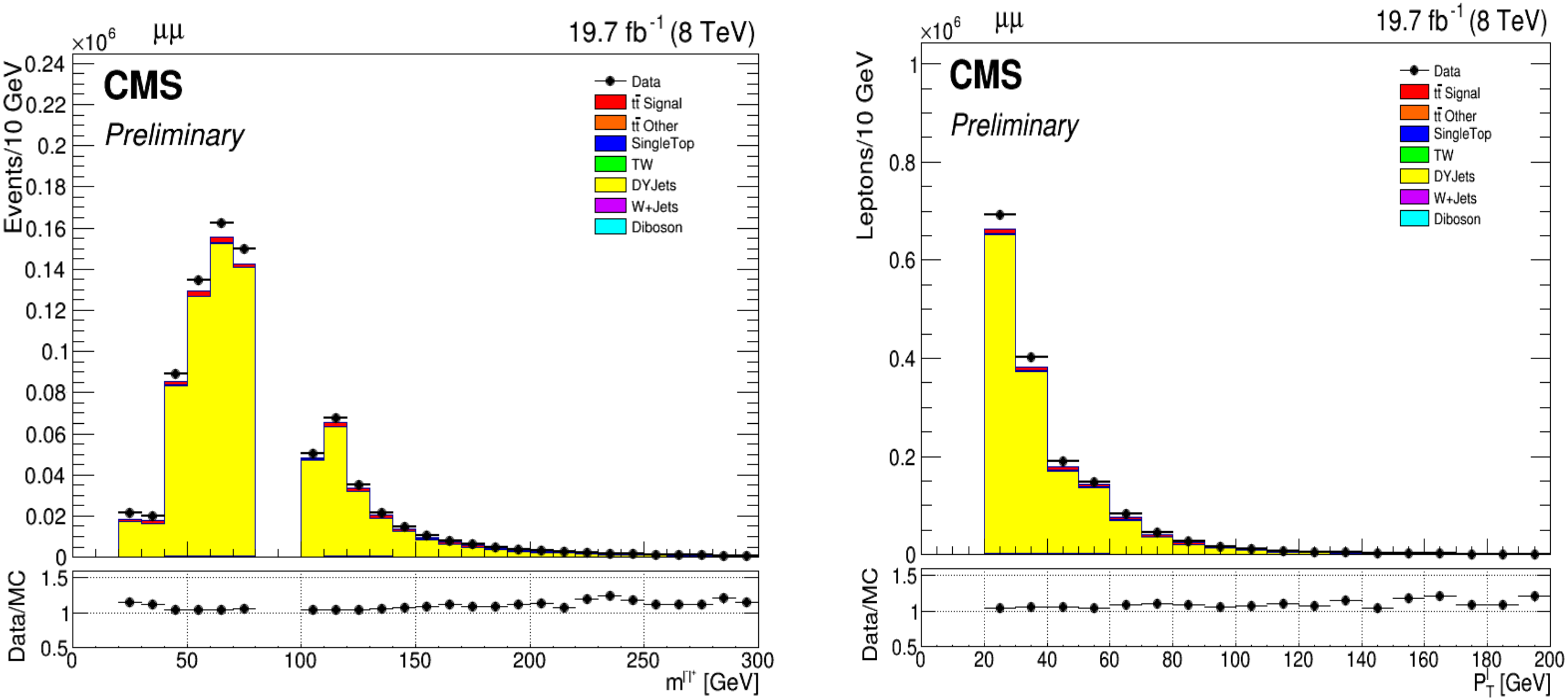
- **Require at least 2 b-tagged jets (CSV loose)**
  In the case of more than two b-tagged jets, two leading ones are selected.

Suppress QCD multi-jet , Z+jets, W+jets processes and backgrounds with no b-jet in the final state

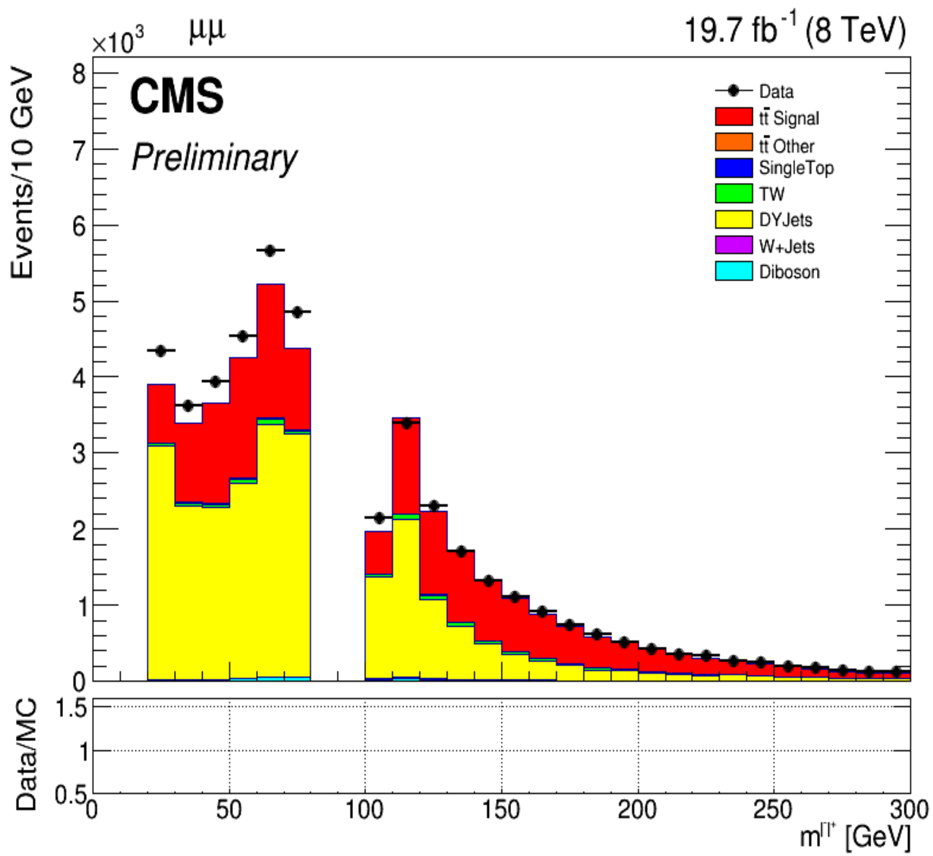
- **Missing transverse energy: MET > 40 GeV**

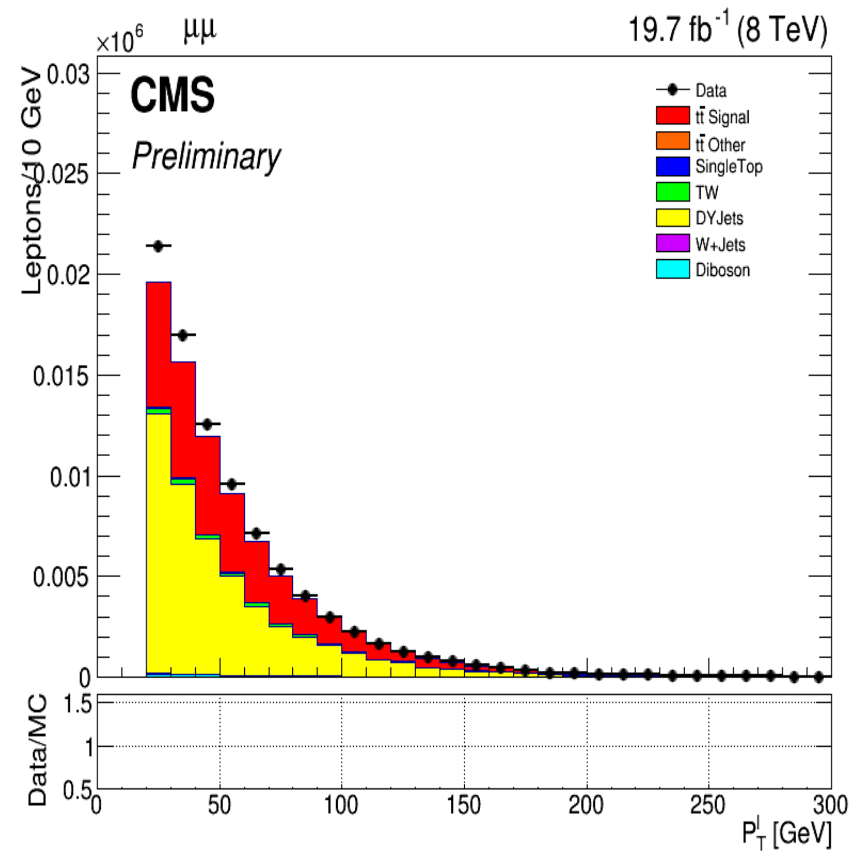
Filter out the large fraction of Z+jets and QCD events

After two lepton and z veto mass cut

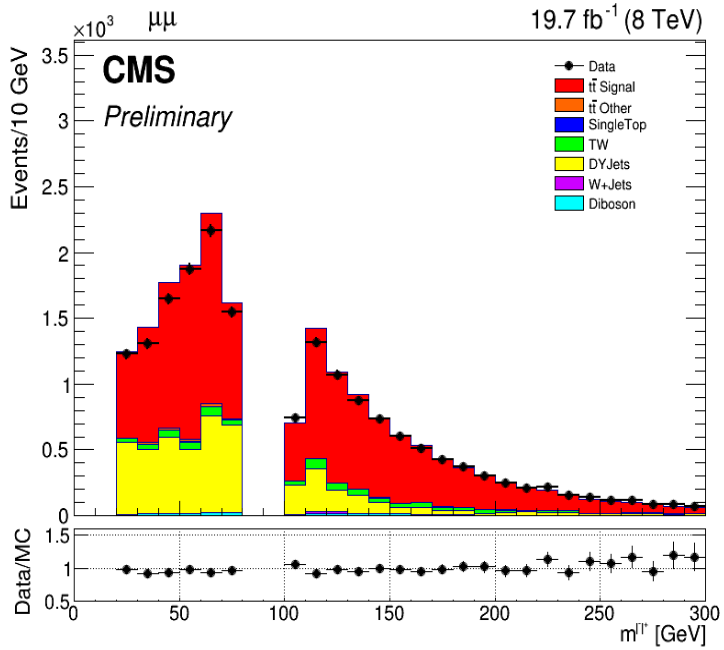


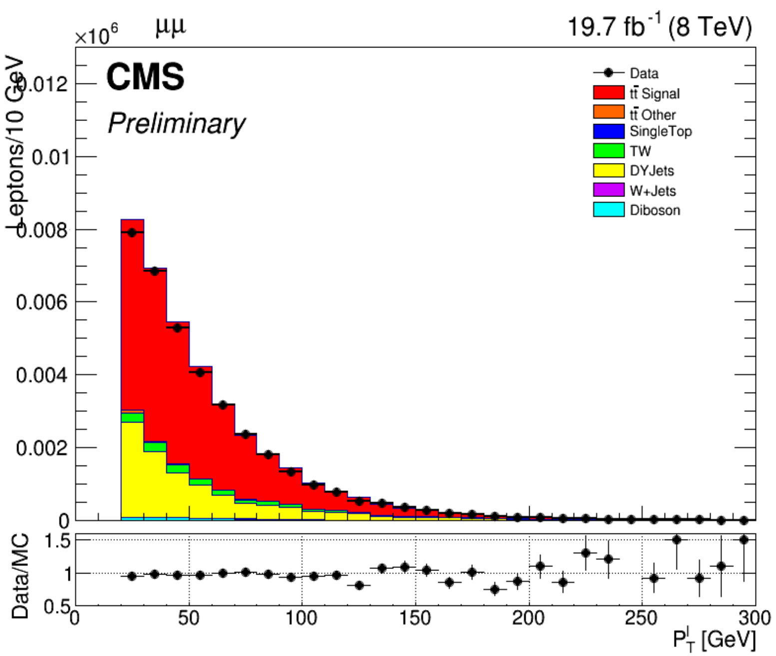
After >=2 jets Requirement





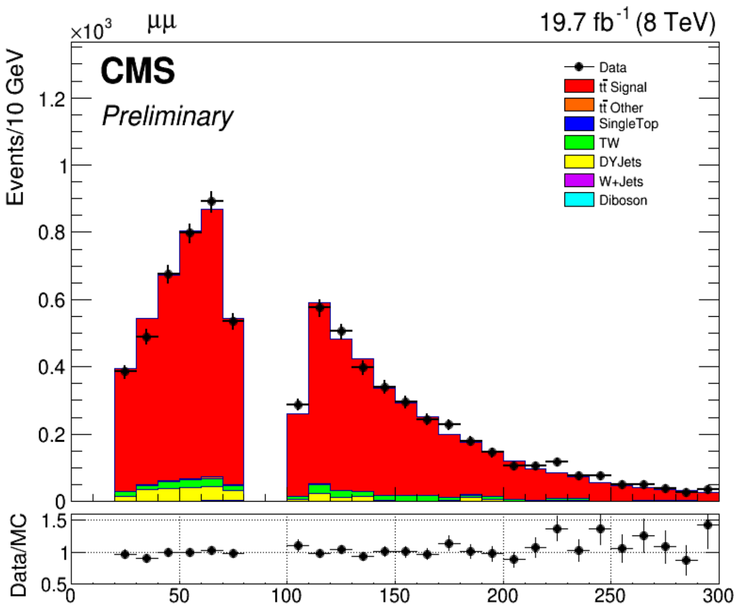
After large missing energy requirement

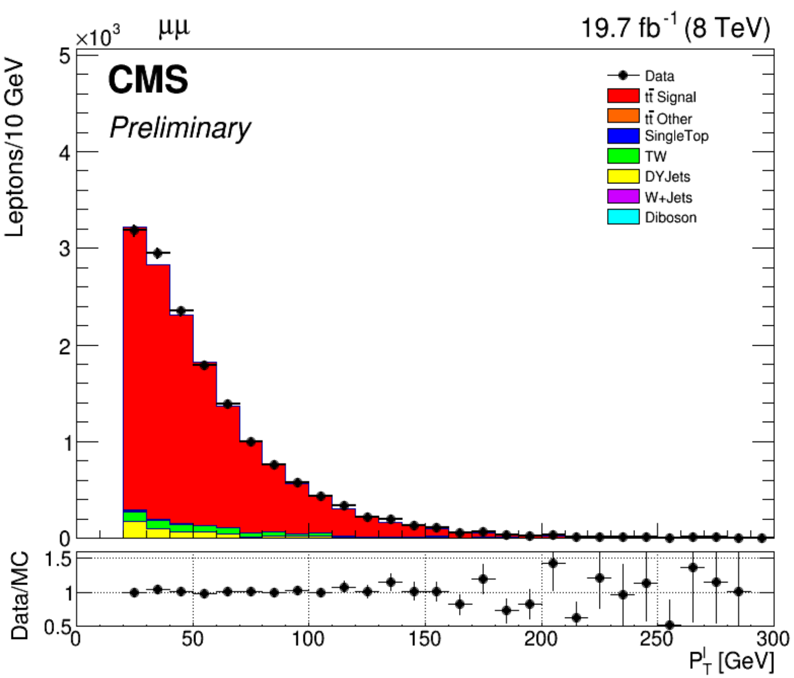




Combination (e-e & μ-μ & e-μ)	>= 2jets	MET
W jets	266.1 ± 52.5	220.7 ± 47.8
DY	44376.8 ± 334.3	10137.7 ± 174.5
Singletop (tW)	3111.2 ± 38.9	2815.9 ± 37.0
Singletop (t,s)	26.7 ± 3.0	23.2 ± 2.8
DiBoson	1299.0 ± 10.0	850.1 ± 8.8
Ttbar other*	457.1 ± 5.9	402.2 ± 5.5
signal	67723.3 ± 56.5	61281.2 ± 54.0
Sum-MC	117260 ± 345.5	75731.1 ± 192.7
Data	122382	75544

After 2 b-tagged requirement





Combination (e-e & μ-μ & e-μ)	MET	>= 2btag
W jets	220.7 ± 47.8	19.1 ± 13.6
DY	10137.7 ± 174.5	605.6 ± 44.2
Singletop (tW)	2815.9 ± 37.0	1054.4 ± 22.5
Singletop (t,s)	23.2 ± 2.8	6.4 ± 1.5
DiBoson	850.1 ± 8.8	49.9 ± 2.2
Ttbar other*	402.2 ± 5.5	126.8 ± 3.1
signal	61281.2 ± 54.0	33350.9 ± 39.5
Sum-MC	75731.1 ± 192.7	35213.1 ± 65.0
Data	75544	36266

Data-MC comparison

- The corrections are applied to:

- ➢ Correct the detector performance and collision conditions.
- ➢ Correct the detector differences in physics modeling and real data.

- **After the corrections, distributions of the MC simulation would be very similar to those observed in the data.**

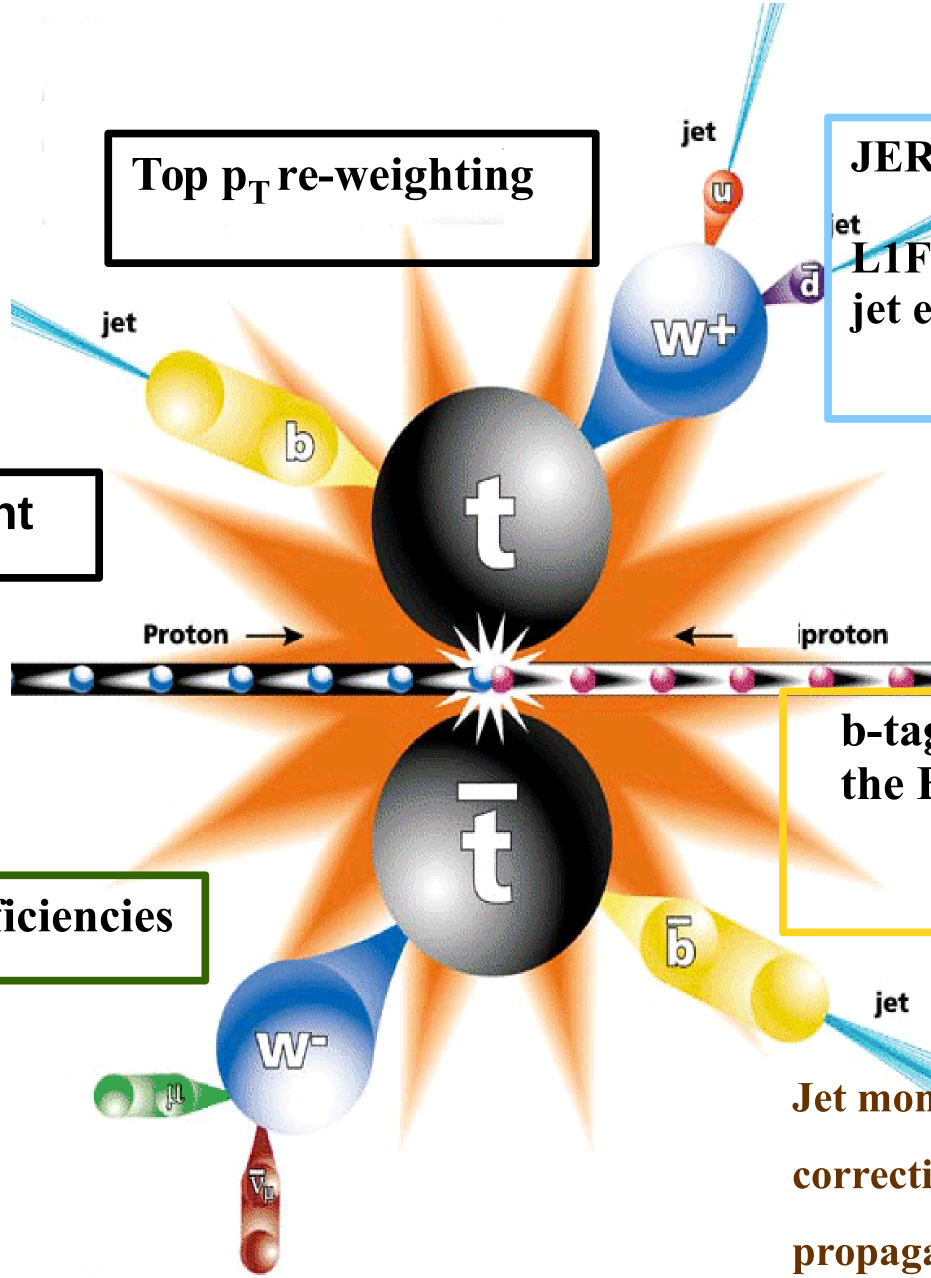
Object & Event Corrections

Top p_T re-weighting

JER and JES corrections

L1Fastjet, L2, L3 corrections
jet energy smearing

pileup interaction weight



b-tag/misstag SF provided by the BTV POG

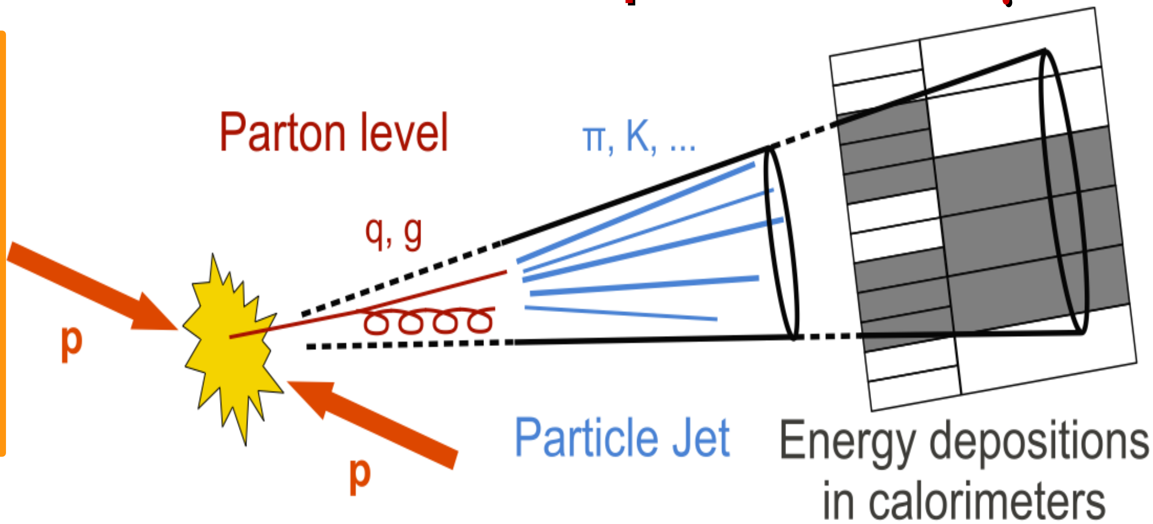
ID, Iso and trigger efficiencies

Jet momentum smearing and corrections are also propagated into MET.

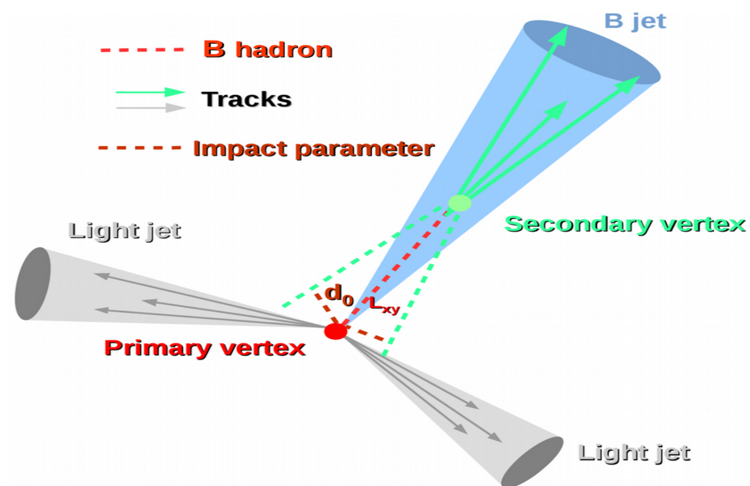
Jet Energy Corrections

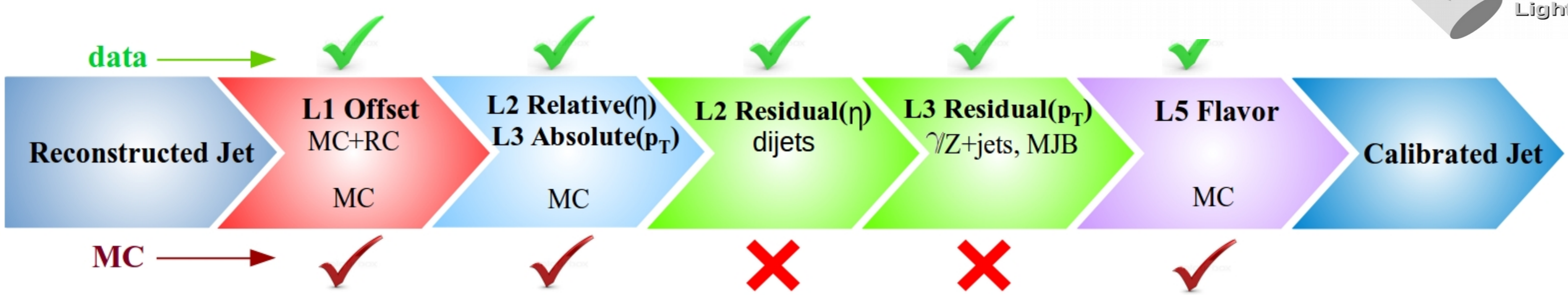
***b* hadron lifetime: $\tau \approx 1.5$ ps $\rightarrow c\tau \approx 450\ \mu m$**

- In general, the four-momenta of the reconstructed jets in the detector-level is not identical to the four-momenta of the generated-jets produced by the partons.

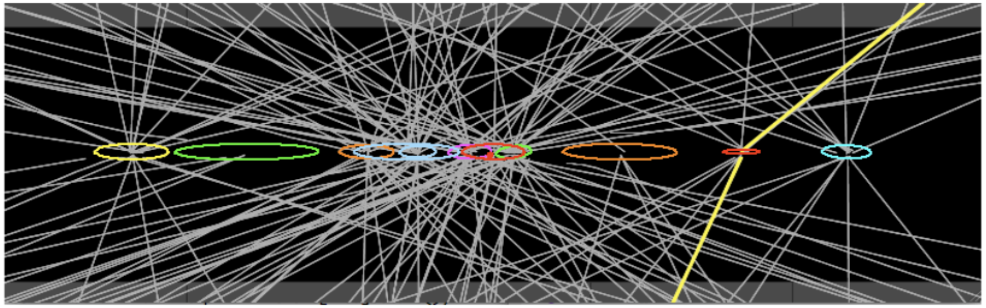


- Jet energy corrections (JEC) are necessarily adopted to relate, on average, the kinematic of raw reconstructed jet to the corresponding particle jet that is independent of the detector response.

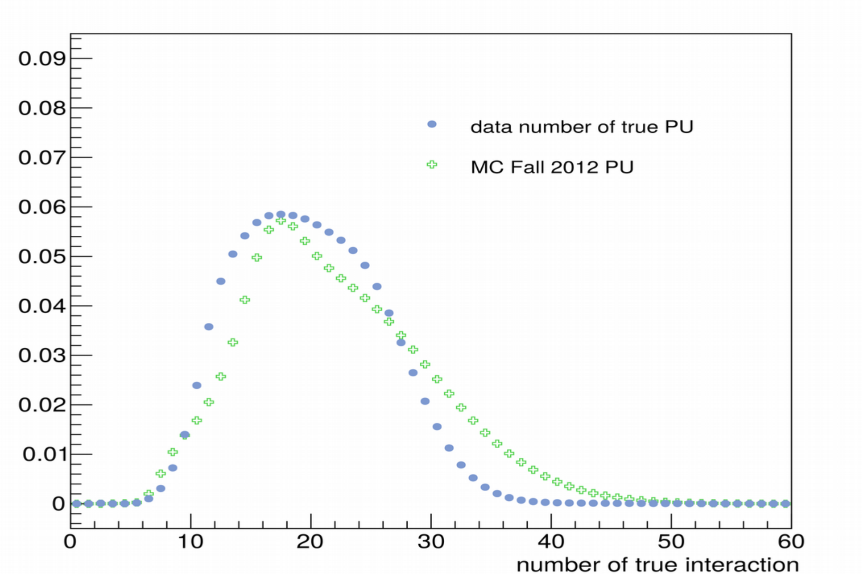


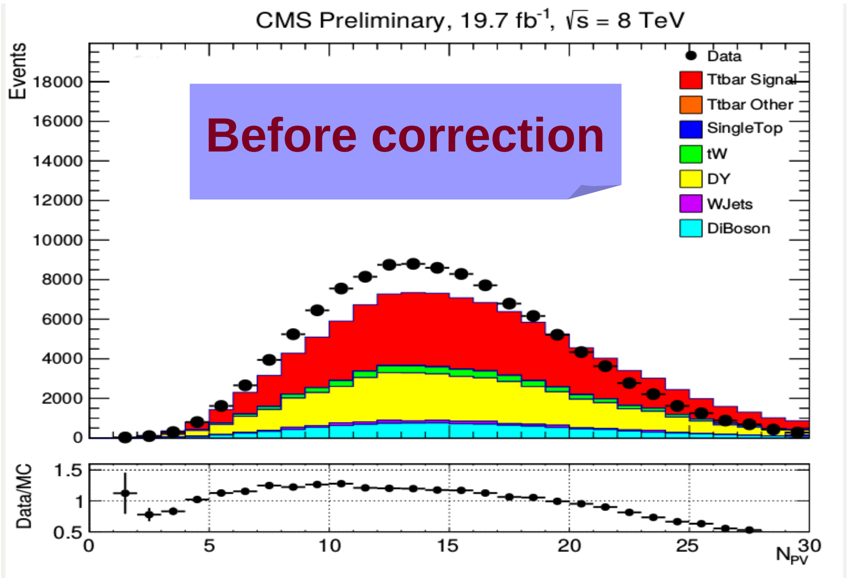


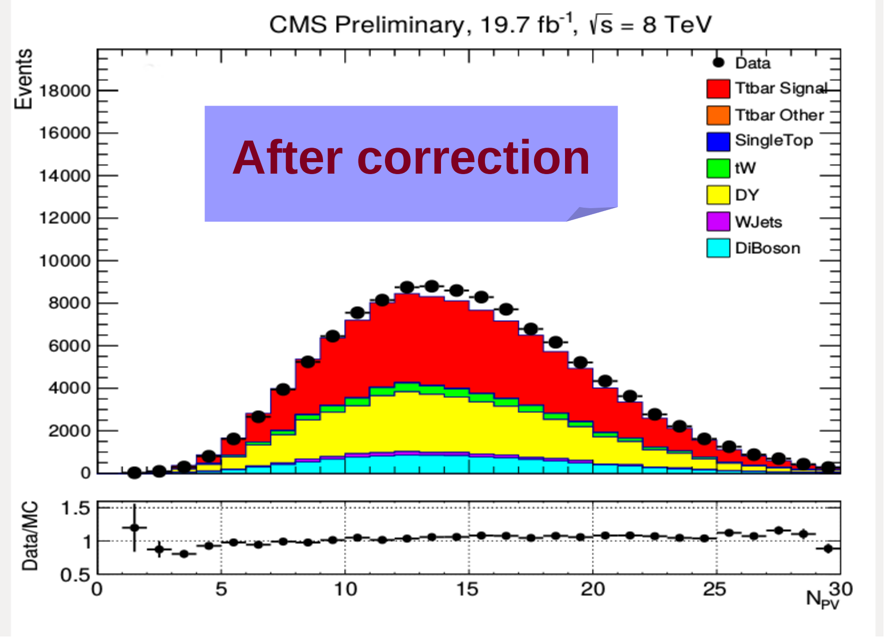
Pile up Correction



$\langle n \rangle = \overline{\mathcal{L}}\,\sigma$







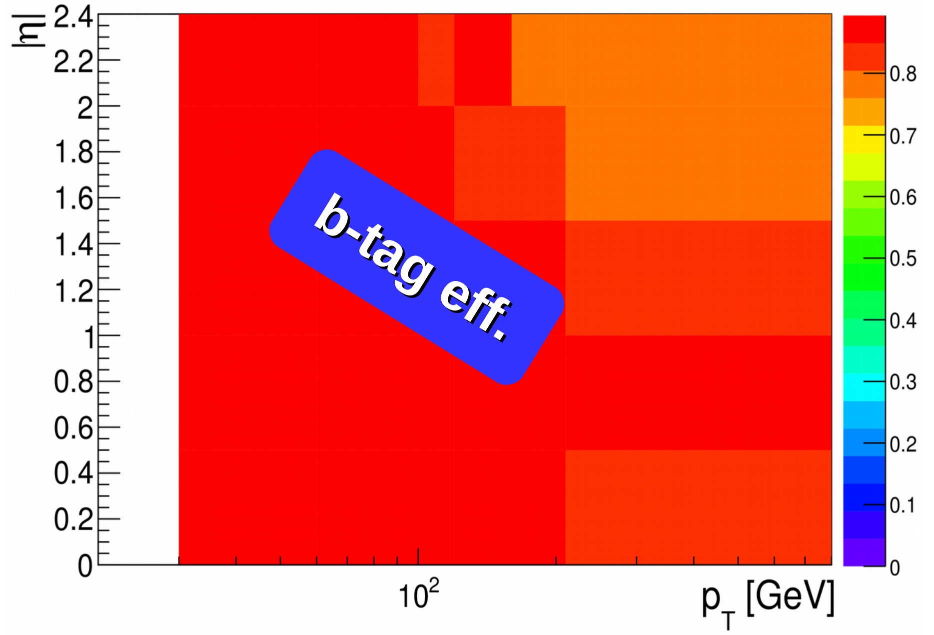
B-tagging and miss-tag efficiency

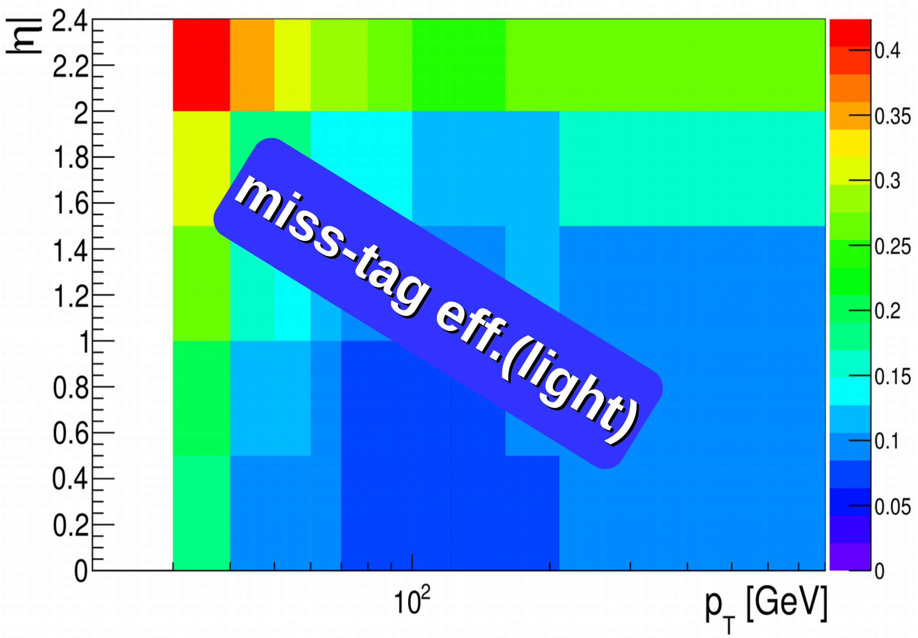
$$\epsilon_f(i,j) = \frac{N_f^{b-tagged}(i,j)}{N_f^{Total}(i,j)}$$

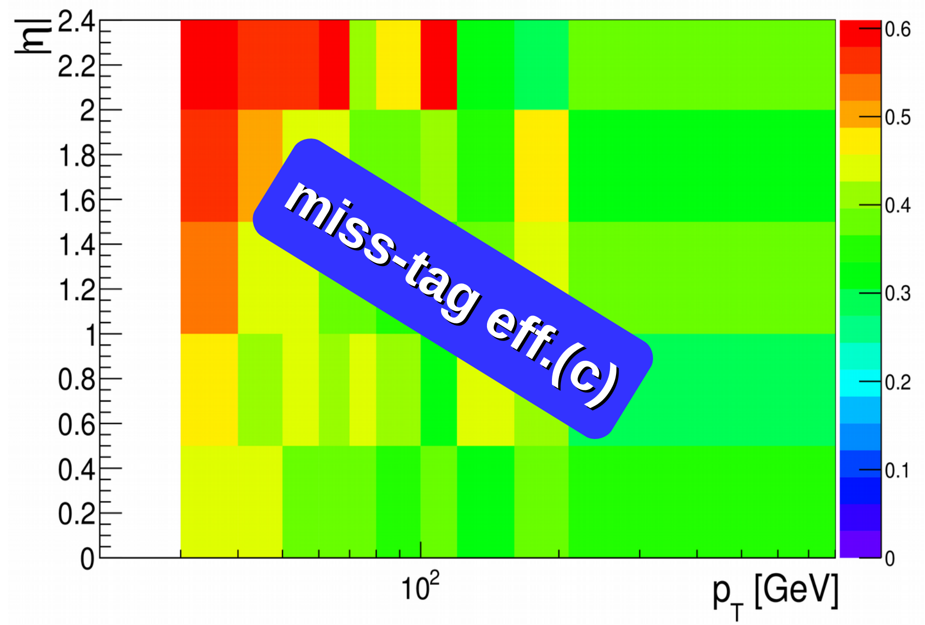
$$P(Data) = \prod_{i=tagged} SF_i \epsilon_i \prod_{j=non-tagged} (1 - SF_j \epsilon_j)$$

$$P(MC) = \prod_{i=tagged} \epsilon_i \prod_{j=non-tagged} (1 - \epsilon_j)$$

$$SF = \frac{P(Data)}{P(MC)}$$



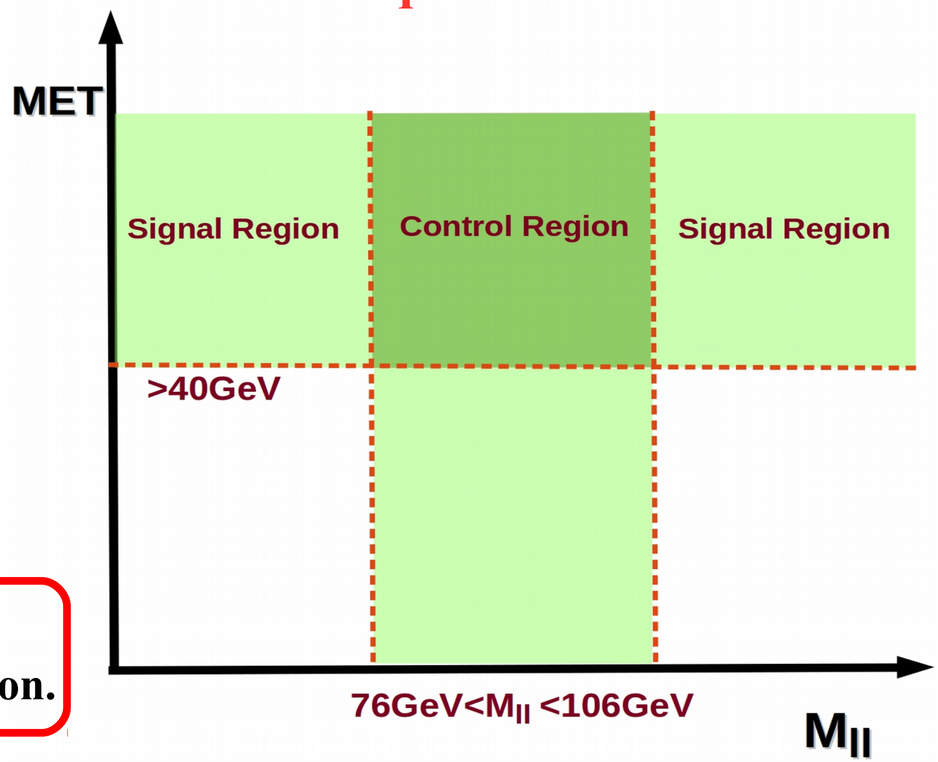




Background estimation

- Unlike the **Drell-Yan** background, the contribution of other backgrounds is estimated purely from the MC simulation.

- The **Drell-Yan** background is evaluated using the **data-driven technique** to minimize uncertainties in the modeling of the MC.



- The number of events inside the signal region is measured from data as:

$$N_{out}^{l^+l^-,obs} = R_{out/in}^{l^+l^-}(N_{in}^{l^+l^-} - 0.5N_{in}^{e\mu}k_{ll})$$

$$R_{out/in} = \frac{N_{DYMC}^{out}}{N_{DYMC}^{in}}$$

K Factor: **To take into account the reconstruction efficiency differences between electron and muon.**

$$k_{ee} = \sqrt{\frac{N^{e^+e^-_{in},loose}}{N^{\mu^+\mu^-_{in},loose}}}$$

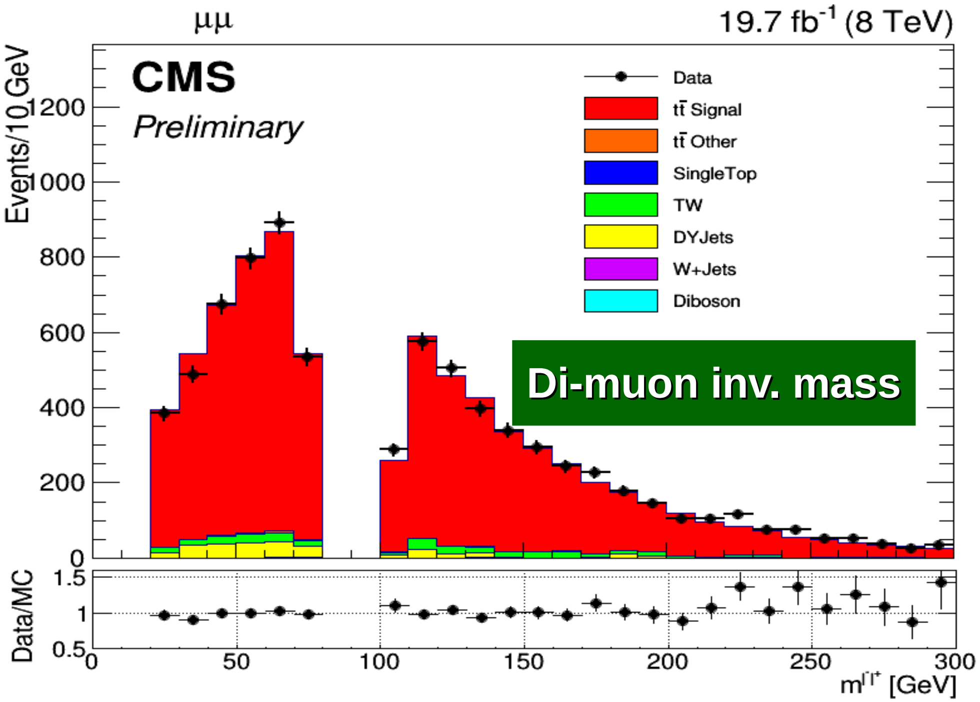
$$k_{\mu\mu} = \sqrt{\frac{N^{\mu^+\mu^-_{in},loose}}{N^{e^+e^-_{in},loose}}}$$

$\mu^-\mu^+$ channel			
	MC DY	Estimated DY	SF
≥ 2 Jets + E_T^{miss}	3151.7 ± 87.1	4043 ± 121.4	1.28 ± 0.05
≥ 2 Jets + E_T^{miss} + ≥ 2 b tag	183.7 ± 22	234.8 ± 31.5	1.27 ± 0.22

Yield comparison

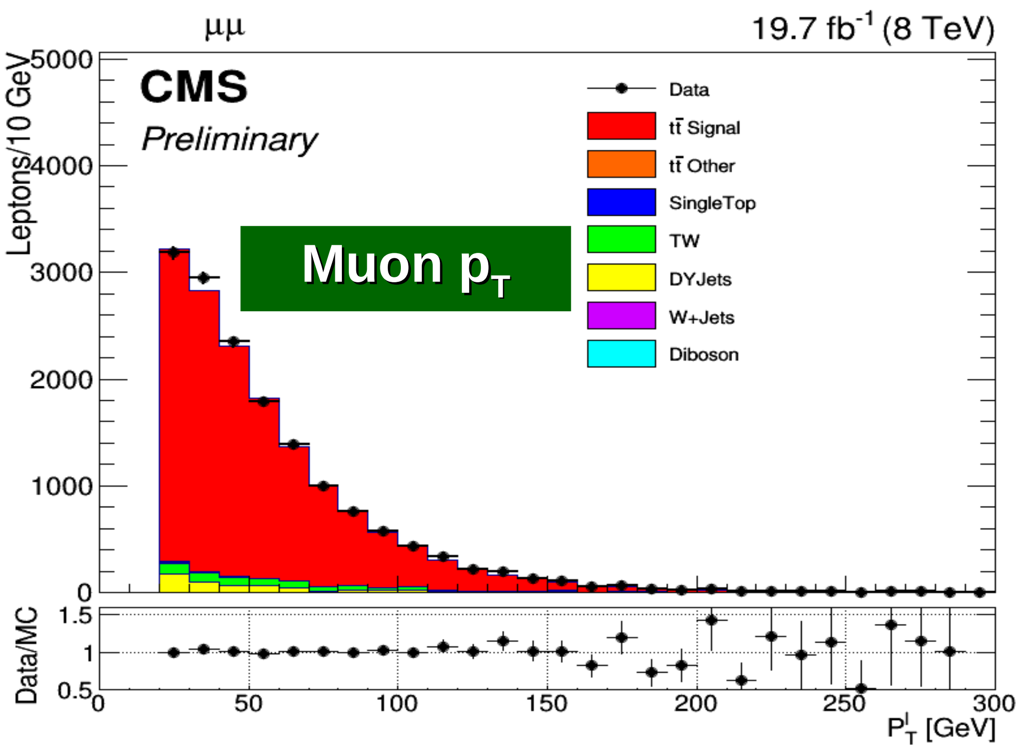
Combination (e-e & μ-μ & e-μ)	>=2 leptons	>= 2jets	MET	>= 2btag	ttbar
W jets	3161.3 ± 180.0	266.1 ± 52.5	220.7 ± 47.8	19.1 ± 13.6	10.4 ± 10.4
DY	1315520 ± 1811.4	44376.8 ± 334.3	10137.7 ± 174.5	605.6 ± 44.2	420.4 ± 36.3
Singletop (tW)	9497.5 ± 67.7	3111.2 ± 38.9	2815.9 ± 37.0	1054.4 ± 22.5	677.4 ± 17.9
Singletop (t,s)	159.5 ± 7.4	26.7 ± 3.0	23.2 ± 2.8	6.4 ± 1.5	4.0 ± 1.1
DiBoson	21470.5 ± 48.2	1299.0 ± 10.0	850.1 ± 8.8	49.9 ± 2.2	29.8 ± 1.6
Ttbar other*	568.7 ± 6.6	457.1 ± 5.9	402.2 ± 5.5	126.8 ± 3.1	102.6 ± 2.8
signal	99205.6 ± 68.6	67723.3 ± 56.5	61281.2 ± 54.0	33350.9 ± 39.5	29840.9 ± 37.1
Sum-MC	1449580 ± 1823.6	117260 ± 345.5	75731.1 ± 192.7	35213.1 ± 65.0	31085.5 ± 55.9
Data	1530445	122382	75544	36266	31881

Control plots

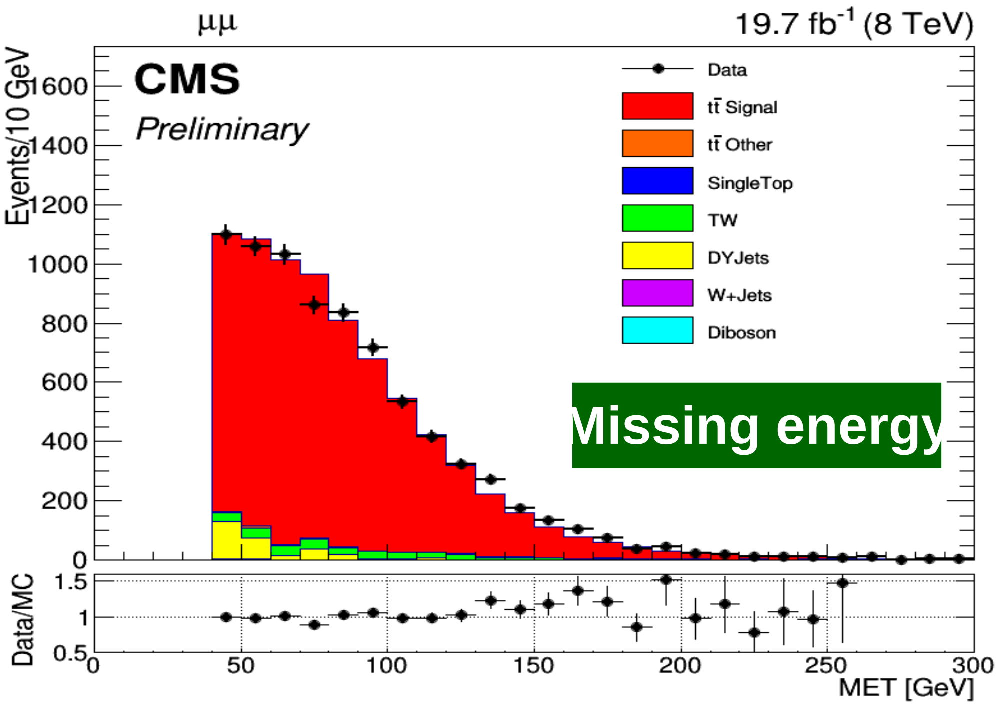


- A comparison of data with expected events from the MC simulation is performed.

- By including all corrections, a good agreement between the data and MC is obtained.



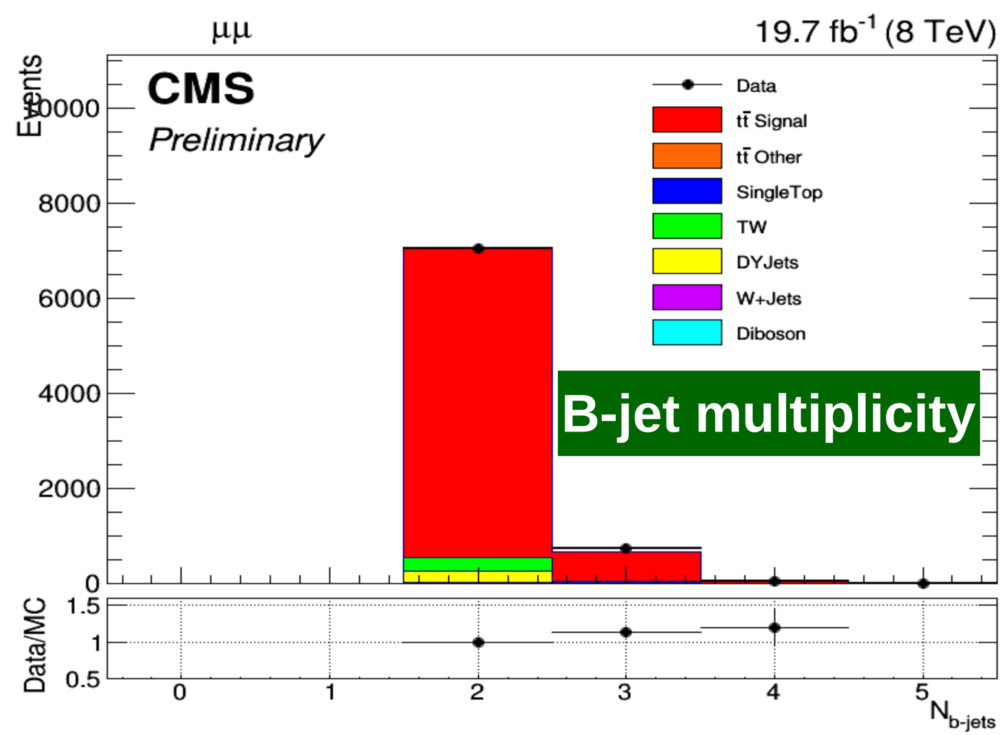
Control plots



- A clean signal region is obtained with **93%** contribution from the **$t\bar{t}$ signal** events.

- The **92%** of **signal** expectation comes from events with **2 b-tagged jets.**

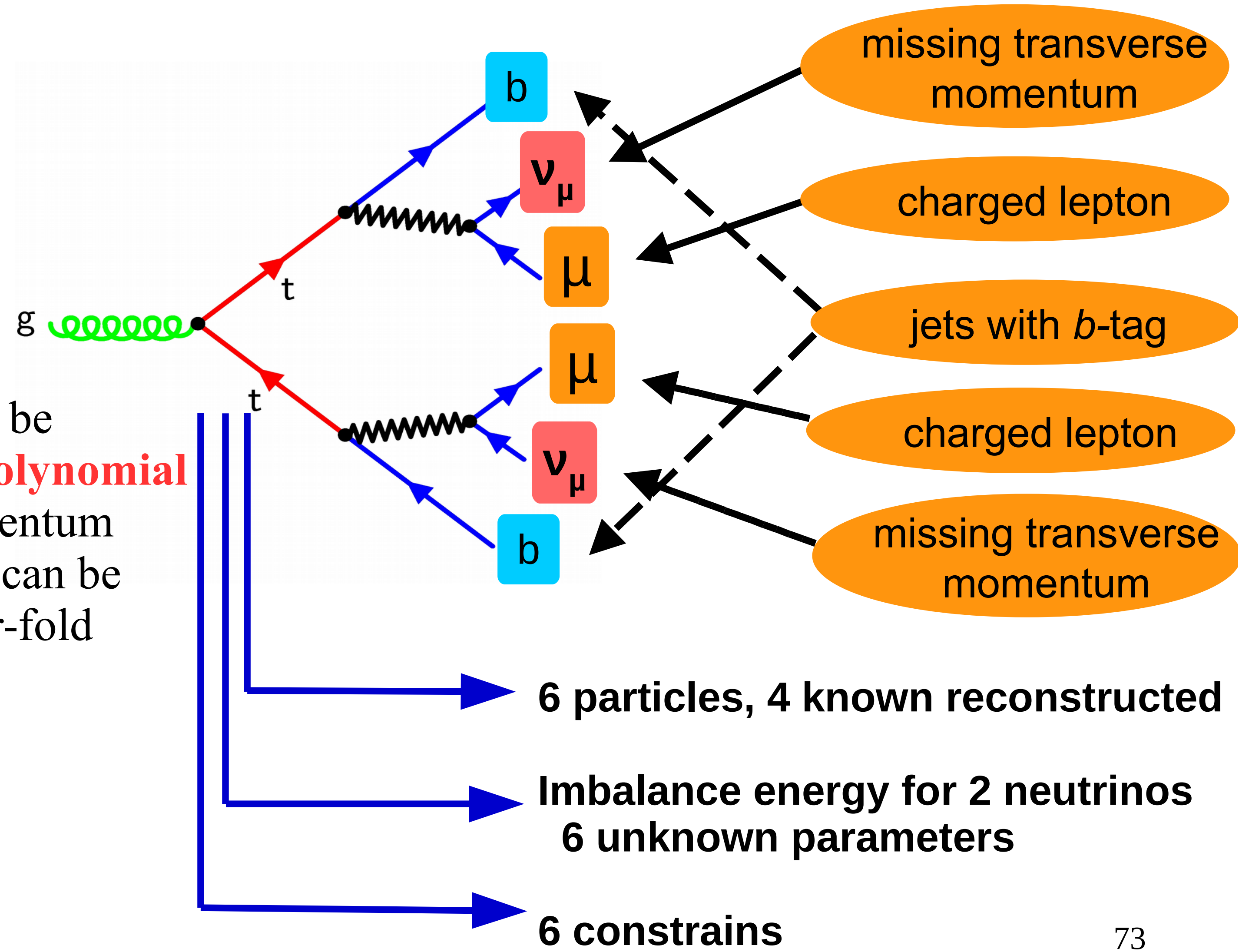
- After the full event selection, the main background contributions come from **tW** and **Z+jets** , with **6%** contamination to the total MC expectation.



Top pair reconstruction

- There are **six unknown components** in the final state of $t\bar{t}$ events.

- The determination of the $t\bar{t}$ pair four-momenta is obtained by using **six constrains** on the kinematic variables.

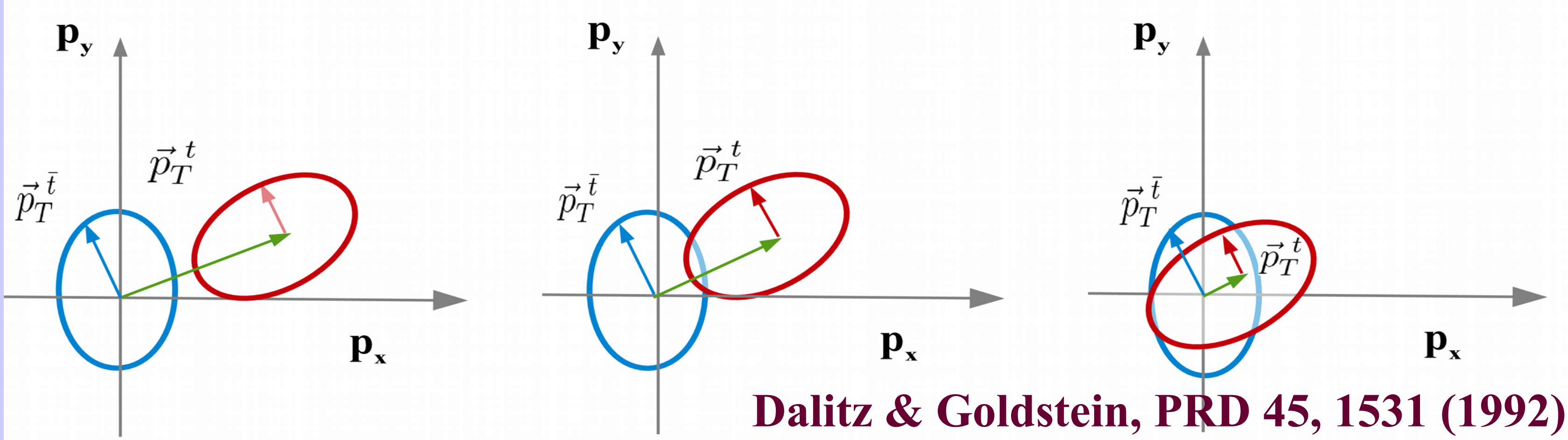


➔ The system of equations can be reduced to a **fourth order polynomial** in one of the neutrino momentum Components. This equation can be solved with a maximum four-fold ambiguity.

Top pair reconstruction ...

- The kinematic equations and measured quantities constrain the transverse momentum of the neutrino and anti-neutrino to lie on ellipses in the p_x-p_y plane.

For each assigned pair of (muon, b-jet), there are up to four solutions.



Dalitz & Goldstein, PRD 45, 1531 (1992)

+

the two-fold ambiguity the b- and b¯ assignment

=

a total of eight neutrino momenta solutions per event

Top pair reconstruction ...

- Several methods are studied in details to select the best candidate as the top pair system.

Method	**Effective method**	**Kinb method**	**AMWT method**
Kinematic inputs	**Reconstructed jets,leps,MET**	**Smeared jets, leps, MET**	**Smeared jets,leps,MET**
Mass inputs (Top & W Boson)	**Smeared using Bright-Wigner dist**	**Fixed to 175 GeV and 80.41 GeV**	**Fixed to 175 GeV and 80.41 GeV**
Combination disambugation	-	**Lep-jets combination With largest sum of weights**	**Lep-jets combination With largest sum weights**
Candidate disambugation	**Solution with min mass ttbar is taken**	**One has highest weight**	**One has highest weight**
Avergaed *t & tbar*	**No average**	**Average over best candidates**	**Average over best candidates**

Top pair reconstruction: AMWT method

The AMWT method:

- The preferred lepton-jet combination as well as the most likely top quark candidate within the fixed combination is determined by assigning a weight to each solution.

$$w(\vec{X}|m_{top}) = [\sum_{Initial\ partons} \underbrace{F(x_1)F(x_2)]}_{\text{production}} \underbrace{p(E^*_{\ell+}|m_{top})p(E^*_{\ell-}|m_{top})}_{\text{decay}}$$

Initial partons → $(u\bar{u}, \bar{u}u, d\bar{d}, \bar{d}d, s\bar{s}, \bar{s}s, g\bar{g})$

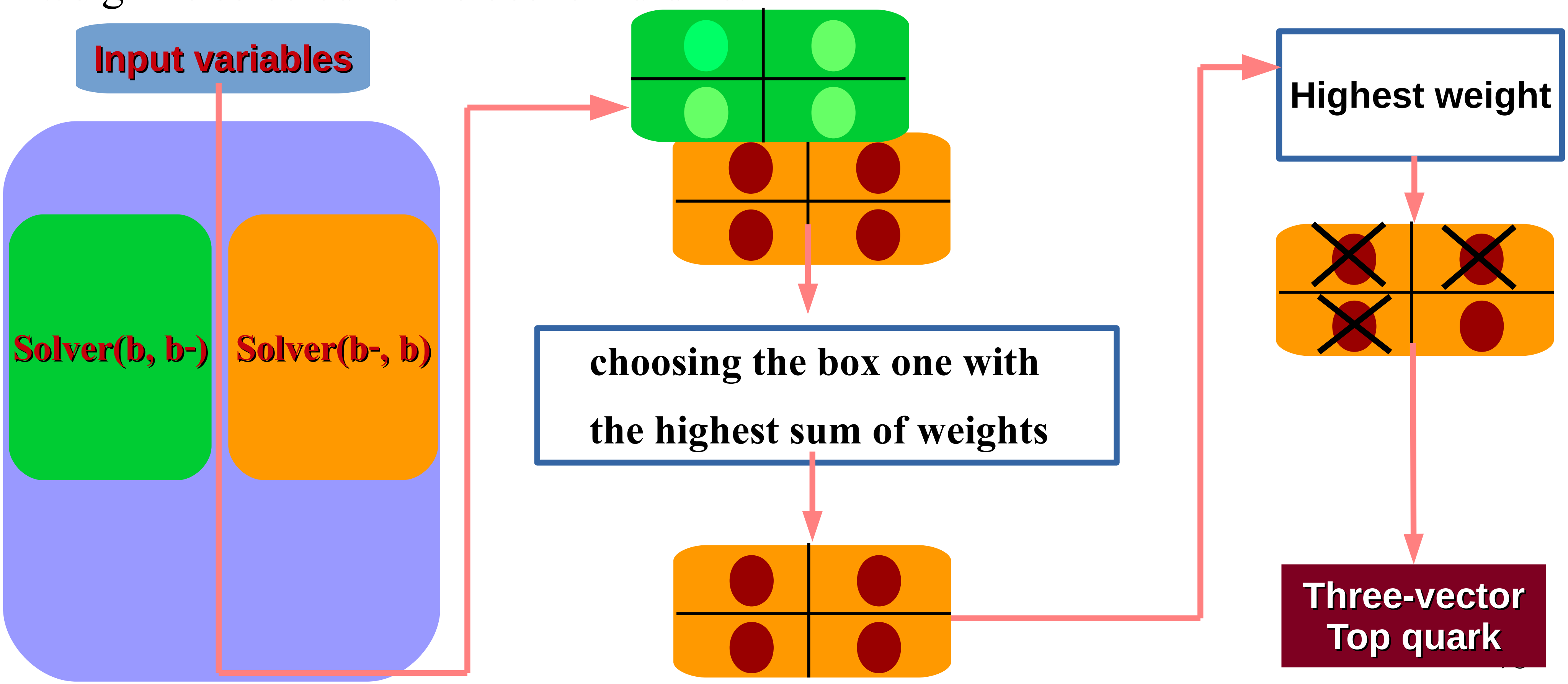
- The probability density of observing muon with energy E in the rest frame of the top quark with mass m_{top} is expressed as:

$$p(E_{\ell^*}|m_{top}) = \frac{4m_{top}E_{\ell^*}(m^2_{top} - m^2_b) - 2m_{top}E_{\ell^*}}{(m^2_t - m^2_b)^2 + m^2_W(m^2_{top} - m^2_b) - 2m^4_W}$$

Top pair reconstruction ...

Strategy to find the best candidate:

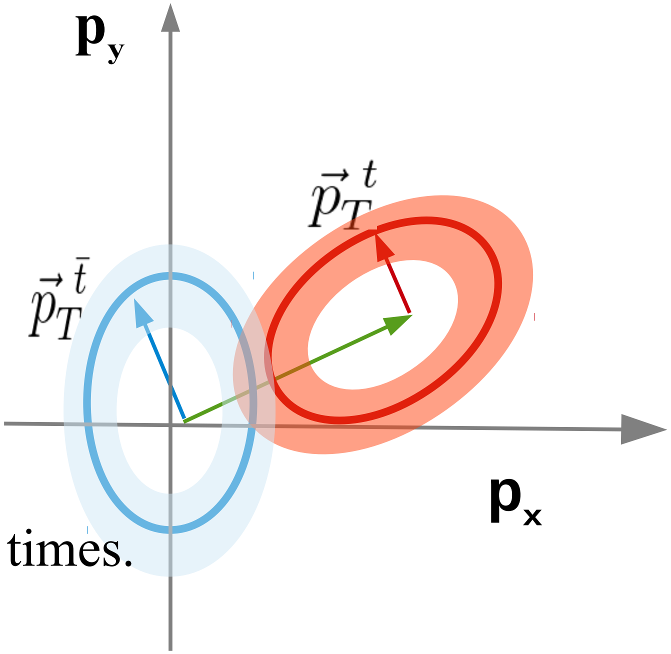
- To resolve the combination ambiguity in each event, one with maximum sum of weights is taken.
- Given the chosen combination with up to four solutions, one with the highest weight is selected as the best candidate.



Top pair reconstruction

- For some events with reconstructed momenta, **no solution is found** .

➢ To compensate the no solution statement, each event is reconstructed using the smearing procedure in both data and MC.



Final top pair reconstruction strategy:

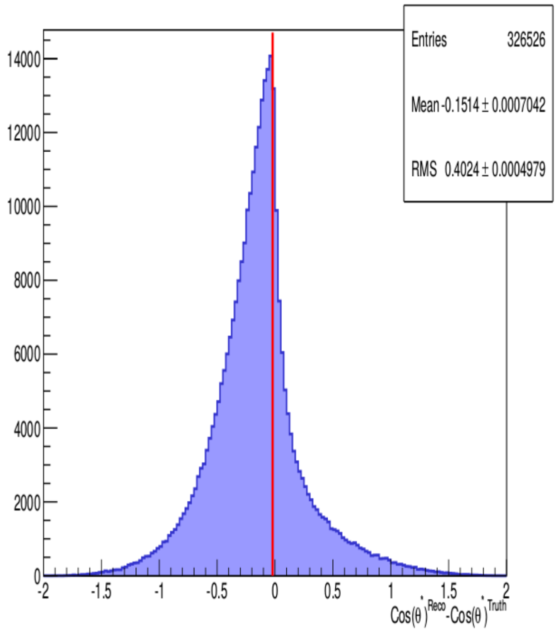
- For each event, the smearing procedure is repeated for 300 times.
- Three momentum vector of the top (anti-top) is extracted

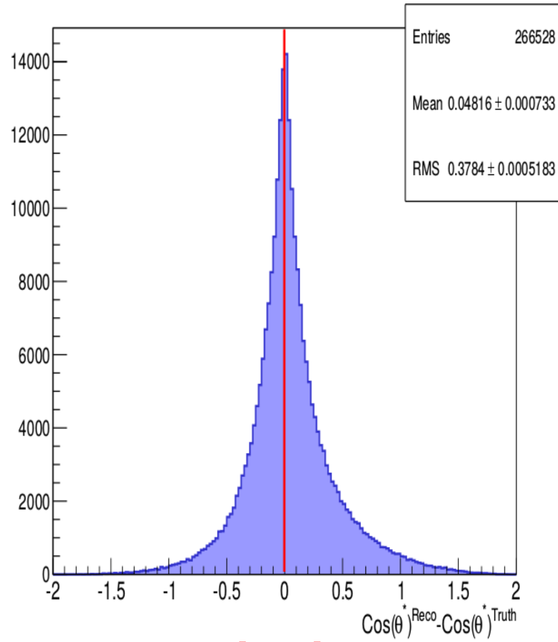
  by averaging over the momentum of the best candidates.

$$< \vec{p}_{top} >= \frac{\sum_{i=1}^{i\leqslant 300} w_i . \vec{p}_{top,i}}{\sum_{i=1}^{\leqslant 300} w_i}$$

- The top quark 4-momenta is determined by the m_{top} = 172.5 GeV constrain.

Response studies



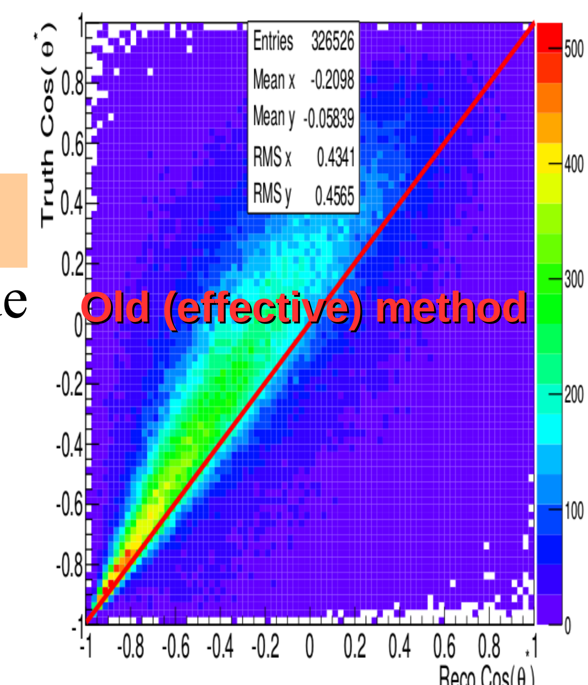


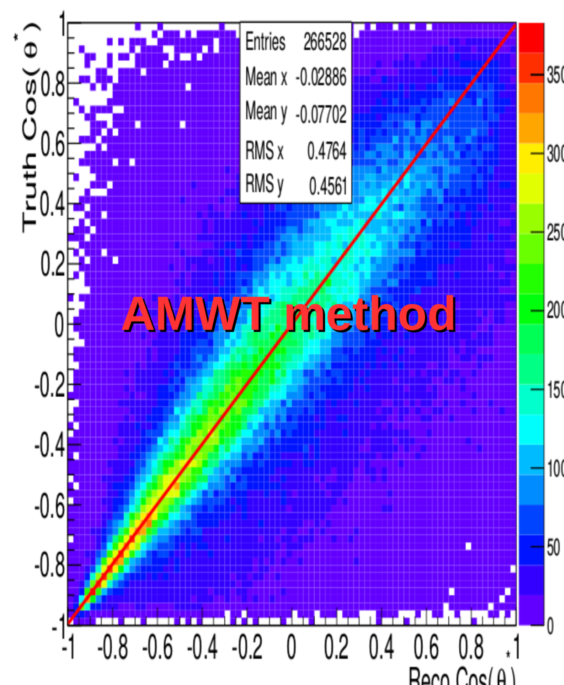
Old (effective) method

AMWT method

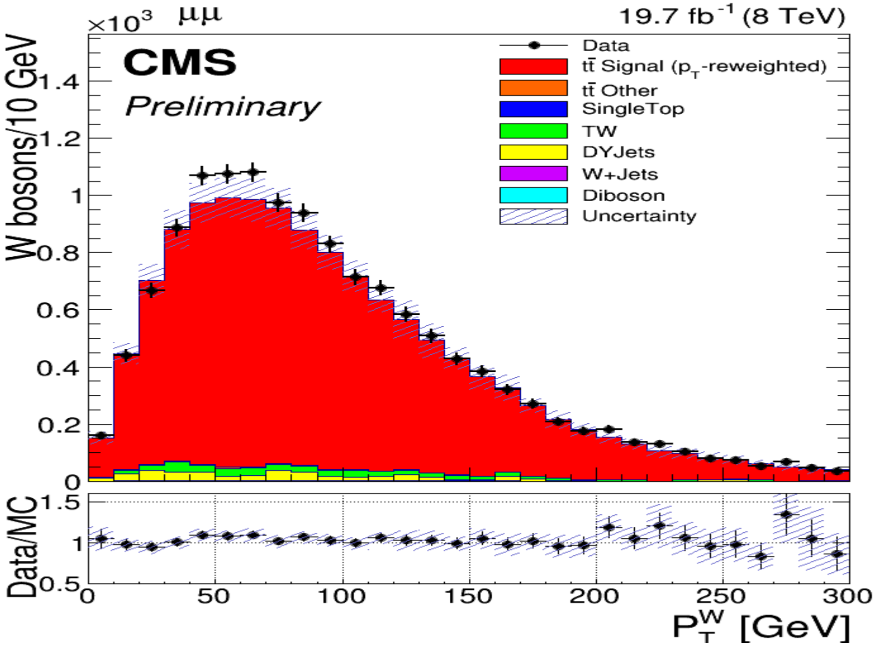
- In comparison of **AMWT** with other techniques, a good resolution with less bias effect for relevant observables like $\mathbf{m_{t\bar{t}}}$ and **cos θ*** is found.

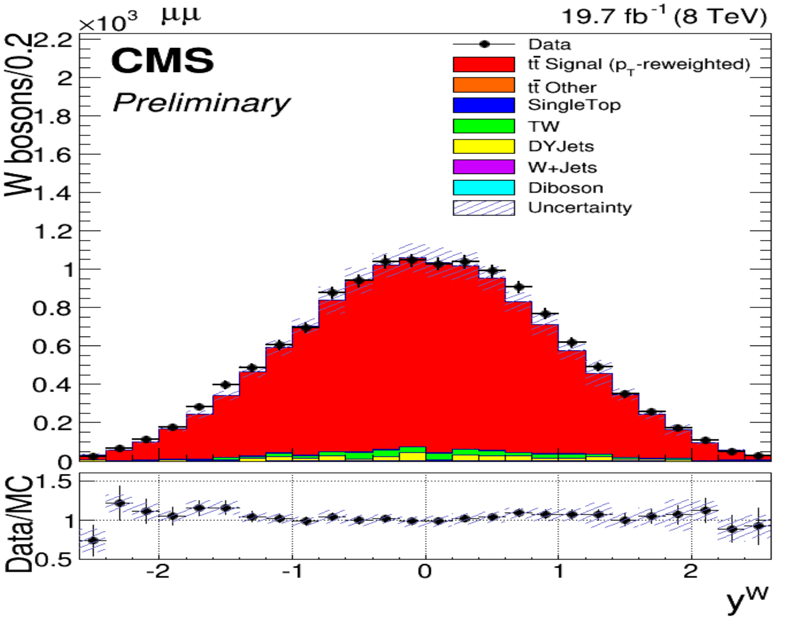
- The difference between the **cos θ*** value from the truth level and the value in the reconstruction level



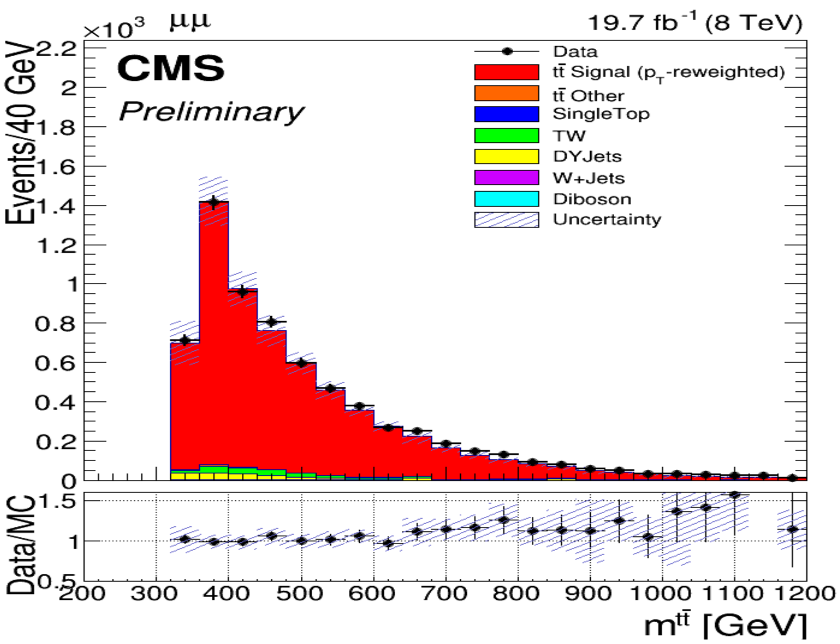


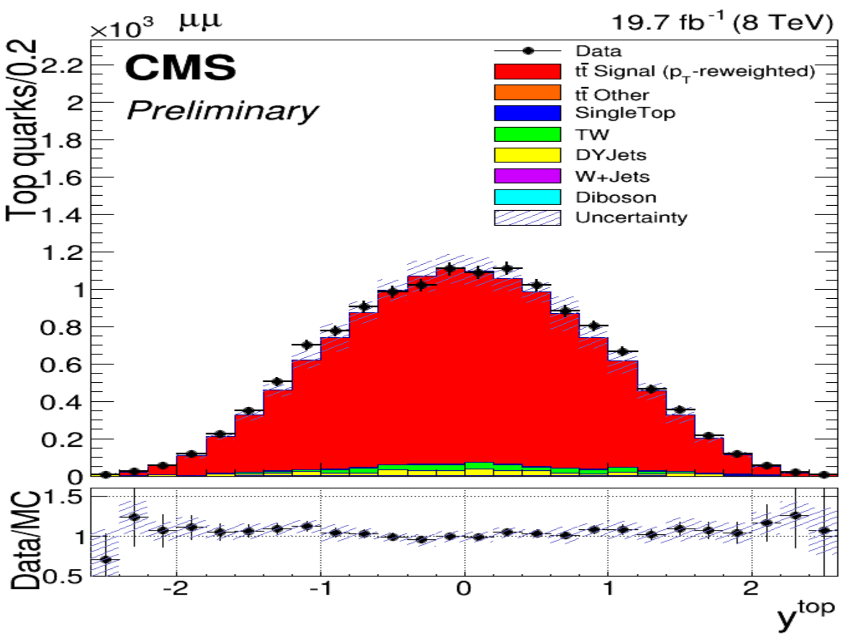
Control plots after top pair reconstruction





The quoted uncertainties include only the statistical fluctuations.





Data-MC comparison

$\mu^-\mu^+$channel	$\geq$ 2 b-tag	$t\bar{t}$
Diboson	12.6 ± 1.1	6.9 ± 0.7
Wjets	0.0 ± 0	0 ± 0
DY	274.2 ± 30.7	178.5 ± 24.6
tW	224.7 ± 10.5	143.4 ± 8.3
SingleTop	0.6 ± 0.4	0.6 ± 0.4
$t\bar{t}$ other	19.5 ± 1.2	16.1 ± 1.1
$t\bar{t}$ signal	7147.4 ± 18.4	6302.7 ± 17.1
Sum MC	7679.0 ± 37.3	6648.2± 31.1
Data	7853 ± 88.6	6808 ± 82.5

- Only the statistical uncertainty on MC samples is included.
- The number of observed events is consistent with MC expectation within the total uncertainty.

Re-weighting technique

- To extract the helicity fractions, the re-weighting method is used. The phase space density for reconstructed **cos(θ*)** distribution at reco-level is given by:

Weight function is applied to each $t\bar{t}$ signal event including those from Tau decay.

$$\rho(\cos\theta^*_{\ell,reco}|\vec{F}^{Free}) \propto \int d\cos\theta^*_{\ell,gen} W(\cos\theta^*_{gen};\vec{F})\,\rho(\cos\theta^*_{\ell,gen}|\vec{F}^{SM})\,\mathcal{R}(\cos\theta^*_{\ell,gen},\cos\theta^*_{\ell,reco})$$

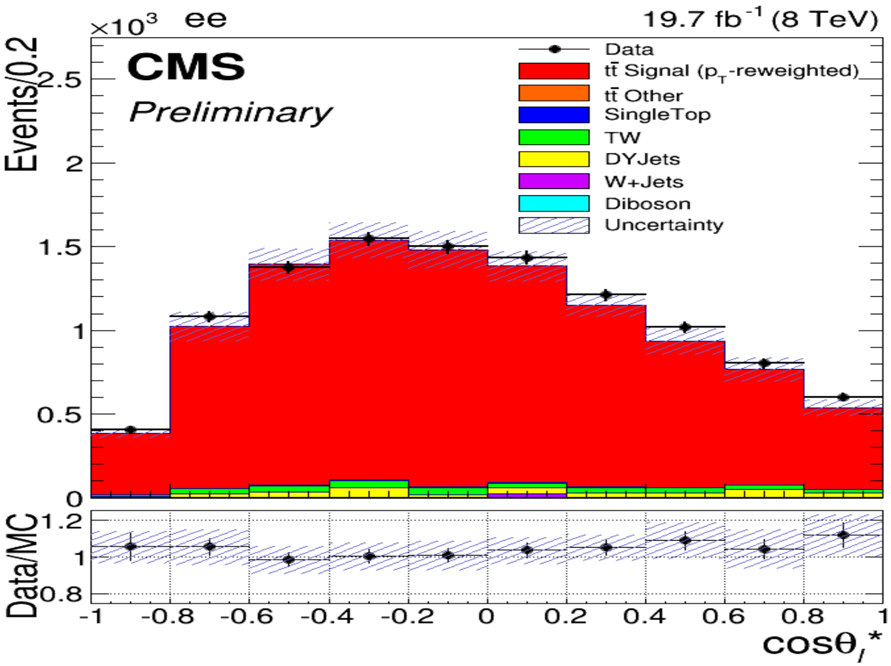
Migration matrix from generated to reconstructed level.

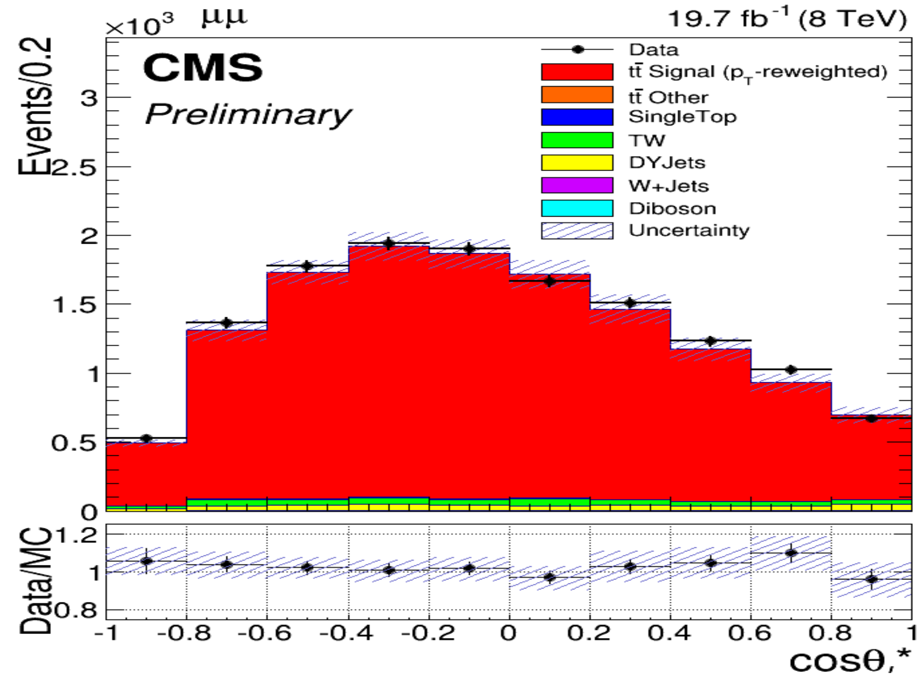
- This equation represents the migration from the **reference SM distribution** with expected $\mathbf{F^{SM}}$ fractions to a free distribution with $\mathbf{F^{Free}}$ parameters **at the detector level**.

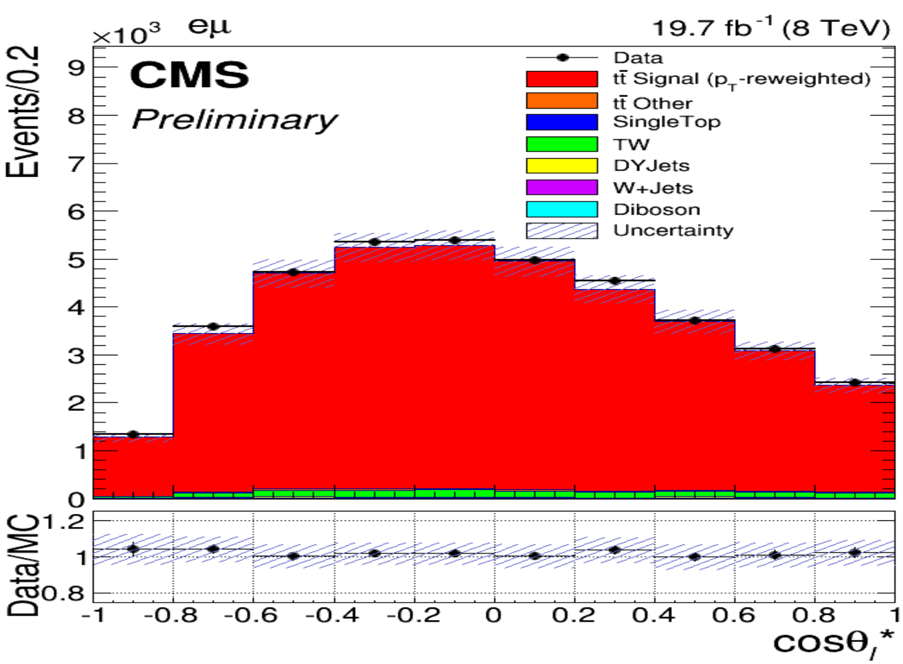
$$W(\cos\theta^*_{gen};\vec{F}) = \frac{\rho^{Free}(\cos\theta^*_{\ell,gen})}{\rho^{SM}(\cos\theta^*_{\ell,gen})}$$

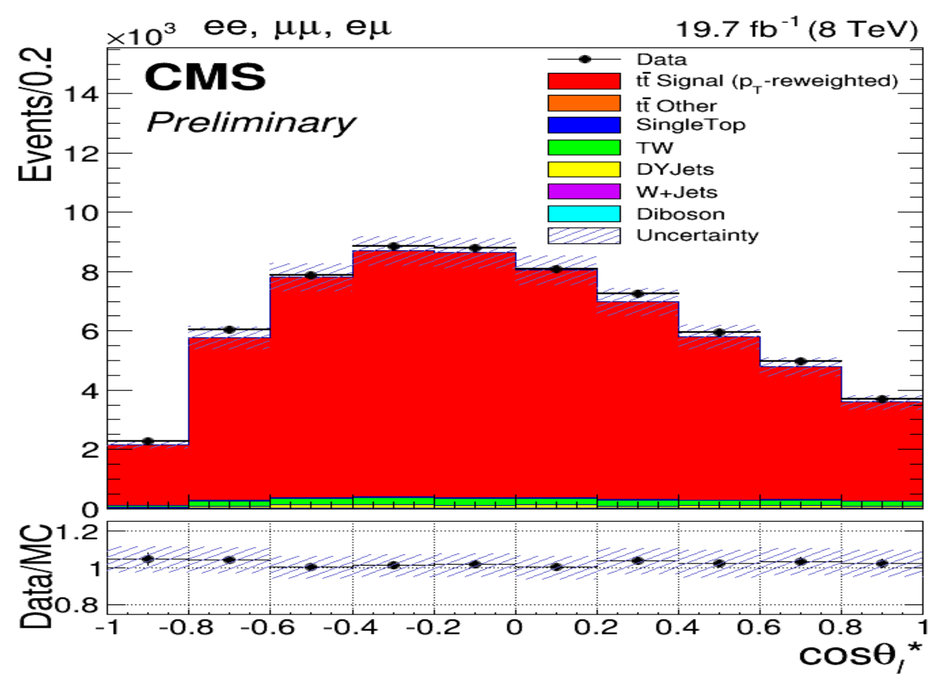
$$= \frac{\frac{3}{8}(1-\cos\theta^*_{\ell,gen})^2F_L^{Free}+\frac{3}{8}(1+\cos\theta^*_{\ell,gen})^2F_R^{Free}+\frac{3}{4}\sin^2\theta^*_{\ell,gen}F_0^{Free}}{\frac{3}{8}(1-\cos\theta^*_{\ell,gen})^2F_L^{SM}+\frac{3}{8}(1+\cos\theta^*_{\ell,gen})^2F_R^{SM}+\frac{3}{4}\sin^2\theta^*_{\ell,gen}F_0^{SM}}$$

Cos(θ*) distributions

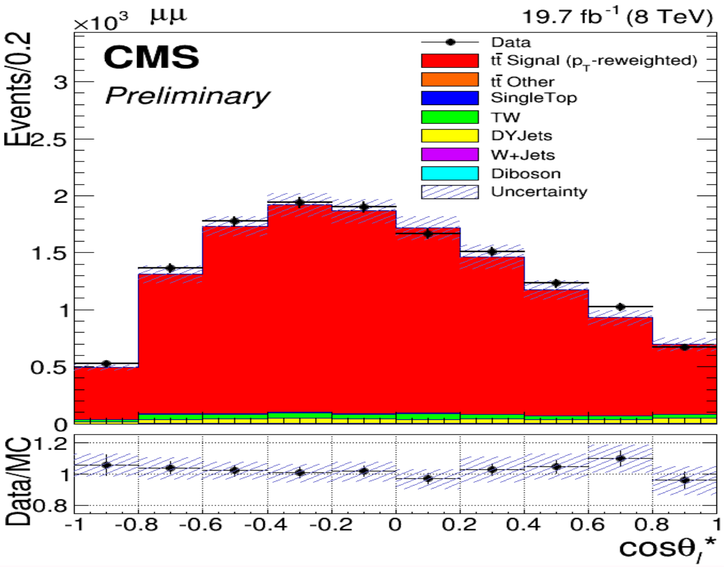








Fitting Method



- Assuming Poisson statistics for **cos(θ*)** distribution, a likelihood function is defined to extract the helicity measurements. The helicity components are determined by a 3-parameter fit with minimizing the likelihood function using the MINUIT2 package.

$$N_{MC}(i;\vec{F}) = N_{BKG}(i) + N_{t\bar{t}}(i;\vec{F})$$

$$N_{t\bar{t}}(i;\vec{F}) = \mathcal{F}_{t\bar{t}}[\sum_{t\bar{t}\ events,\, bin\, i} W(\cos\theta^*_{gen};\vec{F})]$$

$$\mathcal{L}(\vec{F}^{Free}) = \prod_{i\in bins} \frac{(N_{MC}(i;\vec{F}))^{N_{data}(i)}}{N_{data}(i)!} \times e^{-N_{MC}(i;\vec{F})}$$

$$W(\cos\theta^*_{gen};\vec{F}) = W_{lep_1}(\cos\theta^*_{gen};\vec{F}) \times W_{lep_2}(\cos\theta^*_{gen};\vec{F})$$

$$N_{BKG}(i) = N_{single\ top}(i) + N_{DY}(i) + N_{di-boson}(i) + N_{W+jets}(i) + N_{t\bar{t}\ other}(i)$$

Validation of fit method (I)

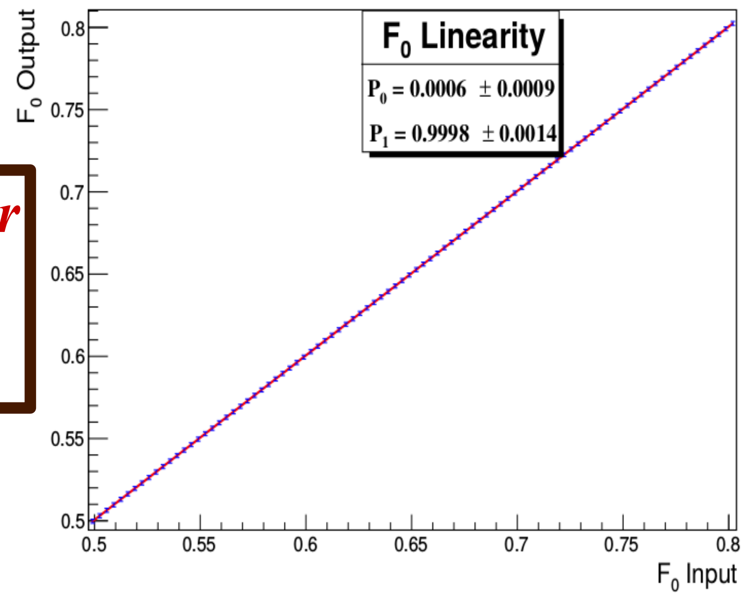
To study the possible biases on the fitting procedure and correctness of returned statistical uncertainty in the helicity fractions, the validation tests have been done.

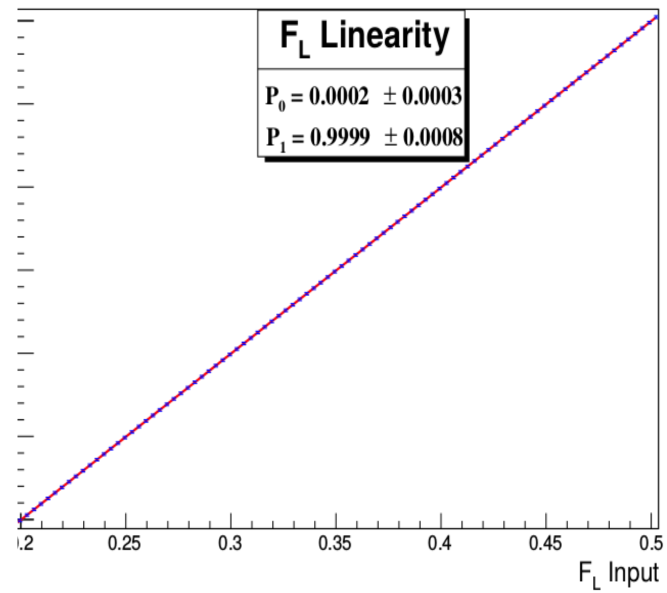
Linearity check:

- **Check the compatibility between any set of fixed input fractions with the output extracted ones.**
- **Generate 300 pseudo-experiments using 1/3 of randomly events in the simulated sample.**
- **The number of pseudo-data events in ith bin of reconstructed cos θ^* is as follow:**

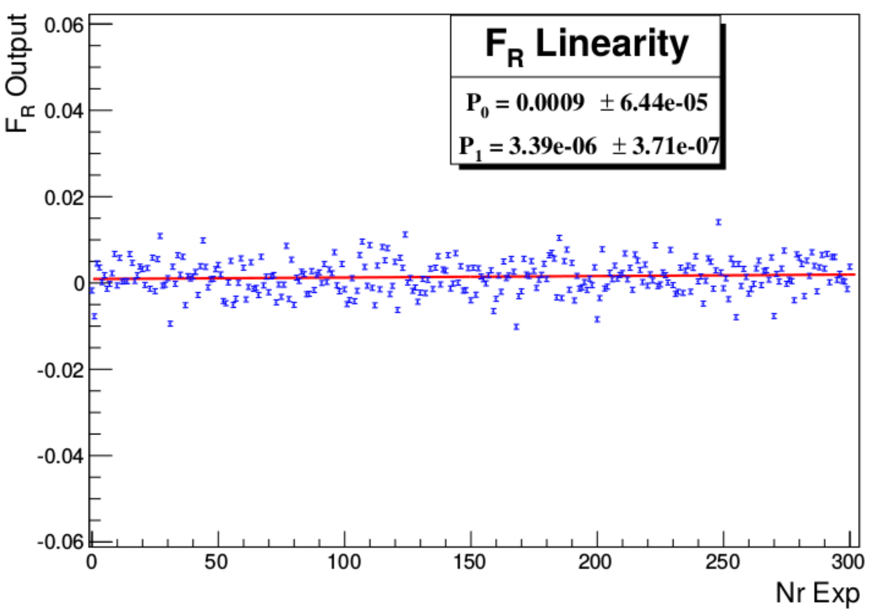
$$N_{pseudo-data}(i;\vec{F}) = \sum_{\text{1/3 of } t\bar{t} \text{ sample, bin i}} \frac{\rho^{Free}(cos\theta^*_{e^\pm,gen})}{\rho^{SM}(cos\theta^*_{e^\pm,gen})} + N^{(1/3)}_{BKG}(i;\vec{F})$$

For each pseudo experiment: The F_R is fixed to the SM value, the input F_0 is varied linearly in 300 steps and F_L is also changed by unitary constraint.





The linear behavior for F_0 and F_L fractions is confirmed.



The result of fitting on F_R is also compatible with the input SM value.

This strategy correctly retrieve the helicity fractions from the data, even when they are far from the SM predicted values.

Pull and Residual check:

- Investigating the statistical properties of the extracted estimators.
- Create 1000 pseudo-experiments with the random event selection from the entire simulated samples normalized to an integrated luminosity.

$$residual = F^{est} - F^{exp}$$

Definition of residual and pull parameters:

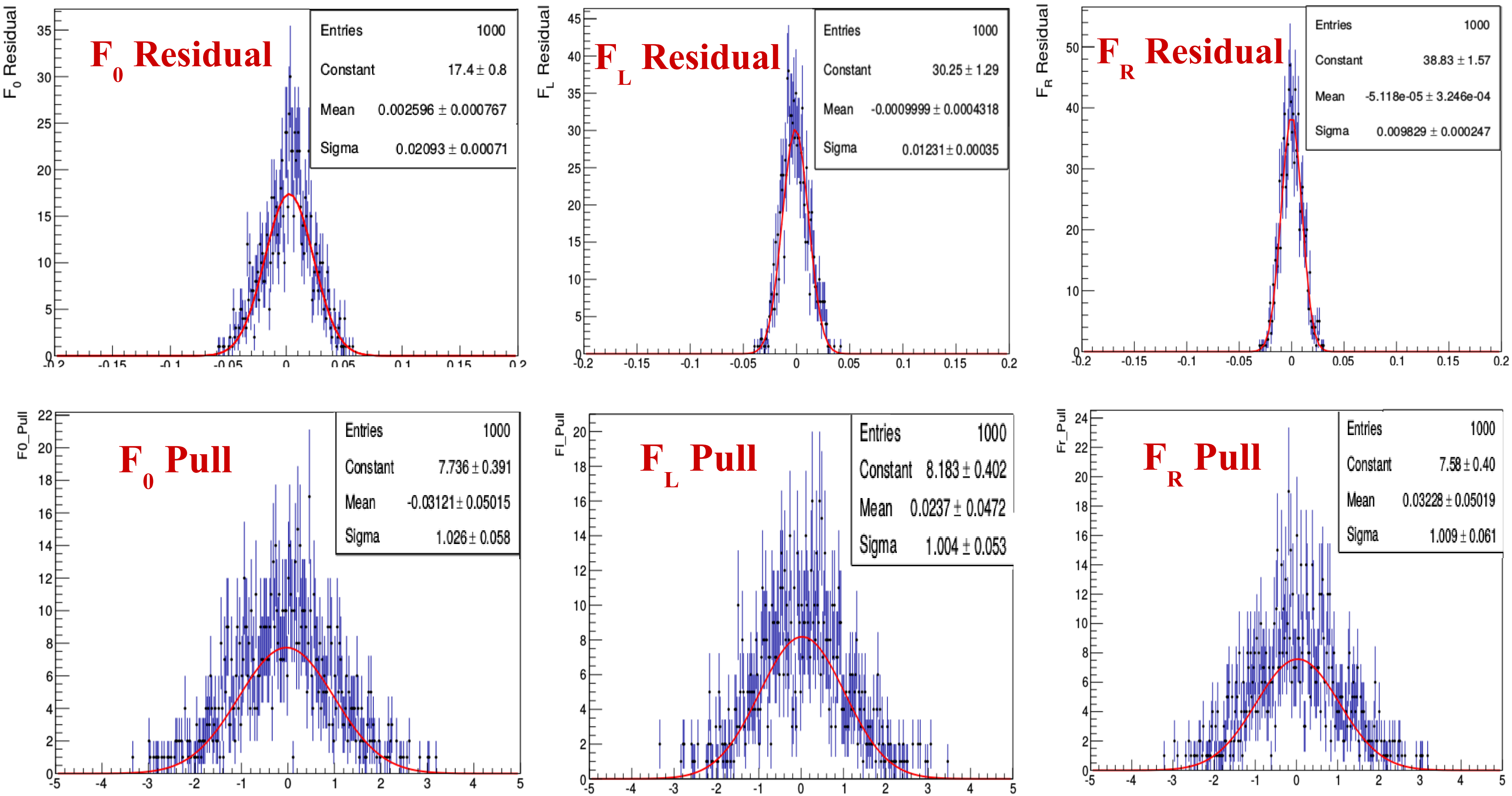
$$pull = \frac{F^{est} - F^{exp}}{\sigma^{est}}$$

Statistical uncertainty on the estimated polarization

- The residual and pull distributions are fitted with Gaussian function.

It is expected the pull and residual distributions are centered close to zero.

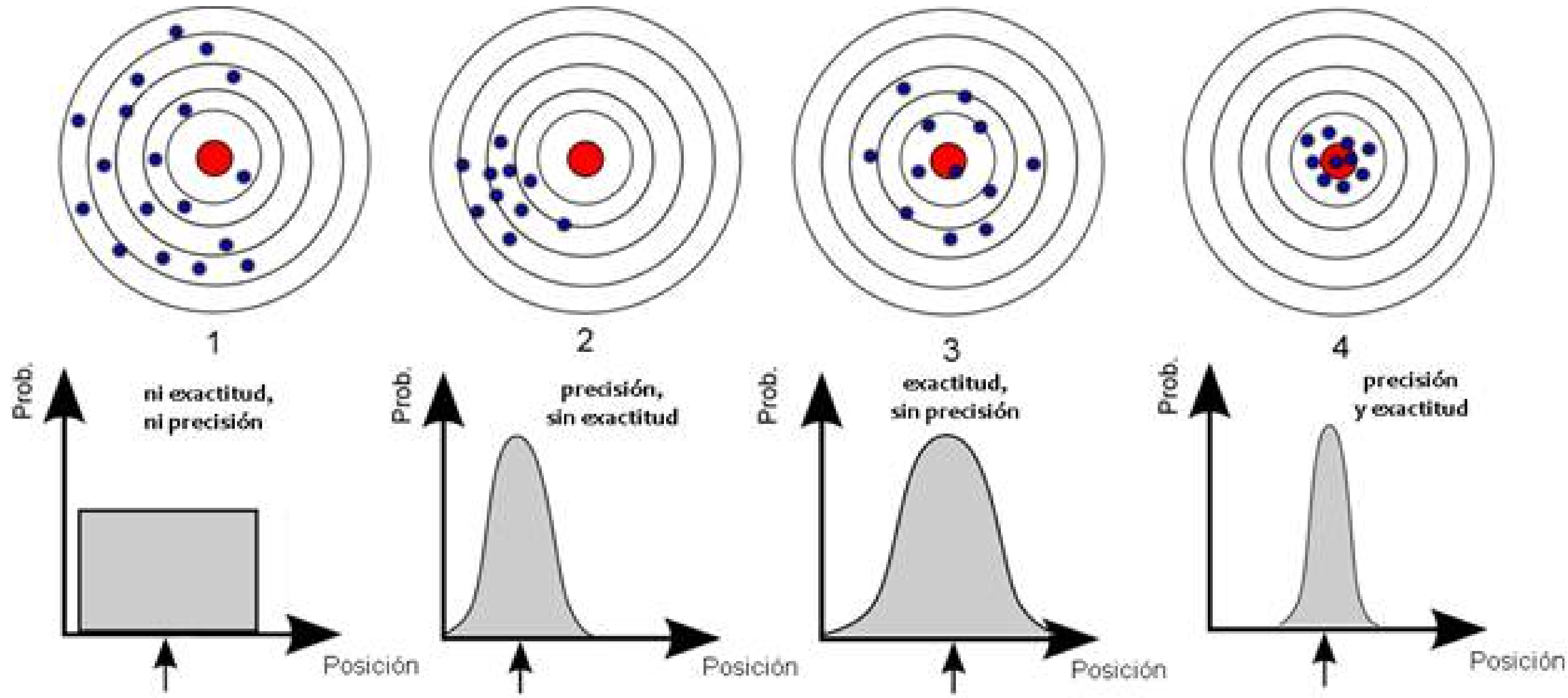
Also the width of Gaussian fit on the pull distributions is compatible with unity.

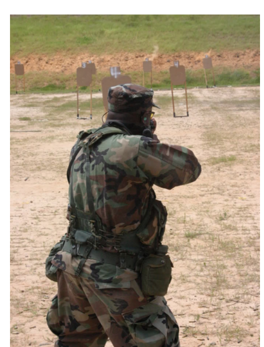


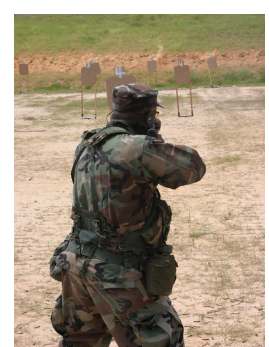
The likelihood estimator does not introduce significant biases.
The uncertainties returned by the fitter are determined properly.

Statistical v.s systematic uncertainty

Statistical unc.	large	small	large	small
Systematic unc.	large	large	small	small







Systematics treatment

Systematic estimation:

➔ To suppress the fluctuation effect of the data, many pseudo-data are produced for each systematic source in the form of up and down templates.

➔ Given the up and down variation, the systematic uncertainty is taken as averaging over the variations relative to the nominal value.

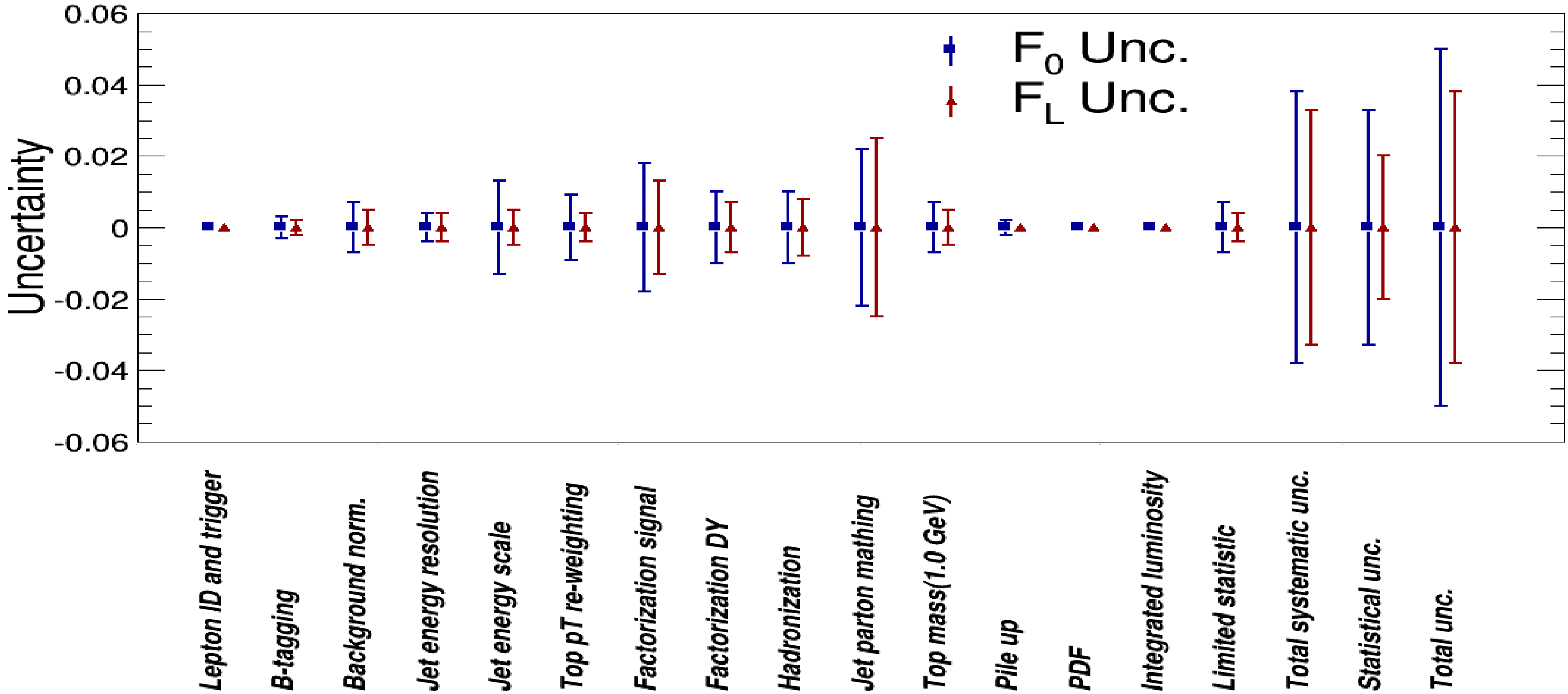
- By assuming no correlation between individual systematic sources, the single uncertainties are added in quadrature to obtain the total uncertainty of F_0 and F_L:

$$\sigma_{total} = \sum_{i=1}^{n} \sigma_i^2$$

- The uncertainties of F_0 and F_L are propagated to the F_R fraction according to the law of error propagation:

$$\delta F_R = \sqrt{\delta F_L^2 + \delta F_0^2 + 2\rho\delta F_L \delta F_0}$$

Systematic uncertainties



- The **renormalization scale and jet-parton matching** sources make the large bias in helicity measurements.
- The helicity measurement is systematic dominant.

Measurements:

Di Electron
F_0 = 0.617 ± 0.037 (stat) ± 0.065 (sys)
F_L = 0.330 ± 0.022 (stat) ± 0.048 (sys)
F_R = 0.053 ± 0.019 (stat) ± 0.047 (sys)

Di Muon
F_0 = 0.636 ± 0.033 (stat) ± 0.038 (sys)
F_L = 0.337 ± 0.020 (stat) ± 0.033 (sys)
F_R = 0.027 ± 0.016(stat) ± 0.038 (sys)

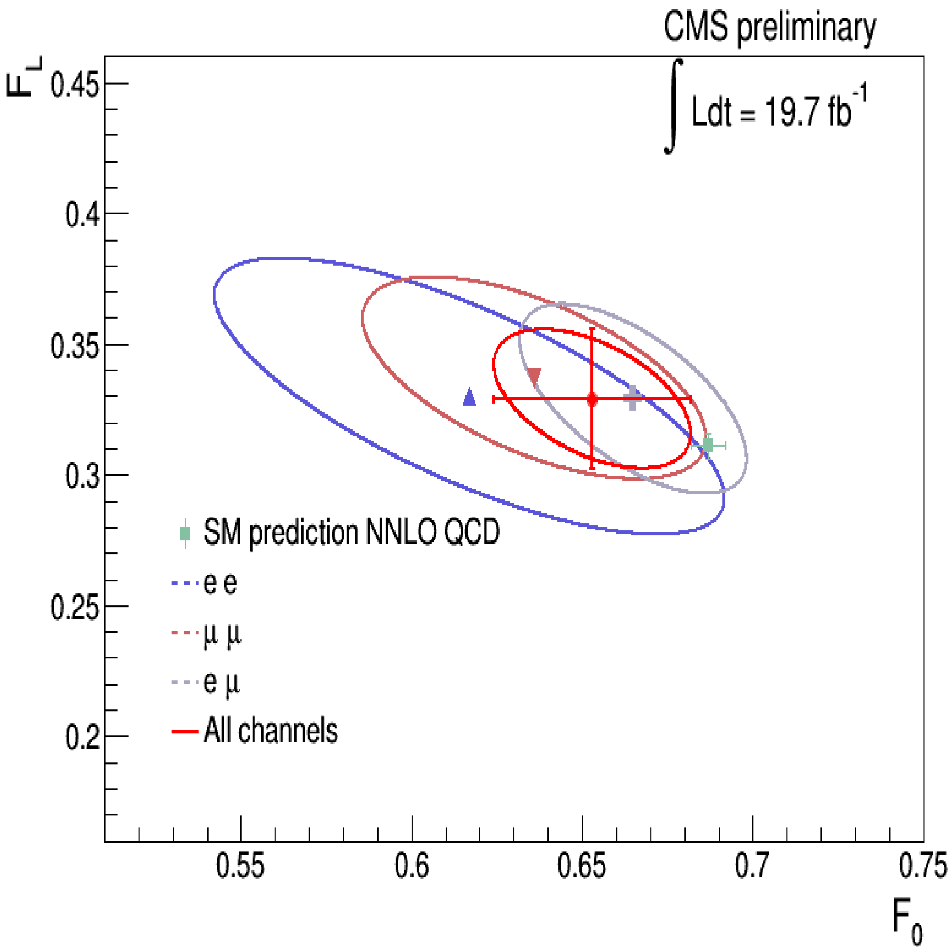
Elec Muon
F_0 = 0.665 ± 0.020 (stat) ± 0.022 (sys)
F_L = 0.329 ± 0.012 (stat) ± 0.032 (sys)
F_R = 0.007 ± 0.009 (stat) ± 0.026 (sys)

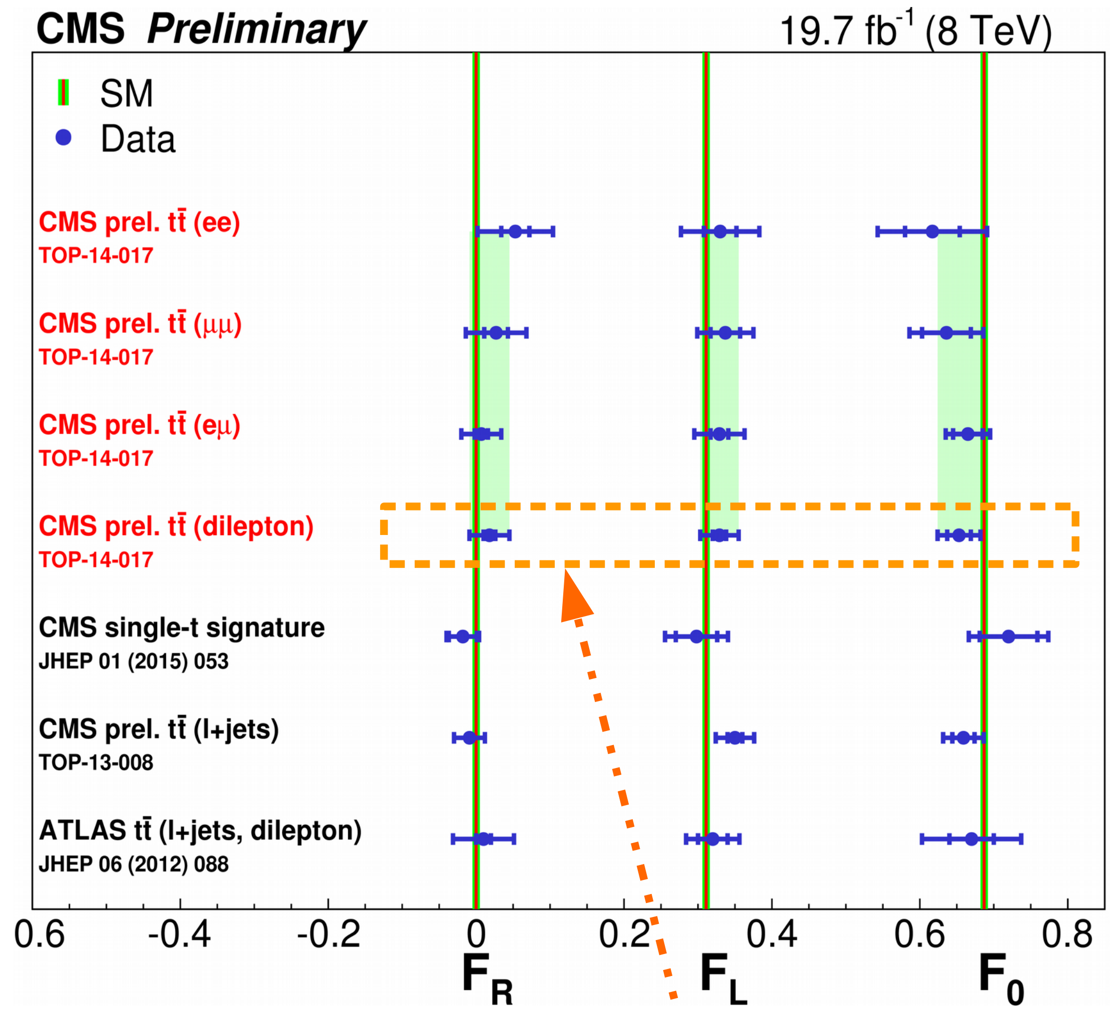
All channels
F_0 = 0.653 ± 0.016 (stat) ± 0.024 (sys)
F_L = 0.329 ± 0.009 (stat) ± 0.025 (sys)
F_R = 0.018 ± 0.008 (stat) ± 0.026 (sys)

- Apart from the **$\mu^+\mu^-$** channel, the helicity fractions are also measured from the best-fit to the data in **e^+e^-, $e^\pm\mu^\mp$**, and **sum of all channels**.

The measured W helicty fractions are compatible with the SM predictions.

Comparison with other experiments



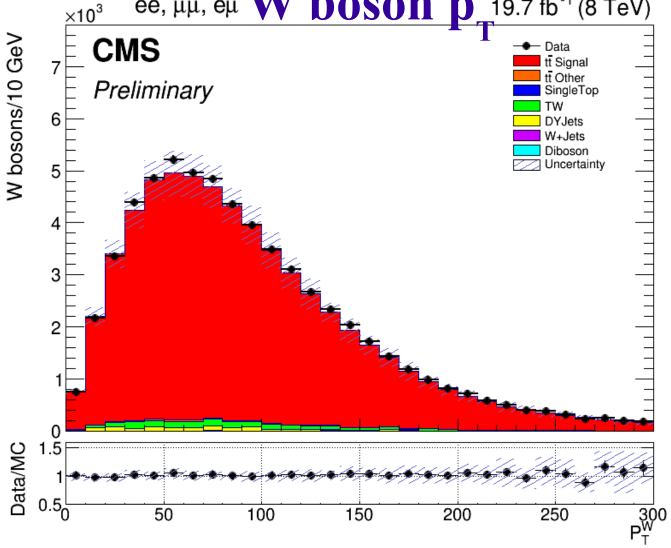


A good agreement with the other experiments as well as SM prediction is observed.

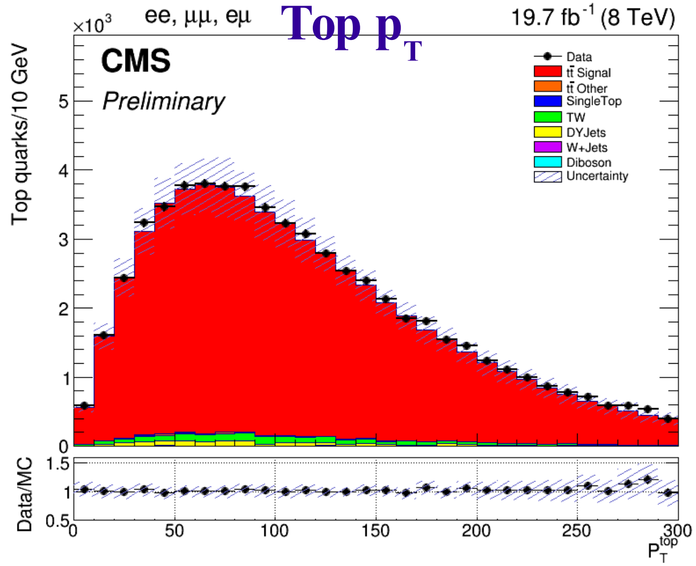
In comparison, the current result for the CMS di-lepton channel is by far the one of the precise measurement !.

Thanks for your attention!

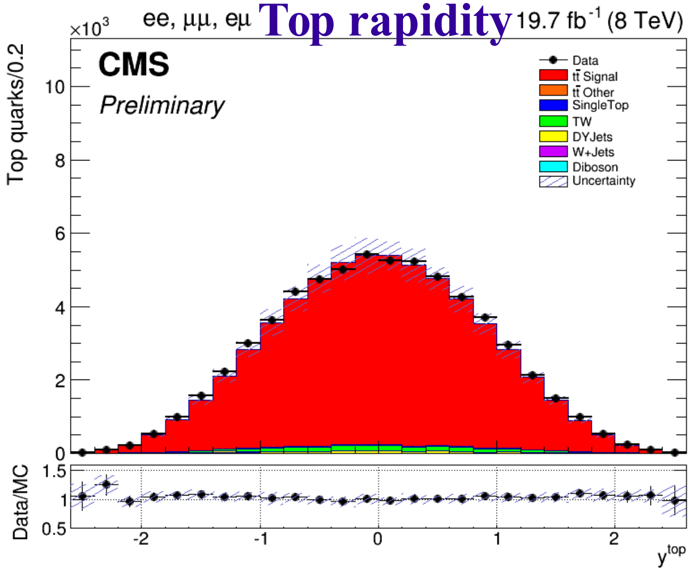
W boson p_T



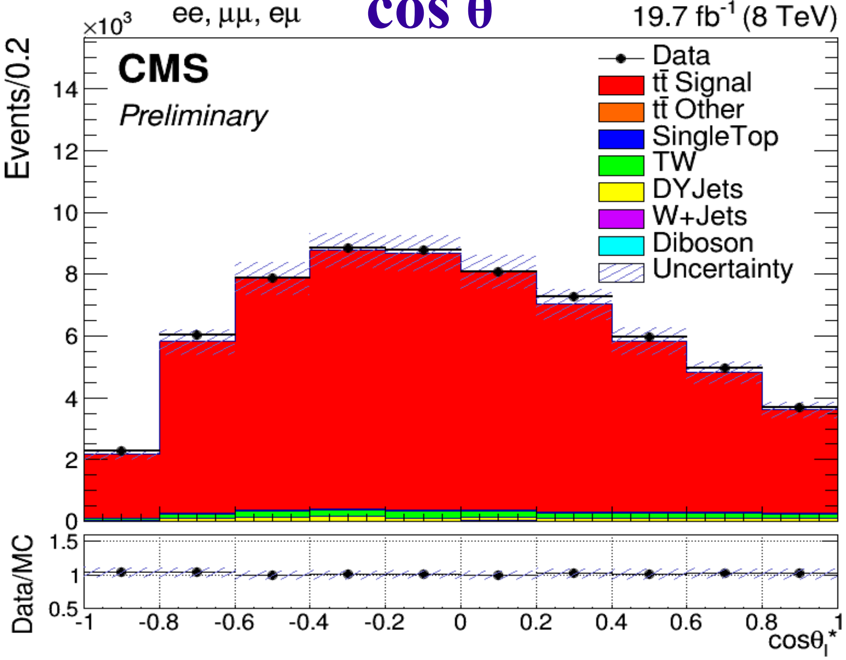
Top p_T



Top rapidity

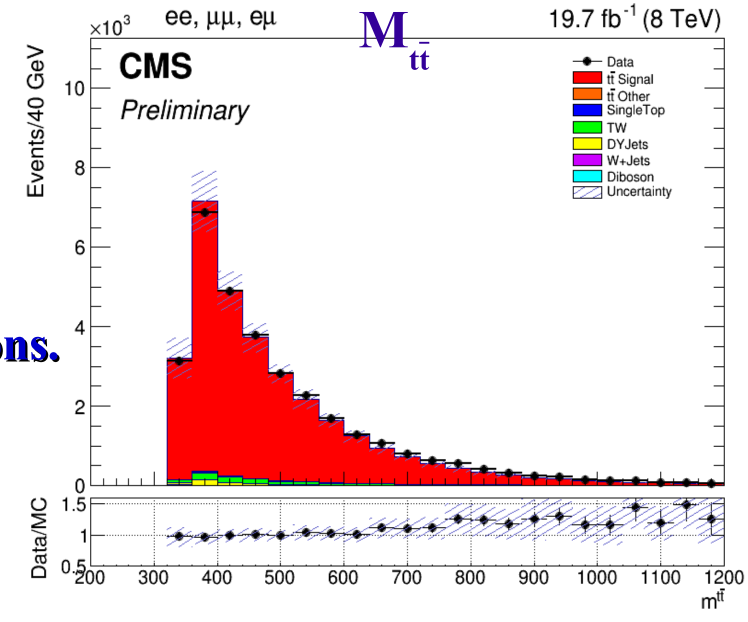


$\cos\theta^*$



The hatched regions display the systematic Uncertainties around the simulated expectations.

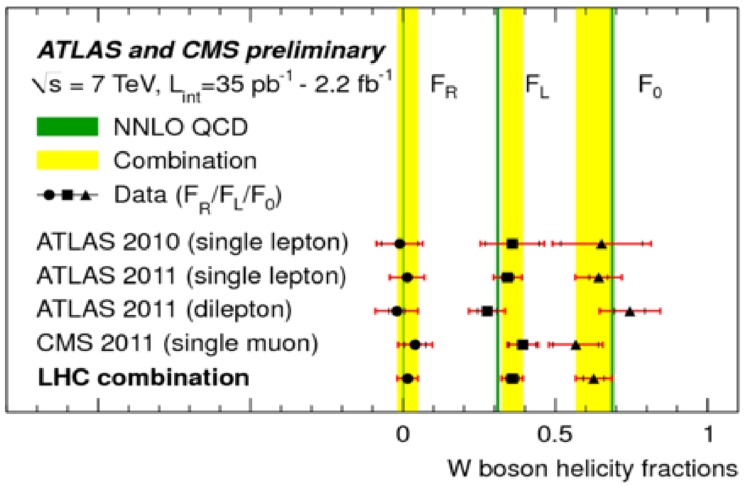
$M_{t\bar{t}}$



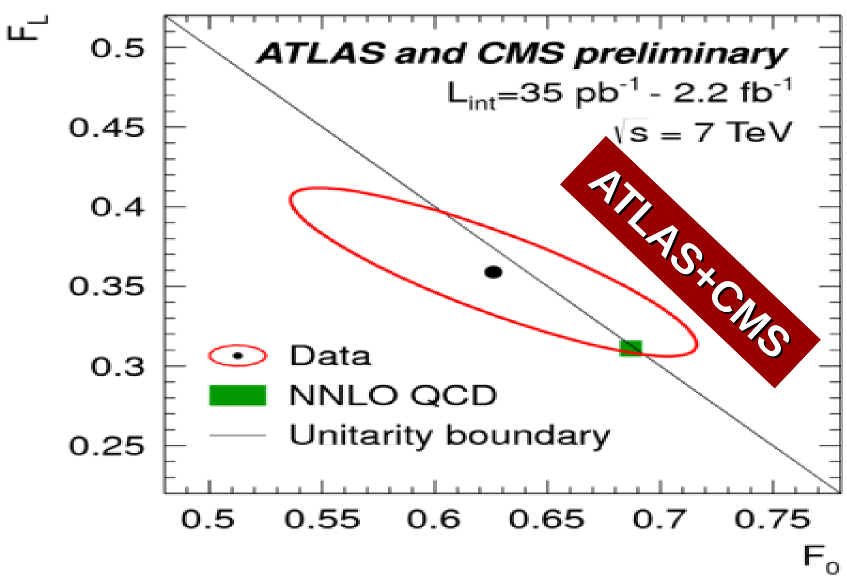
W Helicity at LHC @ 7 TeV

Results with ATLAS+CMS(35pb^{-1}-2.2fb^{-1})

- $t\bar{t}$ events in the lepton+jets final state



ATLAS-CONF-2013-033

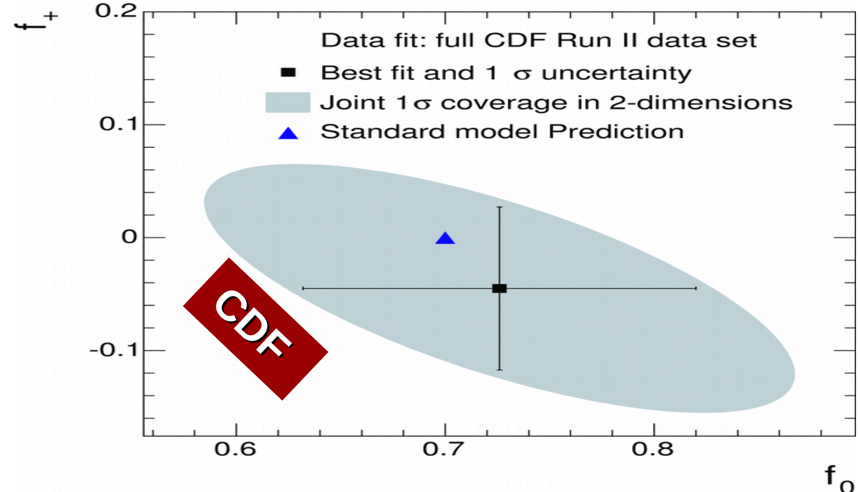


F_0 = 0.626±0.034(stat.)±0.048(syst.)
F_L = 0.359±0.021(stat.)±0.028(syst.)
F_R = 0.015±0.034(stat.+syst.)

W helicity at Tevatron

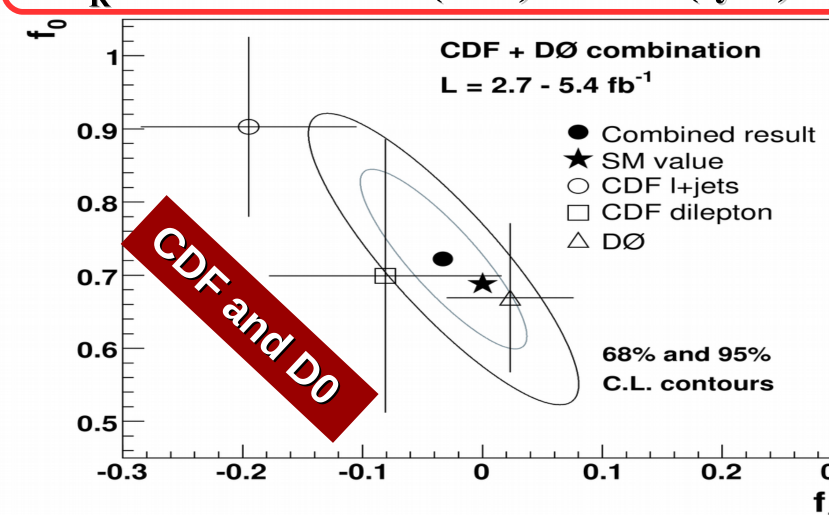
Results with CDF (8.7fb^{-1})

- $t\bar{t}$ events in the lepton+jets final state
- matrix element method



PRD 87 031104(R)

F_0 = 0.726 ± 0.066 (stat.) ± 0.067 (syst.)
F_R = -0.045 ± 0.043 (stat.) ± 0.058 (syst.)



Phys. Rev. D 85, 071106(R)

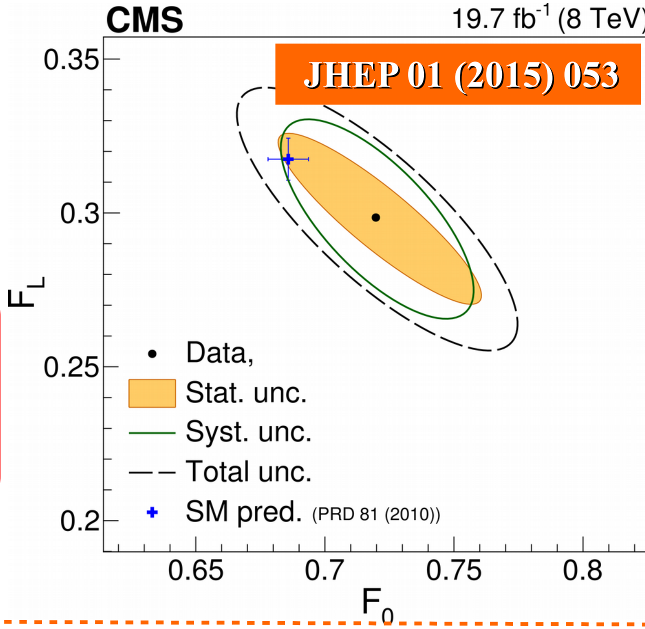
F_0 =0.722 ± 0.062 (stat.) ±0.052 (syst.)
F_R = −0.033 ± 0.034 (stat.) ± 0.031 (syst.)

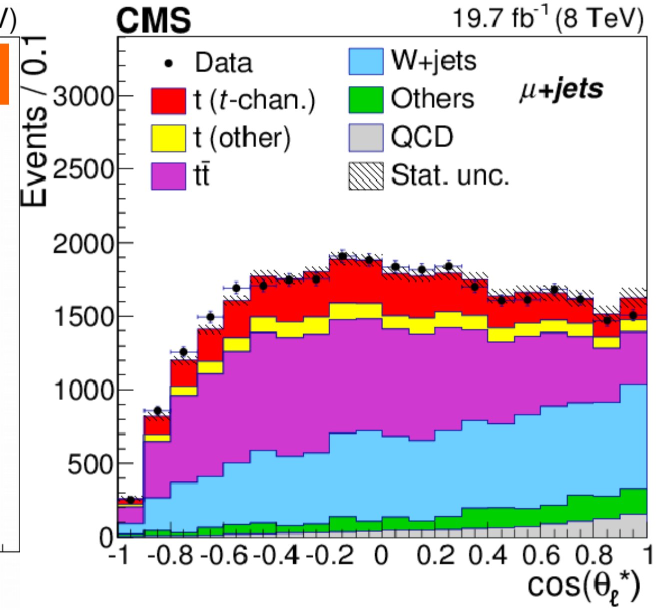
W helicity in single top(t-ch.) signature @ 8 TeV(19.7 fb^{-1})

- W helicity reweighed for single-top, tW and $t\bar{t}$ events
- Cosθ* distribution of observed events fitted with MC weighted distribution
- Free parameters F_0 , F_L

Combination(e+jets, μ+jets):
F_0 =0.720±0.039(stat.)±0.037(syst.),
F_L =0.298±0.028(stat.)±0.032(syst.),
F_R =-0.018±0.019(stat.)±0.011(syst.)

$\Delta F_0 / F_0$ =7.46%, $\Delta F_L / F_L$=14.26%



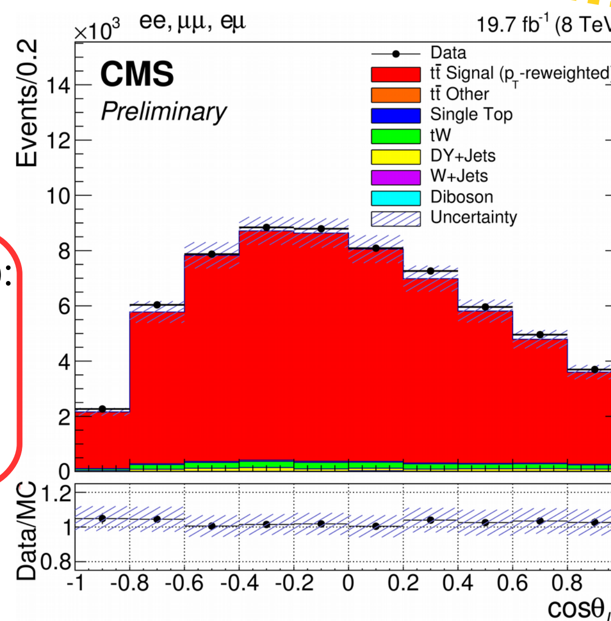


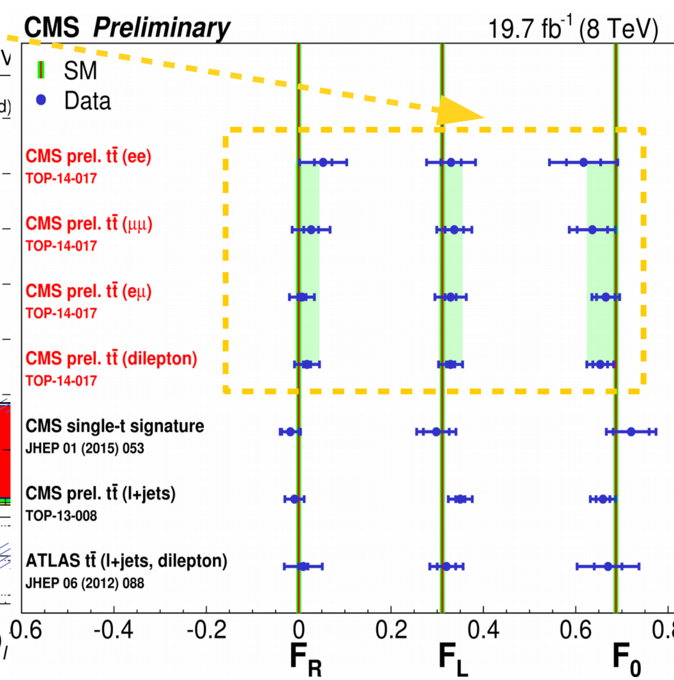
W helicity in top pair(ll+jets) signature @ 8 TeV(19.7 fb^{-1})

- Signal weighted event-by-event
- The weighted distribution of cosθ* fitted to the observed one
- Free parameters: F_0 , F_L
- F_R bounded with $\mathbf{F_0 + F_L + F_R = 1}$

Combination(ee+jets, μμ+jets, eμ+jets):
F_0 =0.653 ± 0.016 (stat) ± 0.024 (sys),
F_L =0.329 ± 0.009 (stat) ± 0.025 (sys),
F_R =0.018 ± 0.008 (stat) ± 0.026 (sys)

$\Delta F_0 / F_0$ =4.41%, $\Delta F_L / F_L$=8.08%





CMS PAS TOP-14-017

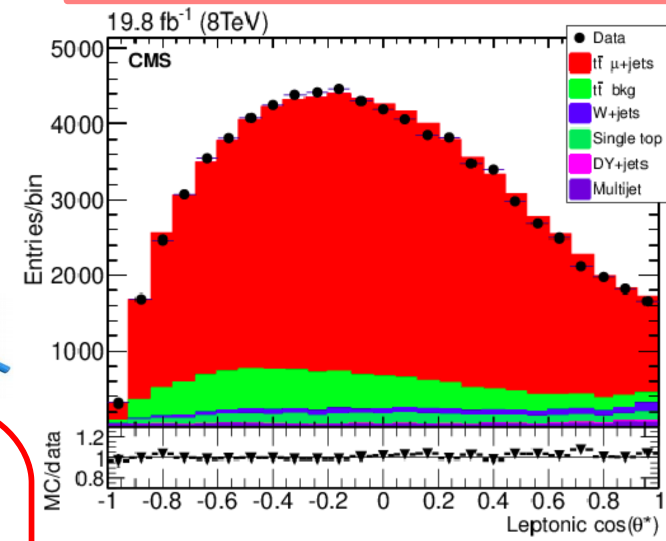
W helicity in top pair(l+jets) signature @ 8 TeV(19.8 fb^{-1})

New

arXiv:1605.09047, submitted to PLB

$$t\bar{t} \rightarrow (W^+b)(W^-\bar{b}) \rightarrow (\ell^+\nu_b)(q\bar{q}\bar{b})$$

- one lepton(e or μ)
- At least four high energetic jets(55, 45, 35, and 20 GeV), two of jets being tagged as b-jets.

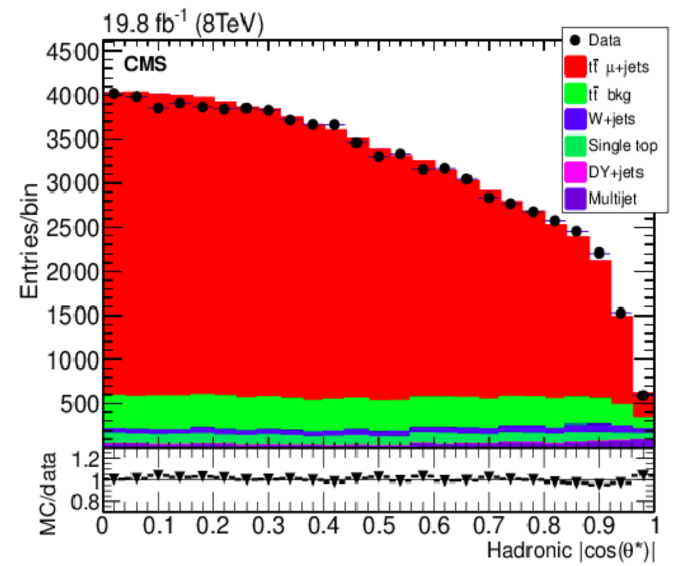


- Main backgrounds: top pair, single top,W+jets, DY+jets
- Vetoing events with additional isolated leptons(e or μ)
- Normalization of multijet background taken from data.
- Transverse mass of the W boson: 30 < M_T < 200 GeV

➡ reduce the multijet background and dilepton $t\bar{t}$ events

- The final sample composition dominated by:

➡ $t\bar{t}$ events, 82% (l+jets), ~10% (other modes), and single top ~ 3.5%



For all processes **containing top quarks**, each event is re-weighted as:

$$w_{\text{lep/had/single-t}}(\cos\theta^*_{\text{gen}};\vec{F}) \equiv \frac{\frac{3}{8}F_L(1-\cos\theta^*_{\text{gen}})^2 + \frac{3}{4}F_0\sin^2\theta^*_{\text{gen}} + \frac{3}{8}F_R(1+\cos\theta^*_{\text{gen}})^2}{\frac{3}{8}F_L^{SM}(1-\cos\theta^*_{\text{gen}})^2 + \frac{3}{4}F_0^{SM}\sin^2\theta^*_{\text{gen}} + \frac{3}{8}F_R^{SM}(1+\cos\theta^*_{\text{gen}})^2}$$

arXiv:1605.09047, submitted to PLB

Combination(e+jets, μ+jets):

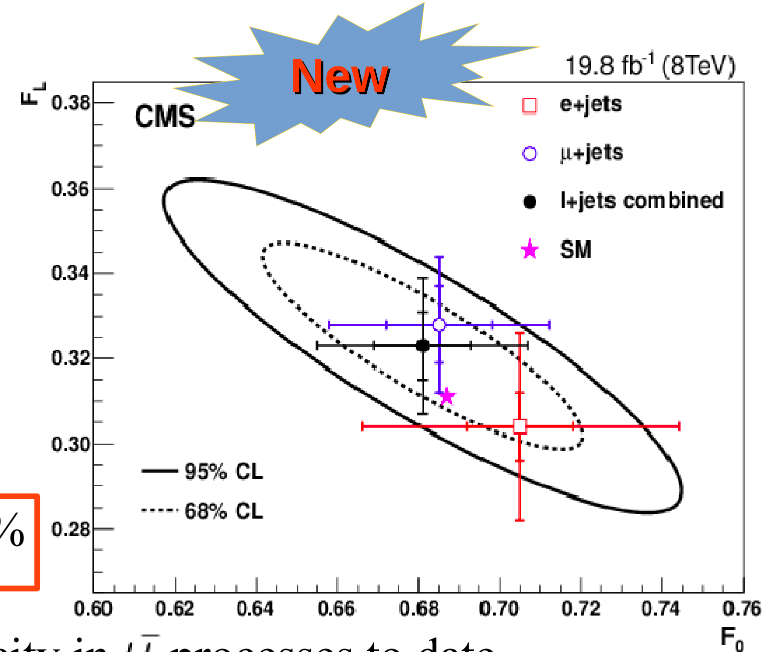
F_0 =0.681± 0.012(stat.) ± 0.023(syst.),

F_L =0.323 ± 0.008(stat.) ± 0.014(syst.).

F_R bounded by the unitary constrain,

➠ F_R =-0.004 ± 0.005(stat.) ± 0.014(syst.)

$\Delta F_0 / F_0$ =3.80%, $\Delta F_L / F_L$=4.99% precision of better than 5%



➠ The most accurate experimental results of W boson helicity in $t\bar{t}$ processes to date.

The potential deviation from the SM can be interpreted in terms of anomalous tWb couplings.

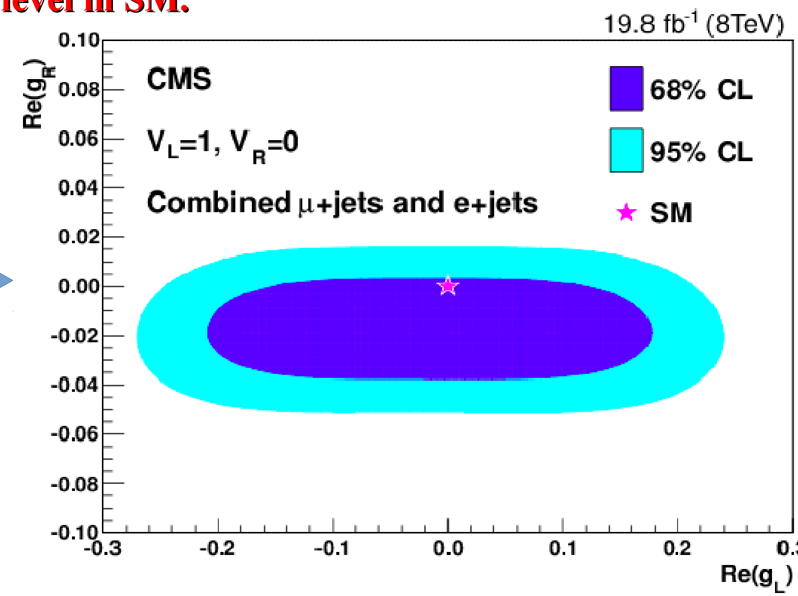
$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + \text{h.c.}$$

Eur.Phys.J. C50 (2007) 519-533

Vector (V_R) and Tensor like couplings (g_L , g_R) are zero @ tree level in SM.

- Fix the two vector couplings to their SM values,

➠ V_L=1 and V_R=0



Searches for Rare Top Decays

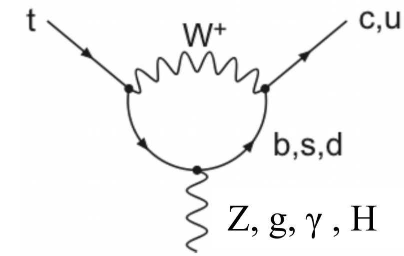
Flavour Changing Neutral Currents

SM: FCNC is forbidden at tree level

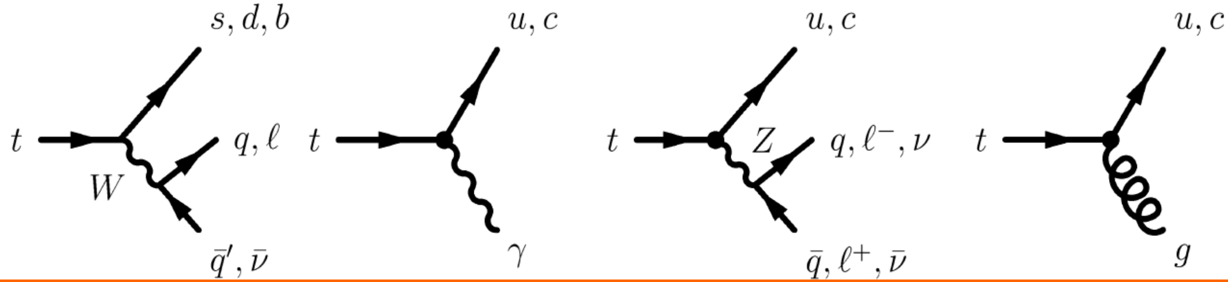
highly suppressed at higher orders O(10^{-13} - 10^{-15}) by GIM Mechanism

BSM: FCNC couplings are enhanced up to O(10^{-4} - 10^{-5})

powerful probe for new physics



To probe FCNC effects in the top sector, a useful approach is to adopt a model independent search.



Process	SM	QS	2HDM	FC 2HDM	MSSM	R SUSY	RS
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	-	-	2×10^{-6}	3×10^{-5}	-
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim10^{-7}$	$\sim10^{-10}$	2×10^{-6}	3×10^{-5}	$\leq10^{-5}$
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	-	-	2×10^{-6}	1×10^{-6}	-
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim10^{-6}$	$\sim10^{-9}$	2×10^{-6}	1×10^{-6}	$\leq10^{-9}$
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	-	-	8×10^{-5}	2×10^{-4}	-
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim10^{-4}$	$\sim10^{-8}$	8×10^{-5}	2×10^{-4}	$\leq10^{-10}$
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	-	10^{-5}	$\sim10^{-6}$	-
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim10^{-5}$	10^{-5}	$\sim10^{-6}$	$\leq10^{-4}$

Acta Phys.Polon.B35,2695(2004), arXiv:1311.2028

The FCNC searches are performed either **in decays of top pair** events or in **single top production**.

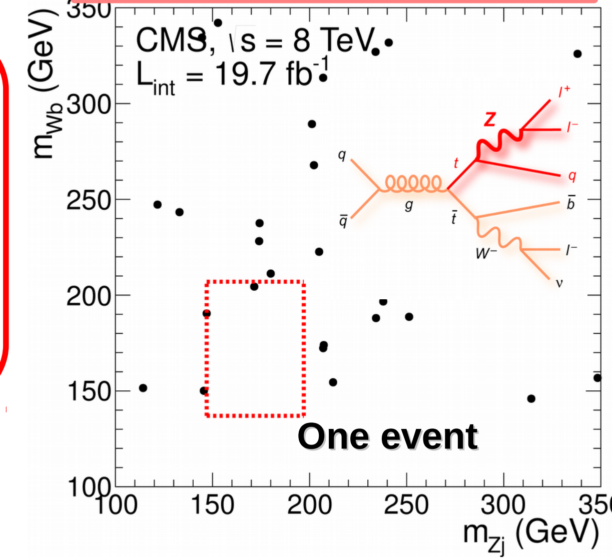
will only cover the most recent results in the next slides.

$t \to Zq(q = u, c)$ in $t\bar{t}$

- 3 isolated leptons(e,μ)
- ≥ 2 jets, only one b-tag
- Missing energy and mass cuts on $\mathbf{m_{Zj}}$ and $\mathbf{m_{Wb}}$

- Main backgrounds: di-boson, DY, $t\bar{t}$, $t\bar{t}$+V
- Data driven BKG estimation via b-tag bins information (0:Diboson, 1: FCNC signal, 2: $t\bar{t}$+X)
- 2D scatter distributions of m_{Wb} -m_{Zj}
- CLs limits from counting the yields

Phys. Rev. Lett. 112 (2014) 171802



Results

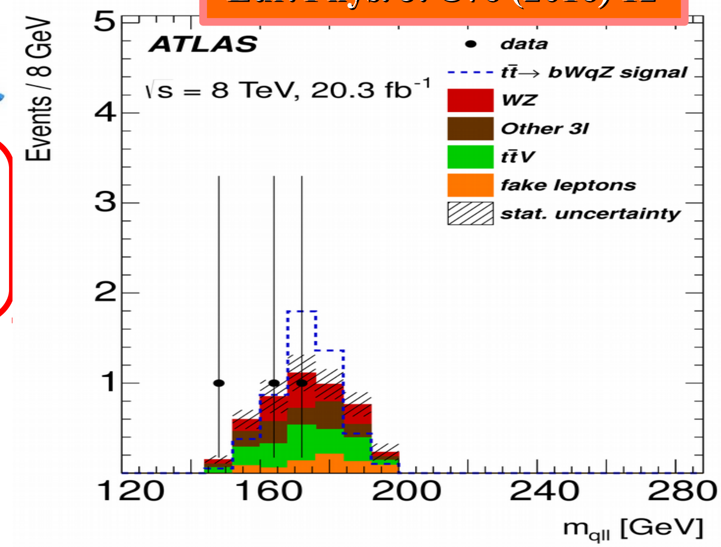
95% limit	-σ	Exp.	+σ	Obs.
8 TeV	0.06%	0.10%	0.13%	0.06%
7+8TeV	0.06%	0.09%	0.13%	0.05%

Main sys. : b-tagging, renormalizaton/factorizaton. scale, PDF

- 3 isolated leptons(e,μ)
- 2-3 jets, 1-2 b-tag
- Missing energy and χ^2 cut(from masses)

Backgrounds from simulation, validated in control regions
CLs limits from the yields

Eur. Phys. J. C76 (2016) 12



Results

95% limit	-σ	Exp.	+σ	Obs.
8 TeV	0.06%	0.08%	0.12%	0.07%

Main sys. :Modeling, b-tagging, Jet energy scale

Search for t → qH decays(CMS):

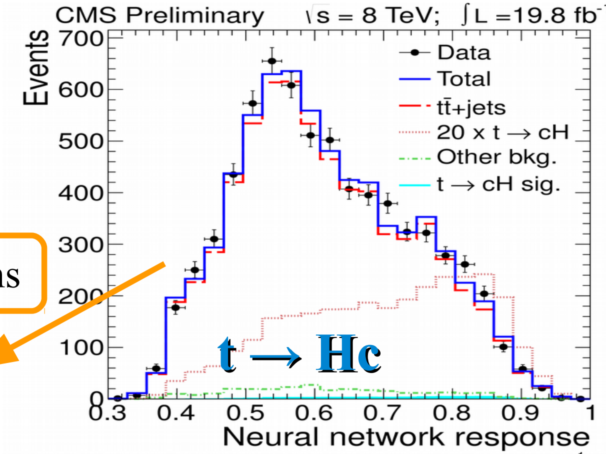
t → Hq → bbq and t → Wb → lνb CMS-PAS-TOP-14-020

One isolated lepton and >= 4 jets (with >= 3 b-jets), 2nd lepton veto

Main background: $t\bar{t}$
Signal extracted with template fit.

Sys: jet energy, PDF, b-tagging, cross sections

B(t → Hc) < 1.16 % (0.89%) for obs.(exp.) at 95% CL
B(t → Hu) < 1.92 % (0.85%) for obs.(exp.)at 95% CL



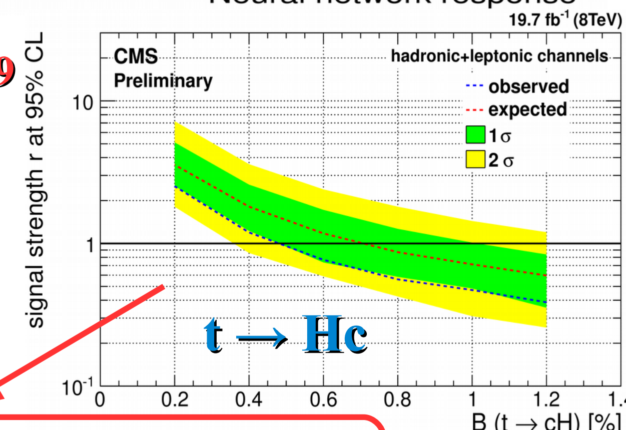
t → Hq → γγq and t → Wb → lνb or qqb CMS-PAS-TOP-14-019

Two high energetic photons
Leptonic channel: one lepton and >= 2 jets (one b-jet)
Hadronic channel: >= 4jets (one b-jet), m_T (W) and top mass cuts.

$t\bar{t}$H, resonant γγ background from MC, **non resonant** γγ background fitted from data
Signal extracted with template fit

Sys: $t\bar{t}$ and background modeling, photonID

B(t → Hc) < 0.47 % (0.71%) for obs.(exp.)at 95% CL
B(t → Hu) < 0.42 % (0.65%) for obs.(exp.) at 95% CL

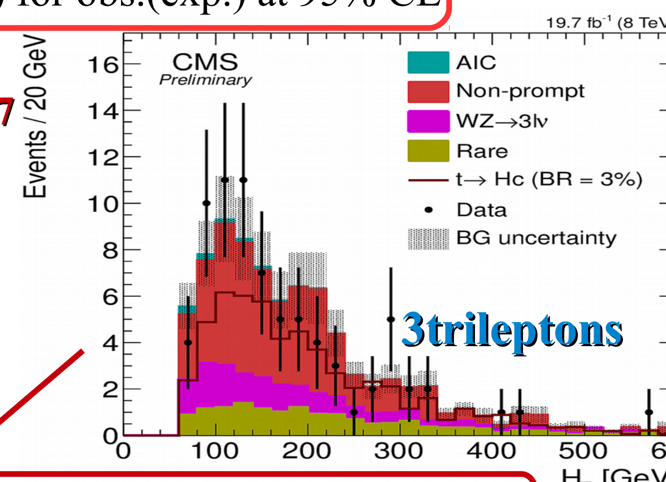


t → Hq → ZZq or WWq and t → Wb → lνb

Three isolated leptons (p_T>20, 10, 10GeV) and >=2 jets CMS-PAS-TOP-13-017

Same-signed di-lepton: Z veto with $|M_{ee} - M_Z| > 15$GeV, MET dep. HT cut
Trilepton: $|M_{OSSF} - M_Z| > 15$GeV, $|M_{lll} - M_Z| > 10$ GeV, $M_{OSSF} > 40$ GeV
WZ(3L), non-prompt (2L), rare SM
Data driven estimation of large non-prompt lepton background, Z→ 3l and charge misidentification.

Sys: Background modeling / cross sections, electron charge misidentification, lepton misidentification



Combined: B(t → Hc) < 0.89 % (obs)at 95% CL

t →Hq→bbq and t→Wb→lνb

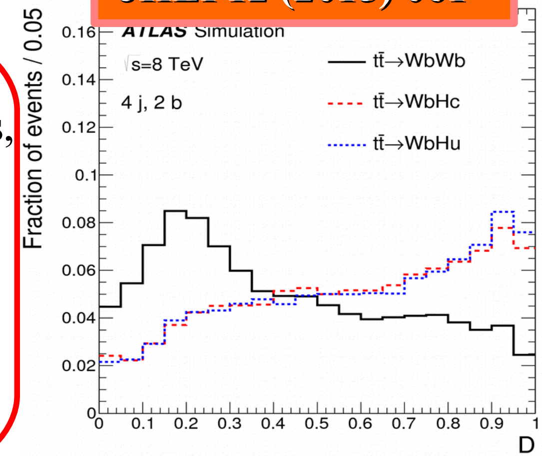
JHEP12 (2015) 061

An isolated lepton(e,mu),
>= four jets (>= 2b-tagged),
Large missing energy

Categories based on (jet, b-tag) multiplicity,
(4j, 3b) and (4j, 4b) are most sensitive channels,
Signal/background discriminant:

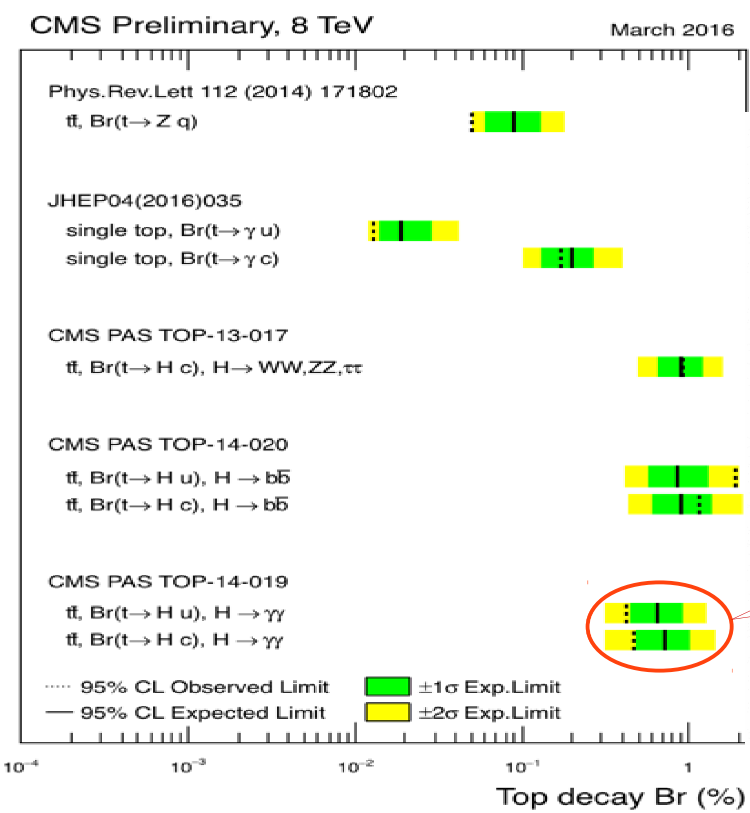
$$D(x) = \frac{P^{sig}(x)}{P^{sig}(x) + P^{bkg}(x)}$$

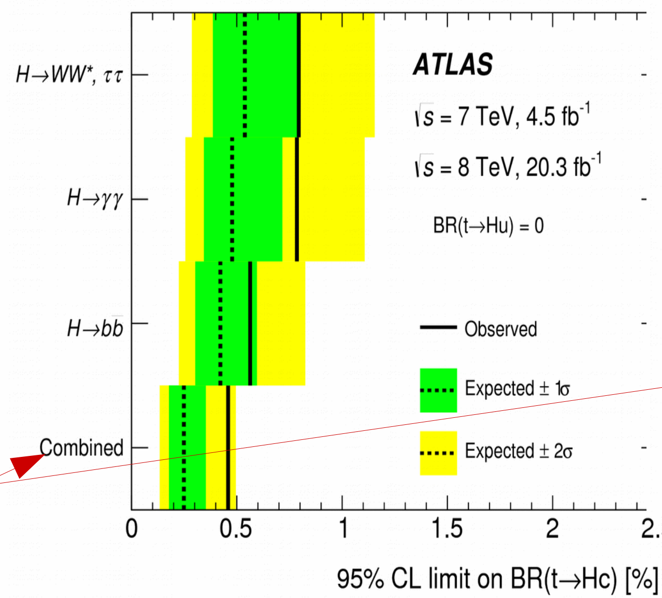
with P^{sig}, P^{bkg} PDFs using the resonances and jet flavour content of final state

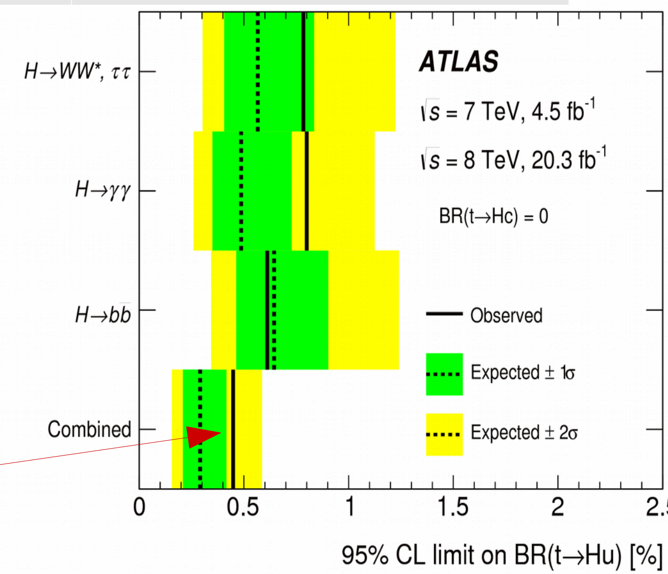


Main sys. $t\bar{t}$+jets modeling,
b-tagging

95% CL.	H→bb obs.(exp.)	H→WW/ττ, γγ, bb
t →Hu	61%(0.64%)	45%(0.29%)
t →Hc	56%(0.42%)	46%(0.25%)







Best limit on tqH interactions measured so far!