CMS Measurements of Single Top Quark Production Cross Section

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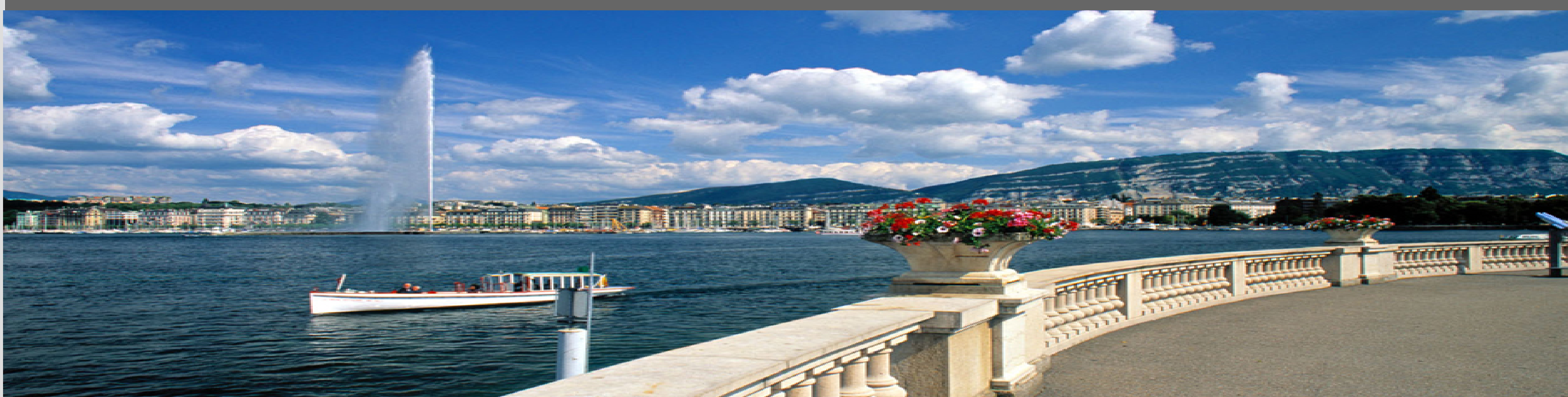


August 2016

Outline

- Motivation to Study the Single Top Quark
- Experimental Setup
- Selected CMS measurements of single top quark
  - S-channel cross section at 8 TeV
  - T-channel cross section (inclusive) at 13 TeV
  - TW-channel cross section at 8 TeV
  - Differential cross section for t-channel at 13 TeV

Top Quark Pair Production

- Top quark was discovered by CDF and D0 experiments in 1995.

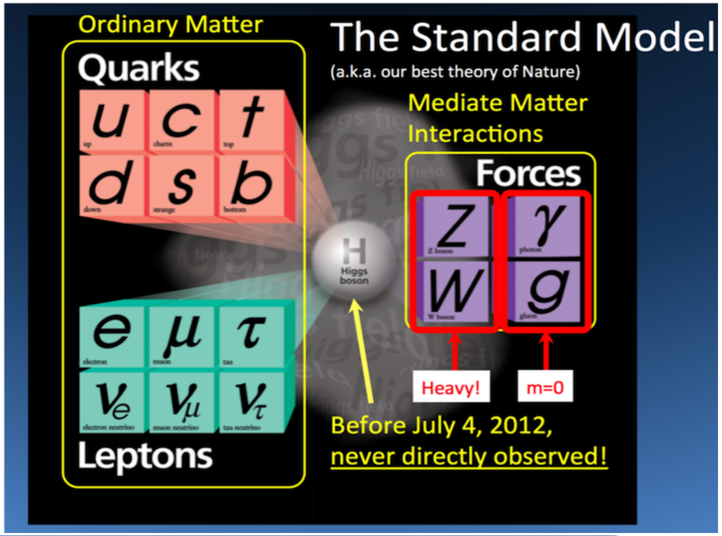
  Phys.Rev.Lett. 74 (1995) 2626–2631
  Phys.Rev.Lett. 74 (1995) 2632–2637

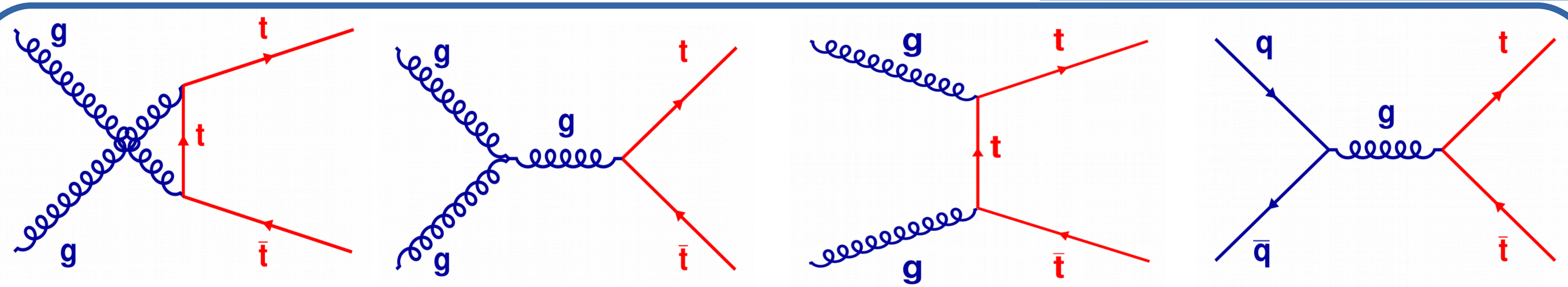
- Top mass measurement : 173.34 ± 0.76 GeV.

- Top decay width is large $\Gamma_t \propto m_t^3$:

  $\Gamma_t = 1.3\ \text{GeV} > \Lambda_{QCD} = 200\ \text{MeV} \rightarrow$

  Decay before hadronization→bare quark



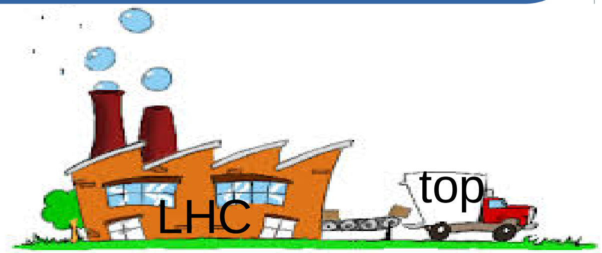


LHC: ~85% gg fusion

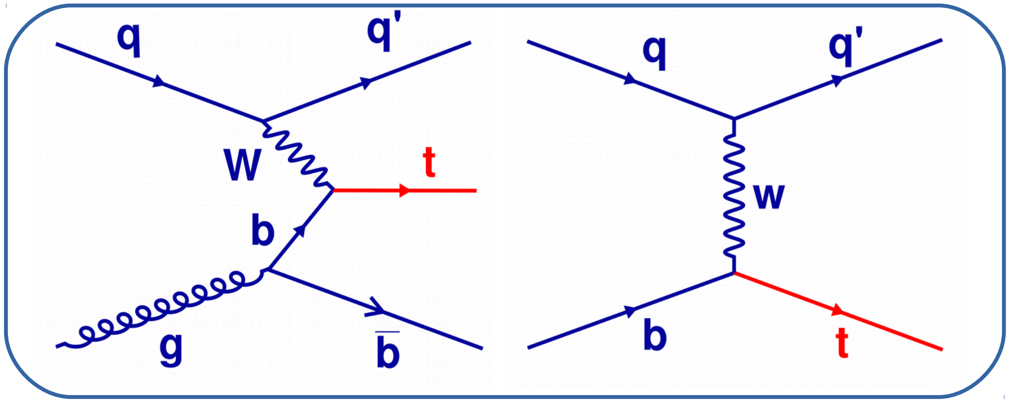
Tevatron: 85% qq' annihilation

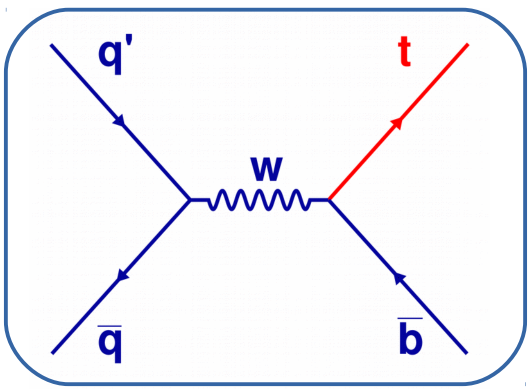
$\sigma_{t\bar{t}}$ = 245.8±9.7 pb LHC 8 TeV

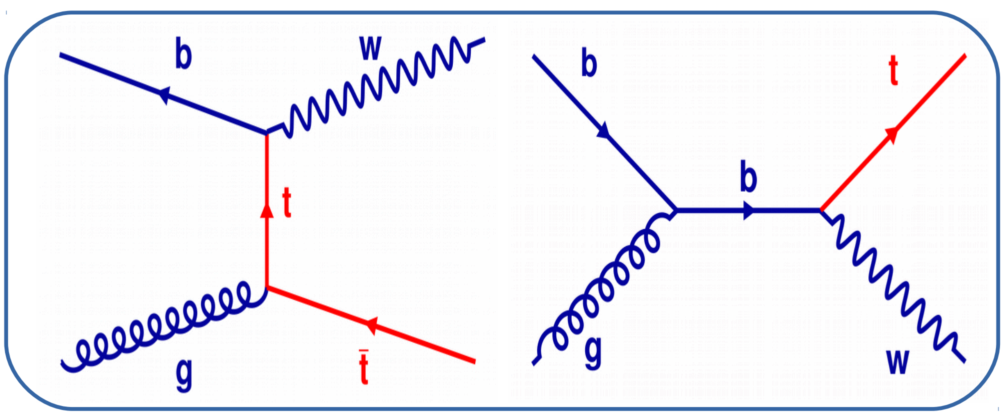
$\sigma_{t\bar{t}}$ = 7.164±0.21 pb Tevatron 1.96 TeV



Single Top Quark Production







	collider	total[pb]
t-channel	LHC 7 TeV	$65.9^{+2.1}_{-0.7}{}^{+1.5}_{-1.7}$
	LHC 8 TeV	$87.2^{+2.8}_{-1.0}{}^{+2.0}_{-2.2}$
	LHC 13 TeV	$216.99^{+6.62}_{-4.64} \pm 6.16$
	Tevatron 1.96 TeV	$2.08^{+0.00}_{-0.03} \pm 0.08$
s-channel	LHC 7 TeV	$4.56 \pm 0.07^{+0.18}_{-0.17}$
	LHC 8 TeV	$5.55 \pm 0.08 \pm 0.21$
	LHC 13 TeV	$10.32^{+0.29}_{-0.24} \pm 0.27$
	Tevatron 1.96 TeV	$1.046^{+0.001}_{-0.007}{}^{+0.042}_{-0.039}$
tW-channel	LHC 7 TeV	$15.6 \pm 0.03^{+0.7}_{-0.8}$
	LHC 8 TeV	$22.2 \pm 0.4 \pm 1.0$
	LHC 13 TeV	$60.20^{+3.03}_{-3.62} \pm 4.59$
	Tevatron 1.96 TeV	$0.14 \pm 0.02^{+0.01}_{-0.02} \pm 0.02$

What are s channel, t channel?

In two particles scattering, where p1 and p2 are the four-momenta of the incoming particles and p3 and p4 are the four-momenta of the outgoing particles:

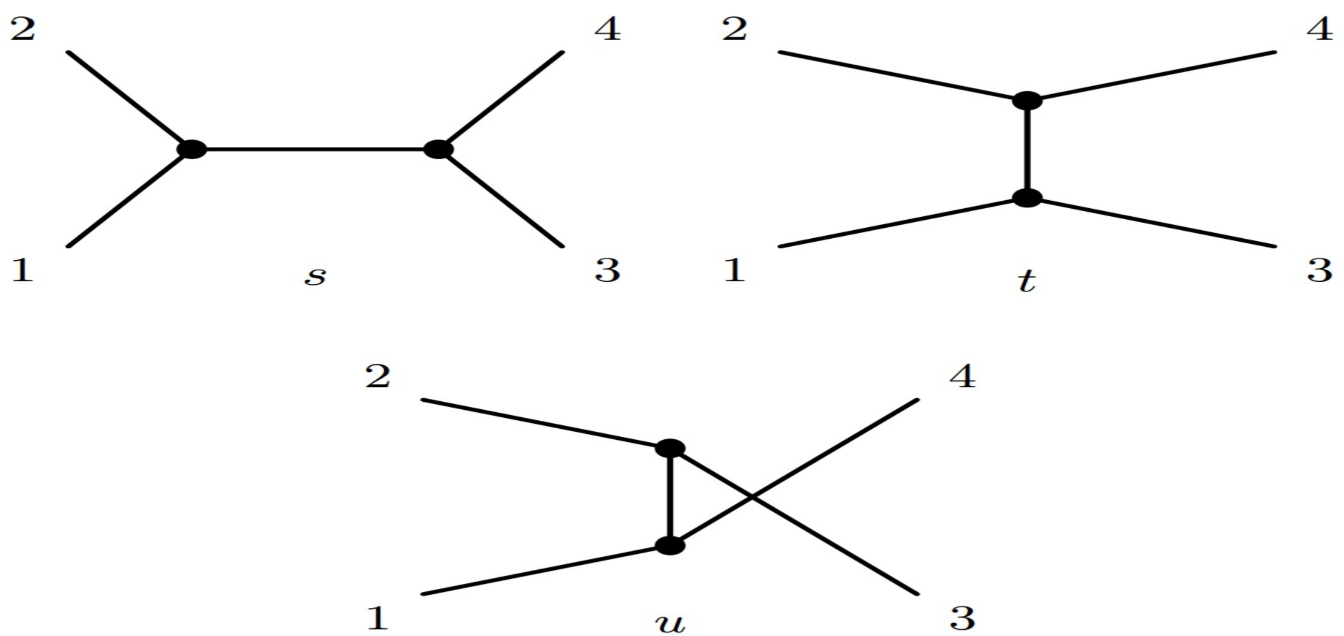
Mandelstam Variables

s=(p1+p2)2=(p3+p4)2

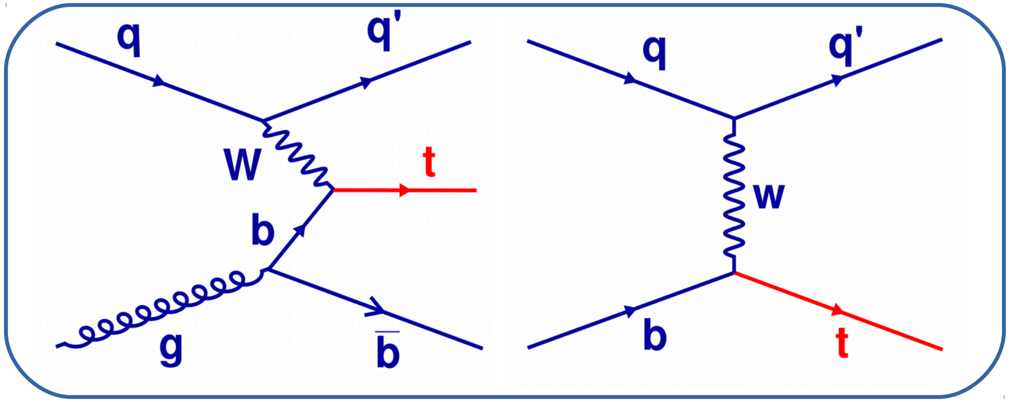
t=(p1−p3)2=(p2−p4)2

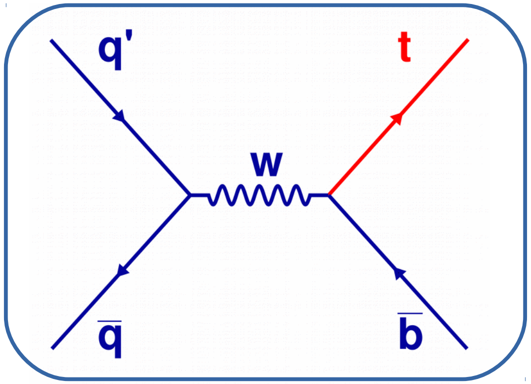
u=(p1−p4)2=(p2−p3)2

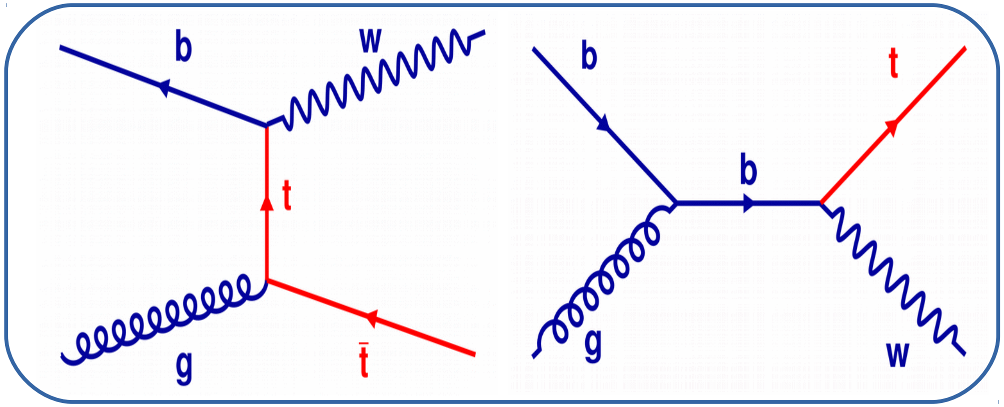
Four-momentum square of the mediator is the reference for the names of different feynman diagrams



Single Top Quark Production

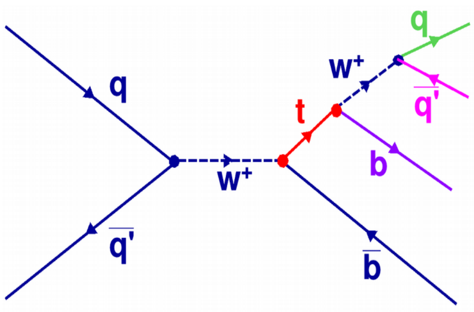




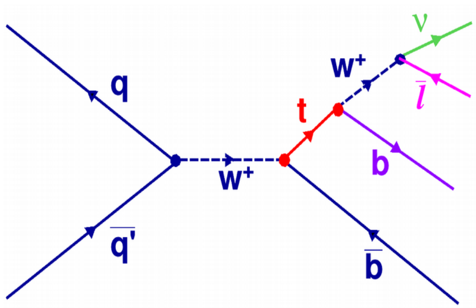


Top Quark Decay

- Top quark decays almost exclusively into a b quark and a W boson.
- W boson decays into quarks (in ~ 67% of cases) or into leptons (in ~ 33% of cases).



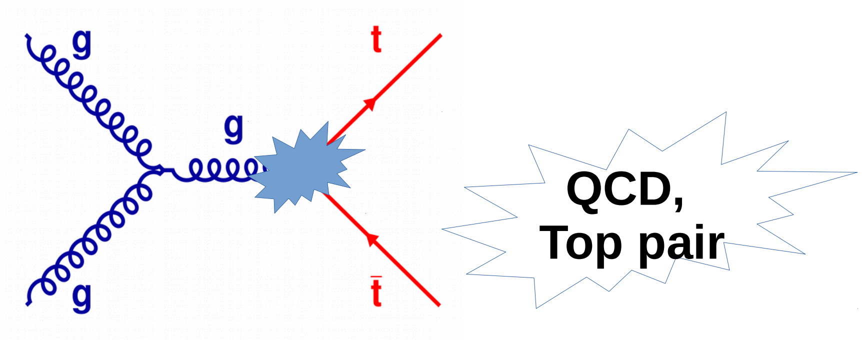
Hadronic decay

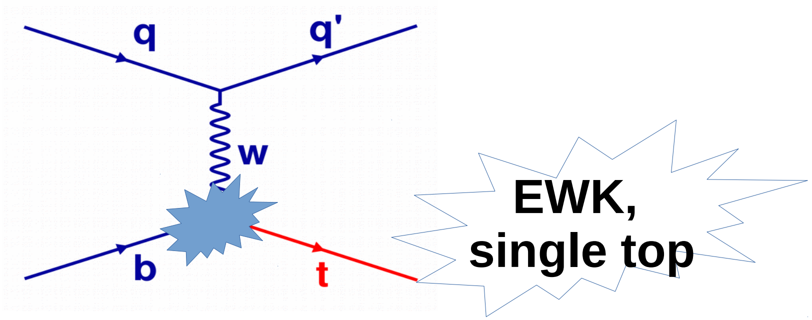


Leptonic decay

Why Single Top ?

Motivation





- Validates the electroweak in the SM
- Direct measurement of the CKM matrix element $|V_{tb}|$, Wtb vertex introduces

$$\frac{-ig}{2\sqrt{2}} V_{tb} \gamma^{\mu} (1 - \gamma^{5})$$

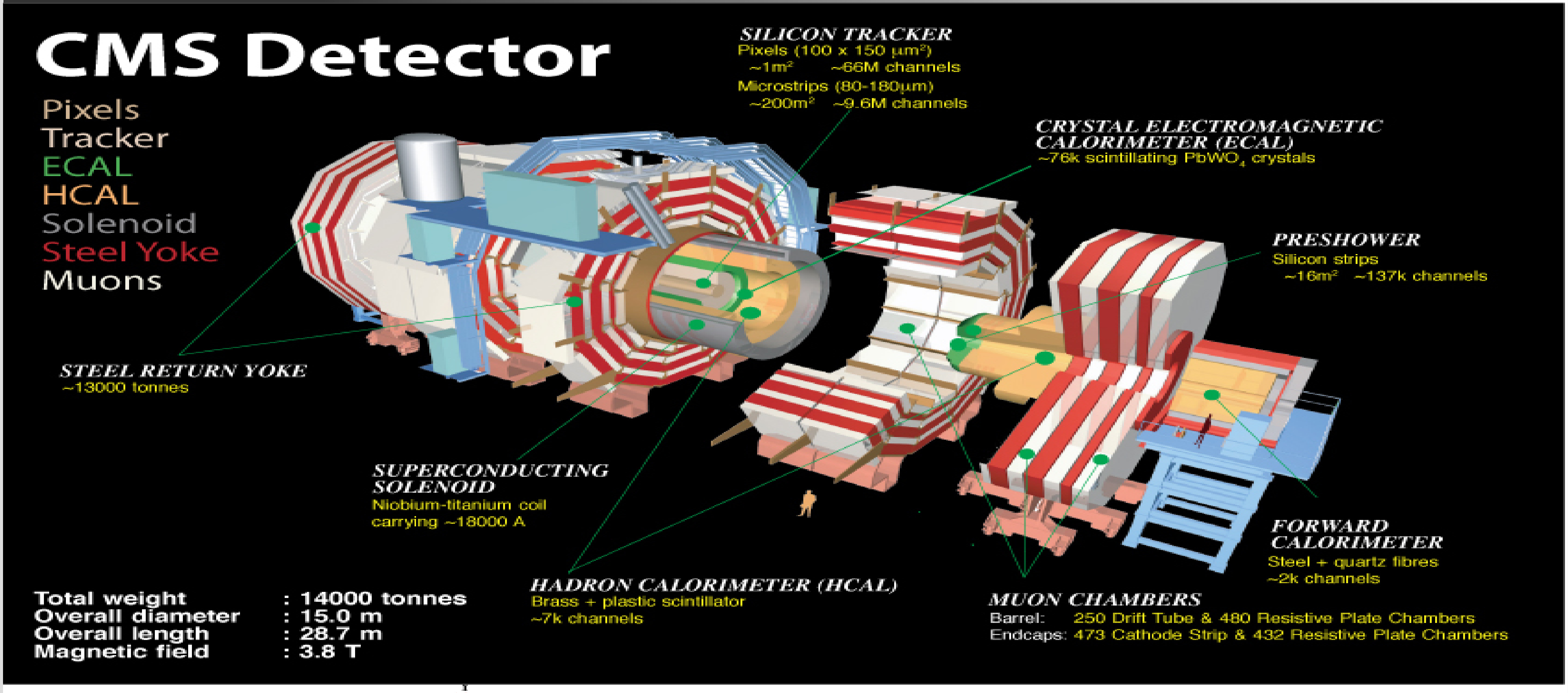
- Measuring the top quark properties, measurement of the top spin polarization in the single top sample
- Cross check of the CPT symmetry, by measuring the difference in the top and anti-top production rate
- Probe the PDFs

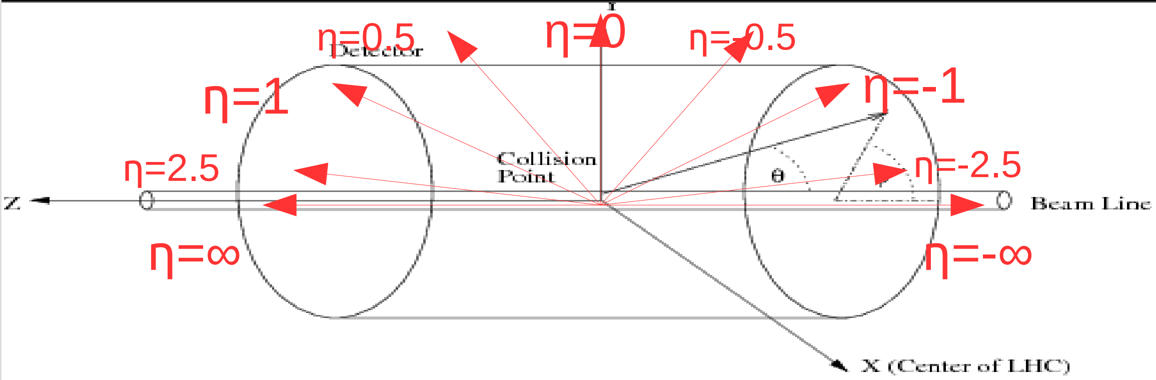
Why Single Top ?

Motivation

- Any deviation from SM prediction in the top properties is a hint for models beyond the SM
- Test anomalous Wtb couplings in the production rates of top and antitop quarks
- Search for FCNC interactions
- Sensitive to new physics that includes new mediators like charged higgs.

Compact Muon Solenoid(CMS)

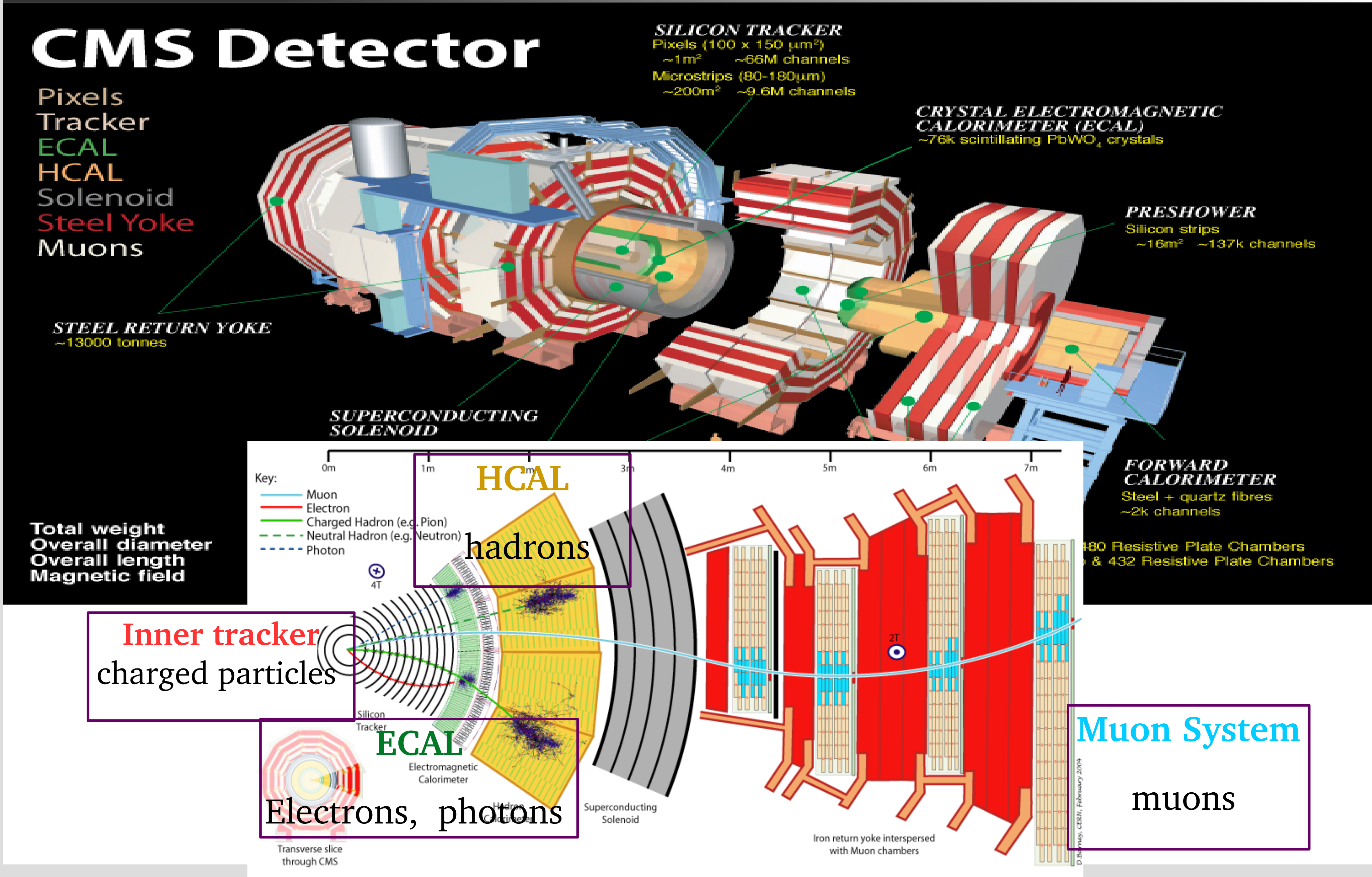




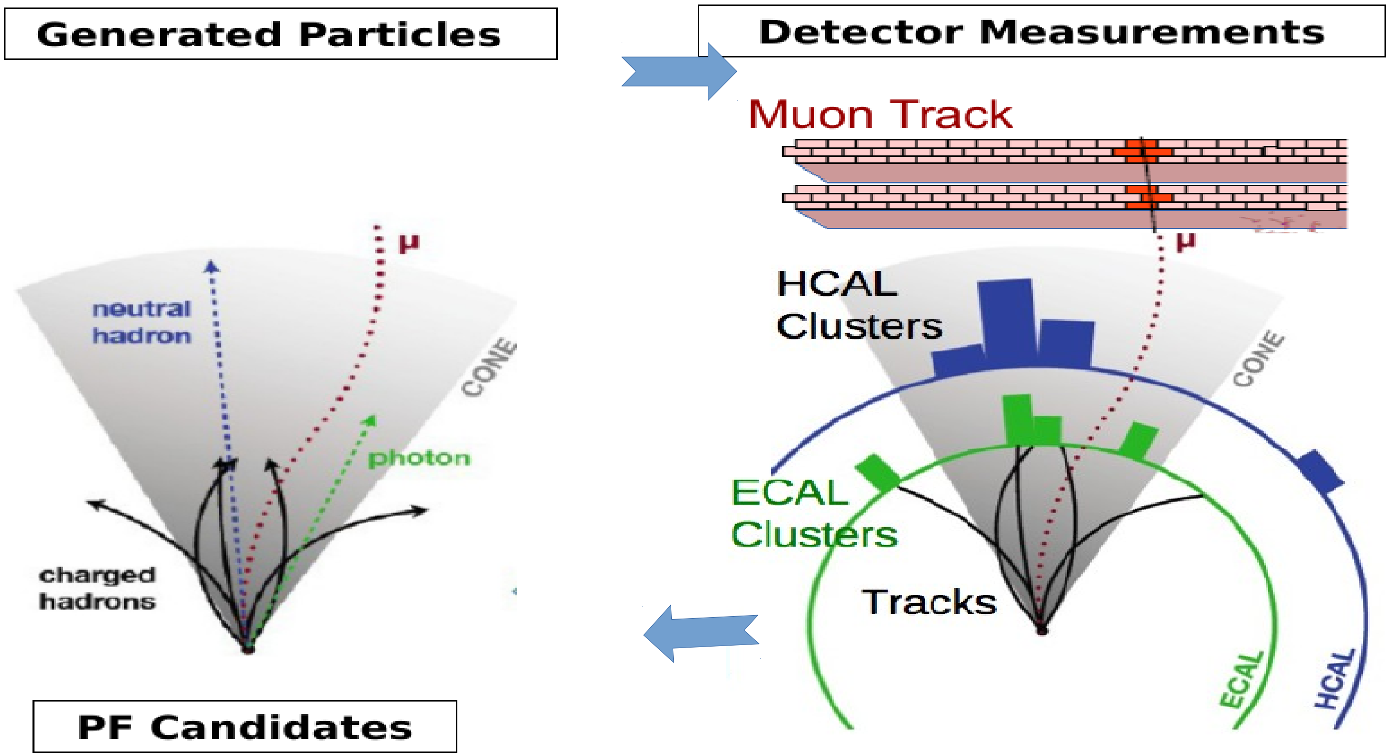
CMS Coordination

$\eta = -\ln(\tan\theta/2)$, θ: polar angle

Compact Muon Solenoid(CMS)



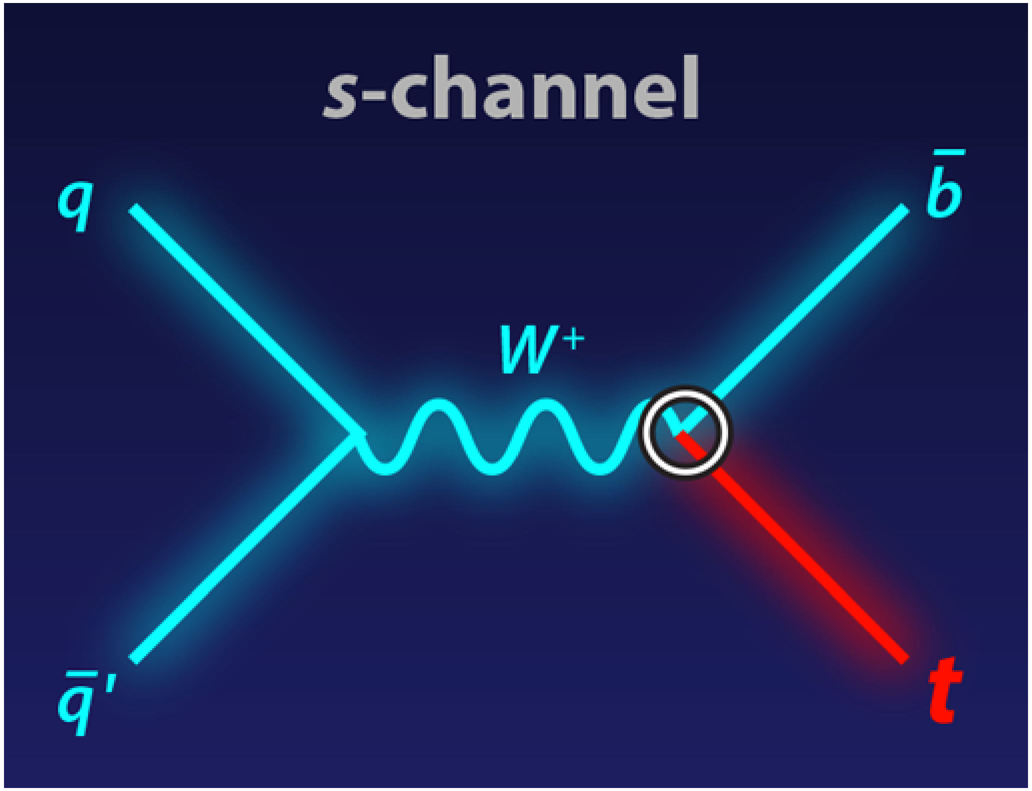
Physics Object Reconstruction



- In Reconstruction: CMS sub-detectors signals are translated to physics objects.
- CMS uses information from it's sub-detectors in the Particle Flow algorithm.
- PF algorithm aims to reconstruct objects back to the particle level.

CMS measurement (8TeV):

Single Top in s-channel



Why single top s-channel has such small cross section?

t-channel	LHC 7 TeV	$65.9^{+2.1\ +1.5}_{-0.7\ -1.7}$
	LHC 8 TeV	$87.2^{+2.8\ +2.0}_{-1.0\ -2.2}$
	LHC 13 TeV	$216.99^{+6.62}_{-4.64} \pm 6.16$
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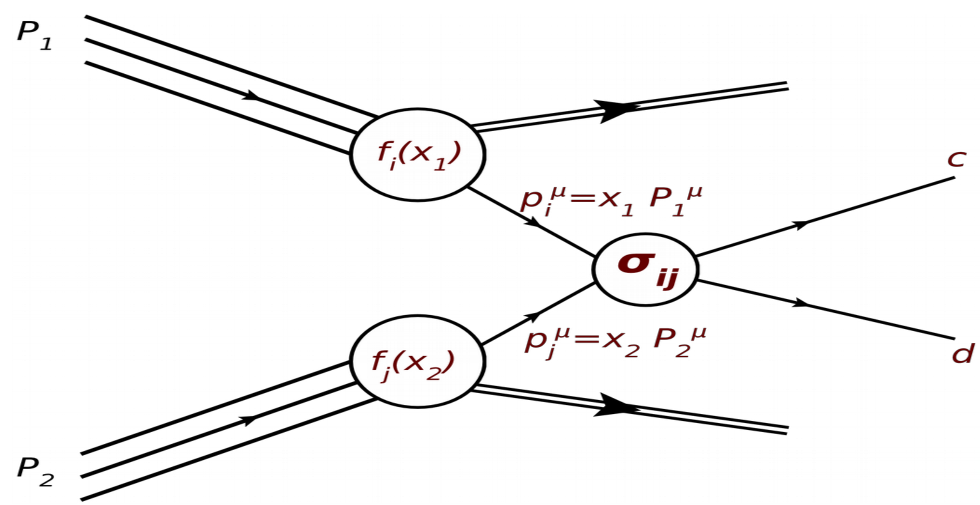
hard scattering in hadron-hadron collisions

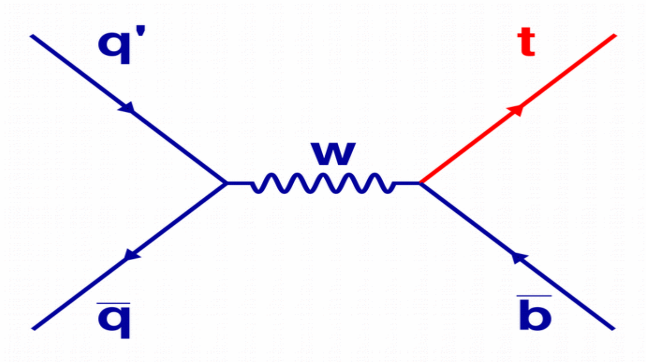
QCD FACTORISATION THEOREM:



PDF is defined as the probability density for finding a particle with a certain longitudinal momentum fraction x at resolution scale Q2.

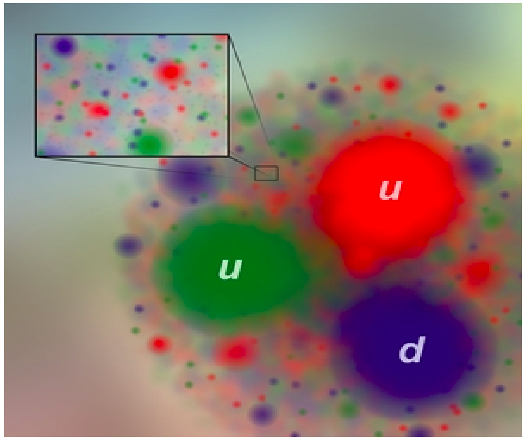
$$\sigma_{ab\to t\bar{t}} = \sum_{ij} \int dx_i\ dx_j\ f_i^{(a)}(x_i, \mu_F^2)\ f_j^{(b)}(x_j, \mu_F^2)\ \hat{\sigma}_{ij\to t\bar{t}}(\hat{s}, m_t, \mu_F, \mu_r, \alpha_s).$$

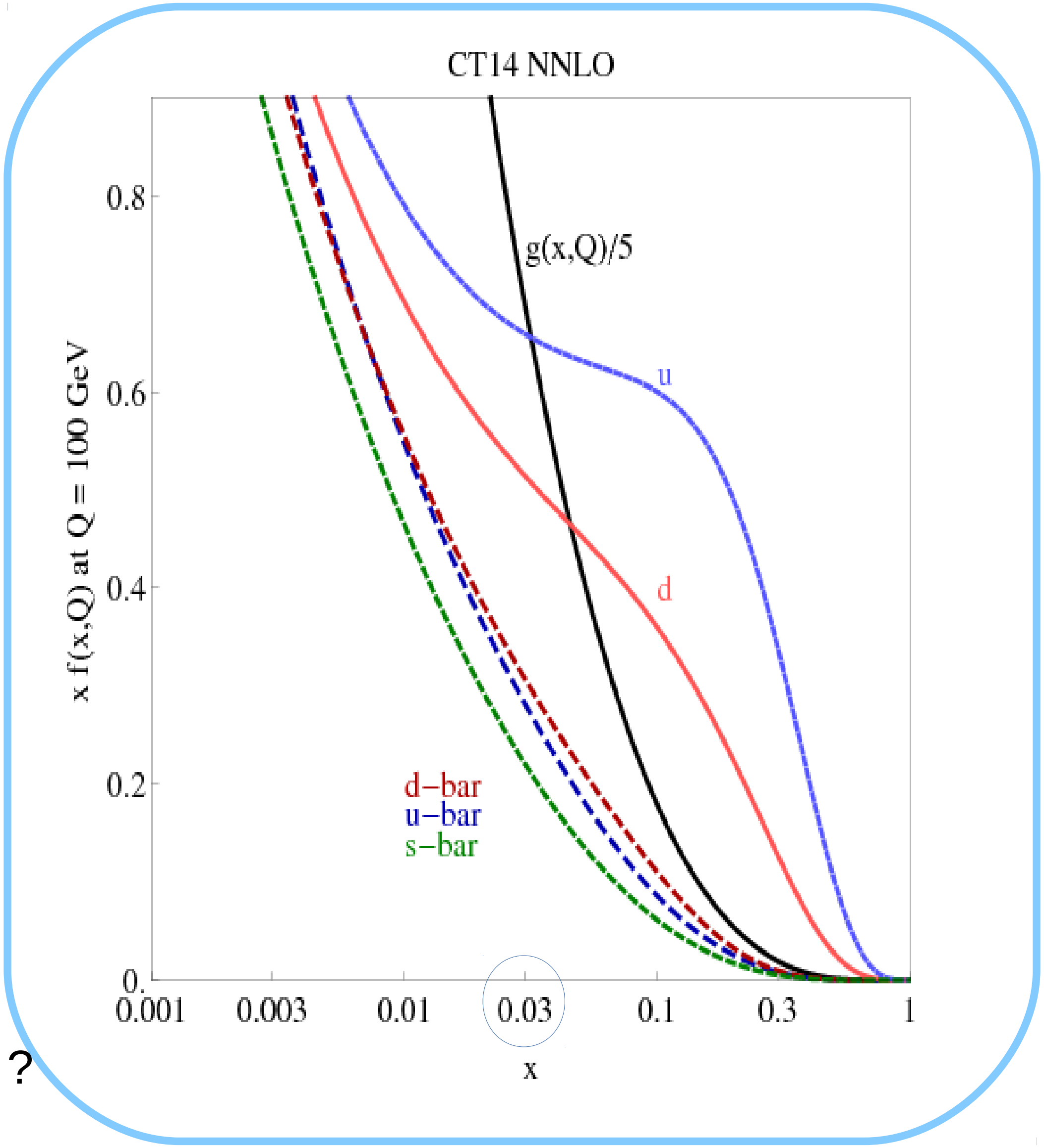
Why s-channel has such small cross section?



need a quark and an anti quark

pdf of antiquarks in proton?

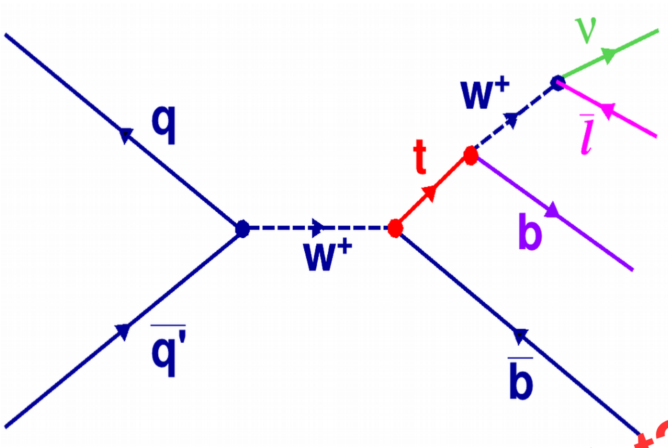




Charge asymmetry in top/anti top production ?

Signal Definition

- Single top produced in s channel and decay leptonically to electron is considered as signal : pp --> t b --> W b b --> e ν b b



- Signal final state topology :

  - one isolated electron ---> directly reconstructed in detector

  - two b quarks, represented by two jets in the event signature, tagged as two b jet

  - one neutrino, escapes undetected, the transverse momentum is taken from MET, longitudinal component is extracted from the W boson mass constraint

- Cascade decay W---> τν ---> eνν is considered as signal

Jet? Bjet?
Next to next slide

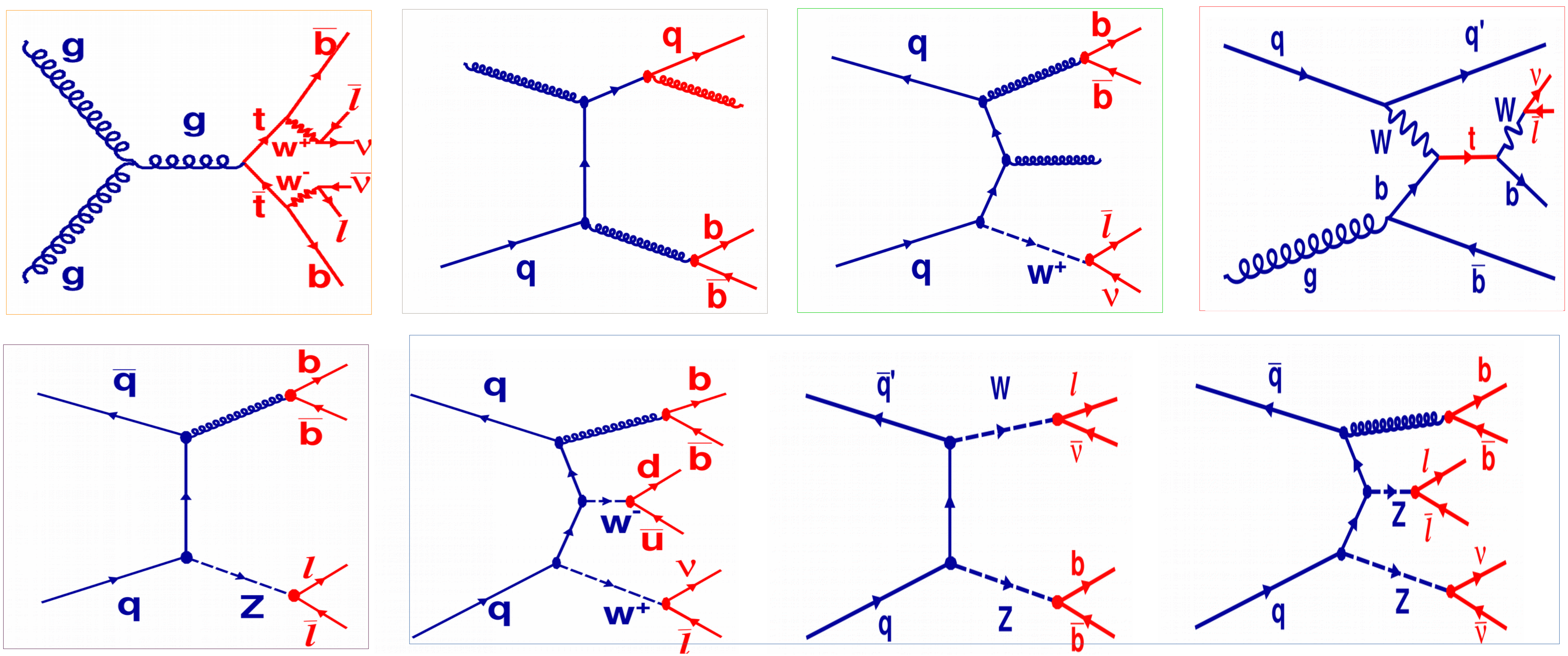
Background Modeling

Backgrounds:
physics processes produce fake signal signature

Having similar objects in the final states

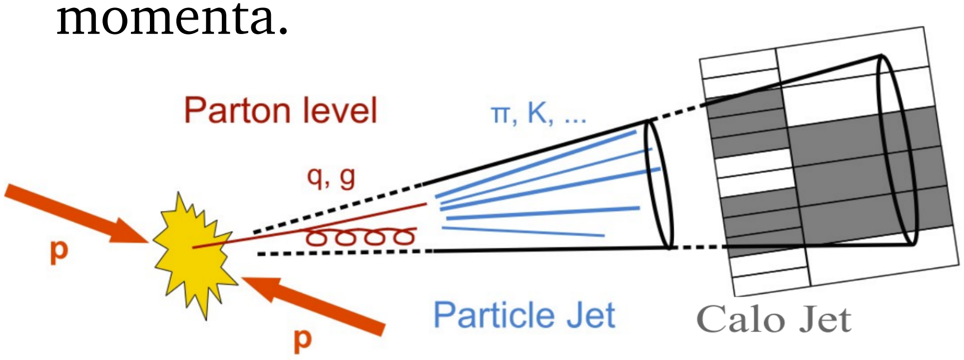
Instrumental effects

Main backgrounds: top quark pair, QCD, W + jets, other single top, Z + jets, diboson



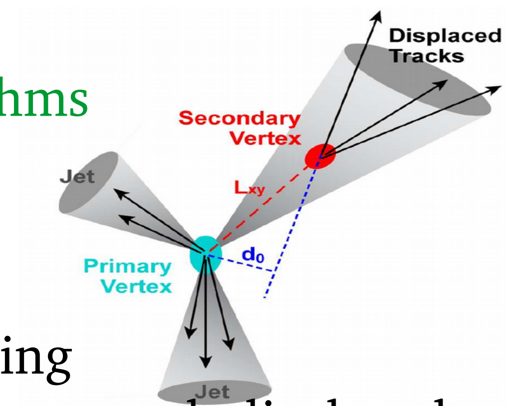
Jet Reconstruction

- PF particles are clustered into jet using Anti-kT clustering algorithm.
- PF particles four-momenta are summed to construct the jet four-momenta.



Heavy-flavor jet tagging

- A jet originating from the hadronization of a b quark referred to as b jet.
- B-tagging algorithms use relatively large masses long lifetime of B hadrons, resulting in a secondary vertex and displaced tracks.

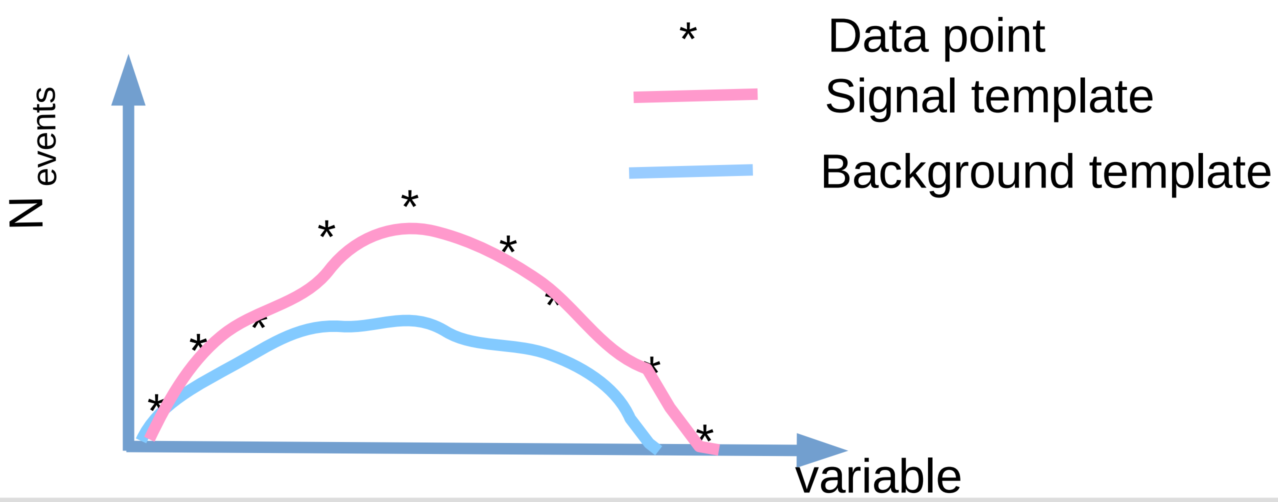


- Jet four-momenta in detector-level ≠ jet four-momenta of the generated-jet.
- Jet Energy Corrections (JEC) and Jet Energy Resolution (JER) scale factors are used.

Cross section measurement methods

Templates Fit

Reconstruct Discriminating variable(ex. HT) → Form signal and Background templates → Perform a likelihood fit Between data and templates



Cross section measurement methods

Cut and Count

$$\sigma_i = \frac{N_{reco,i}}{c_i * A_i * L * B}$$

- Cross section: σ_i (bin i)
- Number of measured signal events: $N_{reco} = N_{\text{observed in data}} - N_{\text{backgrounds}}$
- Correction for detector efficiency: c_i
- Acceptance: A_i
- Integrated luminosity: L
- Branching fraction: B

Data Set

- The main analysis is based on the full data set of the proton proton collisions at 8 TeV recorded in 2012 by the CMS detector corresponding to an integrated luminosity of 19.7 fb^{-1}.

Official CMS Software (CMSSW) :
CMSSW_5_3_11

Detector conditions and object calibrations
Global Tag : FT53-V21A-AN6::All

Primary Dataset : SingleElectron
High Level Trigger (HLT) path : HLT_Ele27_WP80 with 80% trigger efficiency

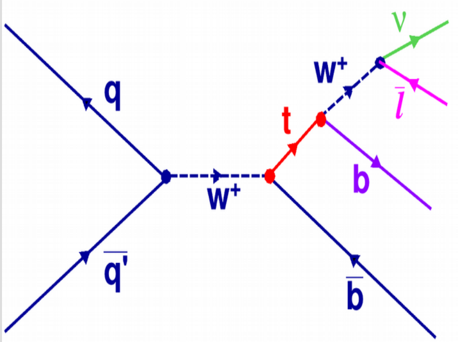
DataSet	Run Range	Integrated Luminosity	Global Tag
/SingleElectron/Run2012A-22Jan2013-v1/AOD	190450-193621	889.3 pb^{-1}	FT53-V21A-AN6::All
/SingleElectron/Run2012B-22Jan2013-v1/AOD	193833-196531	4423.1 pb^{-1}	FT53-V21A-AN6::All
/SingleElectron/Run2012D-22Jan2013-v1/AOD	198022-203742	7146.6 pb^{-1}	FT53-V21A-AN6::All
/SingleElectron/Run2012D-22Jan2013-v1/AOD	203777-208686	7319.0 pb^{-1}	FT53-V21A-AN6::All

Monte Carlo Samples

- Simulated events pass through the CMS full simulation implemented in the Geant4 software.
- Detector conditions and object calibrations, Global Tag : START53_V27::All

Process	$\sigma\,[pb]$
single top, s channel, top (leptonic decay)(*)	1.228(NLLL)[44]
single top, s channel, anti-top (leptonic decay)(*)	0.570(NLLL)[44]
single top, t channel, top (leptonic decay)(*)	17.496(NLLL)[44
single top, t channel, anti-top (leptonic decay)(*)	9.947(NLLL)[44]
single top, tW channel, top	11.1(NNLL)[44]
single top, tW channel, anti-top	11.1(NNLL)[44]
$t\bar{t}$	245.8(NNLL)[141
$W(\rightarrow l\nu)$+1 jet(**)	5,000
$W(\rightarrow l\nu)$+2 jets(**)	1,750
$W(\rightarrow l\nu)$+3 jets(**)	519
$W(\rightarrow l\nu)$+4 jets(**)	214
$Z/\gamma^*(\rightarrow l^+l^-)$ + jets (***)	3,500(NNLO)
WW	57
WZ	32
ZZ	8.3
EM-enriched QCD, $20 < \hat{p}_T < 30$GeV	2454400(LO)
EM-enriched QCD, $30 < \hat{p}_T < 80$GeV	4615893(LO)
EM-enriched QCD, $80 < \hat{p}_T < 170$GeV	183,294.9(LO)
EM-enriched QCD, $170 < \hat{p}_T < 250$GeV	4,586.5(LO)

Event Selection in Signal Sample



- **One isolated lepton**, events with additional lepton are rejected
  - PF electron, E_T > 30 GeV, |η|<2.5
  - PF lepton relative isolation: relIso <0.1
  - electron MVA ID > 0.9
  - electron veto: p_T>20 GeV, relIso<0.15,
  - muon veto: p_T>10 GeV, relIso<0.2

suppress dilepton events from $t\bar{t}$ or Drell-Yan processes

- **Two b tagged jets**
  - AK5 PF Jets
  - p_T > 40 GeV
  - Jet |eta|< 5
  - Jet ID quality cuts
  - CSV tight threshold: discriminator>0.898

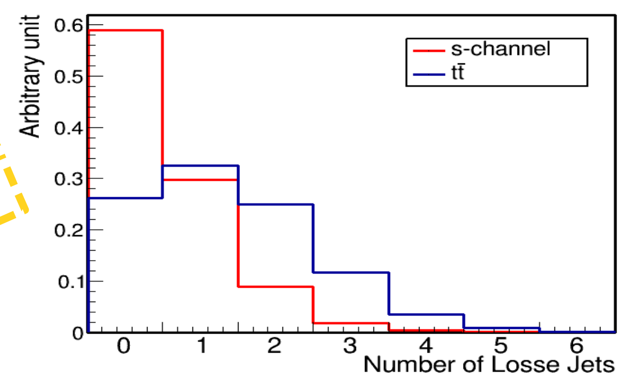
suppress $t\bar{t}$ and QCD multijets events

- **Missing transverse energy**
  - no explicit requirement

In notation "n-jets m-tags",
Signal sample : 2-jets 2-tags

- events with more than one loose jets are rejected
  - usual jet selection, 20 < p_T < 40 GeV

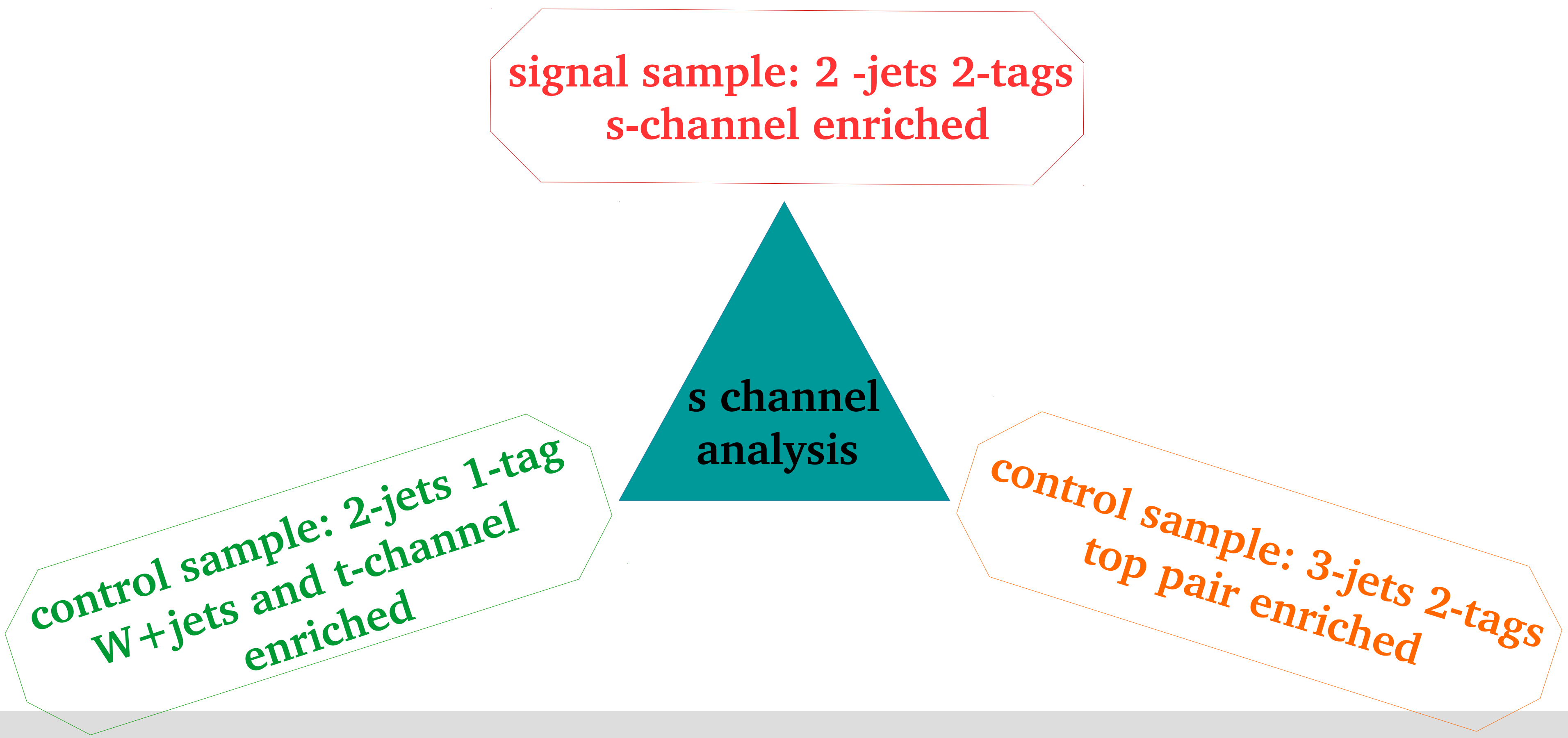
suppress $t\bar{t}$ events



Event Selection in Control Samples

- The primary goal of the control samples is either to study the modeling of the various background processes or to estimate and to constrain their contributions.

- Events divided in various categories based on jet and b jet multiplicity. Definition of selected objects are similar to signal sample.



Simulated Events Weights

- Each simulated event gets a weight which either is determined from the specific properties of the event, or is universal for all the events in given MC sample.

weight originated from difference in pileup distribution in simulation and data

weight for normalization to integrated luminosity of real data

Events weights

weights originated from difference in
- trigger efficiency
- b-tagging efficiency
- lepton ID, Iso efficiency

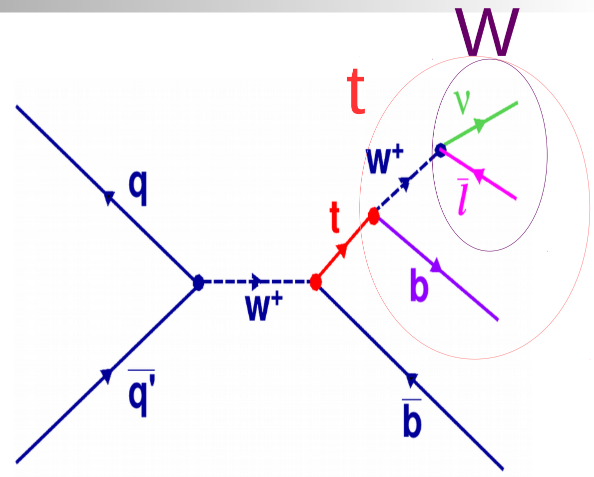
in simulation and data

weight for correcting number of generated events with a more precise cross section than the one used in generation

- JER and JES corrections are applied and propagated to MET.
- Uncertainty on the events weights introduces uncertainty on the measurement.

Top Reconstruction

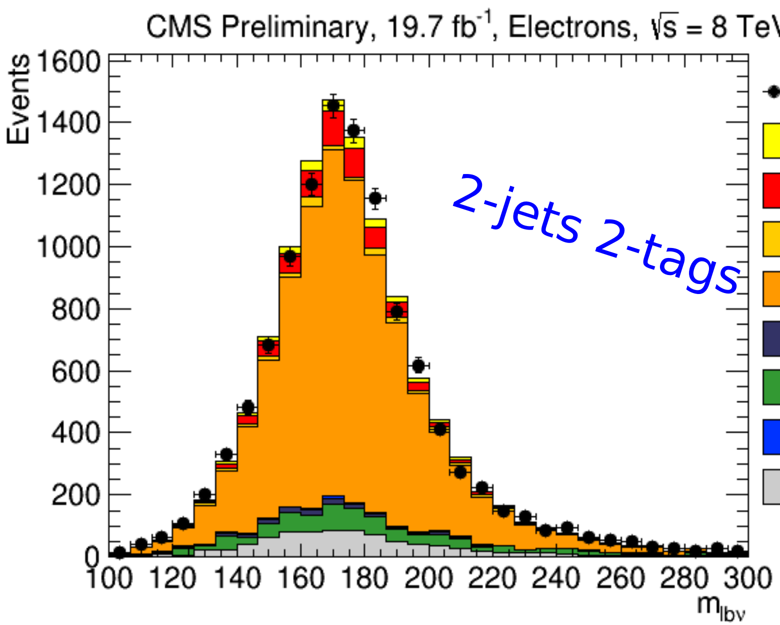
- $M_{lb\nu}$ invariant mass of the top quark candidate
  - Lepton is reconstructed in detector

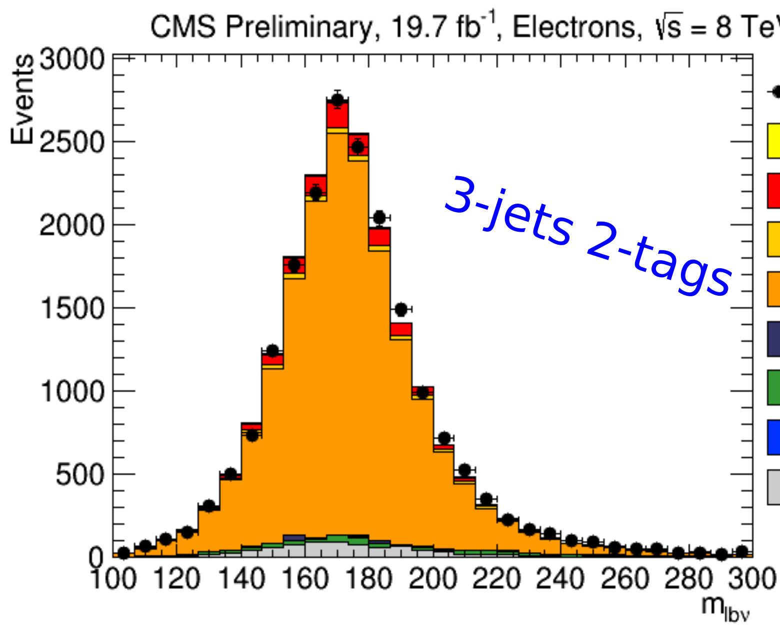


- Neutrino reconstruction:
  - $MET_x = p_{x,\nu}$
  - $MET_y = p_{y,\nu}$
  - W-boson mass constraint → quadratic equation for $p_{z,\nu}$
    - In case of two real solutions: choose the one with the smaller $|p_{z,\nu}|$
    - In case of complex solutions: modify $p_{x,\nu}$ and $p_{y,\nu}$ to have $m_{T,W} = m_W$,
      Recalculate the $p_{z,\nu}$

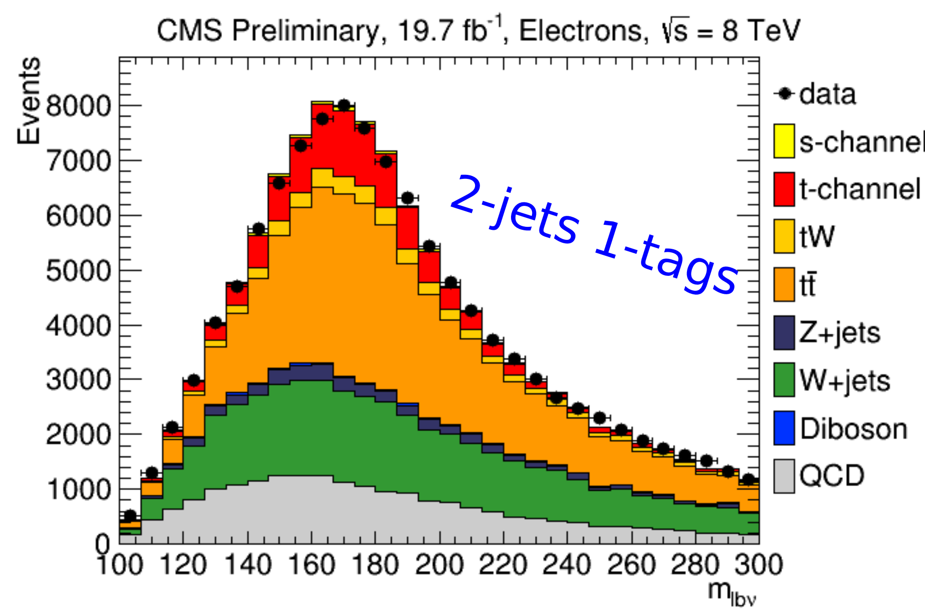
- b-jet assignment
  In 2tag samples: "best-mass-top" method
  In 1tag sample : b-tagged jet

Reconstructed Top Mass in Signal and Control Samples





QCD extracted by a data-driven procedure.



Background Modeling and Estimation

- The shape and the rate of background processes are taken from the simulation with two exceptions: QCD multijets in all samples and W+jets yields in the 2-jets 1-tag sample.

- W+jets global normalization scale factor of 1.6 is used in 2-jets 1-tag.

- QCD multijets process is not well modeled by the MC simulation, its contribution is not reliable.

  - QCD shape is taken from anti-isolated sample in data and normalization from a fit to the BDT distributions.

  "anti-iso" selection *= standard selection with lepton relative isolation* $I_{rel} > 0.1$ *OR MVA ID < 0.9.*

QCD Estimation Strategy

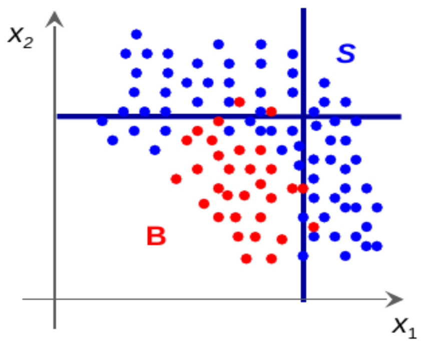
- Three anti-QCD boosted decision trees are trained in the 2-jets 2-tags, 2-jets 1-tag and 3-jets 2-tags categories.

What is Multivariate anlysis? Why?

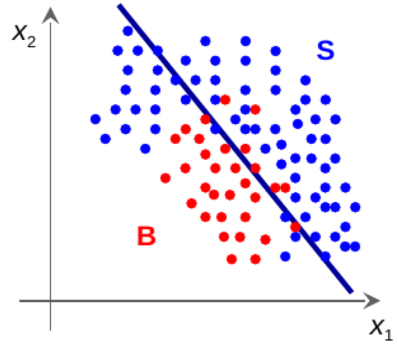
What is BDT?

Multivariate Analysis

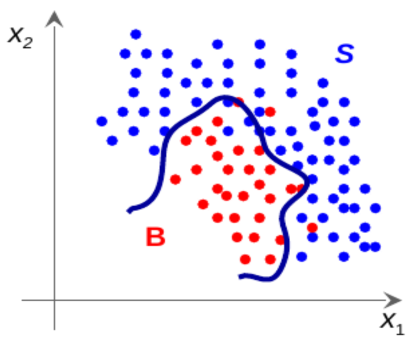
Multivariate Analysis (MVA)



Rectangular cuts



Linear

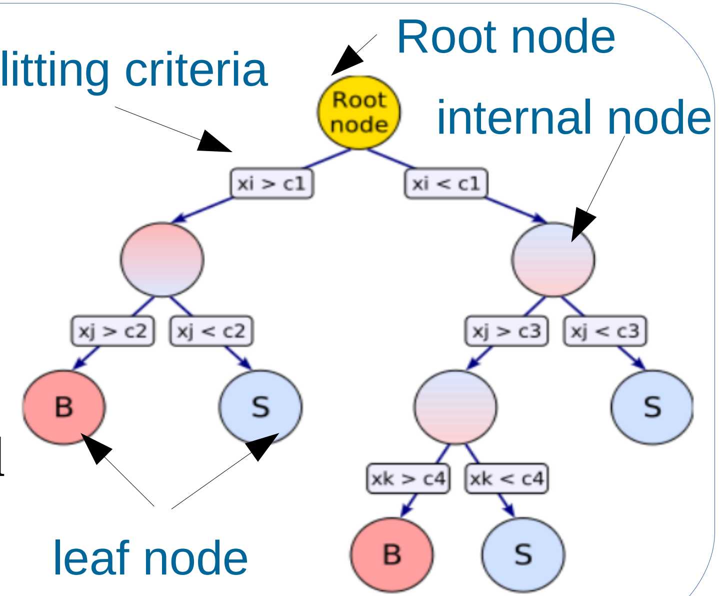


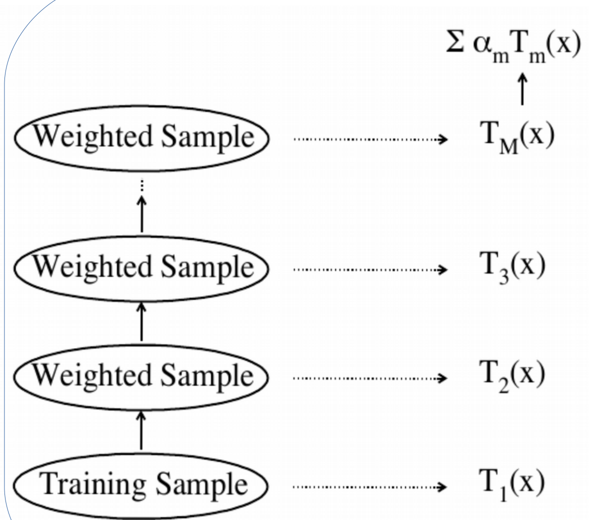
Non-linear (BDT,...)

- MVA is based on machine learning methods.
- An MVA analysis consists of two separate phases: the learning phase where the multivariate method is trained, tested and evaluated, and the application phase where the chosen method is applied on the problem that it has been trained for.
- In a classification multivariate analysis, the machine is learned to separate a given signal from backgrounds, given already known results on a training sample.

Boosted Decision Trees (BDT)

- Decision Trees is an example of MVA, in which a binary tree structure (a series of yes/no decisions) is built to classify events.
- Training a decision tree: process that defines the splitting criteria for each node.
- Depending on the majority of signal and background events in leaf nodes, the events inside that node are labeled as signal (+1) or background (-1).





To stabilize Decision Tree performance, one can use different techniques: e.g. **Boosting.**

Boosting : sequentially apply the DT algorithm to reweighted (boosted) version of training sample, and produce a forest.

The idea behind the boosting is that misclassified events, are given a higher event weight and hence higher importance in the training of the next tree.

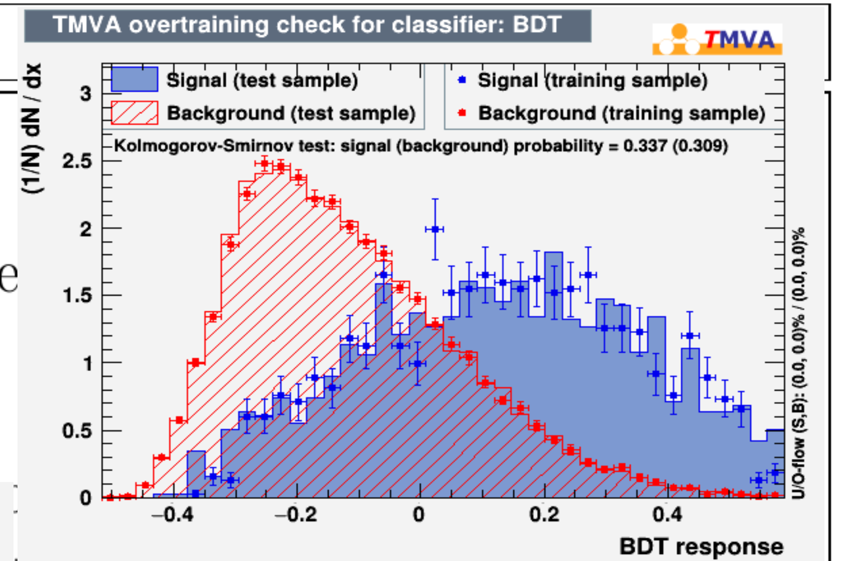
QCD Estimation Strategy

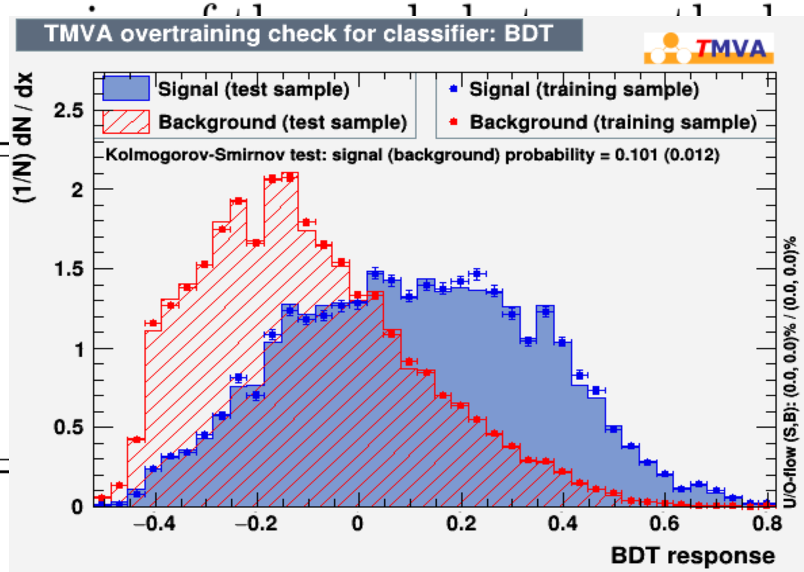
- Three anti-QCD boosted decision trees are trained in the 2-jets 2-tags, 2-jets 1-tag and 3-jets 2-tags categories.
  - Signal: QCD, taken from data with “anti-iso” selection
  - Backgrounds: top pair, W/Z+jets and single top

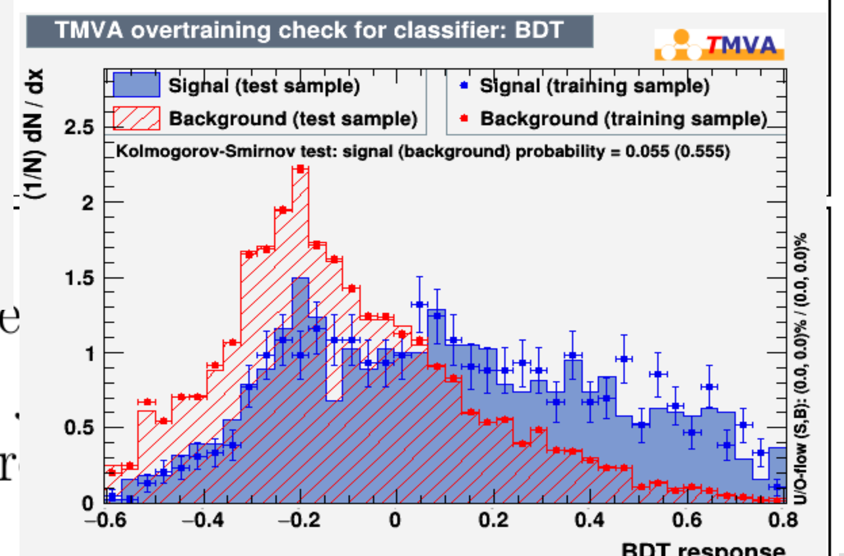
	Variable	Description
2-jets 2-tags	η_ℓ	pseudorapidity of lepton
	m_{T}	transverse W boson mass
	$\Delta R_{b',\ell}(*)$	angular separation of the b-tagged jet with lower b discriminator and the lepton
	H_T	scalar sum of p_{T} of all jets
	$\cos\theta^*$	cosine of the angle between the lepton and the b-tagged jet recoiled against top-quark in the top rest frame
2-jets 1-tag	η_ℓ	pseudorapidity of lepton
	H_T	scalar sum of p_{T} of all jets
	$\Delta\Phi_{\not{E}_{\mathrm{T}},\ell}$	distance in azimuthal angle ($\Delta\Phi$) between $\vec{\not{E}}_{\mathrm{T}}$ and lepton
3-jets 2-tags	η_ℓ	pseudorapidity of lepton
	$\not{E}_{\mathrm{T}}$	missing transverse energy in the event
	$\Delta R_{j1,j3}$	angular separation of the leading jet and the least energetic jet
	$p_{\mathrm{T}}^{lb\nu}$	transverse momentum of the top reconstructed with the best-mass-top method

QCD Estimation Strategy …

	Variable	Description
2-jets 2-tags	η_ℓ	pseudorapidity of lepton
	m_T	transverse W boson mass
	$\Delta R_{b',\ell}(*)$	angular separation of the b-tagge… and the lepton
	H_T	scalar sum of p_T of all jets
	$\cos\theta^*$	… rame
2-jets 1-tag	η_ℓ	
	H_T	
	$\Delta\Phi_{\not{E}_T,\ell}$	
3-jets 2-tags	η_ℓ	
	$\not{E}_T$	missing transverse energy in the e…
	$\Delta R_{j1,j3}$	angular separation of the leading …
	$p_T^{lb\nu}$	transverse momentum of the top r… top method

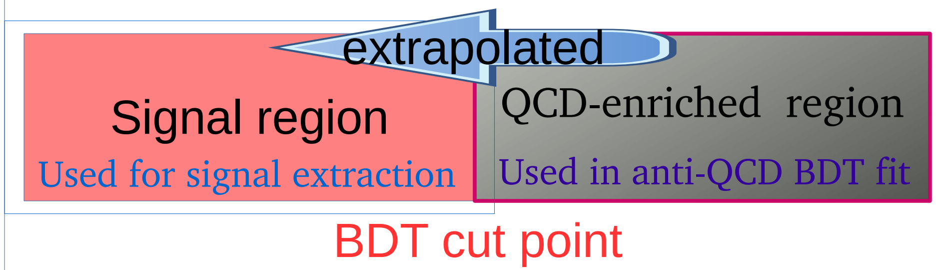




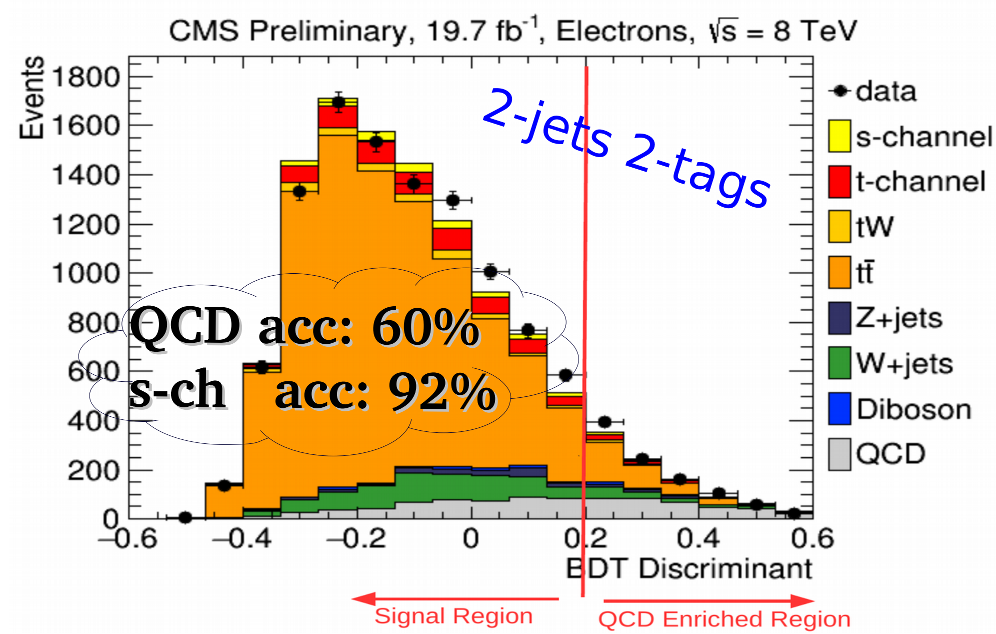


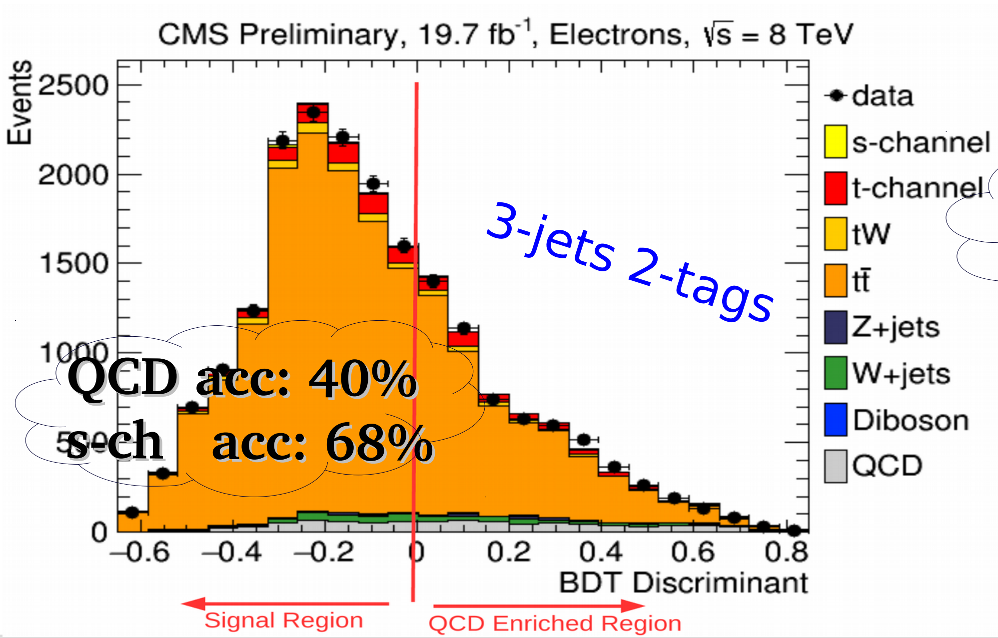
QCD Estimation Strategy ...

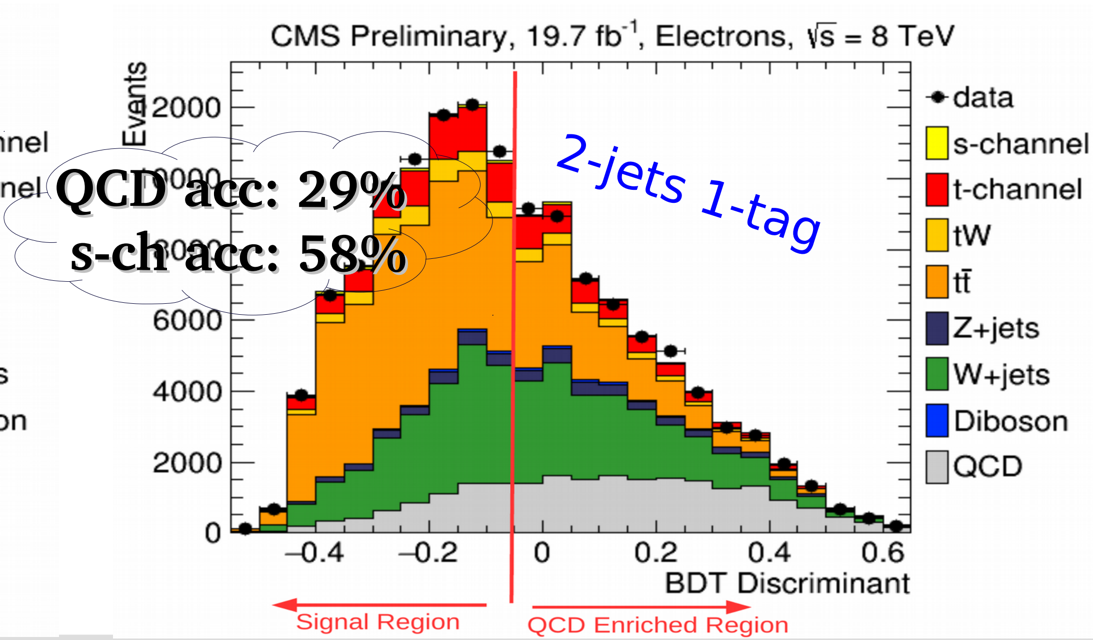
- Divide the sample in two regions: QCD-enriched and signal region



- Events in the QCD-enriched region are eliminated from the analysis







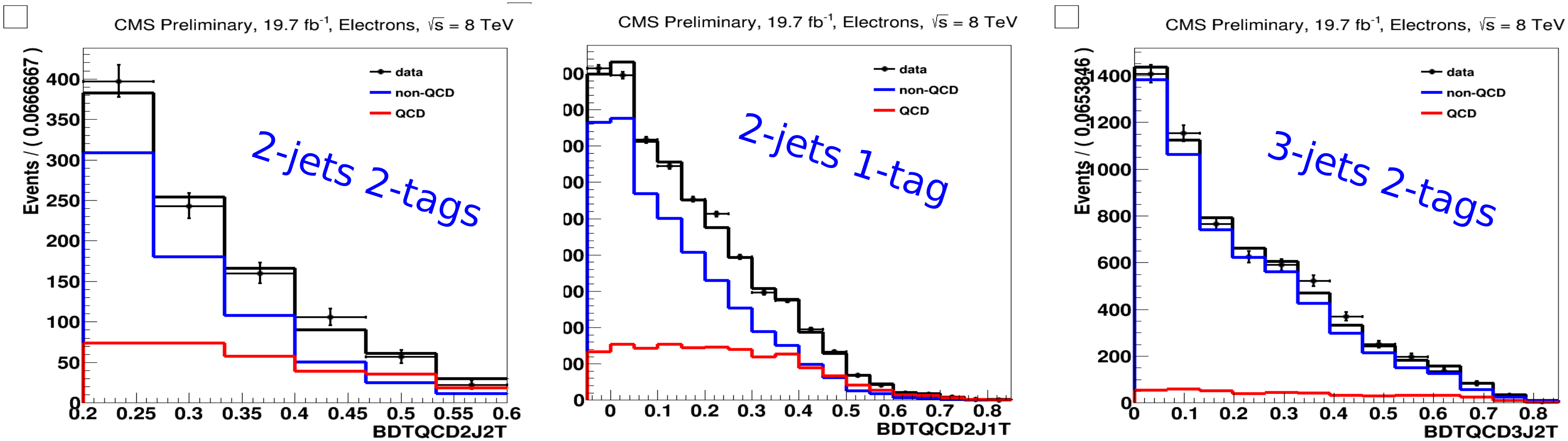
Fit in QCD-Enriched Region

- The maximum likelihood fit to BDT distribution in QCD-enriched region

  F (BDT) = s·S(BDT)+b·B(BDT)

  B(BDT) : template for non-QCD events , obtained from simulation

  S(BDT) : template for QCD events, obtained from anti-isolated sample in collisions data, $\Delta R_{lepton,jet} > 0.3$



Sample	N^{fit}_{QCD}	N^{SR}_{QCD}	QCD uncertainty
2-jets 2-tags	296.7	439.4	17%
2-jets 1-tag	15250.0	6081.3	2.6%
3-jets 2-tags	463.0	313.5	24%

Event Yields

Event yields after selections and background estimation in signal and control samples.

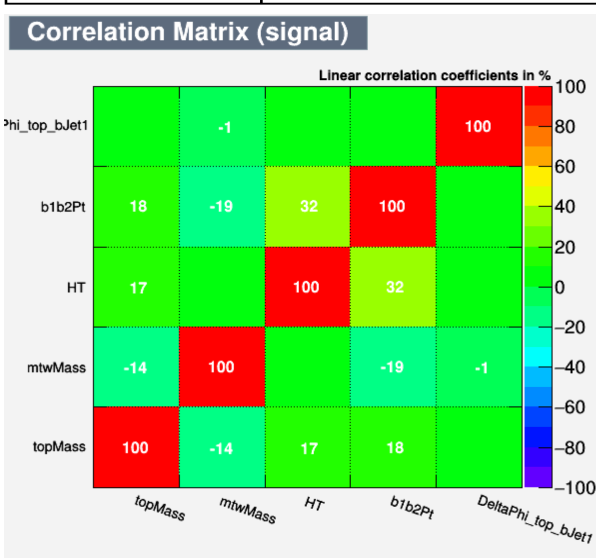
Process	3-jets 2-tags	2-jets 1-tag	2-jets 2-tags
$t\bar{t}$	10838	34373	3943
W + *jets*	201	17443	530
Z + *jets*	32	1732	88
Diboson	17	331	45
QCD	313	6081	291
tW	280	3198	108
t channel	528	6800	374
s channel	48	429	171
Total MC	12254	70387	5550
Data	13512	73895	6301

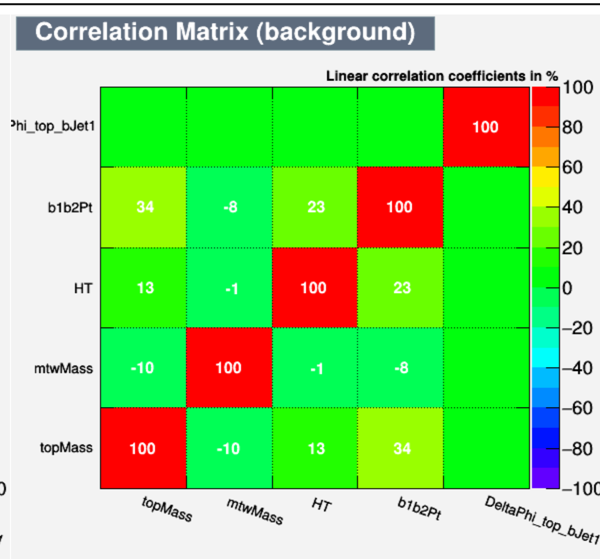
signal /background=0.033

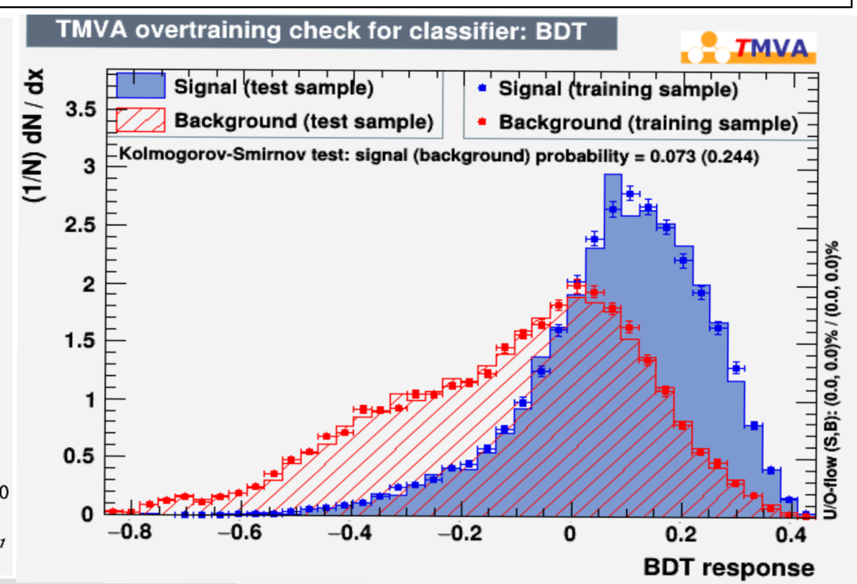
Signal Extraction, s-channel Enriched Region

- A boosted decision trees is trained in 2-jets 2-tags sample.
- In BDT framework: Signal: s-channel Background: rest of physics process involved

Variable	Description
$\Delta\Phi_{top,b1}$	difference in azimuthal angle between top and leading jet
p_{T}^{bb}	vector sum of p_{T} of the two b-tagged jets
m_{T}	transverse W boson mass
H_T	scalar sum of p_{T} of all jets
$m_{\ell b\nu\ best}$	invariant mass of lepton, neutrino and one of the b-tagged jets reconstructed with the best-mass-top method



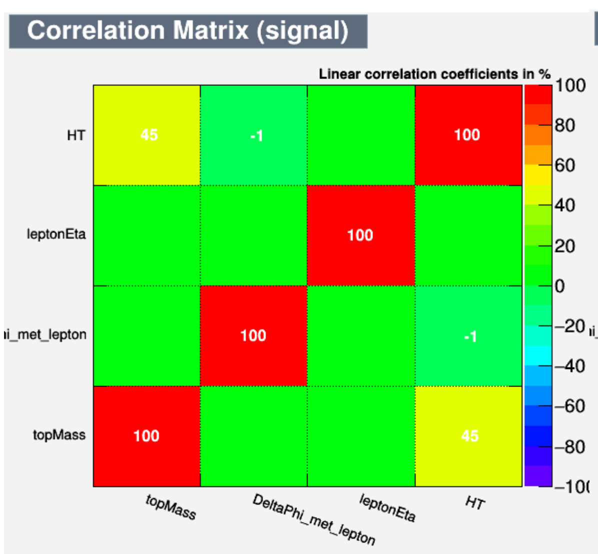


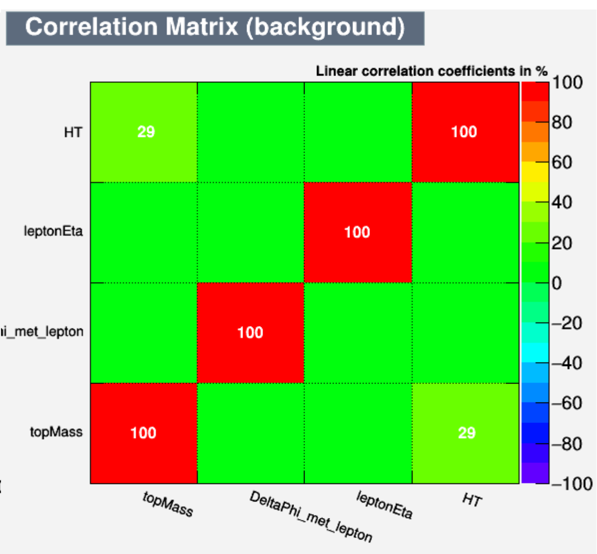


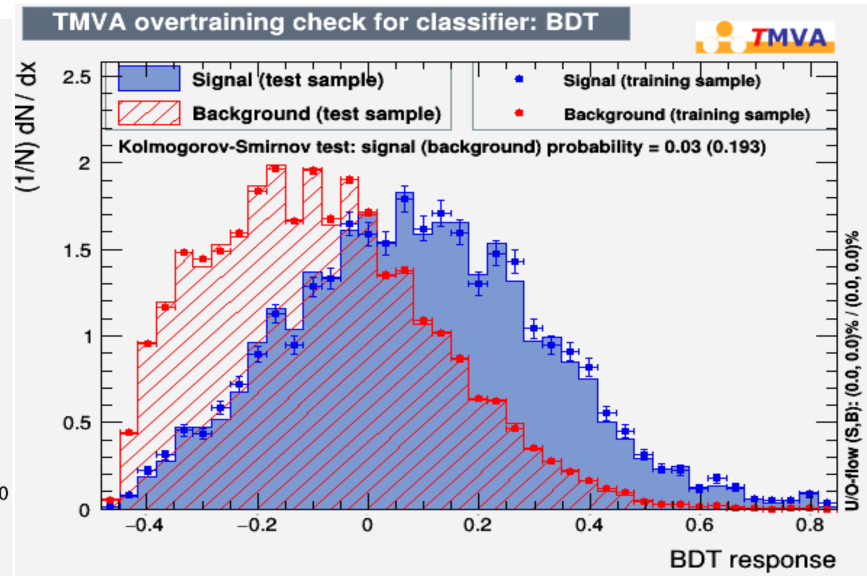
Signal Extraction,W+jets and t-channel Enriched Region

- A boosted decision trees is trained in the 2-jets 1-tag sample.
- In BDT framework: Signal: W+jets Background: rest of physics process involved.

Variable	Description
$m_{\ell b\nu\ best}$	invariant mass of lepton, neutrino and one of the b-tagged jets reconstructed with the best-mass-top method
H_T	scalar sum of p_{T} of all jets
η_ℓ	pseudorapidity of lepton
$\Delta\Phi_{\not{E}_{\mathrm{T}},\ell}$	difference in azimuthal angle between $\vec{\not{E}}_{\mathrm{T}}$ and lepton



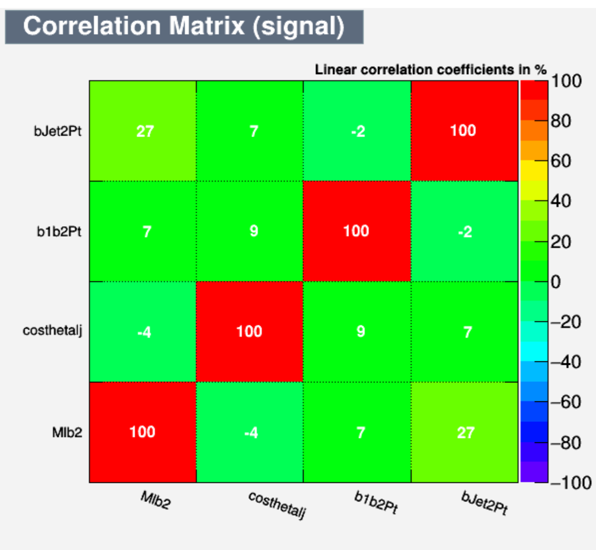


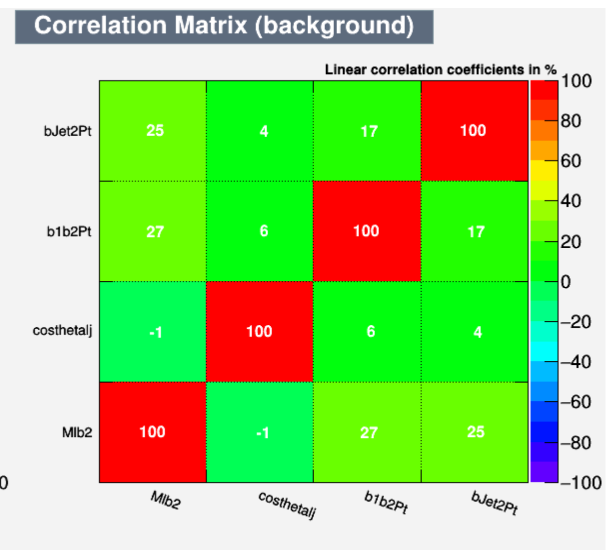


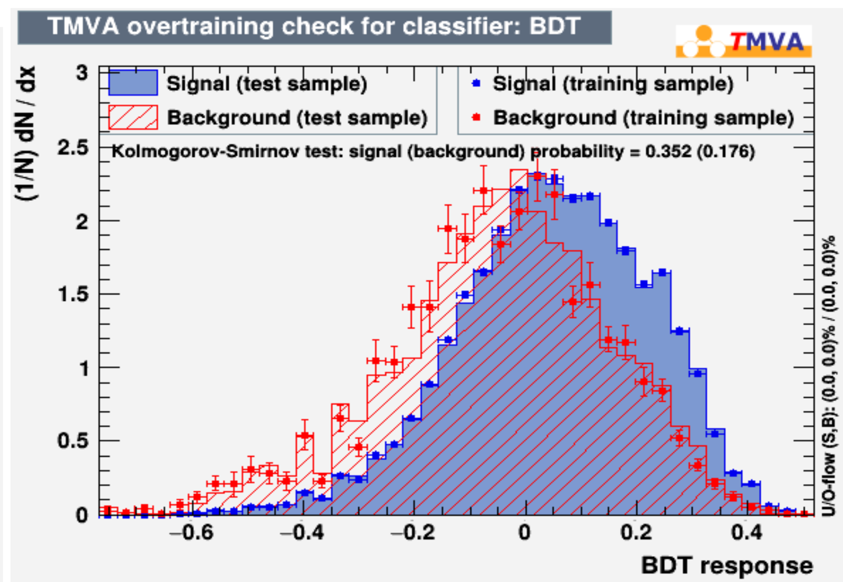
Signal Extraction, Top Pair Enriched Region

- A boosted decision trees is trained in the 3-jets 2-tags sample.
- In BDT framework Signal: top pair, Background : rest of physics process involved.

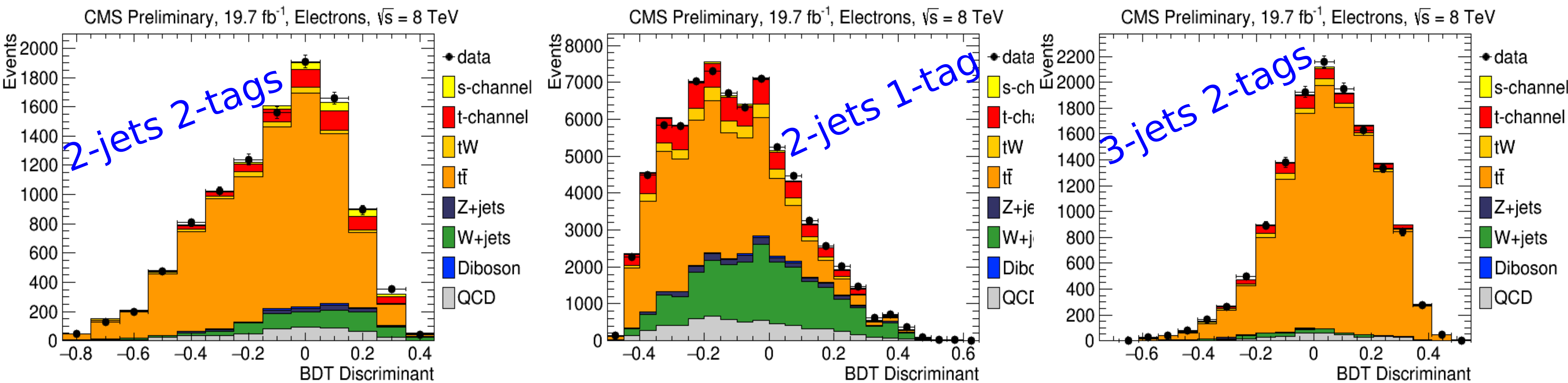
Variable	Description
$\cos\theta^*$	cosine of the angle between the lepton and the b-tagged jet recoiled against top quark in the top rest frame
M_{lb2}	invariant mass of the lepton and the second b-tagged jet
p_T^{b2}	p_T of the second b-tagged jets
p_T^{bb}	vector sum of p_T of the two b-tagged jets







Signal Extraction Strategy



- A simultaneous maximum likelihood fit is performed in BDT distributions in 2-jets 2-tags, 3-jets 2-tags and 2-jets 1-tag bins.
- The statistical evaluation is made using the software THETA.
- Assuming n_i and λ_i as the number of observed and expected events in ith bin, the likelihood function is:

$$L(\theta, \beta | n) = \prod_{i=1}^{N} \frac{\lambda_i^{n_i} e^{-\lambda_i}}{n_i!} \prod_{i=1}^{N_u} \pi(\theta_u)$$

$$\lambda = B + \beta S.$$

signal

Background

- Signal strength modifier β is defined as the ratio of measured cross section and the SM prediction. β is the parameter of interest in the fit.

Systematic Uncertainties

- The individual quantities used to estimate the cross section are not perfectly known, and the obtained measurement is limited by the systematic uncertainties.

Theoretical origin:

- PDF
- Top p_T reweighting
- ME and PS Matching thresholds
- Factorization and renormalization scales

Background normalization:

top pair	10%
T-channel	10%
tW channel	15%
W+jets	20%
Z+jets	20%
Dibosons	30%
QCD	estimation uncertainty

Instrumental origin:

- Unclustered $E_{T,miss}$
- Luminosity
- Lepton trigger, reconstruction
- Jet energy resolution
- b-tagging mis-tagging
- Jet energy scale
- Pile up

Simulation statistics

Systematic Uncertainties …

- Background normalization uncertainties are added in the likelihood model as nuisance parameters.
- Simulation statistics is evaluated using "Barlow-Beeston light" * method by introducing new nuisance parameters in each bin.
- All the other instrumental and theoretical uncertainties are externalised due to:
  - theoretical motivation for theoretical uncertainties.
  - fit instability (fit not converging, asymmetric uncertainties in results).

  Therefore, impact evaluation involves pseudo-data corresponding to $\pm 1\sigma$ shifts for each source, the difference between the fitted value for signal strength in $\pm 1\sigma$ scenarios and the nominal one is taken as the systematic uncertainty.

- Total uncertainty: uncertainties combined together with Barlow method**, which is the proper way for combining asymmetric systematic errors.

* Fitting using finite Monte Carlo samples", Comput. Phys. Commun. 77 (1993) 219.
** R. Barlow, "Asymmetric Systematic Errors", arXiv:physics/0306138.

Results: Significance, Upper Limit and Cross Section

- The significance of the s-channel excess over the background is measured:

Expected Significance	Observed Significance
0.6	2.2

- Observed and expected upper limits (UL) is measured:

	Expected UL	Observed UL
UL on cross section	23.8 [18.3, 33.3] pb	28.8 pb
UL on Cross section/SM prediction	4.3 [3.3, 6.0]	6.8

- The single top cross section in the s-channel is measured to be:

$$\sigma_{\text{s-ch.}} = 16.8\,^{+8.9}_{-9.3}\ \text{pb} \quad = 16.8 \pm 9.1\ (\text{stat} + \text{syst})\ \text{pb}$$

$\sigma_{SM} = 5.55 \pm 0.22$ 8TeV

which is equivalent to an scale factor with respect to the standard model prediction

$$\beta = 3.0 \pm 1.6$$

Relative Impact of Systematic Uncertainties

The uncertainty is shown to be extensively systematic dominant

Uncertainty source	up (%)	down (%)
Statistical	± 14%	
$t\bar{t}$ and single top quark rate	-12.8	14.0
W/Z+jets, diboson rate	-13.8	11.7
QCD rate	4.7	-4.3
* Lepton efficiency	2.2	-1.8
Luminosity	5.3	-5.7
*JER	-9.0	8.7
*JES	-24.5	30.6
*b-tagging	13.9	-13.7
*mis-tag	0.14	-0.6
*Pileup	-6.9	6.5
*Unclustered $\not{E}_T$	0.8	-2.8
* μ_R, μ_F scales	-36	26
* Matching thresholds	-12.1	-11.1
* PDF	6.7	-7.3
*Top quark p_T reweighting	6.8	-7.5
Total uncertainty	±54.4%	

Combining Electron and Muon Channels Analyses at 8TeV

Muon Analysis, 8TeV

- In order to improve the precision of measurement, a combination of electron and muon results is also studied.
- **Event selection is generally similar to electron channel.**
  - HLT path : IsoMu24_eta2p1
  - Muon selection: PF muon and Global muon
    - p_T > 26 GeV, $|\eta|<2.1$
    - PF lepton relative isolation: relIso <0.12
    - muon veto: $p_T>10$ GeV, relIso<0.2
  - Jet selection similar to electron channel
  - Signal and control samples: 2-jets 2-tags, 3-jets 2-tags, 2-jets 1-tag
- **Same strategy for QCD estimation and signal extraction.**

Combined Results: Muon+Electron Channels at 8TeV

- The significance of the s-channel excess over the background is measured:

	Expected Significance	Observed Significance
8 TeV, electron	0.6	2.2
8 TeV, muon	0.8	1.7
8 TeV, muon +electron	0.8	2.3

- The single top cross section in the s-channel is measured to be:

$\sigma_{\text{s-ch.}} = 16.8 \pm 9.1$ pb, $\beta_{\text{signal}} = 3.0 \pm 1.6$ electron channel, 8TeV,

$\sigma_{\text{s-ch.}} = 11.7 \pm 7.5$ pb, $\beta_{\text{signal}} = 2.1 \pm 1.2$ muon channel, 8TeV,

$\sigma_{\text{s-ch.}} = 13.4 \pm 7.3$ pb, $\beta_{\text{signal}} = 2.4 \pm 1.3$ combined, 8TeV.

Combining the 8TeV and 7TeV Analyses

Muon Analysis, 7TeV

- **SM prediction at 7TeV:** $\sigma_{s\text{-channel}} = 4.56 \pm 0.07\,^{+0.18}_{-0.17}$ pb
- The measurement is based on the full 2011 single muon dataset at 7TeV corresponding to an integrated luminosity of 5.1 fb^{-1}
- **Event selection:**
  - HLT Path:
    HLT_IsoMu17_v* in first period of data taking
    HLT_IsoMu17_CentralJet30_BtagIP_v* in second period of data taking
    HLT_IsoMu17_eta2p1_CentralJet30_BtagIP_v*,
  - Muon selection: PF muon, IsGlobal muon and IsTrackerMuon

    - $p_T > 20$ GeV, $|\eta|<2.1$ - PF relIso <0.15

    - muon veto: $p_T>10$ GeV, relIso<0.2
  - Jet selection is similar to 8TeV

    - B-tagging: Track Counting High Purity
- Strategy for the QCD estimation: fit to the m_T distribution (not enough statistics to train BDT)

Combined Results: 7+8TeV

- The significance of the s-channel excess over the background is measured:

	Expected Significance	Observed Significance
8 TeV, muon +electron	0.8	2.3
7 TeV, muon	0.5	0.9
7 + 8 TeV	1.1	2.5

- Observed and expected upper limits (UL) on cross section is measured:

	Expected UL	Observed UL
8 TeV, muon +electron	20.5 [13.4, 26.7] pb	28.8 pb
7 TeV, muon	25.4 [19.0, 36.6] pb	31.4 pb
7 + 8 TeV	3.1 [2.1, 4.0]	4.7

last row: the upper limits on the rate relative to the SM expectation is given.

- The single top cross section in the s-channel is measured to be

$\sigma_{\text{s-ch.}} = 13.4 \pm 7.3$ pb, $\beta_{\text{signal}} = 2.4 \pm 1.3$ combined, 8TeV,

$\sigma_{\text{s-ch.}} = 7.1 \pm 8.1$ pb, $\beta_{\text{signal}} = 1.5 \pm 1.8$ muon channel 7TeV,

$\beta_{\text{signal}} = 2.0 \pm 0.9$ combined, 7+8TeV

Relative Impact of Systematic Uncertainties

- The measurement is limited with the systematics uncertainty.

Source	Uncertainty (%)				
	μ, 7 TeV	μ, 8 TeV	e, 8 TeV	$\mu + e$, 8 TeV	$7+8$ TeV
Statistical	34	15	14	10	11
$t\bar{t}$, single top quark rate	29	15	14	12	14
W/Z+jets, diboson rate	23	11	13	12	12
multijet rate	9	3	5	2	2
Lepton efficiency	14	1	2	1	3
Hadronic trigger	5	-	-	-	1
Luminosity	10	5	6	4	6
JER & JES	66	39	29	34	18
b tagging & mistag	34	15	14	14	16
Pileup	6	11	7	9	7
Unclustered $\not{E}_T$	5	8	2	6	5
μ_R, μ_F scales	54	34	31	30	28
Matching thresholds	43	11	12	7	17
PDF	12	8	7	7	9
Top quark p_T reweighting	3	5	7	6	6
Total uncertainty	115	64	54	55	47

Conclusion

- The observed significance of the combined measurement is 2.5 standard deviations with 1.1 standard deviations expected.

- The observed and expected upper limits on the combined signal strength at 95% confidence level are found to be 4.7 and 3.1, respectively.