Measurement of the W helicity in top pair production with dileptons at 7 TeV using CMS detector at the LHC

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IPM, School of Particles & Accelerators

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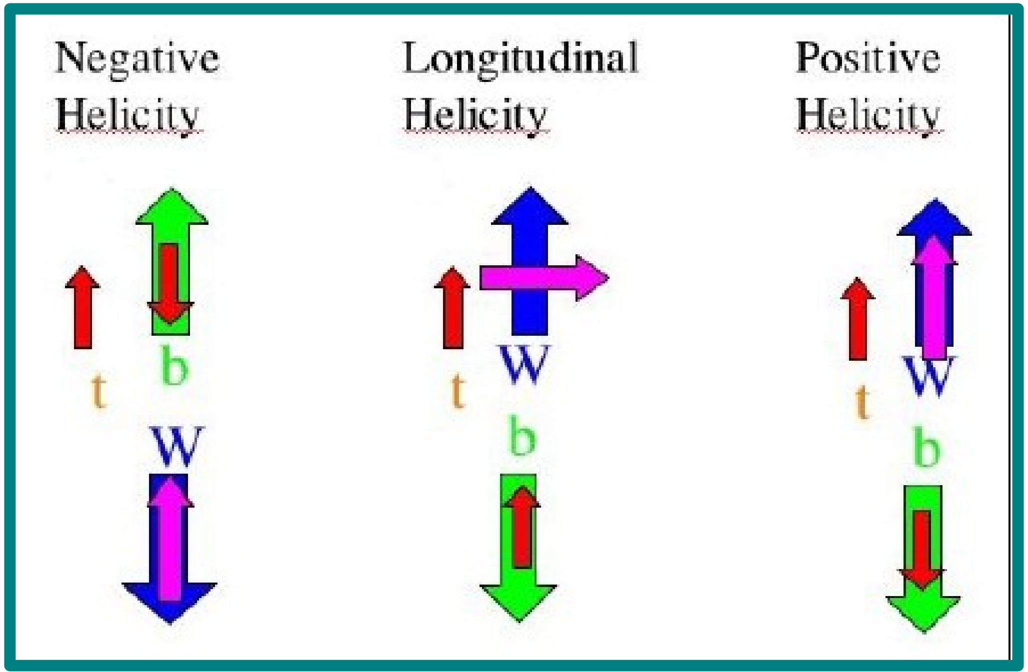
W-Polarization in Theory

- @NNLO, the SM predictions for the W-boson helicity fractions are *(PHYSICAL REVIEW D 81, 111503(R) (2010))*

$$F_0 = 0.687, F_{-1} = 0.311, F_{+1} = 0.0017.$$

- This can be understood since in the limit of massless b-quarks, right-handed W-bosons are suppressed.



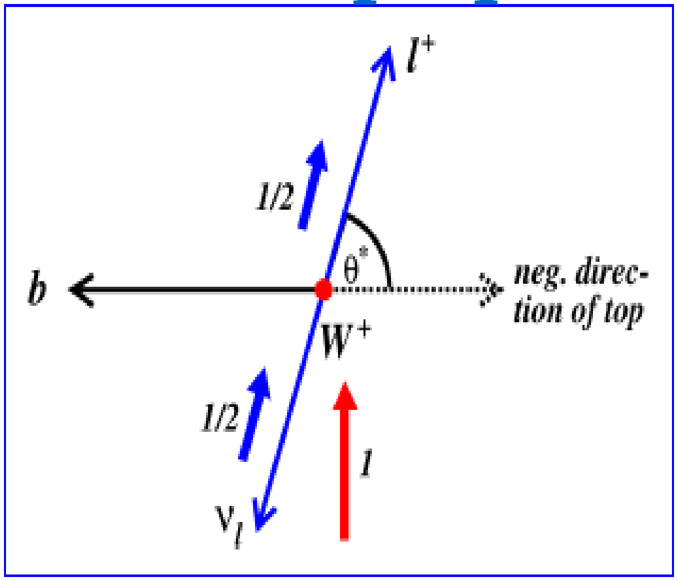
W-Polarization in Experiment

- Find the distribution of $\cos\theta^*$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*}=\frac{3}{8}(1-\cos\theta^*)^2F_-+\frac{3}{8}(1+\cos\theta^*)^2F_++\frac{3}{4}(\sin\theta^*)^2F_0$$

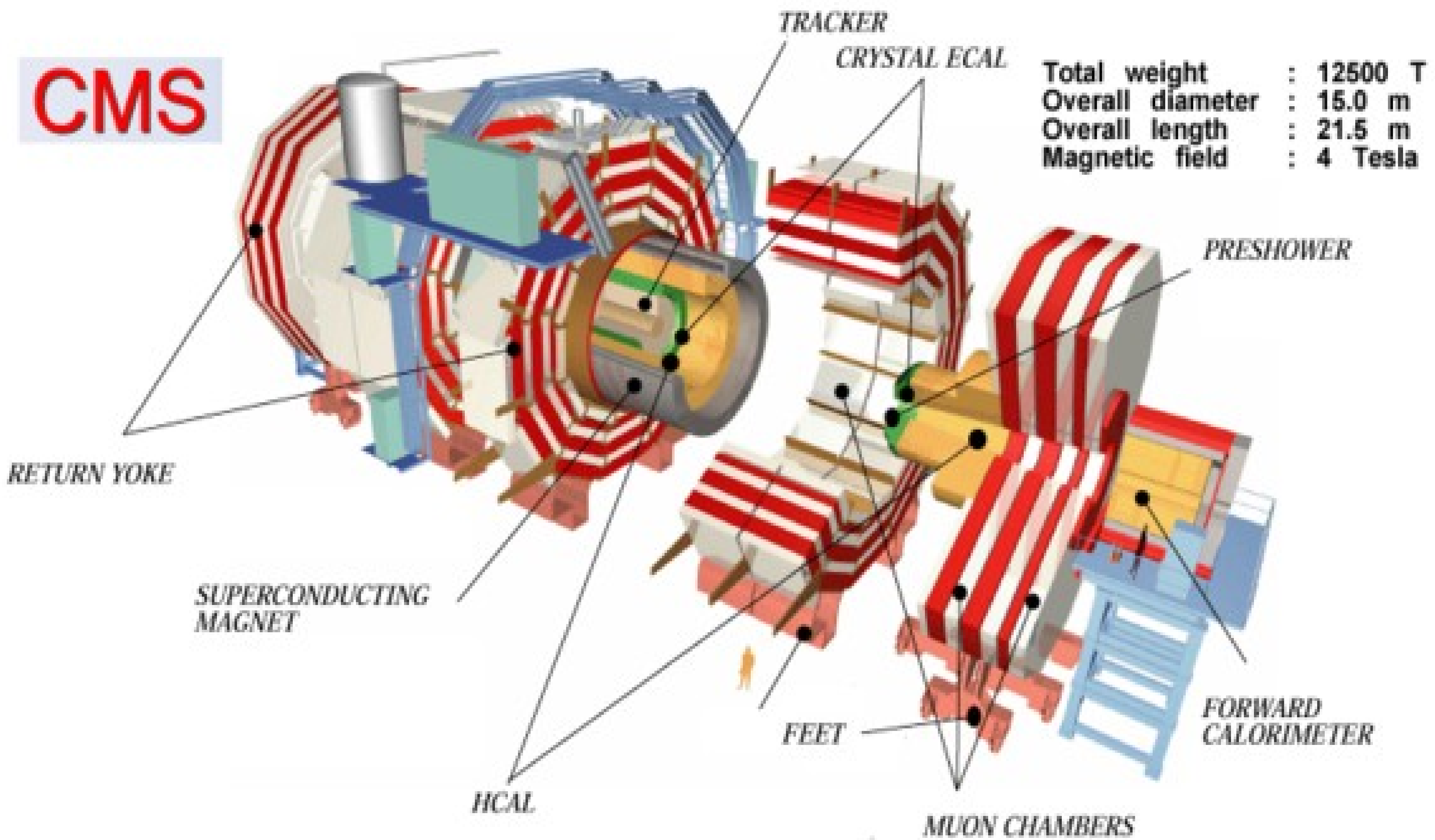
LH RH Long.

- θ^* : the angle in the W-boson rest frame between the direction opposite to the top quark and the direction of lepton



CMS(Compact Muon Solenoid) Detector

- One of the two general-purpose detector of LHC



CMS Detector

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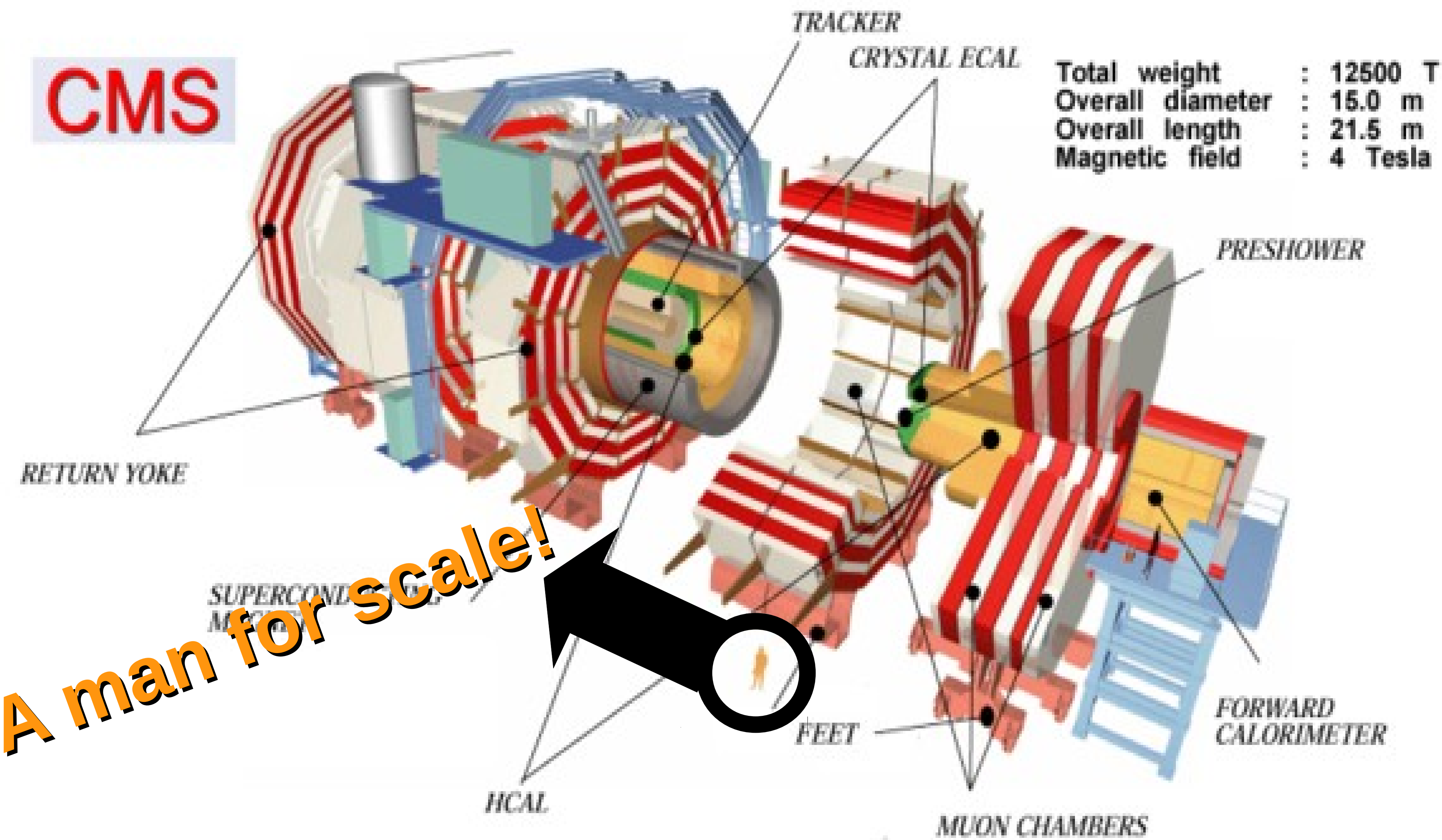
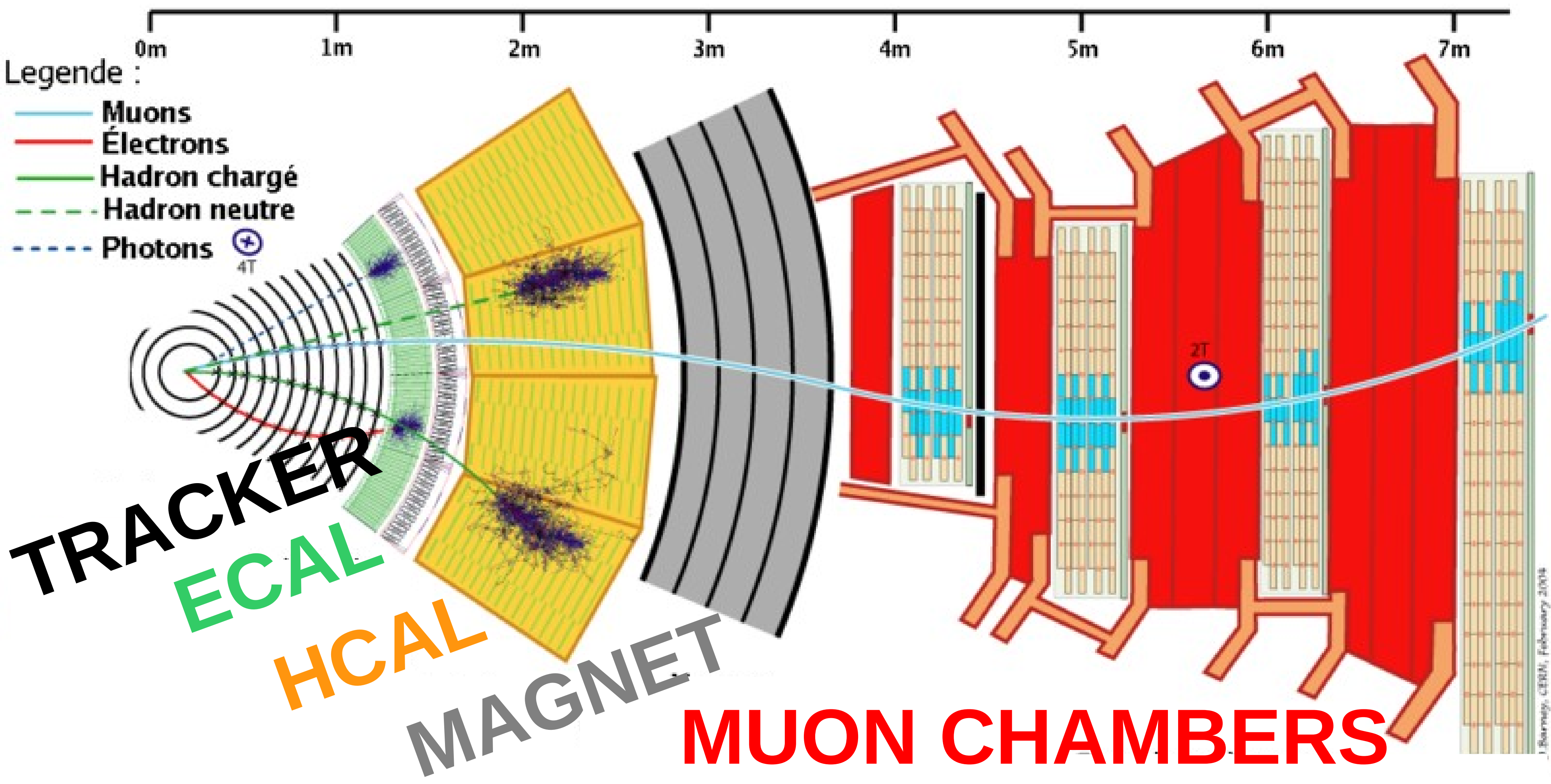


CMS Detector in Transverse View

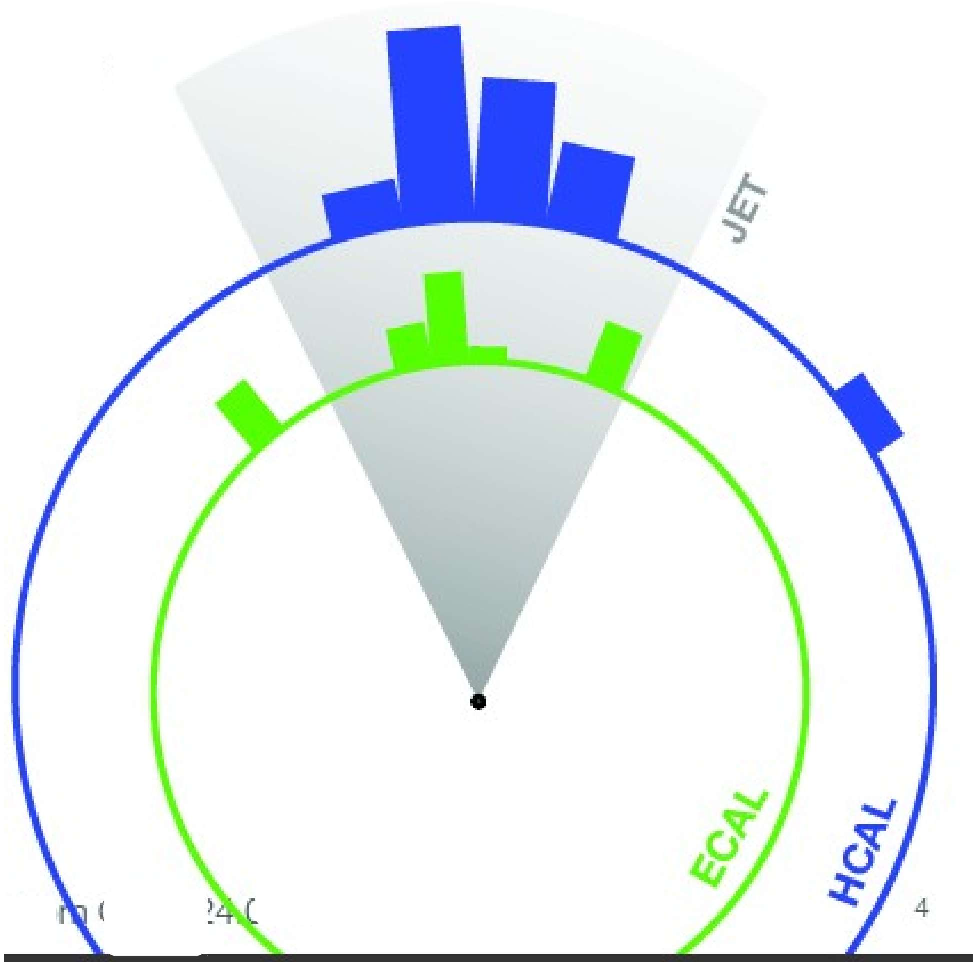
- The only particle can be seen at the detector are *Electrons*, *Photons*, *Muons* and *Hadrons*



Jet Reconstruction at CMS

- **Calorimeter jets:**

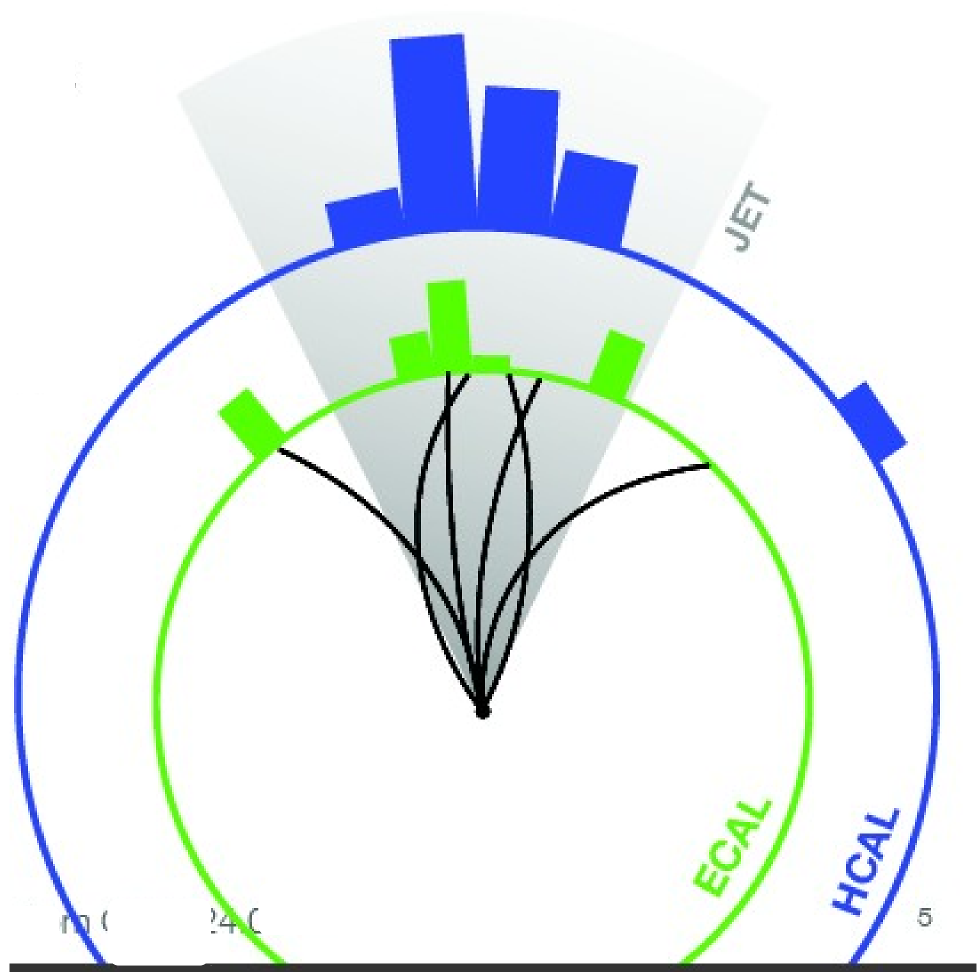
with *calo-towers*



Jet Reconstruction at CMS

- **Calorimeter jets:** with *calo-towers*

- **Jet Plus Track:** correct for tracks

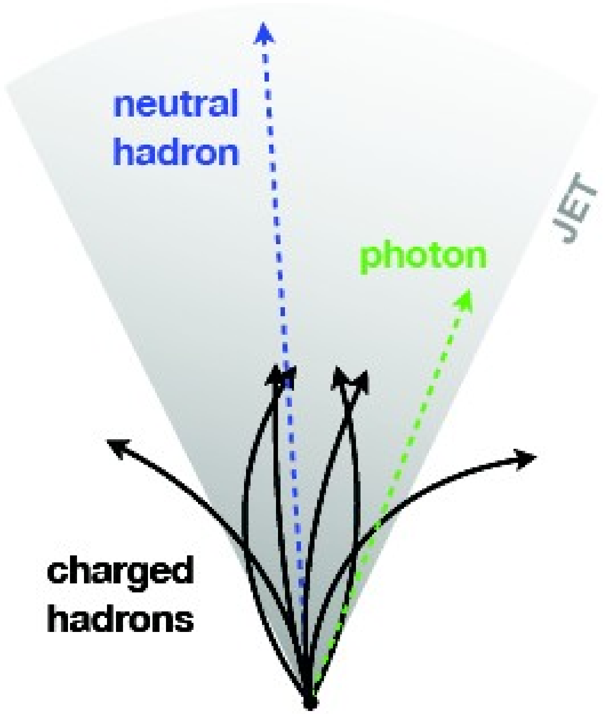


Jet Reconstruction at CMS

- Calorimeter jets: with *calo-towers*

- Jet Plus Track: correct for tracks

- Particle Flow: particle candidates

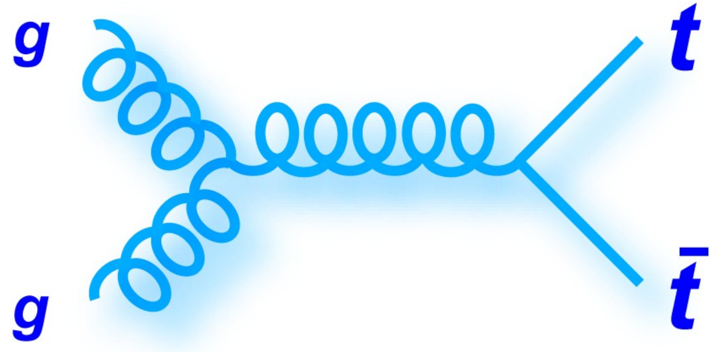


Jet Reconstruction at CMS

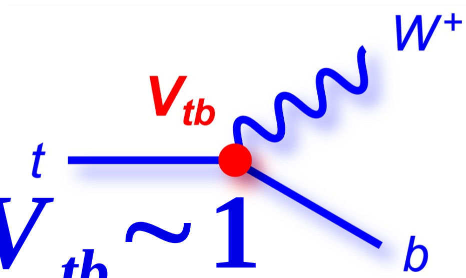
- Calorimeter jets: with *calo-towers*
- Jet Plus Track: correct for tracks
- Particle Flow: particle candidates

1. Simple
2. Worst resolution
3. Improving resolution with tracks
4. Best resolution
5. Used in most analysis

$t\,\bar{t}$ Events Are Selected to Measure W-Polarization

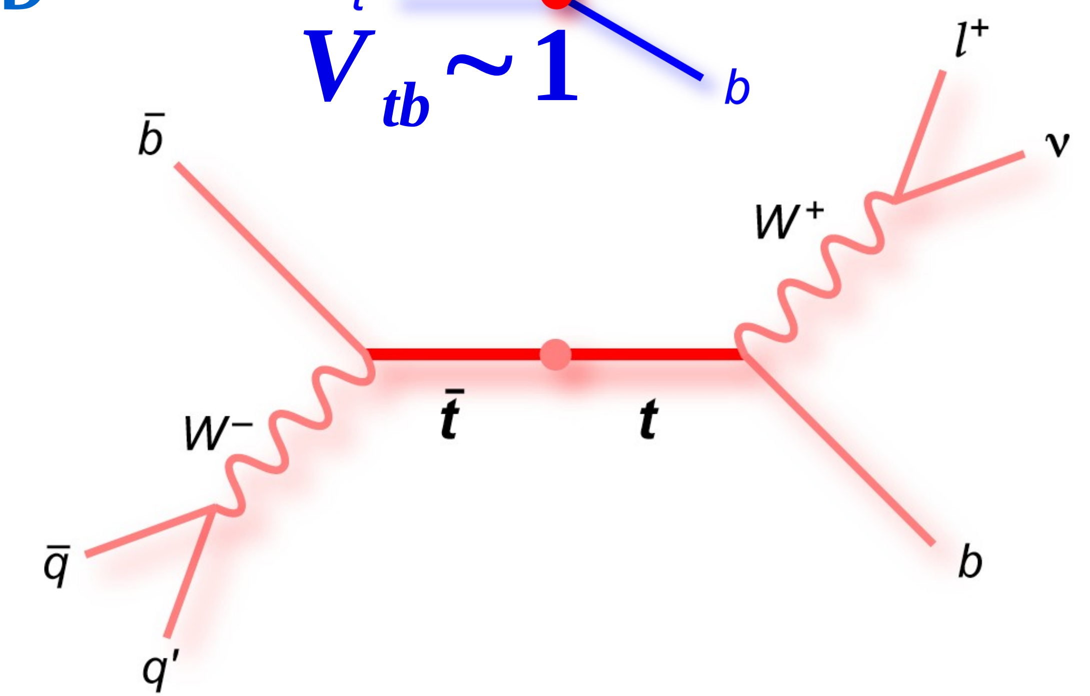


- $t\,\bar{t}$ events are produced via gluon-gluon fusion



- Almost all the time, a top quark decays to a W and b

$V_{tb} \sim 1$



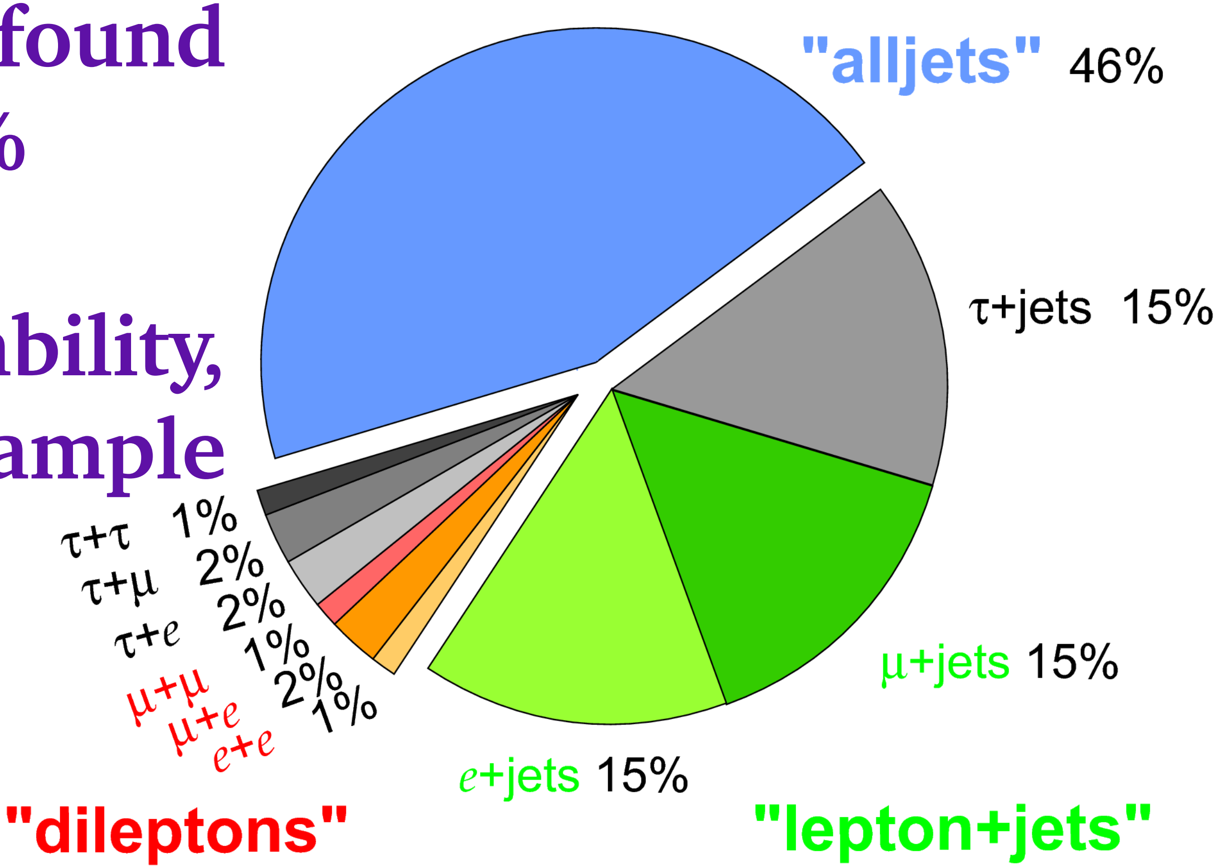
- W-boson decays into hadrons (67%)
- W-boson decays into leptons (33%)

$t\bar{t}$ Dilepton Events

- Only dilepton $t\bar{t}$ events are chosen

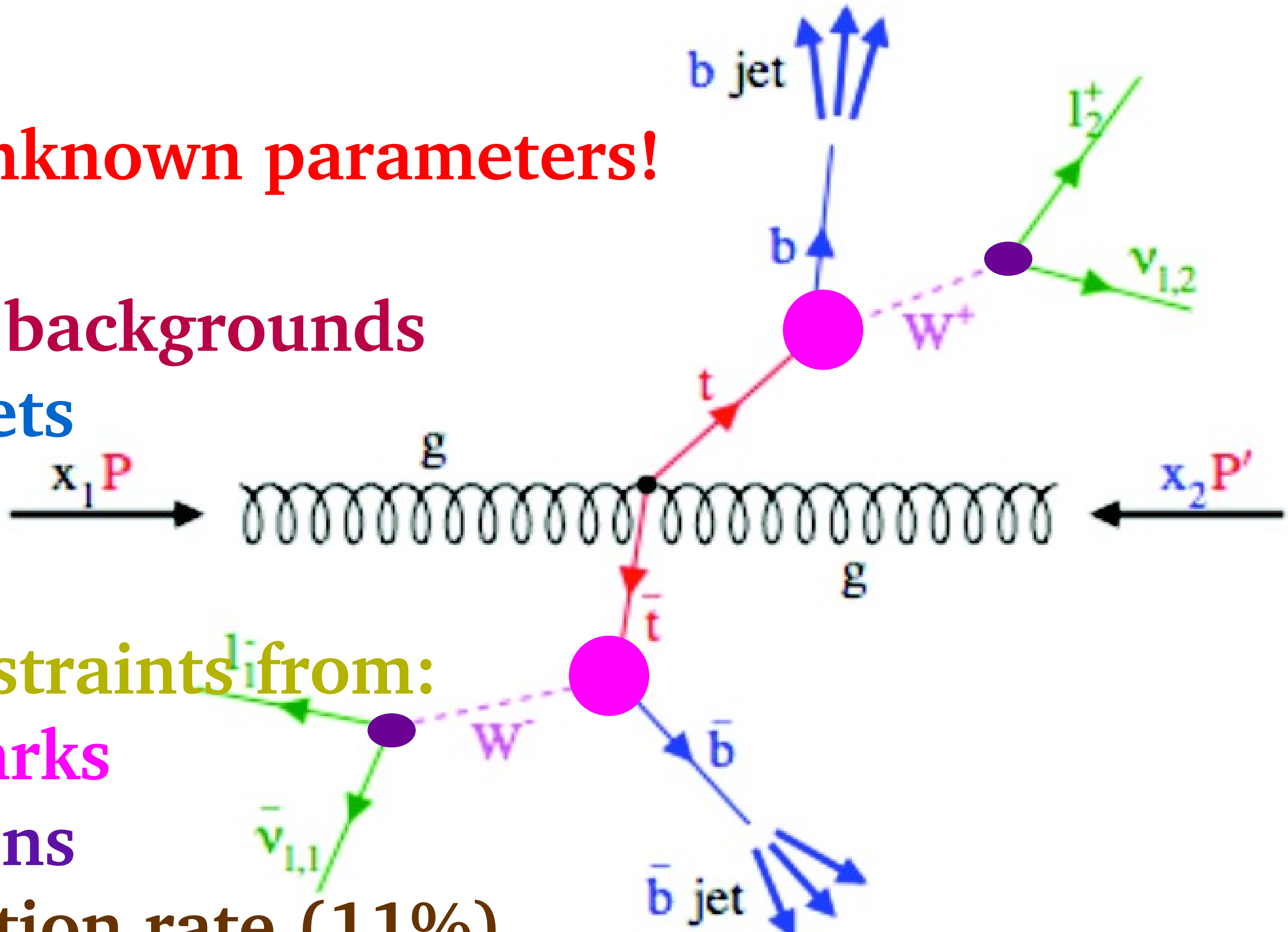
- The probability is found to be 33%*33%~11%

- Very small probability, but still very clean sample at the end



$t\bar{t}$ Dilepton Events: Characteristics

- 2 neutrinos
  - ⇒ 6 unknown parameters!
- 2 leptons
  - ⇒ low backgrounds
- 2 b-quark jets
- 4 mass constraints from:
  - 2 top quarks
  - 2 W bosons
- low production rate (11%)



Finding ν and $\bar{\nu}$ Four-Vectors

- The four-vector of neutrinos are found by solving the 6 equations:

$$(E_T^{miss})_x = p_{\nu_x} + p_{\bar{\nu}_x};$$
$$(E_T^{miss})_y = p_{\nu_y} + p_{\bar{\nu}_y}.$$

$$m_{W^+}^2 = (E_{l^+} + E_\nu)^2 - (p_{l_x^+} + p_{\nu_x})^2 - (p_{l_y^+} + p_{\nu_y})^2 - (p_{l_z^+} + p_{\nu_z})^2;$$
$$m_{W^-}^2 = (E_{l^-} + E_{\bar{\nu}})^2 - (p_{l_x^-} + p_{\bar{\nu}_x})^2 - (p_{l_y^-} + p_{\bar{\nu}_y})^2 - (p_{l_z^-} + p_{\bar{\nu}_z})^2;$$
$$m_t^2 = (E_b + E_{l^+} + E_\nu)^2 - (p_{b_x} + p_{l_x^+} + p_{\nu_x})^2 - (p_{b_y} + p_{l_y^+} + p_{\nu_y})^2 - (p_{b_z} + p_{l_z^+} + p_{\nu_z})^2;$$
$$m_{\bar{t}}^2 = (E_{\bar{b}} + E_{l^-} + E_{\bar{\nu}})^2 - (p_{\bar{b}_x} + p_{l_x^-} + p_{\bar{\nu}_x})^2 - (p_{\bar{b}_y} + p_{l_y^-} + p_{\bar{\nu}_y})^2 - (p_{\bar{b}_z} + p_{l_z^-} + p_{\bar{\nu}_z})^2.$$

- Polynomial equation of degree 4

⇒ { Maximally four solutions for the ν
Maximally four solutions for the $\bar{\nu}$

- The ambiguity should be resolved!
  - The solution minimizing the mass of top pair system

List of Samples

SUMMER11 MC Samples	XSection (pb)
TTJets_TuneZ2_7TeV-madgraph	157.5
WJetsToLNu_TuneZ2_7TeV-madgraph-tauola	31314.0
DYJetsToLL_TuneZ2_M-50_7TeV-madgraph-tauola	2475.
DYJetsToLL_M-10To50_TuneZ2_7TeV-madgraph	9611.0
T_TuneZ2_tW-channel-DR_7TeV-powheg-tauola	7.8
Tbar_TuneZ2_tW-channel-DR_7TeV-powheg-tauola	7.8
WWJetsTo2L2Nu_TuneZ2_7TeV-madgraph-tauola	4.65
WZJetsTo3LNu_TuneZ2_7TeV-madgraph-tauola	0.6
ZZ_TuneZ2_7TeV_pythia6_tauola	4.65
T_TuneZ2_t-channel_7TeV-powheg-tauola	42.5
Tbar_TuneZ2_t-channel_7TeV-powheg-tauola	22

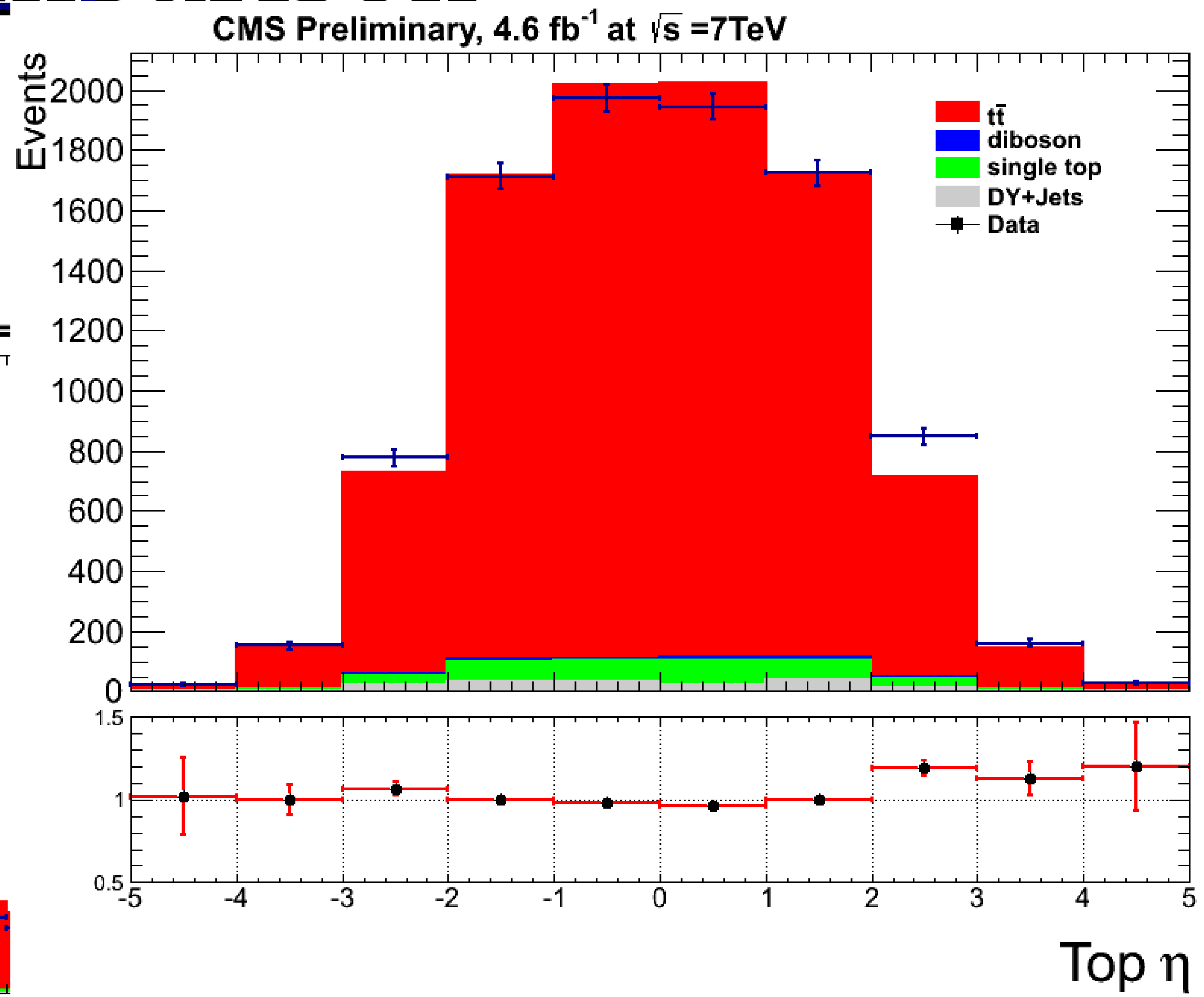
2011 Data	Run2011A	Run2011B v1	Total data
DoubleEelctron	2.044 fb^{-1}	2.485 fb^{-1}	4.529 fb^{-1}
DoubleMuon	1.993 fb^{-1}	2.466 fb^{-1}	4.459 fb^{-1}
MuEG	2.123 fb^{-1}	2.508 fb^{-1}	4.631 fb^{-1}

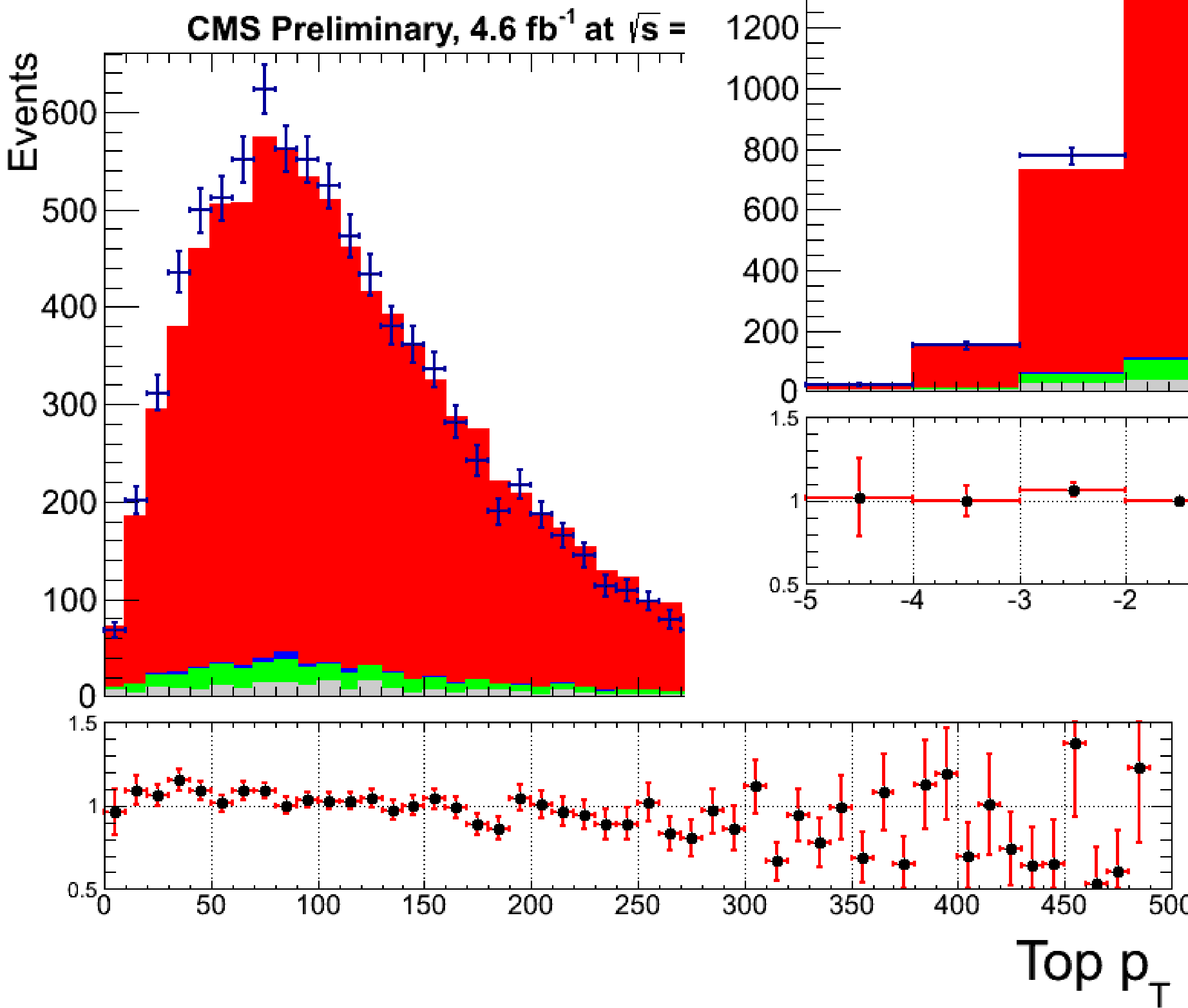
Cut Flow Table

- Several cuts are applied to select signal events
- ~5 fb^{-1} of CMS data from pp collisions at 7 TeV was analyzed
- With this amount of data, about 788k $t\bar{t}$ events have been recorded by the CMS detector

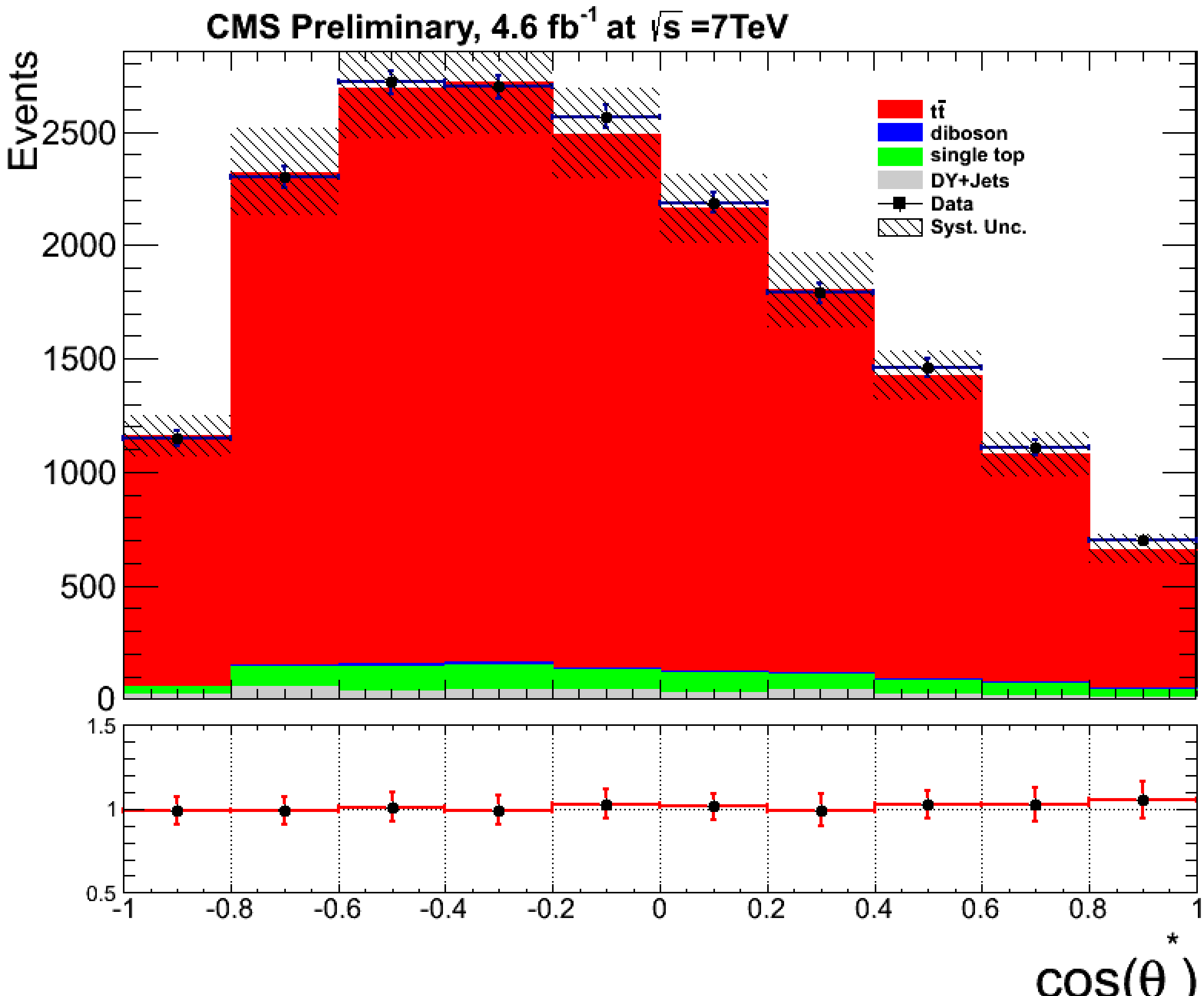
Dataset	Njets	MET	NBjets	$N_{t\bar{t}}$
$t\bar{t}$	13569.6±50.4	12160.2±47.7	9075.0±42.3	8692.3±32.7
SingleTop tW	708.2±7.9	631.4±7.4	410.4±6.2	357.3±4.5
DY $M_{ll} > 10GeV$	16193.2±106.7	2841.3±41.7	206.9±11.8	167.0±9.5
WW	399.4±2.6	353.1±2.4	32.0±0.7	22.8±0.5
SingleTop t	14.6±1.0	12.4±0.9	7.8±0.8	6.5±0.6
WJets	553.3±32.2	448.2±28.8	33.0±7.4	17.0±4.4
WZ	89.6±0.4	70.6±0.4	3.9±0.1	2.7±0.1
ZZ	69.3±0.6	15.4±0.3	2.2±0.1	1.6±0.0
Total(Simulation)	31597.3±122.7	16532.7±70.0	9771.3±45.0	9267.3±34.7
Data	29982	16257	9888	9341

Data-MC Comparison





Constructing Angular Distribution



Fit Method

- A likelihood function is introduced

$$\mathcal{L}(\vec{F}) = \prod_{bin\ i} \frac{N_{MC}(i;\vec{F})^{N_{data}(i)}}{(N_{data}(i))!} \exp\left(-N_{MC}(i;\vec{F})\right),$$

where

$$\begin{aligned} N_{MC}(i;\vec{F}) &= N_{BKG}(i) + N_{t\bar{t}}(i;\vec{F}) \\ N_{t\bar{t}}(i;\vec{F}) &= \mathcal{F}_{t\bar{t}} \left[\sum_{t\bar{t}\text{ events, bin } i} W(\cos\theta^*_{gen};\vec{F}) \right] \\ N_{BKG}(i) &= N_{W+jets}(i) + N_{Drell-Yan+jets}(i) + N_{QCD}(i) + N_{Single-Top}(i) \end{aligned}$$

and the weight function is defined as

$$W(\cos\theta^*_{gen};\vec{F}) \equiv \frac{\rho(\cos\theta^*_{gen})}{\rho^{SM}(\cos\theta^*_{gen})} = \frac{\frac{3}{8}F_L(1-\cos\theta^*_{gen})^2 + \frac{3}{4}F_0\sin^2\theta^*_{gen} + \frac{3}{8}F_R(1+\cos\theta^*_{gen})^2}{\frac{3}{8}F_L^{SM}(1-\cos\theta^*_{gen})^2 + \frac{3}{4}F_0^{SM}\sin^2\theta^*_{gen} + \frac{3}{8}F_R^{SM}(1+\cos\theta^*_{gen})^2}$$

- The W-boson helicity fractions are those which maximize the likelihood function

Measured W-Polarization Fractions

- The heliciy fractions of W bosons from top quark decays are found from the fit method

$$F_0 = 0.698 \pm 0.057$$
$$F_- = 0.288 \pm 0.035$$
$$F_+ = 0.014 \pm 0.027$$

- They are in agreement with the SM expectations
- No BSM effect is found
- Several statistical tests are performed to check if the method works fine
  - Linearity test: the central values are truly estimated
  - Pull distribution: there is no bias on uncertainties

W-Polarization: Systematics

Systematic Source	Fitting F_L, F_0	
	$\pm\delta F_L$	$\pm\delta F_0$
Top QScale	0.027	0.051
Top Mass	0.016	0.003
WZQScale	0.013	0.026
DY XSection	0.009	0.014
W XSection	0.000	0.002
SingleTopTW XSection	0.002	0.008
JES	0.01	0.006
Pile Up	0.014	0.017
PDF	0.004	0.005
Total	0.040	0.063

Summary

- W-polarization fractions from top quark decay in dilepton $t\bar{t}$ events are measured

- Full 2011 data collected by the CMS experiment from proton-proton collisions at 7 TeV is analyzed

- The presented results are approved by the CMS

- Measured helicity fractions of the W bosons are in agreement with the SM prediction

- No new physics is observed

Plan

- To update this analysis using 8 TeV datasets collected at 2012 corresponding to about 20 fb-1

- To study any possible anomalous Wtb couplings

- Two new PhD students have already been joined to the team, *Mr Behnamian* & *Mr Naseri*

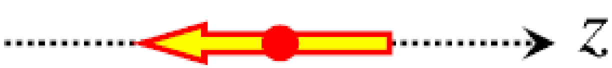
- Seems still more work is needed!

BACK-UP

W-Boson Decay from Theory

- A massive spin-1 boson traveling along the z-axis

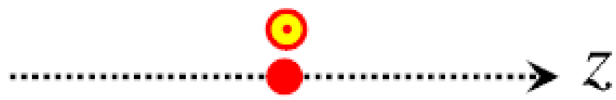
$$\varepsilon_{-}^{\mu} = \frac{1}{\sqrt{2}}(0,1,-i,0);$$



$S_z = -1$

transverse

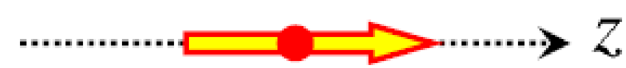
$$\varepsilon_L = \frac{1}{m}(p_z,0,0,E)$$



$S_z = 0$

longitudinal

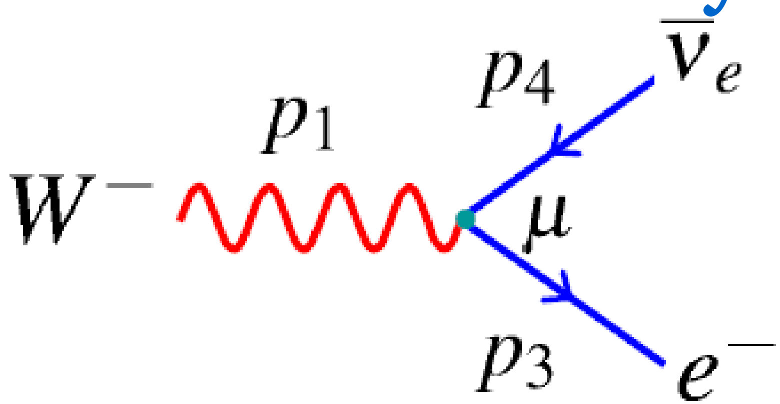
$$\varepsilon_{+}^{\mu} = -\frac{1}{\sqrt{2}}(0,1,i,0)$$



$S_z = +1$

transverse

- Want to calculate W boson decay rate



W-Boson Decay from Theory

- Matrix element for $W^- \rightarrow e^- \overline{\nu}_e$ is

$$-iM_{fi} = \varepsilon_\mu(p_1).\overline{u}(p_3).-i\frac{g_W}{\sqrt{2}}\gamma^\mu \tfrac{1}{2}(1-\gamma^5).v(p_4)$$

which can be written as $M_{fi} = \frac{g_W}{\sqrt{2}}\varepsilon_\mu(p_1).j^\mu$

$$\varepsilon_-^\mu = \frac{1}{\sqrt{2}}(0,1,-i,0)$$

$$\varepsilon_L = (0,0,0,1)$$

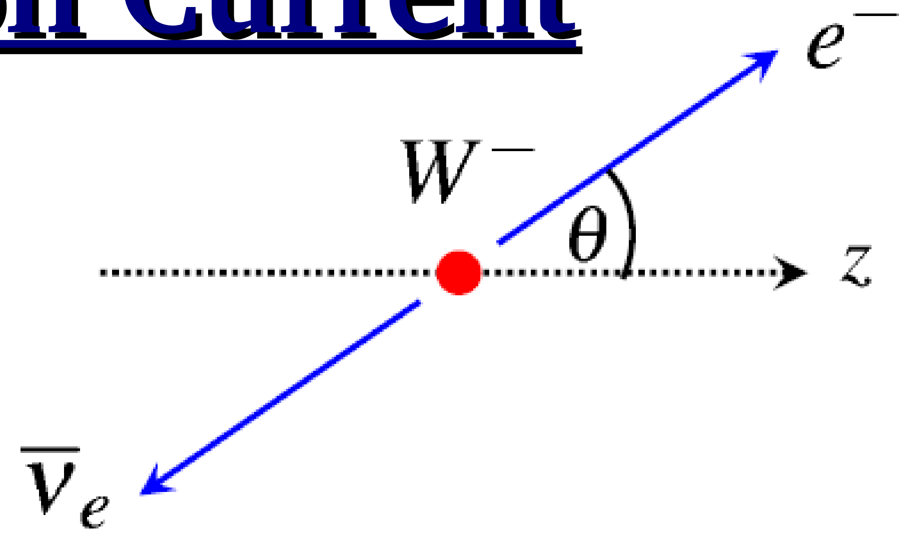
$$\varepsilon_+^\mu = -\frac{1}{\sqrt{2}}(0,1,i,0)$$

W-Boson Polarization

Weak Charged Current

$$j^\mu = \overline{u}(p_3)\gamma^\mu \tfrac{1}{2}(1-\gamma^5)v(p_4)$$

W-Decay: The Lepton Current



- **Working in the COM frame**

$$p_1 = (m_W, 0, 0, 0);$$
$$p_3 = (E, E\sin\theta, 0, E\cos\theta)$$
$$p_4 = (E, -E\sin\theta, 0, -E\cos\theta)$$ **, where** $E = \frac{m_W}{2}$

- **In the ultra-relativistic limit, the lepton current is found to be**

$$j^\mu = \overline{u}(p_3)\gamma^\mu \tfrac{1}{2}(1-\gamma^5)v(p_4) = \overline{u}_\downarrow(p_3)\gamma^\mu v_\uparrow(p_4)$$
$$= 2E(0, -\cos\theta, -i, \sin\theta)$$

Helicity Amplitudes

- Matrix element for the different polarization states

$$M_- = \frac{g_W}{\sqrt{2}}\frac{1}{\sqrt{2}}(0,1,-i,0).m_W(0,-\cos\theta,-i,\sin\theta) = \frac{1}{2}g_W m_W(1+\cos\theta)$$

$$M_L = \frac{g_W}{\sqrt{2}}(0,0,0,1).m_W(0,-\cos\theta,-i,\sin\theta) = -\frac{1}{\sqrt{2}}g_W m_W \sin\theta$$

$$M_+ = -\frac{g_W}{\sqrt{2}}\frac{1}{\sqrt{2}}(0,1,i,0).m_W(0,-\cos\theta,-i,\sin\theta) = \frac{1}{2}g_W m_W(1-\cos\theta)$$

$$|M_-|^2 = g_W^2 m_W^2 \frac{1}{4}(1+\cos\theta)^2$$

$$|M_L|^2 = g_W^2 m_W^2 \frac{1}{2}\sin^2\theta$$

$$|M_+|^2 = g_W^2 m_W^2 \frac{1}{4}(1-\cos\theta)^2$$

Total W-Boson Decay Rate

- The Differential decay rate obtained from

$$\frac{d\Gamma}{d\Omega} = \frac{|p^*|}{32\pi^2 m_W^2}|M|^2$$, where $p^* = \frac{m_W}{2}$

- For a sample of unpolarized W-boson each polarization state is equally likely
- sum over all possible matrix elements and average over the three initial polarization states

$$\begin{aligned} \langle |M_{fi}|^2 \rangle &= \tfrac{1}{3}(|M_-|^2 + |M_L|^2 + |M_+|^2) \\ &= \tfrac{1}{3} g_W^2 m_W^2 \left[\tfrac{1}{4}(1+\cos\theta)^2 + \tfrac{1}{2}\sin^2\theta + \tfrac{1}{4}(1-\cos\theta)^2\right] \\ &= \tfrac{1}{3} g_W^2 m_W^2 \end{aligned}$$

- Total decay rate is found to be $\Gamma(W^- \to e^- \overline{\nu}) = \frac{g_W^2 m_W}{48\pi}$

Differential W-Boson Decay Rate

- From $\frac{d\Gamma}{d\Omega} = \frac{|p^*|}{32\pi^2 m_W^2}|M|^2$ and using total decay rate,

one can derive

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1-\cos\theta^*)^2 F_- + \frac{3}{8}(1+\cos\theta^*)^2 F_+ + \frac{3}{4}(\sin\theta^*)^2 F_0$$

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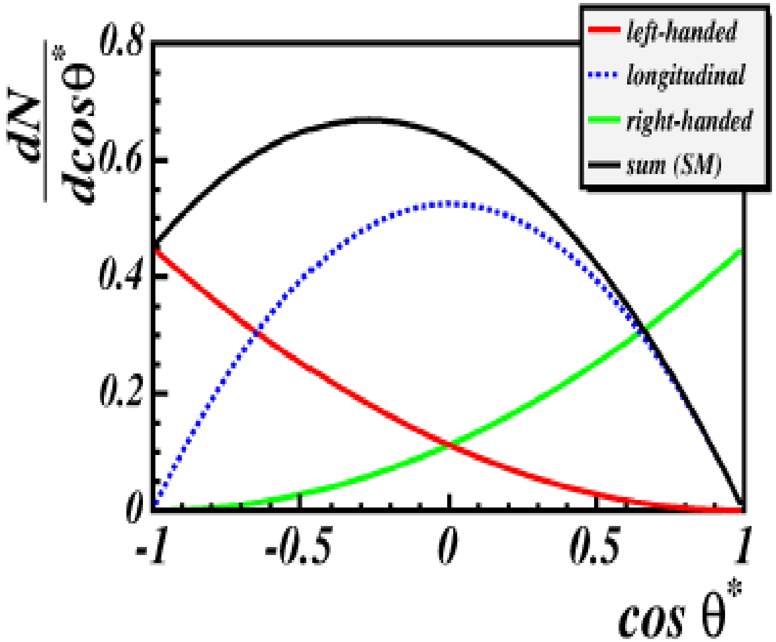

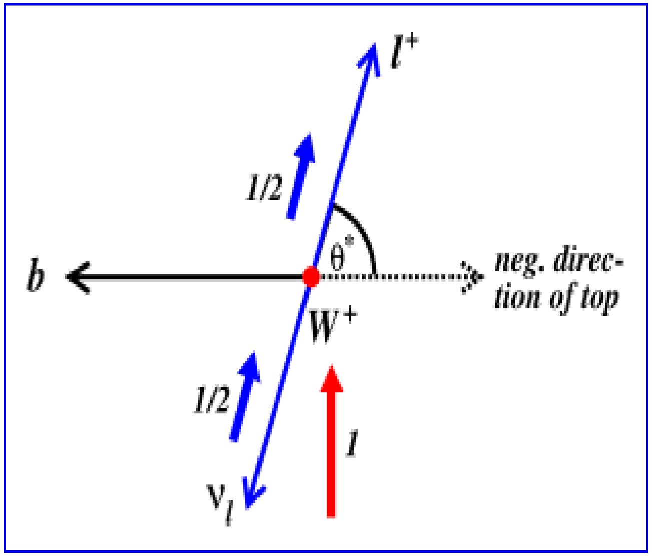

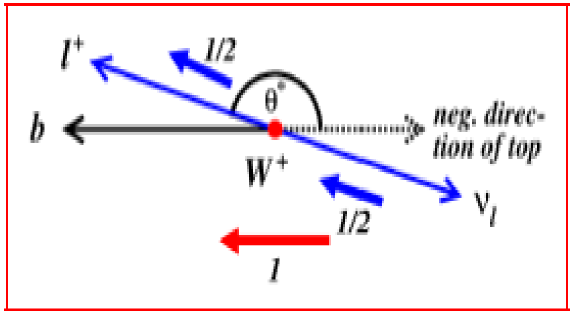

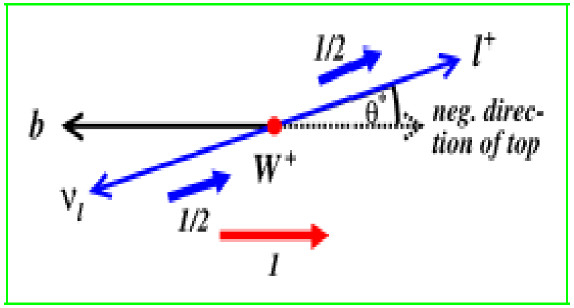

Data-Driven Bkg Estimation of DY

- To reduce the DY contribution to a dilepton data sample, events with 76 < Mll < 106 are excluded
- A scale factor (SF) between DY events predicted by simulation and measured in data is computed in the control region
- This SF is used to normalize the predictions of the simulation outside the veto region expressed here

$$N_{DY}^{out\ (est)} = \frac{N_{DY\ DATA}^{in}}{N_{DY\ MC}^{in}} \cdot N_{DY\ MC}^{out}$$

- Assumed the control region is dominated by DY
- In reality, we should deal with bkgs when measuring $N_{DY\ DATA}^{in}$

Data-Driven Bkg Estimation of DY

- Two different types of bkgs
  - Peaking bkg

    WZ and ZZ give a peakat the Z mass in the dilepton invariant mass distribution, if both selected leptons come from the Z in the case of WZ, or the same Z in the case of ZZ.

    ➡ Neglected because of small contribution
  - Non-peaking bkg

    WW, tt, tW and W+jets give a flat contribution in the dilepton invariant mass distribution, which must estimated from data.

    ➡ Measure number of events in the control region in the e-mu final state

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    ➡ Measure number of events in the control region in the e-mu final state

$$K_{ee,(\mu\mu)} = \sqrt{\left(\frac{N_{in}^{data,ee(\mu\mu)}}{N_{in}^{data,\mu\mu(ee)}}\right)} \text{*1/2}$$

$$N_{DY\ DATA}^{in} = (N_{ll\ DATA}^{in} - k \cdot N_{e\mu\ DATA}^{in})$$

Data-Driven Bkg Estimation of DY

- We've found the following DY scale factors

ee: 1.56 ± 0.042

$\mu\mu$: 1.09 ± 0.037

- For DY in e-mu channel, most of the DY contribution is coming from the Z->tau tau
- The X-section is much lower than inclusive DY, hence small bkg contamination
- In addition, because of the presence of neutrinos coming from tau decays, the dilepton invariant mass is not compatible with the known Z mass and the Z mass peak is shifted to the low masses
- It is rather difficult to estimate the DY contamination in the e-mu channel from data