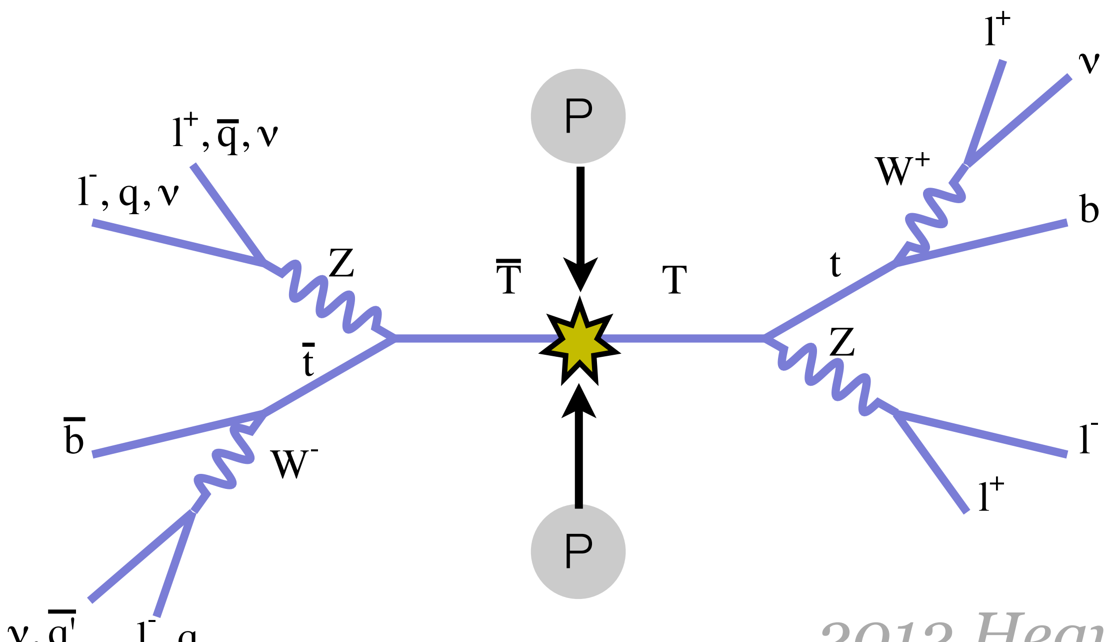
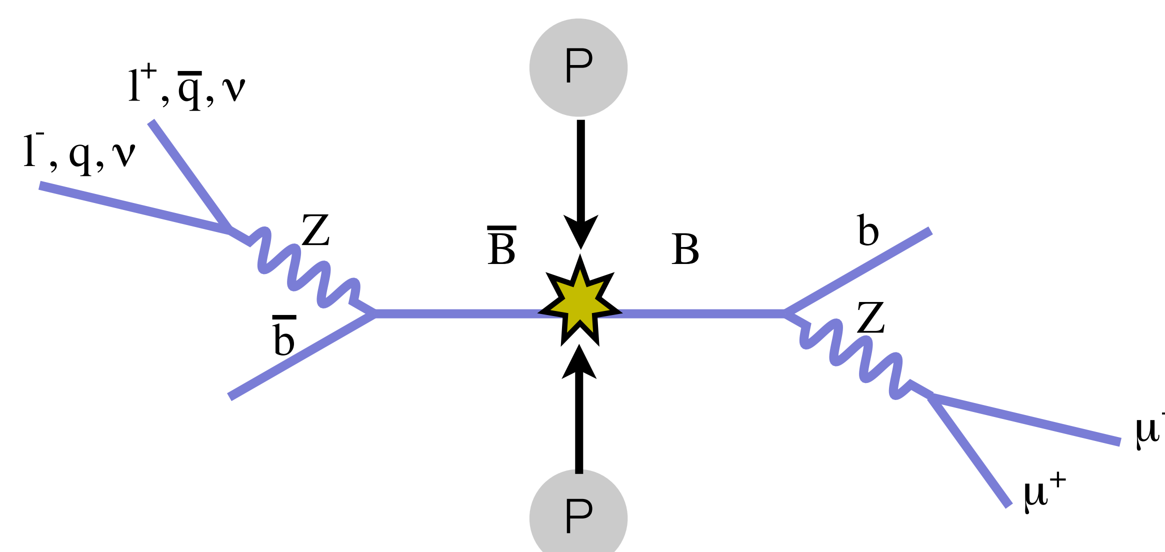
Search for Vector-like Quarks
T → tZ (B → bZ) at $\sqrt{s}$ = 7 TeV in CMS

Yeng-Ming Tzeng (NTU)

On behalf of CMS Collaboration





2012 Heavy Quarks Workshop
Jan. 20, NTU, Taipei (Taiwan)

Outline

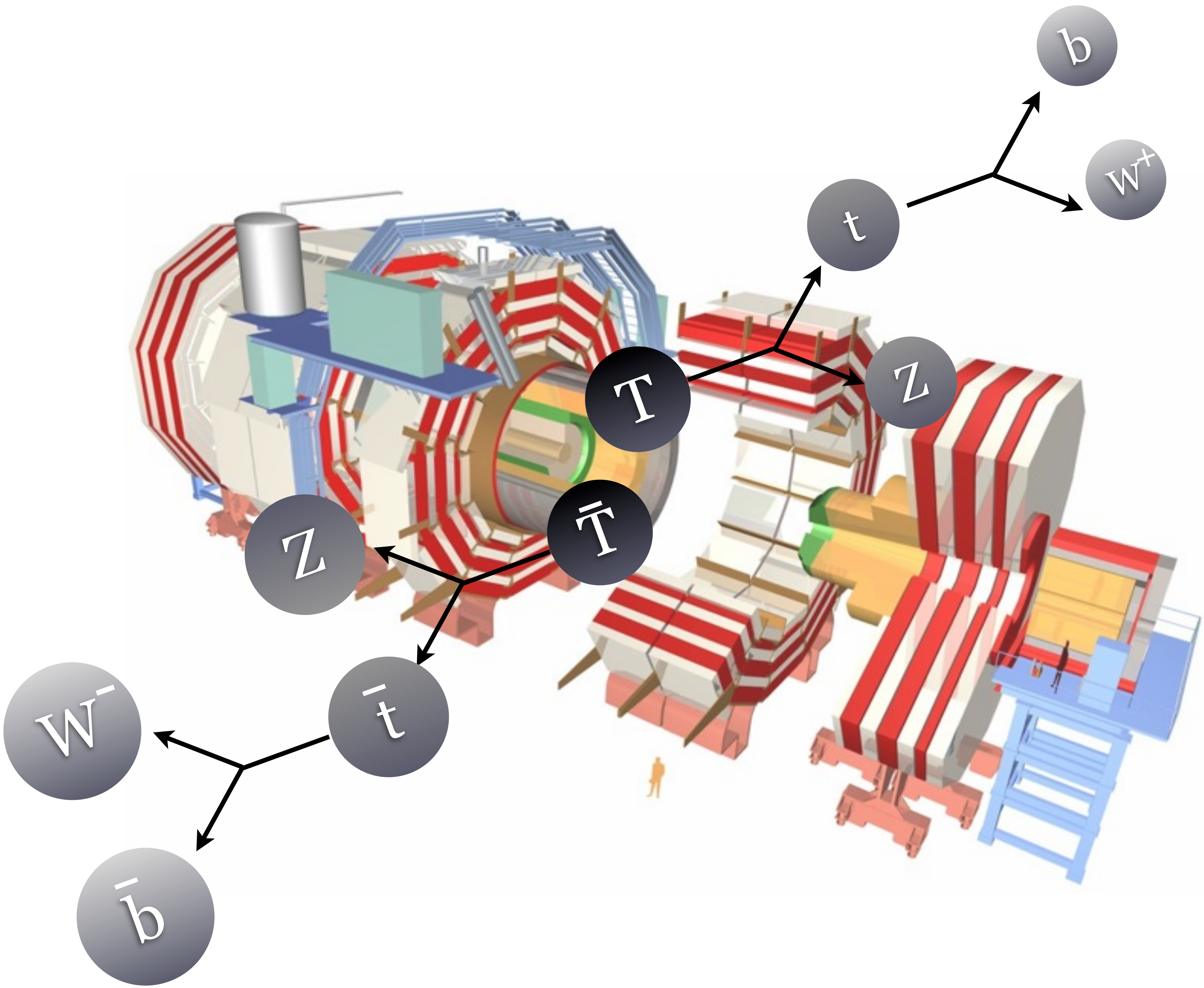
- **Search for a vector-like top quark (*PRL. 107, 271802 (2011), NTU*)**
    - Introduction to a vector-like top quark (T)
    - T → tZ analysis in the CMS detector
        - Event selection, background estimation, systematic uncertainties, and result.
- **Search for a vector-like bottom quark**
    - Review the result from CDF (Phys. Rev. D76, 072006 (2007))
    - Introduction to B → bZ analysis in the CMS detector (***EXO-11-066, NTU***)
- **Conclusion**

Vector-like Top Quark

- **Chiral fermions in the SM**
  - All fermions obey chiral symmetry
  - Left-handed SU(2) doublets : $Q = (u_L, d_L)^T, \; L = (\nu_L, \ell_L)^T,$
  - Right-handed SU(2) singlets : $u_R, \; d_R, \; \ell_R,$
- **Vector-like fermions**
  - LH and RH states : SU(2) N-plets (singlet, doublet, triplet...)
  - Neutral current interaction → vector-like interaction
- **SM + Vector-like charge 2/3 top quark (T)**
  - Flavor changing neutral current (FCNC) via tree level.
  - BF of T→tZ and T→tH can individually reach to 50% (Triplet case, JHEP 1011:159,2010, Yasuhiro Okada...etc).
  - Assuming BF(T→tZ) close to 100% if $m_h > m_T$.

Motivation

- **Many theories postulate vector-like quarks, for example :**
    - Little Higgs model (e.g. Nucl.Phys.Proc.Suppl.117 (2003)40)
    - Warped extra dimensions scenario : ADD + RS (e.g. Phys.Rev.Lett.83:3370-3373,1999)
- **Both models can give a solution to hierarchy problem (SM)**
    - Hierarchy problem between weak and Planck scale
    - Little Higgs model
        - Introduce ***a vector-like top quark*** in order to cancel the divergency from the top loop
    - Warped extra dimensions (4+n)
        - Introduce ***vector-like quarks*** since chiral quarks can not exist when n is odd.

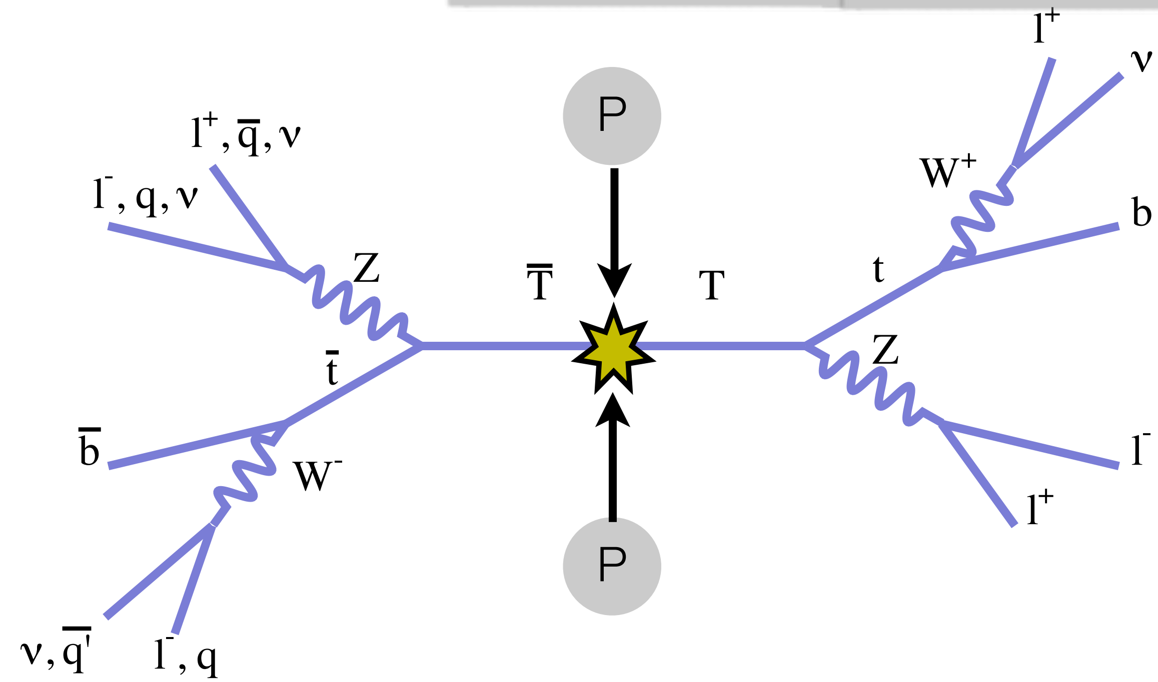

b
W+
t
Z
T
T̄
Z
t̄
W-
b̄

Analysis Strategy

- **Counting experiment**
- **The full decay chain :**

$T\bar{T} \rightarrow tZ\bar{t}Z \rightarrow b\bar{b}W^{+}W^{-}ZZ$

(2 W-bosons + 2 Z-bosons + 2 b-jets)



- **Final states :**

Decay Mode	Branching Fraction
1L+4~8J ($1W_{l\nu}$)	324/900
2L+2~6J ($2W_{l\nu}$)	81/900
2L+6~8J ($1Z_{ll}$)	72/900
3L+4~6J ($1W_{l\nu} + 1Z_{ll}$)	72/900
4L+2~4J ($2W_{l\nu} + 1Z_{ll}$)	18/900
4L+6J ($2Z_{ll}$)	4/900
5L+4J ($1W_{l\nu} + 2Z_{ll}$)	4/900
6L+2J ($2W_{l\nu} + 2Z_{ll}$)	1/900

BF~5.4% for e,μ

$BF(W \rightarrow l\nu) = 1/3$
$BF(Z \rightarrow l^{+}l^{-}) \sim 1/10$

Clean states ⇒ at least 3 leptons (including Z_{ll}) + at least 2 jets

Samples

- **Data : 1.14/fb collected in 2011**

- **MC :**

T(250~550GeV/c^2)

SM background: boson(s), $t\bar{t}$(X), QCD

Process	Cross-section (pb)	Size	Equ. $\mathcal{L}$	Generator
$T\bar{T}$, $M(T) = 250$ GeV/c^2	22.6 (NNLO)	89.7K	4.0 fb^{-1}	Madgraph
$T\bar{T}$, $M(T) = 300$ GeV/c^2	7.99 (NNLO)	86.8K	10.9 fb^{-1}	Madgraph
$T\bar{T}$, $M(T) = 350$ GeV/c^2	3.20 (NNLO)	83.3K	26.0 fb^{-1}	Madgraph
$T\bar{T}$, $M(T) = 400$ GeV/c^2	1.41 (NNLO)	86.0K	61.0 fb^{-1}	Madgraph
$T\bar{T}$, $M(T) = 450$ GeV/c^2	0.66 (NNLO)	87.4K	132 fb^{-1}	Madgraph
$T\bar{T}$, $M(T) = 500$ GeV/c^2	0.33 (NNLO)	85.6K	259 fb^{-1}	Madgraph
$T\bar{T}$, $M(T) = 550$ GeV/c^2	0.17 (NNLO)	90.3K	531 fb^{-1}	Madgraph
W + jets	30059 (CMS)	15.1M	501 pb^{-1}	Madgraph
Z + jets	2939 (CMS)	2.3M	793 pb^{-1}	Madgraph
WW inclusive	43.0 (NLO)	2.1M	47.9 fb^{-1}	Pythia
WZ inclusive	18.0 (NLO)	2.1M	117 fb^{-1}	Pythia
ZZ inclusive	5.9 (NLO)	2.1M	357 fb^{-1}	Pythia
$t\bar{t}$+jets	158 (CMS)	1.2M	7.4 fb^{-1}	Madgraph
$t\bar{t}W$(+jet)	0.144 (LO)	12.5K	86.5 fb^{-1}	Madgraph
$t\bar{t}Z$(+jet)	0.094 (LO)	5.0K	52.7 fb^{-1}	Madgraph
QCD(HT: 100 ~ 250)	7000000 (LO)	9.87M	1.4 pb^{-1}	Madgraph
QCD(HT: 250 ~ 500)	171000 (LO)	4.70M	27.5 pb^{-1}	Madgraph
QCD(HT: 500 ~ 1000)	5200 (LO)	7.33M	1409 pb^{-1}	Madgraph
QCD(HT: 1000 ~ Inf)	83 (LO)	1.71M	20577 pb^{-1}	Madgraph

p.s. Signal NNLO XSec from "HATHOR – HAdronic Top and Heavy quarks crOss section calculatoR" *(arXiv:1007.1327)*

Selection Criteria

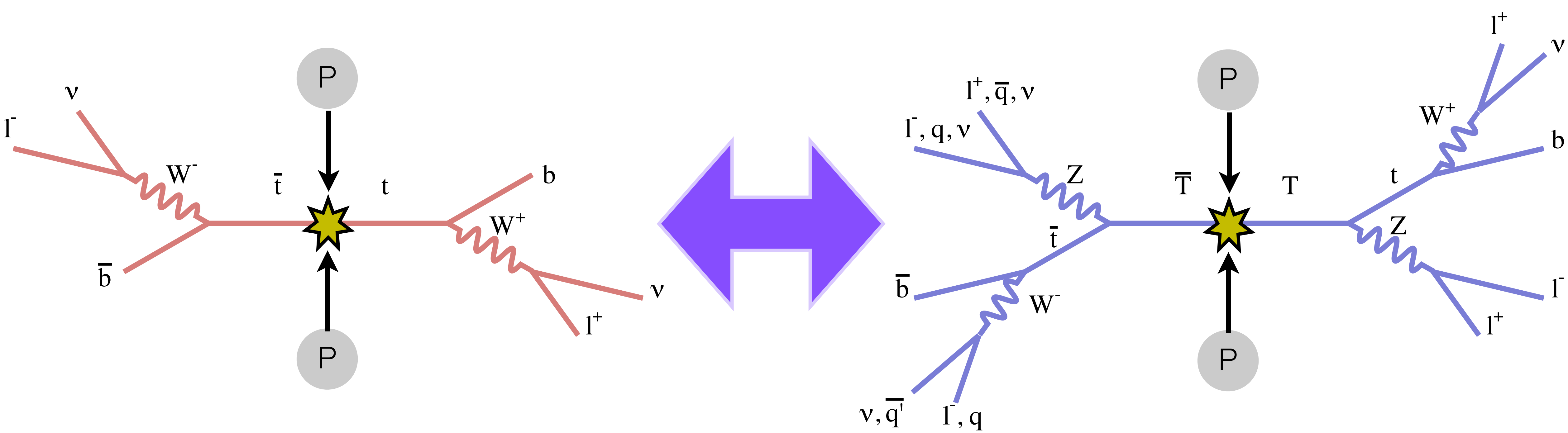
- At least a good primary vertex
- Objects selection:

μ selection	e selection	Jet selection
pT > 15 GeV |η| < 2.4	pT > 20 GeV |η| < 2.5 ΔR(e,μ)>0.1 Reject γ conversion	pT > 25 GeV |η| < 2.4 ΔR(jet,lep)>0.4

- N(lep) ≥ 3, Z_{ll} (60GeV~120GeV), and N(jet) ≥ 2
- R_T = Σ(lep+jet pT) - Σ(leading 2lep+2jet pT) > 80GeV

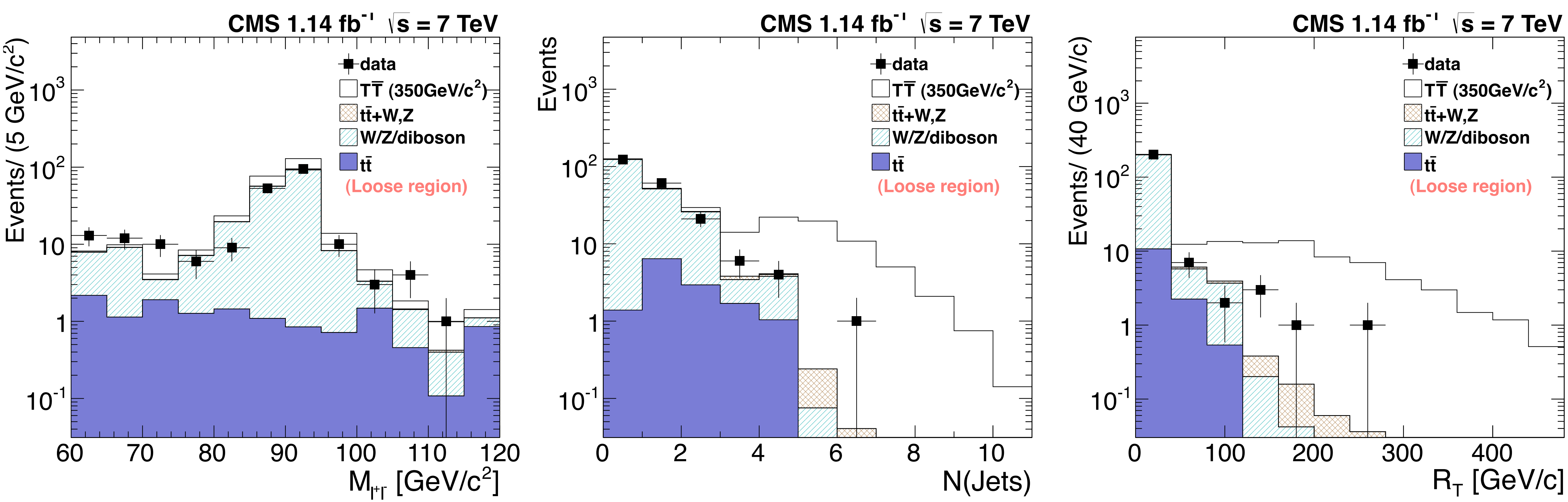
R_T

- **Definition:**
  - *Σ(lep+jet pT) - Σ(leading 2lep+2jet pT)*
- **Purpose:**
  - **Remove the ttbar background which has no leptons or jets to contribute to the R_T for the di-lepton channel.**



Plots in a Loose Region

- **Selection :**
  - At least 3 leptons
  - $Z \rightarrow ll$
  - ~~N(jet) ≥ 2 + R_T > 80 GeV~~

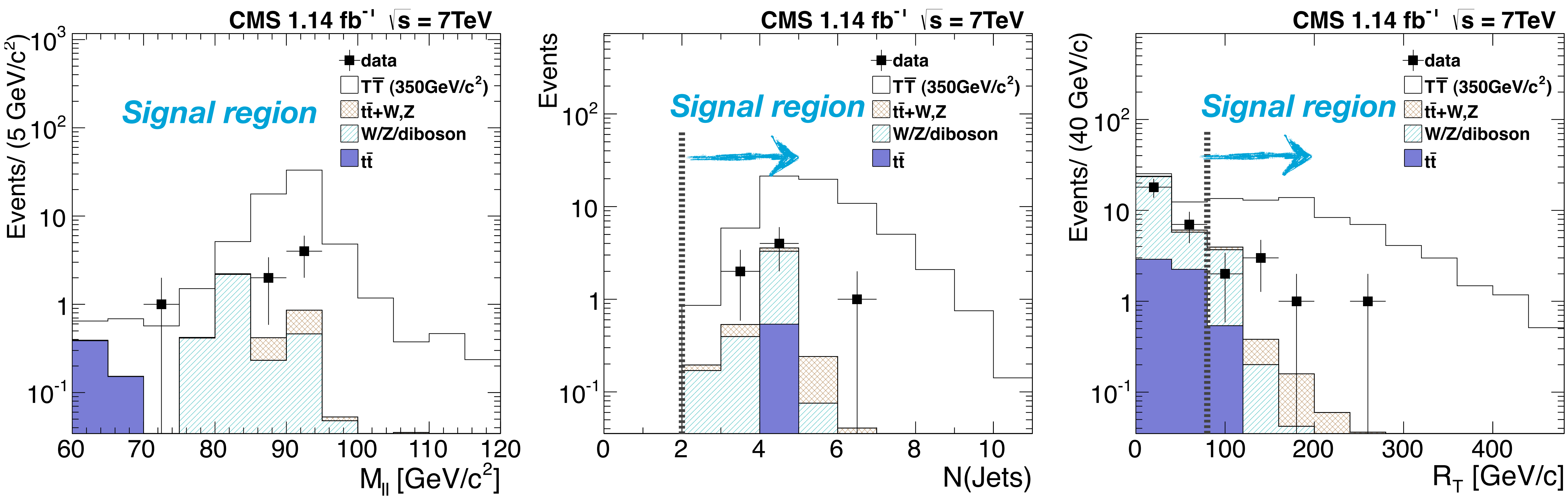


Resulting Plots (Signal Region)

- **Selection :**
  - At least 3 leptons
  - Z→ll
  - N(jet) ≥ 2 + R_T > 80 GeV

T(350GeV)	57.8±11.0
Bkg. (estimated)	4.60±1.04
Data	7

syst.



Background Classifications

- ≤ 2 prompt leptons ($B_{2\ell}$)
    - *Estimated with data-driven method*
    - Z+jets, $t\bar{t}$+jets... (QCD processes also included in this estimation)
- 3 prompt leptons ($B_{3\ell}$)
    - *Obtained from MC*
    - $t\bar{t}$Z(W)+jet, WZ, and ZZ

Data-Driven $B_{2\ell}$ Estimation

Method :

$$N_B = N_{control} \times \varepsilon_f$$

Control region is similar to signal region except for combination of loose and tight leptons

Lepton tight-to-loose ratio is determined from data.

- **Loose and tight leptons :**
  - Tight lepton (T) : Passing lepton selection
  - Loose lepton (L) : Anti-tight lepton
- **Lepton tight-to-loose ratio (ε_f) :**
  - $\frac{N_{T\mu+Le}}{N_{L\mu+Le}}$ and $\frac{N_{L\mu+Te}}{N_{L\mu+Le}}$ in dilepton events

$\varepsilon_{f\mu}$	18.7±0.1%
ε_{fe}	2.0±0.02%

- **$N_{control}$:** 2TLep(Z) + 1LLep + ≥2jets + R_T

	Yields in control region (data)	Scaling ratio	Estimated yields (signal region)
Z + loose μ	13	$\varepsilon_{f\mu}$= 18.7±0.1%	3.02 ± 0.68 (stat. only)
Z + loose e	29	ε_{fe}=2.0±0.02%	

Systematic Uncertainties

Source	Signal	Background		
	$\Delta\epsilon/\epsilon[\%]$	$\Delta B_{2\ell}$	$\Delta B_{3\ell}$	ΔB_{total}
Luminosity	4.5	-	0.1	0.1
Trigger efficiency	2.1	-	-	-
Lepton selection	17	< 0.01	0.3	0.3
Pileup	2.3	0.3	0.06	0.4
PDF	0.2-1.4	-	0.03	0.03
Jet energy scale/resolution	0.8-5.4	0.3	0.2	0.4
Simulated sample statistics	3.0-4.8	-	0.1	0.1
Control region statistics	-	0.7	-	0.7
Background normalization	-	0.2	0.4	0.4
Total	18-20	0.8	0.5	1.0

23% uncertainty (relative to B_{total})

Yields

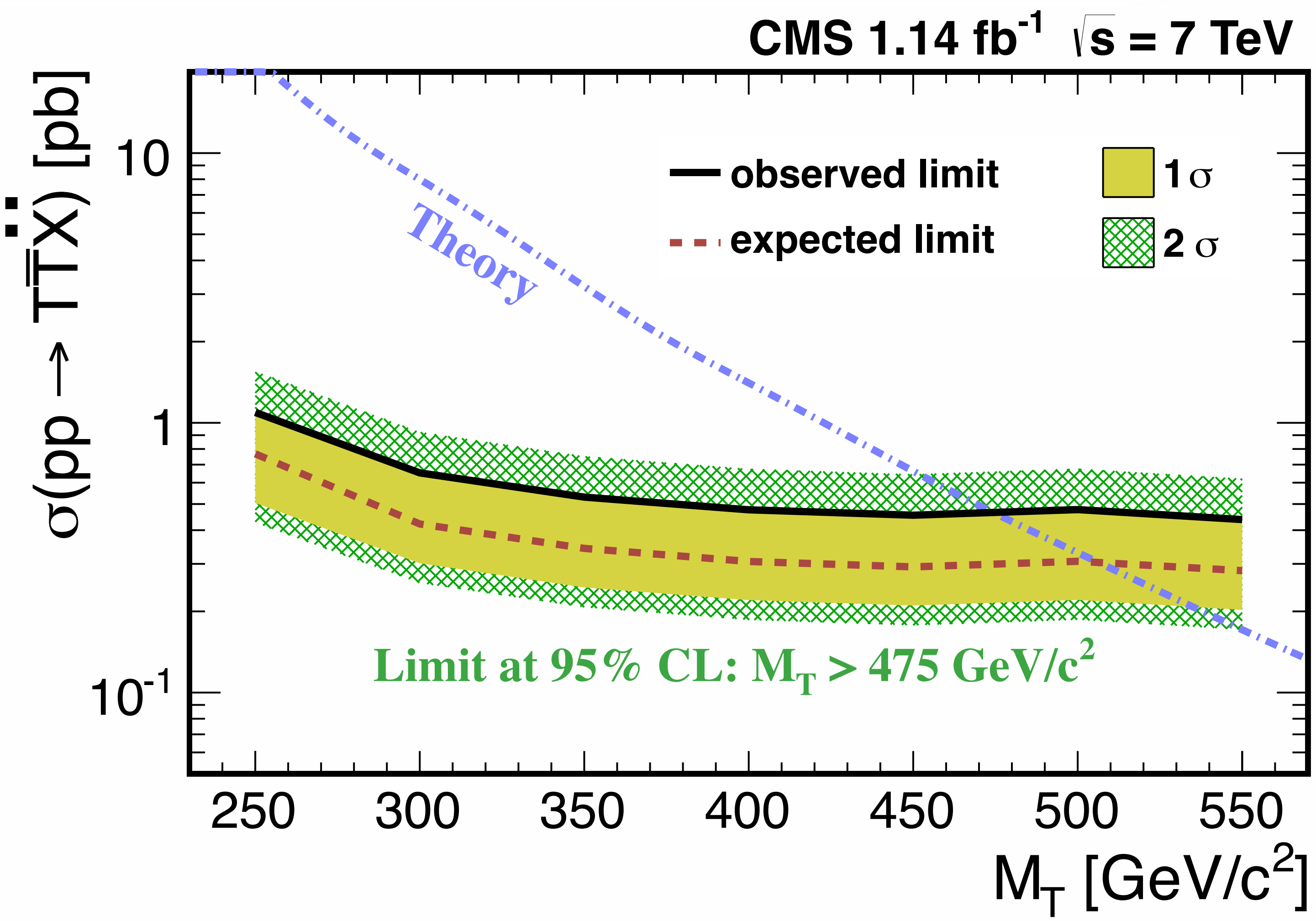
Process	Cross-section (pb)	Yield
$T\bar{T}$, $M(T) = 250$ GeV/c^2	22.6(NNLO)	200
$T\bar{T}$, $M(T) = 300$ GeV/c^2	7.99(NNLO)	118
$T\bar{T}$, $M(T) = 350$ GeV/c^2	3.20(NNLO)	57.8
$T\bar{T}$, $M(T) = 400$ GeV/c^2	1.41(NNLO)	28.3
$T\bar{T}$, $M(T) = 450$ GeV/c^2	0.66(NNLO)	13.9
$T\bar{T}$, $M(T) = 500$ GeV/c^2	0.33(NNLO)	6.63
$T\bar{T}$, $M(T) = 550$ GeV/c^2	0.17(NNLO)	3.74
W + jets	30059(CMS)	< 2.29
Z + jets	2939(CMS)	2.14
WW inclusive	43.0(NLO)	< 0.024
WZ inclusive	18.0(NLO)	0.575
ZZ inclusive	5.9(NLO)	0.348
$t\bar{t}$+jets	158(CMS)	0.465
$t\bar{t}W$(+jet)	0.144(LO)	0.025
$t\bar{t}Z$(+jet)	0.094(LO)	0.631
QCD estimation (data-driven)	-	0.035
SUM(estimated bkg.)	-	4.60 ± 1.04 (syst.)
Data (1.14 fb^{-1})	-	7

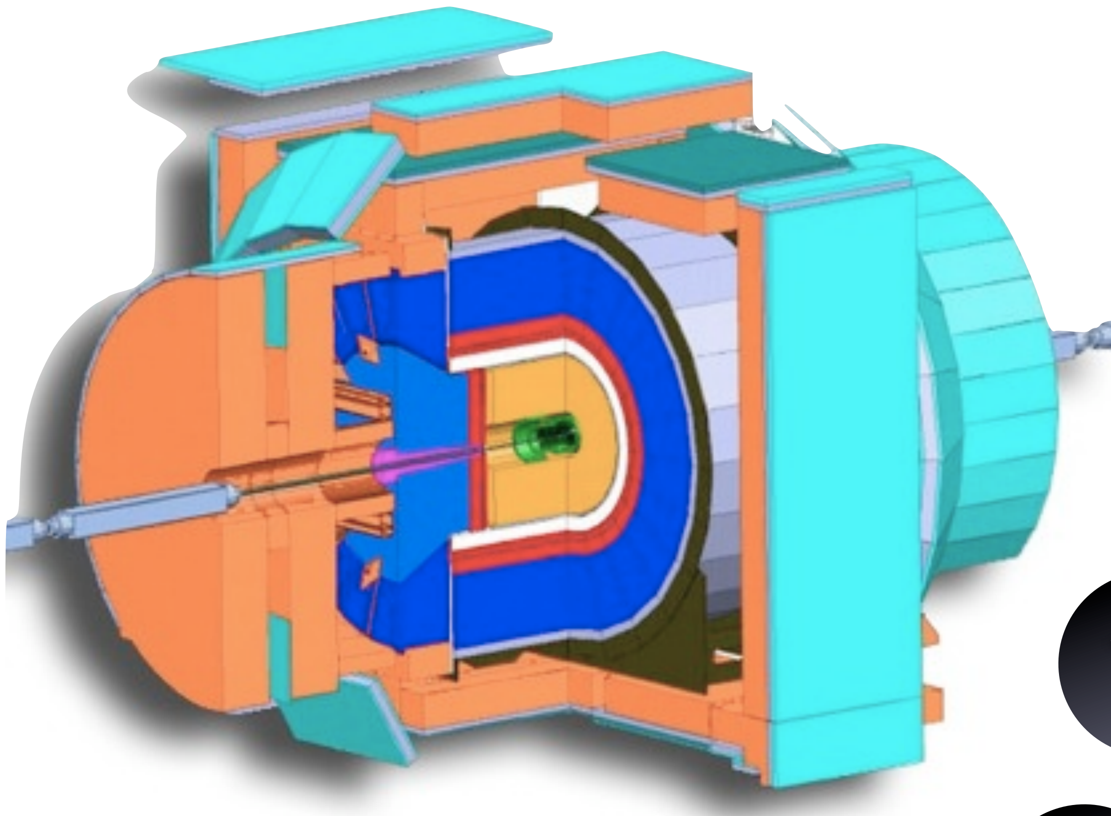
Exclusion Limit

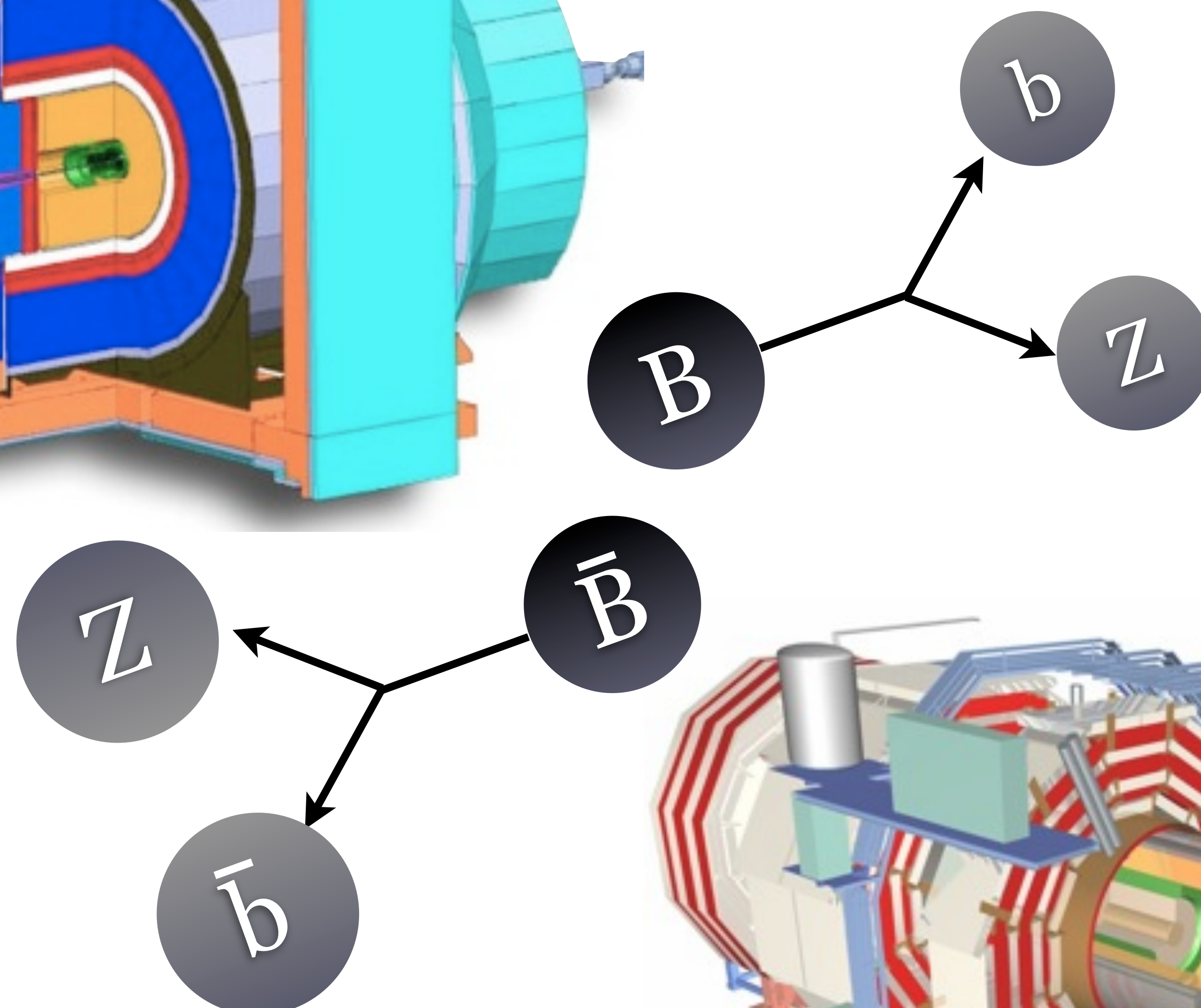
- **Observed limits on X-sec using a Bayesian approach at 95% CL**

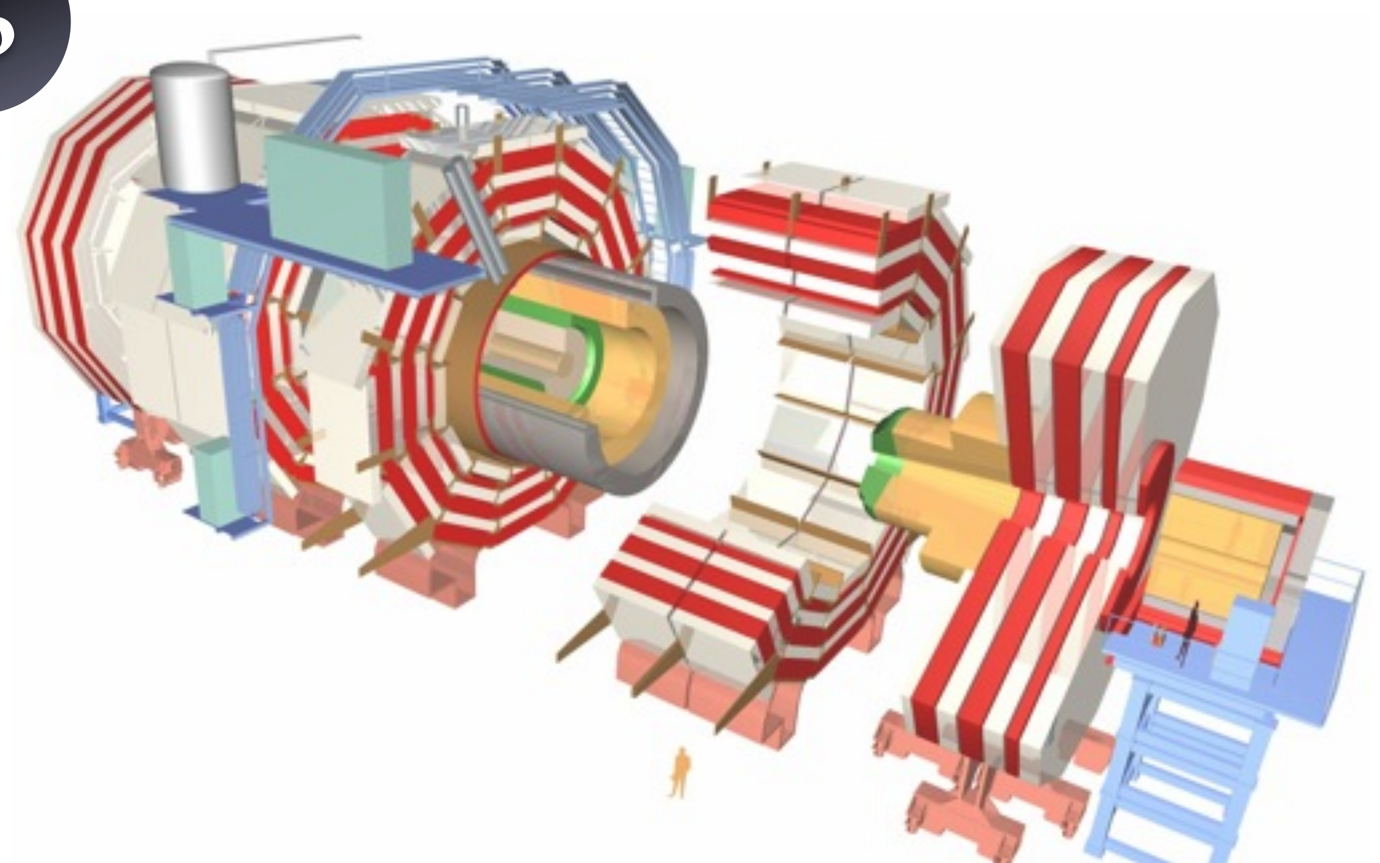
M(T) [GeV/c^2]	250	300	350	400	450	500	550
Observed limit [pb]	1.09	0.65	0.53	0.48	0.45	0.48	0.44

- **By comparing observed limits to the NNLO X-sec:**






b
B
Z
B̄
Z
b̄



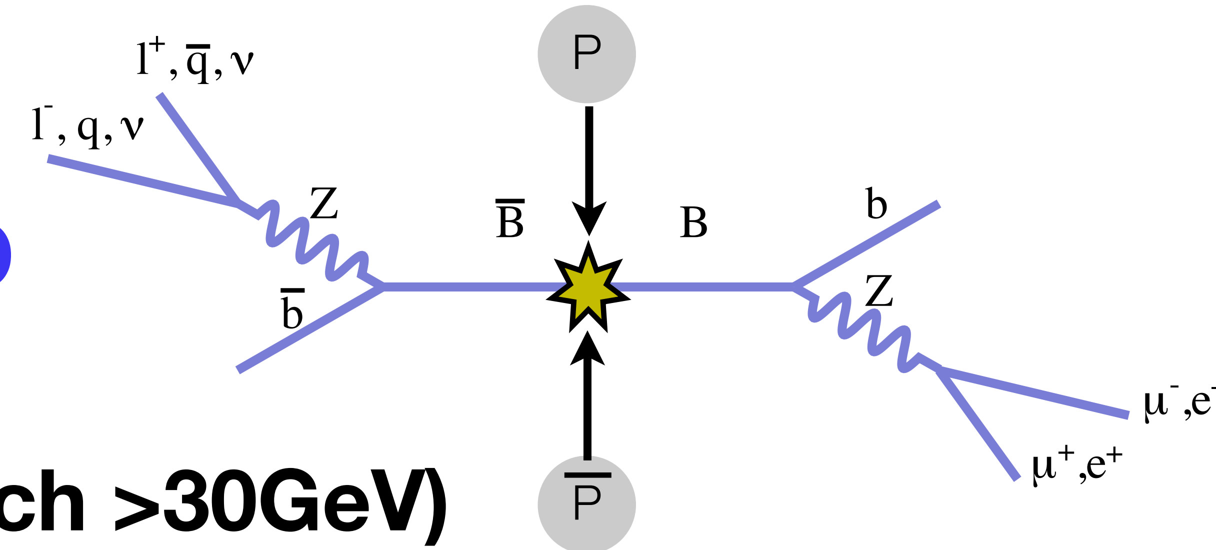
B/b'→bZ (100%) Analysis In CDF

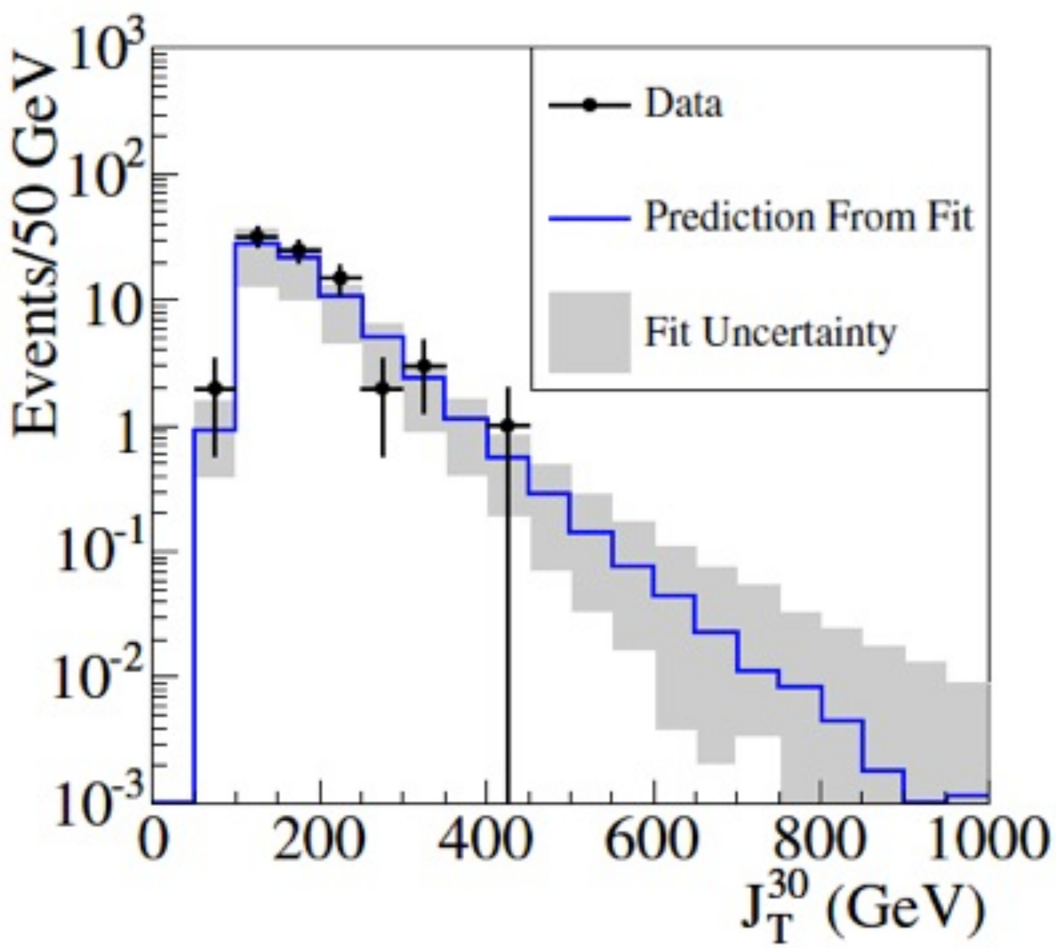
- **The full decay chain :**

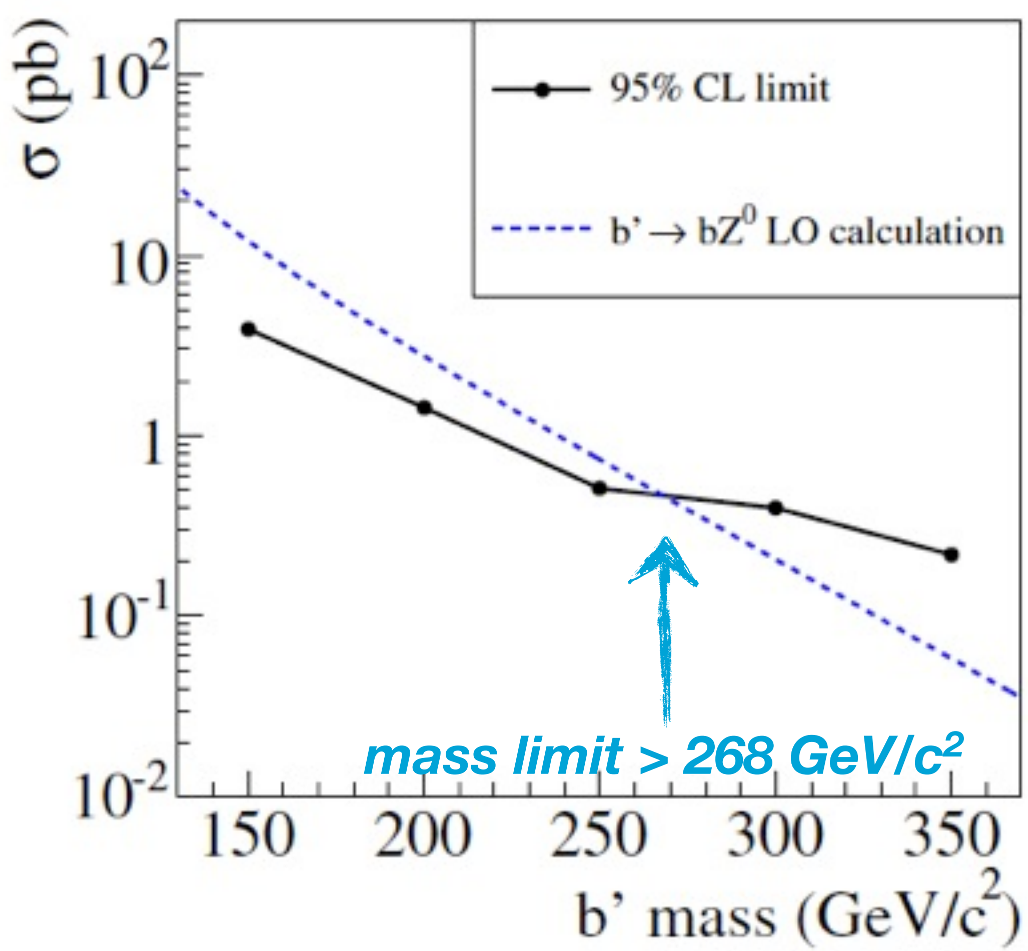
  $B\bar{B} \rightarrow bZ\bar{b}Z$ (in *Z+ 3 jets events*)

  [Phys. Rev. D76, 072006 (2007)**]**

- **J_T^{30} : Scale sum of jets' E_T(each >30GeV)**





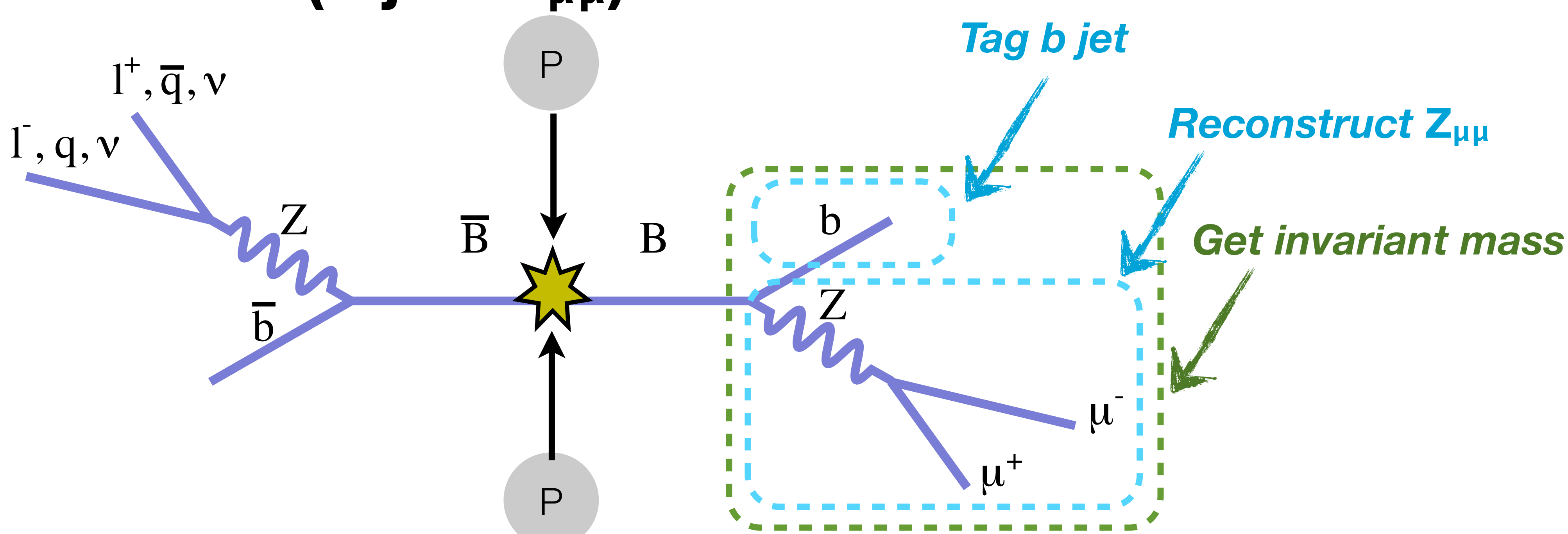


B/b'→bZ (100%) Analysis In CMS

- **Bump hunting experiment**
- **The full decay chain :**

  $B\bar{B} \rightarrow bZ\bar{b}Z$ (in $Z\rightarrow\mu^{+}\mu^{-}$ + 2 jets events)

  [EXO-11-066,NTU]
- **Mass reconstruction (b jet+$Z_{\mu\mu}$) :**



- **Status : In progress.**

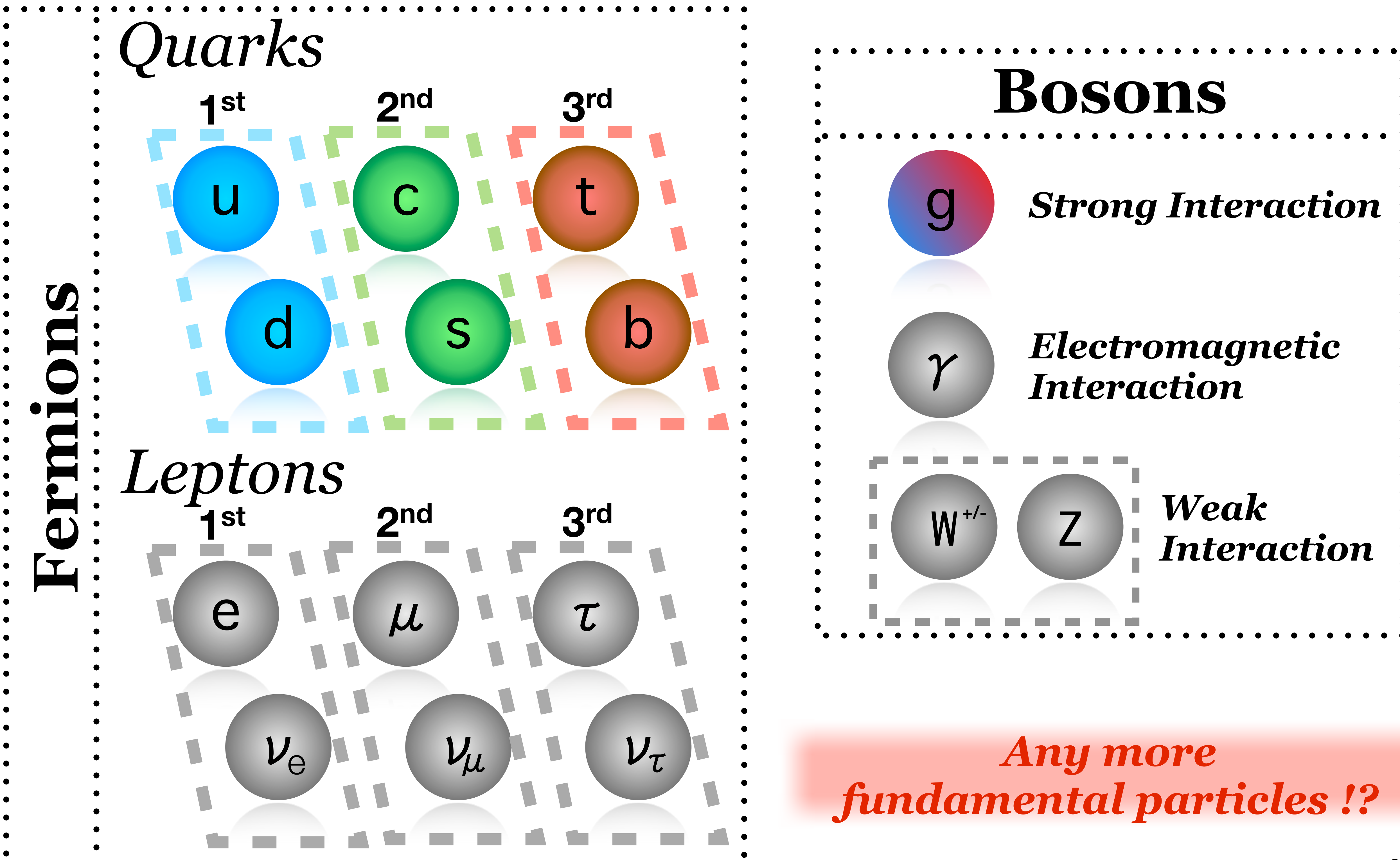
Conclusion

- We report the search for a vector-like charge 2/3 top quark $T \rightarrow tZ$ in pp collisions at 7 TeV. The first result with 1.14 fb^{-1} CMS data is presented :
  - Assuming a 100% branching fraction for the decay $T \rightarrow tZ$, we can set T-quark mass limit up to 475 GeV/c^2 (*PRL. 107, 271802 (2011)*)

- The current result of $B \rightarrow bZ$ is a mass limit of m_B >268 GeV/c^2 from CDF(Phys. Rev. D76, 072006 (2007)). The result from CMS will be presented this year (*EXO-11-066, NTU*).

Backups

Standard Model



Any more fundamental particles !?

Chiral Symmetry

- **The left-handed and right-handed states can individually rotate by any unitary matrix. Then the Lagrangian is unchanged. This symmetry is called chiral symmetry.**

SU(2) N-plets

- **SU(2) singlet : $T_L\ (3,1)_{2/3} + T_R\ (3,1)_{2/3}$**
- **SU(2) doublet : $Q_L\ (3,2)_{1/6} + Q_R\ (3,2)_{1/6}$**

$$Q_{0L} = \begin{pmatrix} T_{0L} \\ B_{0L} \end{pmatrix},\ Q_{0R} = \begin{pmatrix} T_{0R} \\ B_{0R} \end{pmatrix}$$

- **SU(3) triplet : $\Sigma_L\ (3,1)_{2/3} + \Sigma_R\ (3,1)_{2/3}$**

Exotic Q=5/3 fermion

$$\Sigma_{0L} = \begin{pmatrix} X_{0L} \\ T_{0L} \\ B_{0L} \end{pmatrix},\ \Sigma_{0R} = \begin{pmatrix} X_{0R} \\ T_{0R} \\ B_{0R} \end{pmatrix}$$

SU(2) Singlet

- **Consider the subgroup $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$,**

color charge	***weak isospin***	***weak hypercharge***

the left-handed fermions in a representation 27 :

Usual fields: $\binom{u}{d}$, $\bar{u}$, $\bar{d}$, $\binom{\nu}{e^-}$, e^+

$$\underline{27} = \overbrace{(3,2)_{1/6}} + \overbrace{(\bar{3},1)_{-2/3}} + \overbrace{(\bar{3},1)_{1/3}} + \overbrace{(1,2)_{-1/2}} + \overbrace{(1,1)_1}$$

$$+ \underbrace{(3,1)_{-1/3} + (\bar{3},1)_{1/3}} + \underbrace{(1,2)_{1/2} + (1,2)_{-1/2}} + \underbrace{(1,1)_0 + (1,1)_0}$$

Vector Quark   Vector Leptons   2 Neutrinos

(refer to http://cp3.irmp.ucl.ac.be/upload/talk/Goffinet_VLQ.pdf)

T -> tZ at Tree Level

- **Lagrangian interaction and gauge invariant mass term**

$$\mathcal{L}_{mass} = -Y_t\,\bar{t}_{0L}\,H\,t_{0R} - Y_T\,\bar{t}_{0L}\,H\,\mathrm{T}_{0R} - M\,\bar{\mathrm{T}}_{0L}\,\mathrm{T}_{0R} + h.c.$$

- **Fermion mixing**

$$\begin{pmatrix} t_L \\ \mathrm{T}_L \end{pmatrix} = U_L \begin{pmatrix} t_{0L} \\ \mathrm{T}_{0L} \end{pmatrix}, \quad \begin{pmatrix} t_R \\ \mathrm{T}_R \end{pmatrix} = U_R \begin{pmatrix} t_{0R} \\ \mathrm{T}_{0R} \end{pmatrix}$$

where t/T is for Lagrangian basis and t_0/T_0 is for mass eigenbasis

- **Neutral current interaction for t and T :**

$$\mathcal{L}_{NC} = -i\frac{g_Z}{2}\,\bar{t}_0\,\gamma^\mu\,(g_V + g_A\,\gamma^5)\,t_0\,Z_\mu - i\frac{g_Z}{2}\,\kappa\,\bar{\mathrm{T}}_0\,\gamma^\mu\,\mathrm{T}_0\,Z_\mu$$

split into LH & RH

$$= -i\frac{g_Z}{2}\begin{pmatrix}\bar{t}_{0L} & \bar{\mathrm{T}}_{0L}\end{pmatrix}\gamma^\mu Z_\mu \begin{pmatrix} g_V - g_A & \\ & \kappa \end{pmatrix}\begin{pmatrix} t_{0L} \\ \mathrm{T}_{0L} \end{pmatrix}$$

$$- i\frac{g_Z}{2}\begin{pmatrix}\bar{t}_{0R} & \bar{\mathrm{T}}_{0R}\end{pmatrix}\gamma^\mu Z_\mu \begin{pmatrix} g_V + g_A & \\ & \kappa \end{pmatrix}\begin{pmatrix} t_{0R} \\ \mathrm{T}_{0R} \end{pmatrix}$$

Lagrangian basis changed to mass eigenstate

$$= -i\frac{g_Z}{2}\begin{pmatrix}\bar{t}_L & \bar{\mathrm{T}}_L\end{pmatrix}\gamma^\mu Z_\mu\, U_L \begin{pmatrix} g_V - g_A & \\ & \kappa \end{pmatrix} U_L^\dagger \begin{pmatrix} t_L \\ \mathrm{T}_L \end{pmatrix}$$

$$- i\frac{g_Z}{2}\begin{pmatrix}\bar{t}_R & \bar{\mathrm{T}}_R\end{pmatrix}\gamma^\mu Z_\mu\, U_R \begin{pmatrix} g_V + g_A & \\ & \kappa \end{pmatrix} U_R^\dagger \begin{pmatrix} t_R \\ \mathrm{T}_R \end{pmatrix}.$$

Induce non-diagonal term

" $t\gamma^\mu T$ " exist

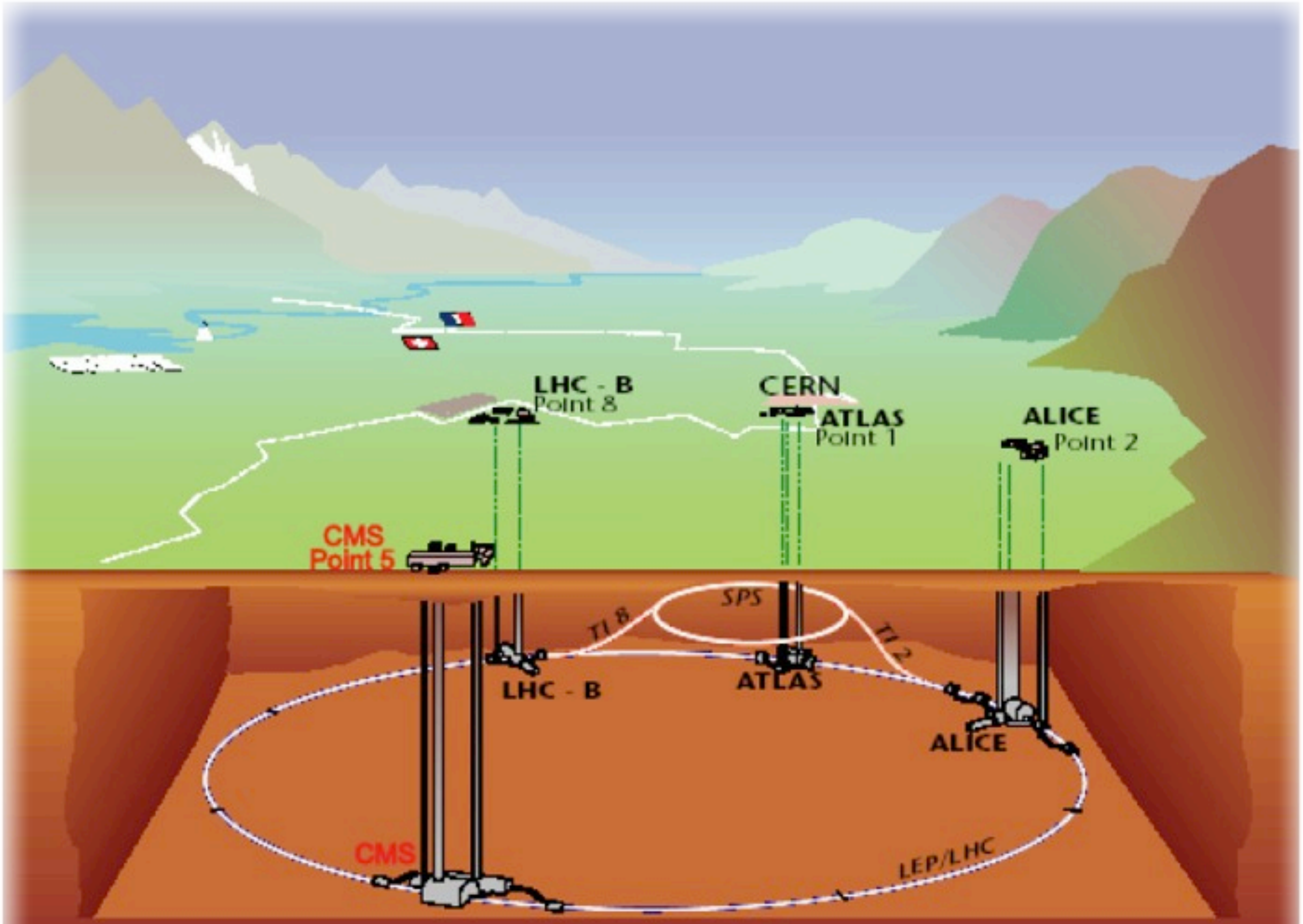
T -> t γ (g) at Loop Level

- **Electromagnetic interaction for t and T :**

$$\begin{aligned}
\mathcal{L}_{QED} &= eQ_t\,(\bar{t}_0\,\gamma^\mu\,t_0 \;+\; \bar{\mathrm{T}}_0\,\gamma^\mu\,\mathrm{T}_0)\,A_\mu \\
&= eQ_t\,((\bar{t}_{0L} + \bar{t}_{0R})\,\gamma^\mu\,(t_{0L} + t_{0R}) + (\bar{\mathrm{T}}_{0L} + \bar{\mathrm{T}}_{0R})\,\gamma^\mu\,(\mathrm{T}_{0\mathrm{L}} + \mathrm{T}_{0\mathrm{R}}))\,A_\mu \\
&(\gamma_5 \text{ anticommutes with the four gamma matrices } \{\gamma_5,\,\gamma_\mu\} = 0.) \\
&= eQ_t\,(\bar{t}_{0L}\,\gamma^\mu\,t_{0L} + \bar{t}_{0R}\,\gamma^\mu\,t_{0R} + \bar{\mathrm{T}}_{0\mathrm{L}}\,\gamma^\mu\,\mathrm{T}_{0\mathrm{L}} + \bar{\mathrm{T}}_{0\mathrm{R}}\,\gamma^\mu\,\mathrm{T}_{0\mathrm{R}})\,A_\mu \\
&= \begin{pmatrix}\bar{t}_{0L} & \bar{\mathrm{T}}_{0\mathrm{L}}\end{pmatrix}\gamma^\mu A_\mu \begin{pmatrix}eQ_t & \\ & eQ_t\end{pmatrix}\begin{pmatrix}t_{0L}\\ \mathrm{T}_{0\mathrm{L}}\end{pmatrix} + \begin{pmatrix}\bar{t}_{0R} & \bar{\mathrm{T}}_{0\mathrm{R}}\end{pmatrix}\gamma^\mu A_\mu \begin{pmatrix}eQ_t & \\ & eQ_t\end{pmatrix}\begin{pmatrix}t_{0R}\\ \mathrm{T}_{0\mathrm{R}}\end{pmatrix} \\
&(\text{Change Lagrangian basis to mass eigenbasis.}) \\
&= \begin{pmatrix}\bar{t}_L & \bar{\mathrm{T}}_\mathrm{L}\end{pmatrix}\gamma^\mu A_\mu\, U_L \begin{pmatrix}eQ_t & \\ & eQ_t\end{pmatrix} U_L^\dagger \begin{pmatrix}t_L\\ \mathrm{T}_\mathrm{L}\end{pmatrix} + \\
&\quad \begin{pmatrix}\bar{t}_R & \bar{\mathrm{T}}_\mathrm{R}\end{pmatrix}\gamma^\mu A_\mu\, U_R \begin{pmatrix}eQ_t & \\ & eQ_t\end{pmatrix} U_R^\dagger \begin{pmatrix}t_R\\ \mathrm{T}_\mathrm{R}\end{pmatrix} \\
&= \begin{pmatrix}\bar{t}_L & \bar{\mathrm{T}}_\mathrm{L}\end{pmatrix}\gamma^\mu A_\mu \begin{pmatrix}eQ_t & \\ & eQ_t\end{pmatrix}\begin{pmatrix}t_L\\ \mathrm{T}_\mathrm{L}\end{pmatrix} + \begin{pmatrix}\bar{t}_R & \bar{\mathrm{T}}_\mathrm{R}\end{pmatrix}\gamma^\mu A_\mu \begin{pmatrix}eQ_t & \\ & eQ_t\end{pmatrix}\begin{pmatrix}t_R\\ \mathrm{T}_\mathrm{R}\end{pmatrix} \\
&= eQ_t\,(\bar{t}\,\gamma^\mu\,t \;+\; \bar{\mathrm{T}}\,\gamma^\mu\,\mathrm{T})\,A_\mu,
\end{aligned}$$

No induce tree level

Large Hadron Collide



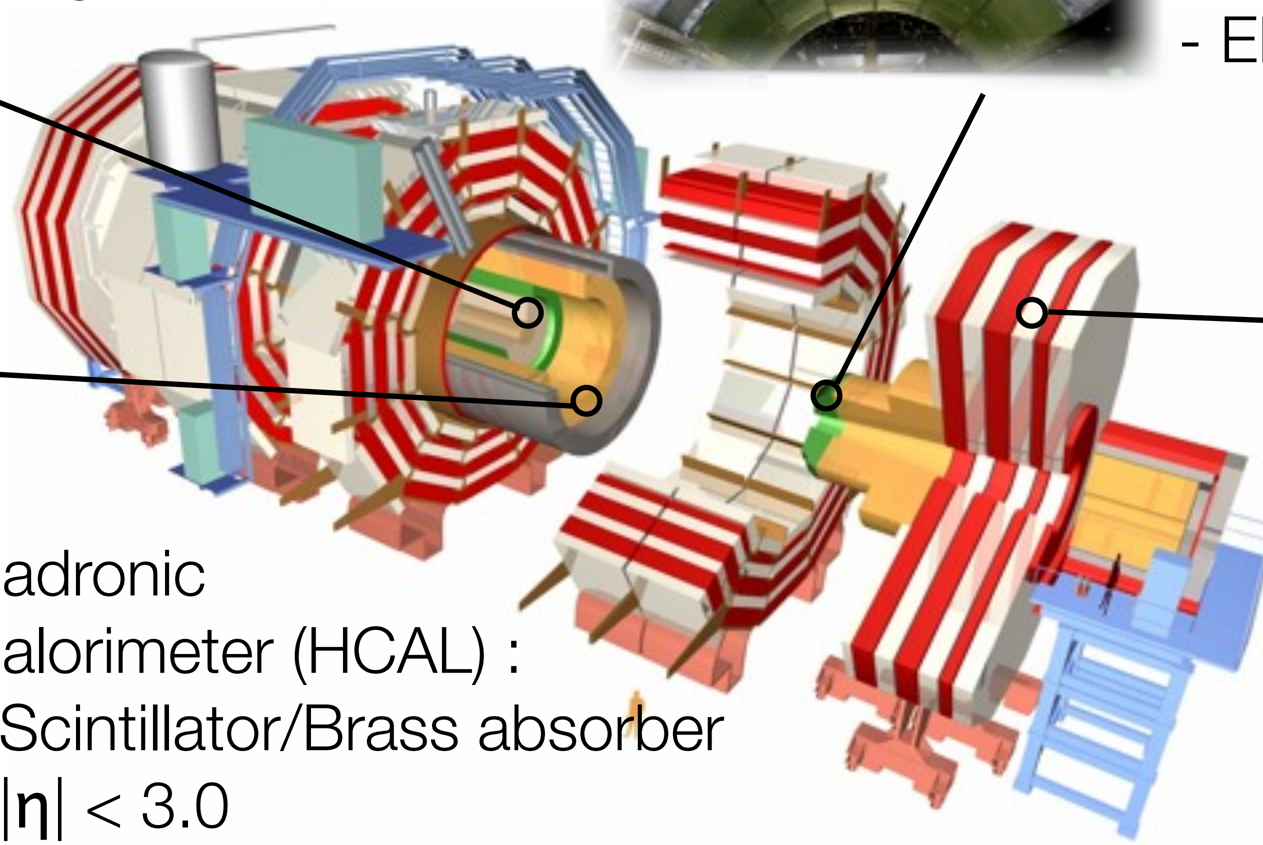
LHC consists of a 27 km ring, and 4 main experiments, ATLAS, CMS, ALICE, and LHCb at depth of 100 m.

Compact Muon Solenoid

Total weight 12500 t, diameter 15 m, length 21.6 m with magnetic field 3.8 Tesla.

Tracker (SST/Pixels) :
- Silicon
- $|\eta| < 2.5$, $\eta = -\ln \tan(\frac{\theta}{2})$
- Charged particle

Electromagnetic Calorimeter (ECAL) :
- $PbWO_4$ crystal
- $|\eta| < 3.0$
- EM particle



Hadronic Calorimeter (HCAL) :
- Scintillator/Brass absorber
- $|\eta| < 3.0$
- Hadron

Muon chamber :
- DT/CSC/RPC
- $|\eta| < 2.4$
- Muon particle

T production

Subprocess N:o	Type	Number of points Generated	Tried	Sigma (mb)
0	All included subprocesses	10000	166866	4.478E-09
81	q + qbar -> Q + Qbar, mass	4592	63824	2.049E-09
82	g + g -> Q + Qbar, massive	5408	103042	2.429E-09

Trigger Paths

- **HLT for data :**

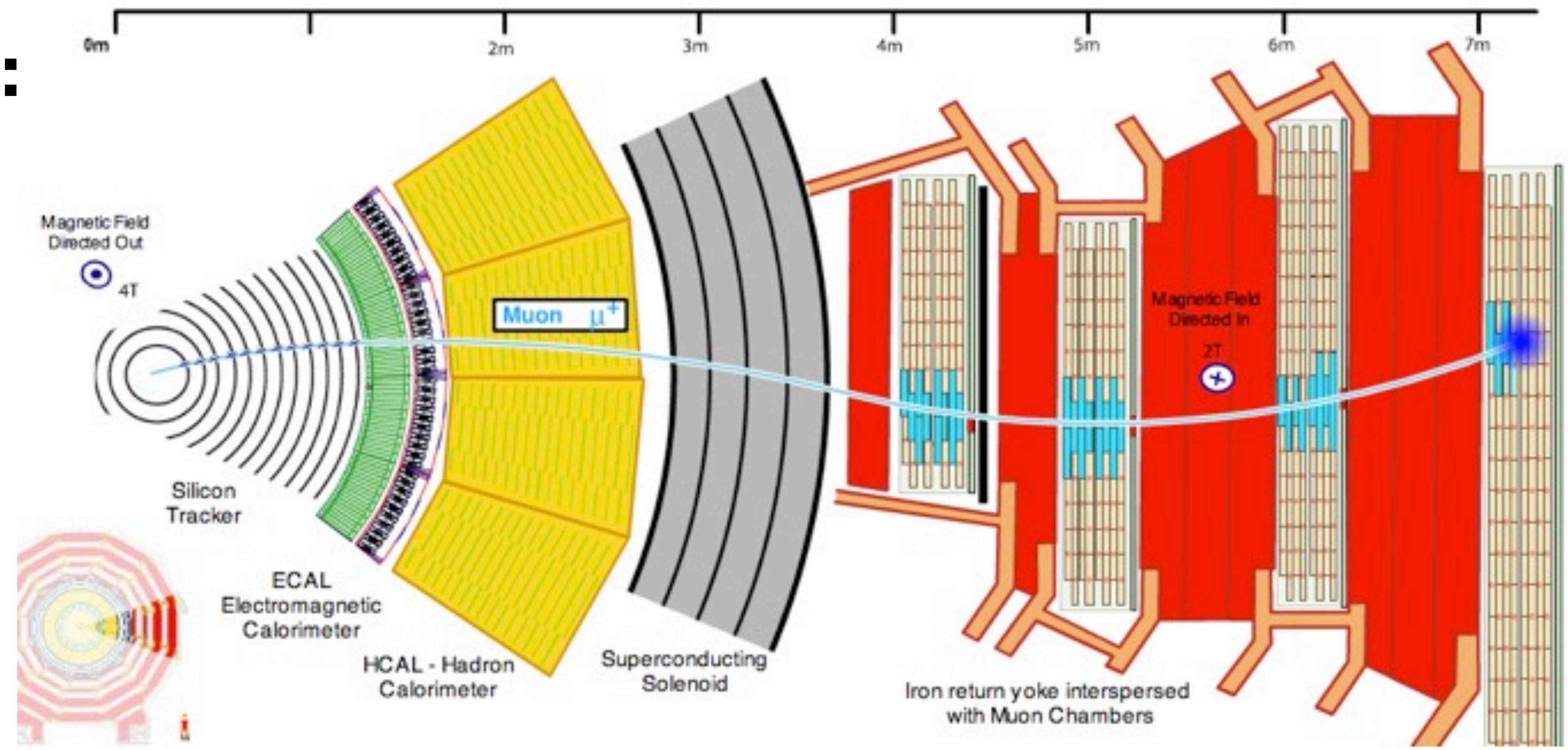
Run Ranges		ee trigger	μμ trigger	eμ trigger
2011 data ($1.14fb^{-1}$)	16040~163869	HLT_Ele17_CaloIdL_CaloIsoVL_Ele8_CaloIdL_CaloIsoVL	HLT_DoubleMu7	HLT_Mu8_Ele17_CaloIdL
	165071~167913		HLT_Mu13_Mu8	

- **HLT for MC :**

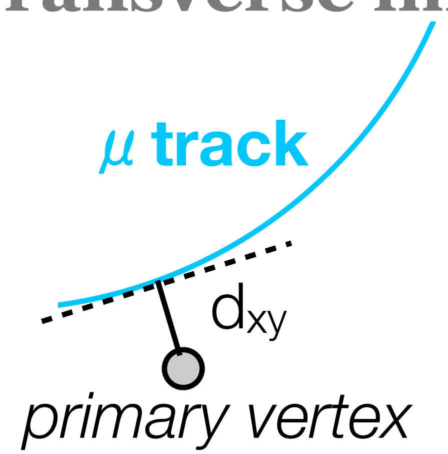
MC sample	ee trigger	μμ trigger	eμ trigger
Spring 11 (Bkg)	HLT_DoubleEle17_SW_L1R	HLT_DoubleMu5	HLT_Mu8_Ele8
Summer 11 (Signal)	HLT_Ele17_CaloIdL_CaloIsoVL_Ele8_CaloIdL_CaloIsoVL	HLT_DoubleMu7	HLT_Mu8_Ele17_CaloIdL

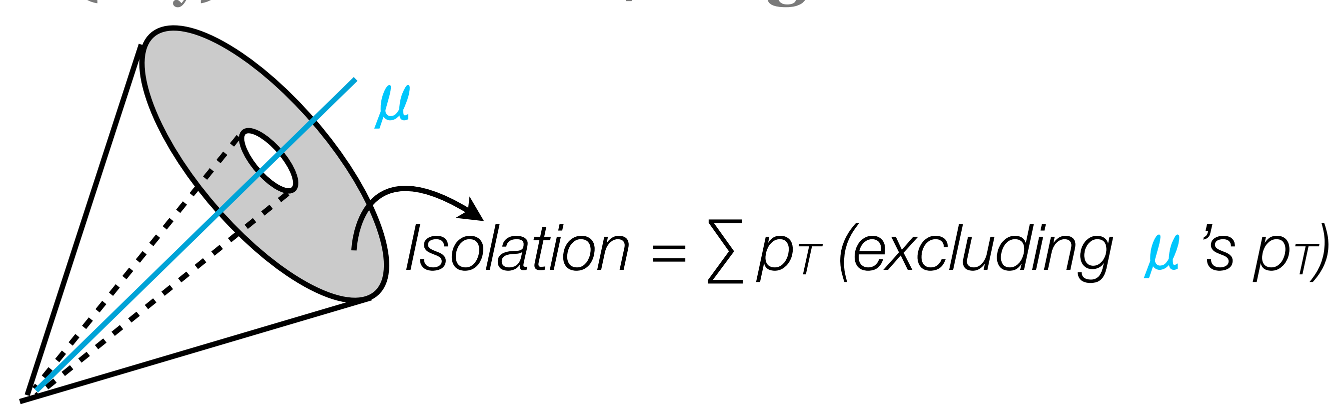
Muon Candidate

- **Reconstruction:**
  - **Tracker + μ chamber**



- **Identification:**
  - **Transverse impact parameter (d_{xy}) + isolated μ + good track**



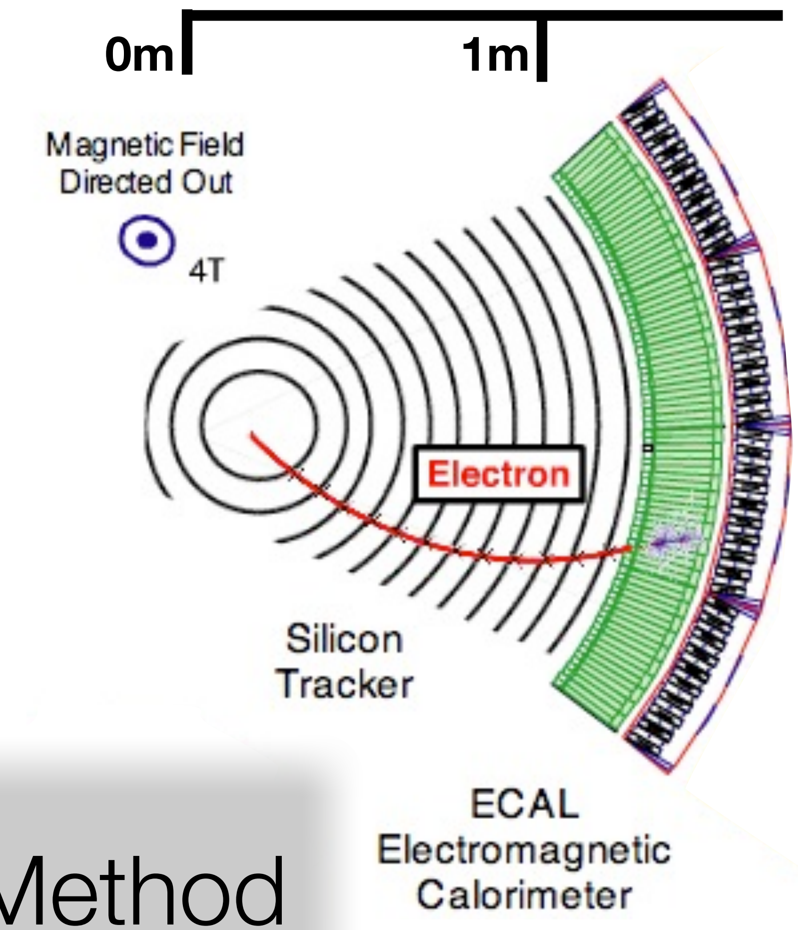


Muon Candidate

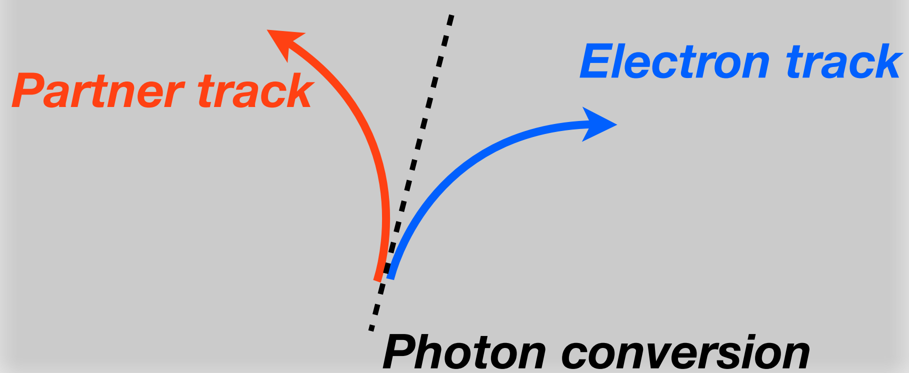
- **Reconstruction:**
  - Found both in inner tracker and muon chamber
- **Identification:**
  - Transverse impact parameter of d_{xy}
  - Track quality
    - Num. of inner track hits
    - Normalized χ^2
    - Num. of pixel layers
    - Num. of segments in muon chamber
  - Isolation in tracker

Electron Candidate

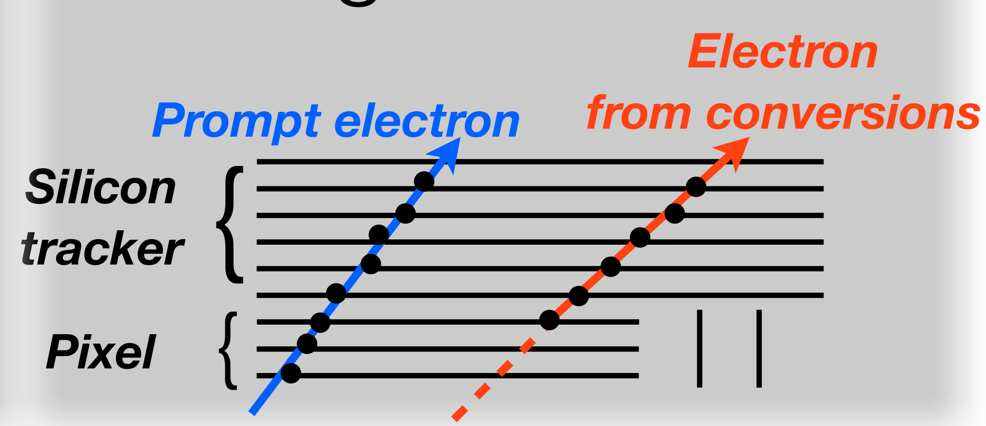
- **Reconstruction:**
  - Reconstructed track in tracker + associated supercluster in ECAL
- **Identification:**
  - d_{xy} + isolated electron + E_{HCAL}/E_{ECAL}
  - Photon-conversion rejection



Geometric Method



Missing Hits Method

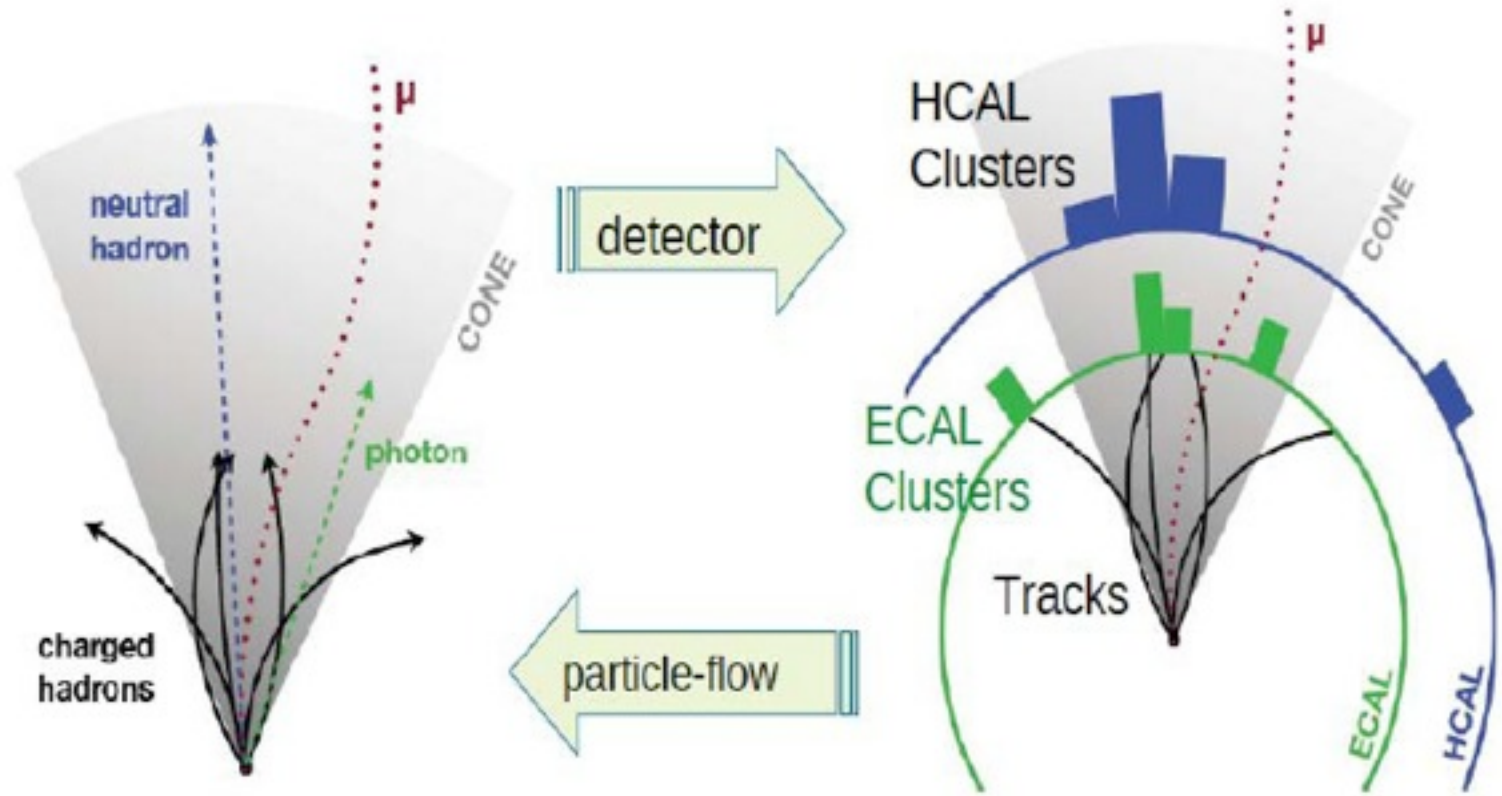


Electron Candidate

- **Reconstruction:**
  - Using reconstructed track in inner tracker and its associated supercluster in ECAL
- **Identification:**
  - Transverse impact parameter of d_{xy}
  - Conversion rejection
    - Missing hits in pixel
    - Partner track
  - Relative isolation in Tracker, ECAL, and HCAL
  - E_{HCAL}/E_{ECAL}
  - $\sigma_{i\eta i\eta}$ (the width of cluster in η direction)
  - $\Delta\Phi_{in}$
  - $\Delta\eta_{in}$

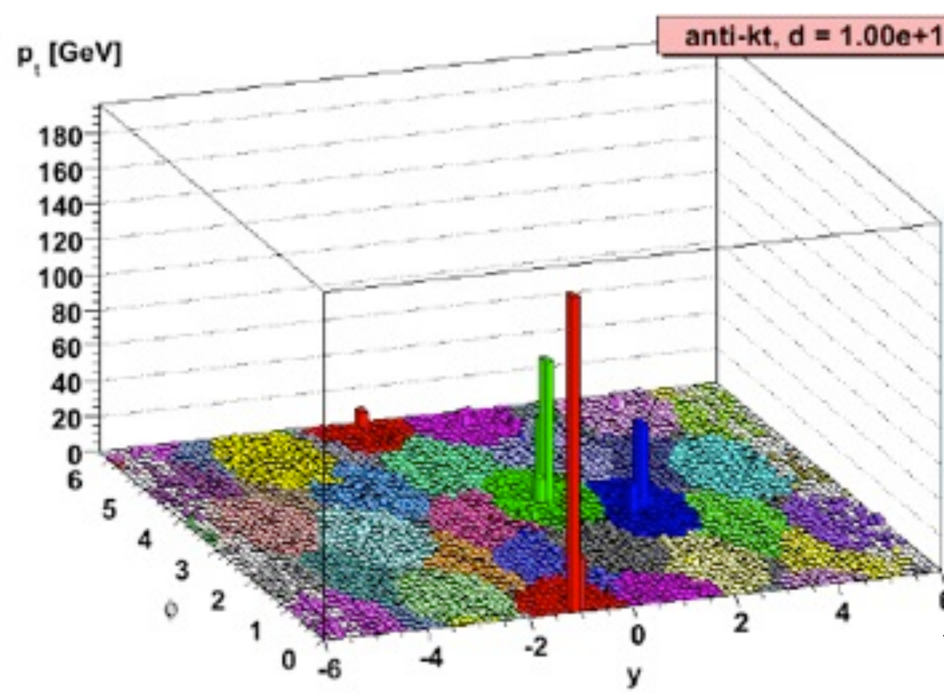
Jet Candidate

- **Reconstruction:**
  - Particle flow info.



  - Anti-k_T algorithm :

$$d_{ij} \equiv \frac{\Delta R_{ij}^2}{max(k_{ti}^2, k_{tj}^2)}$$



Cone-like jets without using stable cones

Jet Candidate

- **Reconstruction:**
  - Based on particle flow information --> remove contributions from other objects (muon, electron, photon...)
  - Using anti-k_T clustering algorithm : $d_{ij} \equiv \frac{\Delta R_{ij}^2}{max(k_{ti}^2, k_{tj}^2)}$
- **Identification:**
  - Reject fake jets from calorimeter and/or readout electronics noise

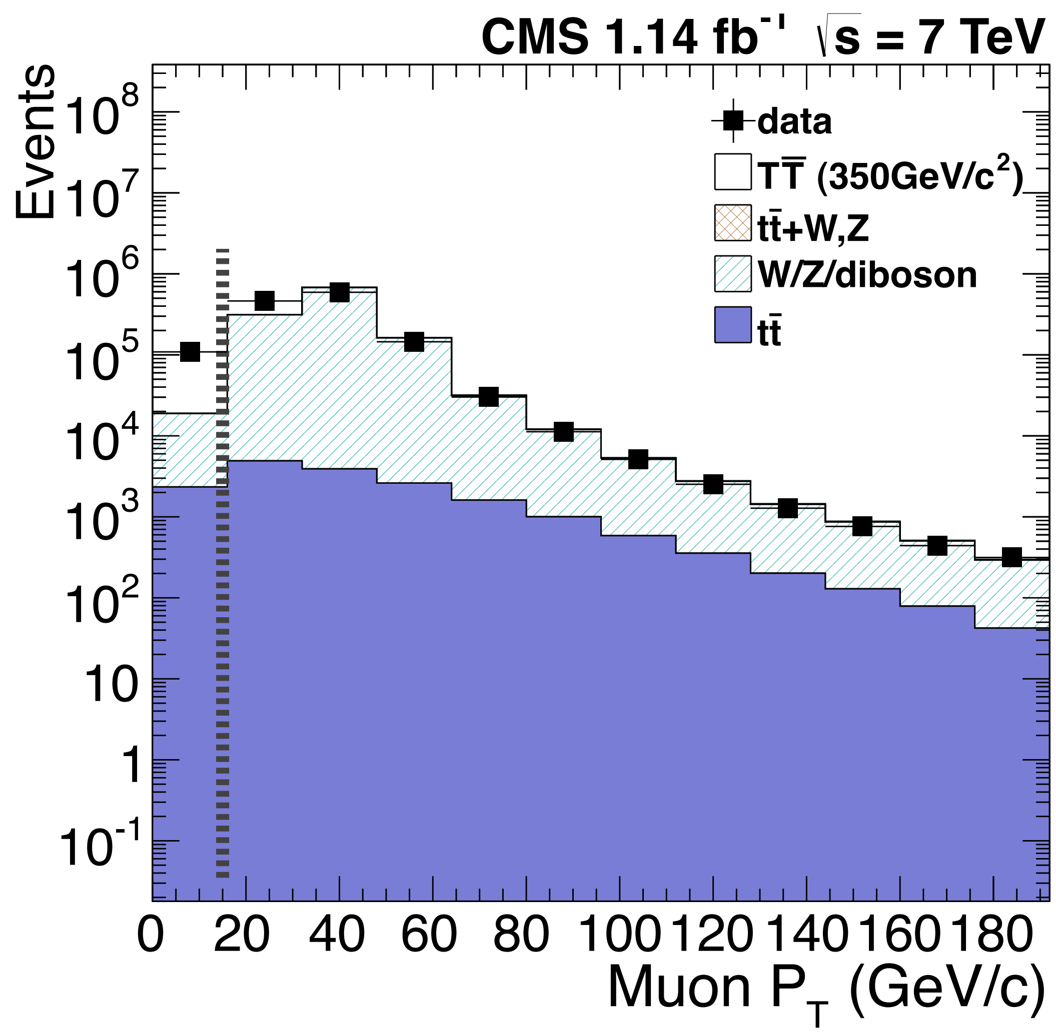
Vertex Reconstruction

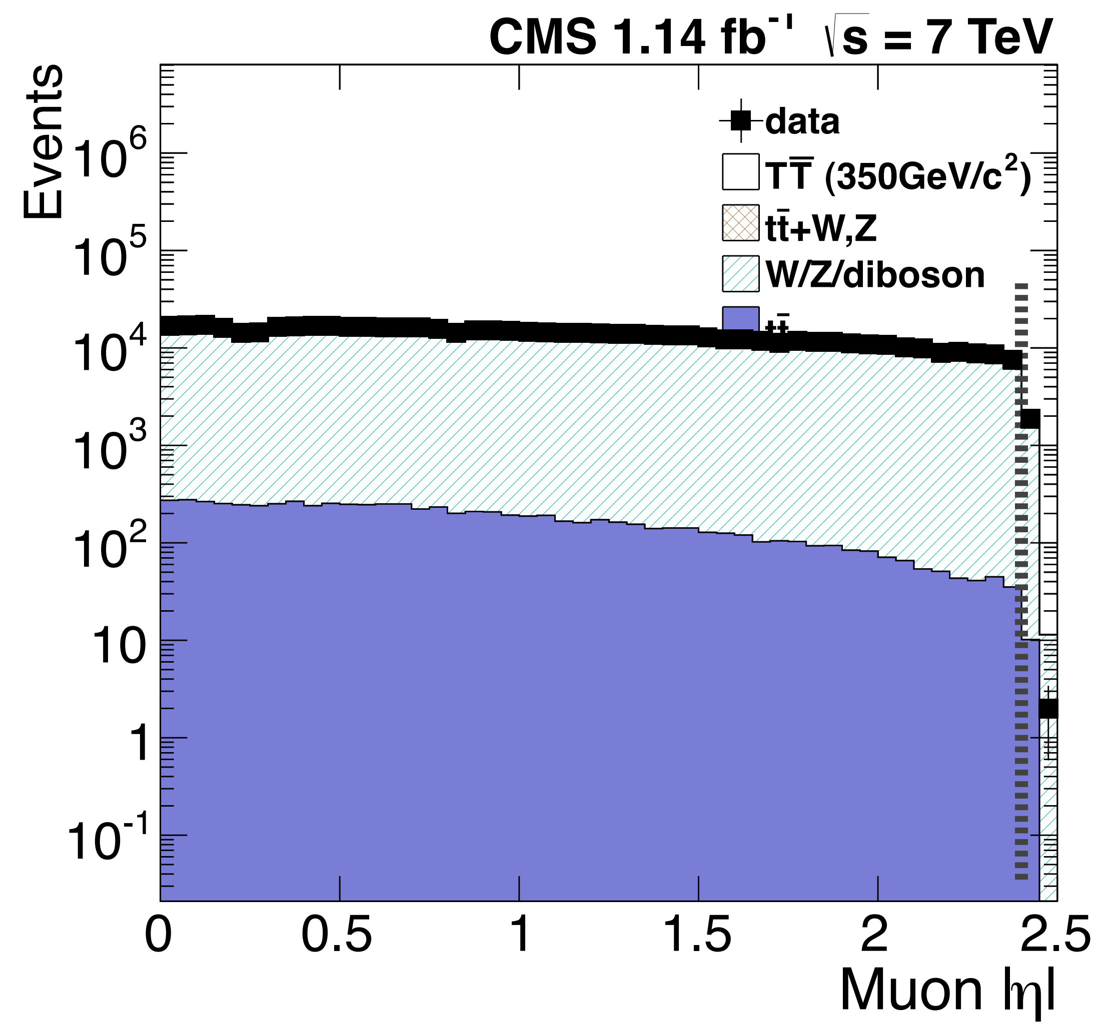
- **Reconstruction**
  - **Vertex finding :**

    Using a triplet in the pixel to apply 1-dimensional search (Z_{IP} : longitudinal impact parameter) to get the vertex candidates
  - **Vertex fitting :**

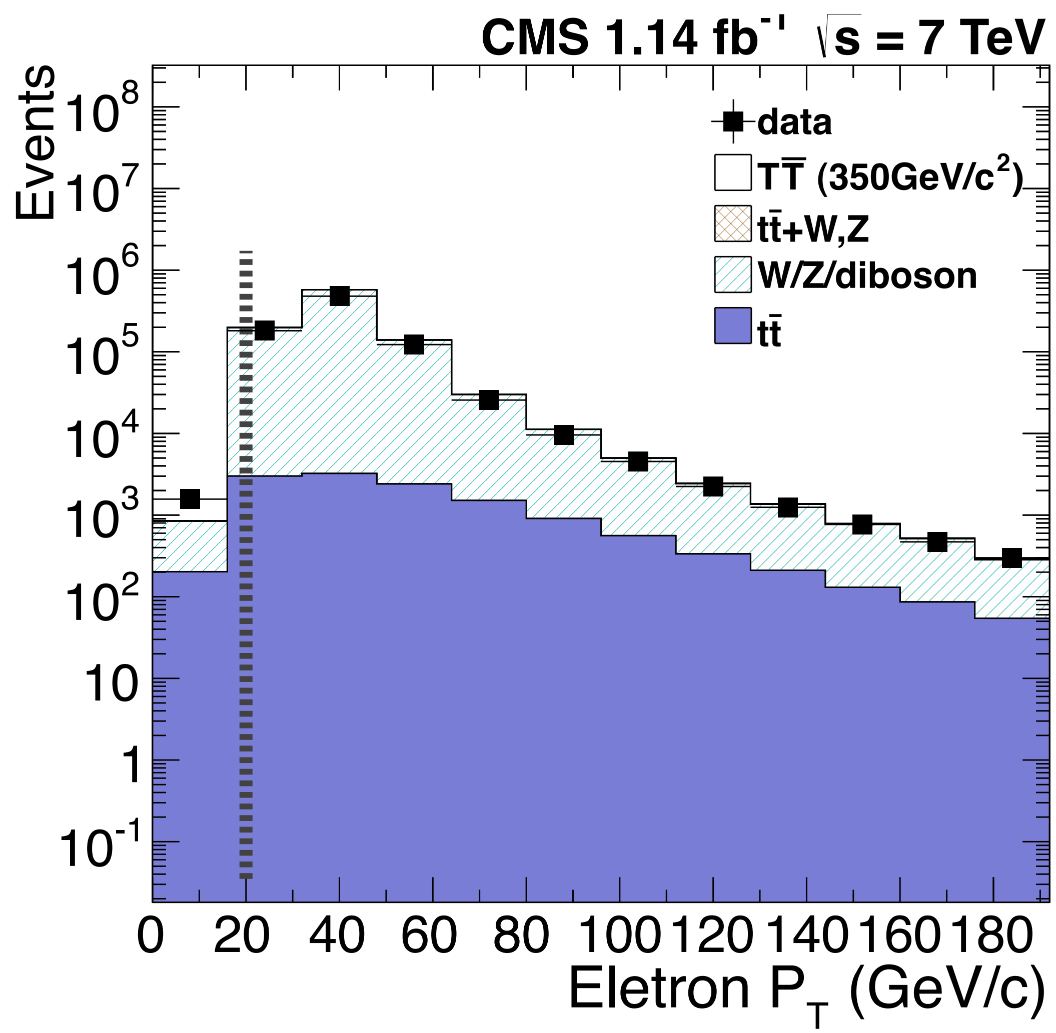
    Refit vertex candidates by using weighted tracks (depends on a distance from the vertex) until the fit converges
- **Vertex selection:**
  - **degrees of freedom>4, $|\rho| < 2$ cm, and $|z| < 24$ cm**

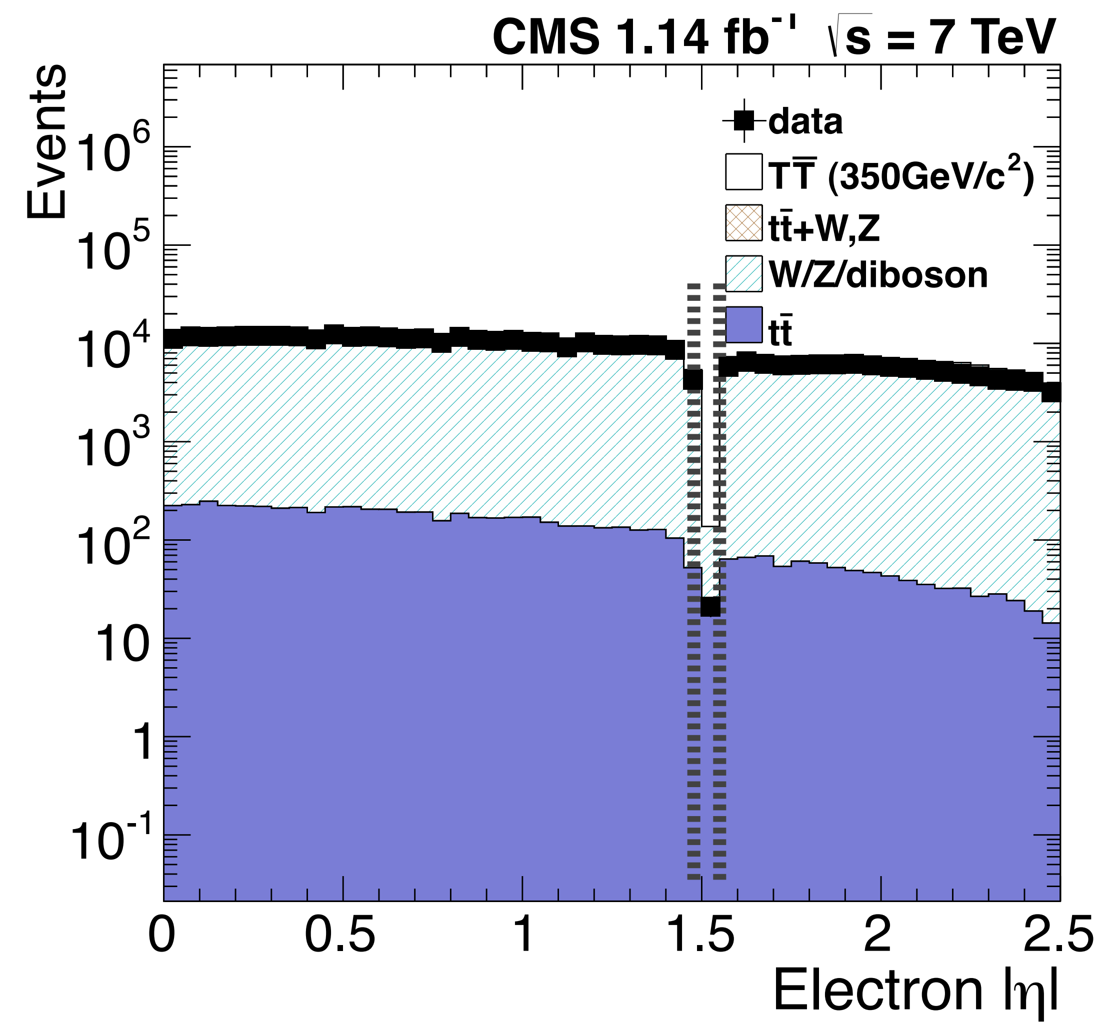
Muon Kinematics





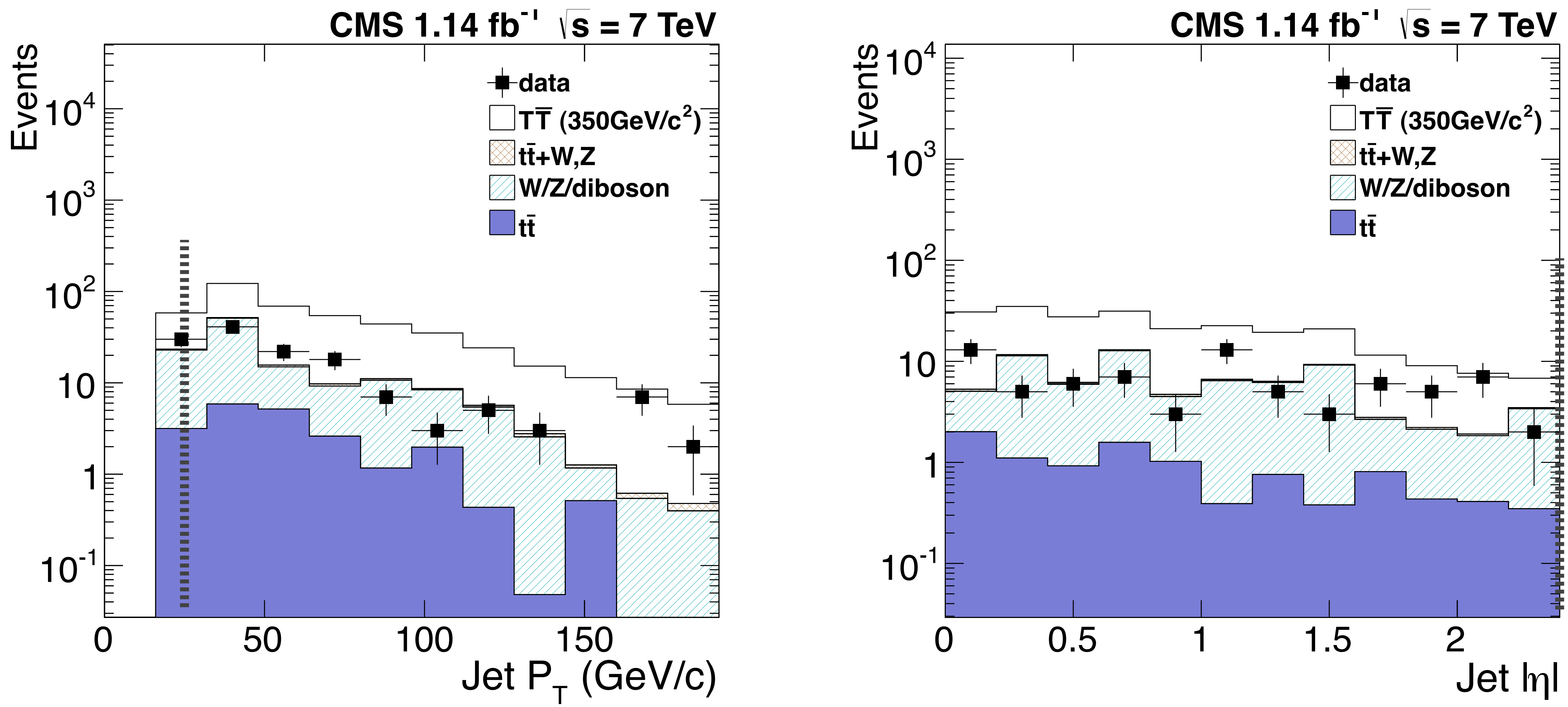
Electron Kinematics





Jet Kinematics

Preselection : N(lep) ≥ 3 + Z



Trigger Efficiency

- **Signal trigger efficiency in MC:** 100% (after full selection)
- **For data:**
  - Estimated by applying scaling factors to signal MC
  - Scaling factors :
    1. Two fully-reconstructed leptons
    2. Data sample passing Jet trigger
    3. Counting di-lepton events passing trigger

Channels	Scaling factor (data/MC)	Fraction (in signal region)
ee	1.000 ± 0.003	44.4%
μμ	0.920 ± 0.019	27.5%
eμ	0.998 ± 0.027	28.1%

} *Weighted scaling factor : 0.979*

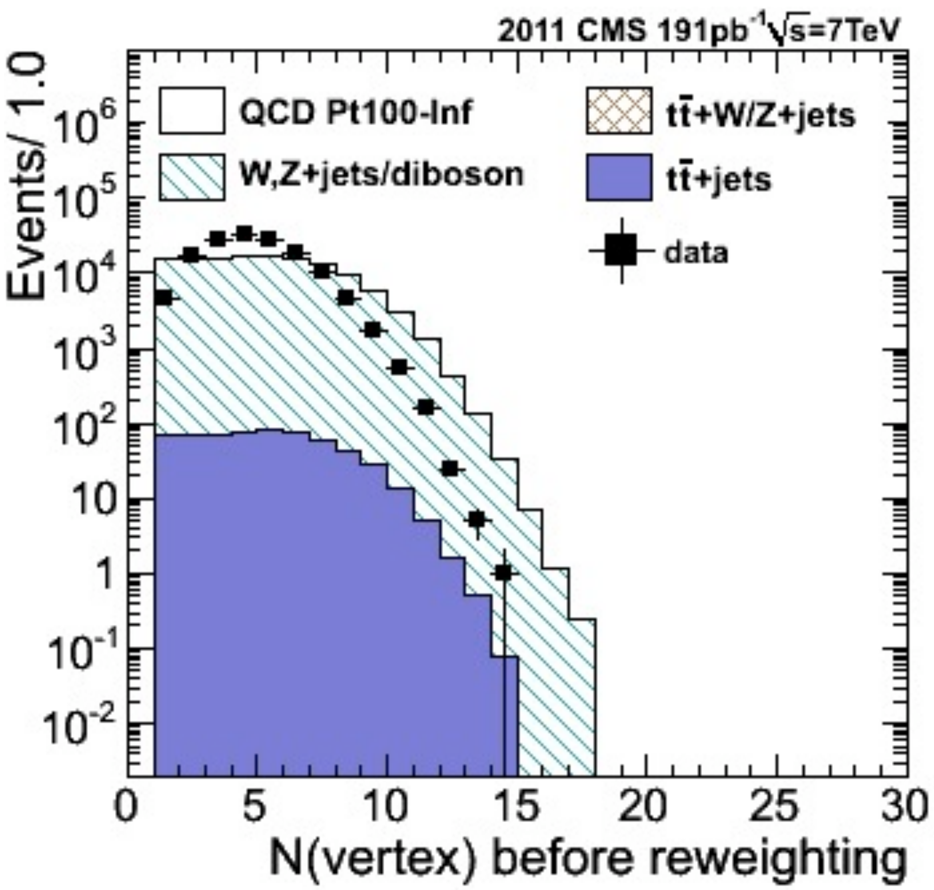
- *Take the inefficiency (1-0.979) = 2.1% as a systematic error*

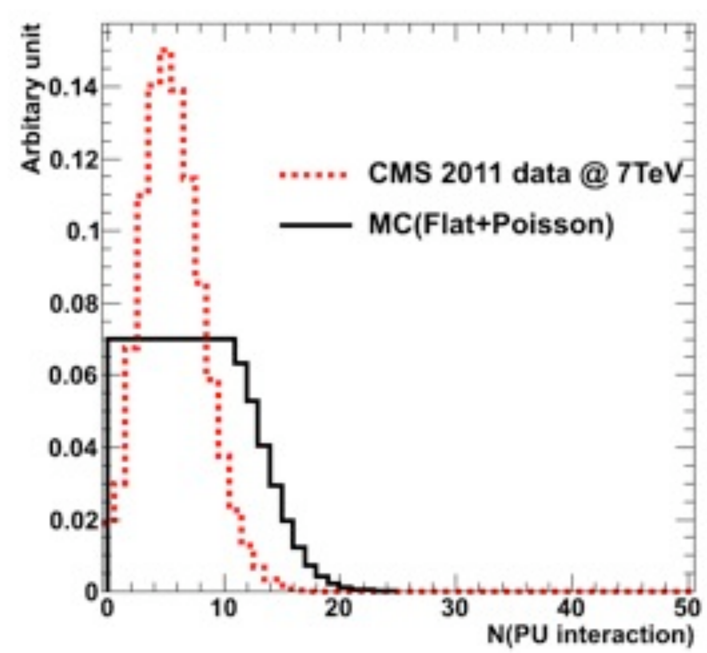
Pile-Up Effect

- ~ 5 pp collisions per bunch crossing under the luminosity condition ($\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$)
- Two methods to reduce the PU effect:
  - PU reweighting to MC samples
  - ρ correction to lepton isolation

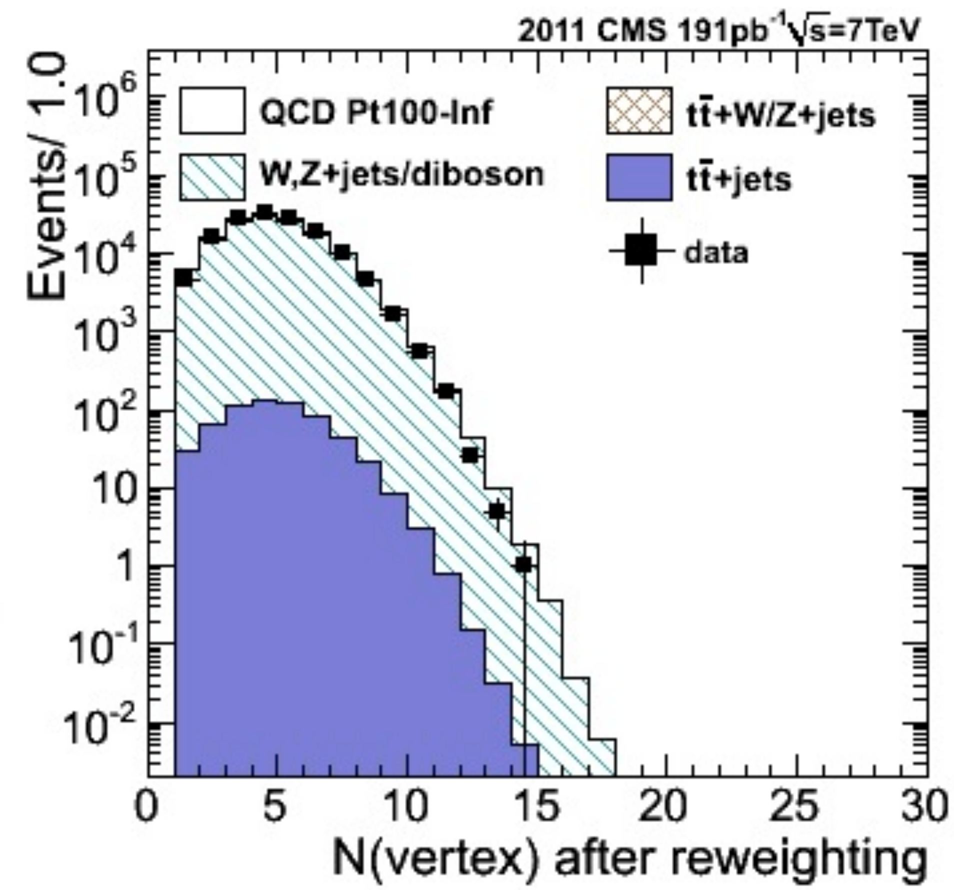
Pile-Up Reweighting

- **The MC samples are simulated by a flat distribution plus a tail described by a Poisson distribution for the number of pile-up interaction. Using "PU reweighting" to correct MC :**
    - **Check the number of vertex --> MC fits in data**





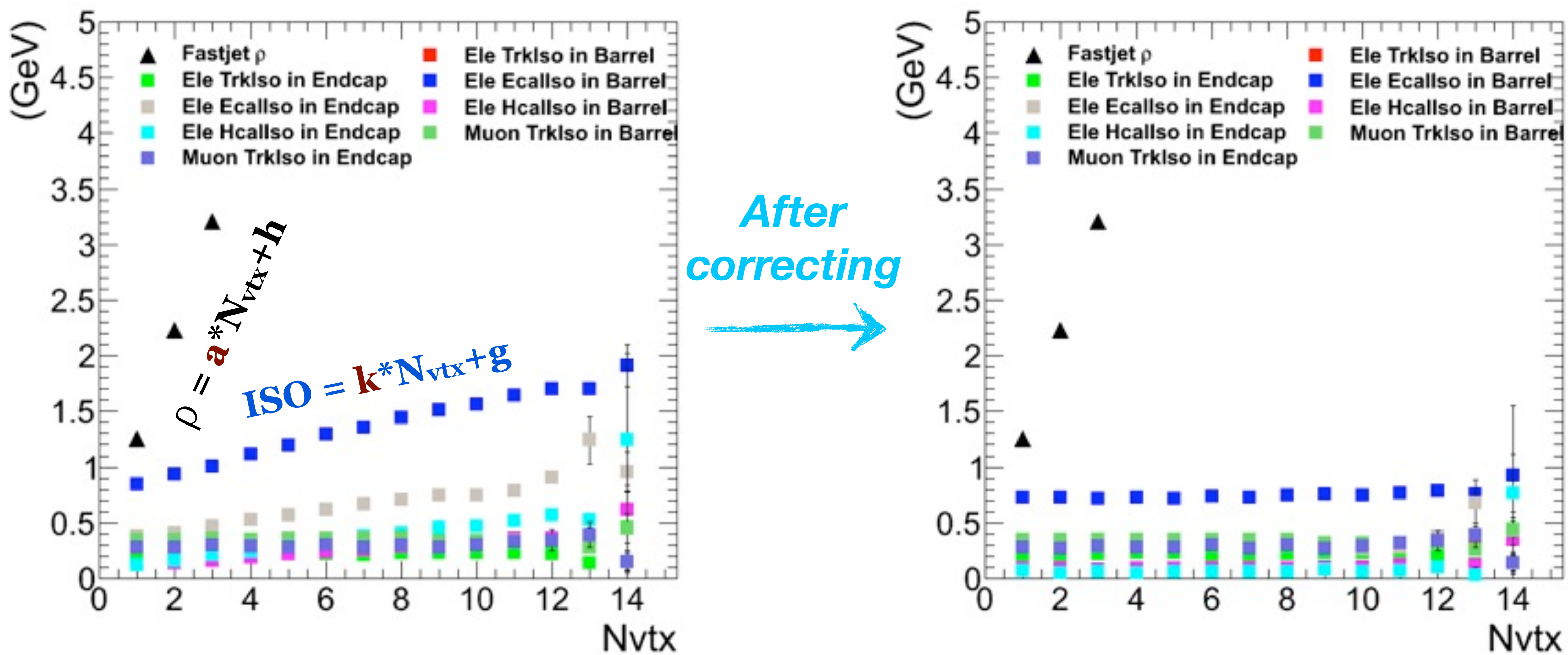
PU reweighting



Applying PU reweighting to every plot and number in this analysis

ρ Correction

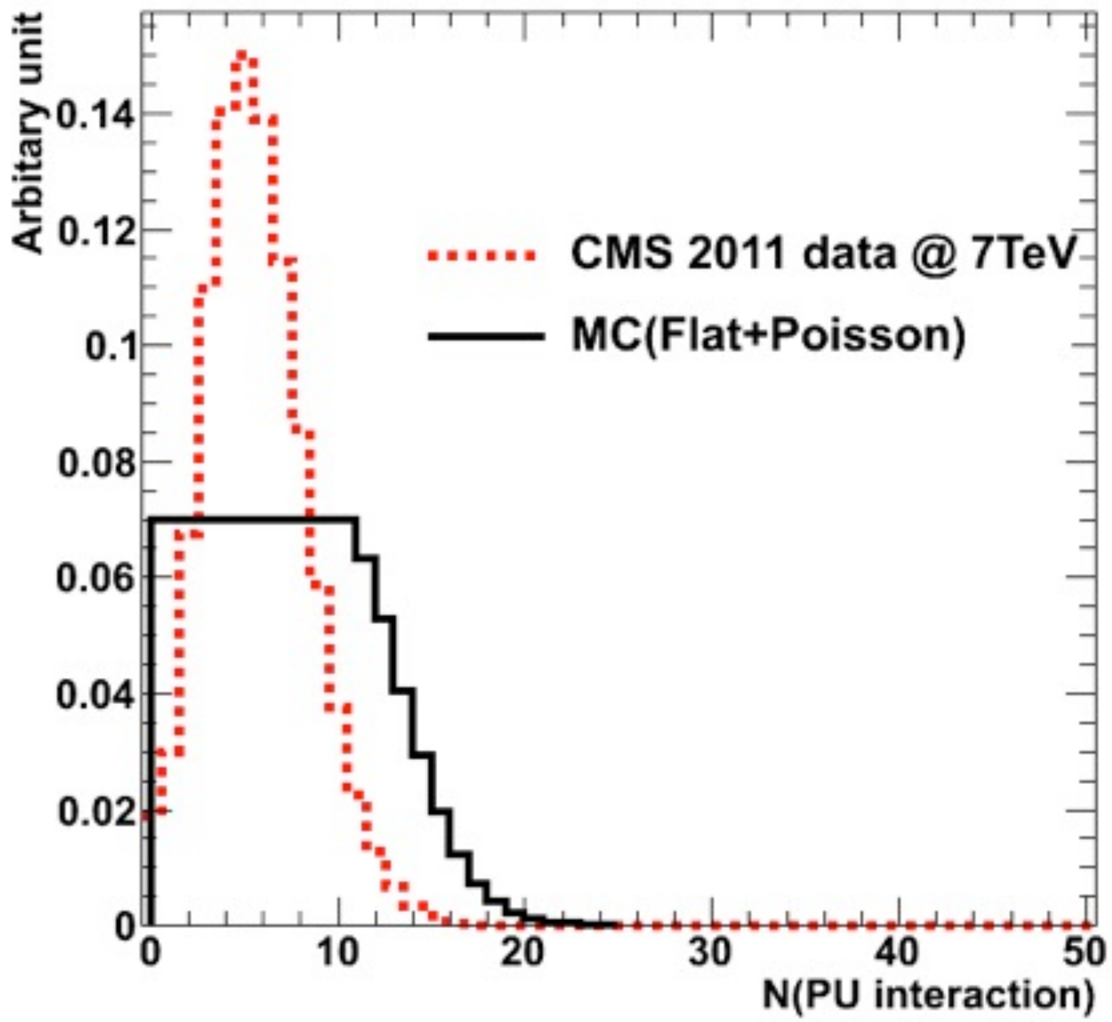
- **Using FastJet to get average energy density (ρ). Apply ρ correction to lepton isolations :** $ISO^{corrected} = ISO - \rho \times A_{Effective}$
  - **Obtain the effective area by considering isolation independent on N(good vertexes) :** $A_{Effective} = slope(ISO)/slope(\rho) = k/a$



(Note. Using Z+jets MC sample)

Pile-Up Distribution

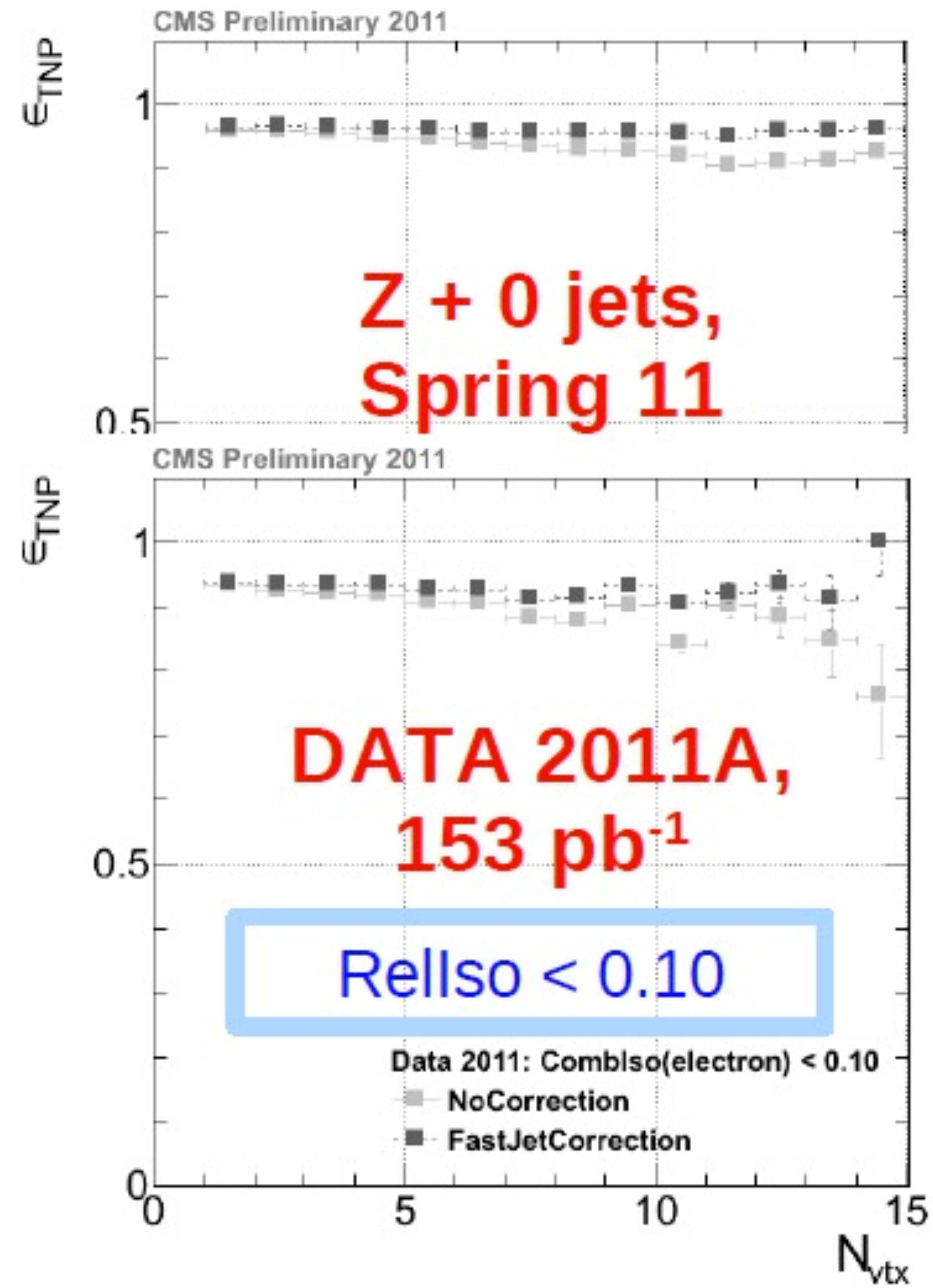
- **PU distribution for data generated by using instantaneous luminosity with the total pp inelastic cross-section of** ***59.7±0.1(stat)±1.1(syst)±2.4(lumi) mb***



(Refer to https://wiki.bnl.gov/conferences/images/4/47/Parallel.SxDNVM.Marone.13042011.talk.pdf)

Validation of ρ Correction

- **Using "tag & probe" to measure isolation efficiency (refer to <u>Validation Of Rho Correction</u>)**



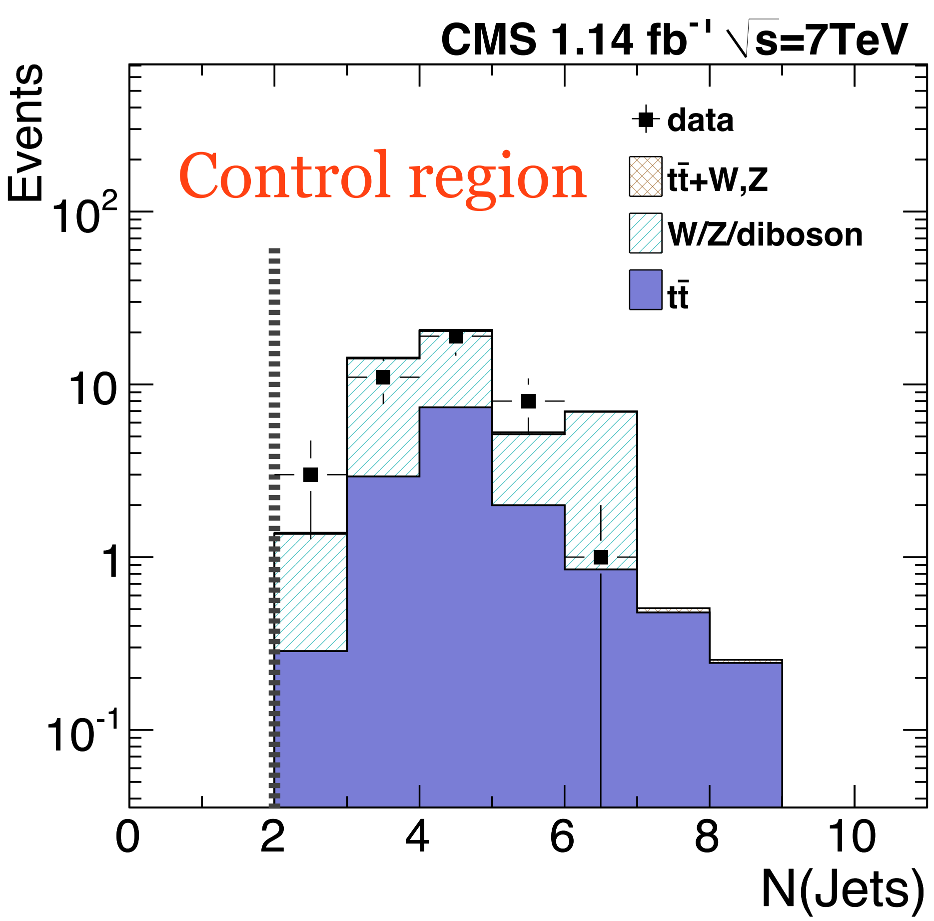
Background Classifications

- **≤ 2 prompt leptons (*$B_{2\ell}$*)**
  - ***Estimated with data-driven method***
  - **Z+jets, $t\bar{t}$+jets... (QCD processes also included in this estimation)**
- **3 prompt leptons (*$B_{3\ell}$*)**
  - ***Obtained from MC***
  - **$t\bar{t}$Z(W)+jet, WZ, and ZZ**

Category	Type I			Type II			Type III
Characteristic	2 prompt ℓ + 1 non-prompt ℓ			3 prompt ℓ			3 non-prompt ℓ
Physics process	Z + jets	$t\bar{t}$ + jets	Sum	$t\bar{t}$Z(W) + jet	WZ/ZZ	Sum	QCD
MC Yield counting	2.14	0.47	2.61	0.67	0.92	1.58	0
Proportion	51.2%	11.1%	62.3%	15.7%	22.0%	37.7%	0%
Estimation method	Data-driven (Section VII.1)			MC-driven			Data-driven (Section VII.2)
Est. yield for MC	3.31 ± 0.74			1.58 ± 0.11			$(1.4 \pm 0.5) \times 10^{-2}$
Est. yield for data	3.02 ± 0.68			1.58 ± 0.11			$(3.5 \pm 1.5) \times 10^{-2}$

Data-Driven Bkg. Estimation

- **Z+jets and $t\bar{t}$+jets estimation :**
  - **Background control region :** additional loose lepton+2 tight leptons(Z) and keep other selections



Check with Z/$t\bar{t}$ +jets MC truth value : 2.61
→ Within statistical error

	Yields in control region (MC)		Scaling ratio	Estimated yields (signal region)
	Z/$t\bar{t}$ +jets	Rest bg.		
Z + loose μ	10.7	0.4	$\varepsilon_{f\mu}$= 18.9±3.2%	3.31 ± 0.74
Z + loose e	37.3	0.9	ε_{fe}= 3.1±1.1%	

	Yields in control region (data)	Scaling ratio	Estimated yields (signal region)
Z + loose μ	13	$\varepsilon_{f\mu}$= 18.7±0.1%	3.02 ± 0.68
Z + loose e	29	ε_{fe}=2.0±0.02%	

Control region stat.

Data-Driven QCD Estimation (Cross-Check)

- **QCD estimation :**
  - **Control region :** ≥ 3 loose leptons + keep other selections

$$N_{QCD} = N_{control} \times (\varepsilon_{f\mu})^{N\mu} \times (\varepsilon_{fe})^{Ne}$$

$1.14\ fb^{-1}$	Yields in control region (data)	Scaling ratio	Estimated yields (signal region)
μ μ μ	5	$(\varepsilon_{f\mu})^3 (\varepsilon_{fe})^0 = (6.5\pm0.1)\times10^{-3}$	
μ μ e	2	$(\varepsilon_{f\mu})^2 (\varepsilon_{fe})^1 = (7.0\pm0.2)\times10^{-4}$	$(3.5\pm1.5)\times10^{-2}$
μ e e	12	$(\varepsilon_{f\mu})^1 (\varepsilon_{fe})^2 = (8.0\pm0.4)\times10^{-5}$	
e e e	22	$(\varepsilon_{f\mu})^0 (\varepsilon_{fe})^3 = (8.0\pm0.2)\times10^{-6}$	

Here is the cross-check for QCD contribution. It is already included in the background estimation.

Systematic Uncertainties

- ***Control region statistics:***
  - Observed data events in control region
- ***Luminosity & Xsec :***
  - Vary the values (lumi±4.5%, tt±11.4%, ttX±50%, W+jets±4%, Z+jets±3%, WW±35%, WZ ±42%, ZZ±27%) in calculation
- ***Lepton ID, Isolation, etc :***
  - 100% difference for MC&data from Z tag&probe + 50% difference of Z & T from GenInfo → 7.7% for each electron and 7.2% for each muon
- ***PDF (hep-ph/0508110) :***
  - Using 40 uncertainty sets (CTEQ61) to re-weight event
- ***Jet energy scale :***
  - Uncertainty associated with Jet pT and η.
- ***Jet resolution :***
  - Increasing 10% of Jet's pT resolution
- ***Pile up :***
  - By varying the data pile-up number with ±1 RMS of the distribution. The uncertainties in signal and bkg estimation are 2.8% and 9.8%, respectively.
- ***MC statistics :***
  - Error propagation with actual MC counts

Bkg Yield v.s. Data

Channel	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$	Total
$B_{2\ell}$	0.2 ± 0.3	0.8 ± 0.5	0.9 ± 0.4	1.1 ± 0.5	3.0 ± 0.8
$B_{3\ell}$	0.3 ± 0.1	0.3 ± 0.1	0.5 ± 0.2	0.5 ± 0.2	1.6 ± 0.5
B_{total}	0.5 ± 0.3	1.1 ± 0.5	1.4 ± 0.5	1.7 ± 0.6	4.6 ± 1.0
Data	0	2	2	3	7

Errors include total systematic uncertainties.

B_{2l} : Z/tt+jets (data-driven method)

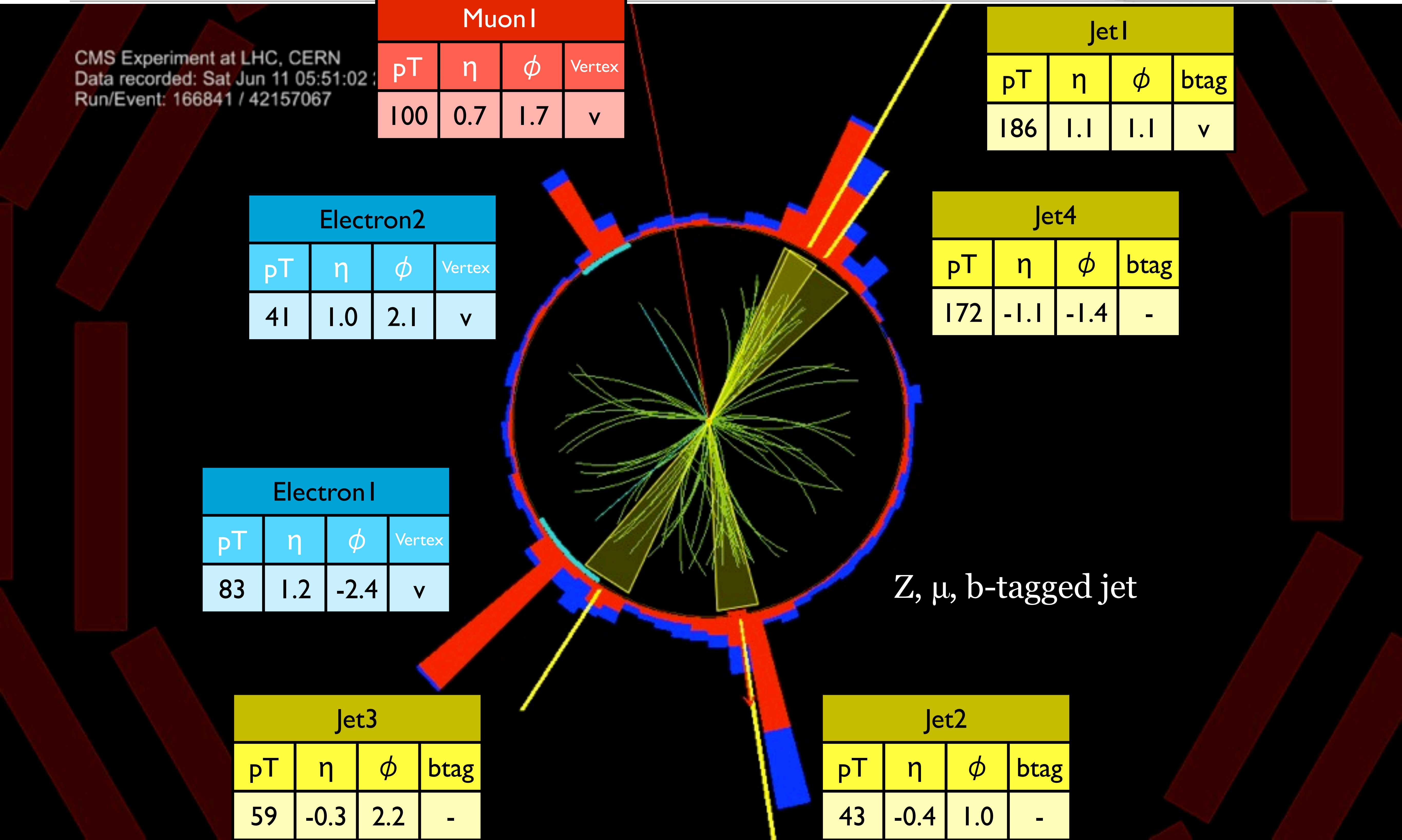
B_{3l} : tt+Z(W) and di-boson (estimated with MC)

Event list

Run	Evt	N(e)	N(μ)	N(jet)	Z_{ll} [GeV]	RS_T [GeV]	S_T [GeV]
165415	406443529	1	2	4	90	164	1,084
165467	398015722	1	2	4	91	120	405
166034	10363825	0	3	6	74	258	859
166699	928956069	0	3	4	88	104	364
166841	42157067	2	1	4	91	142	725
166889	258648939	0	3	3	94	84	429
167102	113554882	2	1	3	89	140	810

Event display in next page

Run 166841 - Evt 42157067



Muon1			
pT	η	ϕ	Vertex
100	0.7	1.7	v

Jet1			
pT	η	ϕ	btag
186	1.1	1.1	v

Electron2			
pT	η	ϕ	Vertex
41	1.0	2.1	v

Jet4			
pT	η	ϕ	btag
172	-1.1	-1.4	-

Electron1			
pT	η	ϕ	Vertex
83	1.2	-2.4	v

Z, μ, b-tagged jet

Jet3			
pT	η	ϕ	btag
59	-0.3	2.2	-

Jet2			
pT	η	ϕ	btag
43	-0.4	1.0	-