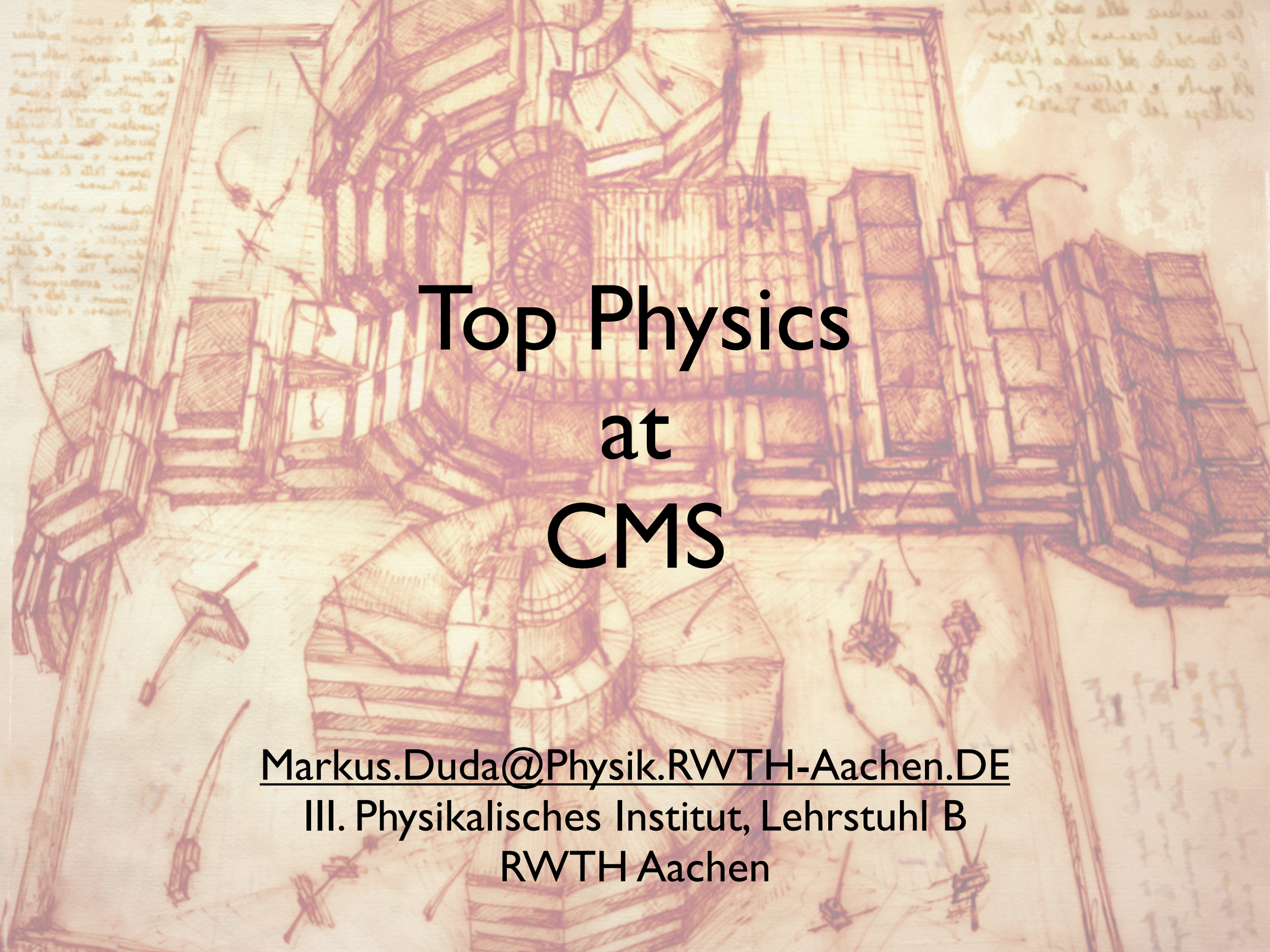

Top Physics at CMS

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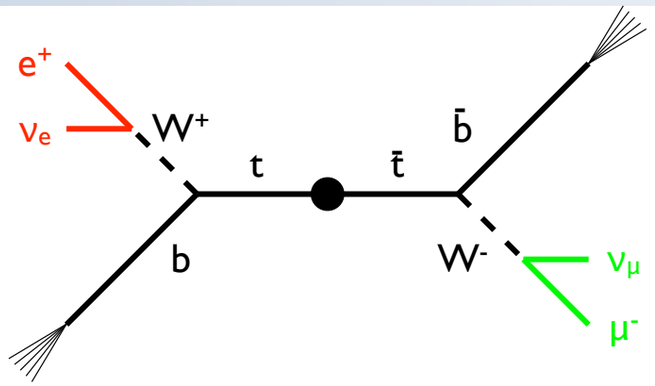
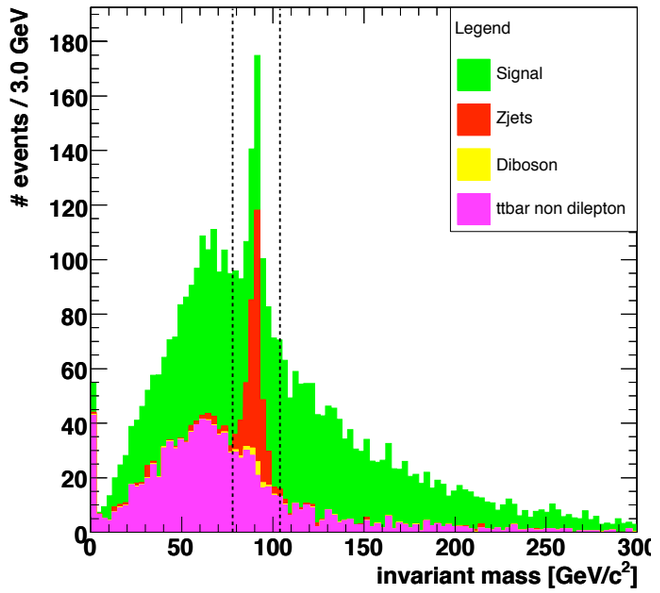
Overview

- top mass determination in $t\bar{t}$ decays
  - di-leptonic (Daiske.Tornier@Physik.RWTH-Aachen.DE)
  - semi-leptonic (Stefan.Kasselmann@Physik.RWTH-Aachen.DE)
  - fully hadronic (Markus.Duda@Physik.RWTH-Aachen.DE)
- W-helicity in $t\bar{t}$ decays (Andreas.Tigges@Physik.RWTH-Aachen.DE)
- spin correlations in $t\bar{t}$ decays (Martina.Davids@Physik.RWTH-Aachen.DE)
- $t\bar{t}\gamma$ events (Thomas.Hermanns@Physik.RWTH-Aachen.DE)

Di-Leptonic

- very clean final state signature with two isolated opposite-sign leptons and two b-jets
- two neutrinos prevent direct reconstruction
- event kinematic still has large sensitivity to m_t





- selection
  - single and di-lepton trigger
  - two isolated opposite-sign leptons with p_T > 20 GeV/c
  - for two same-flavour leptons remove Z mass peak
  - two b-jets with p_T > 30 GeV/c
  - MET > 40 GeV

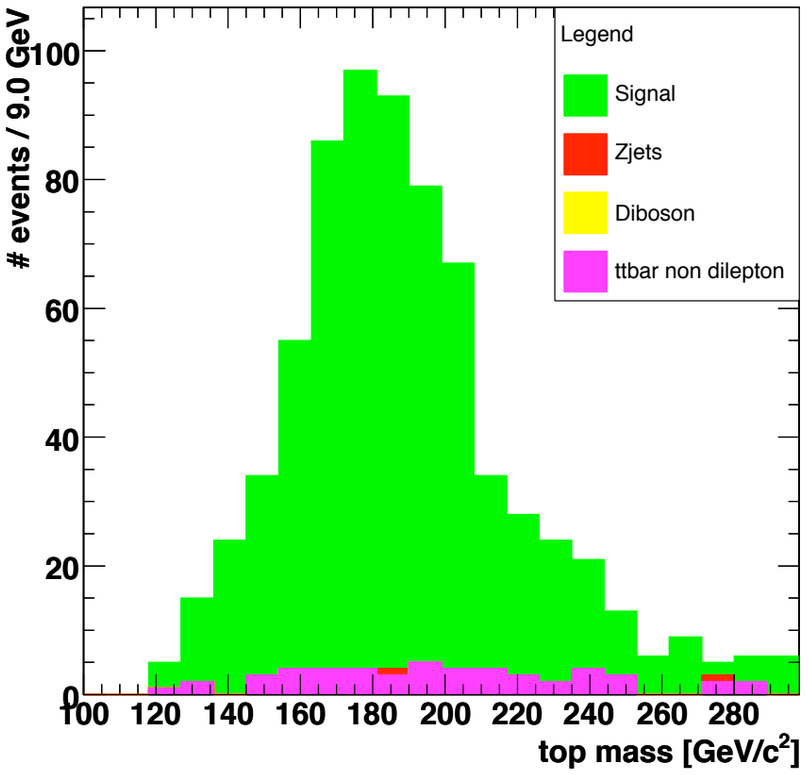
	$t\bar{t}$ dilepton [pb]	other $t\bar{t}$ [pb]	Z+jets [pb]	diboson [pb]	S/B
before selection	54.22	433.78	11055.30	19.73	0.005
L1	45.06	302.34	2967.13	9.64	0.014
HLT	36.41	184.43	2007.67	6.9	0.017
2 isolated leptons	9.60	4.22	48.33	0.240	0.182
2 b-jets	5.30	3.13	2.55	0.031	0.928
lepton inv. mass	4.46	2.88	0.55	0.014	1.292
lepton pt cut	3.07	0.62	0.34	0.013	3.151
$E_{\mathrm{T}}^{\mathrm{miss}}$ cut	2.30	0.43	0.05	0.011	4.748
# high p_{T} jet cut	1.85	0.21	0.03	0.008	7.332
kinematical reco.	0.66	0.05	0.002	0.008	12.167

Di-Leptonic

- event kinematic underconstrained due to two undetected ν

$$
\begin{aligned}
0 &= p_x^{l^+} + p_x^{l^-} + p_x^b + p_x^{\bar{b}} + p_x^\nu + p_x^{\bar{\nu}} \\
0 &= p_y^{l^+} + p_y^{l^-} + p_y^b + p_y^{\bar{b}} + p_y^\nu + p_y^{\bar{\nu}}
\end{aligned}
$$

$$
\begin{aligned}
m_{W^+}^2 &= (E^{l^+} + E^\nu)^2 - \sum_i (p_i^{l^+} + p_i^\nu)^2 \\
m_{W^-}^2 &= (E^{l^-} + E^{\bar{\nu}})^2 - \sum_i (p_i^{l^-} + p_i^{\bar{\nu}})^2 \\
m_t^2 &= (E^{l^+} + E^\nu + E^b)^2 - \sum_i (p_i^{l^+} + p_i^\nu + p_i^b)^2 \\
m_{\bar{t}}^2 &= (E^{l^-} + E^{\bar{\nu}} + E^{\bar{b}})^2 - \sum_i (p_i^{l^-} + p_i^{\bar{\nu}} + p_i^{\bar{b}})^2
\end{aligned}
$$



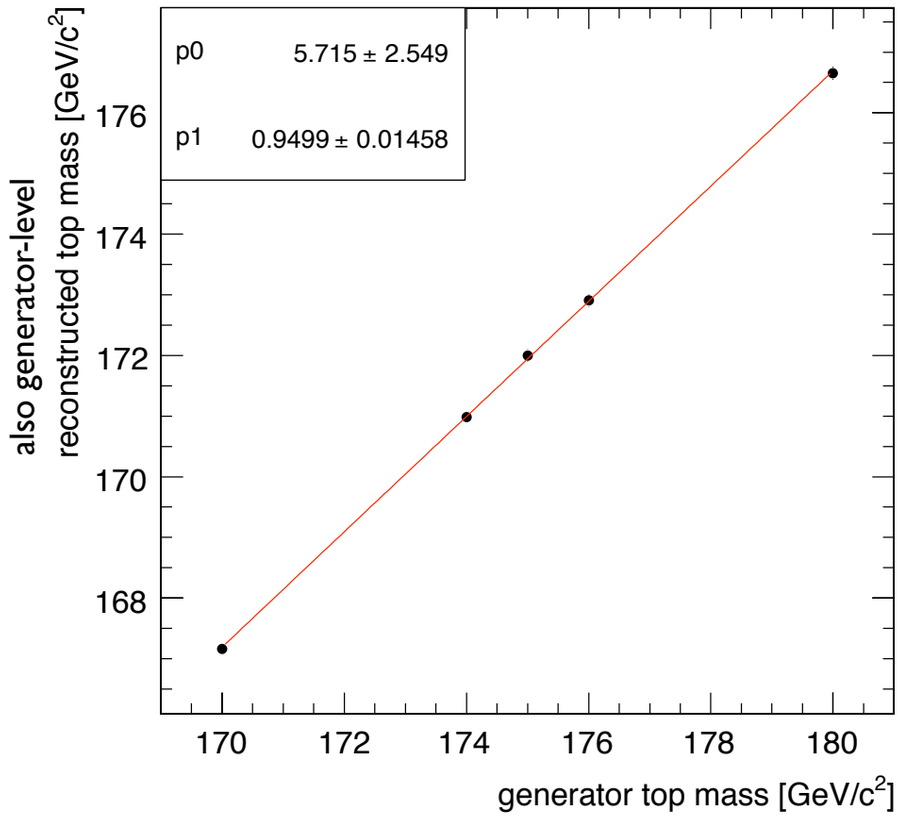
- written as a 4th order polynomial with m_t as parameter

$$
0 = \sum_{i=0}^{4} c_i(M_t, p^{l\pm}, p^b, p^{\bar{b}})(p_x^{\bar{\nu}})^i
$$

- use SM neutrino spectrum for $(p_x^{\bar{\nu}})$

- step through 100 GeV/c² < m_t < 300 GeV/c² and weight kinematic solutions including four-fold ambiguity

Di-Leptonic



	$\Delta m_t[\ \mathrm{GeV}/c^2]$
IS/FS Radiation	0.3
Jet Energy Scale	2.9
Total Systematical Uncertainty	2.9
Statistical Uncertainty (1 fb^{-1})	1.5
Statistical Uncertainty (10 fb^{-1})	0.5

for 1/fb already systematics dominated

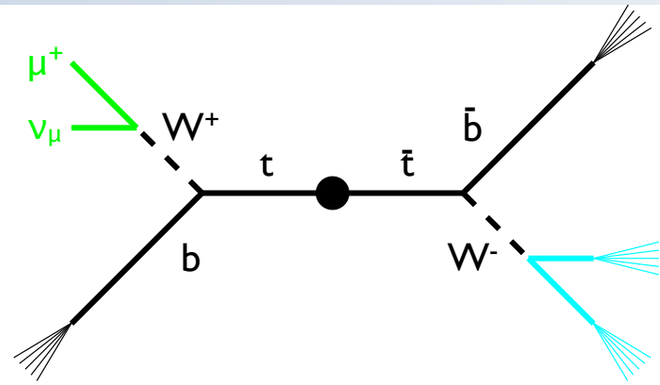
$\Delta m_t = \pm 1.5$ (stat.) ± 2.9 (syst.) GeV/c^2

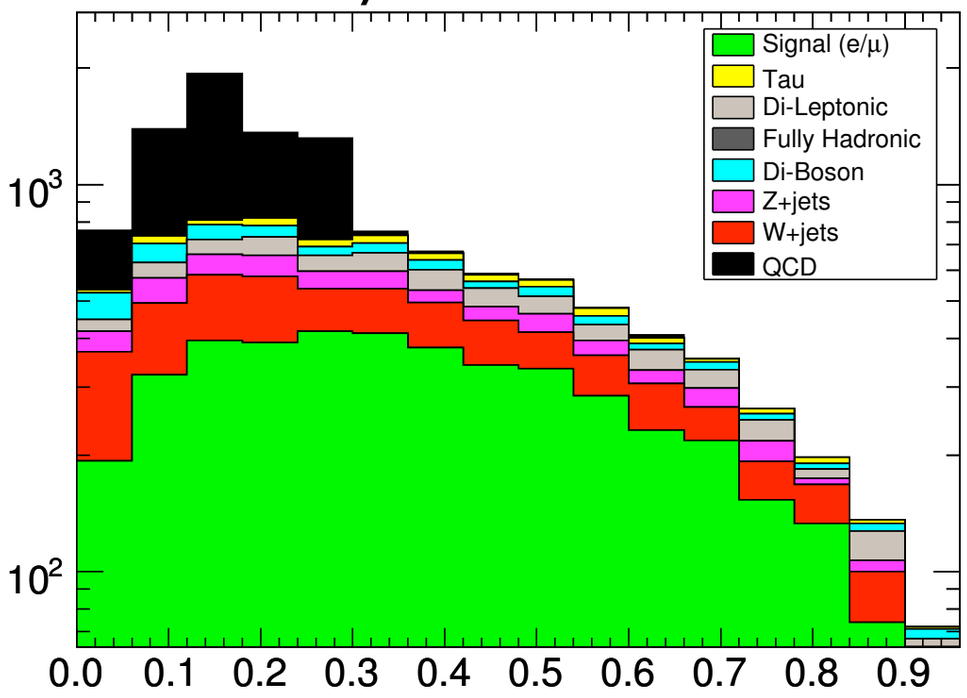
improves with 10/fb of well-understood data to

$\Delta m_t = \pm 0.5$ (stat.) ± 1.1 (syst.) GeV/c^2

Semi-Leptonic

- isolated lepton, MET, two b-jets, two light quark jets
- analysis scenario "First Physics Run"
  - no ECAL endcaps, no E_T, no b-tagging
- selection
  - full L1 and HLT trigger
  - exactly one isolated electron or muon with p_T > 10 GeV/c
  - 4 or 5 jets with p_T > 30 GeV/c, three of them with p_T > 40 GeV/c
  - circularity > 0.3

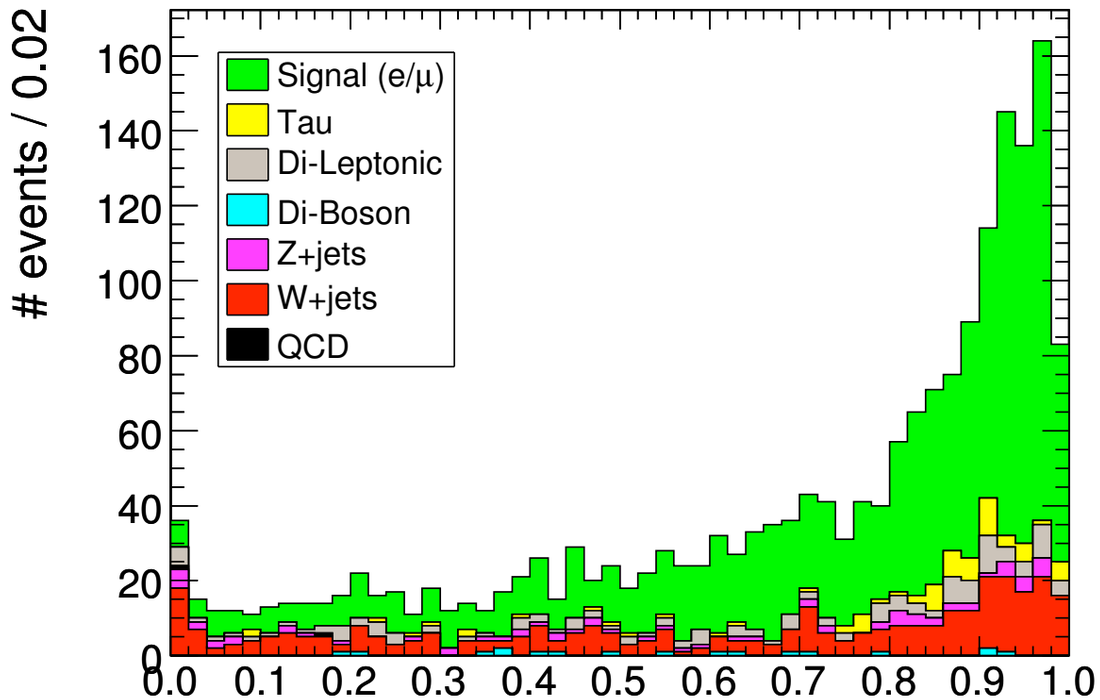


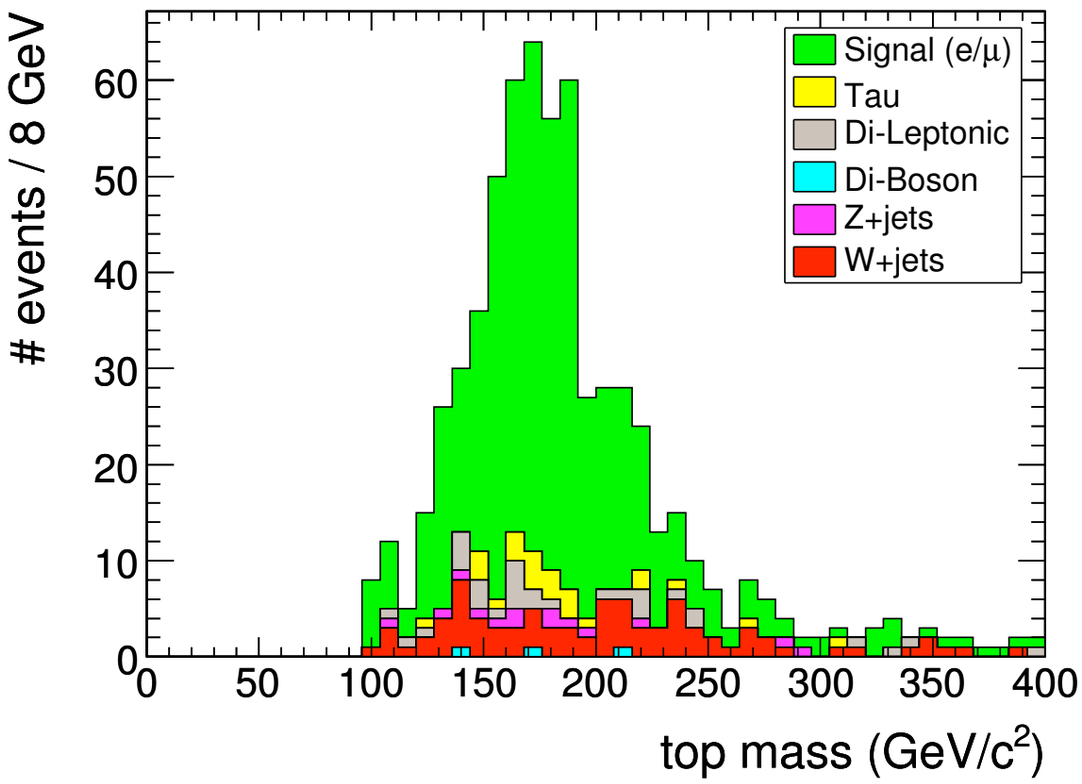


Dataset	Preselected	One lepton	Jet pt	Circularity	5 jets	eff. (%)
Signal:						
Semilept. (e/μ)	**5.972**	**5.460**	**4.355**	**2.638**	**1.845**	**30,89**
Background:						
Semilept. (tau)	377	342	267	141	98	25,97
dileptonic	1.718	1.095	679	419	263	17,00
fully hadronic	20	15	15	7	3	15,31
W + jets	7.664	5.783	2.687	1.239	758	9,89
Z + jets	3.421	1.642	649	317	201	5,88
QCD	13.416	9.502	4.174	156	41	**0,30**
Di-Boson	524	399	174	72	42	8,02
S / B	0,22	0,29	0,50	1,12	**1,31**	

Semi-Leptonic

- use likelihood ratio for top quark reconstruction with the input variables
  - two jet invariant mass
  - two jet angle sum
  - three jet angle sum
  - two jet p_T sum
  - angle between top and antitop
  - angle between lepton and jet
- max. likelihood ratio > 0.9 yields S/B = 2.9
- but still high combinatorical background
- jet pairing purity about 30%, limited by the statistics of the "First Physics Run"





Semi-Leptonic

conservative

$\Delta m_t = \pm 0.2$ (stat.)

± 1.9 (syst.) GeV/c^2

	Standard Selection		
	Gaussian Fit Δm_t (GeV/c^2)	Gaussian Ideogram Δm_t (GeV/c^2)	Full Scan Ideogram Δm_t (GeV/c^2)
Pile-Up	1.9	1.4	1.2
Underlying Event	1.0	0.7	0.5
Jet Energy Scale (light)	2.4	0.1	0.1
Jet Energy Scale (heavy)	1.4	1.3	1.2
Radiation (pQCD)	0.8	0.3	0.2
Fragmentation	0.4	0.4	0.3
b-tagging	2.0	0.5	0.3
Background (∗)	0.4	0.4	0.4
Parton Density Functions	0.1	0.1	0.1
Total Systematical uncertainty	4.9	2.3	1.9
Statistical Uncertainty (10fb^{-1})	0.32	0.36	0.21
Total Uncertainty	4.9	2.3	1.9

long term

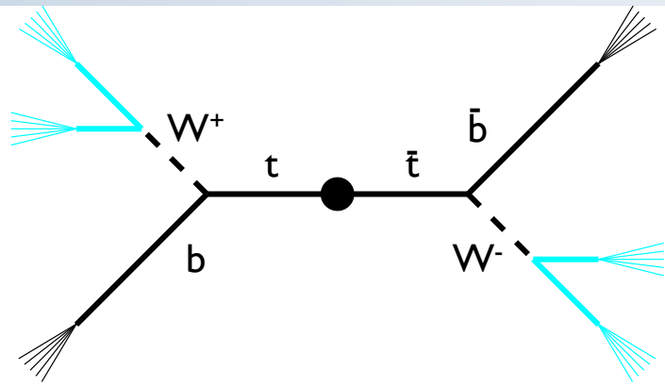
- pileup →1/6
- b-jet energy scale 2%→1.5%
- b-tagging 5%→2%

$\Delta m_t = \pm 0.2$ (stat.)

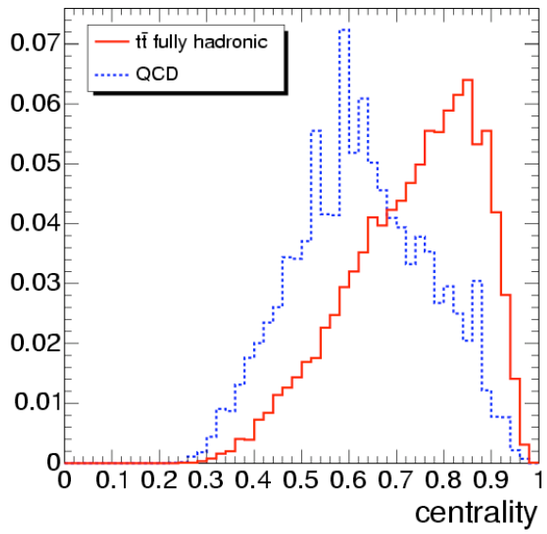
± 1.1 (syst.) GeV/c^2

	Standard Selection		
	Gaussian Fit Δm_t (GeV/c^2)	Gaussian Ideogram Δm_t (GeV/c^2)	Full Scan Ideogram Δm_t (GeV/c^2)
Pile-Up	0.32	0.23	0.21
Underlying Event	0.50	0.35	0.25
Jet Energy Scale (light)	1.80	0.15	0.06
Jet Energy Scale (heavy)	1.05	0.98	0.90
Radiation (pQCD)	0.80	0.27	0.22
Fragmentation	0.40	0.40	0.30
b-tagging	0.80	0.20	0.18
Background	0.30	0.25	0.25
Parton Density Functions	0.12	0.10	0.08
Total Systematical uncertainty	3.21	1.27	1.13
Statistical Uncertainty (10fb^{-1})	0.32	0.36	0.21
Total Uncertainty	3.23	1.32	1.15

Fully Hadronic



- six-jets topology, two b-jets, four light quark jets
- kinematics fully reconstructable
- large background from QCD multi-jet
- selection
- specific multi-jet trigger with online b-tagging
- eventshape variables
- offline b-tagging
- neural network

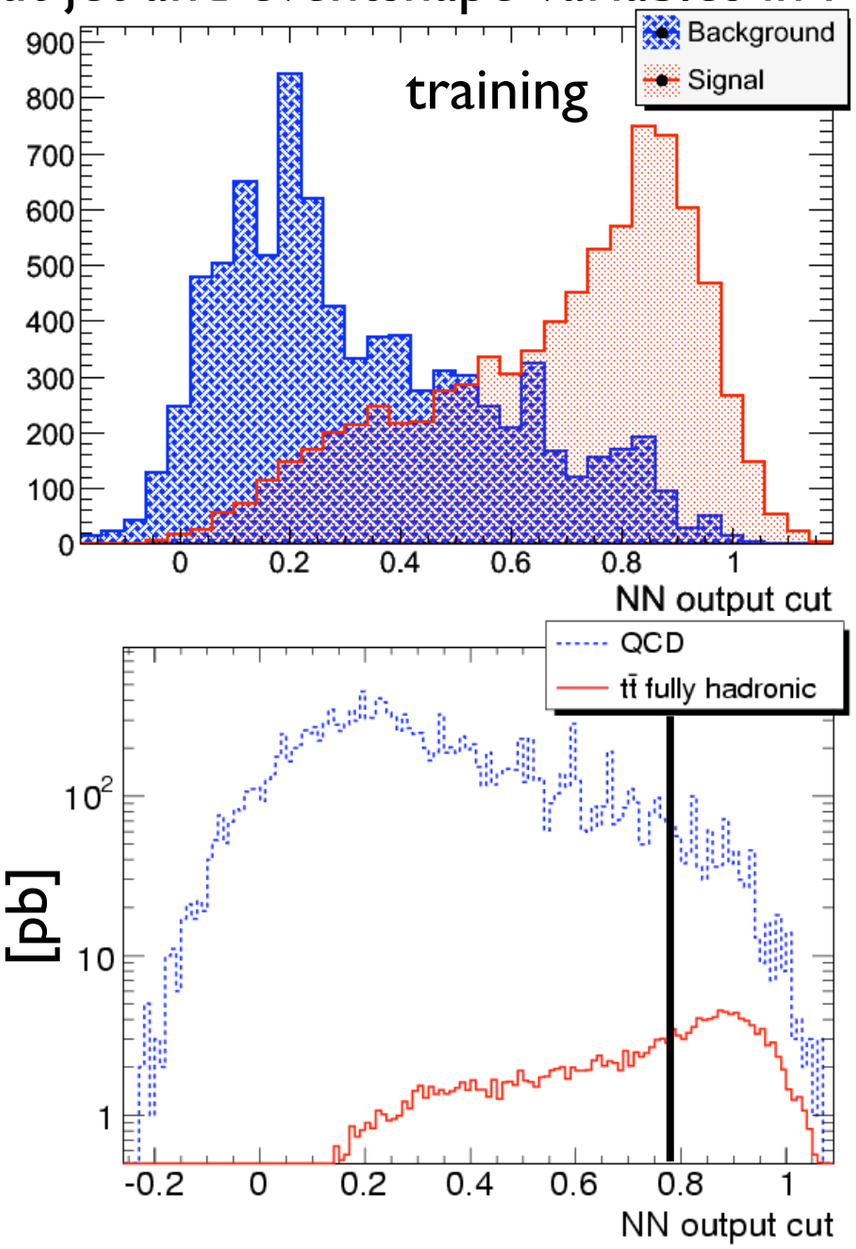


Selection	Requirement	$\sigma\epsilon$ [pb]	$\sigma\epsilon_{\mathrm{QCD}}$ [pb]	S/B
Before Selection (PYTHIA LO)		225	25M	$1/10^5$
Trigger	HLT multi-jet+b-jet	38	11600	1/300
Event	$6 \leq N_{\mathrm{jet}} \leq 8$	35	7900	1/225
	$E_{\mathrm{T}} \geq 30\,\mathrm{GeV}$	15	930	1/60
	centrality ≥ 0.68	9.9	324	1/33
	aplanarity ≥ 0.024	9.0	251	1/28
	$\sum_3 E_{\mathrm{T}} \geq 148\,\mathrm{GeV}$	9.0	229	1/25
b-tagging	1 b-tag	8.6	148	1/17
	2 b-tag	6.0	54	1/9

Fully Hadronic

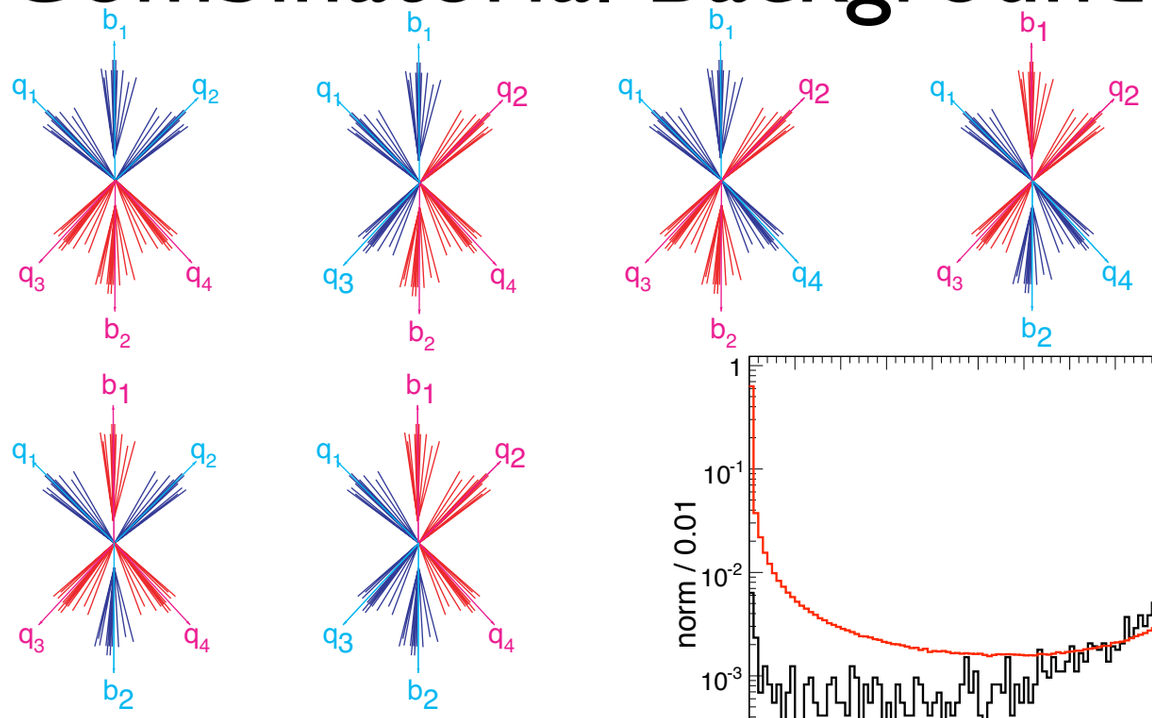
QCD Background

put jet and eventshape variables in NN



improve S/B from 1/25 to 1/10 for same $\epsilon \sim 4\%$
and from 1/9 to 1/3 with 2 b-tags

Combinatorial Background

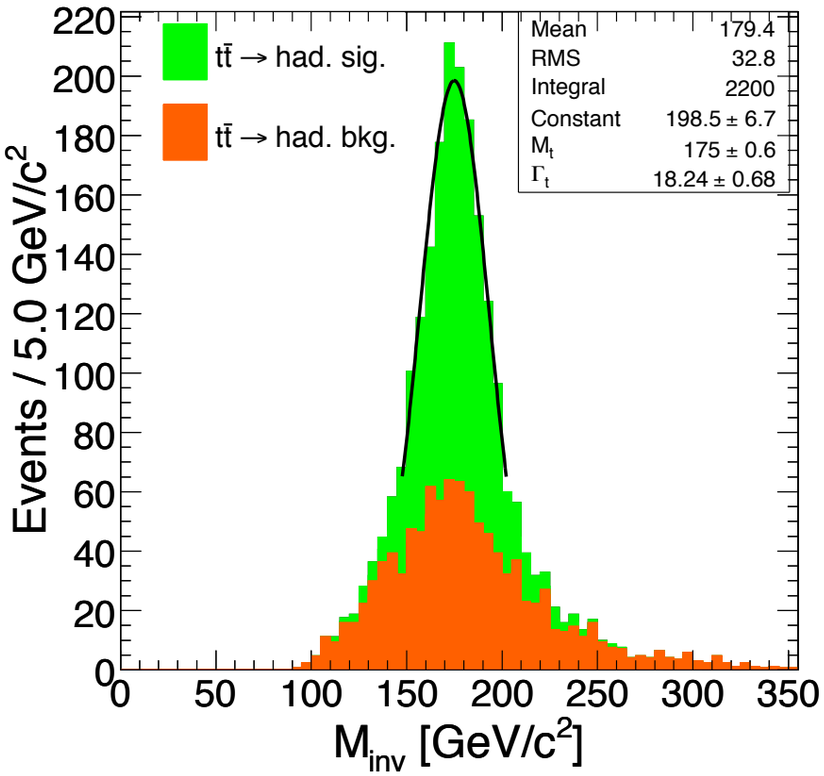


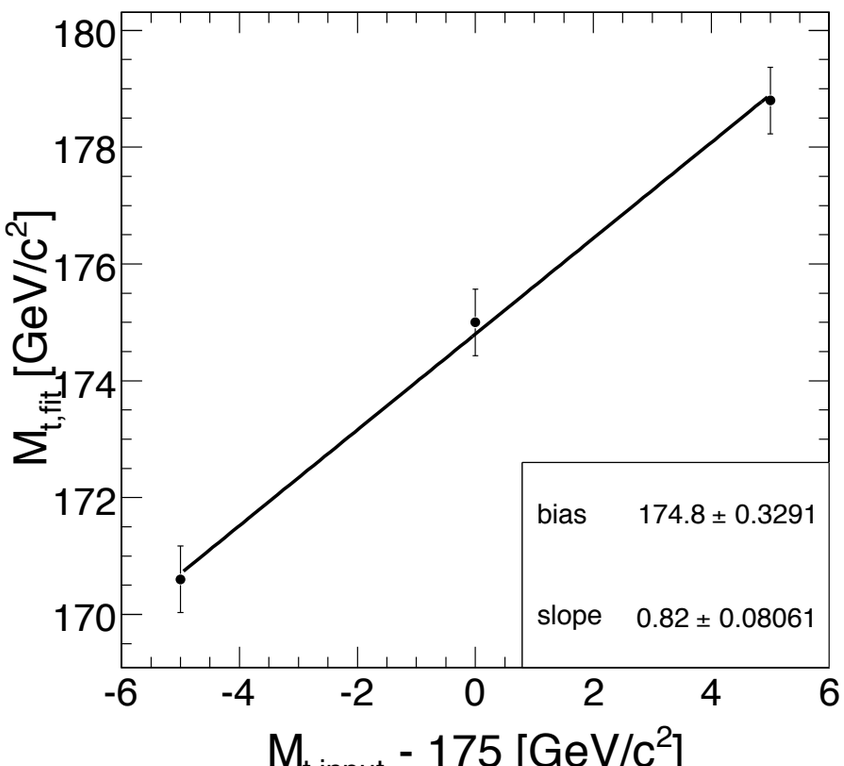
Likelihood Pairing Function

- average of the two W-boson masses
- difference of the two W-boson masses
- sum of the inter-jet angles of the W-boson candidates
- difference of the two top-quark masses
- sum of the inter-jet angles of the top-quark candidates
- angle between the direction of the two top-quark candidates

jet pairing efficiency of ~ 68%

Fully Hadronic





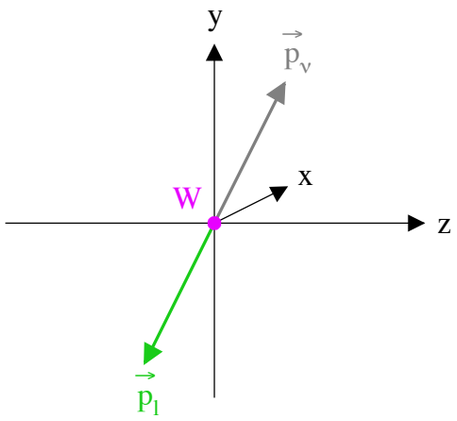
	$\Delta m_t [\,\mathrm{GeV}/c^2]$
Pile Up	0.4
Underlying Event	0.6
PDF	1.4
IS/FS Radiation	2.3
Fragmentation	0.9
Jet Energy Scale	2.3
b-Tagging	0.3
Background	2.0

systematic uncertainties

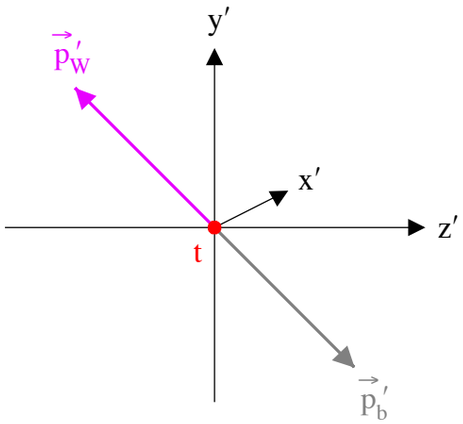
- S/B ~ 2/3, although not enough simulated QCD events (yet) to determine background shape
- for 1/fb already systematics dominated
- $\Delta m_t = \pm 0.6$ (stat.) ± 4.2 (syst.) GeV/c^2

W-Helicity

W boson rest frame



t quark rest frame



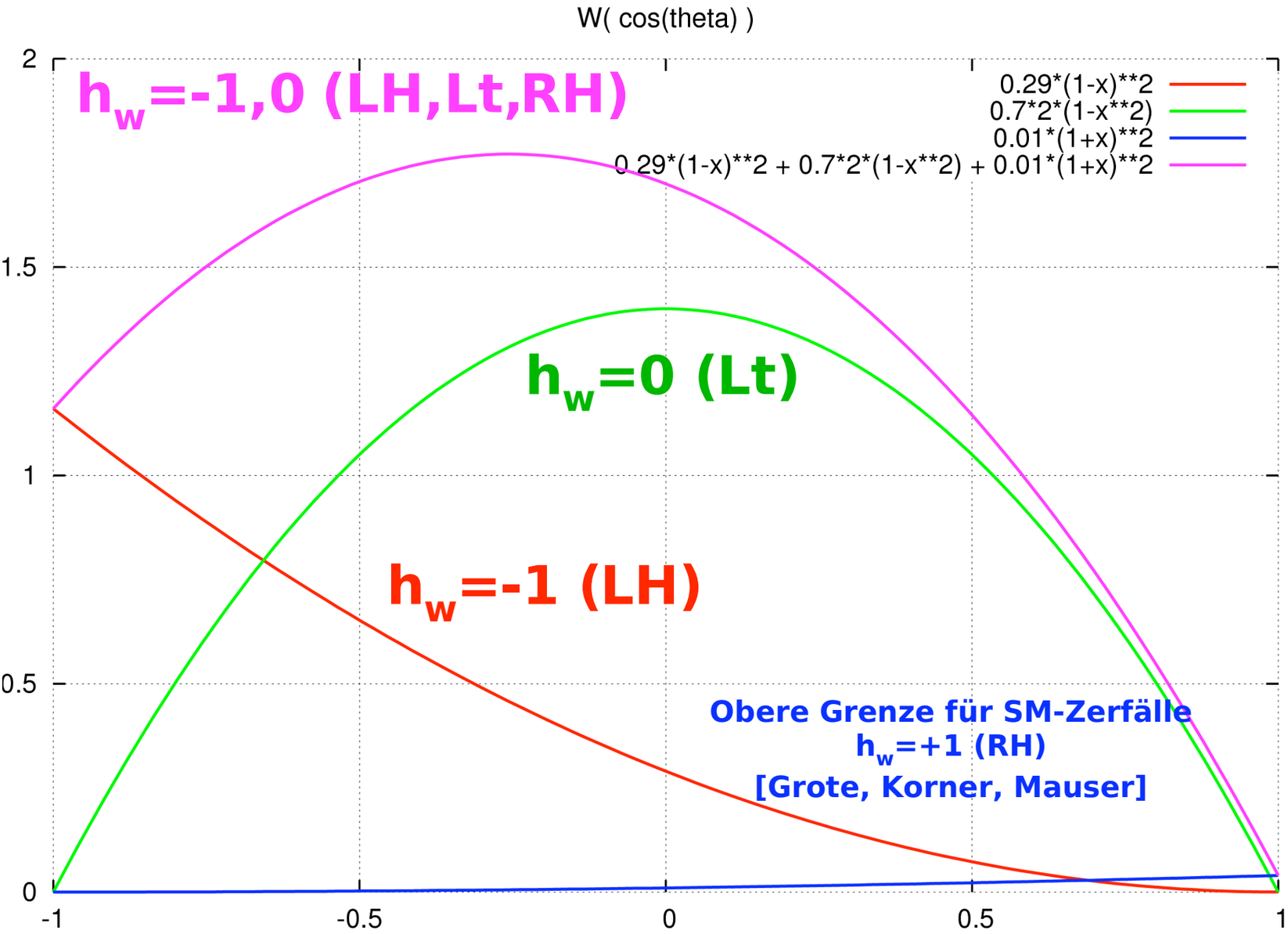
$$\cos\theta_l^* \equiv \frac{\vec{p}_l \bullet \vec{p}'_W}{|\vec{p}_l||\vec{p}'_W|}$$

h=-1	h=0		h=+1
W^+ $\hat{p}z$	W^+ $\hat{p}z$		W^+ $\hat{p}z$
ν_μ μ^+	ν_μ μ^+	ν_μ μ^+	ν_μ μ^+
s_z:			
LH LH	RH LH	LH LH	Lt LH	Lt RH	RH LH	LH LH
X	√	X	√	√	X	√	X
Spinerh. im W-RF verletzt	konsist. mit SM	Spinerh. im W-RF verletzt	konsist. mit SM	konsist. mit SM	Impuls-erh. verletzt	konsist. mit SM	Impuls-erh. verletzt

W-Helicity

distribution of the lepton helicity angle in the SM

$$\frac{1}{N}\frac{dN}{d\cos\theta_l^*} = \frac{3}{8}\frac{1}{1+f}(1-\cos\theta_l^*)^2 + \frac{3}{4}\frac{f}{1+f}\sin^2\theta_l^* \quad \text{with} \quad f = \frac{m_t^2}{2m_W^2}$$



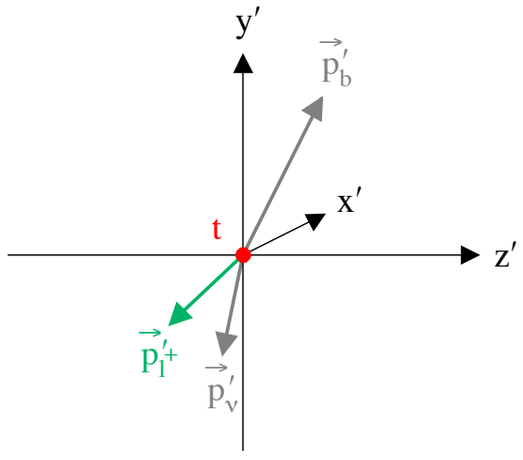
$$\frac{\Gamma(h_W=-1)}{\Gamma_{\text{tot}}} \sim 0.3$$

$$\frac{\Gamma(h_W=0)}{\Gamma_{\text{tot}}} \sim 0.7$$

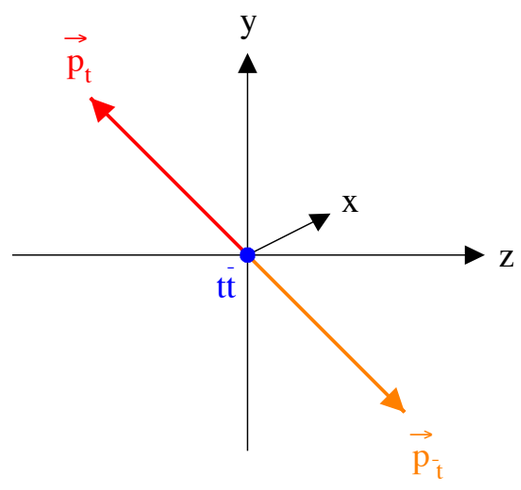
$$\frac{\Gamma(h_W=+1)}{\Gamma_{\text{tot}}} < 0.01$$

Spin Correlations

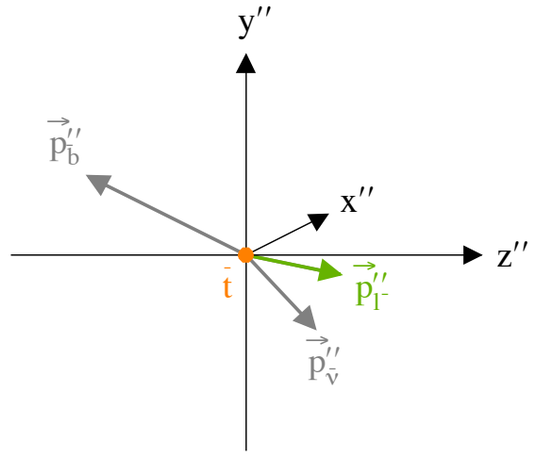
t quark rest frame



$t\bar{t}$ pair rest frame



$\bar{t}$ quark rest frame



$$\cos\theta^*_{l^+} \equiv \frac{\vec{p}'_{l^+} \bullet \vec{p}_t}{|\vec{p}'_{l^+}||\vec{p}_t|} \qquad \cos\theta^*_{l^-} \equiv \frac{\vec{p}''_{l^-} \bullet \vec{p}_{\bar{t}}}{|\vec{p}''_{l^-}||\vec{p}_{\bar{t}}|}$$

- top quark decays before hadronisation due to its short lifetime
- angular distribution of $t\bar{t}$ decay products contains information about the spin correlation of $t\bar{t}$ and SM couplings
- SM theoretical calculations predict an asymmetry coefficient A
  - $A_{gg} = 0.431$
  - $A_{qq'} = -0.469$

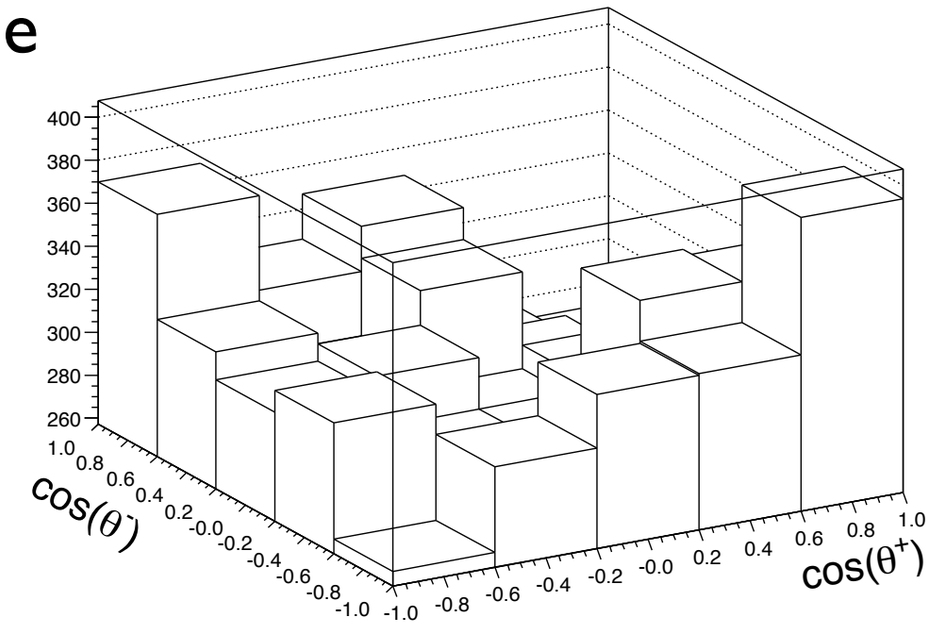
$$A = \frac{N(t_L\bar{t}_L + t_R\bar{t}_R) - N(t_L\bar{t}_R + t_R\bar{t}_L)}{N(t_L\bar{t}_L + t_R\bar{t}_R) + N(t_L\bar{t}_R + t_R\bar{t}_L)}$$

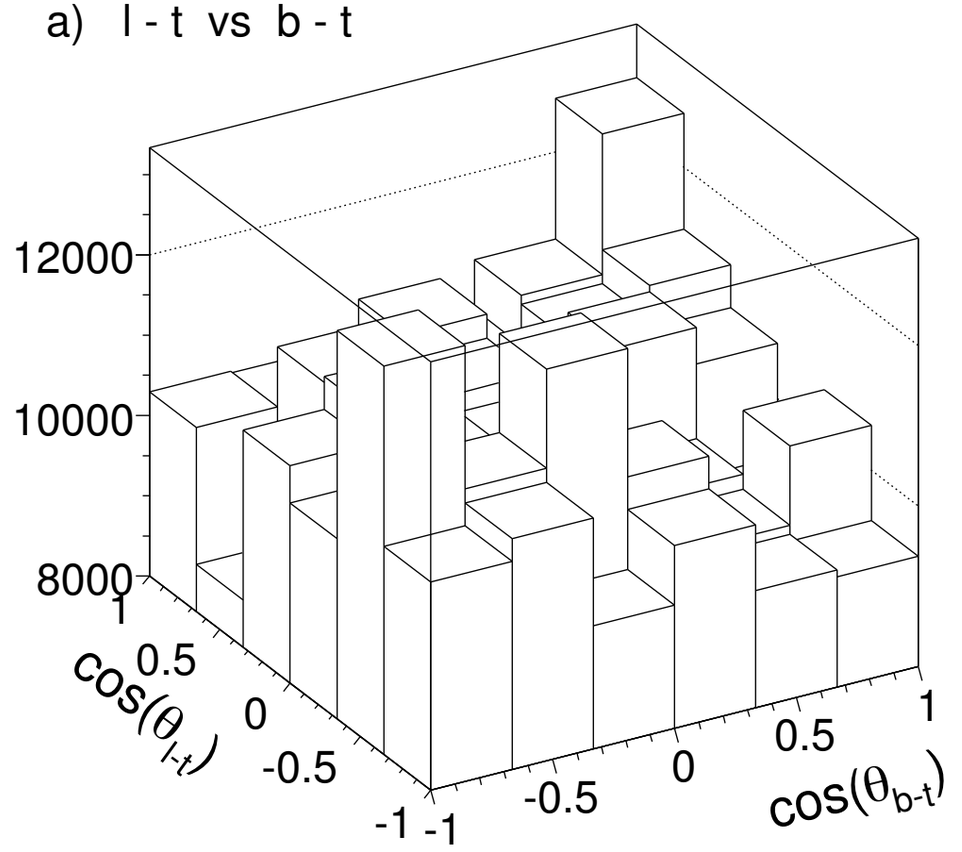
Spin Correlations

- extract the asymmetry coefficient A from double differential angular distributions

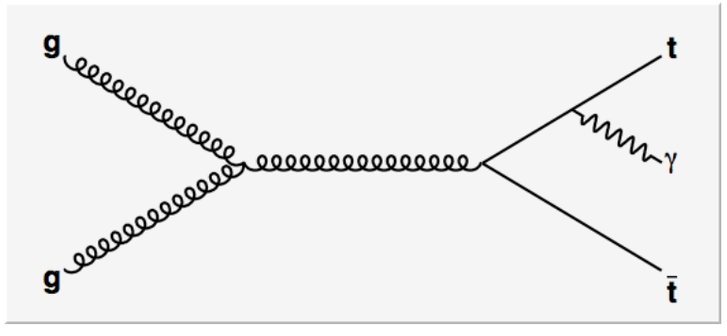
$$\frac{1}{N}\frac{d^2N}{d\cos\theta_1^* d\cos\theta_2^*} = \frac{1}{4}(1 - A\cos\theta_1^*\cos\theta_2^*)$$

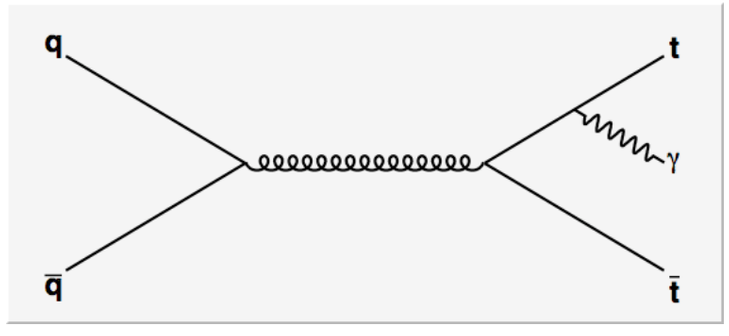
- di-leptonic
  - theoretical: leptons have best spin-analyser quality
  - experimental: leptons are easiest and best reconstructed
  - but the $t\bar{t}$ system is difficult to reconstruct due to the neutrinos, even with top mass constraint
- semi-leptonic (CMS-Note 2006/111)
  - only one spin-analyser is leptonic
  - $t\bar{t}$ system is easy to reconstruct
  - selection described in the note yields $\epsilon \sim 5\%$ and S/B=4.5
  - A = 0.375 ± 0.027(stat.) ± 0.096(syst.)

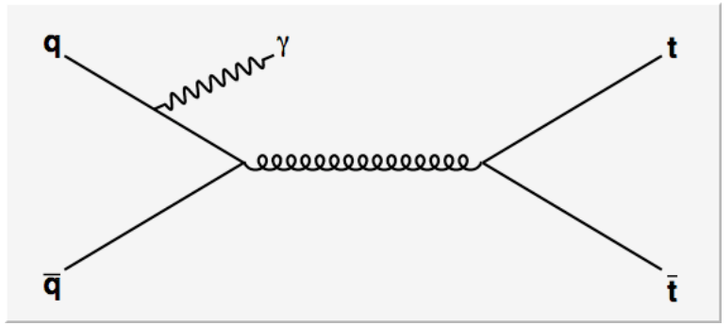




$t\bar{t}\gamma$

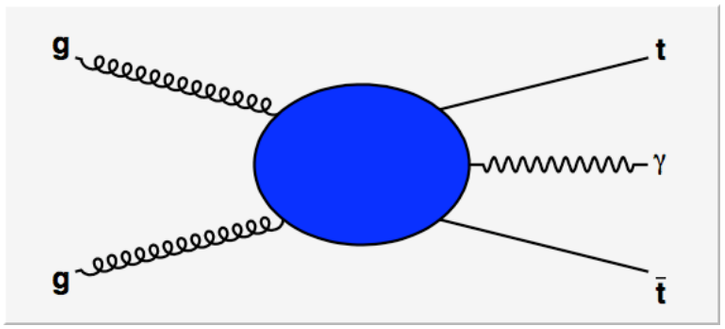


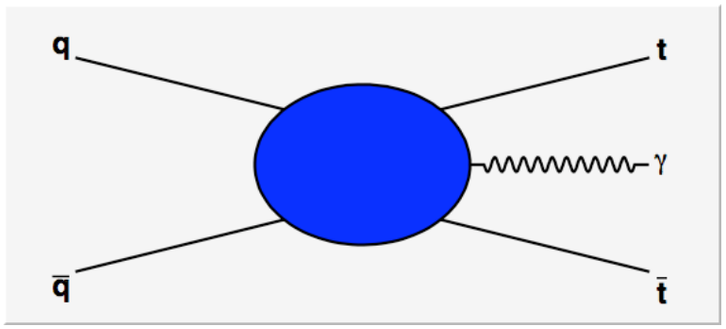




3 classes of diagrams for the hard process,
with the first two signal for top-QED-coupling studies

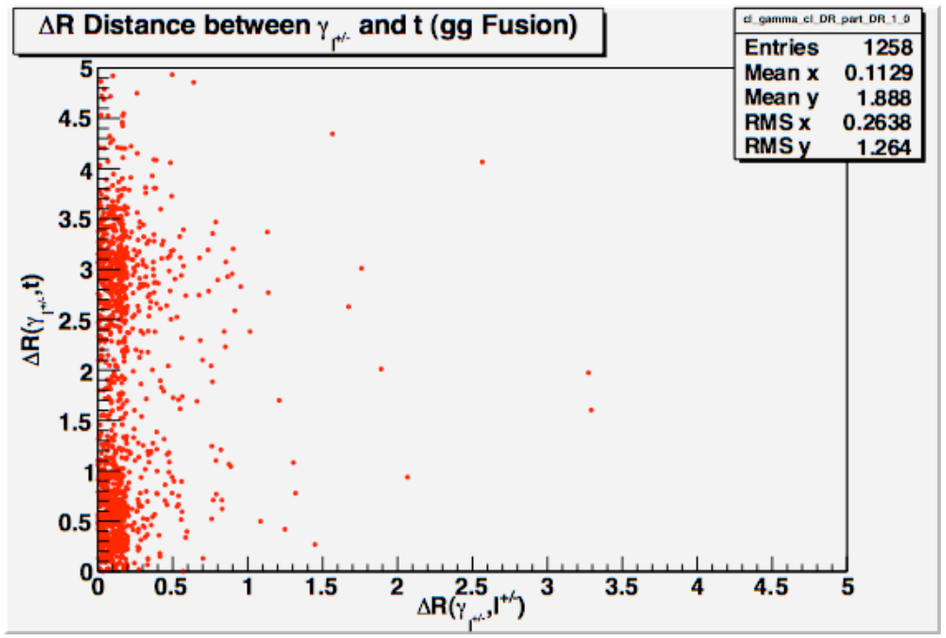
while TopReX implements these diagrams
no distinction between photon radiation off initial quarks
and top quarks in qq' annihilation processes



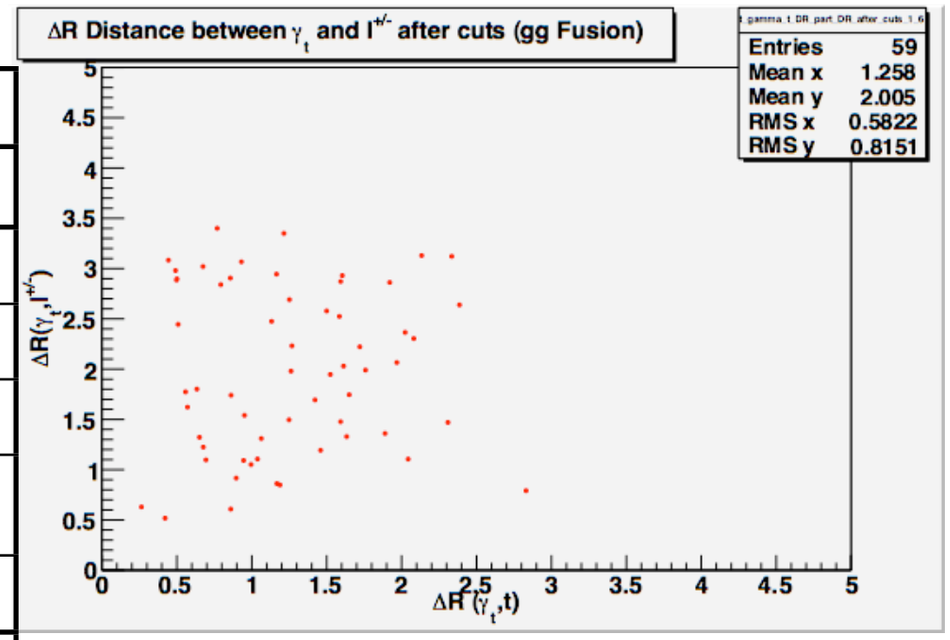


go back to PYTHIA+PHOTOS to develop generator level cuts for
hard photon radiation off top quarks

- use preselection of semi-leptonic top mass analysis
- use cuts on photon properties
  - E_γ>30.0 GeV
  - $|\eta_\gamma|$<2.5
  - ΔR>0.5 between photon and charged particles (b-quarks, W, decay products of W)



Number of photons ...			
... radiated off	preselection	E_γ η_γ cuts	dR cuts
t/tbar	716 (0.8%)	179 (4.9%)	129 (48.5%)
b/bbar	1,658 (1.8%)	251 (6.9%)	53 (19.9%)
W+/W−	0	0	0
charged lepton	83,861 (93.2%)	2,718 (75.0%)	63 (23.7%)
quarks from W	3,737 (4.2%)	473 (13.1%)	21 (7.9%)
total number	89,972 (100%)	3,621 (100%)	266 (100%)

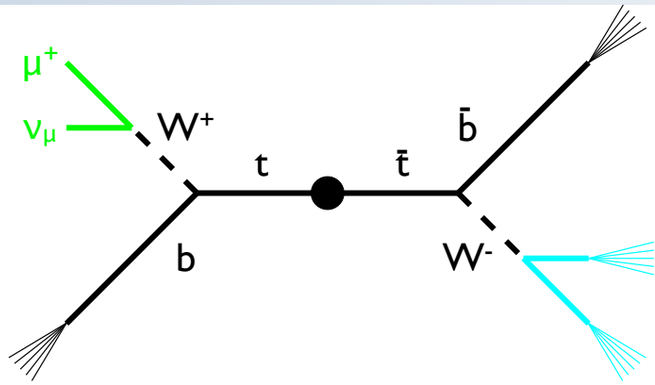


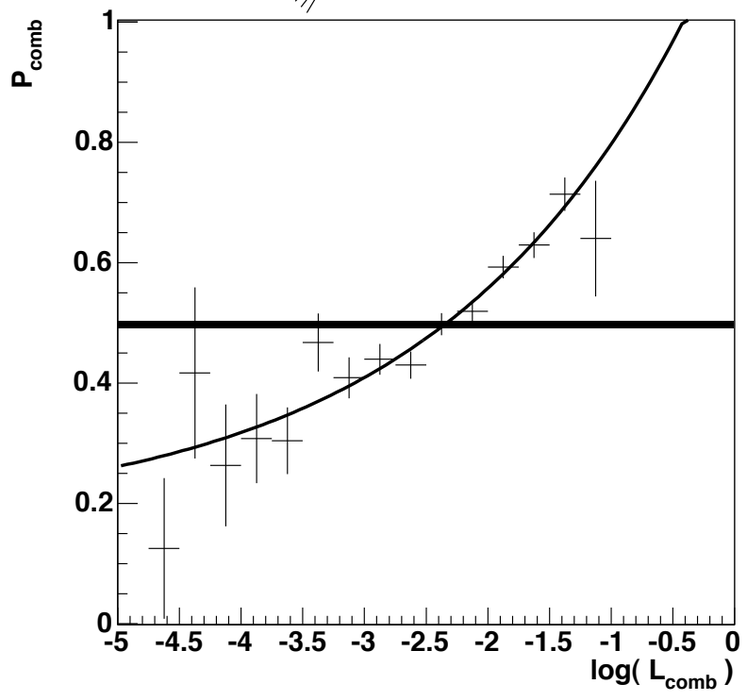
- adapt source code to (new) CMS-software framework
  - implement $t\bar{t}$-selection (lepton+jets) from mass determination
  - add photon selection according to generator studies
  - add kinematic constraints including photon-momentum to selection
- check if generator results also apply for detector-simulated events
- reanalysis of a $t\bar{t}\gamma$ dataset with modified top-QED-couplings
  - try to distinguish between scenarios
  - distribution-generator for modified top-QED-couplings exists (Baur), but no event-generator

Backup

Semi-Leptonic

- isolated lepton, MET, two b-jets, two light quark jets
- selection
  - single-muon trigger
  - isolated muon with p_T > 20 GeV/c
  - four non-overlapping jets with E_T > 30 GeV, two b-tagged, two anti-b-tagged
  - probability of kinematic fit (M_W constraint) P_{χ^2} > 0.2
  - likelihood ratio $L_{signal} \rightarrow P_{sign}$ > 0.8
    - p_T of muon candidate
    - p_T of second muon candidate
    - min E_T among four leading jets
  - likelihood ratio $L_{combined} \rightarrow P_{comb}$ > 0.5
    - ∠(b-jet, muon)
    - ∠(b-jet, W)
    - combined electric charge
    - p_T hadronic top

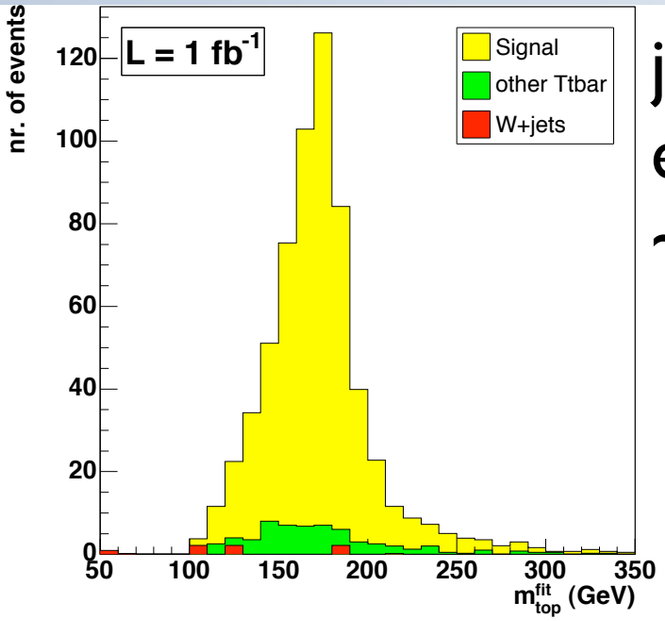




	signal	other $t\bar{t}$	W+4j	Wbb+2j	Wbb+3j	S/B
L1+HLT Trigger	62.2%	5.30%	24.1%	8.35%	8.29%	0.74
4 jets $E_T > 30\,\mathrm{GeV}$	25.4%	1.01%	4.1%	1.48%	3.37%	1.69
$p_T^{\mathrm{lepton}} > 20\,\mathrm{GeV/c}$	24.8%	0.97%	3.9%	1.41%	3.14%	1.72
b-tag criteria	5.5%	0.21%	0.052%	0.47%	0.70%	3.73
No jet overlap	3.0%	0.11%	0.027%	0.25%	0.44%	3.87
P_{χ^2}-cut 20%	1.4%	0.039%	0.0097	0.061	0.07	5.3
P_{sign}-cut 80%	1.2%	0.025%	0.0085	0.052	0.05	6.8
P_{comb}-cut 50%	0.7%	0.013%	0.0036	0.013	0.	8.2
Scaled $\mathcal{L} = 1\,\mathrm{fb}^{-1}$	588	64	6	2	0	8.2

Semi-Leptonic

distribution of the mass of the hadronic decaying top quark for the selected events after applying the kinematic fit imposing M_W constraints



jet pairing efficiency ~ 82%

different mass estimators

	Gaussian Fit	Gaussian Ideogram	Full Scan Ideogram
Bias (GeV/c^2)	-0.84±0.59	-4.35±0.54	-2.58±0.31
Pull	0.82	1.01	1.01
Expected uncertainty for 1fb^{-1} (GeV/c^2)	1.01	1.14	0.66
Expected uncertainty for 10fb^{-1} (GeV/c^2)	0.32	0.36	0.21