Top Mass Measurement at CMS

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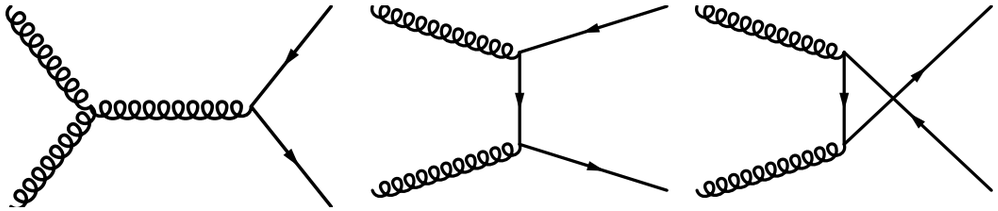
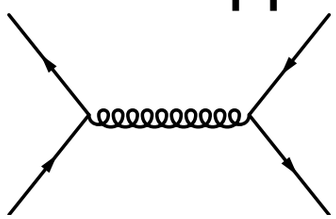
for the
CMS Collaboration

$t\bar{t}$ Physics at LHC

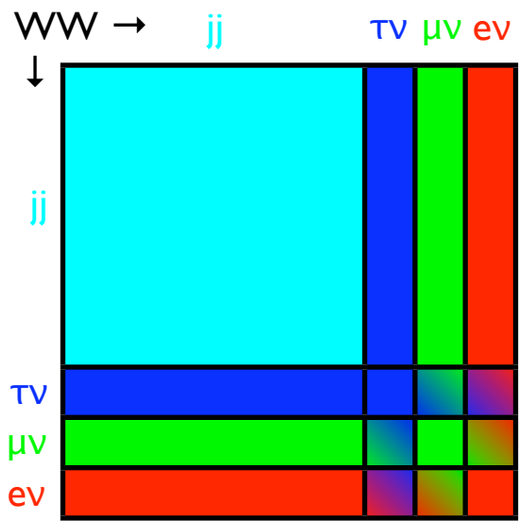
- $\sigma(pp \rightarrow t\bar{t}) \sim 830$ pb (NLO)
- ~90% $gg \rightarrow t\bar{t}$

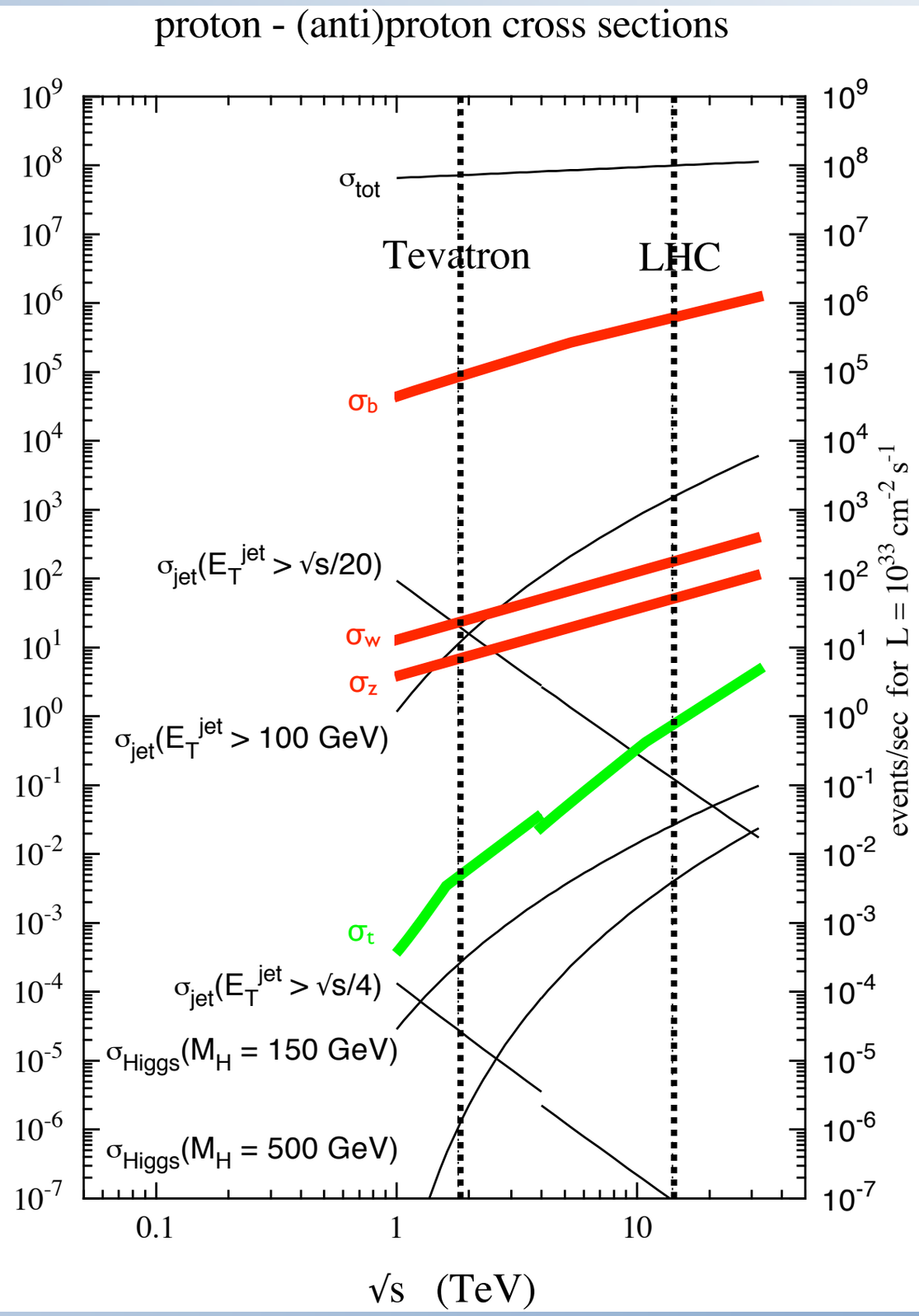


- ~10% $qq' \rightarrow t\bar{t}$



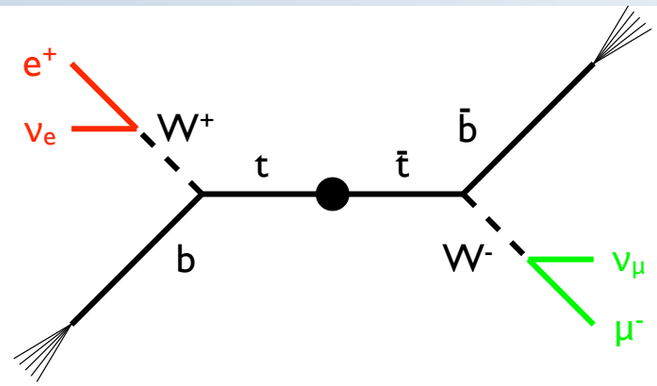
- BR($t \rightarrow bW$) ~100%
- BR($W \rightarrow qq$) ~67%
- BR($W \rightarrow l\nu$) ~11% for each $l = e, \mu, \tau$

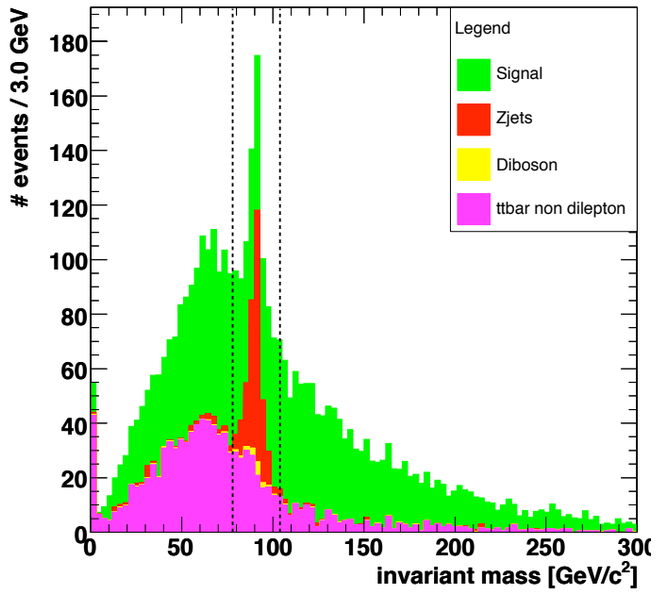




Di-Leptonic

- 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





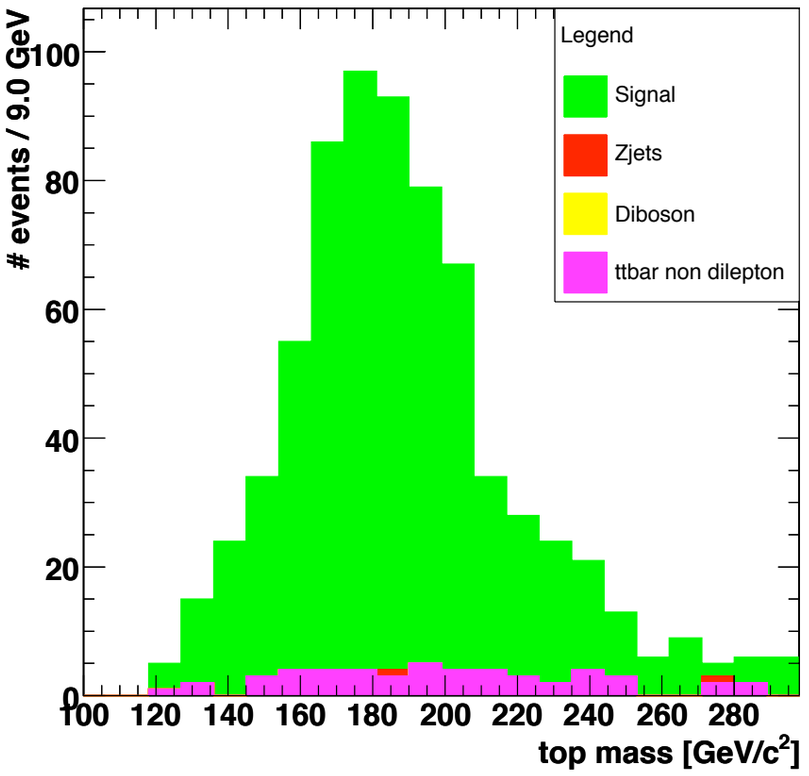
- selection
  - single and di-lepton trigger
  - two isolated opposite-sign leptons with p_T > 20 GeV/c
  - for two same-flavour leptons remove Z mass peak
  - two b-jets with p_T > 30 GeV/c
  - MET > 40 GeV

	$t\bar{t}$ 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

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



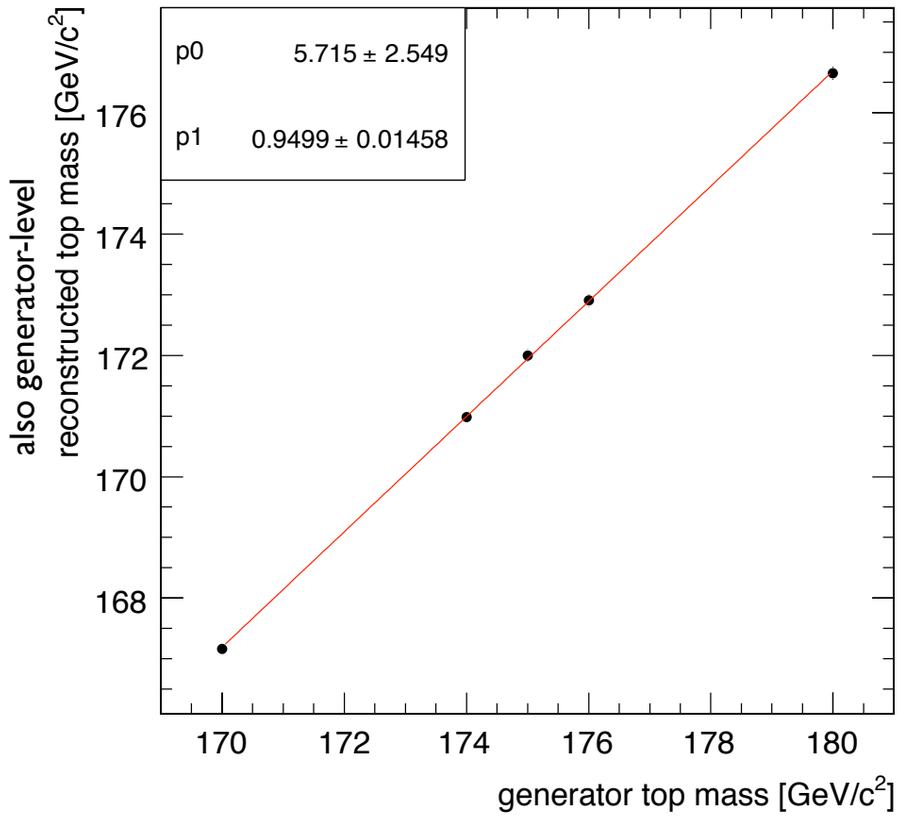
- written as a 4th order polynomial with m_t as parameter

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

- 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

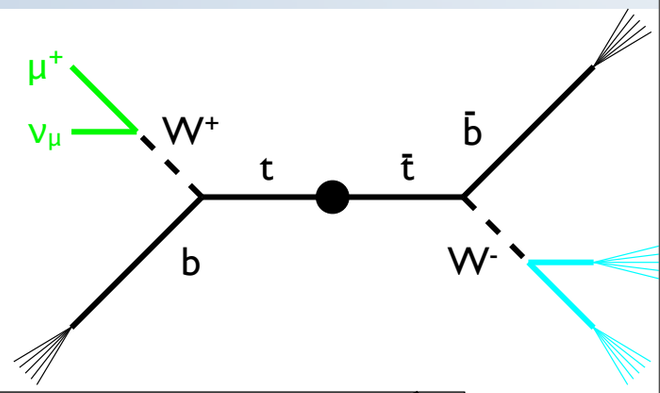
$\Delta m_t = \pm 1.5\ (\mathrm{stat.}) \pm 2.9\ (\mathrm{syst.})\ \mathrm{GeV}/c^2$

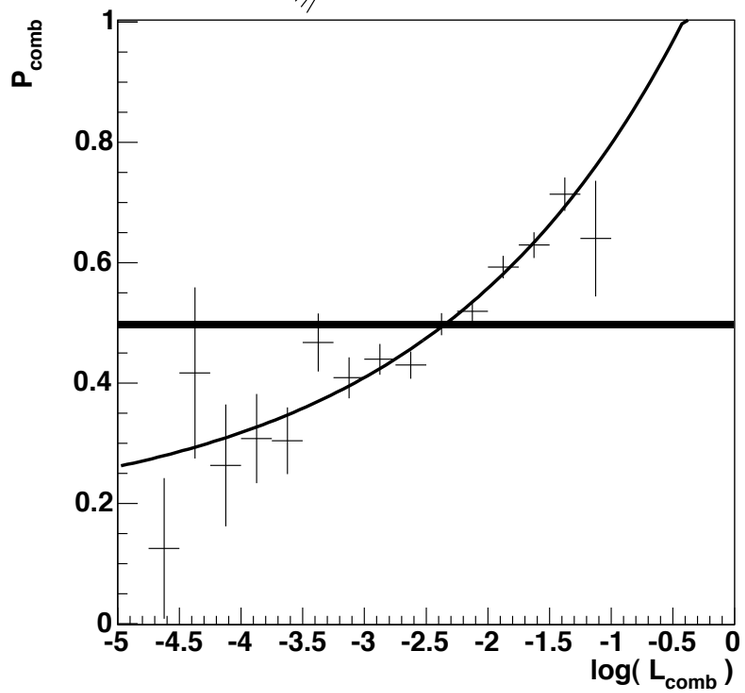
improves with 10/fb of well-understood data to

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

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

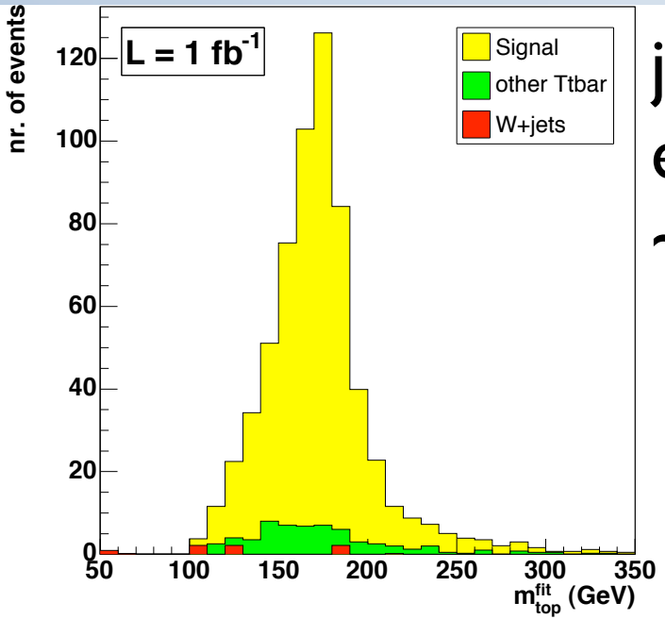




	signal	other $t\bar{t}$	W+4j	Wbb+2j	Wbb+3j	S/B
L1+HLT Trigger	62.2%	5.30%	24.1%	8.35%	8.29%	0.74
4 jets $E_T > 30\,\mathrm{GeV}$	25.4%	1.01%	4.1%	1.48%	3.37%	1.69
$p_T^{\mathrm{lepton}} > 20\,\mathrm{GeV/c}$	24.8%	0.97%	3.9%	1.41%	3.14%	1.72
b-tag criteria	5.5%	0.21%	0.052%	0.47%	0.70%	3.73
No jet overlap	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

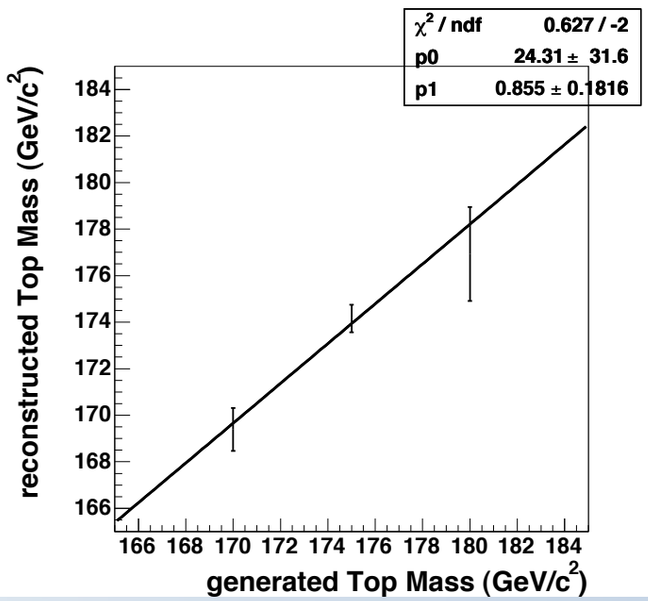
distribution of the mass of the hadronic decaying top quark for the selected events after applying the kinematic fit imposing M_W constraints

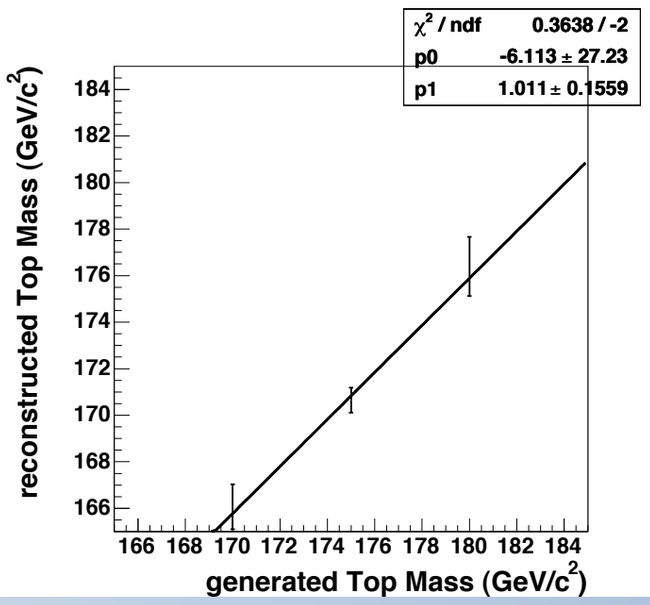


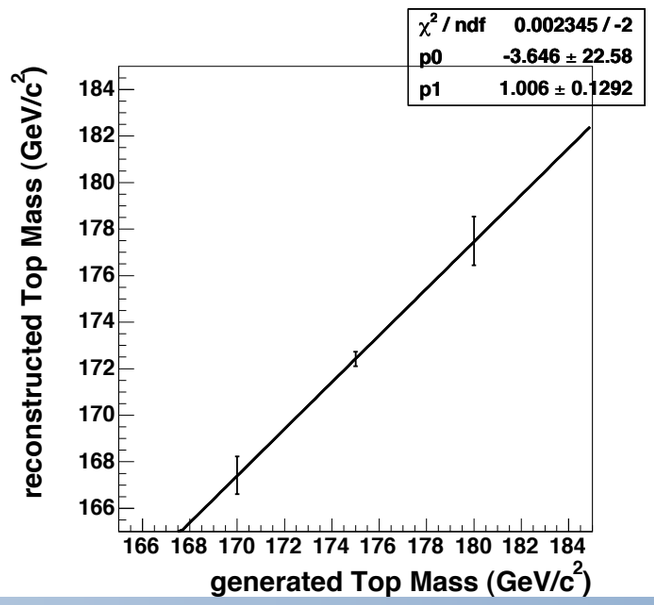
jet pairing efficiency ~ 82%

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







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

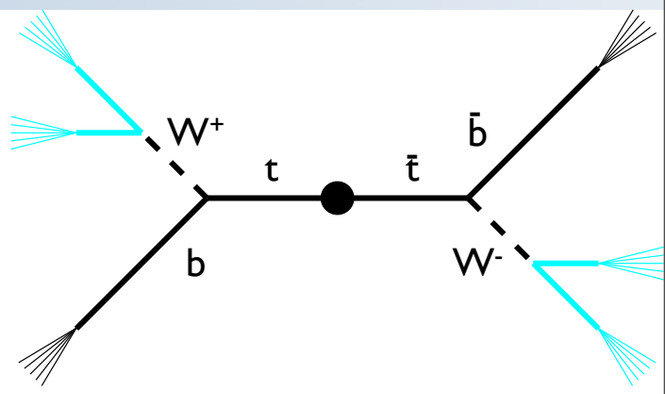
- pileup →1/6
- b-jet energy scale 2%→1.5%
- b-tagging 5%→2%

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

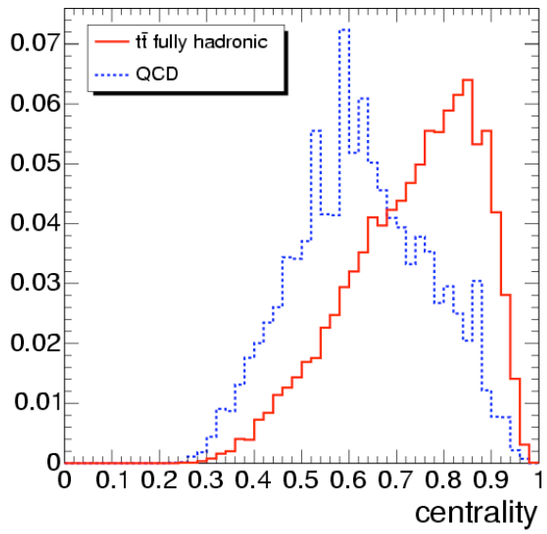
± 1.1 (syst.) GeV/c^2

	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

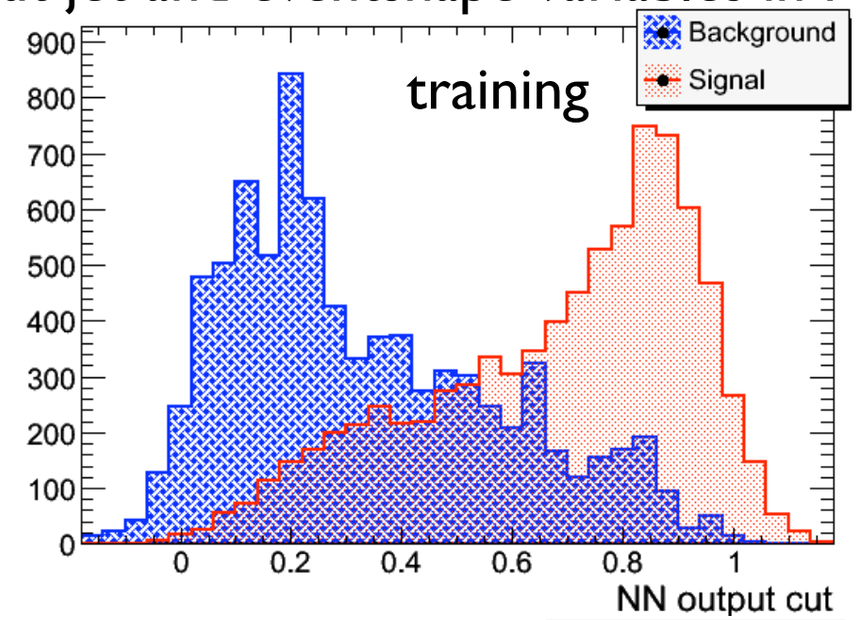


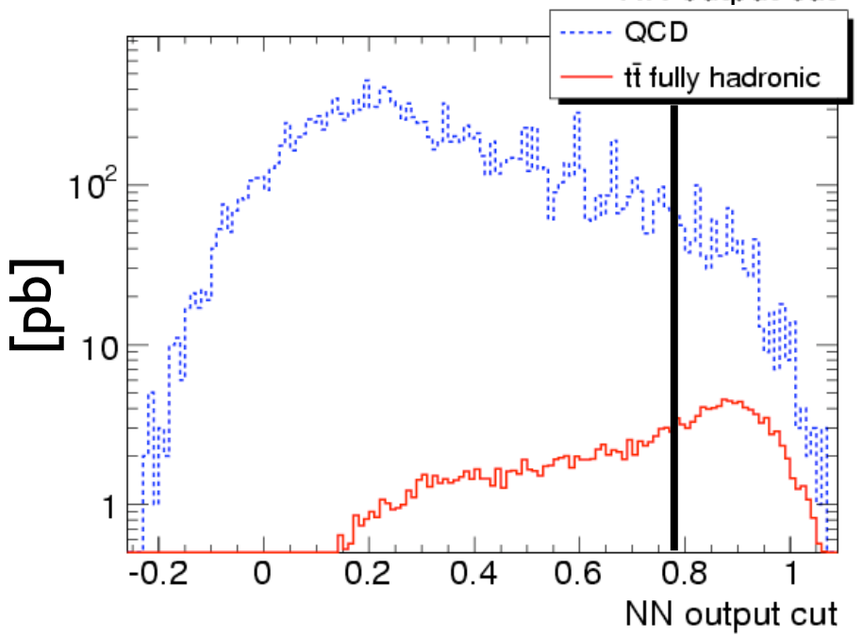
Selection	Requirement	$\sigma\epsilon$ [pb]	$\sigma\epsilon_{\mathrm{QCD}}$ [pb]	S/B
Before Selection (PYTHIA LO)		225	25M	$1/10^5$
Trigger	HLT multi-jet+b-jet	38	11600	1/300
Event	$6 \leq N_{\mathrm{jet}} \leq 8$	35	7900	1/225
	$E_{\mathrm{T}} \geq 30\,\mathrm{GeV}$	15	930	1/60
	centrality ≥ 0.68	9.9	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

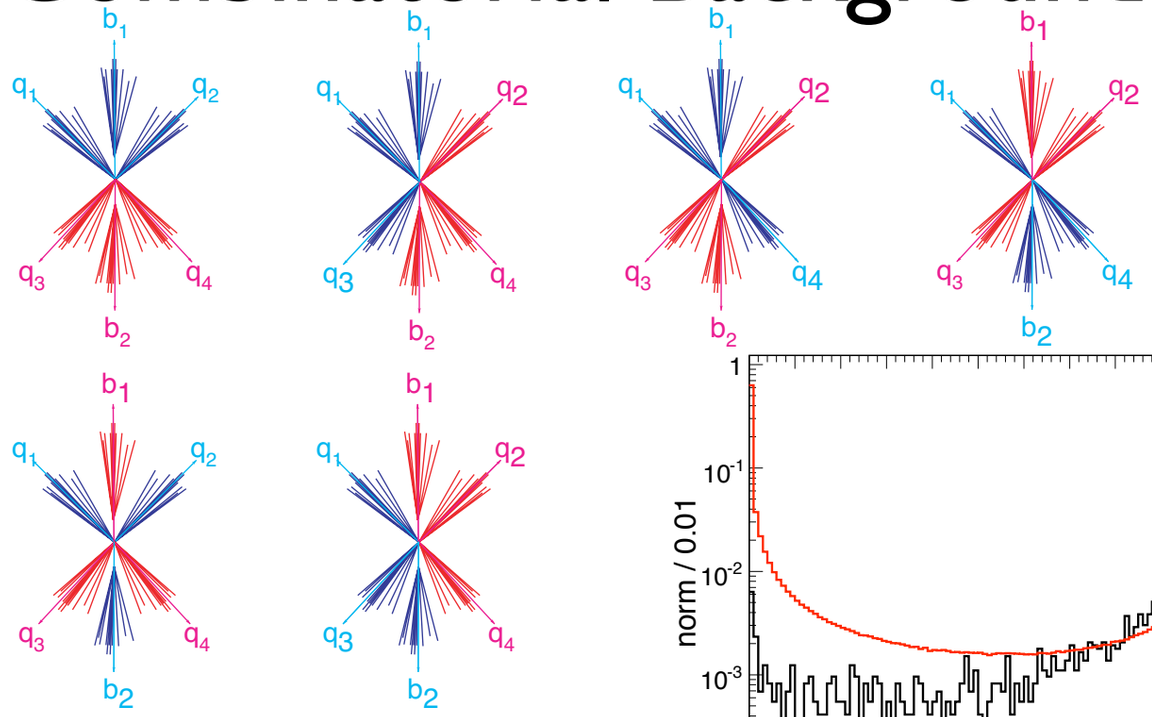
put jet and eventshape variables in NN





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

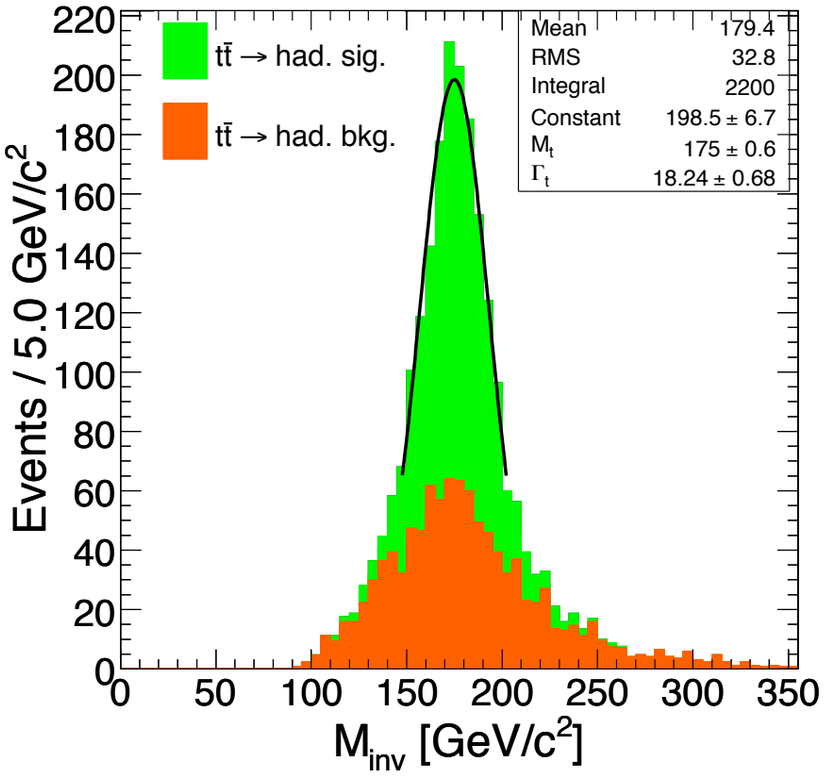


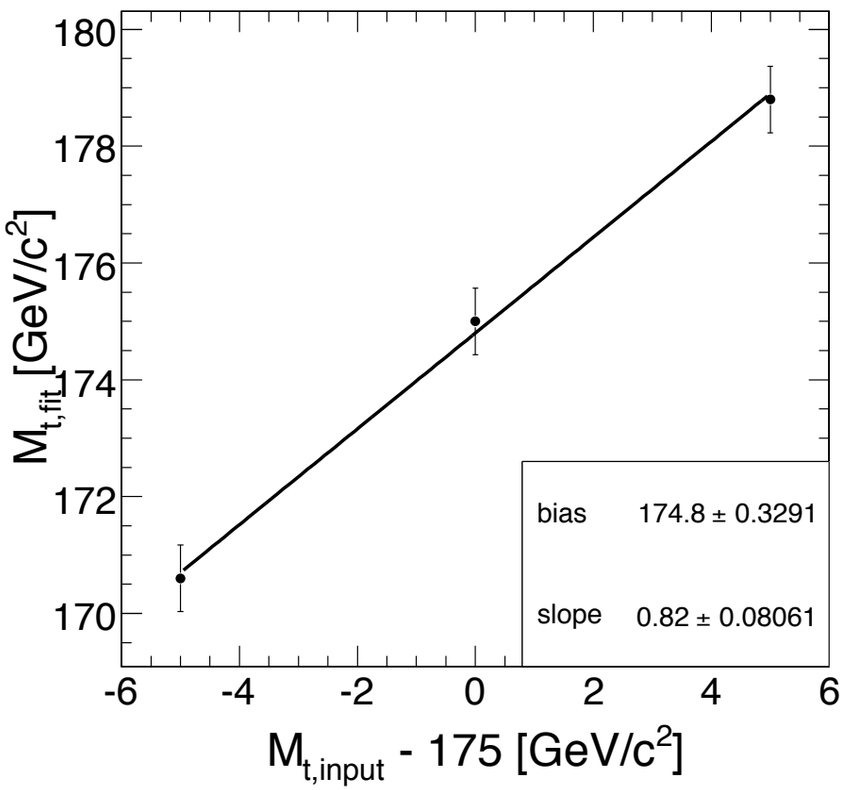
Likelihood Pairing Function

- 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





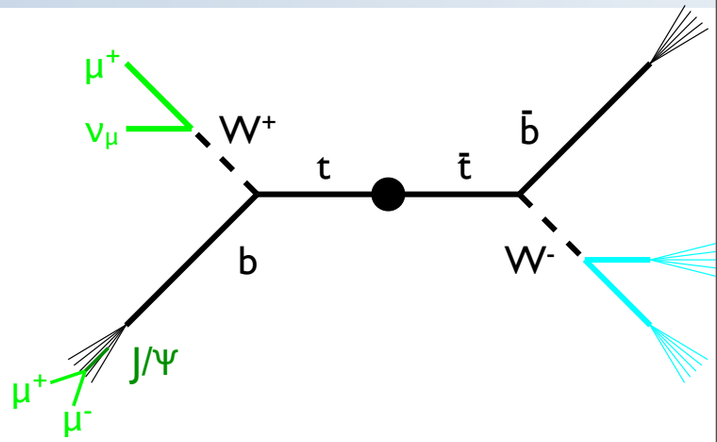
	$\Delta m_t[\ \mathrm{GeV}/c^2]$
Pile Up	0.4
Underlying Event	0.6
PDF	1.4
IS/FS Radiation	2.3
Fragmentation	0.9
Jet Energy Scale	2.3
b-Tagging	0.3
Background	2.0

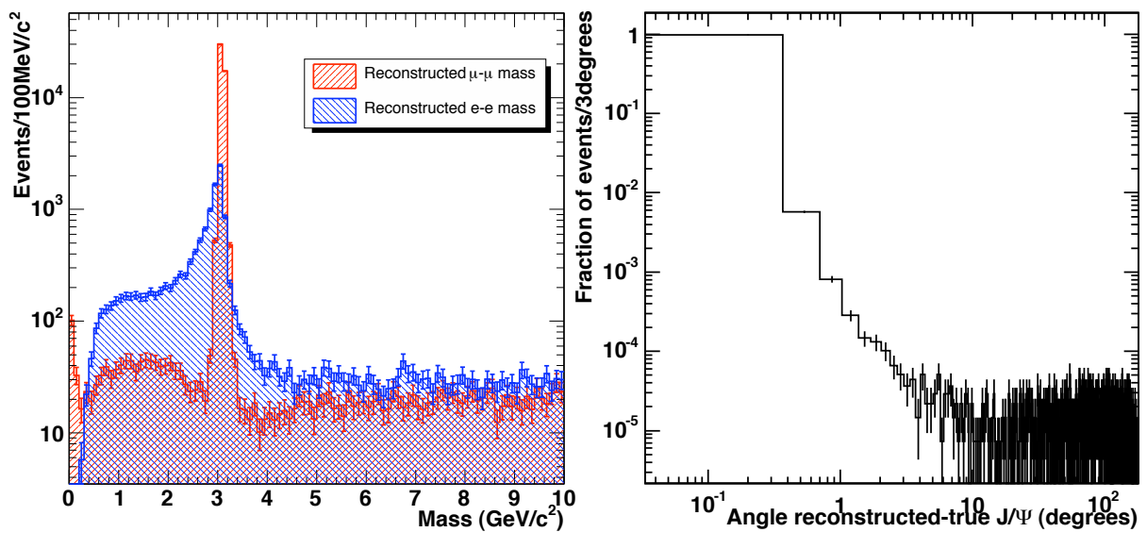
systematic uncertainties

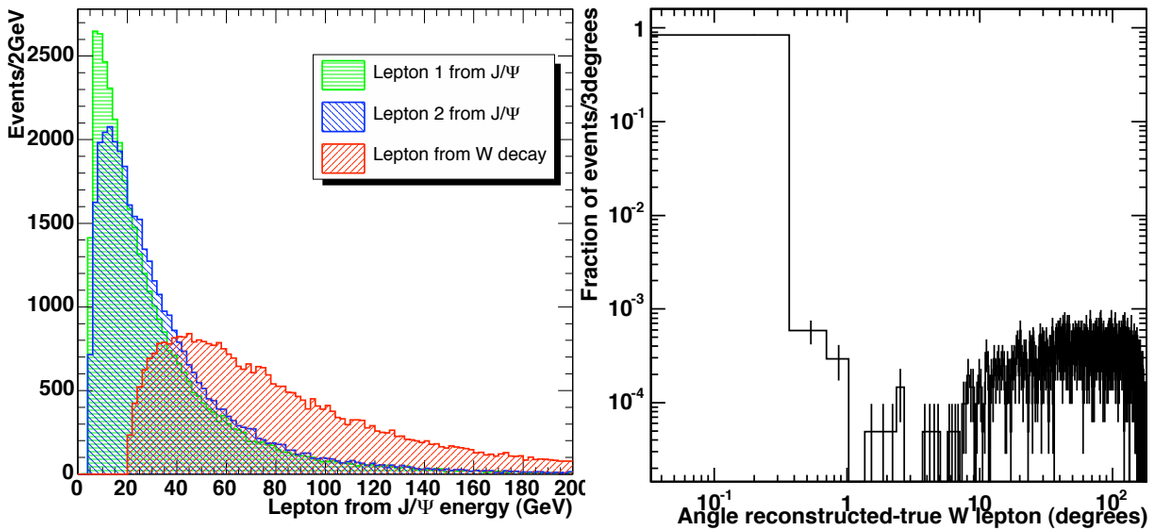
- S/B ~ 2/3, although not enough simulated QCD events (yet) to determine background shape
- for 1/fb already systematics dominated
- $\Delta m_t = \pm 0.6\ (\mathrm{stat.}) \pm 4.2\ (\mathrm{syst.})\ \mathrm{GeV}/c^2$

J/Ψ

- very clean experimental reconstruction
- no b-tagging used, limited use of jet energy
- extremely low branching ratio of the final state
  ~ $5.5 \cdot 10^{-4}$, ~ 4500 events per 10/fb
- selection
  - inclusive lepton trigger
  - same-flavour, opposite-sign leptons with $2.8 < m_{ll} < 3.2$ GeV/c^2 and $2° < \angle(l,l) < 35°$, considered J/Ψ candidate
  - isolated, highest p_T lepton with $p_T > 40$ GeV/c, considered lepton candidate from W from same t
  - only one isolated lepton: $\sum p_{T,jets} > 100$ GeV/c
  - for two isolated same-flavour leptons remove $85 < m_{ll} < 97$ GeV/c^2







J/Ψ

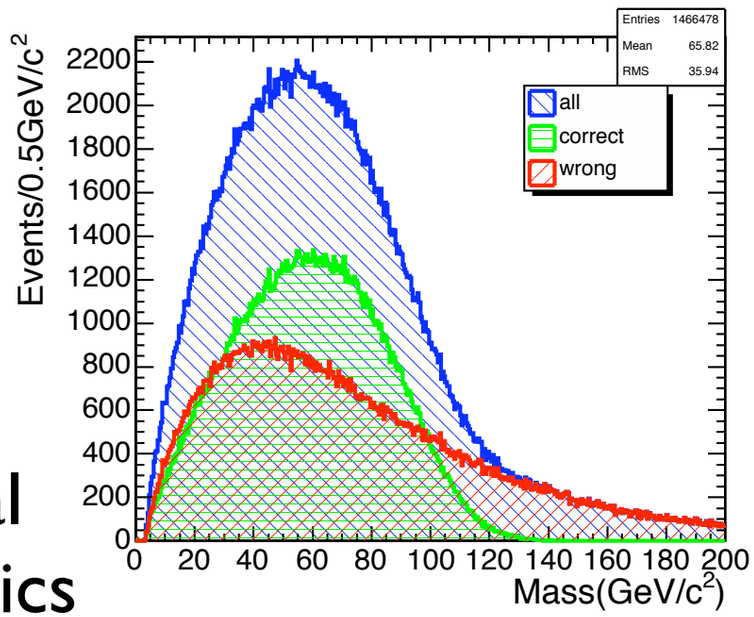
Channel	BR·σ (fb)	ϵ_{trig} (%)	ϵ_{sel} (%)	Events in 10 fb^{-1}	Class
$t\bar{t} \to (b \to J/\Psi)\ell\nu - b\ell\nu$	107	93.9	15.7±0.4	158	S+C
$t\bar{t} \to (b \to J/\Psi)\ell\nu - b\tau\nu$	53	61.1	11.0±0.8	36	S
$t\bar{t} \to (b \to J/\Psi)\ell\nu - bqq$	320	55.3	10.9±0.3	193	S
$t\bar{t} \to (b \to J/\Psi)\tau\nu - b\ell\nu$	53	61.1	10.6±0.8	34	C
$t\bar{t} \to (b \to J/\Psi)\tau\nu - b\tau\nu$	27	14.2	2.8±1.2	1	B
$t\bar{t} \to (b \to J/\Psi)\tau\nu - bqq$	160	7.9	1.5±0.5	2	B
$t\bar{t} \to (b \to J/\Psi)qq - b\ell\nu$	320	55.3	10.7±0.3	190	C
$t\bar{t} \to (b \to J/\Psi)qq - b\tau\nu$	160	7.9	1.5±0.5	2	B
$t\bar{t} \to (b \to J/\Psi)qq - bqq$	959	0.1	0.2±0.5	0	B
$W + N$ jets, $N > 1 \to J/\Psi X$	394	55.3	2.1±0.1	43	B
$Wb\bar{b} + \text{jets} \to J/\Psi X$	196	55.3	1.6±0.1	16	B
$Zb\bar{b} + \text{jets} \to J/\Psi X$	23	93.9	9.4±0.1	20	B
$b\bar{b} \to J/\Psi X$	$1.3{\cdot}10^{9}$	$<2{\cdot}10^{-8}$	<1	<2.6	B

signal TOPREX with high luminosity minbias

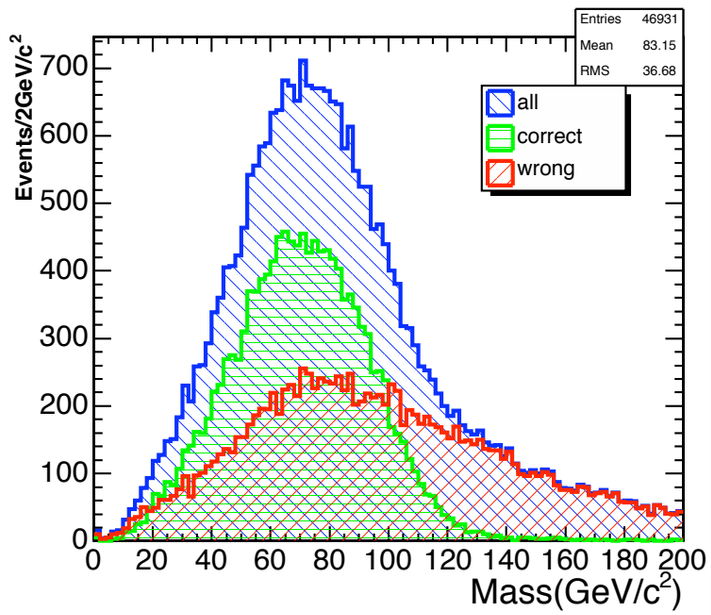
background ALPGEN

S signal
C combinatorial
B physics background

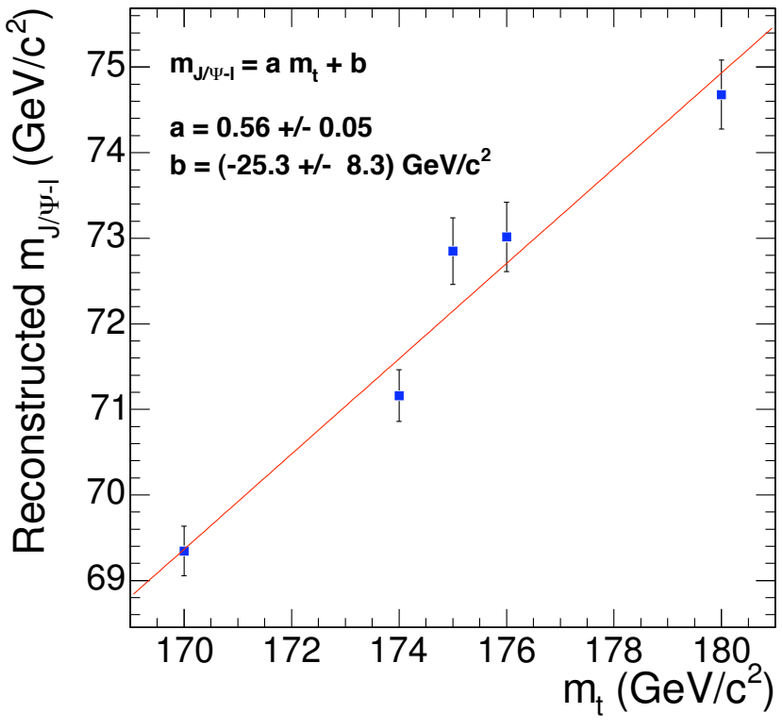
- $m_{J/\Psi-l}$ distributions fitted with quartic polynomial to extract maximum, which is most sensitive to the top mass
- no separation of combinatorial background to increase statistics

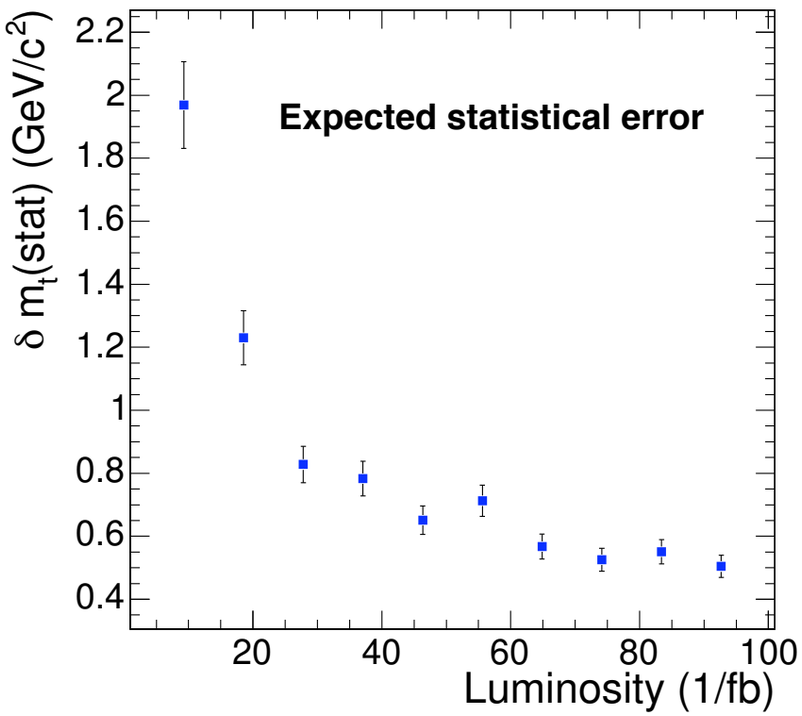


$m_{J/\Psi-l}$ generator-level



$m_{J/\Psi-l}$ full detector simulation





Source	δm_t(GeV/c^2)
Λ_{QCD}	0.31
Q^2	0.56
Scale definition	0.71
b-quark fragmentation	0.51
Light jet fragmentation	0.46
Minimum bias/Underlying event	0.64
Proton PDF	0.28
Total theoretical	1.37
Electron E scale	0.21
Muon p scale	0.38
Electron E resolution	0.19
Muon p resolution	0.12
Jet E scale	0.05
Jet E resolution	0.05
Background knowledge	0.21
Total experimental	0.54
Total systematic	1.47

- for 20/fb already systematics dominated
- $\Delta m_t = \pm 1.2$ (stat.) ± 1.5 (syst.) GeV/c^2

Summary

Top Mass Measurement at CMS

Δm_t(di-leptonic, 1/fb) = ± 1.5 (stat.) ± 2.9 (syst.) GeV/c^2

Δm_t(semi-leptonic, 1/fb) = ± 0.7 (stat.) ± 1.9 (syst.) GeV/c^2

Δm_t(fully hadronic, 1/fb) = ± 0.6 (stat.) ± 4.2 (syst.) GeV/c^2

Δm_t(di-leptonic, 10/fb) = ± 0.5 (stat.) ± 1.1 (syst.) GeV/c^2

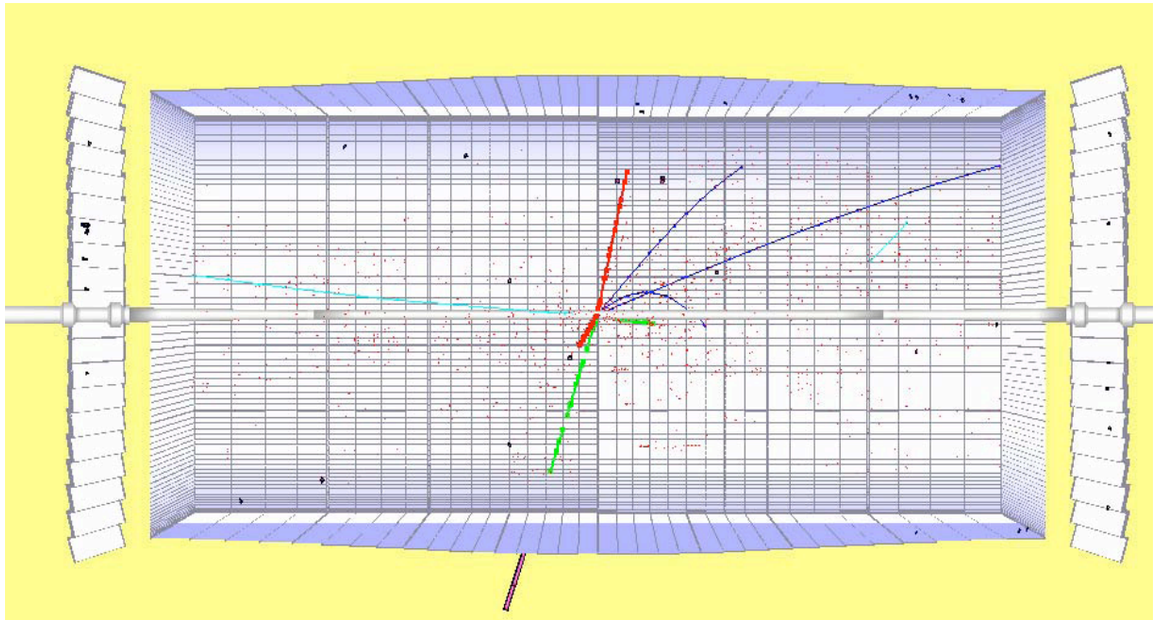
Δm_t(semi-leptonic, 10/fb) = ± 0.2 (stat.) ± 1.1 (syst.) GeV/c^2

Δm_t(J/Ψ, 20/fb) = ± 1.2 (stat.) ± 1.5 (syst.) GeV/c^2

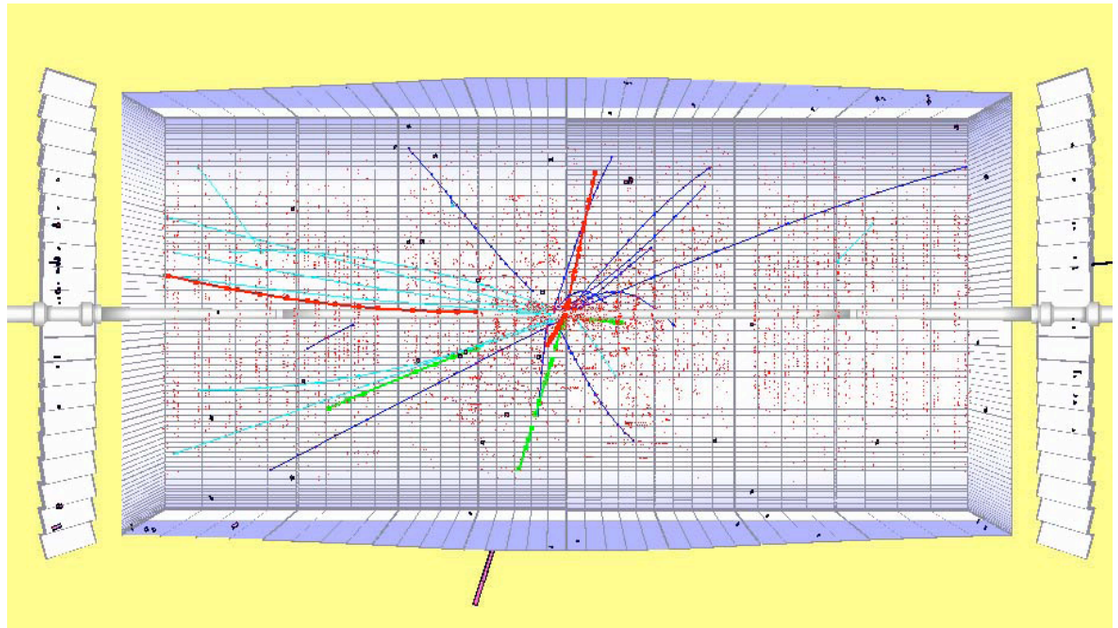
top mass accuracy of O(1 GeV/c^2)
for 10-20/fb of well-understood data

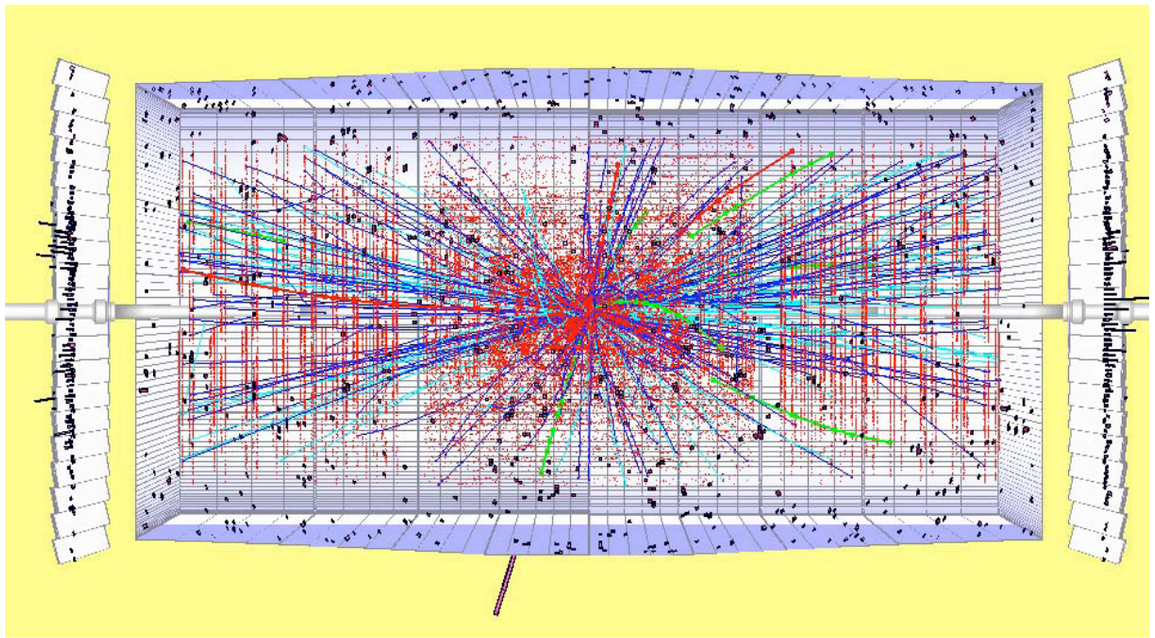
Pileup

$L = 10^{32} cm^{-2} s^{-1}$, 0 MBE

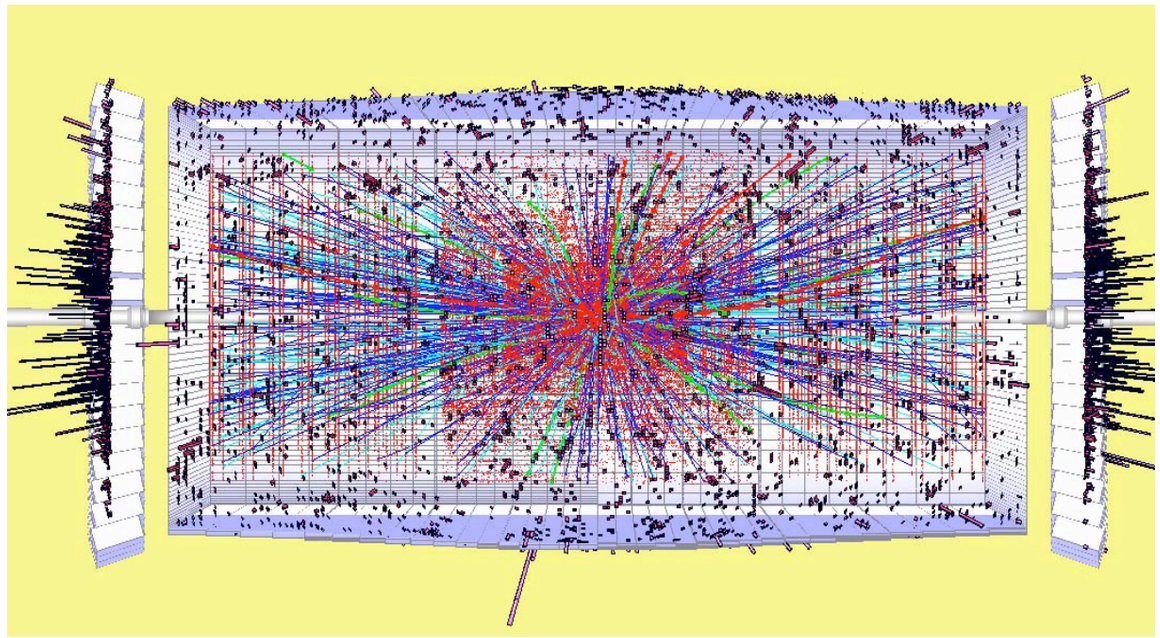


$L = 10^{33} cm^{-2} s^{-1}$, ~2 MBE



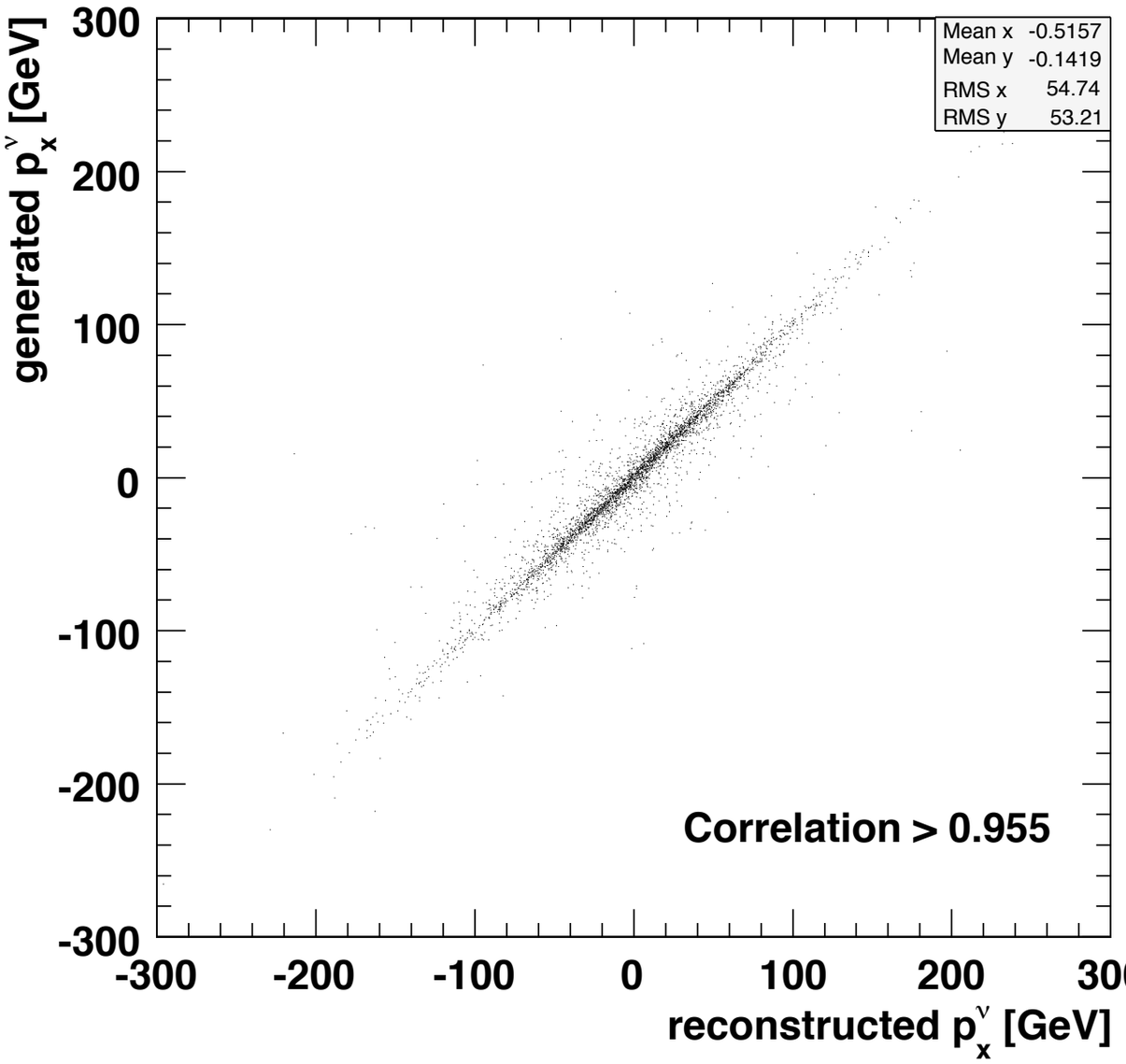


$L = 10^{34} cm^{-2} s^{-1}$, ~20 MBE



$L = 10^{35} cm^{-2} s^{-1}$, ~200 MBE

Di-Lepton Method



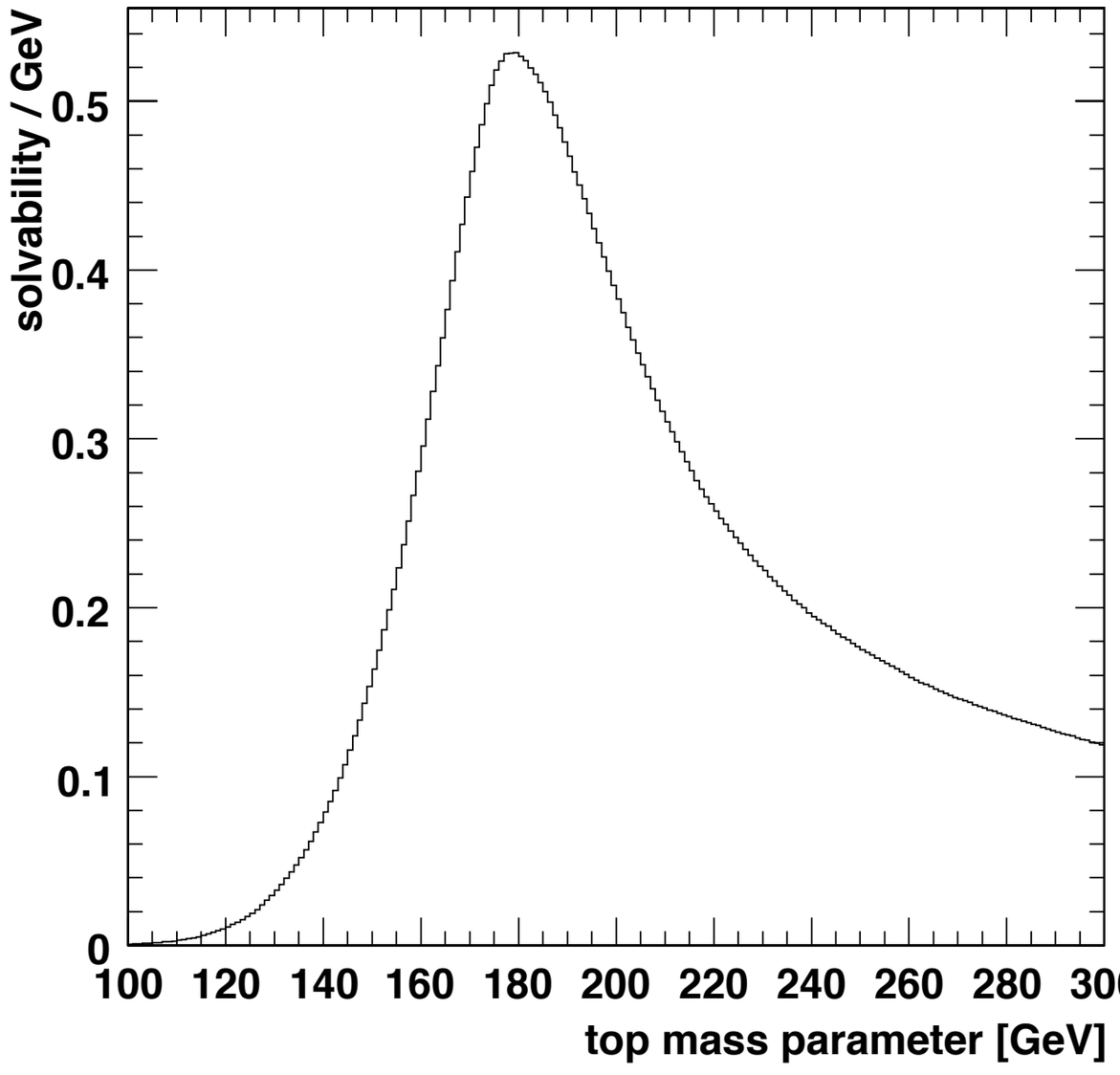
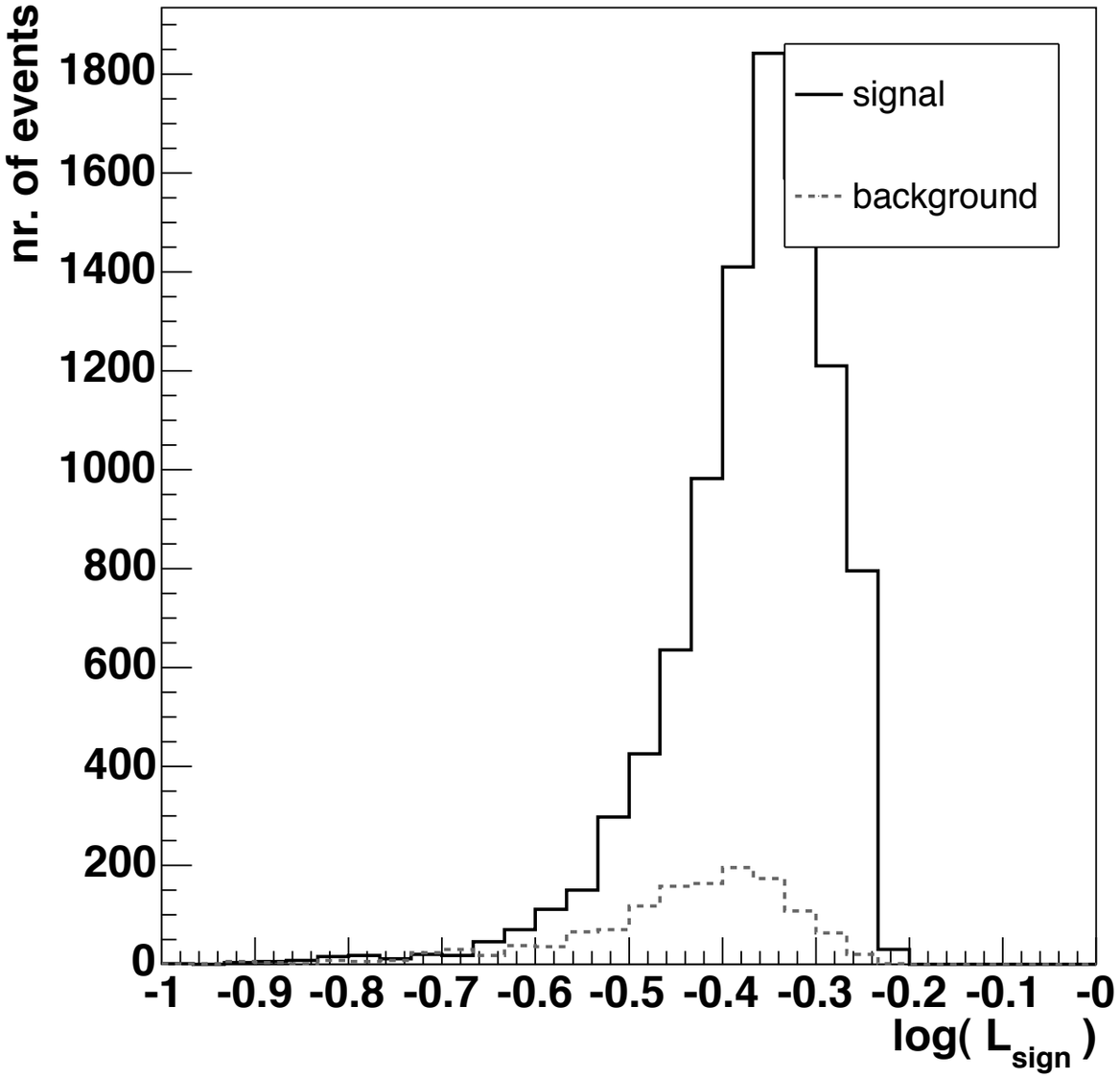
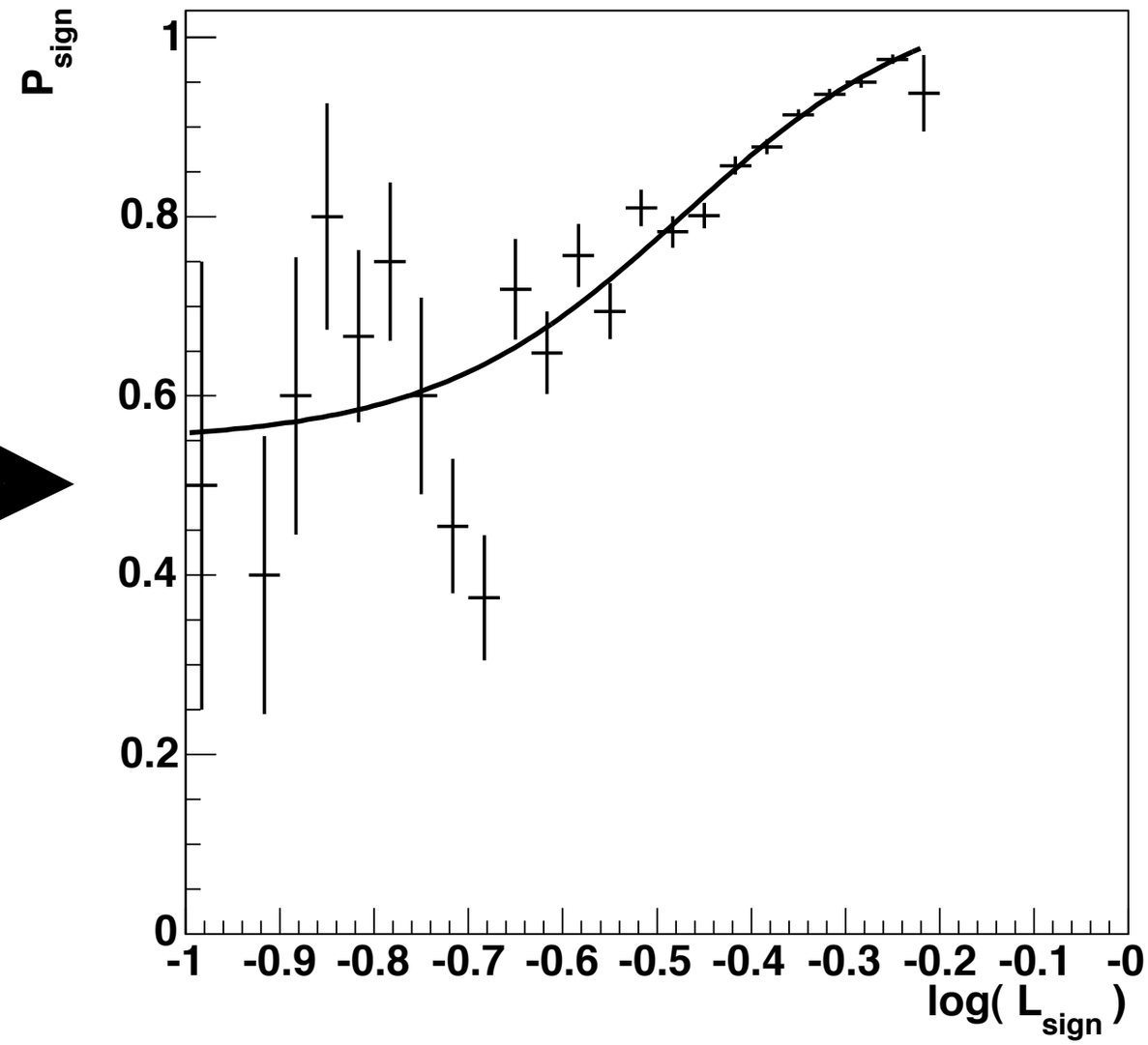


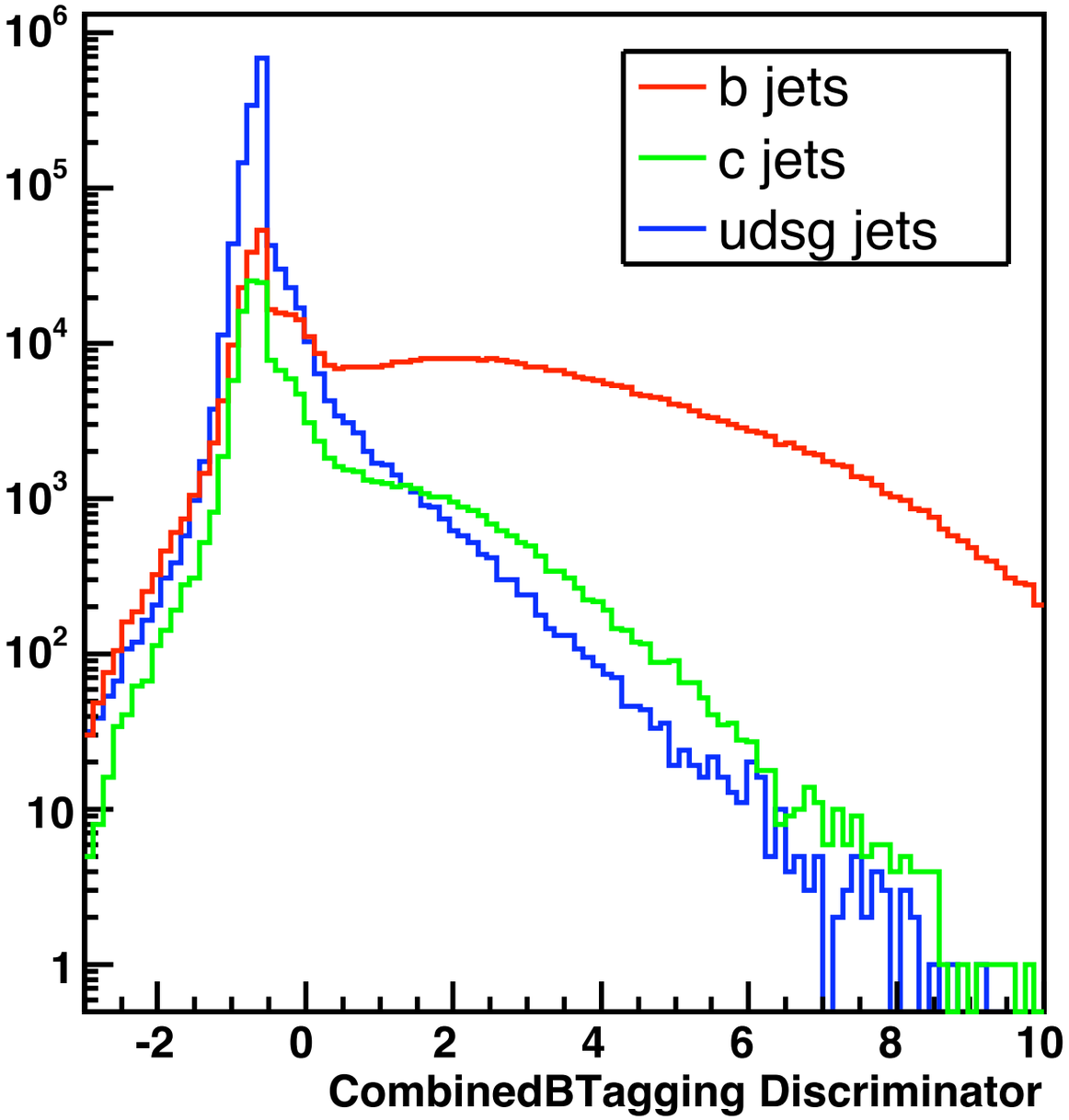
Figure 4: Left: generated neutrino p_x versus reconstructed neutrino p_x. Right: Solvability of the kinematic equation system (both plots use generator level data with $m_t = 175\ \mathrm{GeV}/c^2$).

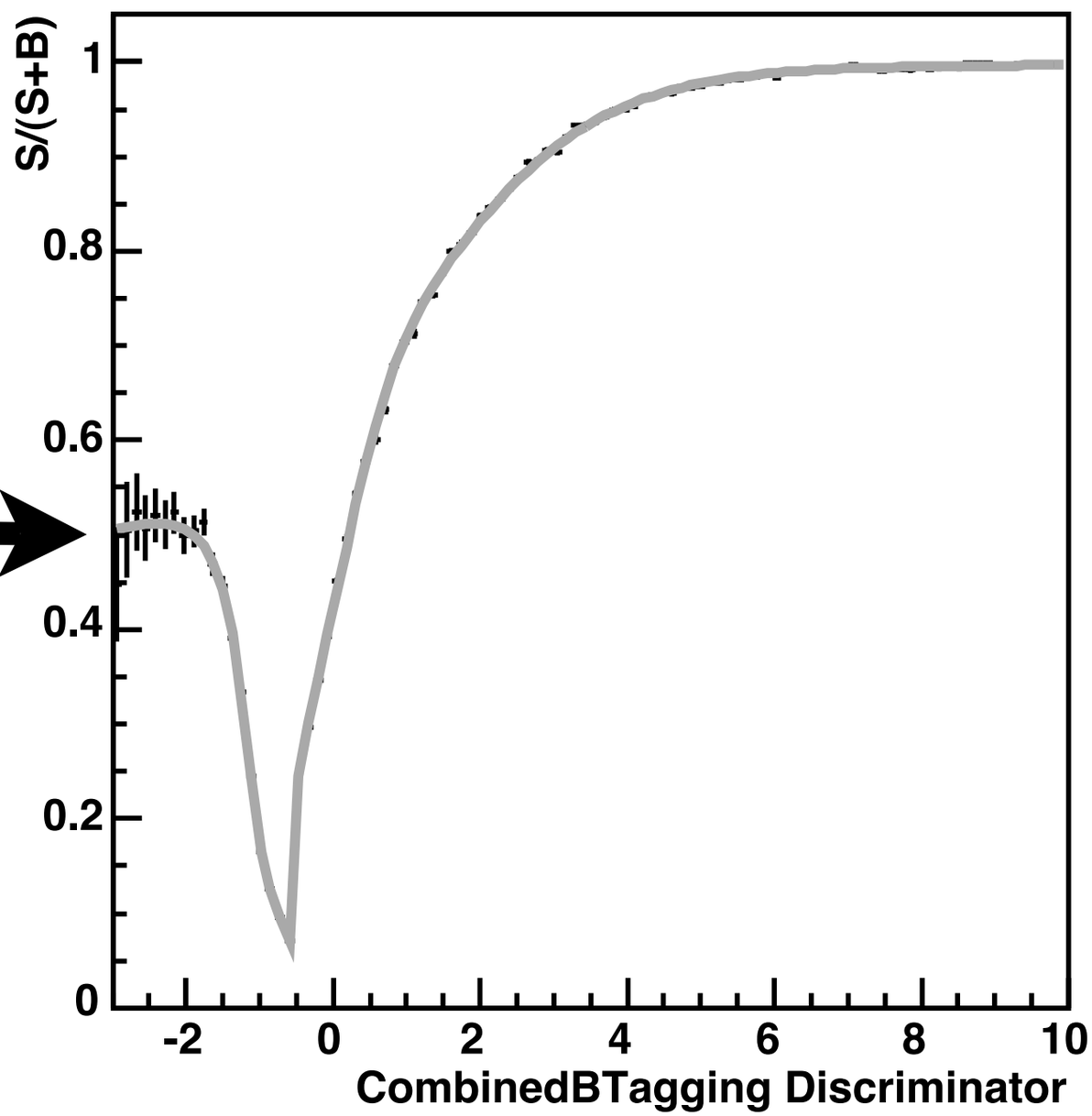
Likelihood Ratio





b-Tagging





combined b-tag discriminant for jets in semi-leptonic
$t\bar{t}$ events originating from different flavoured quarks