Top Quark Prospects at LHCb

By Henry Brown

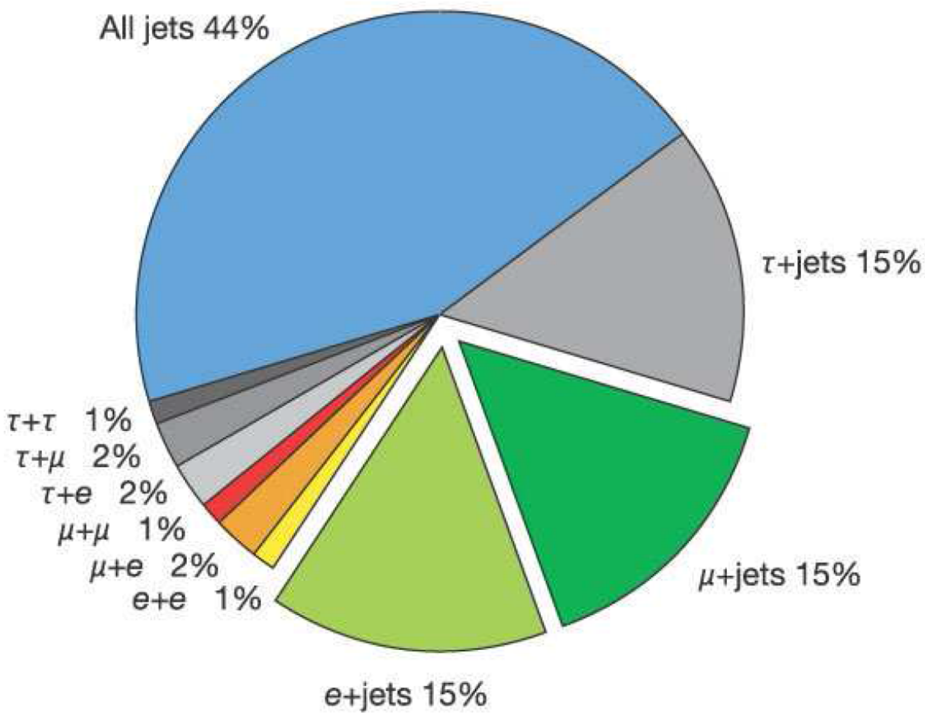
Top Overview

Top Quark Introduction

- Heaviest fundamental particle discovered
  - Mass of ~173 GeV/c^2
  - Decay width Γ=1 GeV > Λ_{QCD} (200 MeV)
    - Decays before hadronization
    - Lifetime ~0.5x10^{-24} s
  - σ @ 8 TeV = 234 $\pm$ 15 pb (NNLO)
    - 14 TeV increases to nearly 1 nb
  - LHC dominated by gluon fusion (85%)
    - Tevatron dominated by $\bar{q}q$ annihilation

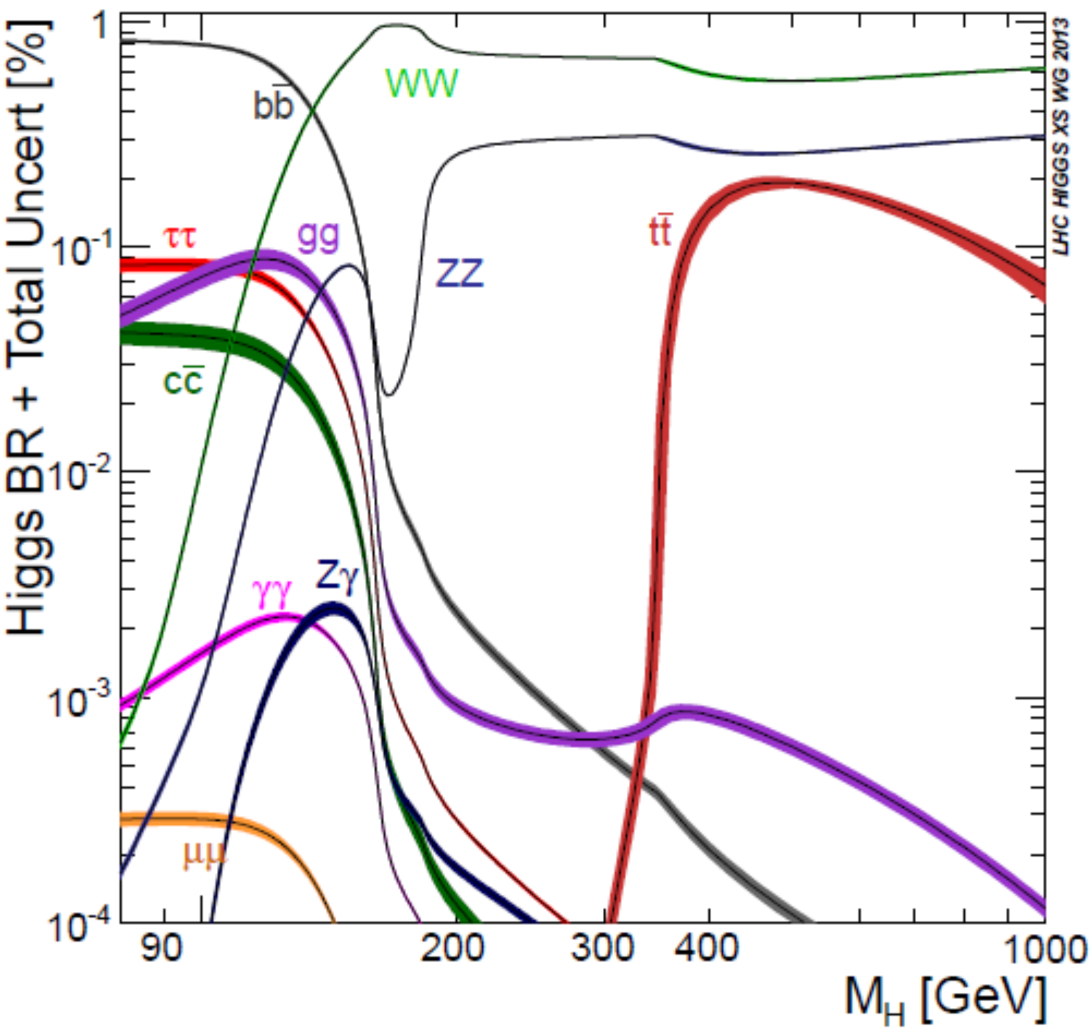
Decay Modes of Top

- CKM matrix means 99.9% of decays are t→Wb
  - Top decays described in terms of W decay modes then
    - All hadronic = W→$\overline{qq}$' resulting in 4 jets + 2 *b*-jets
    - Semileptonic = W→μν + W→q$\bar{q}$'
    - Leptonic = WW→*ll*νν (*l*=μ,e)



Higgs

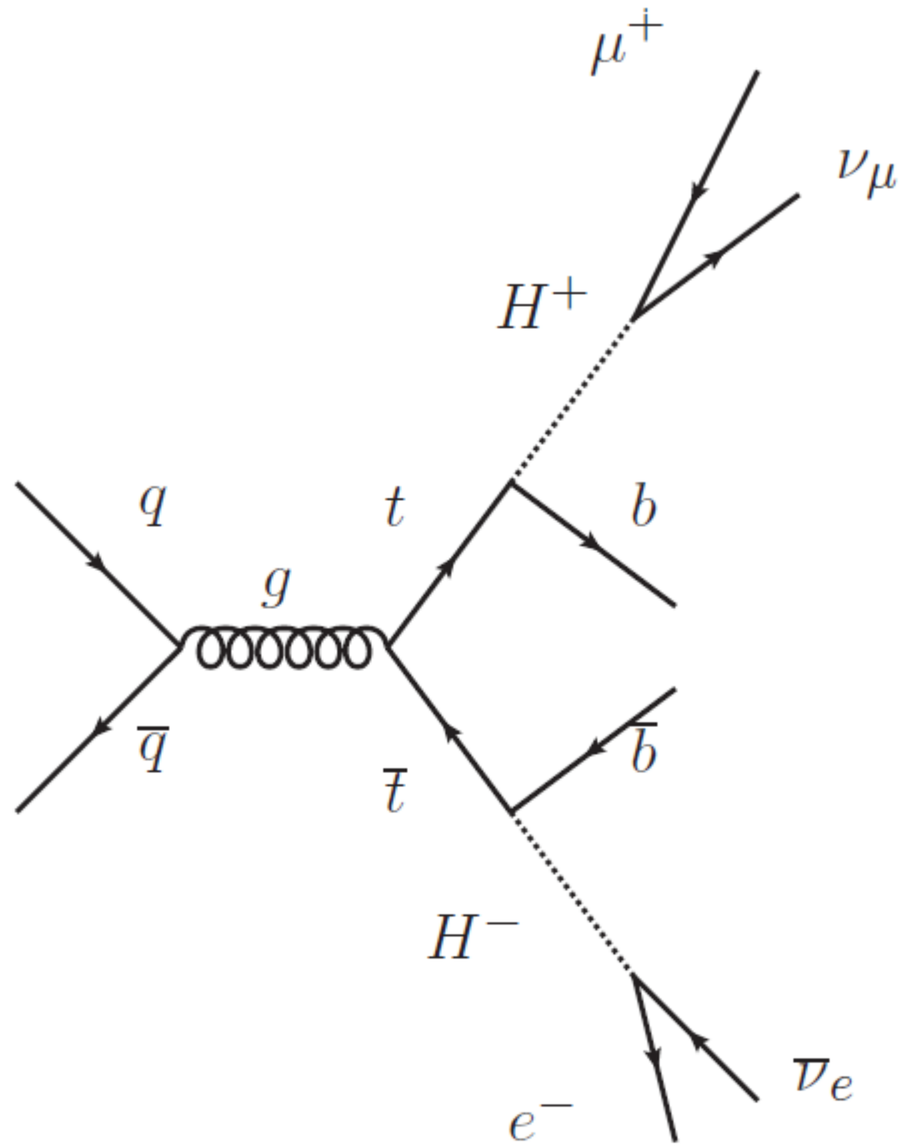
- High mass ($2xm_{top}$) Higgs couples strongly to top quarks



BSM Decays?

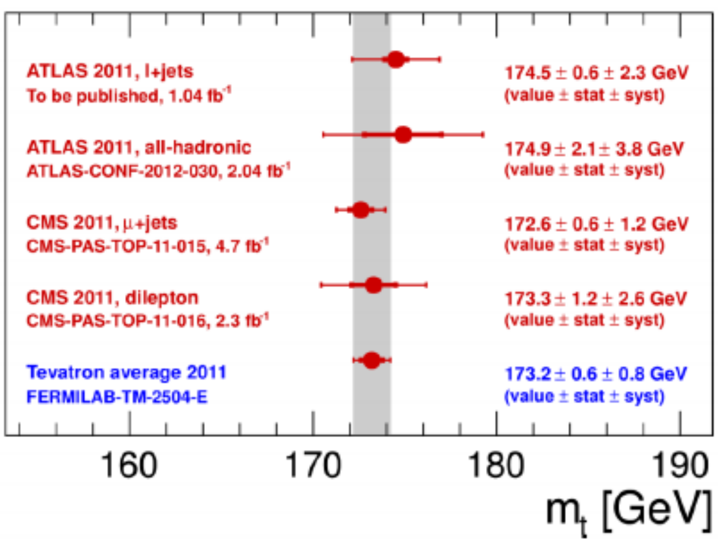
- Potential BSM decay modes as well
  - High mass – high coupling to Higgs
- Light charged Higgs instead of a W?

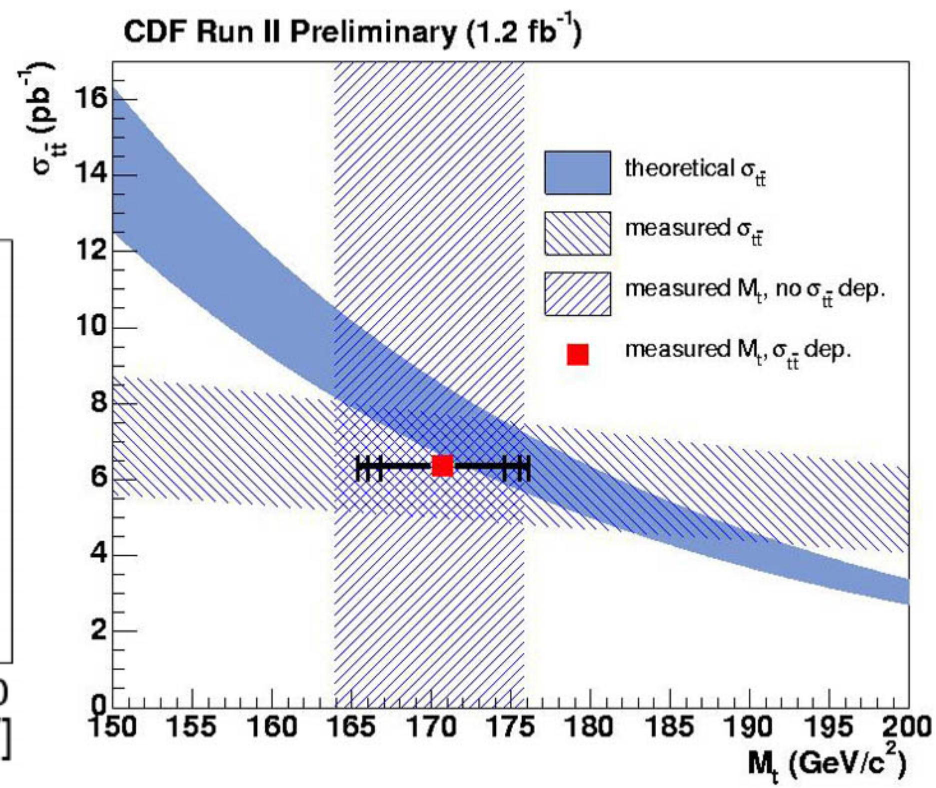
- Further reading: M. Hashemi, arXiv:hep-ph/1305.2096



Top Mass

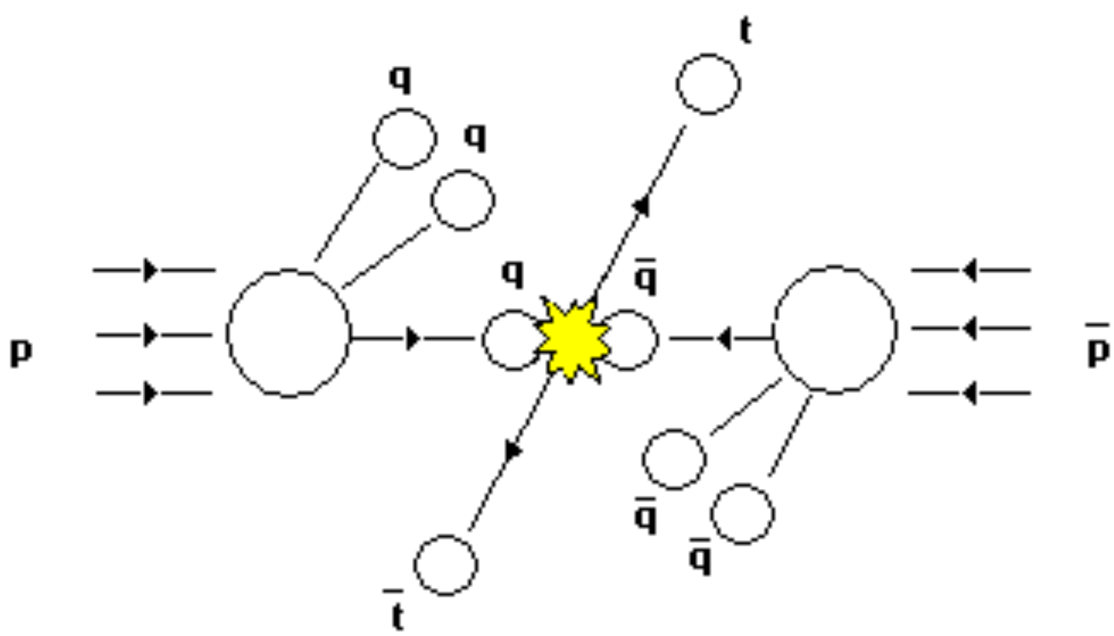
- Top cross-section is sensitive to the mass
- Free parameter of the SM
- Direct and indirect determinations of mass [Not covered in depth here]





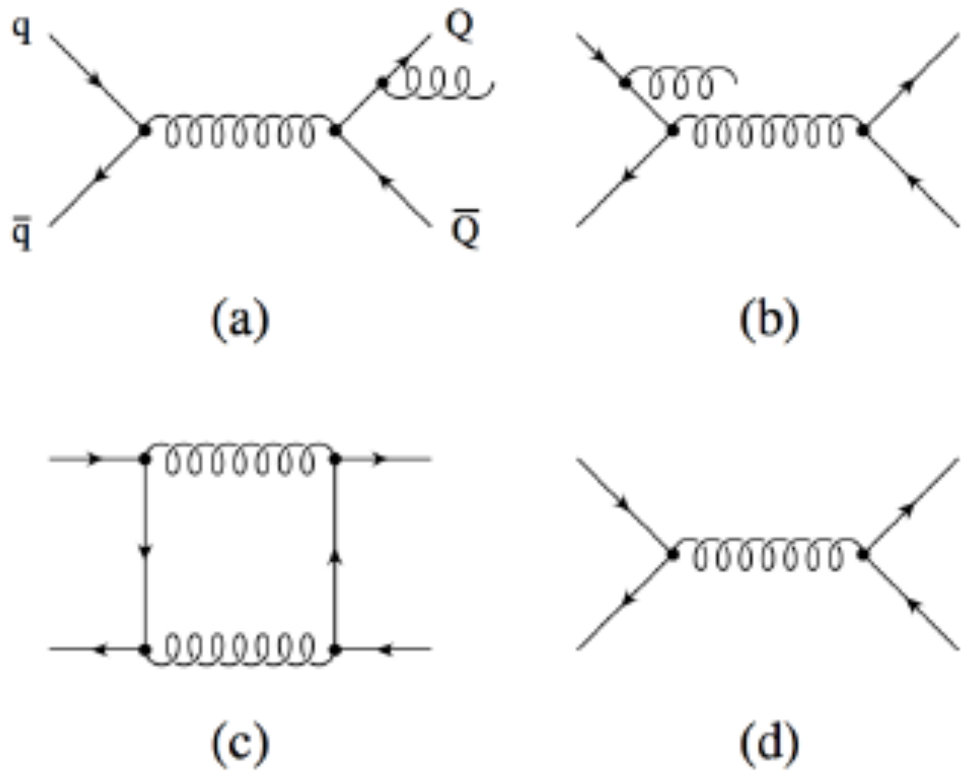
Top Asymmetry Introduction

- There is an asymmetry of top vs antitop as a function of scattering angle between the quark and the incident partons
- Sensitive to BSM corrections (i.e. *Z'*) which may not manifest in significant changes in cross-section



Top Asymmetry Introduction

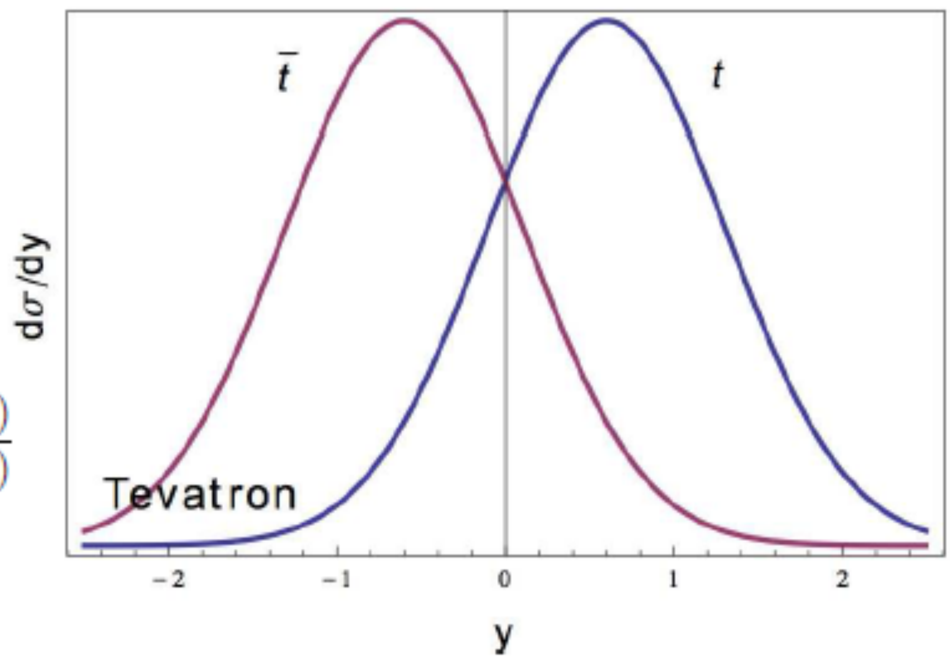
- The top asymmetry is driven by higher order corrections to NLO diagrams
  - i.e. Diagrams (a) and (b) interfere, as does (c) with (d)



Top Asymmetry Tevatron

- Proton-antiproton collisions
- Top preferentially emitted in quark direction
- Measure A_{FB}

$$A_{FB} = \frac{N_t(\cos\theta \geq 0) - N_{\bar{t}}(\cos\theta \geq 0)}{N_t(\cos\theta \geq 0) + N_{\bar{t}}(\cos\theta \geq 0)}$$



Top Asymmetry Tevatron

- CDF Measured:

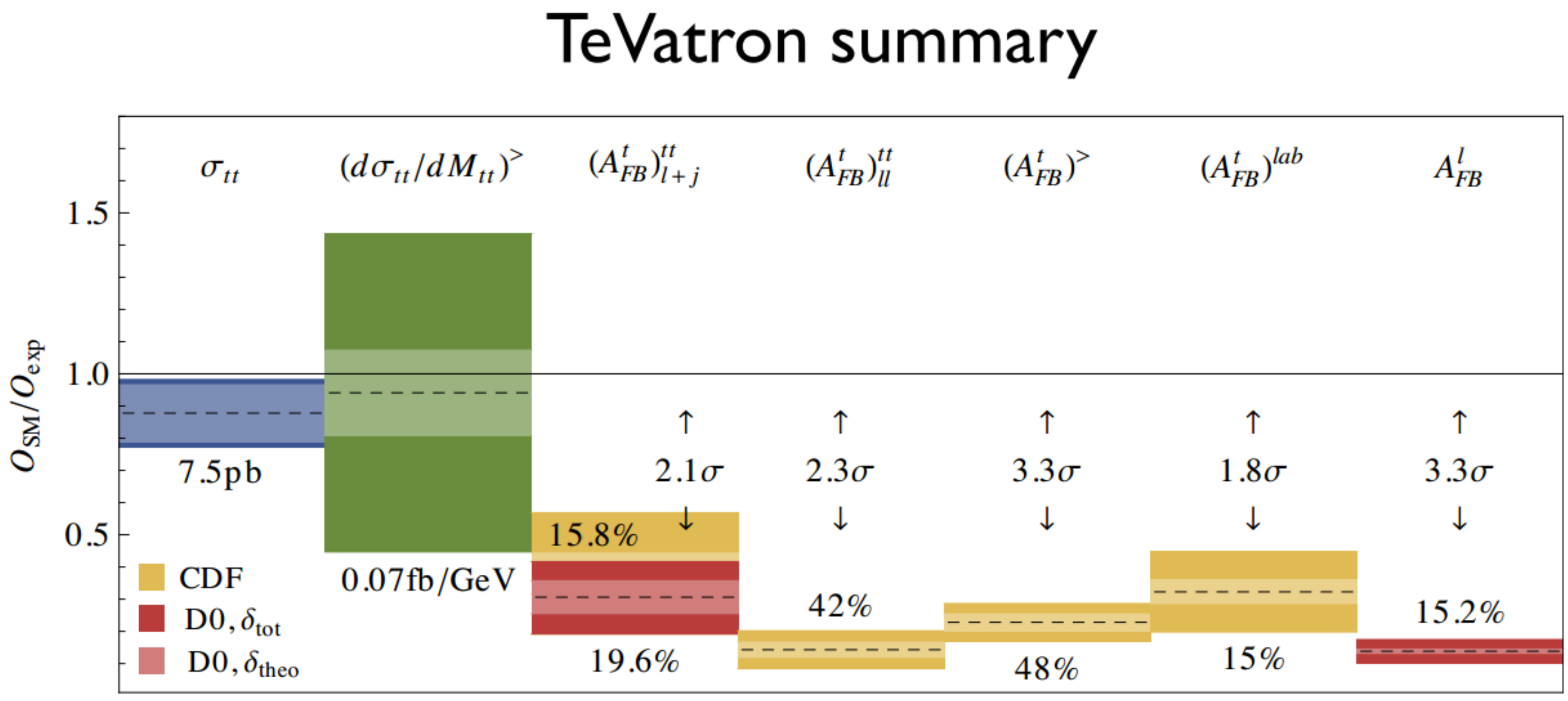
$$A_{FB}(|\Delta y| > 1.0) = 0.611 \pm 0.256$$

- In comparison to SM expectations of:

$$A_{FB}(|\Delta y| > 1.0) = 0.123 \pm 0.018$$

- A lot of other measurements (i.e. high mass top pairs) show typically 2.5-3.5 σ deviation from SM predictions

Some more Tevatron results



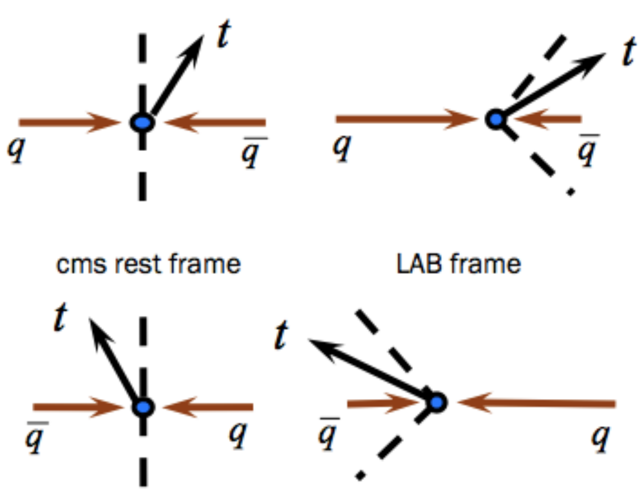
S. Westhoff, arXiv:1108.3341

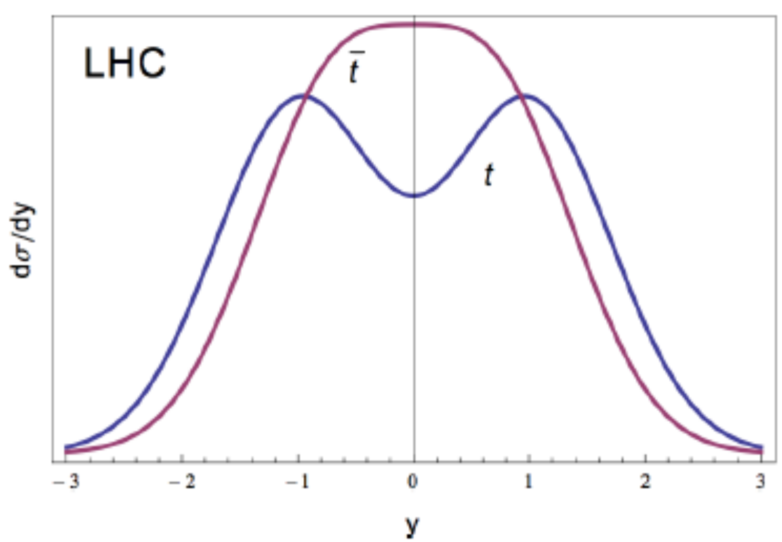
Top Asymmetry LHC

- Proton-proton collider means symmetric starting state
  - Can't tag original quark direction easily
  - Can't measure A_{fb}
- Top emitted preferentially in quark direction
- Valence quarks make this more forward
- Measure A_C – charge asymmetry

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

SM $A_C \sim 0.01$

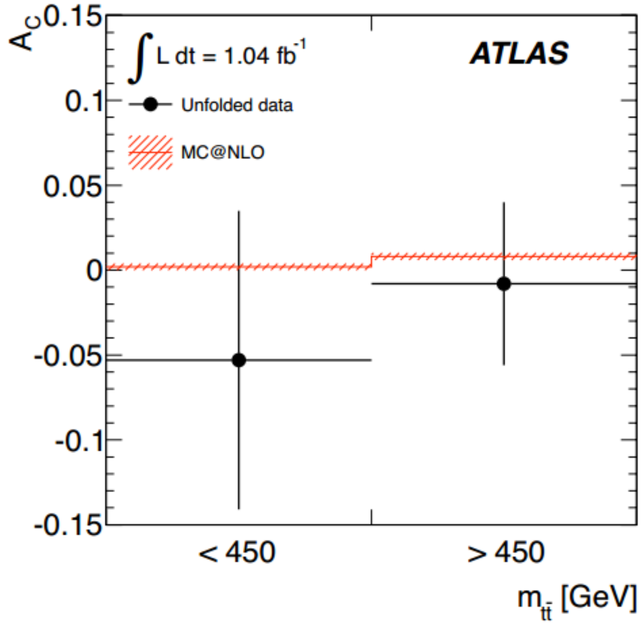




Top Asymmetry LHC

- All results are in agreement with SM.

ATLAS

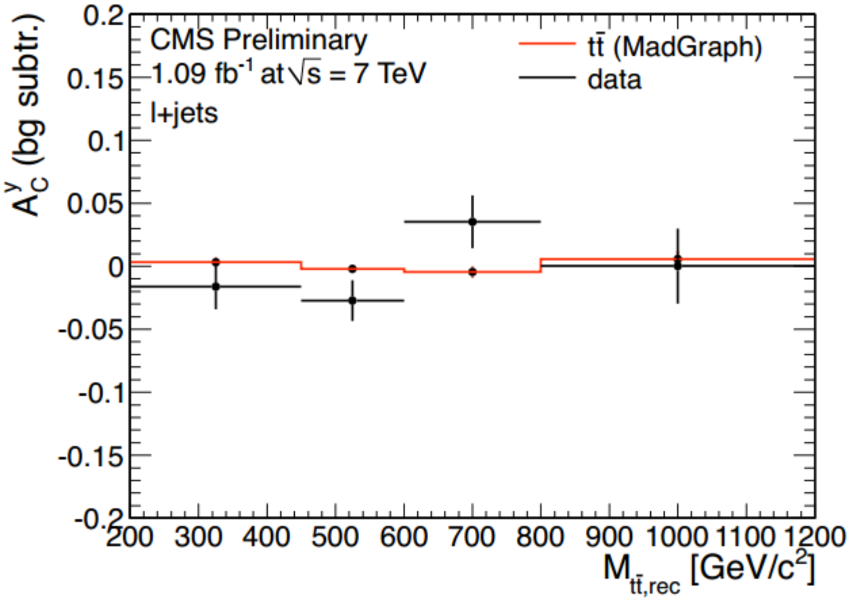


ATLAS result with 1 fb^{-1}
Eur.Phys.J. C72 (2012) 2039

$$A_C = -0.008 \pm 0.035\,(\text{stat.}) \pm 0.032\,(\text{syst})$$

(M_{tt} > 450 GeV)

CMS

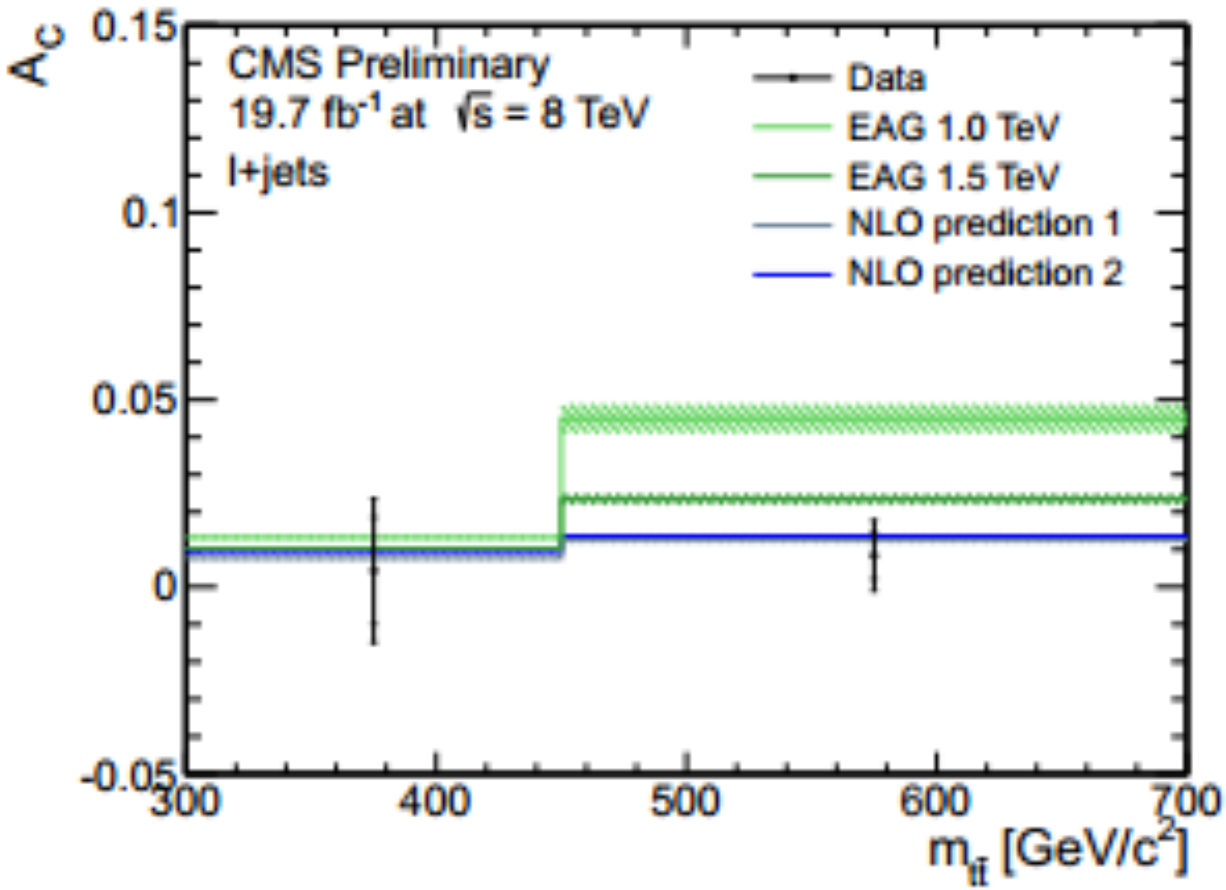


CMS result with 1 fb^{-1}
Phys. Lett. B709 (2012) 28

$$A_C^y = -0.013 \pm 0.026\,(\text{stat.})^{+0.026}_{-0.021}(\text{syst.})$$

Top Asymmetry LHC Future

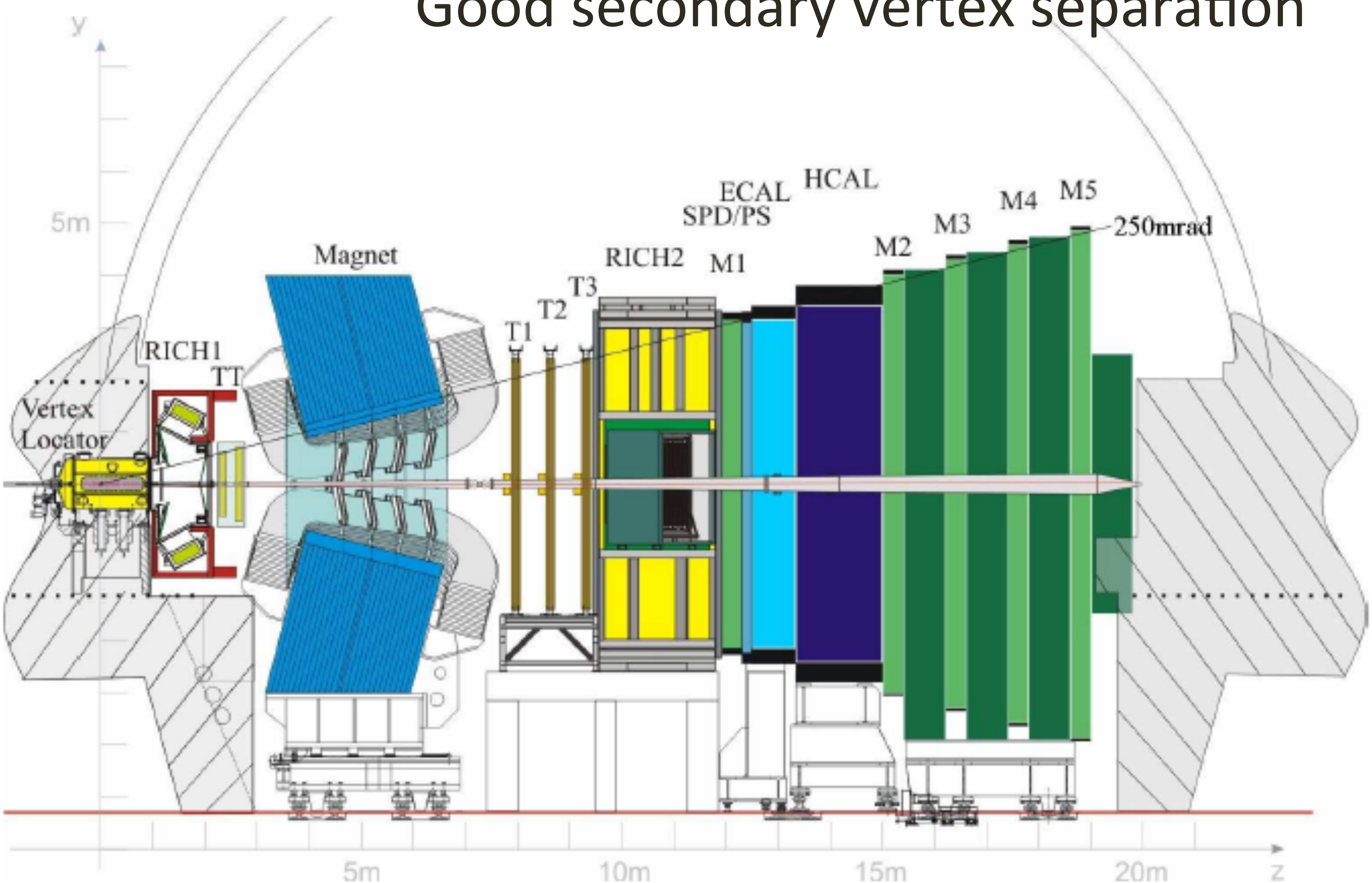
- ATLAS & CMS 8 TeV 20 fb^{-1} papers on the way out soon
- Quickly approaching systematic limits



LHCb

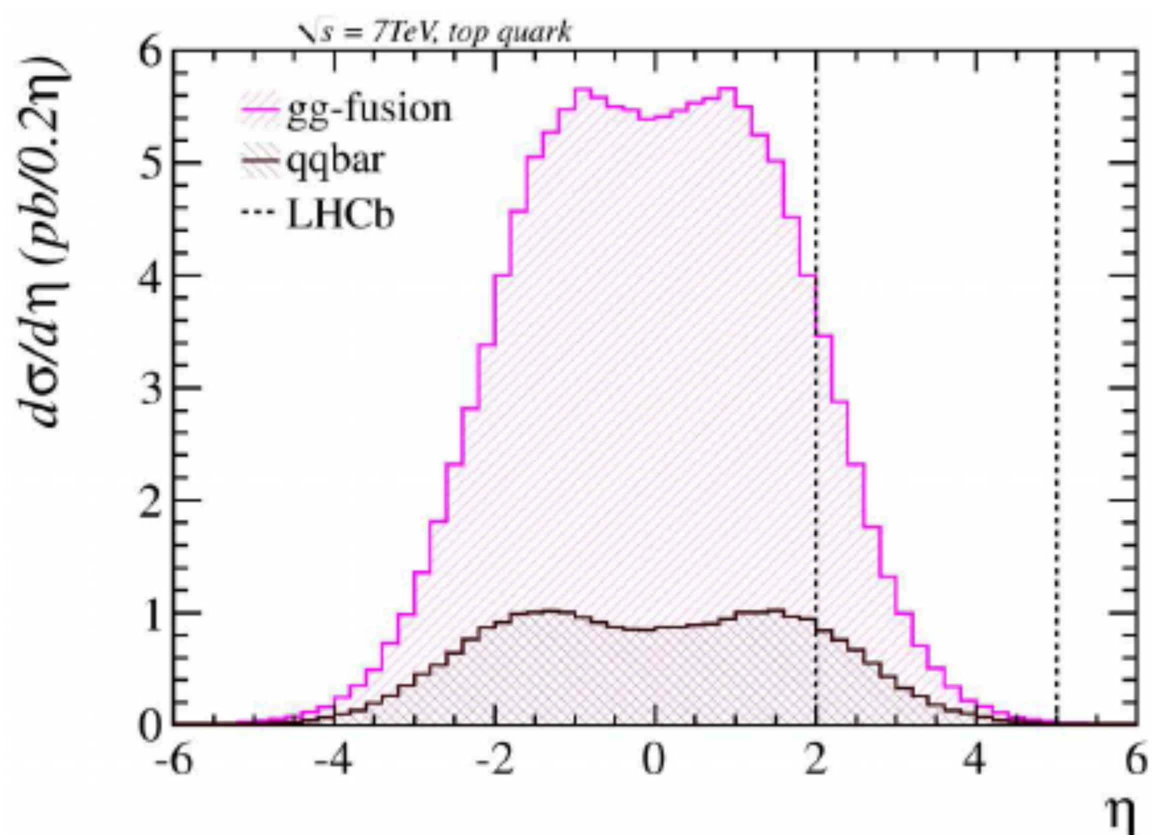
2<η<4.5

Good secondary vertex separation



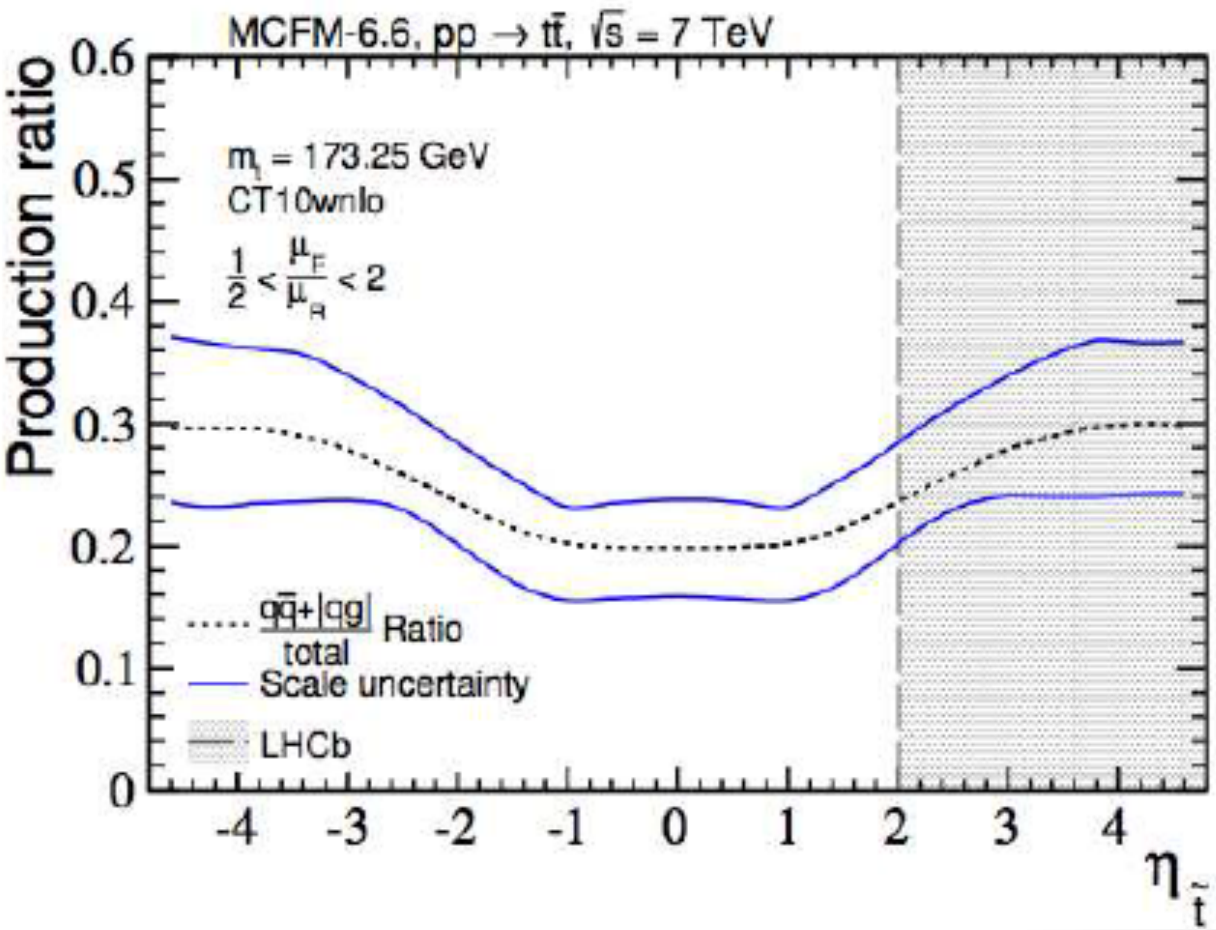
Top Asymmetry LHCb

- Central region detectors subject to high proportion of gluon fusion events
  - Dilutes signal
- Higher rapidity provides better purity



Top Asymmetry LHCb

- LHCb's purity in the high η is better for top asymmetry measurements



Channels

- Generator level expectations

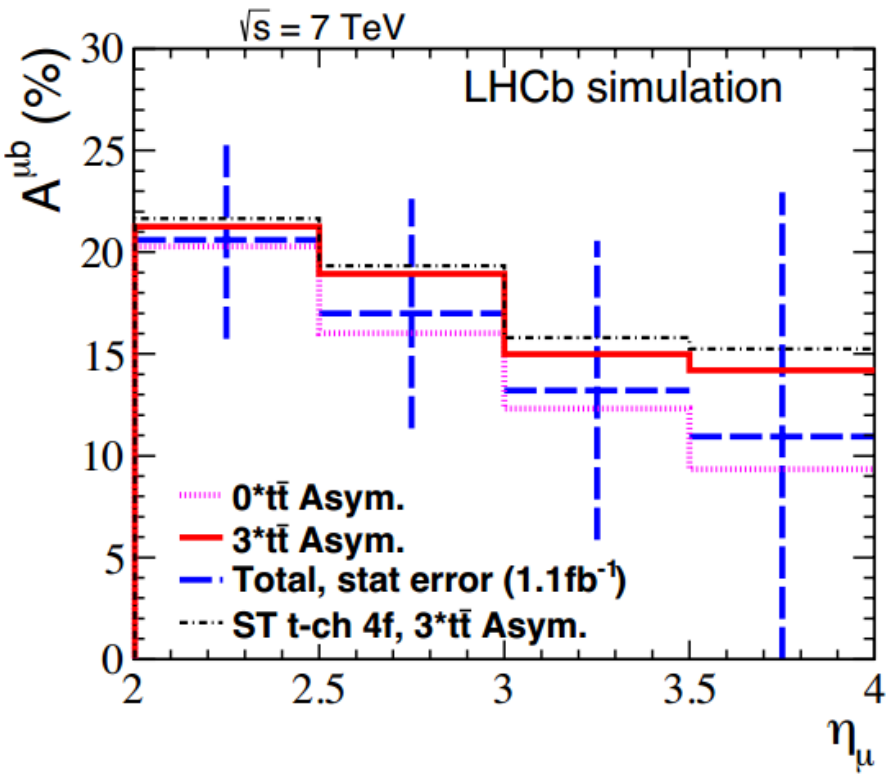
$d\sigma$(fb)	7 TeV			8 TeV			14 TeV		
lb	285	$\pm$	52	504	$\pm$	94	4366	$\pm$	663
lbj	97	$\pm$	21	198	$\pm$	35	2335	$\pm$	323
lbb	32	$\pm$	6	65	$\pm$	12	870	$\pm$	116
$lbbj$	10	$\pm$	2	26	$\pm$	4	487	$\pm$	76
l^+l^-	44	$\pm$	9	79	$\pm$	15	635	$\pm$	109
→ l^+l^-b	19	$\pm$	4	39	$\pm$	8	417	$\pm$	79

For μeb, divide by 2

Top Asymmetry LHCb

$$A^{lb} = \frac{N^{l^+b} - N^{l^-b}}{N^{l^+b} + N^{l^-b}}$$

Channel	7TeV	8TeV	14TeV
$A^t(\%)$	$0.69^{+0.12}_{-0.11}$	$0.55^{+0.1}_{-0.09}$	$0.27^{+0.13}_{-0.12}$
$A^{lb}(\%)$	$2.23^{+0.43}_{-0.68}$	$0.97^{+0.74}_{-0.45}$	$0.54^{+0.39}_{-0.31}$
$A_c(\%)$	$1.75^{+0.67}_{-0.47}$	$1.64^{+0.58}_{-0.67}$	$1.08^{+0.27}_{-0.32}$



- LHCb can do an interesting measurement but requires large amount of luminosity due to low acceptance

Jets!

Jet Reconstruction

- LHCb standard jet reconstruction procedure uses:
  - $\Delta R=0.5$
    - *Note – this is not conical in the high η region!*
  - Anti-kt
  - FastJet (though typically N<000s)
  - Jet P_T required to be > 5 GeV/c
- Currently under a lot of development
  - Z+jet just published

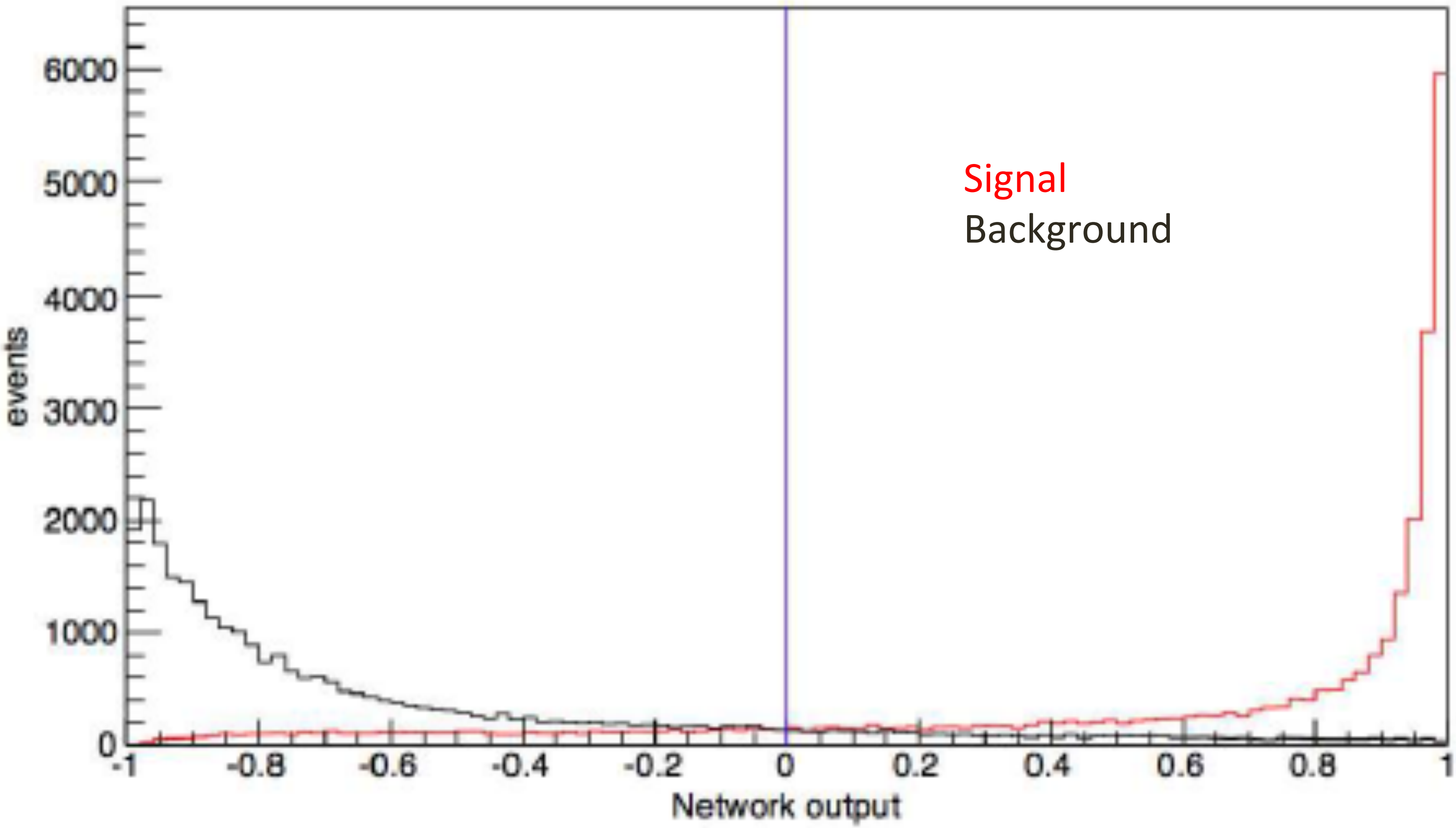
b-Tagging

- *b*-Tagging is fundamental for any top analysis
  - And currently not so straight-forward on LHCb!
  - LHCb is for fully reconstructed *b*-hadrons
- Tagging mechanisms in development – 3 options so far:
  - 1 – BDT looking for displaced vertex
  - 2 – 'Is there a muon'
  - 3 – Neural Network on track + jet scope (Liverpool)
- Jet group is very active and growing quickly
  - *b*-Tagging clearly an area of high interest

Neural Net *b*-tagger

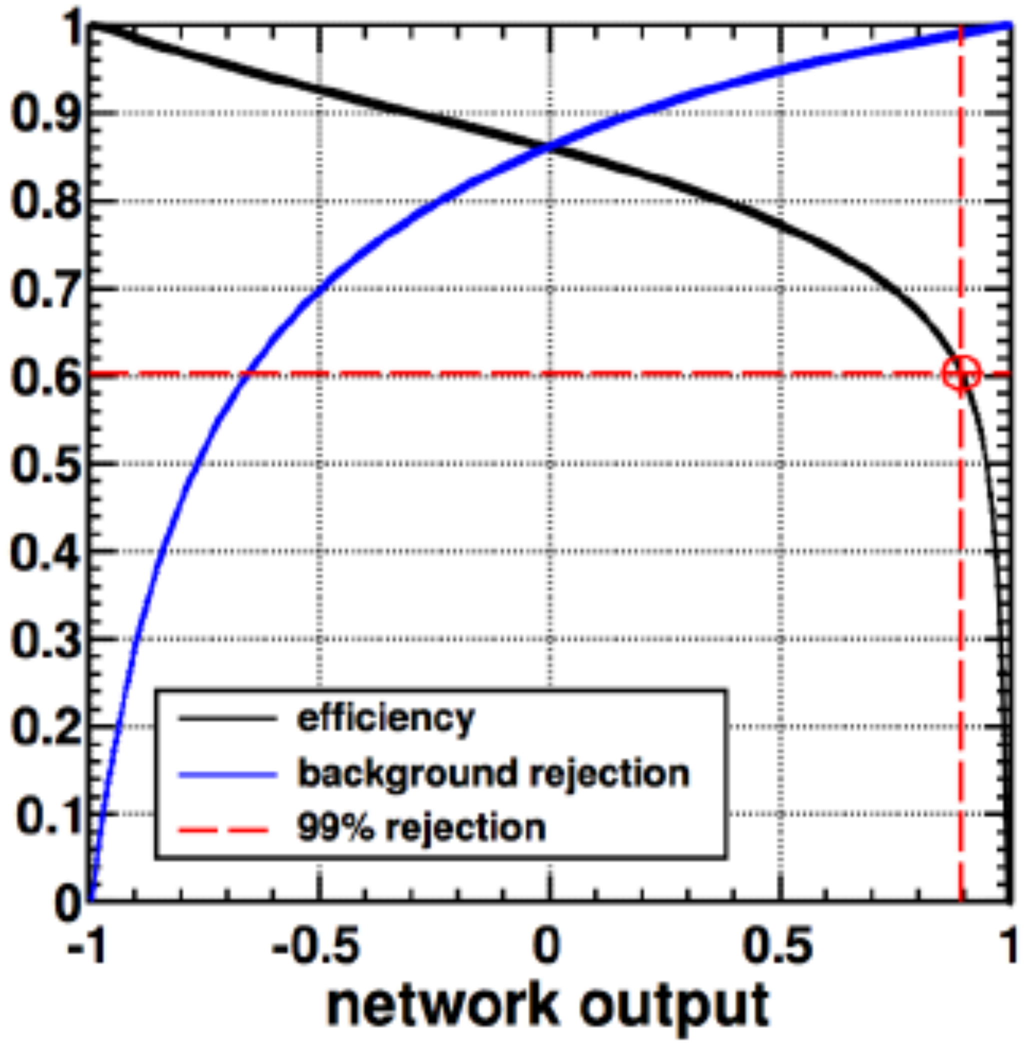
- Using NeuroBayes © by Phi-T
  - Powerful pre-processing (normalisation, missing variables, labels vs significant values, etc)
  - Looks for correlation between the variables
- Currently trained on $b\bar{b}$ MC from MadGraph (fully sim.)
- Minbias for backgrounds
- Minimises the loss function
- Creates output range from -1 to +1
  - -1 very background like
  - +1 very signal like

Output


6000
5000
4000
3000
2000
1000
0
events
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Network output
Signal
Background

Efficiency

~1% light jet acceptance, ~60% *b*-jet efficiency
For nn=0.9



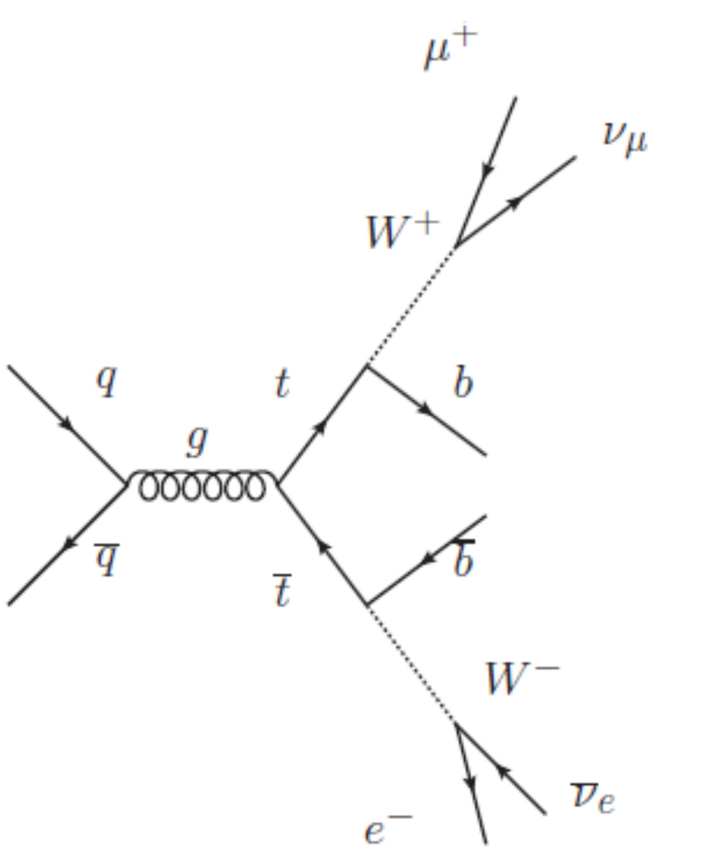
Further Work

- Three big targets:
  - 1 – Data driven *b*-tagger
    - Hard to do without biasing sample
    - Don't want to just look at fully reconstructed *b*-hadrons
  - 2 – Cascade information from all taggers into one unified tagger
    - Optimise the *b*-tagging process
    - But requires a lot of work to 'standardise' taggers in first place
  - 3 – Data driven efficiency & systematics
    - Currently *b*-tagger efficiency taken from MC (see later)
    - Need to improve this for reducing systematics and understanding tagger properly

Preliminary Cross-Section Measurement

Channel

- Dilepton+*b*-jet search
  - Unlike leptons
  - 2x branching ratio of like leptons (i.e. ee or μμ)
  - Additional *b*-jet to improve purity over other backgrounds



Theoretical Prediction

- Generate a fiducial cross-section to decrease extrapolation errors
- Predict how often top pairs will give μ,e with $2.0<\eta_{\mu,e}<4.5$ and $P_T(\mu,e)>15$ GeV/c + generator level *b*-quark $2.0<\eta<4.5$ and $P_T(b)>5$ GeV/c
- Predicted using POWHEG, MSTW, NNPDF and CT10 to get feel for PDF uncertainties

$$\sigma_{\text{fid}}(\sqrt{s} = 8\ \text{TeV}) = 17.5^{+1.2}_{-1.0}(\text{theo.}) \pm 0.2(\text{stat.}) \pm 2.9(\text{PDF})\text{fb}$$

- Expect about 40 top pairs in 2012 2 fb^{-1} data sample!

Backgrounds

- Backgrounds are $Z \rightarrow \tau\tau$, WW, QCD, ZW
  - *Requiring a b-jet loses 50% from signal due to acceptance*
  - *But backgrounds only get b-jets from NLO or mis-ID*
- τ has a lifetime, travels O(mm) before decaying, suppress with impact parameter
- WW topologically looks very similar to top pairs
  - Invariant mass (μ,e) very similar
  - Impact parameter very similar
  - Kinematics very similar
- ZW should be sign symmetric i.e. ++ and -- as likely as +-
- QCD dominated by high IP low isolation events

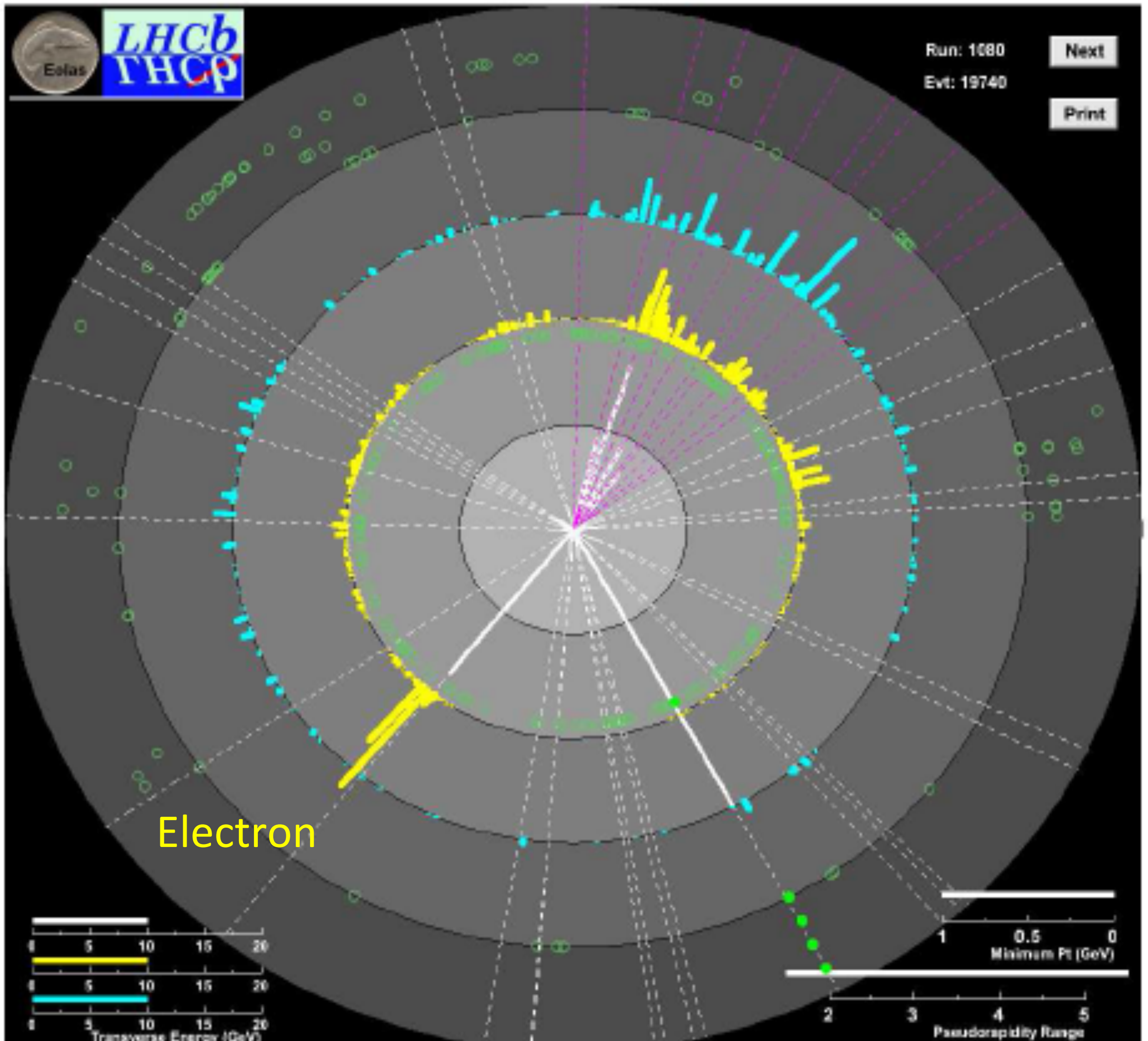
QCD

- Many processes contribute to QCD backgrounds
- Impossible to do from an MC perspective
- Data-driven method is used instead
  - Instead of looking at +- events, look at ++ and -- i.e. same sign rather than unlike sign
- Number of events passing pre-requirements are the same in both channels to within 5%
- Use anti-isolation requirements instead of isolation requirements to test equality

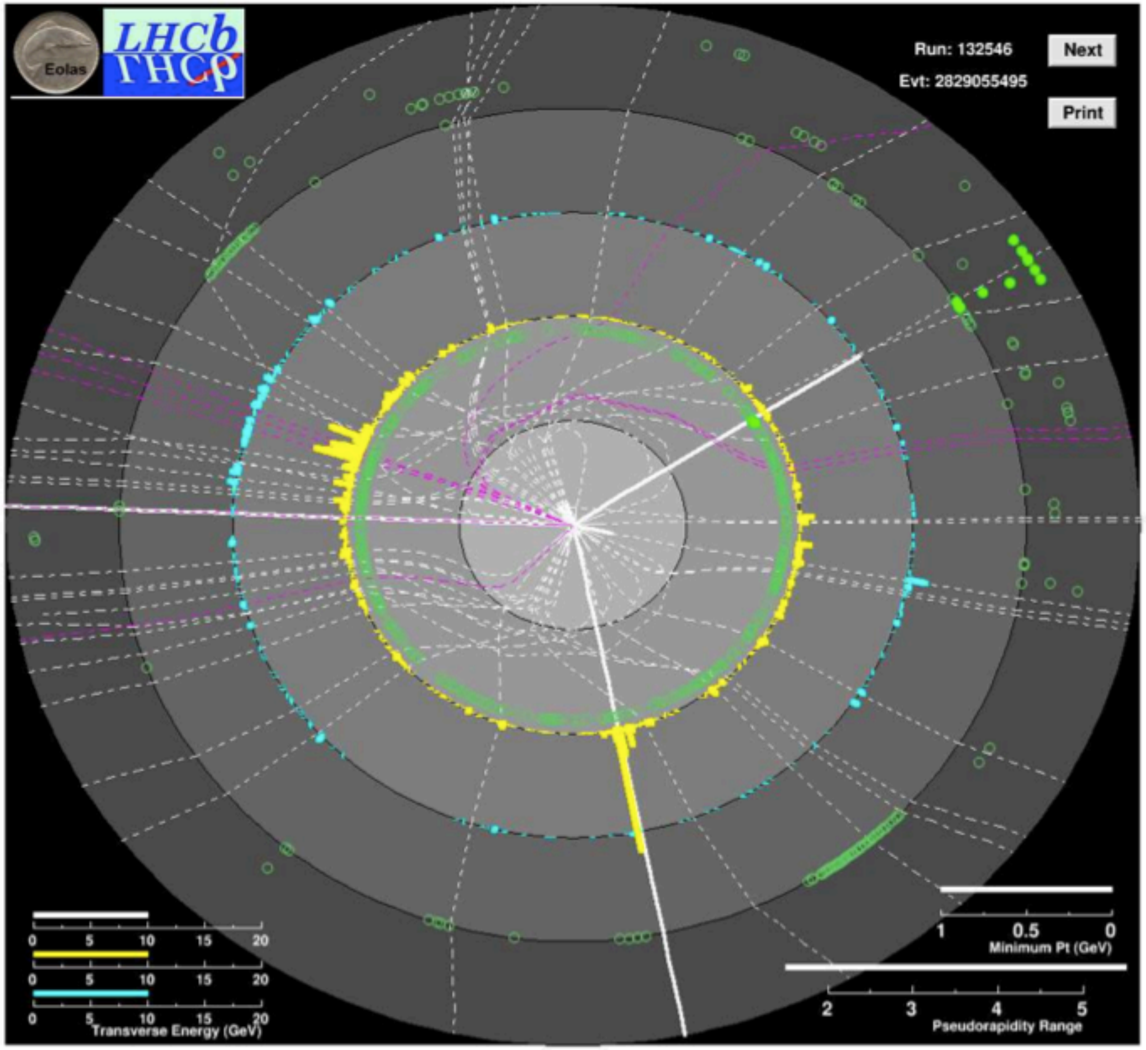
Selection Requirements

- Lepton requirements
  - Require P_T>15 GeV/c
  - Unbiased impact parameter <35 μm
  - Impact Parameter Closest Approach <35 μm
  - Lepton isolation > 90%
- Jet Requirements
  - P_T>5 GeV/c
  - Neural network output >=0.9
- Overall
- Require candidate muon to have passed L0, HLT1, HLT2 triggers for High PT Muon

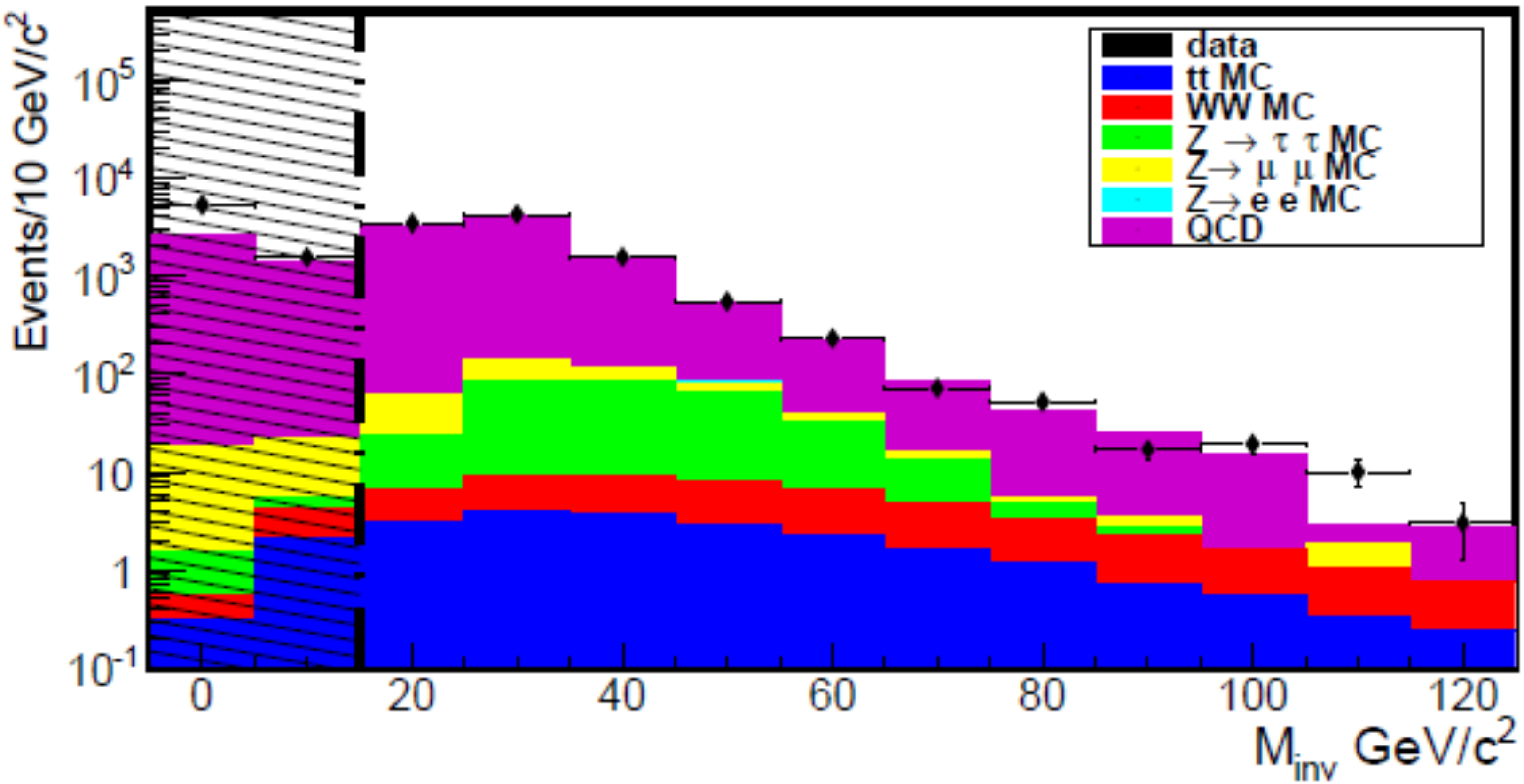
MC Event Display



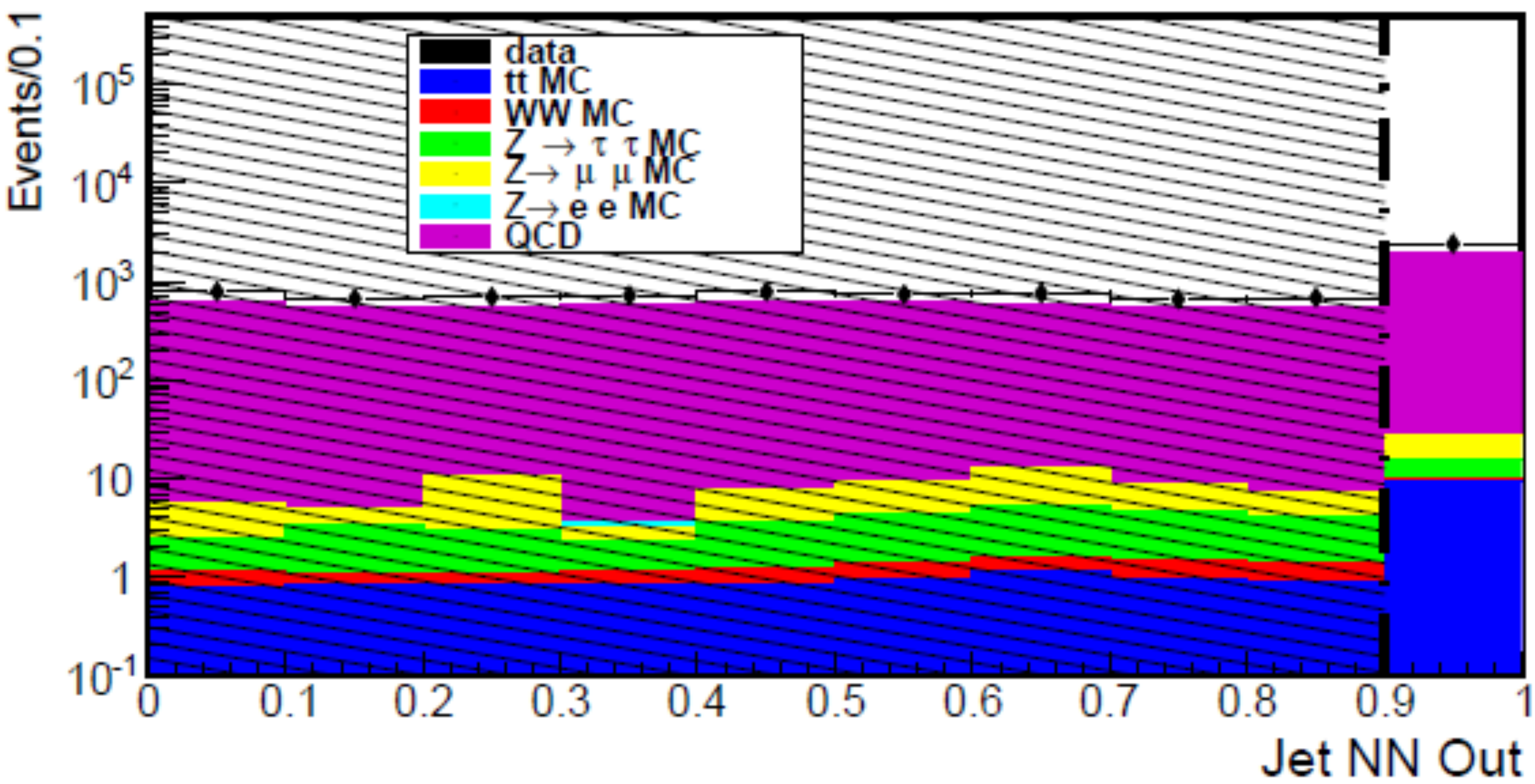
Data Event Display



Invariant Mass



Jet Network Output



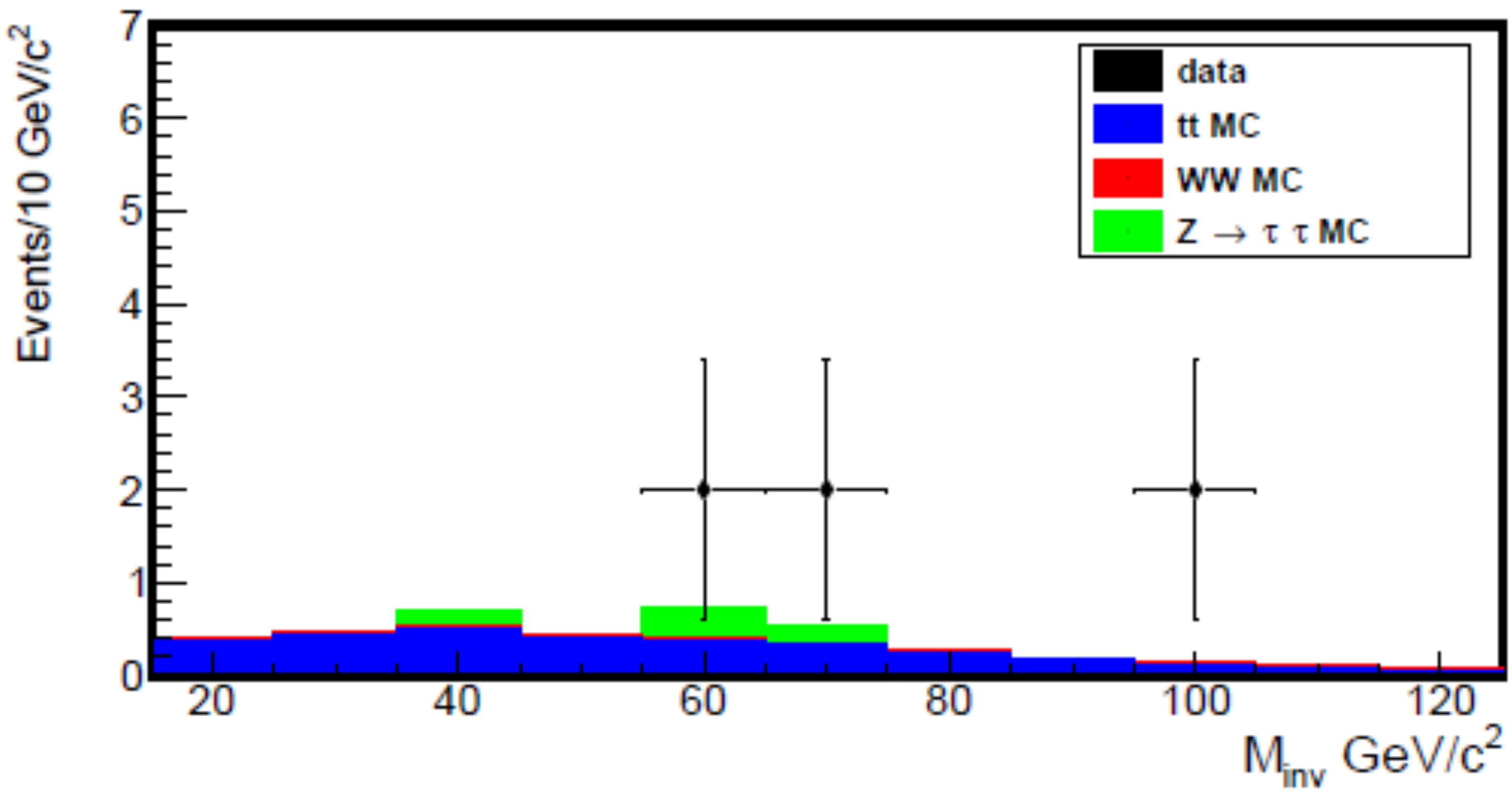
Background Expectation

- Backgrounds for channel selected are comparatively low
- Final state is ~80% pure

Sample	Contributions [Evts/2.01 fb^{-1}]	Statistical Uncertainty
WW	0.32	0.02
$Z \to \tau\tau$	0.65	0.33
QCD	0.00	1.00
Total	0.97	1.05

Final Candidates

- 6 events observed in full data sample
- Expect ~1 to be background



Reconstruction Efficiencies

- All are from MC vs data comparisons except the *b*-tagging efficiency

Parameter	Efficiency	Systematic Uncertainty [%]
ϵ_{trig}	0.756	2.0
ϵ_{GEC}	0.842	2.7
ϵ^{μ}_{track}	0.946	1.5
ϵ^{μ}_{ID}	0.986	1.2
ϵ^{e}_{track}	0.886	2.9
ϵ^{e}_{ID}	0.843	1.2
ϵ_{reso}	0.738	0.7
ϵ_{b}	0.579	16.8
ϵ^{μ}_{veto}	0.979	2.0
Combination	0.186	17.6

Selection Efficiencies

- *Note that the b-tag efficiency is taken in the reconstruction section*

Requirement	Efficiency	Stat. Uncert. [%]	Syst. Uncert. [%]
ncand	0.972	0.9	0.0
$M_{inv(\mu,e)}$	0.925	0.9	4.5
IP_μ	0.992	1.0	0.7
IP_e	0.990	1.0	0.7
$IPCA$	0.954	1.0	1.5
I_μ	0.852	1.0	4.3
I_e	0.793	1.0	0.8
Combined	0.535	2.5	6.5

Cross-Section

- FSR Correction of 1.035

$$\sigma = \frac{N_{sig} - N_{bkg}}{\epsilon_{rec}\epsilon_{sel}\mathcal{L}A}$$

- Final cross-section is

$$\sigma = 24.3^{+14.6}_{-9.7}(\mathrm{stat.}) \pm 6.9(\mathrm{syst.}) \pm 0.9(\mathrm{lum.})\mathrm{fb}$$

- Note: With 6 candidates extremely statistically limited
- Use millions of pseudoexperiments with Gaussian samples of background fluctuations to determine signifiance of ~3.7σ

Outlook

- Systematics are still quite high
  - The *b*-tagging uncertainties need to be reduced (and data-driven)
- Current analysis can measure a ~4.5σ excess
- Fiducial cross-section increases rapidly with centre of mass energy
  - Increases to ~284 ± 24 fb at 14 TeV
    - After reconstruction and selection efficiencies, reconstruct 30 top candidates per fb^{-1}
- Other channels offer higher statistics but lower purity
  - Work being done on μ+*b* at the moment
    - Extremely sensitive to mis-ID rate!

Summary

- LHCb offers an interesting and unexplored phase space for top quark measurements
- Work underway to develop the necessary framework for these
- Preliminary cross-section measurement has been performed in a dilepton+jet channel
- An LHCb asymmetry measurement needs a lot of luminosity for reasonable precision
  - LHCb upgrade!

Some further reading

- R. Gauld, Feasibility of top quark measurements at LHCb and constraints on the large-*x* gluon PDF, arXiv:1311.1810 (2013)
- A. Kagan, J. Kamenik, G. Perez et al., Top LHCb Physics, arXiv:1103.3747 (2011)
- R. Gauld, Measuring Top Quark Production Asymmetries at LHCb, LHCb-PUB-2013-009 (2013)

Backup – Track Net

- Pre-requirements:

Variable	Requirement
IP	<3.00 mm
IP	>0.08 mm
IP_{sig}	>0.5
P_T	>500 MeV/c

- Correlations:

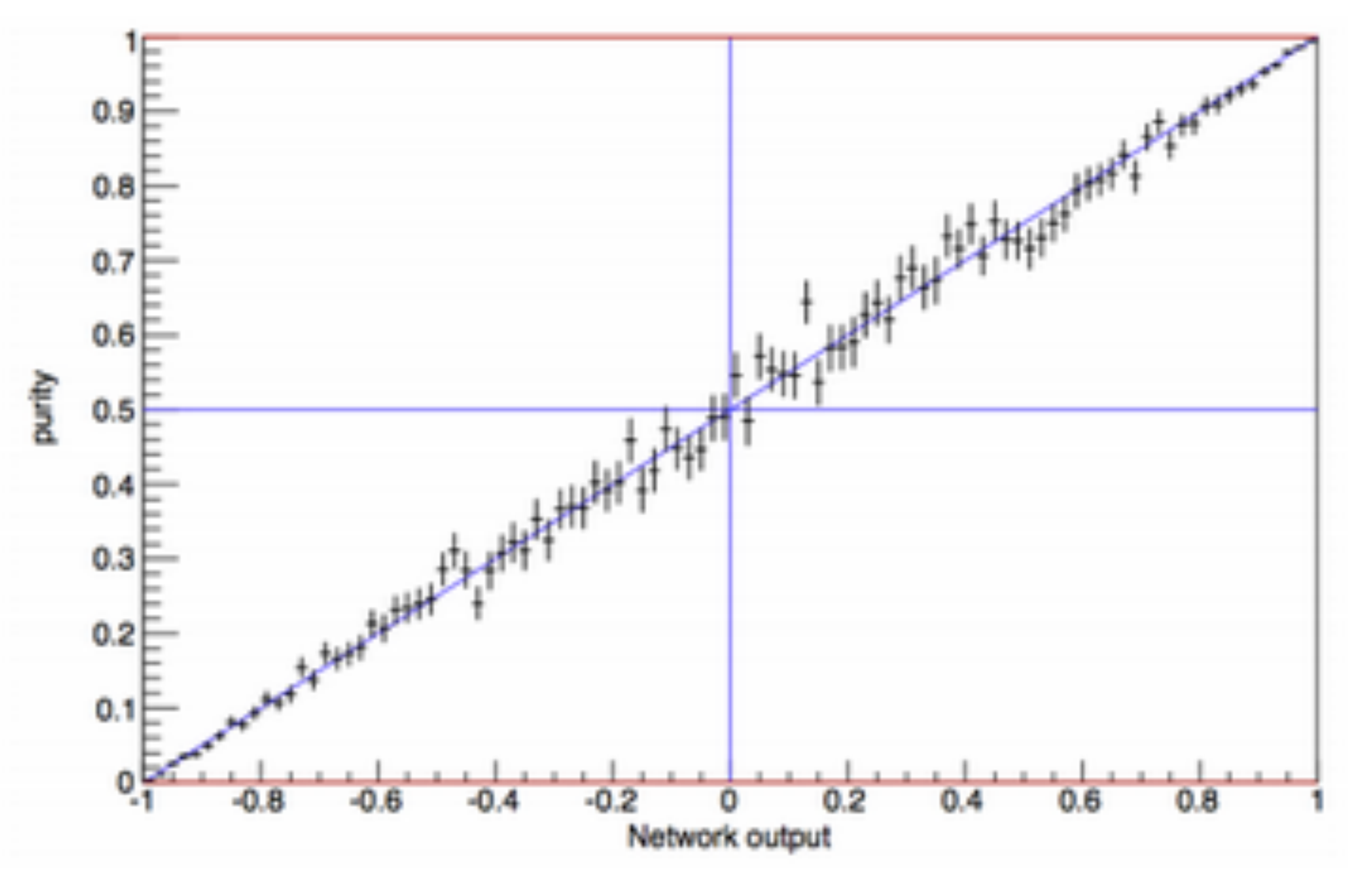
Variable	Correlation with target (σ)
IP	130
σ_{ip}	135
IP_{sig}	176
P_T	93
η	50

Backup – Jet Net

- Require at least 3 tracks. Jet reconstruction imposes minimum of 5 GeV PT requirement

Variable	Correlation with target (σ)
Maximum track network output	138
Jet P_T	65
Maximum Track P_T	33
Average Track IP	24
Track k_T	17
IP tagger sum	19
IP tagger 2nd	11
IP tagger 3rd	8

Backup – NB Loss Function



Backup – Systematics Example

- Taken from comparison of MC (Z) with MC (top) and calibrated to Data (Z). For example, trigger efficiency (tag-and-probe Z→μμ) data

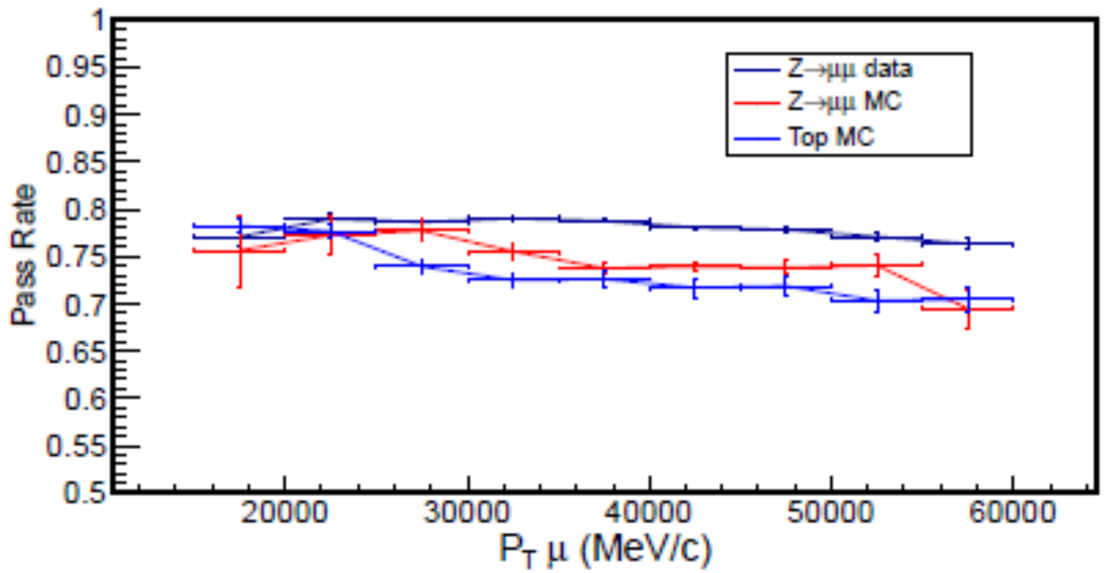
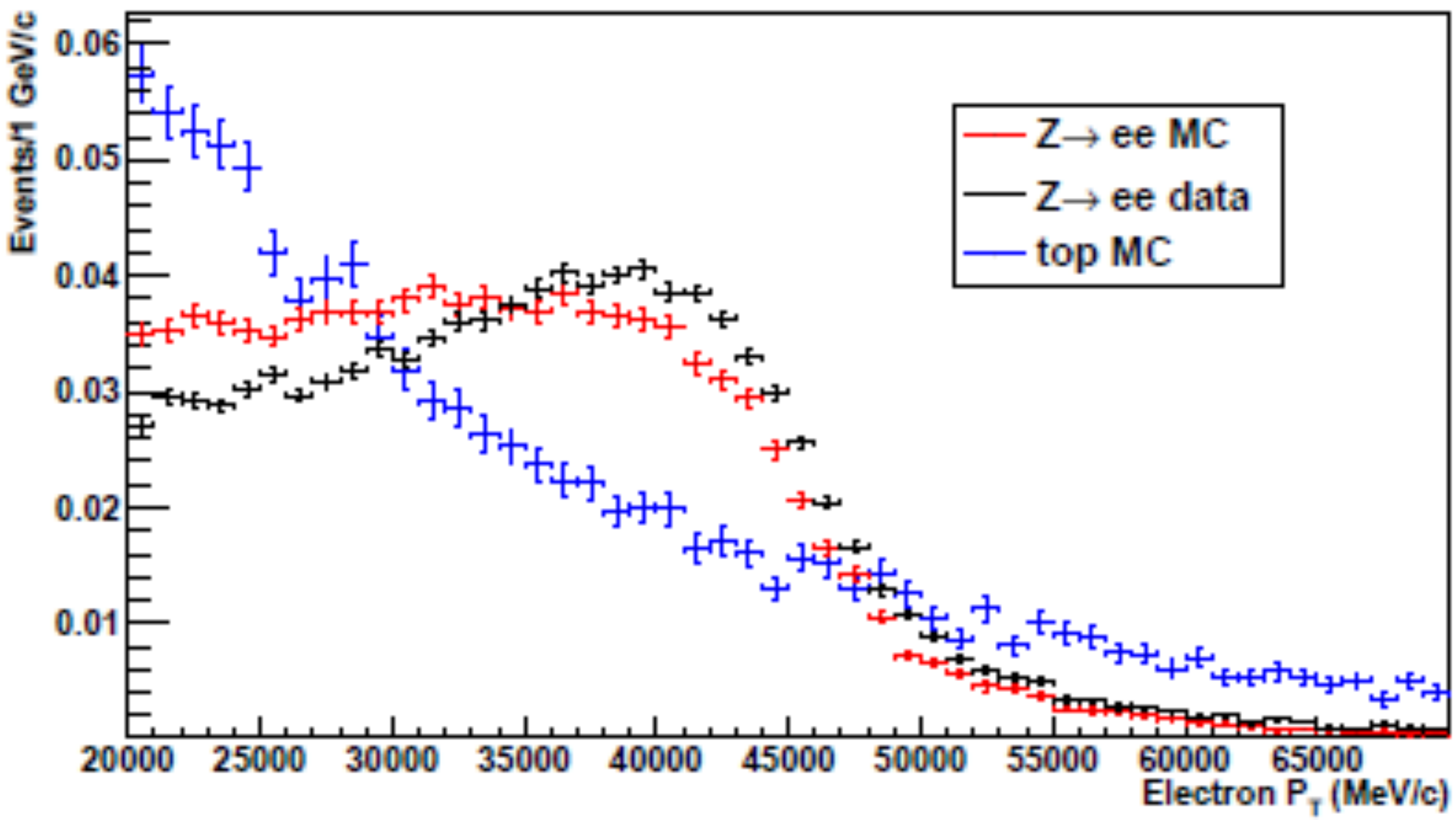


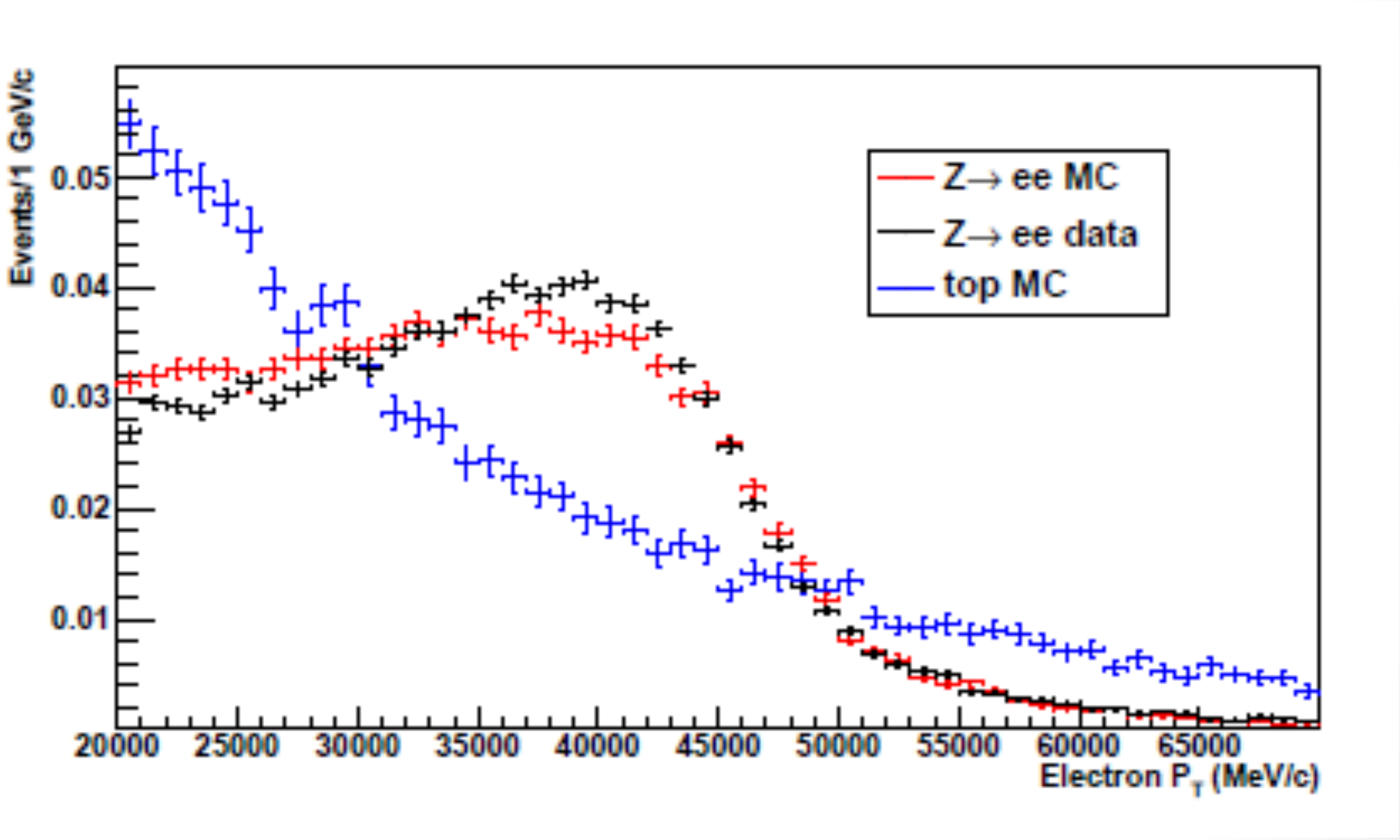
Figure A.15: The $Z \to \mu\mu$ trigger efficiency as a function of transverse momentum.

Backup – Electron Transverse Momentum

- Uncorrected



Backup – Corrected E PT



Backup – ECAL Saturation