Charge Asymmetry Measurements in Top Quark Events at the LHC

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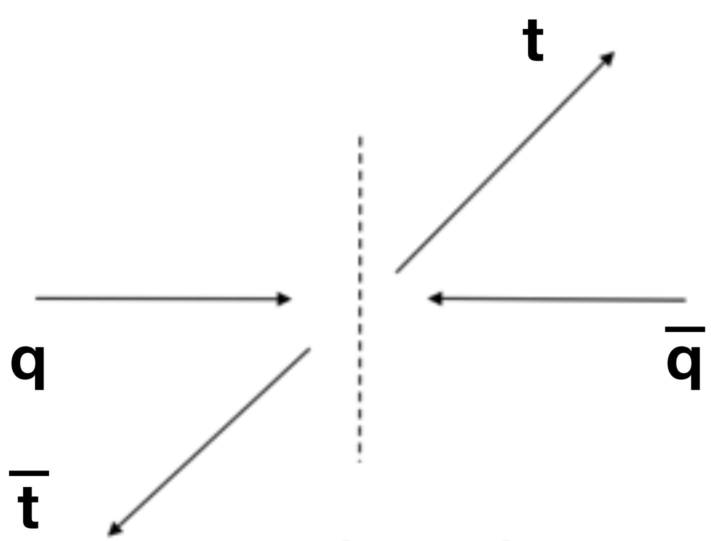
University of Michigan

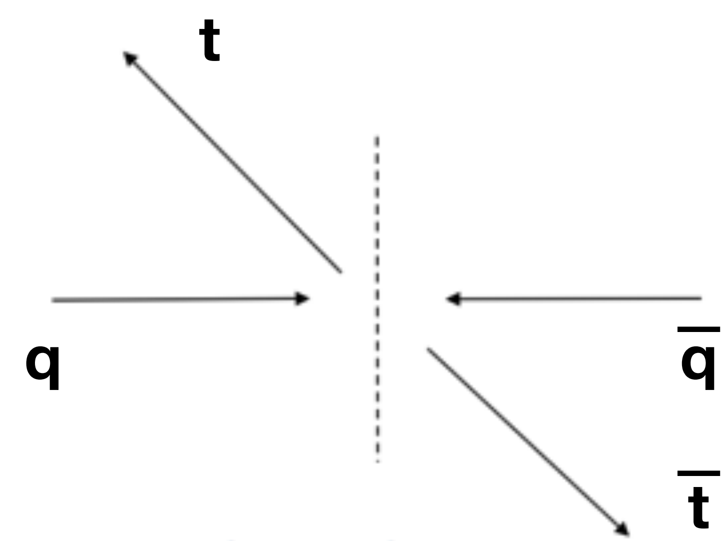
On behalf of the ATLAS and CMS Collaborations

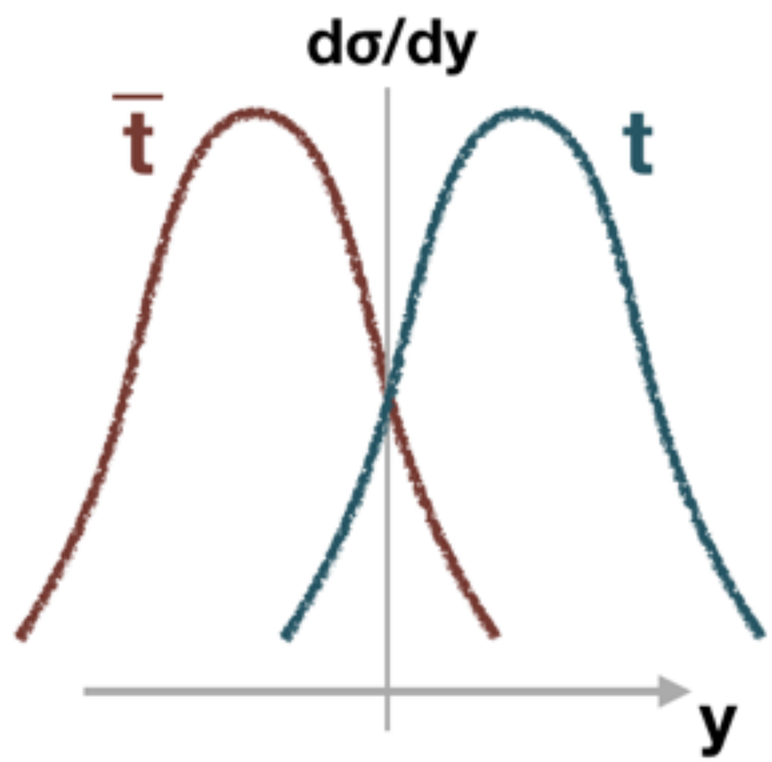
What is the Charge Asymmetry?

- An asymmetry in the differential rate of top quark and anti-top quark production with respect to some direction



happens more often then





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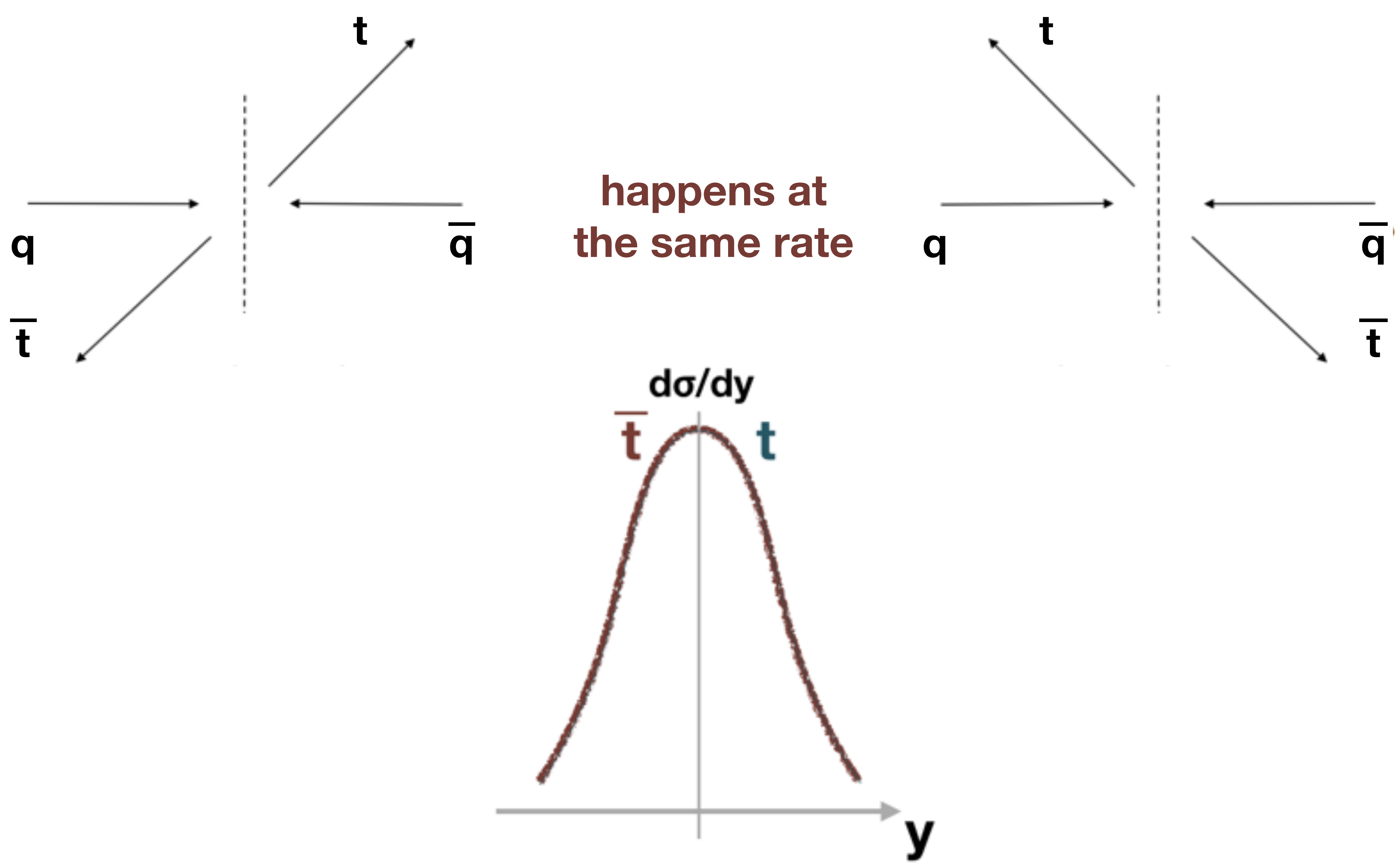

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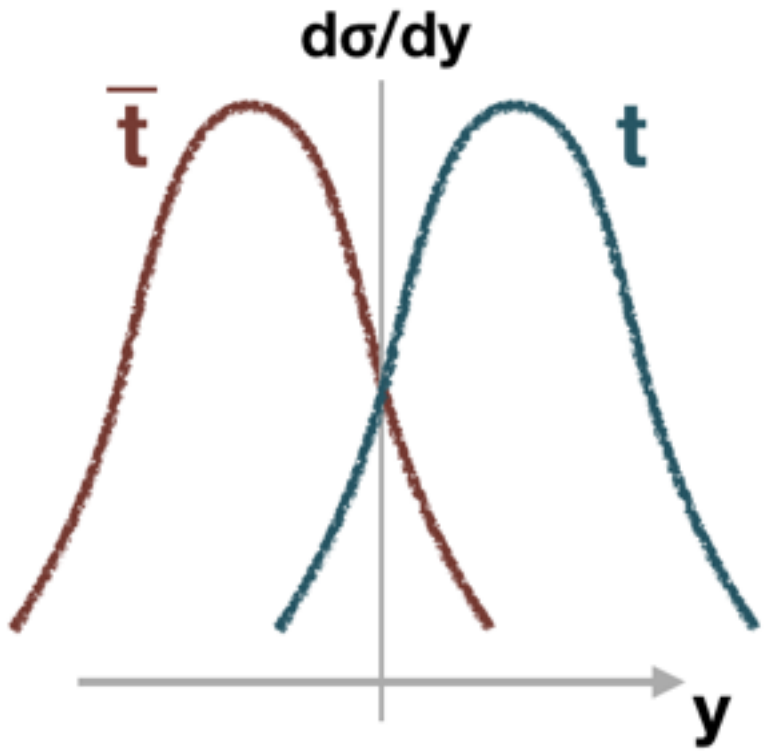


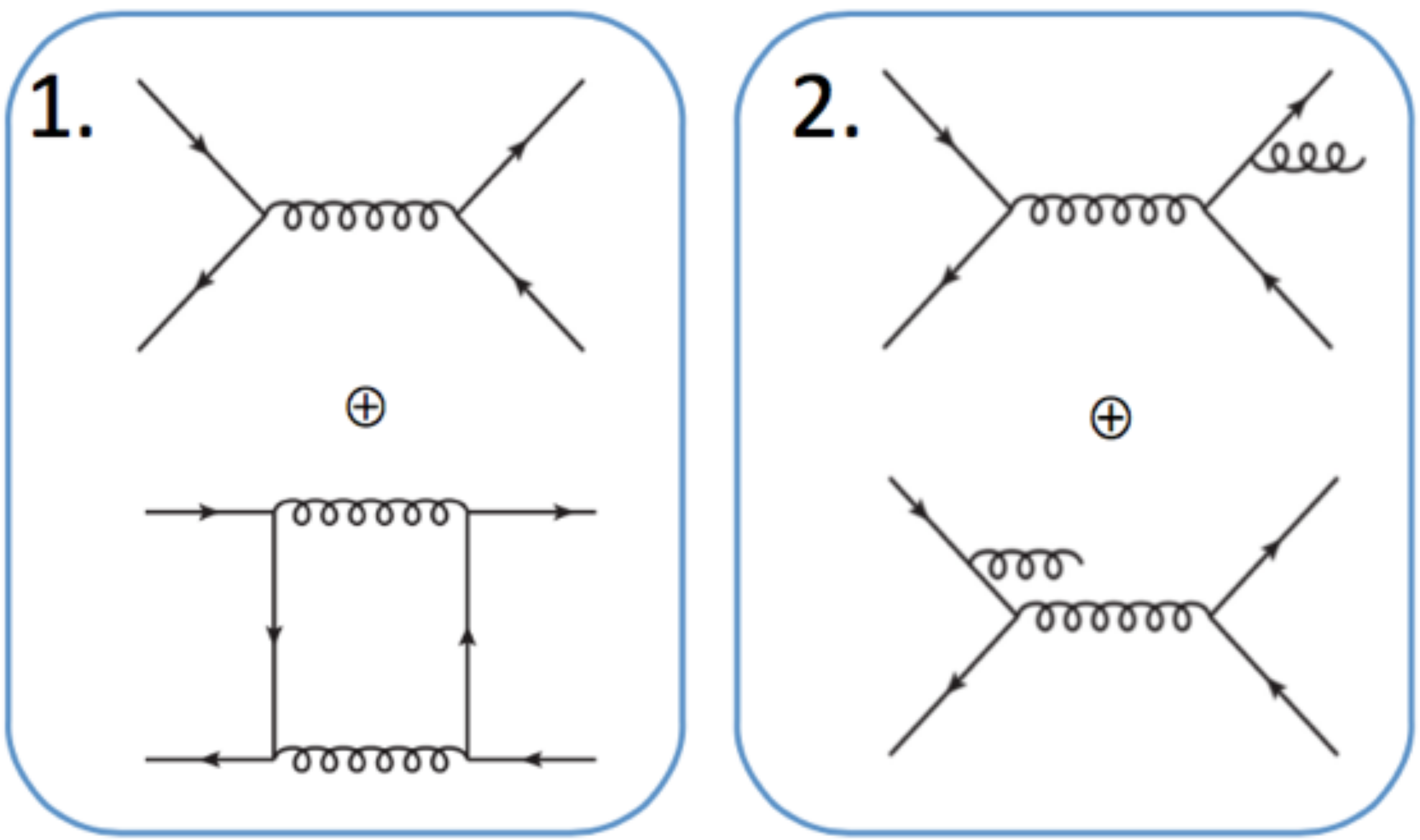
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

with $\Delta y = y_{top} - y_{anti\text{-}top}$

What could cause an Asymmetry

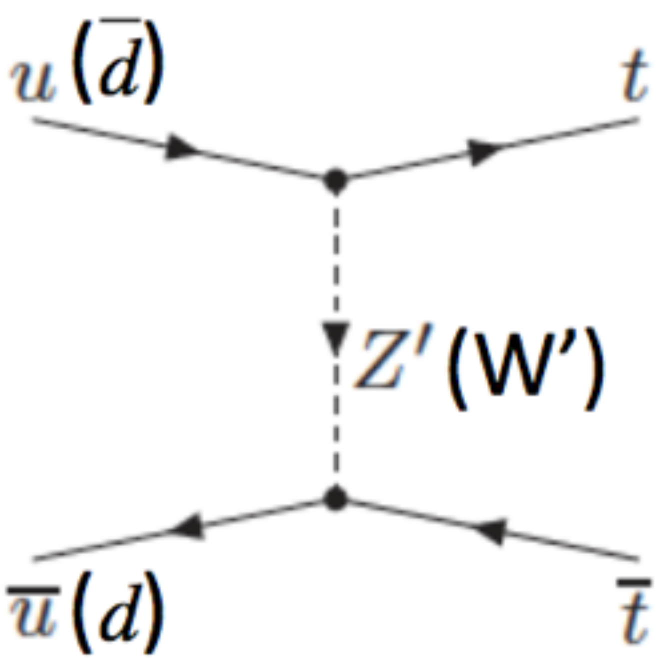
- SM top quark pair production at NLO predicts a non-zero charge asymmetry

- Originates in $q\bar{q} \rightarrow t\bar{t}$ from interference between (1) tree and box diagrams and (2) interference between gluon ISR and FSR



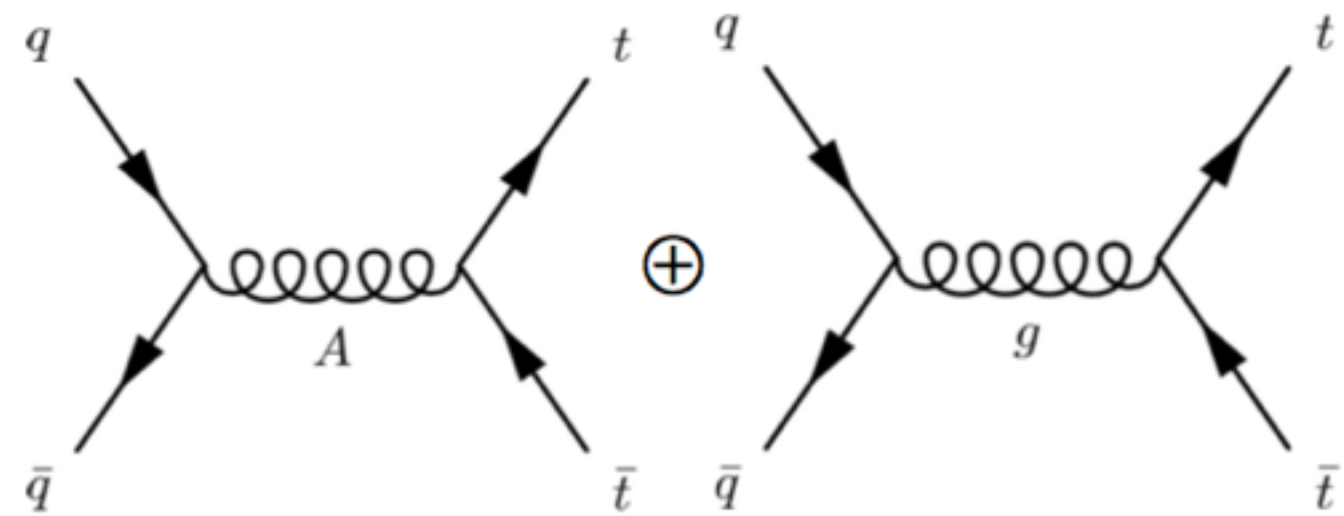
What could cause an Asymmetry

Z' / W'



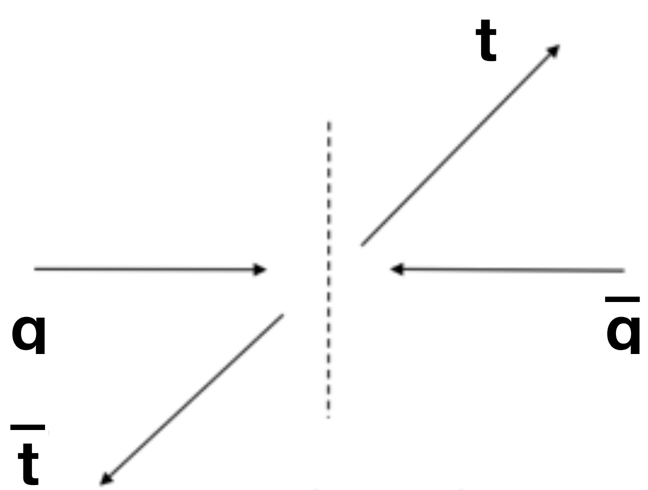
t-channel: exotic flavor changing vector bosons

Axigluon



s-channel: interference between SM QCD and exotic gluons with axial coupling

Tevatron Measurements



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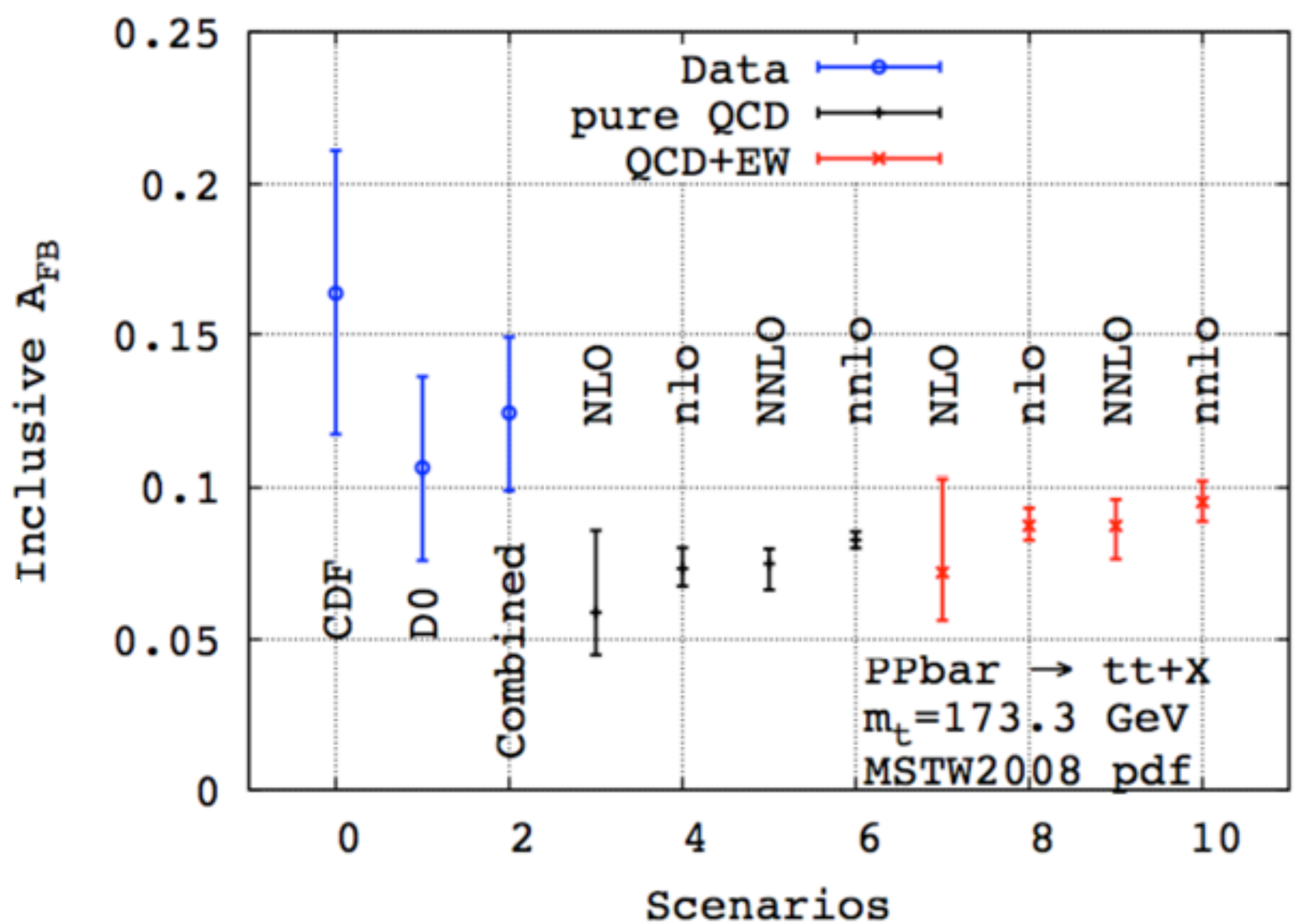
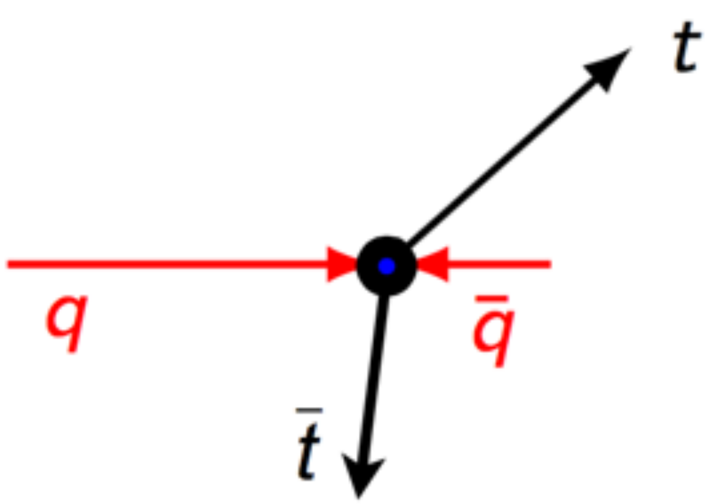


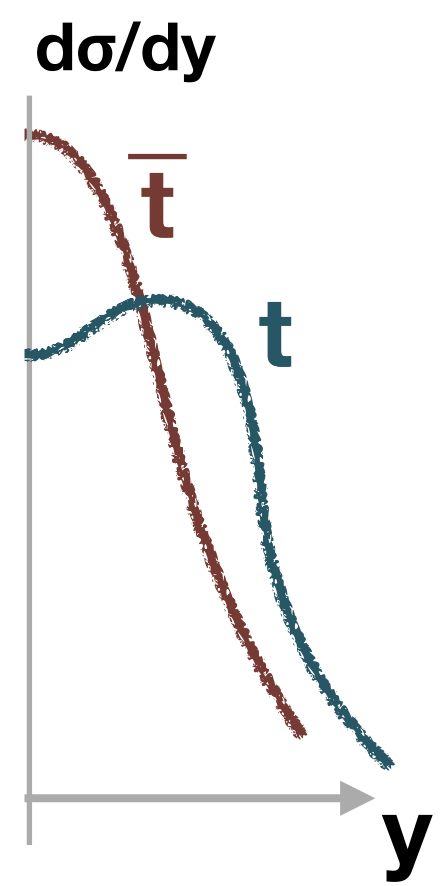
Czakon, Fiedler, Mitov 2015

How we probe it at the LHC

- $q\bar{q}$ interactions do happen: a valence quark will interact with an anti-quark from the sea, which typically has a smaller momentum fraction of the proton
- Since Top quarks (anti-top) are color connected to the incoming parton (anti-parton)

→ we expect top quarks to be produced more forward then anti-tops





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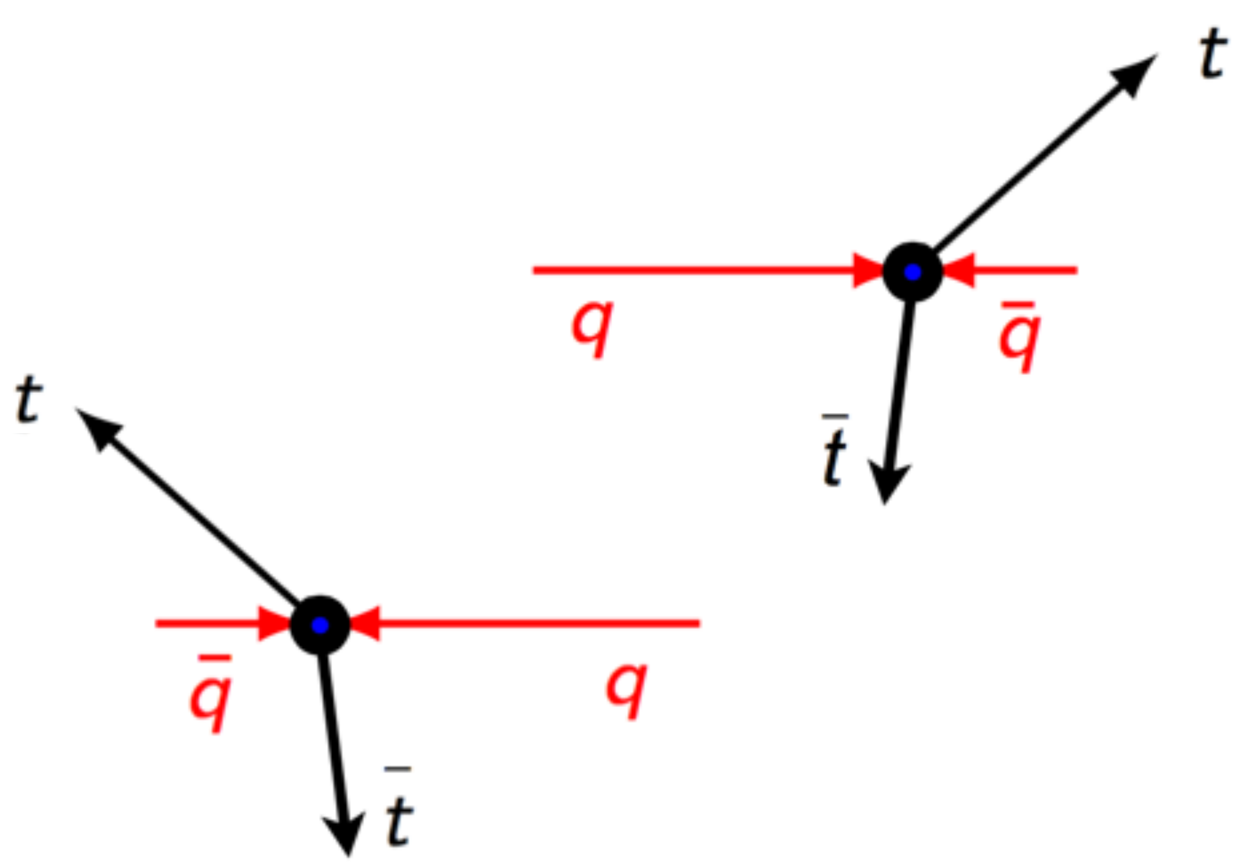

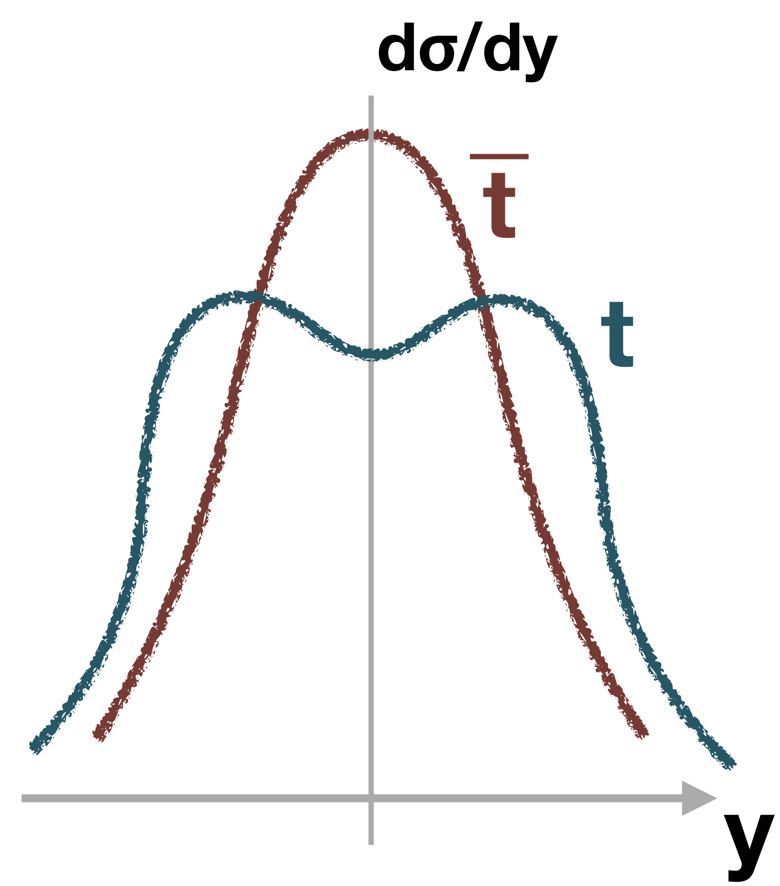

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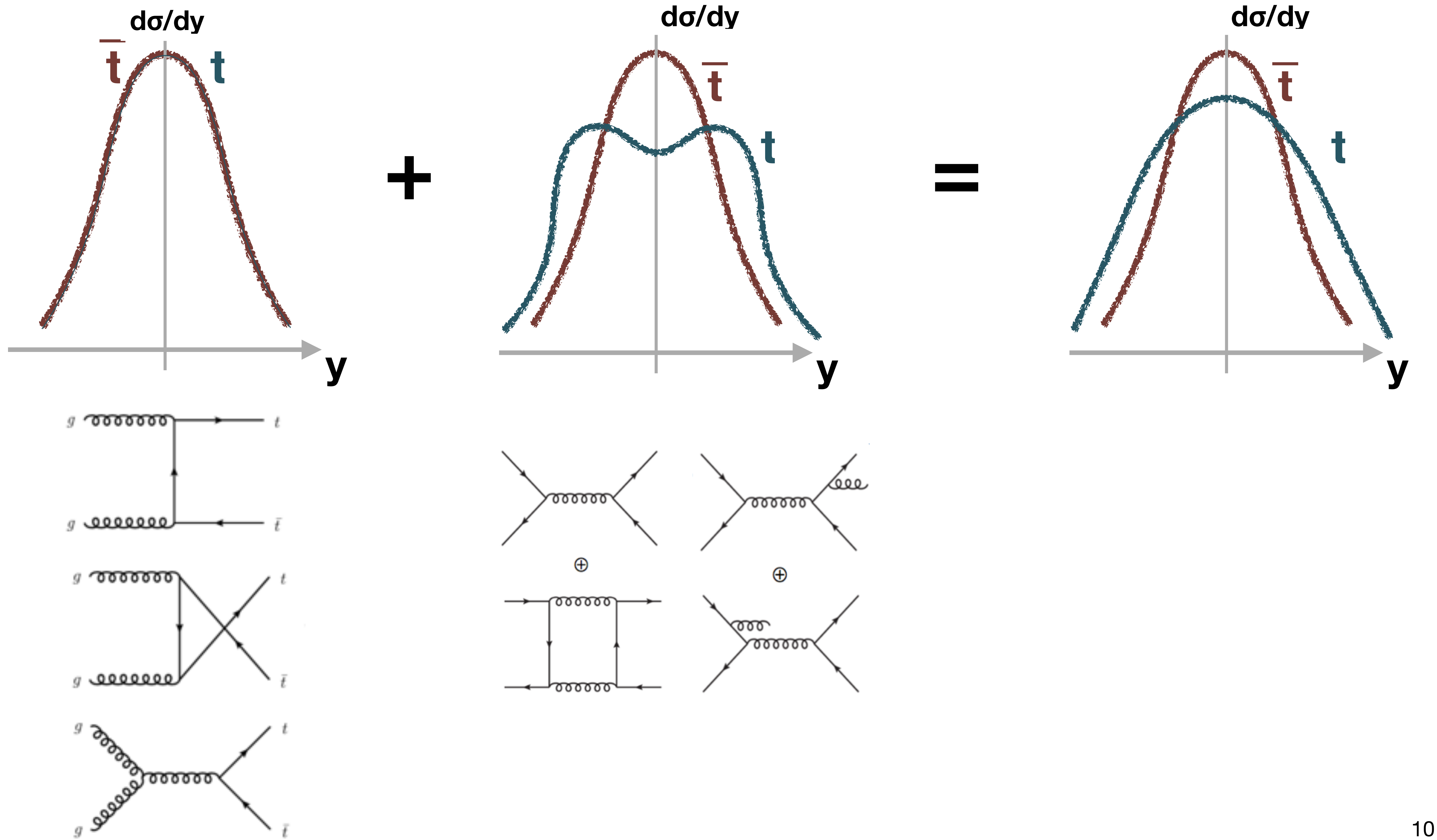
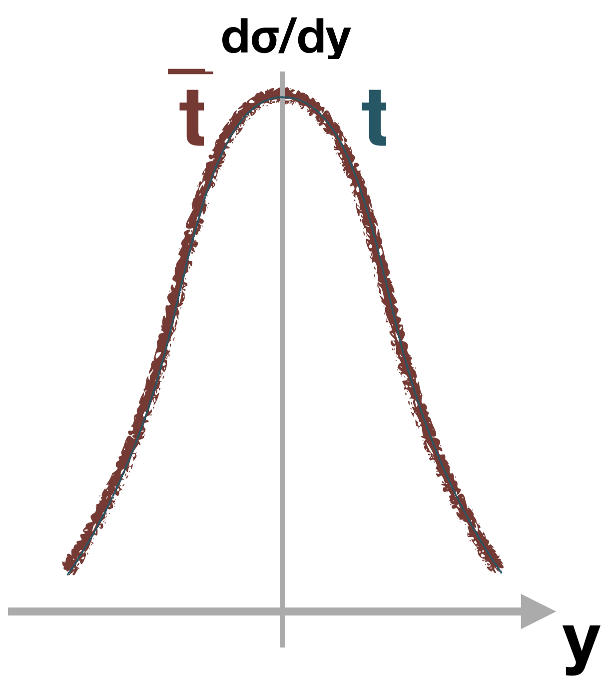


How we probe it at the LHC



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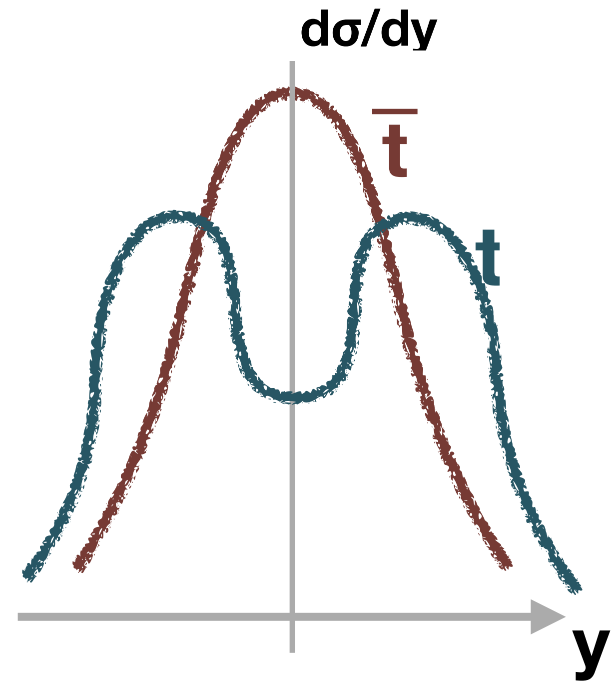

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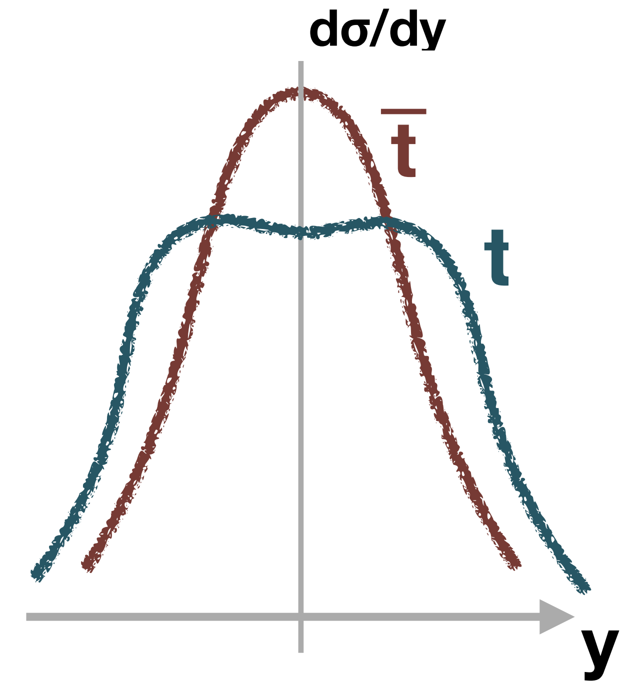

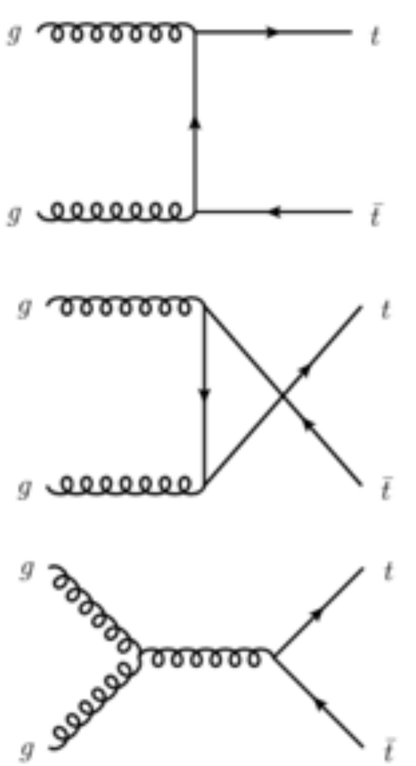

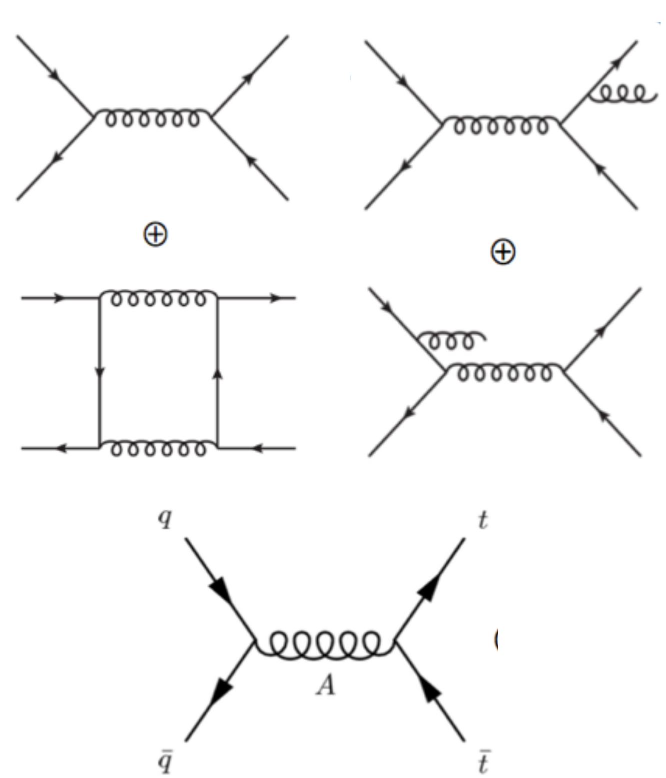

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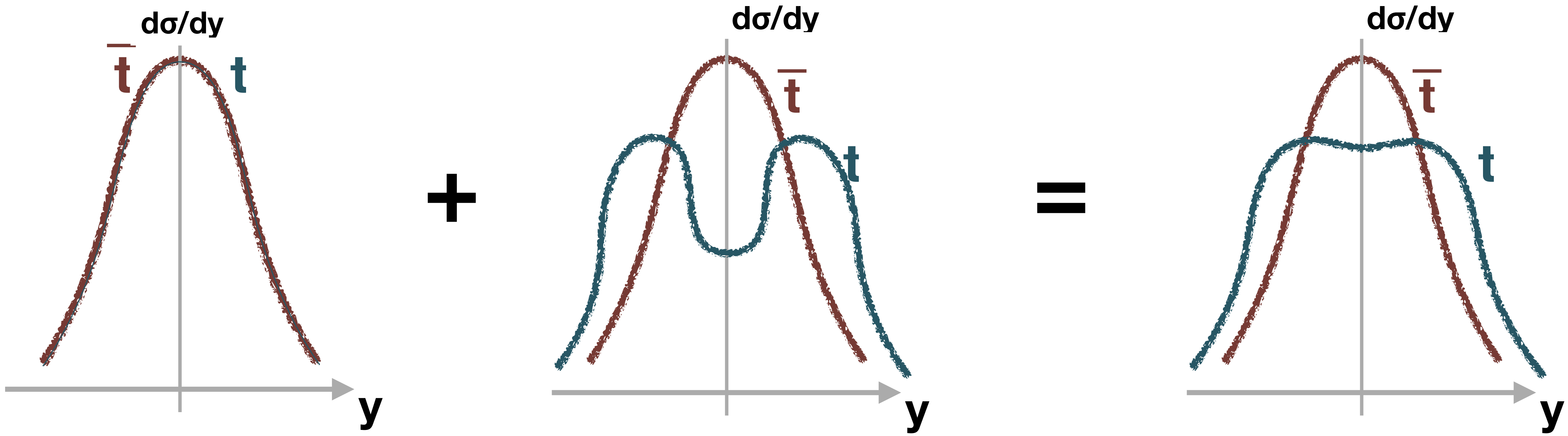
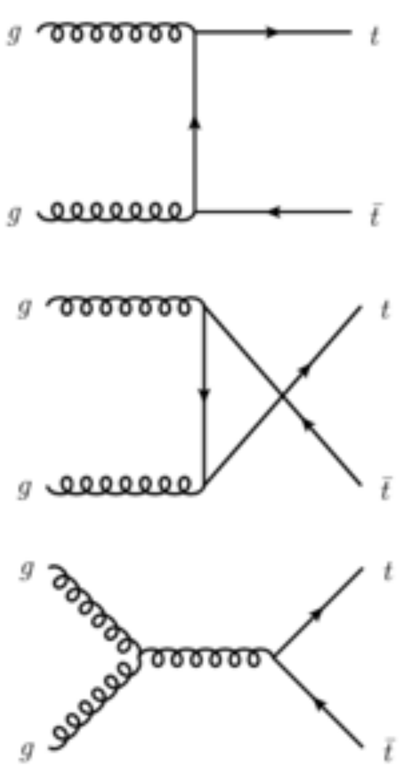
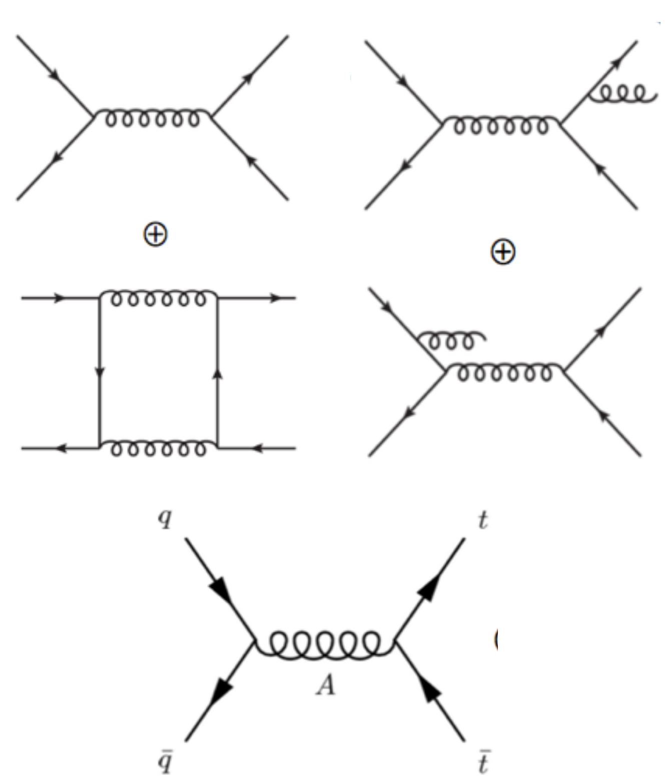






$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

with $\Delta|y| = |y_{top}| - |y_{antitop}|$

Semi-leptonic Measurements

Semi-leptonic Event Selection @ 8 TeV

ATLAS	CMS
1 isolated lepton p_T > 25 GeV (e), 25 GeV (μ) |η| < 2.5	1 isolated lepton p_T > 30 GeV (e), 26 GeV (μ) |η| < 2.5 (e), 2.1 (μ)
≥ 4 jets with p_T > 25 GeV and |η| < 2.5	≥ 4 jets with p_T > 20 GeV and |η| < 2.5
Signal Regions: 0,1, 2+ b-tag jets Efficiency: 70% b-jet, < 1% light jets	≥ 1 b-tagged jet Efficiencies: 65% b-jet, ~1.5% light jets
$E_T^{miss} + m_T^W$ > 60 GeV for 0,1 b-tags E_T^{miss} > 40 (20) GeV for 0 (1) b-tags	m_T^W used in fit to constrain QCD background
S/B ~ 3.5 ~ 60% Background is W+Jets	S/B ~ 4 ~ 60% Background is W+Jets

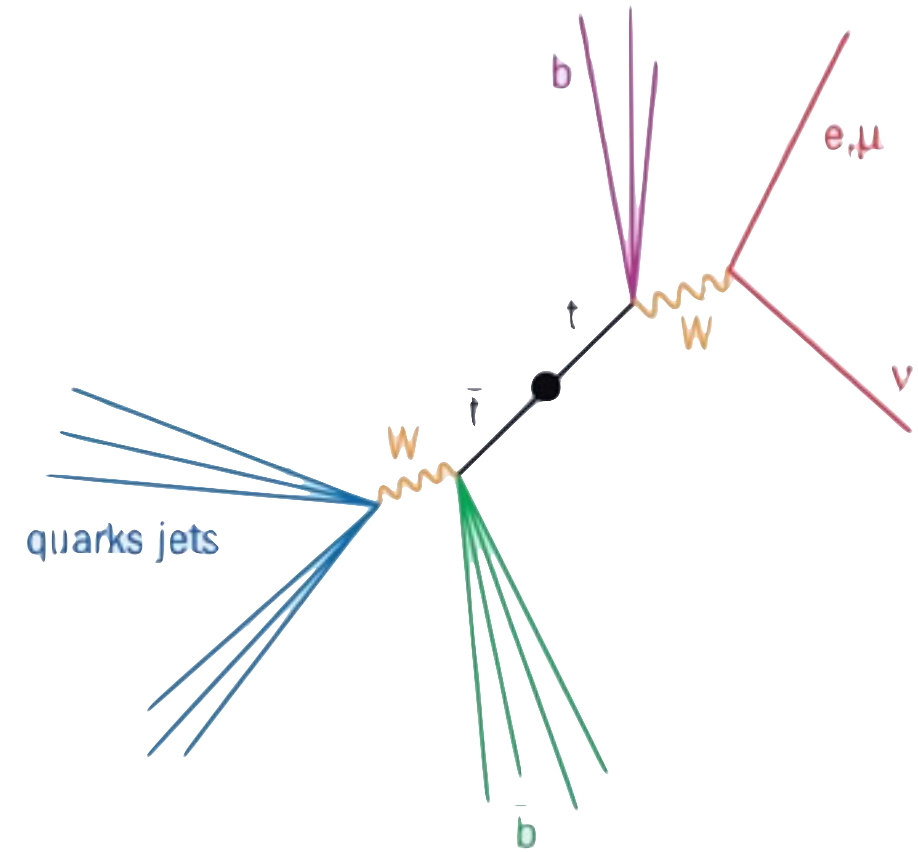
1 Tight lepton

≥ 4 High p_T jets

≥ 1 tagged jet

Kinematic Reconstruction in Semi-Leptonic Decays

- Kinematic fit with 4-vectors of the four jets, lepton, and missing transverse momentum used as inputs
- Constraints on the 'reconstructed' top quark and W-boson mass and width
  - m_t = 172.5 GeV, Γ_t = 1.5 GeV
  - m_W = 80.4 GeV, Γ_W = 2.1 GeV



ATLAS	CMS

ATLAS

$$L = \mathcal{B}(\widetilde{E}_{p,1}, \widetilde{E}_{p,2} | m_W, \Gamma_W) \cdot \mathcal{B}(\widetilde{E}_l, \widetilde{E}_\nu | m_W, \Gamma_W) \cdot \mathcal{B}(\widetilde{E}_{p,1}, \widetilde{E}_{p,2}, \widetilde{E}_{p,3} | m_t, \Gamma_t) \cdot \mathcal{B}(\widetilde{E}_l, \widetilde{E}_\nu, \widetilde{E}_{p,4} | m_t, \Gamma_t) \cdot$$

→ Breit-Wigner's for top quarks and W bosons

$$\mathcal{W}(\hat{E}_x^{miss} | \widetilde{p}_{x,\nu}) \cdot \mathcal{W}(\hat{E}_y^{miss} | \widetilde{p}_{y,\nu}) \cdot \mathcal{W}(\hat{E}_{lep} | \widetilde{E}_{lep}) \cdot$$

→ energy transfer functions

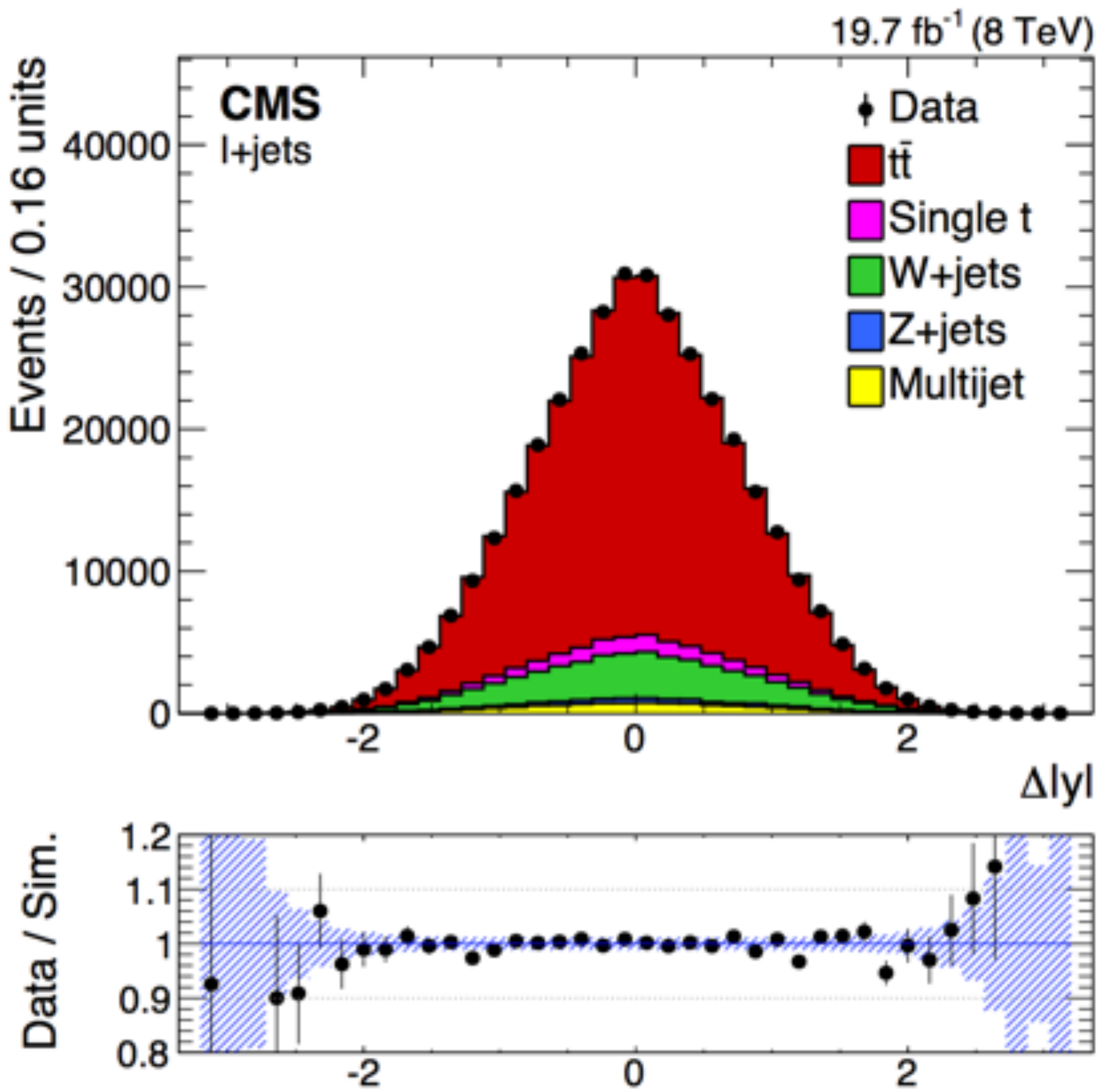
$$\prod_{i=1}^{4} \mathcal{W}(\hat{E}_{jet,i} | \widetilde{E}_{p,i}) \cdot P(b \text{ tag} \mid \text{quark})$$

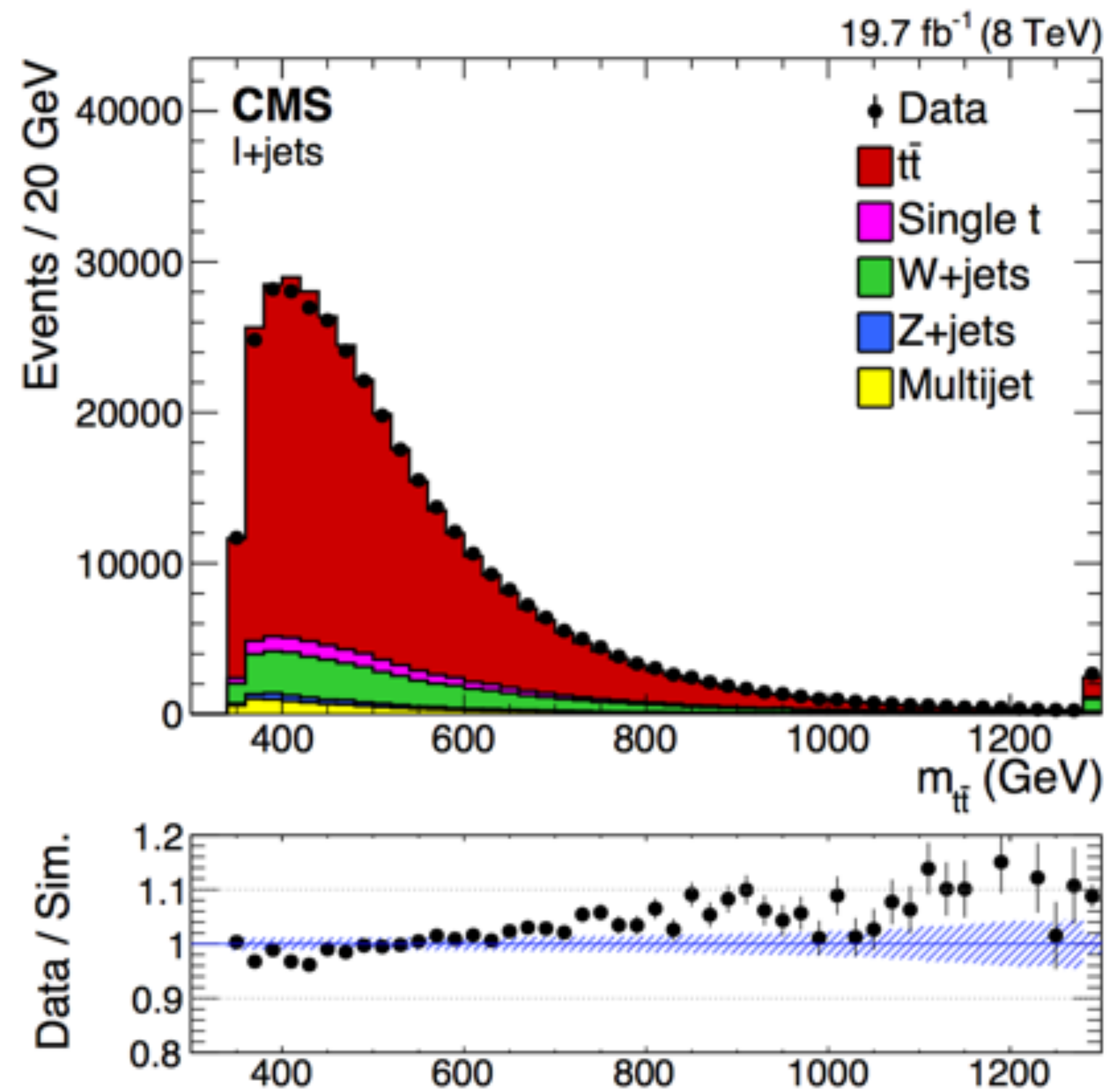
→ favor b-tagged jets in b-positions

CMS

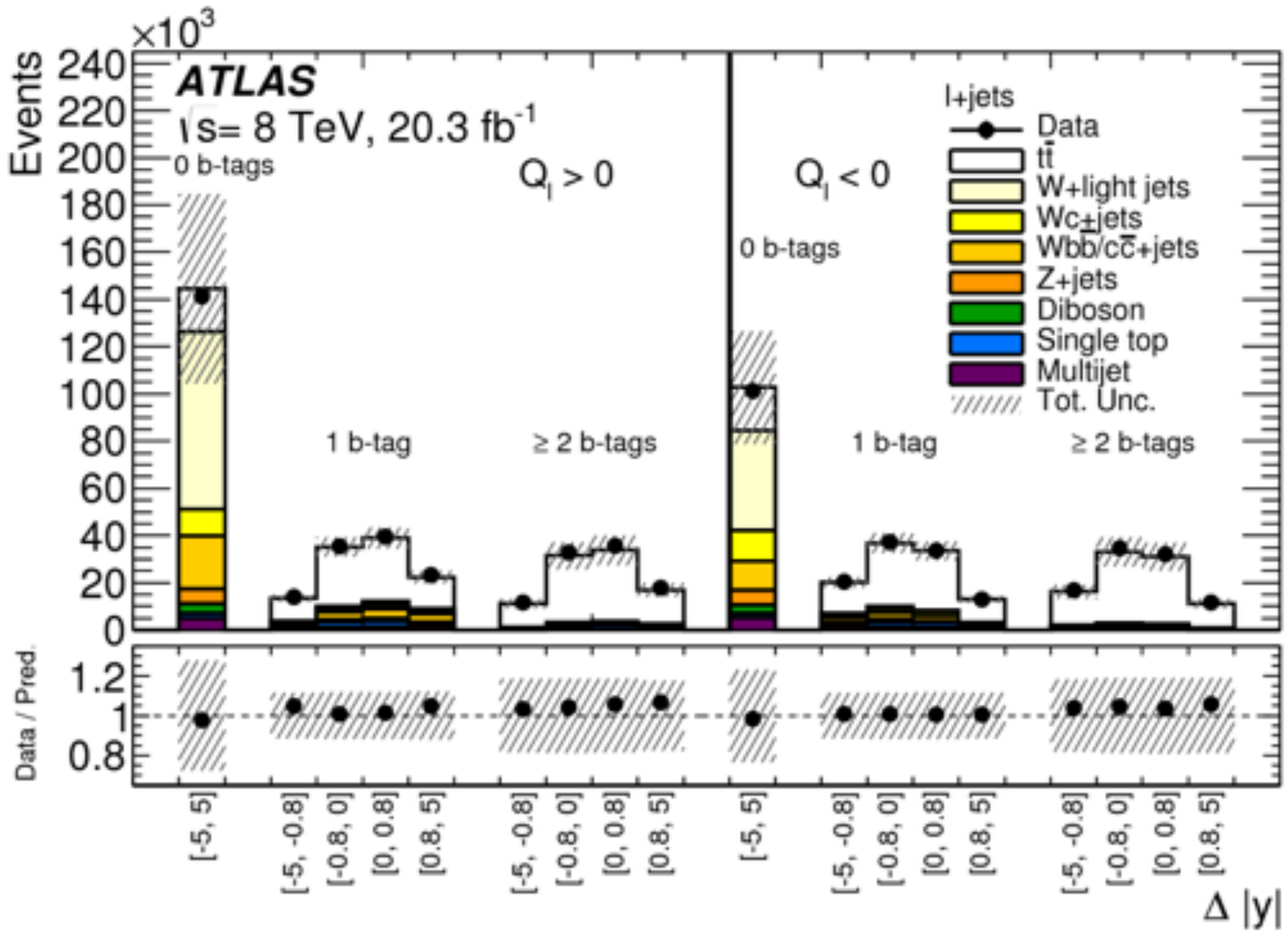
$$\chi^2_{bcd} = \left(\frac{m_W - \hat{m}_{cd}}{\Gamma_W/2}\right)^2 + \left(\frac{m_t - \hat{m}_{bcd}}{\Gamma_t/2}\right)^2 + \sum_{i=bcd} \left(\frac{\delta_i}{r_i}\right)^2$$

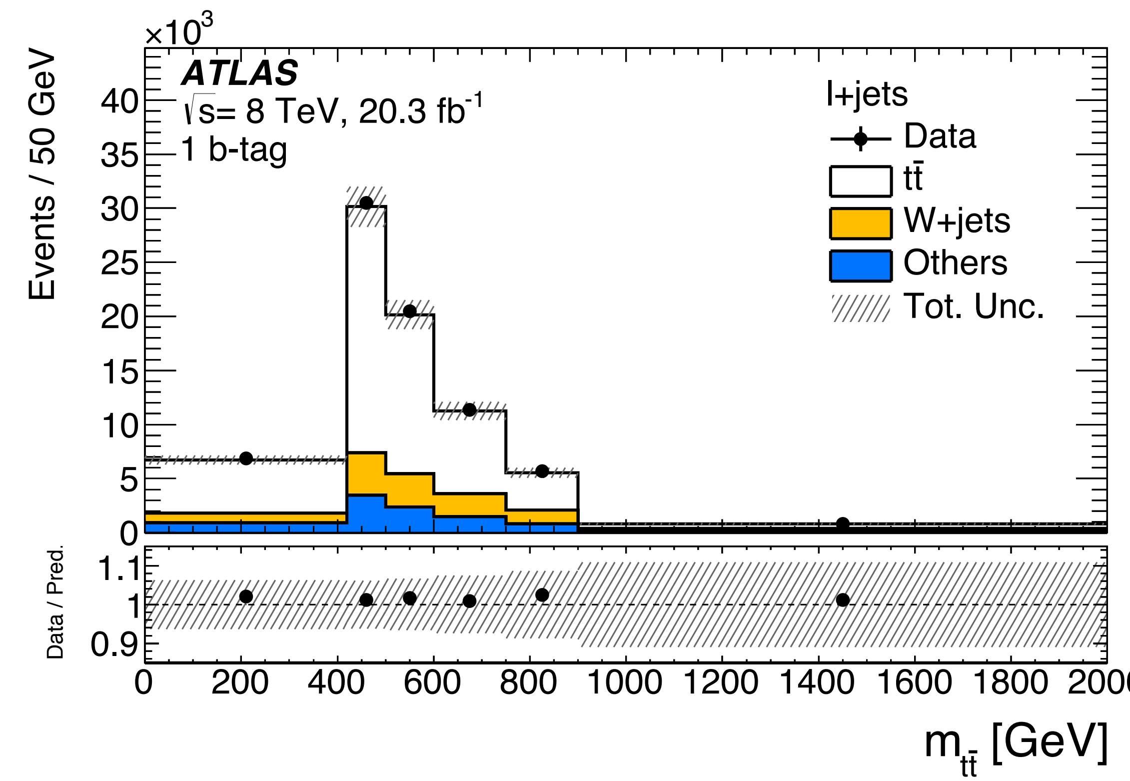
Reconstructed Distributions from CMS

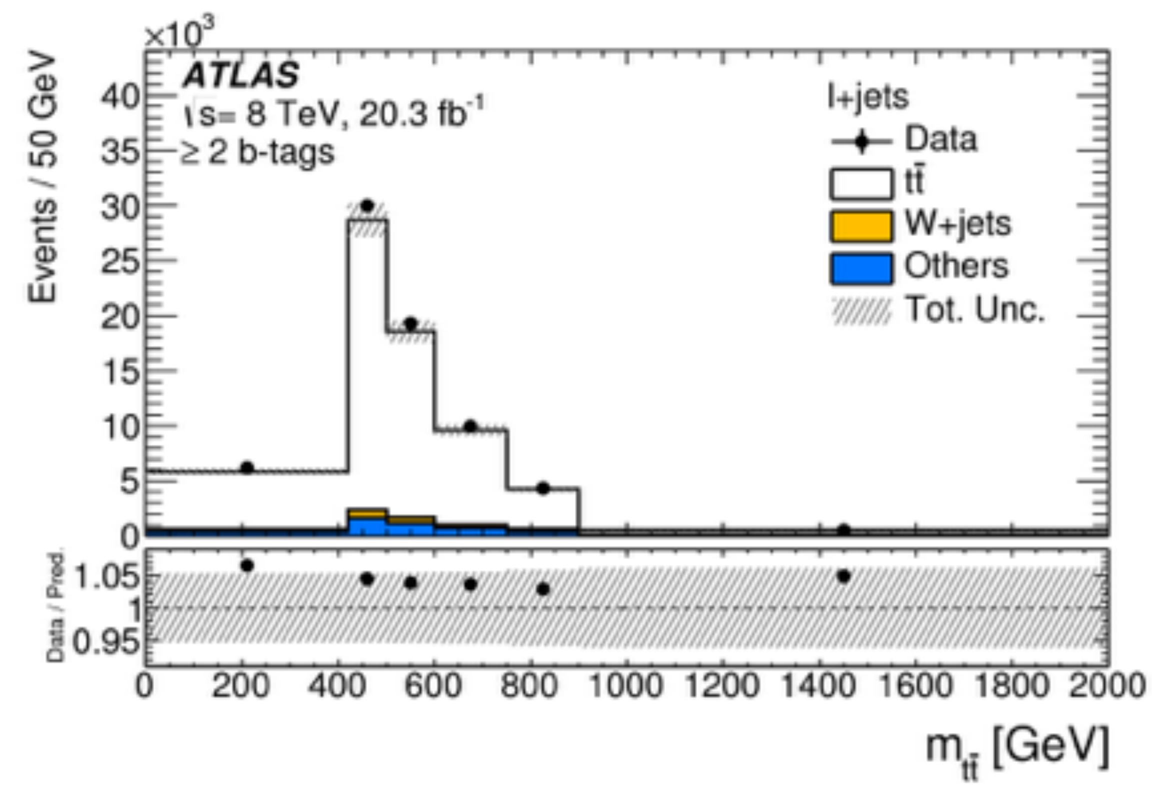




Reconstructed Distributions from ATLAS







Unfolding

ATLAS	CMS
• Fully Bayesian Unfolding technique - no explicit matrix inversion with in-situ handling of systematics	• Regularized Unfolding based on generalized matrix inversion

T: Δ|y| distribution to estimate before resolution and acceptance effects.

D: Δ|y| distribution measured in data distorted by resolution and acceptance.

$$p(T|D) \propto \mathcal{L}(D|T) \cdot \pi(T)$$

L(D|T): likelihood of observing D given T. Compares the effect of acceptance and resolution on a given T with what is measured in data (D).

π(T): prior probability for T. Encompass the prior knowledge or assumptions on the distribution T.

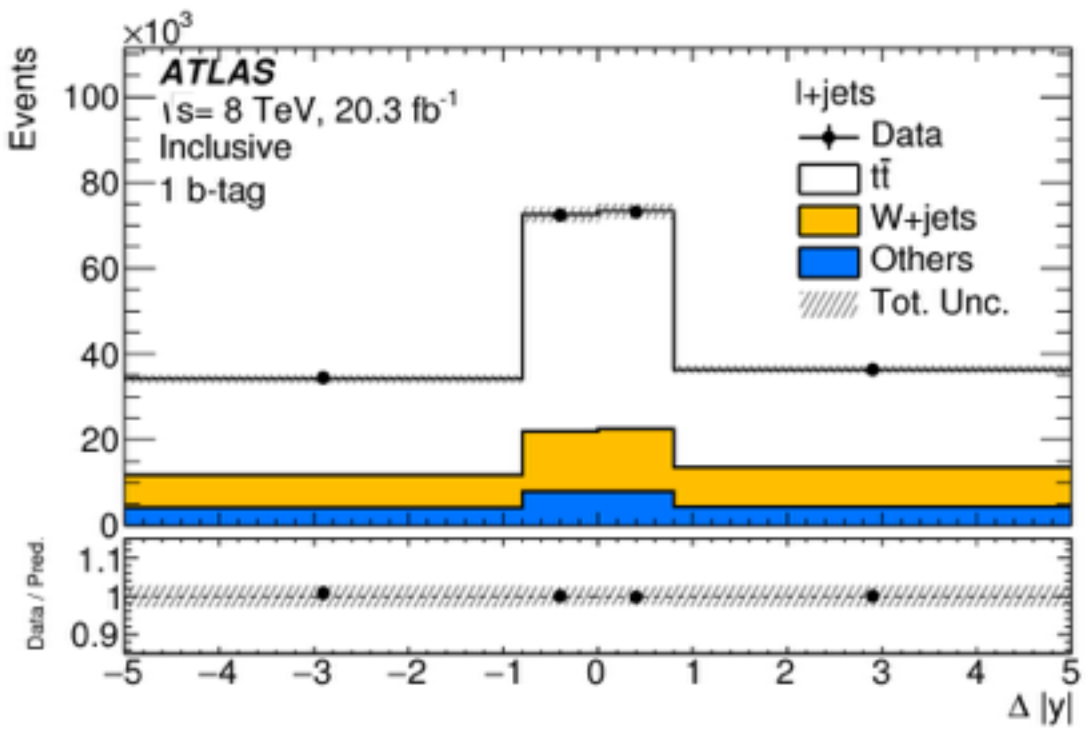
R: reconstructed Δ|y| distribution

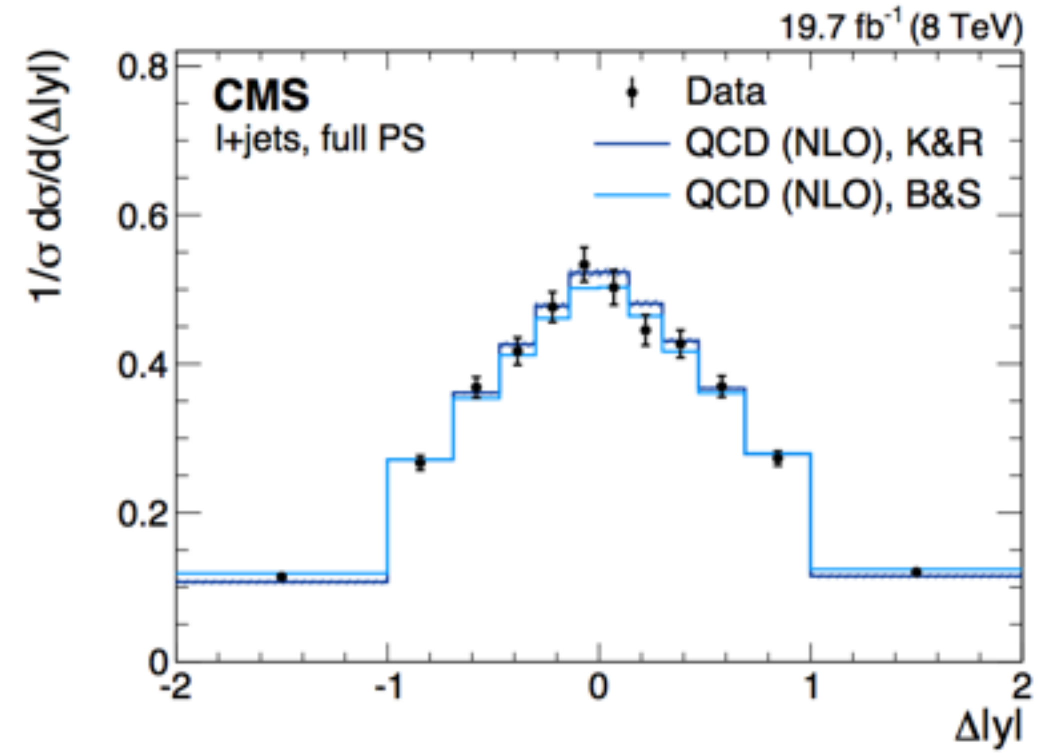
T: parton-level Δ|y| distribution

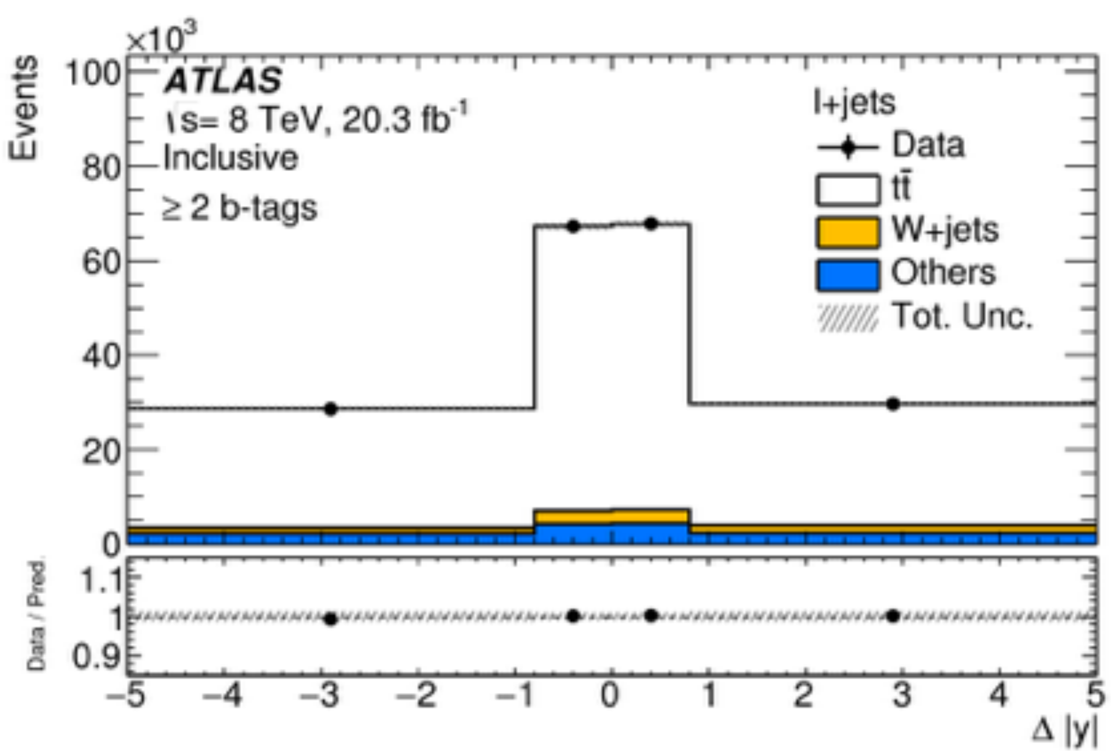
$$R = M \cdot T$$

M: Map of event migrations

Results







		stat	syst	
A_C =	0.0010	± 0.0068	± 0.0037	CMS

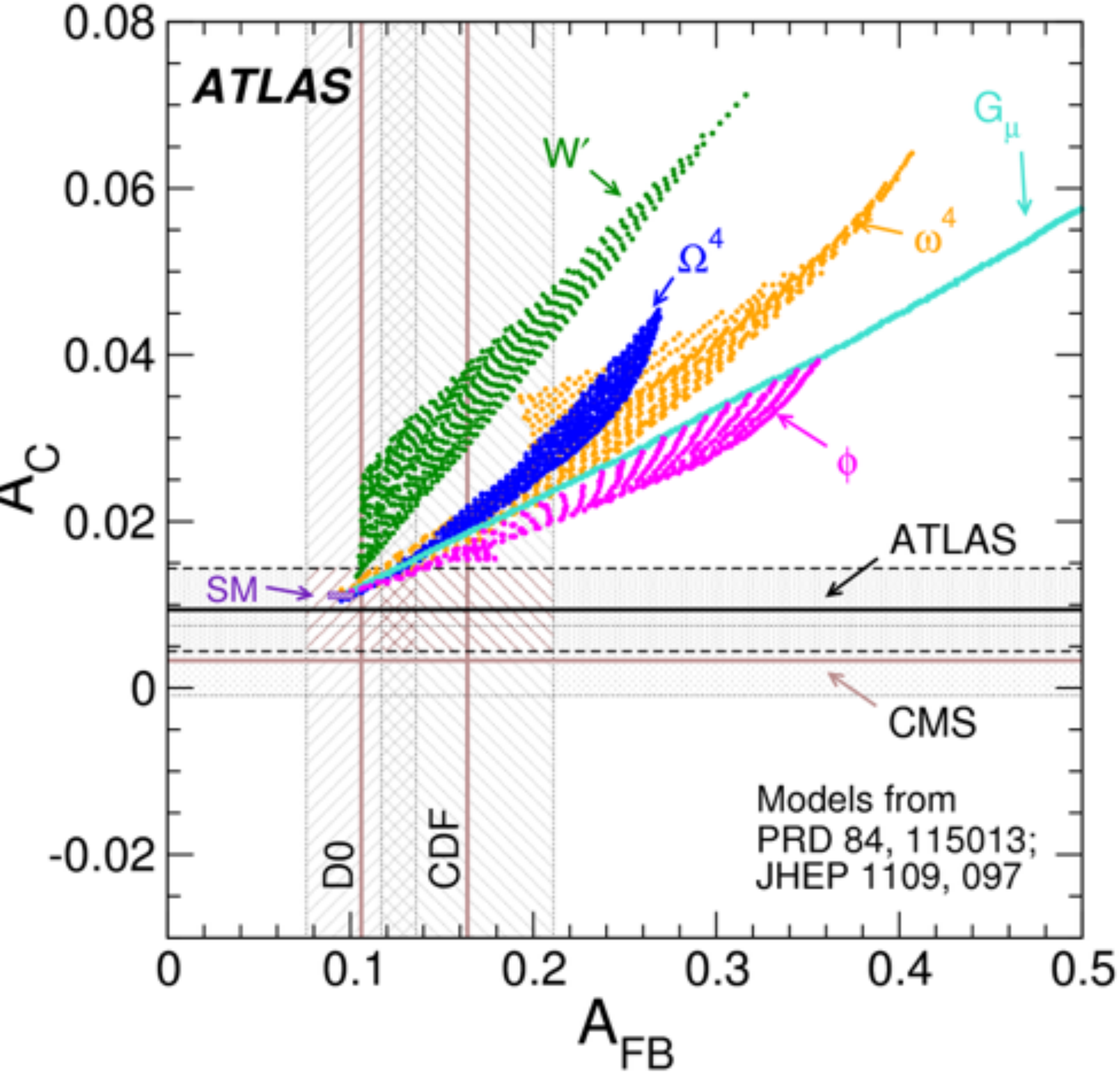
Submitted to Phys.Lett. B arxiv:1507.03119

A_C = 0.009 ± 0.005 *stat+syst* ATLAS

Submitted to EPJC arxiv:1509.02358

A_C = 0.0101 ± 0.0005 NNLO

Kuhn, Rodrigo



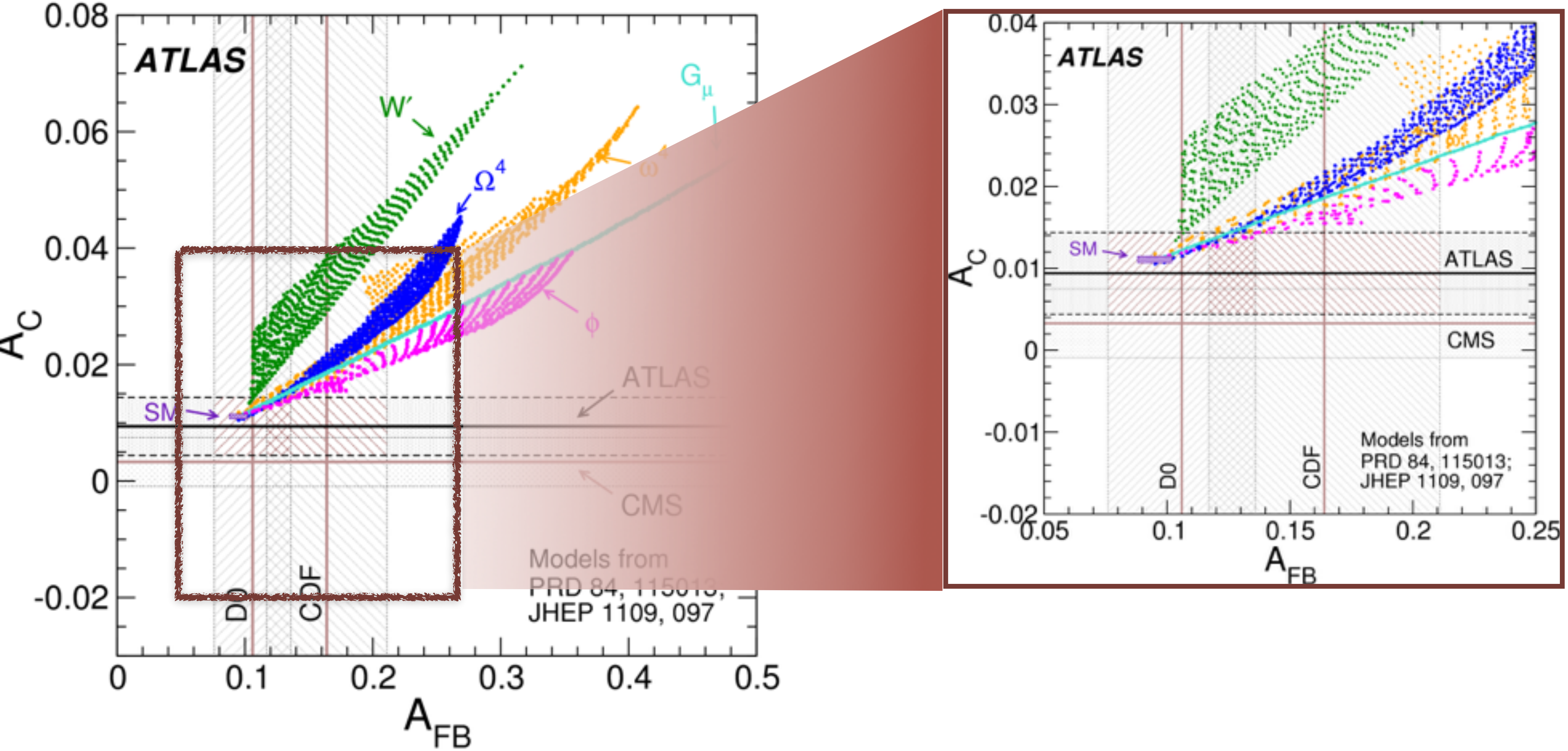
Gμ : A new color-octet neutral vector boson exchanged in the s channel

W′: A charged color-singlet vector boson Z exchanged in the t channel in $d\bar{d} \rightarrow t\bar{t}$

ϕ : A color-singlet scalar doublet with hypercharge –1/2 exchanged in t channel

Ω4 : A charge 4/3 scalar color sextet exchanged in the u channel

ω4 : A charge 4/3 scalar color triplet exchanged in the u channel



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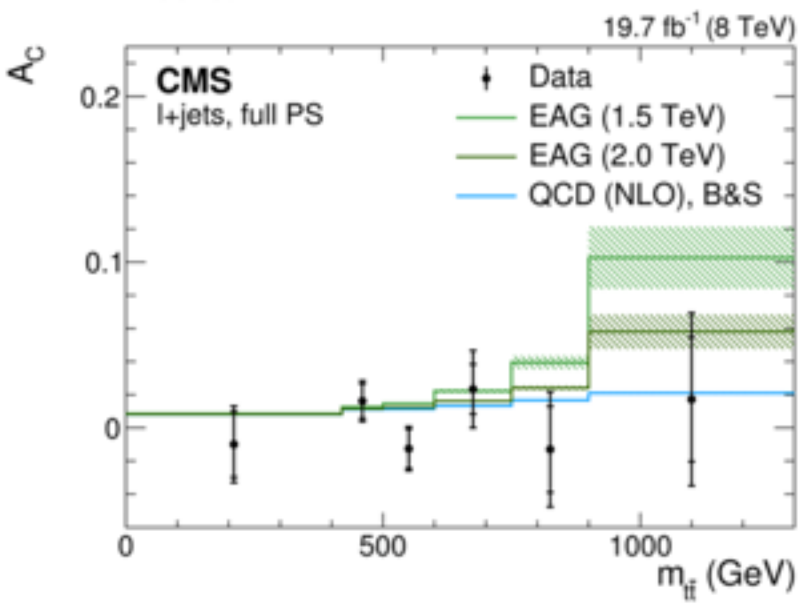
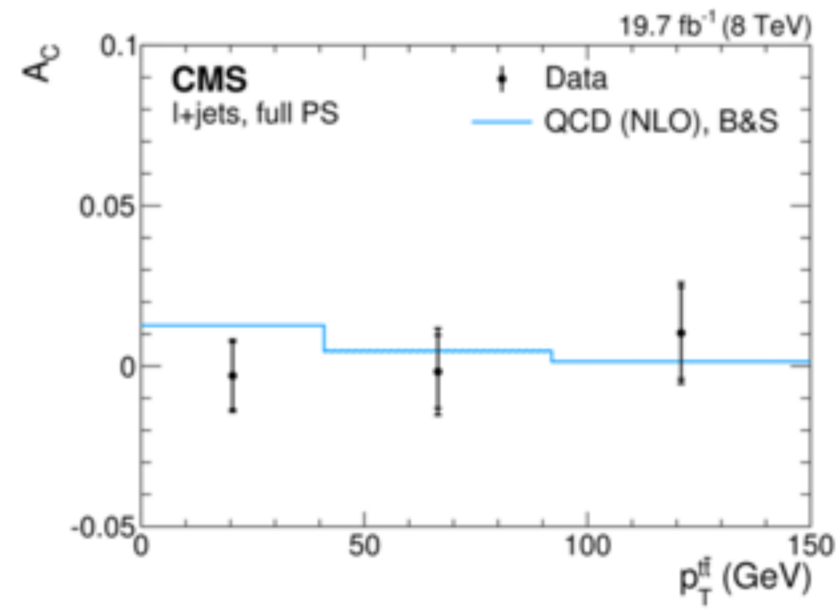


19.7 fb-1 (8 TeV)
CMS
l+jets, full PS
Data
EAG (1.5 TeV)
EAG (2.0 TeV)
QCD (NLO), B&S
A_C
m_tt̄ (GeV)



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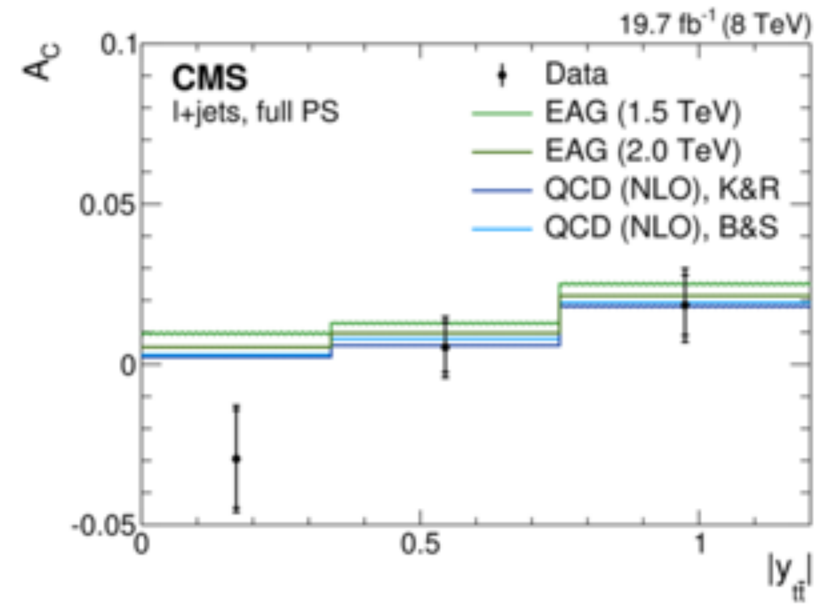
p_T^tt̄ (GeV)



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CMS
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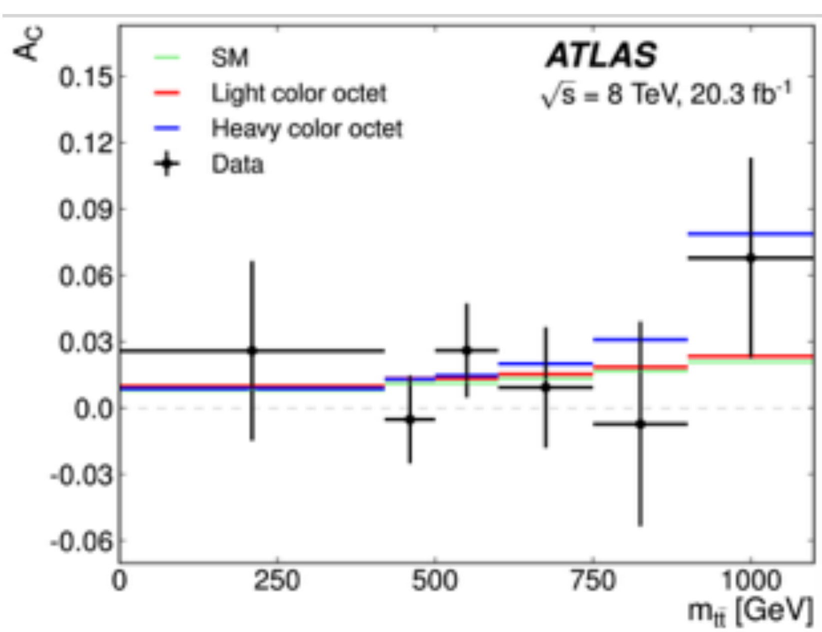
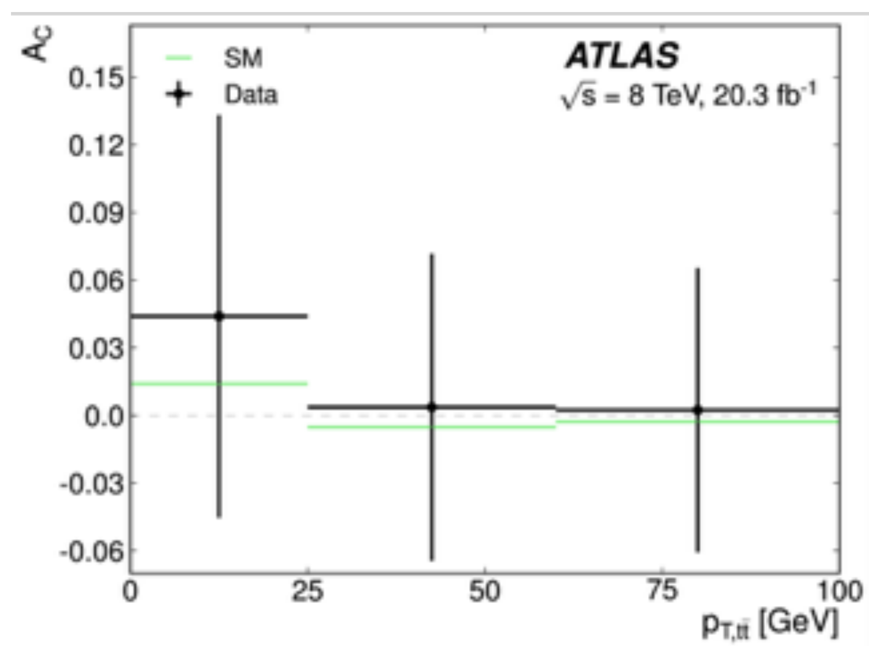
Data
EAG (1.5 TeV)
EAG (2.0 TeV)
QCD (NLO), K&R
QCD (NLO), B&S
A_C
|y_tt̄|



SM
Light color octet
Heavy color octet
Data
ATLAS
√s = 8 TeV, 20.3 fb-1
A_C
m_tt̄ [GeV]



SM
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ATLAS
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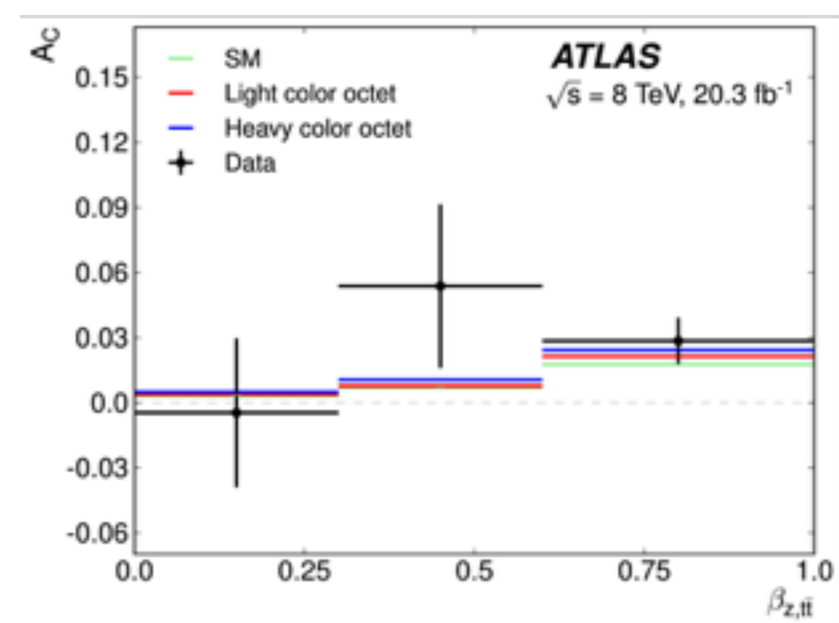
A_C
p_T,tt̄ [GeV]



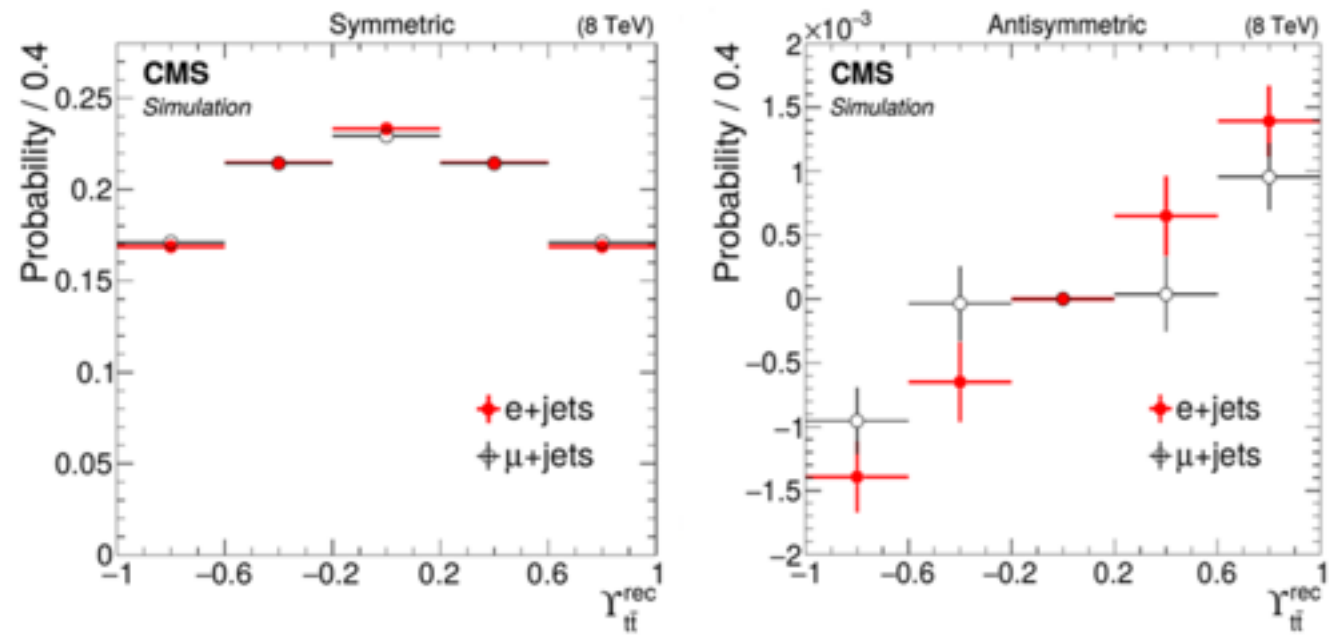
SM
Light color octet
Heavy color octet
Data
ATLAS
√s = 8 TeV, 20.3 fb-1
A_C
β_z,tt̄

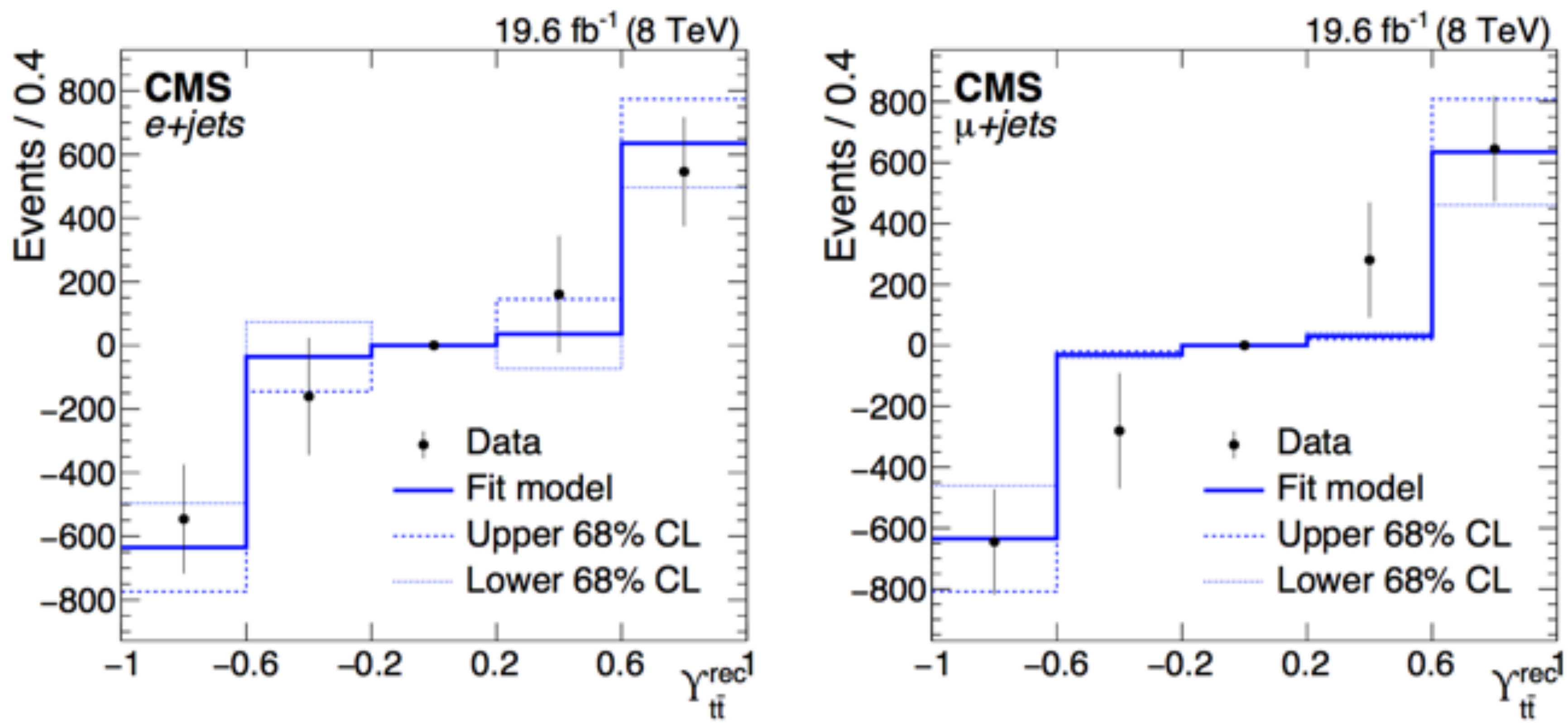
Charge Asymmetry at 8 TeV using Template Method

- Template technique: symmetrized and asymmetric version of MC template fit to reconstructed variable

$$\Upsilon_{t\bar{t}} = \tanh \Delta|y|_{t\bar{t}}$$

- Measure ratio after fit to calculate asymmetry at the parton level

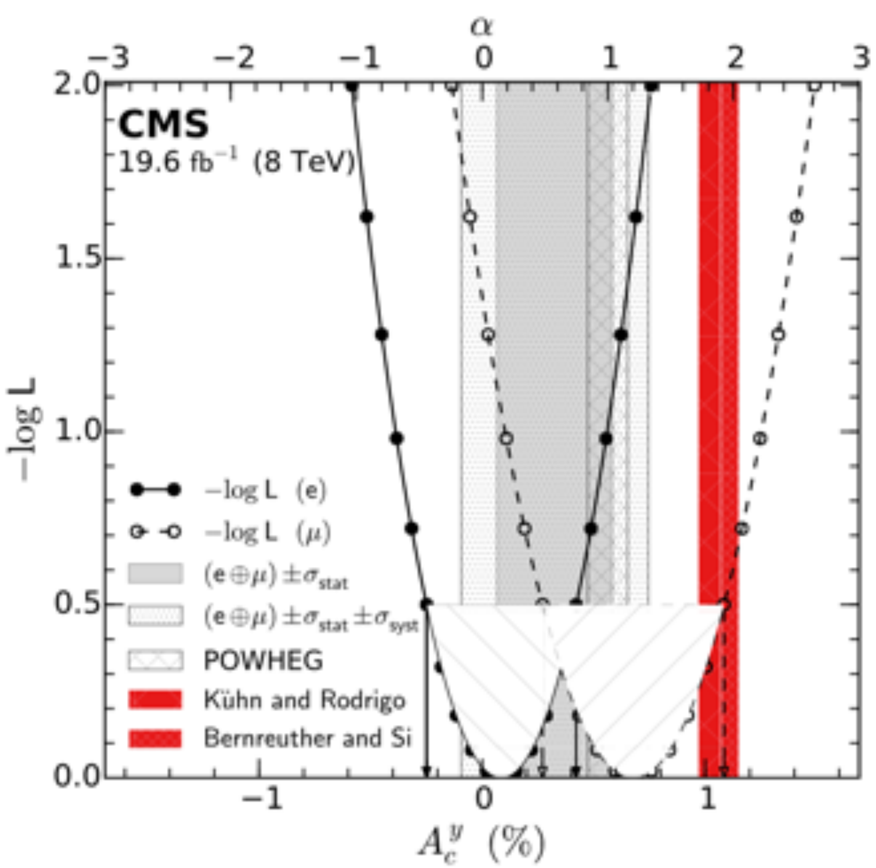


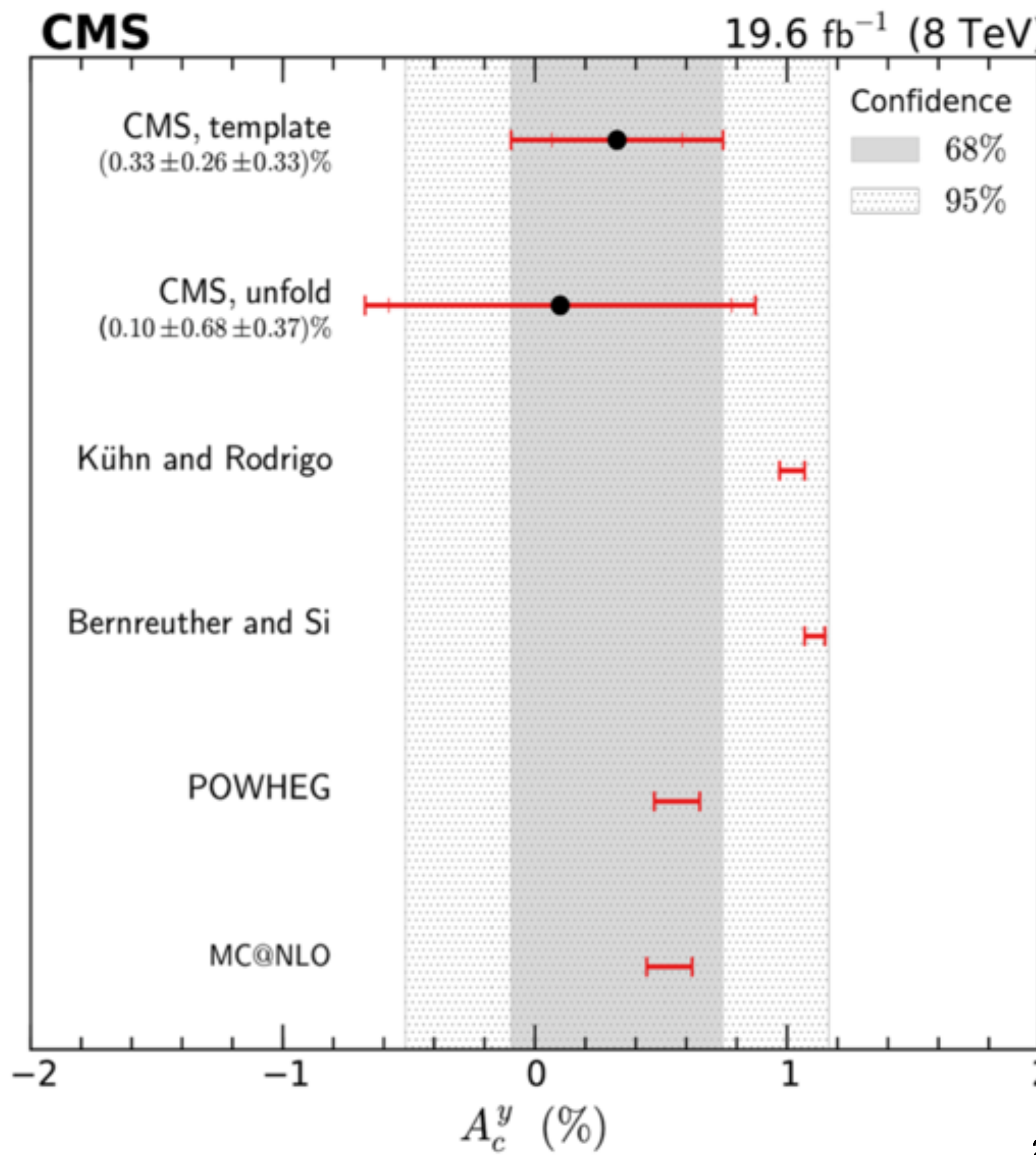


Submitted to Phys. R

Charge Asymmetry at 8 TeV using Template Method

- More model dependent, but significantly smaller statistical uncertainty
- No differential measurements





Submitted to Phys. Rev. D arxiv:1508.03862

Dilepton Measurements

Charge Asymmetry in Di-lepton Decays @ 7 TeV

ATLAS	CMS
2 OS isolated leptons p_T > 25 GeV (e), 20 GeV (μ) $\|\eta\| < 2.5$	2 OS isolated leptons p_T > 20 GeV (e,μ) $\|\eta\| < 2.5$ (e), 2.4 (μ)
≥ 2 jets with p_T > 25 GeV and $\|\eta\| < 2.5$	≥ 2 jets with p_T > 30 GeV and $\|\eta\| < 2.5$
Reject events with 80 < m_{ll} < 100 GeV or < 15 GeV consistent with ~ m_Z or Drell-Yan	Reject events with 76 < m_{ll} < 106 GeV or < 20 GeV consistent with ~ m_Z or Drell-Yan
E_T^{miss} > 60 GeV H_T > 130 GeV in eμ channel	≥ 1 b-tagged jet Efficiency: 70% b-jet, 20% c-jet, 1.5% light jets
S/B ~ 7 Mixture of single top, Z+Jets, Diboson and Fakes	S/B ~ 10 Mixture of single top, Z+Jets, Diboson and Fakes

2 OS Tight leptons

≥ 2 High p_T jets

Reject Z events

Reconstruction and Unfolding

- System is under-constrained due to the neutrinos, so further assumptions on the neutrino pseudo-rapidity

ATLAS

- Reconstruction performed by solving kinematic equations obtained when imposing energy-momentum conservation at each decay vertex
- Fully Bayesian Unfolding is used for corrections

$$p(\mathrm{T}|\mathrm{D}) \propto \mathcal{L}(\mathrm{D}|\mathrm{T}) \cdot \pi(\mathrm{T})$$

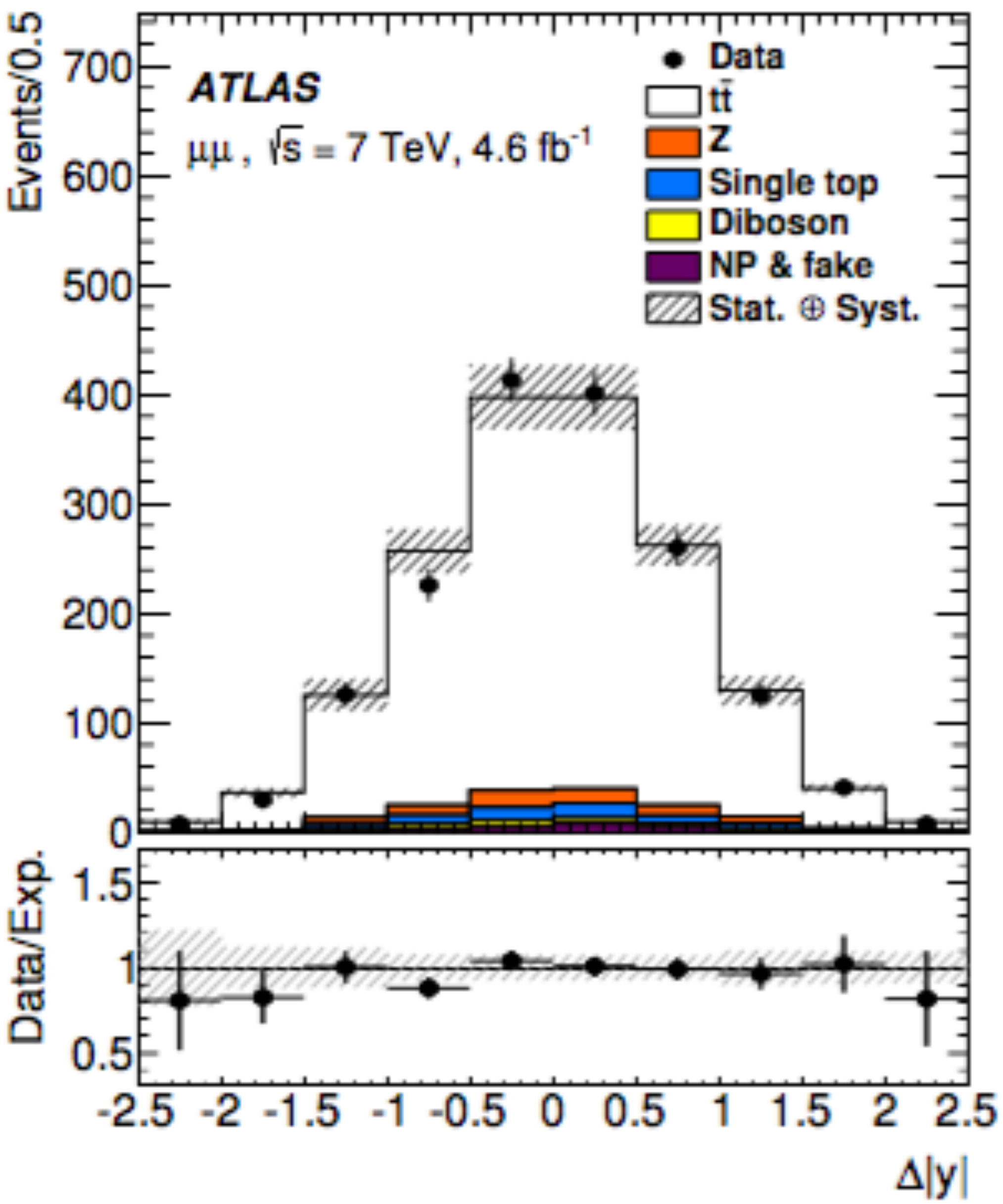
CMS

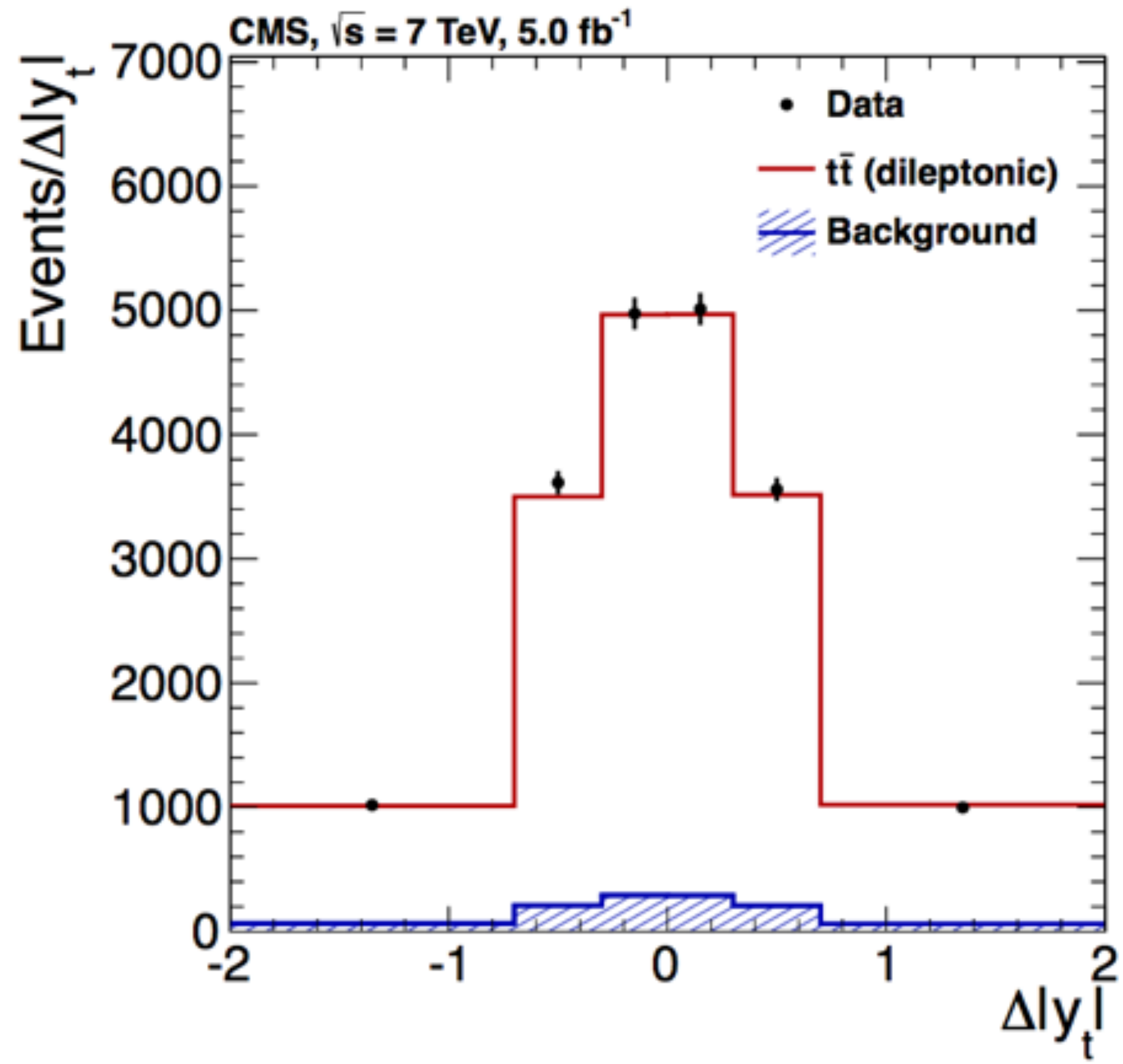
- "Analytical matrix weighting technique" (AMWT) used to find most probable configuration of jets to partons and neutrino kinematics
- Unfolding is performed with singular value decomposition

$$R = M \cdot T$$

Reconstructed Distributions

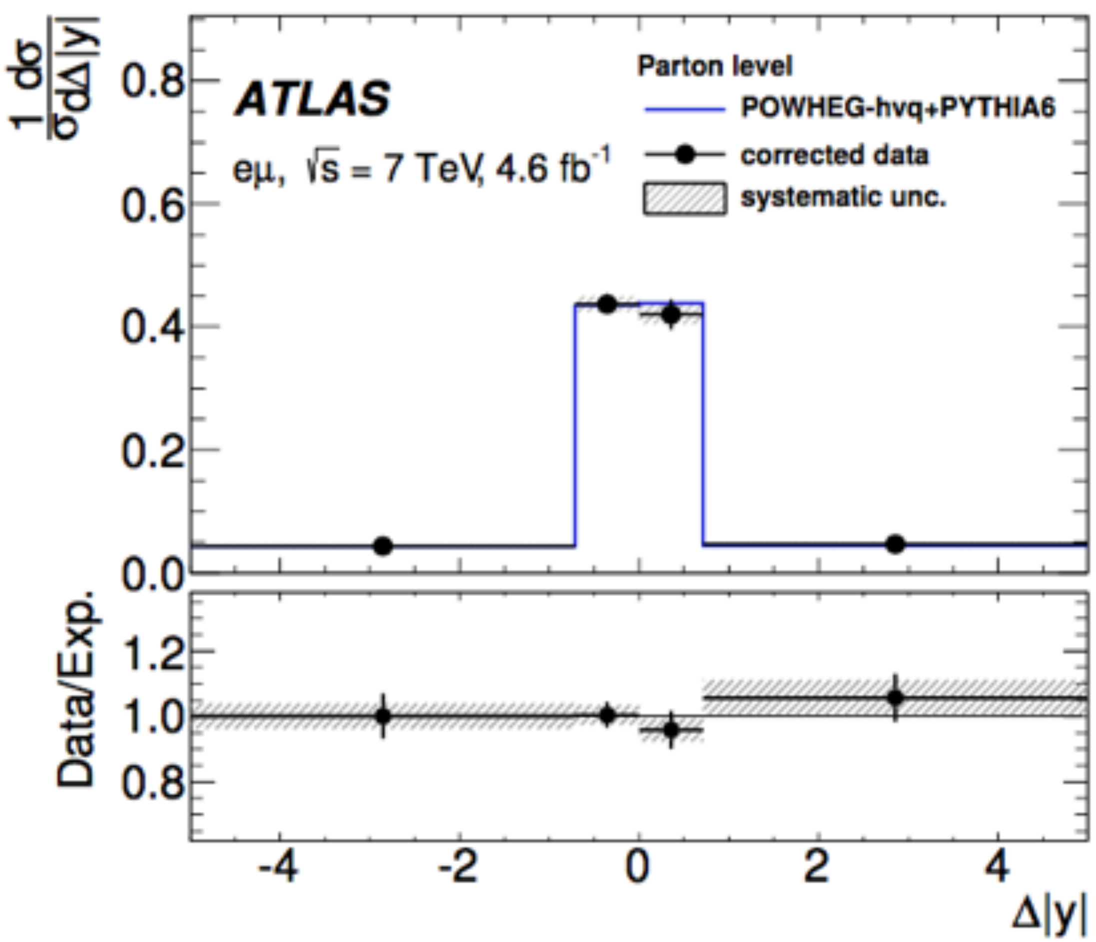
ATLAS	CMS

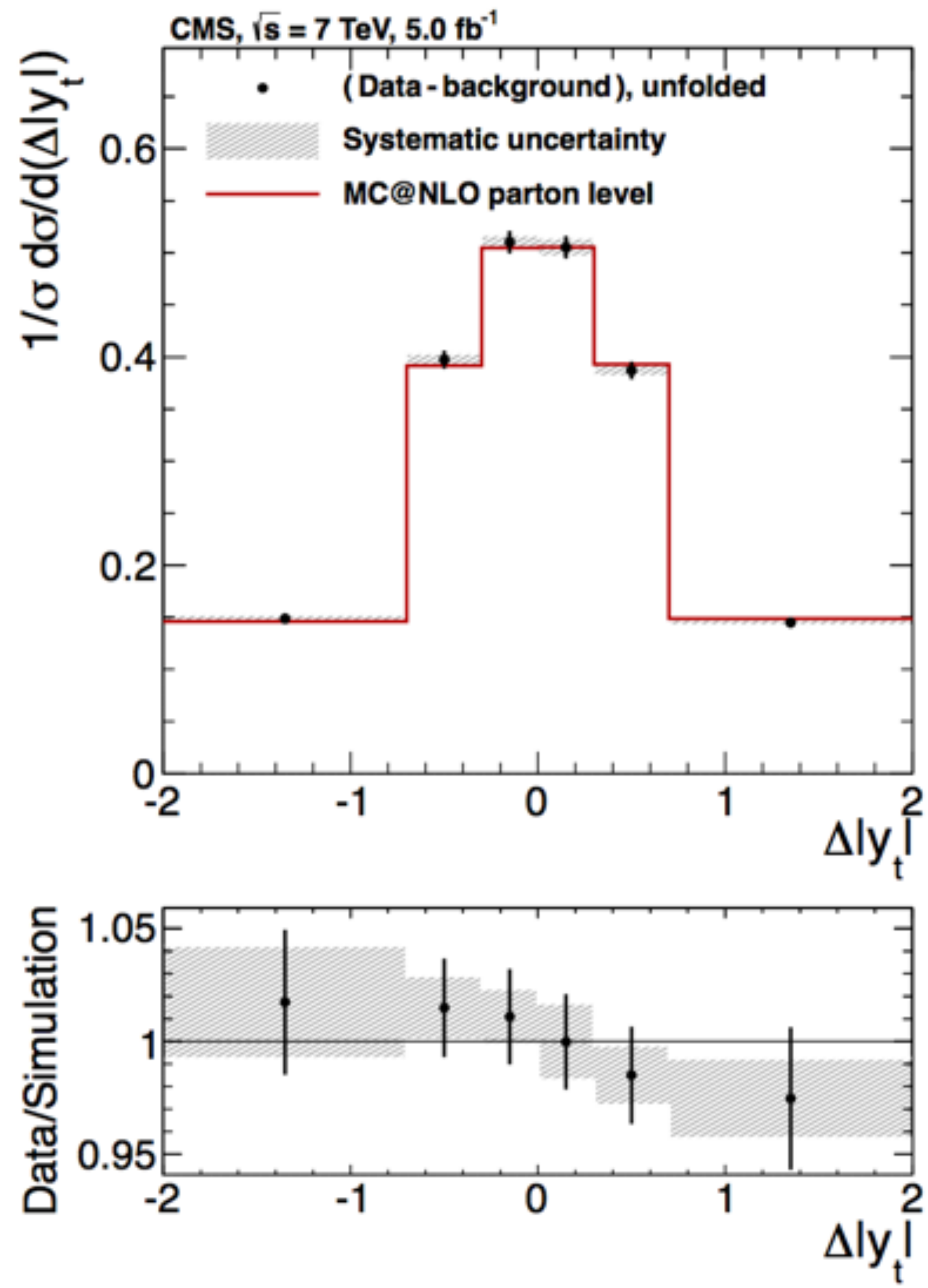




Results in Dileptons

ATLAS	CMS



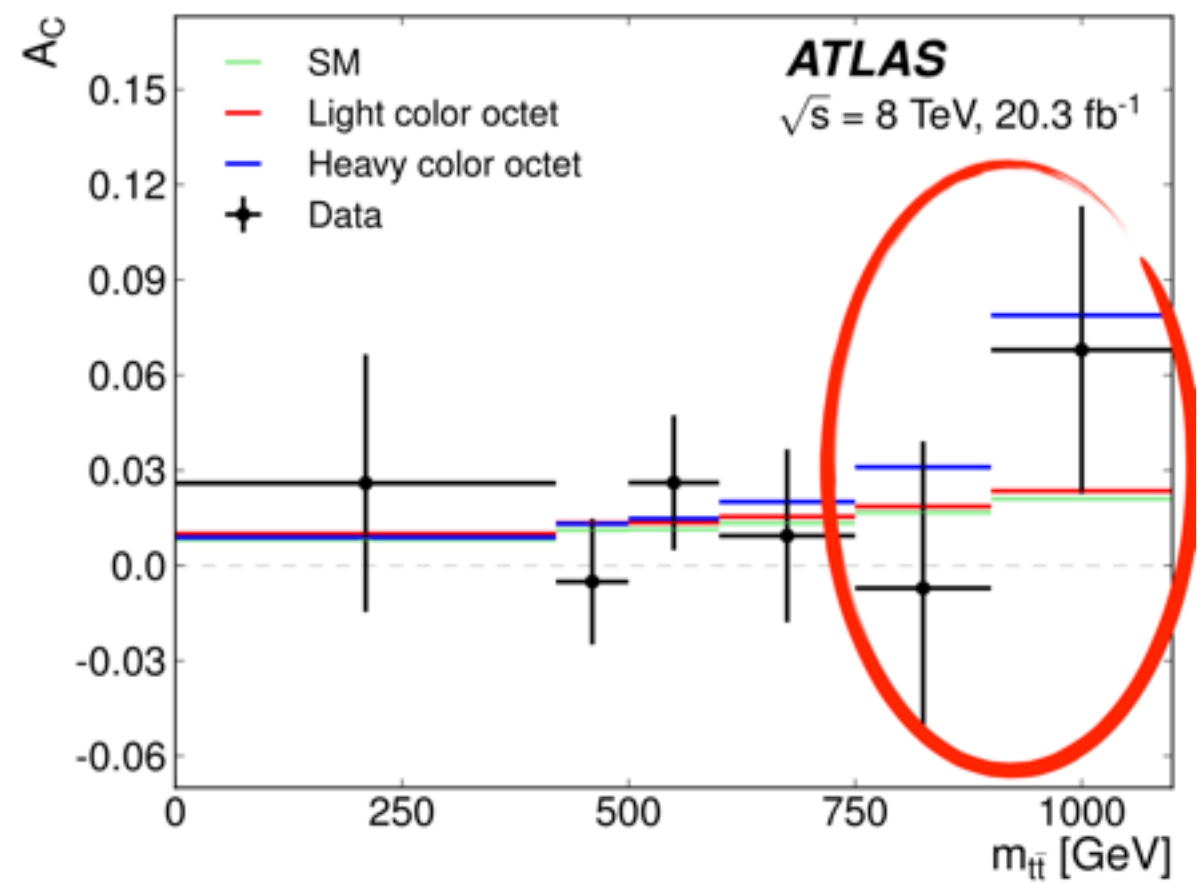


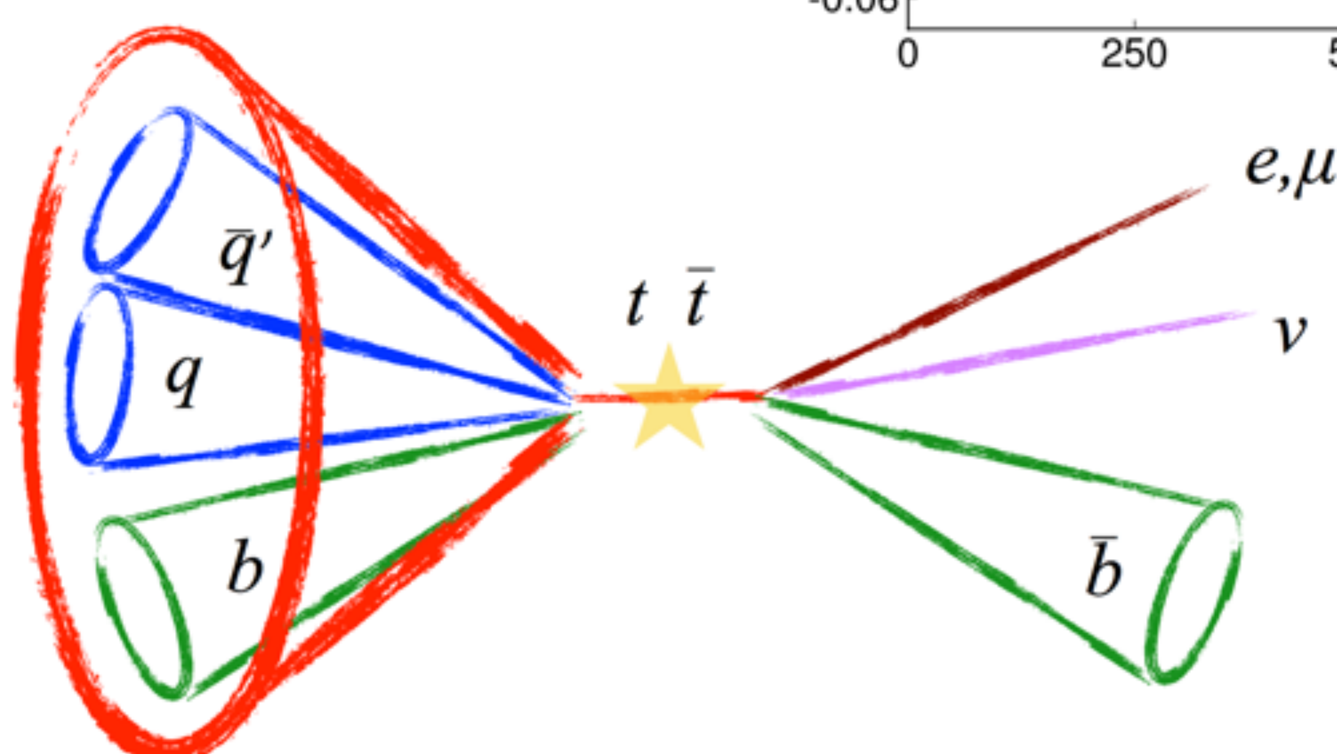
		stat	syst	
A_C	-0.010	± 0.017	± 0.008	CMS
		JHEP 04 (2014) 191 arxiv:1402.3803		
A_C	0.021	± 0.025	± 0.017	ATLAS
		JHEP 05 (2015) 061 arxiv:1501.07383		
A_C	0.0101		± 0.0005	NNLO
				Kuhn, Rodrigo

Boosted

Asymmetry in Boosted Top Quark Events

- Measurement probes the asymmetry in higher energy events and complements the resolved analysis
- Decay products collimated for top quarks produced with $p_T > 300$ GeV
- Boosted top quark events with semi-leptonic decay are identified with large R-jet substructure techniques
- Improved reconstruction at high energy: Correction Assignment Boosted (88%) Resolved (73%)





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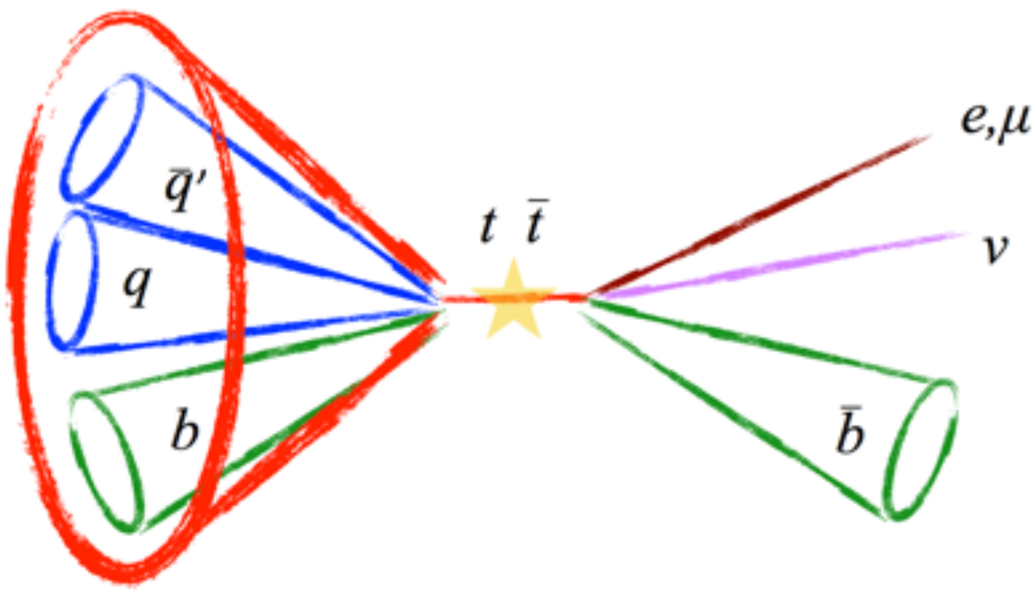

Leptonic Top

Lepton, Small-R Jet

$p_T > 25$ GeV

**mini-isolation*

MET > 20 GeV

MET+MTW > 60 GeV

Hadronic Top

- 1 Anti-k_T R=1.0 Large-R Jet
  Trimmed: r_{sub}=0.3, f_{cut}=5%
- $p_T > 300$ GeV
- m > 100 GeV
- $\sqrt{d_{12}} > 40$ GeV

Other Criteria

$\Delta\phi(\ell,\text{Large-R Jet}) > 2.3$

$\Delta R(\ell,\text{Small-R Jet}) < 1.5$

$\Delta R(\text{Small-R},\text{Large-R}) > 1.5$

≥ 1 b-tagged Jet

$m_{tt} > 750$ GeV**

	e+jets	μ+jets
$t\bar{t}$	4100 ± 600	3600 ± 500
W+jets	263 ± 32	264 ± 32
Single Top	140 ± 20	138 ± 19
Multi-jet	44 ± 8	4 ± 1
Z+jets	40 ± 27	16 ± 11
Dibosons	20 ± 7	18 ± 7
$t\bar{t}V$	37 ± 19	33 ± 17
Prediction	4600 ± 600	4000 ± 500
Data	4130	3600

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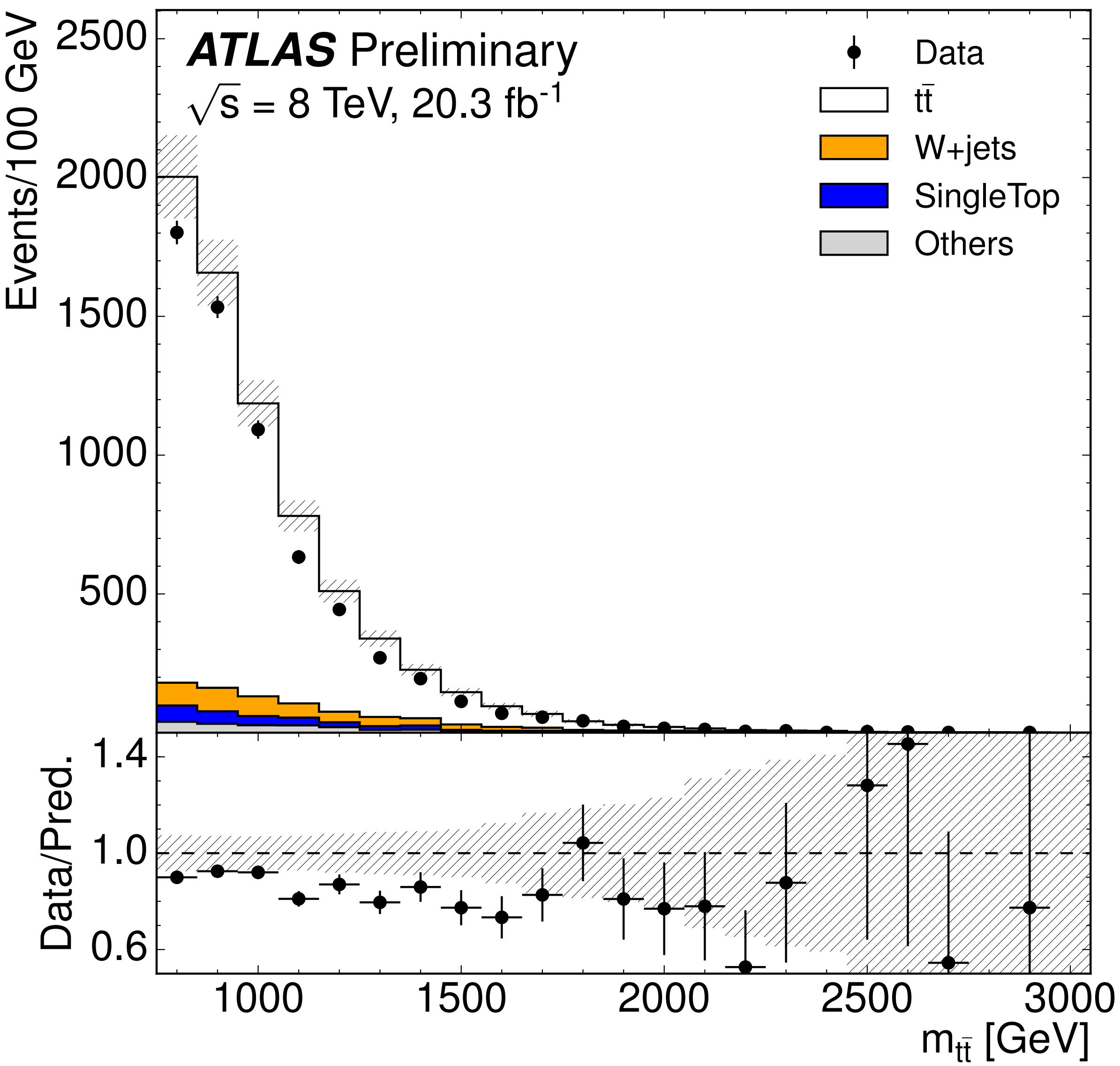
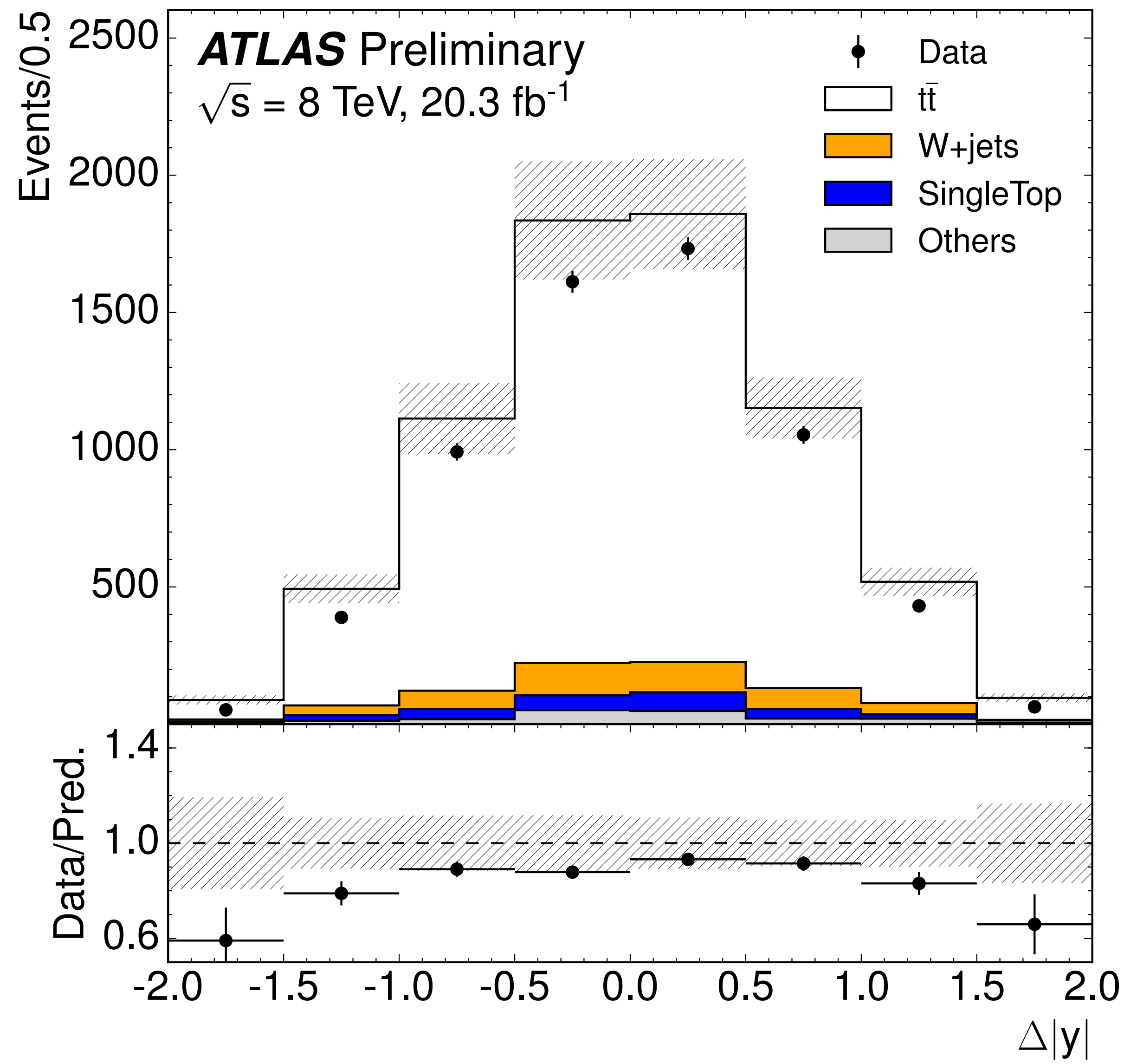
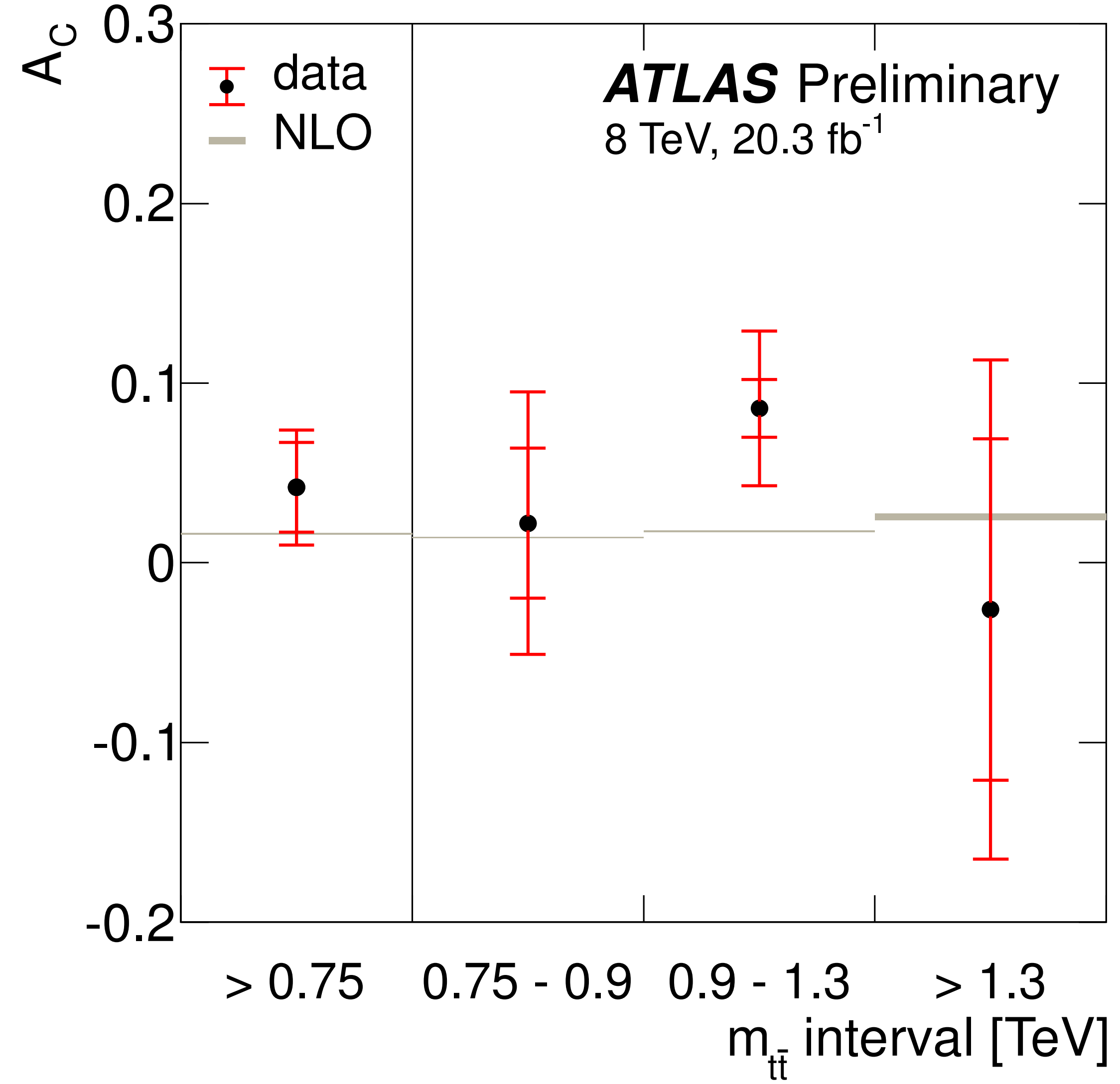


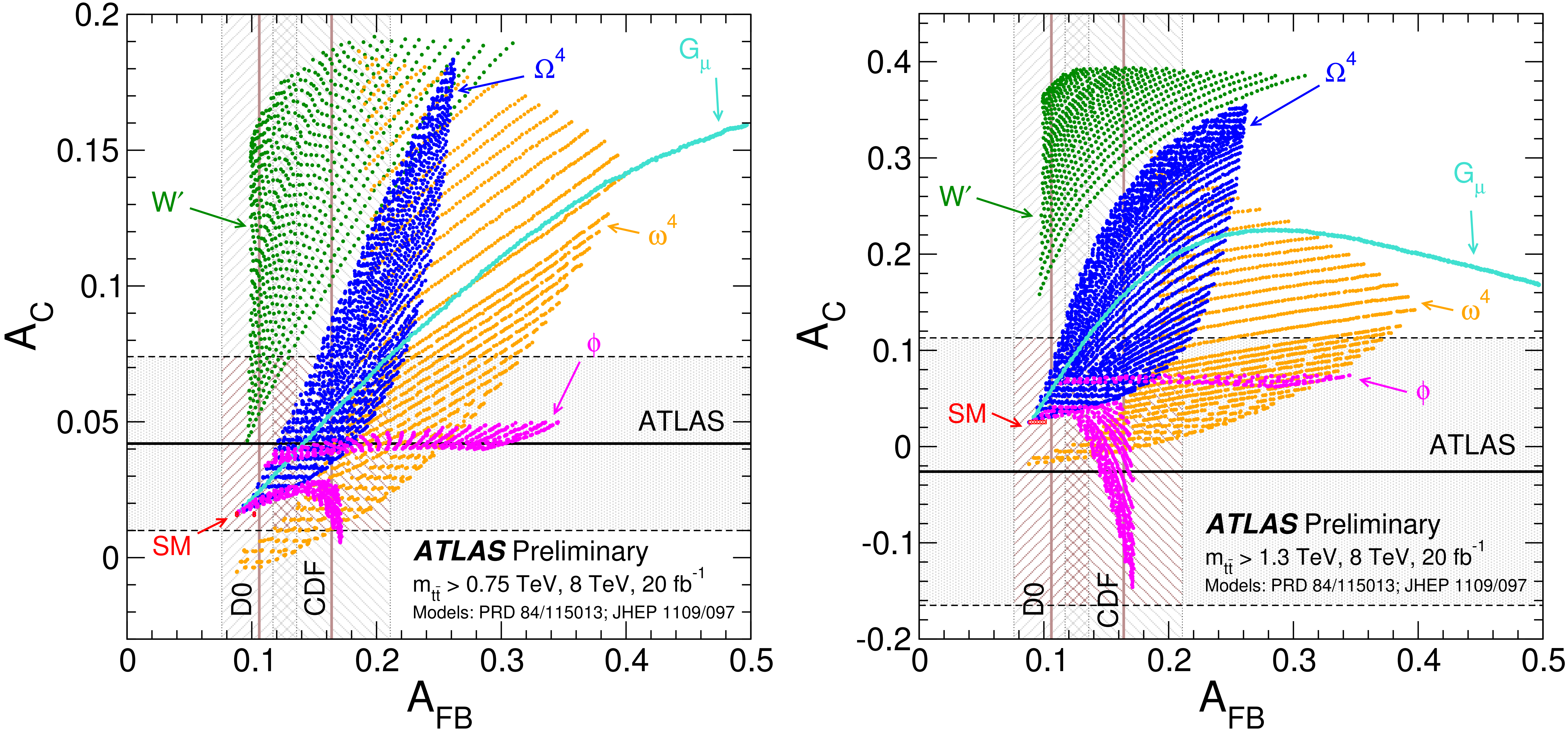


Asymmetry in Boosted Top Quark Events

- Fully bayesian unfolding used to translate reconstructed observables to parton-level distributions
- Measurement limited to fiducial region to remove large uncertainties associated with the forward region of the detector and low mtt events where reconstruction is poor
  - $-2 < \Delta|y| < 2$
  - $750 \text{ GeV} < M_{tt} < 4000 \text{ GeV}$
- Results consistent with Standard Model



$m_{t\bar{t}}$ interval	>0.75 TeV	$0.75-0.9$ TeV	$0.9-1.3$ TeV	>1.3 TeV
measurement	4.2 ± 3.2 %	2.2 ± 7.3 %	8.6 ± 4.3 %	-2.6% $\pm$ 13.9 %
SM prediction	1.60 ± 0.04 %	1.42 ± 0.04 %	1.75 ± 0.05 %	2.55 ± 0.18 %



Gμ : A new color-octet neutral vector boson exchanged in the s channel

W′: A charged color-singlet vector boson Z exchanged in the t channel in $d\bar{d} \rightarrow t\bar{t}$

ϕ : A color-singlet scalar doublet with hypercharge −1/2 exchanged in t channel

Ω4 : A charge 4/3 scalar color sextet exchanged in the u channel

ω4 : A charge 4/3 scalar color triplet exchanged in the u channel

Where things stand and where we are going…

- CMS and ATLAS performing precision measurements that are very close to being systematically limited (CMS Template is)
  - ➡ No deviation from the standard model observed in either inclusive or differential measurements
  - ➡ NNLO effect may be measurable but will take a good amount of more data and some systematic improvements
- Early, Run 2 should focus on probing regions of BSM interest: high energy boosted events or very precise measurements of the asymmetry to limit new physics phase space

Backup

Backgrounds in Semi-leptonic

ATLAS	CMS

ATLAS

- > 80% of background is W+Jets
- Estimated by exploiting natural +/- asymmetry in W production at the LHC

$$A^{\pm} = \frac{N_{W^+} - N_{W^-}}{N_{total}} = \frac{A^{\pm}_{W} \cdot N_W}{N_W + N_{rest}}$$

Channel	ℓ + jets 0-tag	ℓ + jets 1-tag	ℓ + jets 2-tag
$t\bar{t}$	33900 ± 1200	146900 ± 2700	171600 ± 1500
Single top	3400 ± 400	12100 ± 1300	8700 ± 900
W+jets	173000 ± 16000	45000 ± 4000	8600 ± 900
Z+jets	13000 ± 6000	3900 ± 2000	1900 ± 900
Diboson	8000 ± 4000	2000 ± 900	400 ± 200
Multijets	11000 ± 5000	6300 ± 3200	2200 ± 1000
Total background	209000 ± 31000	70000 ± 13000	22000 ± 4000
Total expected	242000 ± 33000	216000 ± 15000	193000 ± 5000
Observed	242420	216465	193418

CMS

- Simultaneous fit of the ∑ 3 highest p_T jets for $m_T(W)$ < 50 GeV and $m_T(W)$ > 50 GeV
- corresponding to events rich in QCD and W+Jets

Process	Electron+jets	Muon+jets
Single top quark (t + tW)	7016 ± 1328	7302 ± 1663
W+jets	22 508 ± 1460	20 522 ± 1606
Z+jets	2345 ± 510	2046 ± 415
QCD multijet	6136 ± 1201	4199 ± 588
Total background	38 005 ± 1491	34 096 ± 1495
$t\bar{t}$	133 130 ± 1521	158 058 ± 1538
Observed data	171 121	192 123

Backgrounds in Dileptons

ATLAS

- Drell-Yan contributions estimated by deriving correction factor to simulation/prediction in events where missing E_T is closely associated with a jet or electron
- Fake Leptons (W+jets, multijet, l+jets top) estimated by applying a matrix-method with elements derived by deriving rates a real or fake lepton will satisfy the isolation criteria
- Single-top and dibosons from simulation

Channel	ee			$e\mu$			$\mu\mu$		
$t\bar{t}$	621	± 5	± 59	4670	± 10	± 325	1780	± 10	± 120
Single top	31.6	± 1.7	± 3.8	230	± 5	± 21	83.9	± 2.7	± 8.3
Diboson	22.8	± 0.9	± 2.6	177	± 3	± 16	61.5	± 1.5	± 6.1
$Z \to ee$ (DD)	20.8	± 1.7	± 1.4		—			—	
$Z \to \mu\mu$ (DD)		—		2.1	± 0.5	± 0.7	77	± 4	± 12
$Z \to \tau\tau$	18.6	± 1.8	± 7.0	170	± 6	± 60	67	± 4	± 25
NP & fake (DD)	19	± 4	± 19	99	± 10	± 63	26.8	± 5.1	± 1.9
Total expected	734	± 8	± 63	5350	± 20	±340	2100	± 10	±130
Data	740			5328			2057		

CMS

- Drell-Yan contributions outside Z mass window estimated by applying MC derived ratio of outside-to-inside window to the amount of data found inside the mass window
- Fake Leptons (W+jets, multijet, l+jets top) estimated by applying a p_T and η dependent parameterization of the probability of faking a lepton to the single-lepton sample
- Single-top and dibosons from simulation

Sample	ee	$\mu\mu$	eμ	All
$t\bar{t}$ (non-dileptonic)	38.3 ± 1.6	4.02 ± 0.45	91.7 ± 2.4	134.0 ± 2.9
W + jets	<2.0	4.7 ± 3.3	11.1 ± 5.1	15.8 ± 6.1
Drell–Yan	30.2 ± 4.4	29.6 ± 4.1	35.0 ± 4.5	94.8 ± 7.5
Diboson	8.27 ± 0.44	10.20 ± 0.47	27.90 ± 0.81	46.4 ± 1.0
Single top-quark	72.5 ± 2.1	86.8 ± 2.2	289.4 ± 4.2	448.7 ± 5.2
Total (background)	149.3 ± 5.5	135.3 ± 5.8	455.1 ± 8.4	740 ± 11
Data	1631	1964	6229	9824