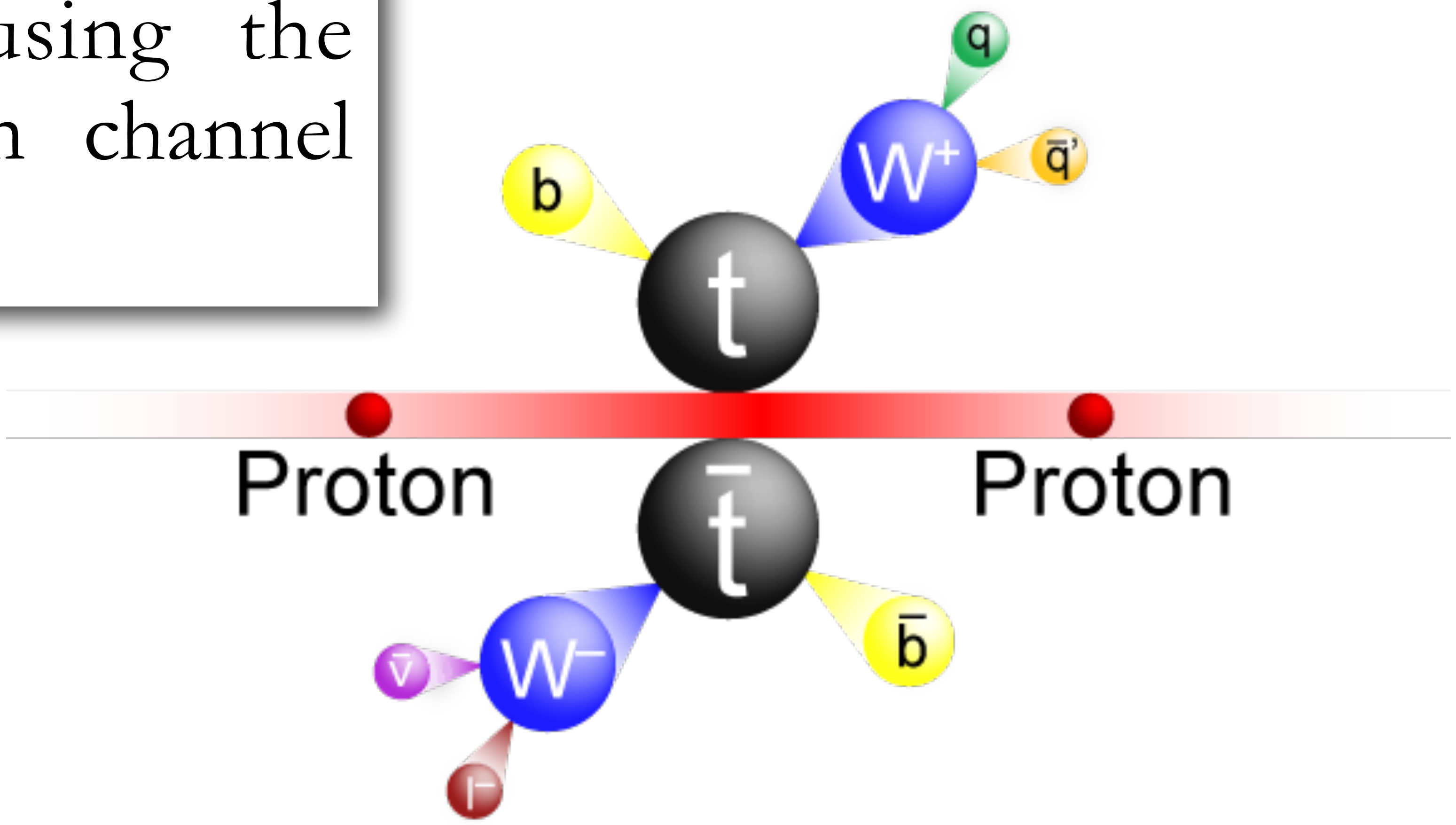
Top Pair Production at the LHC measured by ATLAS

Taylor Childers (CERN)
on behalf of the ATLAS Collaboration

Overview of Top Pair Results

Relative differential top pair cross section calculated using the single lepton channel [Ref. 1]



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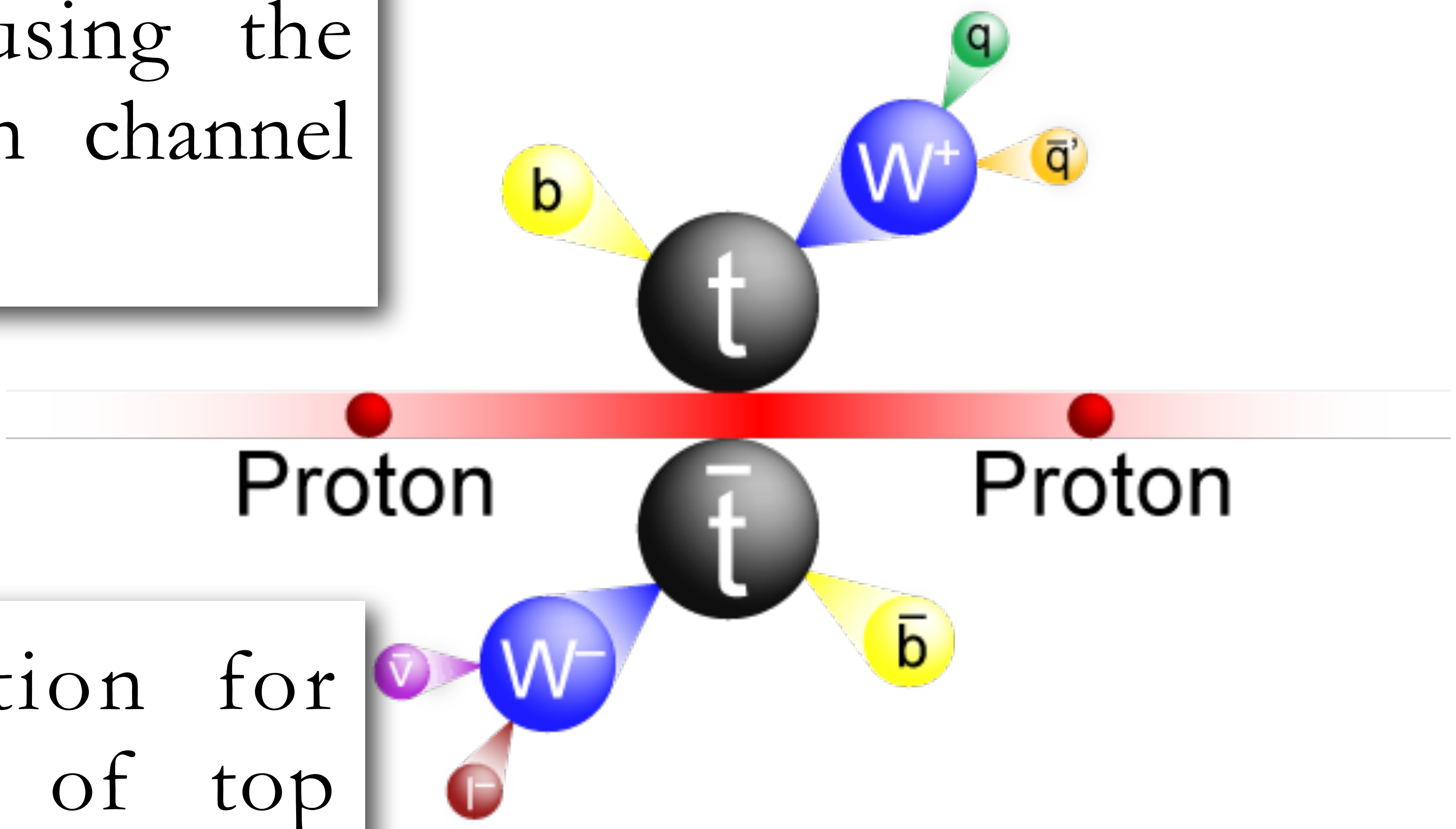

Cross section for production of top pair with additional jets (*tt j*) in the single lepton channel[Ref. 2]

Overview of Top Pair Results

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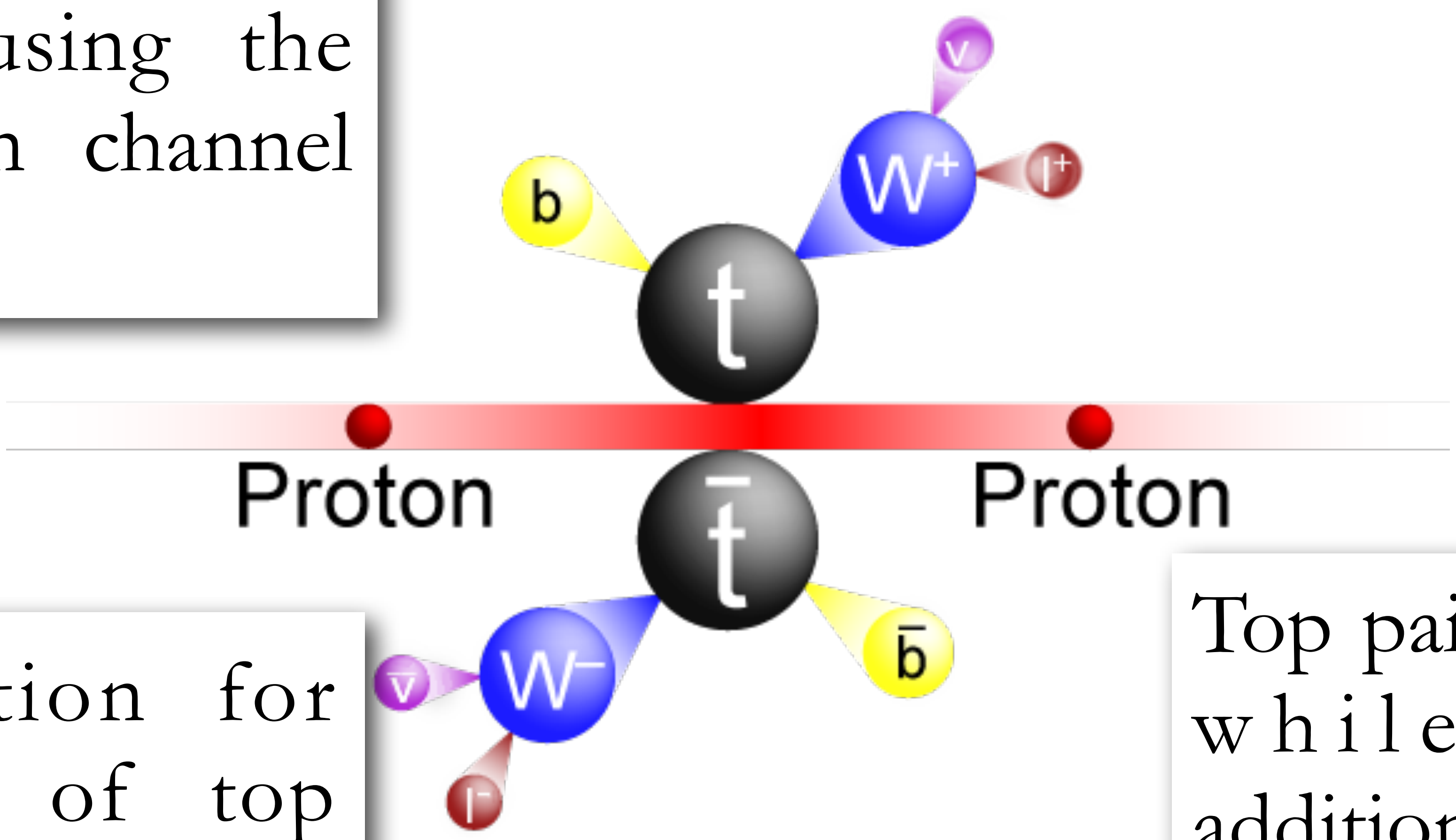


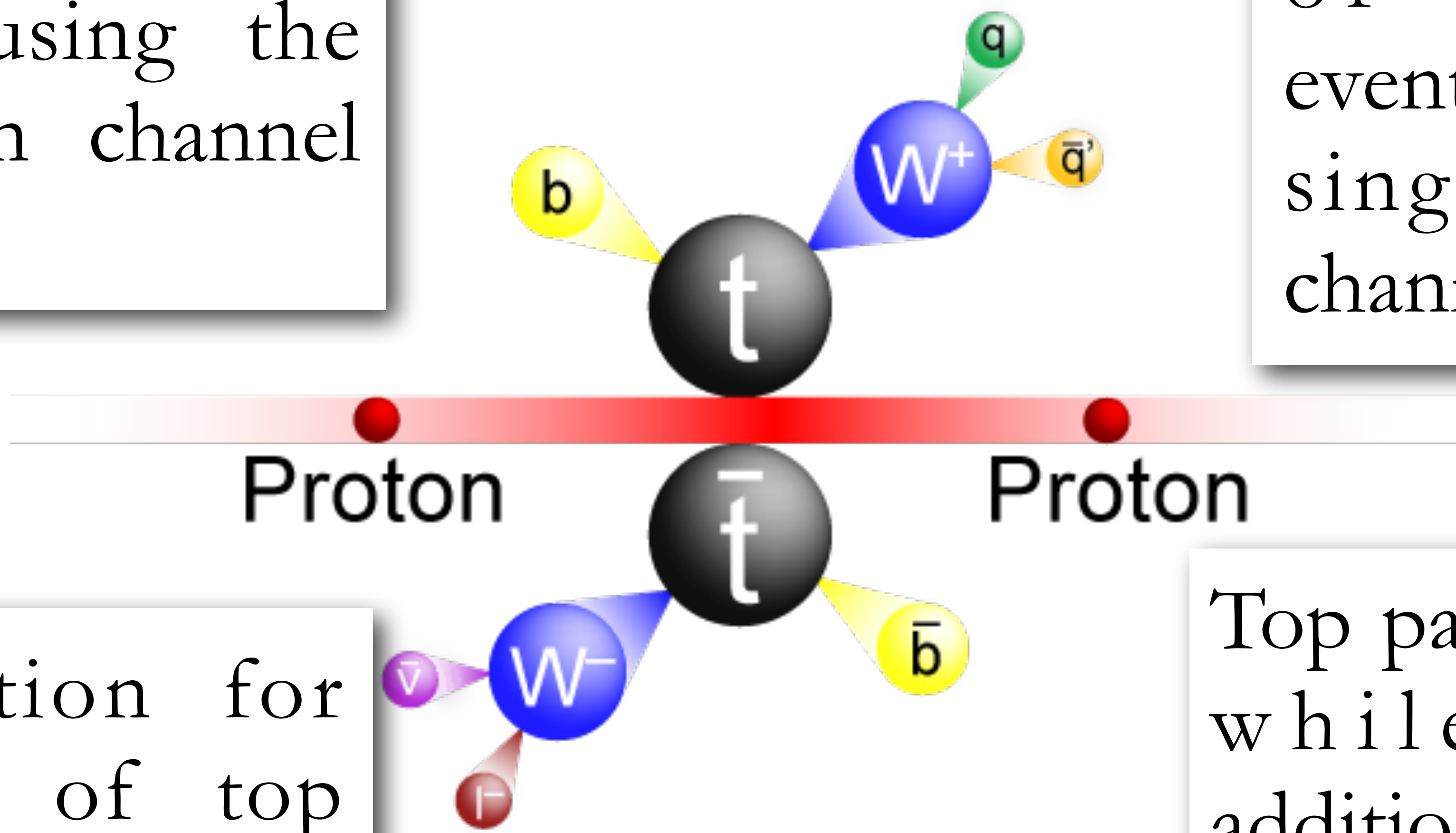
Cross section for production of top pair with additional jets ($t\bar{t}\,j$) in the single lepton channel[Ref. 2]

Top pair production while vetoing additional central jet activity using the dilepton channel [Ref. 3]

Overview of Top Pair Results

Relative differential top pair cross section calculated using the single lepton channel [Ref. 1]

Jet multiplicities of top pair events using the single lepton channel [Ref. 4]



Cross section for production of top pair with additional jets (*tt j*) in the single lepton channel[Ref. 2]

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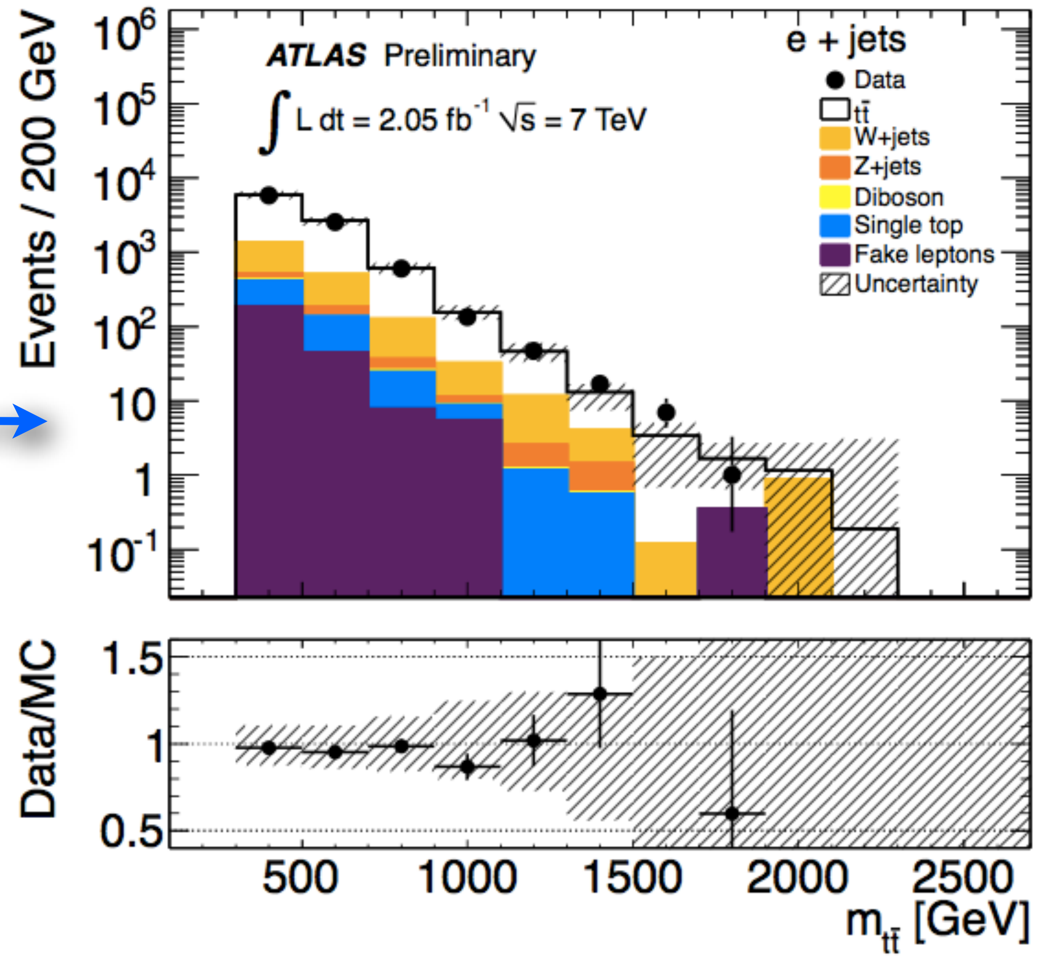
Relative Differential tt Cross Section Measurement

e+jets, μ+jets selected events from data



Details in [1]

Relative Differential tt Cross Section Measurement

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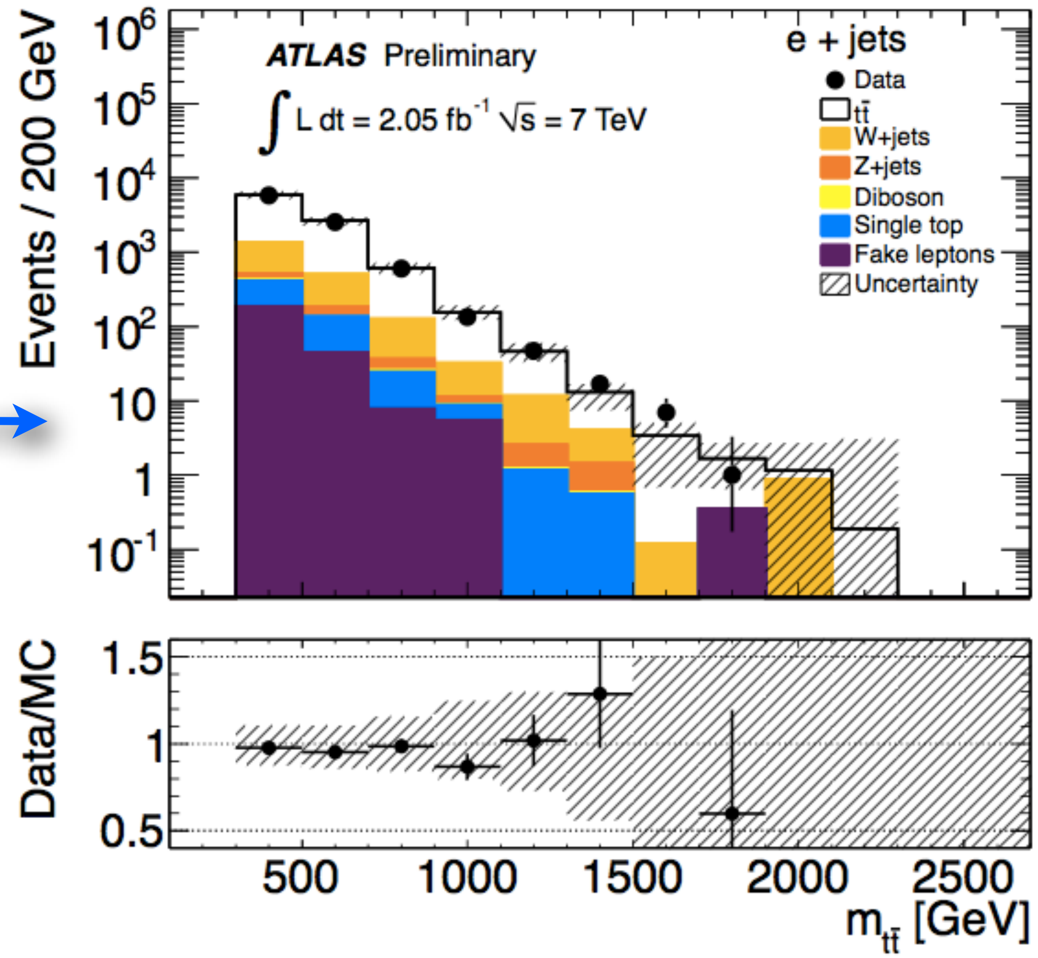
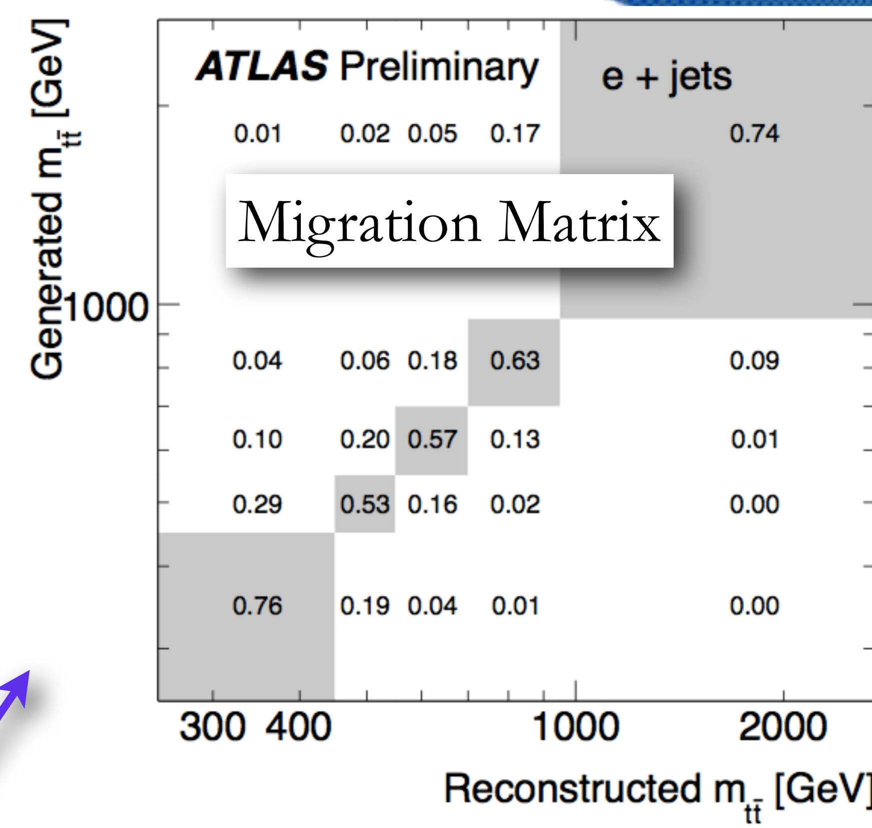
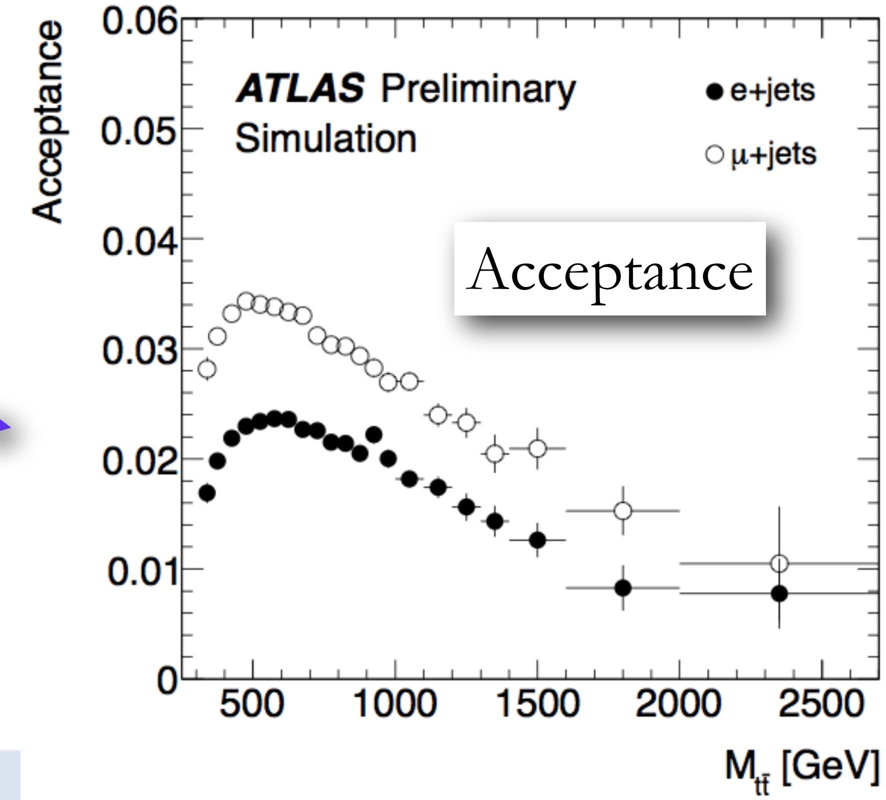




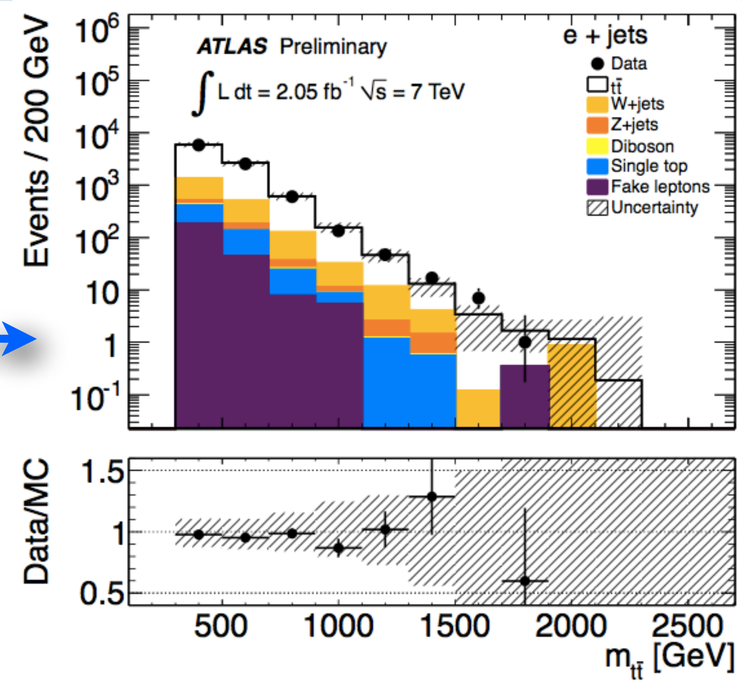
e+jets, μ+jets events from MC



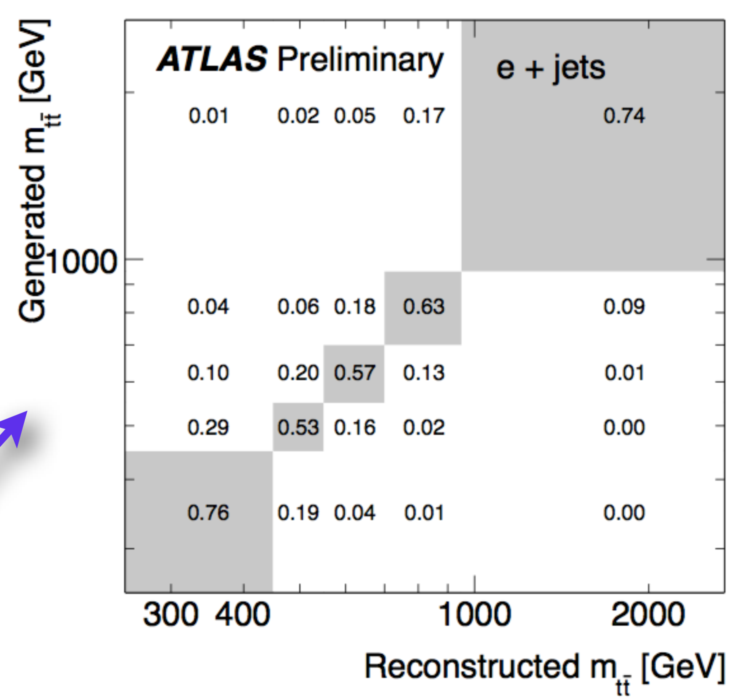
Details in [1]

Relative Differential tt Cross Section Measurement

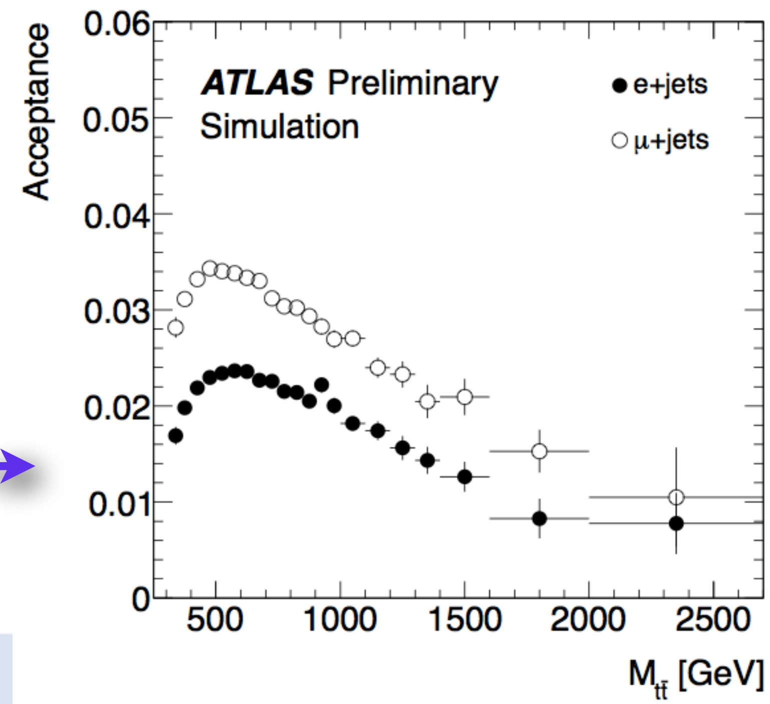
e+jets, μ+jets selected events from data



Unfold detector effects in data using inverted MC migration matrix.



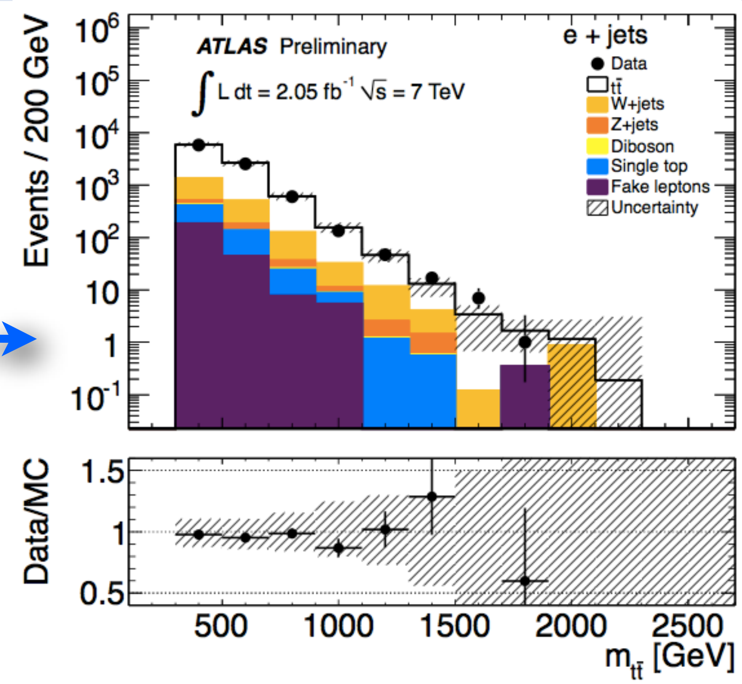
e+jets, μ+jets events from MC



Details in [1]

Relative Differential tt Cross Section Measurement

e+jets, μ+jets selected events from data



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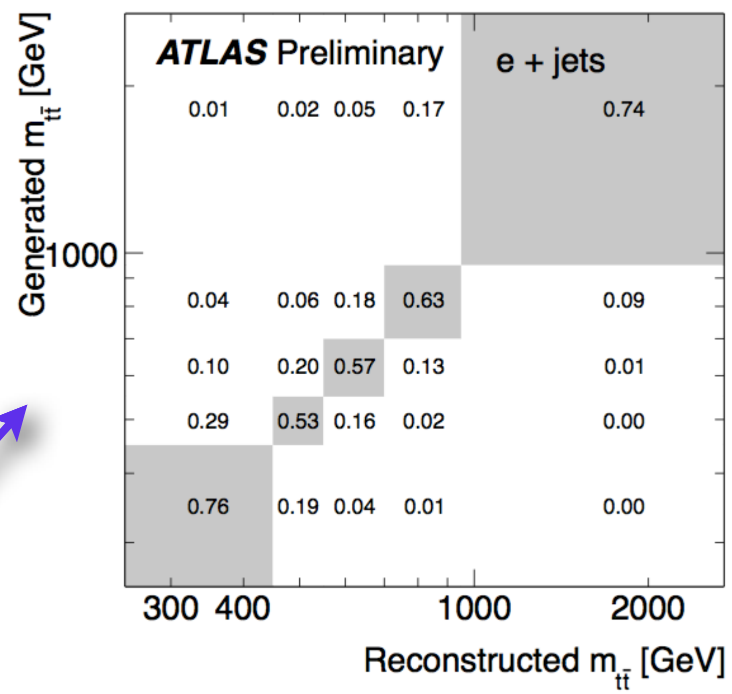
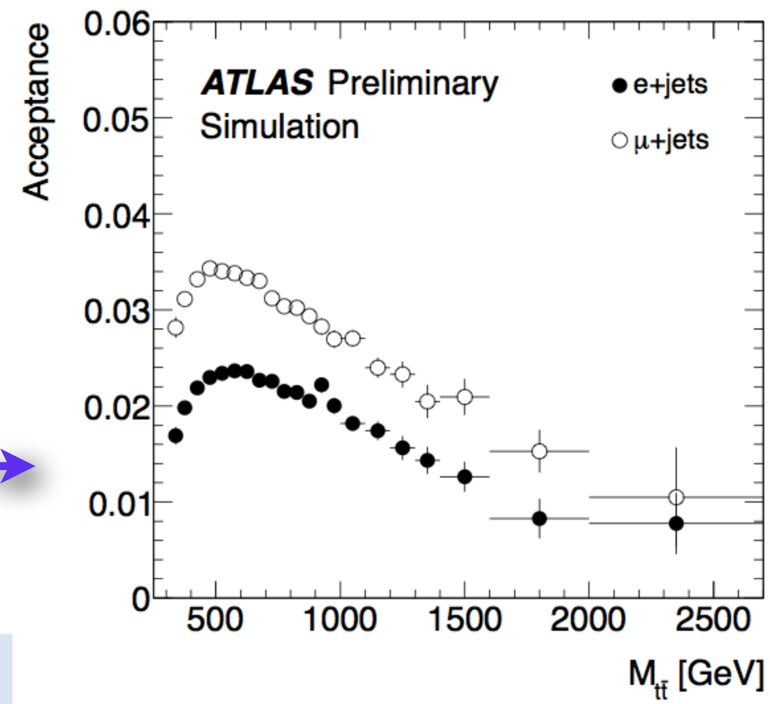


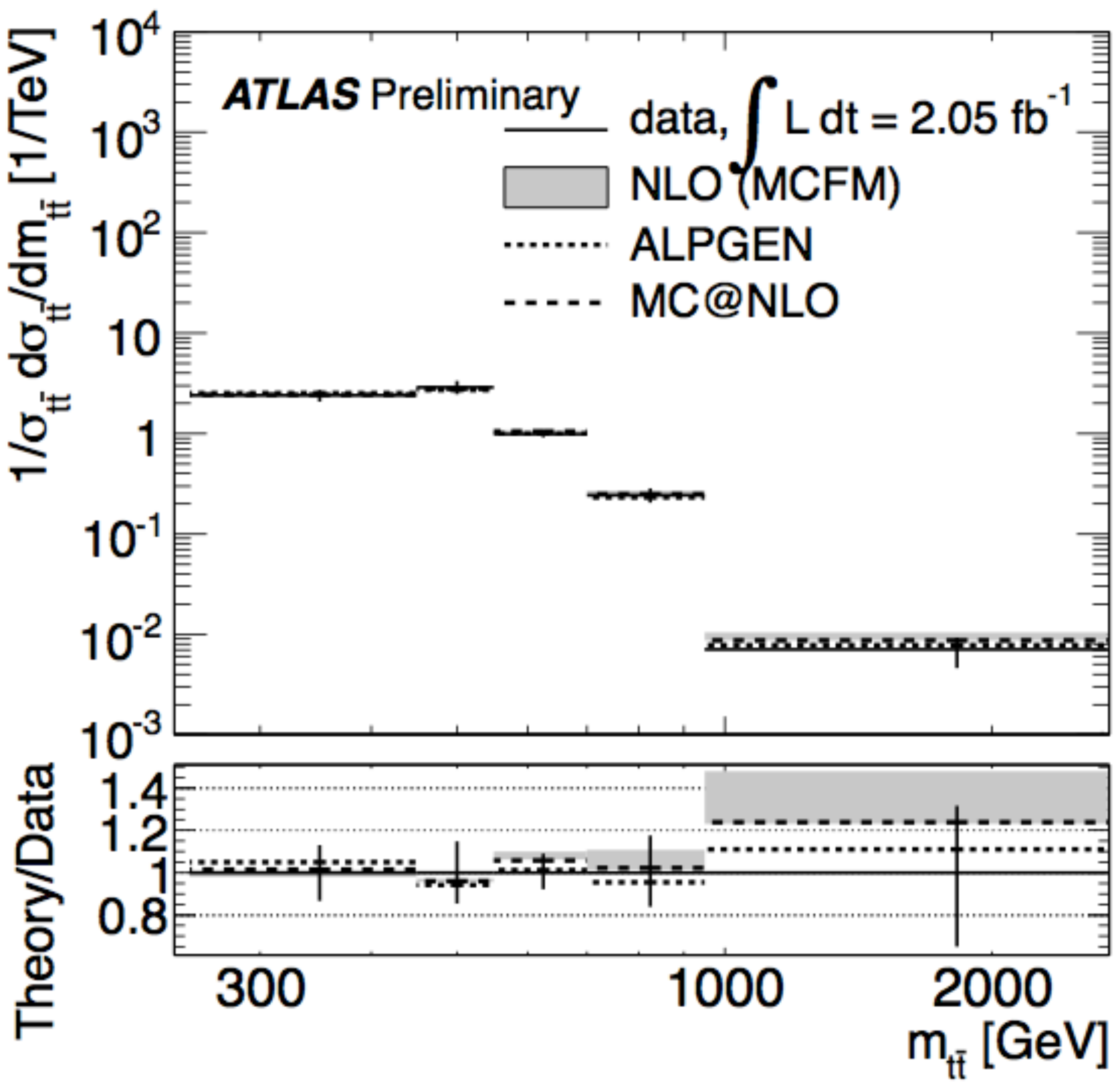
e+jets, μ+jets events from MC



Correct for acceptance, luminosity and branching fraction.

Details in [1]

Relative Differential tt Cross Section Result



σ_{tt}=160 ±25 pb

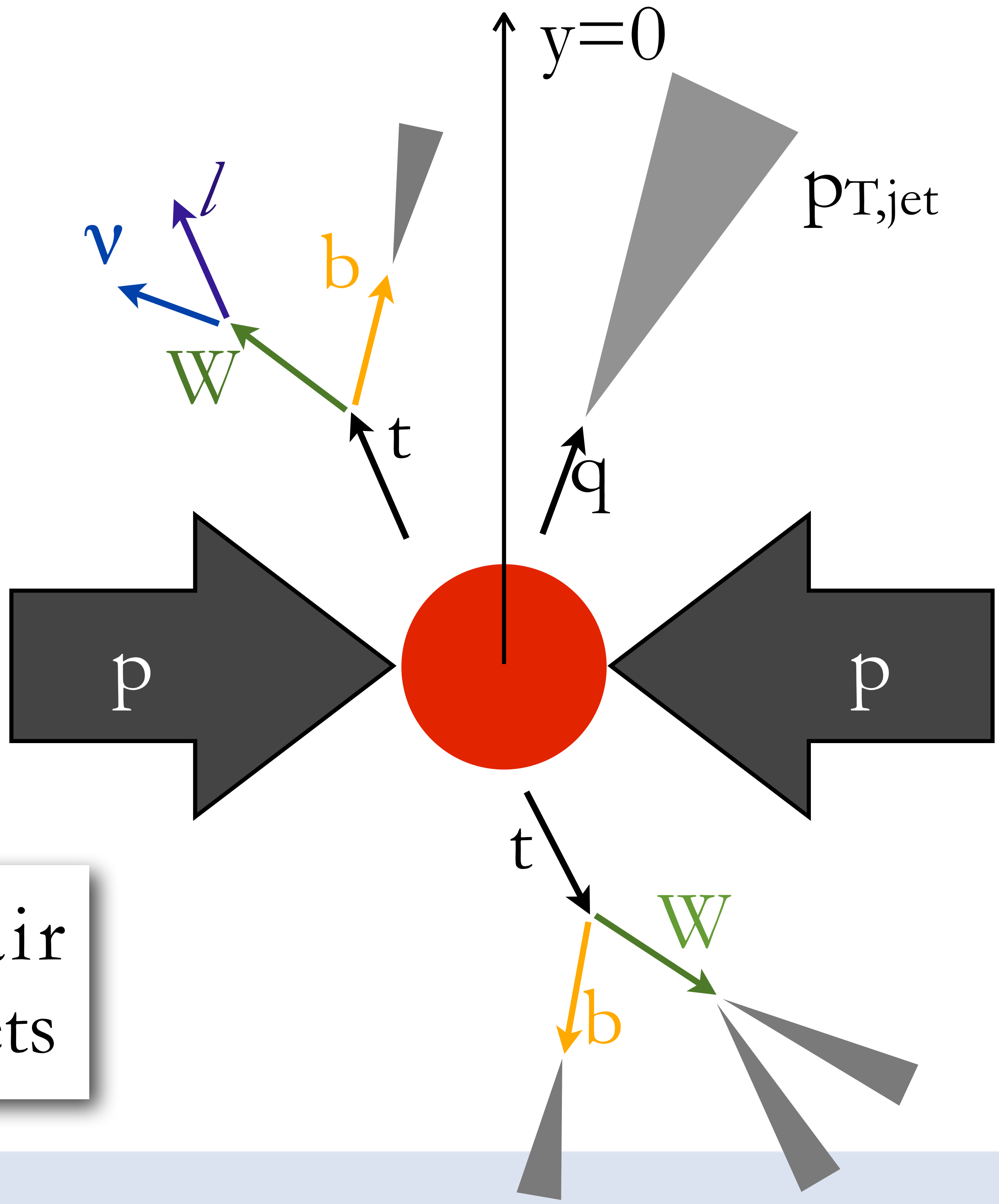
uncertainties = syst. + stat.

sample: e/μ+jets

See backup for $p_{T,tt}$ and y_{tt}

Details in [1]

Cross Section for Top Pair Plus Jets



$t\bar{t}\,j$ = top pair event with one or more jets

Looking at top pair events with additional jets

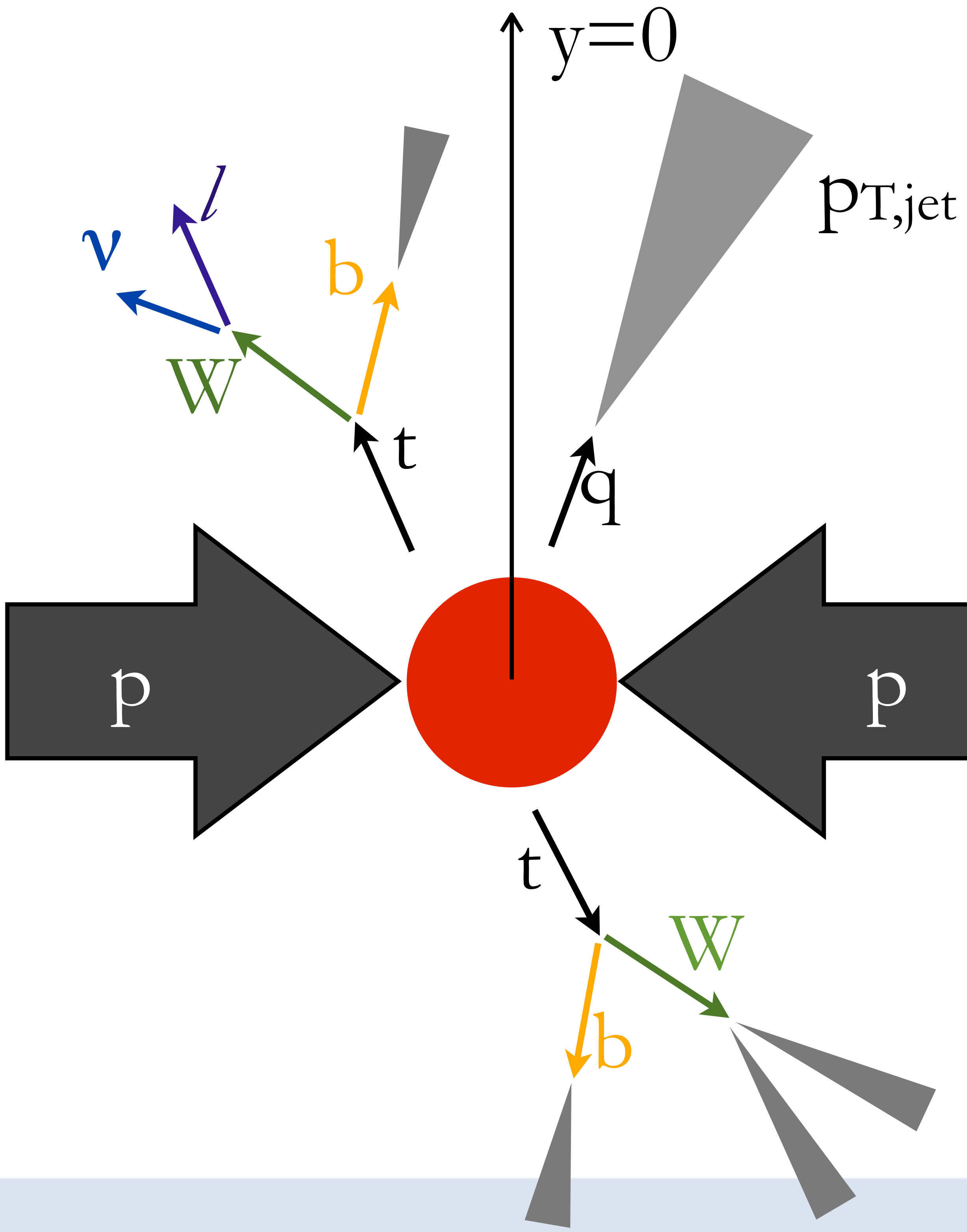
Details in [2]

Cross Section for Top Pair Plus Jets

Two definitions of events containing additional jets using MC particle jets

1. No overlap (within $\Delta R < 0.4$) of a parton originating from a top decay ($t\bar{t}j \rightarrow l$+jets)

2. Events with ≥5 jets ($t\bar{t}j \rightarrow l+\geq$5jets)



Details in [2]

Cross Section for Top Pair Plus Jets

Using definition 1, the total $t\bar{t}j$ cross section is
$\sigma_{t\bar{t}j} = 102 \pm 2(\text{stat.})\ ^{+23}_{-26}(\text{syst.})$ pb

Then the fiducial cross sections are

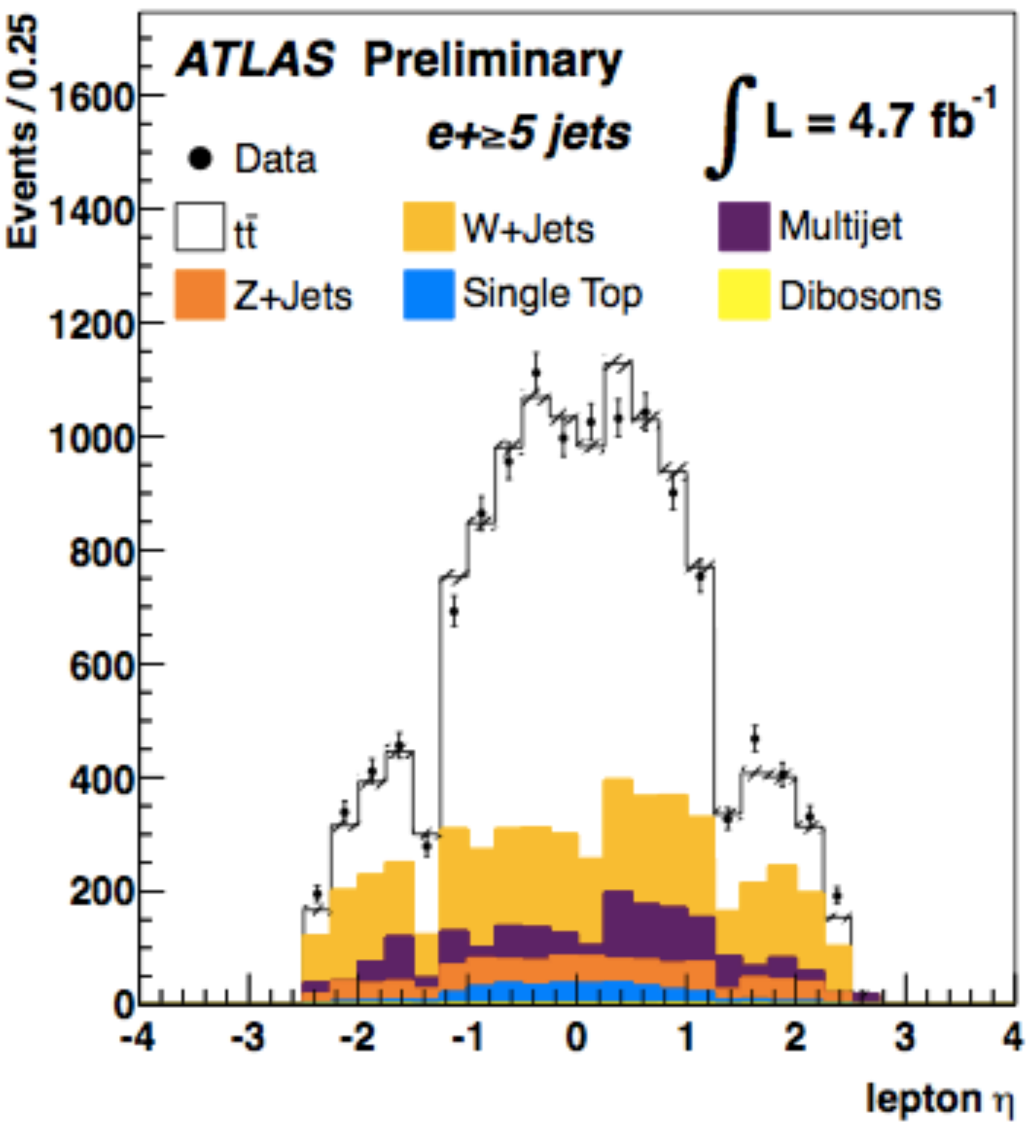
$\sigma_{t\bar{t}j\rightarrow e+jets} = 2.59 \pm 0.09(\text{stat.})\ ^{+0.26}_{-0.46}(\text{syst.})$ pb

$\sigma_{t\bar{t}j\rightarrow \mu+jets} = 3.48 \pm 0.08(\text{stat.})\ ^{+0.43}_{-0.61}(\text{syst.})$ pb

$\sigma_{t\bar{t}j\rightarrow e+\geq 5jets} = 4.09 \pm 0.18(\text{stat.})\ ^{+0.62}_{-0.85}(\text{syst.})$ pb

$\sigma_{t\bar{t}j\rightarrow \mu+\geq 5jets} = 5.27 \pm 0.16(\text{stat.})\ ^{+1.04}_{-1.20}(\text{syst.})$ pb

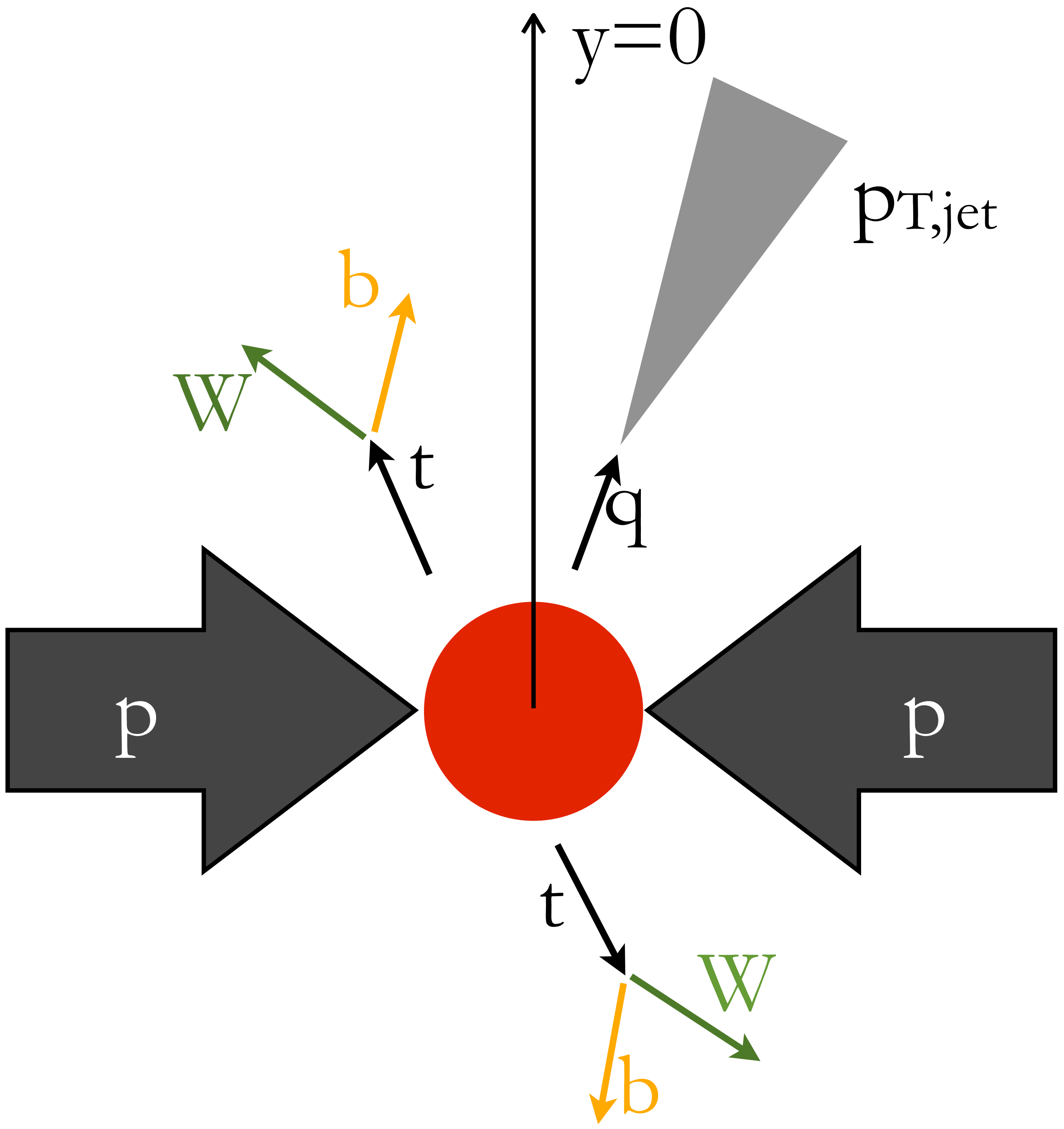
Can also reconstruct a total cross section:
$\sigma_{t\bar{t}} = 189 \pm 4(\text{stat.})$ pb



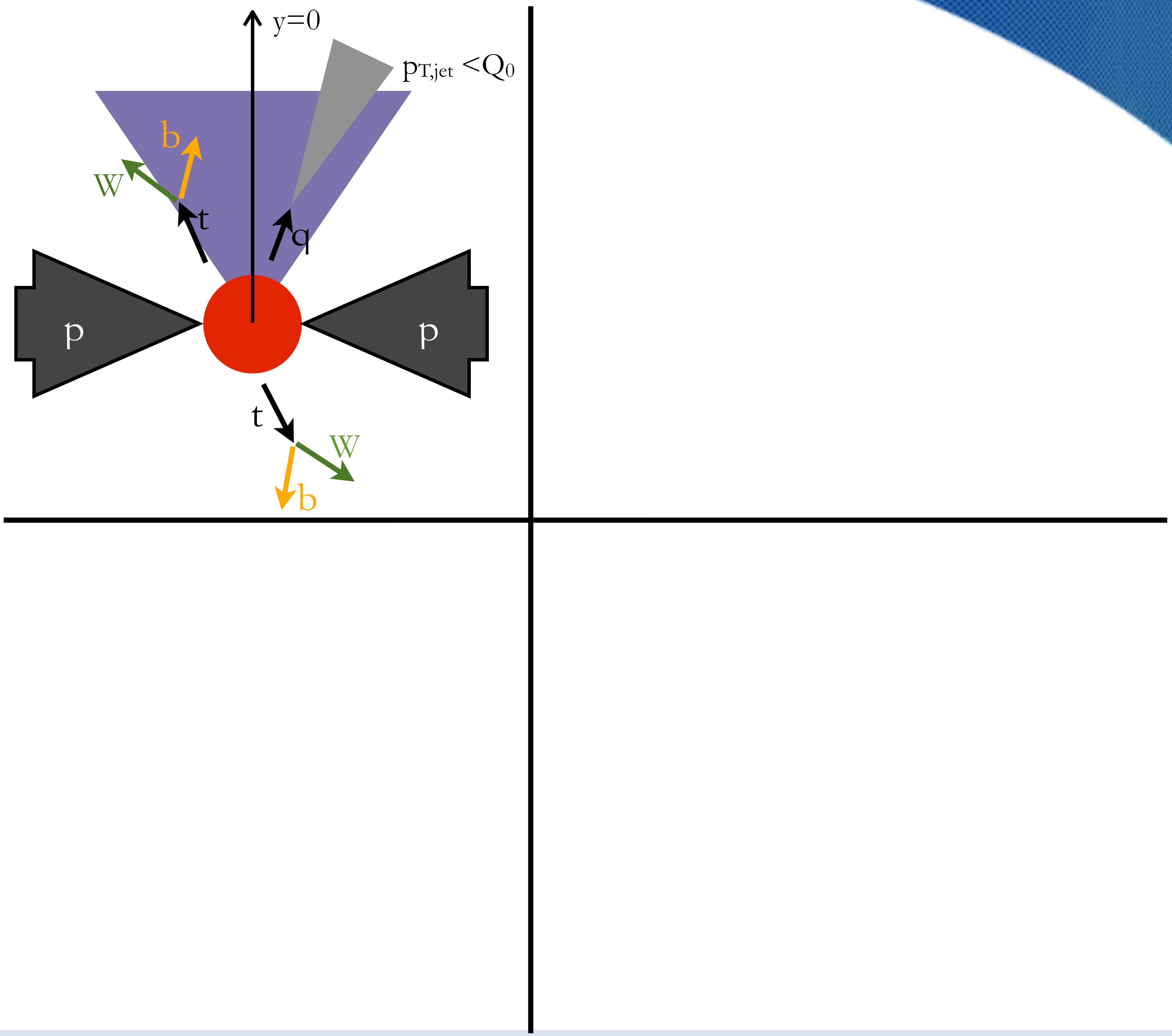
Details in [2]

Gap Fraction Measurement

Measure the fraction of dilepton events without a jet with $p_T > Q_0$ within a defined rapidity range, as a function of Q_0



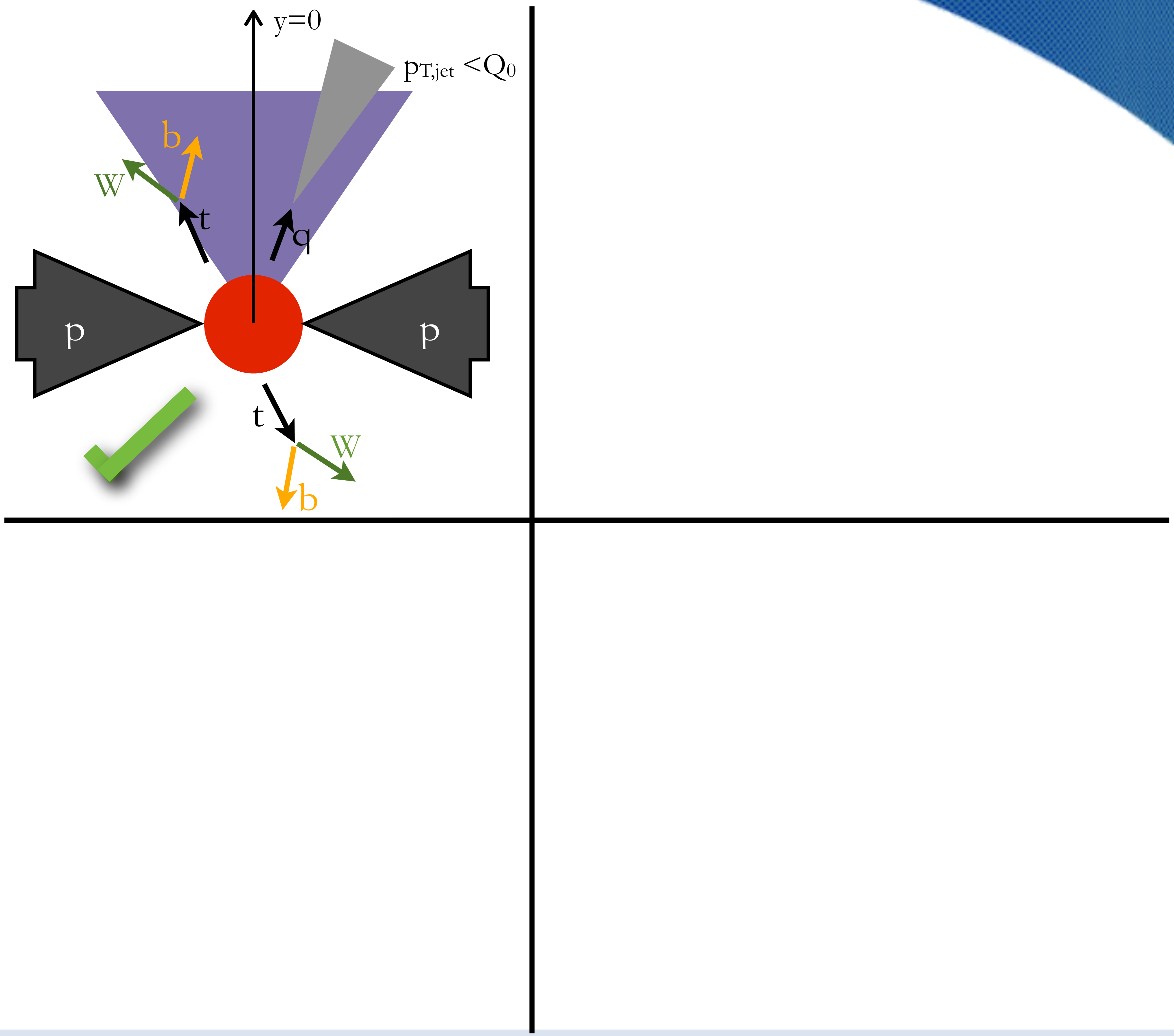
Gap Fraction Measurement



Rapidity Region

Gap Fraction Measurement

Fraction = 1/1



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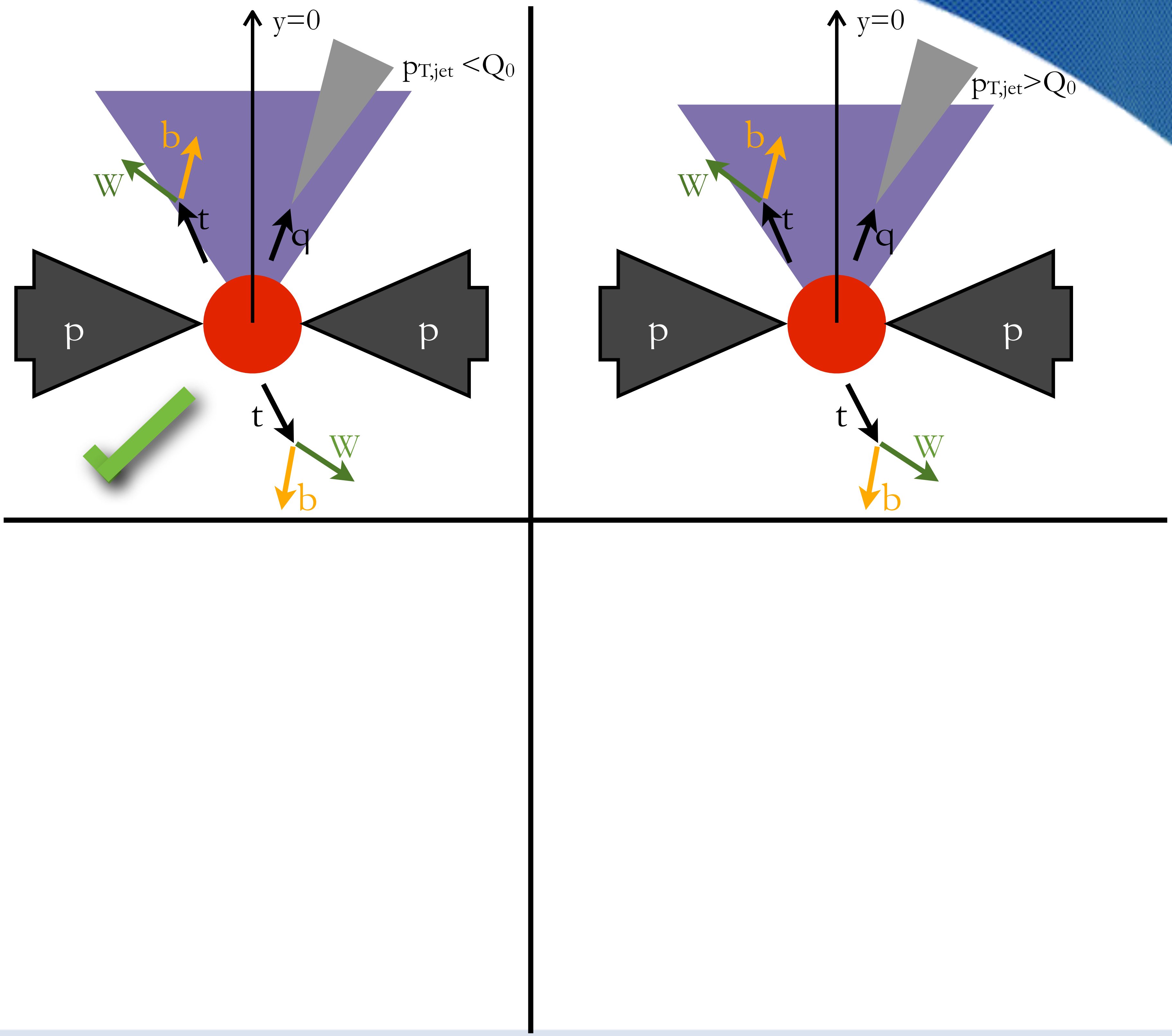
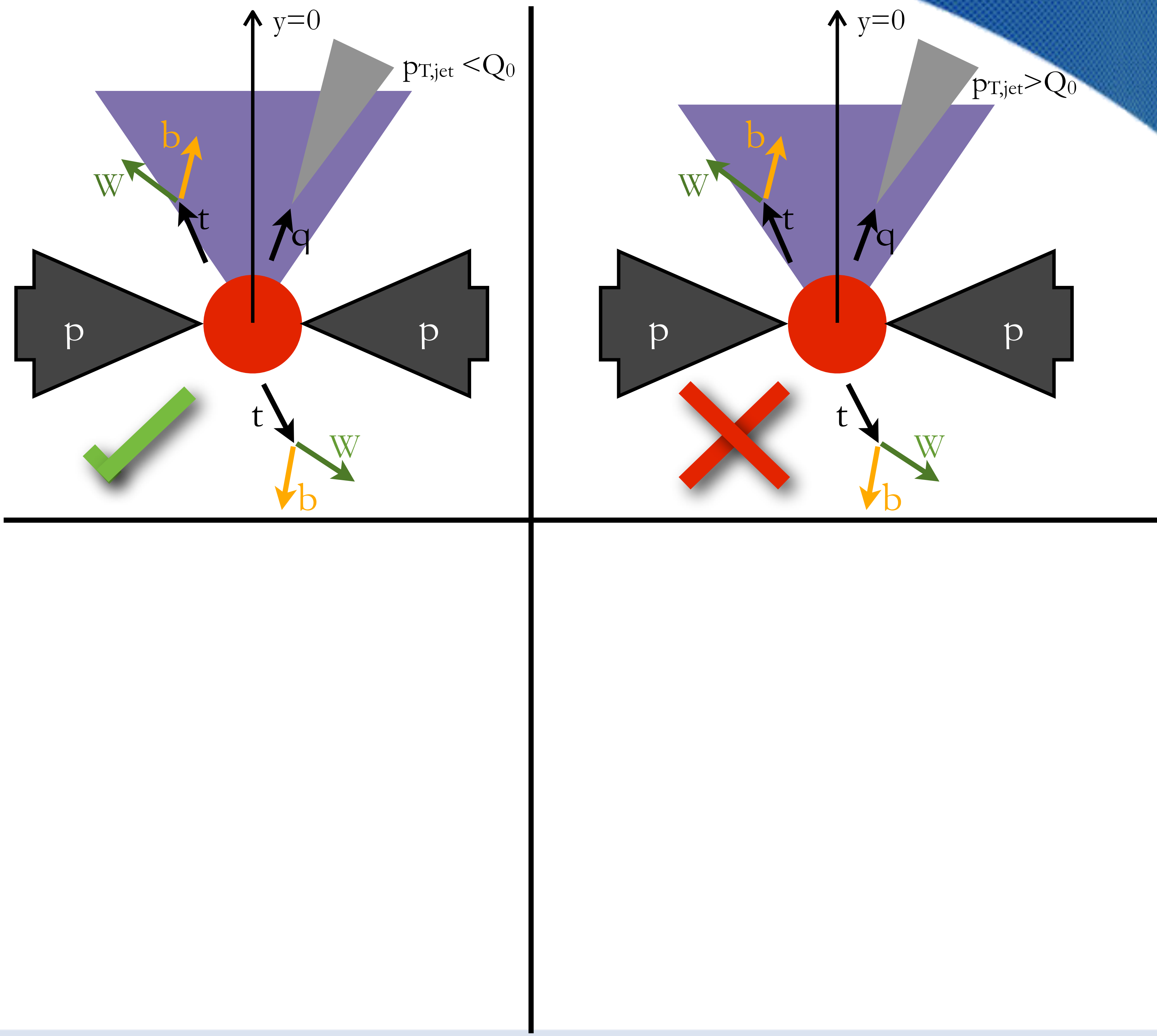


Rapidity Region

Gap Fraction Measurement

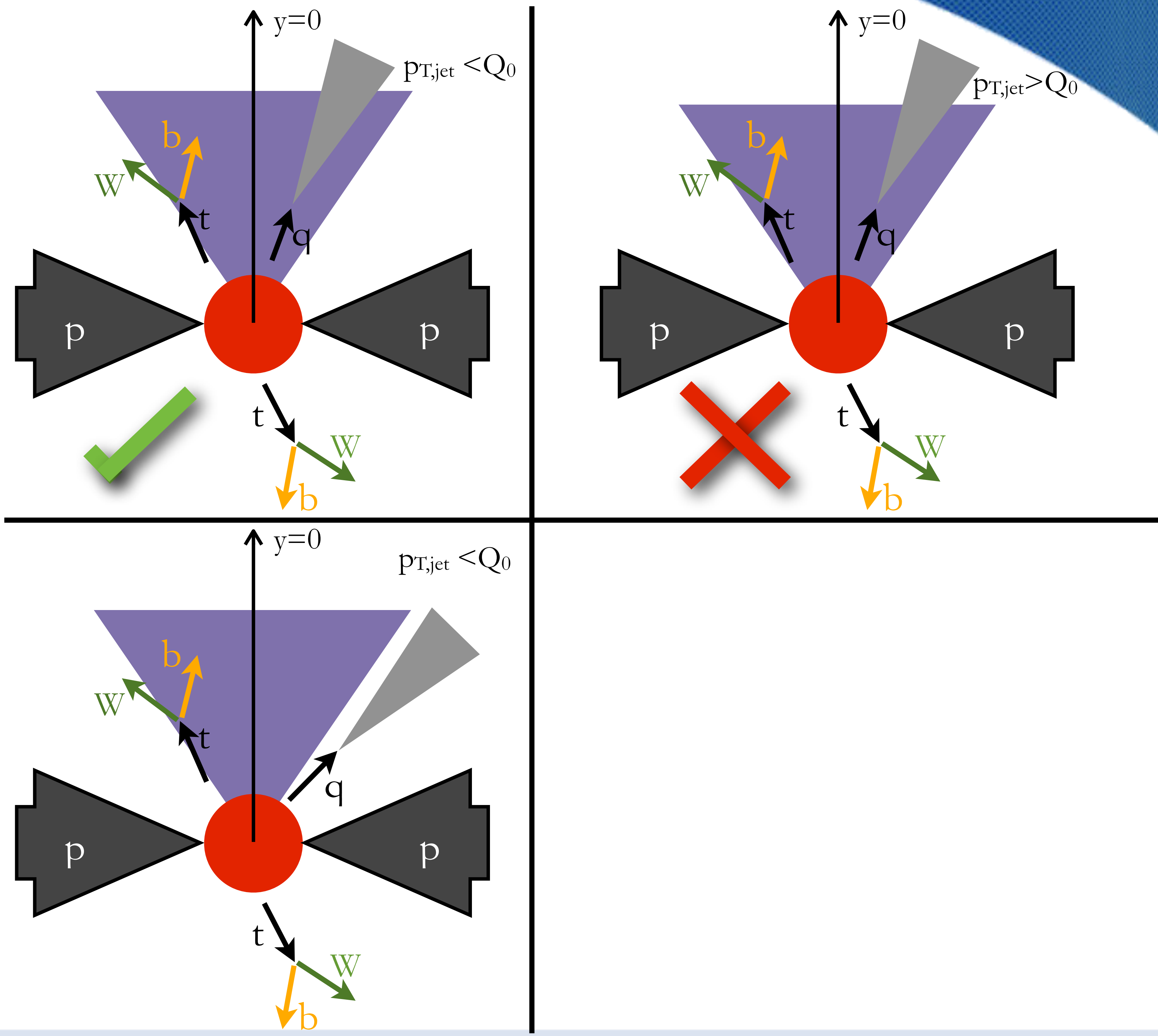
Fraction = 1/2



Rapidity Region

Gap Fraction Measurement

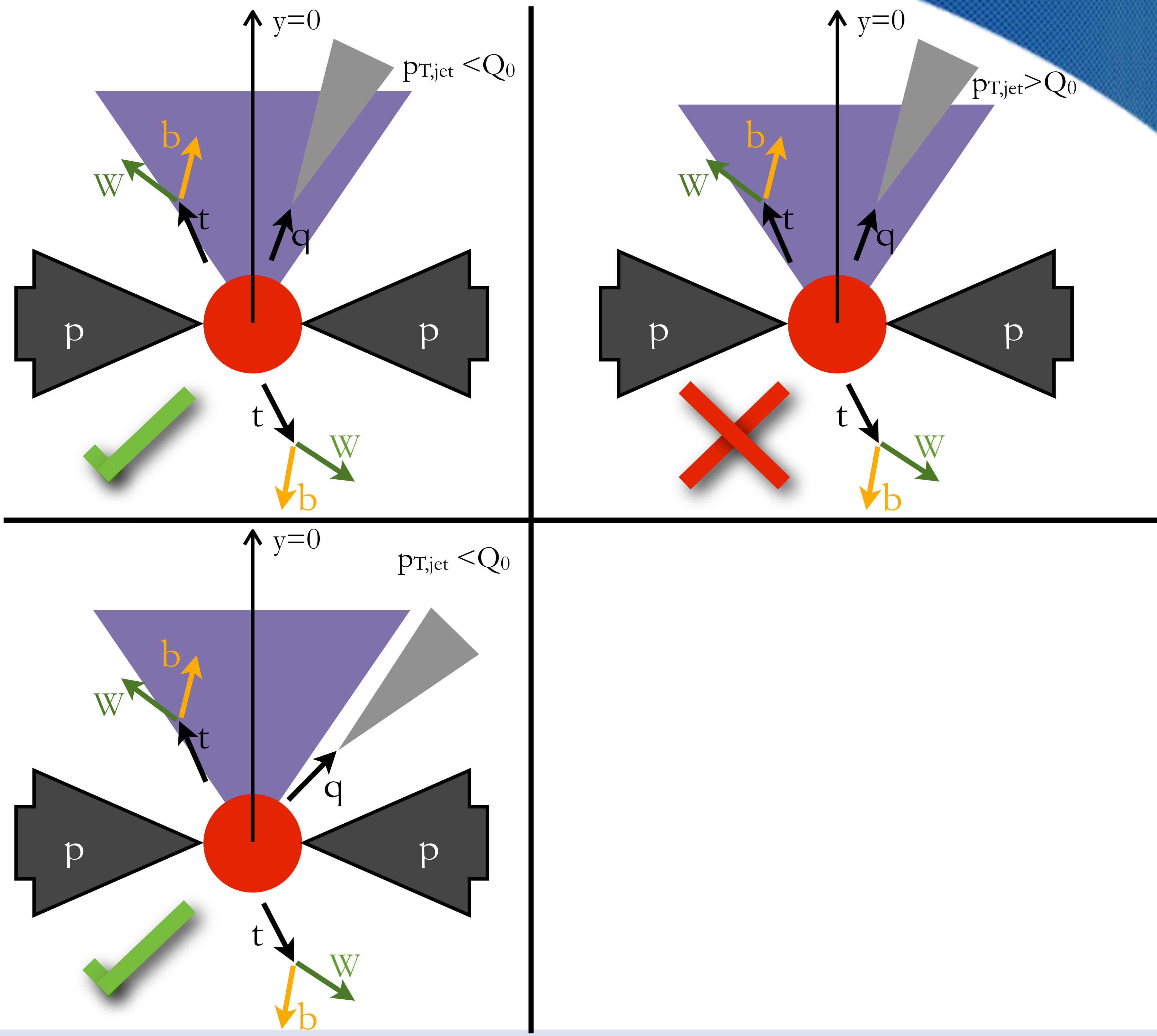
Fraction = 1/2



Rapidity Region

Gap Fraction Measurement

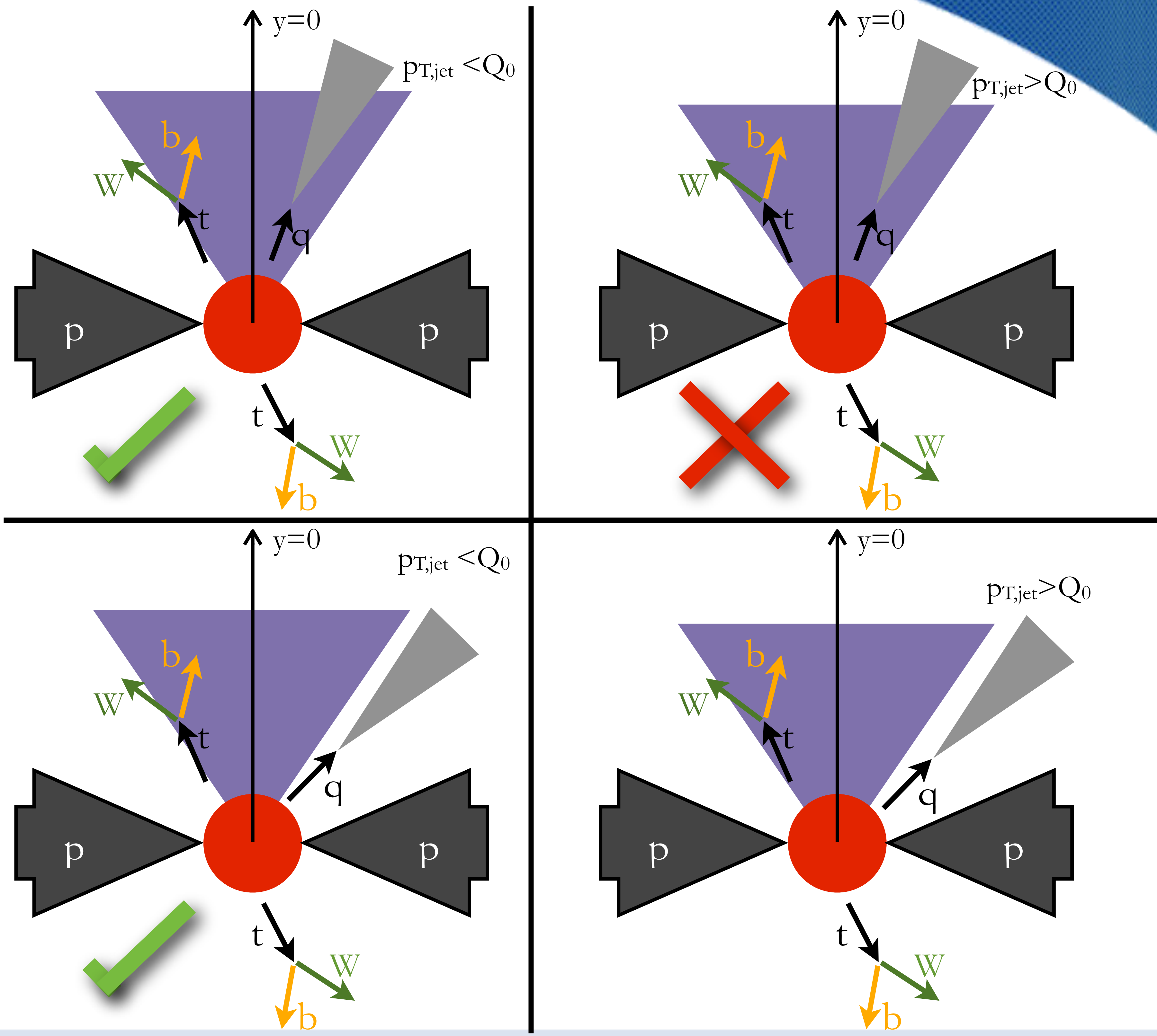
Fraction = 2/3



Rapidity Region

Gap Fraction Measurement

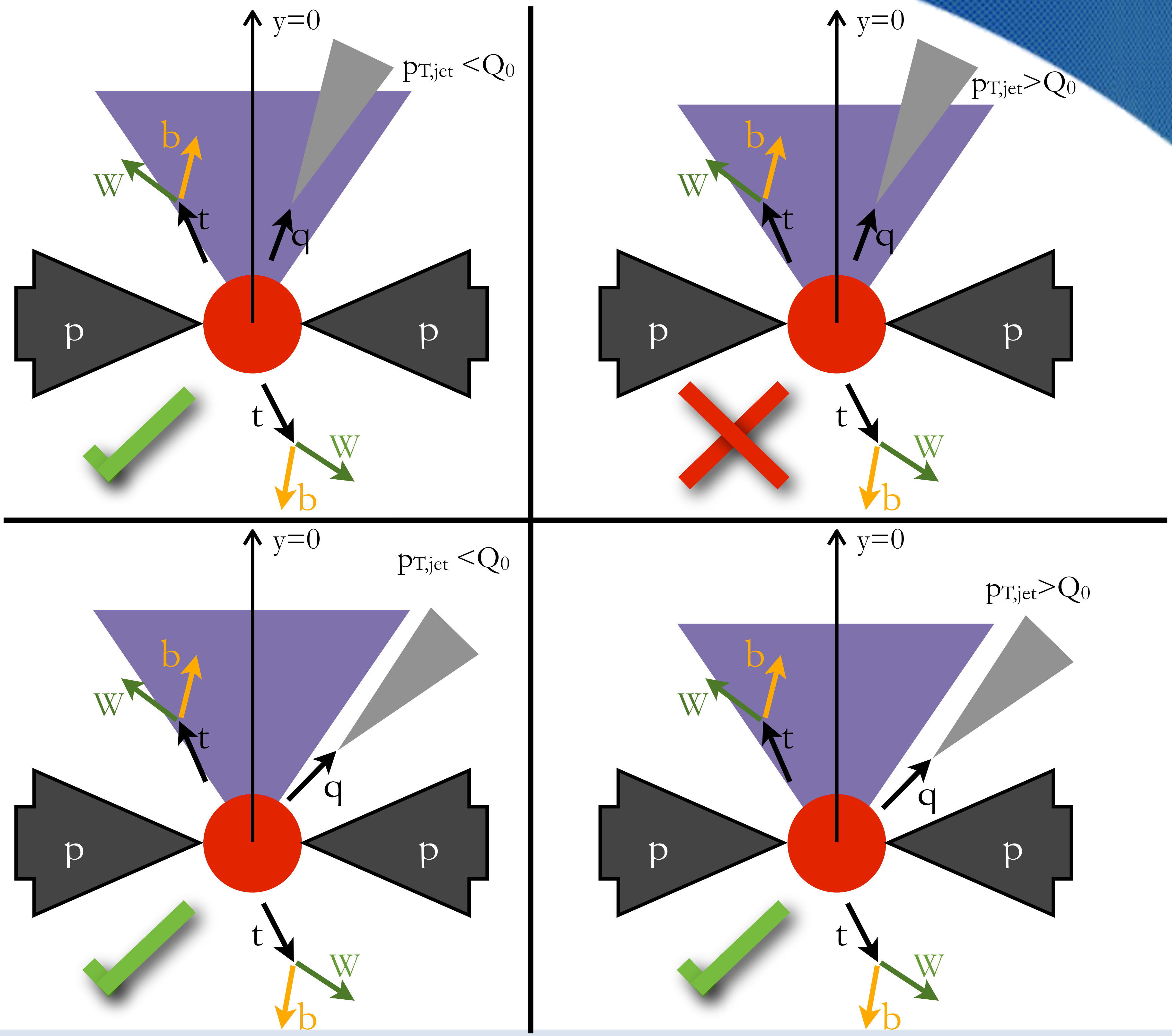
Fraction = 2/3



Rapidity Region

Gap Fraction Measurement

Fraction = 3/4



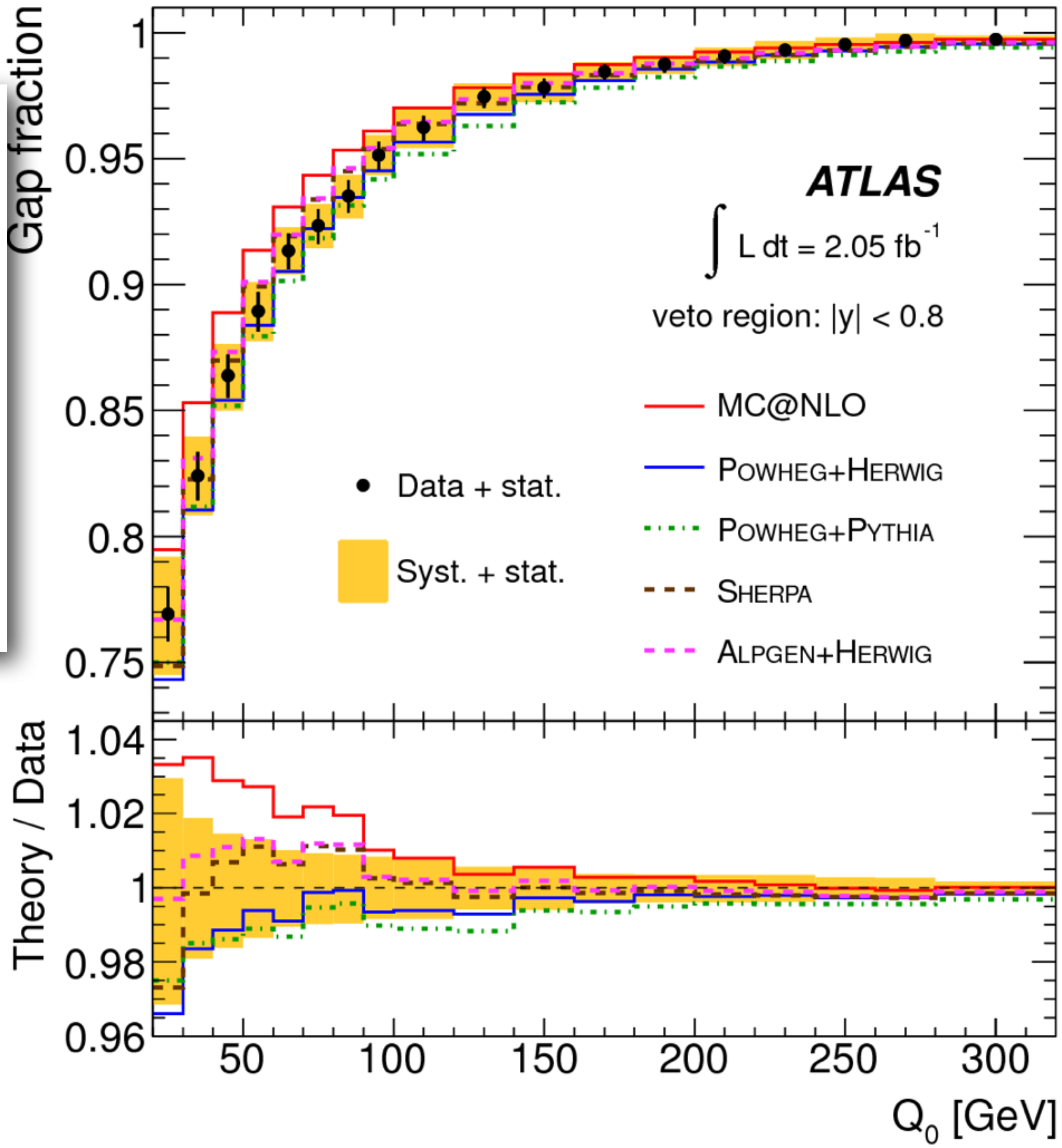
Rapidity Region

Gap Fraction Measurement

Correct number of events for detector effects to arrive at the cross section

↓

$$f_{gap} = \frac{\sigma(Q_0)}{\sigma}$$

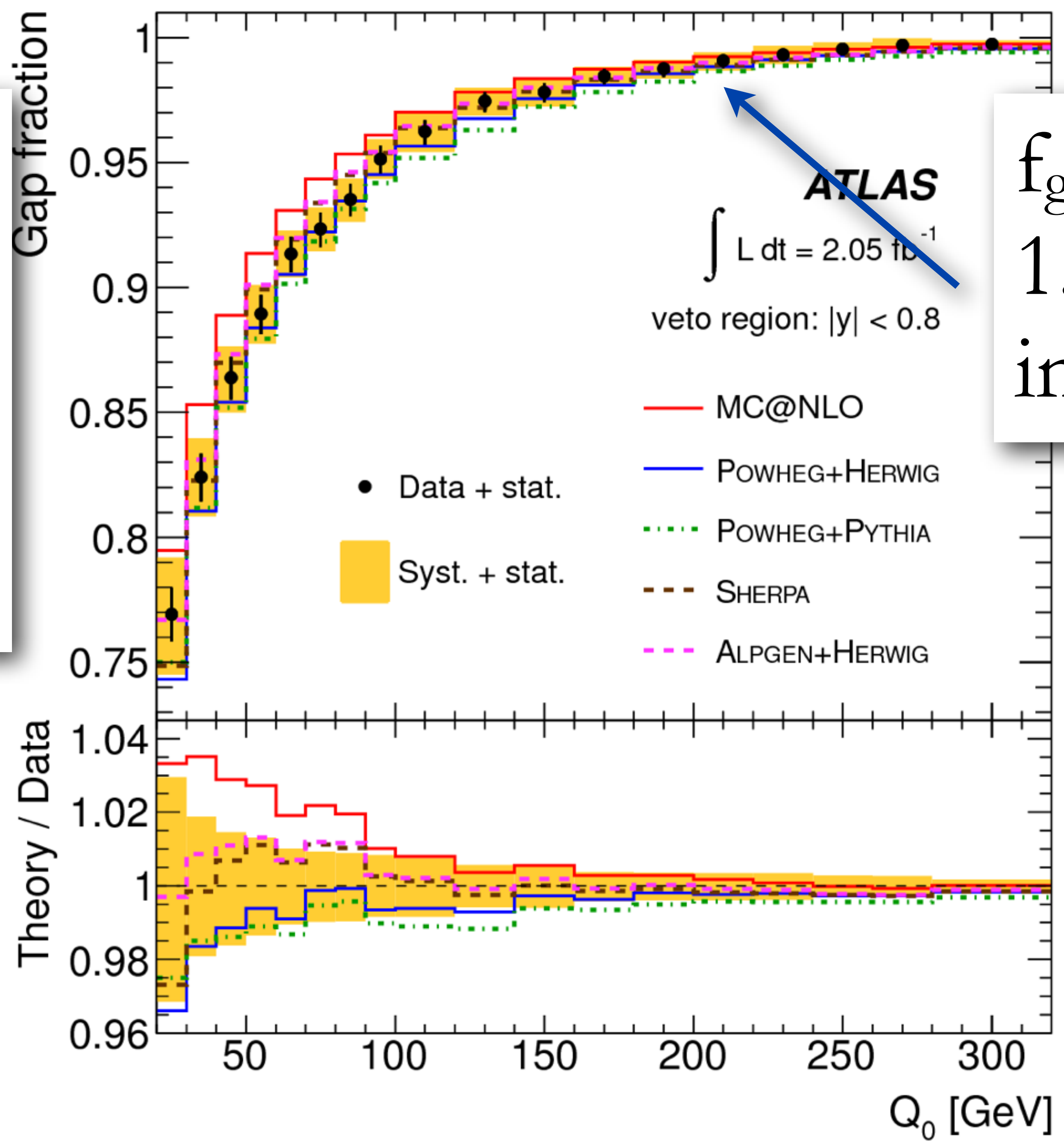


Gap Fraction Measurement

Correct number of events for detector effects and convert to cross section

↓

$$f_{gap} = \frac{\sigma(Q_0)}{\sigma}$$



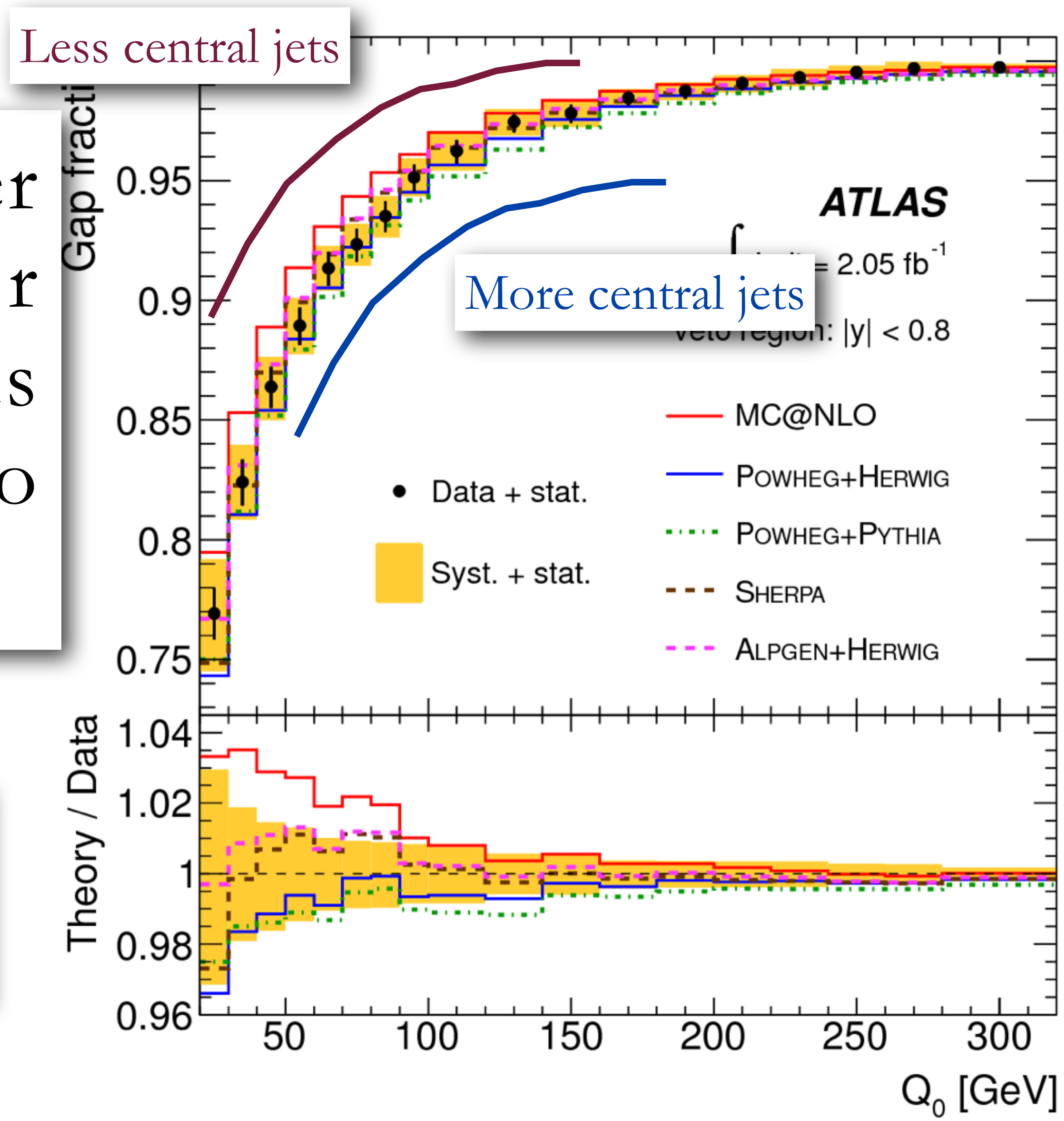
f_{gap} approaches 1.0 as p_T cut increases

Gap Fraction Measurement

Correct number of events for detector effects and convert to cross section

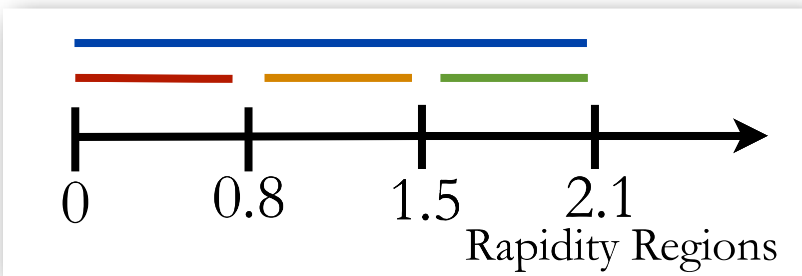
↓

$$f_{gap} = \frac{\sigma(Q_0)}{\sigma}$$

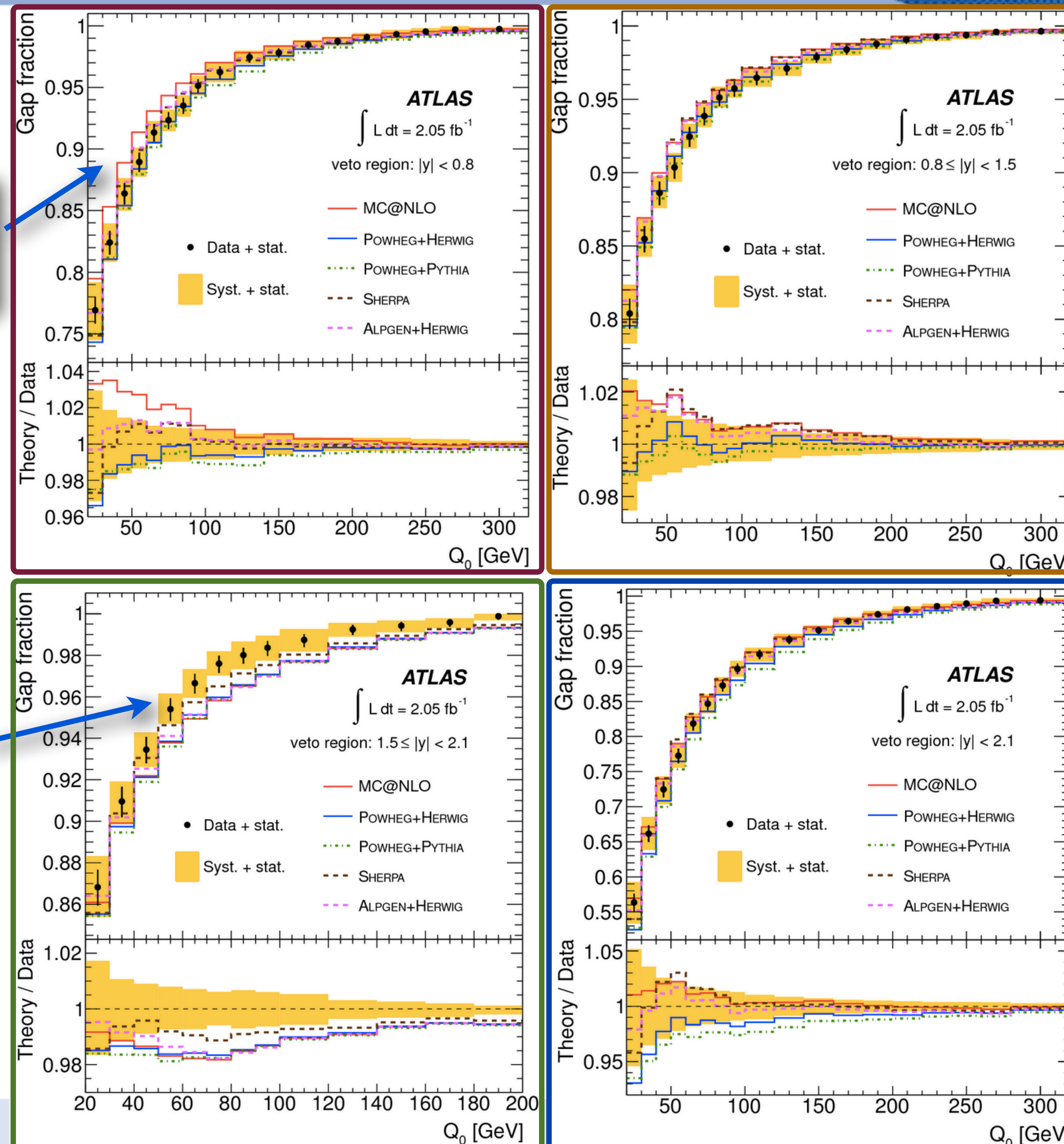


Single Jet Gap Fraction Results

MC@NLO produces fewer central jets



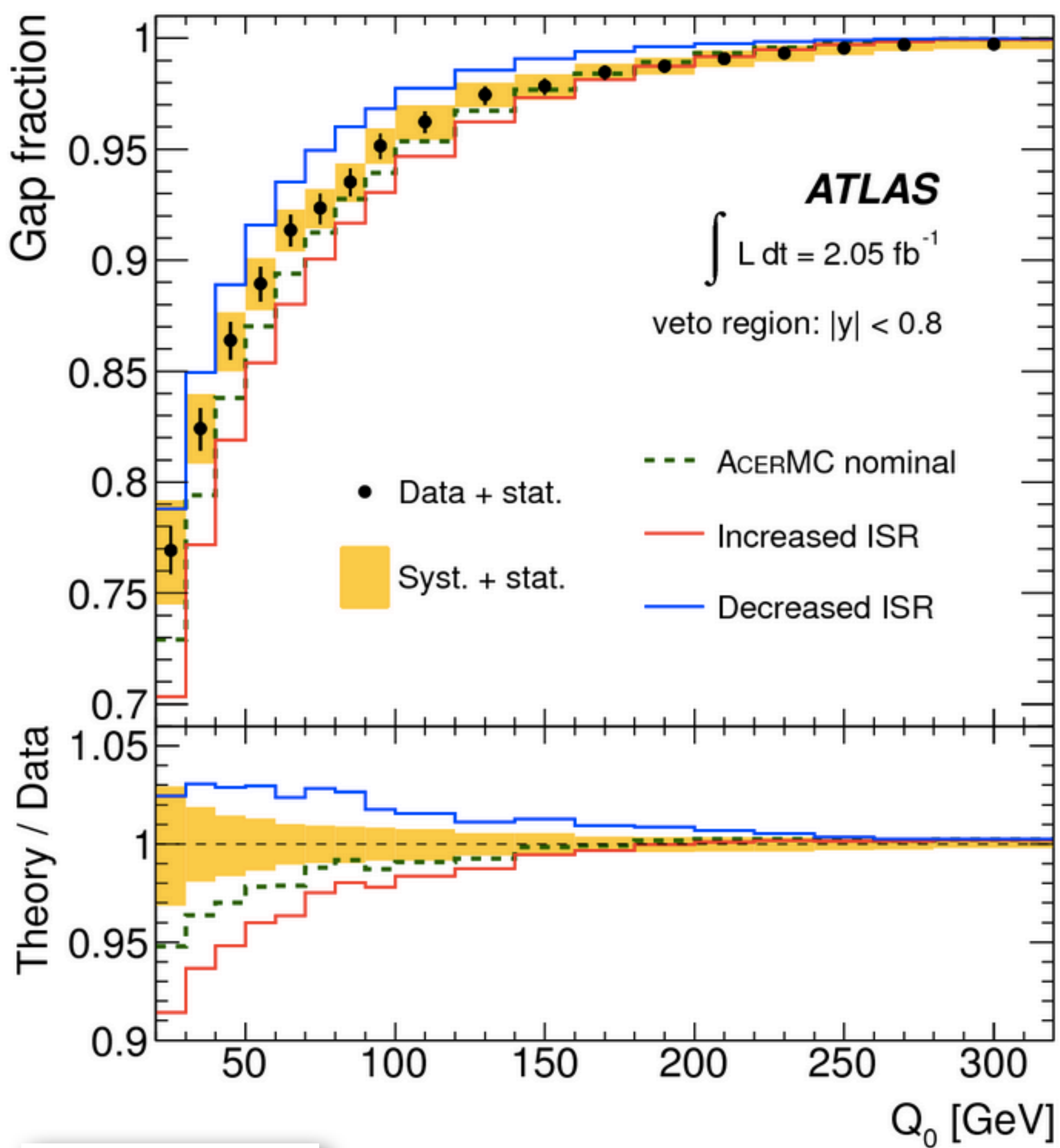
MC producing too much activity

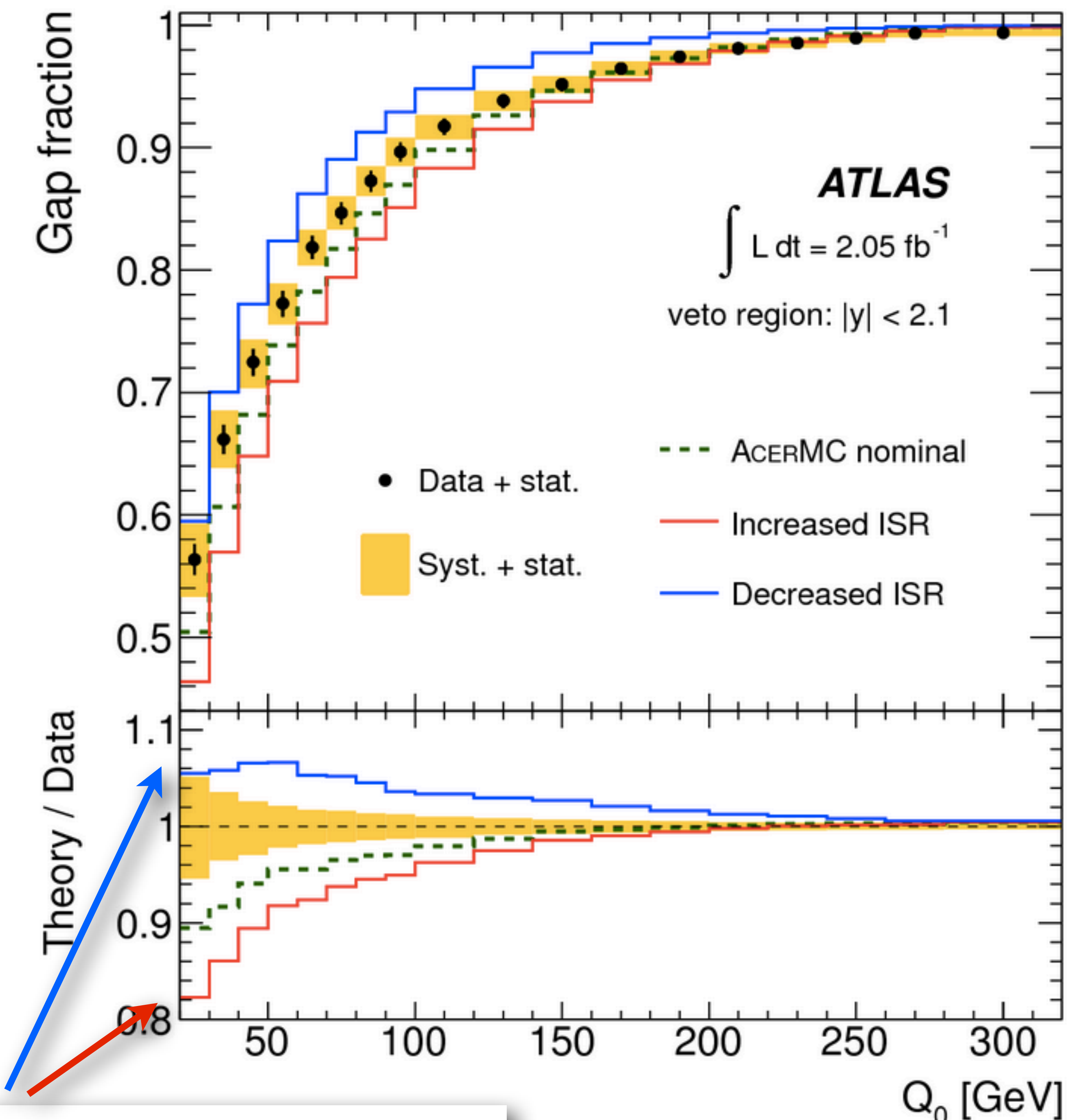


sample: ee, μe, μμ

arXiv:1203.5015

Single Jet Gap Fraction with ISR comparison





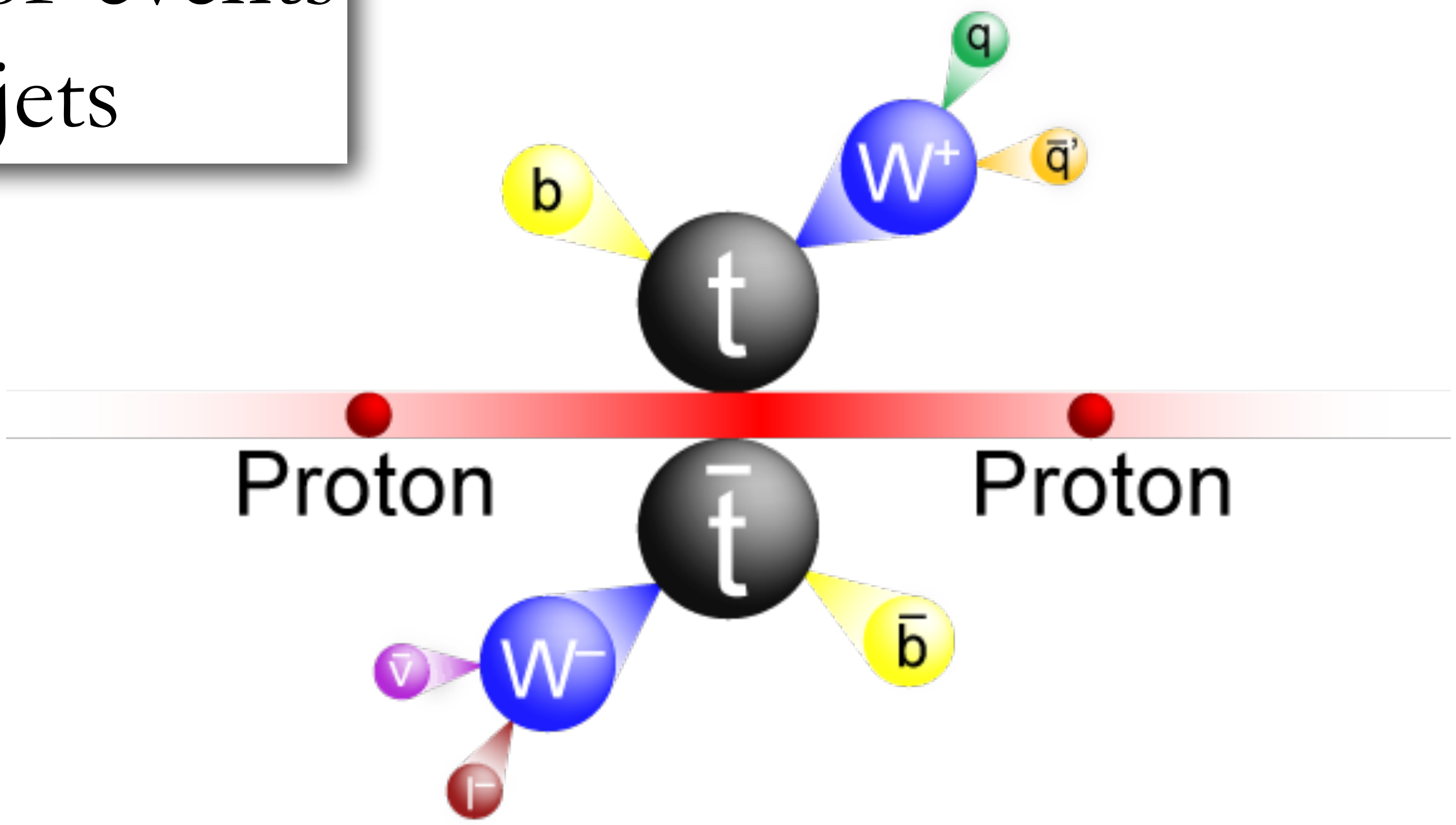
sample: ee, μe, μμ

Measurement constrains modeling of ISR

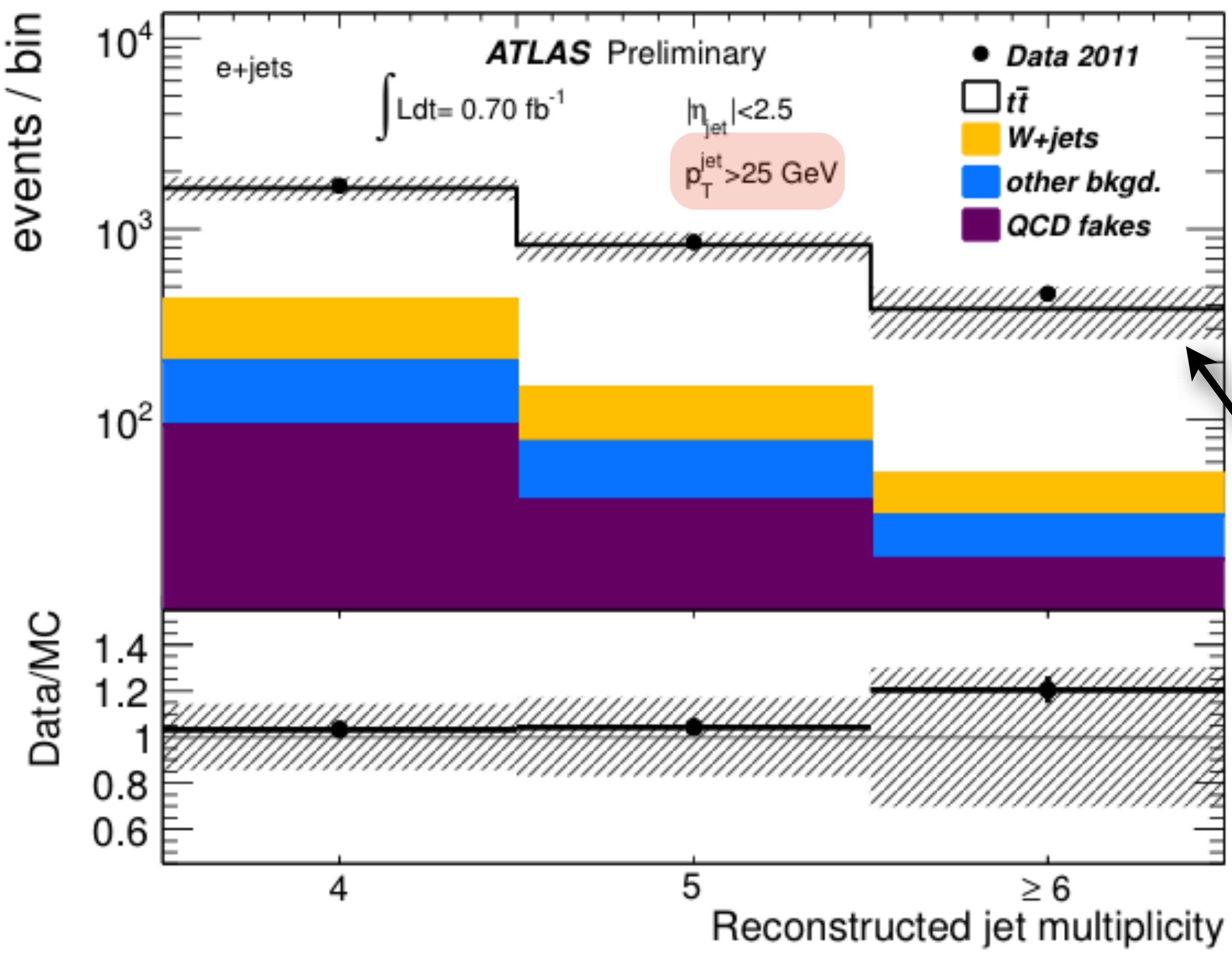
arXiv:1203.5015

Jet Multiplicities for Single Lepton Final States

Looking for events with e/μ+jets



Jet Multiplicities for Single Lepton Final States with Varying p_T-cuts



Require one electron or muon and four jets with p_T>25 GeV

total uncertainties are stat.+syst.

other bkgd. = single tops, dibosons, and Z+jets

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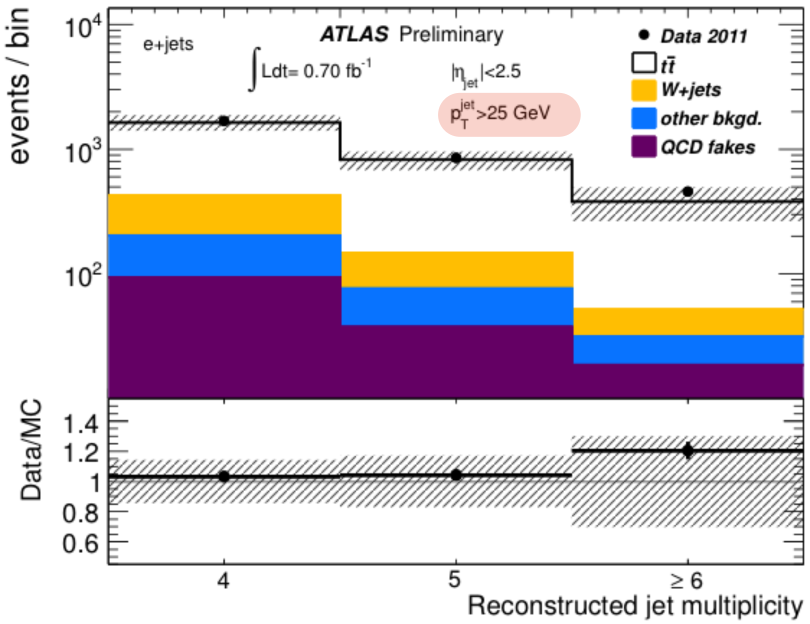
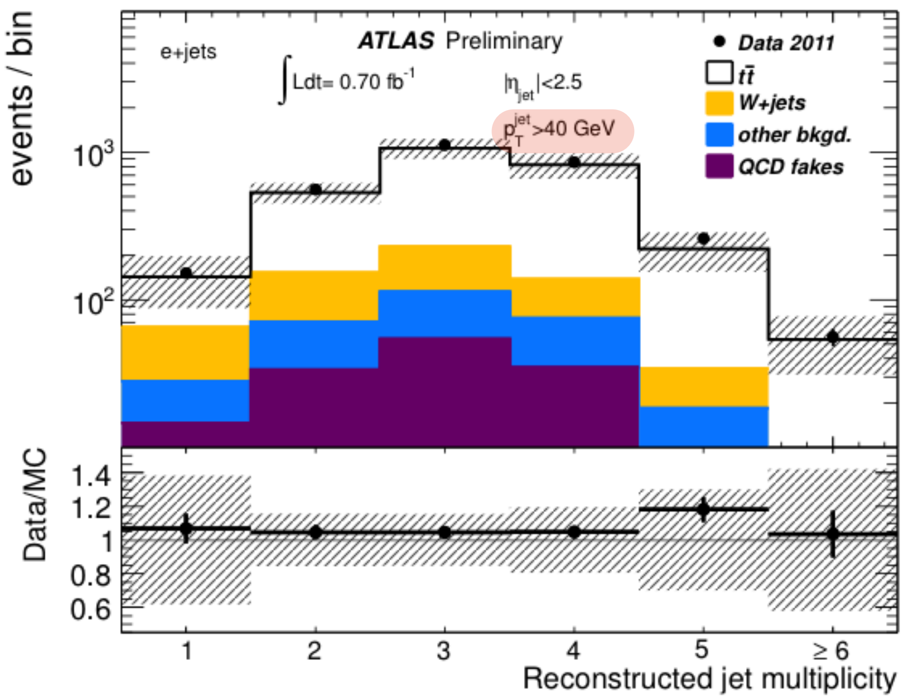
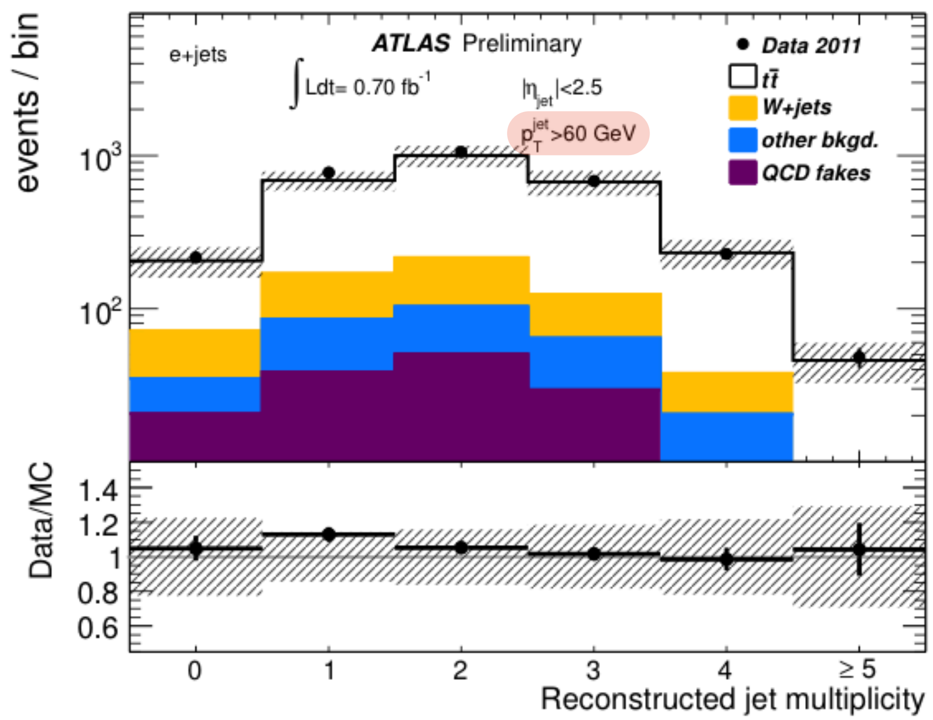
Jet Multiplicities for Single Lepton Final States with Varying p_T-cuts





Jet Multiplicities for three p_T thresholds



Muon channel in backup slides

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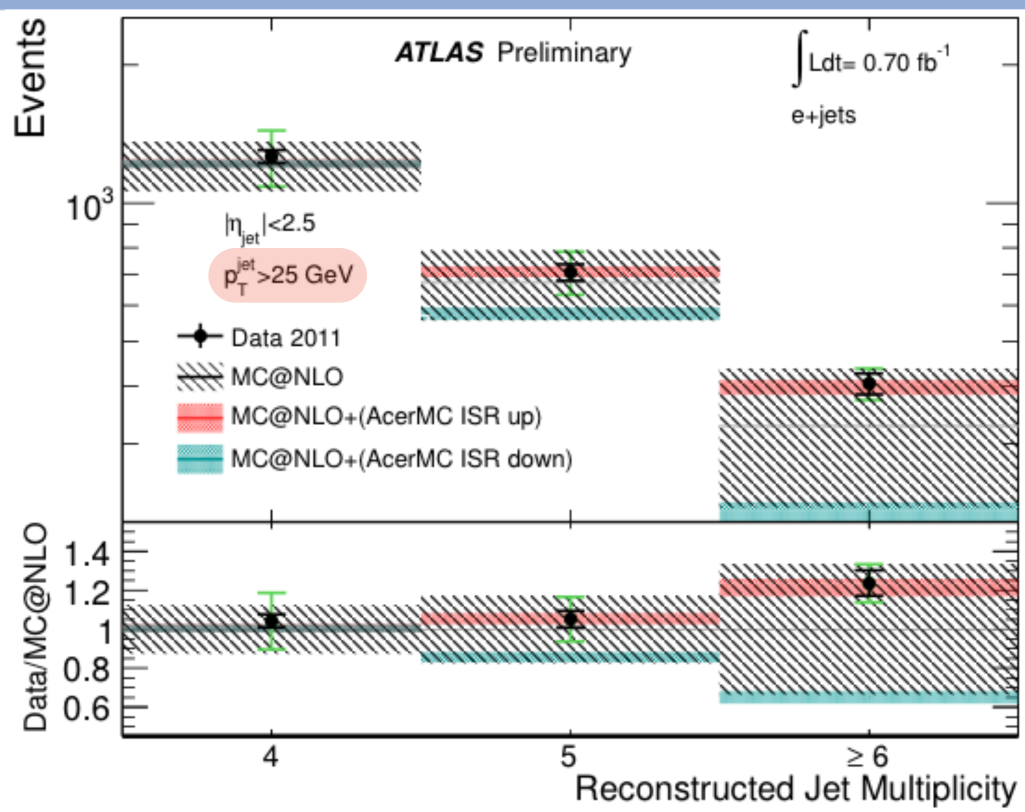
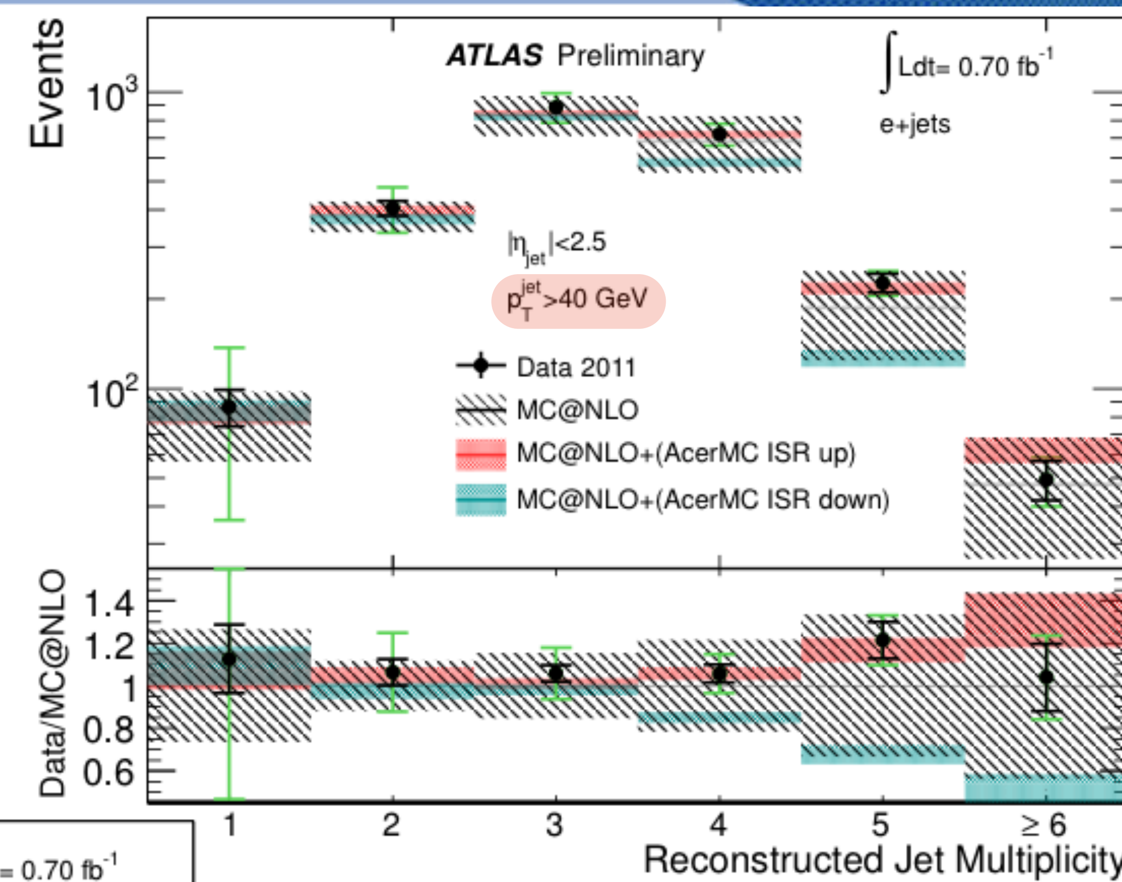
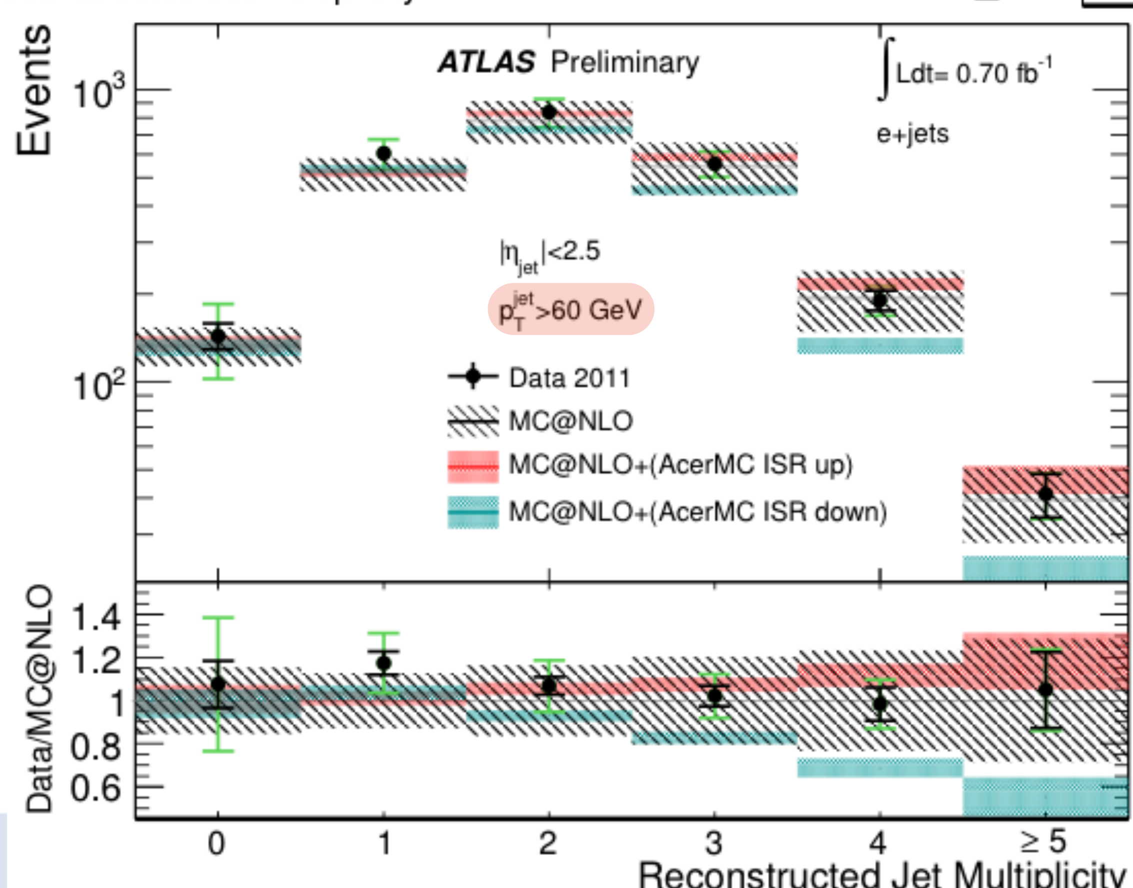
Background Subtracted Jet Multiplicities with Varying p_T-cuts







Background subtracted compared to shifted ISR

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In Summary

- The tt differential production cross section is described well by SM predictions.
- The production cross section for top pair events with additional jets has been measured which can improve the modeling of the underlying event and provides a handle on an important background for other analyses.
- The gap fraction was measured in three rapidity ranges and it was found that all MC models tested produce too much jet activity in the forward rapidity region. This measurement constrains the ISR modeling.
- The jet multiplicities produced in tt events were studied with three jet-p_T cuts and compared to shifted ISR samples. No significant deviation from the SM predictions is seen and within the uncertainties there is no preference for a shift in the ISR.

Backup Slides Follow...

Relative Differential tt Cross Section Details

Simulation

- Simulated tt events generated using MC@NLO with PDFs from CTEQ6.6 ($m_t \equiv$ 172.5 GeV); sample normalized to 164.6 pb (from NNLO prediction using [5])
  - parton showering modeled with HERWIG
  - underlying event modeled with JIMMY
- Single tops generated using MC@NLO
- W/Z bosons in association with jets generated with ALPGEN interfaced to HERWIG/JIMMY with CTEQ6.1
- Di-boson events generated by HERWIG with MRST2007lomod
- Pile-up is simulated with a value of 4-8 interactions per bunch crossing in order to reflect what is seen in the data

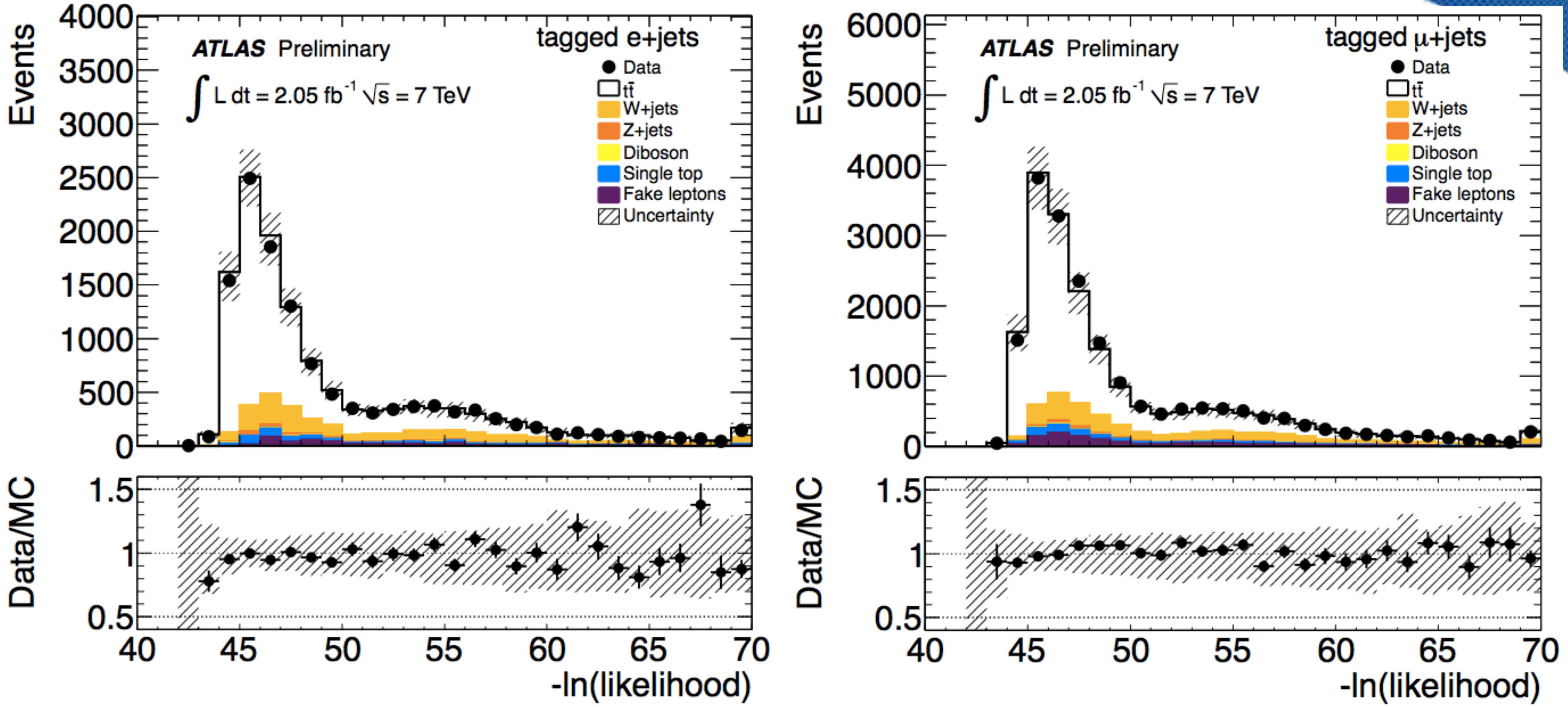
Event Selection

- *l*+jets channel:
  - require single electron (muon) trigger with 20 (18) GeV threshold, respectively.
  - require reconstructed electron (muon) to have E_T > 25 GeV (p_T > 20 GeV)
  - require ≥1 reconstructed primary vertex with 5 high quality tracks
  - require jets to pass quality cuts, event discarded if jet with p_T > 20 GeV is associated with calorimeter noise or activity out of time w.r.t. LHC bunch crossing.
  - require E_T^{miss} > 35(20) GeV for e+jets (μ+jets)
  - require transverse mass, m_T^W,(derived from lepton p_T and E_T^{miss}) > 25(60) GeV - E_T^{miss} for the e+jets (μ+jets)
  - require event to pass kinematic likelihood log(L) > -52
- e+jets channel only (to reduce fake electrons):
  - require ≥4 jets with p_T>25 GeV and $|\eta|$<2.5 and 1 b-tagged jet

Background Estimation

- Fake Leptons
  - Measure the fraction of real/fake 'loose' leptons that pass the 'tight' lepton selections
  - real leptons are measured using $Z \rightarrow ll$ decays
  - fake leptons are measured from data control regions dominated by fake leptons
- W+Jets
  - Uses a data driven method of estimating the number of W+Jets events passing the event selection criteria
- Other backgrounds
  - single top, Z+jets, and di-boson are estimated using MC
  - Z+jets is normalized to the approximate NNLO cross section
  - Di-boson events are normalized to the NLO cross section.
  - Single top normalized to the approximate NNLO cross section.

Event Reconstruction



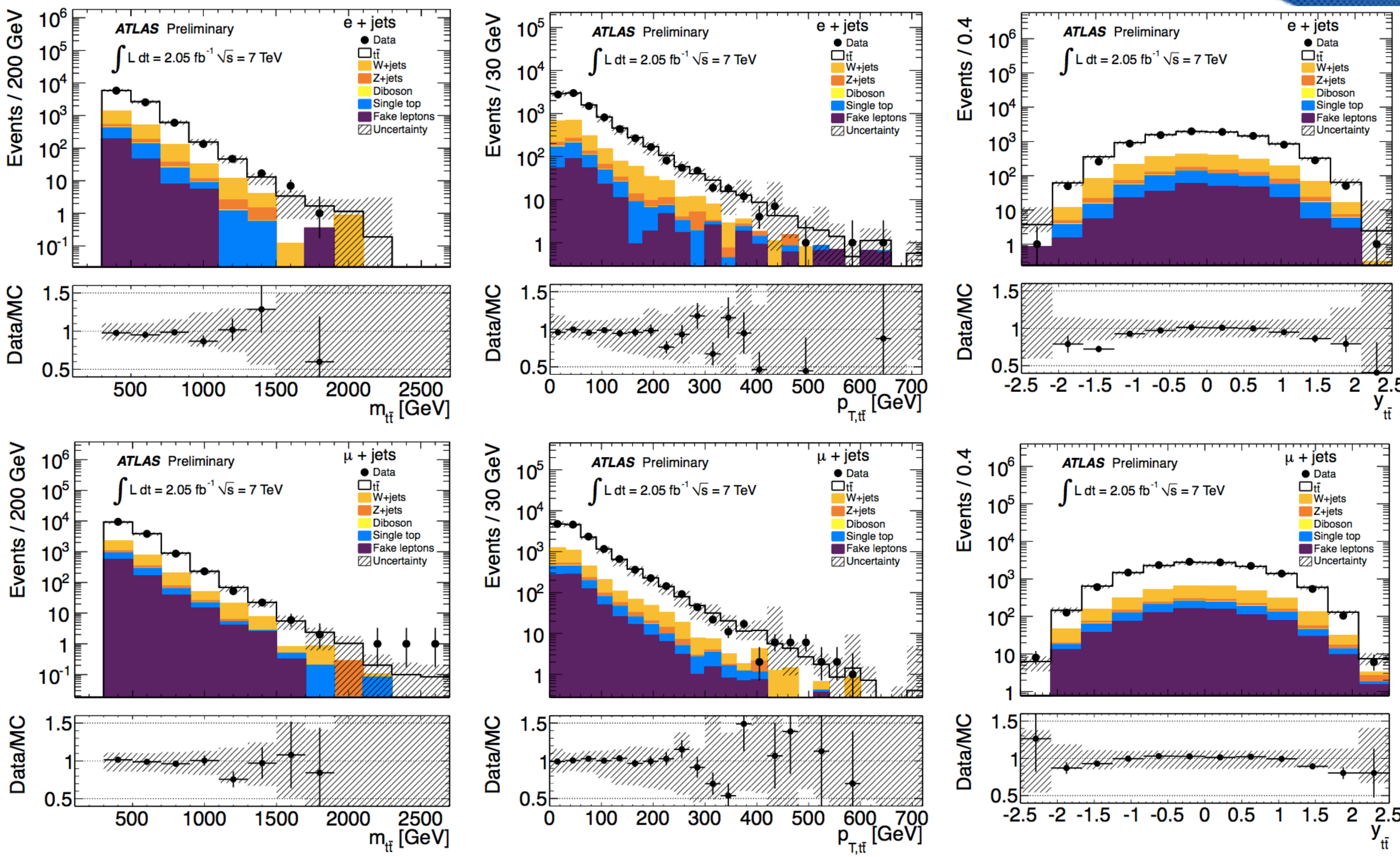
- Full kinematic reconstruction is performed using a likelihood fit of the measured objects to a theoretical leading order representation of the tt decay.

Event Reconstruction

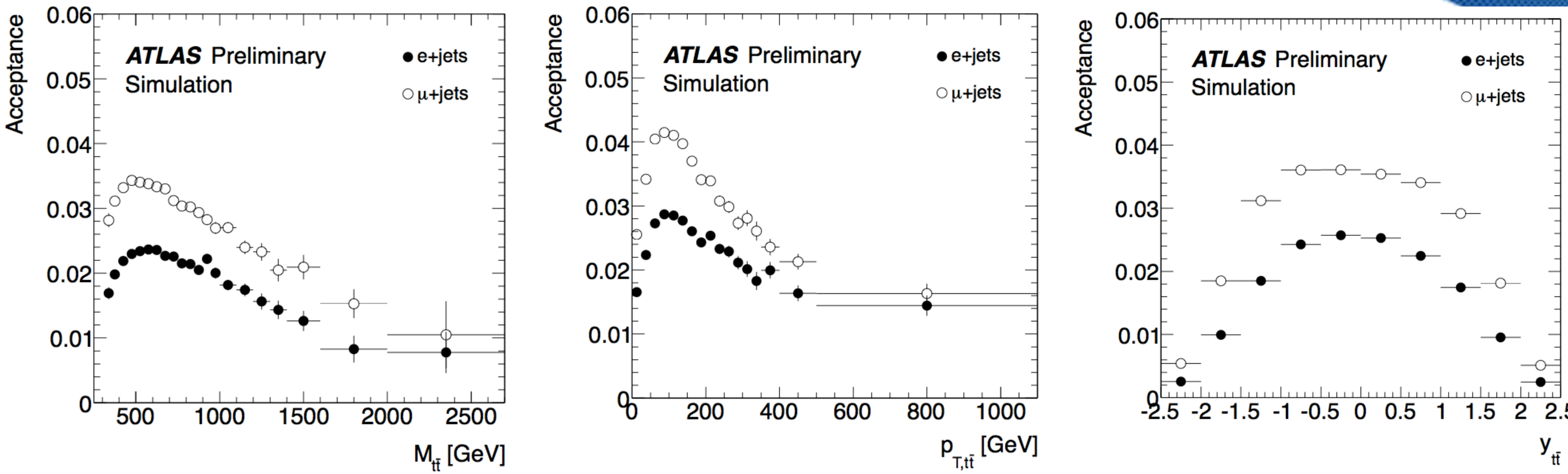
Channel	μ + jets pre-tag	μ + jets tagged	μ + jets L-req	e + jets pre-tag	e + jets tagged	e + jets L-req
tt	15800 ± 1300	13900 ± 1100	11100 ± 700	10700 ± 900	9400 ± 800	7400 ± 500
W+jets	19000 ± 5000	3000 ± 1200	1700 ± 700	13000 ± 3300	2200 ± 900	1300 ± 500
Single top	950 ± 70	760 ± 80	490 ± 50	660 ± 50	530 ± 50	338 ± 32
Z+jets	2200 ± 200	309 ± 34	192 ± 20	1750 ± 330	240 ± 50	154 ± 26
Diboson	298 ± 28	53 ± 7	34 ± 4	181 ± 19	32 ± 5	21 ± 3
Fake-leptons	3400 ± 1700	1100 ± 1100	800 ± 800	2000 ± 1000	400 ± 400	250 ± 250
Signal+bkg	42000 ± 6000	19200 ± 2600	14400 ± 1700	28000 ± 4000	12800 ± 1700	9500 ± 1100
Observed	42327	19254	14416	26488	12457	9187

- Number of predicted and observed events
- Systematic uncertainties are shown

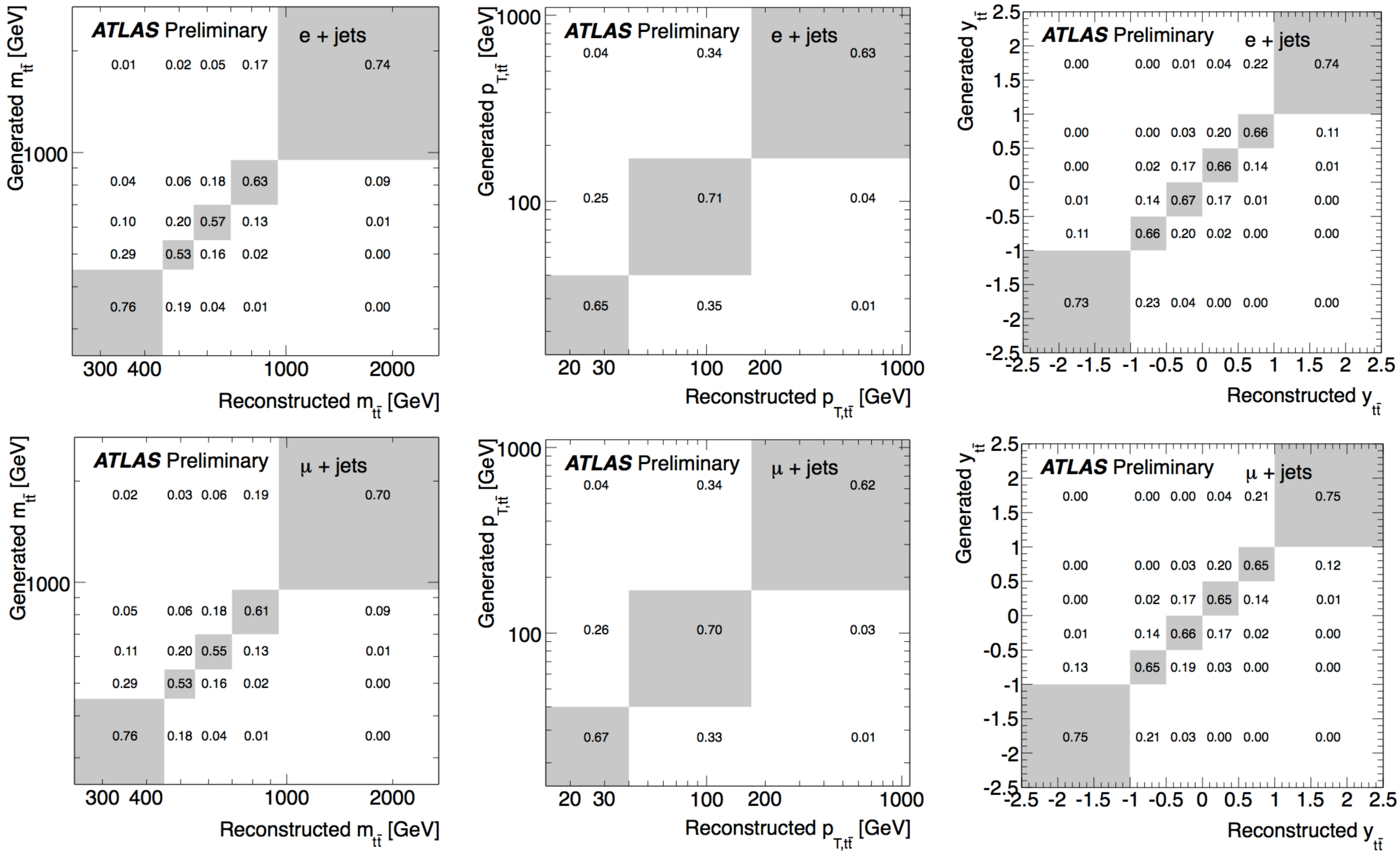
m_{tt}, $p_{T,tt}$, and y_{tt} Event Distributions for e+jets and μ+jets



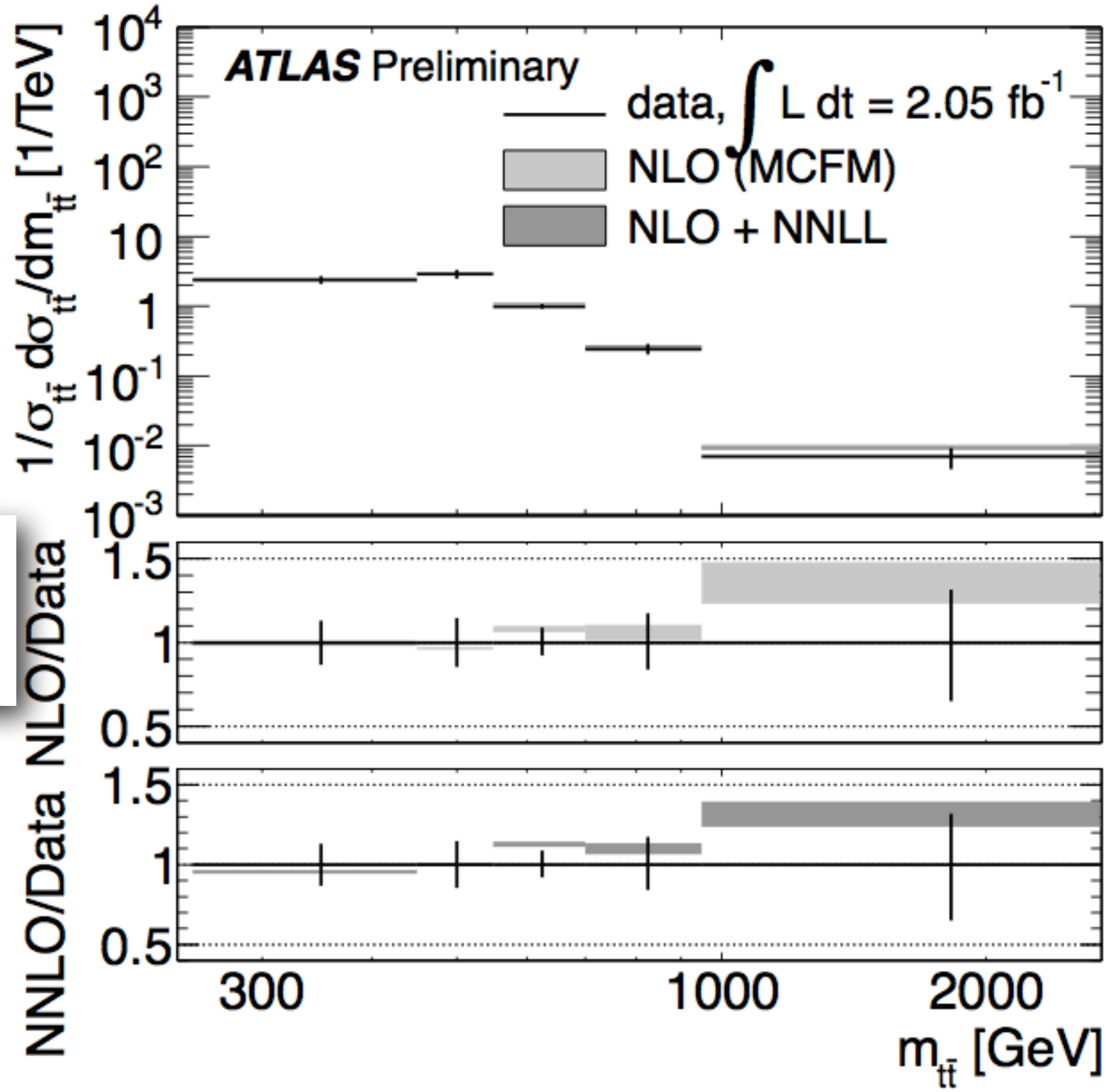
m_{tt}, $p_{T,tt}$, and y_{tt} Acceptance Distributions



Migration Matrices for e+jets and μ+jets

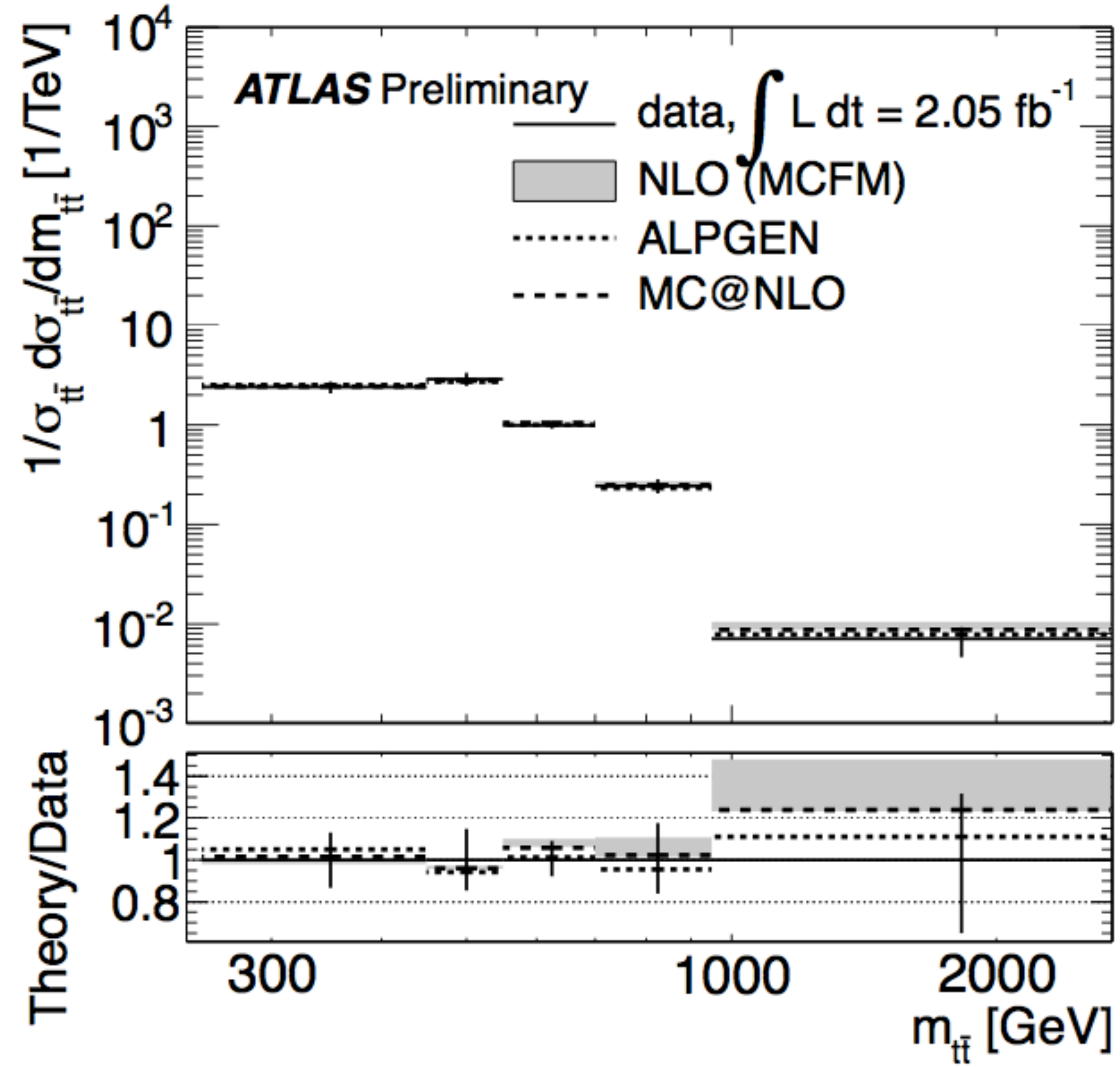


Relative Differential tt Cross Section: m_{tt}



sample:

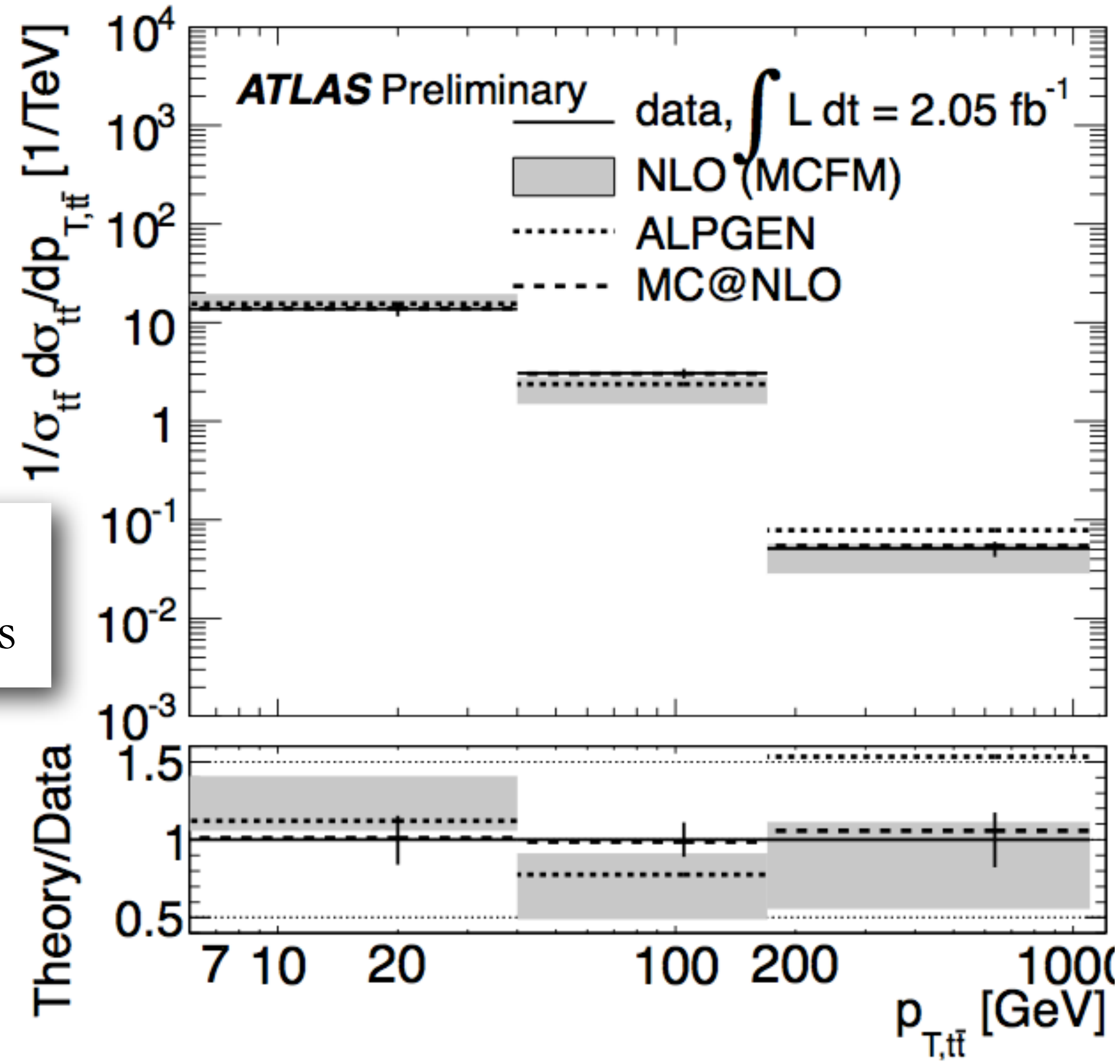
e+jets, μ+jets



- Relative cross-section shown to reduce systematic effects
- Uncertainties include both systematic effects and statistical errors
- Combining the e+jets and μ+jets channels and running the analysis with a single bin gives a total inclusive tt cross section of σ_{tt}=160 ±25 pb which agrees with SM predictions and previous measurements
- MC uncertainties include those from parton distribution functions (PDF), the strong coupling constant and on factorization and renormalization scales (using m_t = 172.5 GeV)
- See backup slides for analysis details (event selection, simulation, etc.)

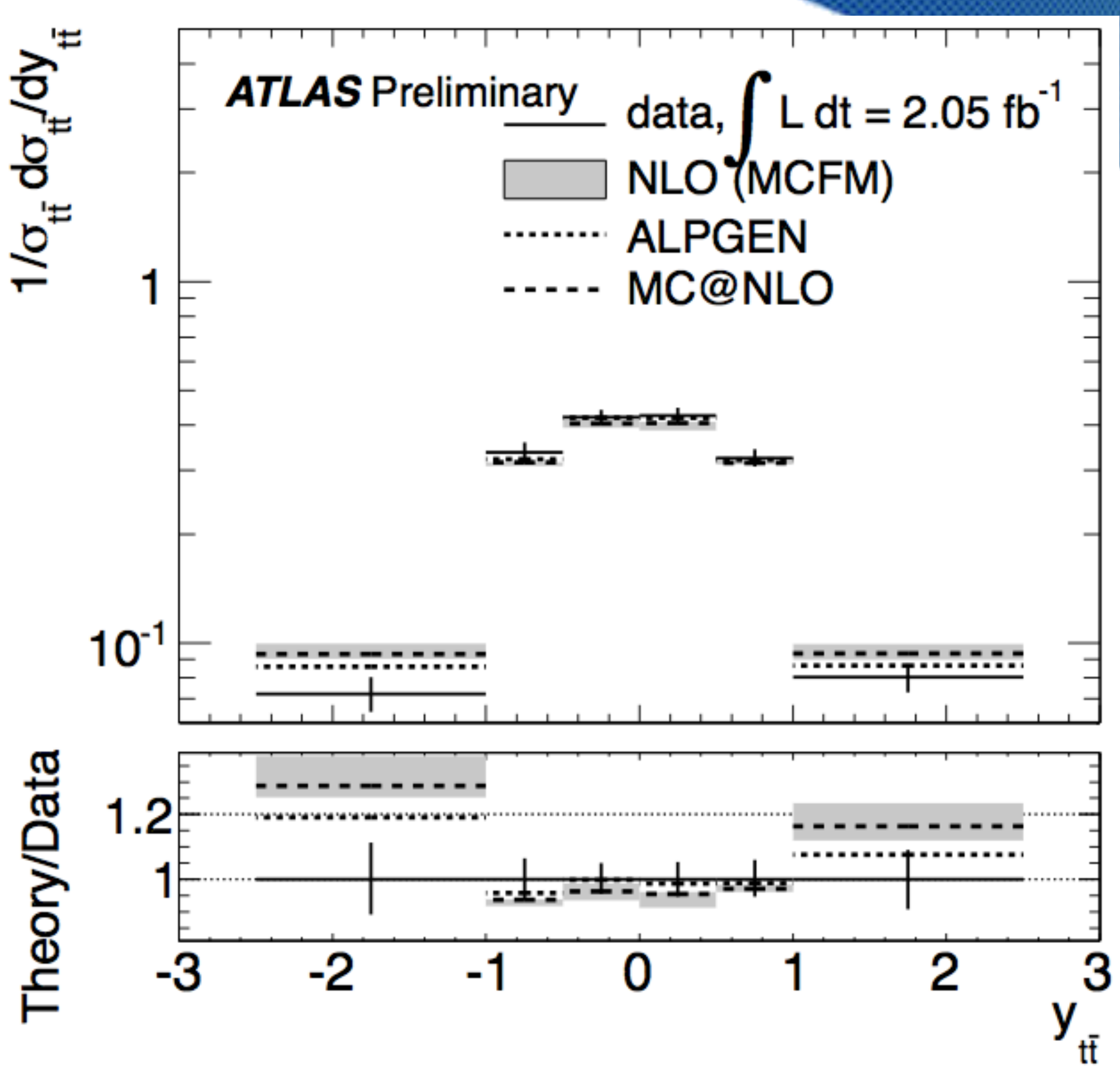
Details in [2]

Relative Differential tt Cross Section: $p_{T,tt}$ and y_{tt}



sample:

e+jets, μ+jets



- Relative cross-section shown to reduce systematic effects
- Uncertainties include both systematic effects and statistical errors
- Jet Energy Scale is the dominant systematic for m_{tt} and $p_{T,tt}$
- Fake Leptons and final state radiation are the dominant systematics for y_{tt}

tt Production with Central Jet Veto Details

Gap Fraction Definitions

- Gap Fraction definition:

$$f_{gap} = \frac{\sigma(Q_0)}{\sigma}$$

- σ = inclusive top pair production cross section
- $\sigma(Q_0)$ is the fiducial cross section for top pair events which do not contain an additional jet with $p_T > Q_0$ in the specified rapidity region
- Alternate definition:

$$f_{gap} = \frac{\sigma(Q_{sum})}{\sigma}$$

- σ is the same
- $\sigma(Q_{sum})$ is the fiducial cross section for top pair events in which the sum-p_T of all additional jets in the rapidity range is less than Q_{sum}

arXiv:1203.5015

Simulation

- NLO predictions:
  - MC@NLO is the same as in the tt production cross section measurement
  - POWHEG using CTEQ6.6 PDF then interfaced to either
    - PYTHIA with underlying event tune AMBT1
    - or HERWIG/JIMMY with underlying event tune AUET1
- LO predictions:
  - ALPGEN with CTEQ6L1 PDF interfaced with HERWIG/JIMMY (AUET1)
    - double counting removed with MLM matching procedure
  - SHERPA with default underlying event tune and the CTEQ6L1 PDF
  - ACERMC interfaced to PYTHIA using MRST2007LO* PDF and AMBT1underlying event

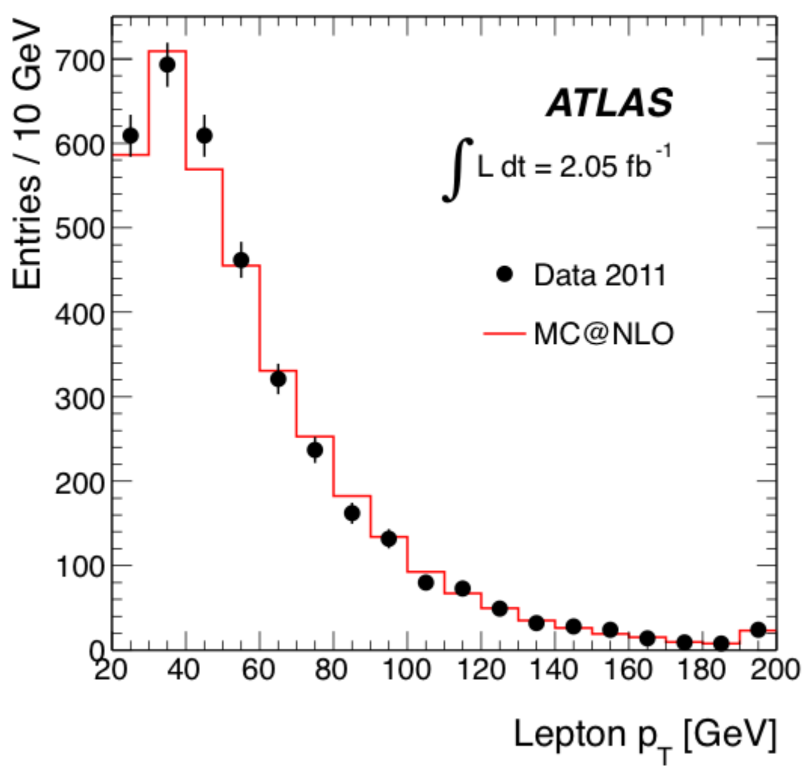
arXiv:1203.5015

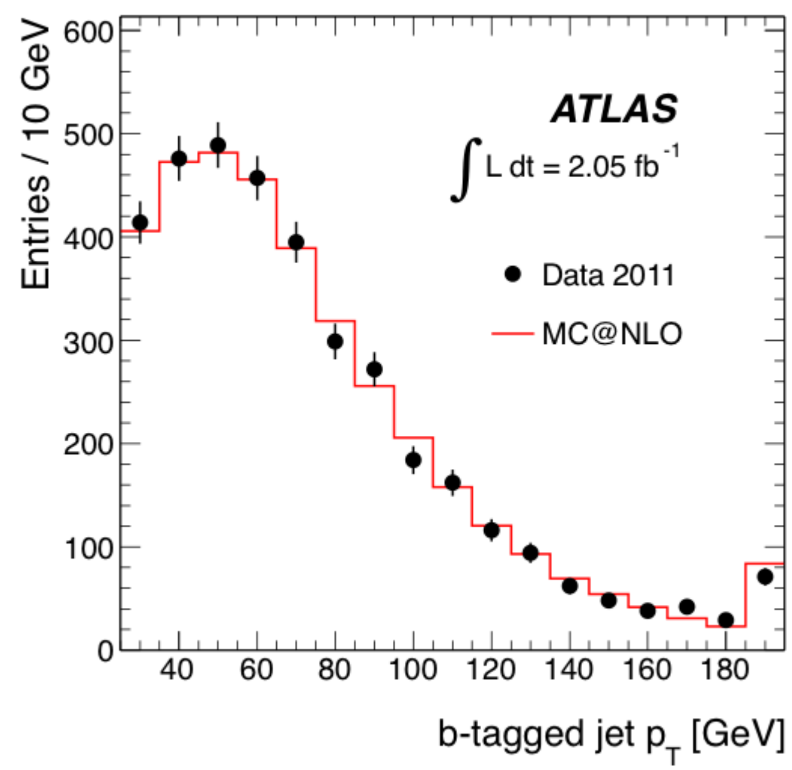
Event Selection

- Electrons: E_T>25GeV and $|\eta|<2.47$ and $1.37<|\eta|<1.52$
- Muons: p_T>20GeV and $|\eta|<2.5$
- Jets:
  - reconstructed using anti-k_t with radius of 0.4 and using clusters of adjacent calorimeter cells calibrated at the EM energy scale
  - correct for detector response and other effects using MC
  - corrected jets required to have p_T>25GeV and $|y|<2.4$ and well separated from electrons or muons ($\Delta R(\eta,\phi)>0.4$)
  - b-jets are identified using the IP3D+SV1 algorithm and are referred to as b-tagged
  - require jet to be fully contained within the tracking detectors $|y|<2.1$
- Require two opposite sign high-p_T leptons and at least b-tagged jets to ensure pure sample
- Require missing E_T>40GeV and dilepton mass, m_{ll}, is not in the range of the Z-boson mass, $|m_{ll}$ - 91GeV$|$ > 10 GeV to remove $Z\rightarrow ll$ backgrounds in the ee/$\mu\mu$ channel
- Require m_{ll}>15GeV to reject backgrounds from vector-meson decays
- Require sum-p_T of all reconstructed objects to be greater than 130GeV to reject $Z\rightarrow\tau\tau$ background in eμ channel
- Number of selected events: 242(ee), 436($\mu\mu$), 1095(eμ)
- Dominant backgrounds are single top production and events in which at least one lepton originates from heavy flavor decay or jet misidentification

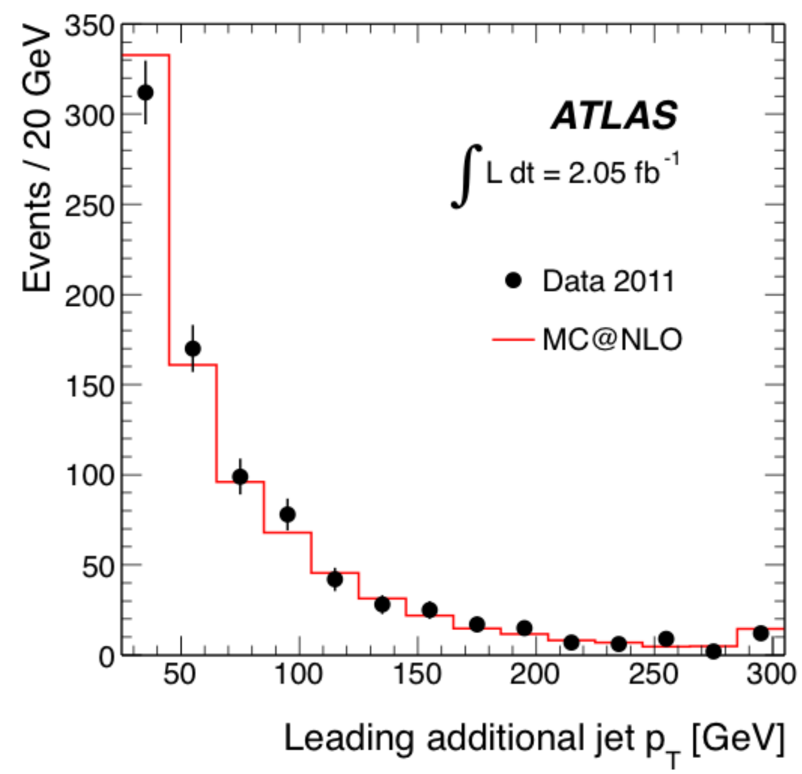
arXiv:1203.5015

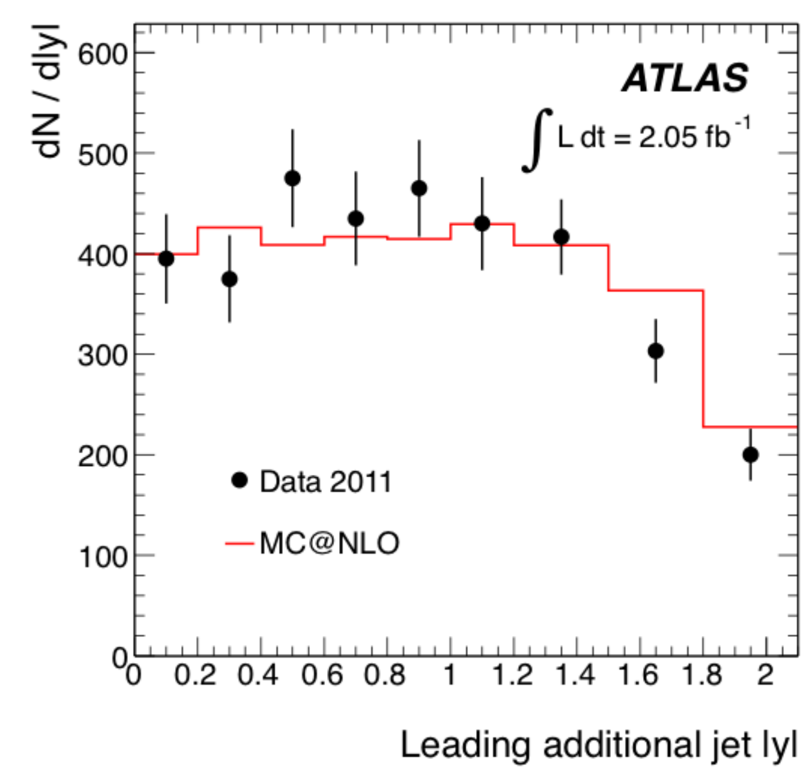
Event Distributions





- Statistical uncertainties only
- For p_T the overflow events are contained in the last bin

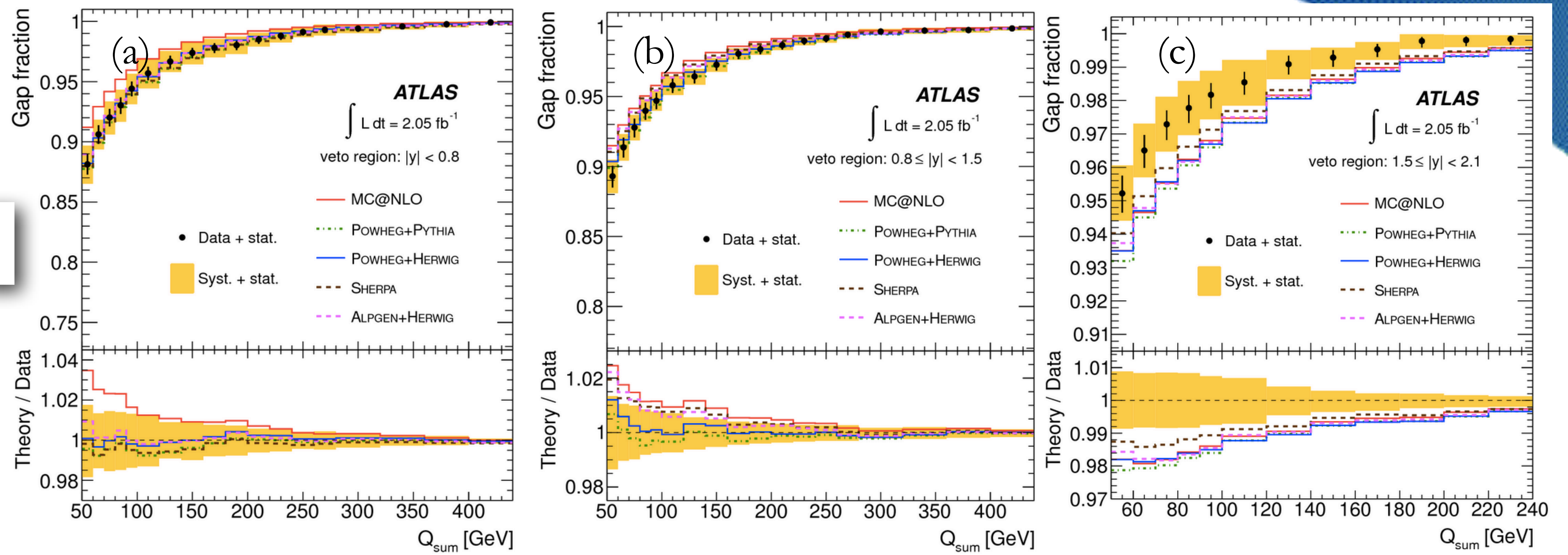




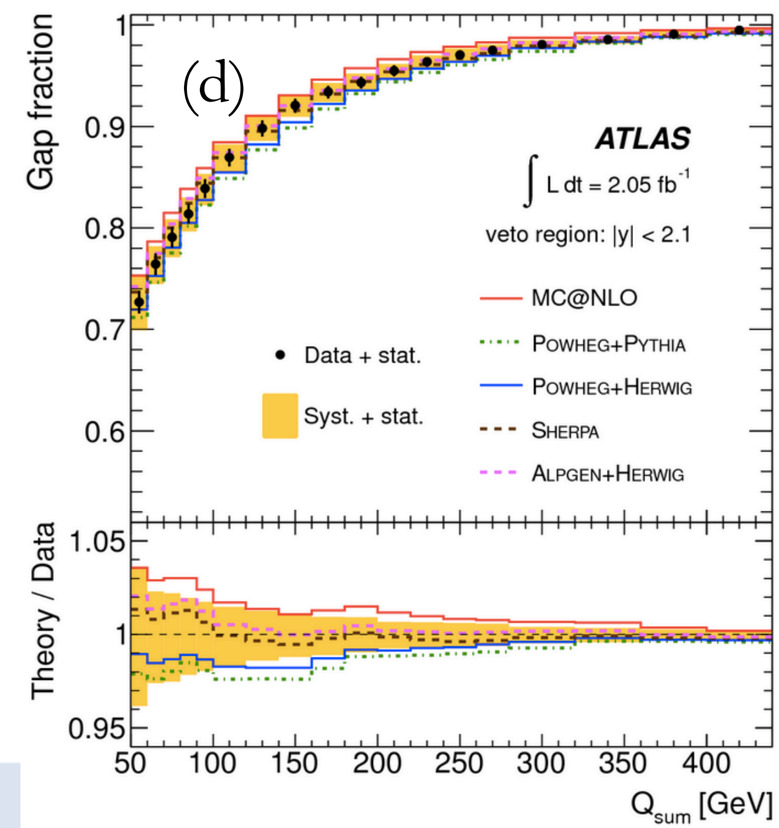
arXiv:1203.5015

Summed Jet Gap Fraction Results

sample: ee, μe, μμ



- Alternate Gap Fraction: $\mathrm{f_{gap}} = \frac{\sigma(Q_{sum})}{\sigma}$
  - σ is still the fiducial cross section for inclusive tt production
  - $\sigma(Q_{sum})$ is the fiducial cross section for events where the summed p_T of additional jets is less than Q_{sum}
- In General, the values are higher than Q_0 which is consistent with probing quark/gluon radiation beyond the first emission
- It can be seen that the MC@NLO and POWHEG generators are performing as well as the LO approximations used by SHERPA and ALPGEN for parton showers in subsequent emissions which indicates higher order theory predictions may be needed to describe the data in all regions of phase space



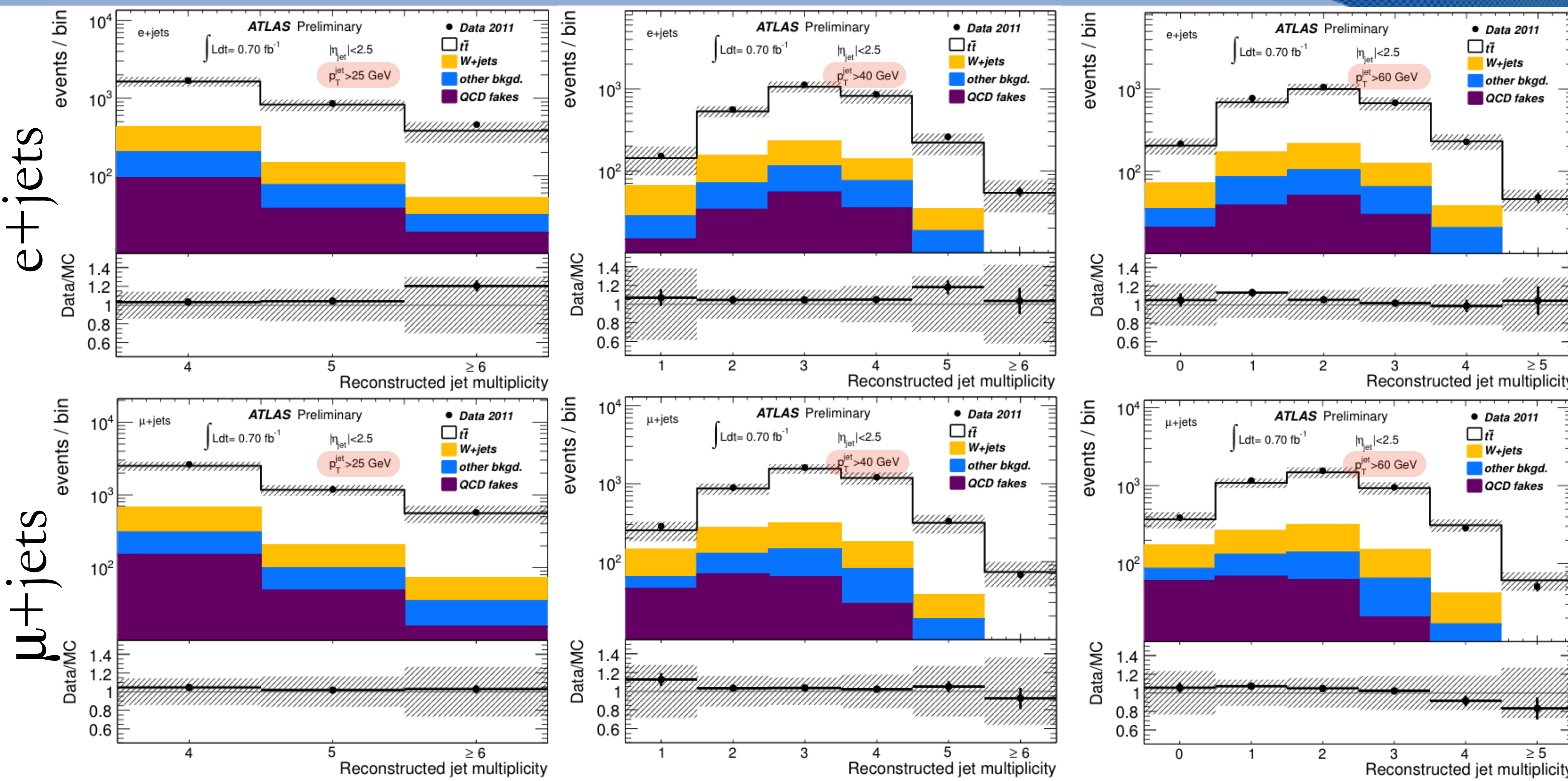
arXiv:1203.5015

Jet Multiplicities in tt Events Details

Details Overview

- Simulation: tt events generated in the same way as the previous two results
- Event Selection:
  - Object requirements are similar to those of the differential tt cross section result
  - require one and only one electron or muon per event plus four jets, each with p_T>25 GeV with one being a b-jet

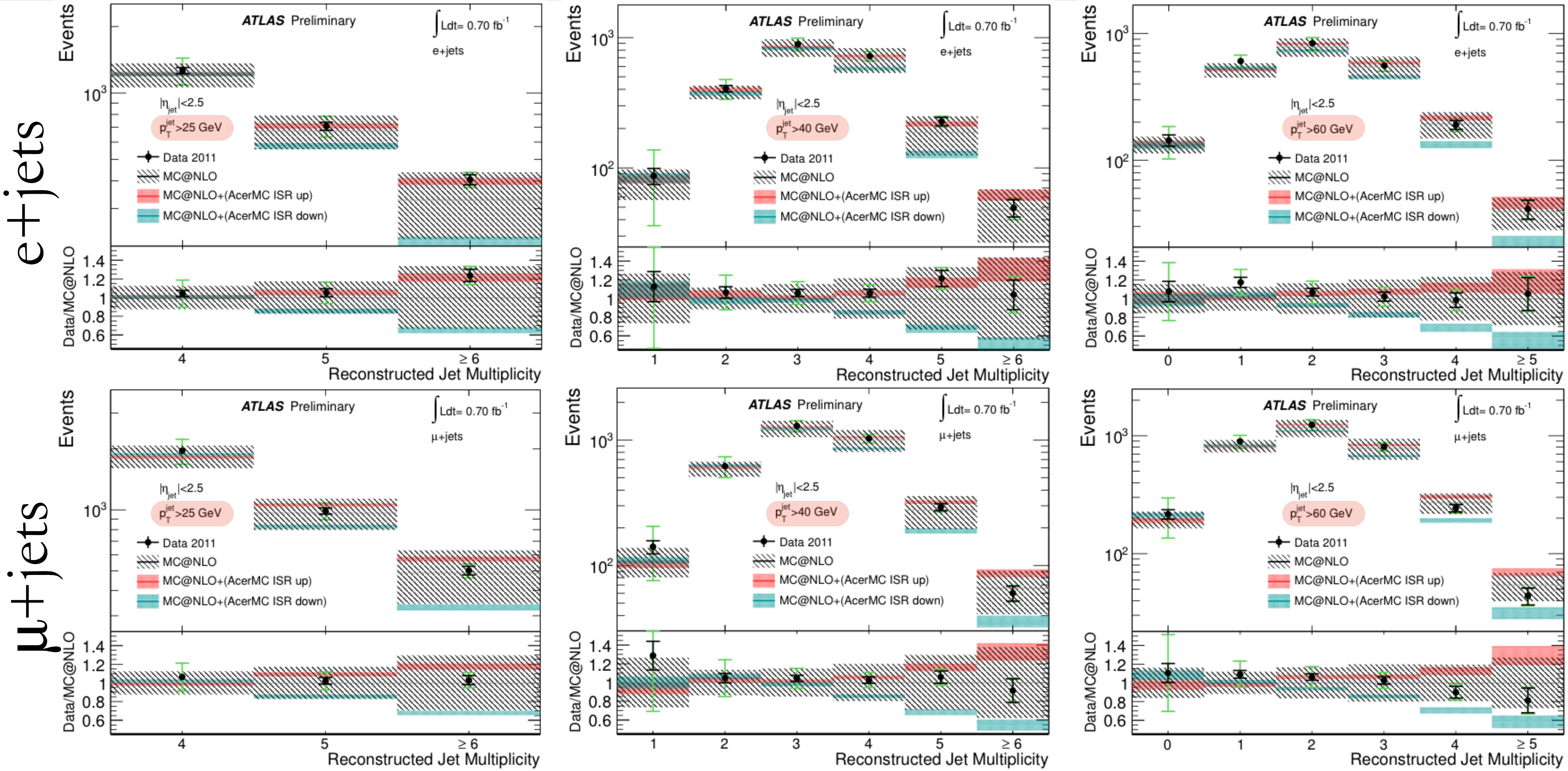
Jet Multiplicities for Single Lepton Final States with Varying p_T-cuts



- Data with backgrounds, other bkgd. includes backgrounds from single tops, dibosons, and Z+jets determined from simulation
- Predictions are in good agreement with the data.
- Shaded bands show the total uncertainty of signal+background

Details in [4]

Background Subtracted Jet Multiplicities with Varying p_T-cuts



- Reconstructed jet multiplicities after background subtraction shown with the ISR shifted ACERMC samples
- Predictions are in good agreement with the data and within current uncertainties neither ISR variation is favored
- Shaded bands show the total uncertainty of the MC

$t\bar{t}j$ Cross Section Measurement Details

$t\bar{t}\,j$ Cross Section Measurement Details

- MC Simulation is similar to the previous analyses
- Event Selection is also similar to the previous analyses
- Analysis uses a kinematic likelihood fit to the data
  - The variables used in the fit are the lepton pseudorapidity and the transformed aplanarity.
  - Plots of these variables can be found in Reference 2

References

1. ATLAS Collaboration, *Measurements of top quark pair relative differential cross-sections with ATLAS in pp collisions at sqrt(s) = 7 TeV*, in print
2. ATLAS Collaboration, *Measurement of the cross section in tt + jets using a kinematic fit method with the ATLAS detector*, ATLAS-CONF-2012-083
3. ATLAS Collaboration, *Measurement of tt production with a veto on additional central jet activity in pp collisions at sqrt(s) = 7 TeV using the ATLAS detector*, arXiv:1203.5015 [hep-ex], CERN-PH-EP-2012-062
4. ATLAS Collaboration, *Reconstructed jet multiplicities from the top-quark pair decays and associated jets in pp collisions at √s = 7 TeV measured with the ATLAS detector at the LHC*, ATLAS-CONF-2011-142
5. ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST 3 (2008) S08003

Theoretical tt cross section

- The tt cross section for pp collisions at a centre-of-mass energy of sqrt(s) = 7 TeV is $\sigma_{tt} = 167^{+17}_{-18}$ pb^{-1} for a top quark mass of 172.5 GeV/c^2. It has been calculated at approximate NNLO in QCD with Hathor 1.2 [1] using the MSTW2008 90% NNLO PDF sets [2] incorporating PDF+α_S uncertainties, according to the MSTW prescription [3], added in quadrature to the scale uncertainty and cross checked with the NLO+NNLL calculation of Cacciari et al. [4] as implemented in Top++ 1.0 [5].

- [1] M. Aliev et al., HATHOR – HAdronic Top and Heavy quarks cross section calculatoR Comput. Phys. Commun.182 (2011) 1034-1046, arXiv:1007:1327 [hep-ph].
- [2] A.D. Martin et al., Parton distributions for the LHC, Eur. Phys. J. C63 (2009) 189-285, arXiv: 0901.0002 [hep-ph]
- [3] A.D Martin et al., Uncertainties on alpha_S in global PDF analyses and implications for predicted hadronic cross sections, Eur. Phys. J. C64 (2009) 653-680, arXiv:0905.3531 [hep-ph]
- [4] M. Cacciari et al., Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation, to appear in Phys. Lett. B, arXiv:1111.5869 [hep-ph]
- [5] M. Czakon and A. Mitov, Top++: a program for the calculation of the top-pair cross-section at hadron colliders, arXiv:1112.5675 [hep-ph]