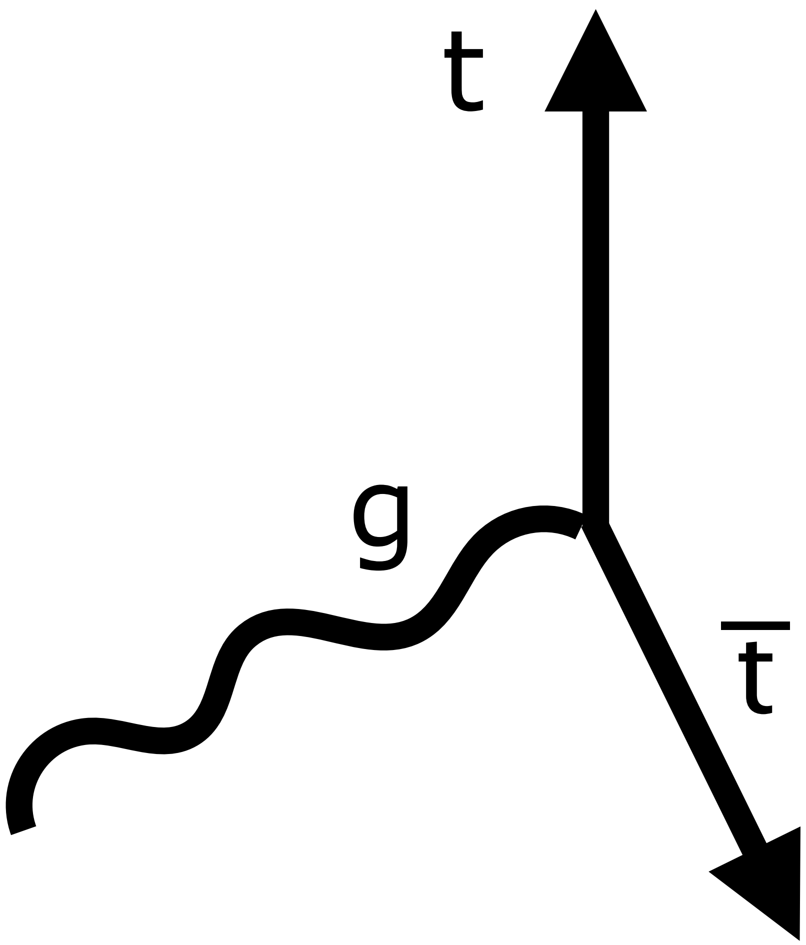
Recent $t\bar{t}$ differential cross-sections measurements

Riccardo Di Sipio, University of Toronto
on behalf of the ATLAS, CMS, CDF and D0 Collaborations

What to measure



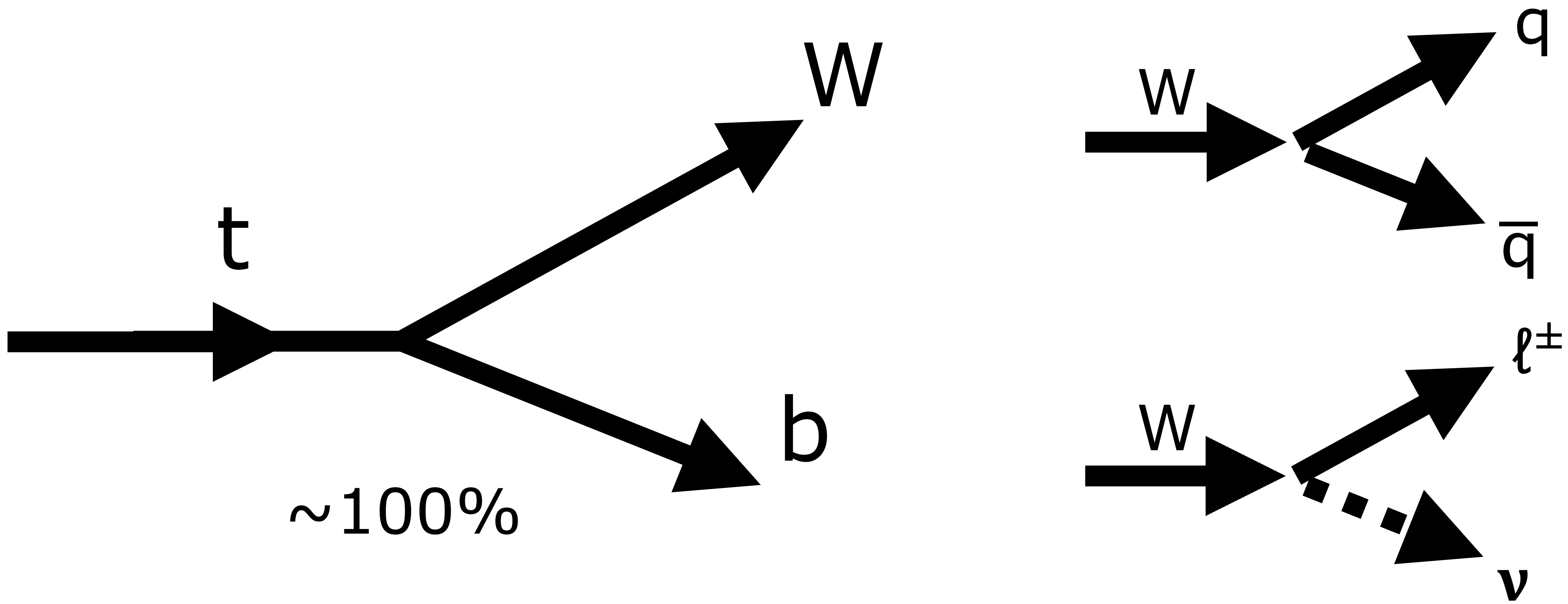
Parton-level view (full phase-space)

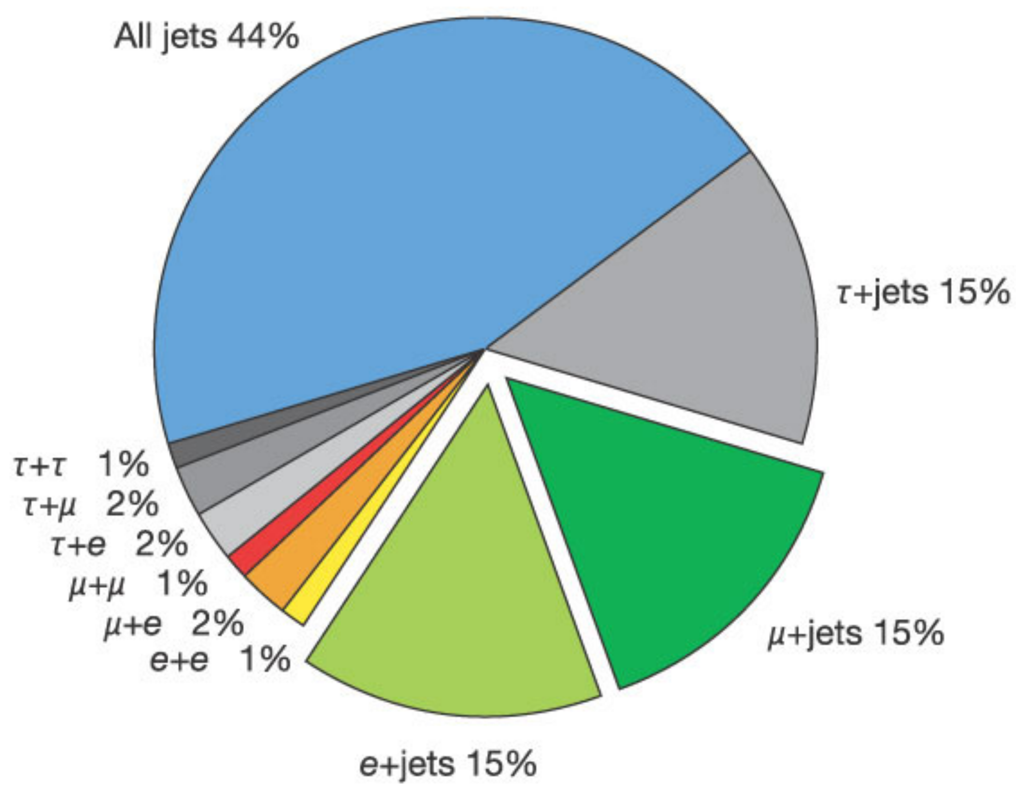
What we're ultimately interested in: the **kinematics** of the two **top quarks**

Testing higher-order calculations not yet matched to parton shower

Depend on the details of the calculation Monte Carlo generators used to assess corrections

Decay channels



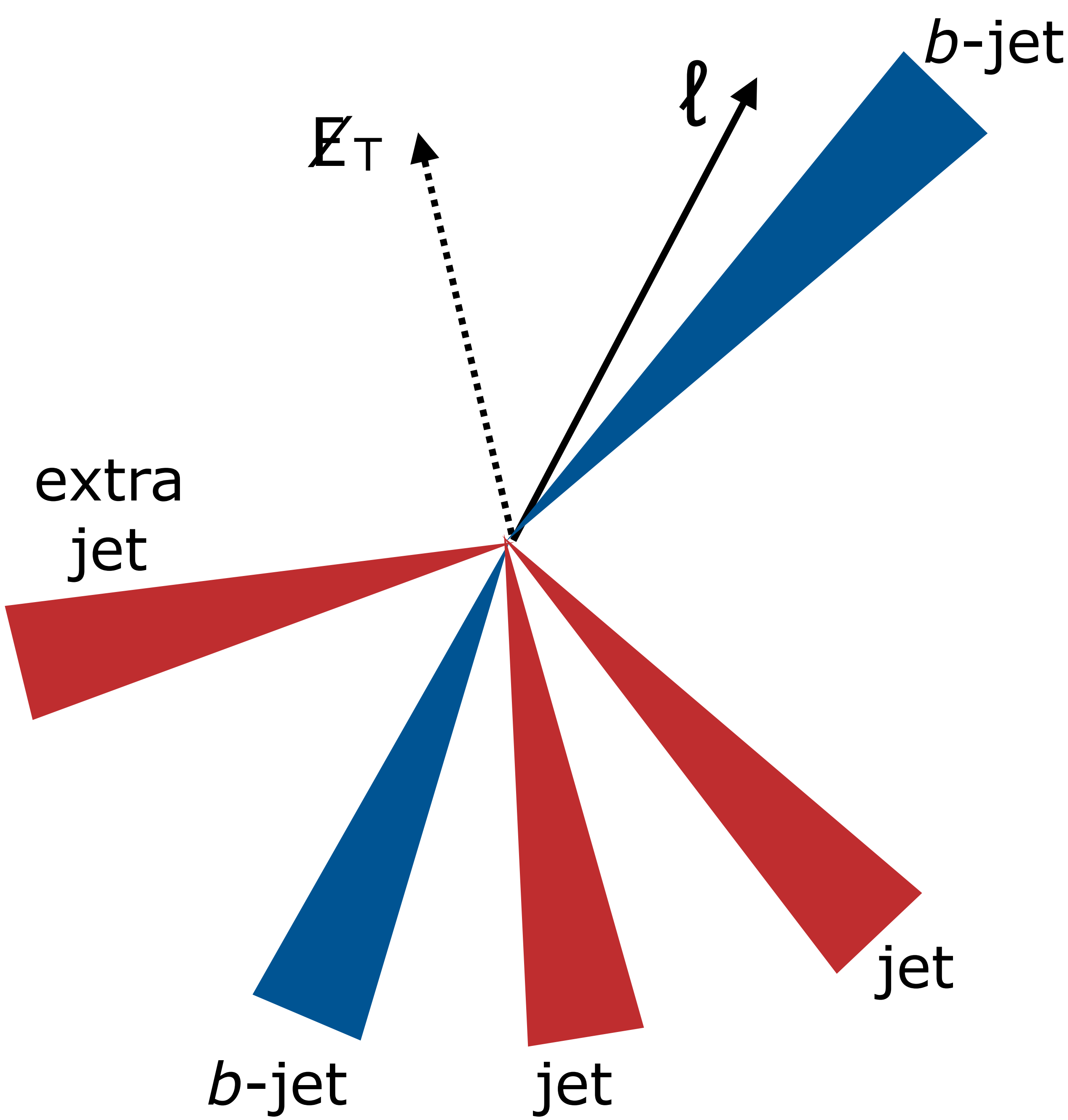


All-hadronic (5/9)
large xs, large multijet bkg

ℓ+jets (4/9)
Good for trigger, S/B

Di-leptonic (1/9)
Small bkg, small stats

What to measure



lepton+jets resolved

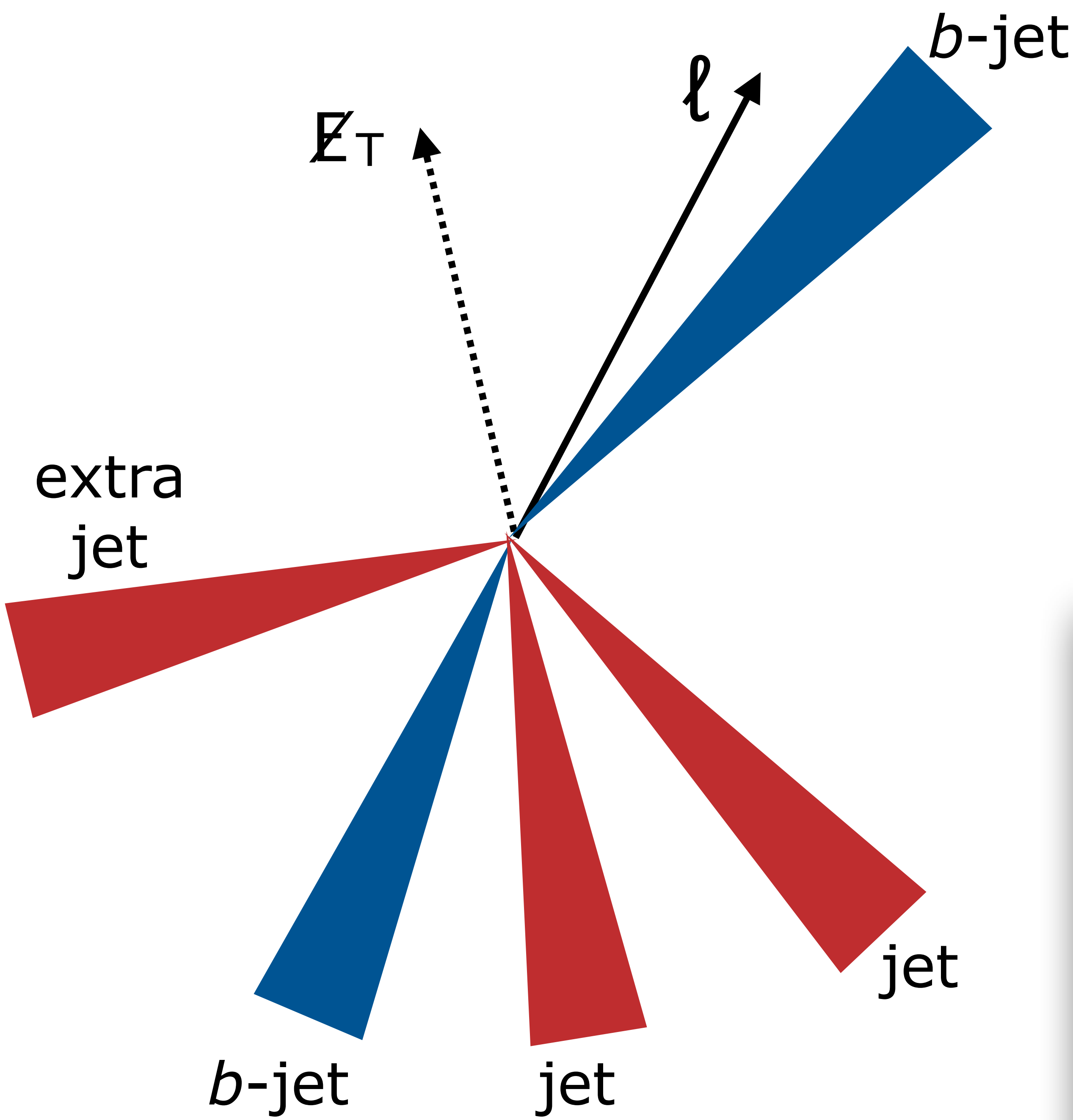
Particle-level view (fiducial phase-space)

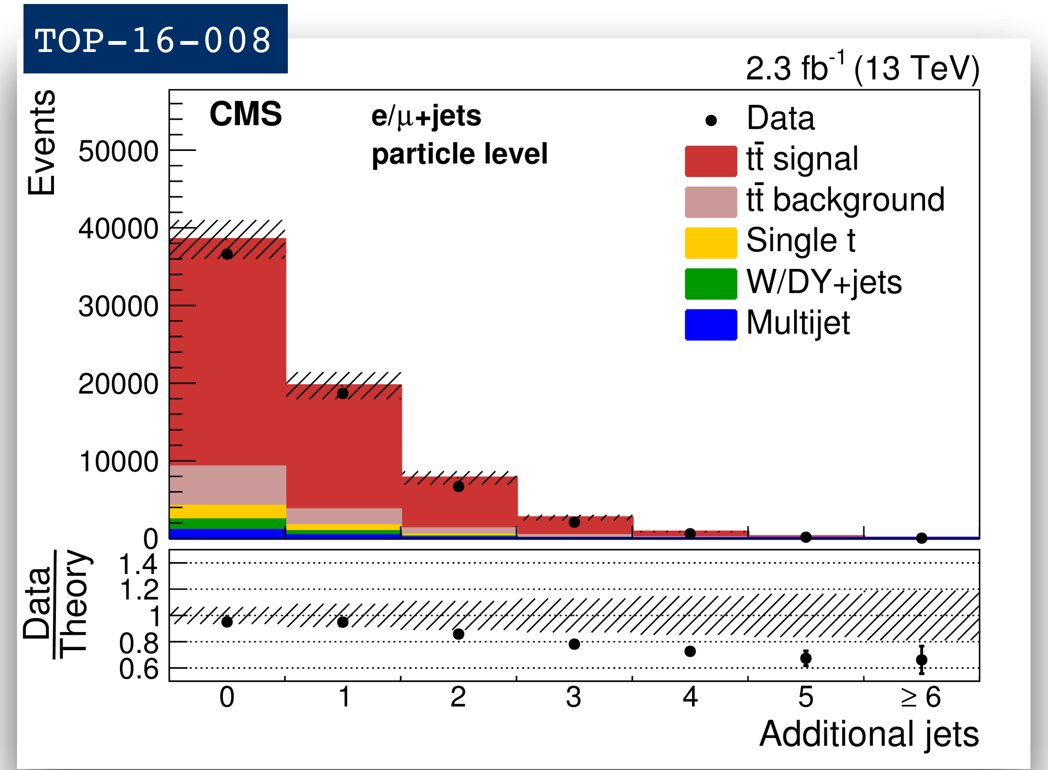
What we actually observe: the **kinematics** of the **final-state objects** (leptons, jets, neutrinos), i.e. the **decay products** of the two top quarks + additional **radiation**

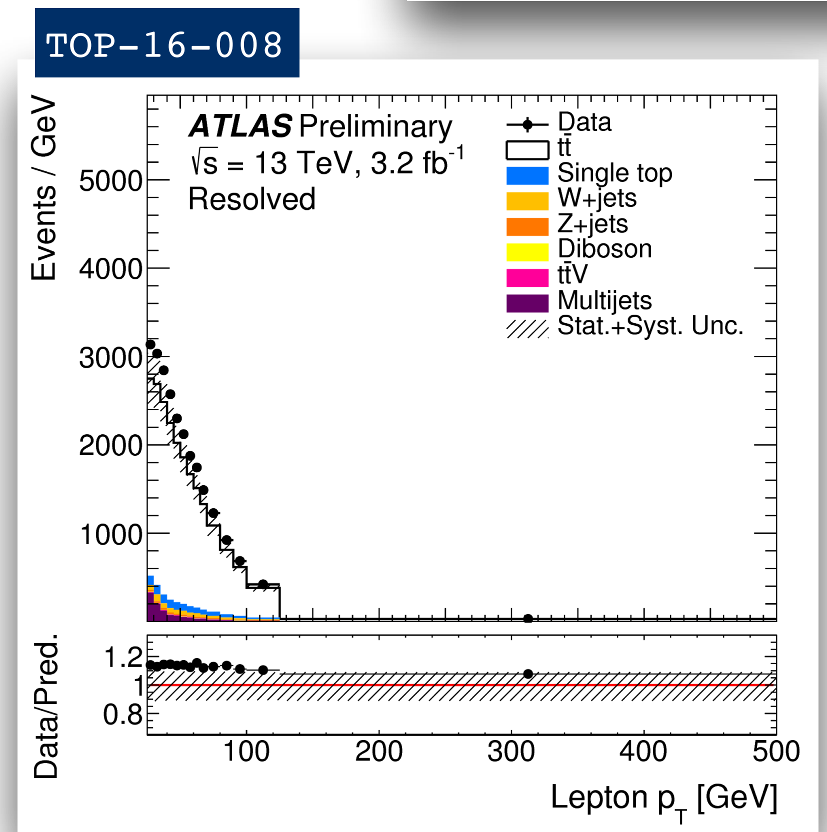
Testing Monte Carlo generators

Minimizes extrapolation between measurement and predictions

What to measure

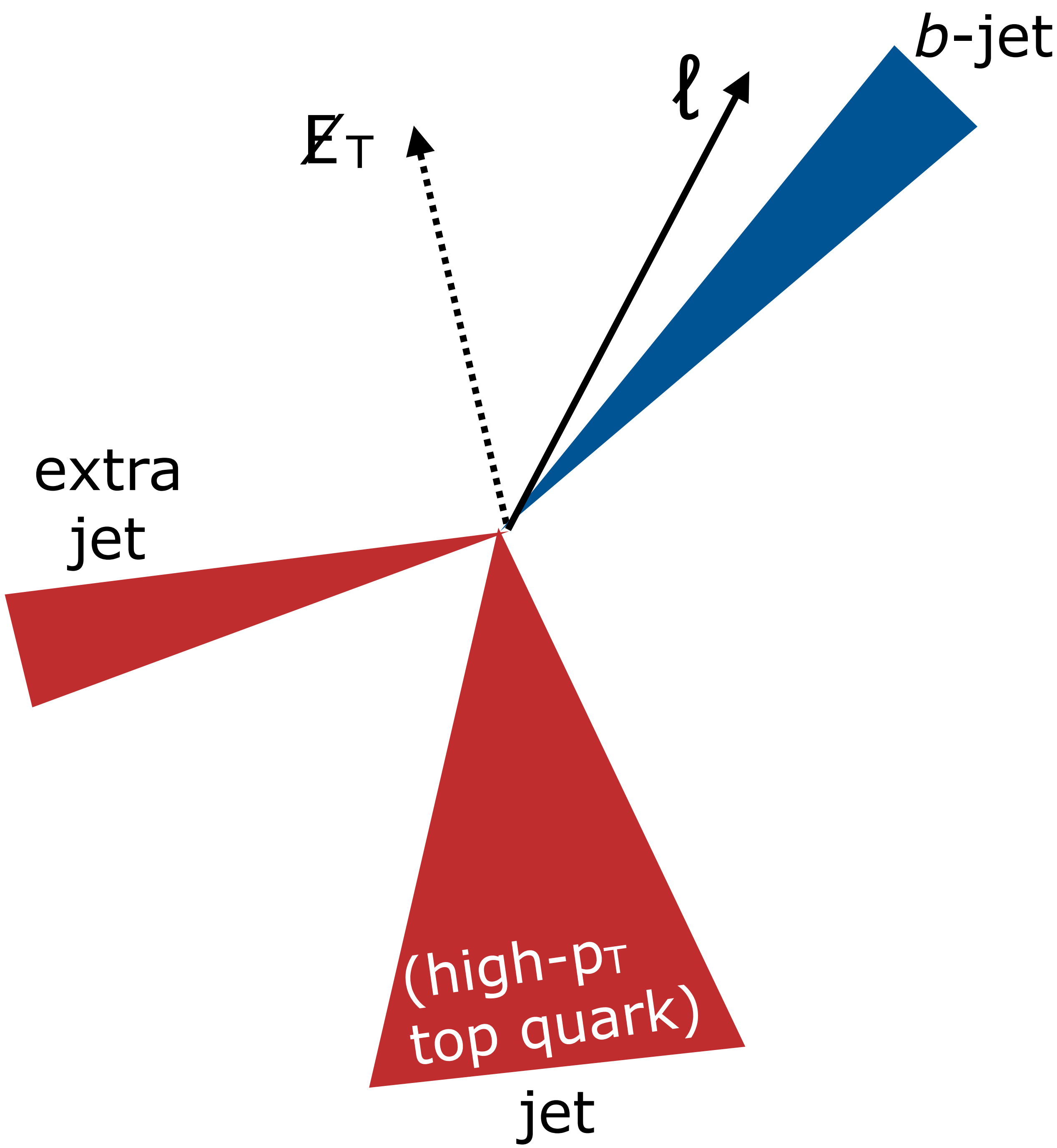






lepton+jets resolved

What to measure



lepton+jets boosted

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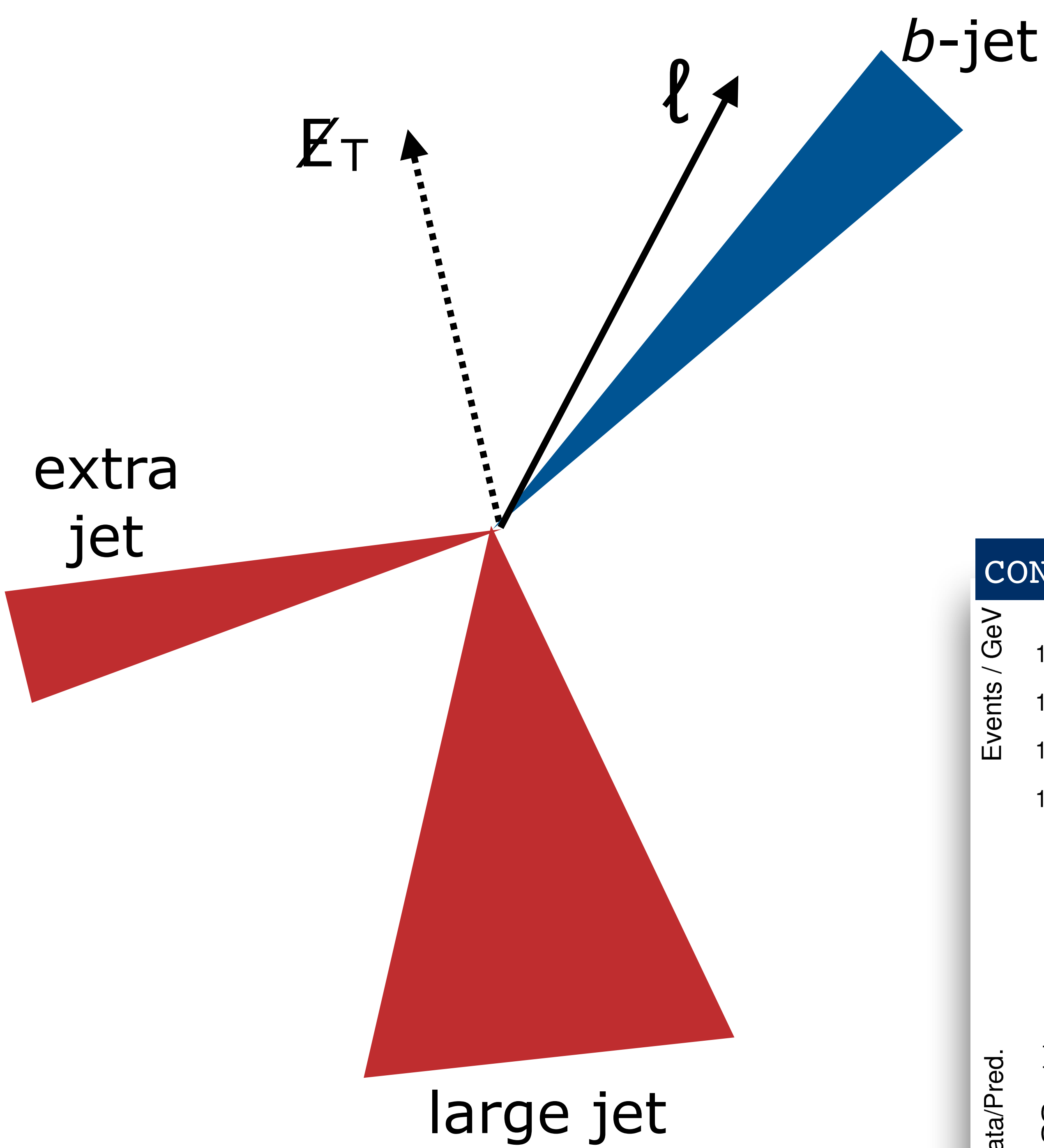
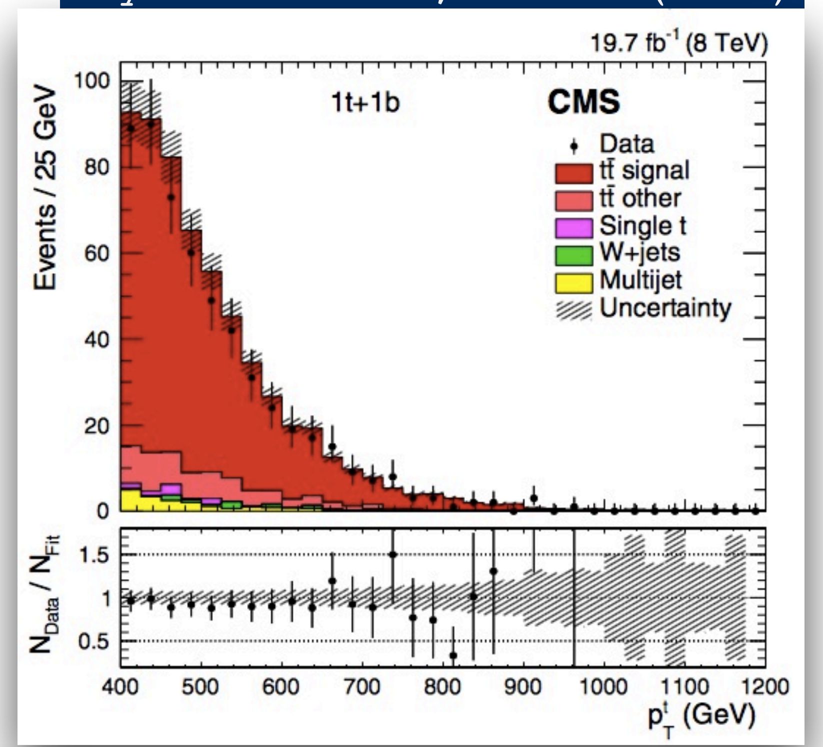


lepton+jets boosted

Phys. Rev. D 94, 072002 (2016)



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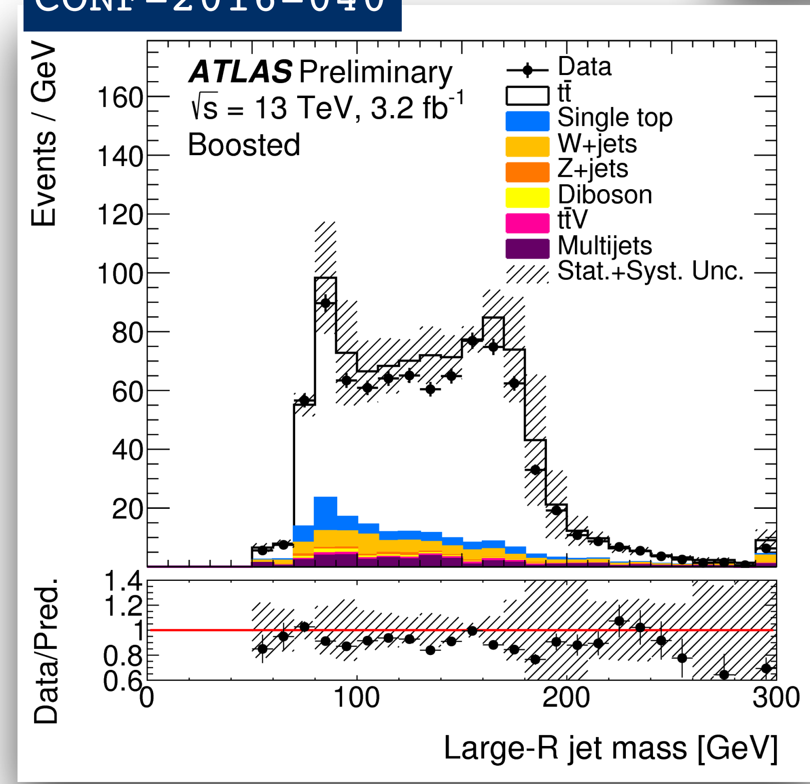
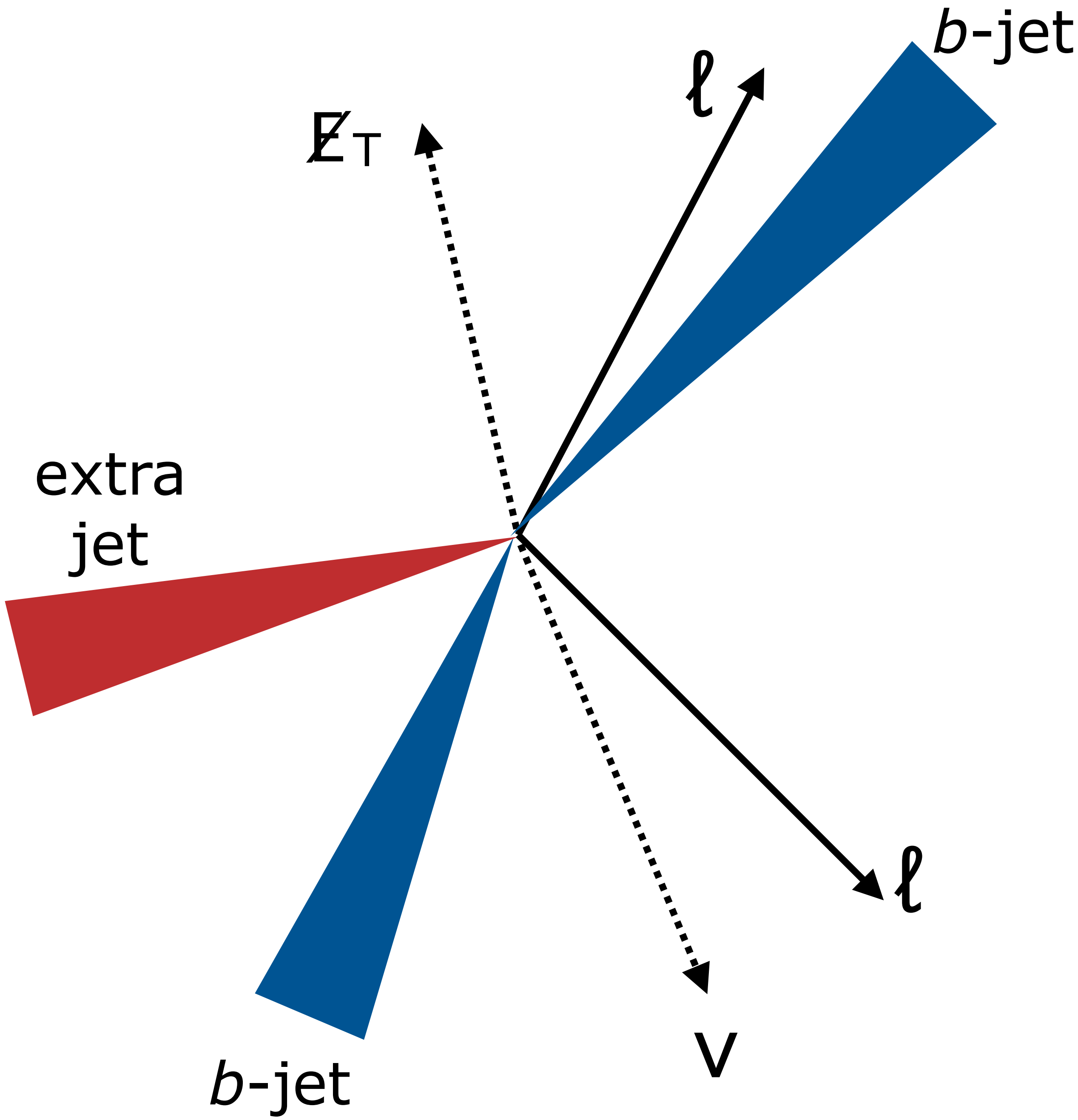


What to measure



dilepton channel

Particle-level view (fiducial phase-space)

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Minimizes extrapolation between measurement and predictions

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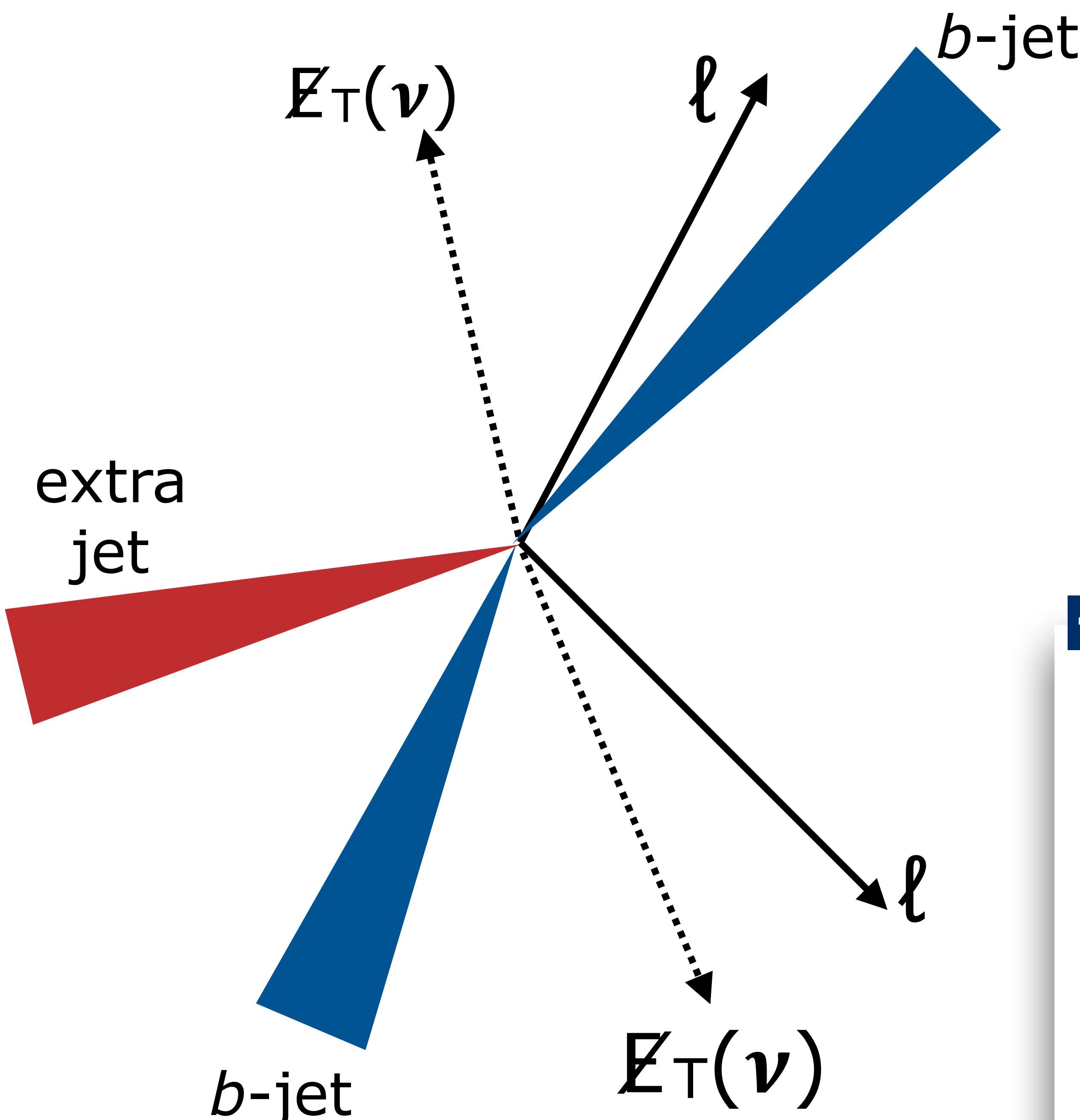
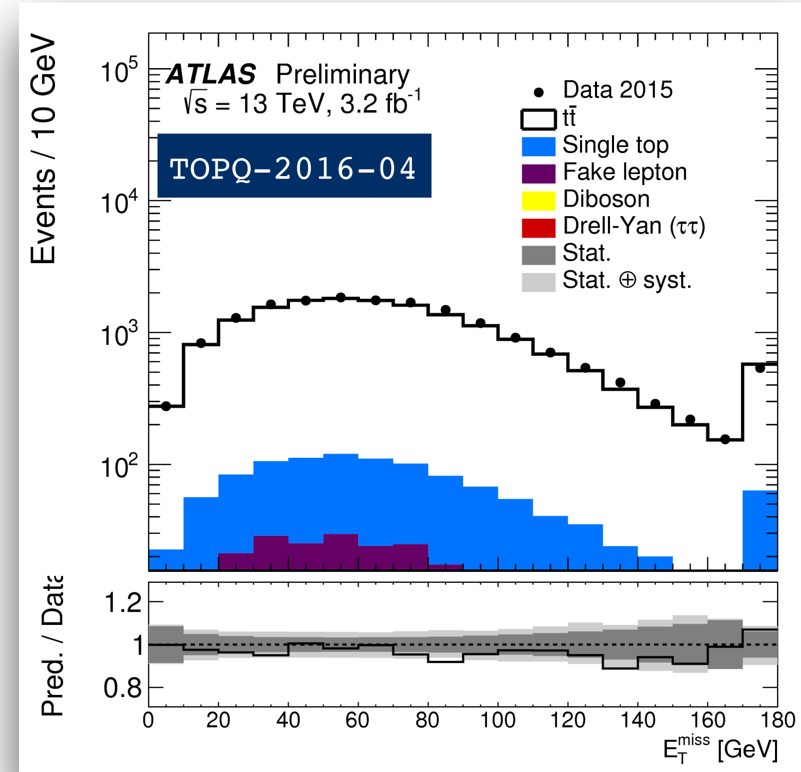
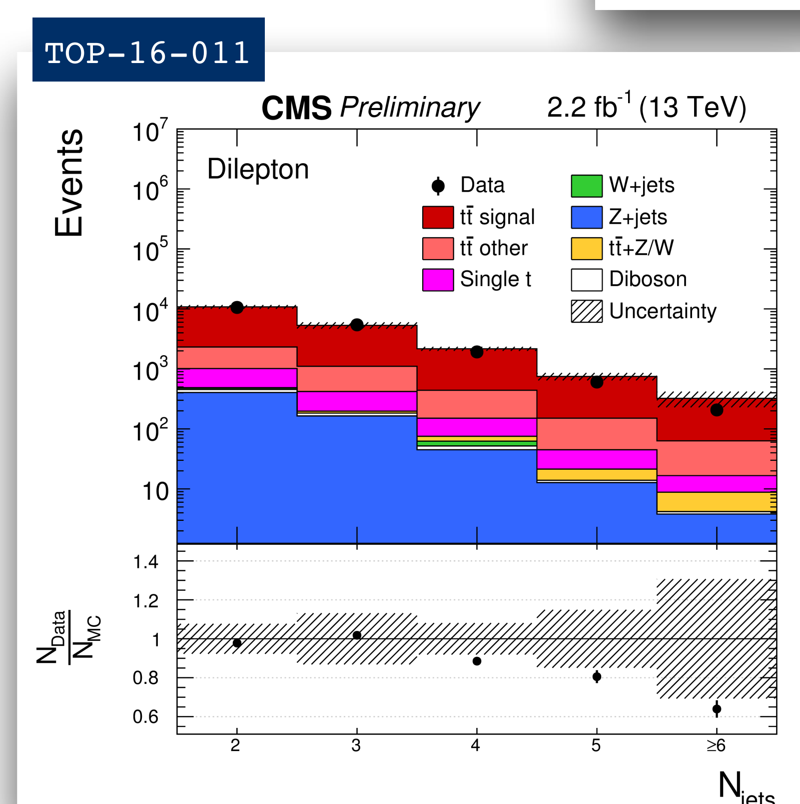
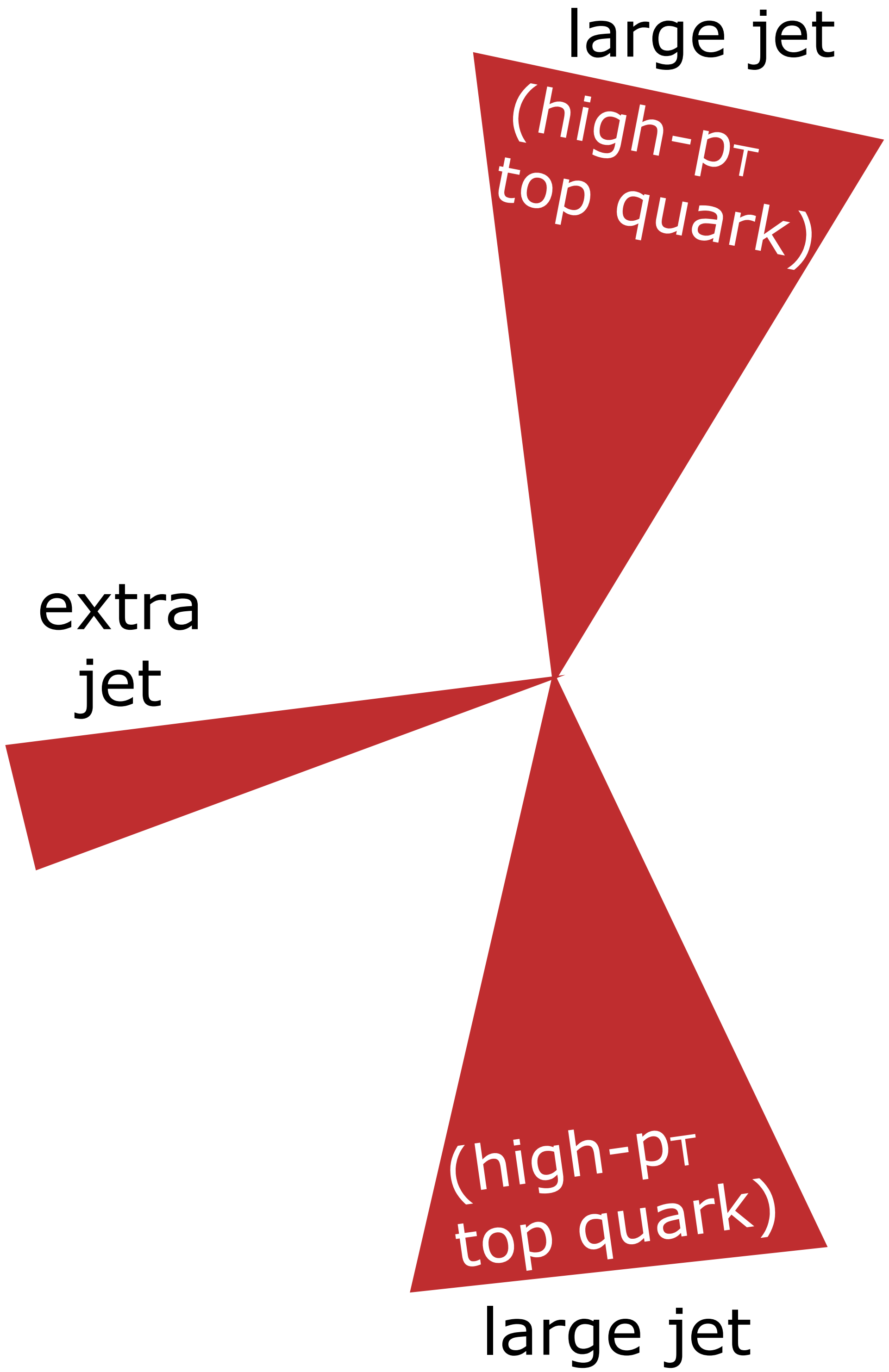






dilepton channel

What to measure



all-hadronic boosted

Particle-level view (fiducial phase-space)

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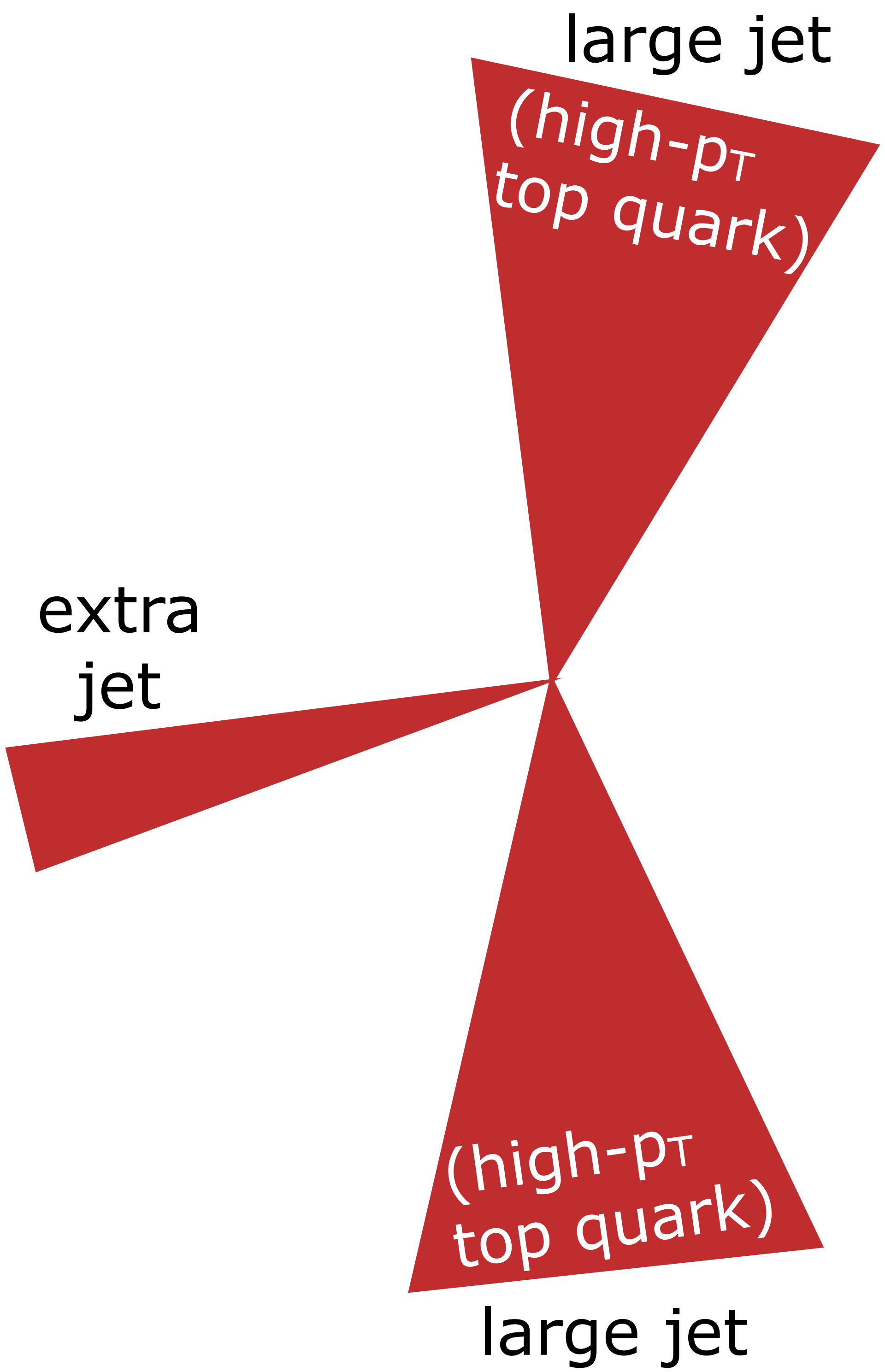

all-hadronic boosted

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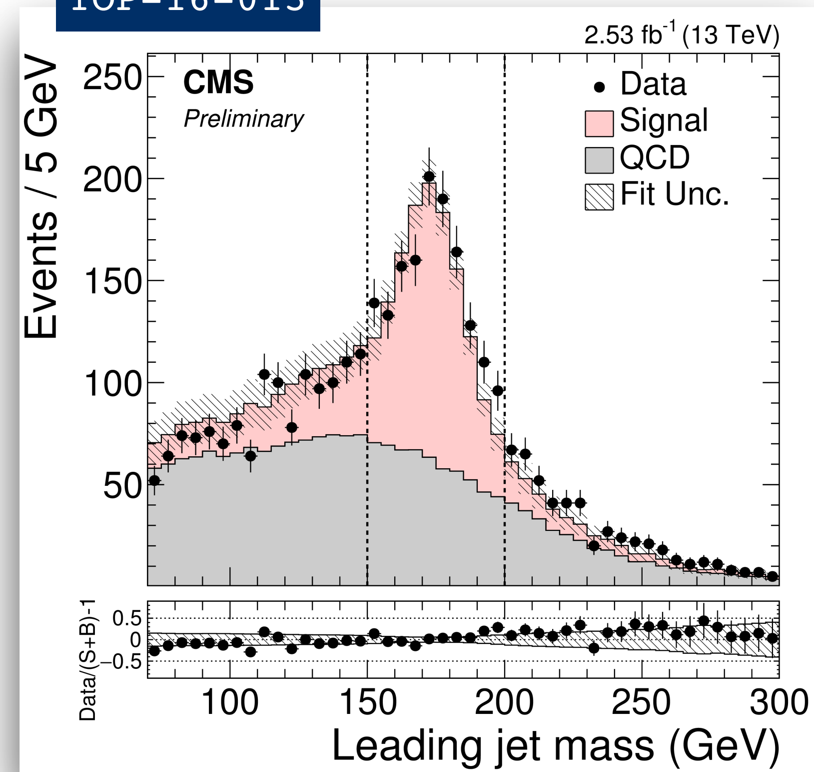
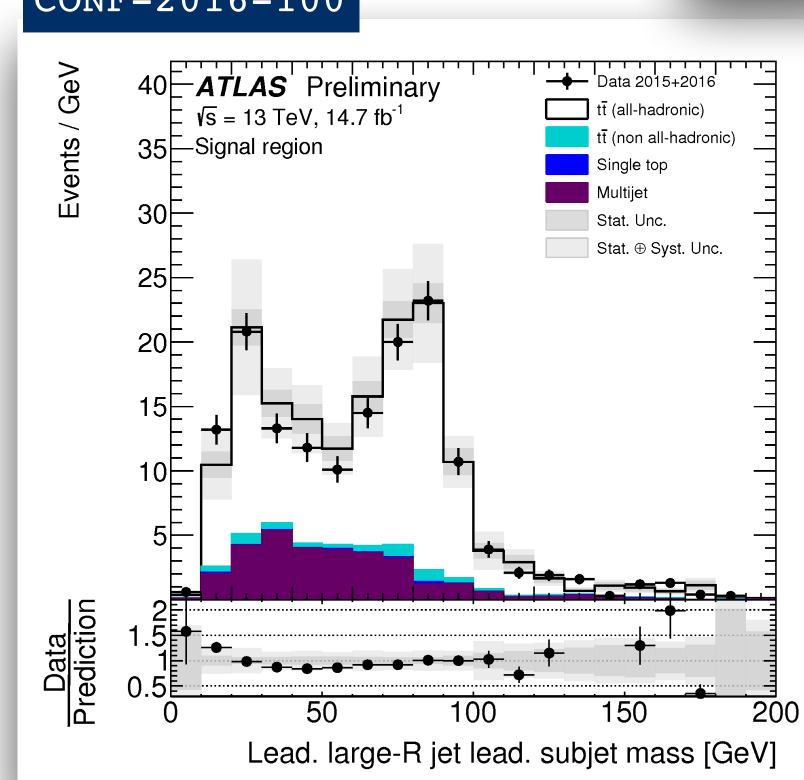
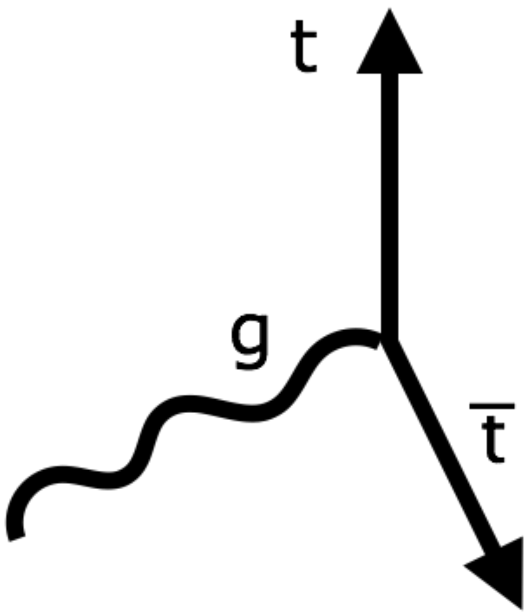
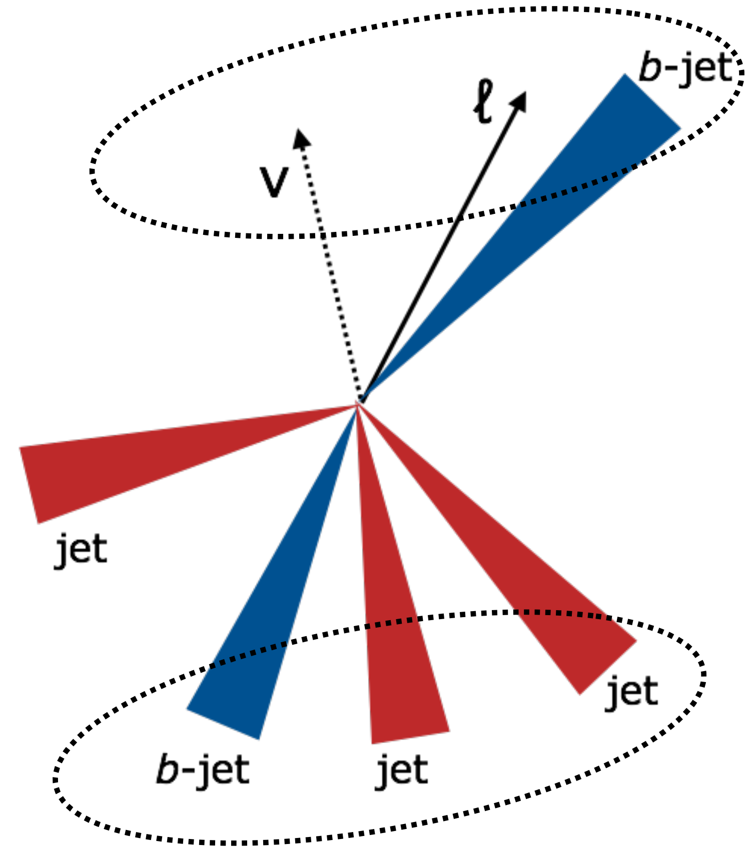


CONF-2016-100



How to measure





Parton-level top quarks
Selection based on navigation of the MC truth tree

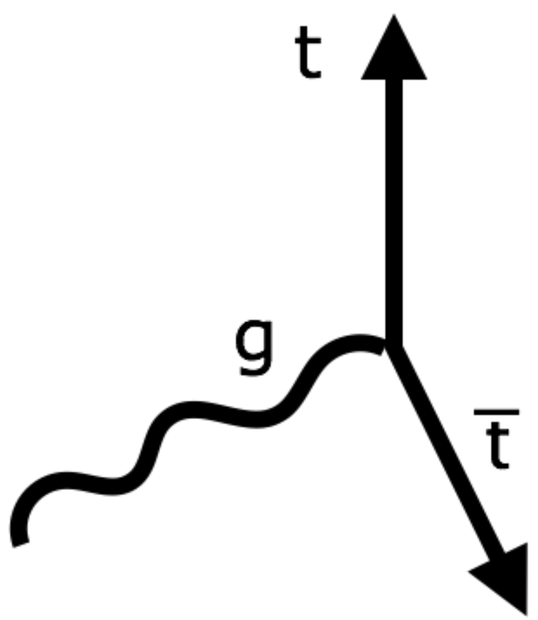
Generator-dependent, usually associated with large systematic uncertainties

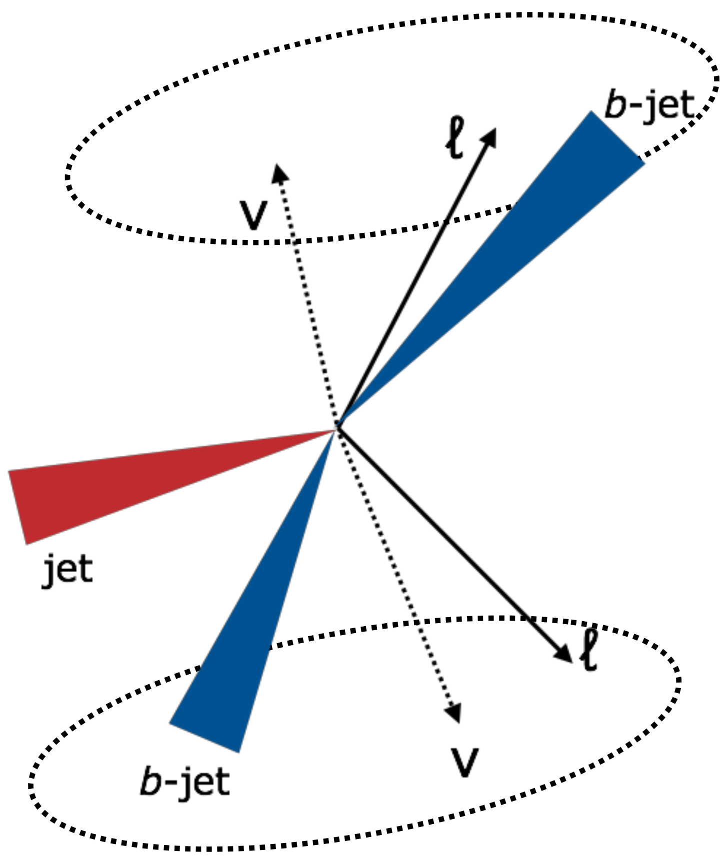
Pseudo-top reconstruction
Proxy to parton-level top quarks to reduce systematic uncertainties wrt parton-level. Limited by jet measurement, b-tagging, modelling

Reconstructs decay chains by applying kinematic constraints such as m_W, m_t to stable particles

Algorithm agreed upon among theorists and experimentalists (see Rivet)

How to measure





Parton-level top quarks
Selection based on navigation of the MC truth tree

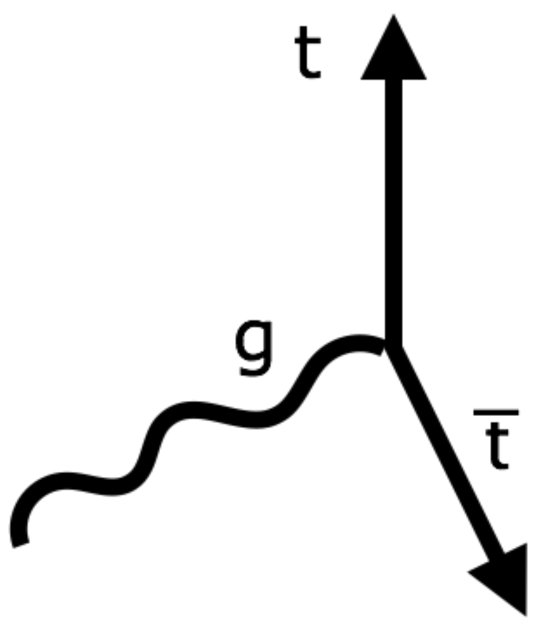
Generator-dependent, usually associated with large systematic uncertainties

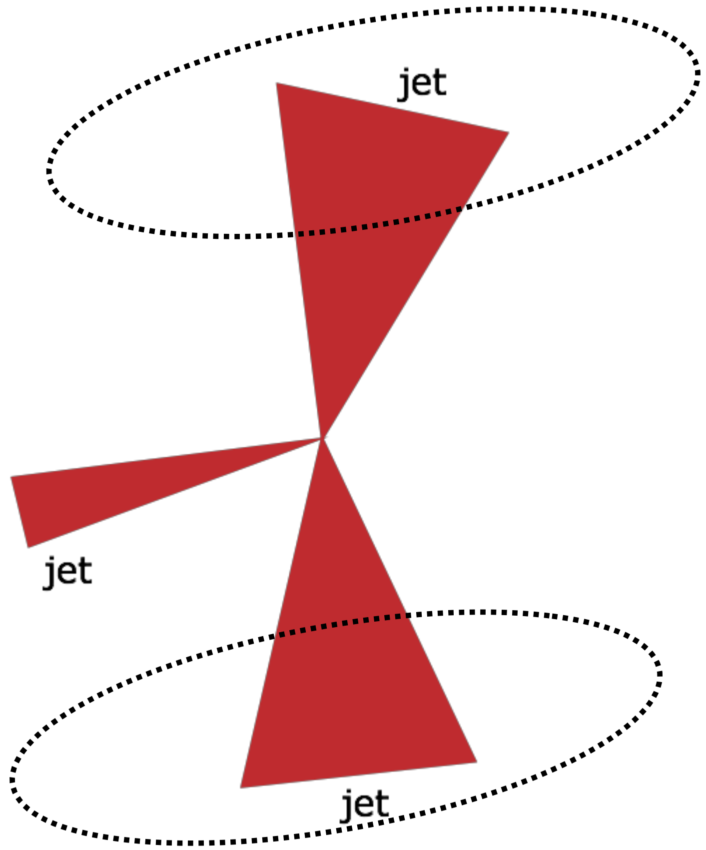
Di-lepton reconstruction
Proxy to parton-level top quarks to reduce systematic uncertainties wrt parton-level

Reconstructs decay chains by applying kinematic constraints ("Neutrino weighting") to stable particles to find optimal longitudinal component of momenta PLB 752, 18 (2016)

Limited by stats, b-tagging, modelling

How to measure





Parton-level top quarks
Selection based on navigation of the MC truth tree

Generator-dependent, usually associated with large systematic uncertainties

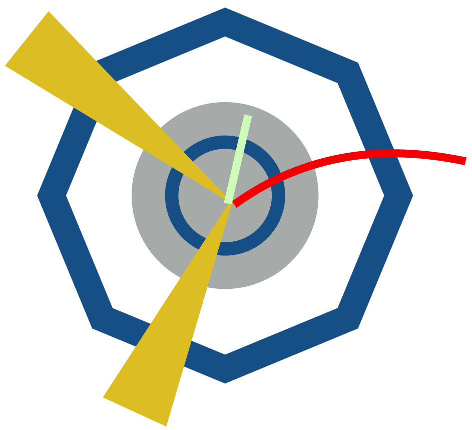
Large-R jets reconstruction
Hadronic decay of a high-p_T top quark contained in a large-R jet

Straightforward kinematic reconstruction based on stable particles

Limited by stats, large-R jet measurement, b-tagging, modelling

Experiment ↔ Theory

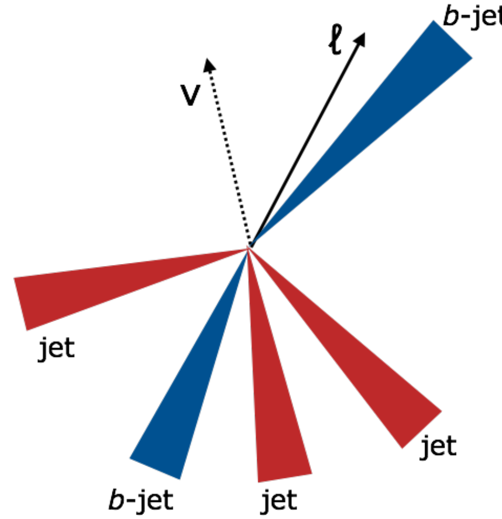
Experiments



Correct for
detector effects

Unfolding

Particle-level
(fiducial phase-space)



Unfolding

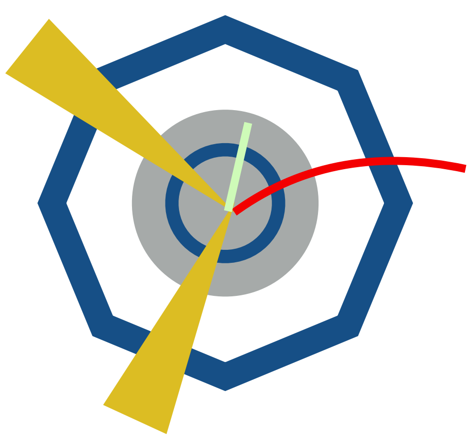
Sharing

Rivet, HEPData

Rivet routines,
HEPData db

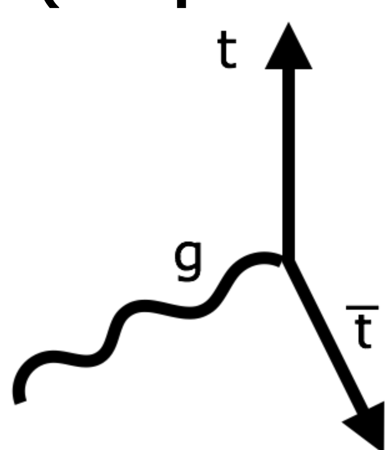
Short term
Let theorists compare data vs MC generators, BSM models

Long term
Persistent data ensure longevity of measurements



Unfolding

Parton-level
(full phase-space)



What we can do

Test perturbative QCD

- Impact of higher-order corrections, e.g. NNLO+NNLL
- Test different jet-matching schemes, tune MC parameters
- Test different parton-shower and hadronization models

Improve knowledge about the structure of the proton

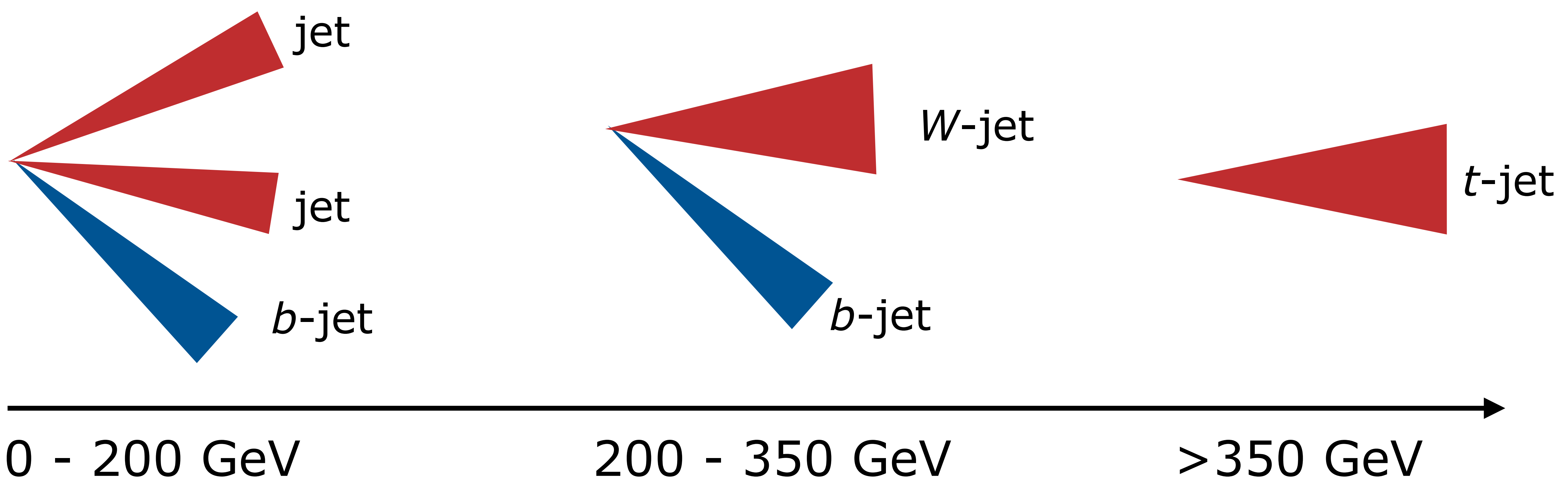
- Constrain gluon PDF
- Extract α_s, m_{top}

Search for beyond the Standard Model physics

- Look for deviations in differential cross-sections
- Reduce modelling uncertainty to enhance sensitivity to BSM

Top quark p_T, y

- Top p_T probably the most important observable
- Sensitive to final state radiation
- Measurement up to ~1 TeV spans different **kinematic regimes**, thus **reconstruction methods**
- Many sources indicate data/theory disagreement at high-p_T



ℓ+jets, Particle level

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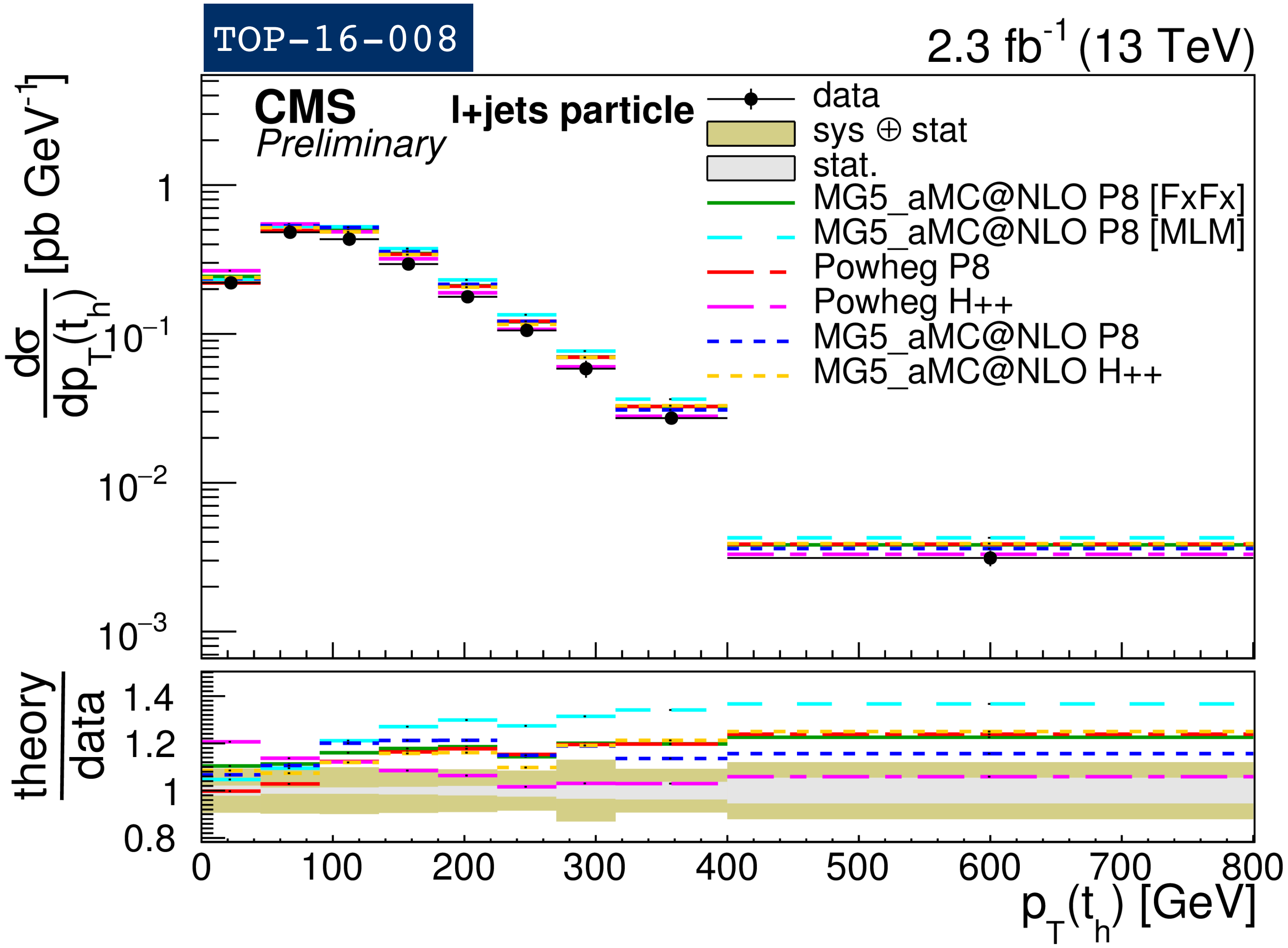

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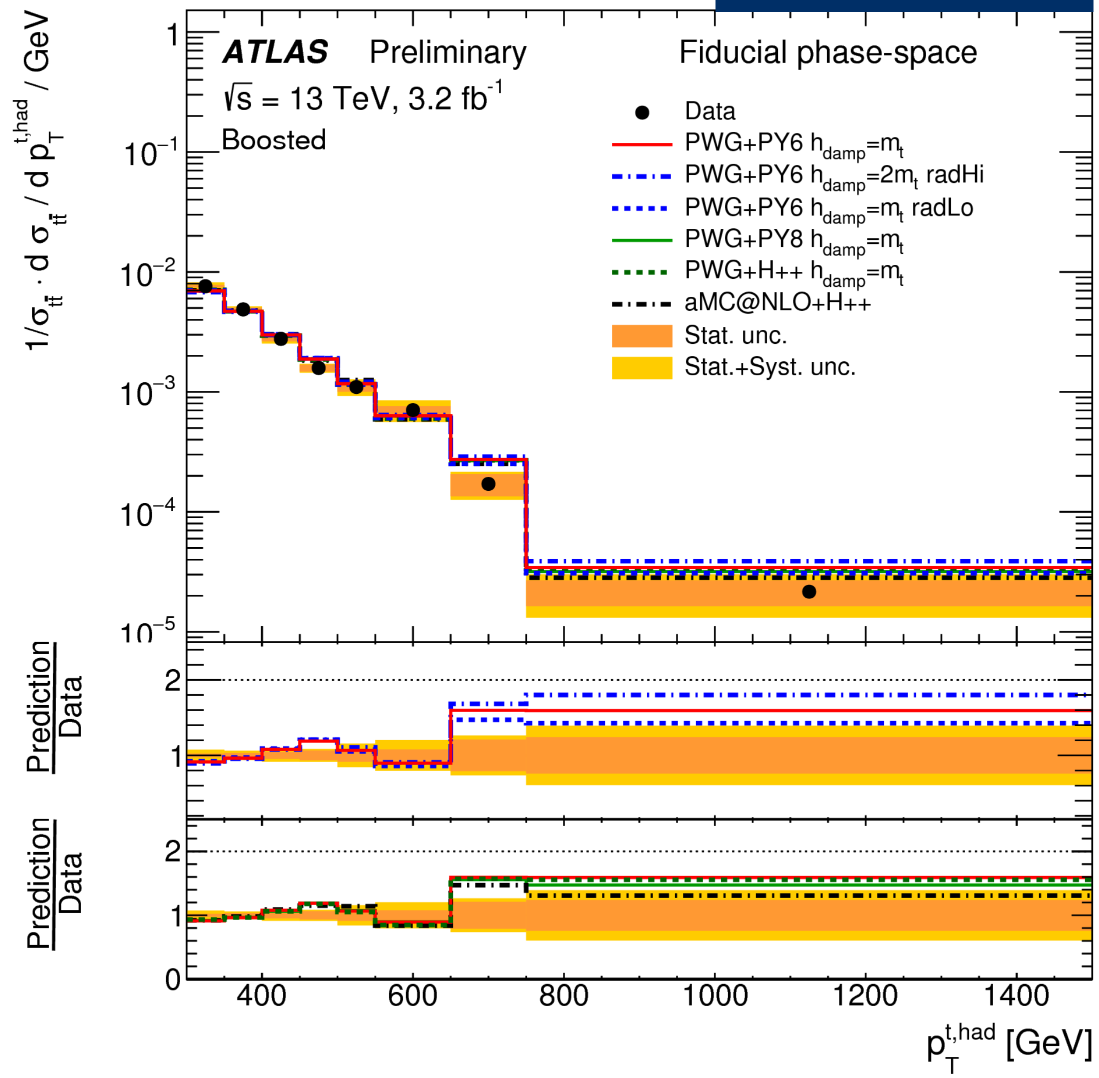

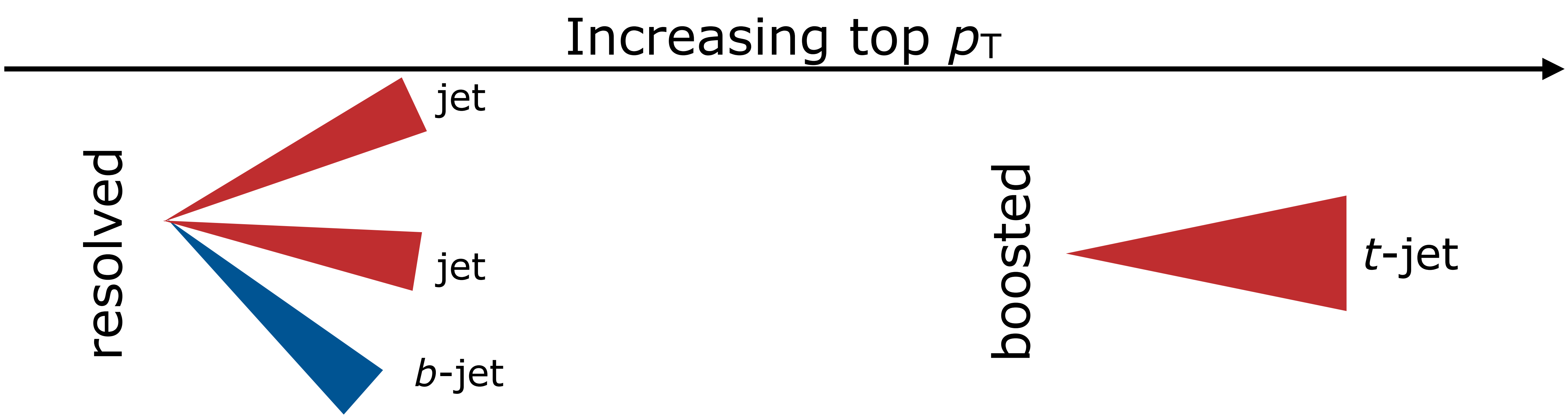

ℓ+jets, Particle level, resolved

TOP-16-008

Source	Particle level [%]	Parton level [%]
Statistical uncertainty	1–5	1–5
Jet energy scale	5–8	6–8
Jet energy resolution	<1	<1
$\vec{p}_T^{miss}$ (non jet)	<1	<1
b tagging	2–3	2–3
Pileup	<1	<1
Lepton selection	3	3
Luminosity	2.7	2.7
Background	1–3	1–3
PDF	<1	<1
Fact./ren. scale	<1	<1
Parton shower scale	2–5	2–9
POWHEG+PYTHIA8 vs. HERWIG++	1–5	1–12
NLO event generation	1–5	1–10
m_t	1–2	1–3

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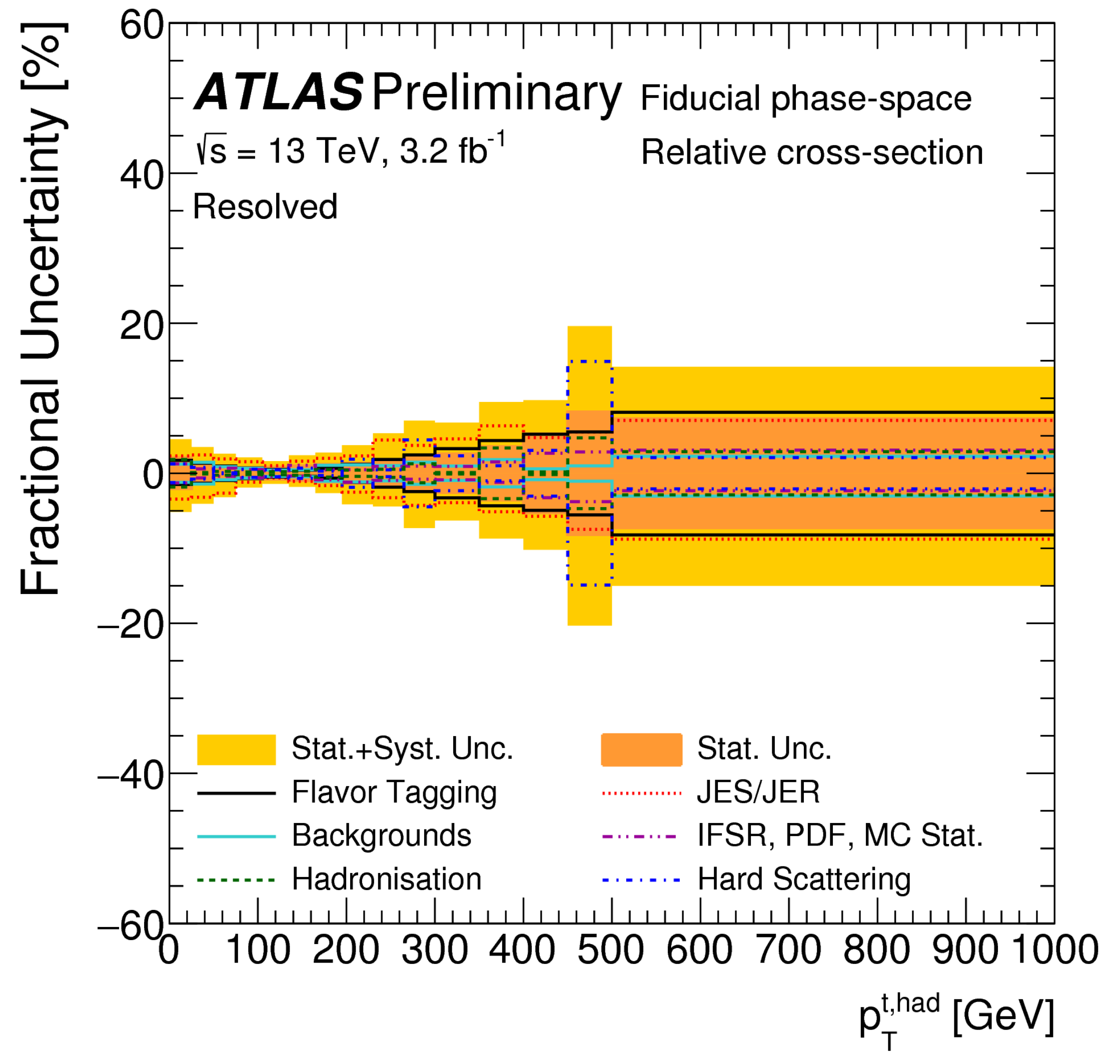
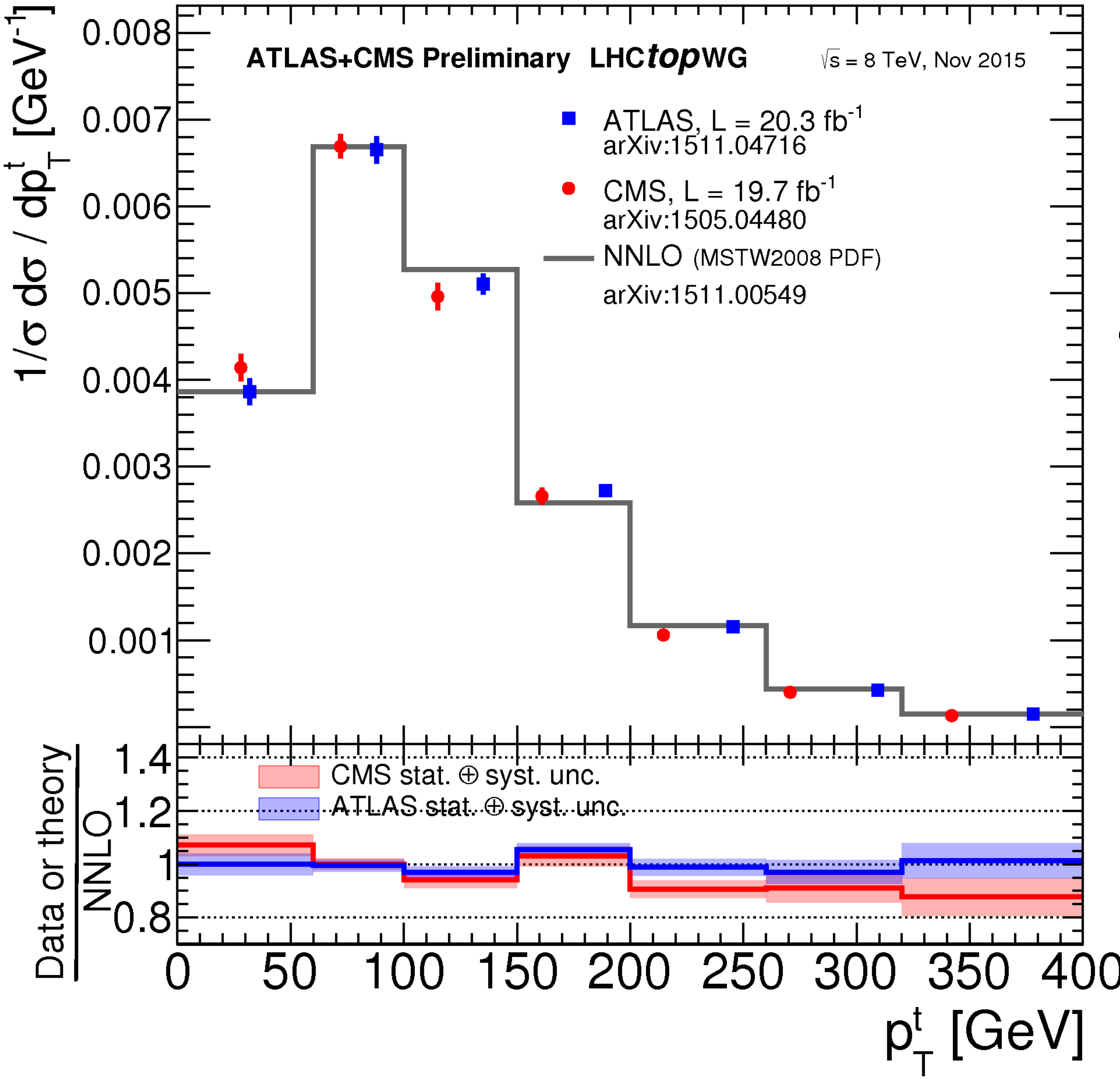


Largest systematics: jet energy scale, b-tagging efficiency, MC modelling

ℓ+jets, Parton level

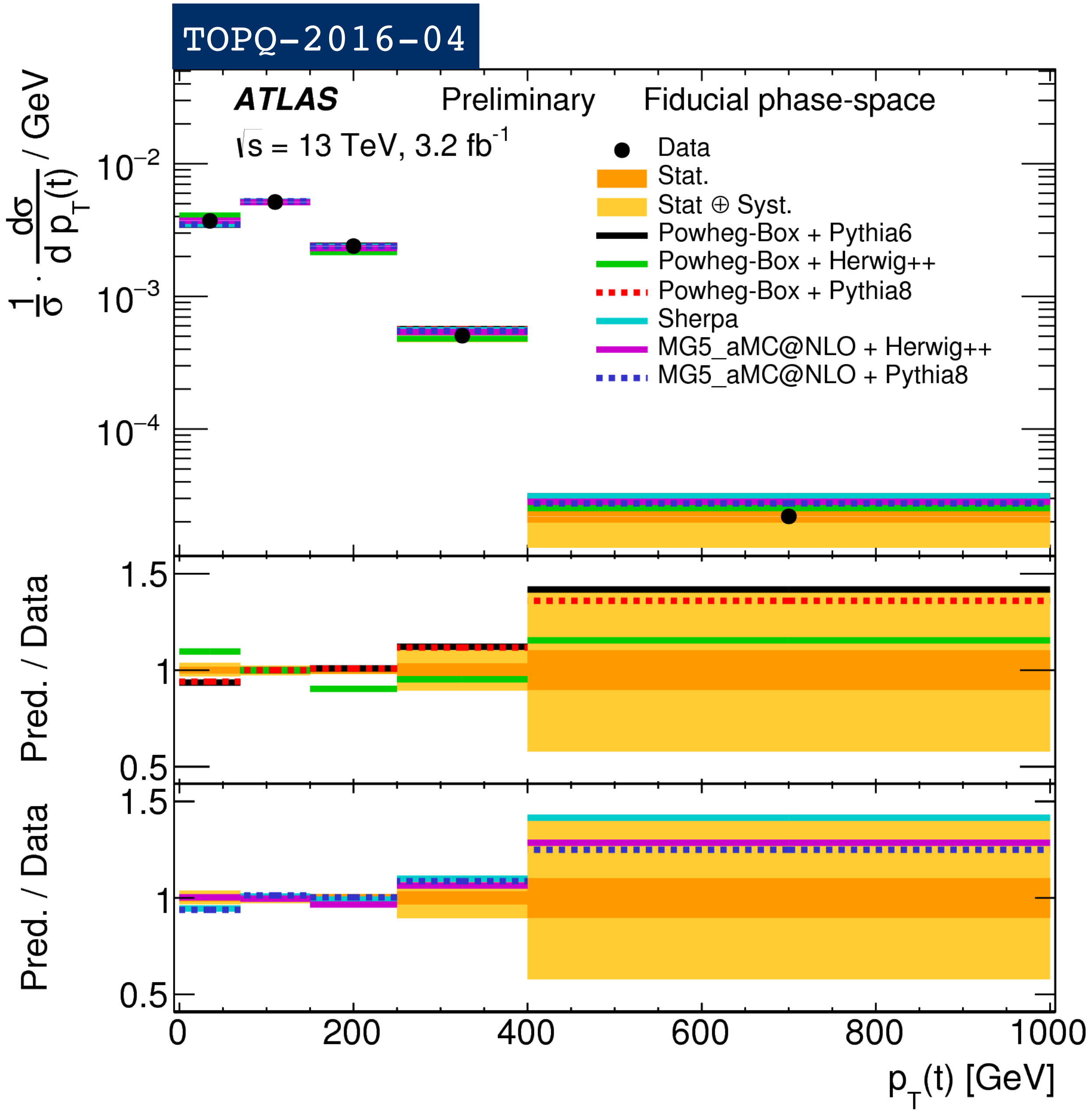


Run 1
ATLAS+CMS legacy

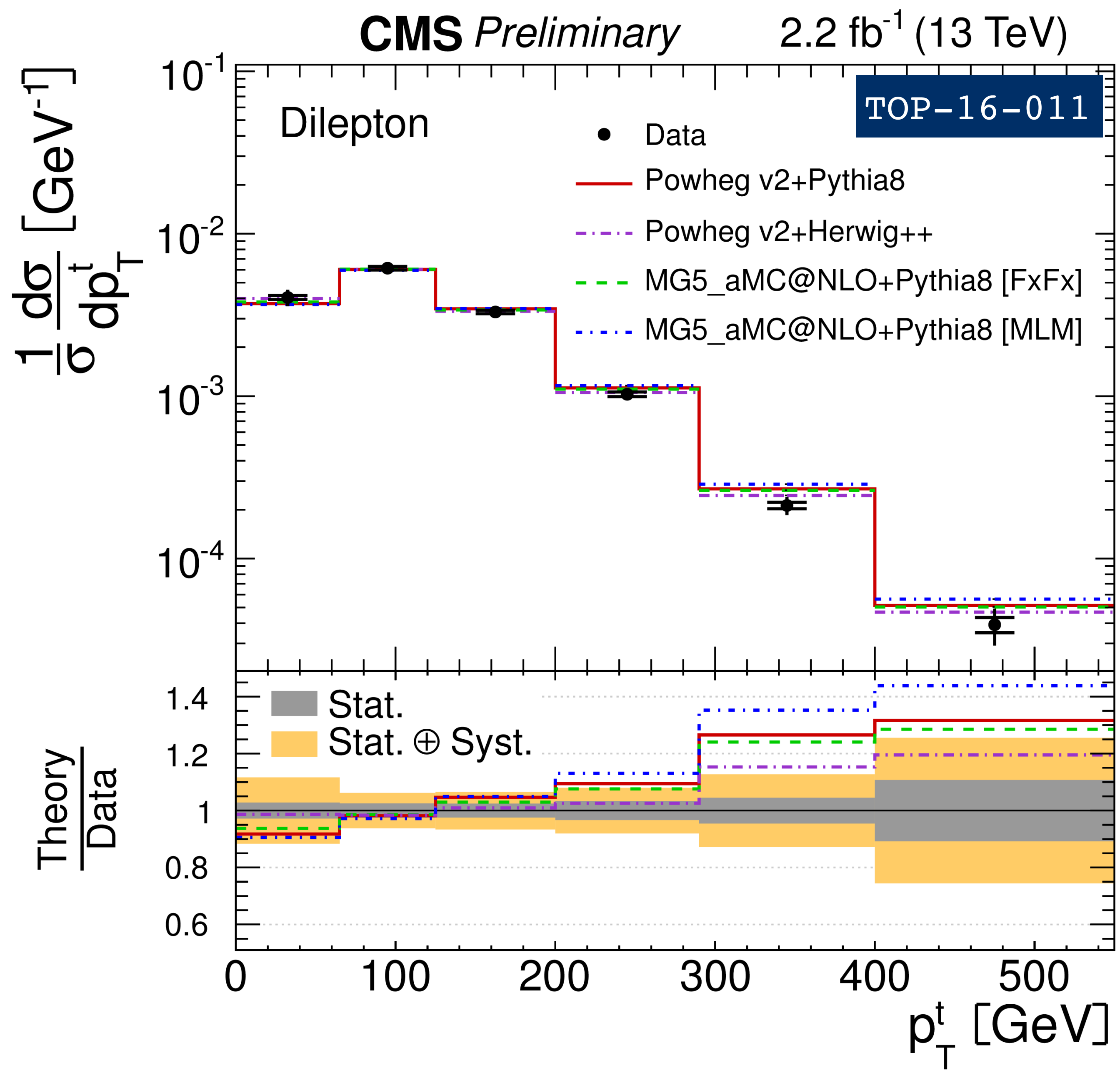
NNLO corrections *are* important!

Good agreement up to high p_T

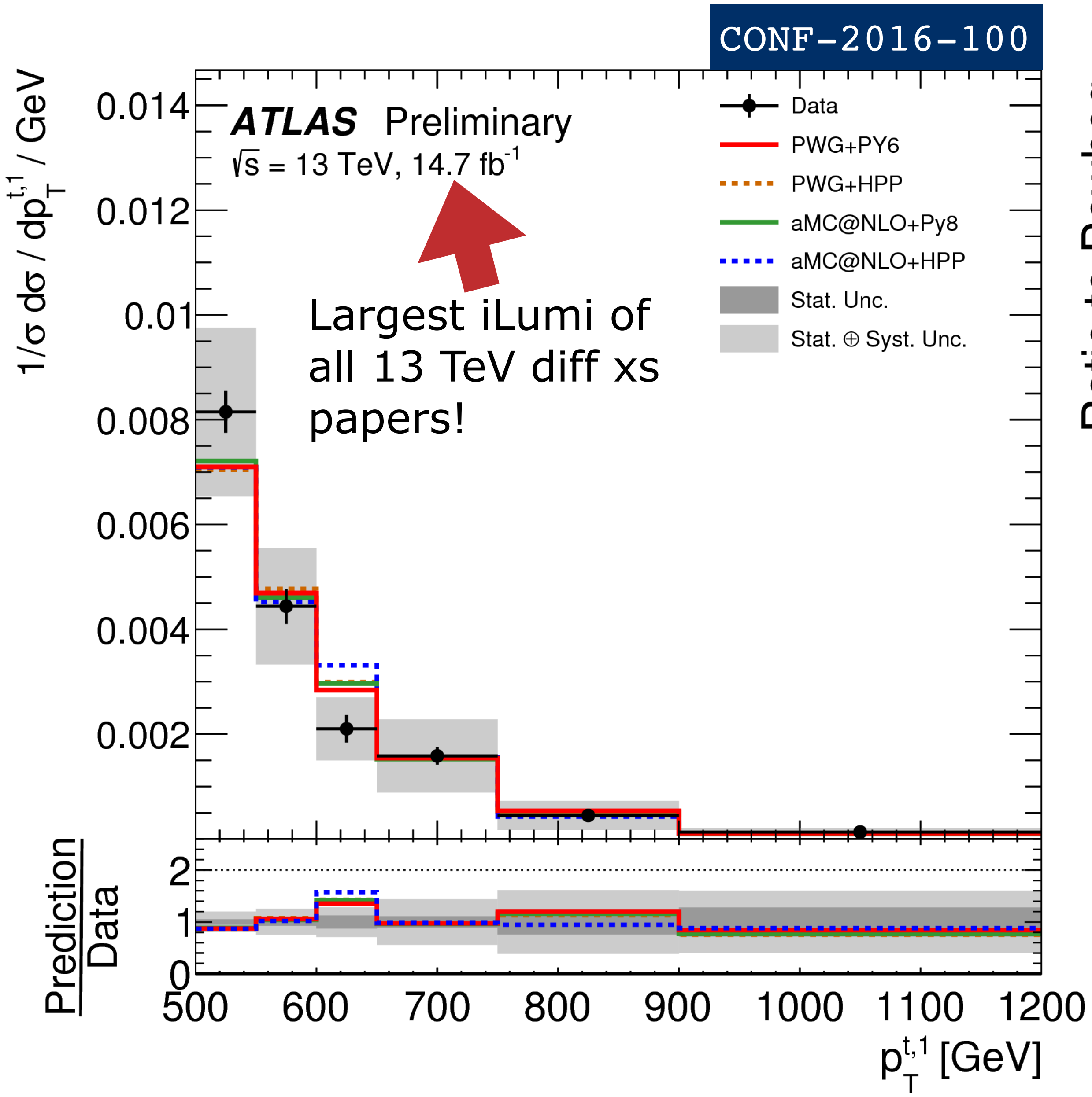
Dilepton, Particle level



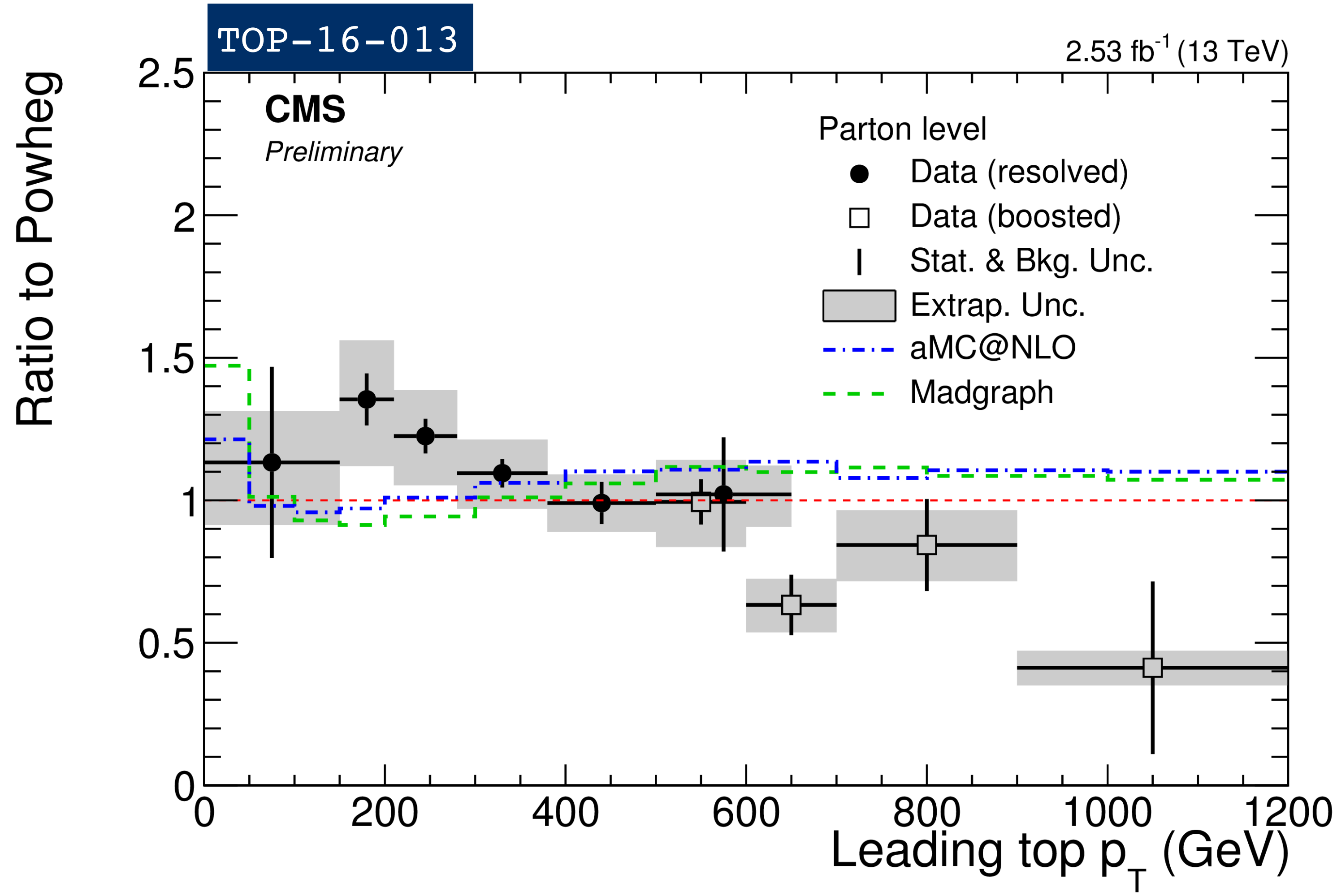
Dilepton, Parton level



All-hadronic, Particle level

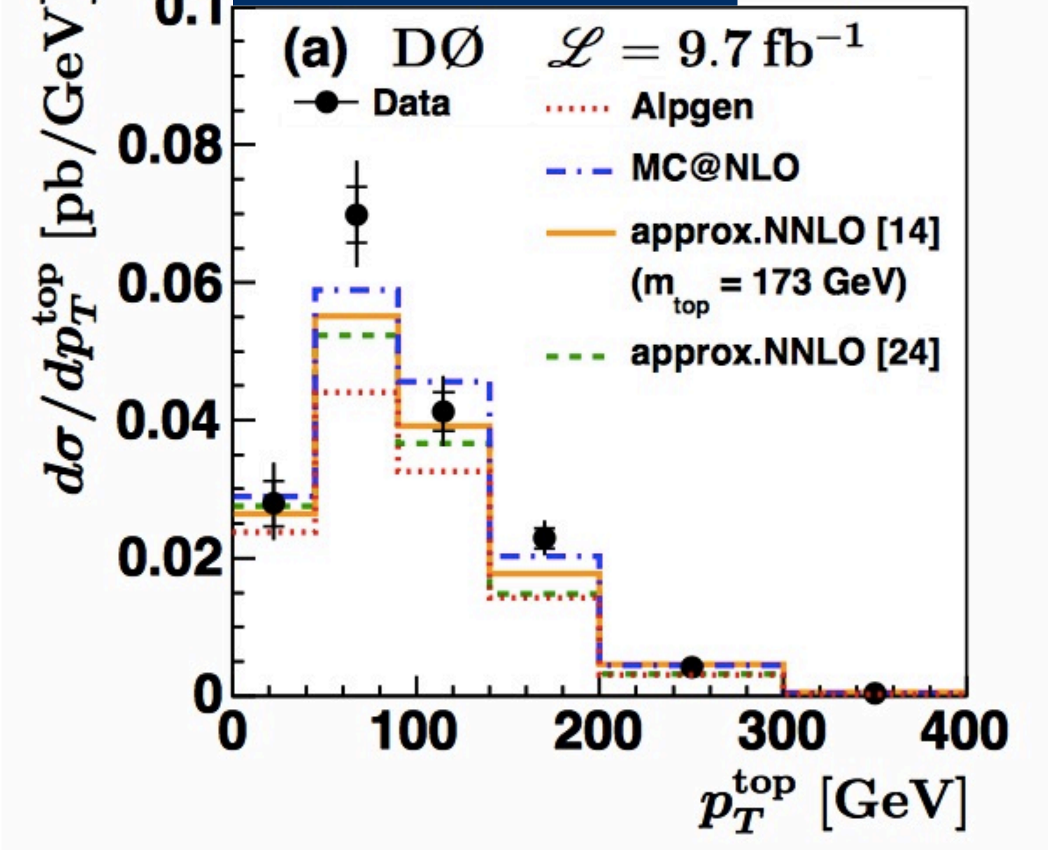


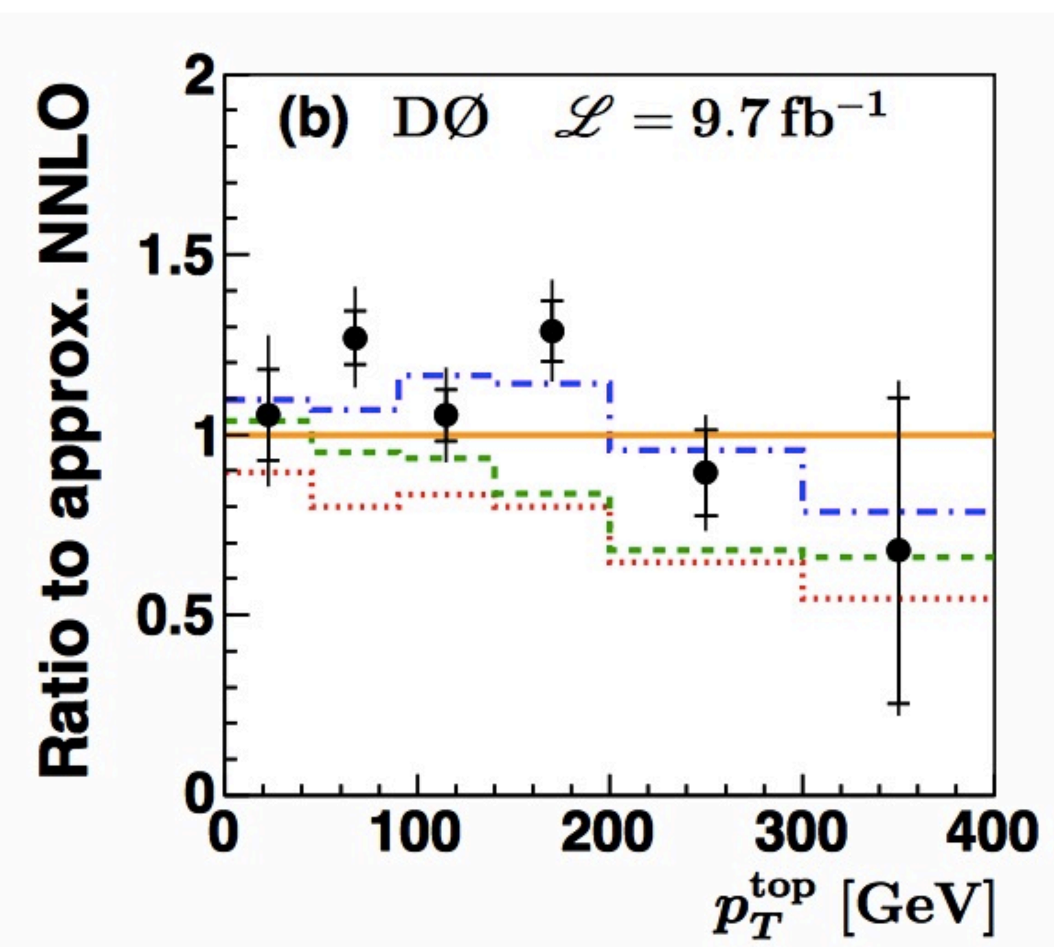
All-hadronic, Parton level



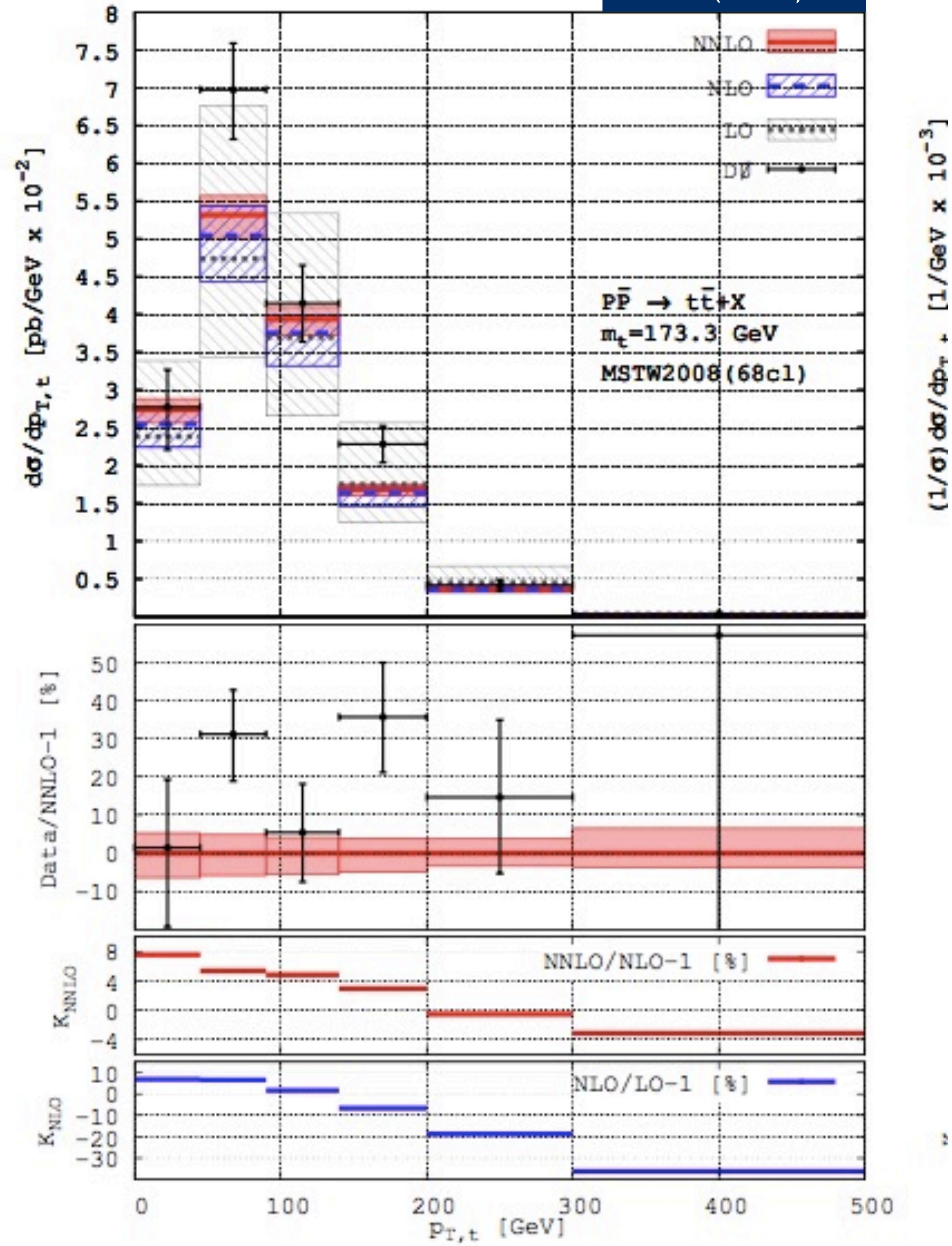
NB: this is the **leading-p_T** top
In other channels only the **average** of both top quarks is presented

PRD90, 092006 (2014)



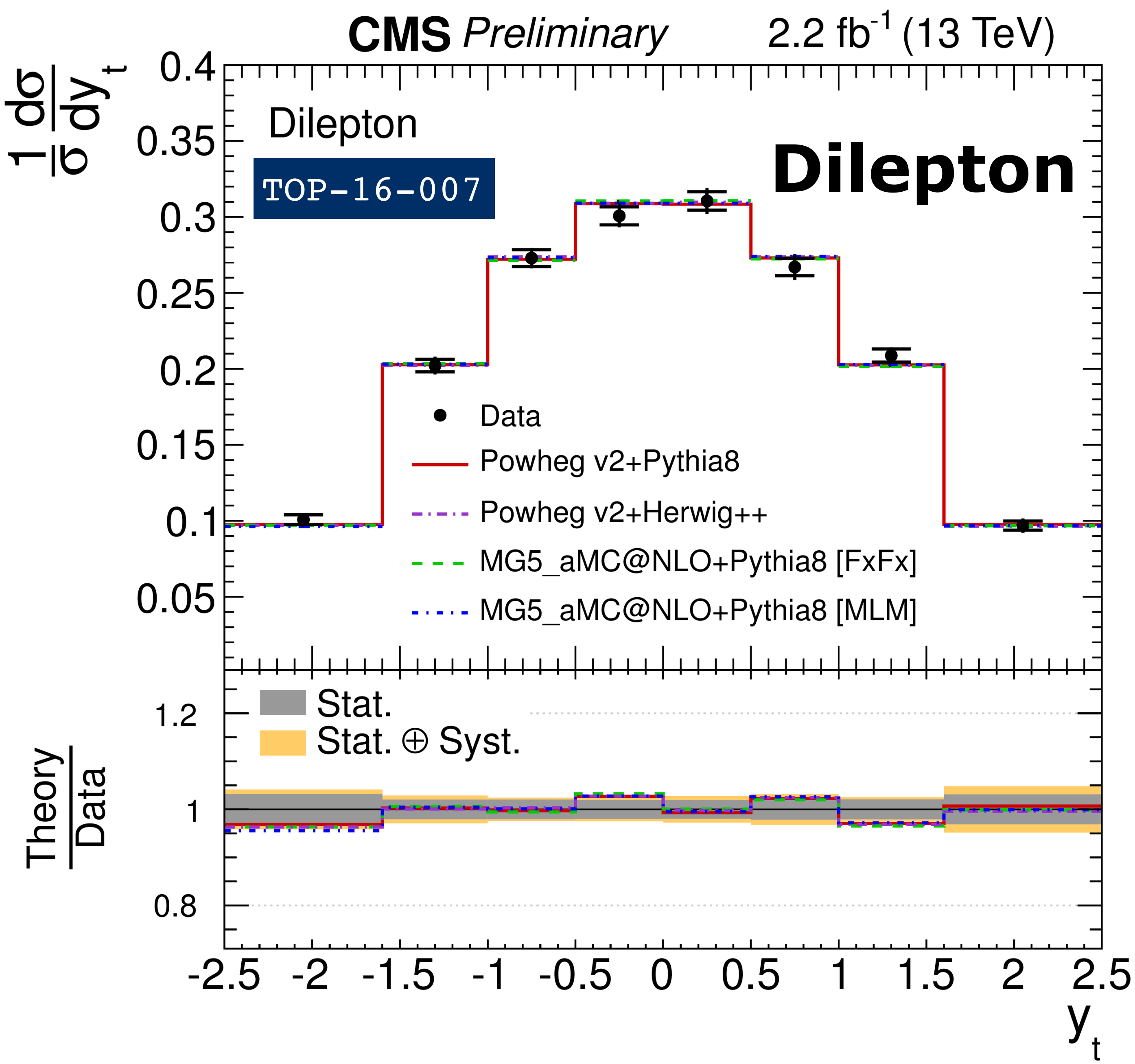


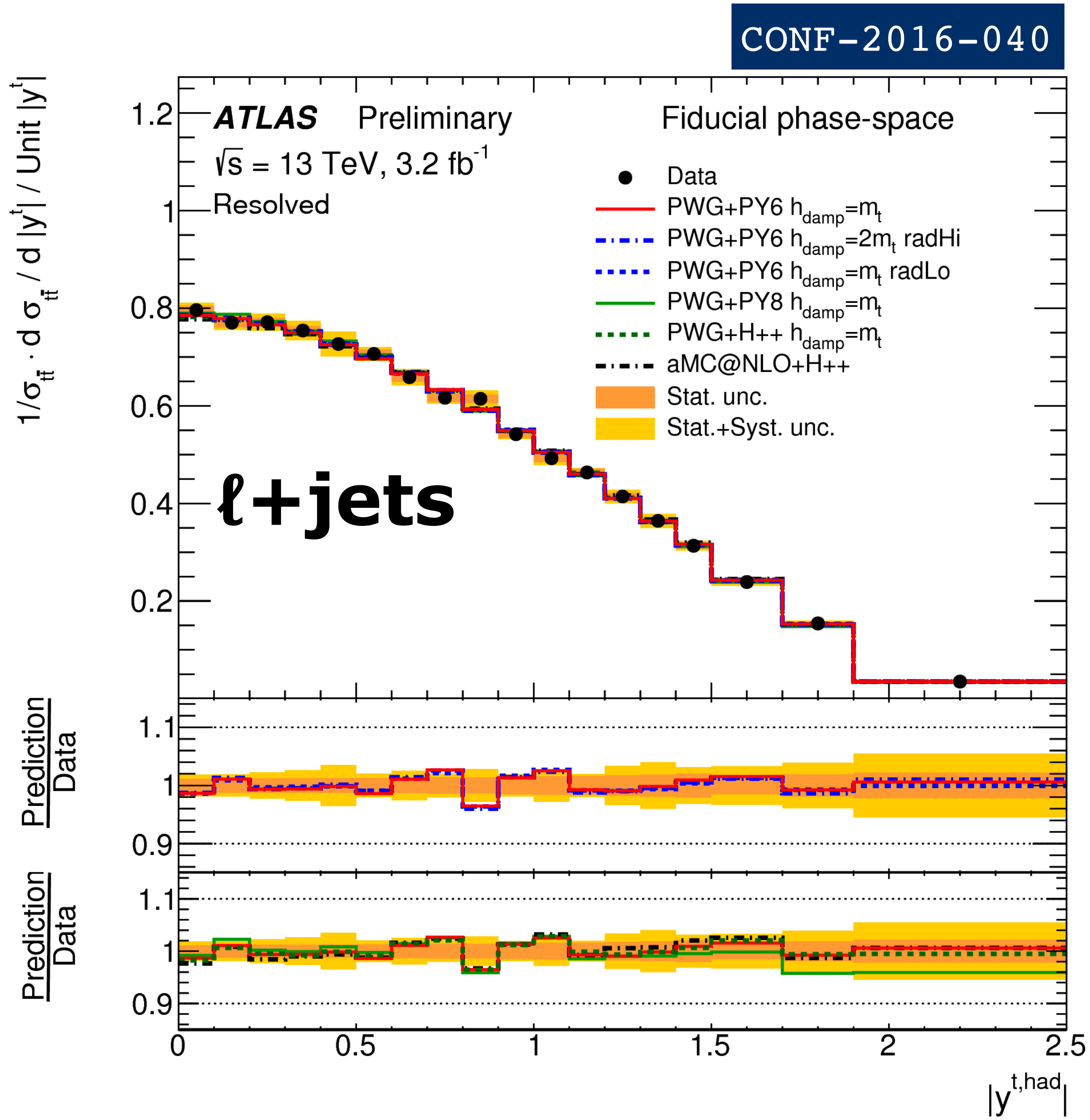
JHEP05(2016)034



Top-Quark Rapidity

Data/MC **seems well-modelled in all channels**





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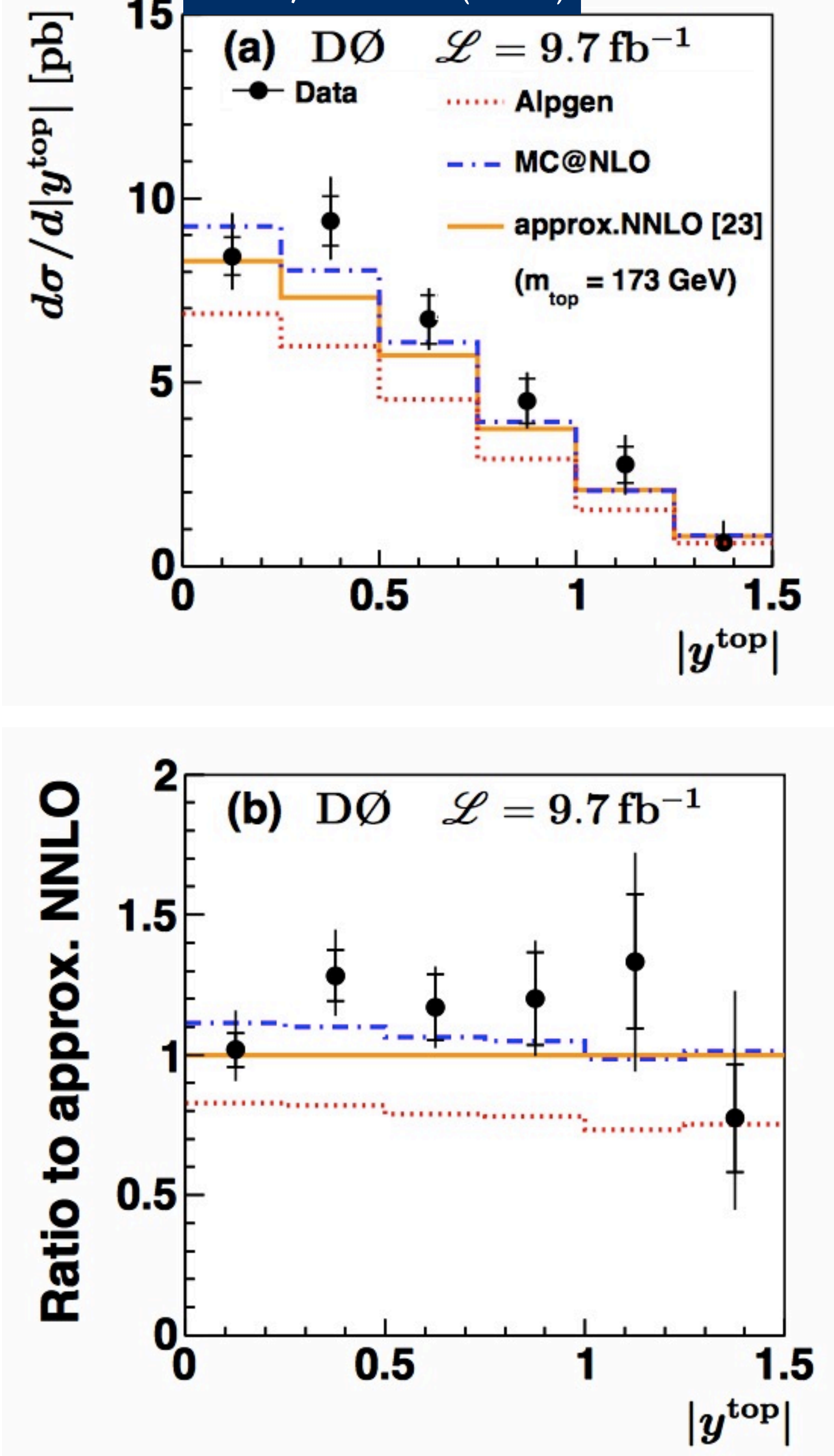

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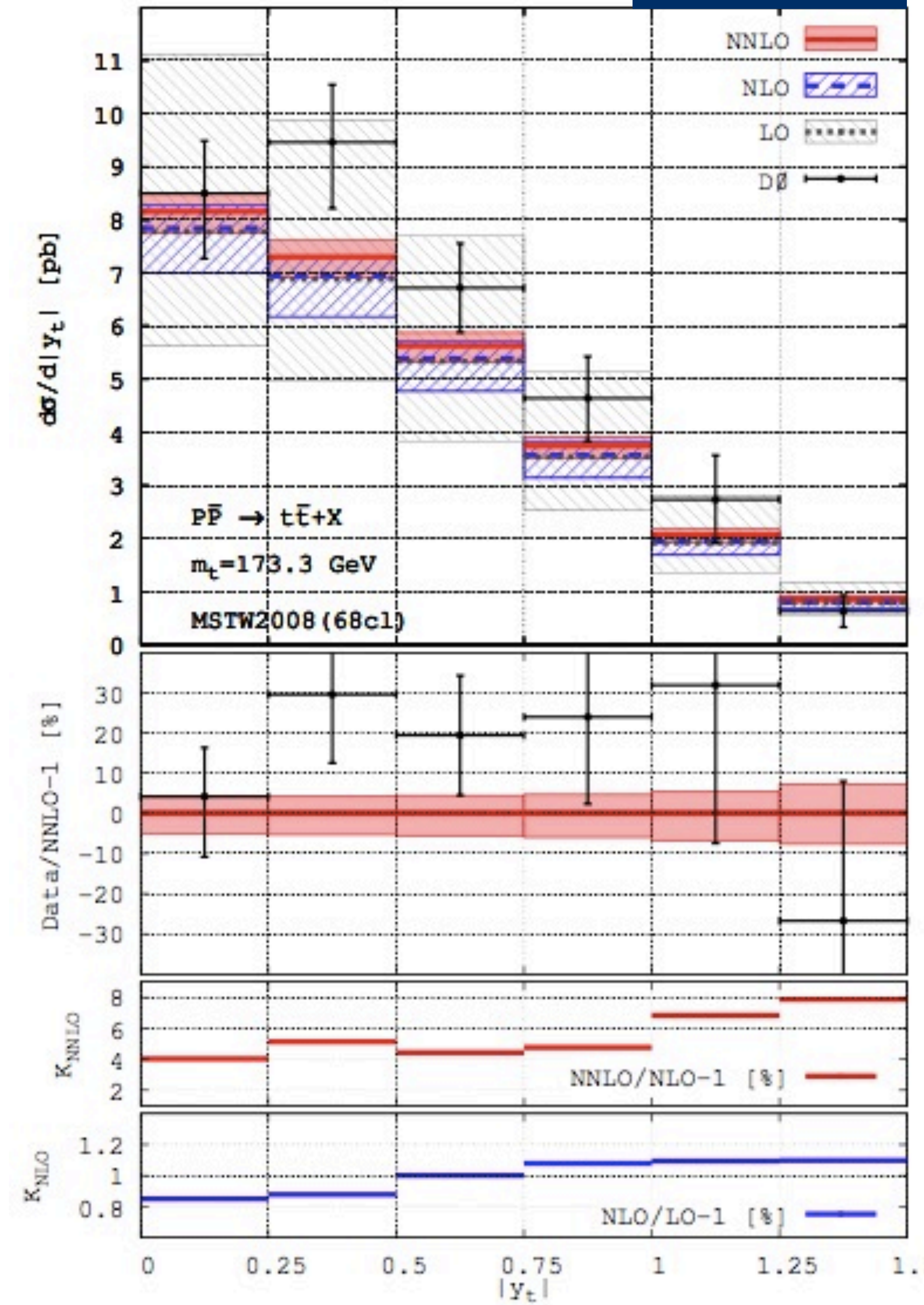
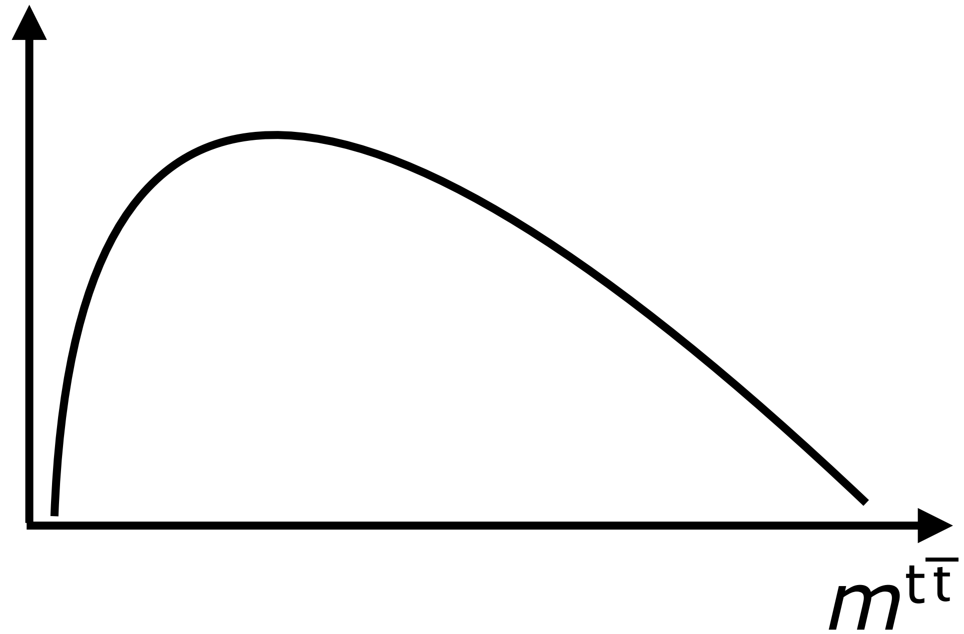
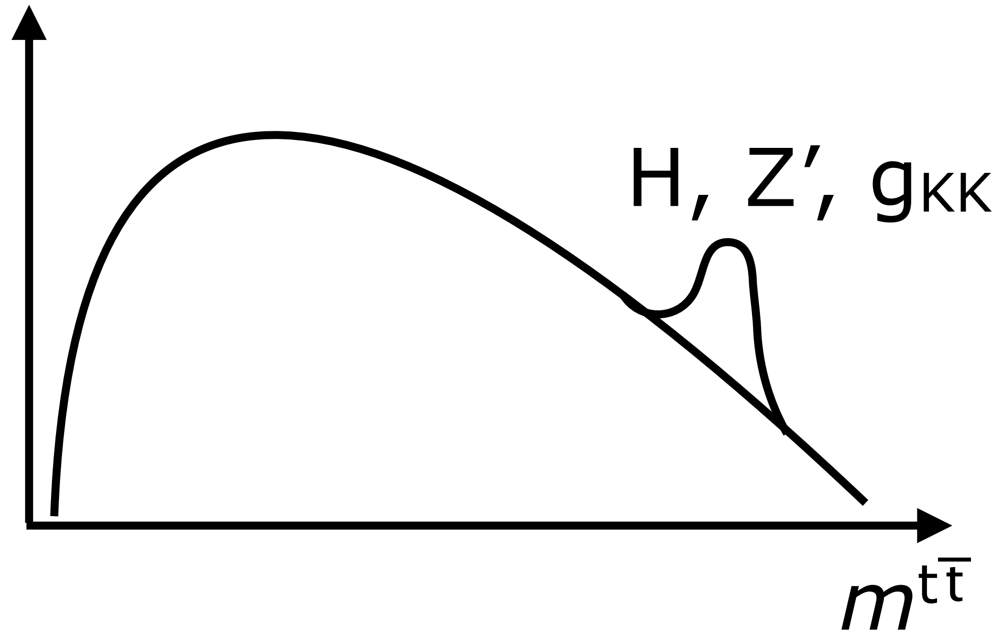


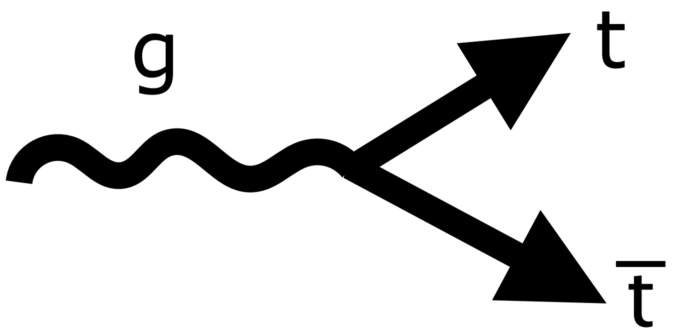
$m^{t\bar{t}}$, $p_T^{t\bar{t}}$, $y^{t\bar{t}}$

- Mass probably the most *intriguing* observable
- Appearance of bumps or dips can signal the presence of BSM resonant states or SM/BSM interference



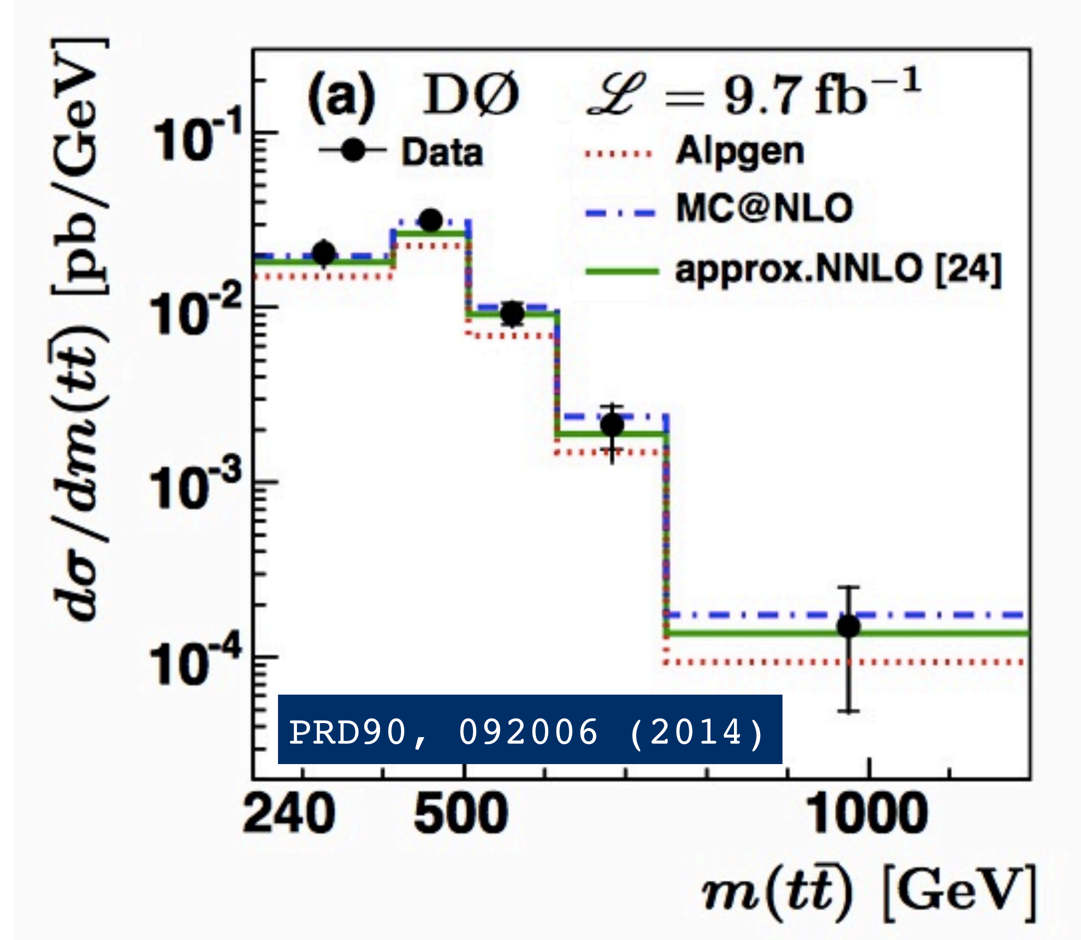


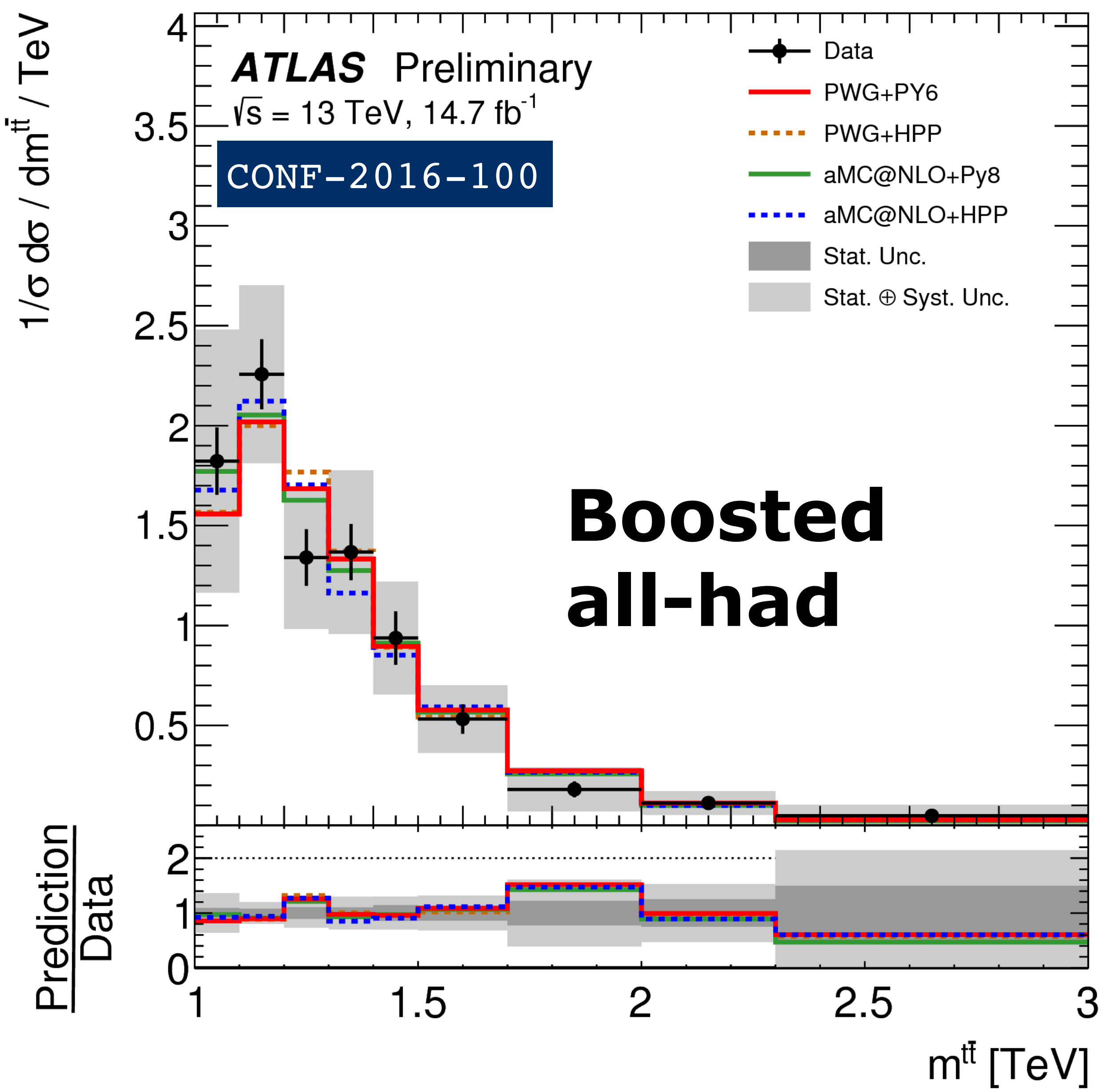
- $p_T^{t\bar{t}}$ sensitive to additional radiation (e.g. initial-state radiation)
- Rapidity sensitive to parton distribution functions, especially when binned in mass

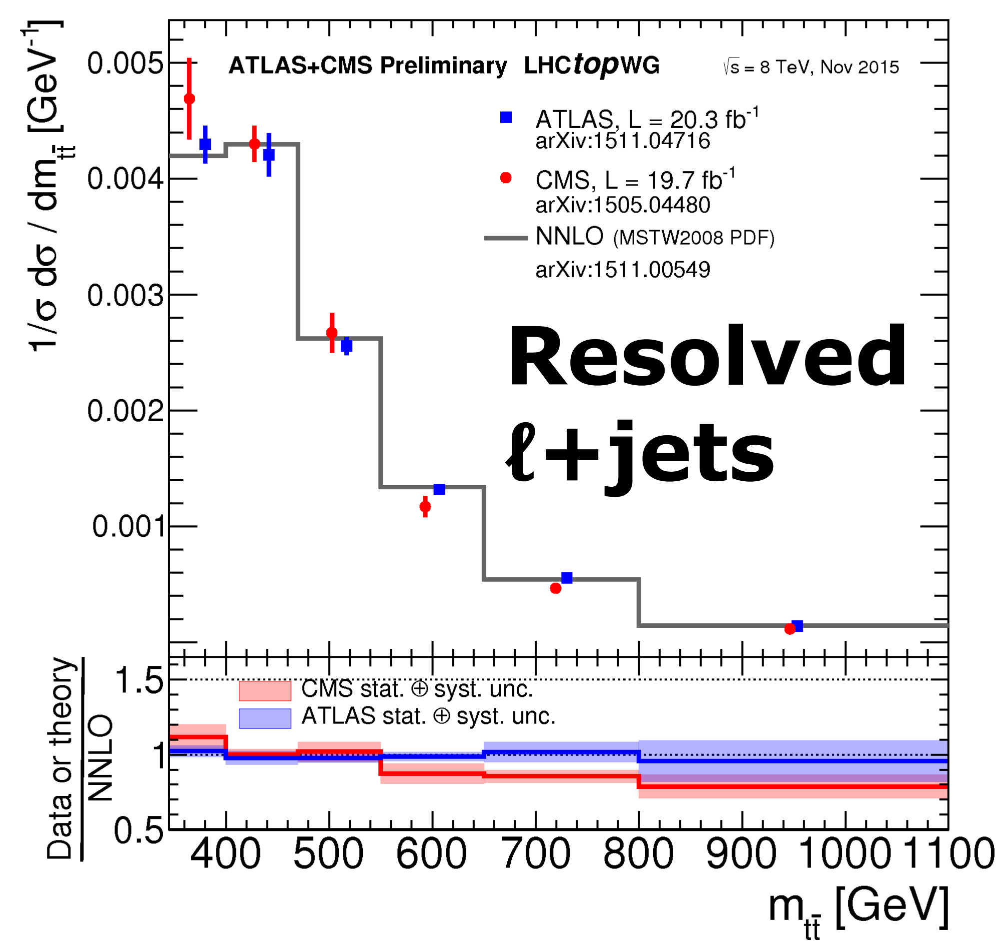


$t\bar{t}$ system invariant mass

Data/MC **seems well-modelled**
Resolution limits bump hunting
All-Hadronic boosted promising
(no neutrinos, only two jets)



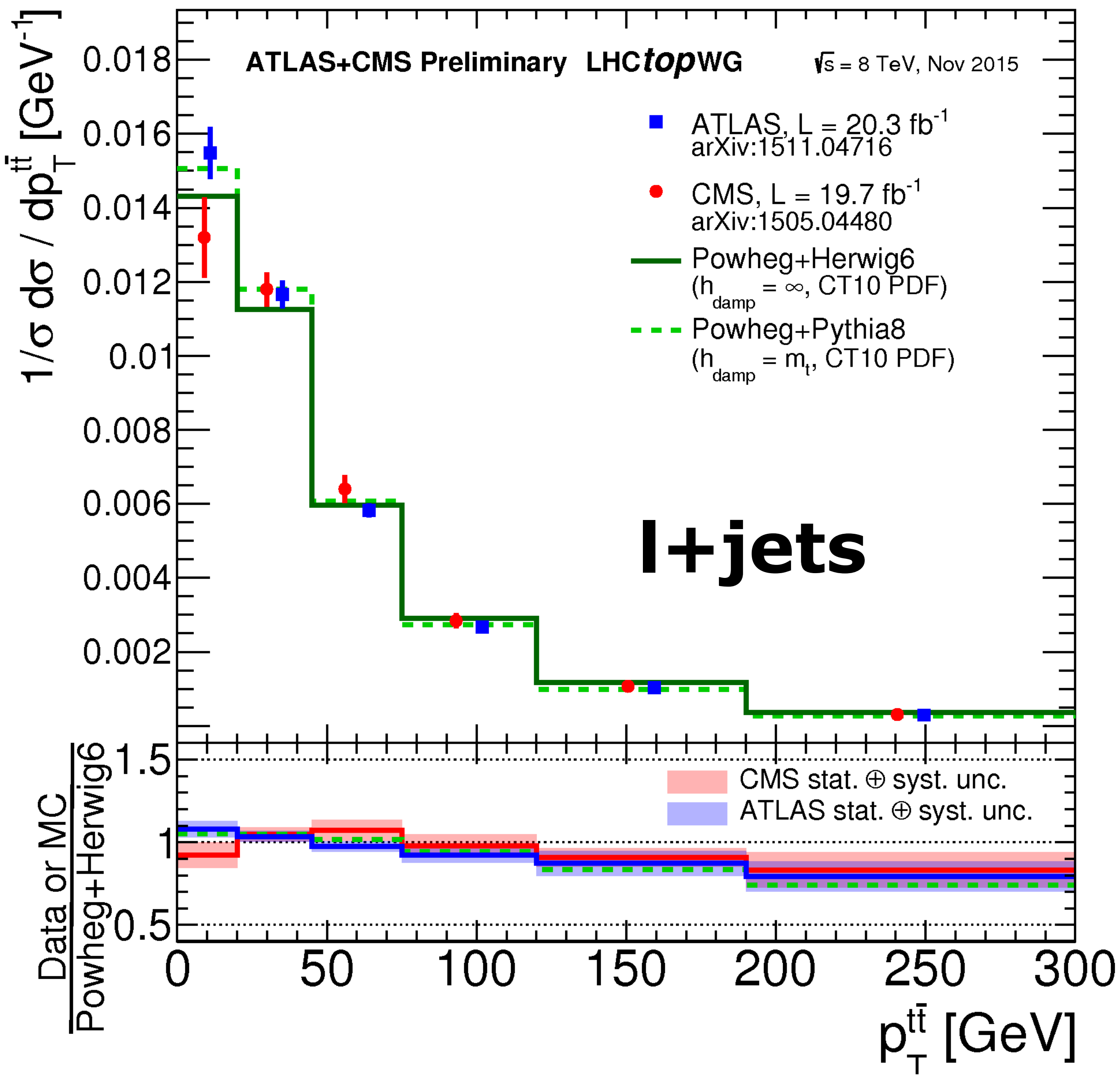


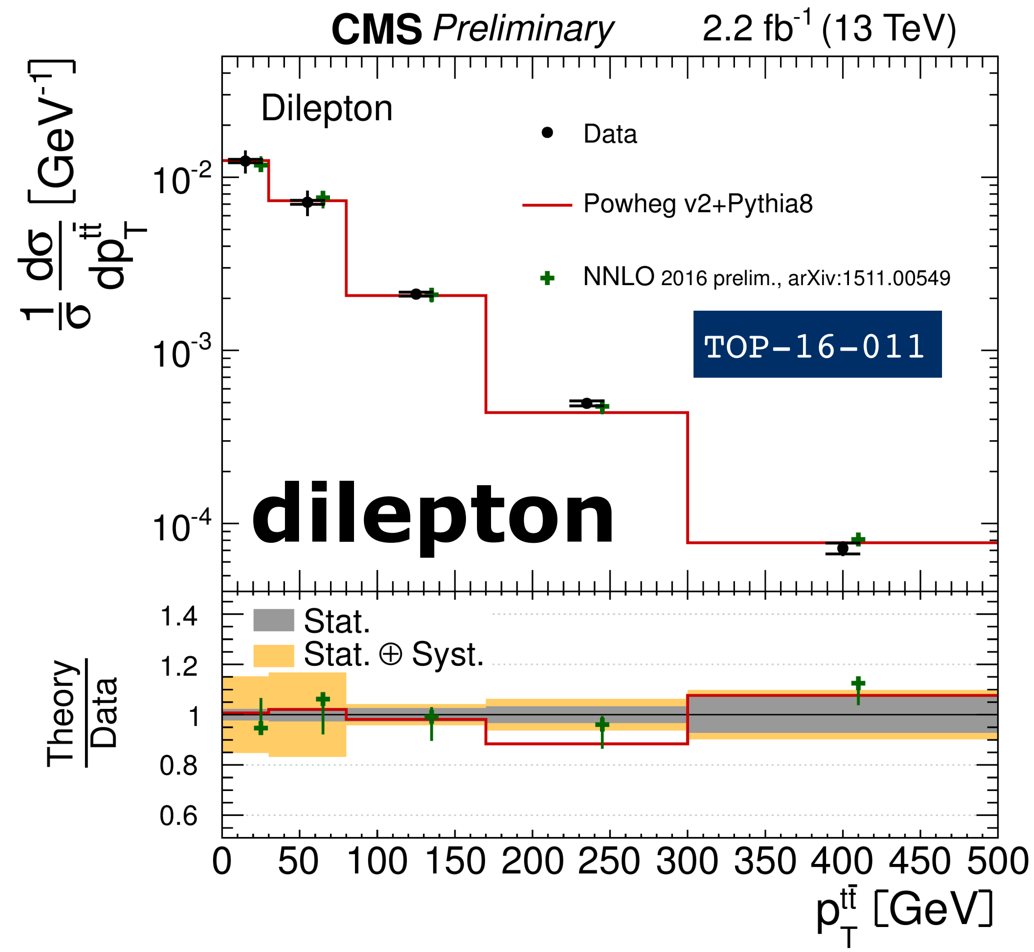


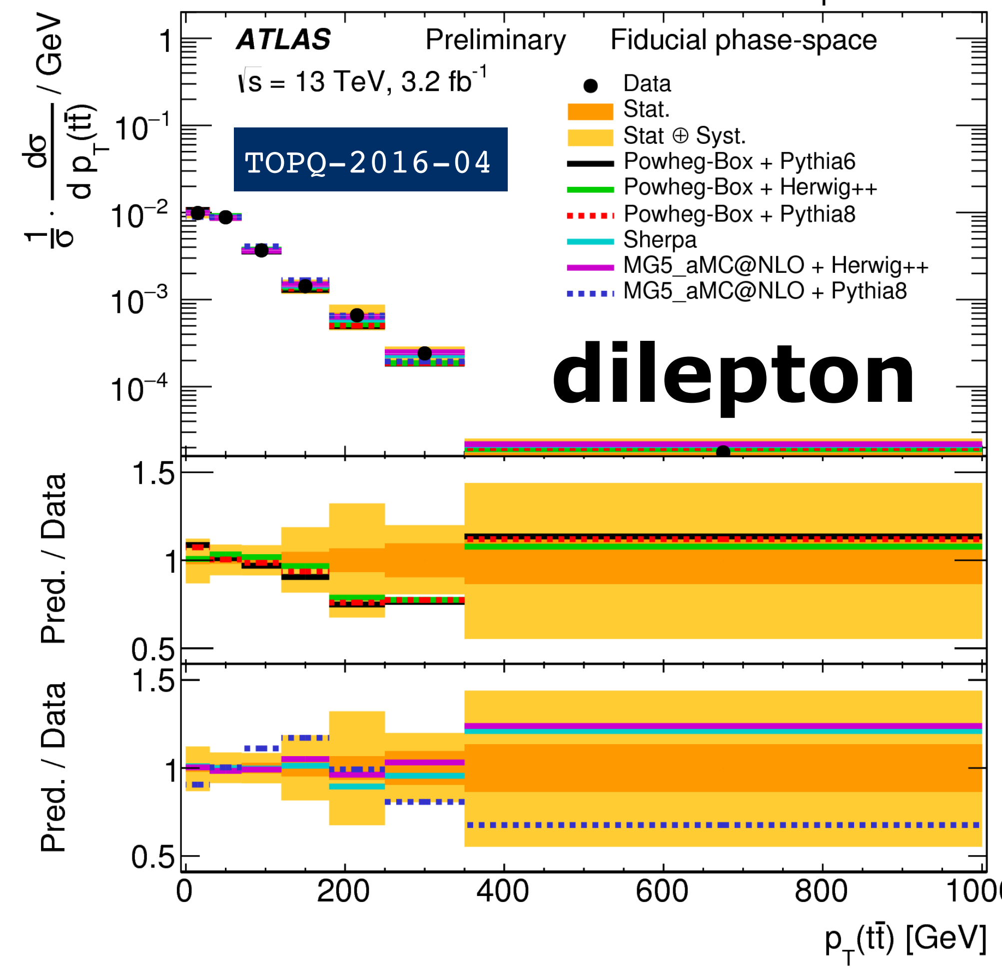
$t\bar{t}$ system transverse momentum

Data/MC **seems better modelled** by **NNLO** than **NLO+NNLL**

Additional radiation **constrain** Monte Carlo generators (POWHEG)







$t\bar{t}$ system rapidity

Tendency to be overestimated in the forward region
Sensitive to choice of PDF set

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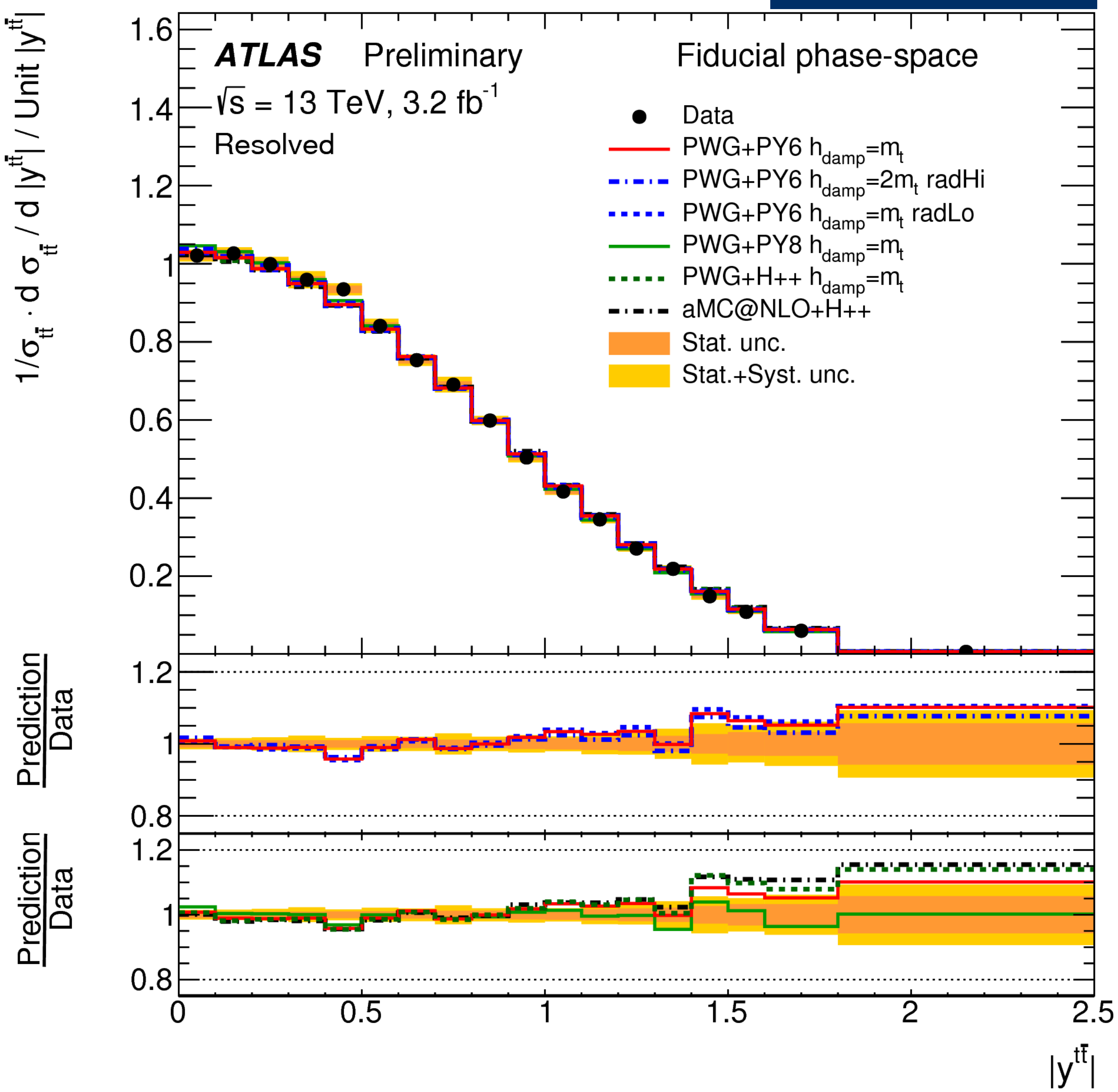
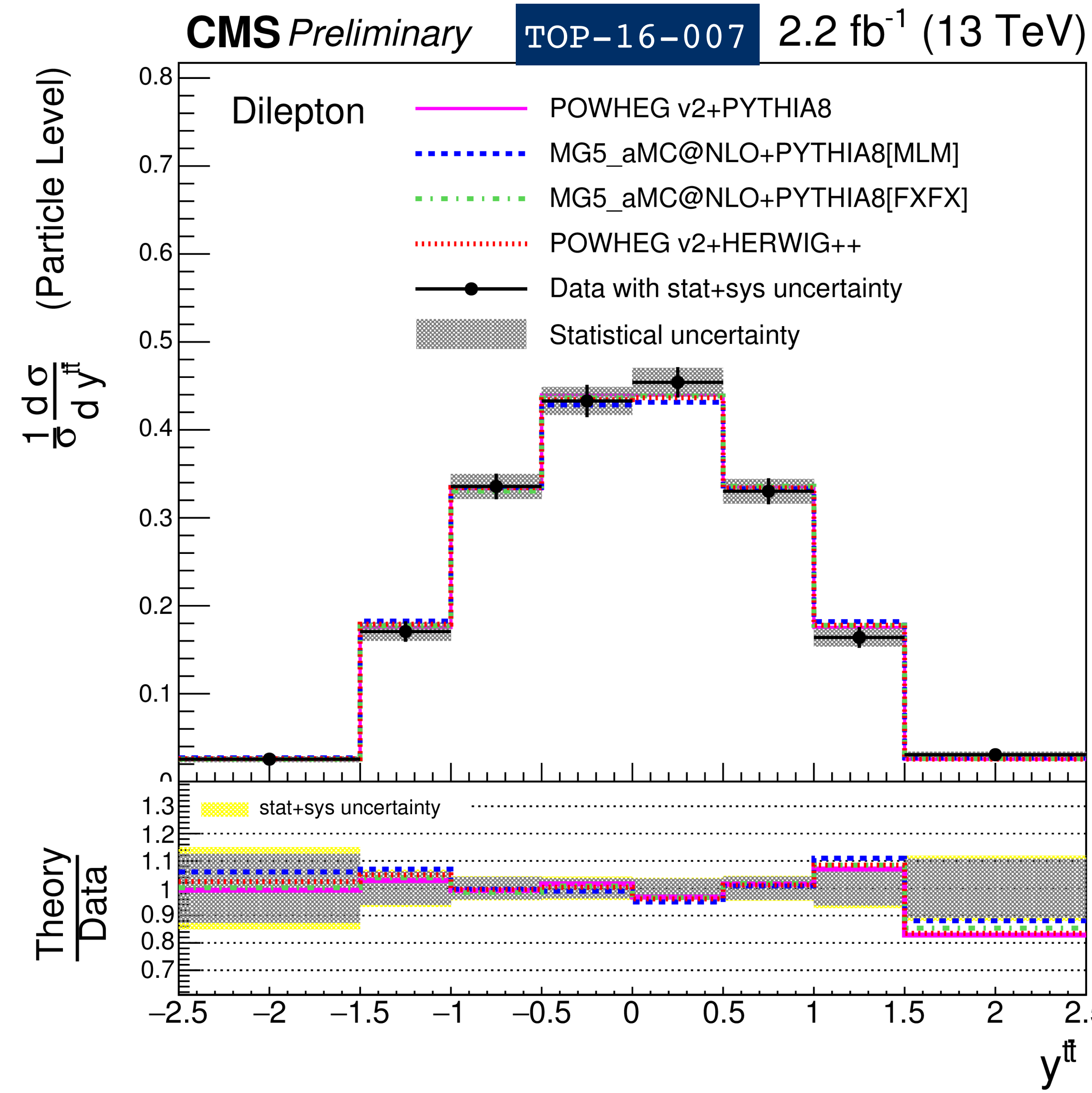


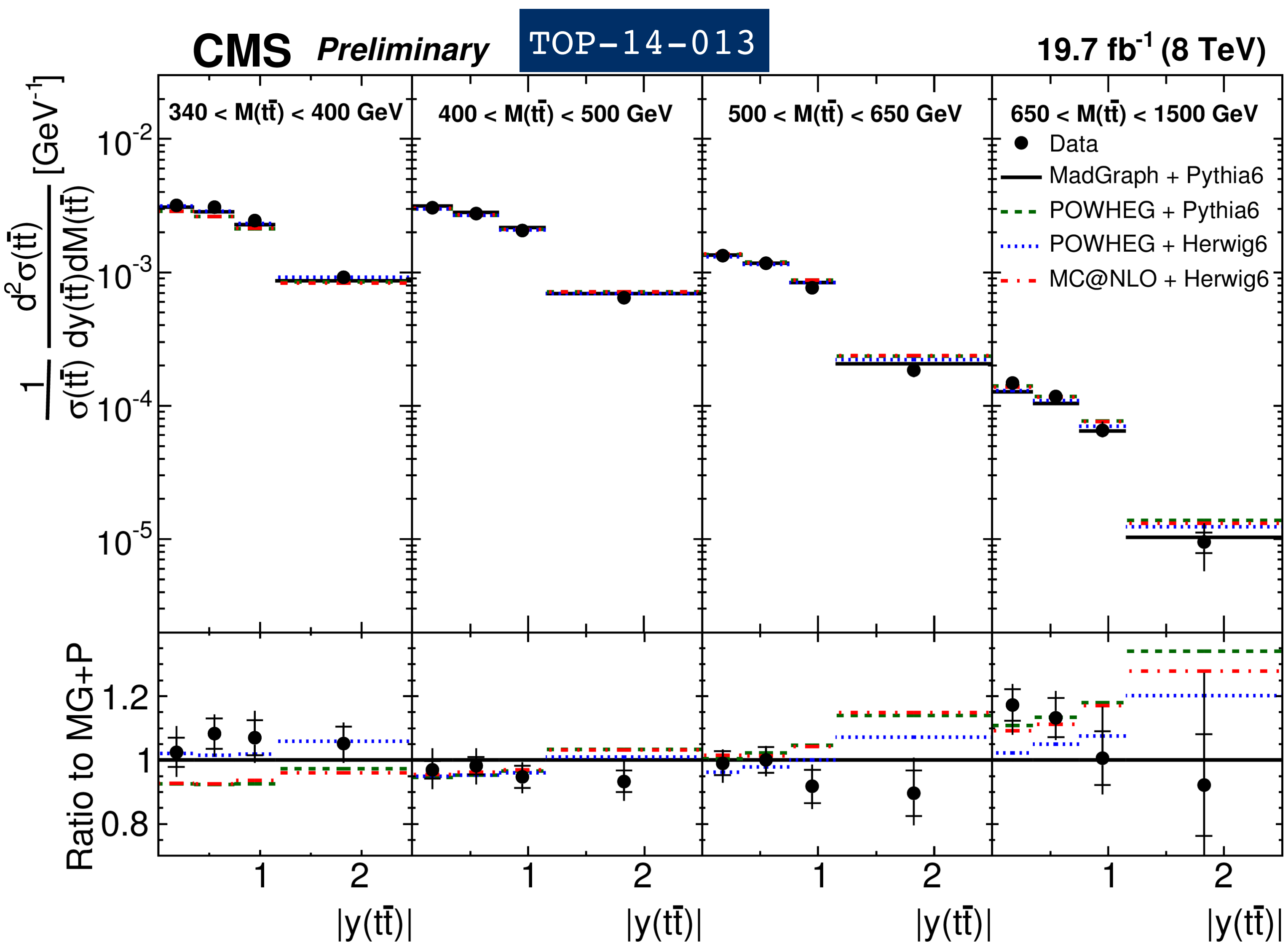
TOP-16-007

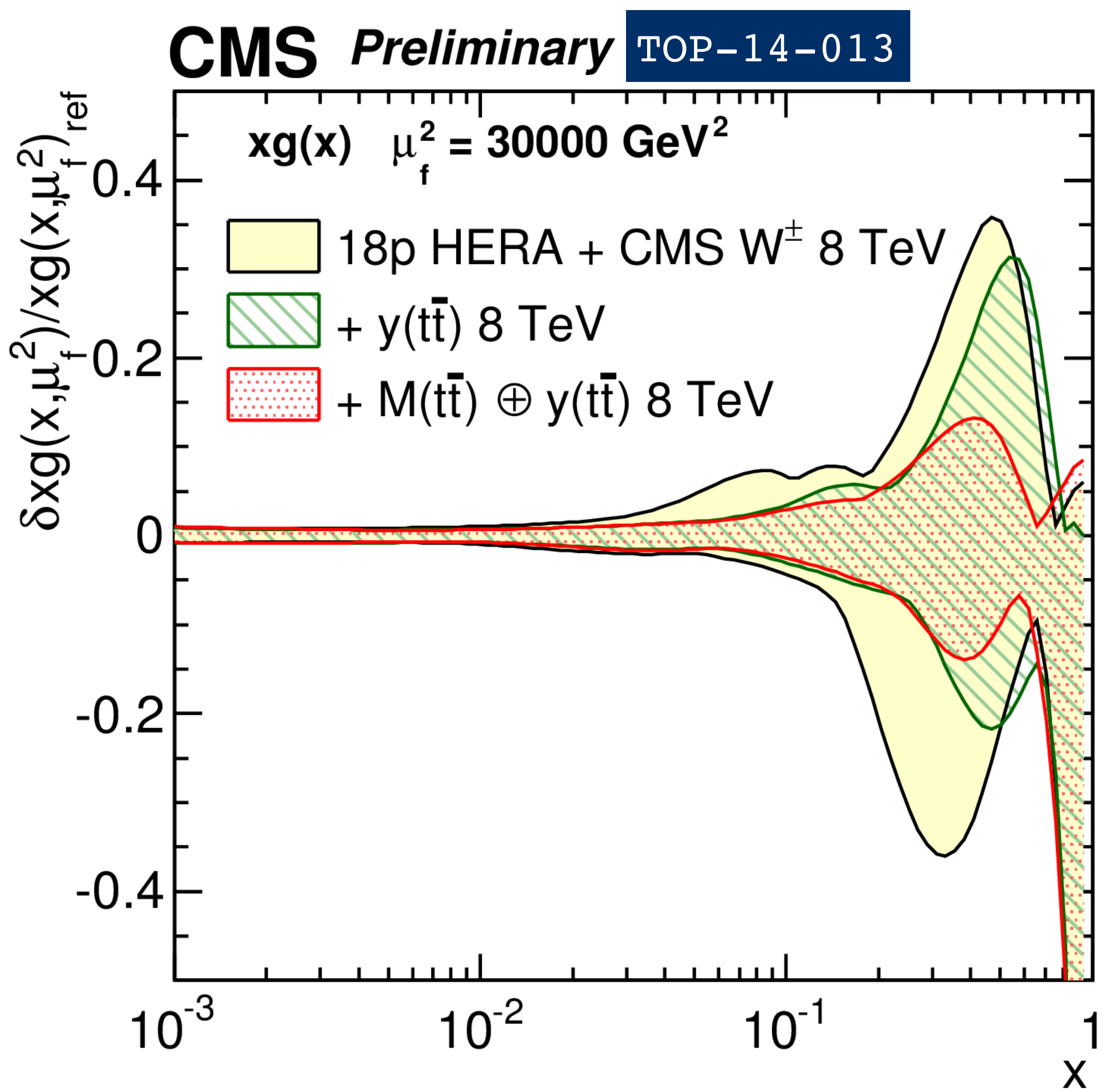


$t\bar{t}$ system rapidity

Double-differential measurement constrains **gluon PDF**

$$x = \frac{M(t\bar{t})}{\sqrt{s}} e^{\pm y(t\bar{t})}$$



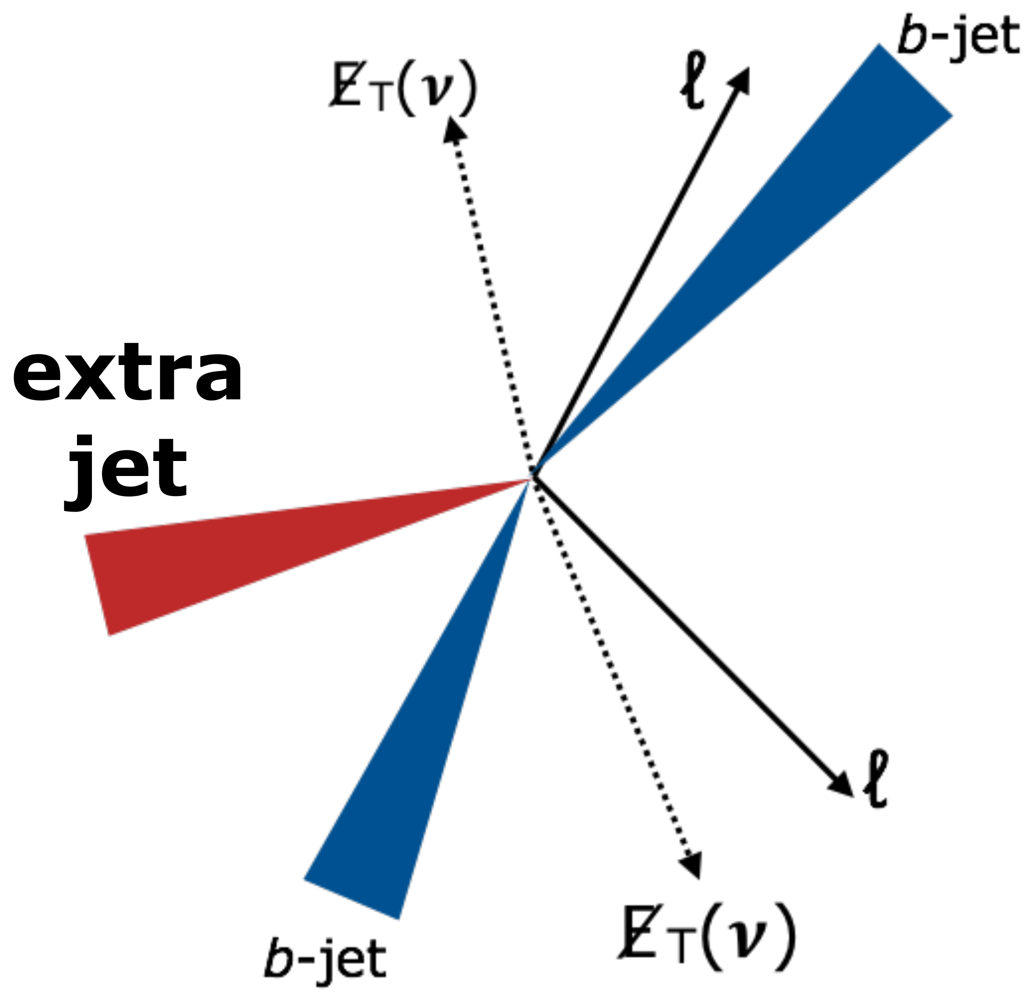


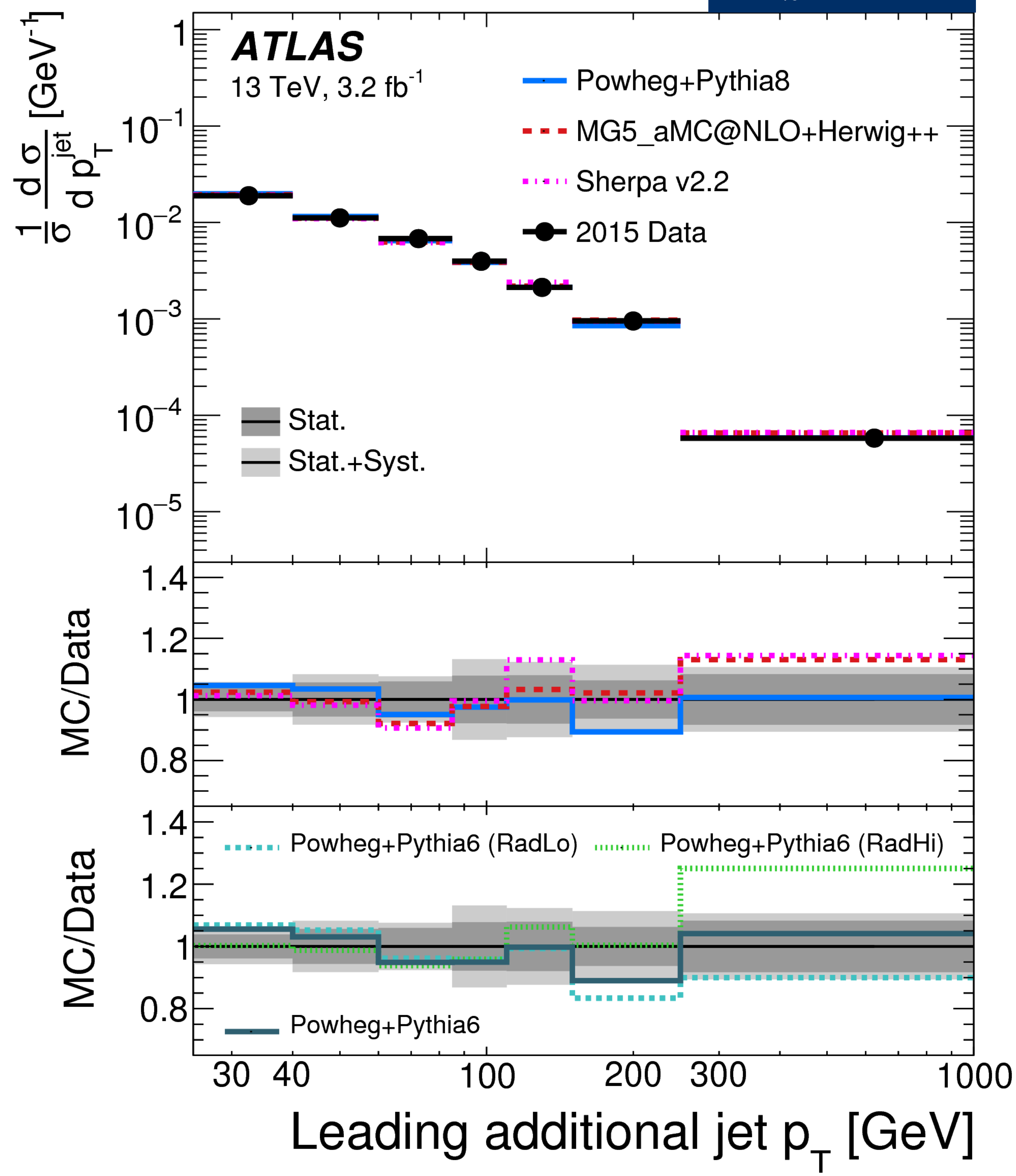
Fit PDF

Extra jets activity

TOPQ-2015-17

Additional radiation (I/FSR) critical test of **NLO** corrections, **parton shower** models and M.E./P.S. **matching** schemes

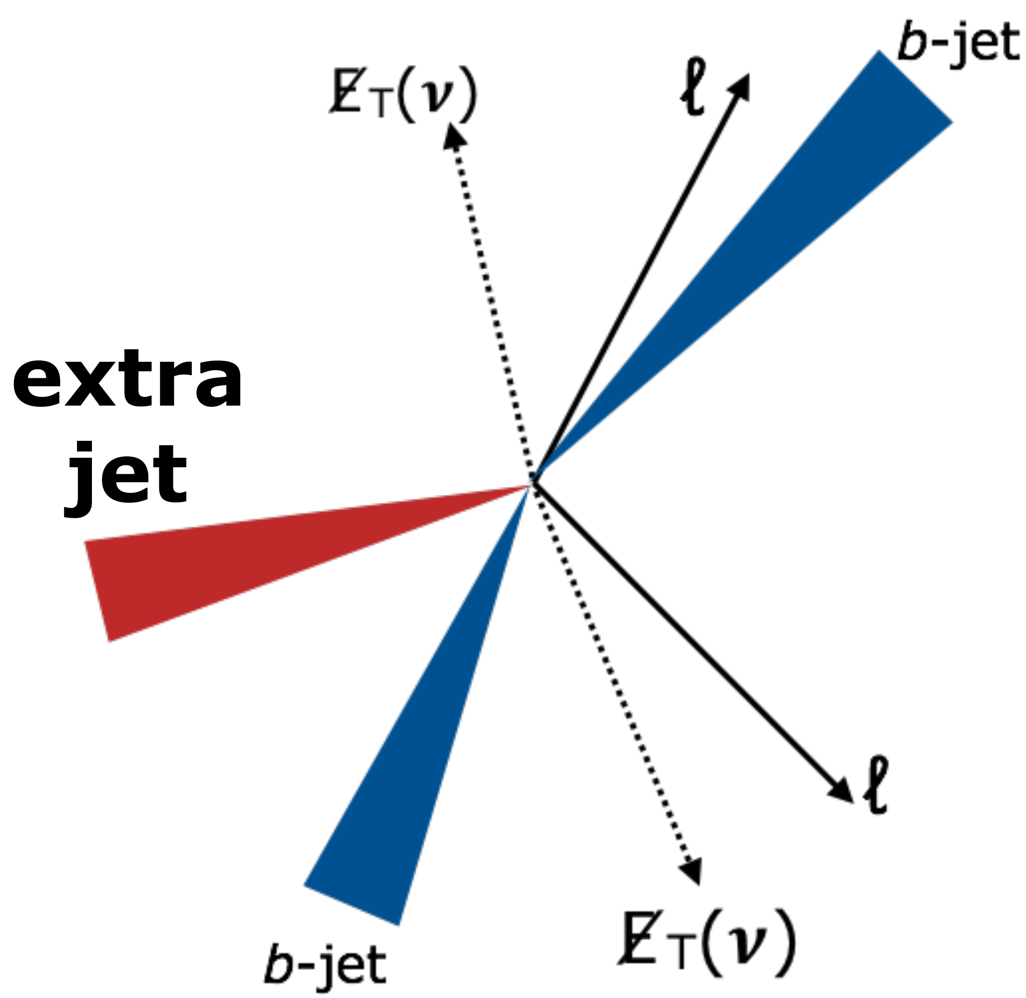


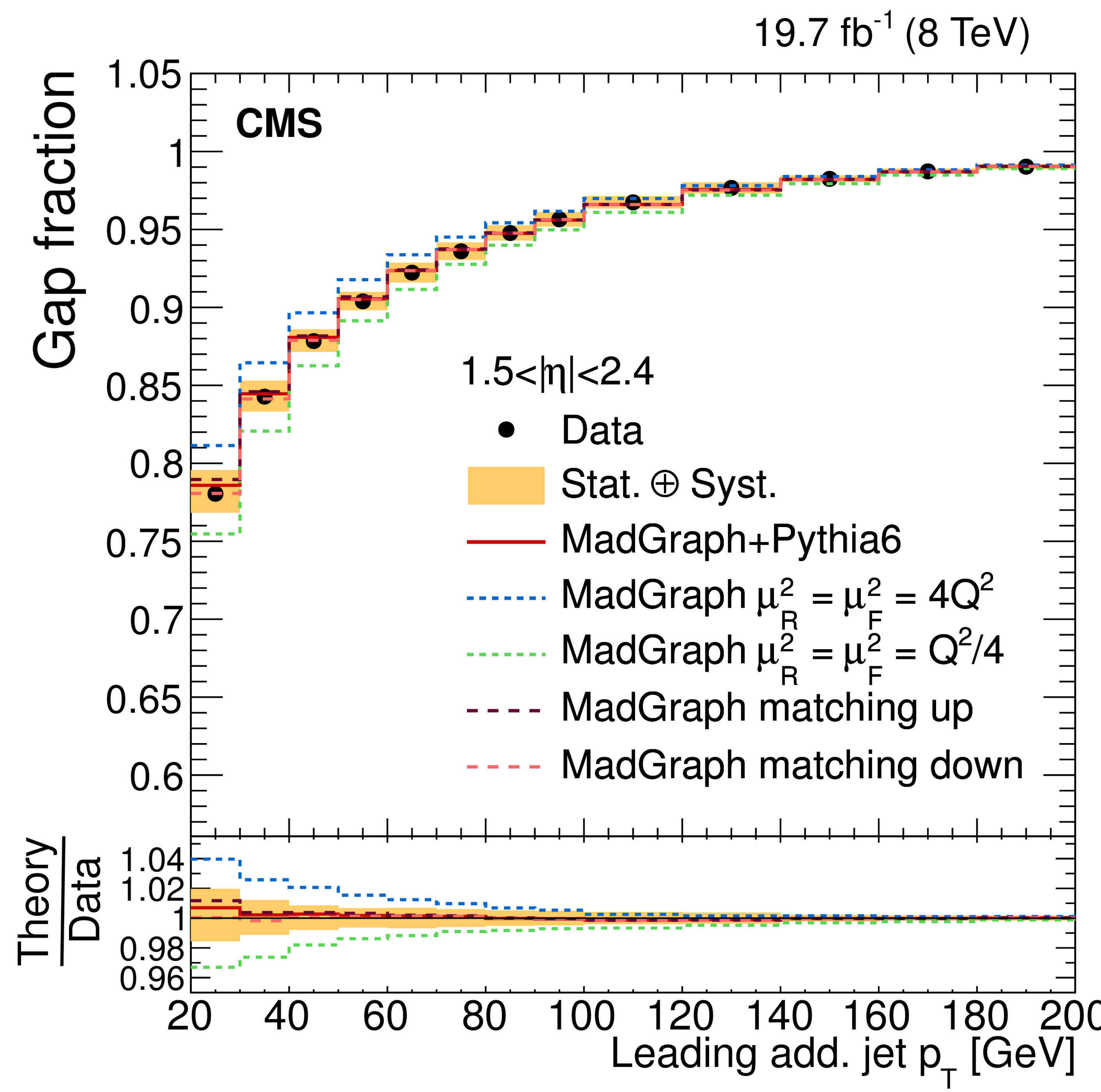


Extra jets activity

EPJC 76(2016)379

Additional radiation (I/FSR) critical test of **NLO** corrections, **parton shower** models and M.E./P.S. **matching** schemes





Summary

- Top-quark pairs differential cross-sections instrumental to **constrain theory** and **search for BSM** physics
- **NLO** generators (particle level) and **NNLO** calculations (parton level) constrained by data
  - NNLO corrections **improve** data/theory agreement in **top transverse momentum**
- Entering the era of **boosted tops** and **double-differential** cross-sections

Backup

Recent results $\sqrt{s}$ = 13 TeV

	ℓ+jets	dilepton	all-hadronic
ATLAS	CONF-2016-040 resolved/boosted, particle	TOPQ-2016-04 resolved, particle TOPQ-2015-17 jet activity	CONF-2016-100 boosted, particle
CMS	TOP-16-008 resolved, parton/particle	TOP-16-007 resolved, particle TOP-16-011 resolved, parton	TOP-16-013 resolved/boosted, parton

Recent results $\sqrt{s}$ = 7/8 TeV

	ℓ+jets	dilepton	all-hadronic
ATLAS	Phys. Rev. D93(2016) 032009 boosted, parton/particle EPJ C76 (2016) 538 resolved, parton/particle JHEP 06(2015)100 resolved, parton/particle	PRD 94 092003(2016) resolved, parton	
CMS	Phys. Rev. D 94 (2016) 052006 resolved, particle Phys. Rev. D 94, 072002 (2016) boosted, parton/particle EPJC 75(2015)542 resolved, parton	TOP-14-013 resolved, parton (2D) EPJC 75(2015)542 resolved, parton EPJC 76(2016)379 jet activity	Eur. Phys. J. C 76 (2016) 128 resolved, parton/particle

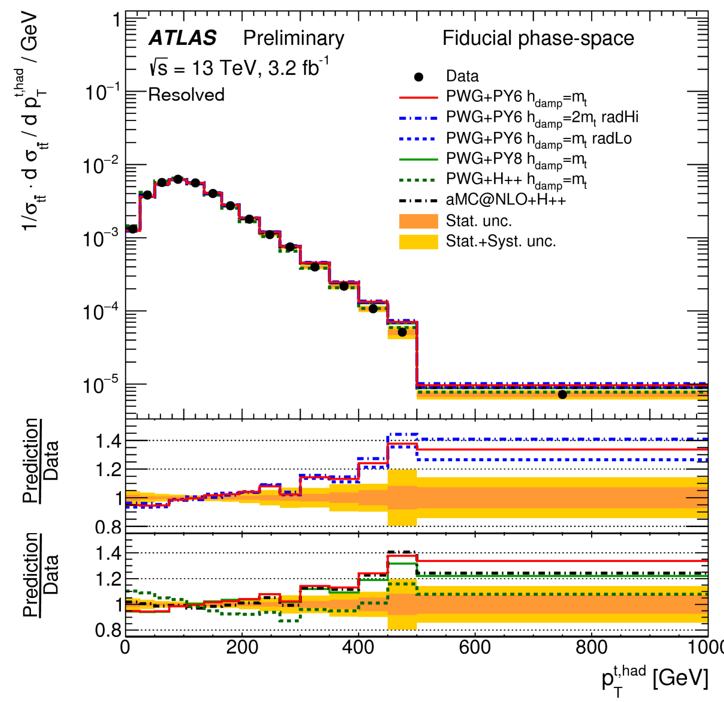
Recent results √s = 1.96 TeV

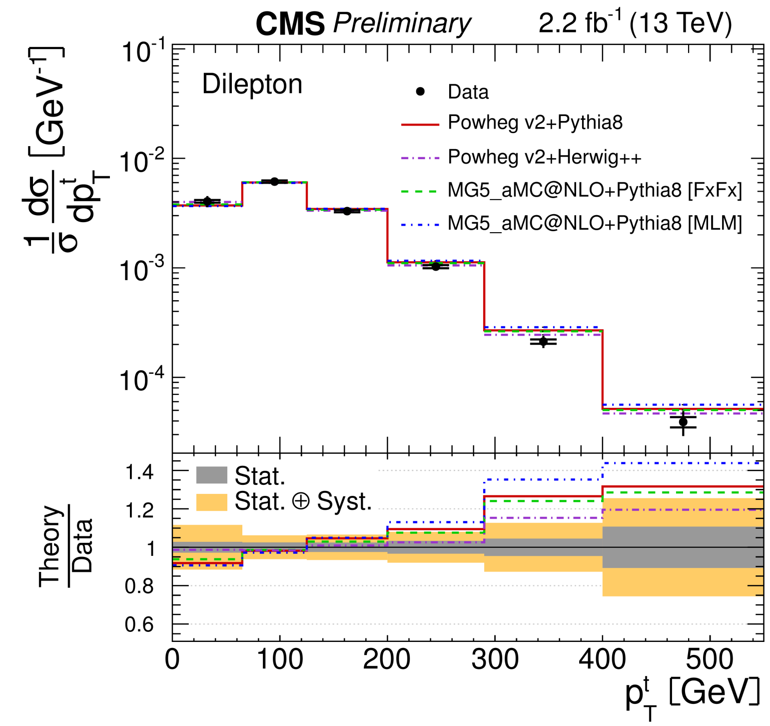
	ℓ+jets	dilepton	all-hadronic
CDF	PRL 111, 182002 (2013) resolved, parton cosθ		
D0	Phys. Rev. D 90, 092006 (2014) Phys.Lett.B693:515-521, 2010 resolved, parton		

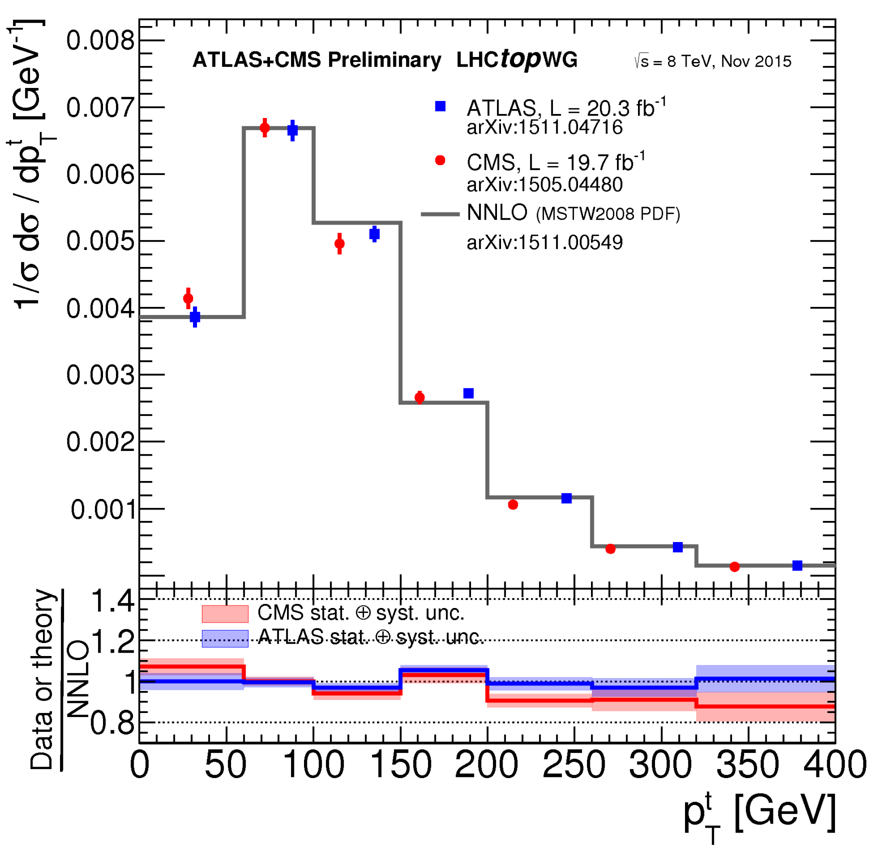
Top quark p_T

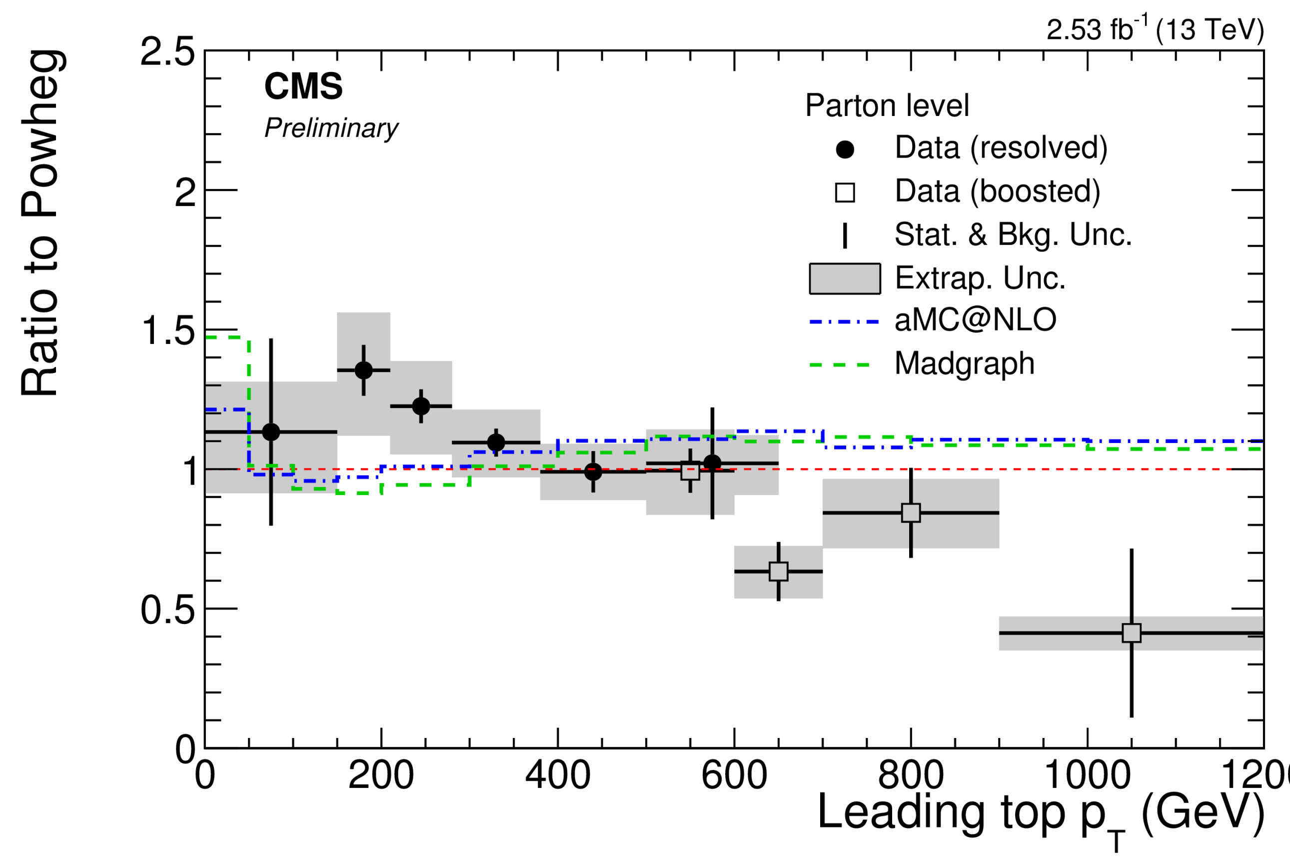
Data/MC **improves** at high pT if **NNLO** corrections are taken into account

Calculations not yet matched to parton shower

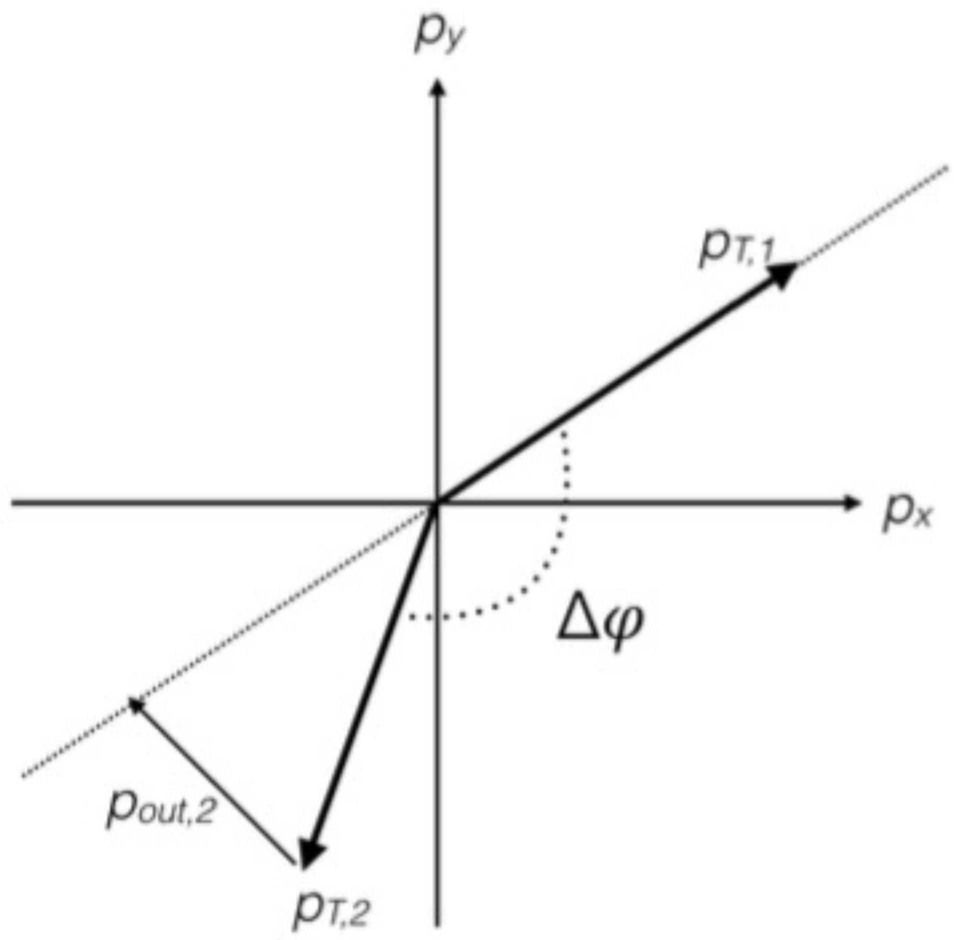


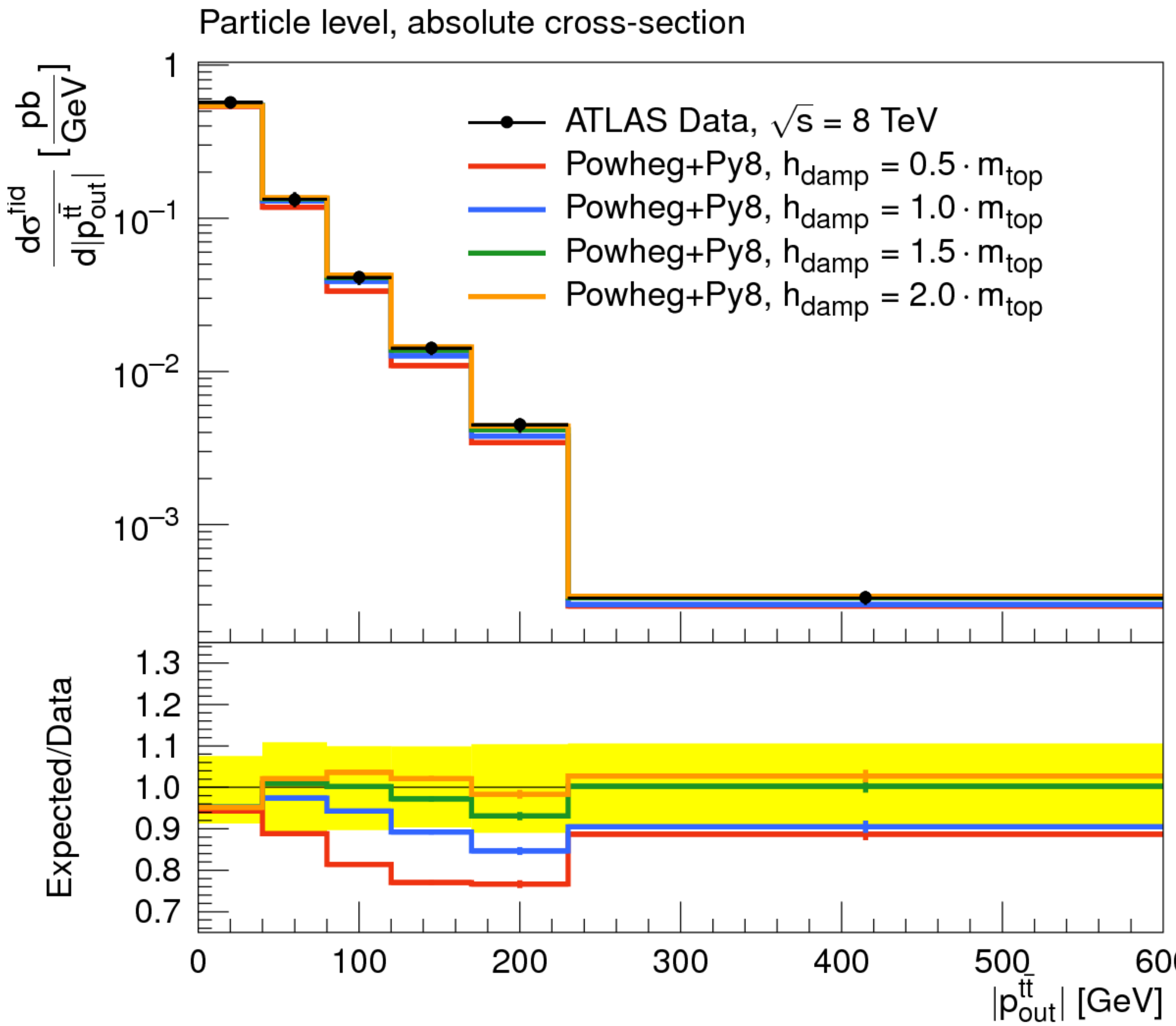




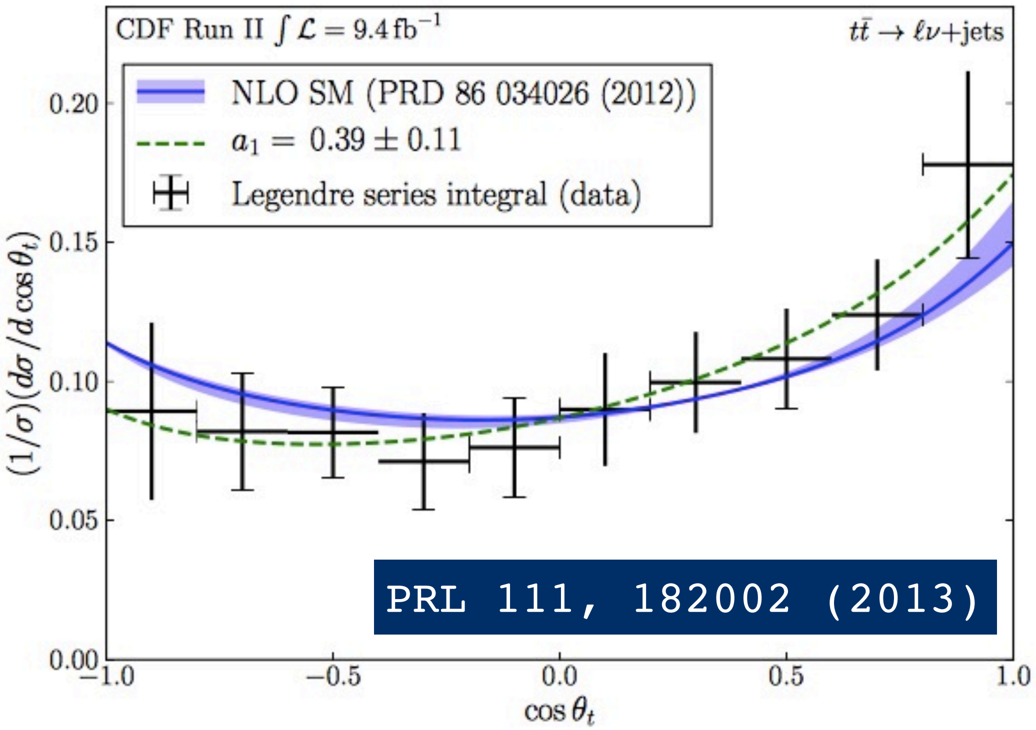


Others - $p_{out}^{t\bar{t}}$

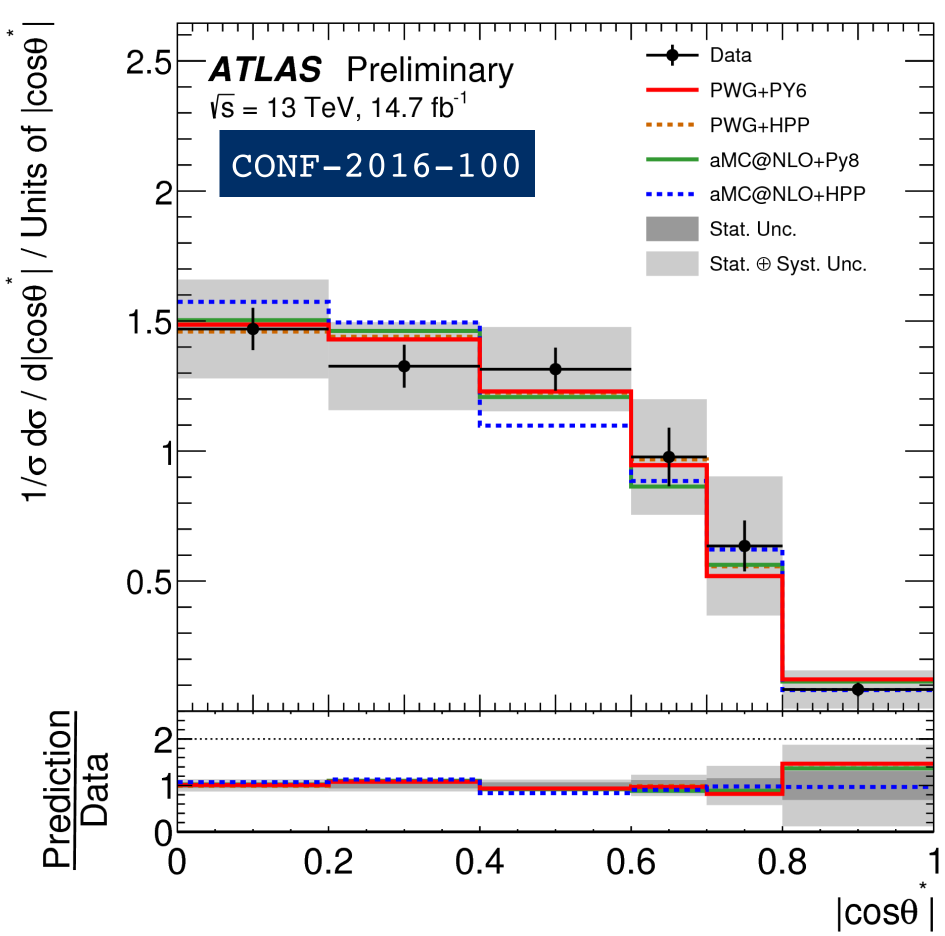




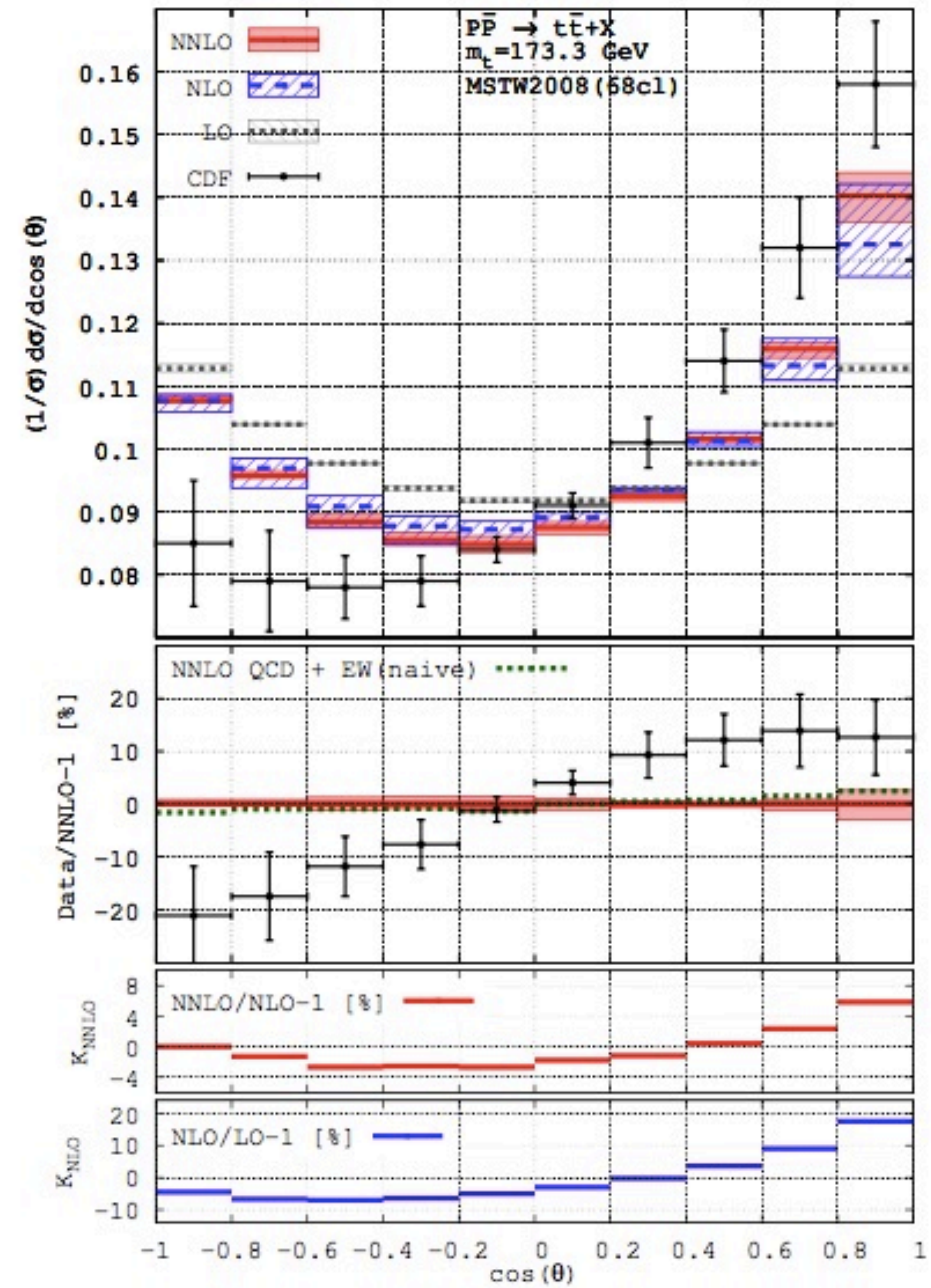
Others - cosθ



CDF Run II ∫ℒ = 9.4 fb⁻¹
tt̄ → ℓν+jets
NLO SM (PRD 86 034026 (2012))
a₁ = 0.39 ± 0.11
Legendre series integral (data)
PRL 111, 182002 (2013)
(1/σ)(dσ/d cos θ_t)
cos θ_t



ATLAS Preliminary
√s = 13 TeV, 14.7 fb⁻¹
CONF-2016-100
Data
PWG+PY6
PWG+HPP
aMC@NLO+Py8
aMC@NLO+HPP
Stat. Unc.
Stat. ⊕ Syst. Unc.
1/σ dσ / d|cosθ*| / Units of |cosθ*|
Prediction / Data
|cosθ*|



NNLO
NLO
LO
CDF
pp̄ → tt̄+X
m_t=173.3 GeV
MSTW2008(68cl)
(1/σ) dσ/dcos(θ)
NNLO QCD + EW(naive)
Data/NNLO-1 [%]
NNLO/NLO-1 [%]
K_NNLO
NLO/LO-1 [%]
K_NLO
cos(θ)