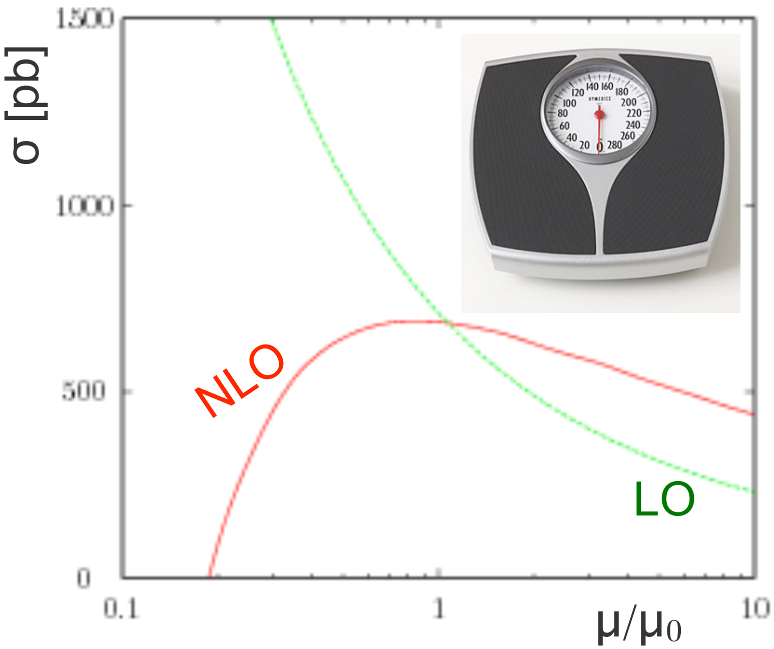
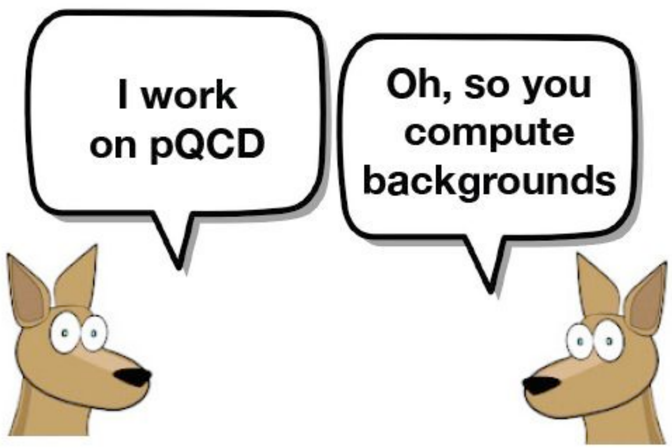
Scale choices for complex processes

Kalanand Mishra, *Fermilab*



Snowmass 2013: Energy Frontier Workshop on QCD Physics, FNAL, January 31, 2013

Outline



- Experimental results on QCD radiation in
  - -ttbar+jj, ttbar+bb, WW+jj, H+jj, ...
- In the framework of fixed order ME +PS calculation
  - -Effect of fact/renorm. scale, ME-PS matching threshold
  - -$N_{jets}/N_{partons}$ and phase space dependence
- Will also discuss some issues related to signal acceptance
  - -jet veto efficiency and systematics

Not a survey of results. Focus on few topics of interest.
The choice of topics has experimentalist's bias.

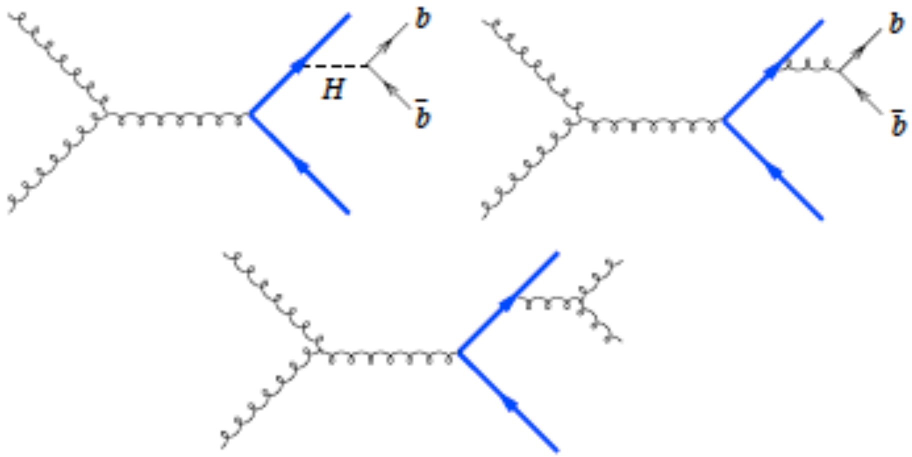
What I will NOT talk about !!!

NLO revolution

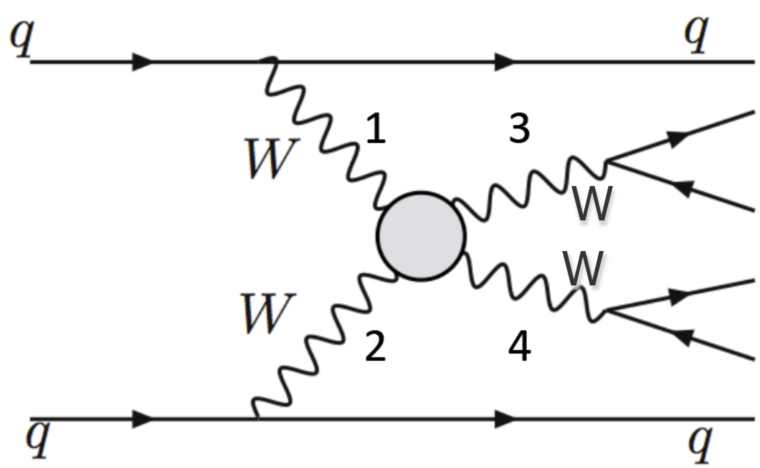
- Thanks to heroic efforts of many individuals, we have NLO+PS generators available to experimental community as of December 2012
  - -aMC@NLO
  - -SherpaNLO
- Have started generating and validating several processes of interest
  - -Multijet, W/Z/γ+jets, Wγ/Zγ+ 0,1,2 jets
  - -WW, WZ, ZZ + 0,1,2 jets
  - -tt, ttW, ttZ, tbZ, ttH + 0,1,2 jets
  - -WWW, WWZ, WZZ, H + 0,1,2 jets
- Currently sorting out various wrinkles, expect data results starting in Fall 2013.

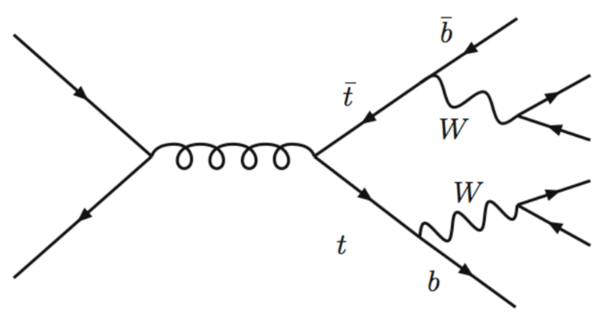
Starting with $t\bar{t}$+jets process

1. ttH, WH (H→bb)



2. H(→WW)+2jet, VBF H→WW, ...





- Background for Higgs signal in many decay modes
- Significant scale dependence for shape and normalization of background
- A priori choice of scale is not clear: $\xi\, m_t$ or $\xi\, H_T$ or $\xi\, \sqrt{(m_t^2 + \Sigma p_T^2)}$ or $\xi\, \sqrt{(m_t^2 + \Sigma m_{eff}^2)}$, or ...?

Quark and gluon radiation in $t\bar{t}$ events

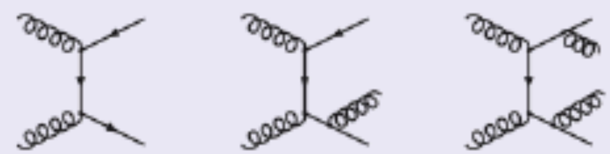
- At LHC, the fraction of $t\bar{t}$ events produced with additional hard jets is high
  - Sizable uncertainty from QCD radiation in many analyses
  - Theory predictions and models need to be tuned and tested with measurements
- Large samples of $t\bar{t}$ events provide a great opportunity to study the details of the $t\bar{t}$ production mechanisms
- Potential of constraining QCD radiation at the scale of the top quark mass
  - Differential $t\bar{t}$ production cross section vs. p_T(top), p_T($t\bar{t}$)
  - Jet multiplicity in $t\bar{t}$ and associated jets
  - $t\bar{t}$ with veto on additional jets

Also see talk on this topic by Maria Aldaya in TOP LHC WG meeting: https://indico.cern.ch/conferenceDisplay.py?confId=217721

An example of generator setup (CMS)

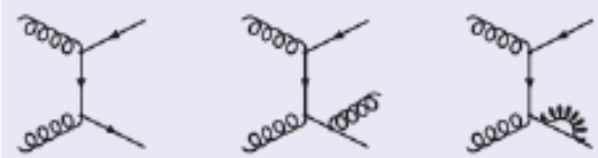
process	ME	PS	method	PDF	Tune
$t\bar{t}$ + jets	MadGraph v5.x	Pythia v6.42x	ME+PS	CTEQ6L1	Z2(*)
$t\bar{t}$	POWHEG-box 1.0	Pythia v6.42x	NLO	CTEQ6M	Z2(*)
$t\bar{t}$	MC@NLO v3.41	Herwig v6.520	NLO	CTEQ6M	

- Matrix Element + Parton Shower generators
  - Better description of high multiplicities
  - ISR/FSR modelling via ME from assumed Q^2 variation
  - Matching procedure to remove double counting between partons produced by ME and PS



tree level diagrams with up to 3 partons

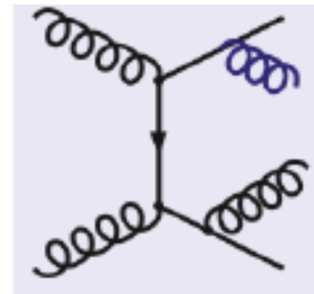
- Next to Leading Order generators
  - More accurate in normalization
  - Smaller uncertainty on Q^2



real + virtual corrections

- MadGraph(+Pythia) is the default for most of the analyses
  - Uncertainty on radiation covered by variations of Q^2 and ME-PS matching

Simulation of radiative corrections



- The 'Q² scale' variation addresses 2 aspects:
  - renormalisation and factorisation scale (ME)
  - amount of initial and final state radiation (ISR/FSR)

- For each event, Q^2 is defined as:

$$Q^2 = m_t^2 + \sum p_T^2 \text{ (MadGraph)}$$

$$Q^2 = m_t^2 \text{ (POWHEG/MC@NLO)}$$

  - Q^2 varied up (down) by a factor 4.0 (0.25)

- Parton showering:
  - p_T-ordered evolution scale of ISR/FSR
  - shares Q^2 factor α_S scale with ME
  - implicitly: starting scale changes with ΔQ^2

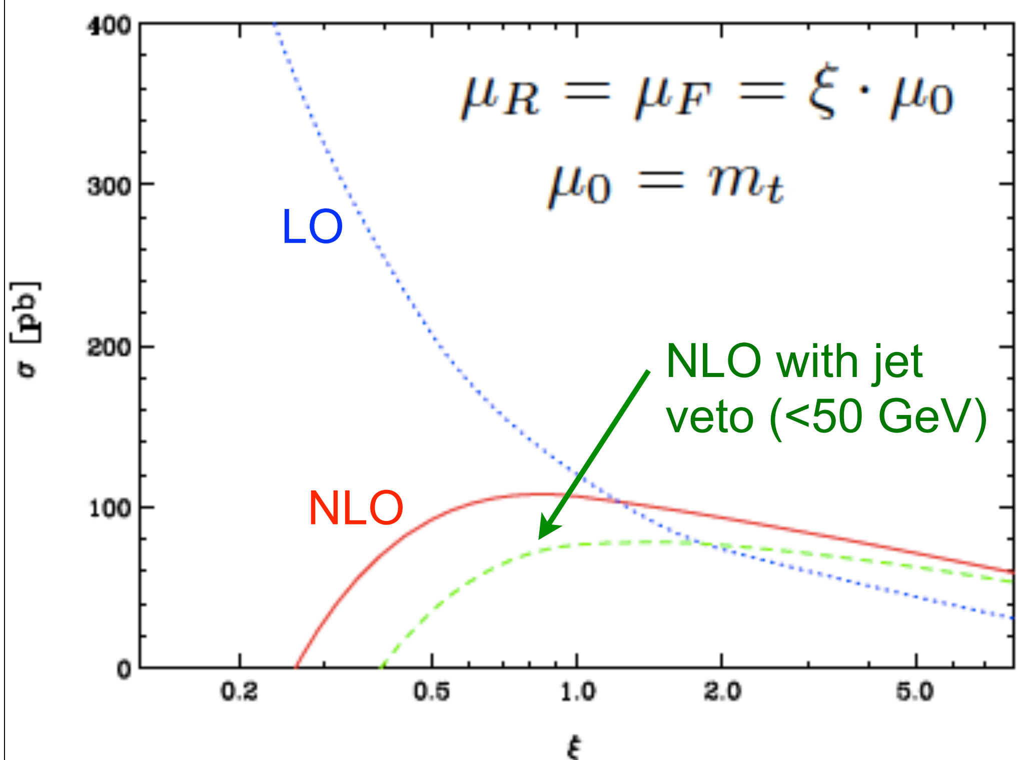
- MadGraph uses:
  - tree-level diagrams for hard radiation and interferences (up to 3 final-state partons for ttbar)
  - parton showering for soft and collinear region (with Pythia 6.42X)
  - matching via ktMLM, thresholds varied by factor 0.5 to 2.0 (nominal = 20 GeV)

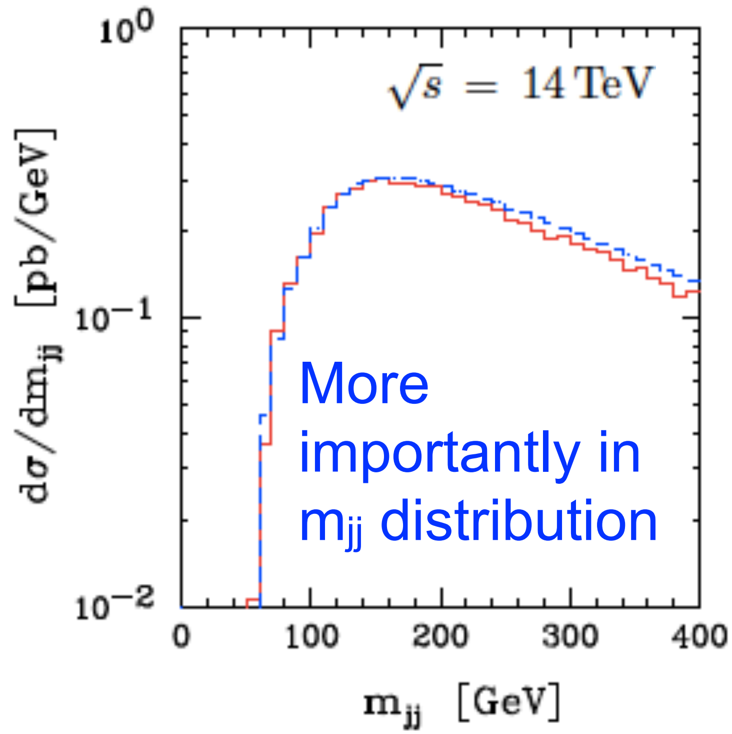
$t\bar{t}$+jj: scale dependence

arXiv:1002.4009, Bevilacqua et al

arXiv:0807.1223, Dittmaier et al

Large dependence for cross section



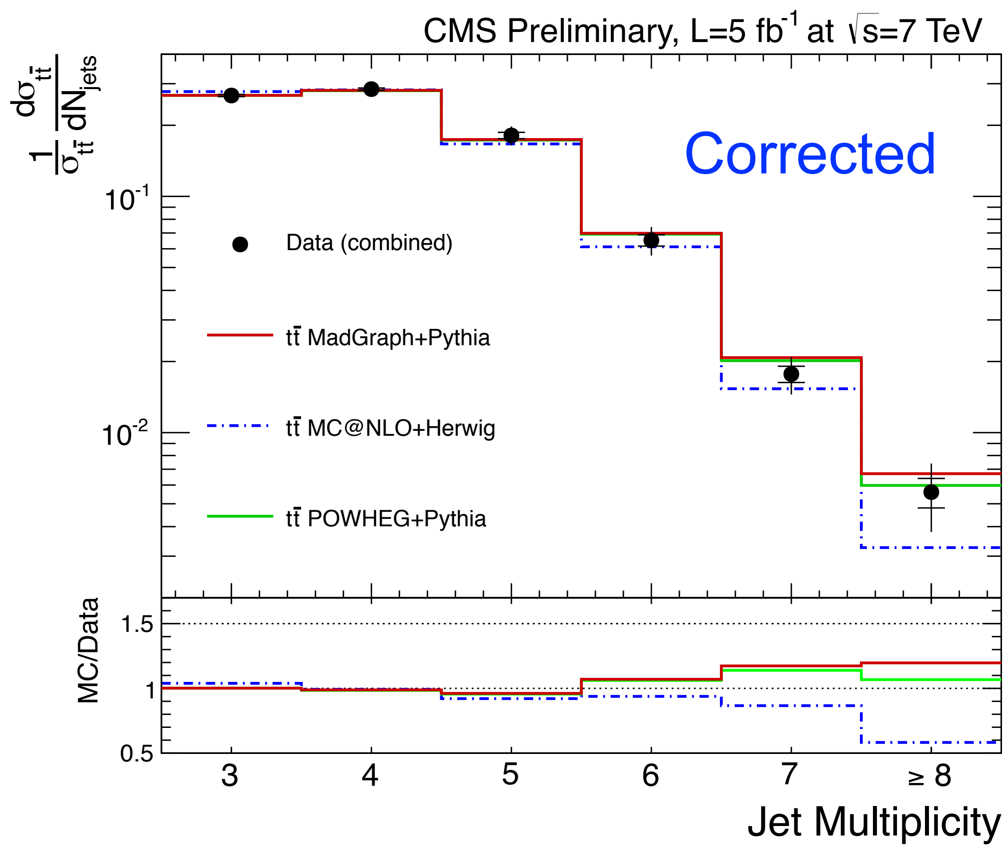


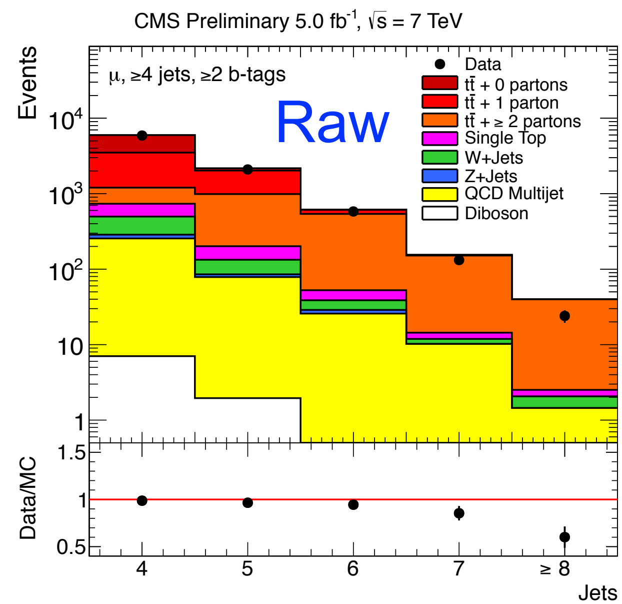
PROCESS	CONTRIBUTION
$pp \to t\bar{t}jj$	100 %
$qg \to t\bar{t}qg$	47.1 %
$gg \to t\bar{t}gg$	43.8 %
$qq' \to t\bar{t}qq'$, $q\bar{q} \to t\bar{t}q'\bar{q}'$	6.2 %
$gg \to t\bar{t}q\bar{q}$	1.6 %
$q\bar{q} \to t\bar{t}gg$	1.2 %

What the data are telling us: $t\bar{t}$+jets xsec vs N_{jets}

TOP-12-018

- Semi-leptonic channel: ≥3jets, p_T > 35 GeV, |η| <2.4, ≥2 b-tags
- Corrected to particle level, in visible phase space → jets: p_T > 35 GeV, |η| < 2.4

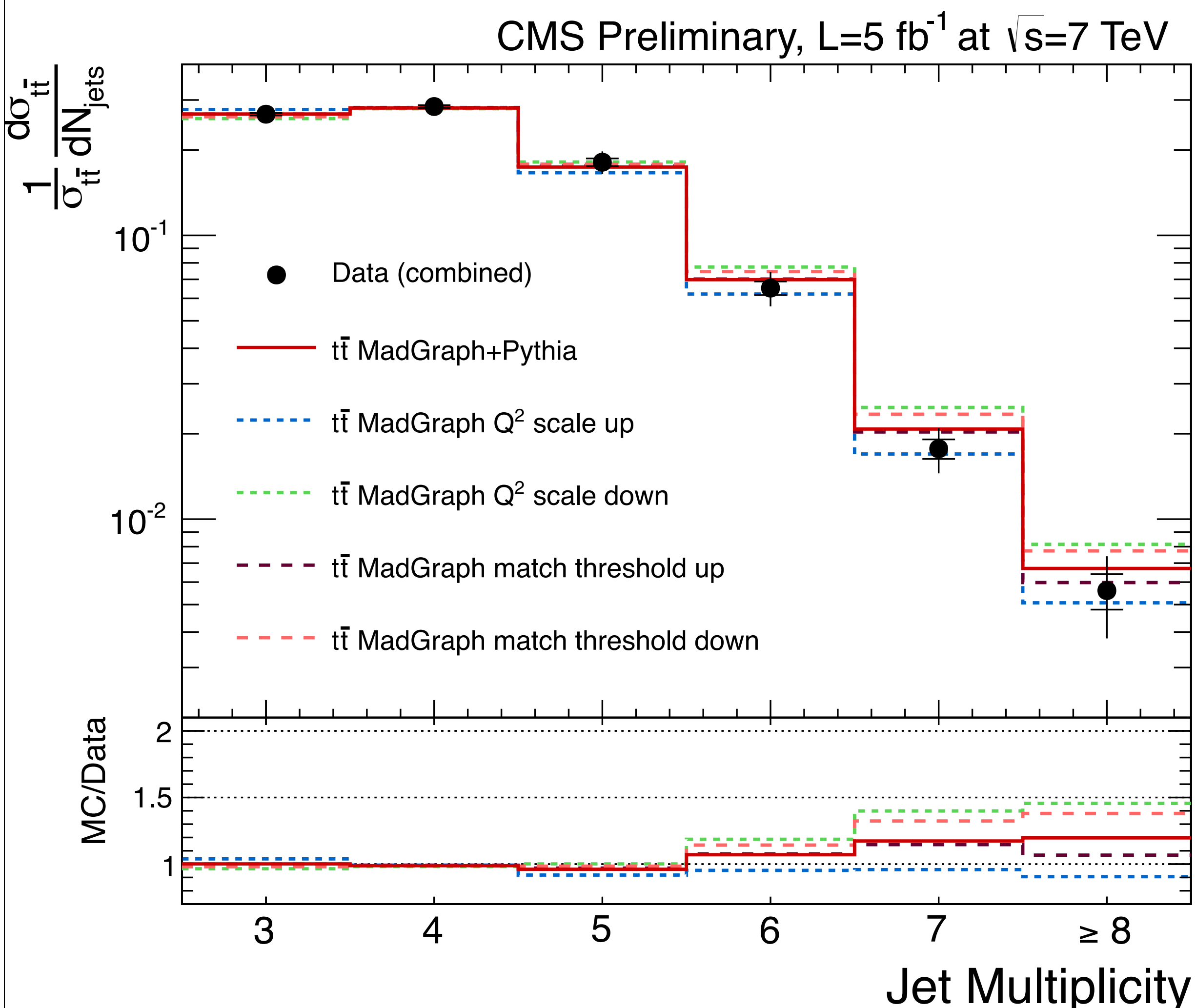




In general good agreement between data and predictions, MC@NLO+Herwig underestimates large N_{jets}.

Factorization/ renormalization scale

TOP-12-018

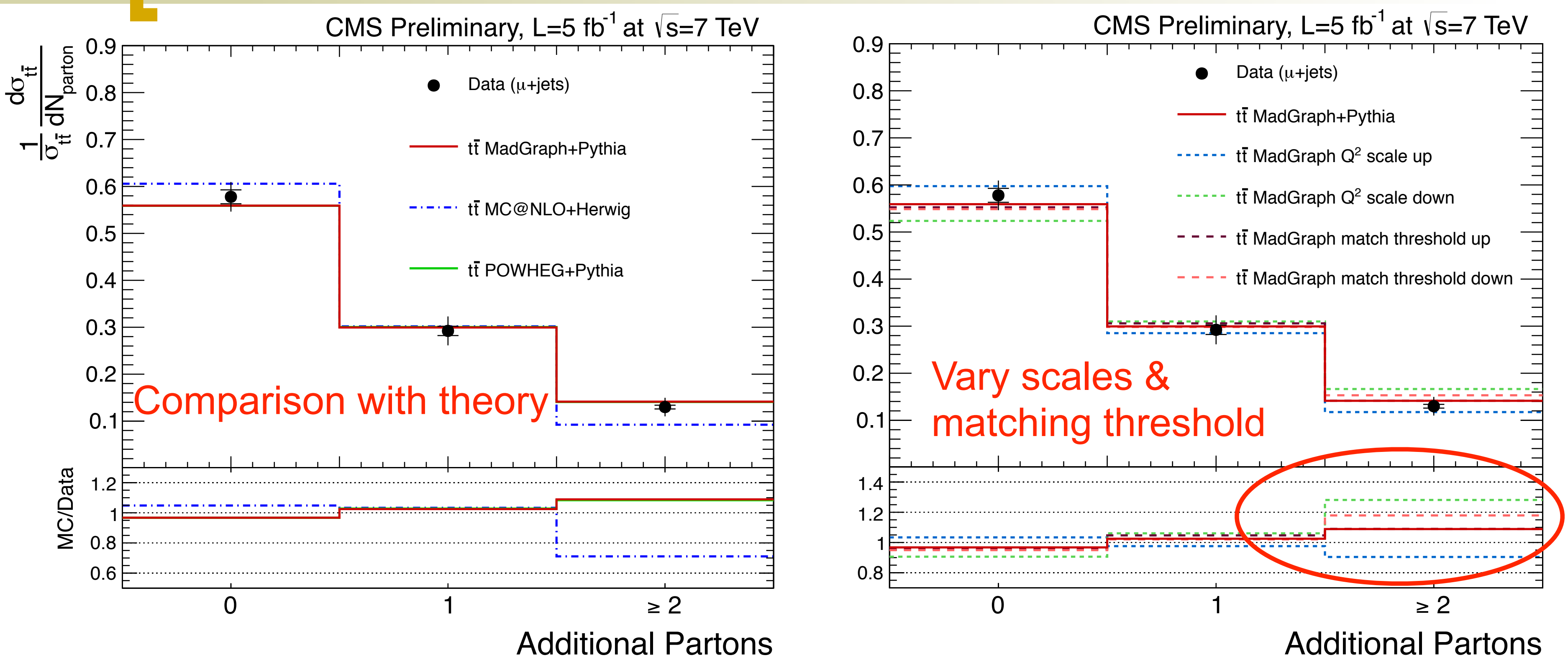


- Sensitive to modeling of radiation in MadGraph: data better described by larger scales.
- Matching and scale uncertainties grow with additional jets in the event → but can be constrained using data now.

Similar behavior seen in dilepton channel.

Vs. additional parton multiplicity

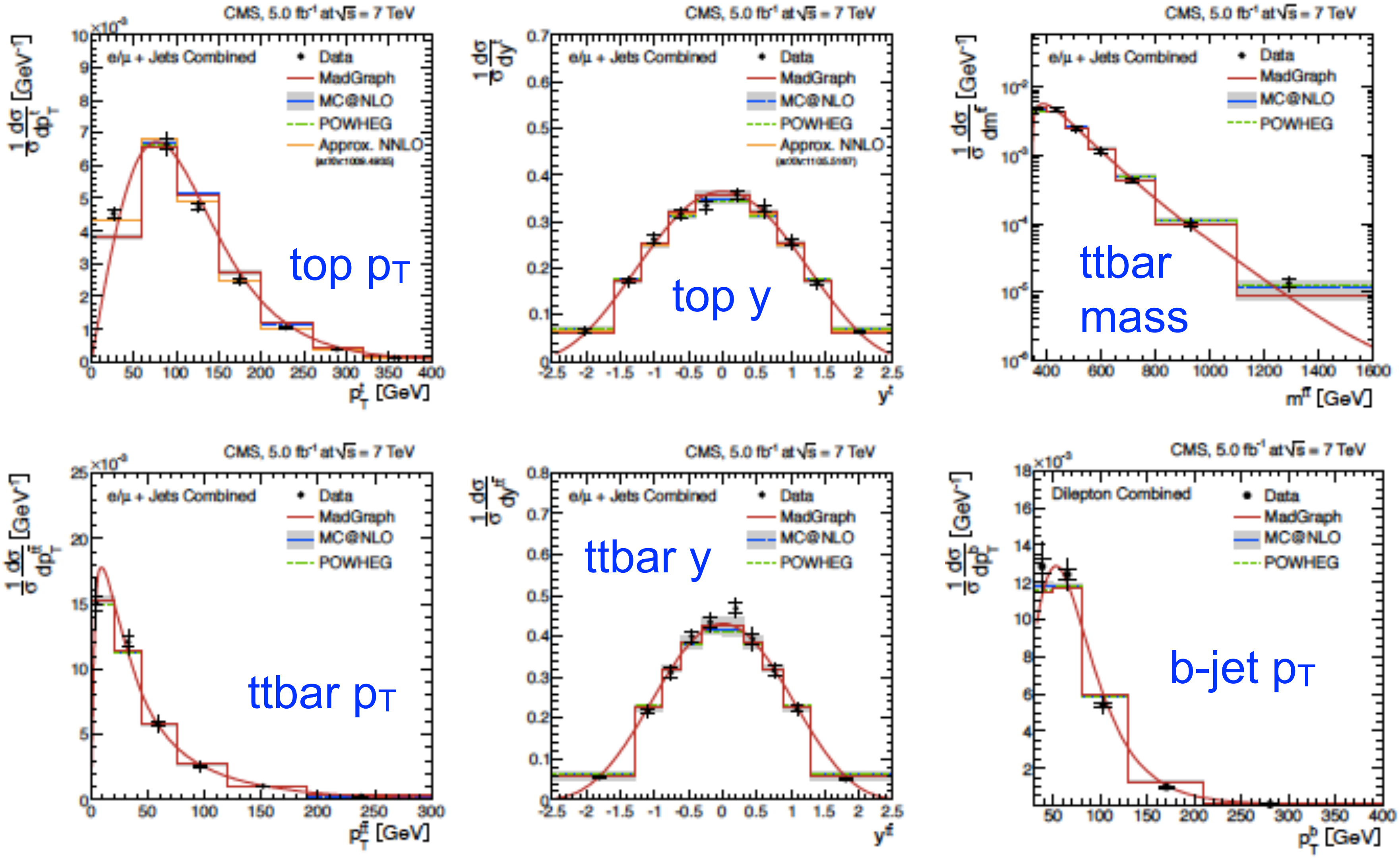
TOP-12-018



- Categorize $t\bar{t}$ MC events with N(genJets) NOT matching any top decay products in $\Delta R > 0.5 \rightarrow$ originating from additional partons
- Template fit for the 3 categories in data: 0,1,2+ additional partons
- Higher Q^2 tends to describe data better

More differential distributions at particle level

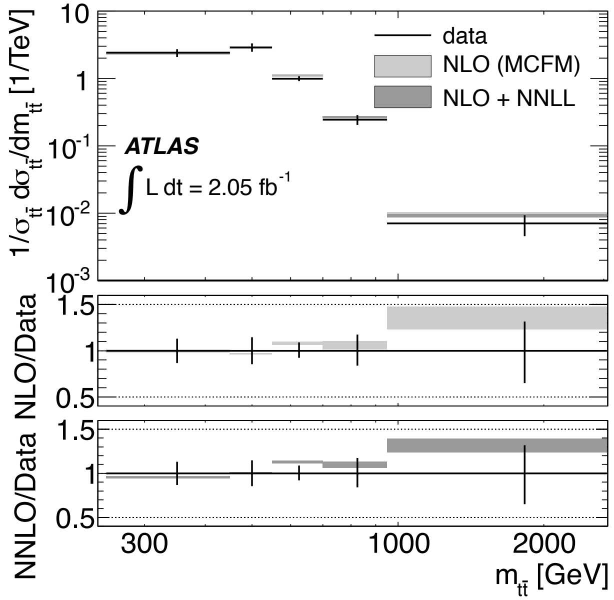
TOP-12-018

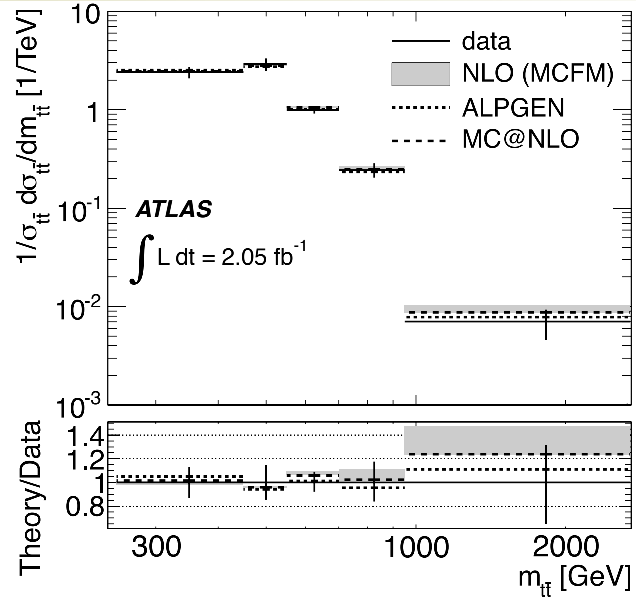


Comparisons at particle level: Alp, MC@NLO, MCFM

arXiv: 1207.5644

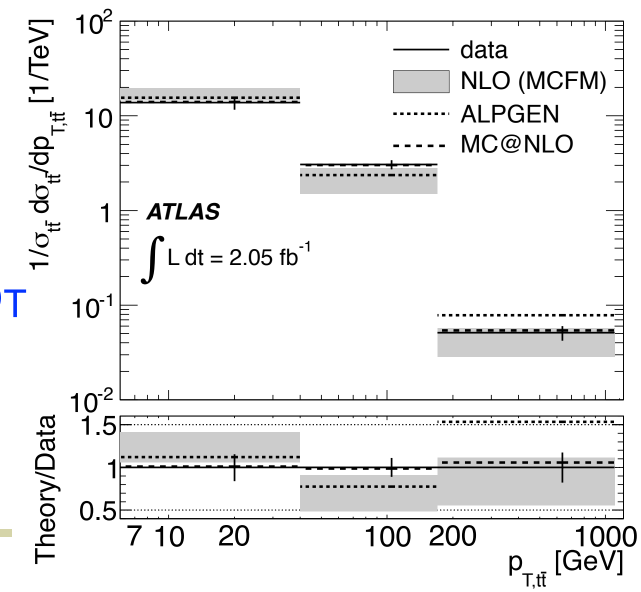
ttbar mass

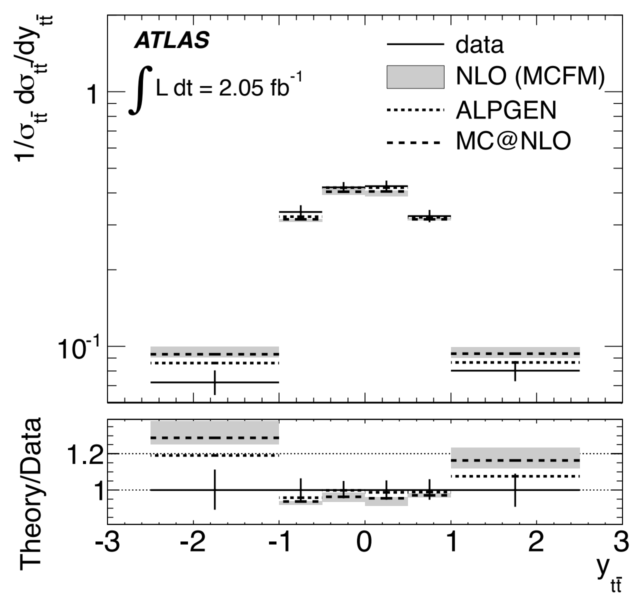




ttbar mass

ttbar p_T





ttbar rapidity

Extra jet veto

- Quantify jet activity arising from quark and gluon radiation produced with the ttbar system with a jet veto:

$$f(p_T) = \frac{N(p_T)}{N_{total}}$$

$$f(H_T) = \frac{N(H_T)}{N_{total}}$$

N_{total}: total number of selected events

$N(p_T)$: events which do not contain 1 (2) additional jet p_T above a certain threshold

Sensitive to the leading- (2nd leading-) p_T emission

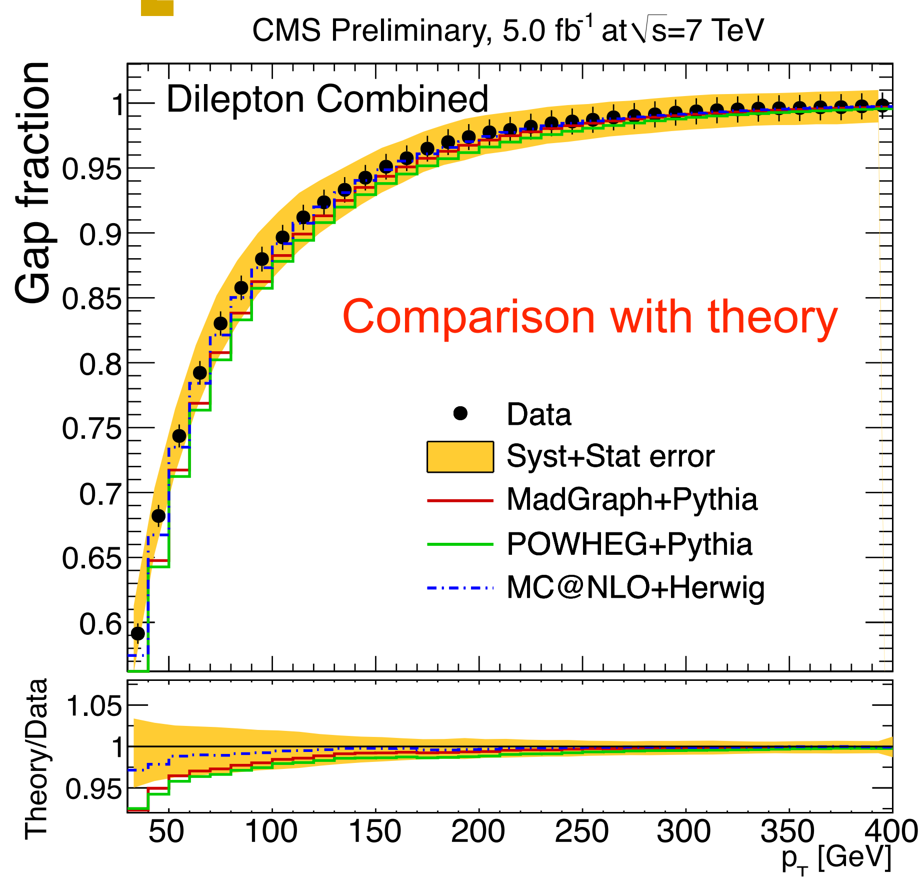
$N(H_T)$: events in which the scalar p_T sum of all additional jets is below a certain threshold

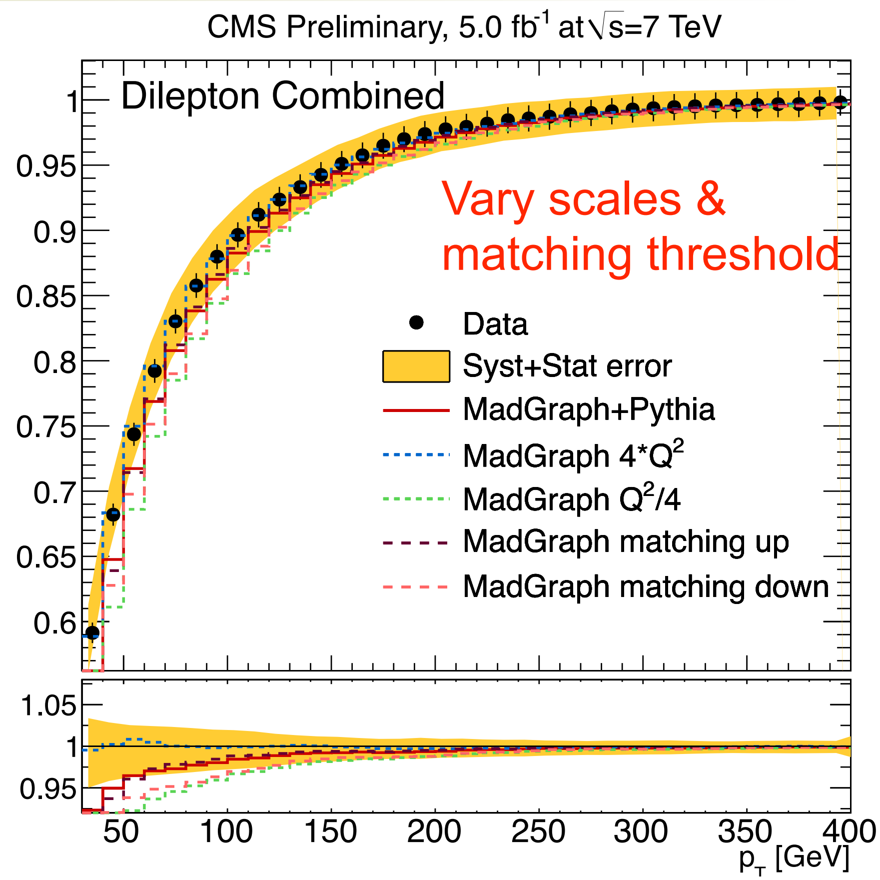
Sensitive to all hard emissions accompanying the ttbar system

- Corrected back to particle level within visible phase space
- Corrected for detector effects using MadGraph
- Compare to:
  - MadGraph+Pythia, MC@NLO+Herwig, POWHEG+Pythia
  - MadGraph with varied scales: Q^2, matching

Jet veto efficiency vs additional jet p_T

TOP-12-023



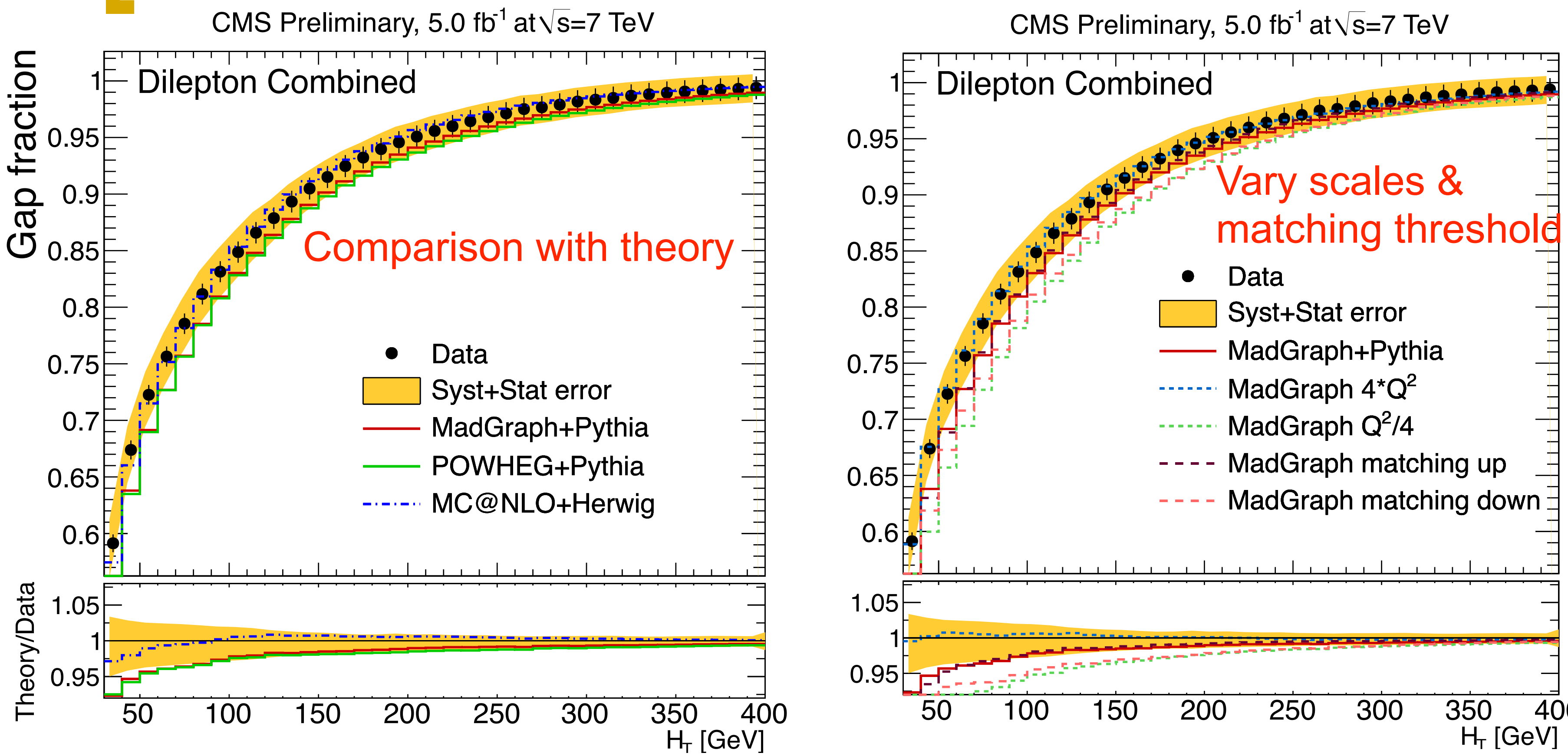


- MC@NLO+Herwig provides better description of data for 1st additional jet (shown here) but overestimates for 2nd extra jet

- Higher Q^2 describes data better
- Experimental precision better than spread spread from Q^2 variation → data can provide constraints

Jet veto efficiency vs H_T

TOP-12-023 arXiv:1203.5015

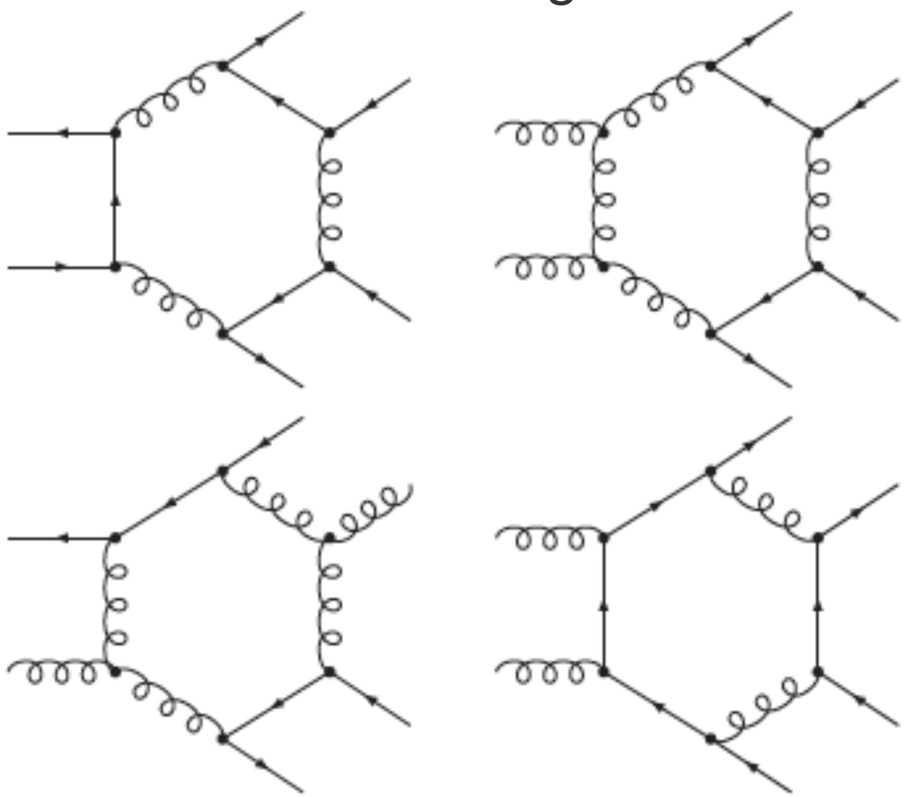


- Same conclusions as on previous slide
- With suitable choice of Q^2, Madgraph+Pythia describes data well

Curious case of $t\bar{t}+b\bar{b}$

arXiv:0905.0110, Bredenstein et al

Some NLO diagrams

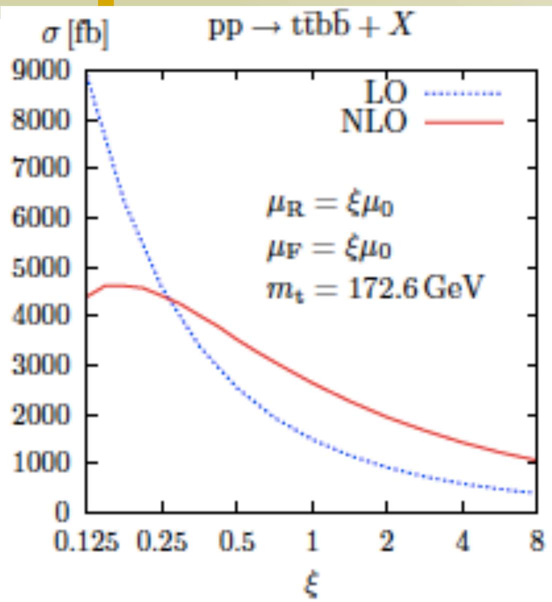


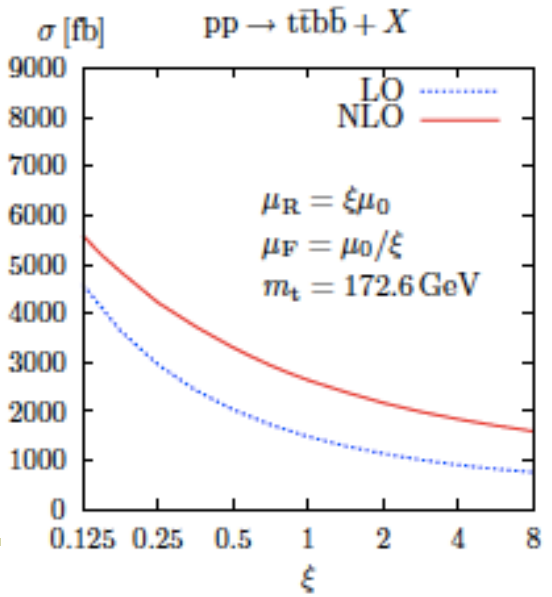
Study a generic family of factorization and renormalization scales expressed in terms of m_t and m_{bb}.

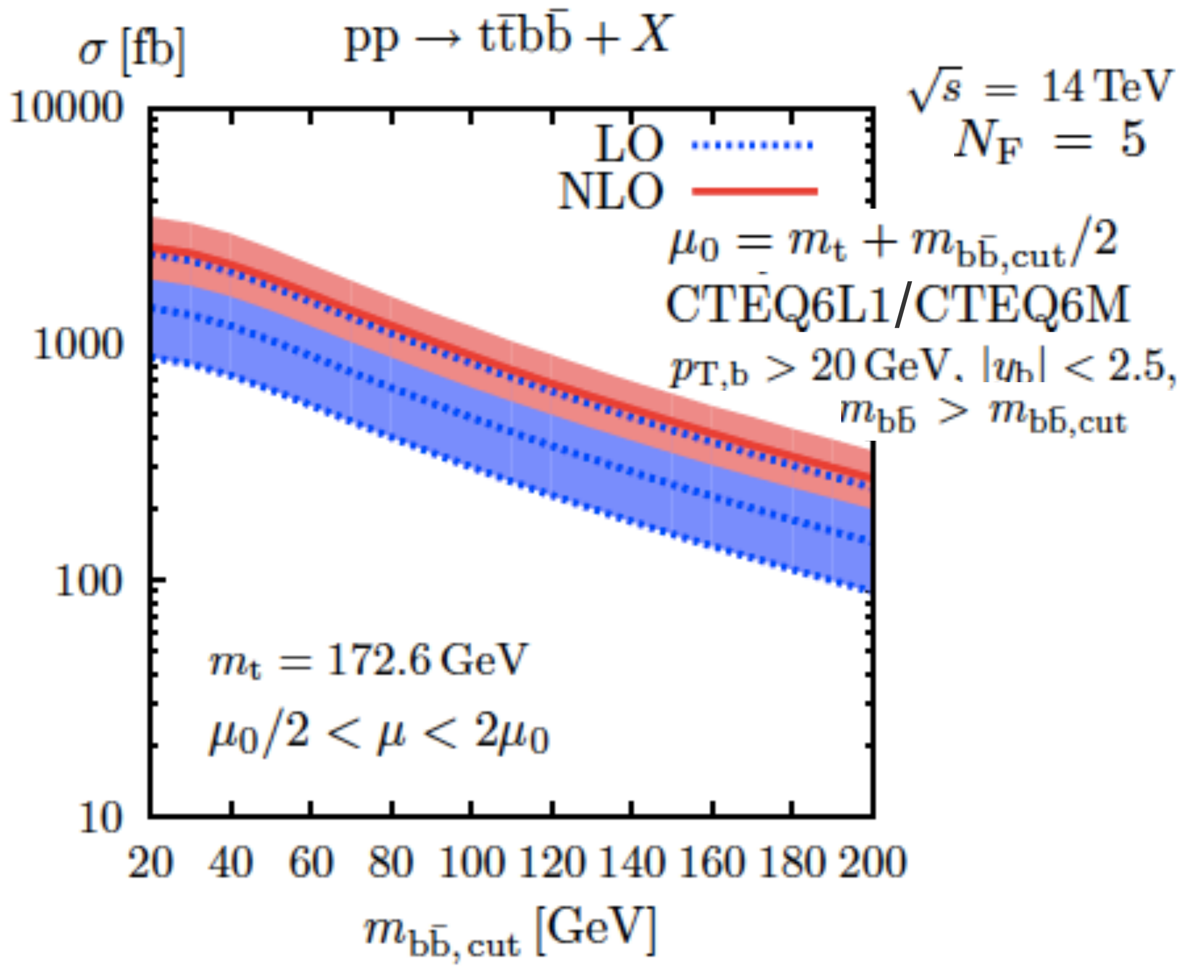
- Important bkg for ttH
- Large NLO correction
  - At the central scale, k-factor = 1.77
  - Mostly from gg diagrams
  - A veto on extra jets (p_T < 50 GeV) reduces the k-factor to 1.2
- Varying the scale up or down by a factor 2 changes the cross section by 70% in LO and by 34% in NLO.

$t\bar{t}+b\bar{b}$: scale dependence

arXiv:0905.0110



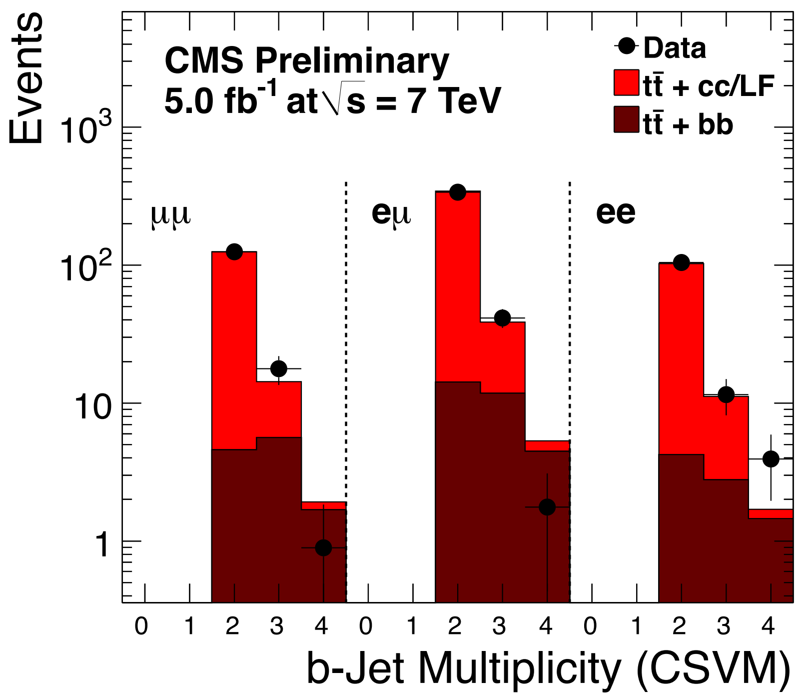


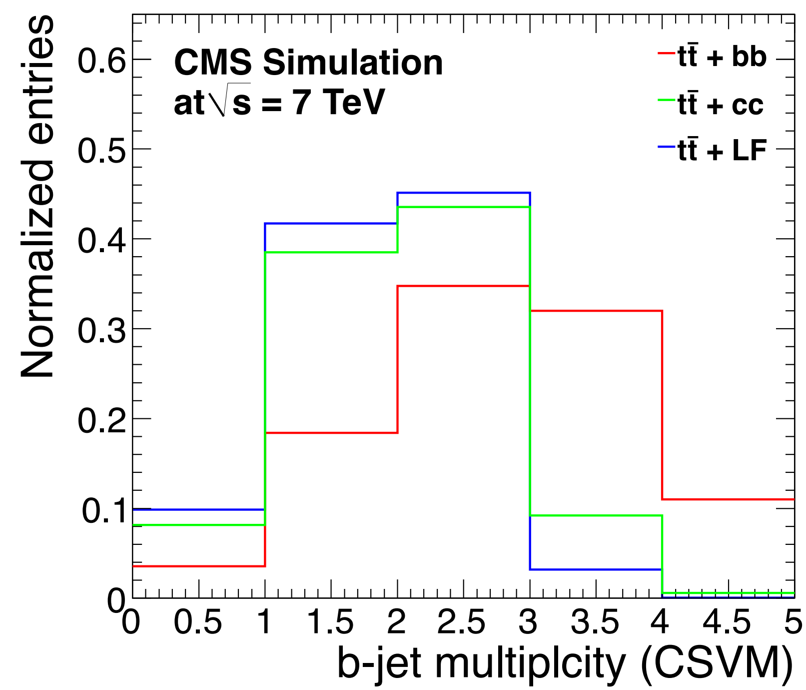


What the data are telling us ?

TOP-12-024

- ttbb and ttjj modeled using the Madgraph
  - -up to 4 additional partons including b quarks, jet p_T > 30 GeV
- Factorization and renormalization scales as on the previous slide
  - -uncertainty estimated by varying μ by factors of 2 up/down





What the data are telling us ?

TOP-12-024

#1. That the default scale choice provides a good modeling of data within the uncertainties

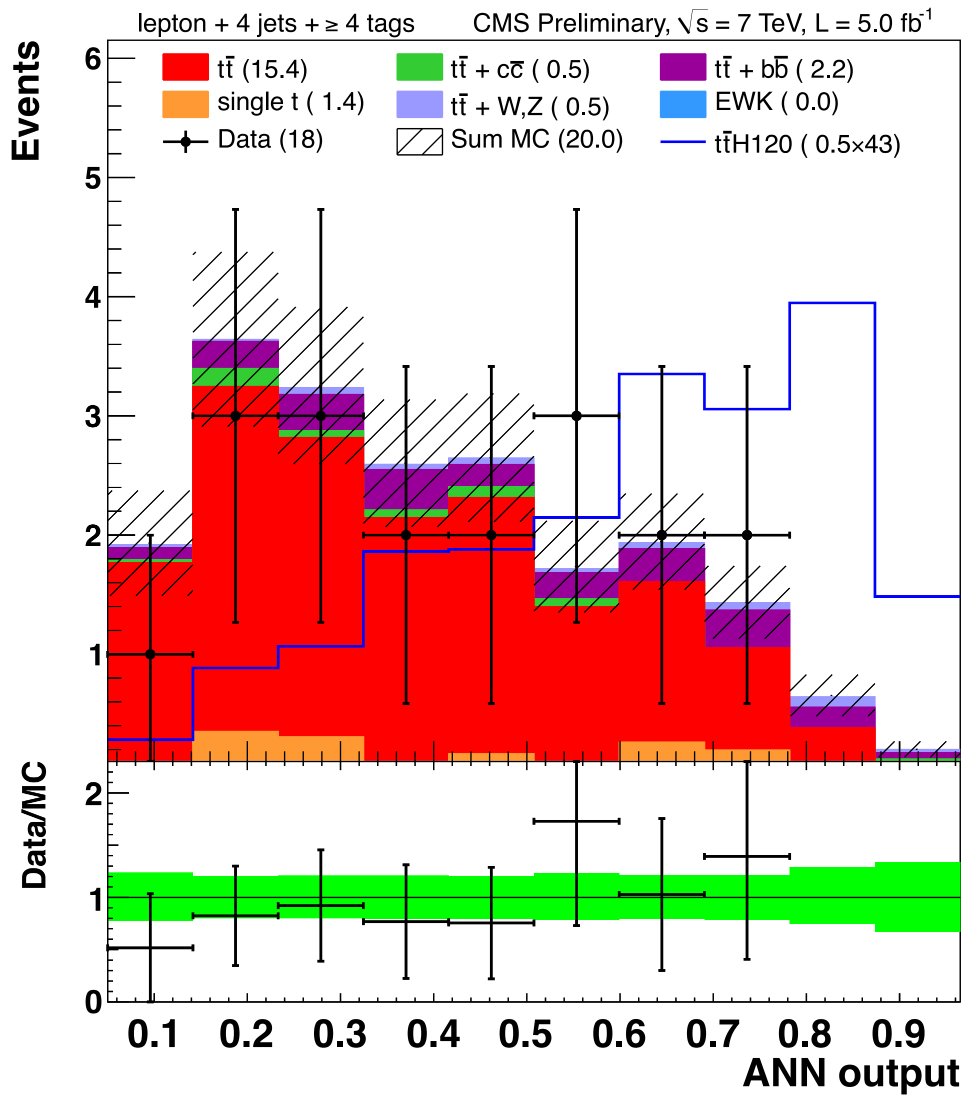
#2.

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 3.6 \pm 1.1(\text{stat.}) \pm 0.9(\text{syst.})\%$$

Source	$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ (%) (CSVM)	$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ (%) (CSVT)
Pile-up	0.5	0.5
JES	3.0	2.0
b-tag (heavy flavor)	6.0	4.0
b-tag (light flavor)	+23 -19	+18 -15
MC gen.	3.0	3.0
Q^2 scale	6.0	6.0
Total uncertainty	+25 -21	+20 -17

Experimental uncertainty (flavor tagging) is much larger than the scale uncertainty. Need better experimental precision to constrain the latter.

Example of scale uncertainty in signal extraction



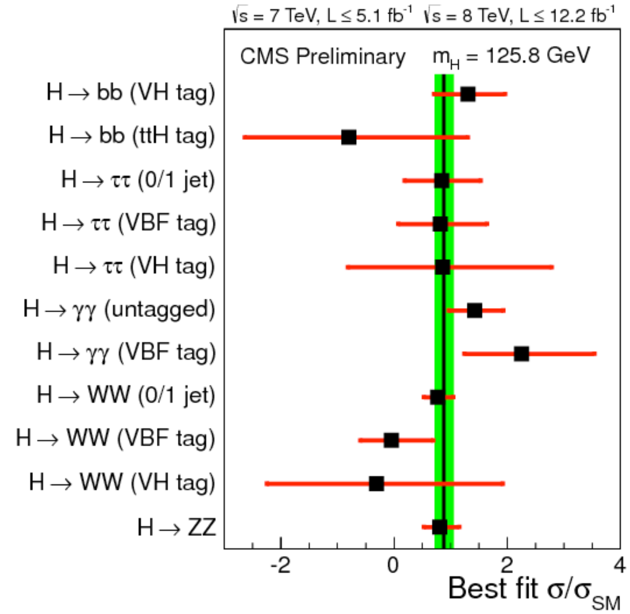
HIG-12-025

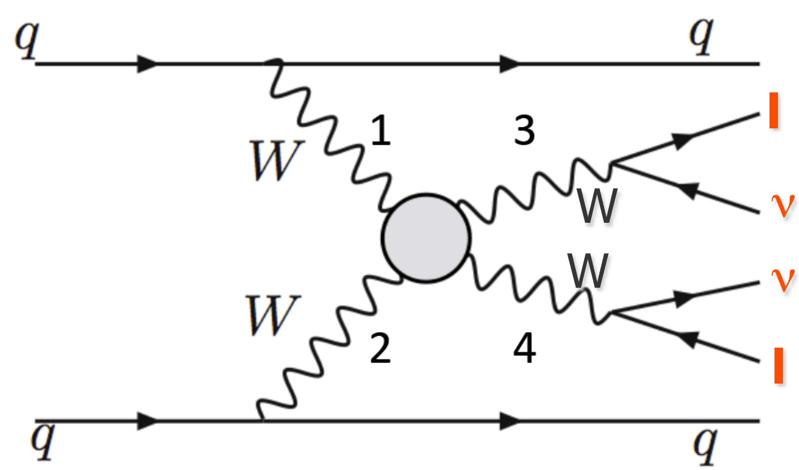
- Distribution of MVA output in events containing lepton + MET + 4 b-jets
- MC uncertainty includes scale uncertainty (μ varied up/down by a factor 2) and uncertainty from exclusive jet binning

Diboson and Higgs

WW+jets as background to Higgs

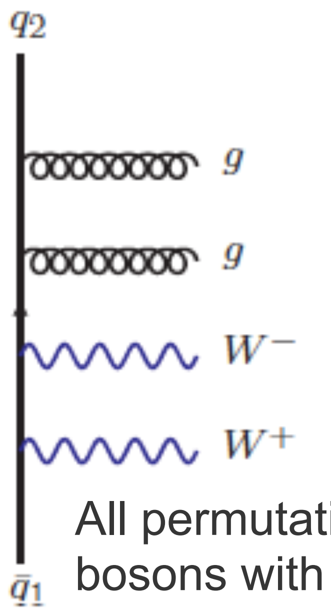
- Higgs signal sorted into 0,1,2+ jet bins
  - → allows identification of backgrounds in each bin
  - →30% of Higgs created with one jet, ~15% with ≥2 jets
- H (→ WW)jj created through vector boson fusion (VBF) as well as gluon fusion (GF)
  - → VBF has characteristic forward jets
  - → WW (+ jets) is irreducible background to both
- GF contamination in VBF sample is pretty high, at 10-40% level





WWjj @LO: two distinct strong production processes

Two quark, two gluon processes:

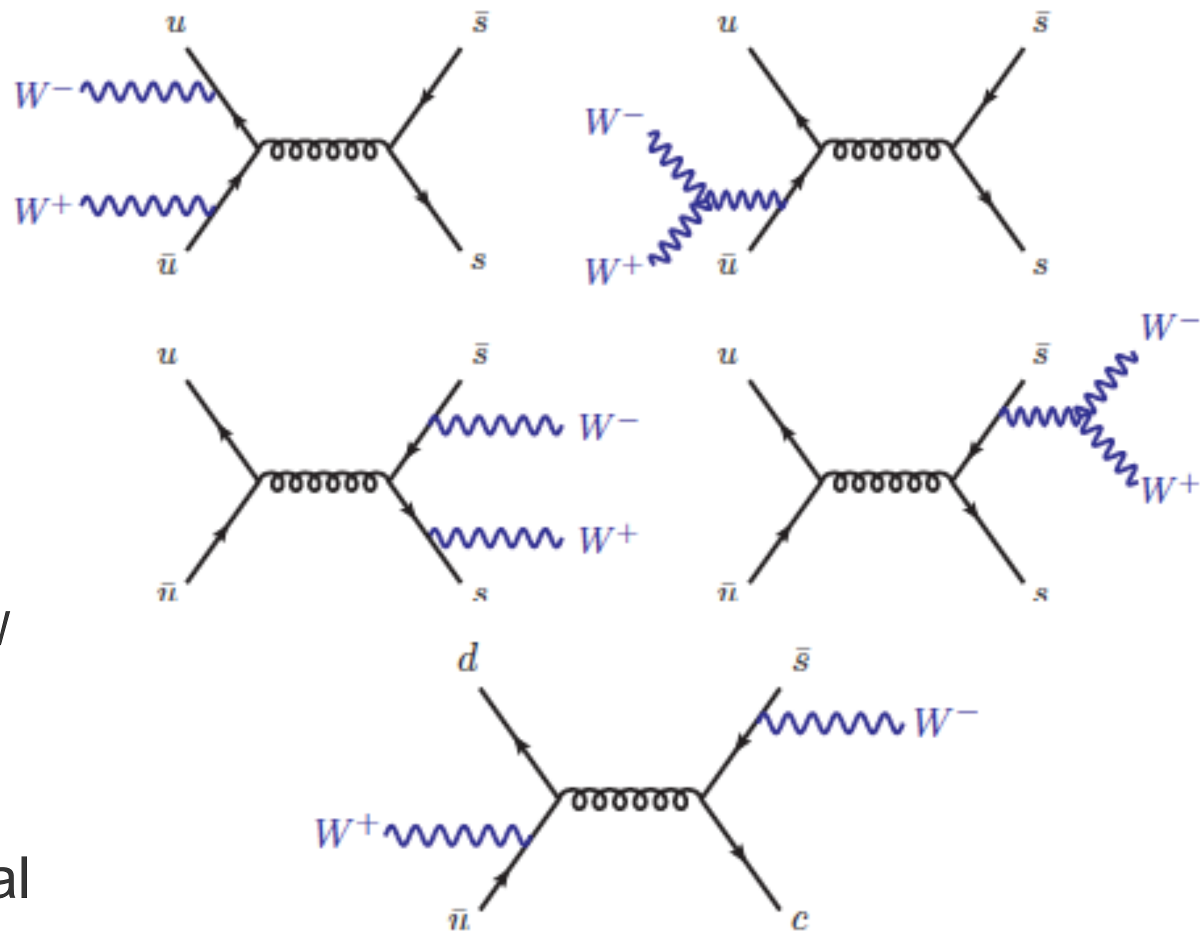


All permutations of W bosons with gluons

For detail see Melia et al

arXiv:1104.2327
arXiv:1205.6987

Four quark processes:

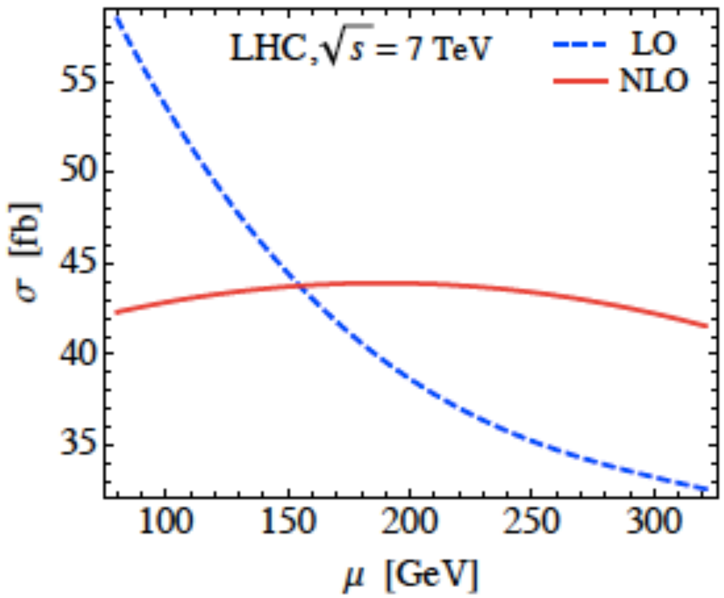


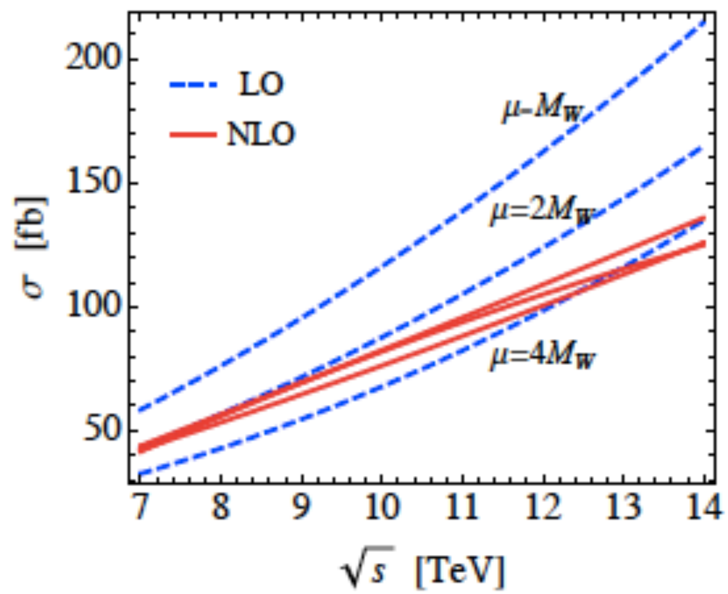
Also t-channel contributions → Complicated flavor structure

Large dependence on fact./renorm. scale

$$\mu_F = \mu_R = \mu$$

arXiv:1104.2327



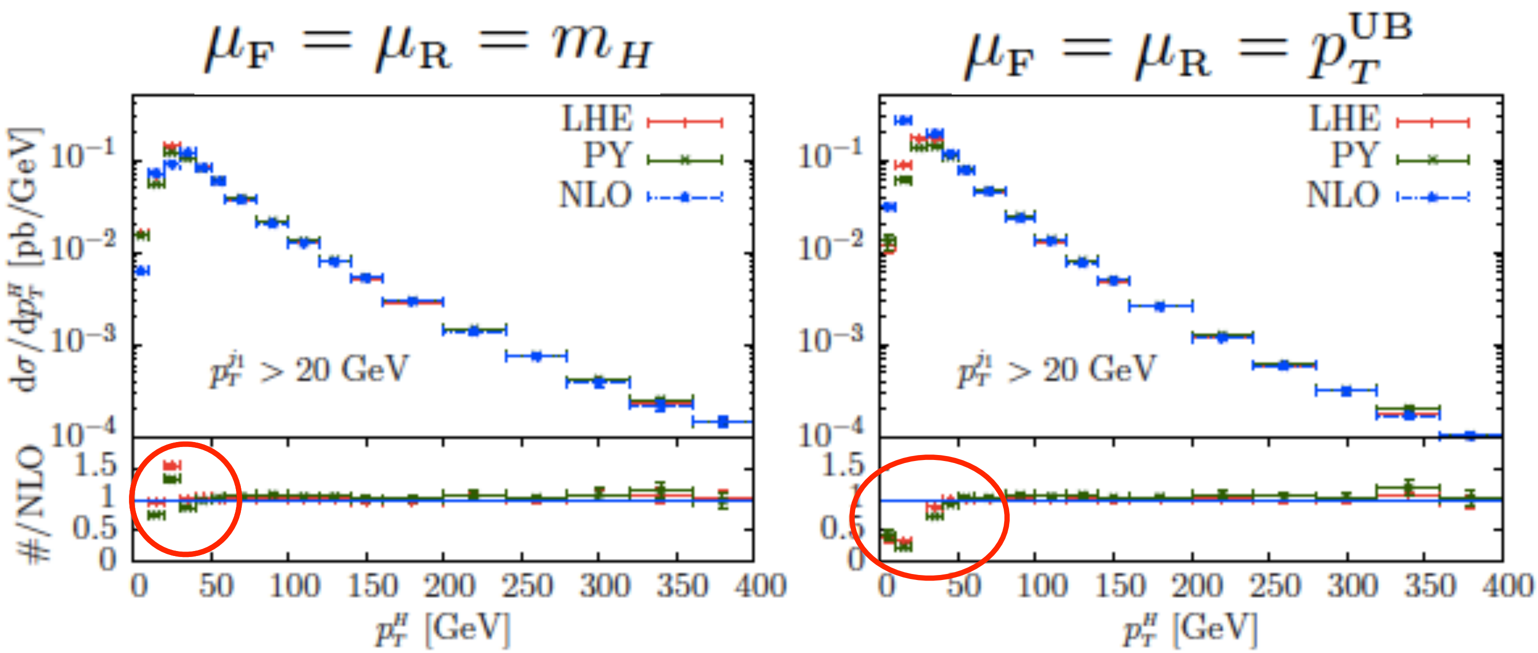


- σ_{LO} = 46 ± 13 fb, σ_{NLO} = 42 ± 1 fb
- "Optimal" factorization/renormalization scale: $2m_W$ at $\sqrt{s}$ = 7 TeV, $4m_W$ at $\sqrt{s}$=14TeV
- Uncertainty reduced at NLO by order of magnitude

Scale dependence in gg→H+jj production

arXiv:1202.5475
(Campbell, Ellis et al)

An irreducible background for VBF Higgs



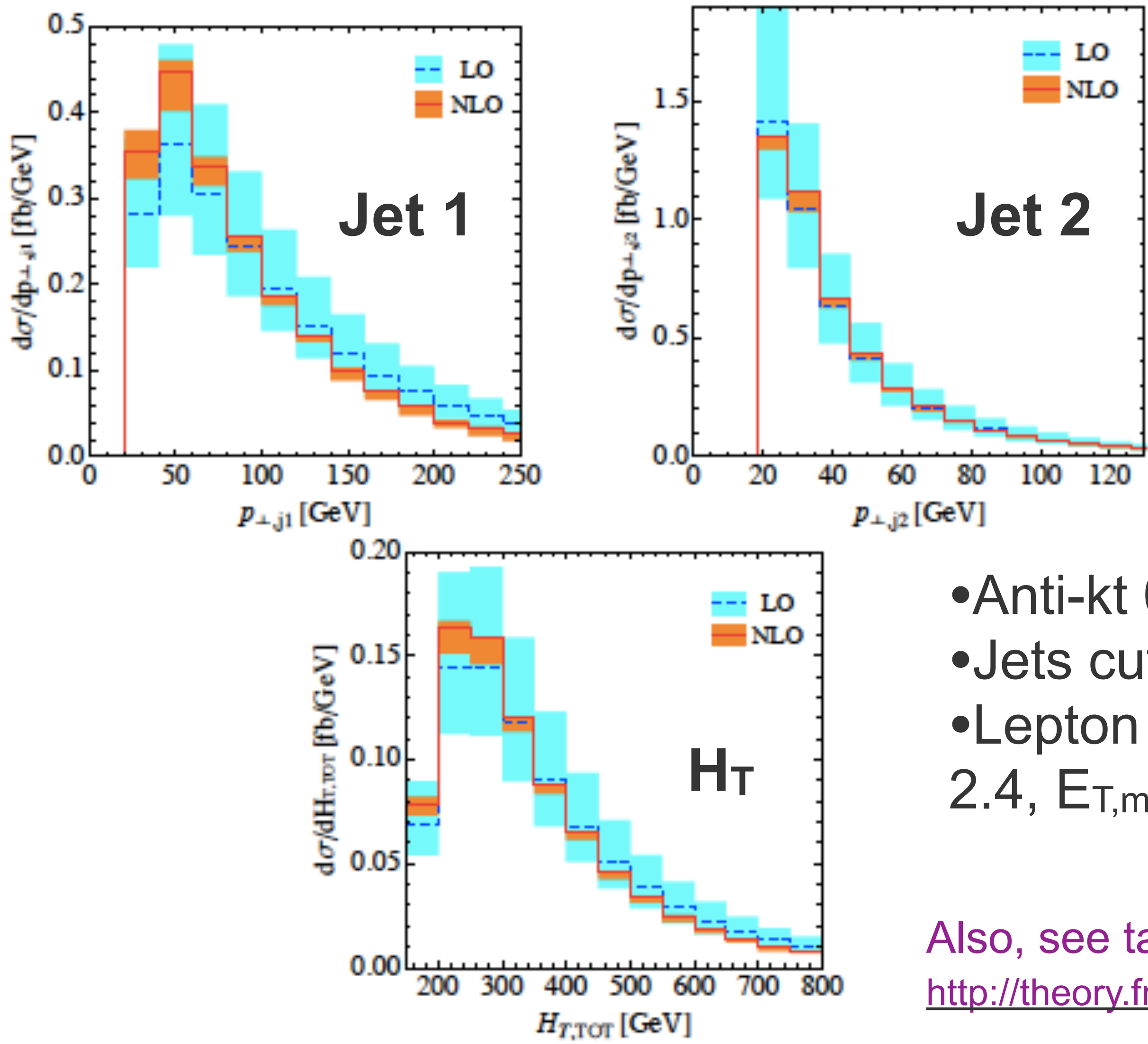
LHE = Powheg Box

PY = Powheg +Pythia

NLO = full NLO MCFM

Scale dependence significant only for low p_T H

Large LO-NLO difference in shape



arXiv:1104.2327

NLO greatly reduces the scale uncertainty

Event selection

- Anti-kt 0.4 jets
- Jets cuts: p_T > 30 GeV, |η| < 3.2
- Lepton cuts: p_T > 20 GeV, |η| < 2.4, $E_{T,miss}$ > 30 GeV

Also, see talk by Raoul Röntsch at FNAL
http://theory.fnal.gov/seminars/seminars2013.html

What the are data telling us: WWjj yield

HIG-12-042

Both W's decay leptonically

17 /fb

m_H	H $\to W^+W^-$	pp $\to W^+W^-$	WZ+ZZ +$Z/\gamma^* \to \ell^+\ell^-$	Top	W + jets	$W\gamma^{(*)}$	all bkg.	data
2-jet category $e\mu$ final state								
120	1.7 ± 0.2	0.8 ± 0.5	0.1 ± 0.0	0.9 ± 0.3	0.3 ± 0.2	0.1 ± 0.1	2.2 ± 0.6	2
125	2.8 ± 0.4	0.9 ± 0.5	0.1 ± 0.0	1.5 ± 0.5	0.3 ± 0.2	0.1 ± 0.1	2.9 ± 0.8	2
130	4.4 ± 0.6	1.3 ± 0.7	0.1 ± 0.0	1.6 ± 0.5	0.3 ± 0.2	0.1 ± 0.1	3.4 ± 0.9	4
160	11.7 ± 1.5	1.2 ± 0.6	0.0 ± 0.0	1.5 ± 0.5	0.0 ± 0.0	0.1 ± 0.1	2.9 ± 0.8	4
200	9.3 ± 1.2	2.5 ± 1.2	1.7 ± 1.6	4.6 ± 1.3	0.3 ± 0.4	0.0 ± 0.0	9.1 ± 2.4	8
400	3.9 ± 0.5	3.5 ± 2.2	1.7 ± 1.6	4.6 ± 1.3	0.0 ± 0.0	0.0 ± 0.0	9.8 ± 3.0	7
600	1.4 ± 0.2	1.6 ± 1.0	0.0 ± 0.0	1.9 ± 0.8	0.3 ± 0.2	0.0 ± 0.0	3.7 ± 1.3	3
2-jet category $ee/\mu\mu$ final state								
120	1.0 ± 0.1	0.5 ± 0.3	3.2 ± 1.5	0.7 ± 0.2	0.8 ± 0.5	0.1 ± 0.1	5.2 ± 1.7	9
125	1.5 ± 0.2	0.5 ± 0.3	4.4 ± 1.3	0.7 ± 0.2	0.8 ± 0.5	0.1 ± 0.1	6.5 ± 1.5	11
130	2.3 ± 0.3	0.5 ± 0.3	4.8 ± 1.6	0.8 ± 0.2	0.8 ± 0.5	0.1 ± 0.1	7.0 ± 1.7	11
160	7.4 ± 1.0	0.5 ± 0.3	3.8 ± 3.8	0.9 ± 0.3	0.1 ± 0.1	0.0 ± 0.0	5.2 ± 3.8	5
200	4.9 ± 0.6	1.5 ± 0.7	4.4 ± 3.0	2.0 ± 0.5	0.5 ± 0.4	0.0 ± 0.0	8.3 ± 3.2	9
400	2.7 ± 0.4	1.4 ± 0.9	0.1 ± 0.0	3.6 ± 1.1	0.2 ± 0.4	0.0 ± 0.0	5.3 ± 1.4	8
600	1.1 ± 0.1	0.5 ± 0.4	0.0 ± 0.0	1.4 ± 0.6	0.1 ± 0.1	0.0 ± 0.0	2.0 ± 0.7	2

Require $\Delta\eta(j,j) > 3.5$, $m(j,j) > 500$ GeV, pT (j) > 30 GeV

... Well, not much beyond a rough agreement. Need more data !!!

Extra jet veto systematics: an important example

$\sqrt{s}$ = 8 TeV, L = 3.5 fb^{-1}

Channel	$2\ell'2\nu$
W^+W^-	684 ± 50
$t\bar{t}$ and tW	132 ± 23
W+ jets	60 ± 22
WZ and ZZ	27 ± 3
Z/γ^*+jets	43 ± 12
$W\gamma^{(*)}$	14 ± 5
Total background	275 ± 35
Signal + background	959 ± 60
Data	1111

Main systematics:

Jet veto (+PDF) 4.6%

Luminosity 4.4%

arXiv:1301.4698

WW→2l2v cross section at 8 TeV (CMS)

Signal extracted in 0-jet bin. Cross section extrapolated to full phase space.

σ = 69.9 ± 2.8 (stat) ± 5.6 (sys) ± 3.1 (lum) pb

NLO prediction (MCFM): 57.3 ± 2.4 pb

1.8σ above NLO prediction

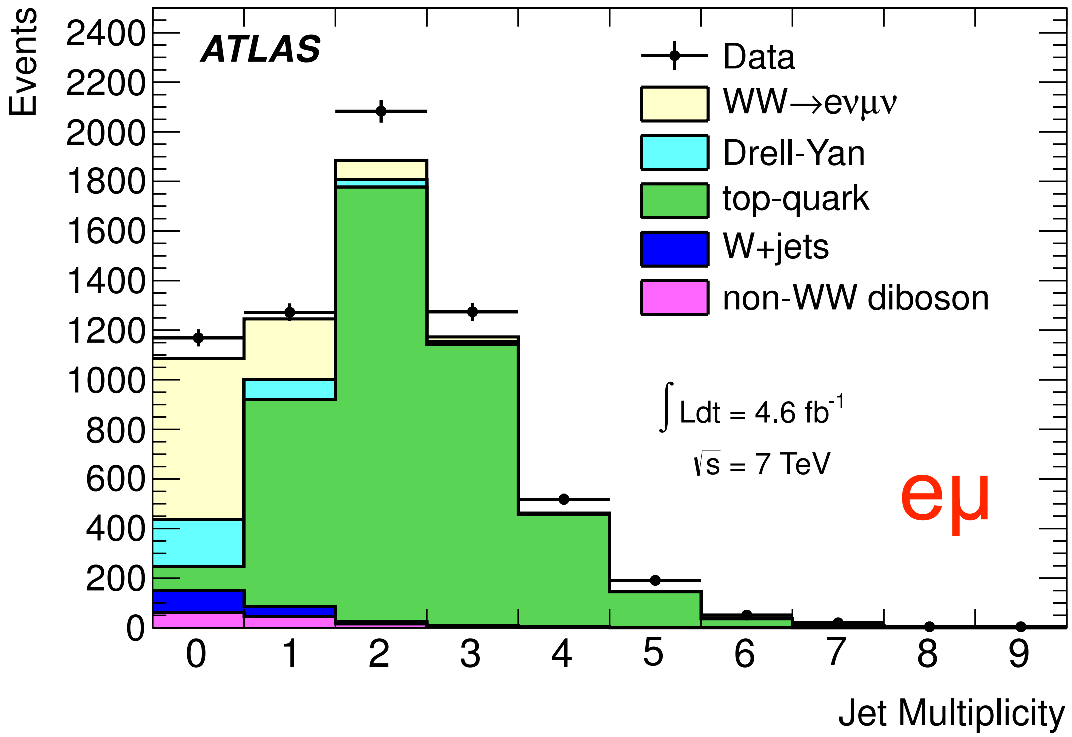
Could be a conspiracy of syst bias & upward fluctuation, but has generated some buzz ...

Charginos Hiding In Plain Sight

David Curtin,[1] Prerit Jaiswal,[1,2] and Patrick Meade[1]

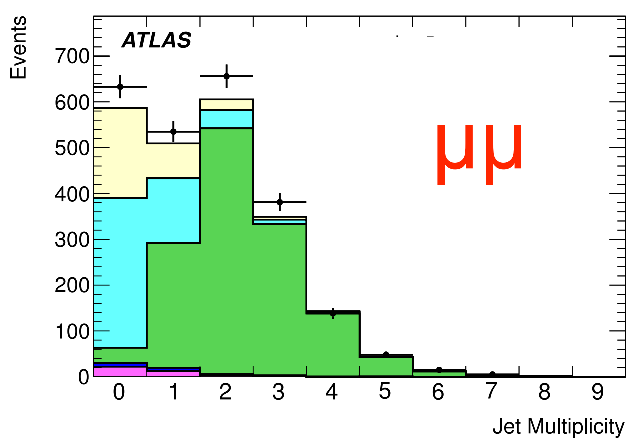
arXiv:1206.6888v2

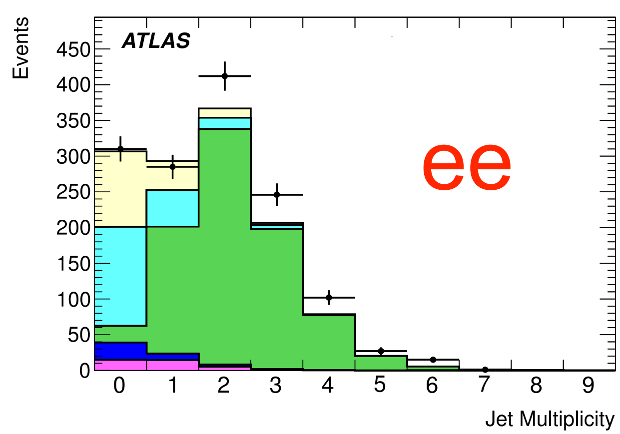
Extra jet veto efficiency



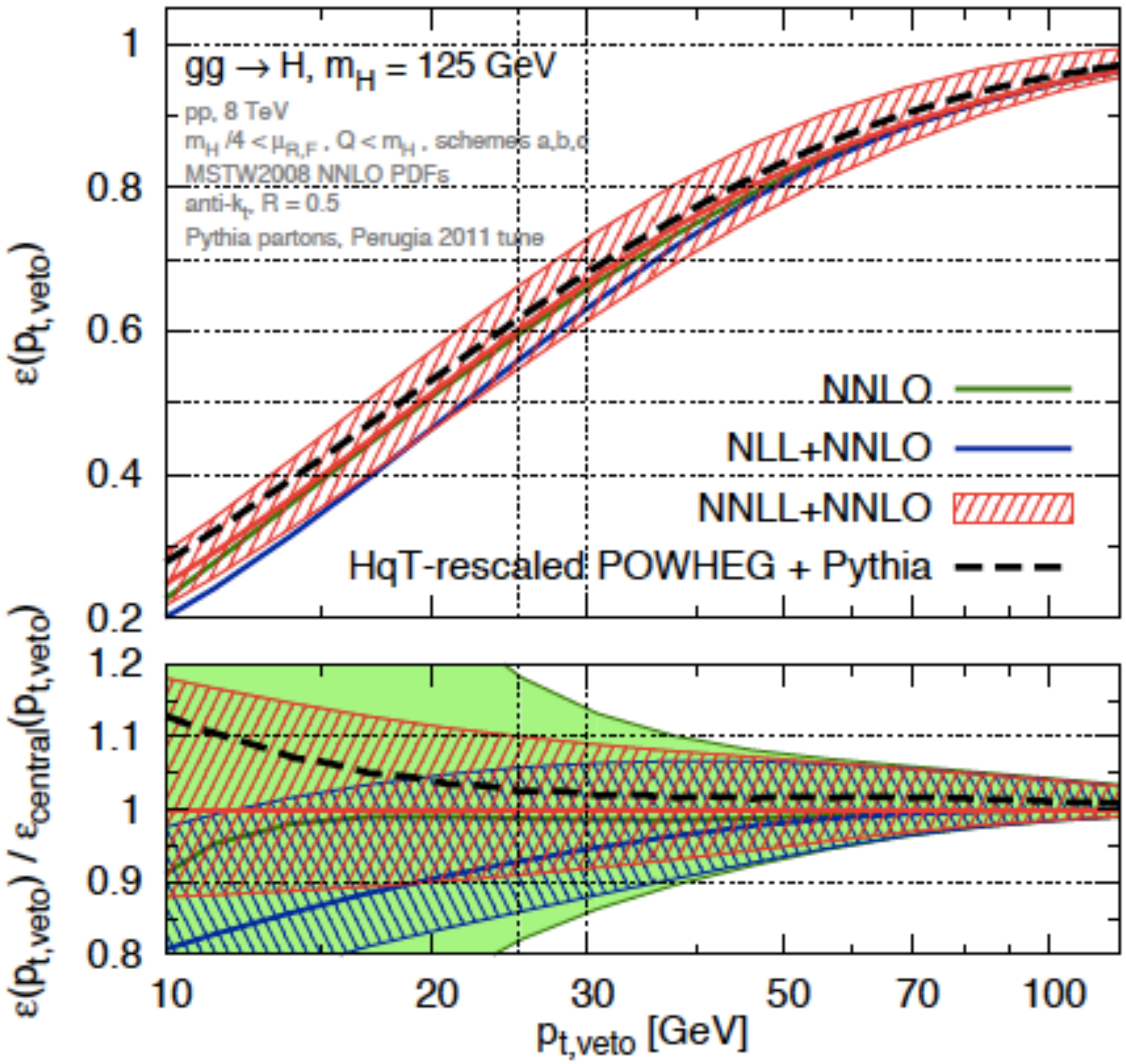
arXiv:1210.2979

- Experimentally jet veto necessary given the S/B
  - But currently cause large syst uncertainty
- In case of WW production, signal acceptance is small in 2-jet bin and tiny in ≥2 jet bin
  - But tt+jets is overwhelming





Extra jet veto efficiency: NNLO resummation



arXiv:1206.4998
(Banfi, Monni, Salam, Zanderighi)
http://jetvheto.hepforge.org/

- Experimentally jet veto necessary given the S/B
  - -But currently cause large syst uncertainty
- NNLL resummation reduces jet-veto efficiency by ~30%
- New proposal for 0,1-jet correlation matrix (efficiency & σ_{tot} uncorr.)

Also, see talk by Matthias Neubert at SUSY 2012

Summary

- Study scale dependence in several abundant SM processes
  - In the framework of MG/Alp/Sherpa/MC@NLO + PS
  - Scale & threshold variations have significant effect on kinematic distributions for high N_{jets} and tails
  - Data are providing important constraints in some cases

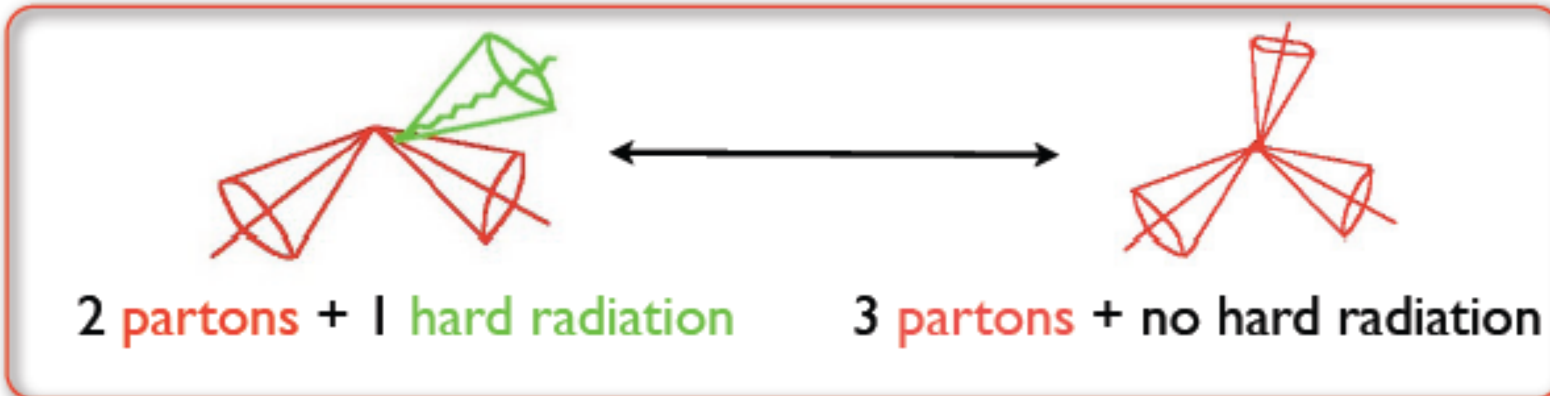
- WW+jets and H+jj show large dependence on the choice of factorization/renormalization scale
  - Not enough data to constrain in a meaningful way

- Jet veto efficiency a significant syst in many measurements
  - Theoretical tools becoming available to reduce it
  - Also exploring data control samples to control this systematics

BACKUP SLIDES

Introduction: matrix element + parton shower

Example: X + 3 partons vs X + 2 partons

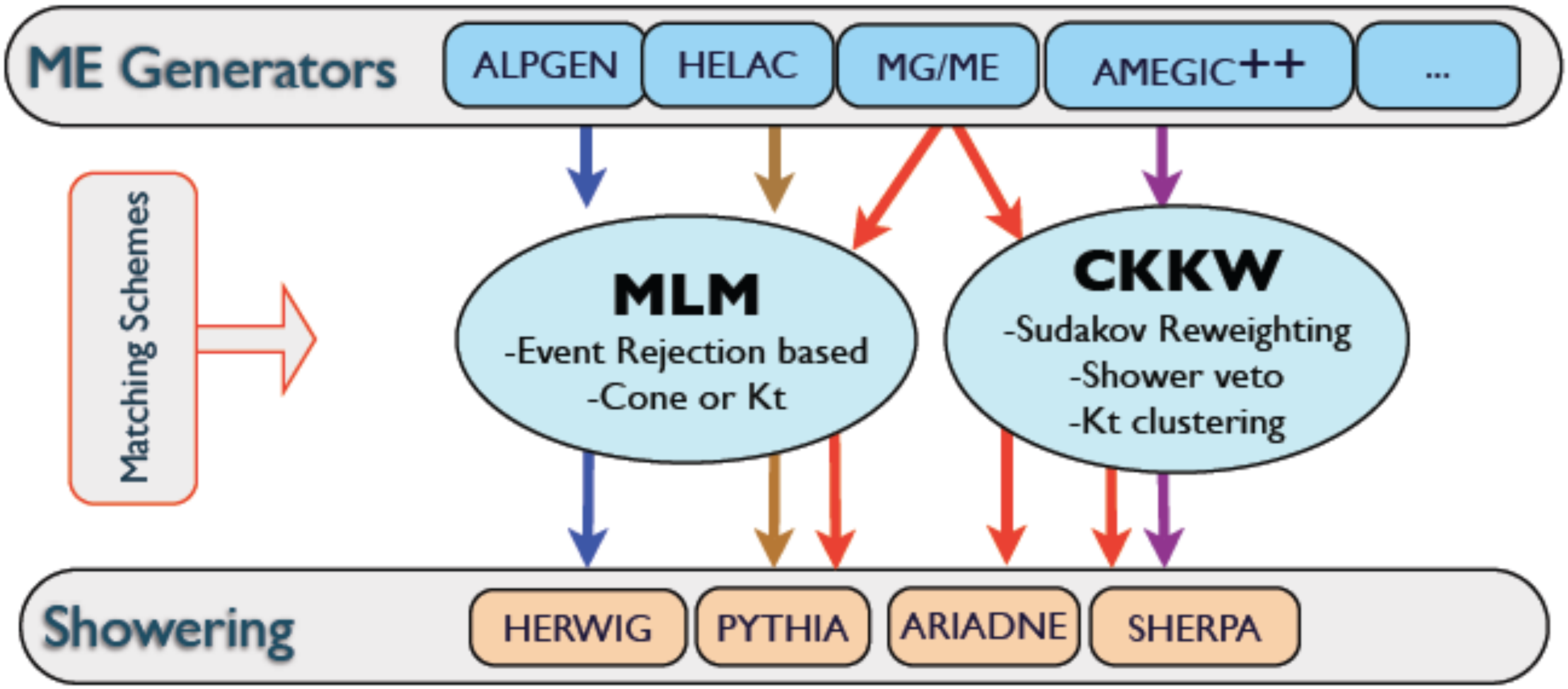


ME and PS overlap

⇨ If you add all multiplicities: wrong cross-section.

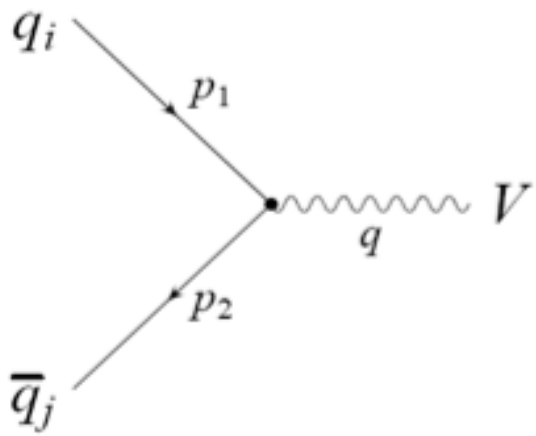
What is available on the market?

https://cp3.irmp.ucl.ac.be/projects/madgraph/attachment/wiki/MGTalks/



Introducing the problem

But let's start with something simple:
vector boson production at Leading Order



$$V = \gamma^*, W^\pm, Z$$

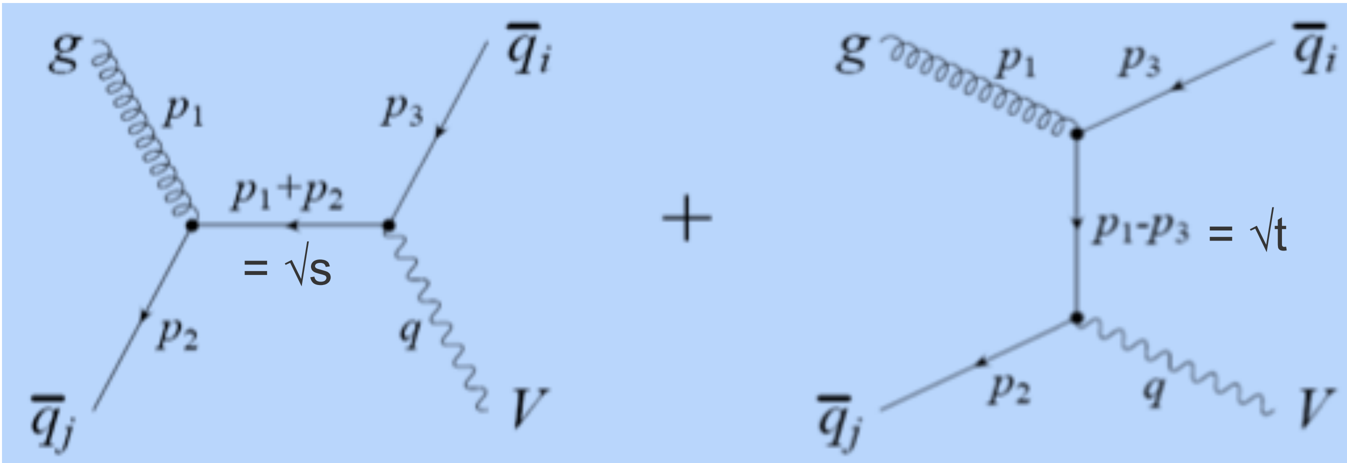
$$q^2 = Q^2$$

$$\sigma^{(0)}_{q\bar{q}} = \frac{4\pi^2\alpha}{3S} \sum_{i,j} C_{ij} \int_{z_0}^{1} dz \, (q_{0i} \otimes \bar{q}_{0j} + \bar{q}_{0j} \otimes q_{0i}) \left(\frac{z_0}{z}\right) \delta(1-z)$$

where $\sqrt{S}$ is the hadronic cm energy, $z_0 = Q^2/S$, and C_{ij} specifies EW couplings.

Factorization scale

W/Z + jets production at LHC at LO from qg initial state



Collinear singularity due to gluon splitting at $(p_1-p_3)^2 = 0$

$$\sigma^{(1)}_{g\bar{q}} = \frac{\pi\alpha\alpha_s}{3S}\sum_{i,j} C_{ij}\int_{Q^2}^{S}\frac{ds}{s^2}\left(g\otimes\bar{q}_j + \bar{q}_j\otimes g\right)\left(\frac{s}{S}\right)$$

$$\times\int_{-\infty}^{0} dt\int_{-\infty}^{0} du\,\delta(s+t+u-Q^2)\left[\frac{s}{-t}+\frac{-t}{s}-\frac{2uQ^2}{st}\right]$$

Solution: integrate the leading behavior 1/t from 0 to $-\mu^2$.

$d\sigma^{(1)}_{g\bar{q}}/dt \sim 1/t$ as $t \to 0$: a collinear divergence

Why it matters?

- The hadronic cross section σ, calculated to **all** orders in perturbative QCD, is independent of μ
  - BUT fixed-order results depend on μ

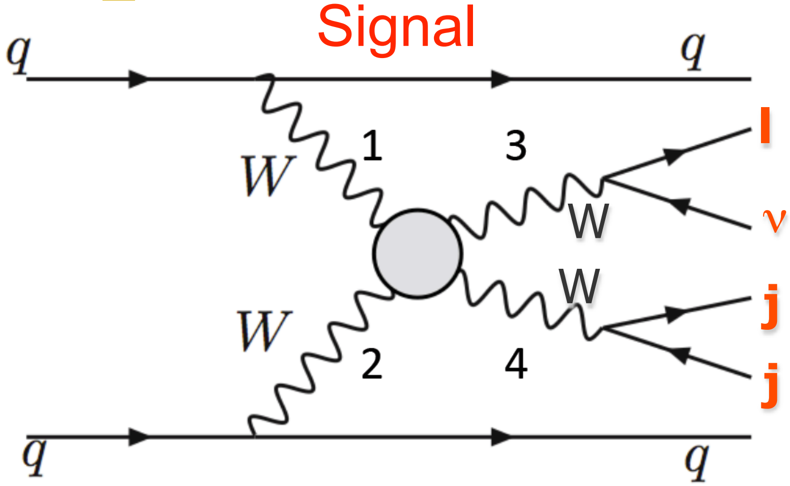
- This dependence is often significant at LO and NLO, and is reduced at higher orders

- When higher-order calculations are not available, we are left with a theoretical prediction that depends strongly on μ
  - true for most dominant processes at the LHC: multi-jet, γ/W/Z + jets, tt, ...
  - large error on μ, sometimes many ambiguous choices

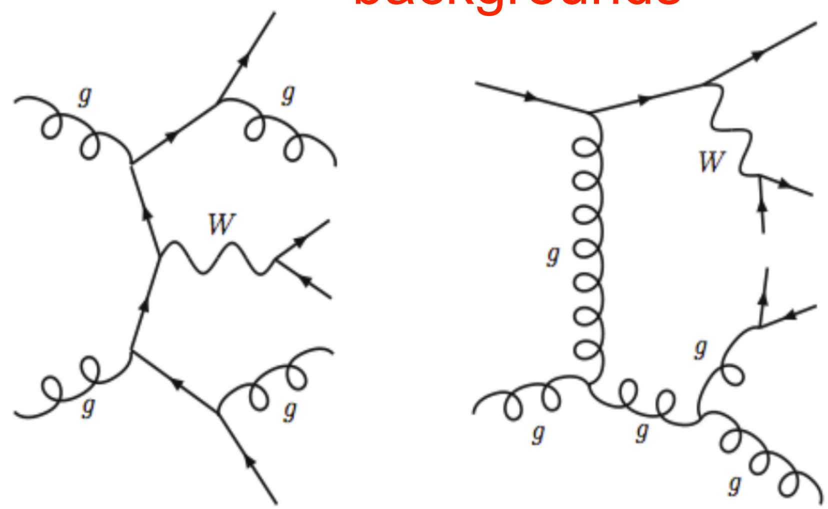
- Causes significant uncertainty in background estimation for signal events of interest, new physics searches

Semileptonic: also have to deal with W+4j & ttbar

Signal



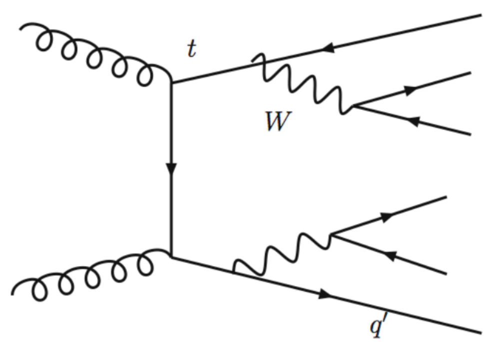
backgrounds

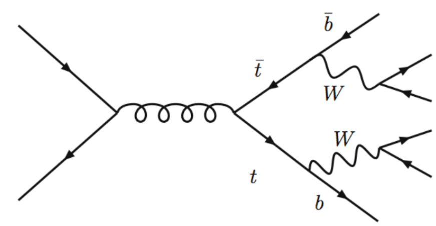


W+2jets+2tag jets: ~10 pb

WW+2tag jets: ~0.1 pb (for semileptonic WW)

- Δη between tag jets > 4
- Invariant mass > 600 GeV





$t\bar{t}$ with 2 tag jets: ~10 pb

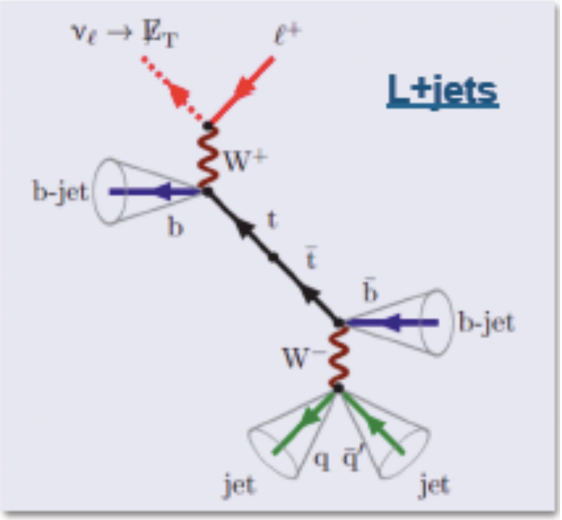
This is weird corner of phase space for both backgrounds. Need good modeling of angular distributions, jet veto.

TTbar event selection

Lepton+jets:

- Exactly 1 isolated high-p_T lepton (μ or e)
  - μ, e: $p_T > 30$ GeV, $|\eta| < 2.1$ (also $|\eta| < 2.5$ for e)
- Veto additional leptons
- Analysis-dependent jet selection (≥ 3 jets, $p_T > 30$ GeV, $|\eta| < 2.4$)
- ≥ 2 b-tagged jets

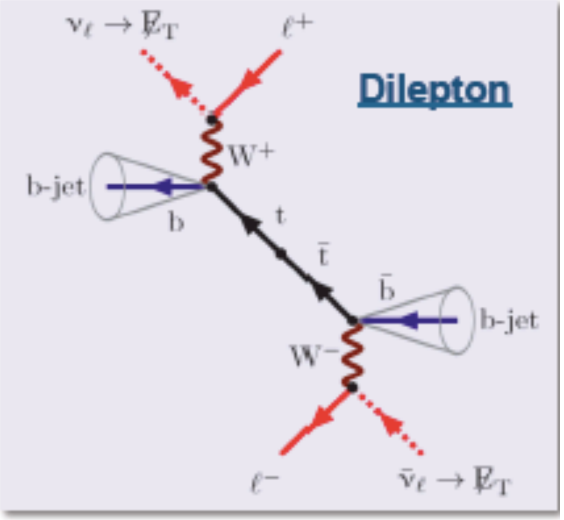
(Kinematic reconstruction of the ttbar system)



Dileptons:

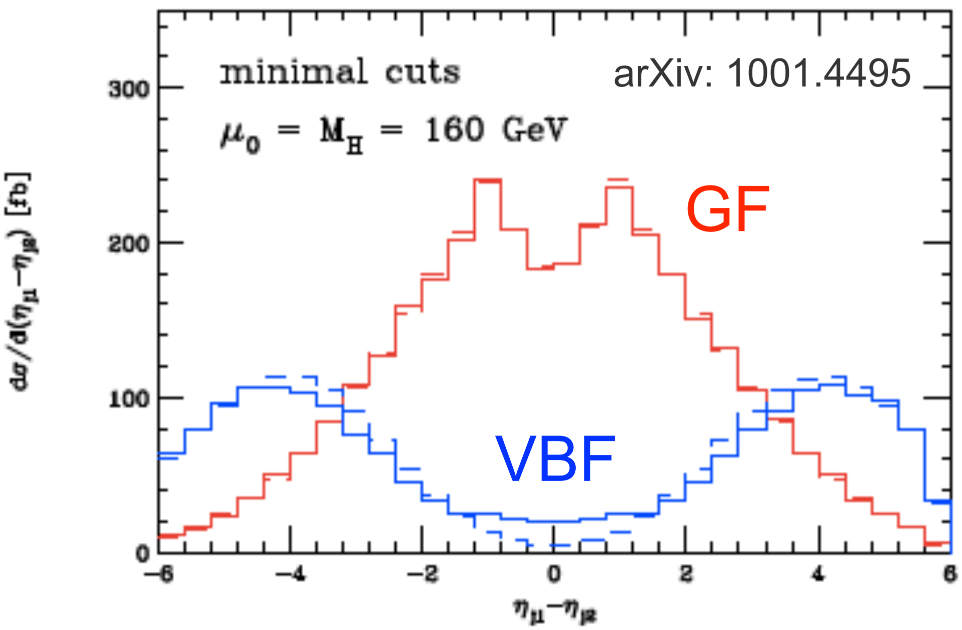
- 2 opp.-sign, high-p_T isolated leptons (ee, $\mu\mu$, μe)
  - μ, e: $p_T > 20$ GeV, $|\eta| < 2.4$
- QCD veto: $m_{ll} < 12$ GeV
- ≥ 2 jets, $p_T > 30$ GeV, $|\eta| < 2.4$
- ≥ 1 b-tagged jets
- ee, $\mu\mu$ channels: $E_T^{miss} > 30$ GeV, $|m_{ll} - m_Z| > 15$ GeV

Kinematic reconstruction of the ttbar system



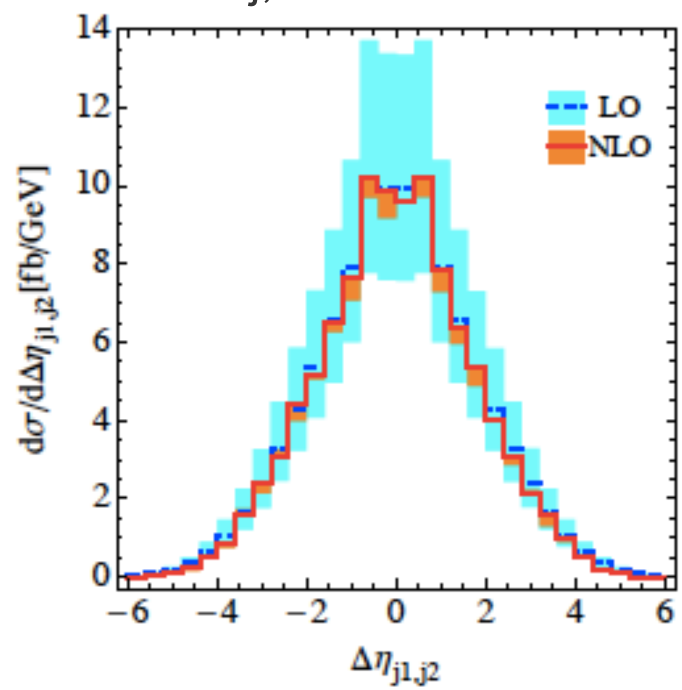
Today's signal is tomorrow's background !

Most separation between VBF and GF comes from Δη (j1, j2).



→Typical analysis uses Δη > 4

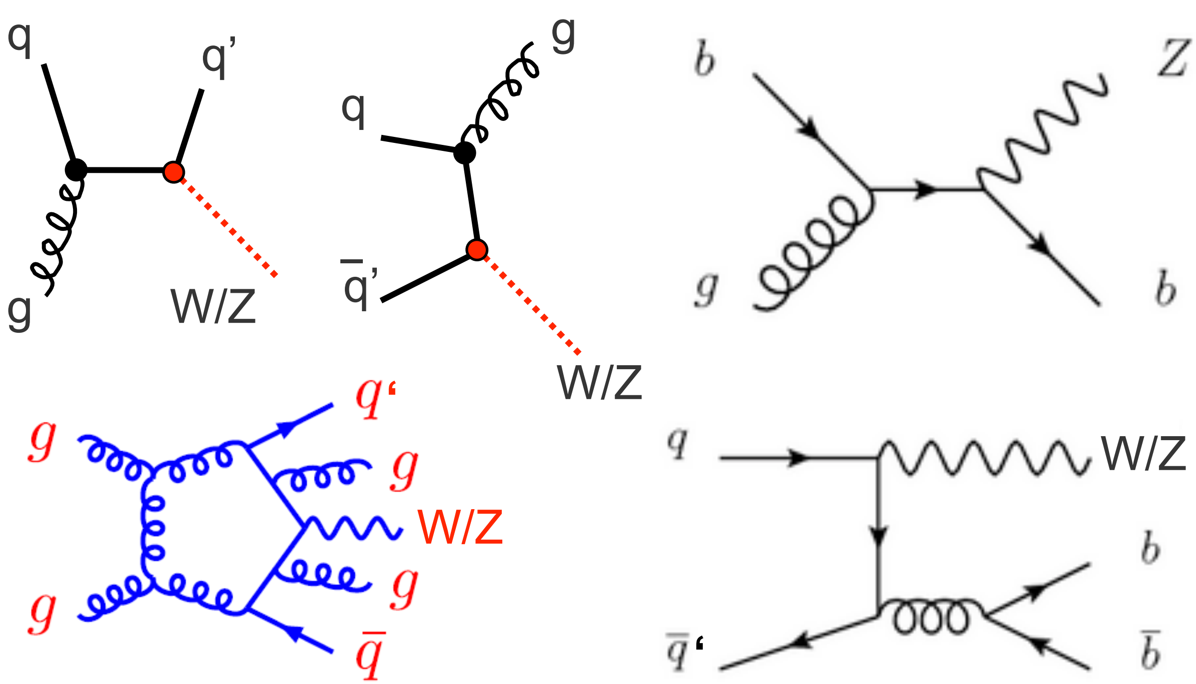
WW+2j, arXiv:1104.2327



- The same cut also goes a long way in suppressing WW+jj background.
- NLO shape for WW+jj needed to keep signal acceptance syst under control

Quark and gluon radiation in W/Z events

a ubiquitous source of background for virtually any signal at the LHC



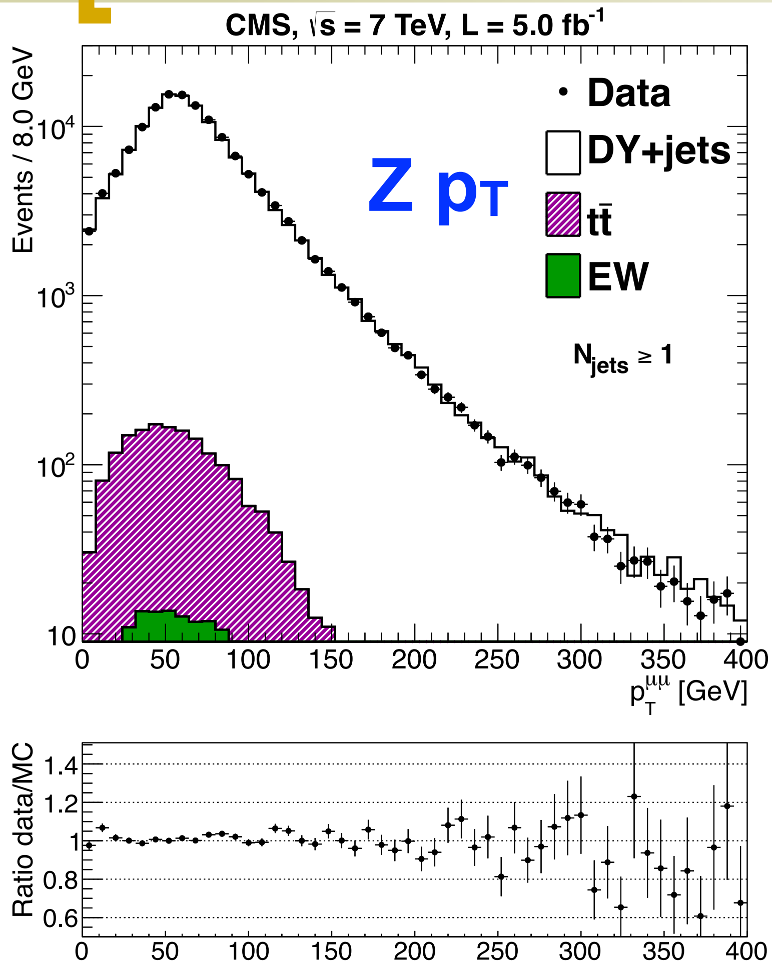
Availability of large datasets allows for constraining the unknown parameters in fixed order ME +PS computation

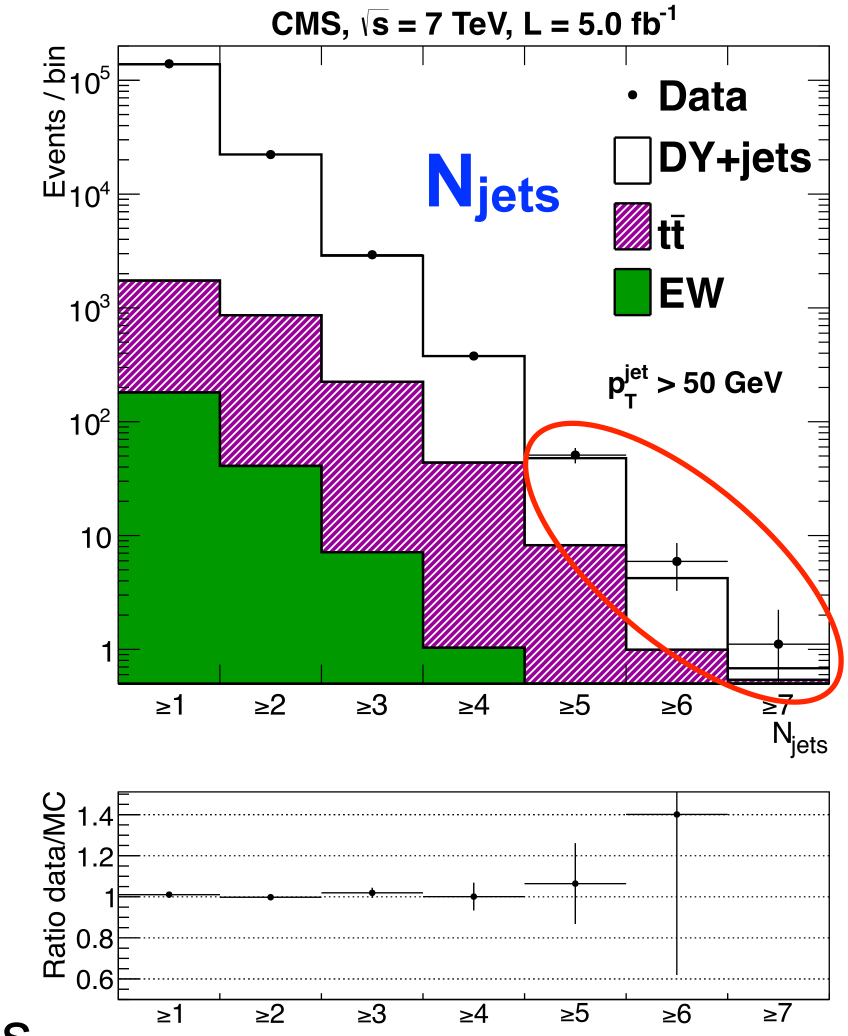
Default generator settings for W/Z+jets

	ATLAS	CMS
ME	ALPGEN 2.13	Madgraph-5 1.3.30
PS	Pythia 6.4.21	Pythia 6.4.22
Matching threshold	20 GeV (MLM)	20 GeV (MLM)
UE tune	AUET1/2	Z2
Default PDF	CTEQ6L1	CTEQ6L1
Fact./Renorm. scale	$m_V^2 + \sum_{\text{partons}} (p_T^2)$	$\sqrt{[m_V^2+p_{T,V}^2]}$ dynamic

Differential distribution in N_{jets}

arXiv:1301.1646



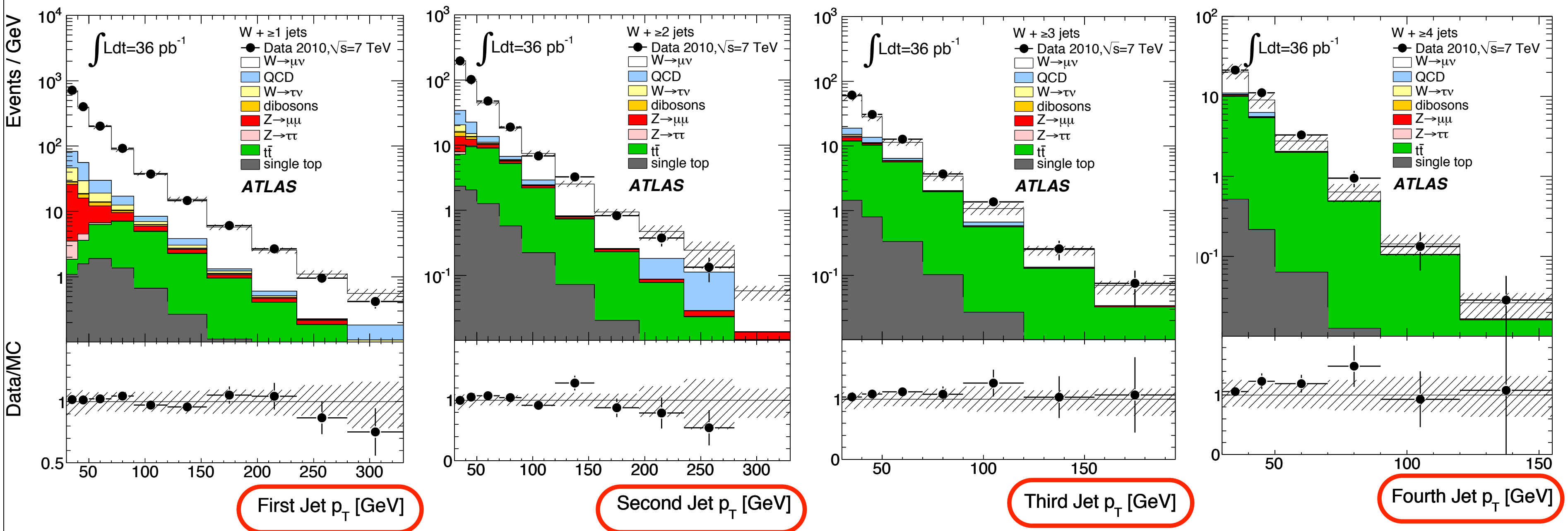


Discrepancies in the tails

Differential distributions for each N_{jets}

arXiv:1201.1276

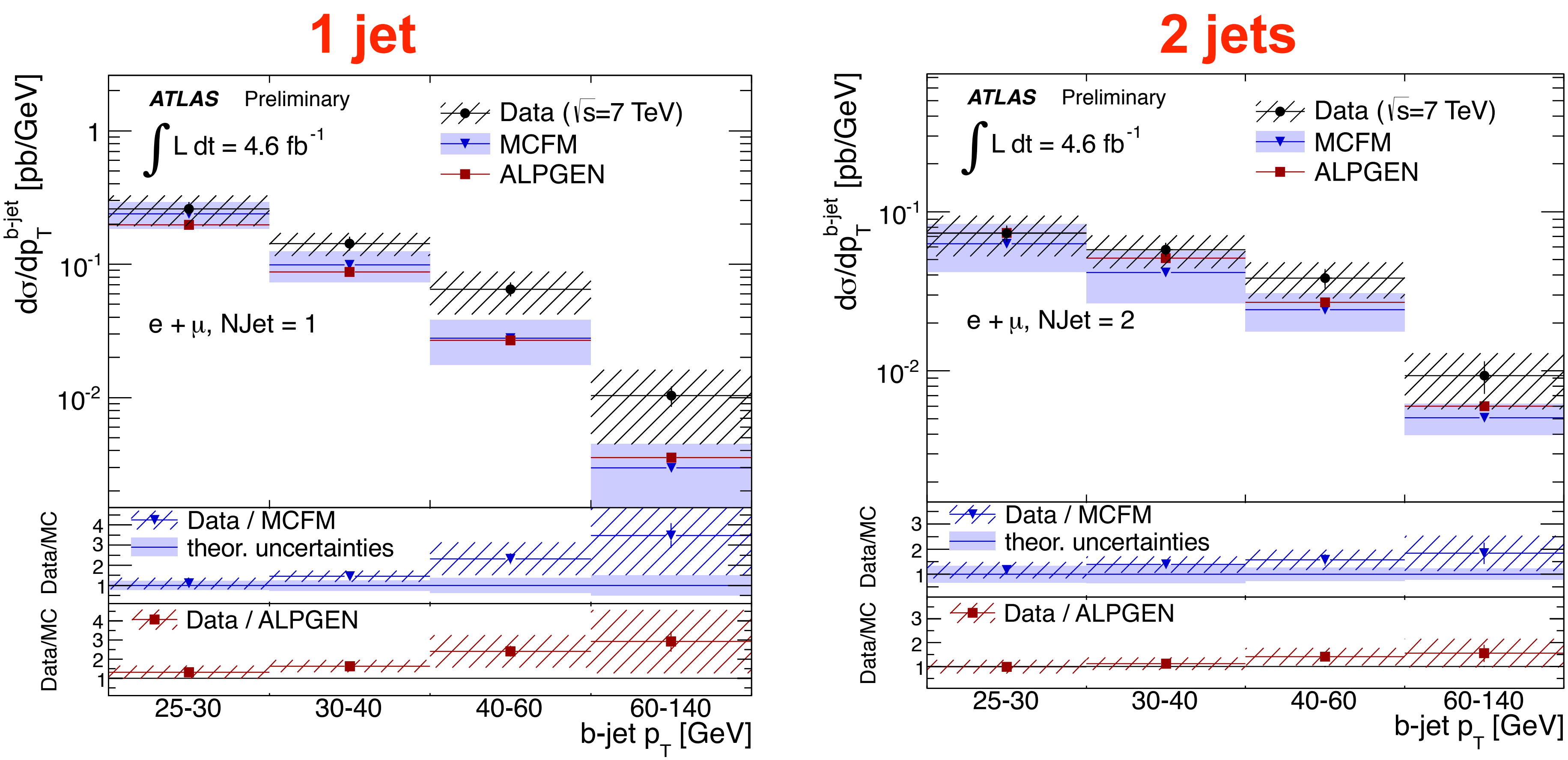
p_T distributions of the leading four jets in W+jets events



These distributions are very useful in comparing with the predictions of pQCD. E.g., We already see small discrepancies in the tails even in 2010 data.

W+b-jets production

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-156/

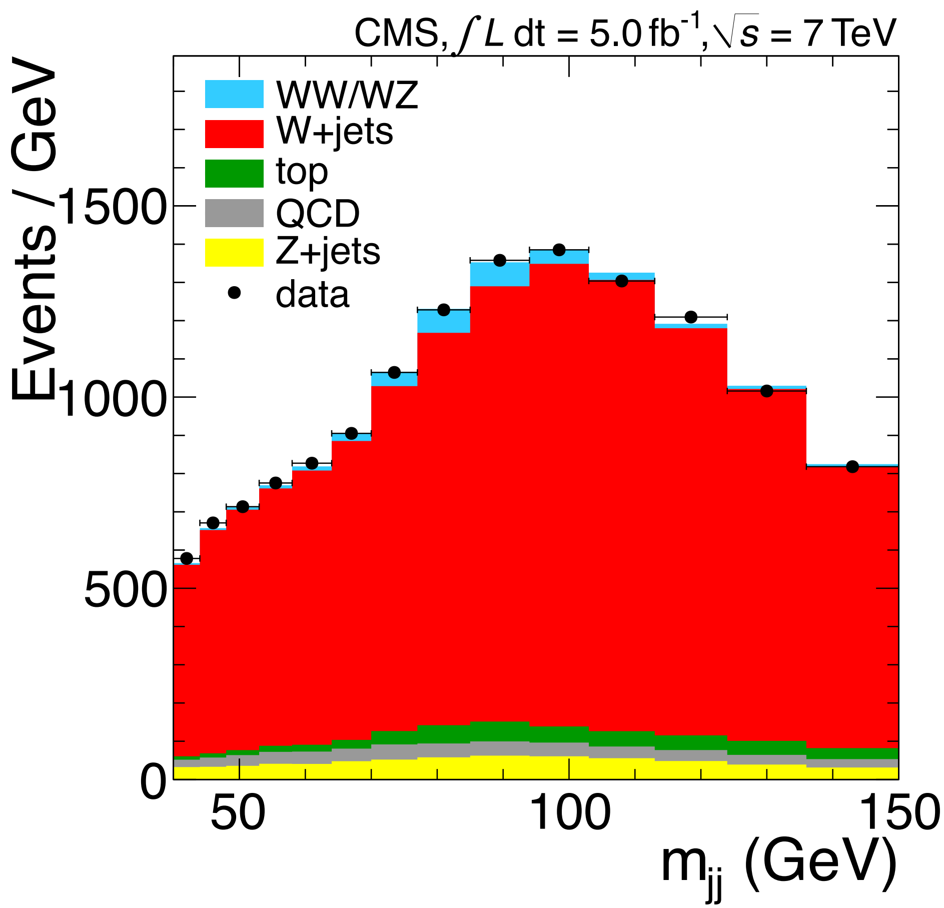


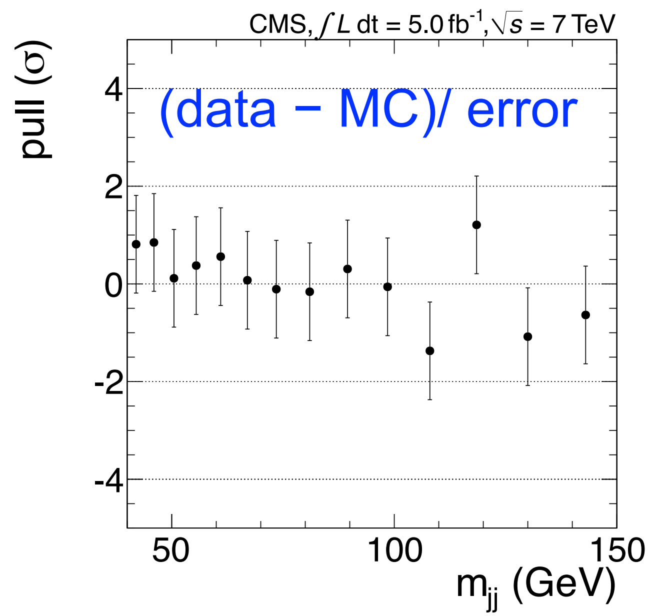
Do data prefer a different scale than used in simulation ?

Factorization/ renormalization scale in W+2-jet

arXiv:1210.7544

Dijet mass in W+2-jet events



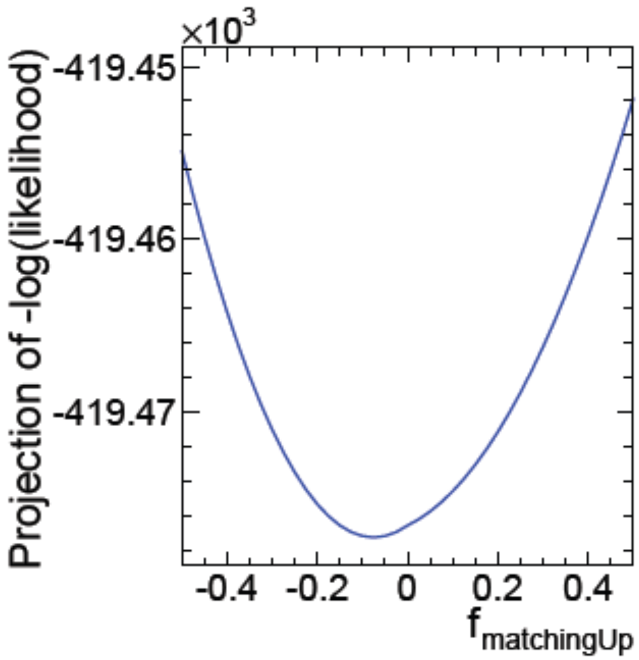


Had to vary factorization/ renormalization scale and ME-PS matching threshold to be able to model data satisfactorily

Factorization/ renormalization scale in W+2-jet

Needed to float factorization/renormalization scale & ME-PS matching threshold to get good modeling of data

$$\mathcal{F}_{\mathrm{W+jets}} = \alpha\, \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q'^2) + \beta \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu'^2, q_0^2) + (1 - \alpha - \beta) \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q_0^2),$$



- α (scale ↑ or ↓) and β (matching ↑ or ↓) consistent between e/μ data
- Data prefer smaller value for ME-PS matching threshold than 20 GeV