Hard QCD: Summary

John Campbell - Bruce Mellado - Nikos Varelas

Fermilab U. Wisconsin at Madison U. Illinois at Chicago

QCD@LHC
MSU
August 20-24, 2012

The Hard QCD Program

- >30 presentations in the Hard QCD program
- It is impossible to cover all QCD results presented in this workshop in a 20-minute talk
  - Apologies for the ones left out
- Thanks to all speakers for the excellent presentations and the fruitful discussions!

Jet Substructure

Boost 2012: A Feast of Data

shared tools ⊗ Monte Carlo = Profit

Vermilion

FastJet

http://fastjet.fr

Christopher Vermilion

Standard library of jet algorithms

Now includes extensive set of jet measurements, manipulations

Coming soon: fastjet/contrib: project to collate user-submitted tools

SpartyJet

http://projects.hepforge.org/spartyjet

Extends FastJet with flexible I/O, Python control, GUI browser

Easy to build up complicated analyses, add in pile-up, etc.

Rivet

http://projects.hepforge.org/rivet

Really nice package for standardized experimental analysis write-up

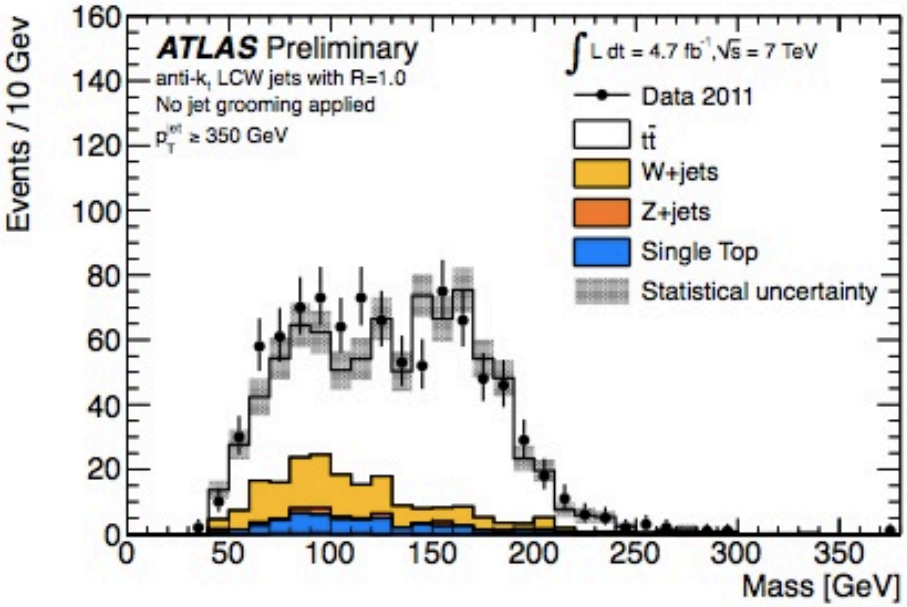
Major caveat: designed to run on unfolded data or MC

All three of these being used in Boost 2012 follow-up

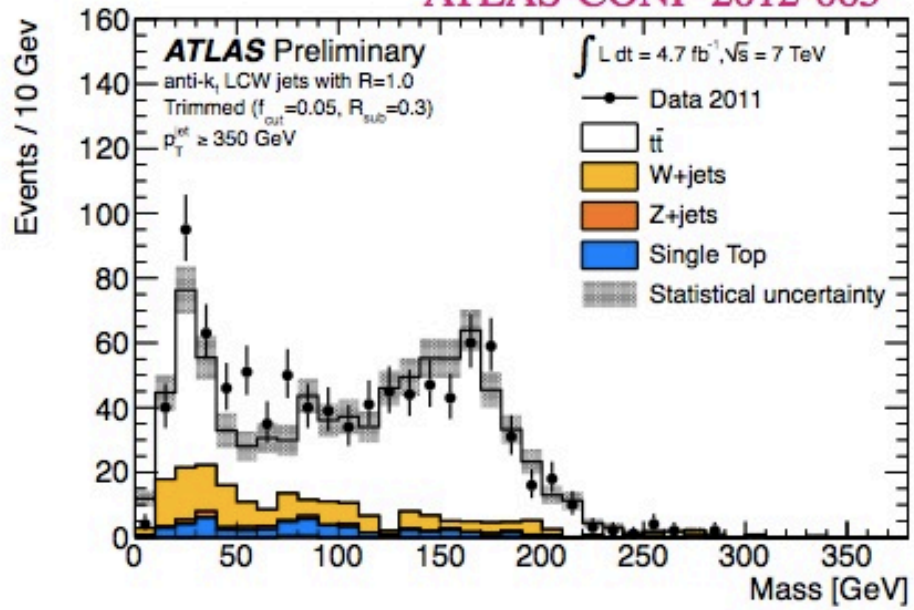
Commissioning boosted object tools with SM top quarks (I)

Enriched sample of boosted tops using semi-leptonic (μ) selection and high-p_T fat jets

ATLAS-CONF-2012-065



anti-k_t, $R = 1.0$, ungroomed

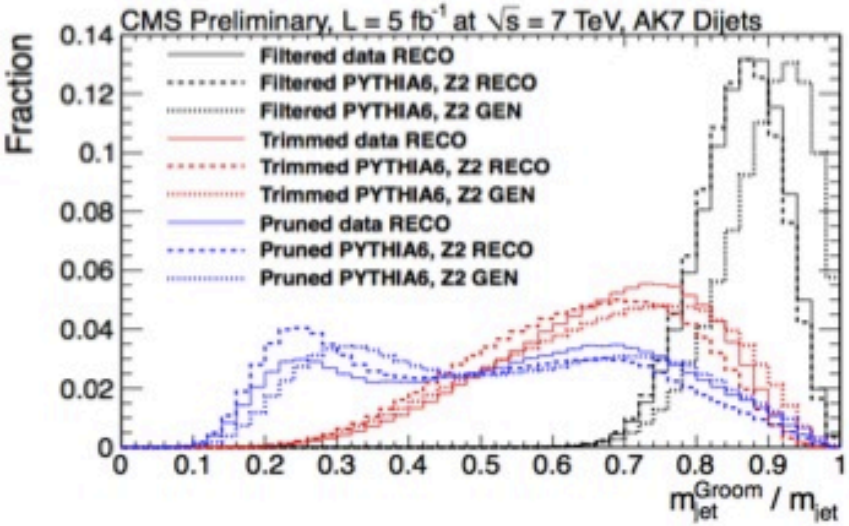


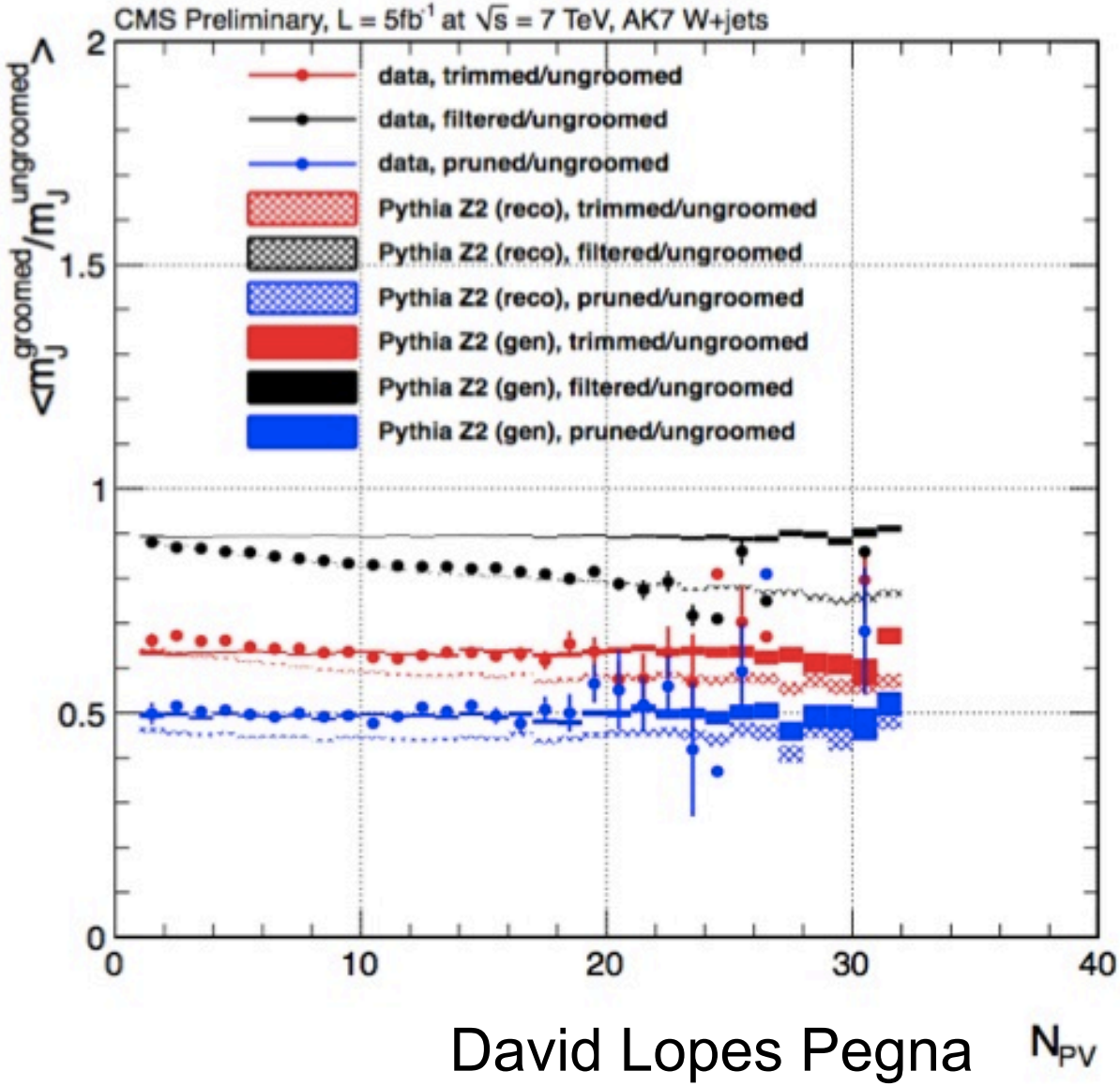
anti-k_t, $R = 1.0$, trimmed

- Significant increase in the purity of the top mass peak between $120 < M^{\text{jet}} < 200$ GeV
- Narrower top mass peak after trimming that is well described by the data
- Rate of boosted tops is well-predicted by MC@NLO top MC
  - *implicit limits from this plot alone*
- b-tag requirement highlights improvement in mass resolution from trimming

David Miller

Grooming Algorithms, CMS





- Grooming in simulation more aggressive than data
- PU-independent for the most aggressive grooming
- Dependence for filtering nicely reproduced in simulation

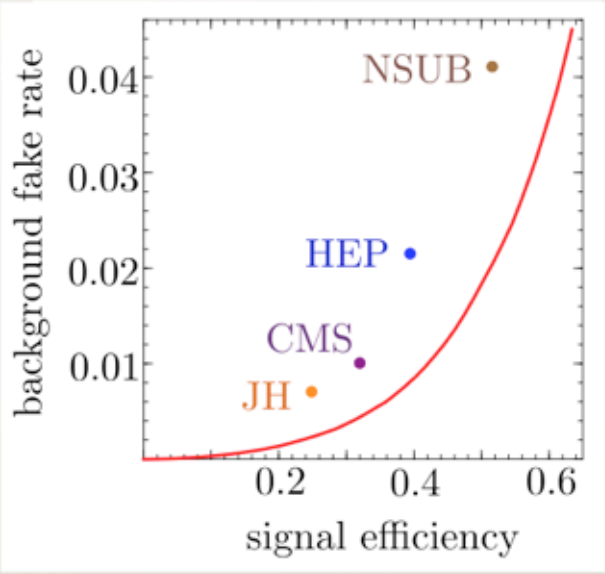
David Lopes Pegna

Shower deconstruction

Soper

Comparison to other top tagging methods

- Johns Hopkins top tagger
- HEP top tagger
- CMS top tagger
- N-subjettiness as a top tagger

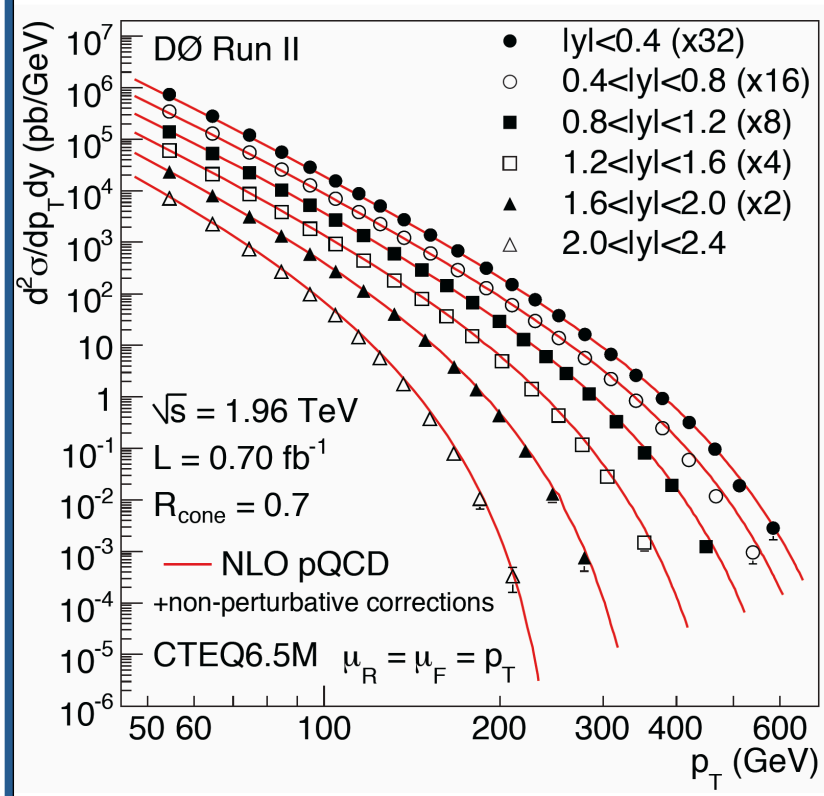


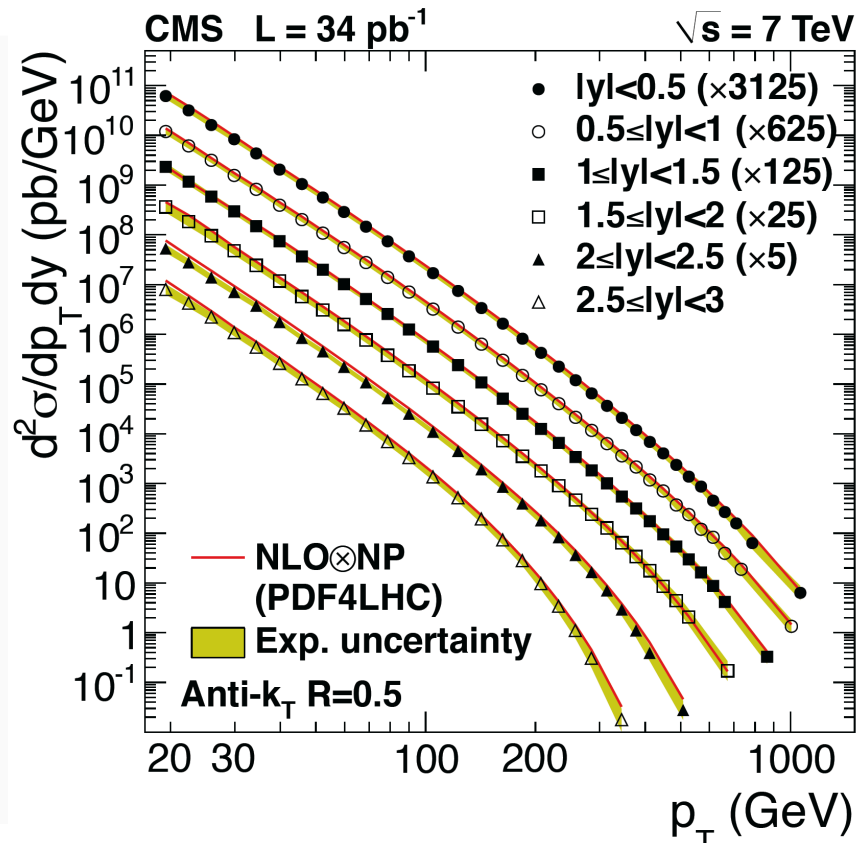
Jets with 600 GeV $< p_T <$ 700 GeV

Jet Production

Inclusive Jets: Tevatron →LHC

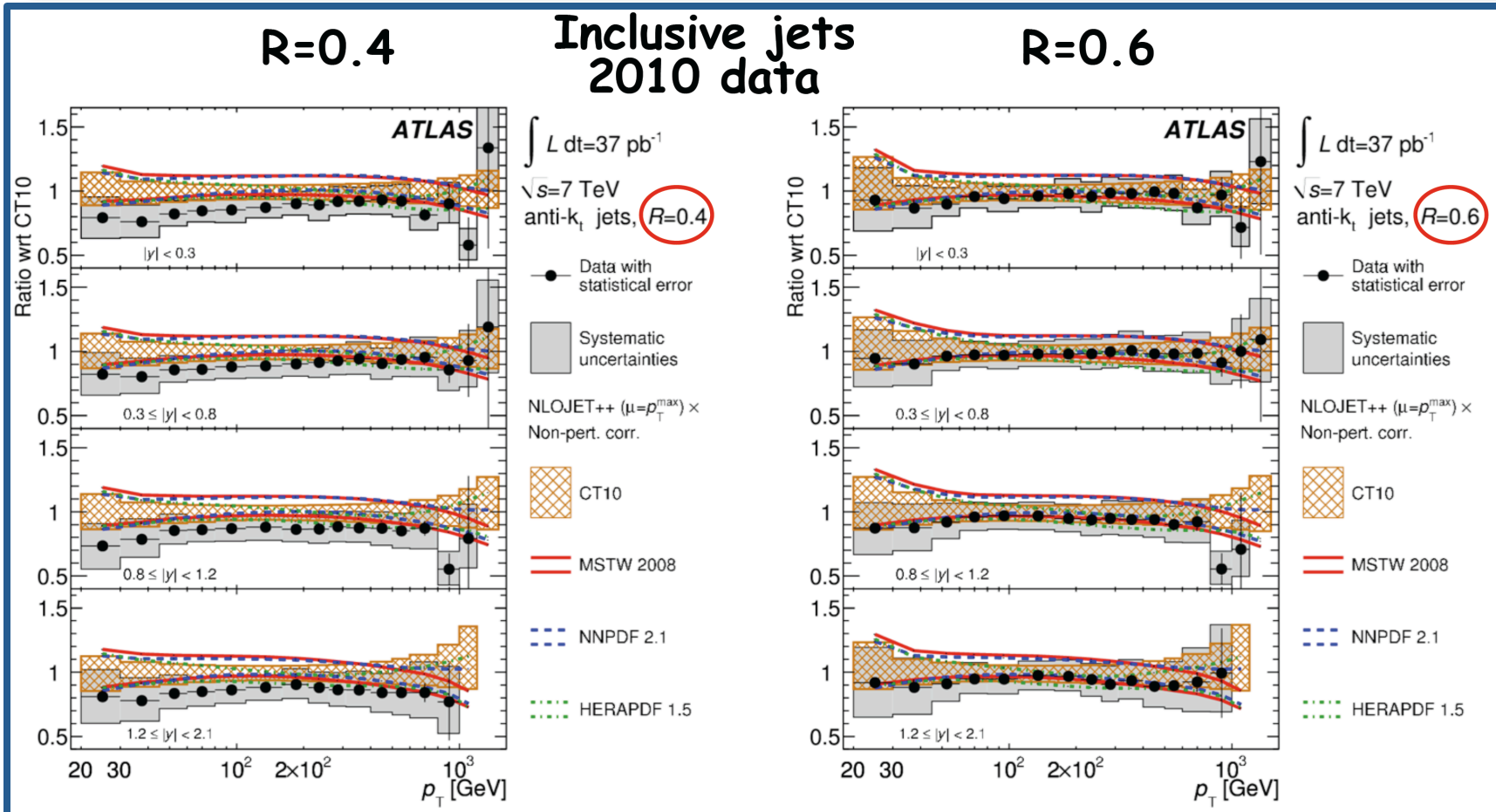
Tevatron and LHC with 2010 data





- Inclusive jets are one of the most elementary measurements at hadron colliders
- LHC experiments covered more phase space with 2010 data than Tevatron (lower and higher in p_T, higher in $|y|$), but had less reach at high x

Inclusive Jets: a closer look



- Inclusive jet results are in good agreement with NLO predictions
  - However, some hints that prediction is not as good for smaller cone sizes
  - High |y|, high p_T has maybe some tendency to be low

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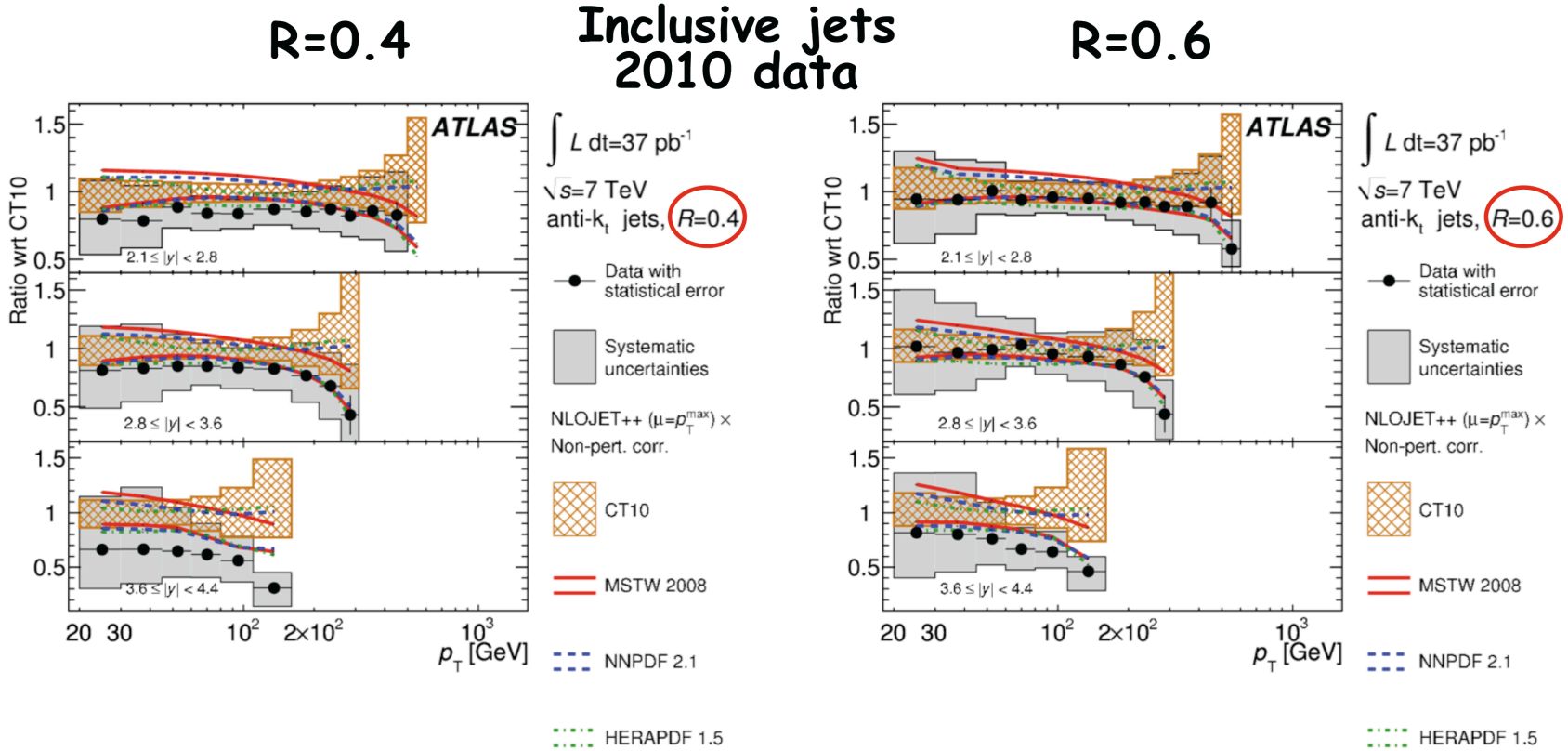

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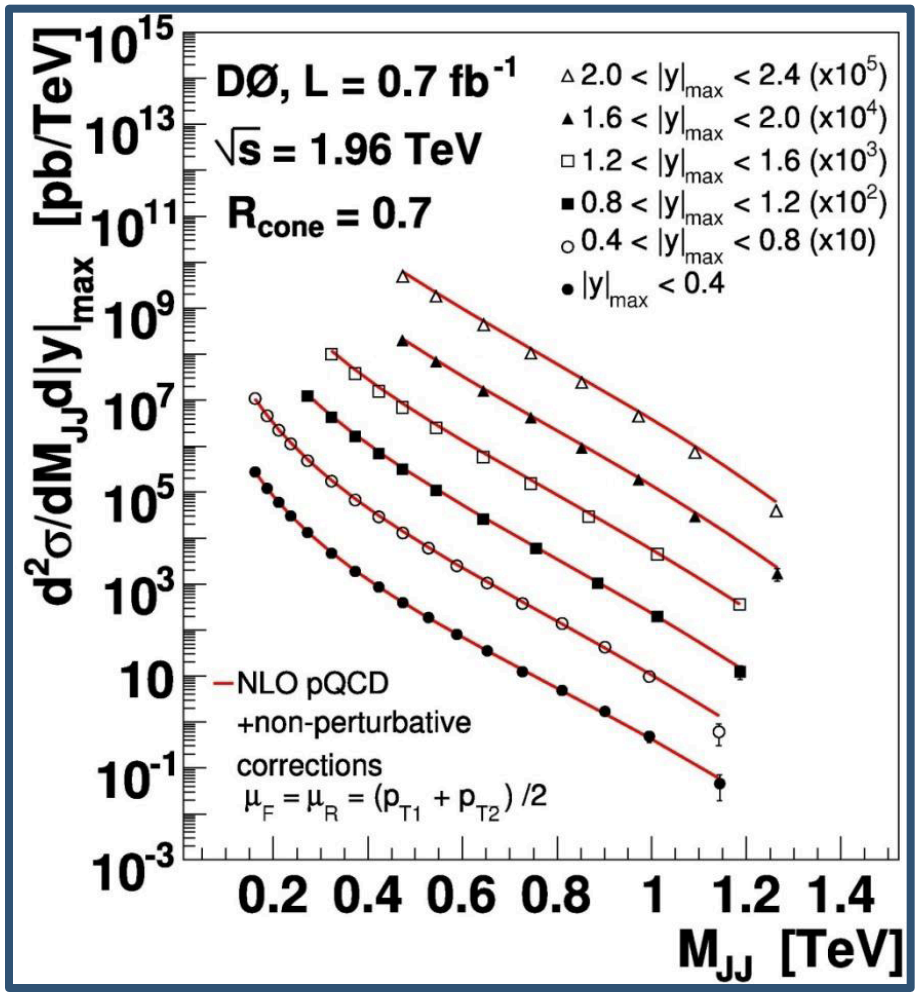
Campbell/Mellado/Varelas QCD@LHC – Aug. 24, 2012

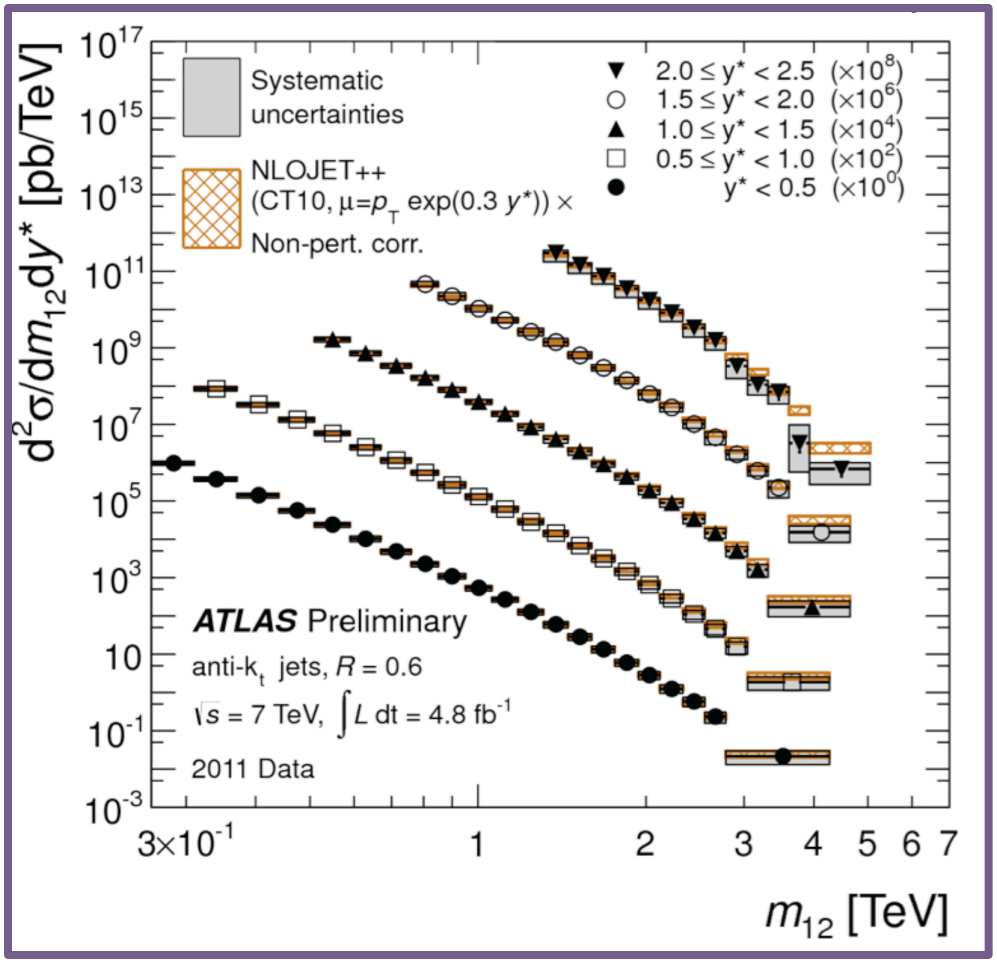
Wobisch

Dijet Cross Sections

- Tevatron
- Comparisons to NLO×NP

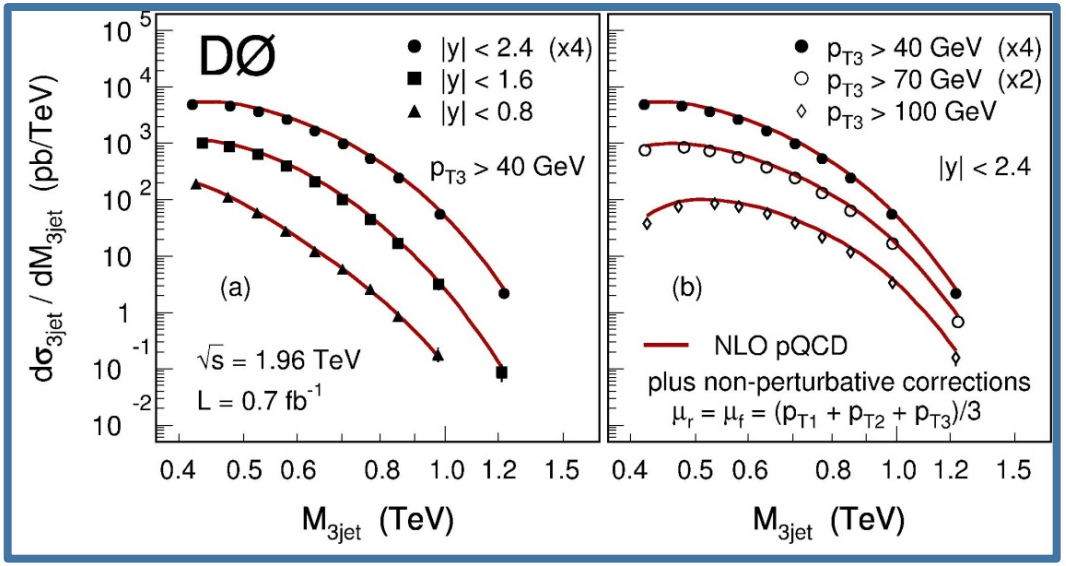


- LHC (7 TeV)
- Comparisons to NLO×NP

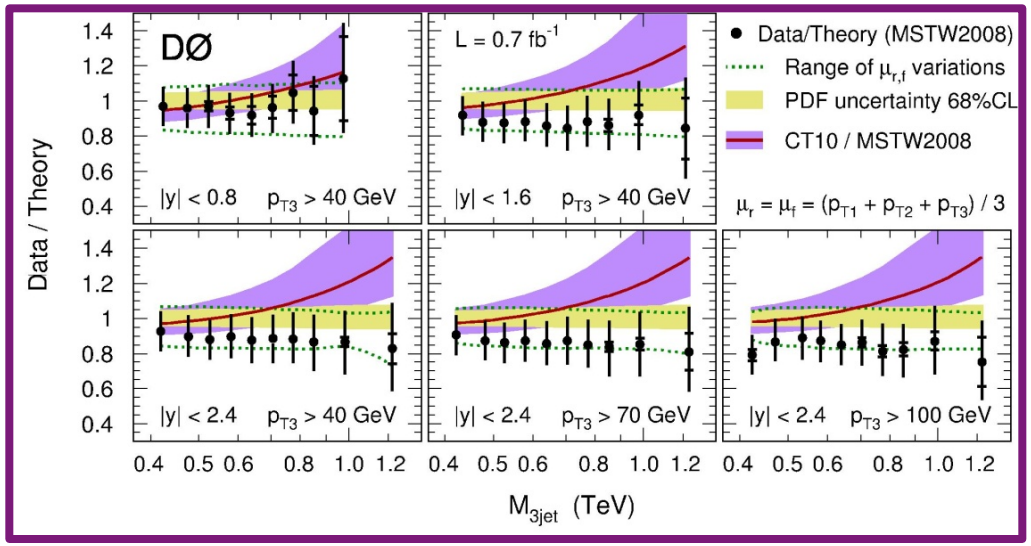


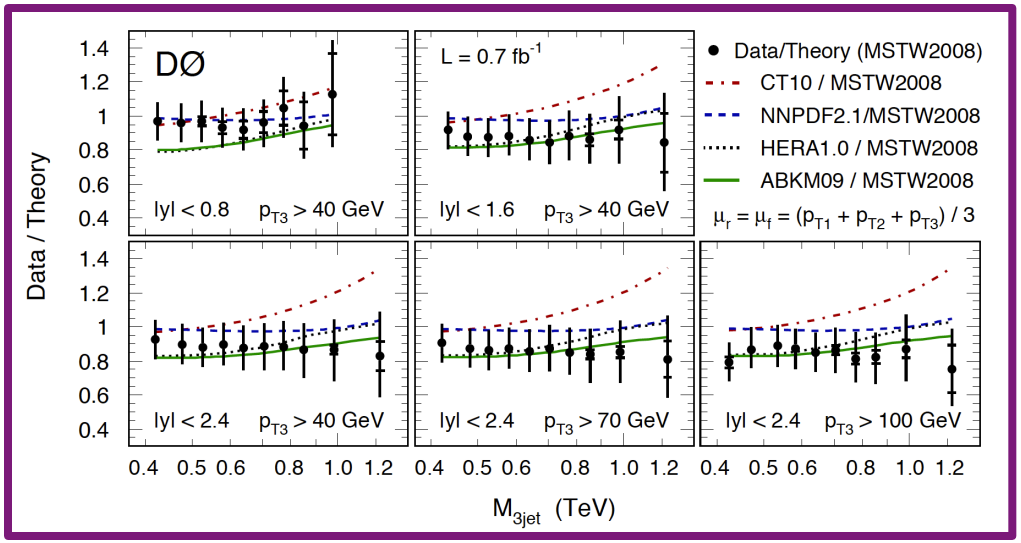
Wobisch

3-Jet Production at Tevatron

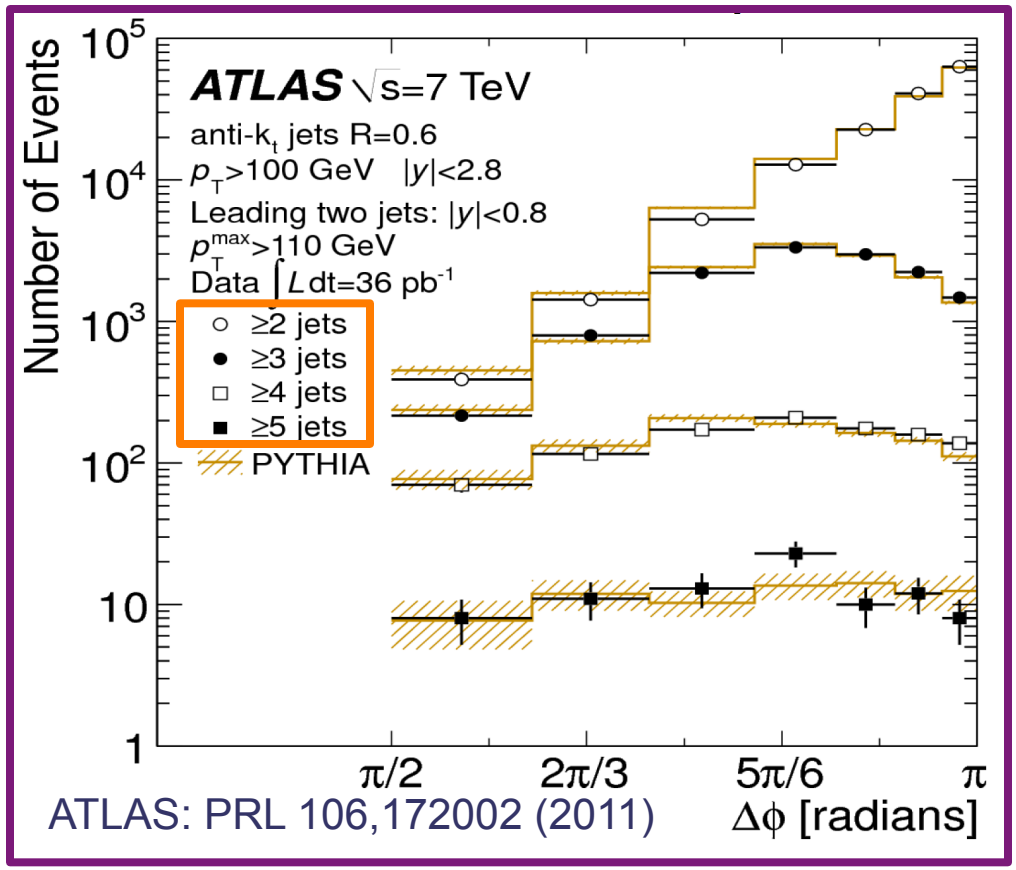


- 3-Jet Mass Cross Section ($d\sigma_{3jet}/dM_{3jet}$) in three rapidity bins and three p_{T3} bins
- Comparisons to NLO×NP with several PDF choices
- Potential impact of 3-jet data in PDF fits (need of NNLO)

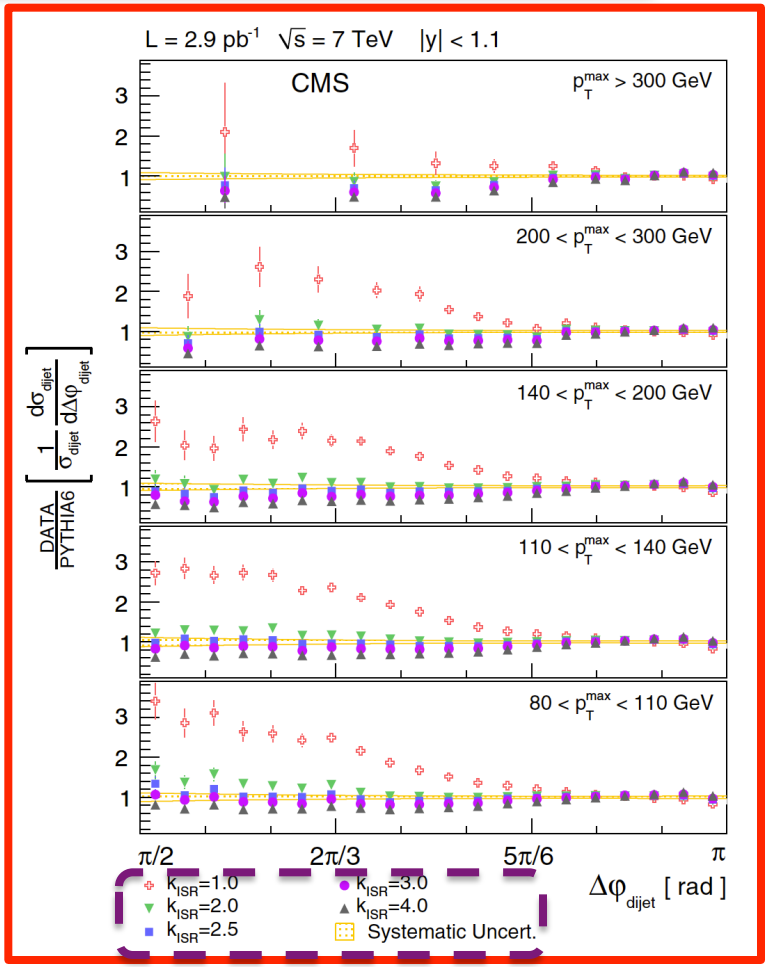




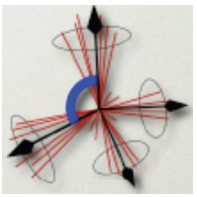
Dijet Azimuthal Distributions

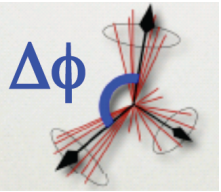


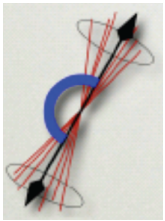
ATLAS: PRL 106,172002 (2011)



CMS: PRL 106, 122003 (2011)



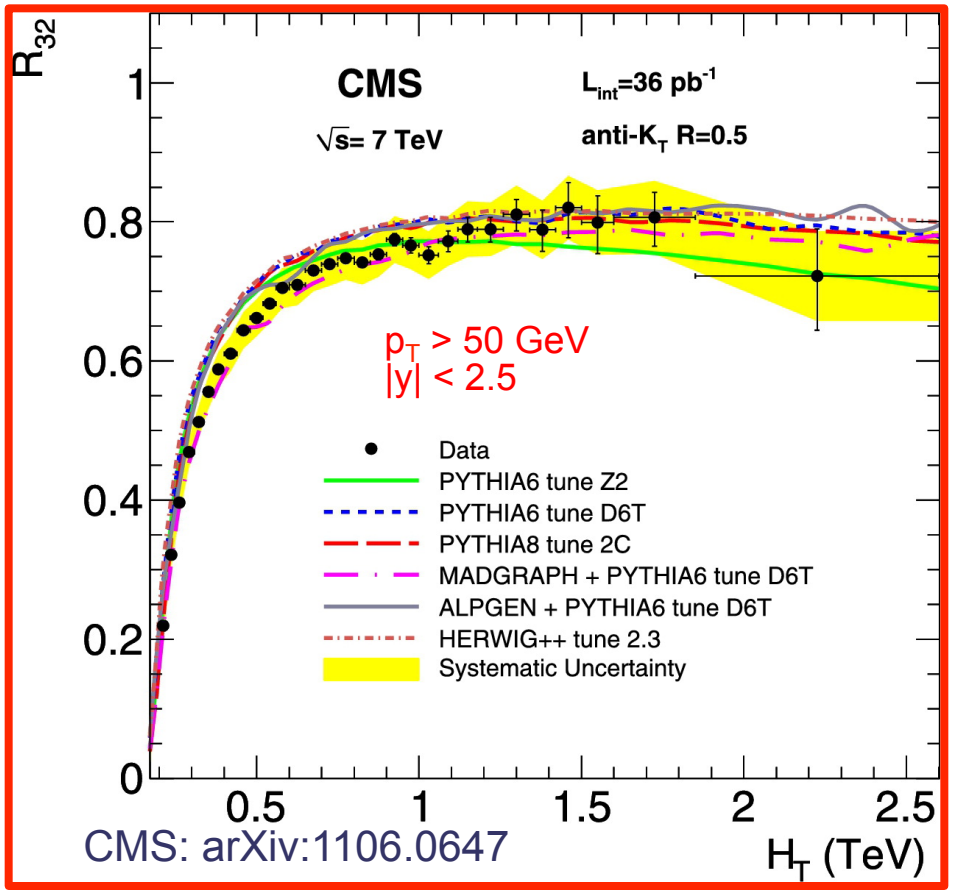




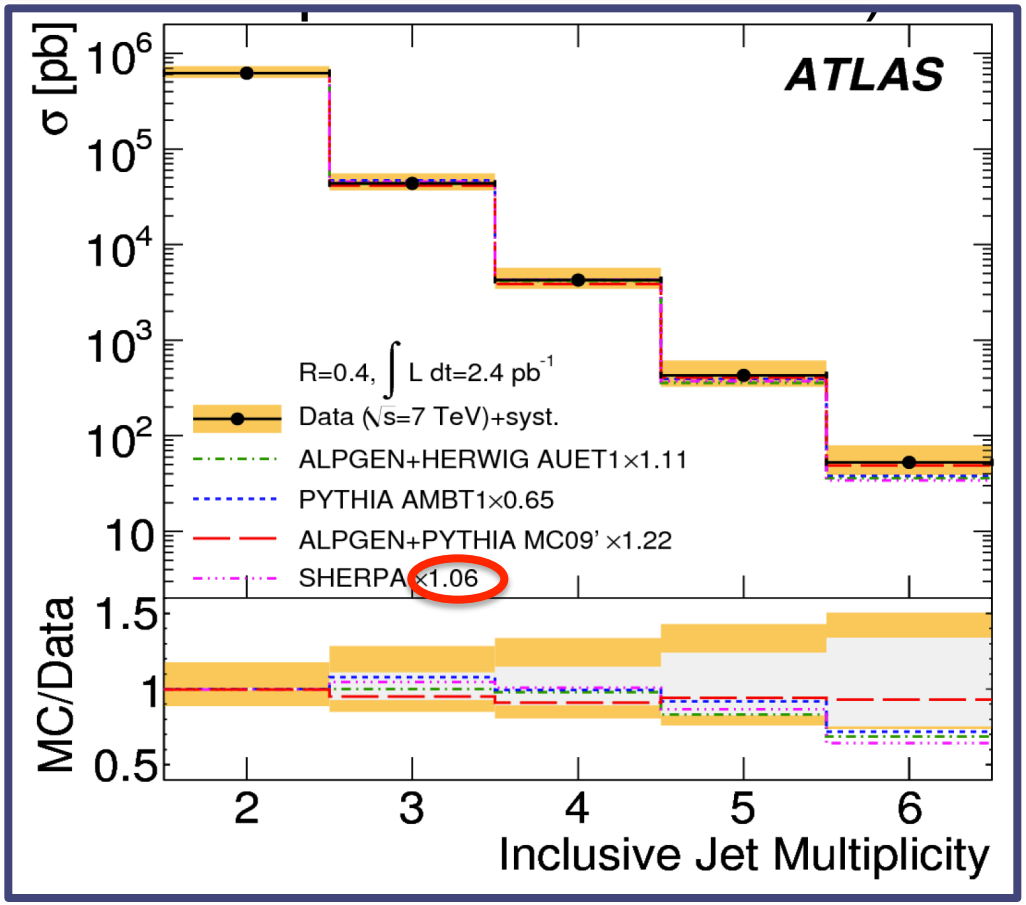
- $d\sigma_{diet}/d\Delta\phi_{dijet}$: Sensitive to Initial State Radiation Data/Theory
- Can be used to tune PYTHIA ISR (as it was done with the Tevatron data)

Multijet Production at LHC

$$R_{3/2} = \sigma_{3\text{-}jet} / \sigma_{2\text{-}jet} = \frac{\sum \quad + \ldots}{\sum \quad + \quad + \ldots}$$



CMS: arXiv:1106.0647



ATLAS: arXiv:1106.0647

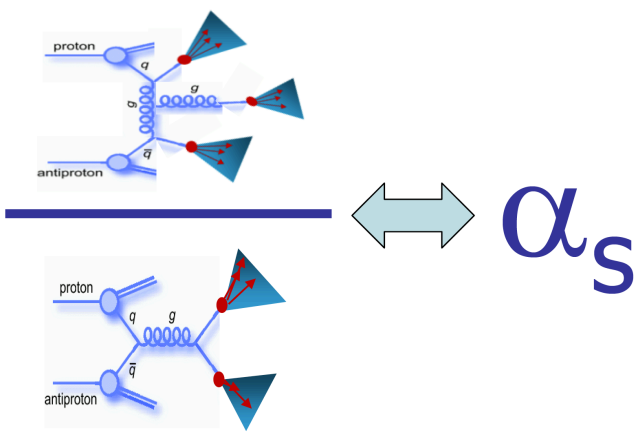
- LO multi-leg MCs agree better with the data
- SHERPA gives the best normalization

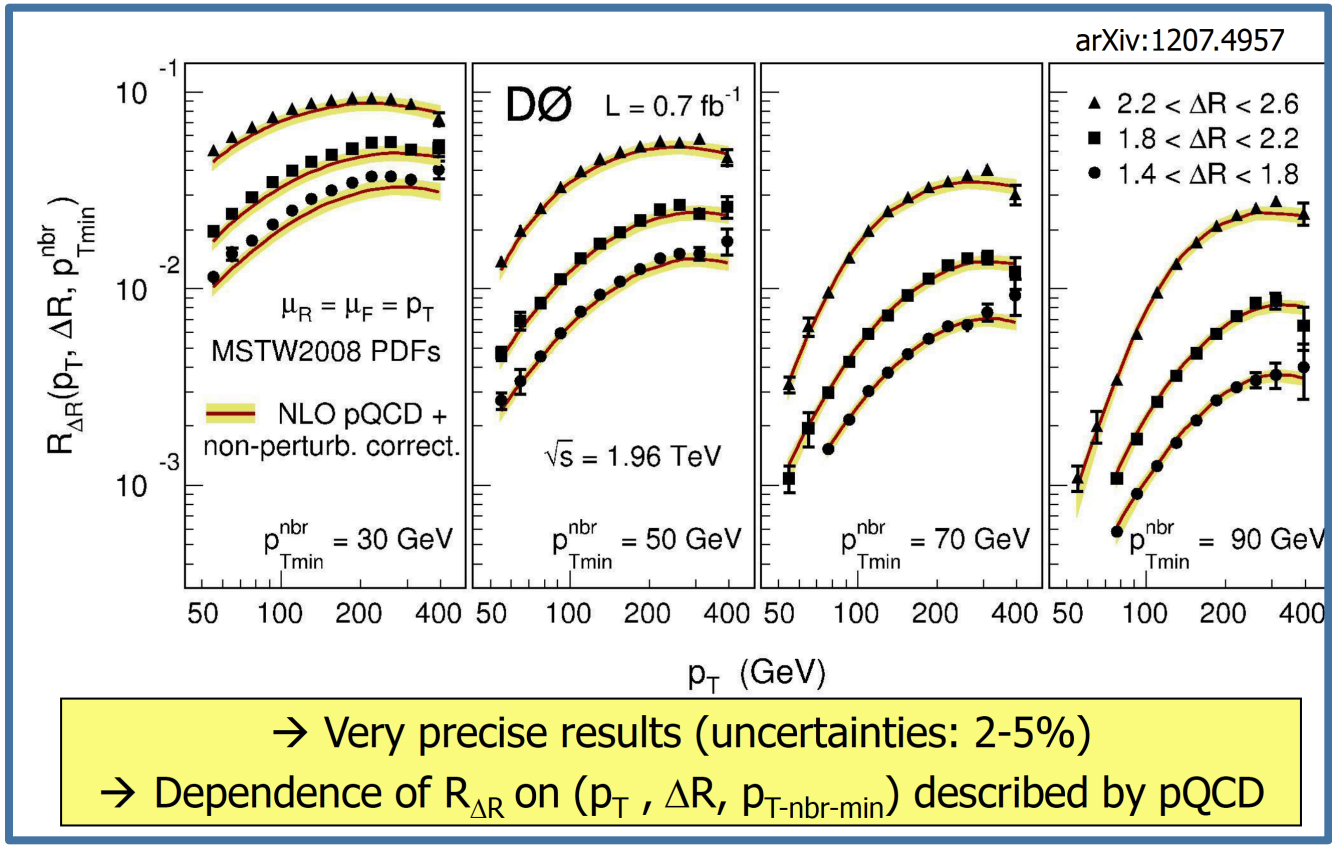
α_s Determination at Tevatron (1)

- Use a new observable variable: $R_{\Delta R}$

Wobisch

$R_{\Delta R}$
average number of neighboring jets
for jets from an inclusive jets sample





→ Very precise results (uncertainties: 2-5%)
→ Dependence of $R_{\Delta R}$ on (p_T , ΔR, $p_{T\text{-nbr-min}}$) described by pQCD

α_s Determination at Tevatron (2)

Wobisch

$$\alpha_s(M_Z) = 0.1191^{+0.0048}_{-0.0071}$$

→ Extract α_s from $R_{\Delta R}$ data

Use $p_{Tnbr\text{-}min}$ >= 50, 70, 90 GeV

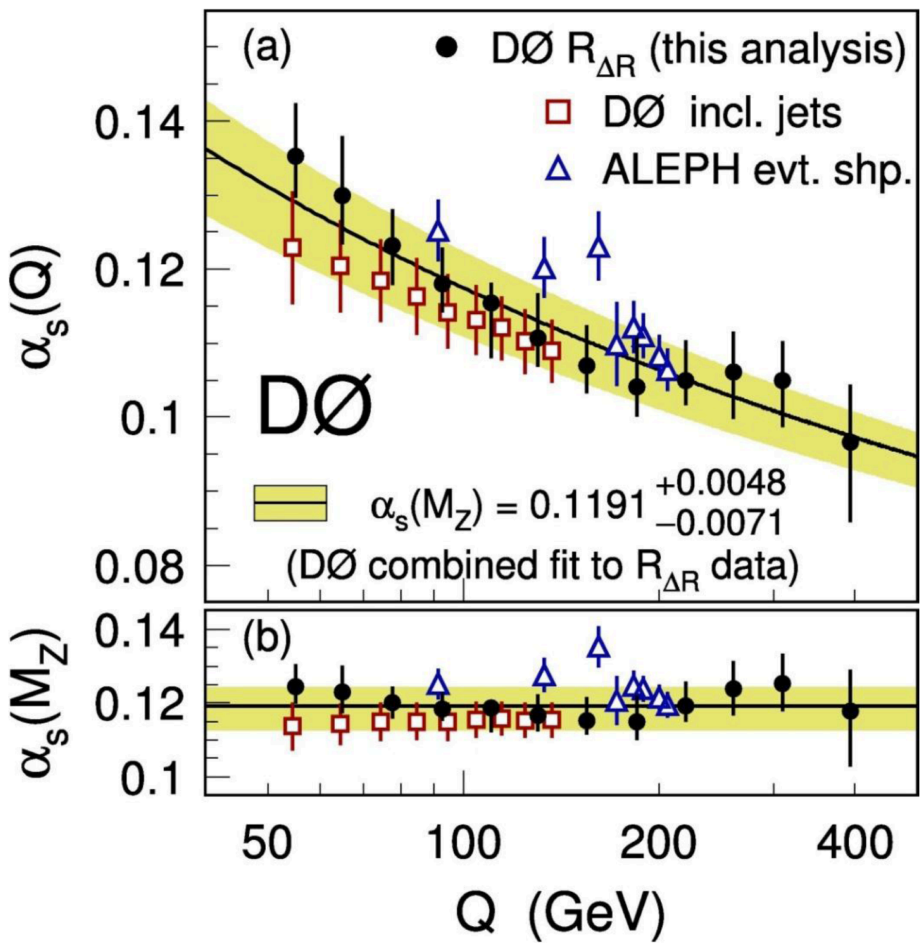
At each p_T, combine all data points with different $p_{T\text{-}nbr\text{-}min}$ and ΔR requirments

Determine results for $\alpha_s(p_T)$ at 12 p_T values

→ $\alpha_s(p_T)$ results up to 400 GeV

→ $\alpha_s(p_T)$ decreases with p_T as predicted by the RGE

arXiv:1207.4957

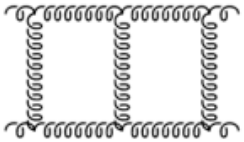


Jet production at NNLO

- End of decade(s)-long program finally in sight
  - predictions available on timescale of one year (really!)

Aim: "leading colour gluons-only"

$pp \to 2$ jets to demonstrate proof of concept



- Integrated subtraction terms combined with two-loop matrix elements in four-gluon process
  A. Gehrmann-De Ridder N. Glover, J. Pires, TG
- involves:
  - integrated four-parton tree-level antenna functions: $\mathcal{F}_4^0$
  - convolutions of three-parton tree-level antenna functions: $\mathcal{F}_3^0 \otimes \mathcal{F}_3^0$
  - integrated three-parton one-loop antenna functions: $\mathcal{F}_3^1$
  - interplay of antenna functions with parton distribution counterterms
- observe: analytic cancellation of infrared poles
- numerical optimization ongoing

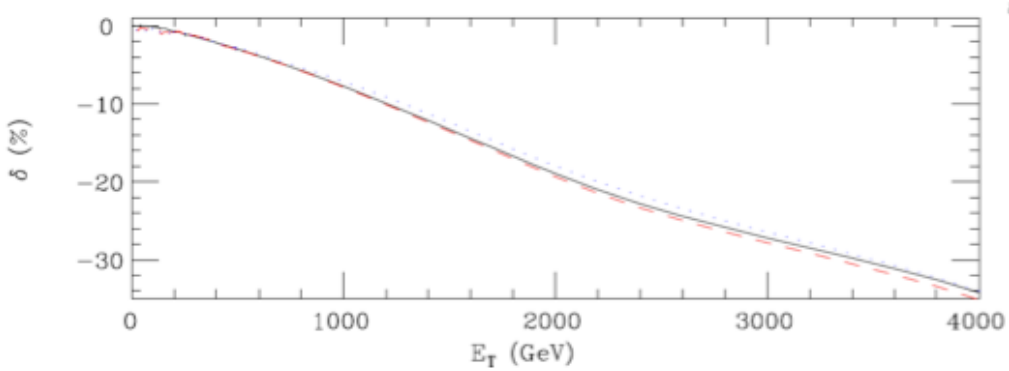
next step: incorporate processes with external quarks
(J. Currie, N. Glover)

Gehrmann

- Discussion: how to distribute results, e.g. for pdf fits
- n-tuples?

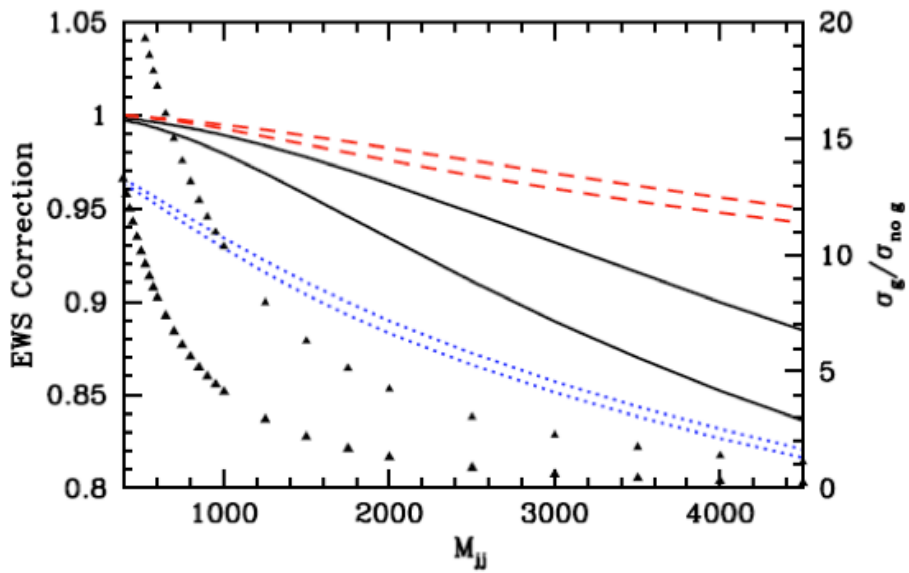
EW corrections

Wackeroth



Weak $\mathcal{O}(\alpha)$ corrections to the E_T^j distribution at the 14 TeV LHC

Moretti, Nolten, Ross, hep-ph/0606201



and the 7 TeV (lower curves) and 14 TeV LHC (upper curves)

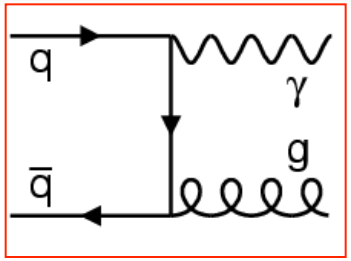
Manohar and Trott, arXiv:1201.3926

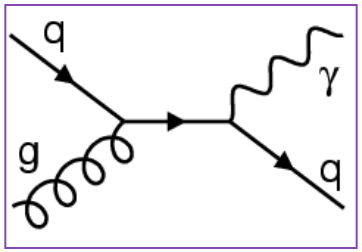
- Large effect in multi-TeV region

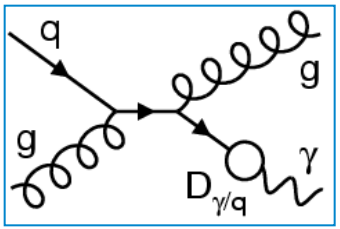
Direct Photons

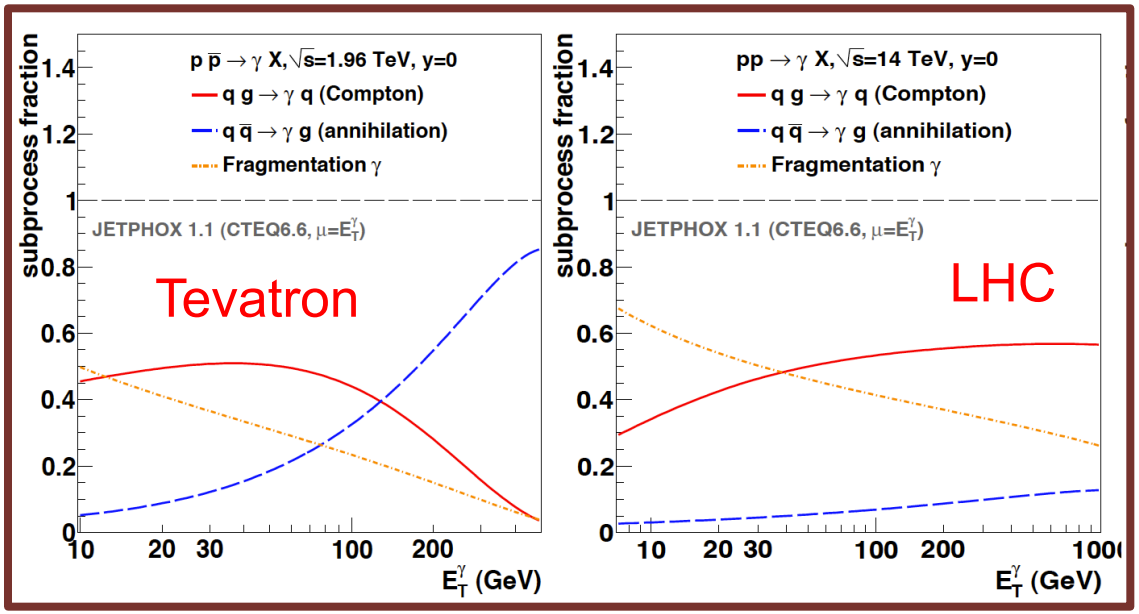
Direct Photon Production

- Photon processes:
  - Annihilation
  - Compton (dominate at LHC)
- Also fragmentation contributes
  - But suppressed with isolation
- Directly sensitive to hard scatter
- Important for QCD studies, gluon PDFs, background to many discovery channels
- Challenging measurement
- Large QCD jet background
  - Observable: isolated photons









R.Ichou & D.d' Enterria arXiv:1005.4529 (2010)

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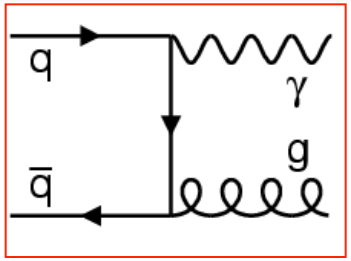
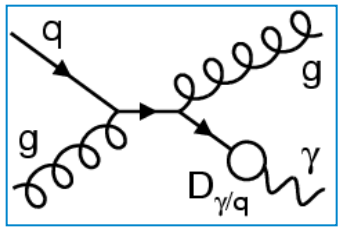
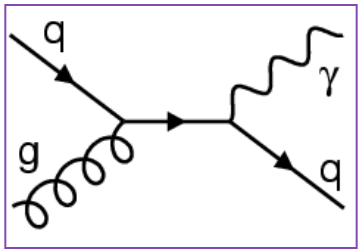
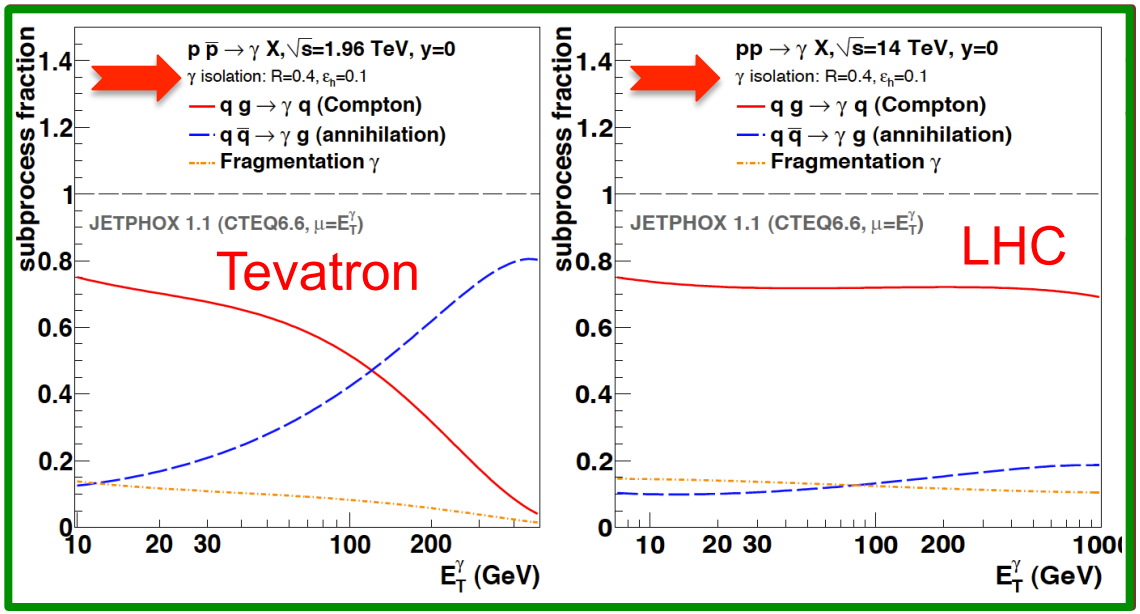






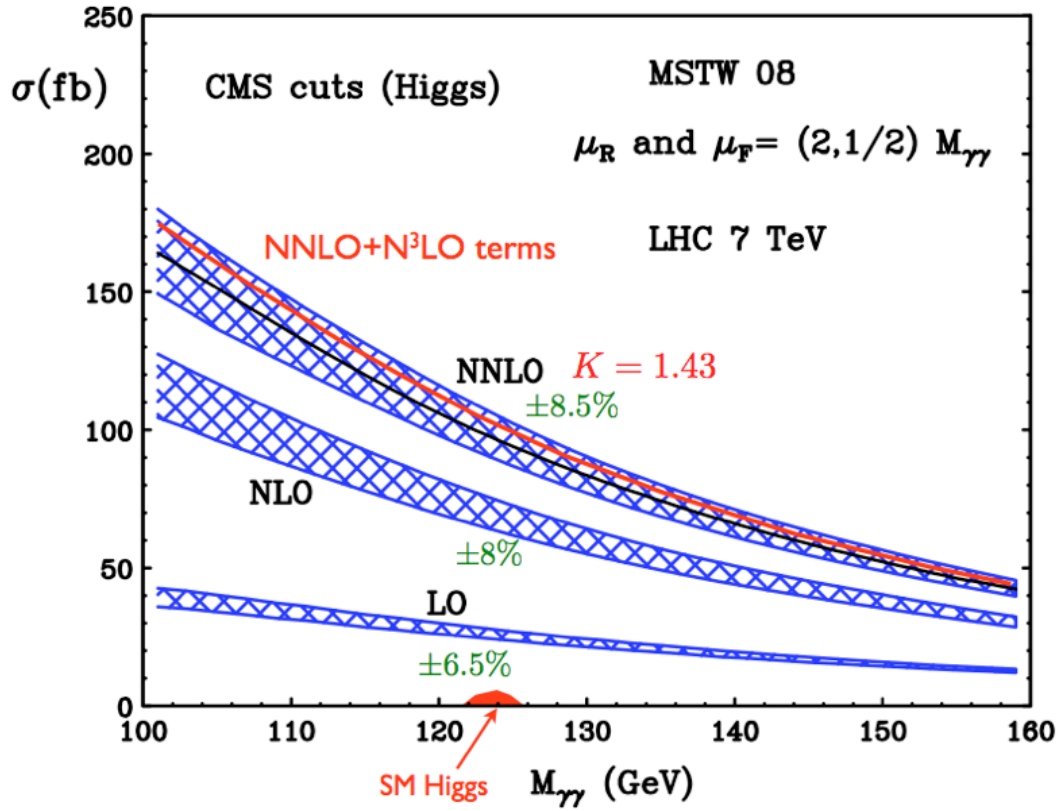


R.Ichou & D.d' Enterria arXiv:1005.4529 (2010)

Diphotons at NNLO

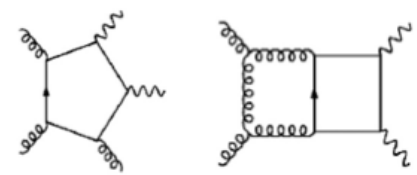
de Florian

- Many benefits at NNLO
  - large corrections (~50%), better description (e.g. Guillet shoulder), all partonic channels, reliable uncertainty estimate



- Computed using pragmatic approach: smooth 'Frixione' cone
- Advocate dropping higher-order N³LO terms

α_s^3 Bern, Dixon, Schmidt (2002)



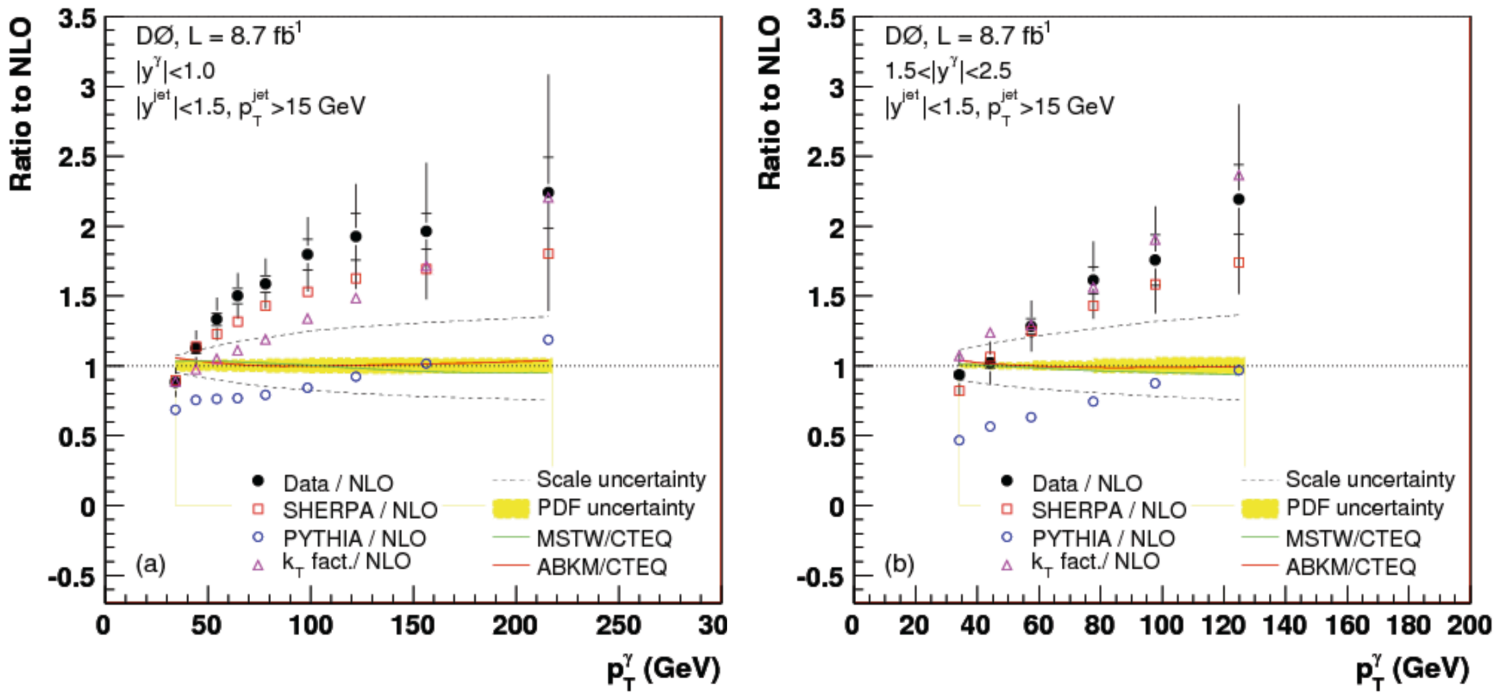
Some N³LO terms known to contribute ~5%

Photon + HF at Tevatron

Vellidis

Comparisons – γ+b: D0

arXiv:1203.5865 (submitted to PLB)

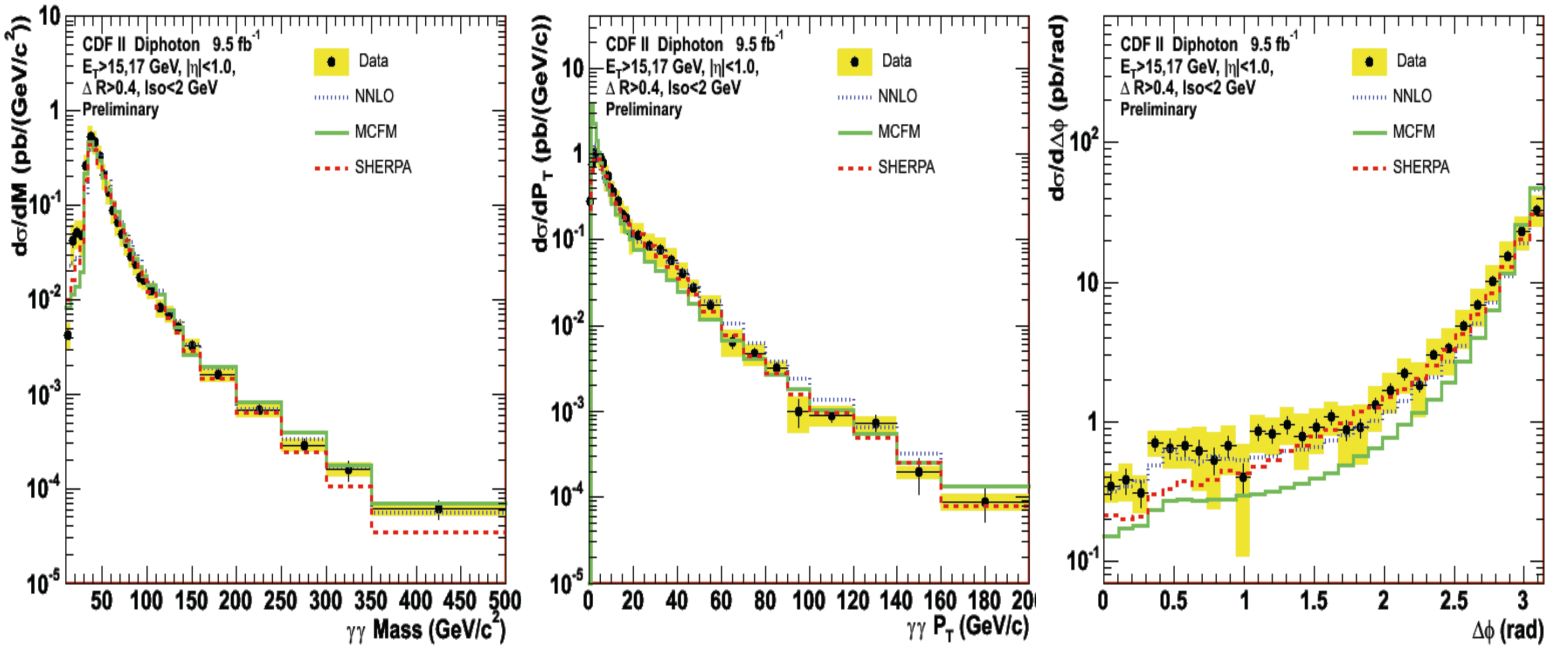


- NLO and Pythia differ from the data by up to a factor of 2
- Sherpa and k_T model are in good agreement with the data
- Little sensitivity to the PDF choice between MSTW and ABKM

Diphotons at Tevatron

Vellidis

Differential cross sections

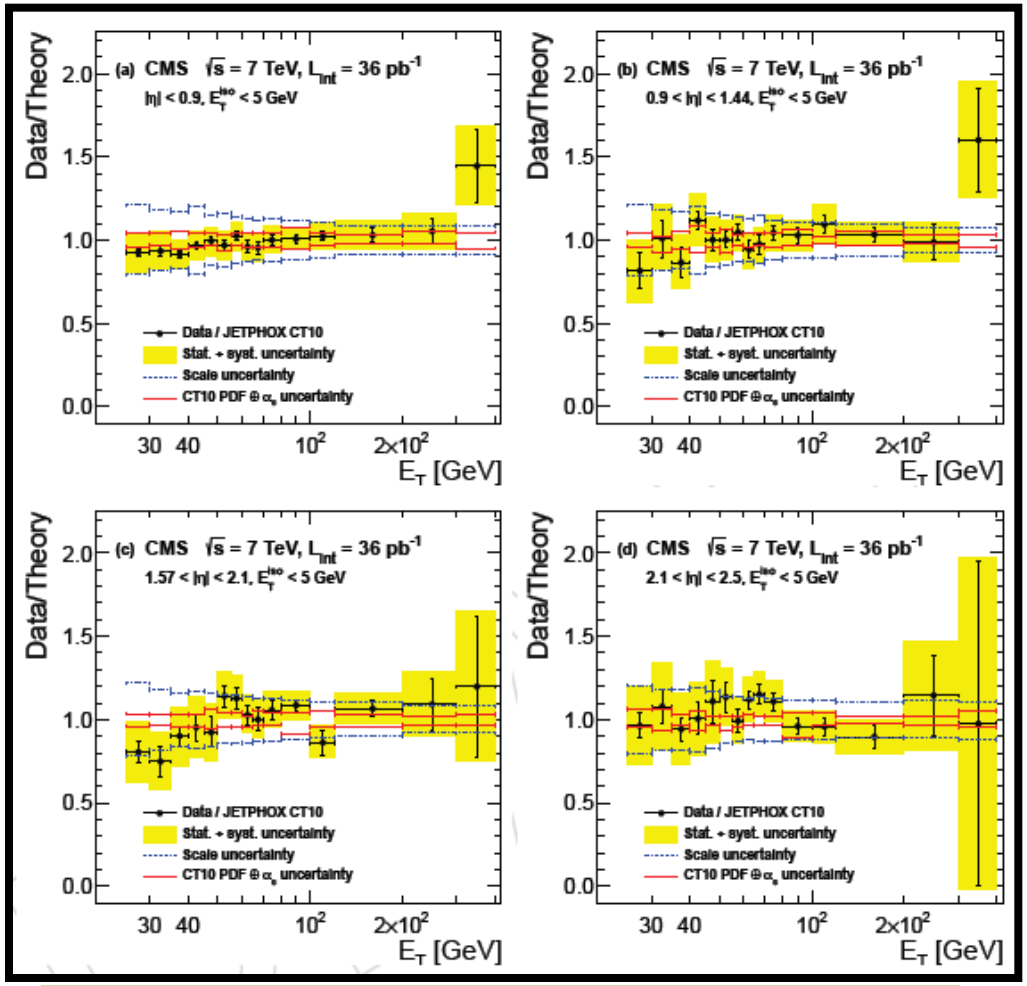


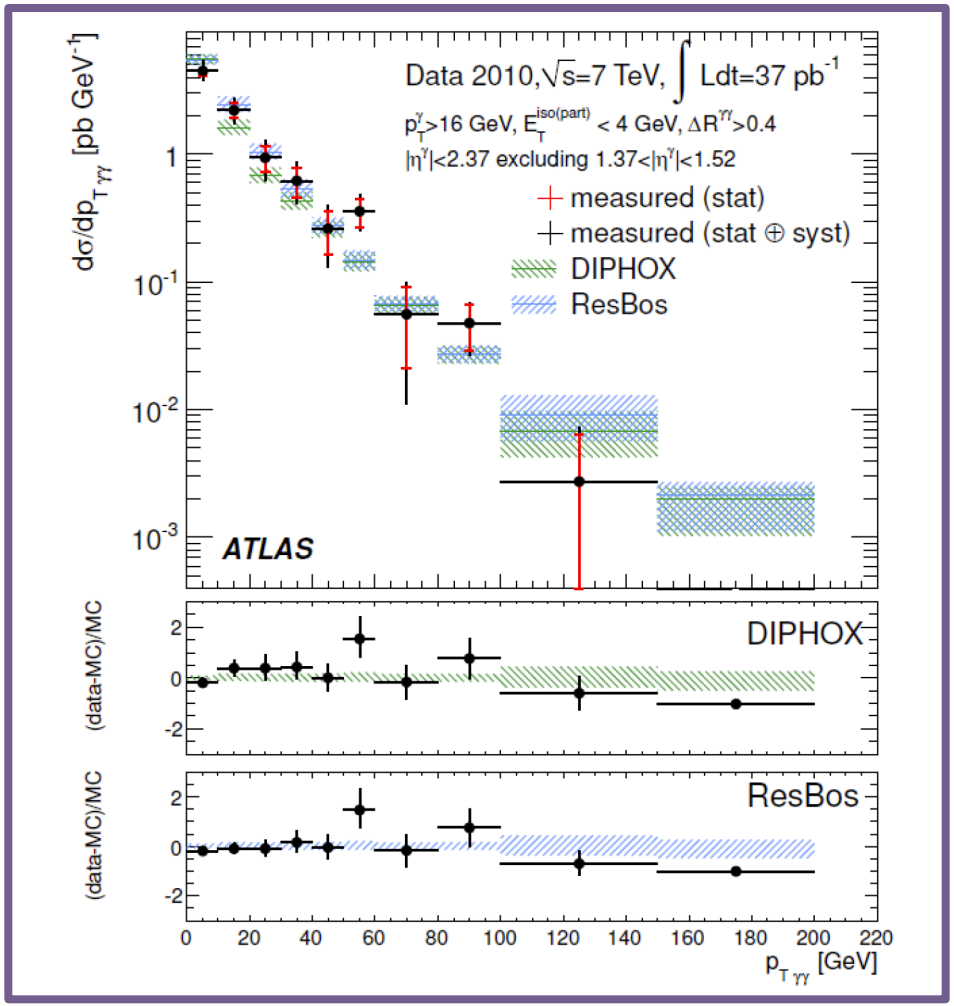
- Good agreement between data and theory for $M_{\gamma\gamma}$>30 GeV/c^2
- SHERPA and NNLO describe the "shoulder" of the data at $P_T(\gamma\gamma)$ = 20 – 50 GeV/c
- Only NNLO describes the full $\Delta\phi_{\gamma\gamma}$ data spectrum

Costas Vellidis, FNAL

(Di)Photons at LHC

CMS: PRD 84, 052011 (2011)





ATLAS: PRD 85, 012003 (2012)

- Data/theory: Overall agreement with NLO QCD
- Experimental uncertainties ≥ PDF uncertainty
- Theory scale uncertainty > PDF uncertainty

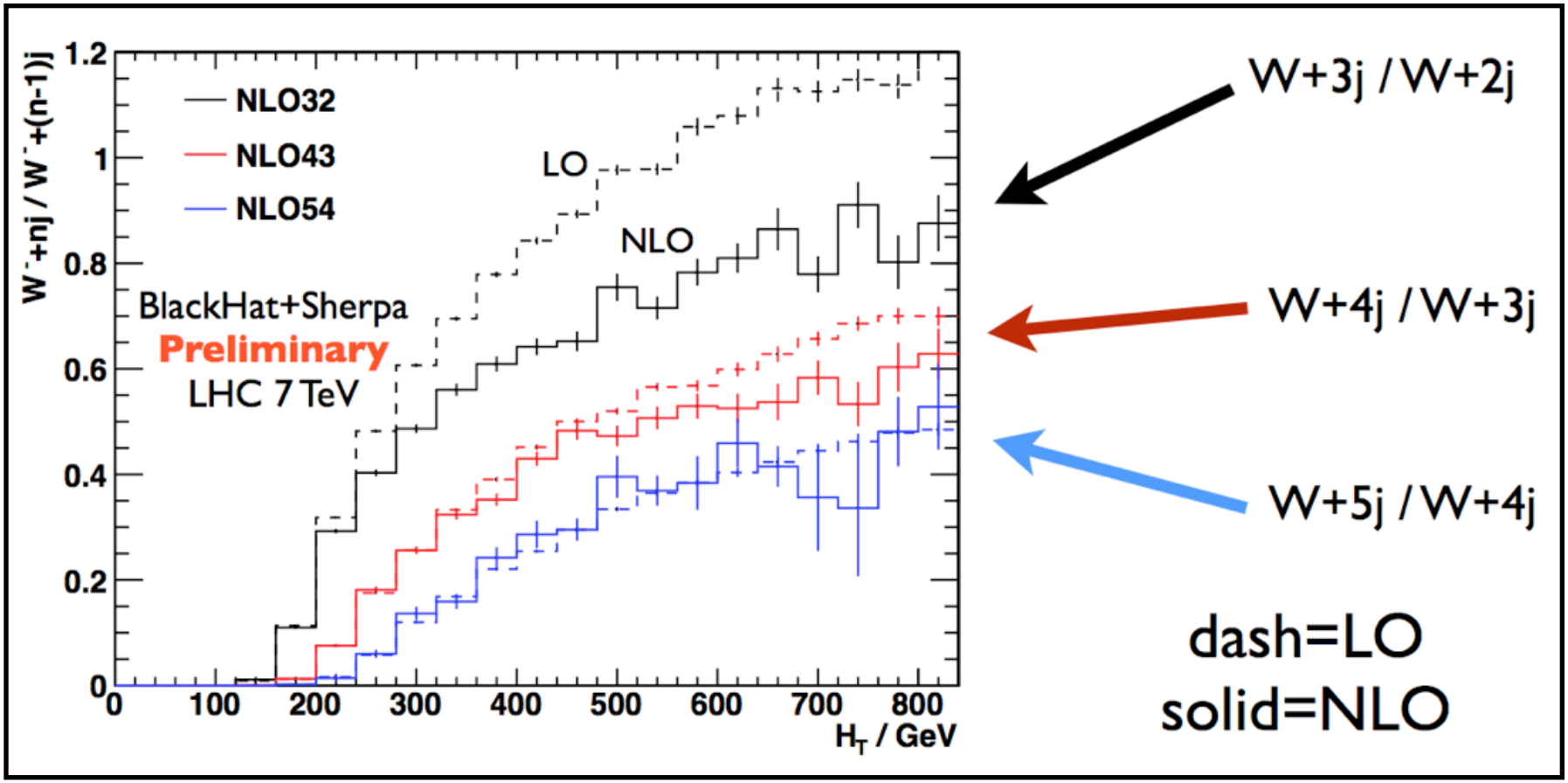
Carminati, Chetluru

W/Z+jets

W+5 jets at NLO

Ozeren

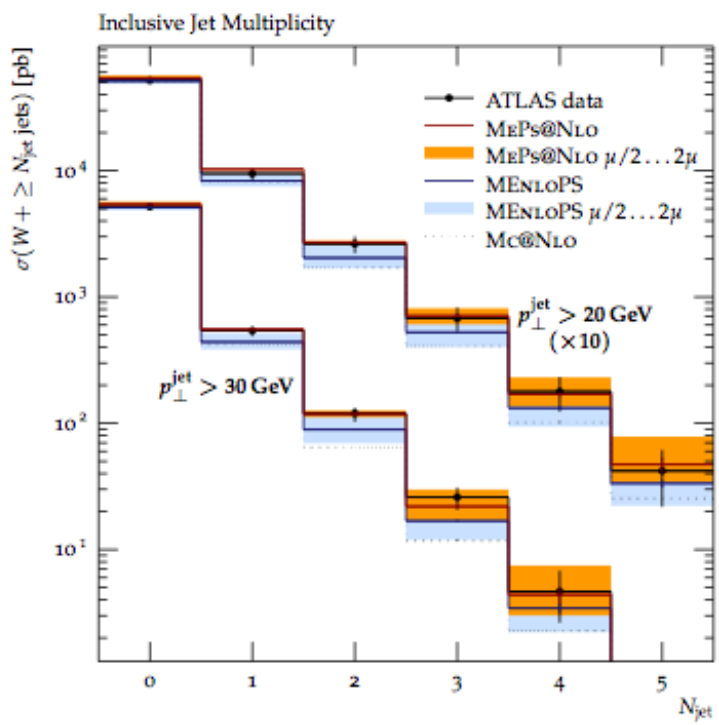
- BlackHat: preliminary results presented for jet ratios



- Coming soon: web-page for distributing n-tuples with sample analysis routines, easy variation of scales, pdfs

MEPS@NLO in Sherpa

- Merging procedure at NLO ("on steroids"?)
- First hadron collider application: W+jets (up to 2 at NLO)



$pp \to W$+jets (0,1,2 @ NLO; 3,4 @ LO)

- $\mu_{R/F} \in [\frac{1}{2}, 2]\, \mu_{\text{def}}$
  scale uncertainty much reduced
- NLO dependece for
  $pp \to W$+0,1,2 jets
  LO dependence for
  $pp \to W$+3,4 jets
- $Q_{\text{cut}} = 30$ GeV
- good data description

ATLAS data Phys.Rev.D85(2012)092002

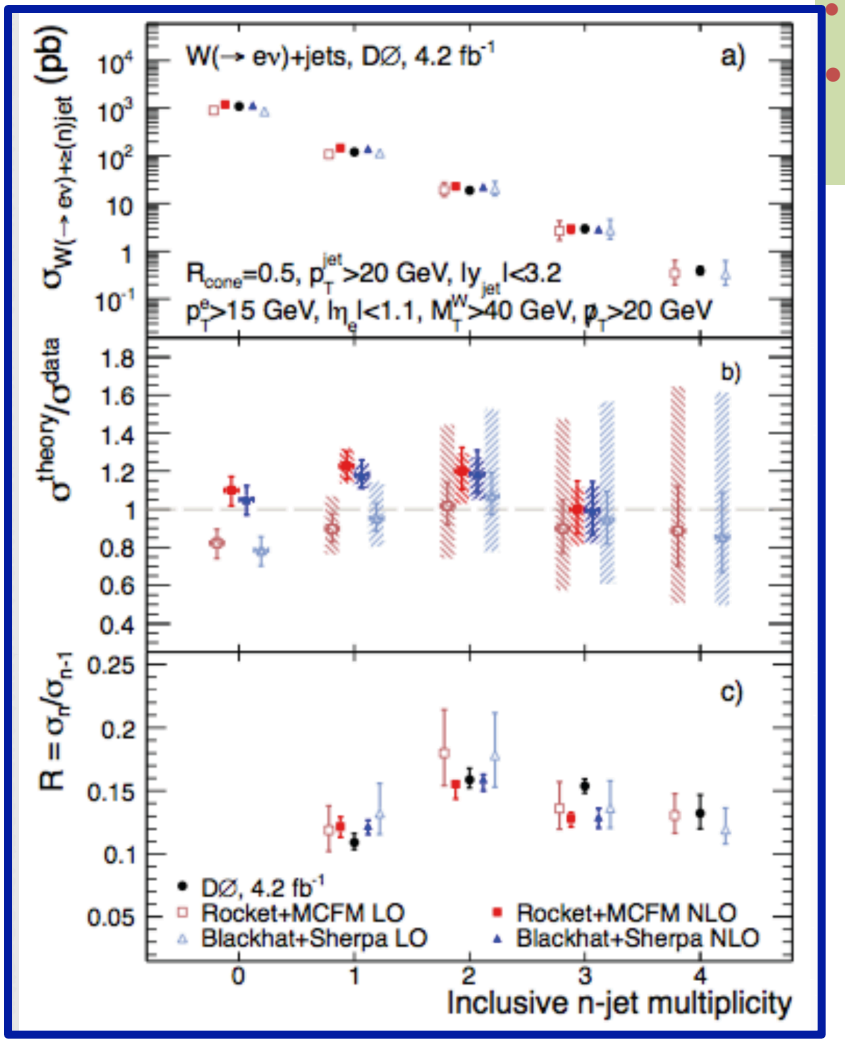
Schoenherr

W/Z + Jets at Tevatron

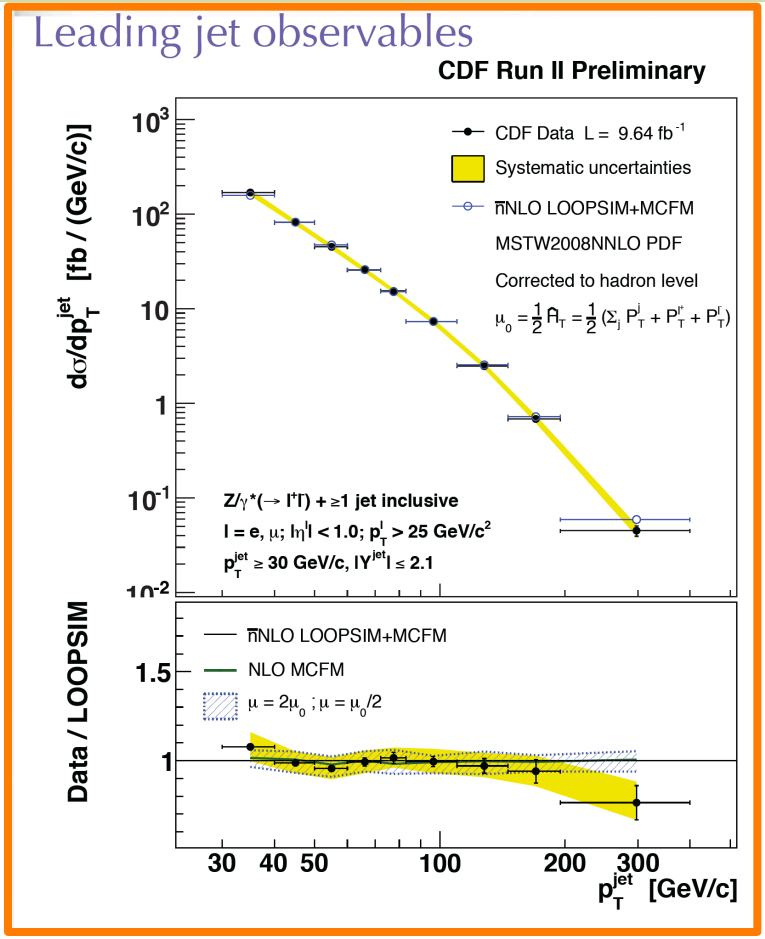
Lammers

Jet multiplicity

- Comparisons of jet multiplicities with NLO up to W+3 jets
- Good agreement Rocket+MCFM and BLACKHAT+SHERPA
- Good agreement of LOOPSIM+MCFM and MCFM with leading jet p_T in Z+jets data



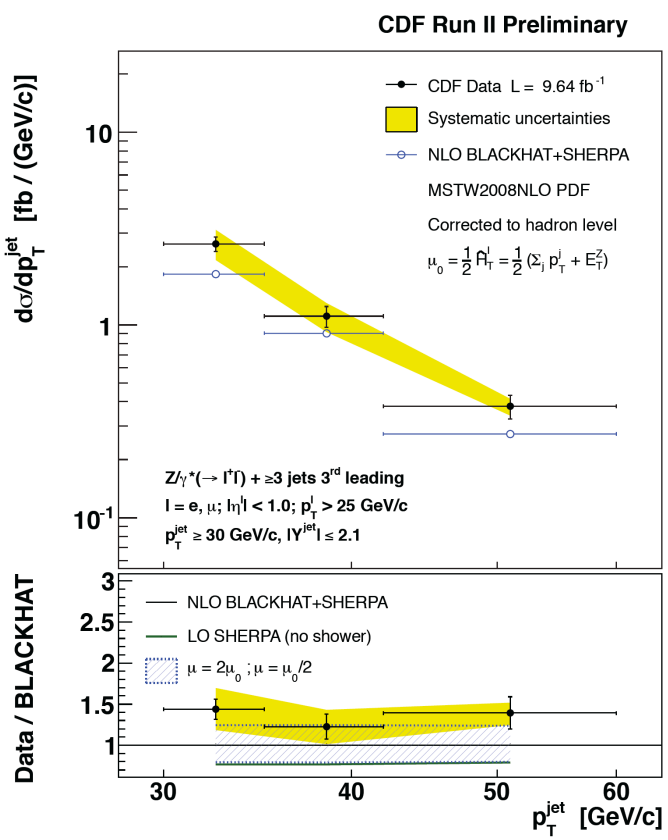
D0: arXiv:1106.1457 (2011)

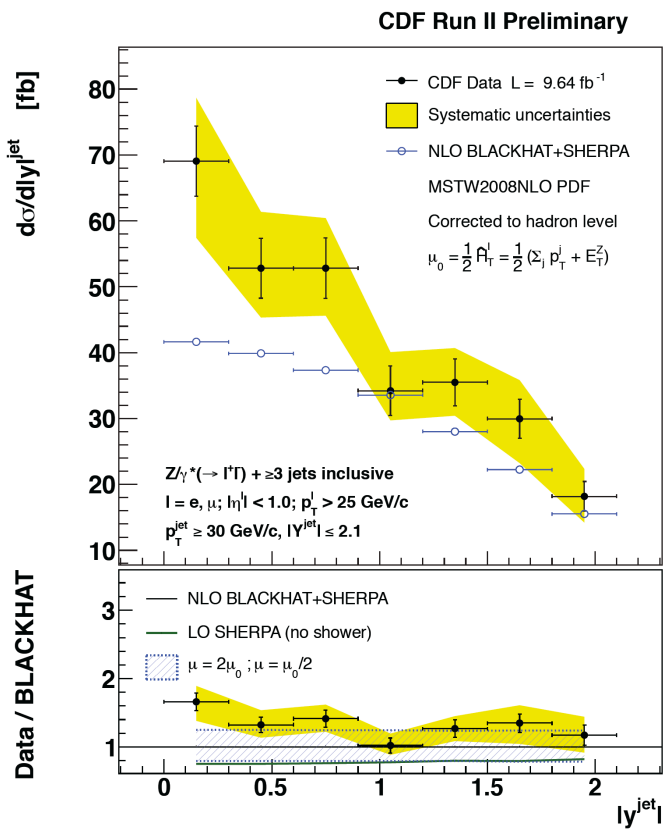


Z + 3jets at Tevatron

Lammers

Direct measurement of jet kinematics with large multiplicities





3rd jet observables

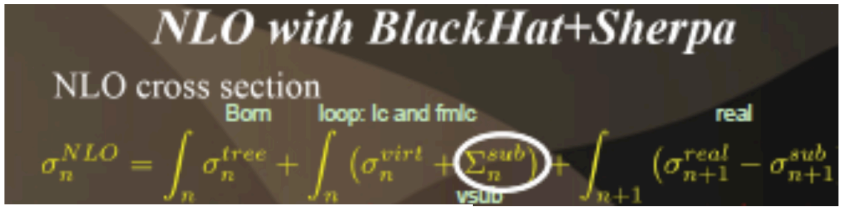
Data uncertainties are generally comparable or smaller than theory

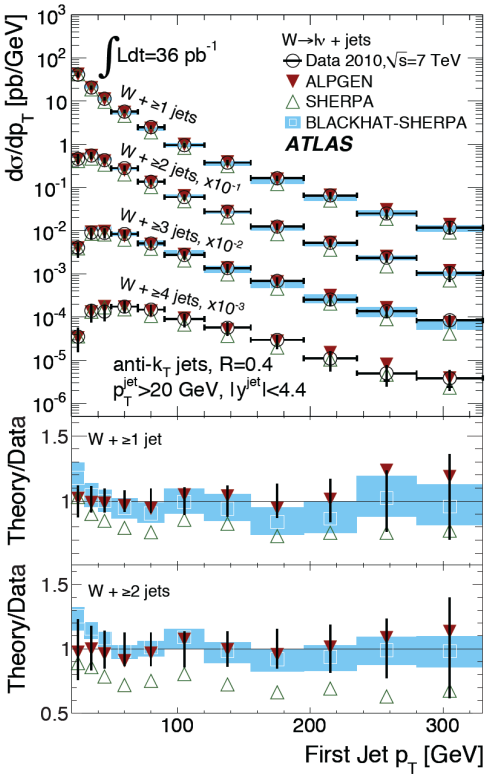
NLO Z+3 jet predictions recently calculated

W/Z + Jets at LHC

Mishra

- Accurate predictions for W/Z+jets production at the LHC are available
  - Monte Carlo event generators
    - NLO + parton shower (MC@NLO, POWHEG...)
    - LO (many legs) + parton shower (Alpgen, MadGraph, Sherpa)
  - Parton level codes for distributions at NLO
    - BlackHat, Rocket...
- Modern parton distribution functions
  - LHC data start to contribute to PDF fits



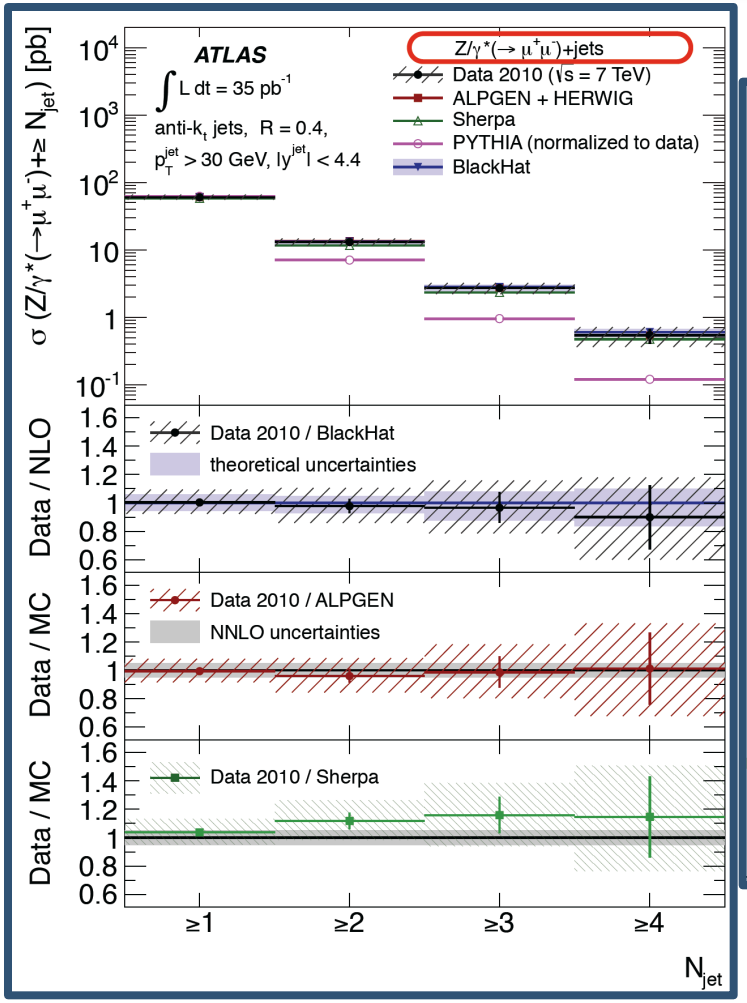


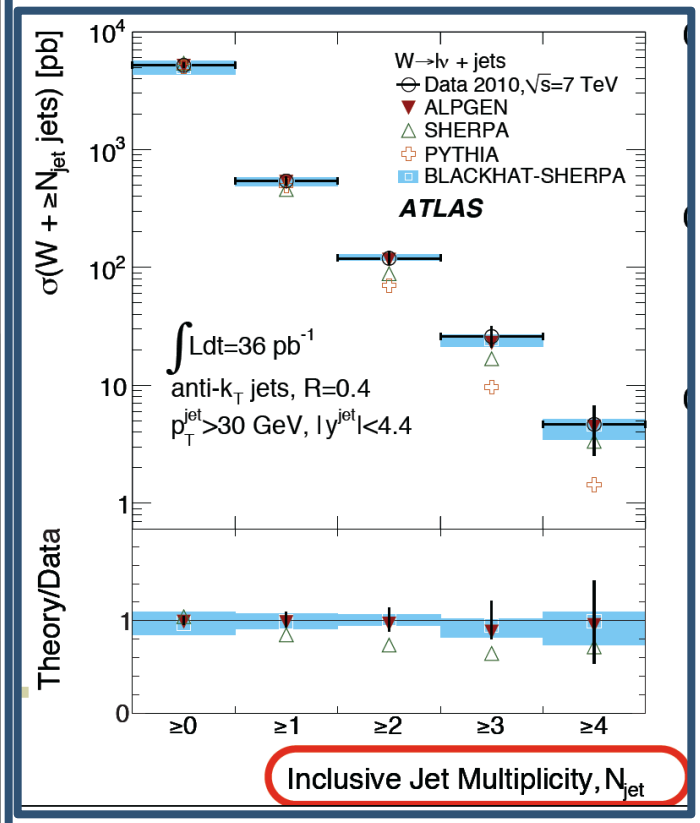
A comprehensive summary in J. Huston's talk at Cambridge, March 6, 2012. www.talks.cam.ac.uk/talk/index/32618

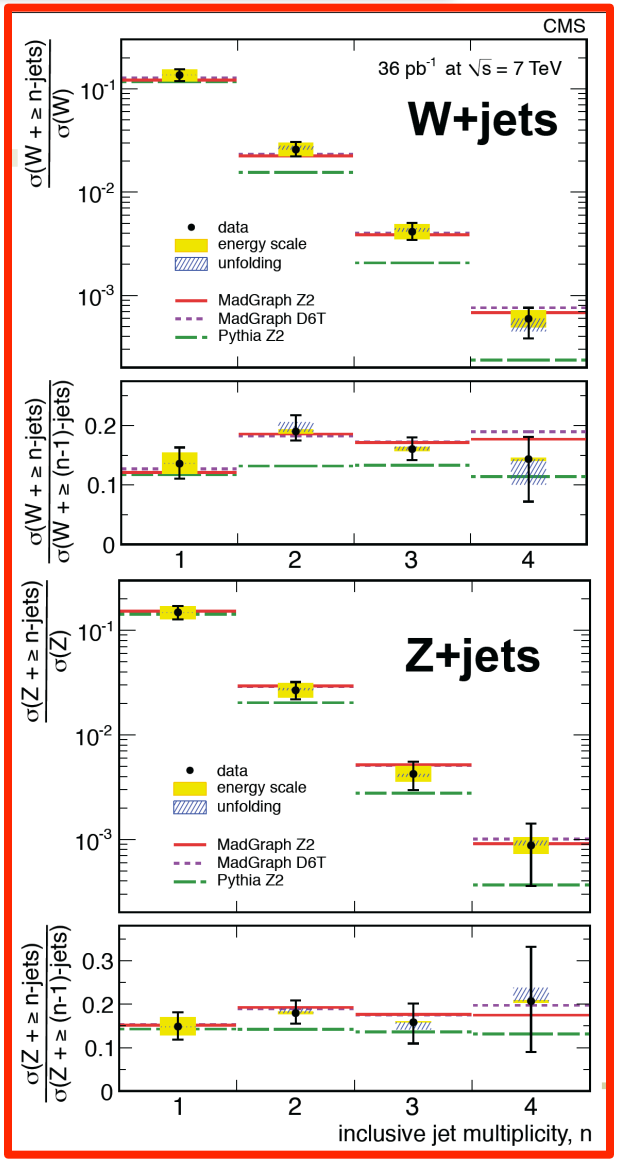
Breaking news: W+5 jets at NLO

W/Z + Jets at LHC: Jet Multiplicity

Mishra



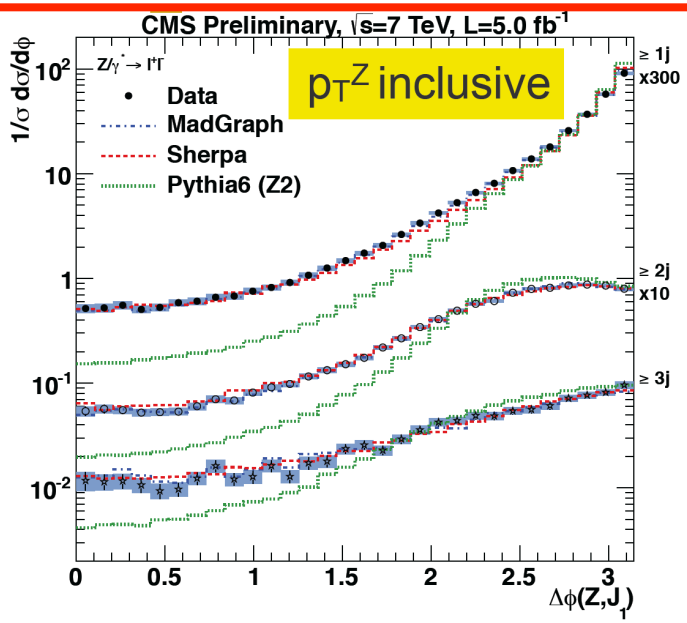


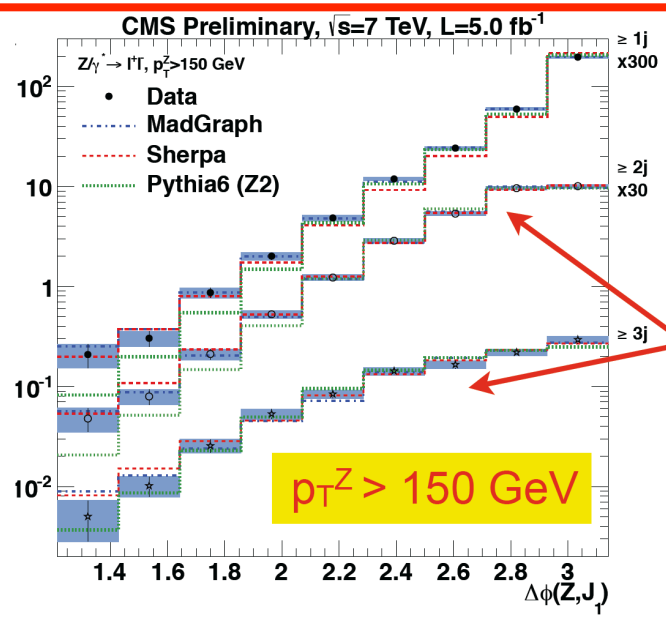


- Good agreement with Matrix Element + Parton Shower
- Poor agreement with PYTHIA

Z + Jets at LHC: Azimuthal Distributions

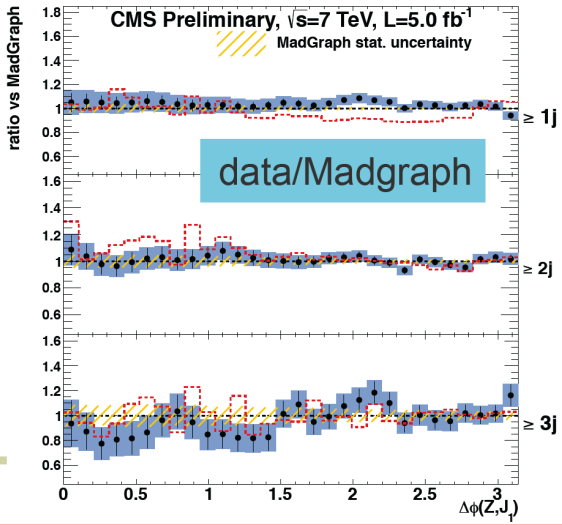
Mishra

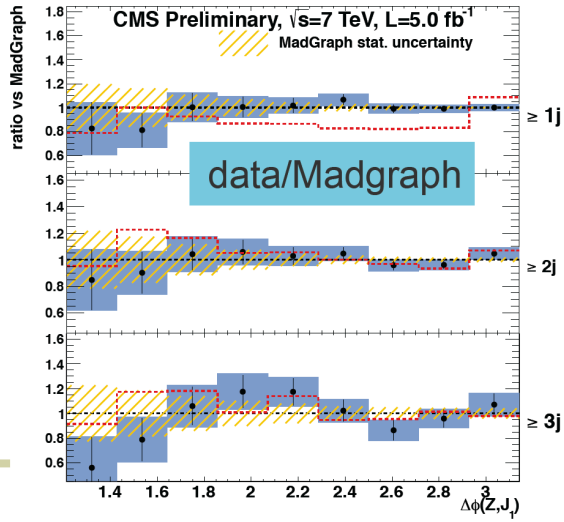




Error bars: data stat
Shaded: data syst
Hatched: MC stat

Distribution gets flatter with increase in N_{jets}, i.e., the correlation b/w Z & J1 gets weaker.

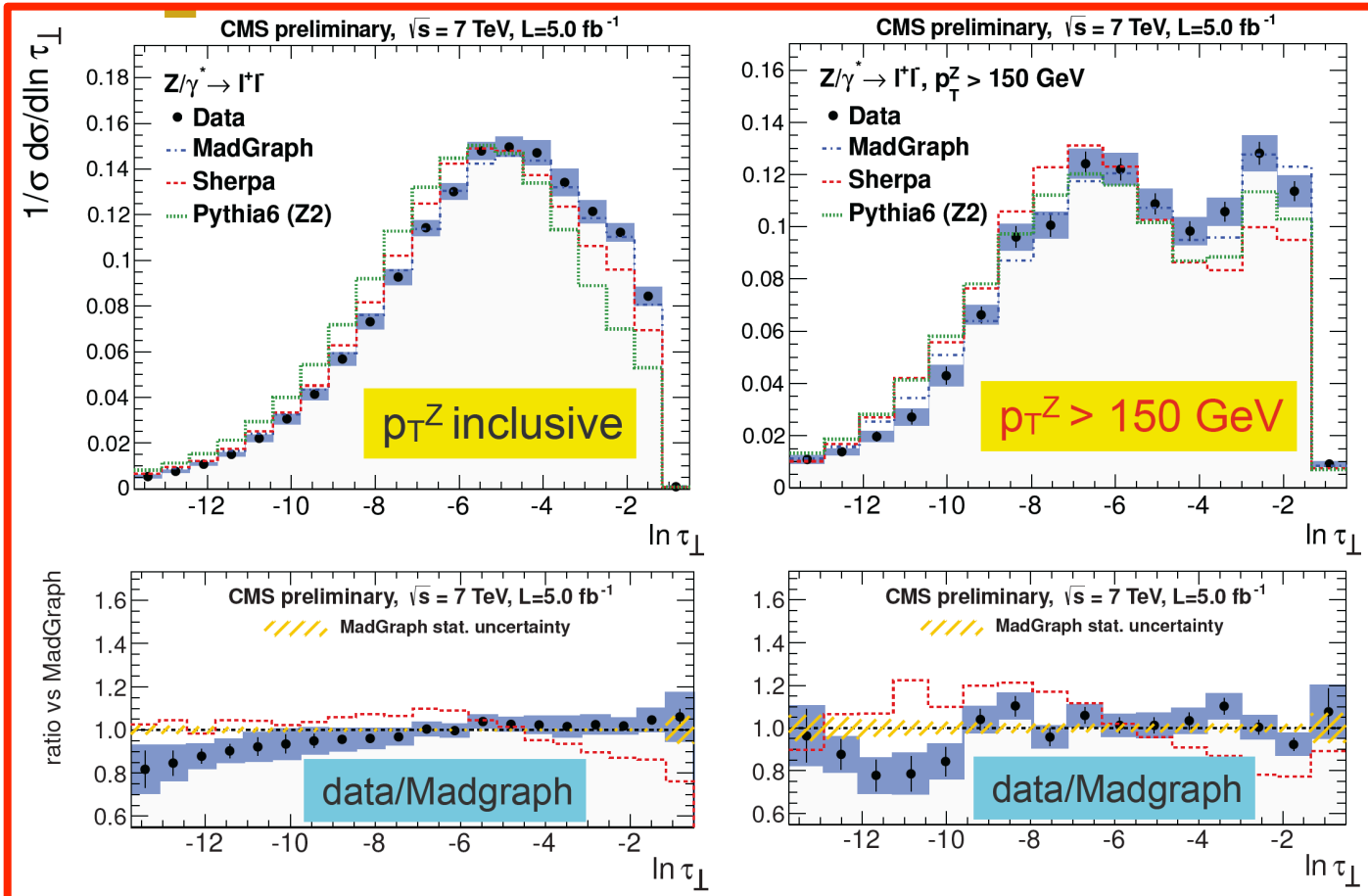




Both Sherpa (version 1.3.1, default tune) and Madgraph give a good description of data. Pythia is unable to describe multi-jet configurations.

Z + Jets at LHC: Event Shapes

Mishra



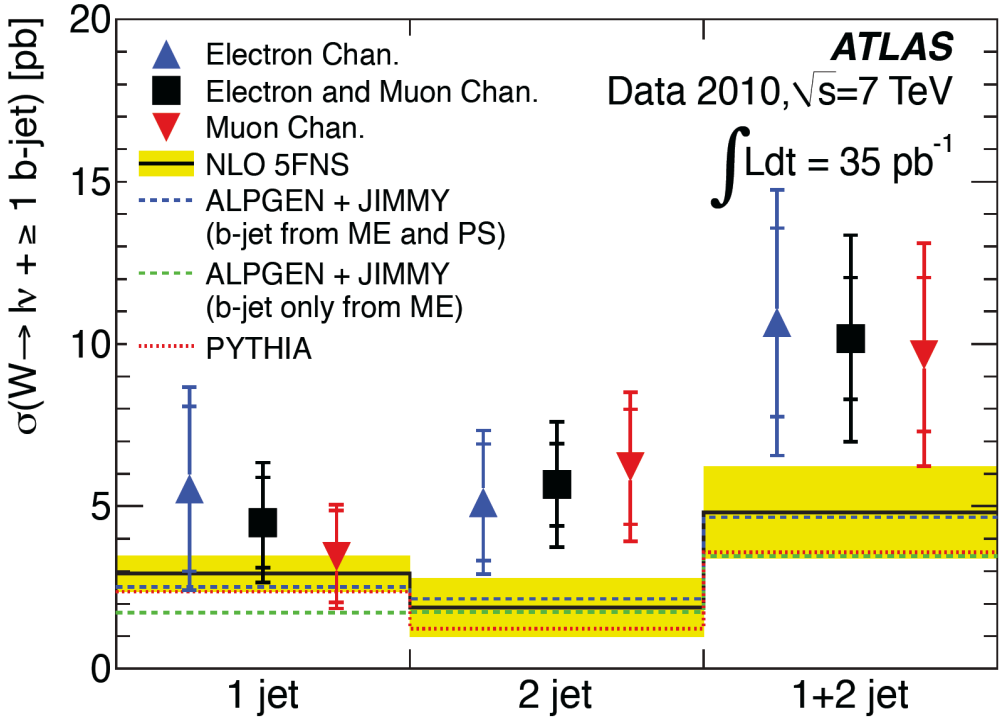
- Madgraph shows nice agreement with data
- Sherpa is shifted left
  - -Consistent with the pattern observed in ΔΦ distributions
  - -Fewer events with high N_{jets}

- The requirement on p_T^Z shifts the distribution towards lower values
- The selection enhances Z+1 jet topologies

W/Z + HF at LHC

Mishra

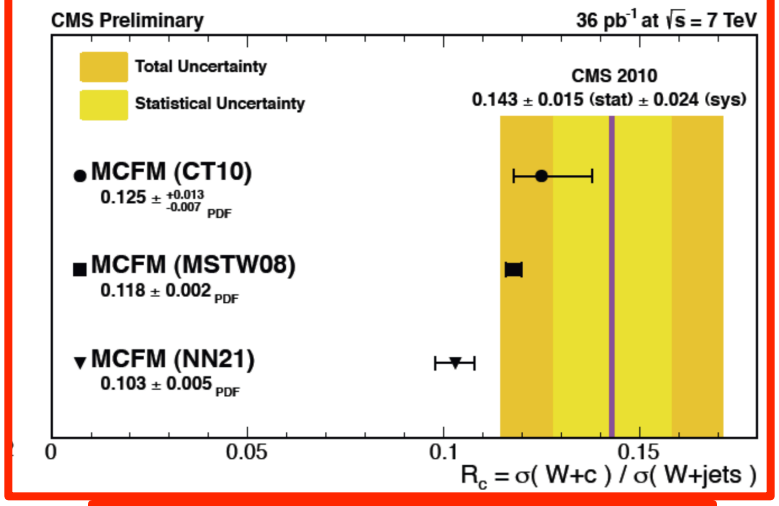
arXiv:1109.1470, Phys. Lett. B707 (2012) 418



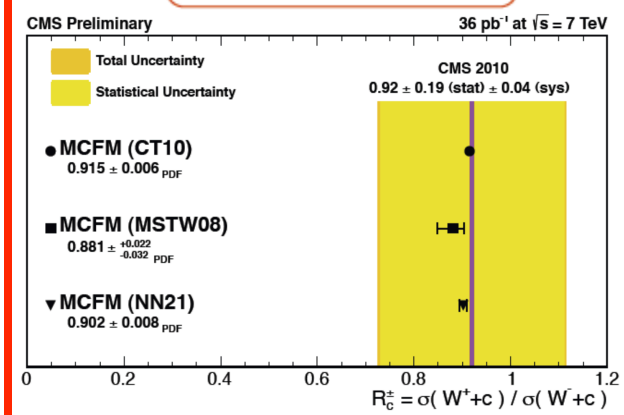
Some tension between theory & measurement, but need more data to conclude

Main systematic uncertainties: b-tag efficiency & purity, theory uncertainty (via acceptance), ttbar contribution, JES.

$\sigma(W+c)/\sigma(W+jets)$



$\sigma(W^+\bar{c})/\sigma(W^-c)$



$R^{\pm}_c \neq 1$ because of d/dbar PDF difference, result compatible with s=sbar PDF see hep-ph/1203.6781

Jet bins and vetoes

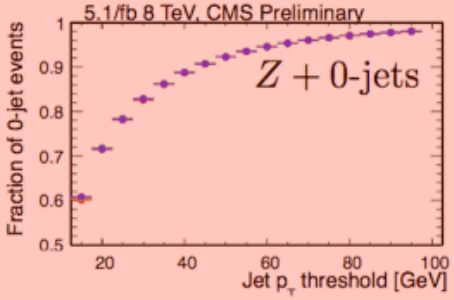
Stewart

- Much recent work on theory predictions in jet bins/with vetoes.

- Jet bins analyses are of growing importance experimentally
- Exclusive Jet bin theory should be validated with W+jets and Z+jets: $\sigma_0(p_{T1}^{\rm cut}), \sigma_1(p_{T1}^{\rm cut}, p_{T2}^{\rm cut}), \ldots$

  vary: rapidity cut,
  veto variable (eg. $\mathcal{T}_{\rm jet}$)

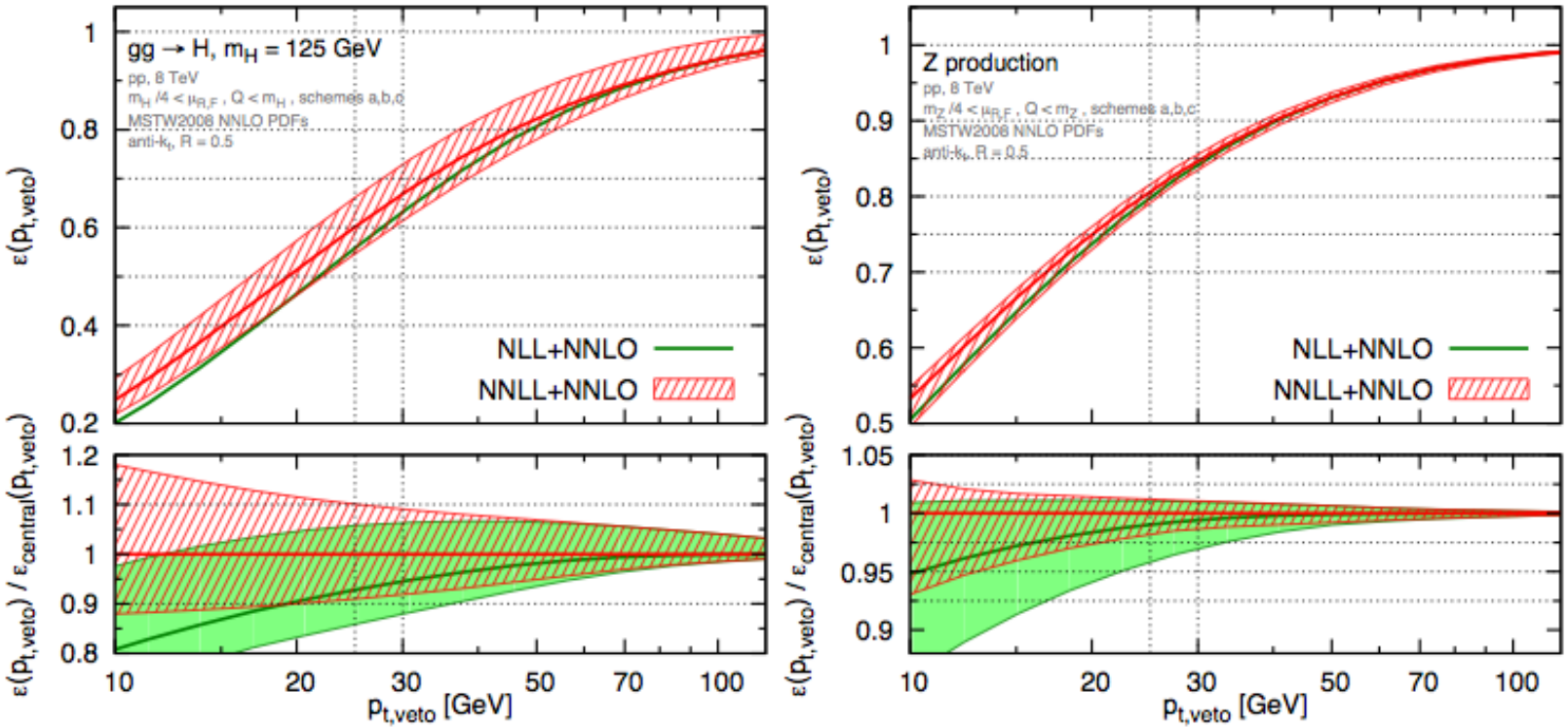
  ask: Fixed Order vs Resummation?
  Uncertainties reasonable?



- Resummed calculations for Boson + 1 jet: first theory results
- A calculation of the Higgs + 0-jet cross section at one higher order (N3LL) is feasible for $\mathcal{T}_{\rm cm}^{\rm cut}$, and may also be possible for $p_T^{\rm cut}$ if there is a factorization theorem.

NLL+NNLO predictions

Monni

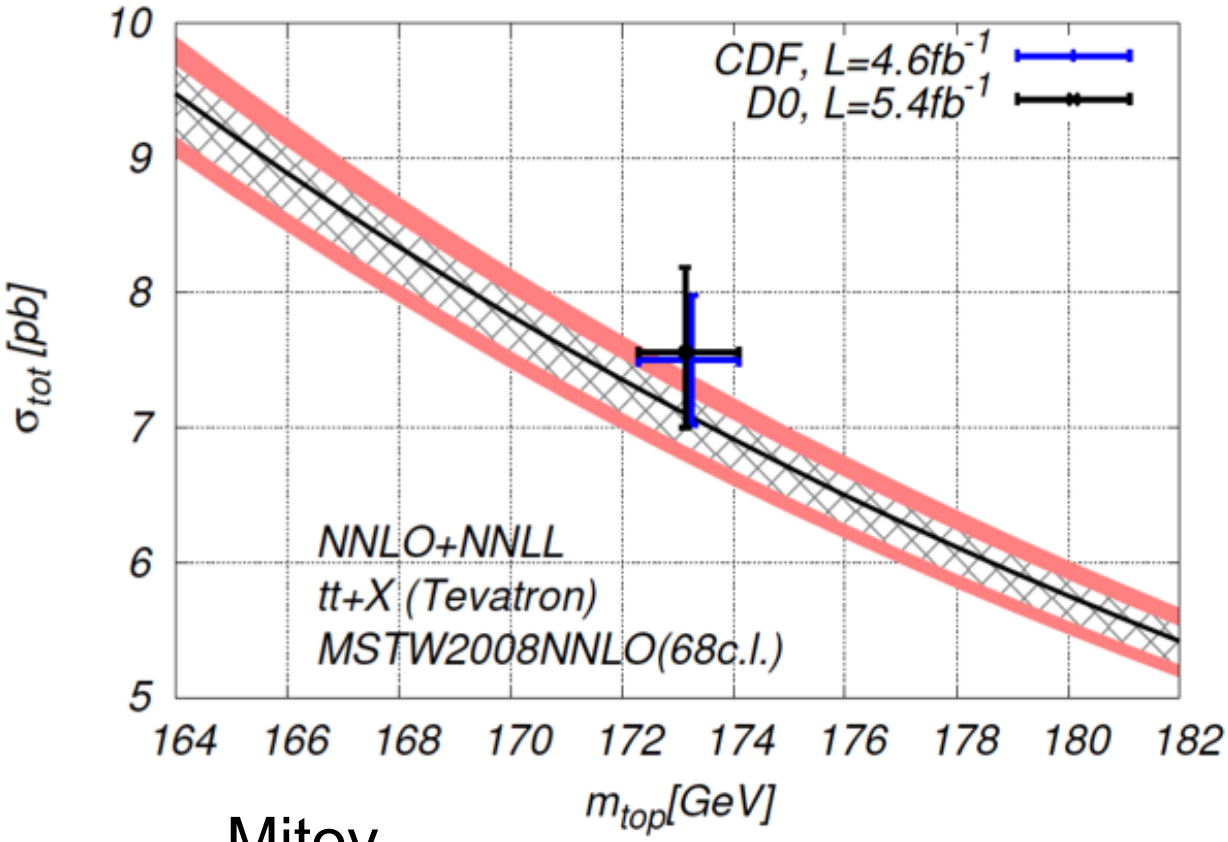


- Jet veto efficiency increased by $6-8\%$ in the region $25-30$ GeV when going from NLL to NNLL in the Higgs case. Moderate effect for Z-production ($\leq 1\%$)

Top Production

Top cross section @ NNLO

- All-fermionic channels done → most Tevatron phenomenology



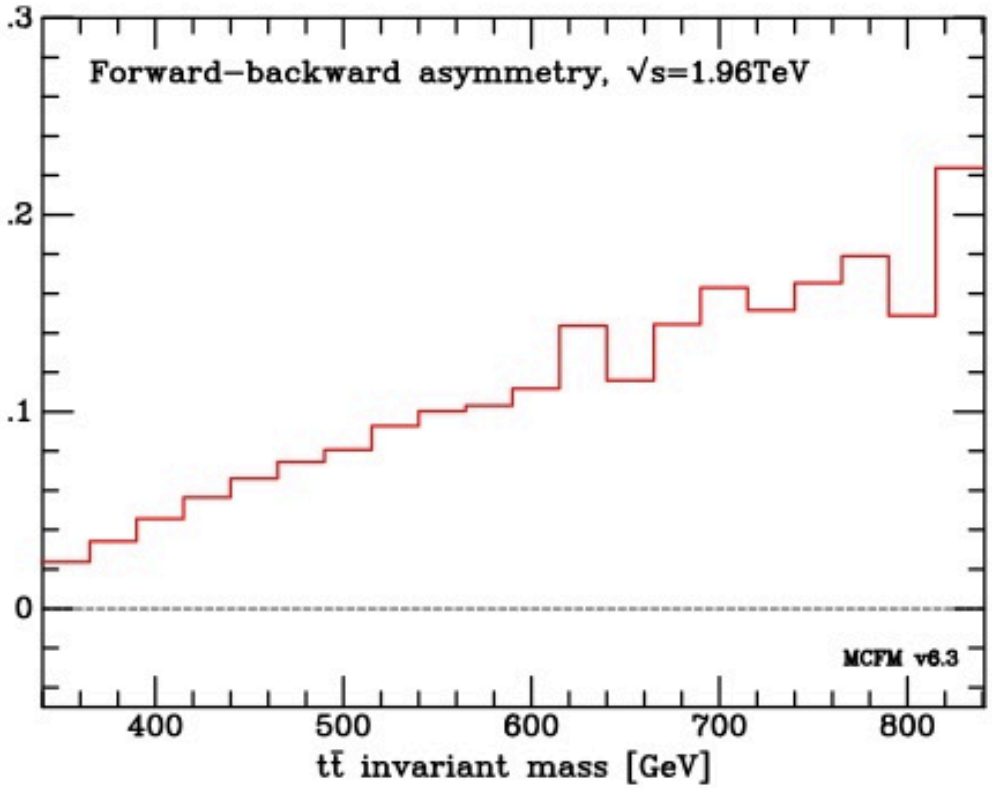
Mitov

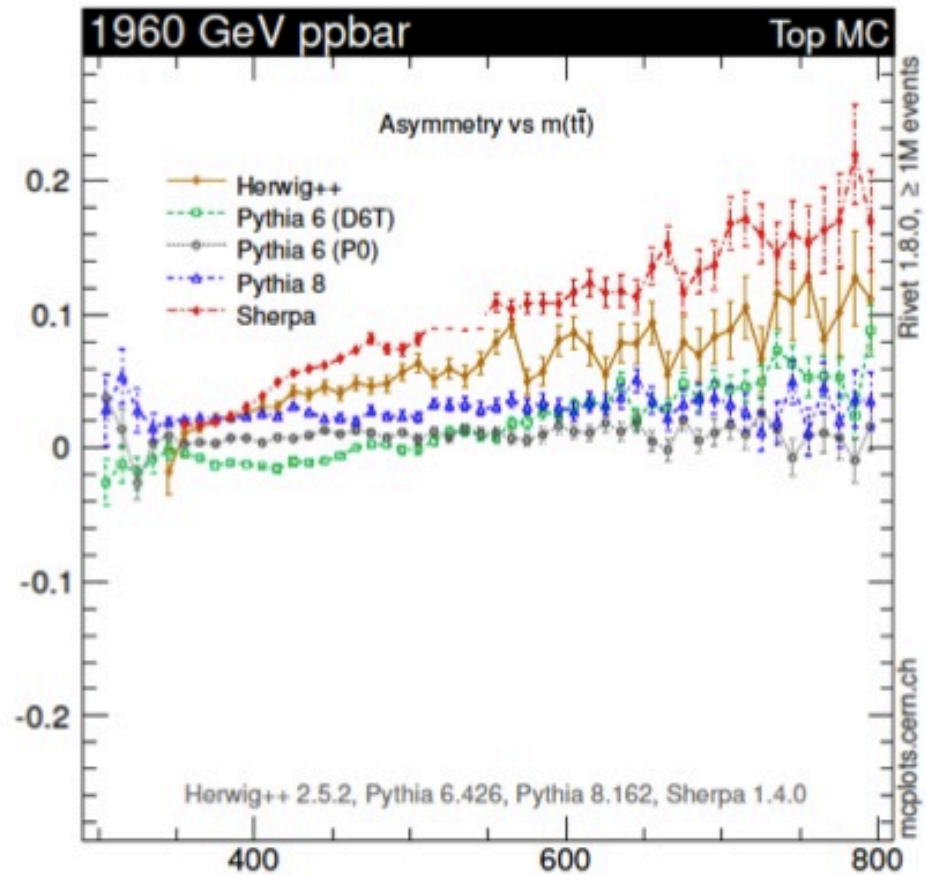
- qg channel
  - completed, prelim. result: 1% correction
  - checks, analysis ongoing

- gg channel
  - hard at work, "on track"

Parton shower asymmetry

Keith Ellis

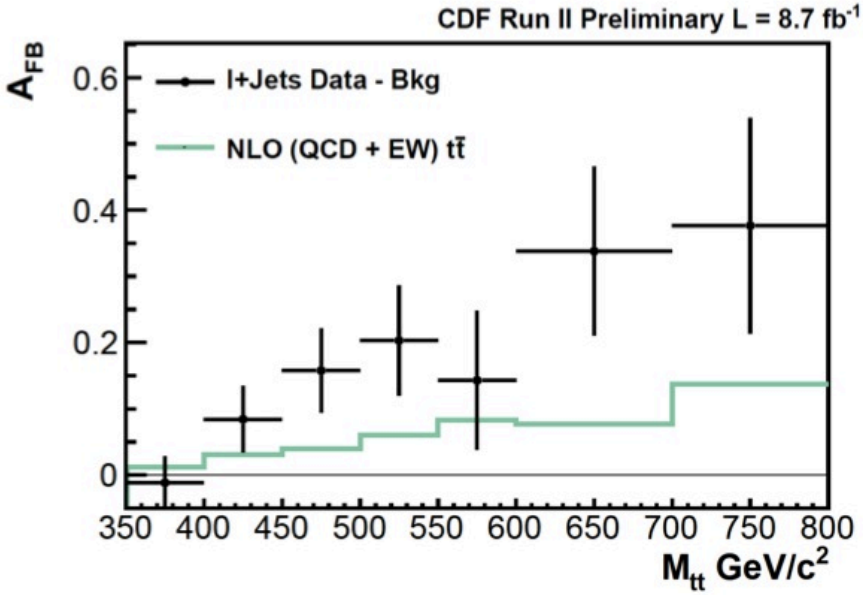


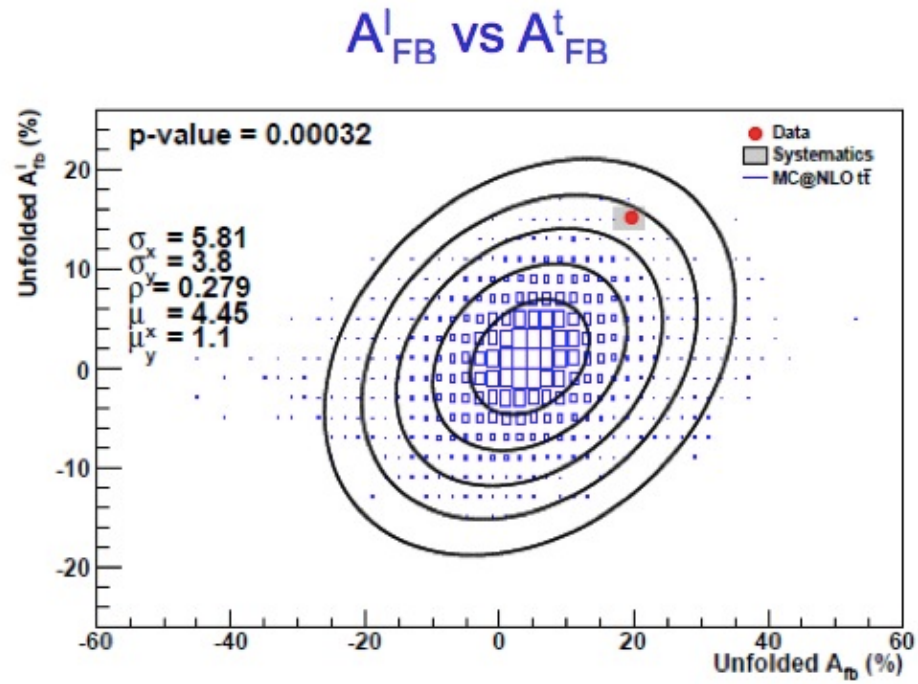


Top processes in MCFM

Keith Ellis

* Top pole approximation is a consistent approximation scheme to describe processes involving top quarks.
* MCFM now includes ttbar, t-channel single top, s-channel single top, ttW, with decay and radiation in the decay. It provides the most sophisticated possible NLO treatment of these processes within the context of the top pole approximation.
* At the LHC we will have the possibility of studying top production in exquisite detail.
* Asymmetries and spin correlations give a window into top production dynamics, and are calculable in perturbation theory.





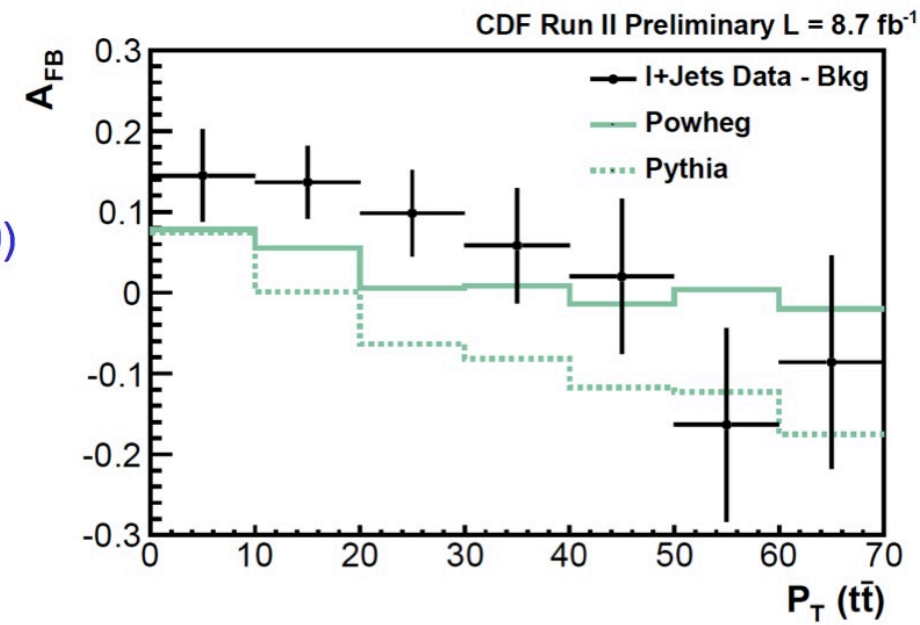
Status of Backward-Forward asymmetry

in l+jets

- inclusive asymmetry in agreement CDF+D0
- linear M_{tt} and Δy dependence of A_{fb} in tt system (CDF)
  - slopes 3σ from zero and 2σ larger than NLO prediction
- measured 2-3σ asymmetry in the lepton alone (CDF+D0)
  - mass dependence (CDF)
- p_t(tt) dependence agrees with Poweg/Pythia + offset

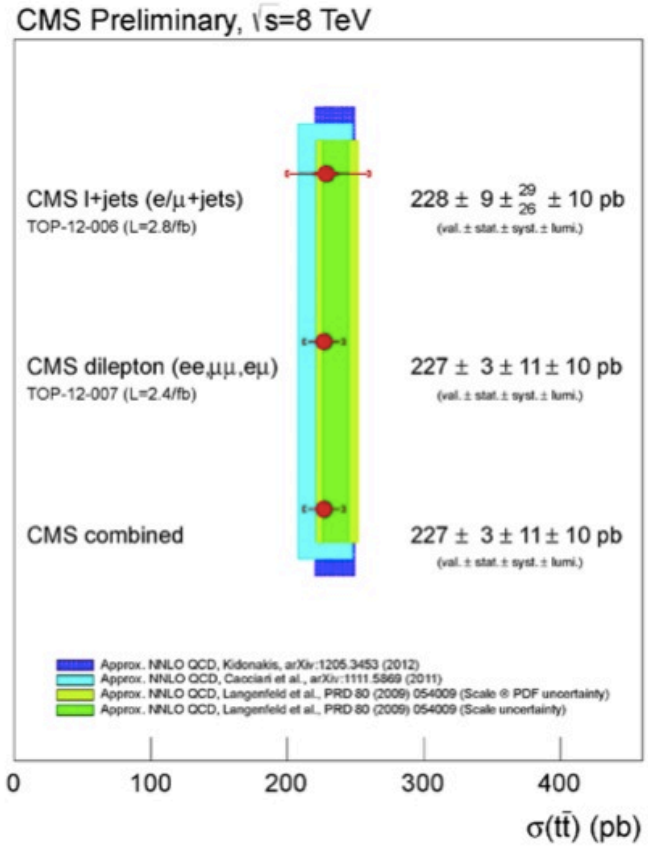
in dileptons

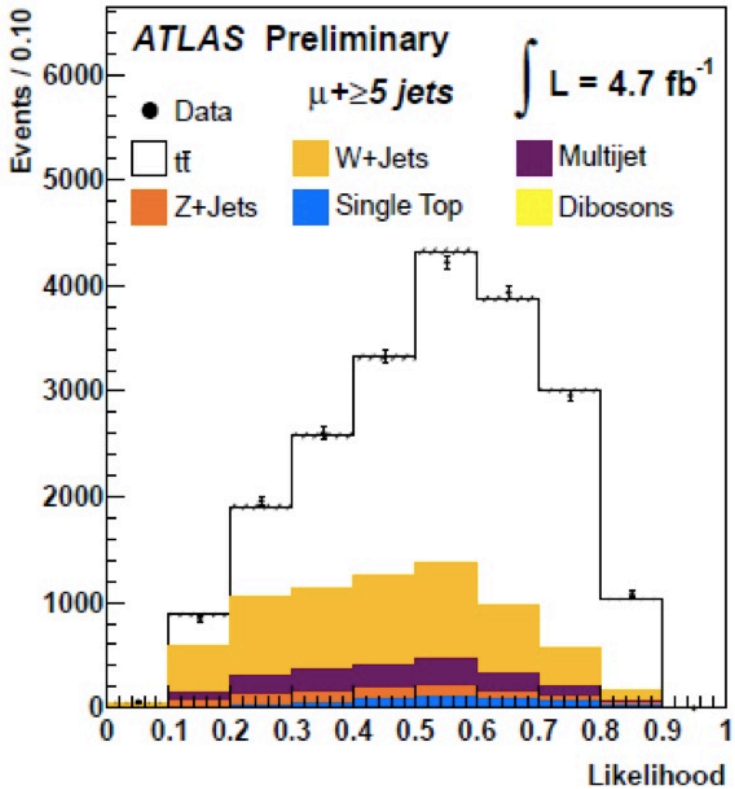
- significant A_{FB} in reco tt and ll Δy at CDF
- no significant A_{FB} in any lepton variable at D0

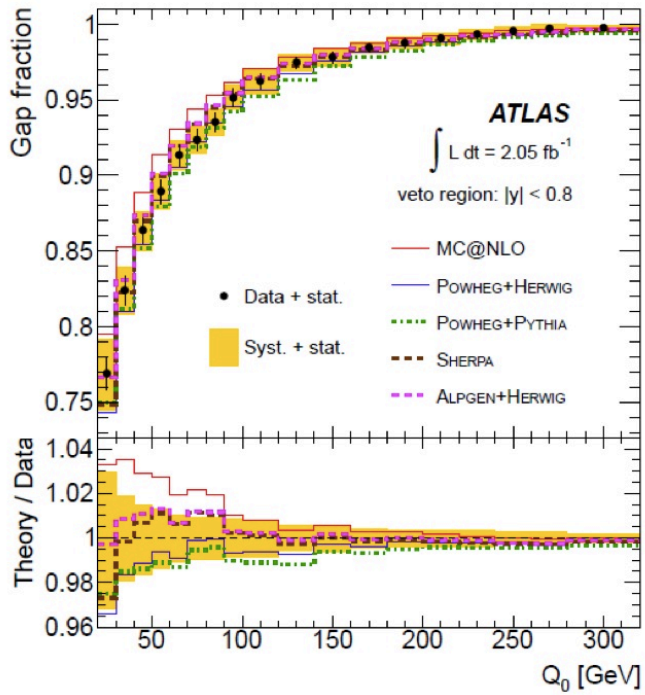


Top @ LHC

Frank-Peter Schilling







ttbar with jet veto

$$\sigma_{t\bar{t}} = 227 \pm 3\,(\text{stat.}) \pm 11\,(\text{syst.}) \pm 10\,(\text{lumi})\ \text{pb}$$

$$\sigma_{t\bar{t}j} = 102 \pm 2(\text{stat.})^{+23}_{-26}(\text{syst.})\ \text{pb}$$

$$\sigma_{t\bar{t}j}/\sigma_{t\bar{t}}^{\text{incl}} = 0.54 \pm 0.01(\text{stat.})^{+0.05}_{-0.08}(\text{syst.})$$

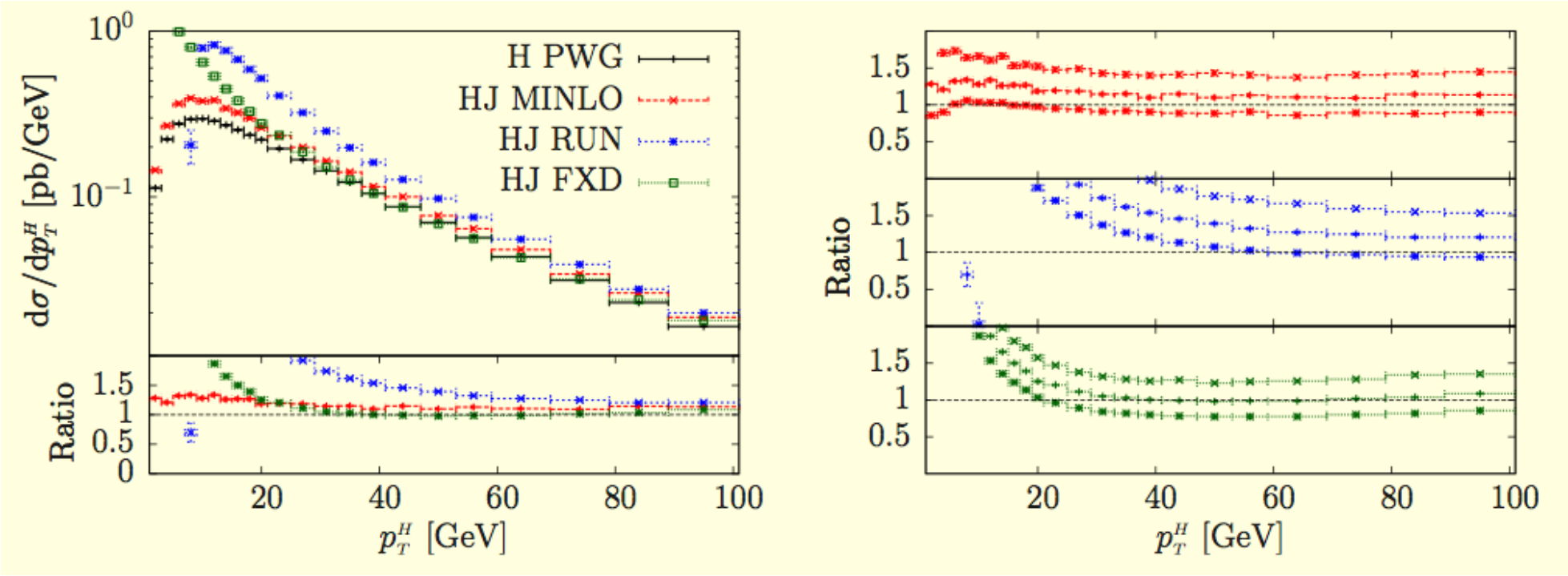
Campbell/Mellado/Varelas

Event Generators

POWHEG BOX

Nason

- MINLO: new scale-setting procedure
  - inclusion of Sudakov logs improves usual NLO behavior



- Coming soon: easy scale/pdf changes in POWHEG events, GoSam interface for more NLO, NLO+PS in resonance decays

aMC@NLO

Zaro

Limitations in v4

- Identification of FKS i/j pair hardcoded and based on particles identities rather than on interactions
  - Difficult to generalize to new models or non-QCD perturbations
- 4glu R2 too much complicated to be implemented in Fortran
  - Virtuals for processes with 4glu vertices incomplete
- No finite width effects in the loops

Improvements in v5

- Splitting of legs based on the interactions in the model, and on their perturbation (QCD, QED...)
  - Fully model independent, possibility to extend to non-QCD perturbation
- 4glu R2 available, treated as sum of different color/lorentz structures
  - Any virtual ME can be generated
  - Also loop-induced processes available
- Complex-mass scheme soon available

- 2012: migration from MG4 to MG5 for speed and more versatility
- Aim for public release by end of the year

MadFKS

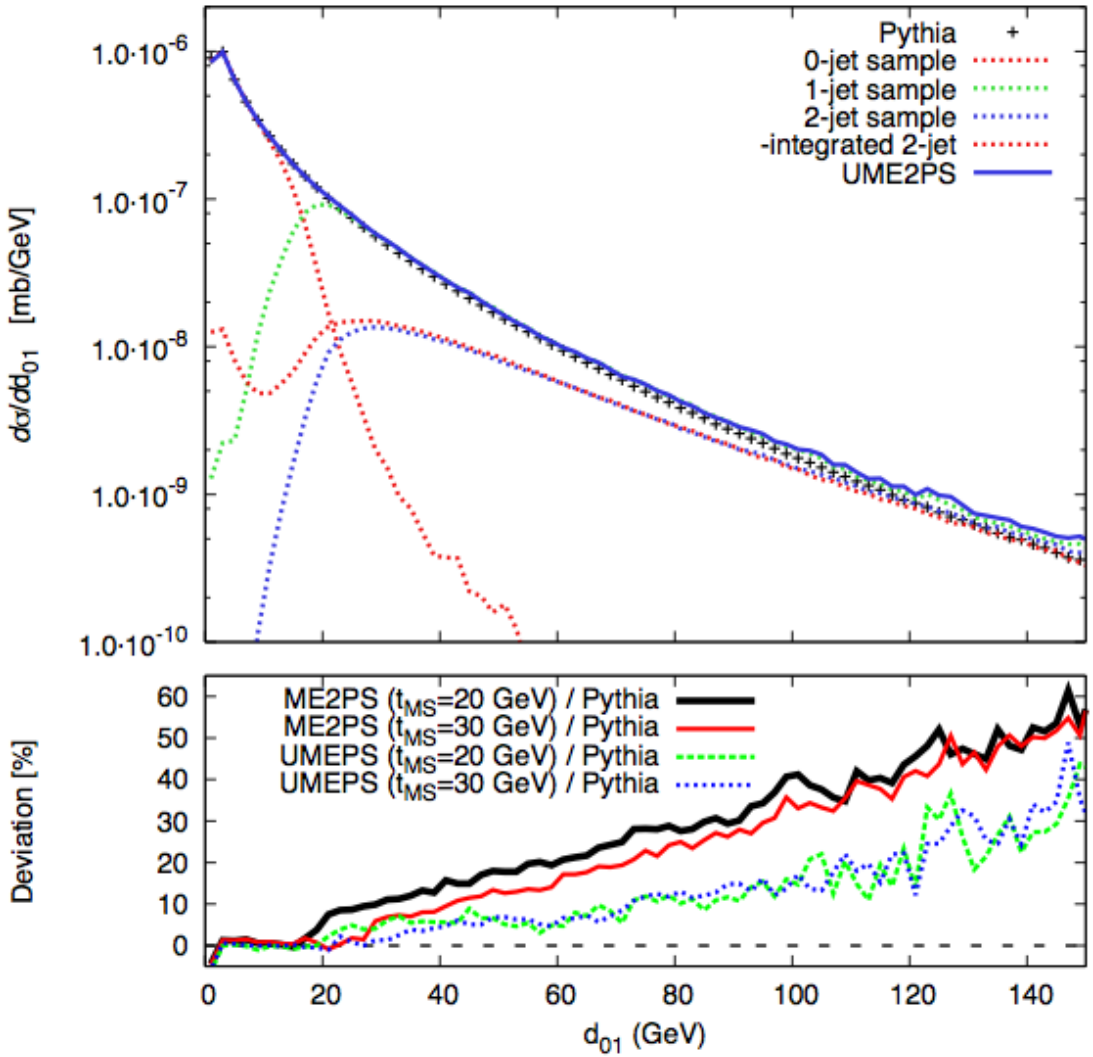
- Drastic speed improvement on code-generation (for pp > 3j ~ 15 mins)
- More compact code structure, sum/MC over different real emissions
  - Reduction channel number for multichannel integration (real > born), possibility to use real MEs not based on Feynman diagrams

MadLoop

- Speed improvements:
  - Recycle trees used in different diagrams
  - Call CutTools after helicity sum
  - Exploit open-loops techniques (expected time improvements ~ 10)
- Multiprecision support

CKKW-L in Pythia 8

Prestel



- Steps towards alternative NLO merging.
- "UMEPS": unitary MEPS → "UNLOPS"

…and finally

- Thanks to the organizing committee
  - Johannes Bluemlein, Keith Ellis, Walter Giele, Nigel Glover, Michelangelo Mangano, Fred Olness
- Thanks to the conveners
  - John Campbell, Albert de Roeck, Sasha Glazov, Pedro Jiminez-Delgado, Bruce Mellado, Pavel Nadolsky, Nikos Varelas
- Thanks to Brenda and Cathy for all of their logistical support
- Thanks to Steve Ellis for attending every session by evo
- …and most of all, thanks to you for coming to MSU for this workshop

- Make plans for QCD@LHC 2013 at …