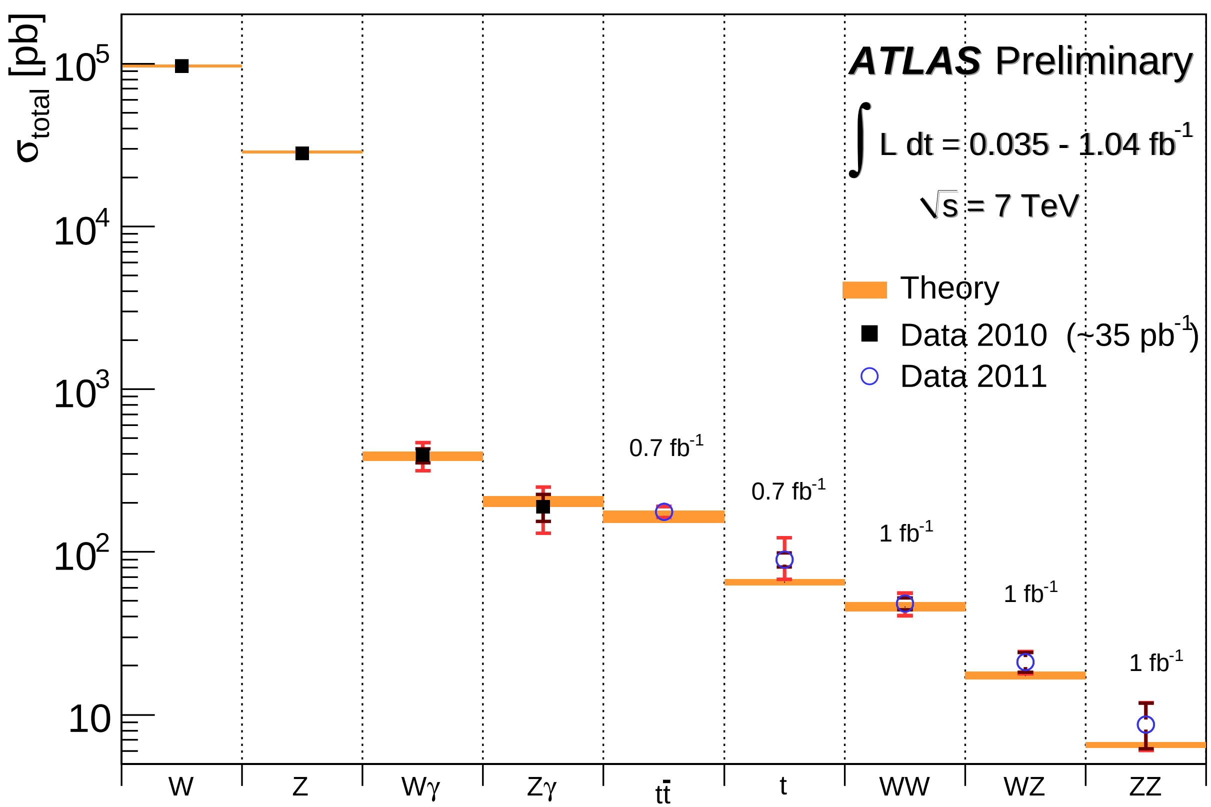
Summary of Hard QCD

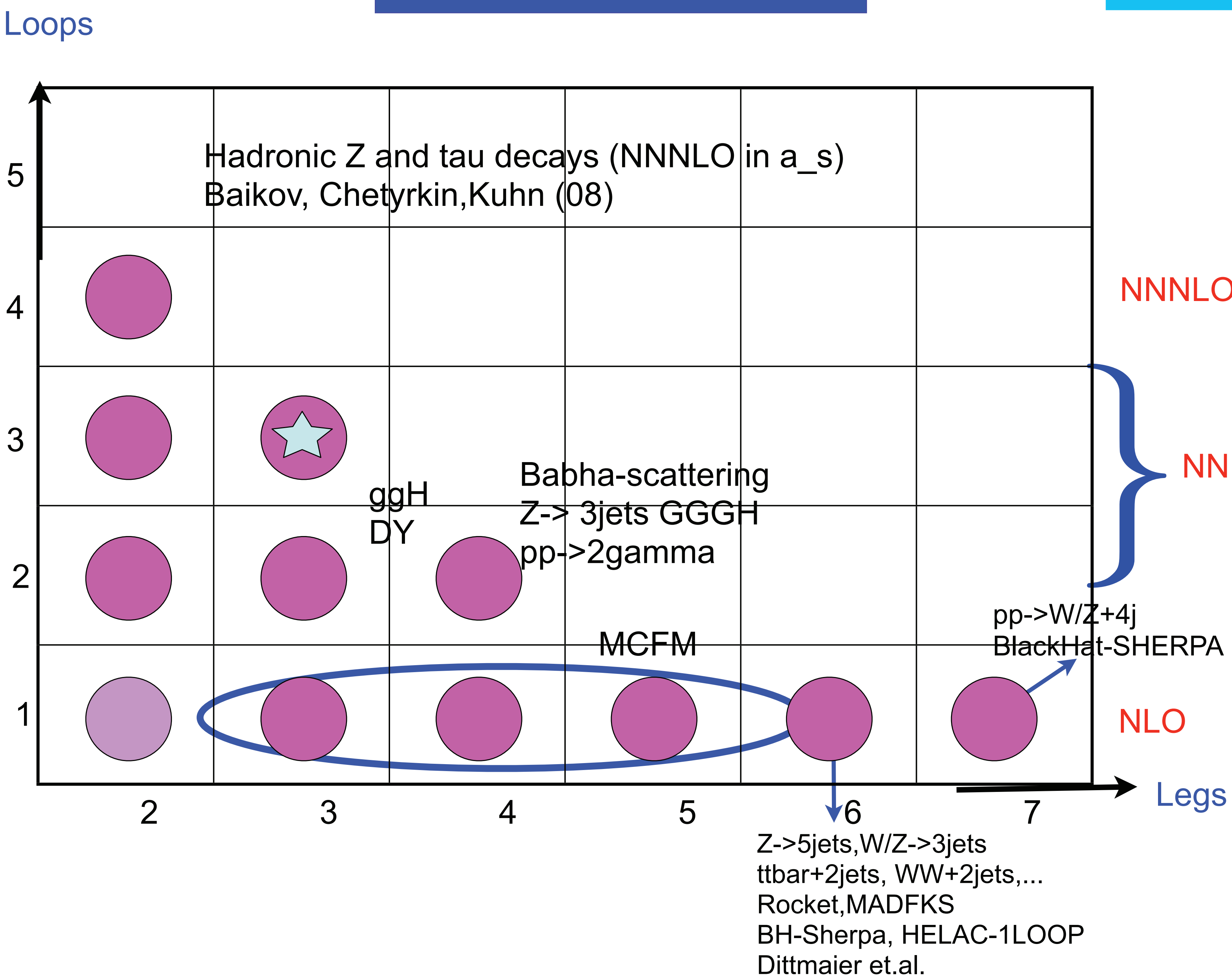
Michael Begel
Walter Giele
Klaus Rabbertz

- There were many interesting talks in our sessions... ...but I'm not going to summarize the presentations.
  - Thanks to all the speakers for the high-quality talks!
- We were impressed with the level of progress over the past several years:
  - Precision measurements from the LHC
  - Higher-order and resummed calculations
  - Advances in event generators
- But some challenges remain...



What is available?

Zoltan Kunszt



Dienstag, 23. August 2011

Recent developments for NLO codes

Zoltan Kunszt

- BlackHat + Sherpa: W/Z+ 4jets
  - improvements: First use of N = 4 derived expressions (Dixon, Henn, Plefka, & Schuster)

    Six quark subprocesses are included

- CutTools+HELAC: ttbar+2jets (Bevilacqua, Czakon, Papadopoulos, Worek)
- Rocket: W^+W^- + 2jets (Melia, Melnikov, Rontsch,Zanderighi)

  ttbar+1photon with top decay (Melnikov, Schultze, Scharf)

- New implementations
  - Samurai: Mastrolia, Ossola, Reiter, & Tramontano (OPP)
  - NGluon: Badger, Biedermann, & Uwer (D-dim. unitarity)
  - MadLoop: Hirschi, Frederix, Frixione, Garzelli, Maltoni, & Pittau
  - GPU implementation: Giele, Stavenga, Winter
  - Unordered colordressed amplitudes Giele, ZK, Winter

- Analytic work
  - Badger, Campbell, Ellis (pp->Wbbar); Badger, Sattler, Yundin (pp->ttbar)
  - Almeida, Britto, Feng & Mirabella

Nigel Glover

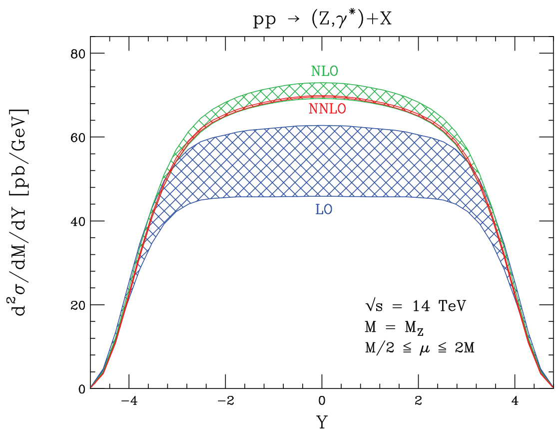
NNLO calculations for $2 \to 2$ processes

$$\mathrm{d}\sigma = \sum_{i,j} \int \frac{d\xi_1}{\xi_1}\frac{d\xi_2}{\xi_2} f_i(\xi_1,\mu_F^2) f_j(\xi_2,\mu_F^2) \mathrm{d}\hat{\sigma}_{ij}(\alpha_s(\mu_R),\mu_R,\mu_F)$$

$$\mathrm{d}\hat{\sigma}_{ij} = \mathrm{d}\hat{\sigma}_{ij}^{LO} + \left(\frac{\alpha_s(\mu_R)}{2\pi}\right)\mathrm{d}\hat{\sigma}_{ij}^{NLO} + \left(\frac{\alpha_s(\mu_R)}{2\pi}\right)^2 \mathrm{d}\hat{\sigma}_{ij}^{NNLO} + \mathcal{O}(\alpha_s^3)$$

Processes of interest

- ✓ $pp \to 2$ jets
- ✓ $pp \to \gamma$+jets
- ✓ $pp \to \gamma\gamma$
- ✓ $pp \to V$+jet
- ✓ $pp \to t\bar{t}$
- ✓ $pp \to VV$
- ✓ $pp \to H$+jet
- ✓ ...



Massively reduced theoretical error

Anastasiou, Dixon, Melnikov, Petriello (04)

– p. 2

Nigel Glover

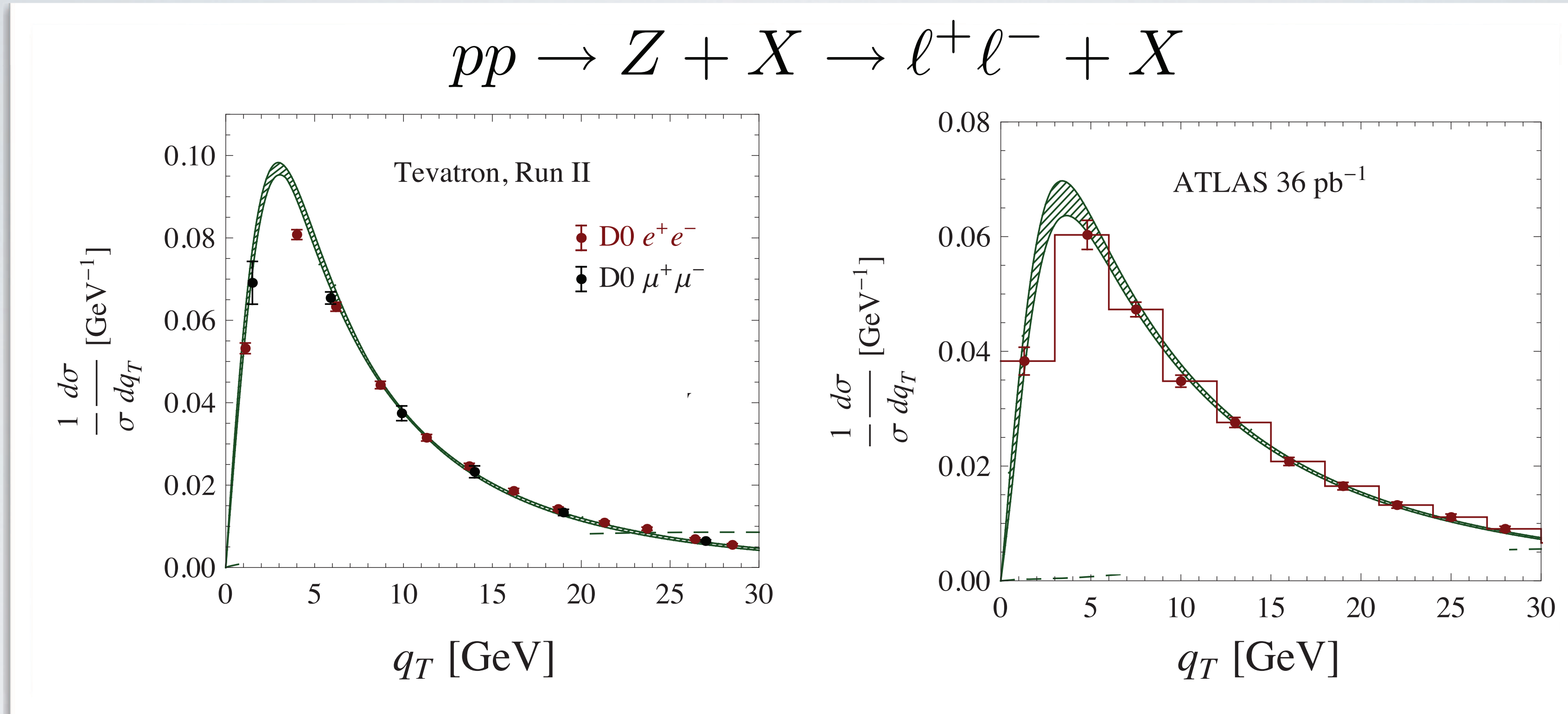
Applications to LHC processes

- ✓ All relevant matrix elements for $pp \to 2$ jet and $pp \to V + 1$ jet processes available for some time
- ✓ Can expect to have parton-level NNLO predictions for $pp \to 2$ jet and $pp \to V + 1$ jet in next couple of years
- ✓ Hope for significant reduction in theory (renormalisation scale/factorisation scale) dependence
- ✓ LHC already has increased dynamic range for jet studies - rapidity, transverse energy.
- ✓ Combined with excellent experimental jet energy scale uncertainty, there is the opportunity for improved measurements of
  - ✓ Parton distributions
  - ✓ Strong coupling
  - ✓ Internal structure of the jet
  - ✓ Rapidity gaps between the jets

– p. 12

Thomas Becher

TRANSVERSE MOMENTUM SPECTRUM



q_T spectrum of electroweak bosons (i.e. Z,W, γ^*, H) is one of the most basic quantities that can be measured at hadron collider.

Benchmark process, important for W-mass determination, Higgs search. New results both from Tevatron and LHC

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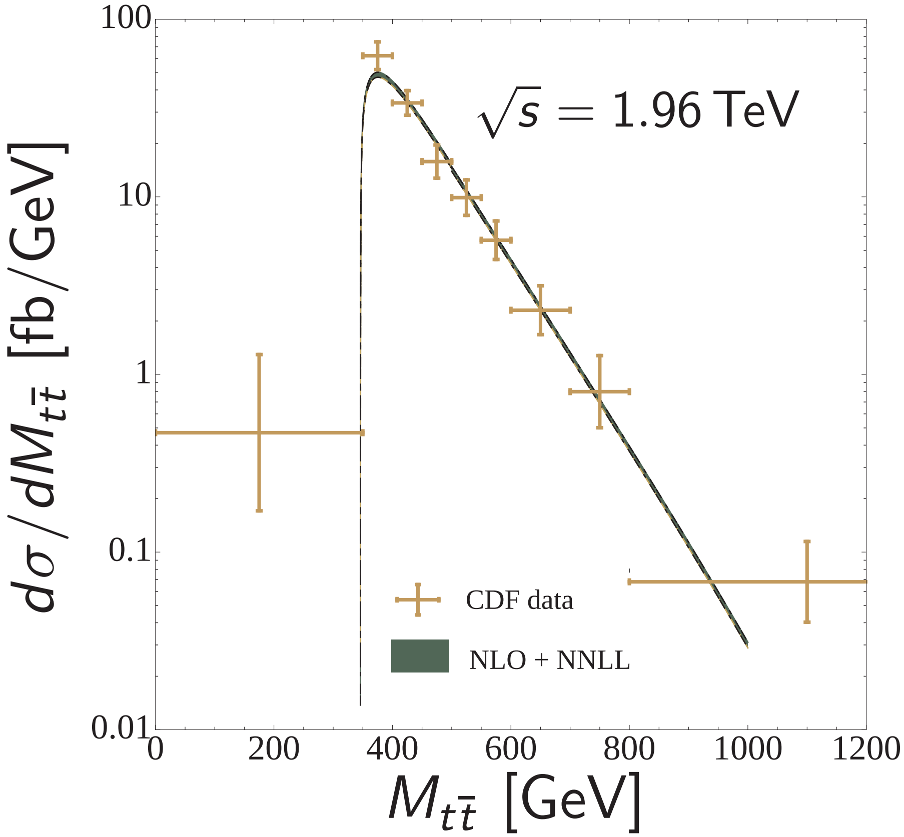
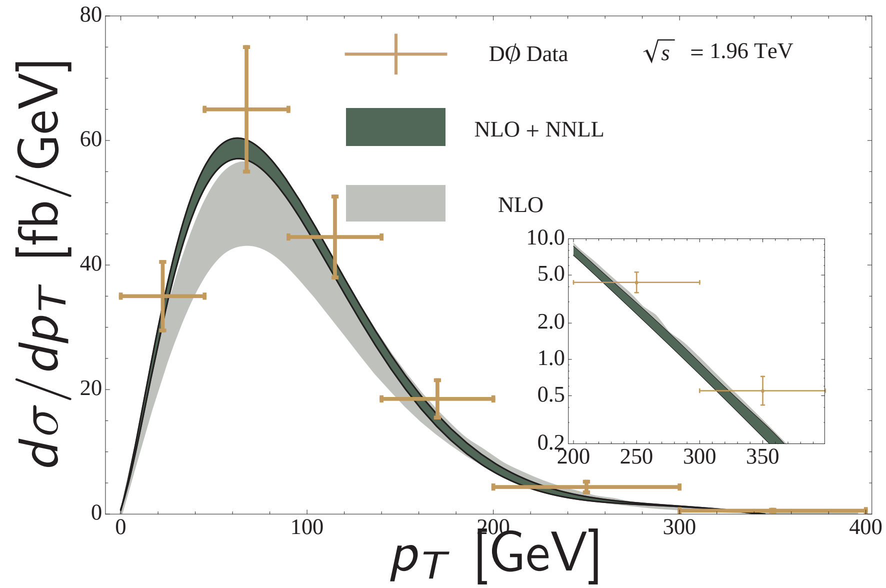
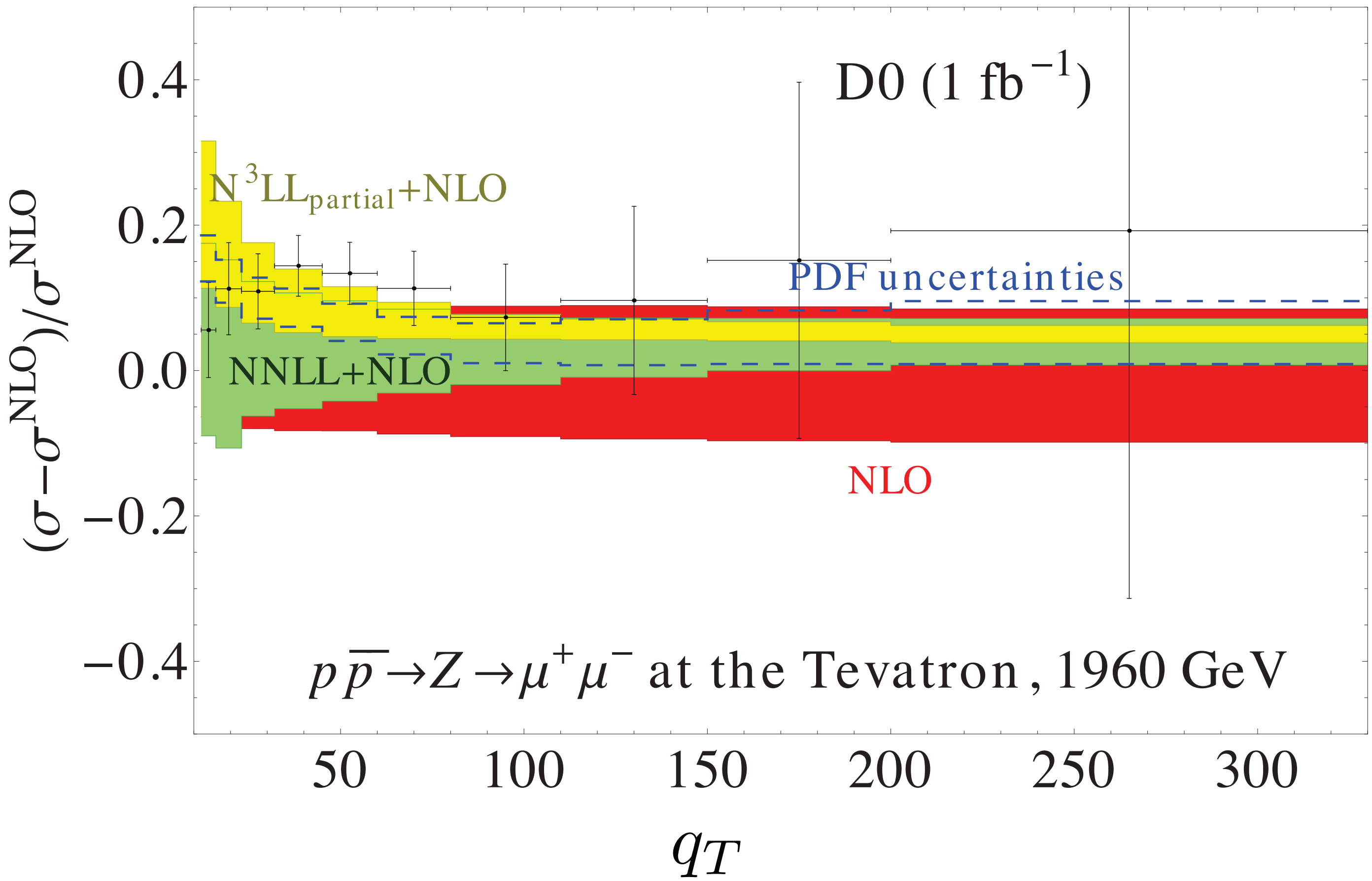
Invariant mass and p_T distributions at NLO+NNLL vs. Tevatron data





- $M_{t\bar{t}}$ and p_T distributions at NLO+NNLL from [Ahrens et. al.]
- normalization and shape of distributions consistent with data
- can also study rapidity distributions (but no measurements so far)



TB, Lorentzen, Schwartz, 1106.4310

Moderate shift of the central value, but much reduced scale dependence, below PDF uncertainty.

Editorial Comment

- We appreciate the variety of calculations coming on the market
  - we’re glad people are generally making their code public
  - otherwise, we’d like distribution of usable NTUPLEs of 4-vectors
  - it would also help if more codes were optimized for speed
    - may not be possible for the automated calculation frameworks

Example

NLO with BlackHat+Sherpa

NLO cross section

Born   loop: lc and fmlc   real

$$\sigma_n^{NLO} = \int_n \sigma_n^{tree} + \int_n \left(\sigma_n^{virt} + \Sigma_n^{sub}\right) + \int_{n+1} \left(\sigma_{n+1}^{real} - \sigma_{n+1}^{sub}\right)$$

vsub

BlackHat

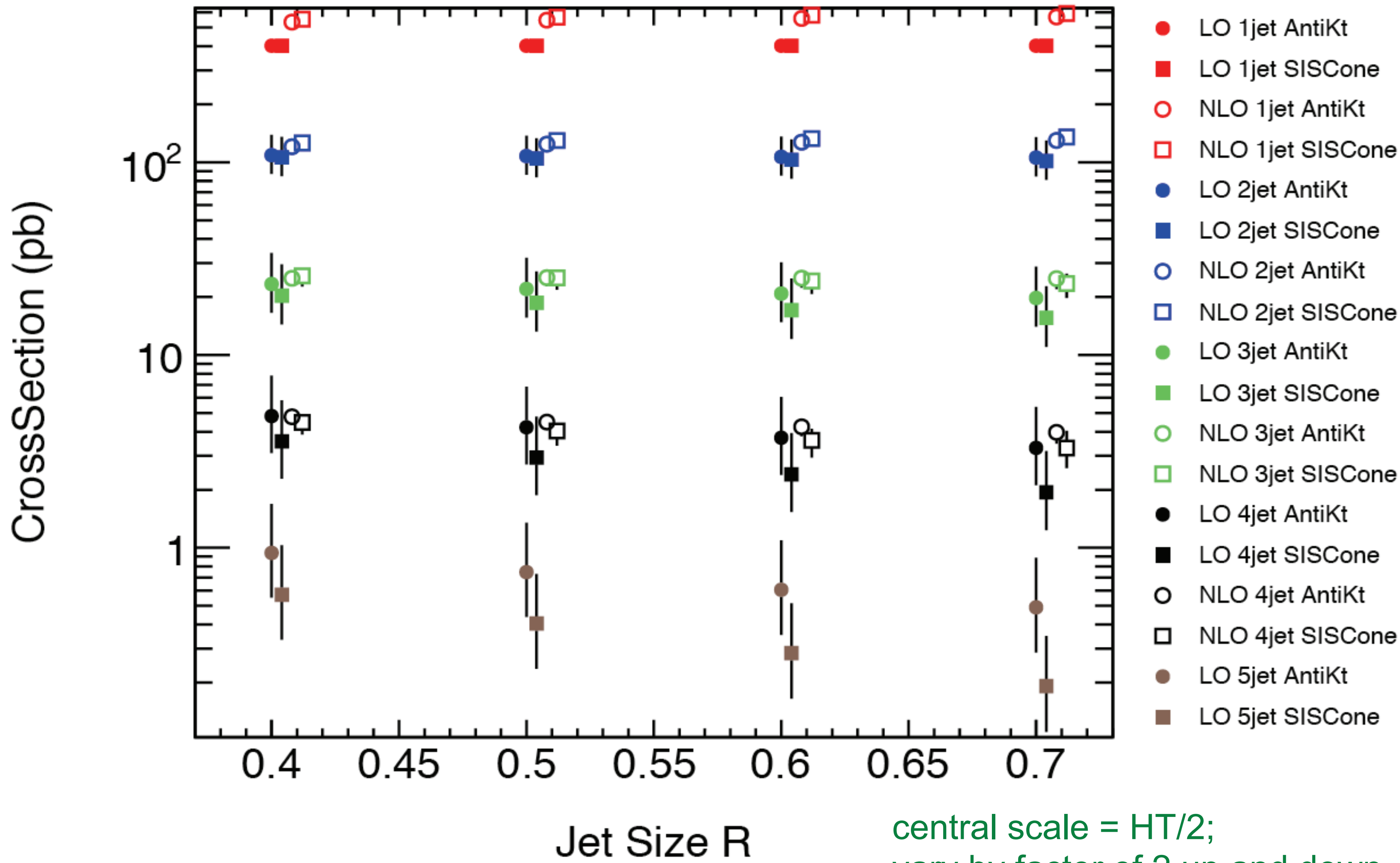
so this is not Sherpa the parton shower, but Sherpa used as a (very efficient) fixed order matrix element generator

Sherpa

Logistics

- So total file disk space is quite large, multi-TB (and there are many events to be processed)
  - I bought a 20TB disk specifically for this purpose
- But they're divided into few GB files (Blackhat +SJ)
- So we can make our analysis parallel using 350 nodes at MSU
- Possible to run through W + 4 jet NLO analysis in ~few hours (much faster without the scale variations)

Look at jet size, algorithm dependences; scale uncertainty



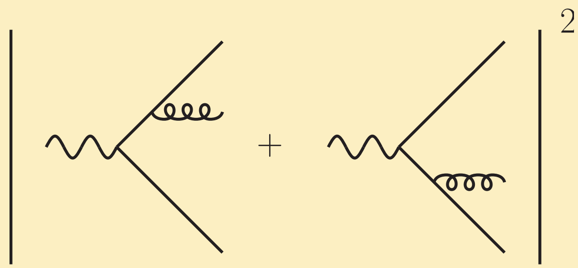
central scale = HT/2;
vary by factor of 2 up and down

Marek Schönherr

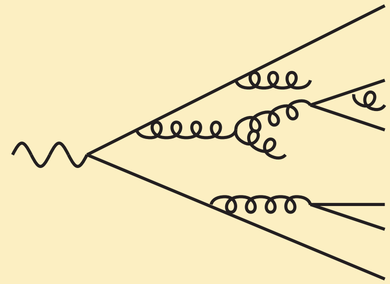
(NLO)ME vs. PS

Approaches to real emission corrections

(NLO) Matrix Element



Parton Shower



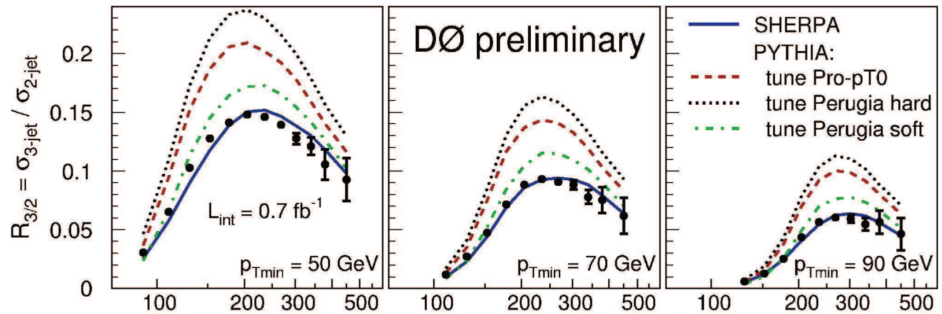
+ **Exact** to fixed order
– Perturbative series breaks down due to **large logarithms**

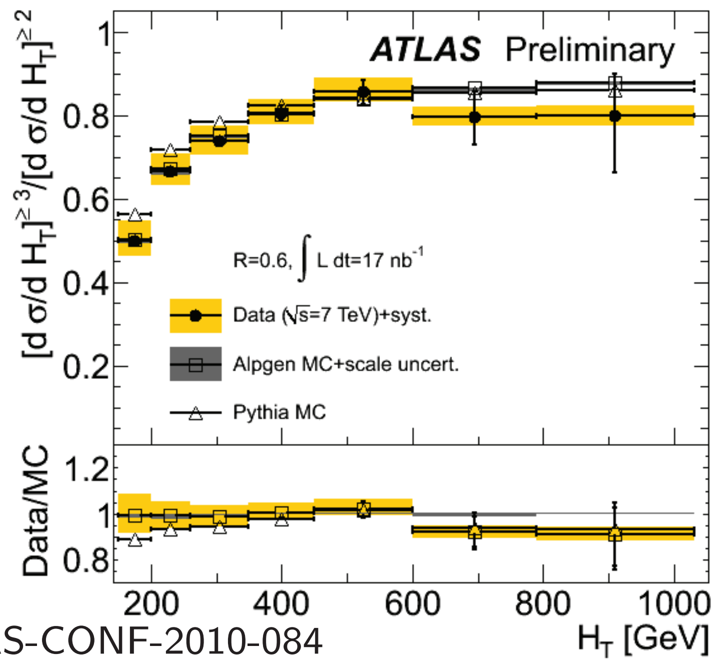
+ Resums logarithms to **all orders**
– Only **approximation** to real emission ME

Combine Advantages ⇒ ME⊗PS, NLO⊗PS, MENLOPS

- avoid double-counting by dividing phase space ⇒ Q_{cut}
- **ME** to describe **hard radiation**, **PS** for **intrajet evolution**

Ratio of 3- & 2-jet rate DØ Note 6032-CONF

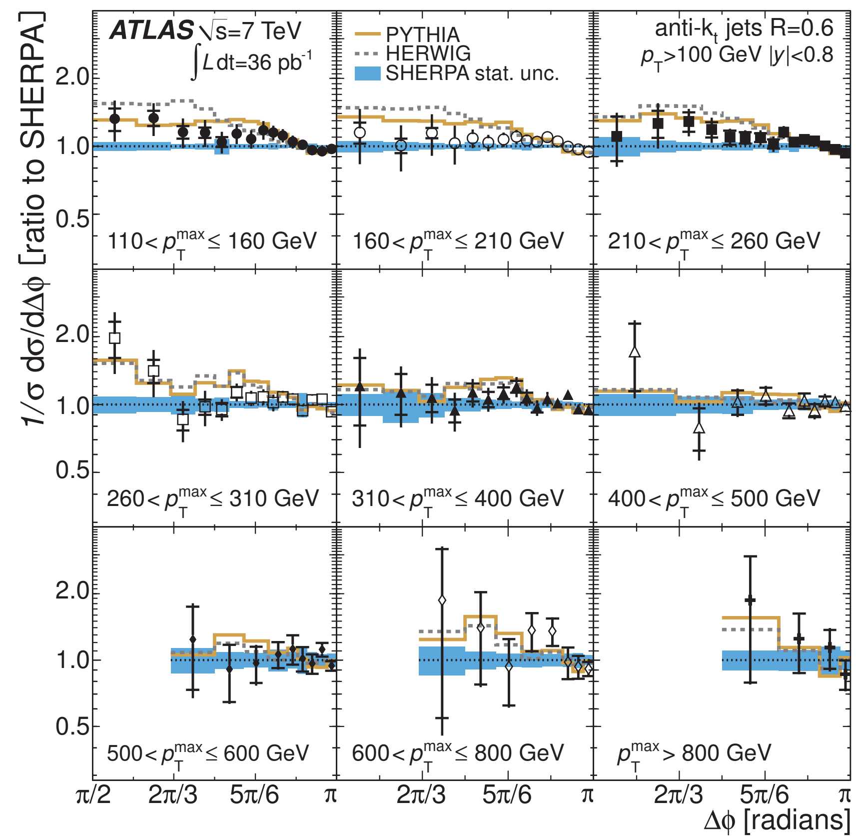




ATLAS-CONF-2010-084

Higher-order ME improve predictions for jet correlations & relative rates

Dijet decorrelation (MC vs. data)



Multi-leg ME⊗PS "standard" by now

[ATLAS] arXiv:1102.2696

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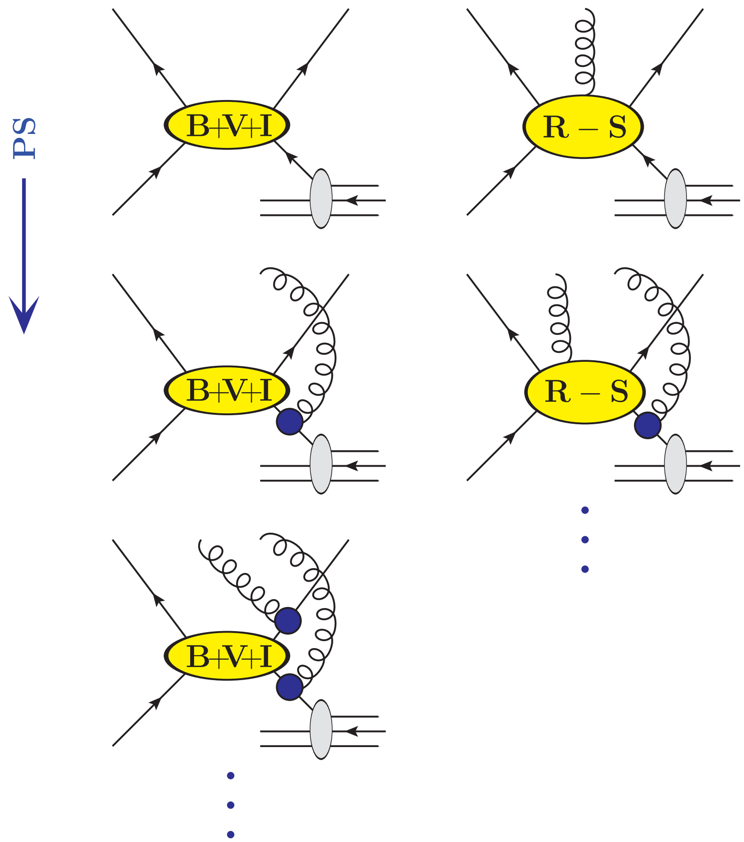
NLO challenge: B-, V-, I- and S-terms kinematically different from R



Requirements for NLO⊗PS:

- Preserve resummation as in PS
- Implement $\mathcal{O}(\alpha_s)$ accuracy from ME

Problems much like for ME⊗PS:

- **Real-emission term and PS populate same phase-space region**
- **Naively adding PS on top of ME leads to double-counting**

Unlike for ME⊗PS one cannot simply divide up the phase space !

Zoltan Kunszt

Virtual NLO matrix elements as plugins into NLO Parton Shower MC's

MC@NLO : - Well tested for many processes
- Matches NLO to HERWIG and HERWIG++
- Angular ordered Parton Shower
- One may have negative weights
- Available also for PHYTIA

Frixione, Webber (03)

POWHEG: - Parton Showers can be interfaced
- HERWIG, SHERPA, PHYTIA
- Only positive weights, resumming subleading non-logarithmic corrections
- Modular, POWHEGBOX can use existing NLO calculations

WW,WZ,ZZ (Melia et.al.)

NLO results HELAC (Kardos et.al.),

HERWIG++, SHERPA (Hoeche et.al)

Nason (04)
Frixione, Nason, Oleari (07)

Marek Schönherr

Available processes*

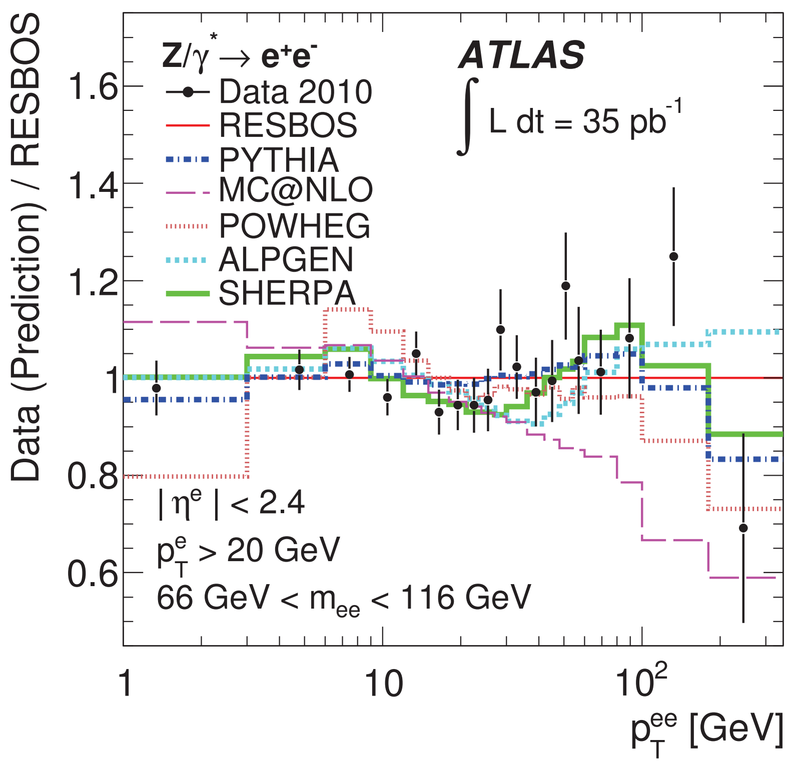
	POWHEG			MC@NLO	
Process	POWHEG-BOX	HERWIG++	SHERPA	MC@NLO	aMC@NLO
$e^+e^- \to jj$	✗	✓	✓	✗	✗
DIS	✗	✓	✓	✓	✗
$pp \to W/Z$	✓	✓	✓	✓	✗
$pp \to H$ (GF)	✓	✓	✓	✓	✗
$pp \to V + H$	✗	✓	✓	✓	✗
$pp \to VV$	✗	✓	✓	✓	✗
VBF	✓	✓	in prep.	✗	✗
$pp \to Q\bar{Q}$	✓	✗	✗	✓	✗
$pp \to Q\bar{Q} + j$	✓	✗	✗	✗	✗
single-top	✓	✗	✗	✓	✗
$pp \to V + j$	✓	✗	in prep.	✗	✗
$pp \to V + jj$	in prep.	✗	in prep.	✗	✗
$pp \to H + j$ (GF)	✗	✗	in prep.	✗	✗
$pp \to H + t\bar{t}$	✓	✗	✗	✗	✓
$pp \to W^+W^+jj$	✓	✗	✗	✗	✗
$pp \to V + b\bar{b}$	✓	✗	in prep.	✗	✓
diphotons	?	✓	in prep.	✗	✗
dijets	✓	✗	in prep.	✗	✗

* Table includes SM processes presented so far. Automated codes and toolkits can, in principle, be used for any process.

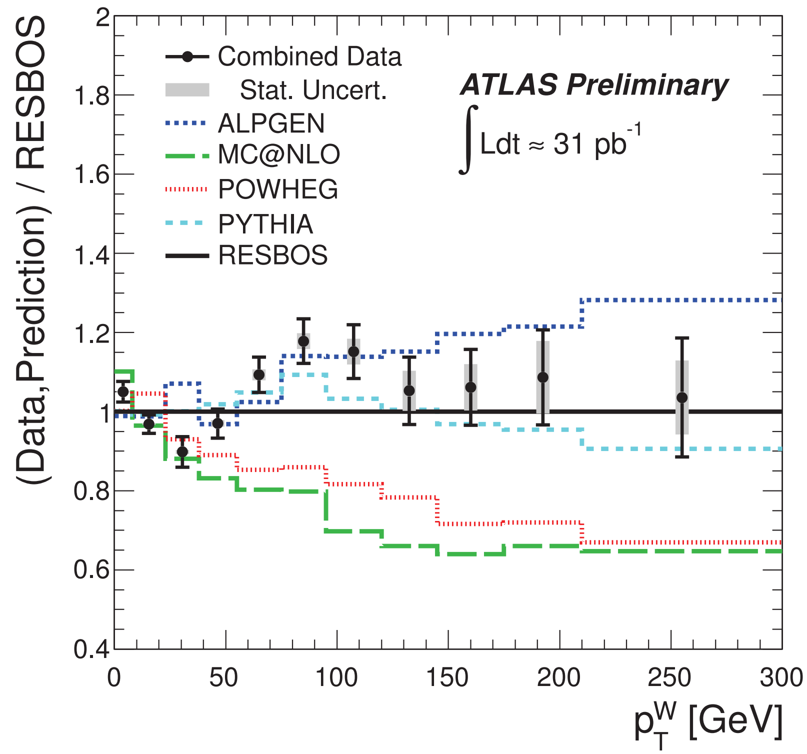
W and Z p_T

The measurement of the boson p_T is sensitive to dynamic effects of strong interaction, complementary to associated production of bosons with jets.

CERN-PH-EP-2011-095



Resbos shows good agreement with data, indicating importance of resummation.



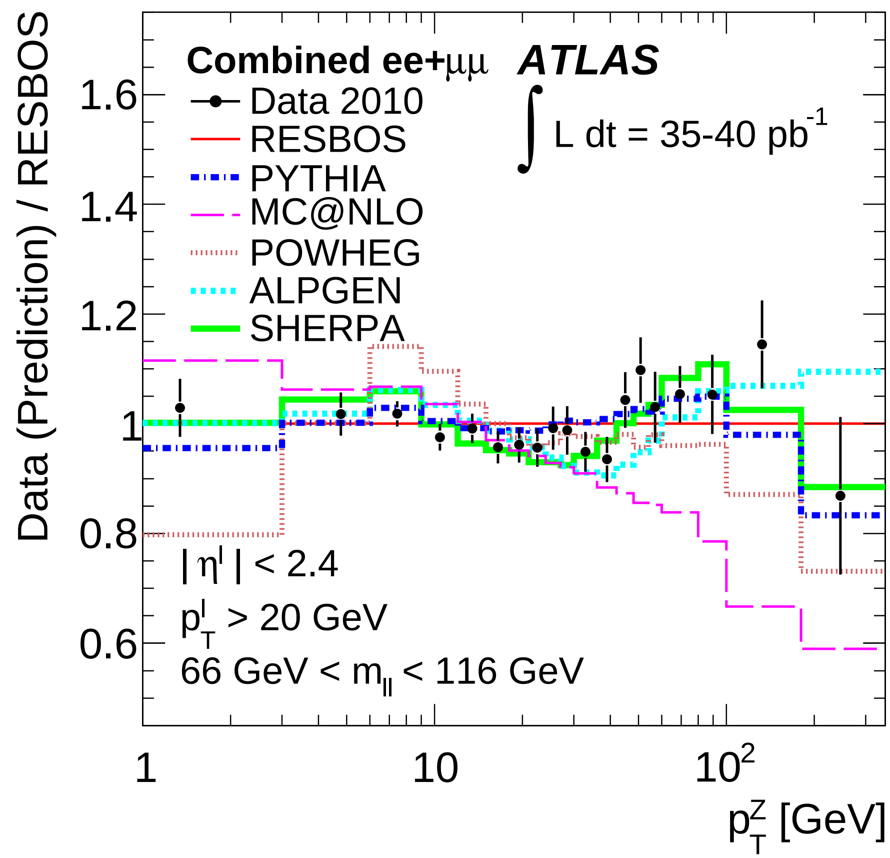
For $p_T^W > 120$ GeV Pythia and Resbos agree in predicting a softer spectrum than Alpgen and Sherpa

First corrected p_T^W measurement, precision comparable to p_T^Z

Editorial Aside

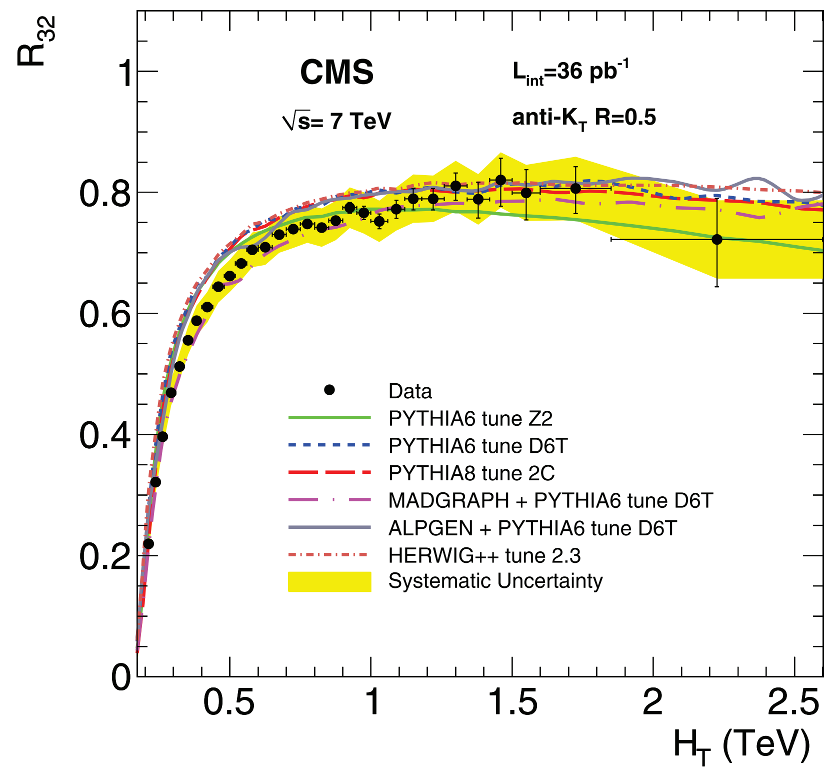
BROOKHAVEN NATIONAL LABORATORY

- There was a lot of discussion about the presentation of these plots.
  - theorists wanted Theory/Data to better compare calculations
  - experimentalists preferred to minimize impact of fluctuations
- It was suggested to use parameterized fits for the comparison to smooth out fluctuations. However,
  - not every distribution has a simple parameterization
  - non-physics parameterizations aren't likely to survive the editorial board review process
- Some theorists prefered to also have pure NLO curves on comparison plots



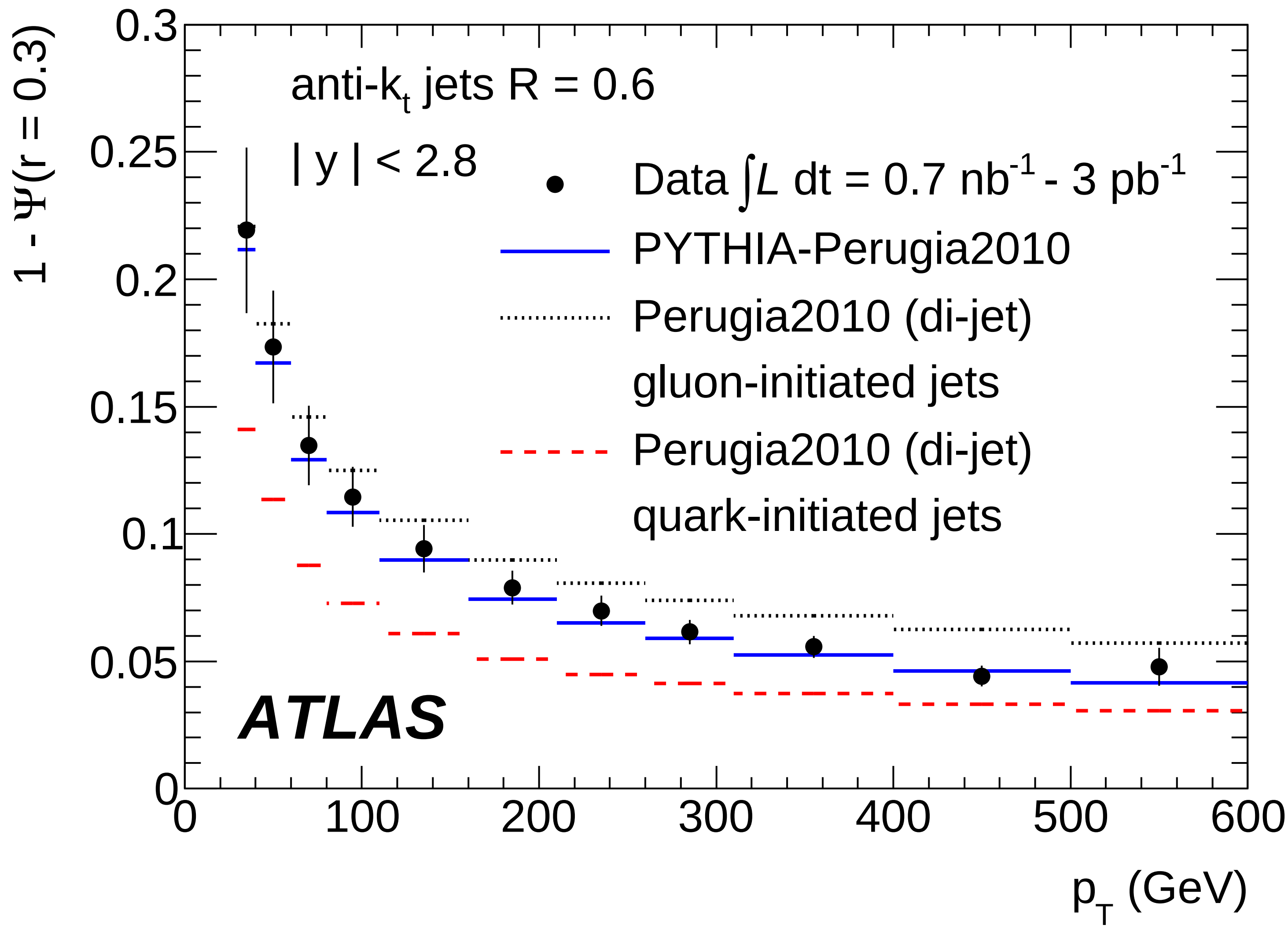
Editorial Aside, continued

- Theorists often complain that experimental results are compared to MC tunes focused on a specific experiment which obscures interpretation of the consistency between data and theory.
  - experiment-focused tunes are very useful for MC-based studies, efficiencies, acceptances, etc
  - these should be shown to provide confidence in the correction procedure, but not for their specific physics interpretation



- We propose that results from multiple experiments be compared to a small collection of well-chosen tunes
  - tune error bands (like the PDF error bands) would help
  - analysis should be stored in a Rivet module to allow more comparisons

- Jet substructure studies have matured well beyond comparisons of quark- and gluon-initiated jets in event generators:



- Jet substructure studies have matured well beyond comparisons of quark- and gluon-initiated jets in event generators:
  - calculations and measurements of jet mass
  - boosted objects $\rightarrow$ coalesced jets
    - $W \rightarrow jj$ and $Z \rightarrow b\bar{b}$
    - top quark decays
    - searches for H and $X \rightarrow t\bar{t}$
    - applications to other searches (e.g., SUSY)
- This is an exciting new direction in jet physics

Highly boosted objects such as high p_T Higgs decay to products which have narrow opening angle. Can end up in single jet.
Recall

$$M^2 = z(1-z)p_t^2\theta_{12}^2$$

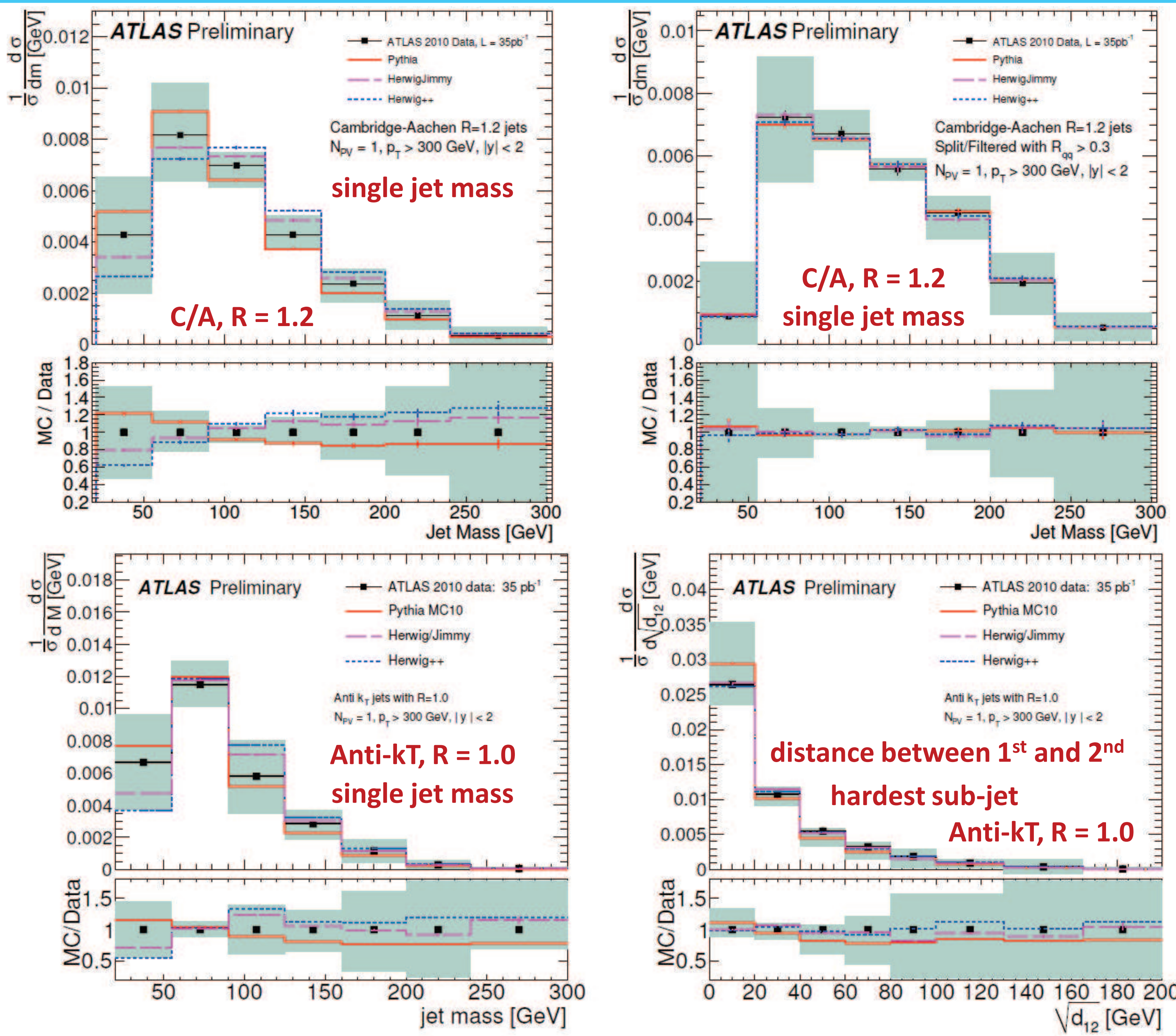
For $R \geq \frac{M}{\sqrt{z(1-z)}p_t}$ we will get a single jet. For $p_t \sim 500$ GeV , $M \sim 100$ Gev $R \geq 0.6$ implies that 75 percent of such decays will be clustered to a jet.

Invariant mass distribution is first clue to identity of jet. Significant issue arises of QCD jet backgrounds.

$$\frac{1}{\sigma}\frac{d\sigma}{dM^2} \sim \frac{1}{M^2}\alpha_s \ln \frac{R^2 p_t^2}{M^2}$$

For $p_t \gg M$ this can be significant contamination even at masses of a 100 GeV.
Remove QCD background and optimise the construction of the mass.

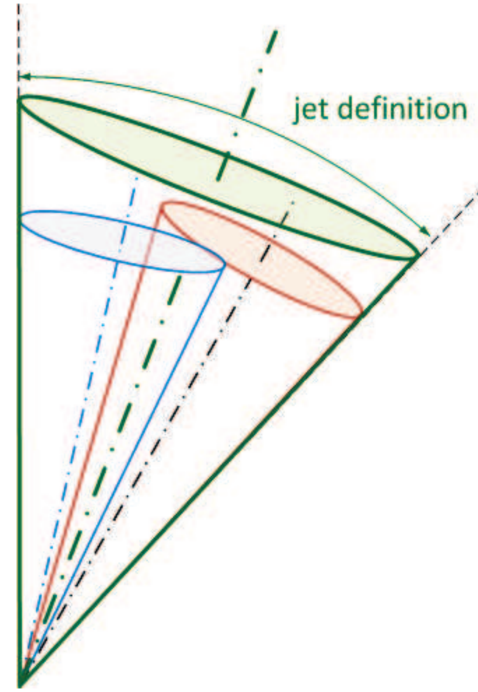
Fully Unfolded Jet Mass & Substructure



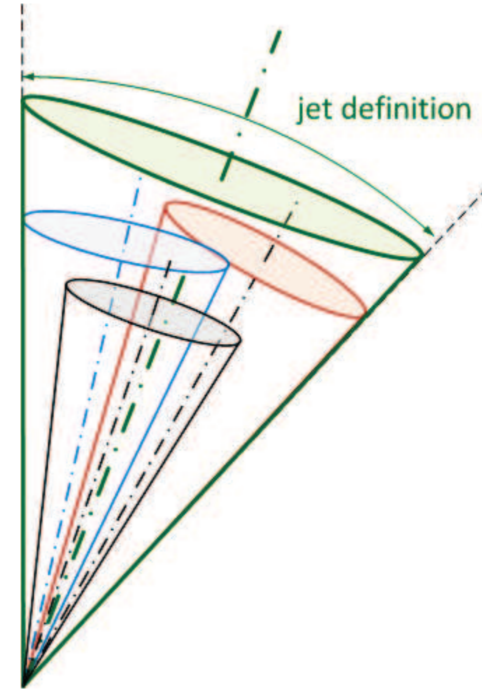
(all plots from **ATLAS CONF-2011-073**)

Particle flow inside a jet hints to source

- Jet can be a discovery tool by itself
  - In particular most interesting for boosted (new) heavy particle like Kaluza-Klein excitations
  - But also interesting for Standard Model particles like boosted top quarks
- Usefulness depends on the ability to resolve decay structure
  - E.g., 2-prong (like W) or 3-prong (top) decays
  - Resolution scale given by mass of particle (or by particle hypothesis) – to be reflected with detector capabilities



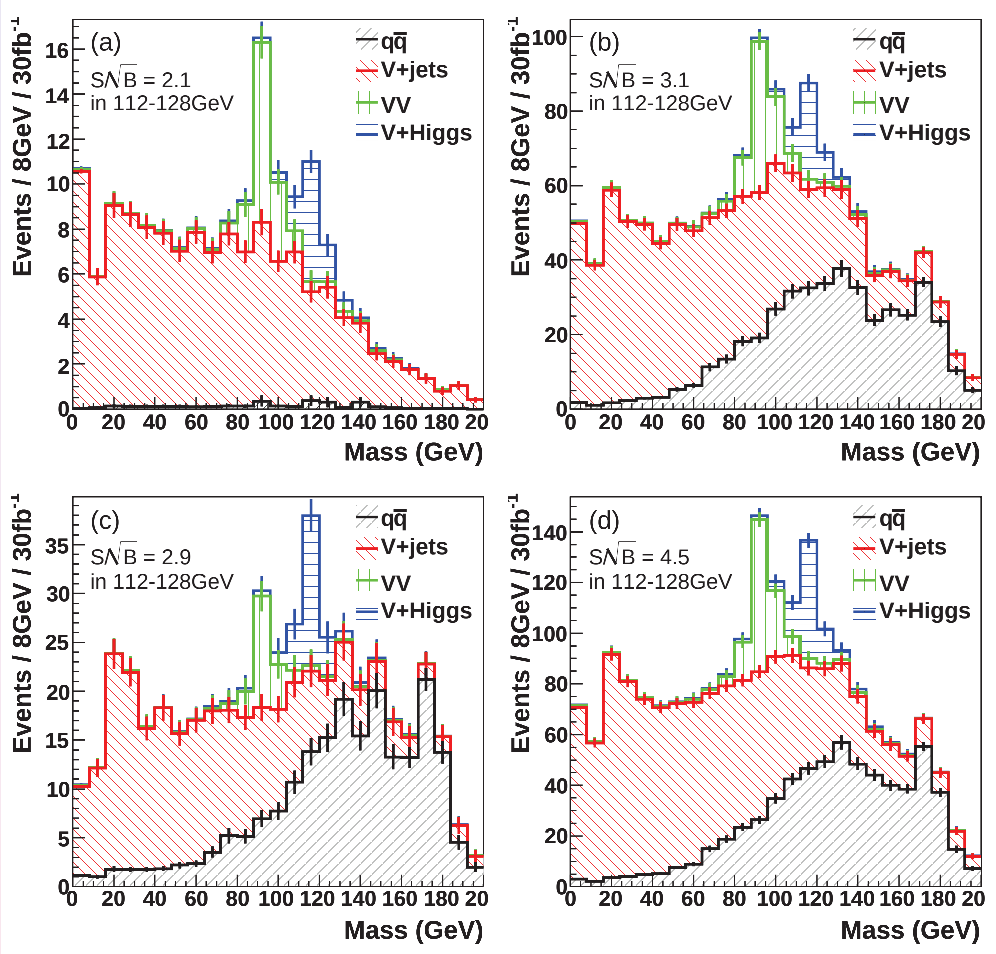
2 – prong decay inside reconstructed jet, e.g. from $W \to q\bar{q}$ (SM) or heavy new object like $\phi \to gg$ or $Z' \to q\bar{q}$ (BSM)



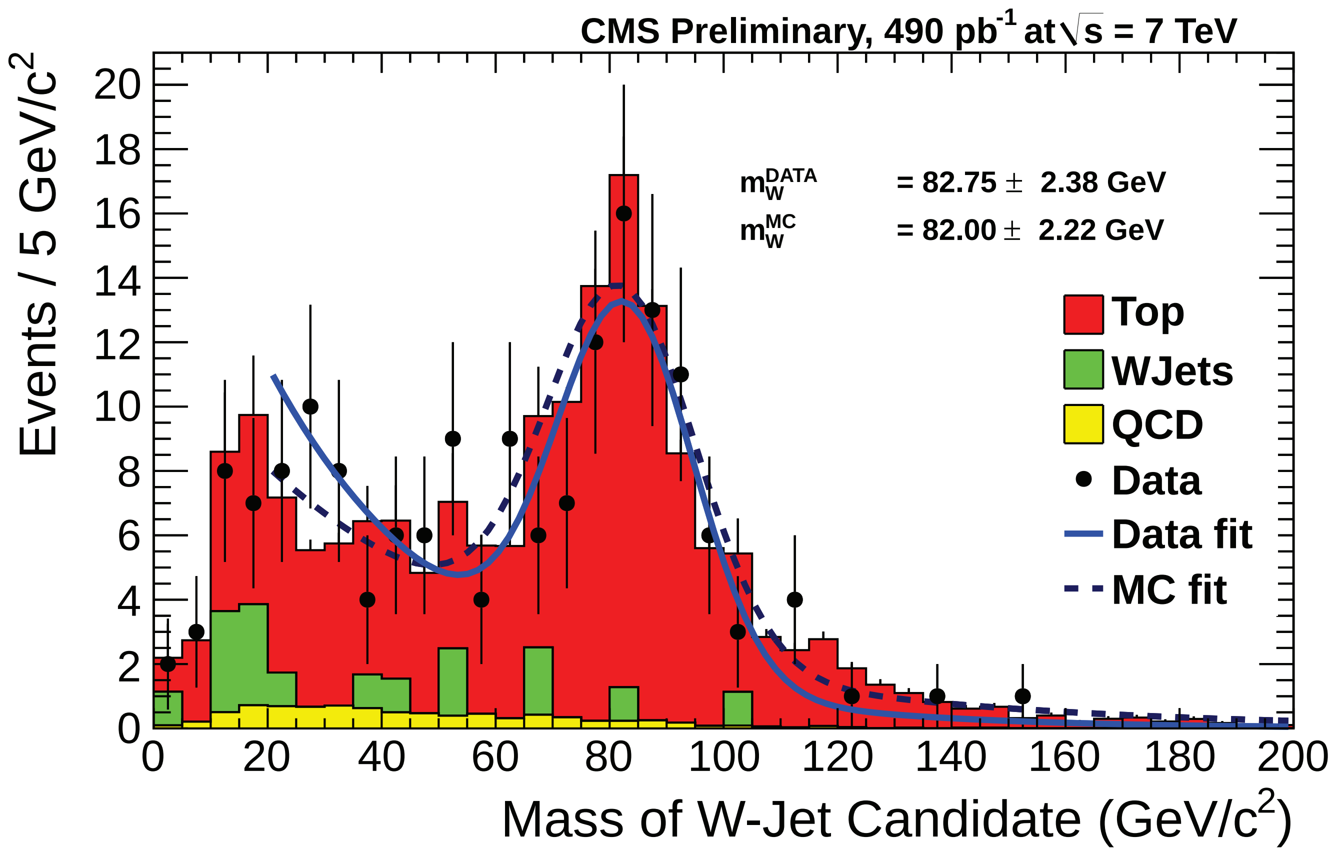
3 – prong decay inside reconstructed jet, e.g. from $t \to q\bar{q}b$ (SM) or heavy new object like $\phi_{KK} \to Q\bar{Q}b + X$ or $t' \to q\bar{q}b$ (BSM)

QCD@LHC
St Andrews
August 22-26, 2011

Mrinal Dasgupta



An unpromising channel rescued.



W mass measurement from **within jets** using the jet pruning algorithm. This is a boosted muon-plus-jets sample, and what is plotted is the mass of the highest mass jet in the hemisphere away from the muon. From this plot we can extract the subjet jet energy scale comparison between data and MC, which is measured to be 1.00 ± 0.04. This plot can also be used to measure the efficiency of the *W* mass cut in the data and the Monte Carlo, which can be used to extract the data-to-MC scale factor. Combining the efficiency scale factor of the "mu" cut (see below), the data-to-MC scale factor of the *W* tagging algorithm is 0.93 ± 0.13.

Future Directions

We asked people for a wish list for the next few years:

- triple differential cross section measurements
- NNLO calculations for QCD processes
- measure asymmetry in $t\bar{t}$ rapidity distribution
- explorations of the *Wjj* “signal” seen by CDF
- extending the rapidity range of event shape measurements
- flexibility in the jet radius (**scan** over multiple radii)
- multijet cross section calculations out beyond 10 jets
- better guidance as to good choices of scale
- boosted object measurements

- the expectation is that we should perform so many high-quality QCD measurements that the results from the Tevatron, Fixed Target, LEP, and HERA become obsolete

- Thanks to the conference organizers and our hosts for the beautiful Scottish weather and countryside, nice venue, and open schedule that fostered discussion.

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- Especially, many thanks for the Whisky!