CTEQ

Experimental summary: theory-experiment interplay at the LHC

J. Huston

Michigan State University

IPPP, Durham

Two advertisements

…a good example of theory-experiment interplay

THE SM AND NLO MULTILEG WORKING GROUP:
Summary Report

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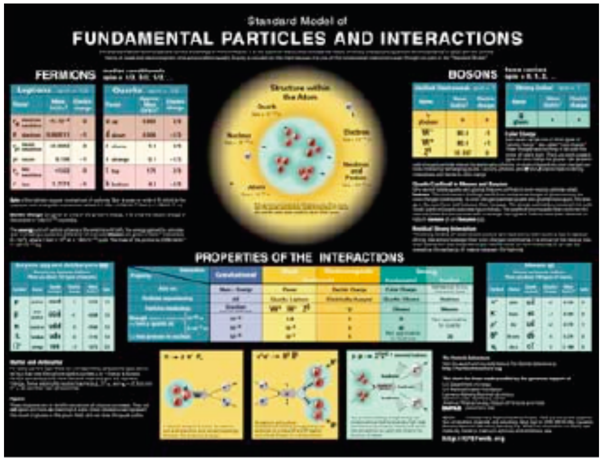
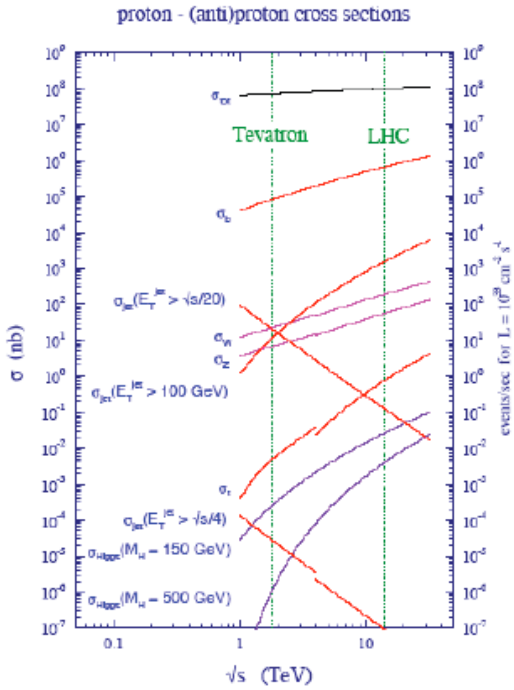
…another (actually two others)

CTEQ

Understanding cross sections at the LHC

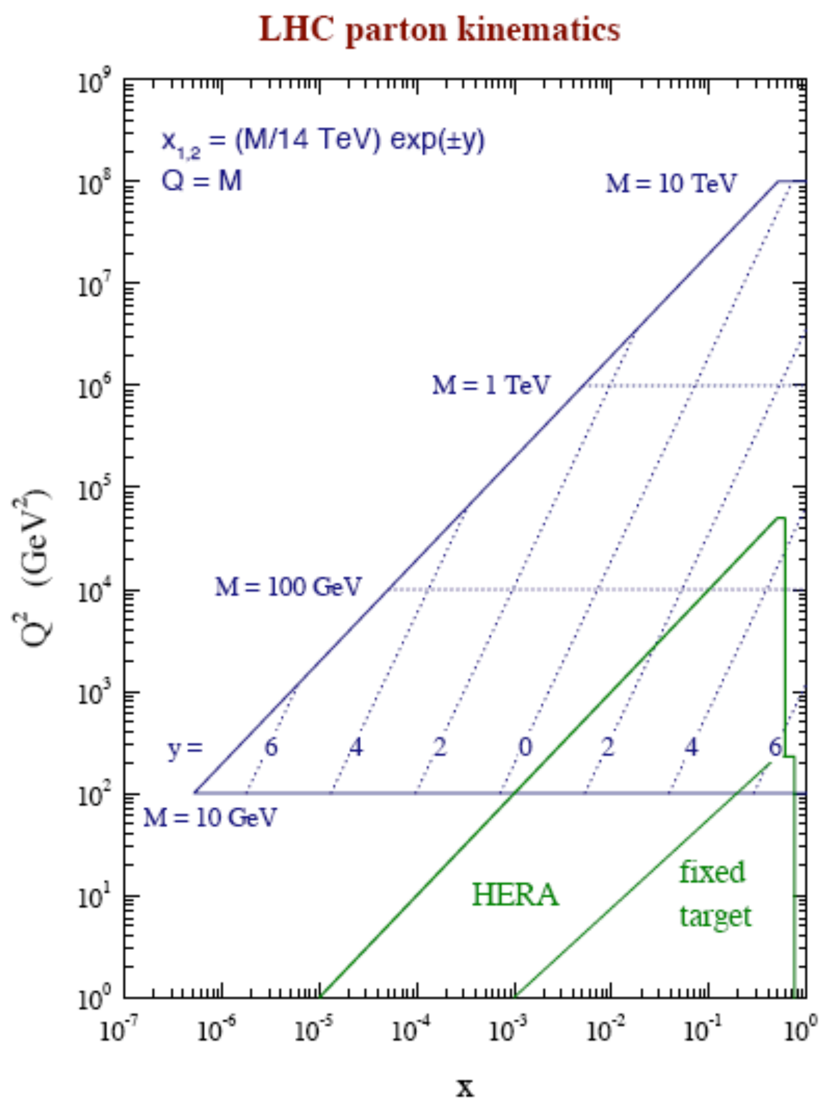
- We're all looking for BSM physics at the LHC
- Before we publish BSM discoveries from the early running of the LHC, we want to make sure that we measure/understand SM cross sections
  - detector and reconstruction algorithms operating properly
  - SM backgrounds to BSM physics correctly taken into account
  - and, in particular, that QCD at the LHC is properly understood





Cross sections at the LHC

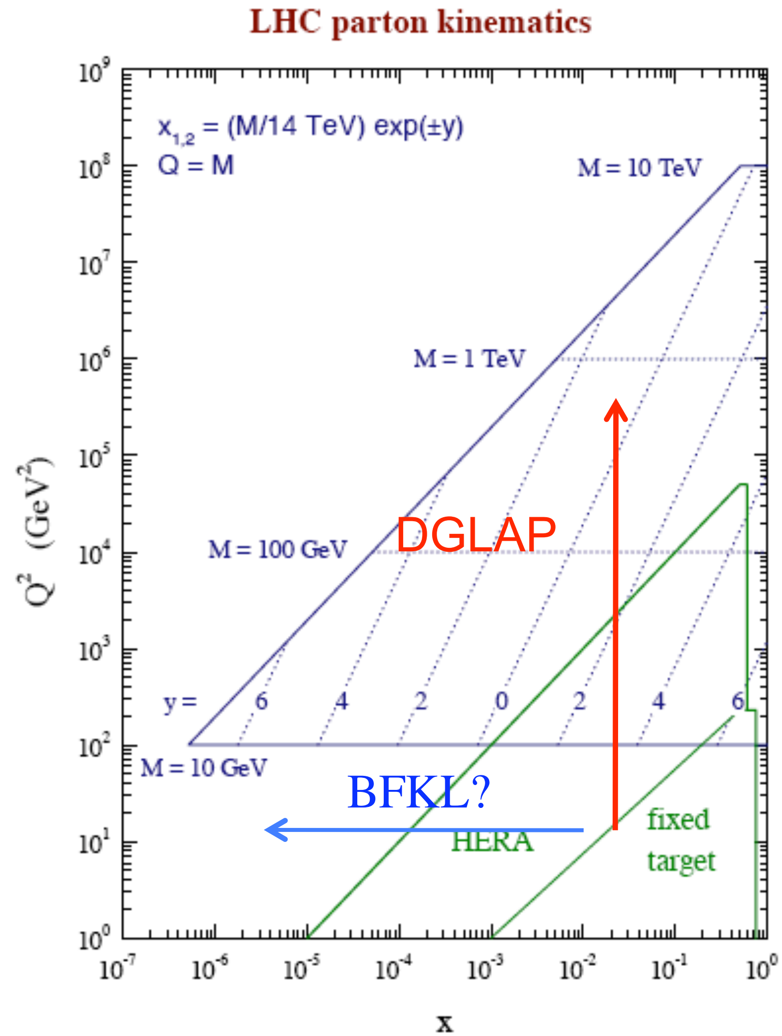
- Experience at the Tevatron is very useful, but scattering at the LHC is not necessarily just “rescaled” scattering at the Tevatron
- Small typical momentum fractions x for the quarks and gluons in many key searches
  - dominance of gluon and sea quark scattering
  - large phase space for gluon emission and thus for production of extra jets
  - intensive QCD backgrounds
  - or to summarize,…lots of Standard Model to wade through to find the BSM pony



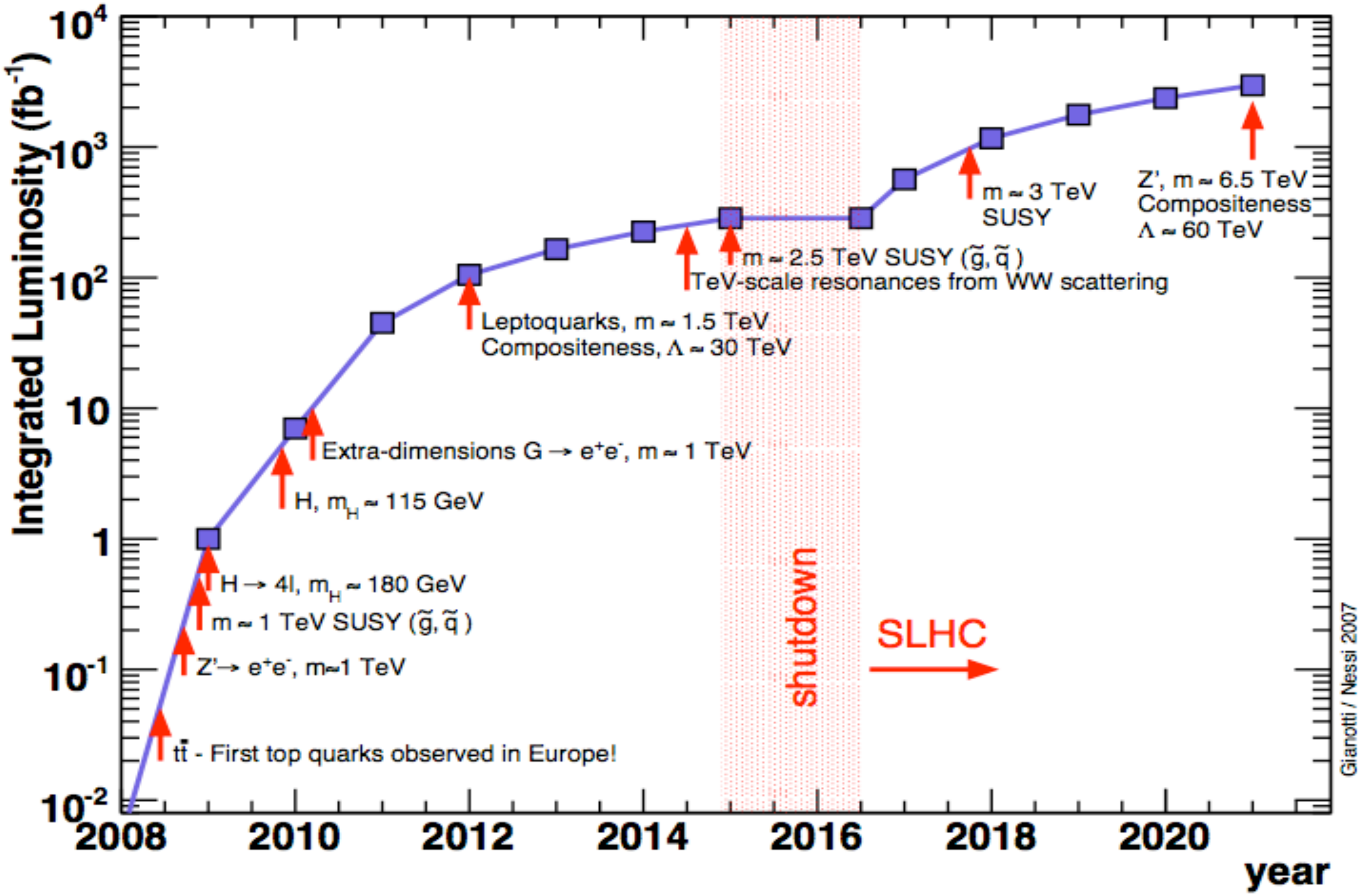
Cross sections at the LHC

- Note that the data from HERA and fixed target cover only part of kinematic range accessible at the LHC
- We will access pdf's down to 10^{-6} (crucial for the underlying event) and Q^2 up to 100 TeV^2
- We can use the DGLAP equations to evolve to the relevant x and Q^2 range, but…
  - we're somewhat blind in extrapolating to lower x values than present in the HERA data, so uncertainty may be larger than currently estimated
  - we're assuming that DGLAP is all there is; at low x BFKL type of logarithms may become important (see Jeppe's talk)← invariant

$$\frac{d\sigma}{dM^2 dy} = \frac{\hat{\sigma}_0}{Ns}\left[\sum_k Q_k^2\left(q_k(x_1, M^2)\bar{q}_k(x_2, M^2) + [1 \leftrightarrow 2]\right)\right]$$



What we would like



C T E Q

What we have (at least for the next two years)

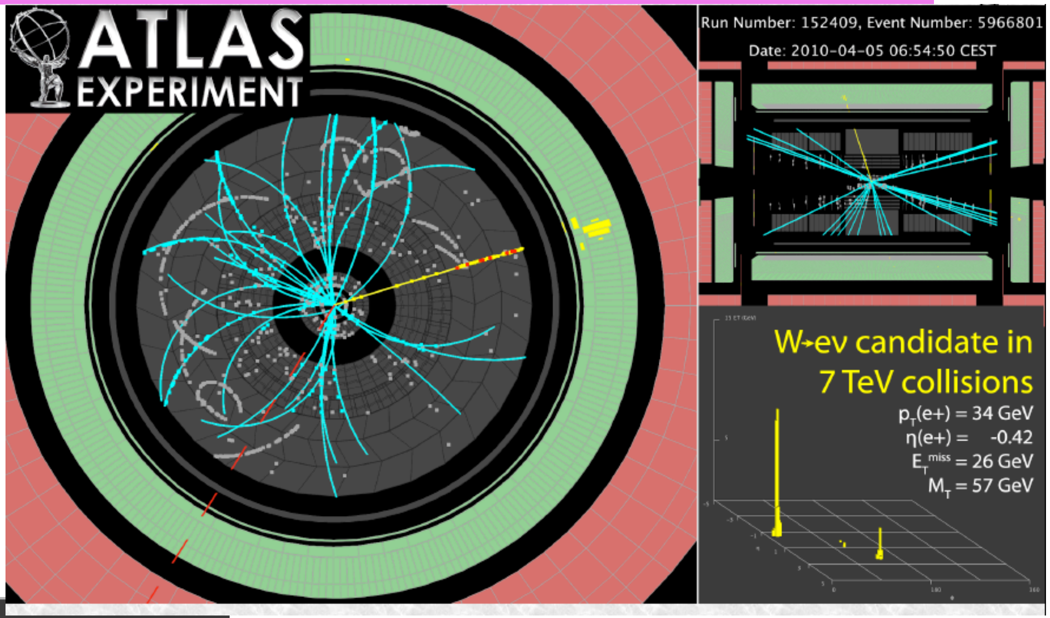
…with 1 fb^{-1} expected in 2010-11   so ~90M W events expected; 150K tT

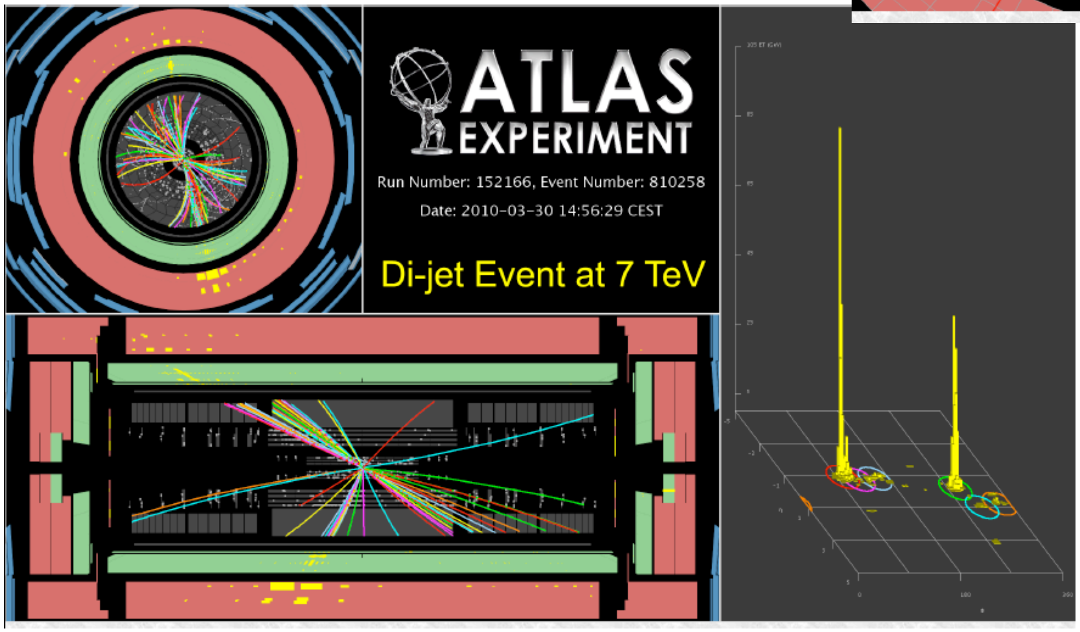
…data-driven backgrounds before discovery   Bruce Mellado

Table 1: Cross Sections (in fb unl… of Standard Model Processes from MCFM 5.3

√s (TeV)	Tevatron	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Order
W/Z production (PROC = 1/6, 31, 21/26, 51)					W and Z cross sectio		are in pb		NLO Vbb calculation: mb=0, pTb>20 GeV, $\|\eta_b\|$<2.5,							
W^+ (pb)	11,920	12,735	20,889	29,072	37,244	45,390	53,491	61,552	69,562	77,524	85,434	93,296	101,096	108,859	116,594	NLO
W^- (pb)	11,920	6,974	12,499	18,315	24,295	30,375	36,519	42,703	48,924	55,147	61,378	67,611	73,839	80,060	86,270	NLO
Z (pb)	7,153	5,415	9,475	13,687	17,991	22,351	26,750	31,174	35,613	40,065	44,519	48,974	53,431	57,881	62,329	NLO
W^+bb	2,179	1,655	3,645	5,870	8,347	10,970	13,967	16,405	19,412	23,110	26,575	29,507	32,658	35,438	39,442	NLO
W^-bb	2,179	685.0	1,733	3,062	4,538	6,054	8,090	10,357	12,153	14,160	17,119	19,042	20,893	24,093	27,282	NLO
Zbb	2,436	1,464	4,367	8,780	14,177	20,728	28,550	36,554	47,675	55,801	67,427	79,247	89,256	101,498	111,897	NLO
WW/WZ/ZZ production (PROC = 61, 71/76, 81)					Cross sections are fo		n-shell Zs									
W^+W^-	12,004	4,471	10,608	17,973	25,771	34,675	43,657	53,275	63,093	73,149	83,244	93,112	104,250	114,695	125,565	NLO
W^+Z	1,770	1,093	2,697	4,633	6,794	9,131	11,574	14,112	16,734	19,424	22,217	24,974	27,851	30,741	33,639	NLO
W^-Z	1,770	404.0	1,154	2,178	3,406	4,801	6,317	7,935	9,648	11,437	13,290	15,217	17,216	19,254	21,295	NLO
ZZ	1,422	541.0	1,344	2,311	3,405	4,547	5,782	7,047	8,325	9,665	11,075	12,454	13,878	15,318	16,745	NLO
Top production (PROC = 157, 180/185, 161/166, 171/176, 196)							$^+$ is top, t^-	anti-top!			$Q^2=Mt^2$, no pT and η cut on q/b					
t^+t^-	7,112	2,047	10,855	29,530	59,663	102,018	156,879	224,232	303,905	395,598	498,975	613,717	739,426	875,735	1,022,376	NLO
t^+W^-	69.31	75.88	396.9	1,086	2,192	3,759	5,710	8,153	11,018	14,166	17,740	21,645	26,101	30,361	35,726	NLO
t^-W^+	69.31	75.93	394.0	1,076	2,188	3,763	5,717	8,155	11,037	14,177	17,900	21,706	26,062	30,709	35,785	NLO
t^+q (t-channel)	1,025	1,609	5,577	11,936	20,428	30,706	42,572	55,785	70,249	85,867	102,488	119,904	138,050	157,255	176,674	NLO
t^-q (t-channel)	1,025	589.6	2,320	5,387	9,738	15,327	21,975	29,705	38,300	47,789	58,072	69,141	80,843	93,151	106,114	NLO
t^+b (s-channel)	470.9	279.4	680.3	1,148	1,655	2,185	2,734	3,298	3,871	4,453	5,041	5,643	6,242	6,851	7,465	NLO
t^-b (s-channel)	470.9	101.3	287.5	534.0	822.5	1,141.8	1,484	1,846	2,224	2,615	3,019	3,430	3,849	4,282	4,719	NLO
ttZ	6.465	0.502	3.622	10.52	17.18	34.05	48.74	66.92	86.09	106.6	128.2	150.7	174.2	199.0	223.7	LO

Some early presents





Bill Murray

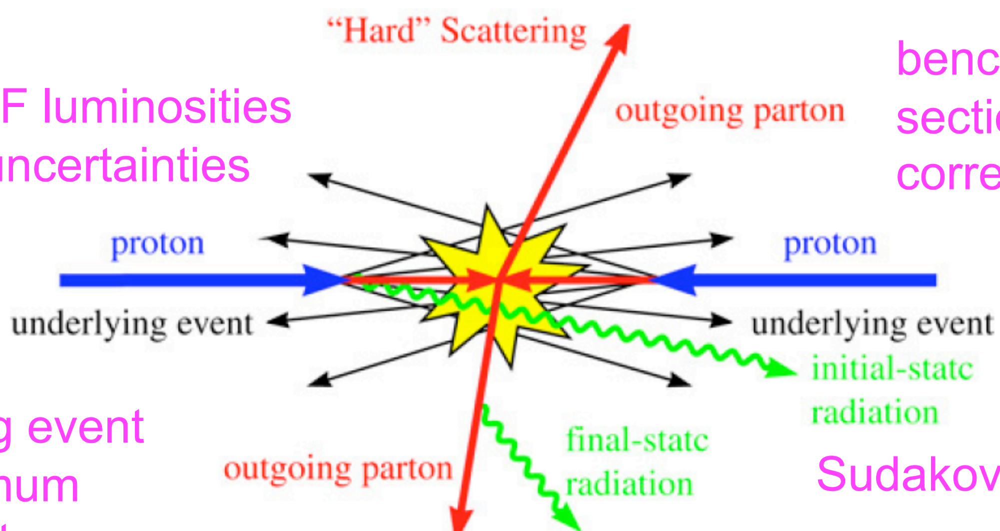
Understanding cross sections at the LHC

…but to understand cross sections, we have to understand QCD (at the LHC)

LO, NLO and NNLO calculations
K-factors

PDF’s, PDF luminosities
and PDF uncertainties

benchmark cross
sections and pdf
correlations



underlying event
and minimum
bias events

Sudakov form factors

jet algorithms and jet reconstruction

Parton distribution functions and global fits

- Calculation of production cross sections at the LHC relies upon knowledge of pdf's in the relevant kinematic region
- Pdf's are determined by global analyses of data from DIS, DY and jet production
- ~~Two~~ Three major groups that provide semi-regular updates to parton distributions when new data/ theory becomes available
  - MRS->MRST98->MRST99 ->MRST2001->MRST2002 ->MRST2003->MRST2004 ->MSTW2008
  - CTEQ->CTEQ5->CTEQ6 ->CTEQ6.1->CTEQ6.5 ->CTEQ6.6->CT09->CT10
  - NNPDF1.0->NNPDF1.1->NNPDF1.2->NNPDF2.0

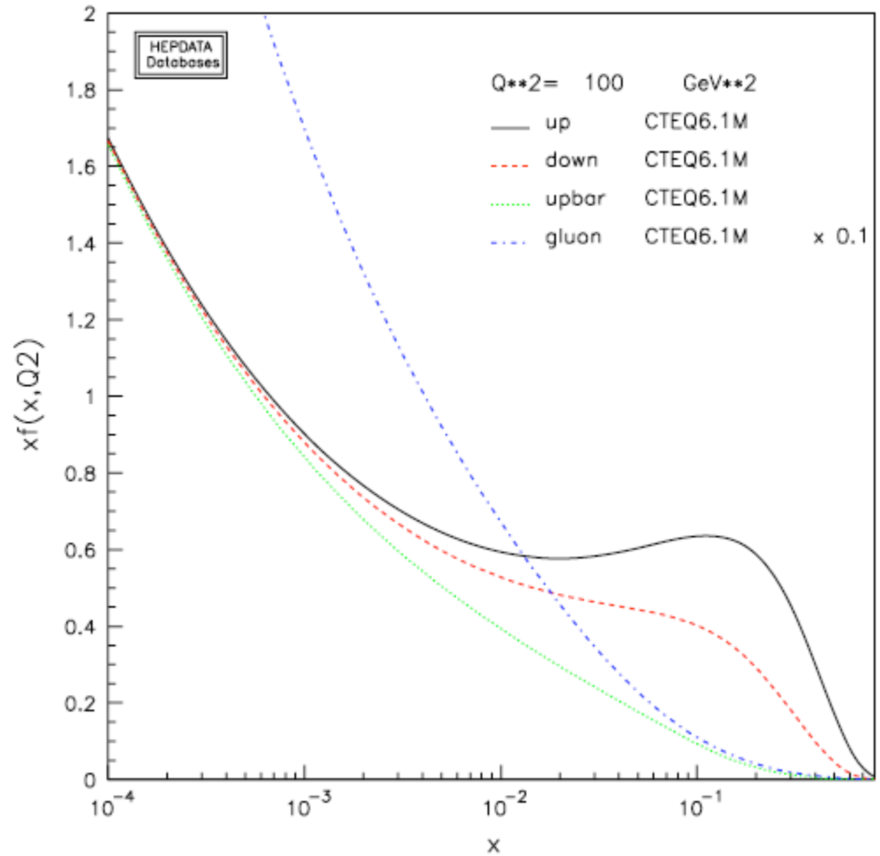


Figure 27. The CTEQ6.1 parton distribution functions evaluated at a Q of 10 GeV.

PDF uncertainties at the LHC (14 TeV)

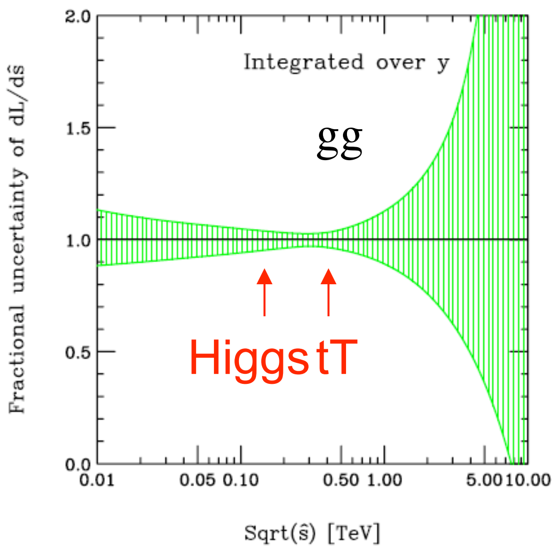


Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

Note that for much of the SM/discovery range, the pdf luminosity uncertainty is small

Need similar level of precision in theory calculations

It will be a while, i.e. not in the first fb^{-1}, before the LHC data starts to constrain pdf's

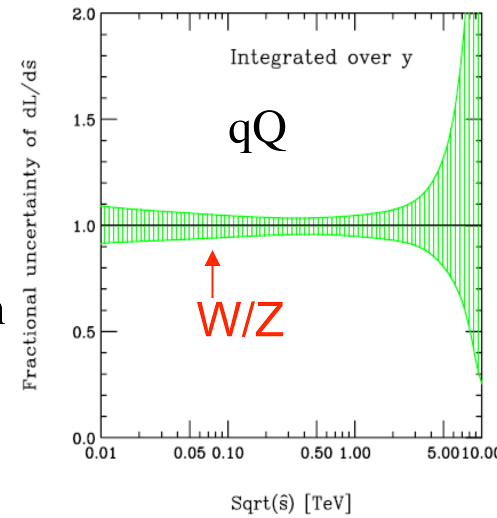


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d} + u\bar{u} + s\bar{s} + c\bar{c} + b\bar{b} + \bar{d}d + \bar{u}u + \bar{s}s + \bar{c}c + \bar{b}b$.

NBIII: tT uncertainty is of the same order as W/Z production

I had a question the other day from an ATLAS student wondering why the PDF uncertainty for W + n jet was less than for W + (n-1) jet

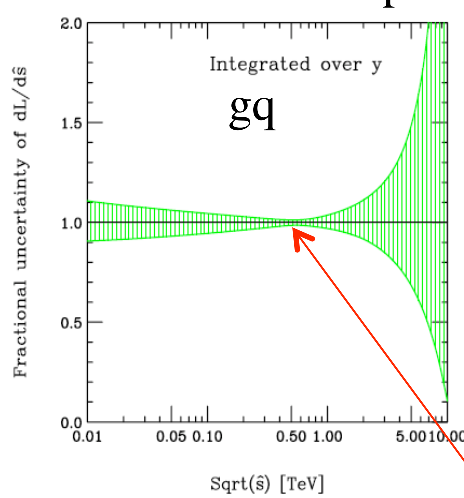


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d + u + s + c + b) + g(\bar{d} + \bar{u} + \bar{s} + \bar{c} + \bar{b}) + (d + u + s + c + b)g + (\bar{d} + \bar{u} + \bar{s} + \bar{c} + \bar{b})g$,

NB I: the errors are determined using the Hessian method for a $\Delta\chi^2$ of 100 using only experimental uncertainties,i.e. no theory uncertainties

NB II: the pdf uncertainties for W/Z cross sections are not the smallest

Ratios:LHC to Tevatron pdf luminosities

- Processes that depend on qQ initial states (e.g. chargino pair production) have small enchancements
- Most backgrounds have gg or gq initial states and thus large enhancement factors (500 for W + 4 jets for example, which is primarily gq) at the LHC
- W+4 jets is a background to tT production both at the Tevatron and at the LHC
- tT production at the Tevatron is largely through a qQ initial states and so qQ->tT has an enhancement factor at the LHC of ~10
- Luckily tT has a gg initial state as well as qQ so total enhancement at the LHC is a factor of 100
  - but increased W + jets background means that a higher jet cut is necessary at the LHC
  - known known: jet cuts have to be higher at LHC than at Tevatron

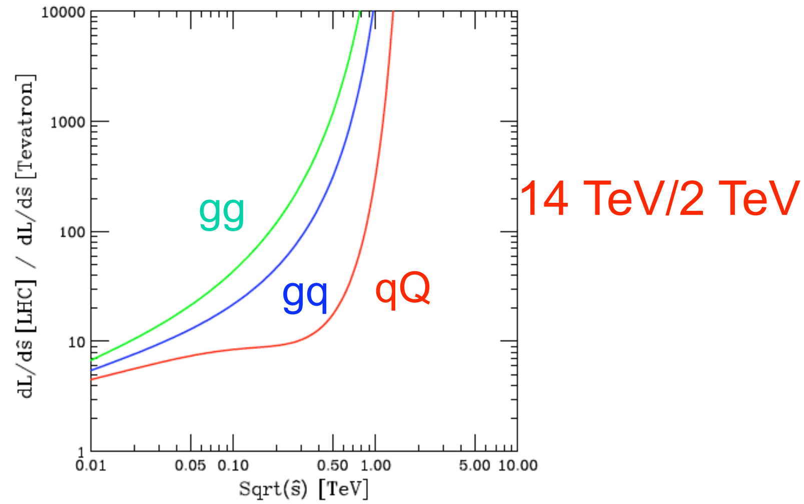


Figure 11. The ratio of parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y at the LHC and Tevatron. Green=gg (top), Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$ (middle), Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$ (bottom).

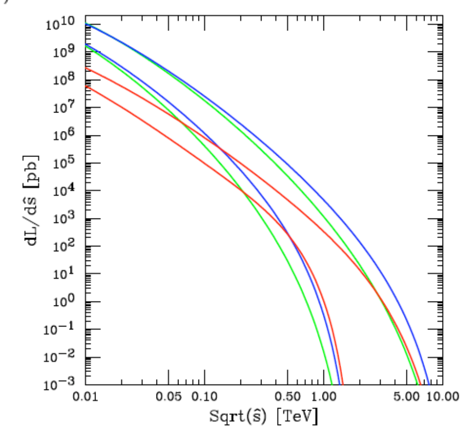


Figure 10. The parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$. The top family of curves are for the LHC and the bottom for the Tevatron.

Benchmarks: W/Z agreement

- We'll be reliant at the beginning (and throughout) of the LHC on benchmark cross sections
- The primary benchmarks are the W and Z cross sections
- CTEQ6.1 predictions agreed with MRST2004 predictions
- CTEQ6.6 predictions disagreed with MRST2004 predictions
- Inclusion of heavy quark mass effects affects DIS data in x range appropriate for W/Z production at the LHC
- …but MSTW2008 also has increased W/Z cross sections at the LHC due at least partially to improvements in their heavy quark scheme
  - now CTEQ6.6 and MSTW2008 in good agreement

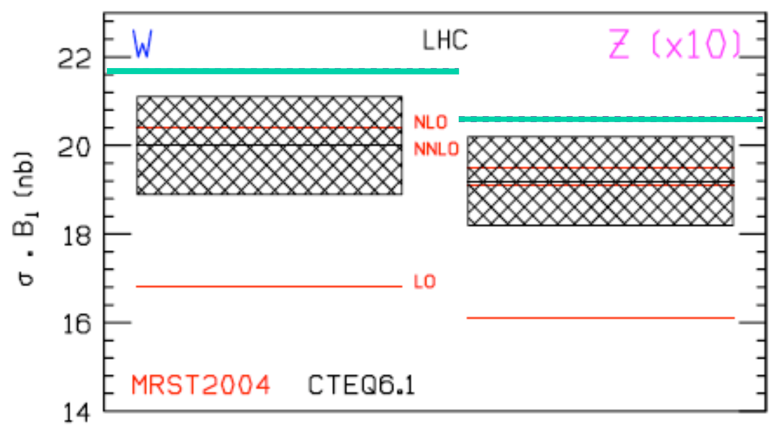


Figure 80. Predicted cross sections for W and Z production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.

CTEQ6.5(6)

MSTW08

Correlations with Z, tT

- correlations among cross sections/PDFs will be very important/useful, especially with respect to benchmark processes

define a correlation cosine between two quantities; basically the cosine of the angle between the two gradients in eigenvector space

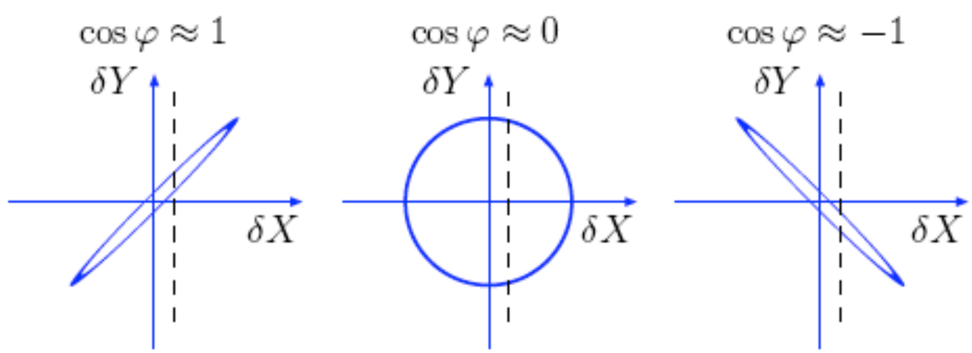
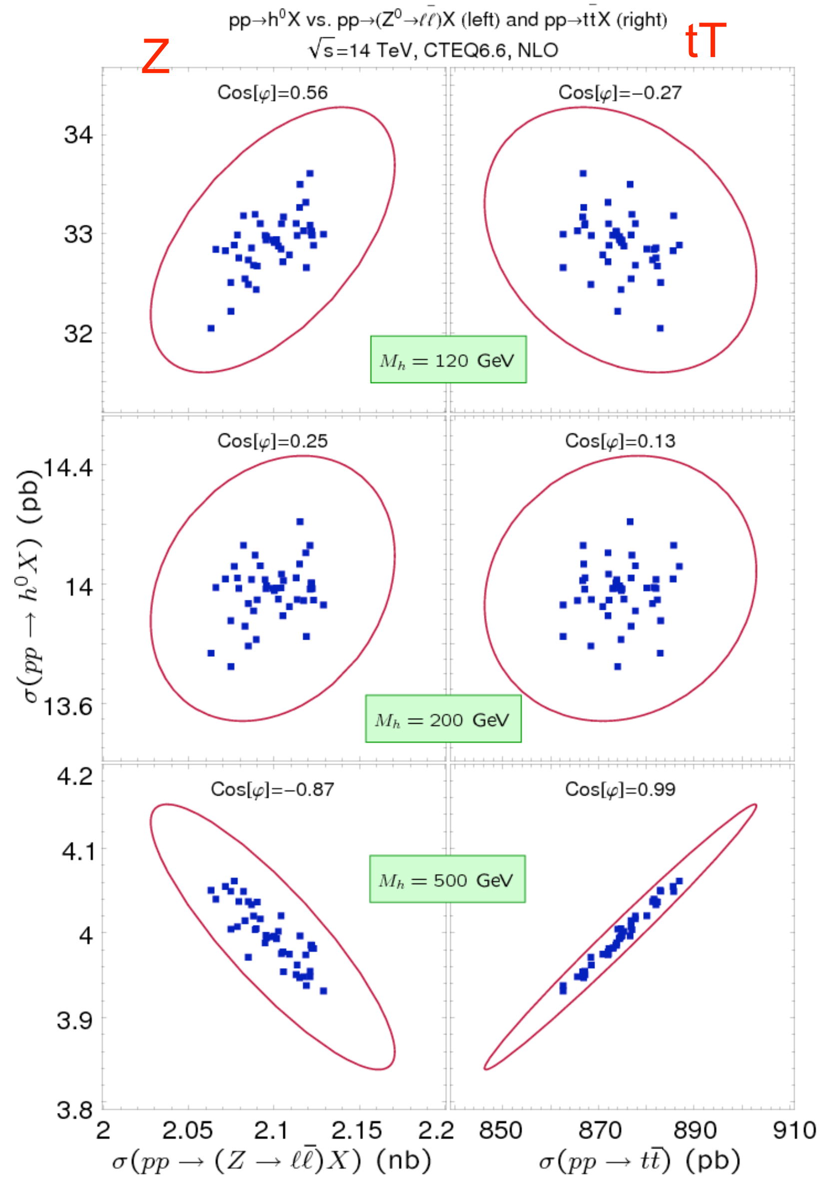


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

- If two cross sections are very correlated, then cosφ~1
- …uncorrelated, then cosφ~0
- …anti-correlated, then cosφ~-1



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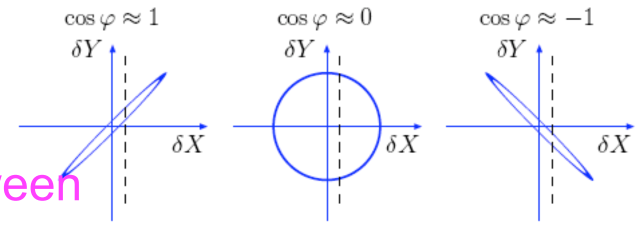
Correlations with Z, tT

Define a correlation cosine between two quantities



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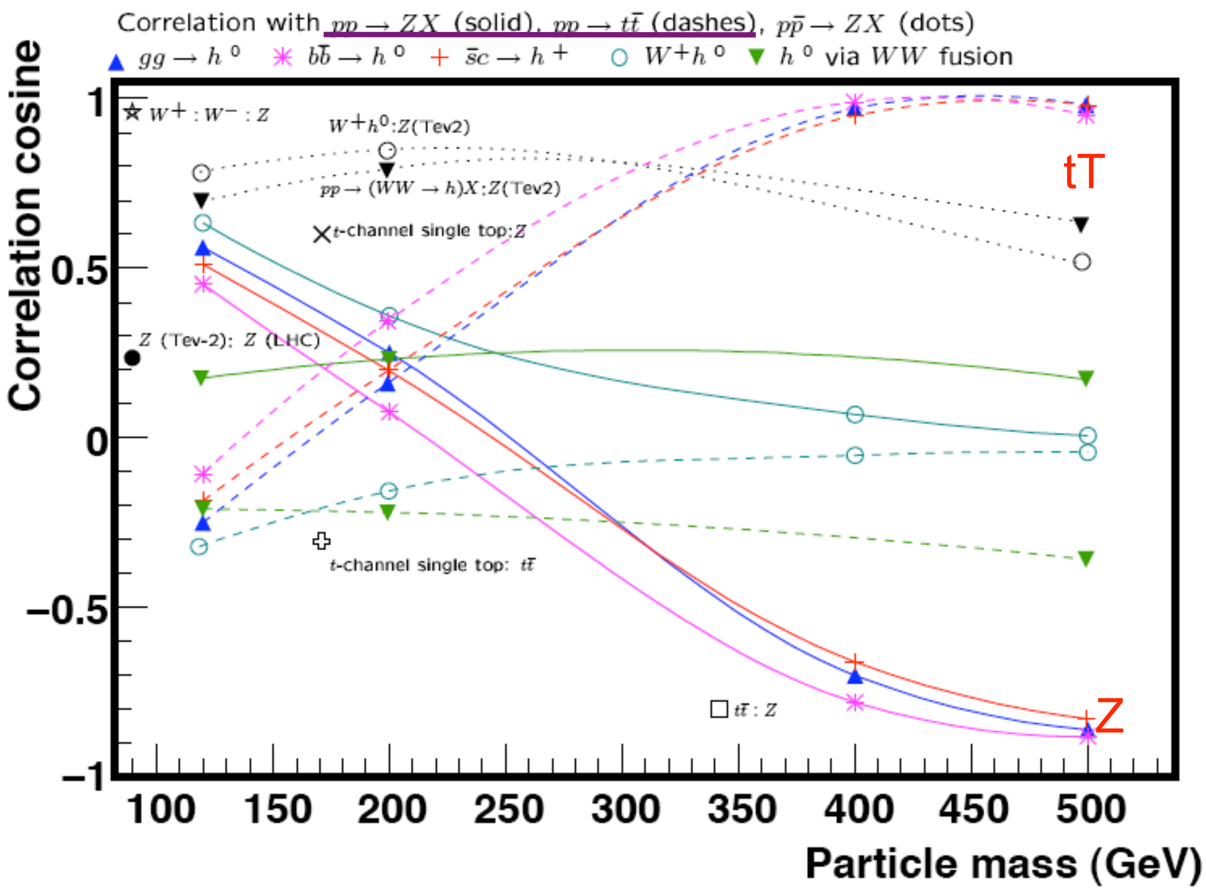
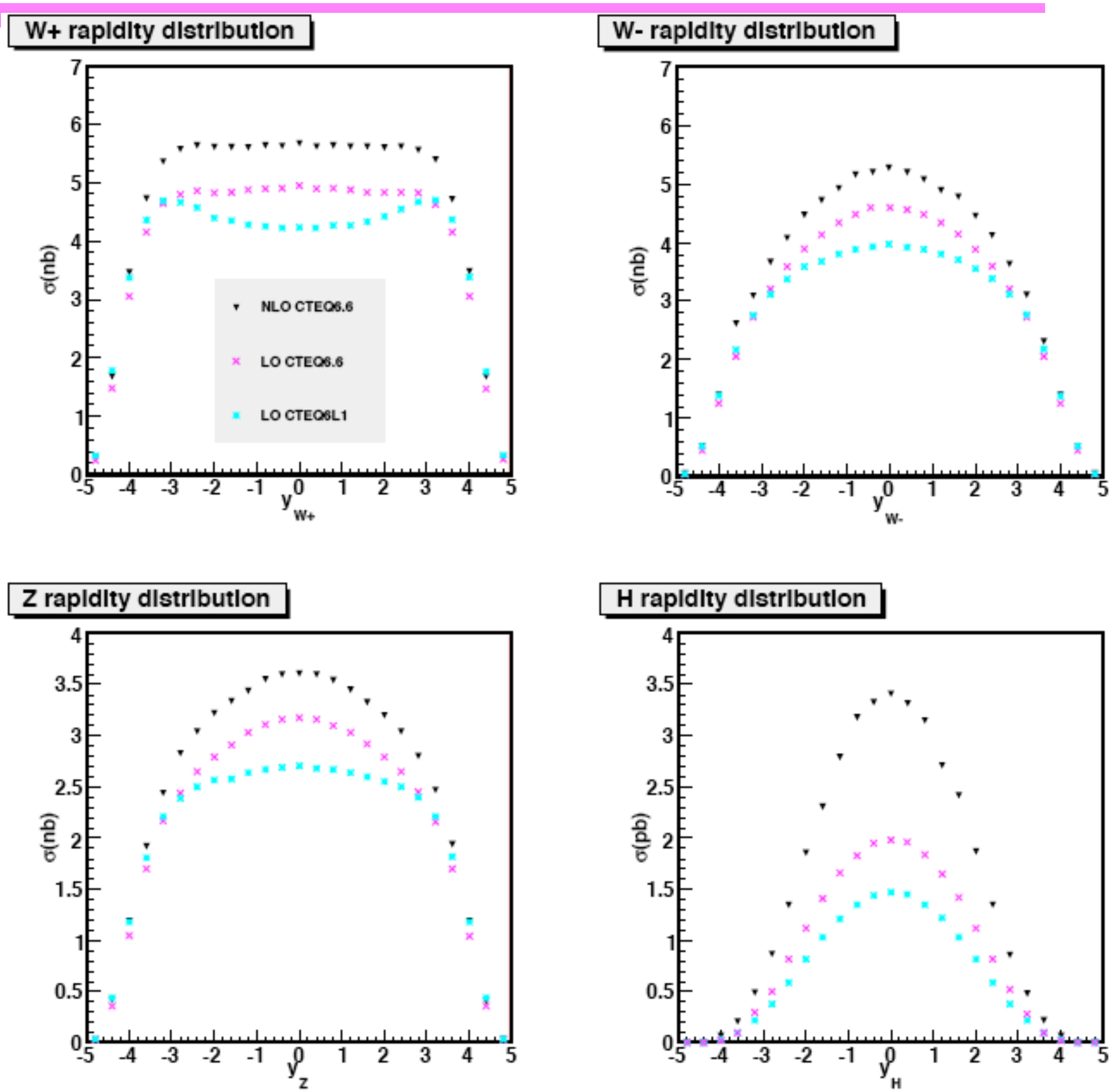


- Note that correlation curves to Z and to tT are mirror images of each other
- By knowing the pdf correlations, can reduce the uncertainty for a given cross section in ratio to a benchmark cross section **iff** $\cos\phi > 0$;e.g. $\Delta(\sigma_{W}+/\sigma_{Z})$~1%
- If $\cos\phi < 0$, pdf uncertainty for one cross section normalized to a benchmark cross section is larger
- So, for gg->H(500 GeV); pdf uncertainty is 4%; $\Delta(\sigma_H/\sigma_Z)$~8%

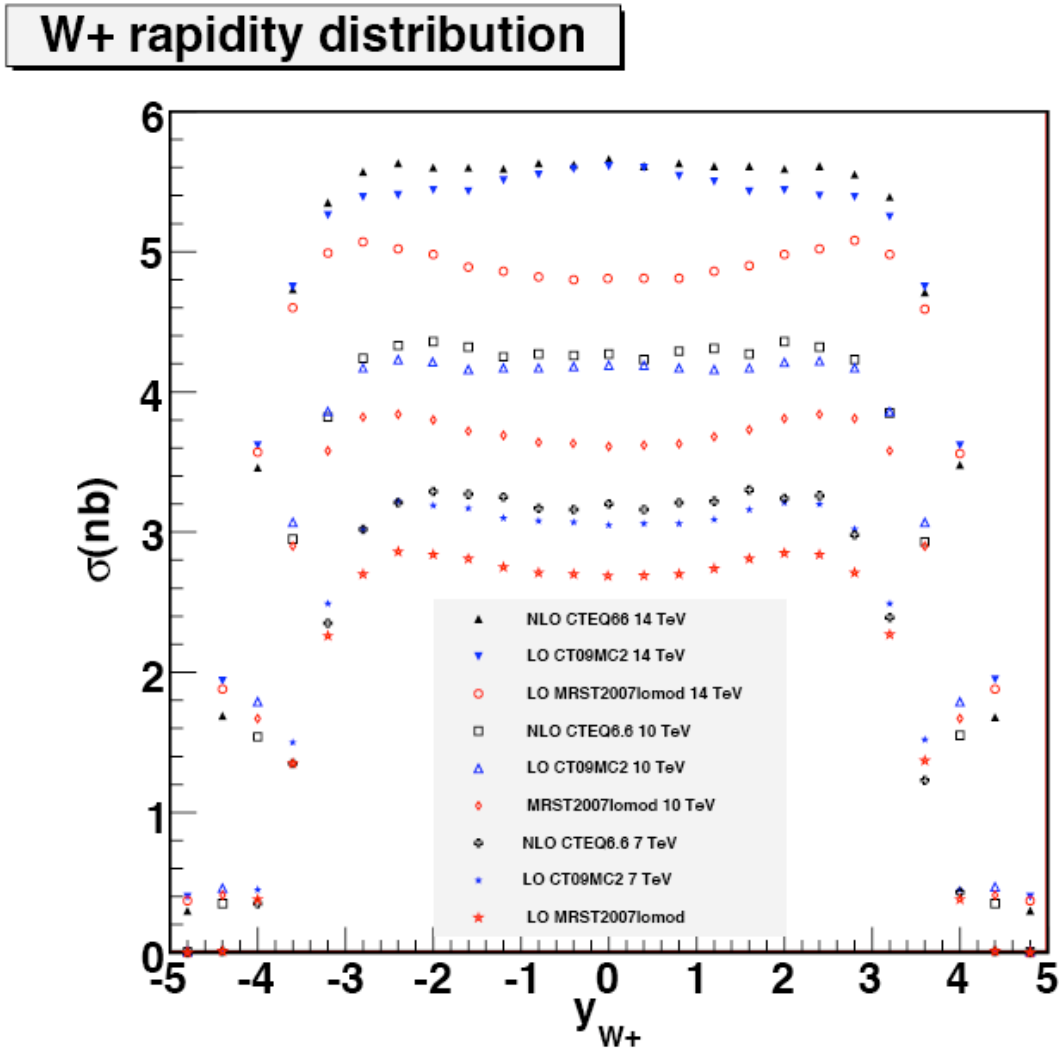
LO and NLO distributions

- The shapes for the cross sections shown to the right are well-described by LO matrix elements using NLO PDFs, but there are distortions that are evident when LO PDFs are used
- Normalizations are not fully described using LO matrix elements (K-factor)



CTEQ modified LO PDFs (LO*)

- Mod LO W^+ rapidity distribution agrees better with NLO prediction in both magnitude and shape
- Agreement at 7 and 10 TeV (not in fit) even better
- MRST2007lomod PDFs also provide better agreement with NLO prediction



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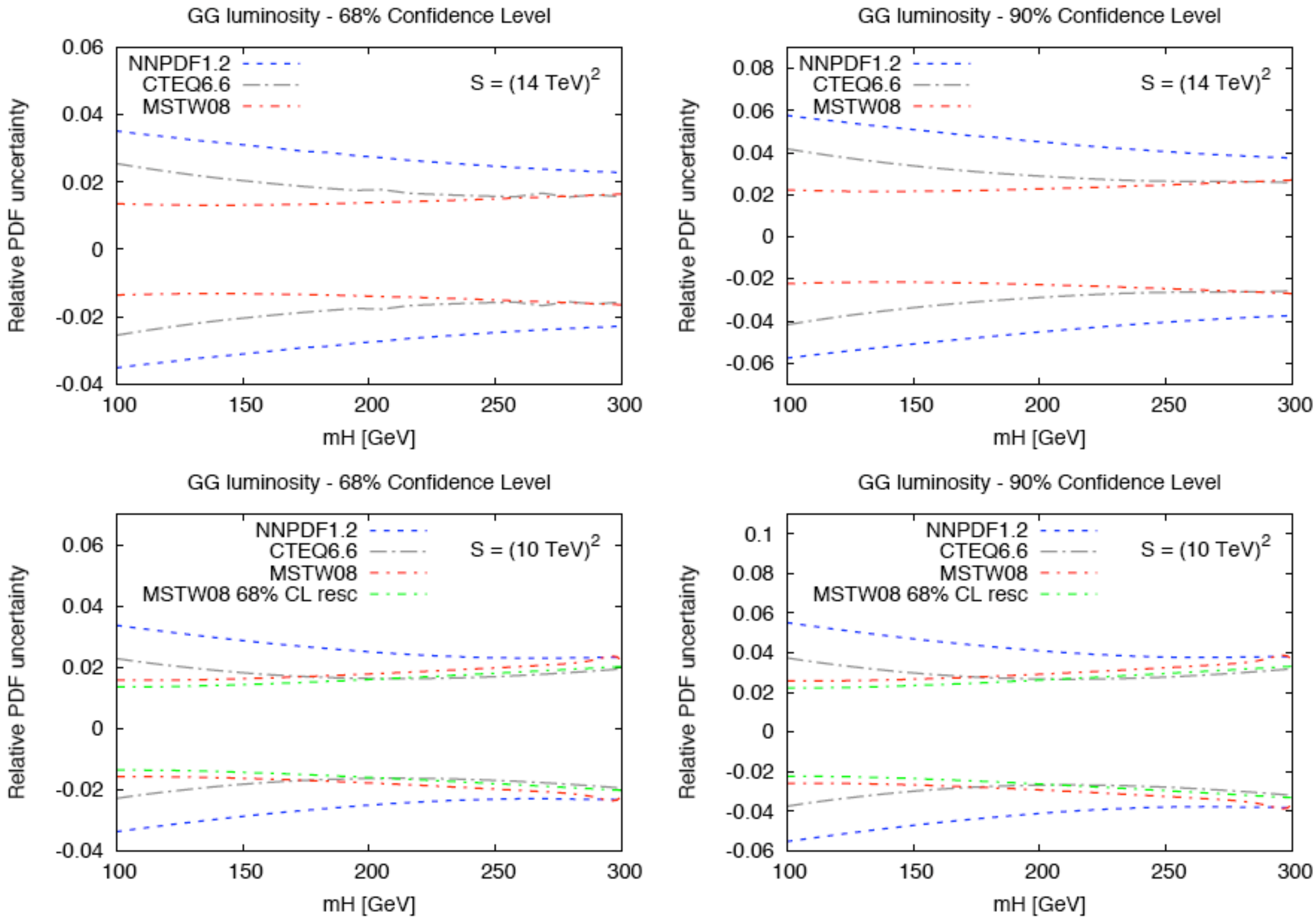
Cross sections and uncertainties

- In the ATLAS Higgs group, we've just gone through an exercise of compilation of predictions for Higgs production at LO/NLO/NNLO at a number of LHC center-of-mass energies
- This has involved a comparison of competing programs for some processes, a standardization of inputs, and a calculation of uncertainties, including those from PDF's
  - from eigenvectors in CTEQ/MSTW
  - using the NNPDF approach
- This is an exercise that other physics groups will be going through as well, both in ATLAS and in CMS
  - ATLAS Standard Model group now, for example
- There are a lot of tools/ procedures out there now, and a lot of room for confusion
- …and an impression that there are large differences for PDF uncertainties among the different PDF groups

PDF luminosity uncertainty differences are not so great

- See A. Vicini's talk in last PDF4LHC meeting



PDF errors

- So now, seemingly, we have more consistency in the size of PDF errors, at least for this particular example
- The eigenvector sets represent the PDF uncertainty due to the experimental errors in the datasets used in the global fitting process
- Another uncertainty is that due to the variation in the value of α_s
- It has been traditional in the past for the PDF groups to publish PDF sets for variant values of α_s, typically over a fairly wide range
  - experiments always like to demonstrate that they can reject a value of $\alpha_s(m_Z)$ of 0.128
- MSTW has recently tried to better quantify the uncertainty due to the variation of α_s, by performing global fits over a finer range, taking into account any correlations between the values of α_s and the PDF errors
- …more recent studies by CTEQ and NNPDF have shown that for their PDF's the correlation between α_s errors and PDF errors is small enough that the two sources can be added in quadrature

$\alpha_s(m_Z)$ and uncertainty

- A complication of comparisons of different PDFs is that different values of α_s and of its uncertainty are used in global fits
- CTEQ and NNPDF use the world average (actually 0.118 for CTEQ and 0.119 for NNPDF), where MSTW2008 uses 0.120, as determined from their fit
- Latest world average (from Siggi Bethke->PDG)
  - $\alpha_s (m_Z) = 0.1184 +/- 0.0007$
- What does the error represent?
  - Siggi said that only one of the results included in his world average was outside this range
  - suppose we're *conservative* and say that +/-0.002 is a 90% CL
- Could it be possible for all global PDF groups to use the world average value of α_s in their fits, plus a prescribed range for its uncertainty (if not 0.002, then perhaps another acceptable value)?
- I told Albert that if he could persuade everyone of this, that I personally would nominate him for the Nobel Peace Prize

(My) interim recommendation for ATLAS (and for the LHC community)

- Cross sections should be calculated with MSTW2008 and CTEQ6.6
- Upper range of prediction should be given by upper limit of error prediction using prescription for combining α_s uncertainty with error PDFs
  - in quadrature for CTEQ6.6
  - using α_s eigenvector sets for MSTW2008
- Ditto for lower limit
- So for a Higgs mass of 120 GeV at 14 TeV, the gg cross section limits would be 34.9 pb (defined by the CTEQ6.6 lower limit, α_s=0.120) and 41.4 pb (defined by the MSTW2008 upper limit)
  - note that central predictions for CTEQ6.6 (35.74 pb) and MSTW2008 (38.45 pb) are different not because of the gluon distribution (which coincide very closely in the relevant x range), but because of the different values of α_s used
- Where possible, NNPDF predictions (and uncertainties) should be used as well in the comparisons

Progress: PDF Benchmarking 2010

- Benchmark processes, all to be calculated

  (i) at NLO (in MSbar scheme)

  (ii) in 5-flavour quark schemes (definition of scheme to be specified)

  (iii) at 7 TeV [and 14 TeV] LHC

  (iv) for central value predictions and +-68%cl [and +- 90%cl] pdf uncertainties

  (v) and with +- α_s uncertainties

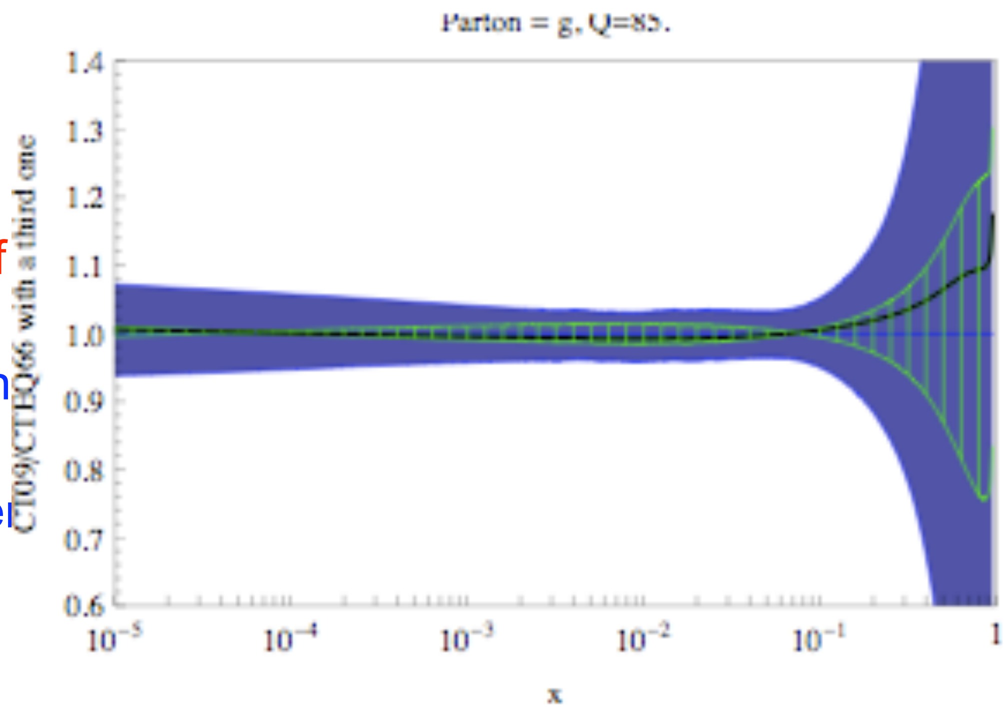
  (vi) repeat with $\alpha_s(m_Z)$=0.119

(prescription for combining with pdf errors to be specified)

- Using (where processes available) MCFM 5.7
  - gzipped version prepared by John Campbell using the specified parameters (and the new CTEQ6.6 α_s series)
- See extra slides for processes

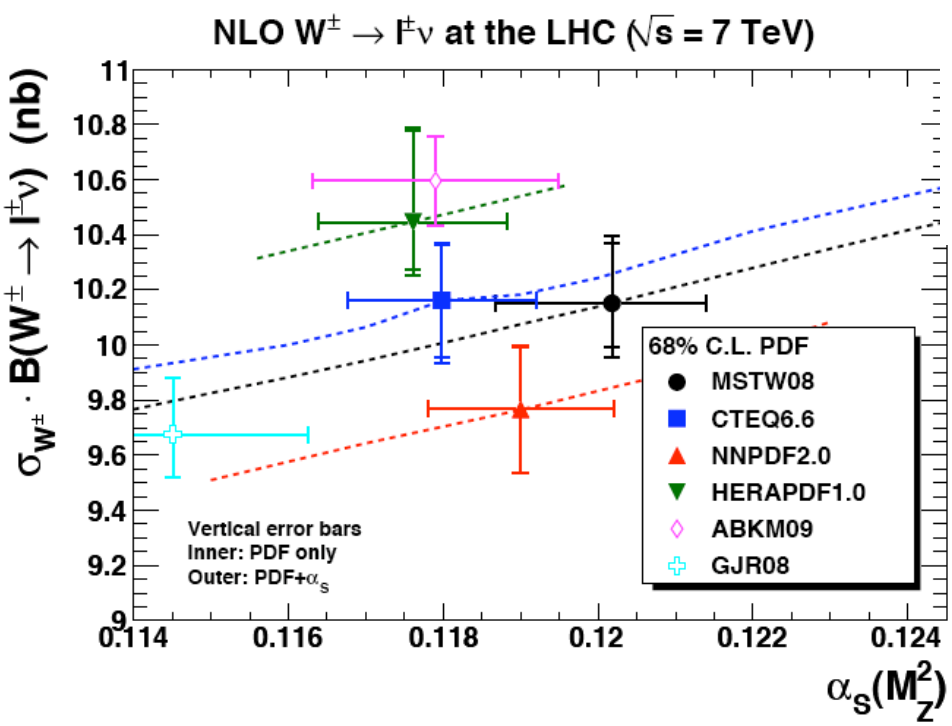
Aside: new CTEQ6.6 α_s series

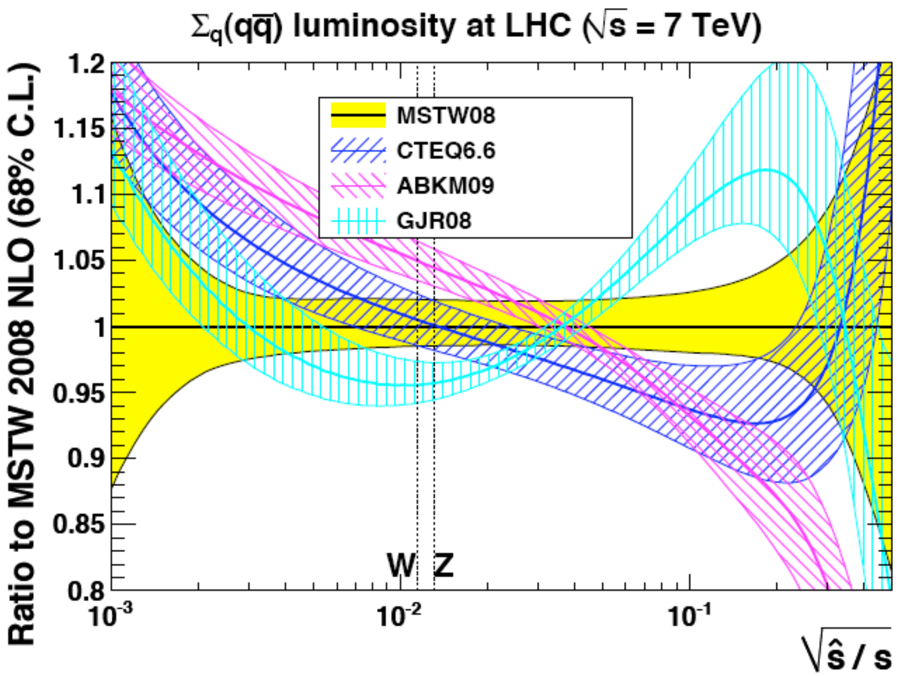
- CTEQ6.6 central $\alpha_s(m_Z)$ value=0.118
- Error PDFs with α_s values of
  - 0.116
  - 0.117
  - 0.118
  - 0.119
  - 0.120
  - available in current version of LHAPDF
- Change in gluon from α_s variation roughly half that of PDF error
- NB: lack of strong correlation over this as range means that errors (PDF+α_s) can be added in quadrature



Preliminary benchmark results: W+

- CTEQ and MSTW agree; NNPDF is low, but no GM-VFNS included yet

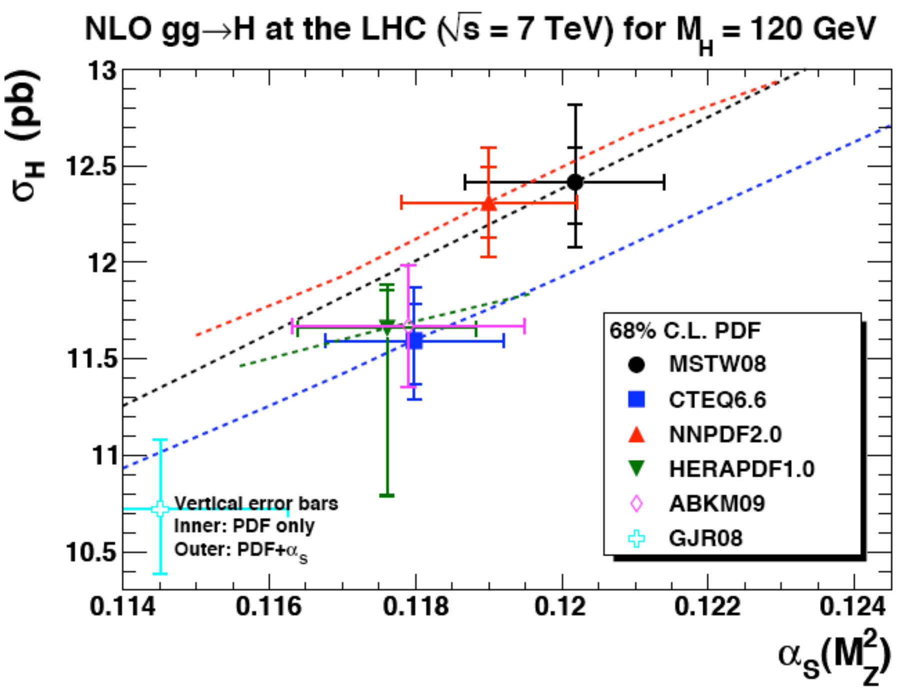


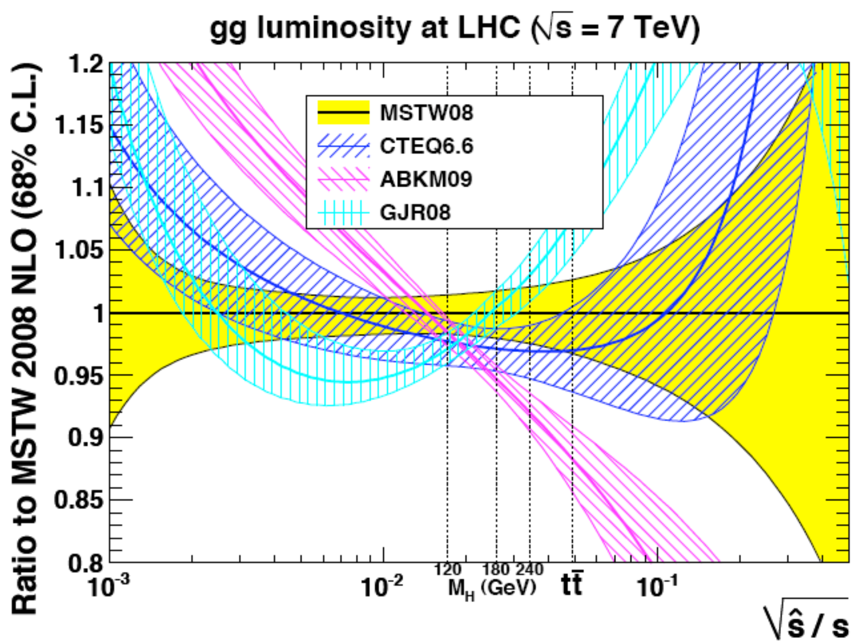


G. Watt, PDF4LHC Mar 26

Preliminary results: Higgs

- Still some remaining differences, but results from different groups are reasonably consistent , especially if consistent value of $\alpha_s(m_Z)$ is used



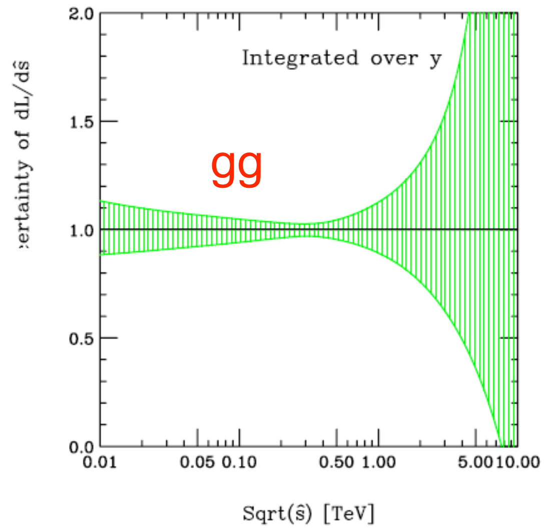


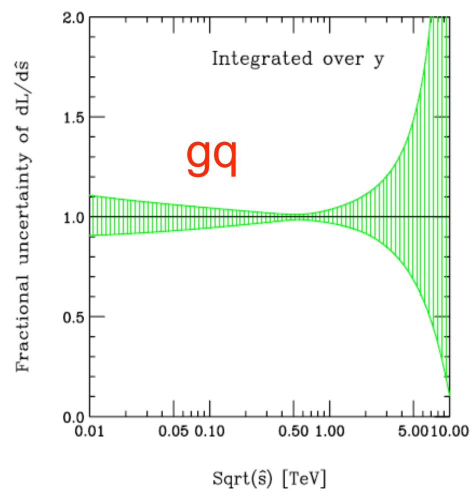
G. Watt, PDF4LHC meeting Mar 26

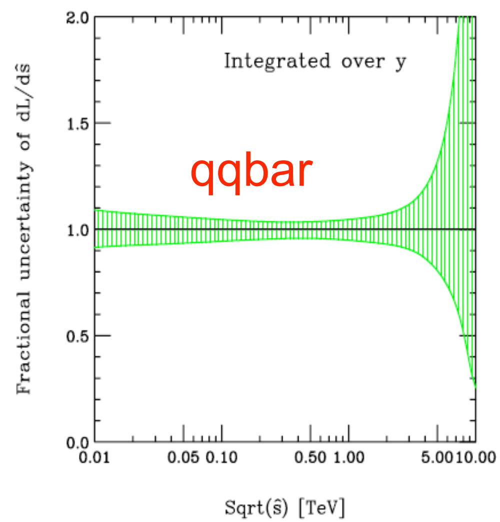
More discussion at Freiburg meeting next week

The “Future”

- How well do we know PDFs going into the start of LHC running?
- For much of the kinematic region, the uncertainty is pretty small
- Primarily because of the precision data that came from HERA
- And the precision will improve as the final HERA data sets are released to the public







The Future, continued

- Of course, as the LHC data comes in, we will use it in future PDF fits
- But in order to be useful, the precision has to be high, and most early data will not fulfill that requirement
- The global fits are dominated not by statistical errors but by systematic errors…and the correlations

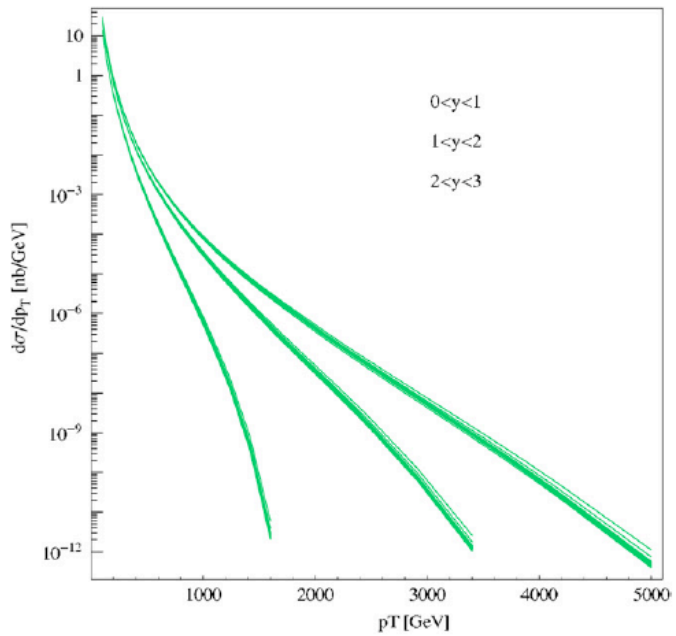


Figure 104. Inclusive jet cross section predictions for the LHC using the CTEQ6.1 central pdf and

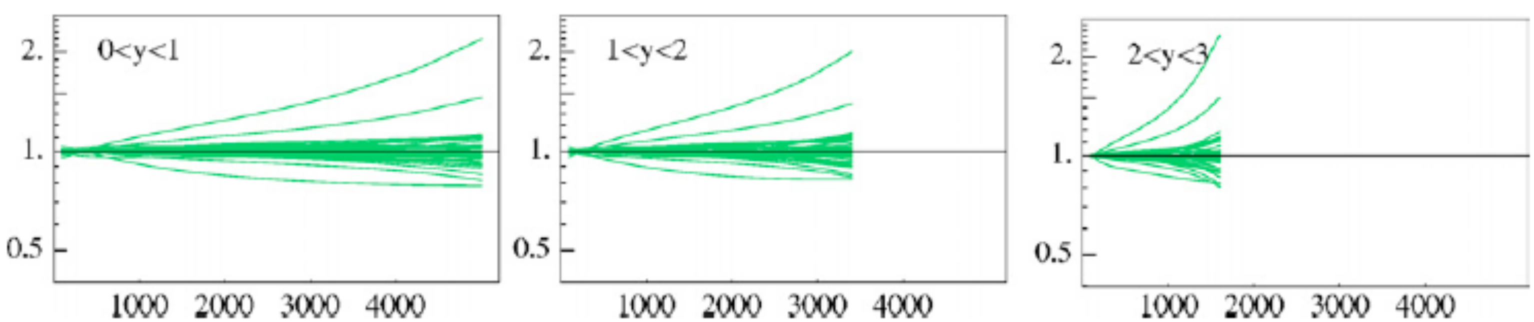


Figure 105. The ratios of the jet cross section predictions for the LHC using the CTEQ6.1 error pdfs to the prediction using the central pdf. The extremes are produced by eigenvector 15.

Jets: the LHC will be a very jetty place

- Total cross sections for tT and Higgs production saturated by tT (Higgs) + jet production for jet p_T values of order 10-20 GeV/c

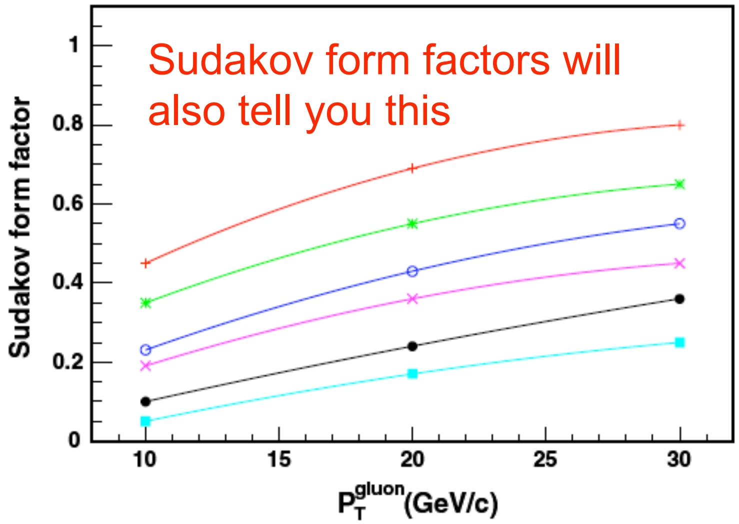


Figure 22. The Sudakov form factors for initial-state gluons at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton *x* values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

- indication that can expect interesting events at LHC to be very *jetty* (especially from gg initial states)
- jet cuts are higher at LHC than at Tevatron

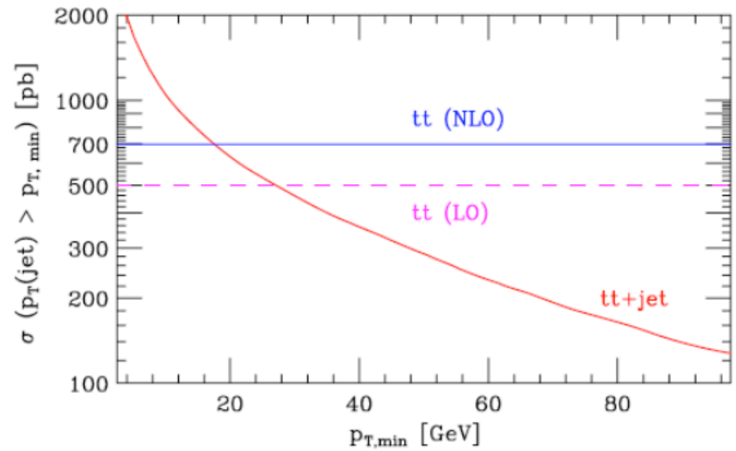


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

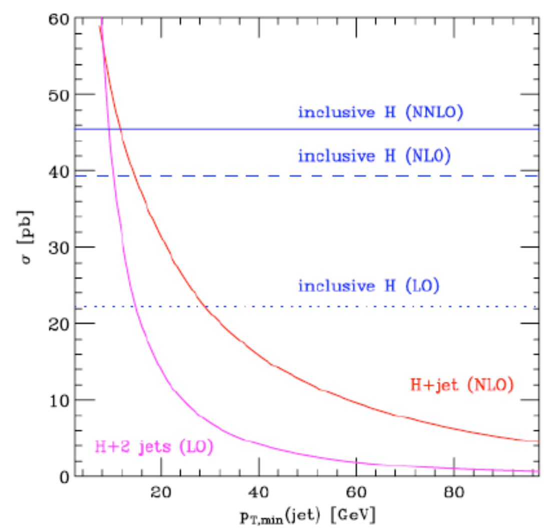


Figure 100. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

Dynamic range

- Interested in jets from 20-30 GeV/c to several TeV/c
- There is a tendency to think of jets as *static objects* such as electrons, muons or photons
- Jets (and QCD) have a rich dynamic structure that is not fully probed with a single jet algorithm or a single jet size
  - for example ,at the LHC, we will be more interested in jet masses and jet substructure
- We need to have a different mindset at the LHC than at the Tevatron

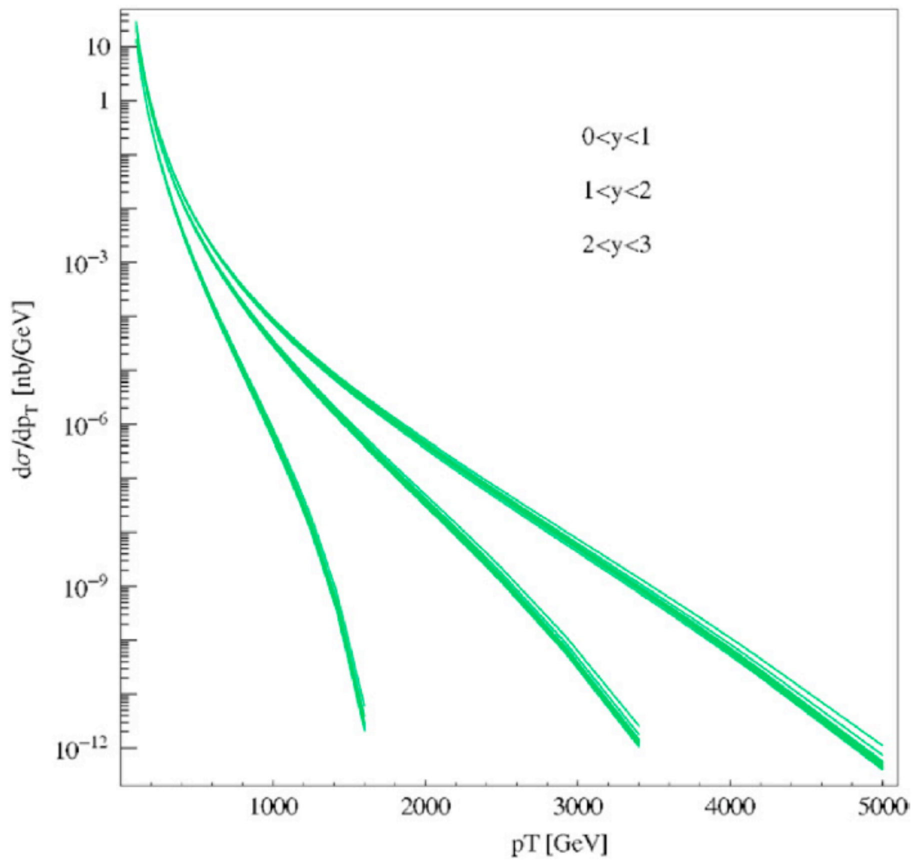
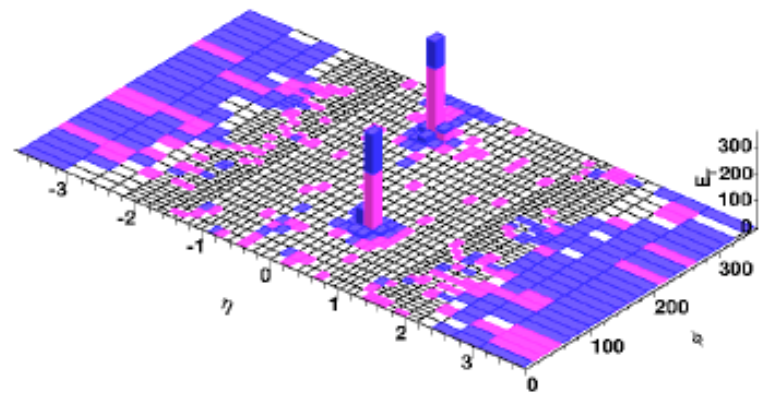


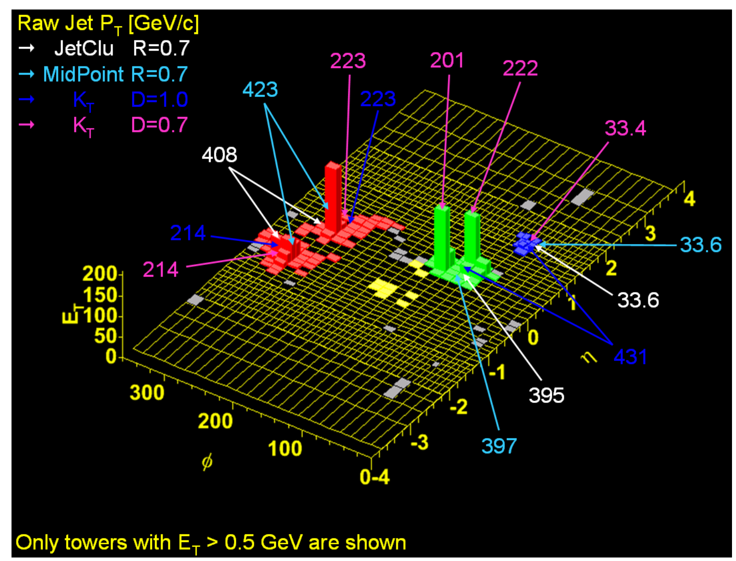
Figure 104. Inclusive jet cross section predictions for the LHC using the CTEQ6.1 central the 40 error pdfs.

Jet algorithms

- For some events, the jet structure is very clear and there's little ambiguity about the assignment of towers to the jet
- But for other events, there is ambiguity and the jet algorithm must make decisions that impact precision measurements
- If comparison is to hadron-level Monte Carlo, then hope is that the Monte Carlo will reproduce all of the physics present in the data and influence of jet algorithms can be understood
  - more difficulty when comparing to parton level calculations
- We need to get in the mindset for the use of multiple jet algorithms/ parameters for physics analyses
  - and of course all results corrected to the hadron level, as per Frank's suggestion

CDF Run II events





Comparison of k_T and cone results

- …at the Tevatron
- Remember
  - at NLO the k_T algorithm corresponds to Region I (for D=R); thus at parton level, the cone algorithm is always larger than the k_T algorithm
- Let's check this out with CDF results after applying hadronization corrections
  - similar results for all rapidity regions
- Nice confirmation of the perturbative picture

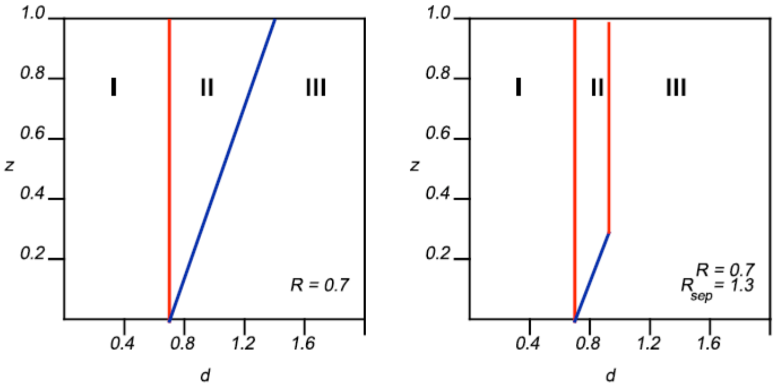
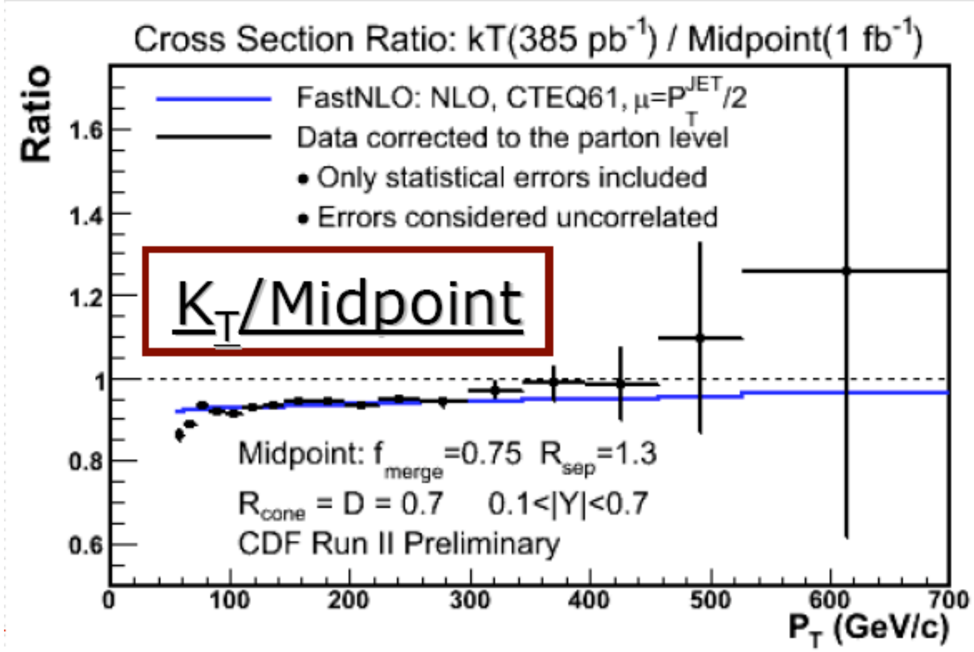


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.



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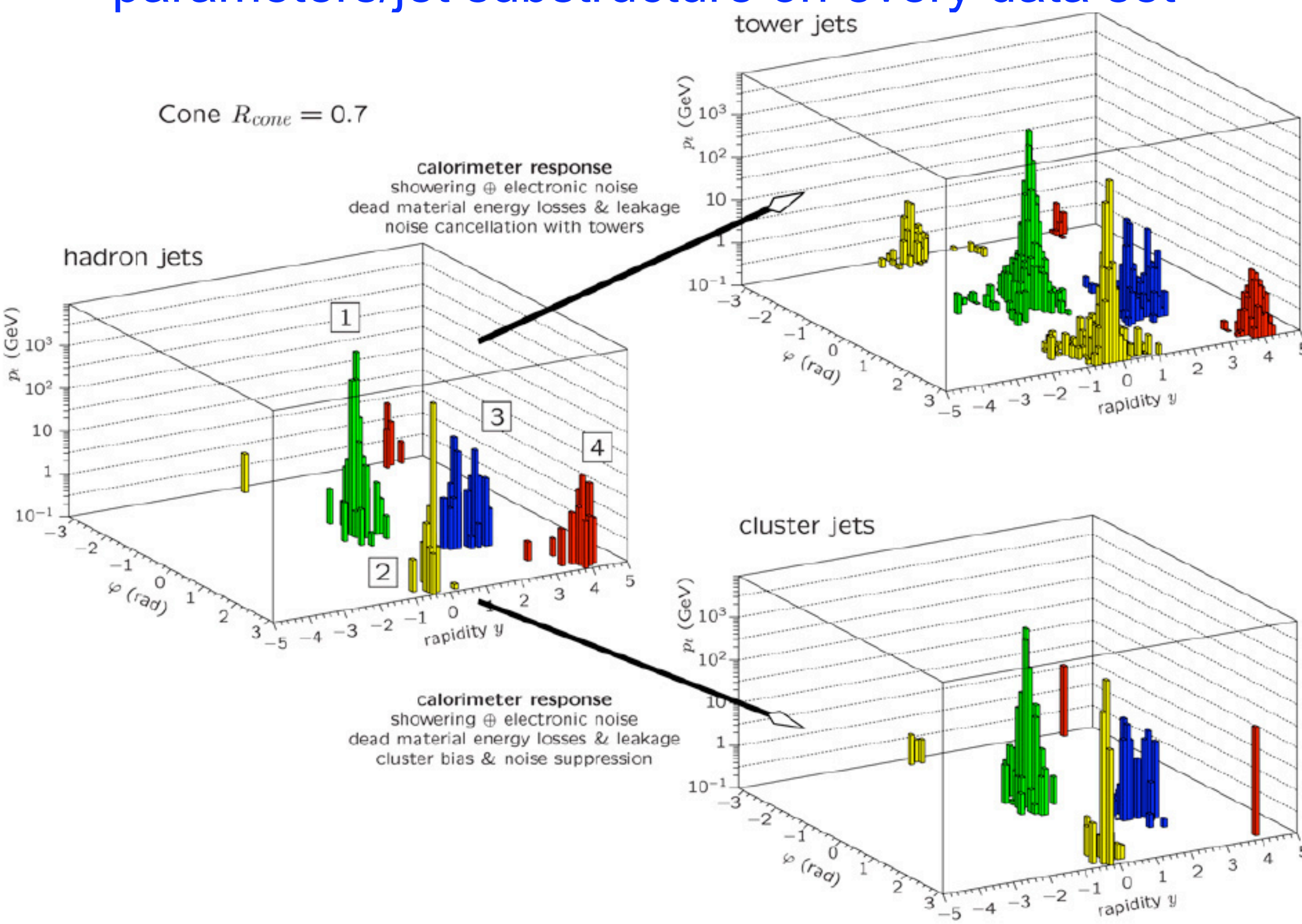
ATLAS jet reconstruction

- Using calibrated topoclusters, ATLAS has a chance to use jets in a dynamic manner not possible in any previous hadron-hadron calorimeter, i.e. to examine the impact of multiple jet algorithms/ parameters/jet substructure on every data set

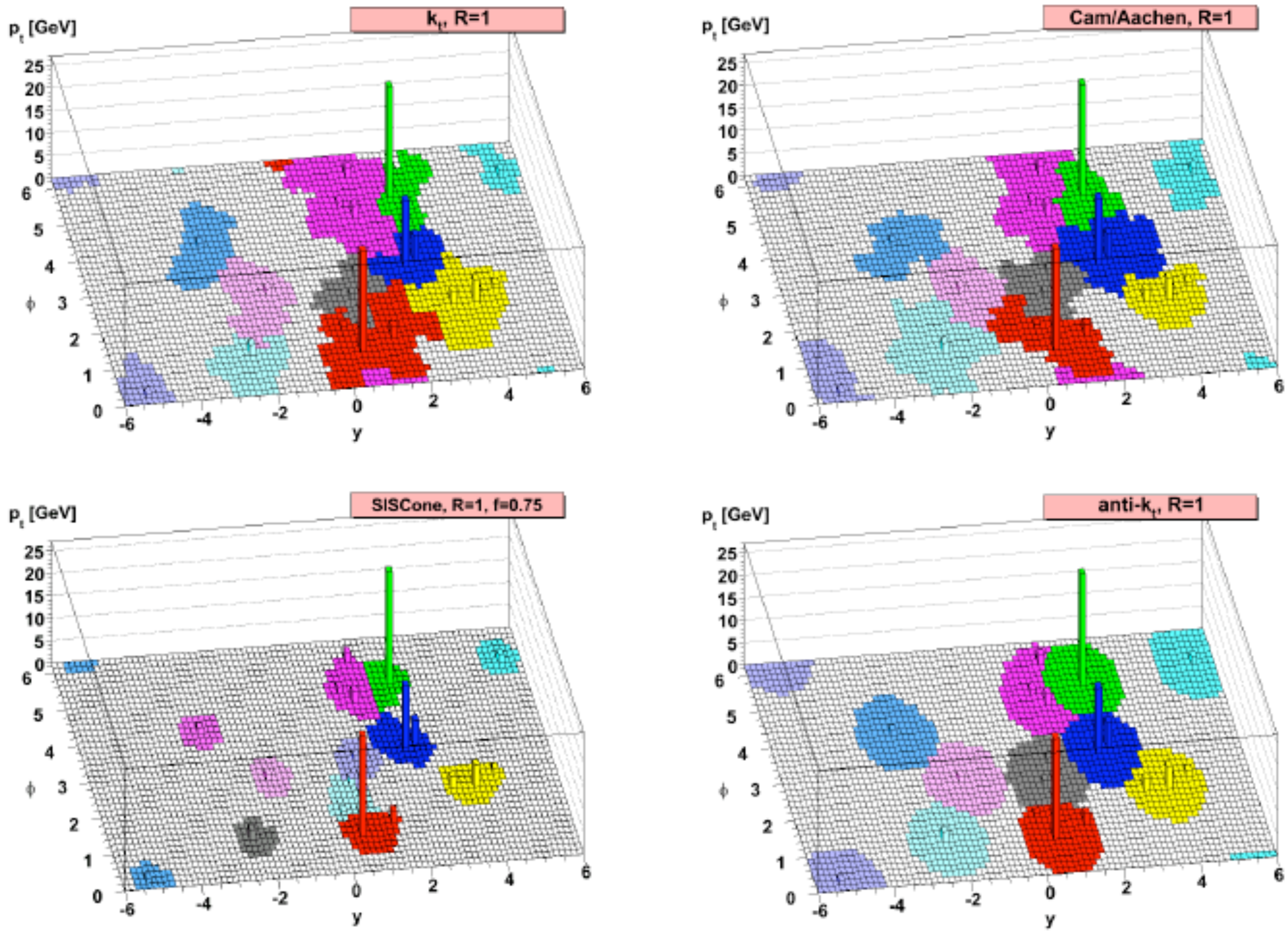


blobs of energy in the calorimeter correspond to 1/few particles (photons, electrons, hadrons); can be corrected back to hadron level

rather than jet itself being corrected

similar to running at hadron level in Monte Carlos

Useful concept: jet areas



determined by clustering ghost particles of vanishing energy

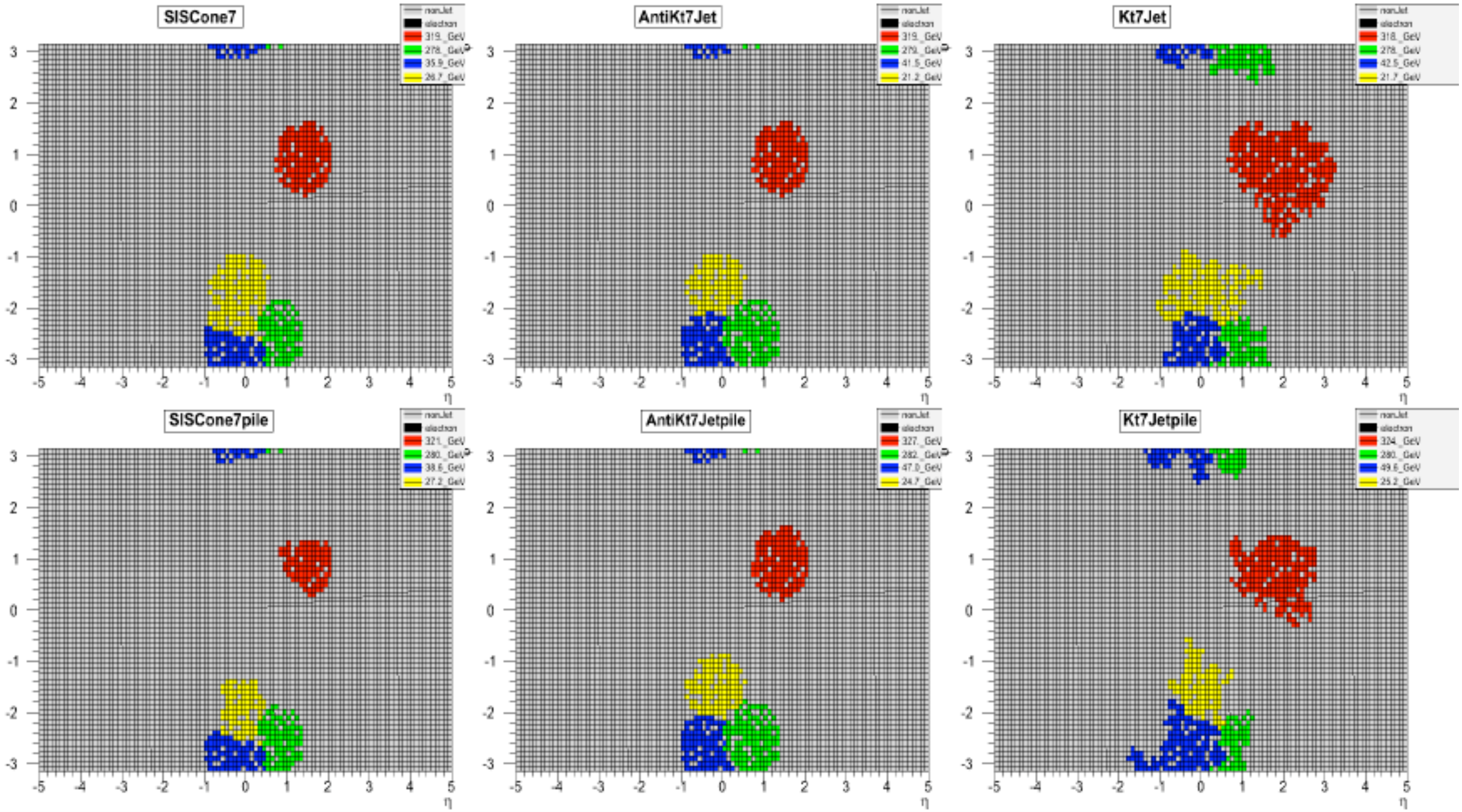
note that the k_T algorithm has the largest jet areas, SISCone the smallest and anti-k_T the most regular

Cacciari, Salam, Soyez

Jet areas in presence of pileup

- Single W+4jets event, all matched to partons.
- SIScone and kT show decreased area in presence of pileup

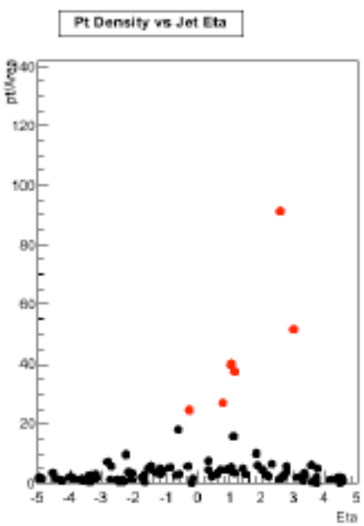
pileup nibbles away at perimeter of jet

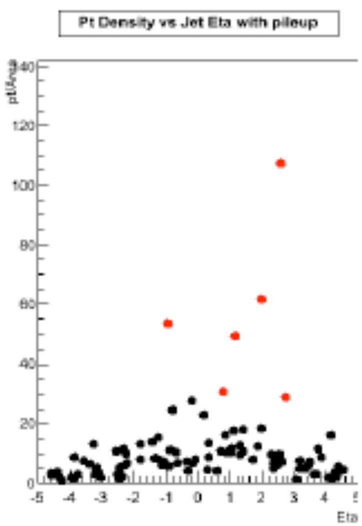


Area-based correction

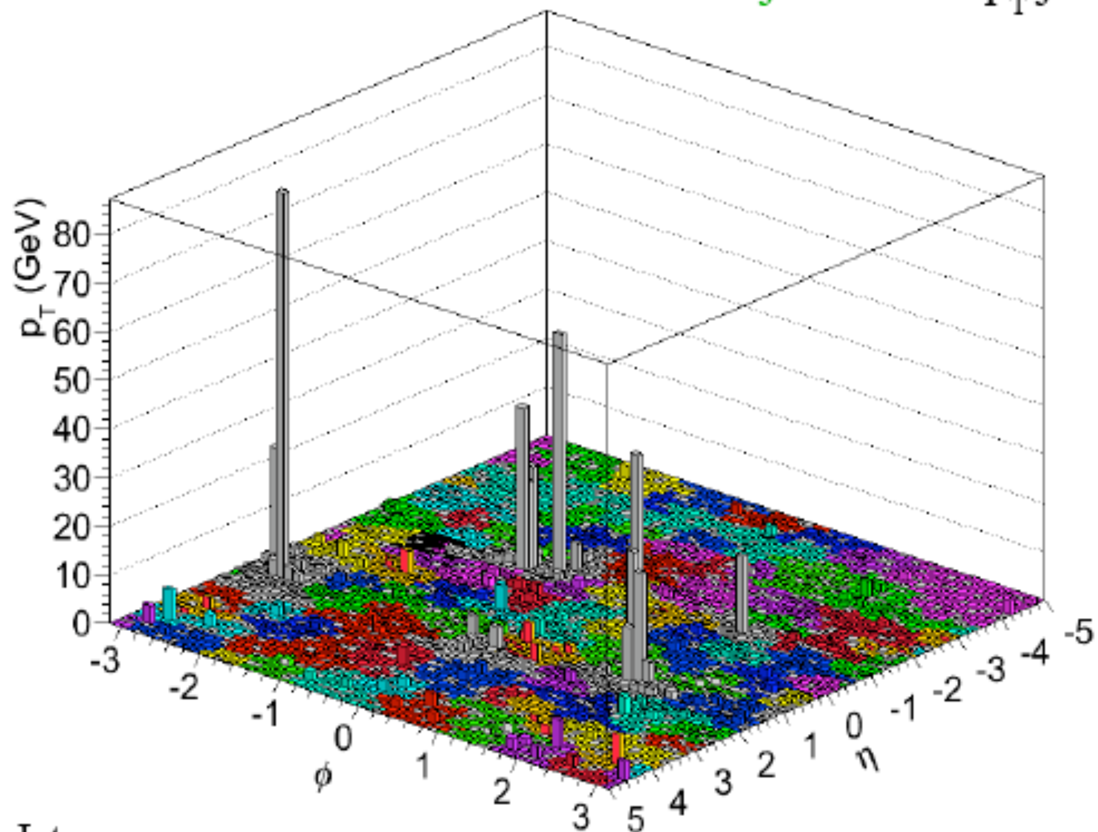
1) Find low p_T jets in event. (< 10GeV) We use kT5jet.
2) From these, find average/median pT density of event ρ
3) Determine area A of signal jets
4) Subtract “pileup/UE”estimate

$$p_{Tcorr} = p_T - \rho A$$





W+5j event with kT5Jets
Gray jets = Signal Jets
Colored jets = Low p_T jets



- Black points used to find pT density
- Red points are then corrected according to Jet area

See presentations of Brian Martin in ATLAS jet meetings.

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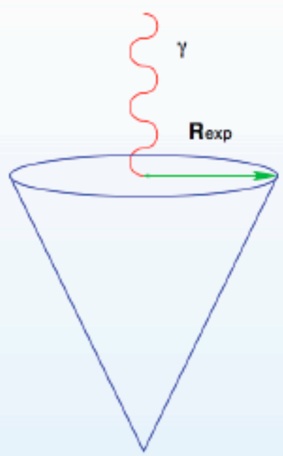
Photons at the LHC: isolation

- From a theoretical perspective, it's best to apply a *Frixione-style* isolation criterion, in which the amount of energy allowed depends on the distance from the photon; this has the advantage of removing the fragmentation contribution for photon production, as well as discriminating against backgrounds from jet fragmentation
- But most of the energy in an isolation cone is from underlying event/pileup
- At Les Houches, we developed:
  - (1) an implementation of the Frixione isolation appropriate for segmented calorimeters
  - (2) a hybrid technique that separates the UE/pileup energy from fragmentation contributions using the jet density approach

Isolation criterion

courtesy J.P.Guillet



$E_T^{had} \leq E_{T\,max}$ inside
$(y - y_\gamma)^2 + (\phi - \phi_\gamma)^2 \leq R_{exp}^2$

Large Log. when $R_{exp} \to 0$ and $E_{T\,max} \to 0$

Other isolation criterion (S. Frixione)
where $E_{T\,max} = F(r)$

- **Action Items:**
  - Susan, Joey, Kajari, Jean-Philippe
- **Exp** :
  Look again in detail at the Frixione criterium, what is the impact at LHC of UE/PU, of fragmentation; see if some "hybrid" (simple cone vs Frixione) can be found, suitable for exp. application.
- **Theory**:
  use existing (and possibly upgraded) codes to study difference in x-sections obtained with Frixione-criterium and some "pedestal" allowed in the central cone
- Look also at **"democratic" approach**

SpartyJet

Sparty

J. Huston, K. Geerlings,
Brian Martin
Michigan State University

P-A. Delsart, Grenoble

If interested for ATLAS, please contact
Brian.thomas.martin@cern.ch

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FastJet vs SpartyJet

What this is NOT.

- These tools have different purposes despite some overlap.
- Being developed with different goals in mind

What this IS.

- SpartyJet is being developed to allow FastJet to be used in more ways, more readily
- Increase usage of FastJet through helpful interfaces and analysis tools

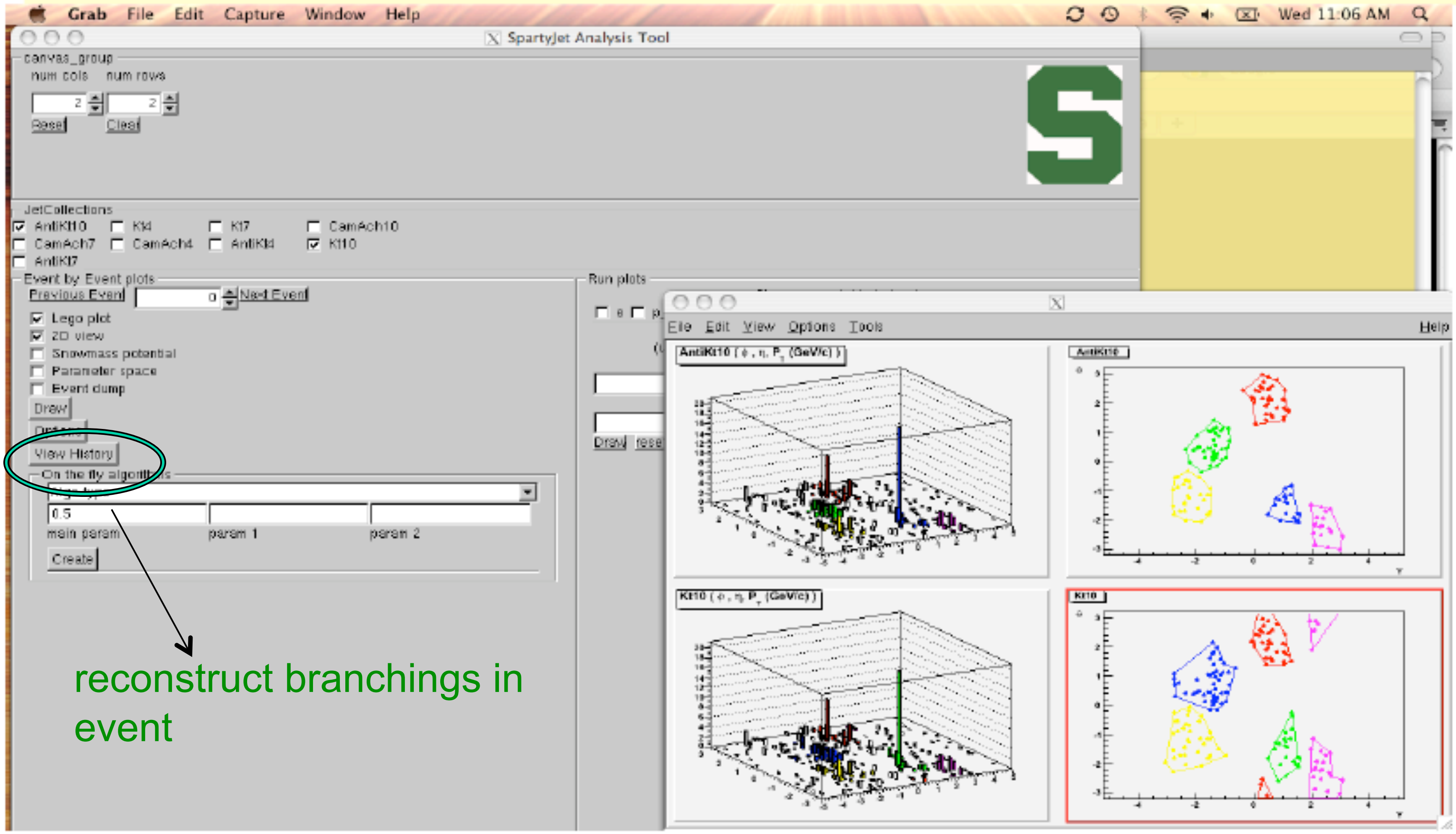
SJ Authors: *Joey Huston, Pierre-Antoine Delsart, Kurtis Geerlings*

FJ Authors: *Matteo Cacciari, Gavin Salam and Gregory Soyez*

Gui interface

guiExample.py

```
./guiExample.py
```



reconstruct branchings in event

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Parton level Monte Carlo generators

- Programs that do NLO calculations, such as MCFM, are parton-level Monte Carlo generators in which (weighted) events and counter-events are generated
  - for complicated processes, such as W + 2 jets, there can be many counter-events (24), corresponding to the Catani-Seymour subtraction terms, for each event
  - only the sum of all events (events + counter-events) is meaningful, since many positive and negative weights need to cancel against each other; if too few events are generated, or if the binning is too small, can have negative results
  - in general, cannot connect these complex NLO matrix elements to parton showering…although that's the dream/plan
    - processes such as W,Z,WW,ZZ,Higgs, ttbar, single top,… have been included in NLO parton shower Monte Carlo programs like MC@NLO, Powheg
    - state of the art now is Z + 1 jet (I believe)

MCFM

- Many processes available at LO and NLO
  - note these are partonic level only
- Option for ROOT output (see later)
- mcfm.fnal.gov

$p\bar{p} \to W^\pm/Z$	$p\bar{p} \to W^+ + W^-$
$p\bar{p} \to W^\pm + Z$	$p\bar{p} \to Z + Z$
$p\bar{p} \to W^\pm + \gamma$	$p\bar{p} \to W^\pm/Z + H$
$p\bar{p} \to W^\pm + g^\star\,(\to b\bar{b})$	$p\bar{p} \to Zb\bar{b}$
$p\bar{p} \to W^\pm/Z + 1\text{ jet}$	$p\bar{p} \to W^\pm/Z + 2\text{ jets}$
$p\bar{p}(gg) \to H$	$p\bar{p}(gg) \to H + 1\text{ jet}$
$p\bar{p}(VV) \to H + 2\text{ jets}$	$p\bar{p} \to t + X$
$pp \to t + W$	

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State of the art

Relative order	2->1	2->2	2->3	2->4	2-5	2->6
1	LO					
α_s	NLO	LO				
α_s^2	NNLO	NLO	LO			
α_s^3		*NNLO*	NLO	LO		
α_s^4				NLO	LO	
α_s^5						LO

- LO: well under control, even for multiparticle final states
- NLO: well understood for 2->1, 2->2 and 2->3; first calculations of 2->4 (W +3 jets, ttbb)
- NNLO: known for inclusive and exclusive 2->1 (i.e. Higgs, Drell-Yan); work on 2->2 (Higgs + 1 jet)

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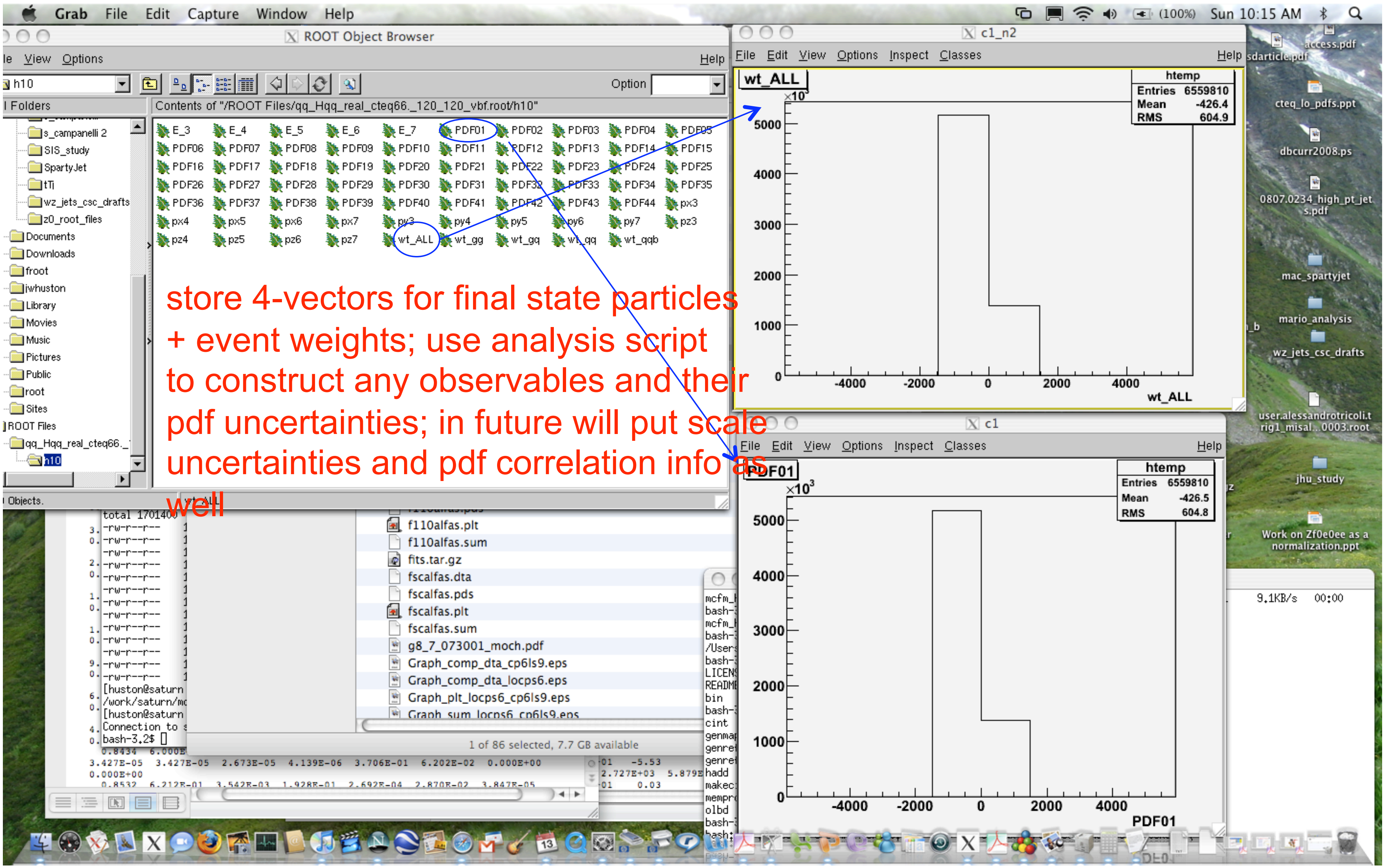
Some issues/questions

- Once we have the calculations, how do we (experimentalists) use them?
- Best is to have NLO partonic level calculation interfaced to parton shower/hadronization
  - but that has been done only for relatively simple processes and is very (theorist) labor intensive
    - still waiting for inclusive jets in MC@NLO, for example
- Even with partonic level calculations, need public code and/or ability to write out ROOT ntuples of parton level events
  - so that can generate once with loose cuts and distributions can be re-made without the need for the lengthy re-running of the predictions
  - what is done for example with MCFM for CTEQ4LHC
    - but 10's of Gbytes for file sizes

MCFM has ROOT output built in; standard Les Houches format has been developed



store 4-vectors for final state particles + event weights; use analysis script to construct any observables and their pdf uncertainties; in future will put scale uncertainties and pdf correlation info as well

K-factors

- Often we work at LO by necessity (parton shower Monte Carlos), but would like to know the impact of NLO corrections
- K-factors (NLO/LO) can be a useful short-hand for this information
- But caveat emptor; the value of the K-factor depends on a number of things
  - PDFs used at LO and NLO
  - scale(s) at which the cross sections are evaluated
- And often the NLO corrections result in a shape change, so that one K-factor is not sufficient to modify the LO cross sections

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K-factor table

- Some rules-of-thumb
- NLO corrections are larger for processes in which there is a great deal of color annihilation
  - gg->Higgs
  - gg->γγ
  - *K*(gg->tT) > *K*(qQ -> tT)
  - these gg initial states want to radiate like crazy (see Sudakovs)
- NLO corrections decrease as more final-state legs are added
  - *K*(gg->Higgs + 2 jets) < *K*(gg->Higgs + 1 jet) < *K*(gg->Higgs)
  - unless can access new initial state gluon channel
- Can we generalize for uncalculated HO processes?
- What about effect of jet vetoes on K-factors? Signal processes compared to background. Of current interest.

	Typical scales		Tevatron K-factor			LHC K-factor		
Process	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
W+1jet	m_W	$p_T^{\rm jet}$	1.42	1.20	1.43	1.21	1.32	1.42
W+2jets	m_W	$p_T^{\rm jet}$	1.16	0.91	1.29	0.89	0.88	1.10
WW+jet	m_W	$2m_W$	1.19	1.37	1.26	1.33	1.40	1.42
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.48
$t\bar{t}$+1jet	m_t	$2m_t$	1.13	1.43	1.37	0.97	1.29	1.10
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51
Higgs	m_H	$p_T^{\rm jet}$	2.33	–	2.33	1.72	–	2.32
Higgs via VBF	m_H	$p_T^{\rm jet}$	1.07	0.97	1.07	1.23	1.34	1.09
Higgs+1jet	m_H	$p_T^{\rm jet}$	2.02	–	2.13	1.47	–	1.90
Higgs+2jets	m_H	$p_T^{\rm jet}$	–	–	–	1.15	–	–

Table 2: K-factors for various processes at the Tevatron and the LHC calculated using a selection of input parameters. In all cases, the CTEQ6M PDF set is used at NLO. $\mathcal{K}$ uses the CTEQ6L1 set at leading order, whilst $\mathcal{K}'$ uses the same set, CTEQ6M, as at NLO. For most of the processes listed, jets satisfy the requirements $p_T > 15$ GeV/c and $|\eta| < 2.5$ (5.0) at the Tevatron (LHC). For Higgs+1,2jets, a jet cut of 40 GeV/c and $|\eta| < 4.5$ has been applied. A cut of $p_T^{\rm jet} > 20\ GeV/c$ has been applied for the $t\bar{t}$+jet process, and a cut of $p_T^{\rm jet} > 50\ GeV/c$ for WW+jet. In the W(Higgs)+2jets process the jets are separated by $\Delta R > 0.52$, whilst the VBF calculations are performed for a Higgs boson of mass 120 GeV. In each case the value of the K-factor is compared at two often-used scale choices, where the scale indicated is used for both renormalization and factorization scales.

Casimir for biggest color representation final state can be in

Simplistic rule

$C_{i1} + C_{i2} - C_{f,max}$

L. Dixon

Casimir color factors for initial state

K-factor table with the modified LO PDFs

K-factors for LHC slightly less K-factors at Tevatron

K-factors with NLO PDFs at LO are more often closer to unity

Process	Typical scales μ_0	μ_1	Tevatron K-factor $\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	LHC K-factor $\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}''(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15	0.95
W+1jet	m_W	$p_T^{\rm jet}$	1.42	1.20	1.43	1.21	1.32	1.42	0.99
W+2jets	m_W	$p_T^{\rm jet}$	1.16	0.91	1.29	0.89	0.88	1.10	0.90
WW+jet	m_W	$2m_W$	1.19	1.37	1.26	1.33	1.40	1.42	1.10
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.19	1.09
$t\bar{t}$+1jet	m_t	$2m_t$	1.13	1.43	1.37	0.97	1.29	1.10	0.85
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51	–
Higgs	m_H	$p_T^{\rm jet}$	2.33	–	2.33	1.72	–	2.32	1.43
Higgs via VBF	m_H	$p_T^{\rm jet}$	1.07	0.97	1.07	1.23	1.34	0.85	0.78
Higgs+1jet	m_H	$p_T^{\rm jet}$	2.02	–	2.13	1.47	–	1.90	1.33
Higgs+2jets	m_H	$p_T^{\rm jet}$	–	–	–	1.15	–	–	1.13

Table 3: K-factors for various processes at the LHC calculated using a selection of input parameters. Have to fix this table. In all cases, the CTEQ6M PDF set is used at NLO. $\mathcal{K}$ uses the CTEQ6L1 set at leading order, whilst $\mathcal{K}'$ uses the same set, CTEQ6M, as at NLO and $\mathcal{K}''$ uses the modified LO (2-loop) PDF set. For Higgs+1,2jets, a jet cut of 40 GeV/c and $|\eta| < 4.5$ has been applied. A cut of $p_T^{\rm jet} > 20\ GeV/c$ has been applied for the $t\bar{t}$+jet process, and a cut of $p_T^{\rm jet} > 50\ GeV/c$ for WW+jet. In the W(Higgs)+2jets process the jets are separated by $\Delta R > 0.52$, whilst the VBF calculations are performed for a Higgs boson of mass 120 GeV. In each case the value of the K-factor is compared at two often-used scale choices, where the scale indicated is used for both renormalization and factorization scales.

mod LO PDF

Note K-factor for W < 1.0, since for this table the comparison is to CTEQ6.1 and not to CTEQ6.6, i.e. corrections to low x PDFs due to treatment of heavy quarks in CTEQ6.6 "built-in" to mod LO PDFs

CTEQ

IP3

An experimenter's wishlist

Run II Monte Carlo Workshop

Single Boson	Diboson	Triboson	Heavy Flavour
$W+\leq 5j$	$WW+\leq 5j$	$WWW+\leq 3j$	$t\bar{t}+\leq 3j$
$W+b\bar{b}\leq 3j$	$W+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}\leq 3j$	$W+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 5j$	$ZZ+\leq 5j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 3j$	$Z+b\bar{b}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{t}+H+\leq 2j$
$Z+c\bar{c}+\leq 3j$	$ZZ+c\bar{c}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{b}\leq 2j$
$\gamma+\leq 5j$	$\gamma\gamma+\leq 5j$	$ZZZ+\leq 3j$	$b\bar{b}+\leq 3j$
$\gamma+b\bar{b}\leq 3j$	$\gamma\gamma+b\bar{b}\leq 3j$		single top
$\gamma+c\bar{c}\leq 3j$	$\gamma\gamma+c\bar{c}\leq 3j$		
	$WZ+\leq 5j$		
	$WZ+b\bar{b}\leq 3j$		
	$WZ+c\bar{c}\leq 3j$		
	$W\gamma+\leq 3j$		
	$Z\gamma+\leq 3j$		

Realistic NLO wishlist

- Was developed at Les Houches in 2005, and expanded in 2007 and 2009
- Calculations that are important for the LHC AND do-able in finite time
- I wanted to add (but didn't)
  - needed accuracy for calculation from experimental perspective
    - what are asymptotic experimental uncertainties for example?
    - are EW corrections necessary?
  - what is impact of a jet veto cut?

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [4, 5]; Campbell/Ellis/Zanderighi [6]. ZZjet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [7]
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [8]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [9, 10]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [11] and WWZ by Hankele/Zeppenfeld [12] (see also Binoth/Ossola/Papadopoulos/Pittau [13])
4. $pp \to t\bar{t}\, b\bar{b}$	relevant for $t\bar{t}H$ computed by Bredenstein/Denner/Dittmaier/Pozzorini [14, 15] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [16]
5. $pp \to V$+3jets	calculated by the Blackhat/Sherpa [17] and Rocket [18] collaborations
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$ computed by Bevilacqua/Czakon/Papadopoulos/Worek [19]
7. $pp \to VV\, b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
8. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [20–22]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	$q\bar{q}$ channel calculated by Golem collaboration [23]
NLO calculations added to list in 2009	
10. $pp \to V$+4 jets	top pair production, various new physics signatures
11. $pp \to Wb\bar{b}j$	top, new physics signatures
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
Calculations beyond NLO added in 2007	
13. $gg \to W^*W^*\ \mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
14. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
15. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
16. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

Table 1: The updated experimenter's wishlist for LHC processes

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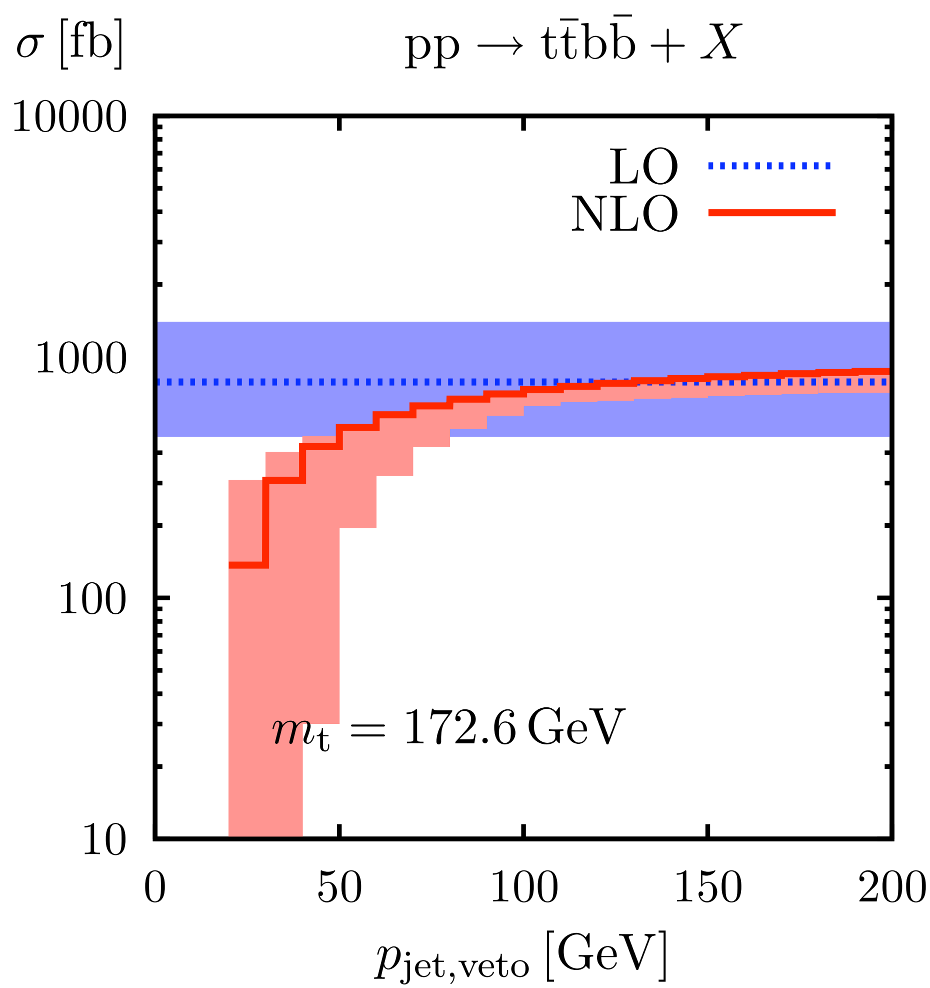
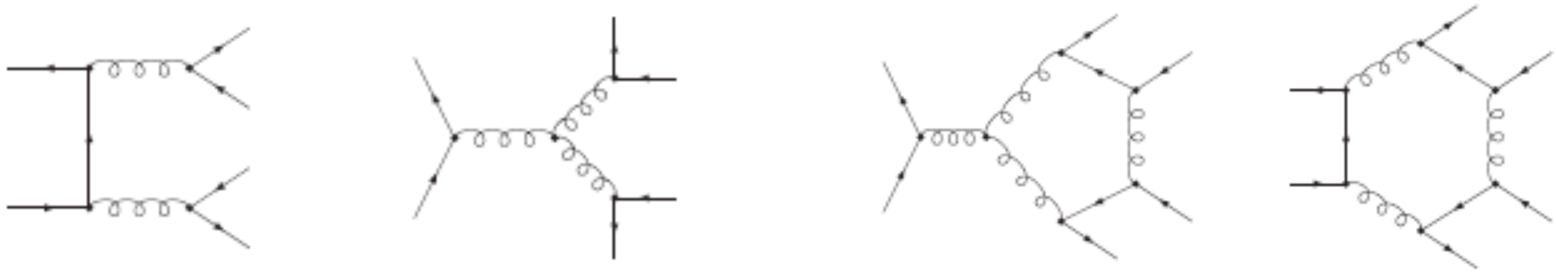


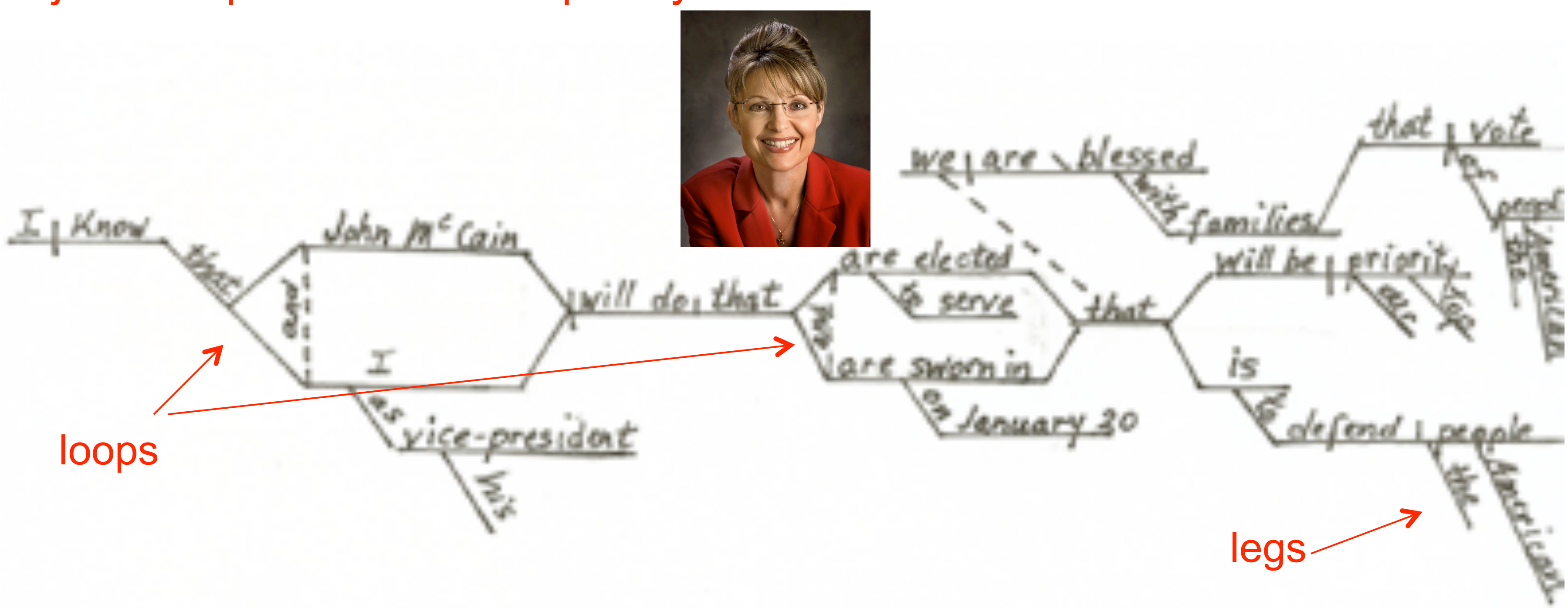
Loops and legs

2->4 is very impressive



but just compare to the complexity of the sentences that Sarah Palin uses

.



Choosing jet size

- Experimentally
  - in complex final states, such as W + n jets, it is useful to have jet sizes smaller so as to be able to resolve the n jet structure
  - this can also reduce the impact of pileup/ underlying event

- Theoretically
  - hadronization effects become larger as R decreases
  - for small R, the ln R perturbative terms referred to previously can become noticeable
  - this restriction in the gluon phase space can affect the scale dependence, i.e. the scale uncertainty for an n-jet final state can depend on the jet size,
  - for example, the scale uncertainty for inclusive jet production at the LHC is smallest for a jet size of 0.7
  - related to impact of jet veto on perturbative stability of NLO calculation

Another motivation for the use of multiple jet algorithms/parameters (i.e. SpartyJet) in LHC analyses.

C T E Q

Now consider W + 3 jets

A good system for understanding both experimental and theoretical issues at the LHC.

Consider a scale of m_W for W + 1,2,3 jets. We see the K-factors for W + 1,2 jets in the table below, and recently the NLO corrections for W + 3 jets have been calculated, allowing us to estimate the K-factors for that process.

Process	Typical scales μ_0	μ_1	Tevatron K-factor $\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	LHC K-factor $\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}''(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15	0.95
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$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.19	1.09
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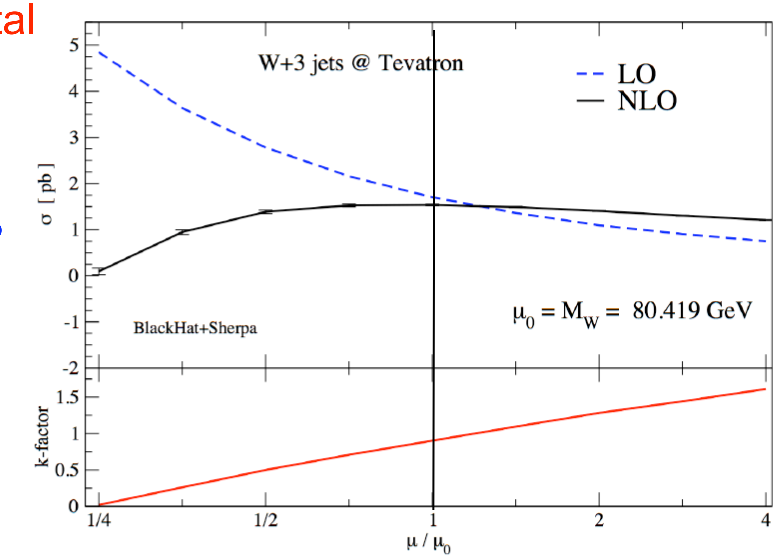
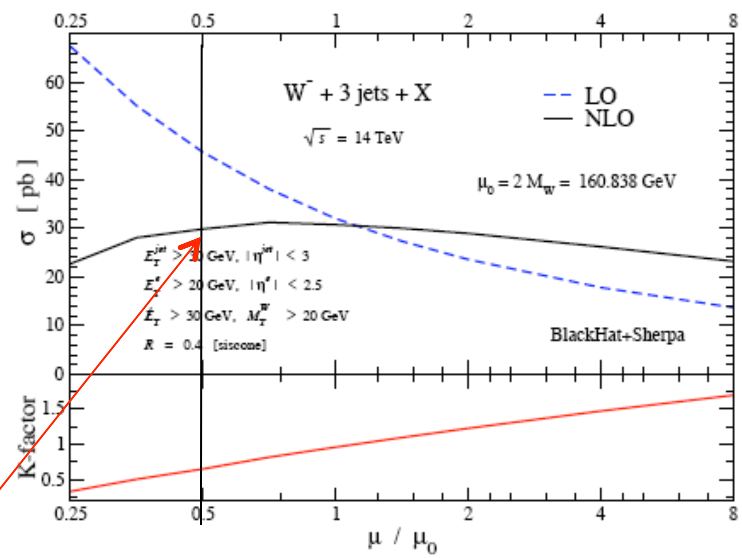
Higgs	m_H	$p_T^{\rm jet}$	2.33	–	2.33	1.72	–	2.32	1.43
Higgs via VBF	m_H	$p_T^{\rm jet}$	1.07	0.97	1.07	1.23	1.34	0.85	0.78
Higgs+1jet	m_H	$p_T^{\rm jet}$	2.02	–	2.13	1.47	–	1.90	1.33
Higgs+2jets	m_H	$p_T^{\rm jet}$	–	–	–	1.15	–	–	1.13

Table 3: K-factors for various processes at the LHC calculated using a selection of input parameters. Have to fix this table. In all cases, the CTEQ6M PDF set is used at NLO. $\mathcal{K}$ uses the CTEQ6L1 set at leading order, whilst $\mathcal{K}'$ uses the same set, CTEQ6M, as at NLO and $\mathcal{K}''$ uses the modified LO (2-loop) PDF set. For Higgs+1,2jets, a jet cut of 40 GeV/c and $|\eta| < 4.5$ has been applied. A cut of $p_T^{\rm jet} > 20$ GeV/c has been applied for the $t\bar{t}$+jet process, and a cut of $p_T^{\rm jet} > 50$ GeV/c for WW+jet. In the W(Higgs)+2jets process the jets are separated by $\Delta R > 0.52$, whilst the VBF calculations are performed for a Higgs boson of mass 120 GeV. In each case the value of the K-factor is compared at two often-used scale choices, where the scale indicated is used for both renormalization and factorization scales.





Is the K-factor (at m_W) at the LHC surprising?

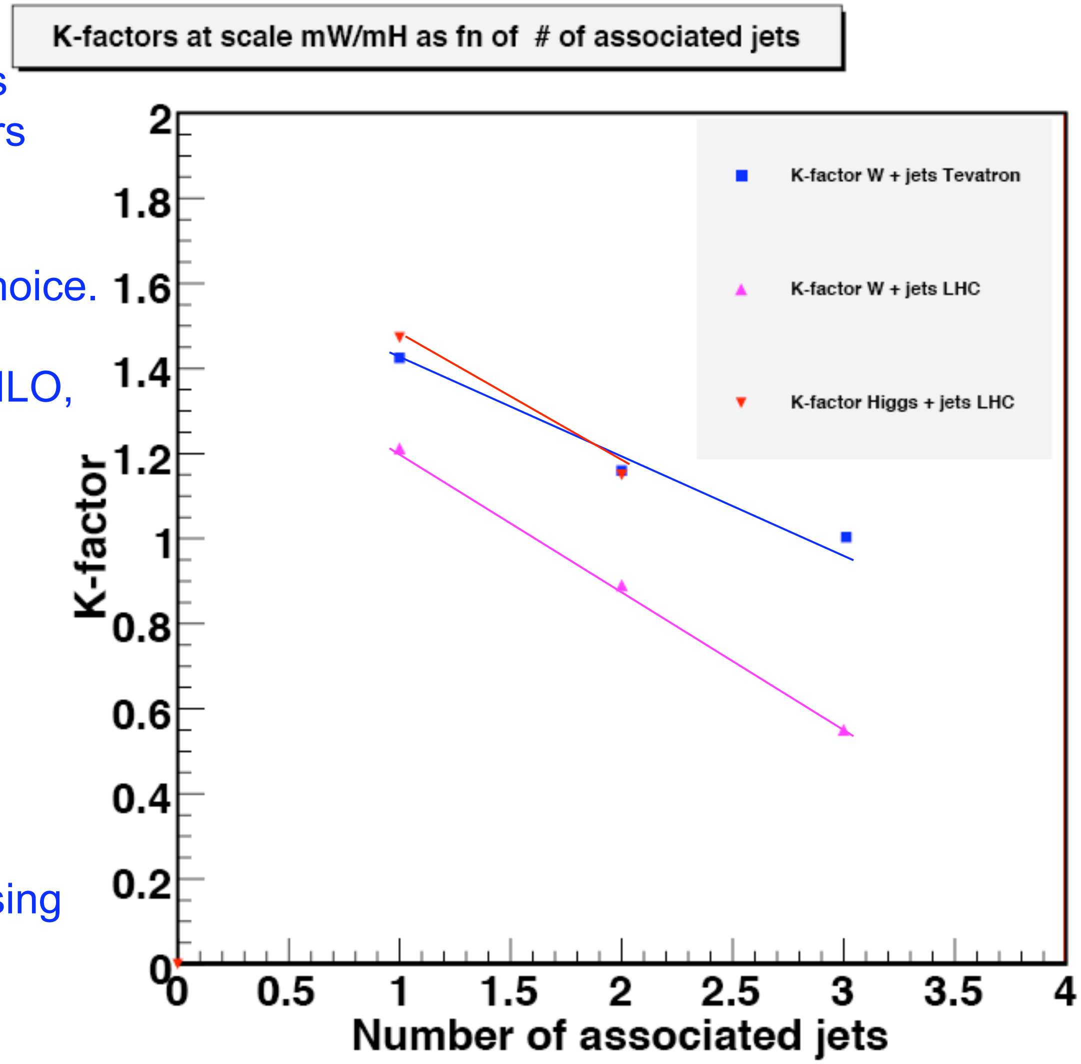
Is the K-factor (at m_W) at the LHC surprising?

The K-factors for W + jets (p_T>30 GeV/c) fall near a straight line, as do the K-factors for the Tevatron. By definition, the K-factors for Higgs + jets fall on a straight line.

Nothing special about m_W; just a typical choice.

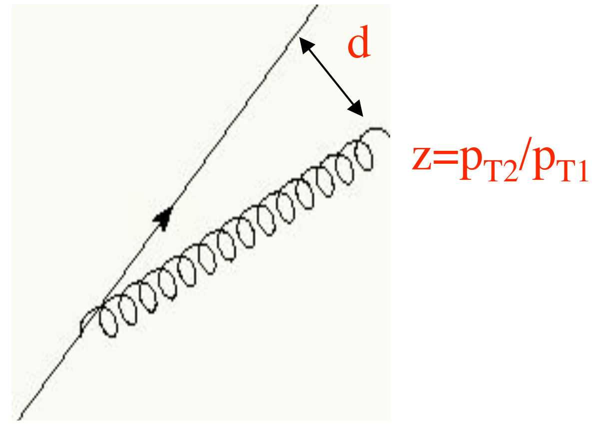
The only way to know a cross section to NLO, say for W + 4 jets or Higgs + 3 jets, is to calculate it, but in lieu of the calculations, especially for observables that we have deemed important at Les Houches, can we make some rules of thumb?

Related to this is:
- understanding the reduced scale dependences/pdf uncertainties for cross section ratios we have been discussing
-scale choices at LO for cross sections uncalculated at NLO



Jet algorithms at LO/NLO

- Remember at LO, 1 parton = 1 jet
- By choosing a jet algorithm with size parameter D, we are requiring any two partons to be > D apart
- The matrix elements have $1/\Delta R$ poles, so larger D means smaller cross sections
  - it's because of the poles that we have to make a ΔR cut
- At NLO, there can be two (or more) partons in a jet and jets for the first time can have some structure
  - we don't need a ΔR cut, since the virtual corrections cancel the collinear singularity from the gluon emission
  - **but there are residual logs that can become important if D is too small**
- Increasing the size parameter D increases the phase space for including an extra gluon in the jet, and thus increases the cross section at NLO (in most cases) → not true for WbB, for example



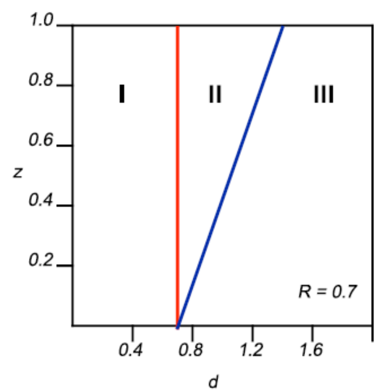


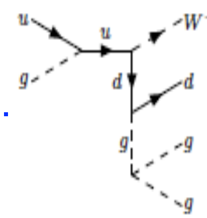
Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

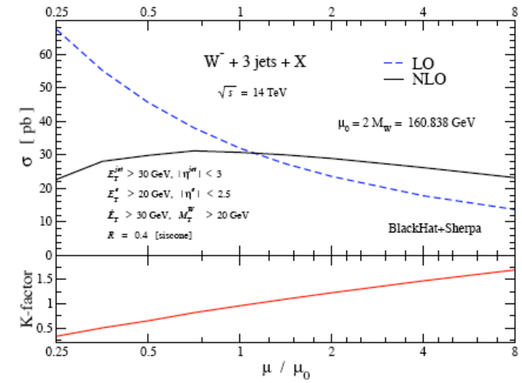
For $D=R_{cone}$, Region I = k_T jets, Region II (nominally) = cone jets; I say nominally because in data not all of Region II is included for cone jets

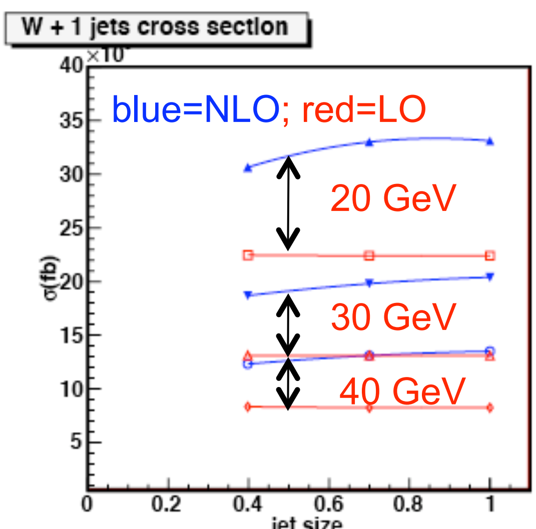
C T E Q

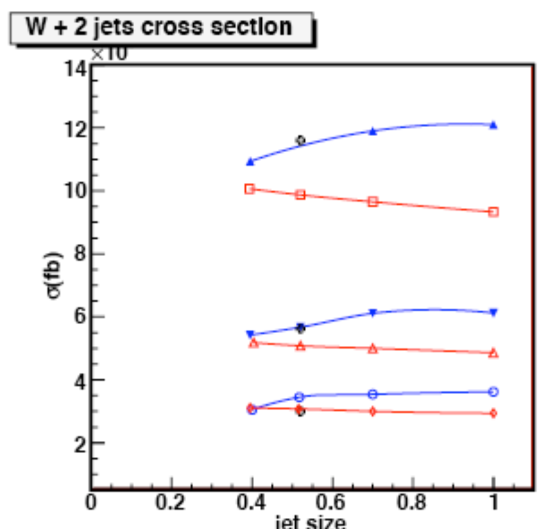
Is the K-factor (at m_W) at the LHC surprising?

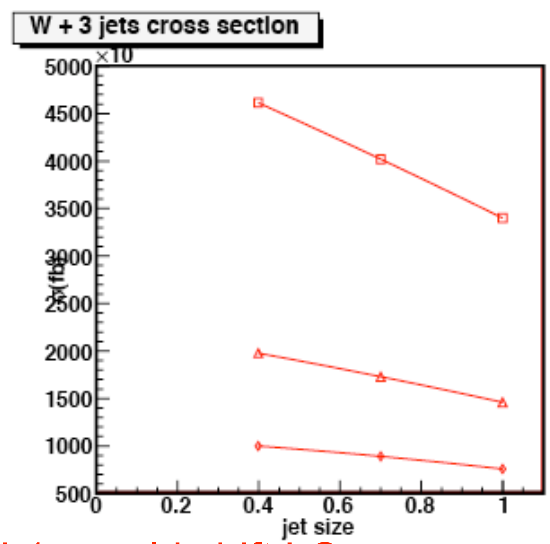
The problem is not the NLO cross section; that is well-behaved.
The problem is that the LO cross section sits ‘too-high’. The reason (one of them) for this is that we are ‘too-close’ to the collinear pole (R=0.4) leading to an enhancement of the LO cross section (double-enhancement if the gluon is soft (~20 GeV/c)). Note that at LO, the cross section increases with decreasing R; at NLO it decreases.
The collinear dependence gets stronger as n_{jet} increases.
The K-factors for W + 3 jets would be more *normal* (>1) if a larger cone size and/or a larger jet p_T cutoff were used. But that’s a LO problem; the best approach is to use the appropriate jet sizes/jet p_T’s for the analysis and understand the best scales to use at LO (matrix element + parton shower) to approximate the NLO calculation (as well as comparing directly to the NLO calculation).









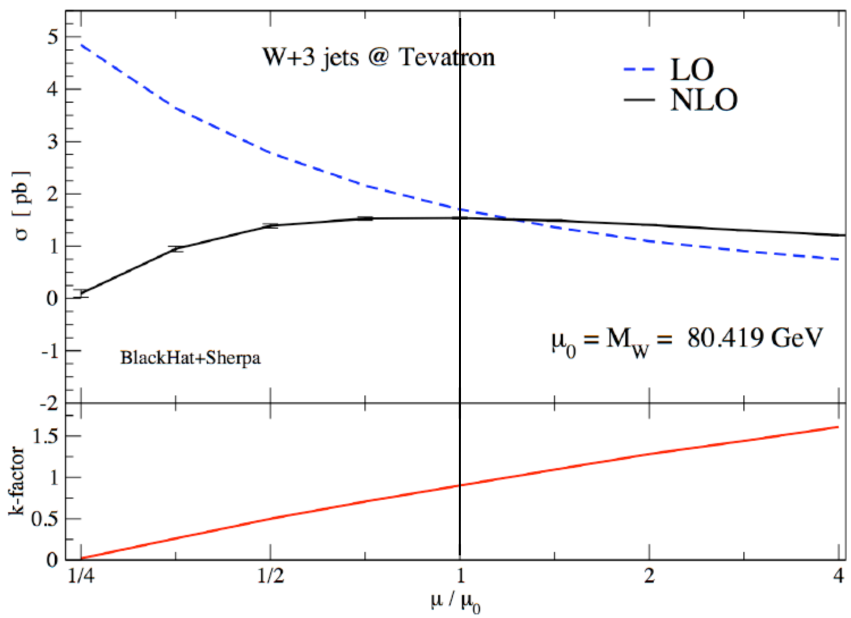


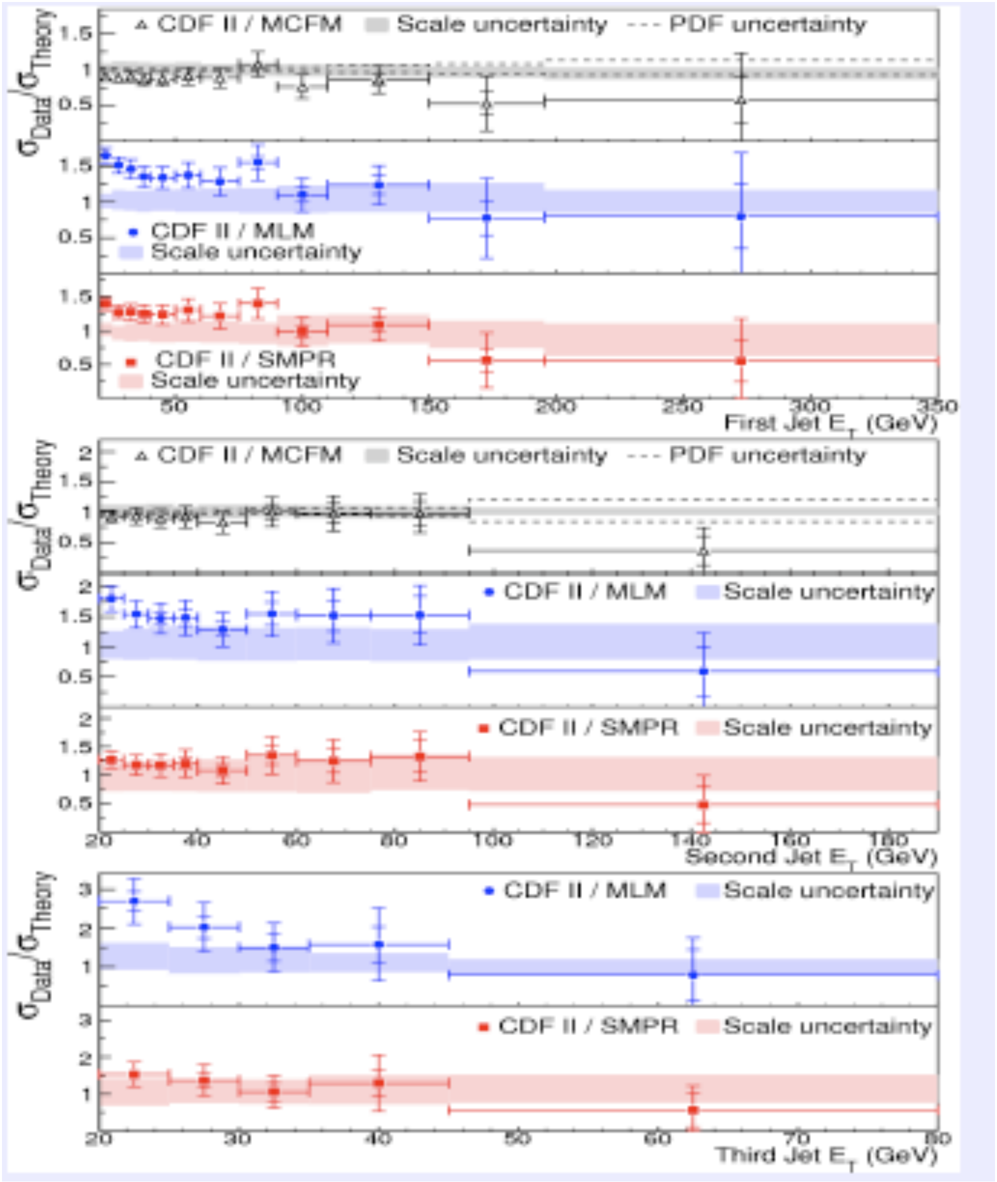
For 3 jets, the LO collinear singularity effects are even more pronounced.

NB: here I have used CTEQ6.6 for both LO and NLO; CTEQ6L1 would shift LO curves up

W + jets at the Tevatron

- At the Tevatron, m_W is a reasonable scale (in terms of K-factor~1)

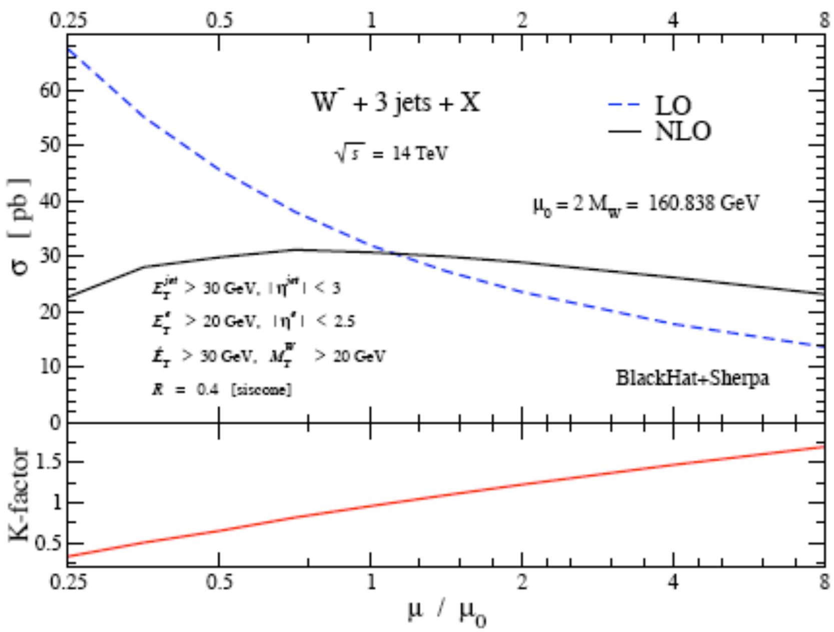


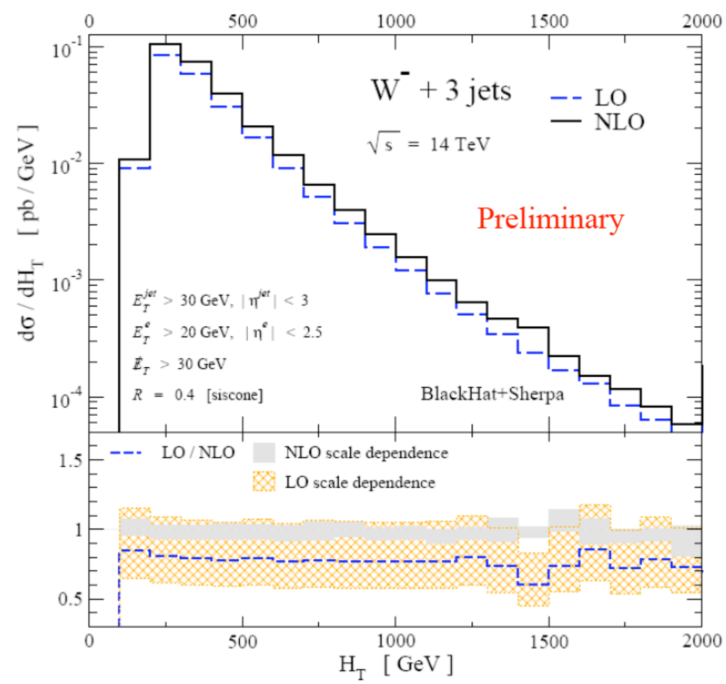


W + 3 jets at the LHC

A scale choice of m_W would be in a region where LO >> NLO. In addition, such a scale choice (or related scale choice), leads to sizeable shape differences in the kinematic distributions. The Blackhat people found that a scale choice of H_T worked best to get a constant K-factor for all distributions that they looked at. Note that from the point-of-view of only NLO, all cross sections with scales above ~100 GeV seem reasonably stable.

$H_T = \sum_j E_{T,j}^{\text{jet}} + E_T^e + \not{E}_T$ distribution





mu = H_T

Some other observables in Blackhat paper

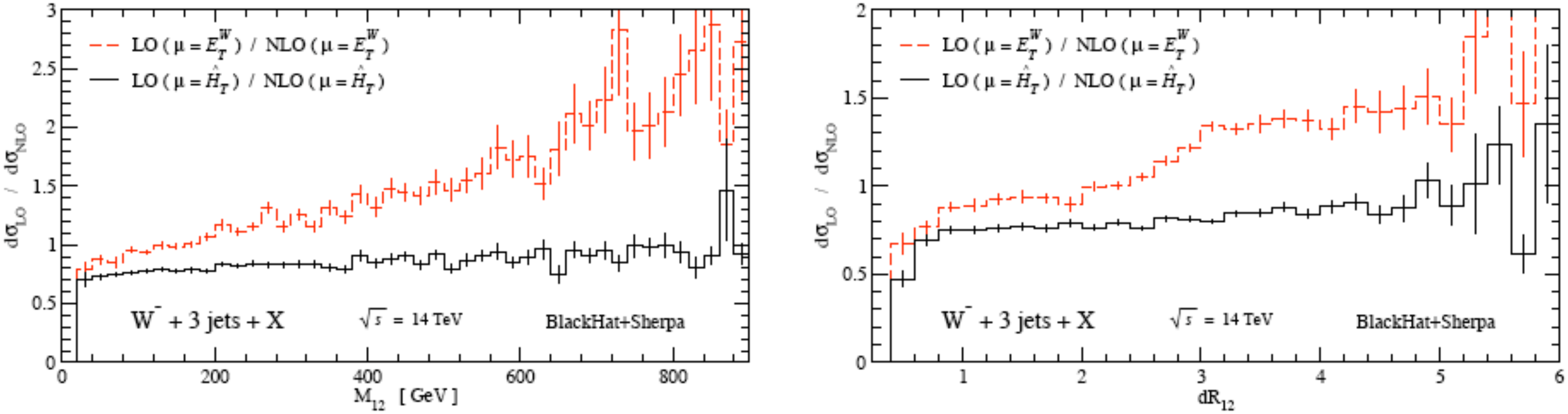


FIG. 12: Ratios of LO to NLO predictions for the distributions in the di-jet invariant mass (left panel) and ΔR separation (right panel) for the leading two jets in $W^- +$ 3-jet production at the LHC. In each panel, the dashed (red) line gives the scale choice $\mu = E_T^W$, while the solid (black) line gives the (much flatter) ratio for $\mu = \hat{H}_T$.

Soft collinear effective theory (SCET) suggests scales on the order of $1/4M^2_{had} + M^2_W$, where M_{had} is the invariant mass of the jets

Darren Forde

CTEQ

CKKW

- Applying a CKKW-like scale also leads to better agreement for shapes of kinematic distributions
- Why do two very different scales (H_T and CKKW) lead to similar agreement between LO and NLO predictions for W + 3 jets?
  - see Les Houches proceedings/Darren's talk/Giulia's talk

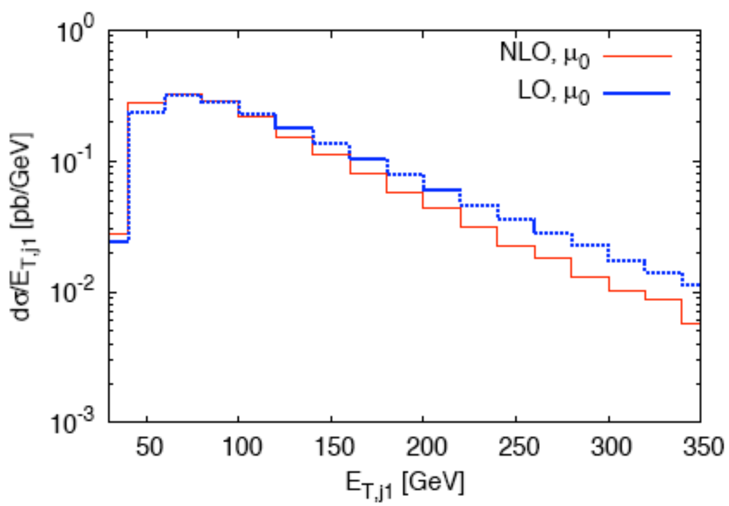


FIG. 3: The transverse momentum distribution of the leading jet for $W^+ + 3$ jet inclusive production cross section at the LHC. All cuts and parameters are described in the text. The leading color adjustment procedure is applied.

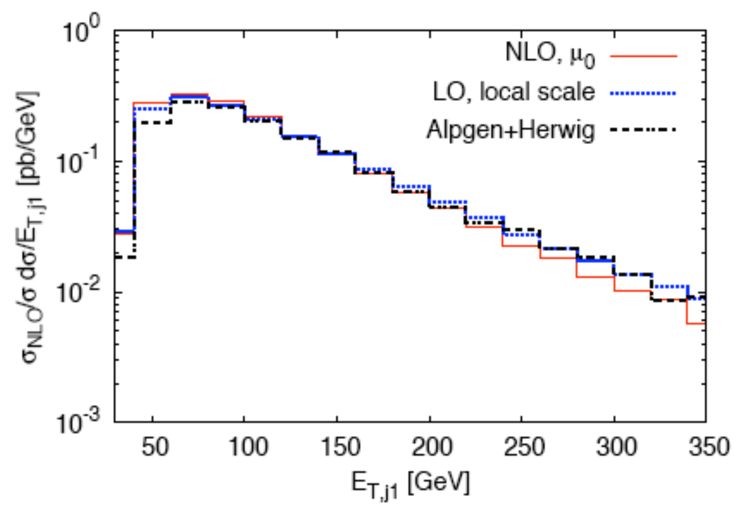


FIG. 4: The transverse momentum distribution of the leading jet for $W^+ + 3$ jet inclusive production cross section at the LHC. All cuts and parameters are described in the text. The leading color adjustment procedure is applied. All LO distributions are rescaled by constant factor, to ensure that the LO and NLO normalizations coincide.

0910.3671 Melnikov, Zanderighi

CTEQ

- From Les Houches NLM writeup
  - Hoeche, Huston, Maitre, Winter, Zanderighi
- First direct comparison of Blackhat and Rocket results for W + 3 jets
- Also look at systematics of comparison with Sherpa
  - level of agreement for 3rd jet depends on number of partons included in matching

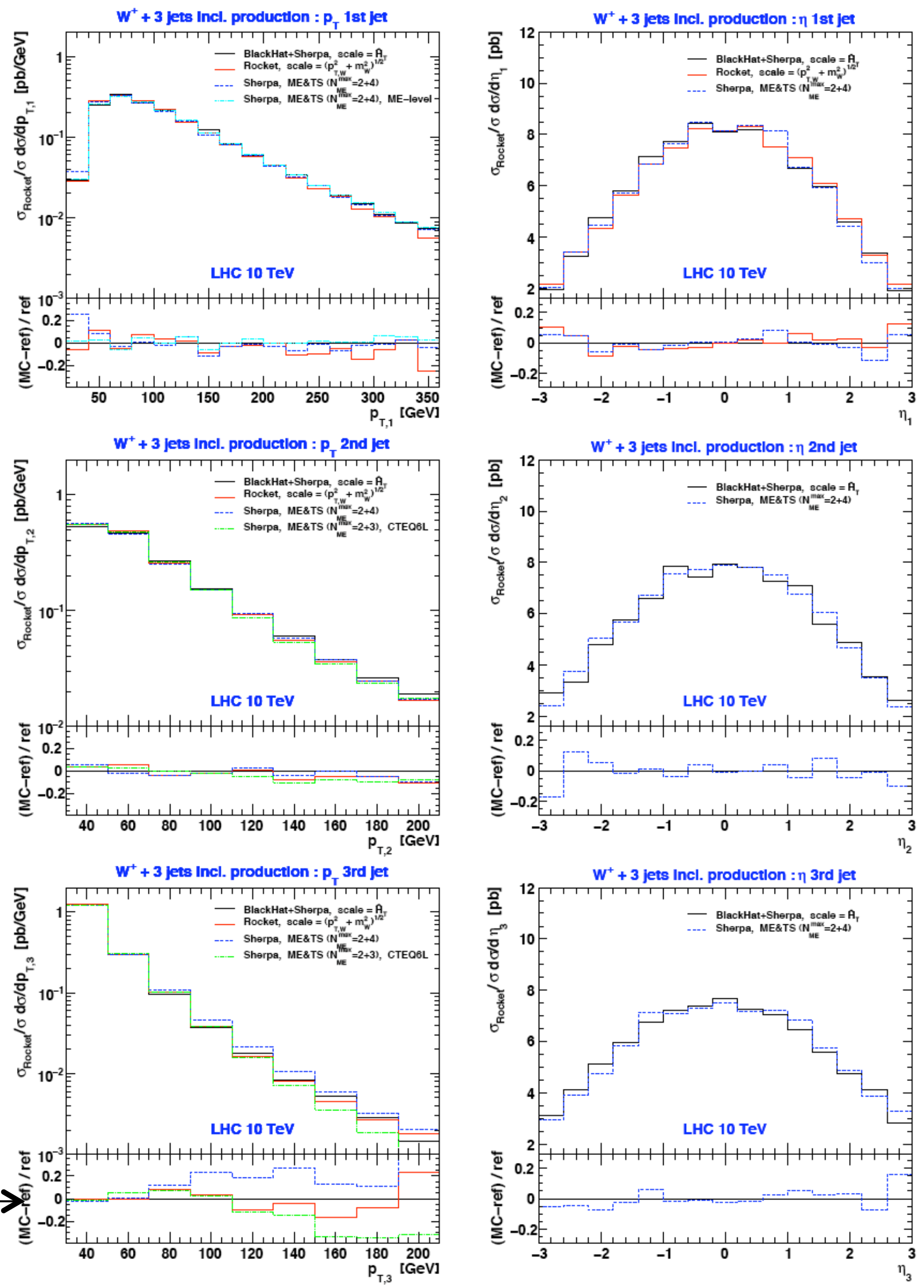


Fig. 18: The transverse momentum distributions (left) and pseudo-rapidity distributions (right) of the three hardest jets in $W^+ + \geq 3$ jet production at the LHC. Predictions at NLO obtained from the BLACKHAT+SHERPA (black line) and ROCKET (red line) codes are compared to LO results from SHERPA using the ME&TS merging. All curves have been rescaled to the ROCKET NLO cross section of Table 5; BLACKHAT+SHERPA is used as the reference; cuts and parameters are detailed in Section 12.2

Proposed common ntuple output

- A generalization of the FROOT format used in MCFM
- Writeup in NLM proceedings

Table 4: Variables stored in the proposed common ROOT ntuple output.

ROOT Tree Branch	Description
Npart/I	number of partons (incoming and outgoing)
Px[Npart]/D	Px of partons
Py[Npart]/D	Py of partons
Pz[Npart]/D	Pz of partons
E[Npart]/D	E of partons
x1/D	Bjorken-x of incoming parton 1
x2/D	Bjorken-x of incoming parton 2
id1/I	PDG particle ID of incoming parton 1
id2/I	PDF particle ID of incoming parton 2
fac_scale/D	factorization scale
ren_scale/D	renormalization scale
weight/D	global event weight
Nuwgt/I	number of user weights
user_wgts[Nuwgt]/D	user event weights
evt_no/L	unique event number (identifier)
Nptr/I	number of event pointers
evt_pointers[Nptr]/L	event pointers (identifiers of related events)
Npdfs/I	number of PDF weights
pdf_wgts[Npdfs]/D	PDF weights

```
LhaNLOEvent* evt = new LhaNLOEvent();
evt->addParticle(px1,py1,pz1,E1);
evt->setProcInfo(x1,id1,x2,id2);
evt->setRenScale(scale);
...
```

Another class **LhaNLOTreeIO** is responsible for writing the events into the ROOT tree and outputting the tree to disk. In addition to the event-wise information global data such as comments, cross sections etc can be written as well. An example is shown below:

```
LhaNLOTreeIO* writer = new LhaNLOTreeIO(); // create tree writer
writer->initWrite(''test.root'');
...
writer->writeComment(''W+4 jets at NNLO''); // write global comments
writer->writeComment(''total cross section: XYZ+/-IJK fb'');
...
writer->writeEvent(*evt); // write event to tree (in event loop)
...
writer->writeTree(); // write tree to disk
```

Similarly, a tree can be read back from disk:

```
LhaNLOTreeIO* reader = new LhaNLOTreeIO(); // init reader
ierr=reader->initRead("test.root");
if (!ierr) {
  for (int i=0; i< reader->getNumberofEvents();i++) {
    event->reset();
    ierr=reader->readEvent(i,*event);
    ...
  }
}
```

Thomas Binoth 1965-2010

- This accord should make the kinds of discussion we're having here easier (in the future)
- Binoth Les Houches Accord

ABSTRACT: Many highly developed Monte Carlo tools for the evaluation of cross sections based on tree matrix elements exist and are used by experimental collaborations in high energy physics. As the evaluation of one-loop matrix elements has recently been undergoing enormous progress, the combination of one-loop matrix elements with existing Monte Carlo tools is on the horizon. This would lead to phenomenological predictions at the next-to-leading order level. This note summarises the discussion of the next-to-leading order multi-leg (NLM) working group on this issue which has been taking place during the workshop on Physics at TeV colliders at Les Houches, France, in June 2009. The result is a proposal for a standard interface between Monte Carlo tools and one-loop matrix element programs.

Dedicated to the memory of, and in tribute to, Thomas Binoth, who led the effort to develop this proposal for Les Houches 2009. Thomas led the discussions, set up the subgroups, collected the contributions, and wrote and edited this paper. He made a promise that the paper would be on the arXiv the first week of January, and we are faithfully fulfilling his promise. In his honor, we would like to call this the Binoth Les Houches Accord.
The body of the paper is unchanged from the last version that can be found on his webpage
http://www.ph.ed.ac.uk/~binoth/NLOLHA_CURRENT_VERSION.pdf

Preprint typeset in JHEP style - PAPER VERSION

A proposal for a standard interface between Monte Carlo tools and one-loop programs

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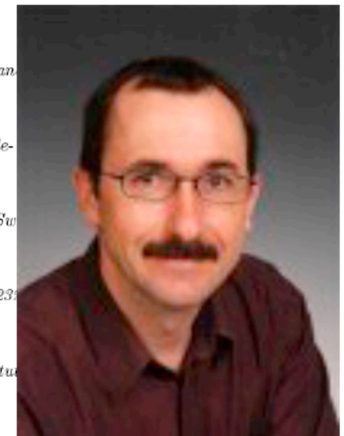
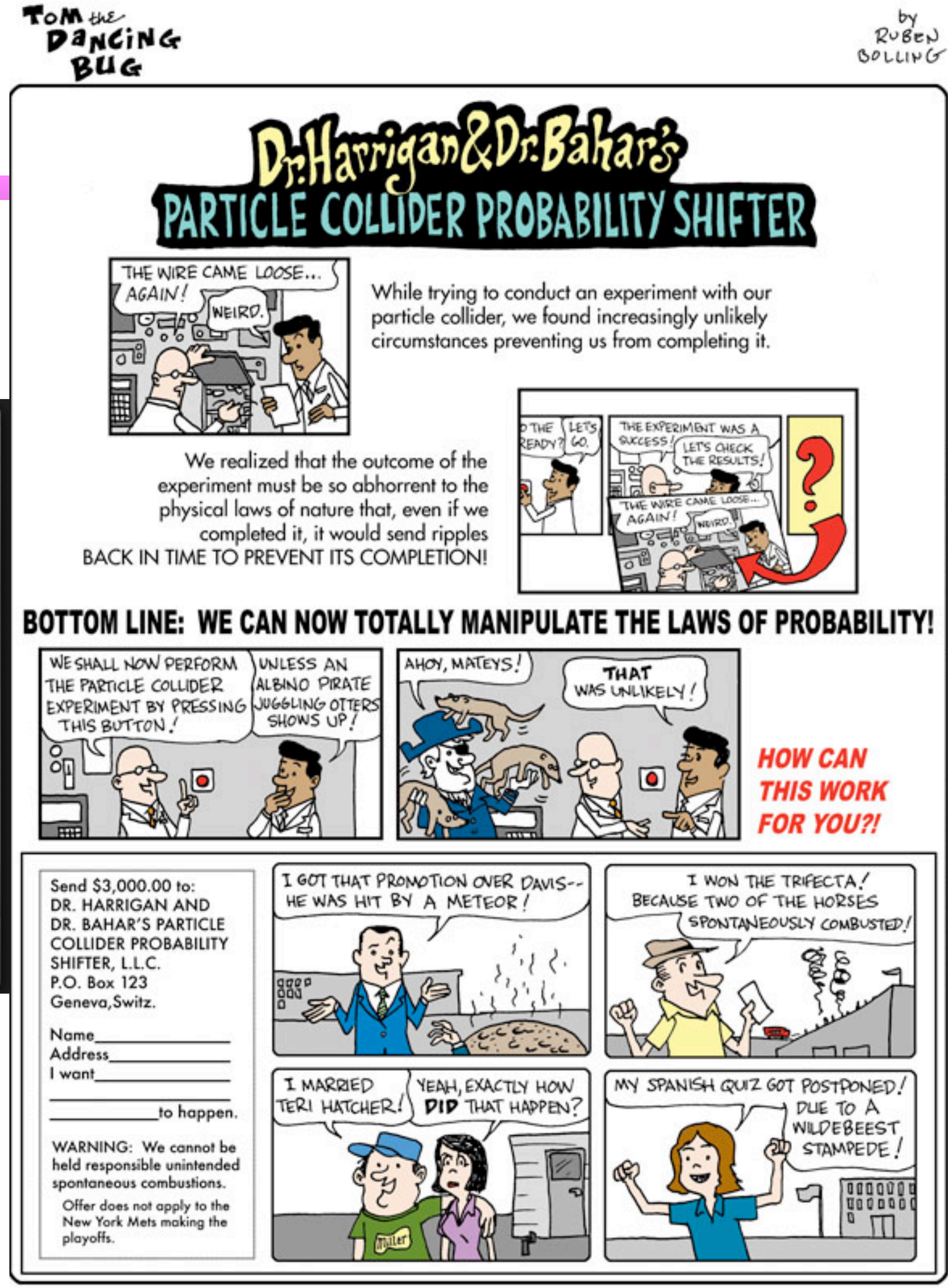


CTEQ

The LHC now seems poised for discoveries

…unless



Extra slides

More Sarah Palin

- Sarah Palin moves beyond the standard model

Cross Sections

1. W^+, W^-, and Z total cross sections and rapidity distributions total cross section ratios W^+/W^- and $(W^+ + W^-)/Z$ rapidity distributions at y = -4,-3,...,+4 and also the W asymmetry: A_W(y) = $(dW^+/dy - dW^-/dy)/(dW^+/dy + dW^-/dy)$ using the following parameters taken from PDG 2009
   - M_Z=91.188 GeV
   - M_W=80.398 GeV
   - zero width approximation
   - $G_F=0.116637 \times 10^{-5}$ GeV^{-2}
   - other EW couplings derived using tree level relations
   - BR(Z-->ll) = 0.03366
   - BR(W-->lnu) = 0.1080
   - CKM mixing parameters from eq.(11.27) of PDG2009 CKM review

$$V\_CKM = \begin{matrix} 0.97419 & 0.2257 & 0.00359 \\ 0.2256 & 0.97334 & 0.0415 \\ 0.00874 & 0.0407 & 0.999133 \end{matrix}$$

   - scales: $\mu_R = \mu_F = M_Z$ or M_W

Cross Sections

2. gg->H total cross sections at NLO

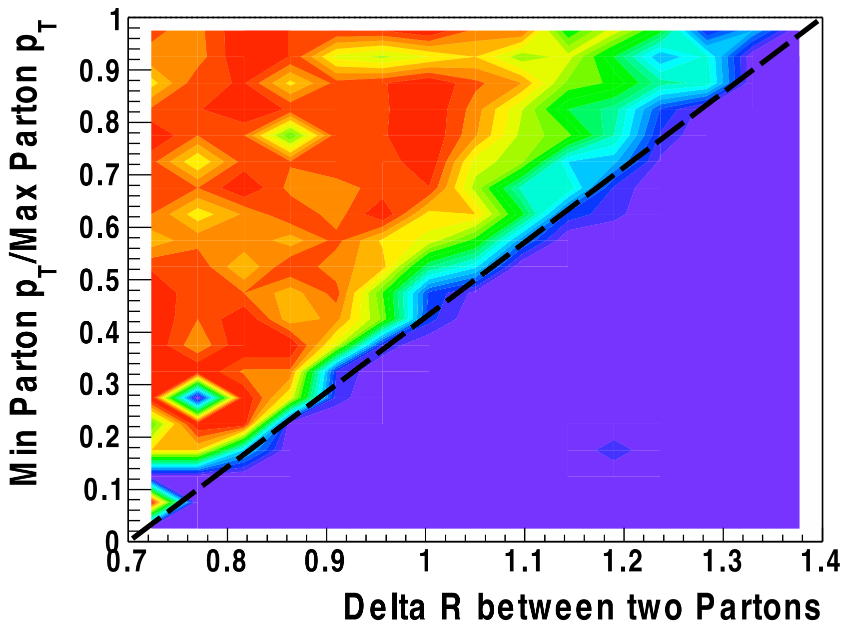
- M_H = 120, 180 and 240 GeV
- zero Higgs width approximation, no BR
- top loop only, with m_{top} = 171.3 GeV in sigma_0
- scales: $\mu_R = \mu_F = M_H$

3. ttbar total cross section at NLO

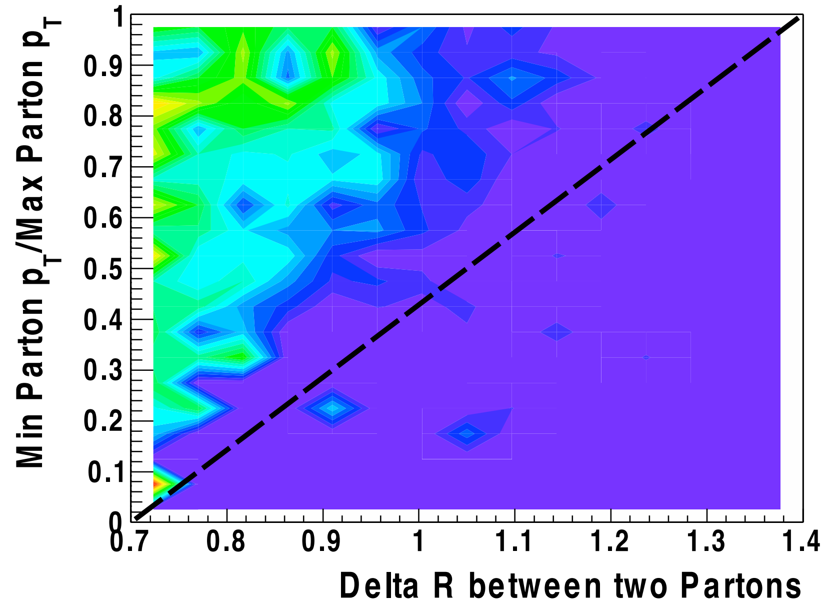
- m_{top} = 171.3 GeV
- zero top width approximation, no BR
- scales: $\mu_R = \mu_F = m_{top}$

Jets and R_{sep}

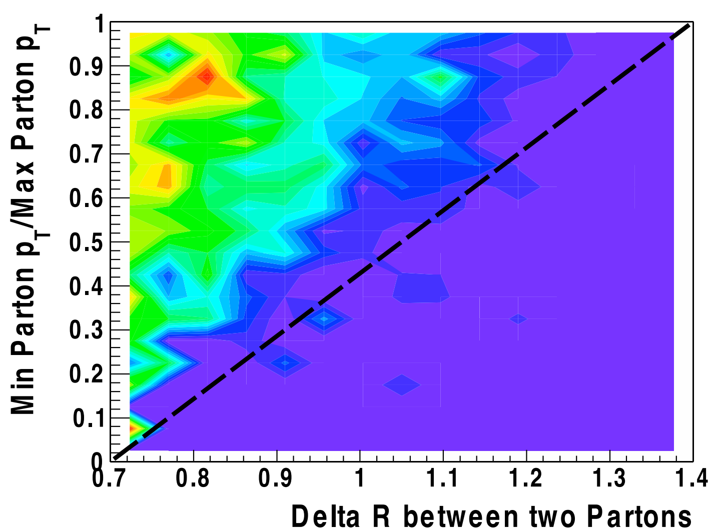
Parton Level



Hadron Level



Detector Level



2 widely separated partons that would be reconstructed in a single jet, are not, at the hadron or detector level