C T E Q

Discovering the Standard Model and Beyond at the LHC

…and the tools we'll need

J. Huston

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Some references

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Hard interactions of quarks and gluons: a primer for LHC physics

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Abstract

In this paper, we will develop the perturbative framework for the calculation of hard-scattering processes. We will undertake to provide both a reasonably rigorous development of the formalism of hard-scattering of quarks and gluons as well as an intuitive understanding of the physics behind the scattering. We will emphasize the role of logarithmic corrections as well as power counting in α_S in order to understand the behaviour of hard-scattering processes. We will include 'rules of thumb' as well as 'official recommendations', and where possible will seek to dispel some myths. We will also discuss the impact of soft processes on the measurements of hard-scattering processes. Experiences that have been gained at the Fermilab Tevatron will be recounted and, where appropriate, extrapolated to the LHC.

(Some figures in this article are in colour only in the electronic version)

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Review

Jets in hadron–hadron collisions

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arXiv:07122447 Dec 14, 2007

Abstract

In this article, we review some of the complexities of jet algorithms and of the resultant comparisons of data to theory. We review the extensive experience with jet measurements at the Tevatron, the extrapolation of this acquired wisdom to the LHC and the differences between the Tevatron and LHC environments. We also describe a framework (SpartyJet) for the convenient comparison of results using different jet algorithms.
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Keywords: Jet; Jet algorithm; LHC; Tevatron; Perturbative QCD; SpartyJet

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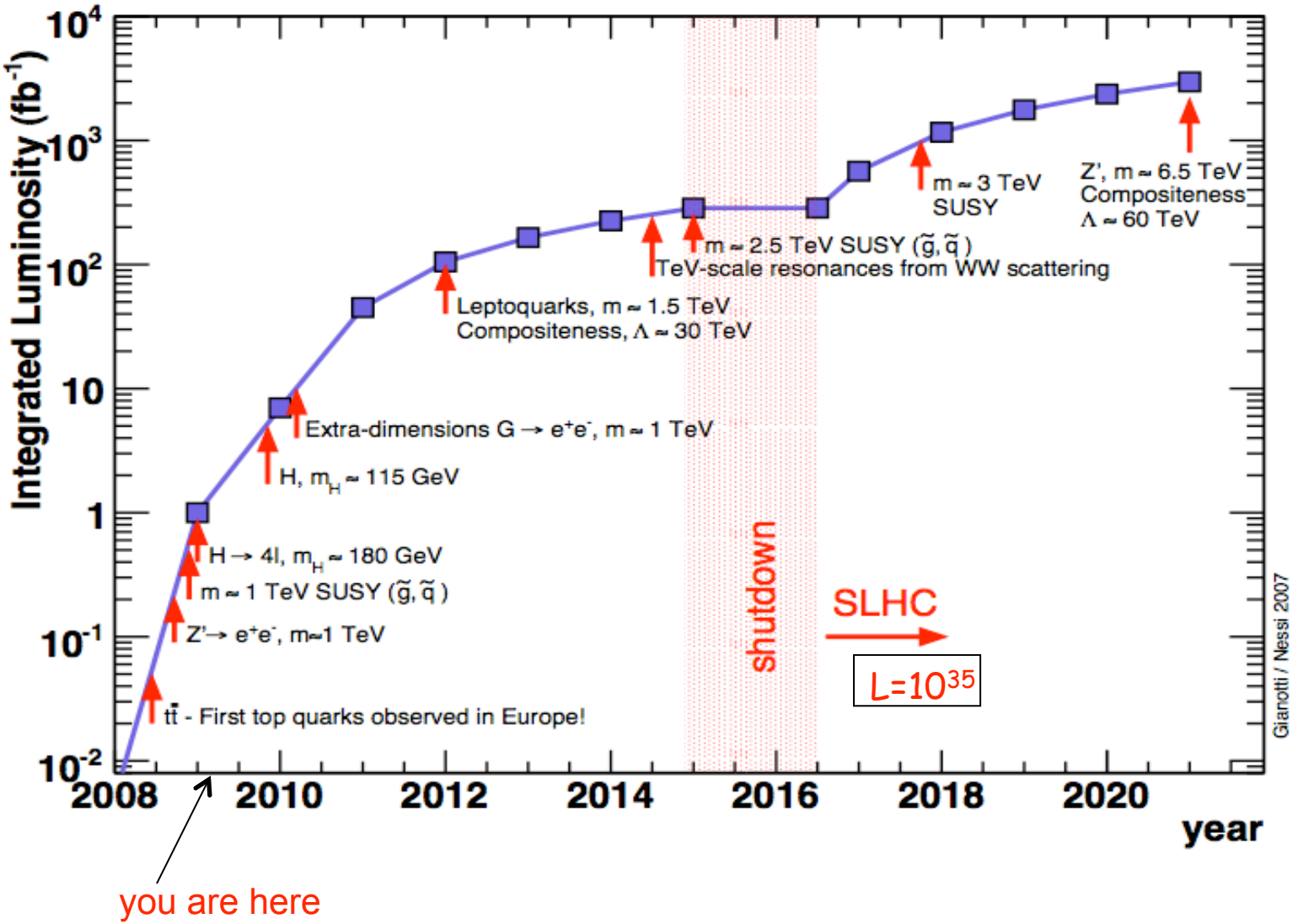
Donald Rumsfeld

- I will not be referring to Donald Rumsfeld in this talk…as I have in previous talks at BNL

- Besides, who needs to, now that we have Sarah Palin…at least until 2012

We'll look back on early LHC trouble in 15 years and laugh

LHC vs time: a wild guess ...



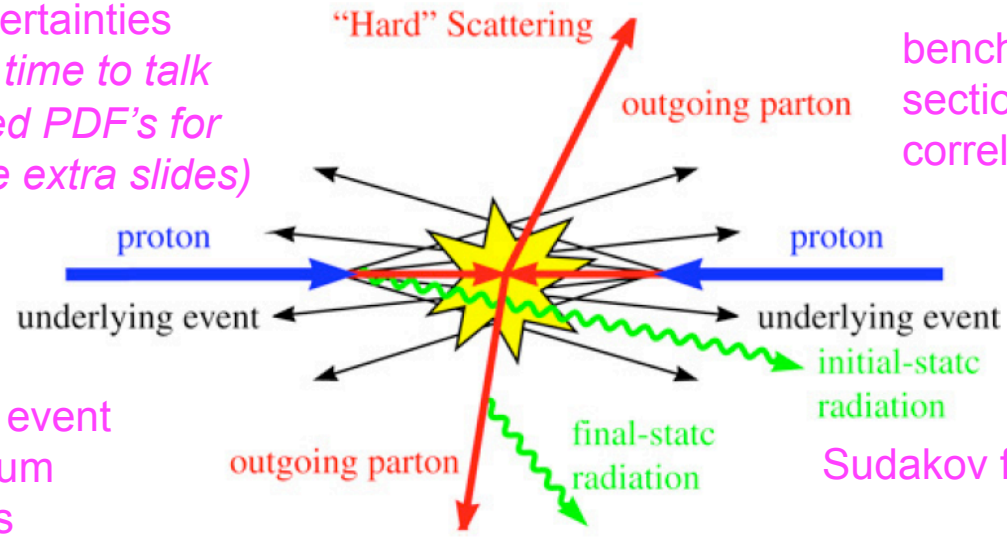
you are here

…but before looking back

Understanding SM physics at the LHC

LO, NLO and NNLO calculations
K-factors

PDF's, PDF luminosities
and PDF uncertainties
(I won't have time to talk about modified PDF's for MC's, but see extra slides)



benchmark cross sections and pdf correlations

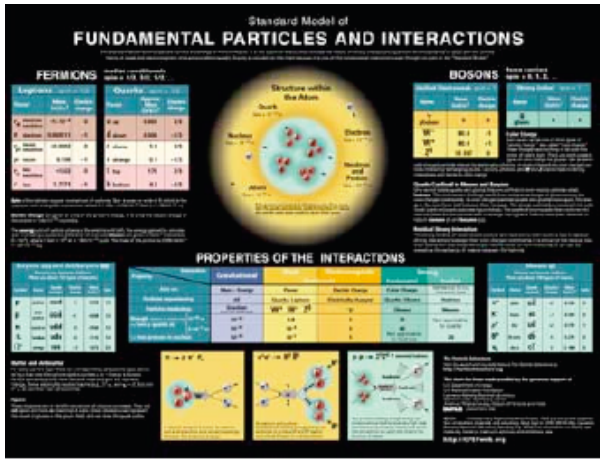
underlying event
and minimum
bias events

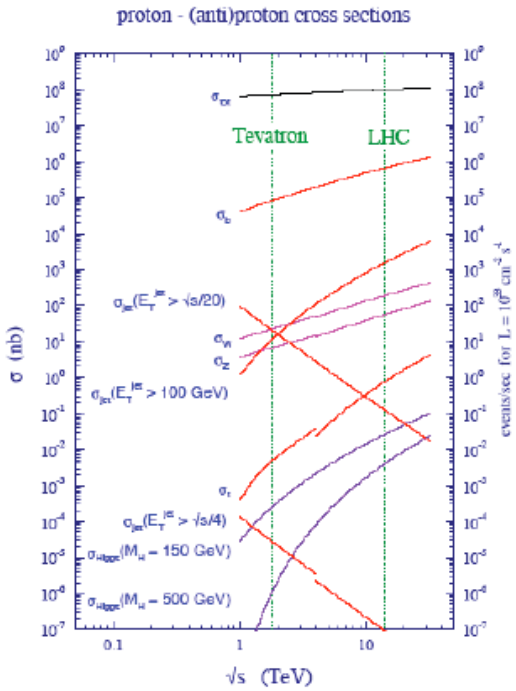
Sudakov form factors

jet algorithms and jet reconstruction
(I'll leave this to Gregory…but see extra slides)

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 physics understood properly
  - SM backgrounds to BSM physics correctly taken into account





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 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->new pdfs to be named later

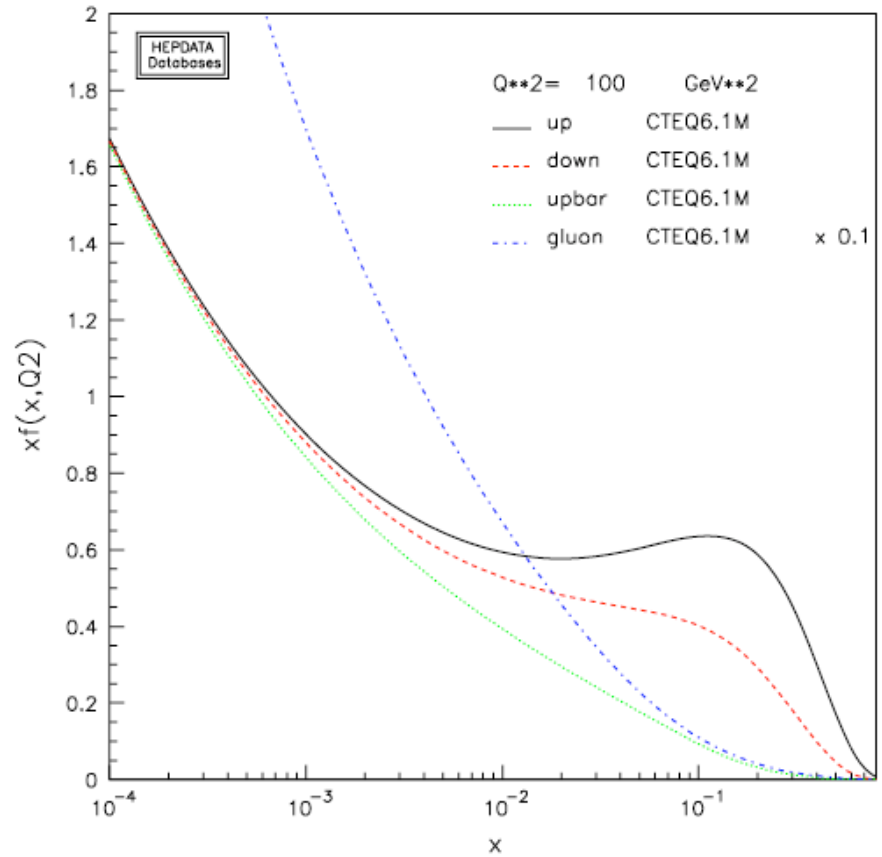
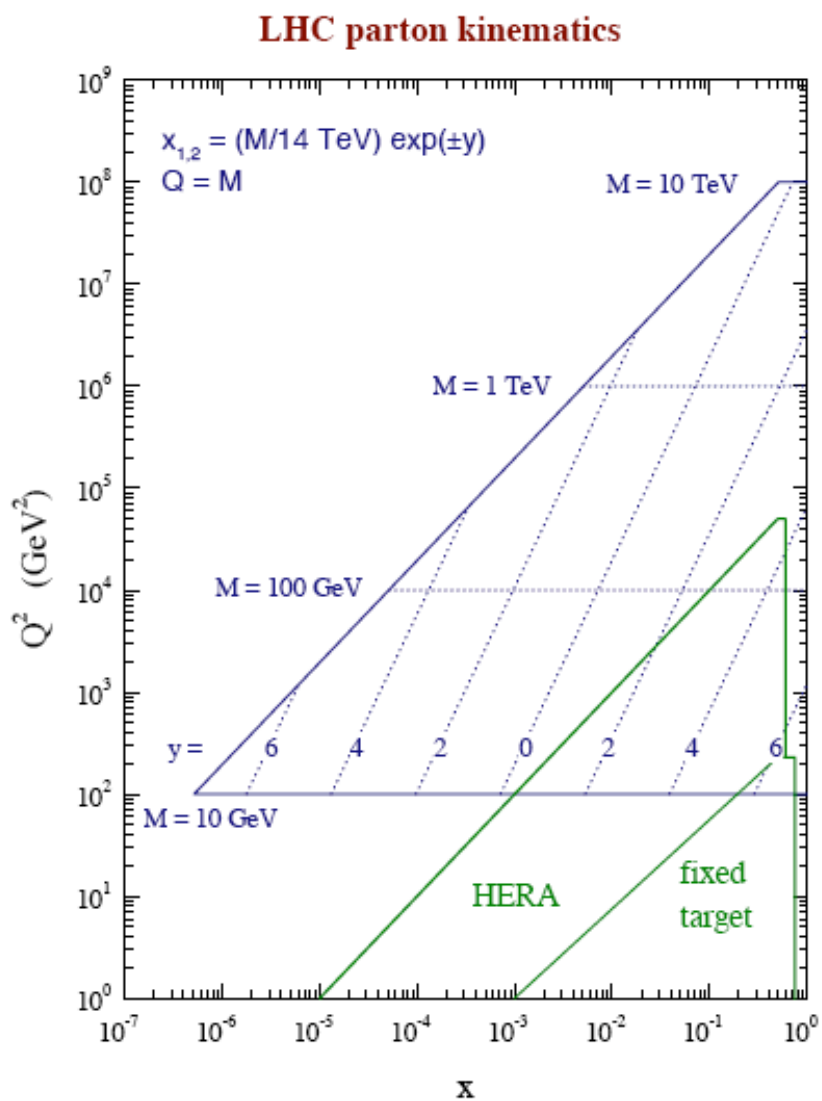


Figure 27. The CTEQ6.1 parton distribution functions evaluated at a Q of 10 GeV.

Cross sections at the LHC

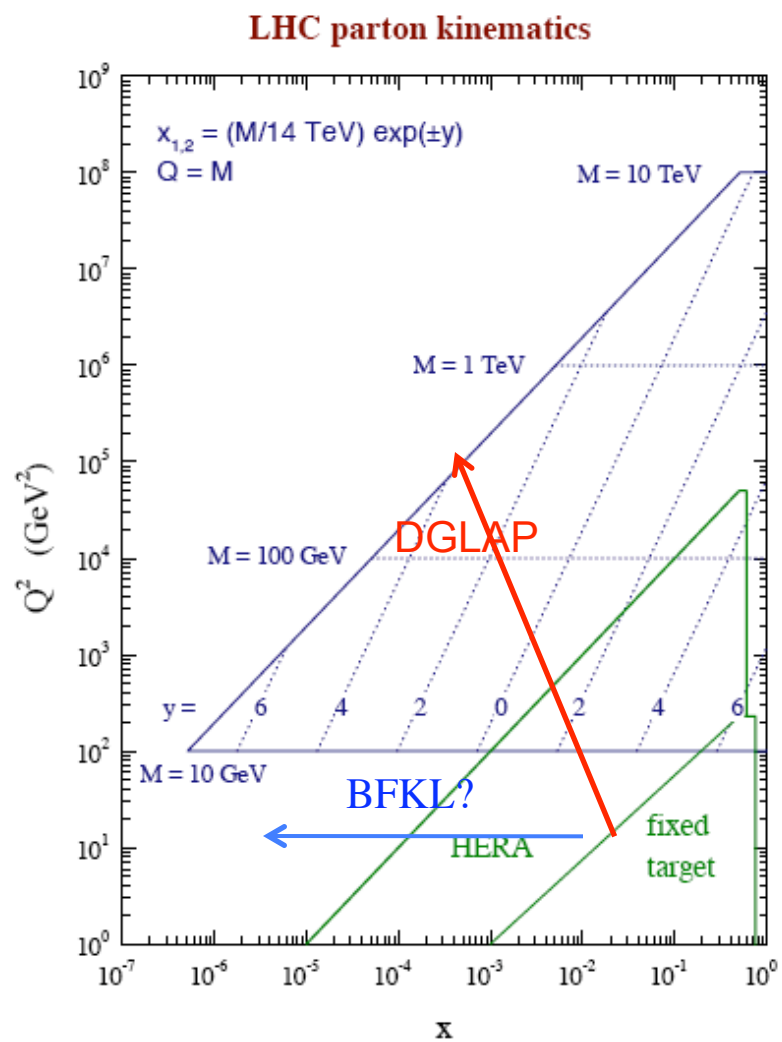
- Experience at the Tevatron is very useful, but scattering at the LHC is not necessarily just “rescaled” scattering at the Tevatron
- Small typical momentum fractions x in many key searches
  - dominance of gluon and sea quark scattering
  - large phase space for gluon emission and thus for production 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

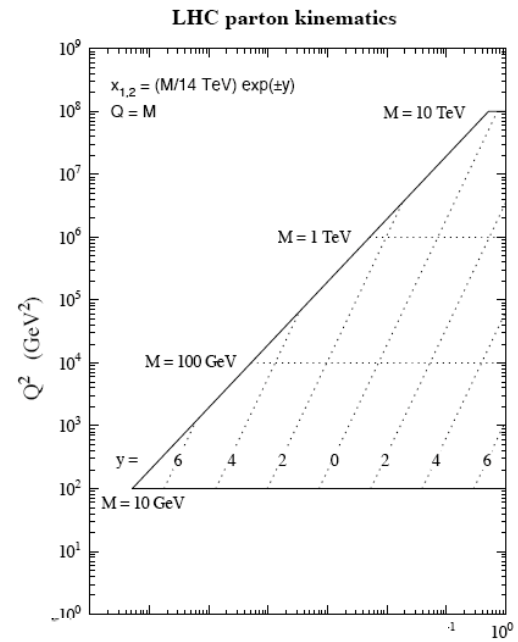
- Note that the data from HERA and fixed target cover only part of kinematic range accessible at the LHC
- We will access pdf's down to 1E-6 crucial for the underlying event) and Q^2 up to 100 TeV^2
- We can use the DGLAP equations to evolve to the relevant x and Q^2 range, but…
  - we're somewhat blind 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
- NB: DGLAP understanding of HERA (+other) works well only at NLO/ NNLO

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



Parton kinematics at the LHC

- To serve as a handy "look-up" table, it's useful to define a parton-parton luminosity (a la EHLQ)
- Equation 3 can be used to estimate the production rate for a hard scattering at the LHC as the product of a differential parton luminosity and a scaled hard scatter matrix element



$$\frac{dL_{ij}}{d\hat{s}\,dy} = \frac{1}{s}\,\frac{1}{1+\delta_{ij}}\left[f_i(x_1,\mu)f_j(x_2,\mu) + (1 \leftrightarrow 2)\right] . \qquad (1)$$

The prefactor with the Kronecker delta avoids double-counting in case the partons are identical. The generic parton-model formula

this is from the CHS review paper

$$\sigma = \sum_{i,j} \int_0^1 dx_1\, dx_2\, f_i(x_1,\mu)\, f_j(x_2,\mu)\, \hat{\sigma}_{ij} \qquad (2)$$

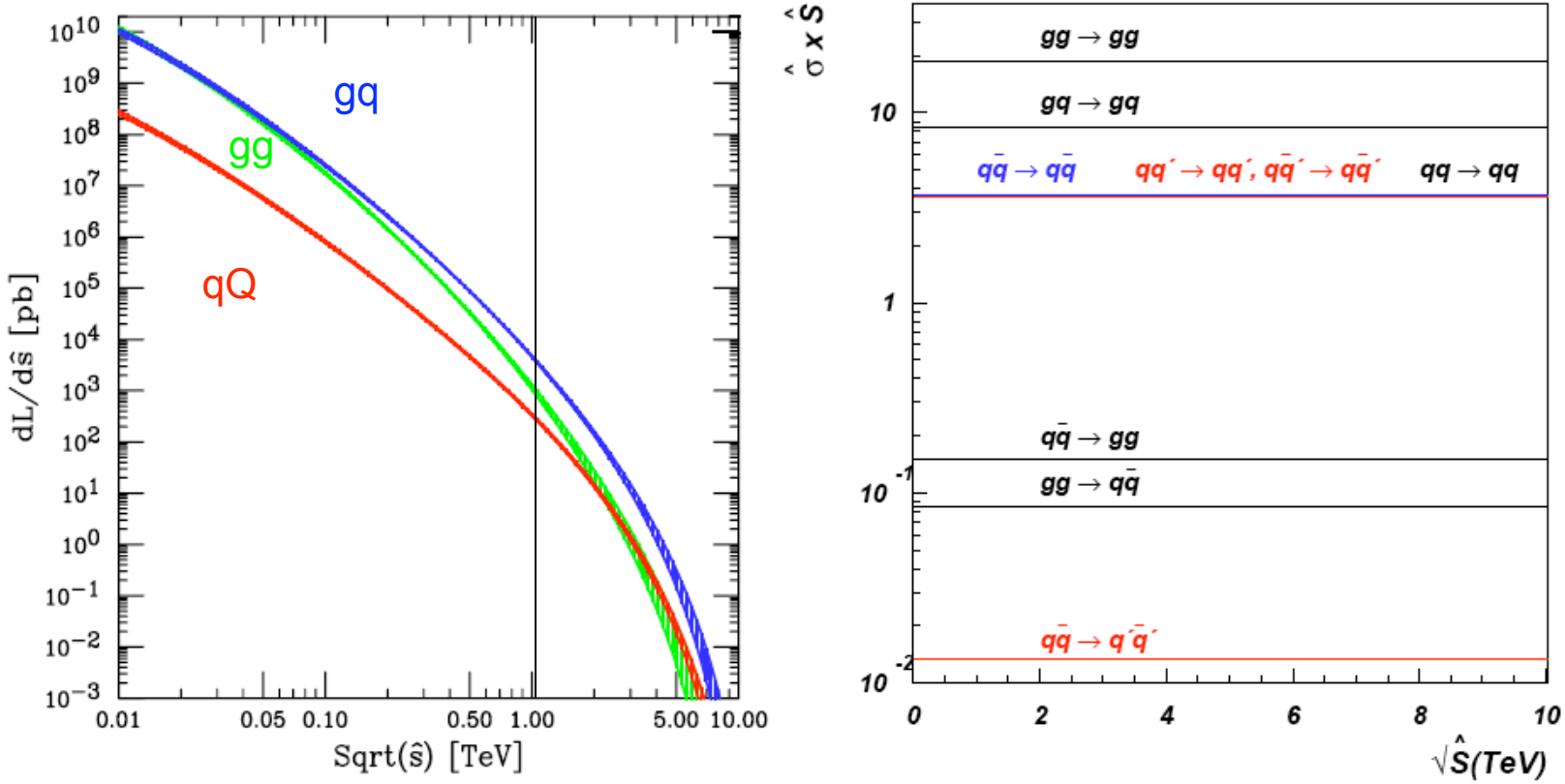
can then be written as

$$\sigma = \sum_{i,j} \int \left(\frac{d\hat{s}}{\hat{s}}\, dy\right) \left(\frac{dL_{ij}}{d\hat{s}\,dy}\right) (\hat{s}\,\hat{\sigma}_{ij}) \ . \qquad (3)$$

Cross section estimates

$$\sigma = \frac{\Delta\hat{s}}{\hat{s}}\left(\frac{dL_{ij}}{d\hat{s}}\right)(\hat{s}\,\hat{\sigma}_{ij})$$

for the gluon pair production rate for $\hat{s}$=1 TeV and $\Delta\hat{s} = 0.01\hat{s}$, we have $\frac{dL_{gg}}{d\hat{s}} \simeq 10^3$ pb and $\hat{s}\,\hat{\sigma}_{gg} \simeq 20$ leading to $\sigma \simeq 200$ pb



for p_T=0.1* sqrt(s-hat)

Fig. 2: Left: 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=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$. Right: parton level cross sections $[\hat{s}\hat{\sigma}_{ij}]$ for various processes

PDF luminosities as a function of y

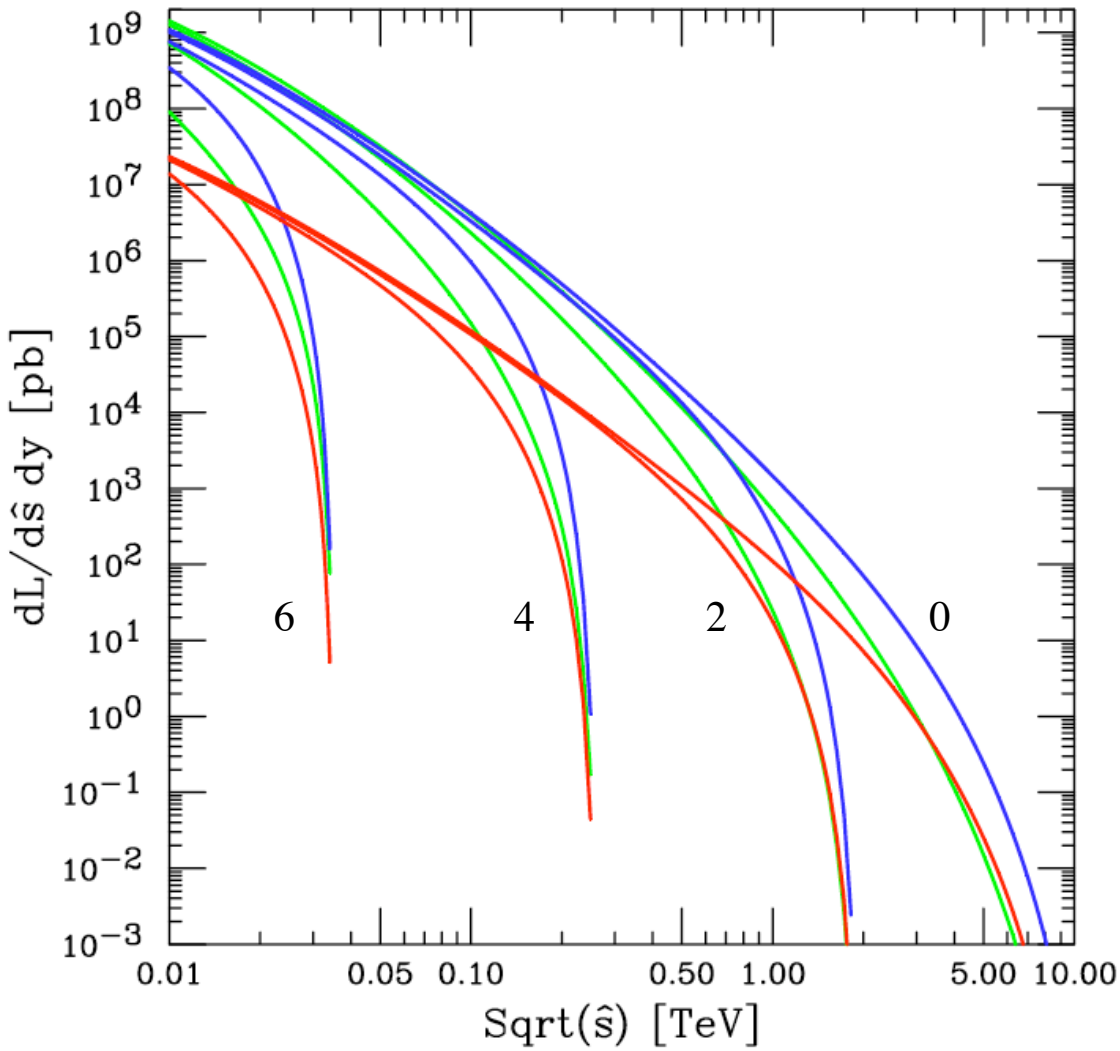


Fig. 3: dLuminosity/dy at $y = 0, 2, 4, 6$. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$.

PDF uncertainties at the LHC

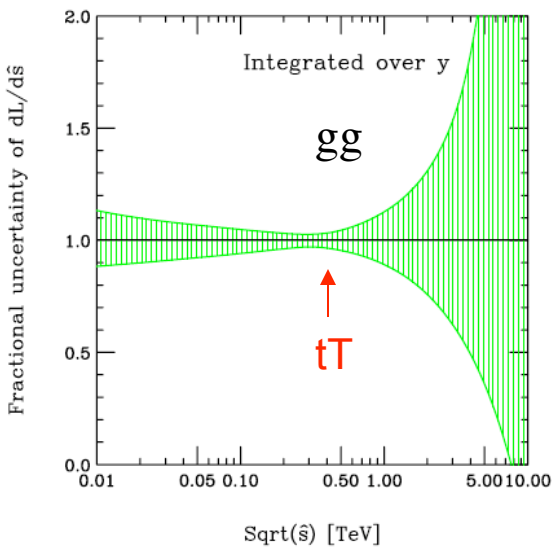


Fig. 4: Fractional uncertainty of gg luminosity integrated over y.

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

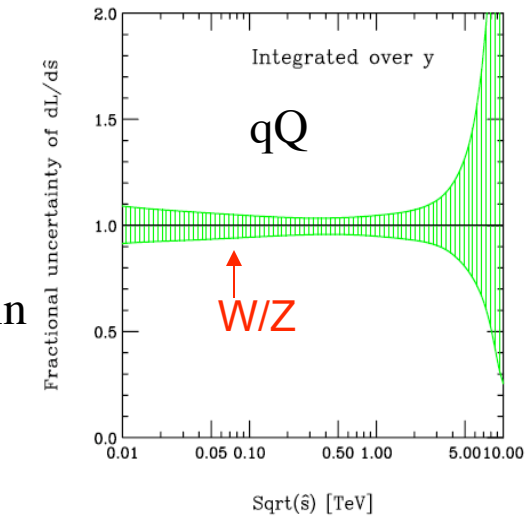


Fig. 7: Fractional uncertainty for Luminosity integrated over y for $d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$.

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

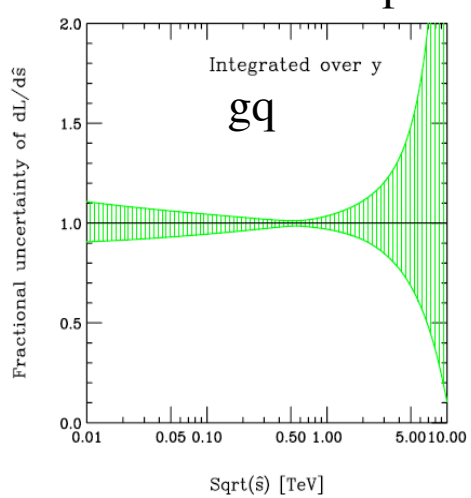
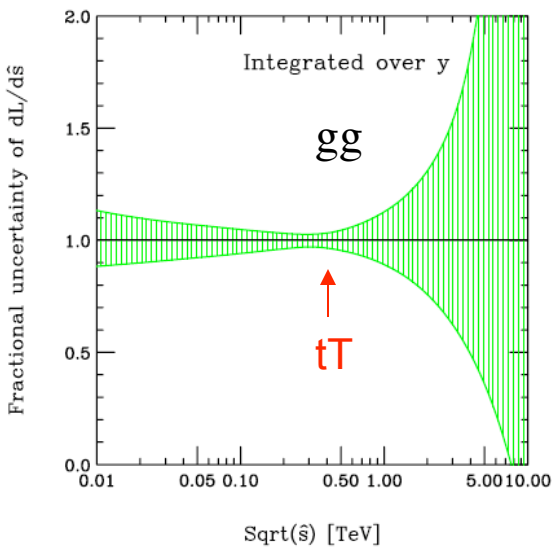


Fig. 6: Fractional uncertainty for Luminosity integrated over y for $g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$,

NB I: the errors are determined using the Hessian method for a Dc^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

PDF uncertainties at the LHC



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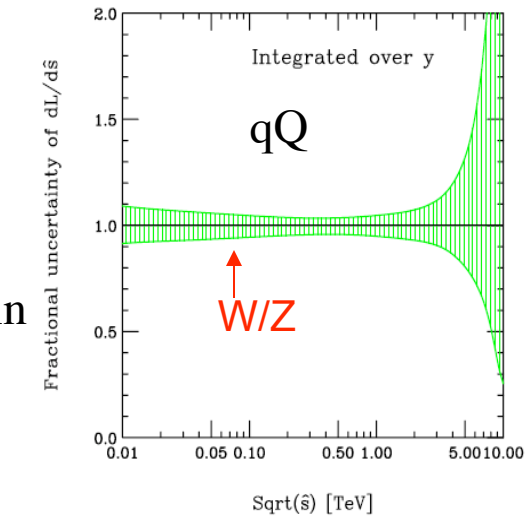

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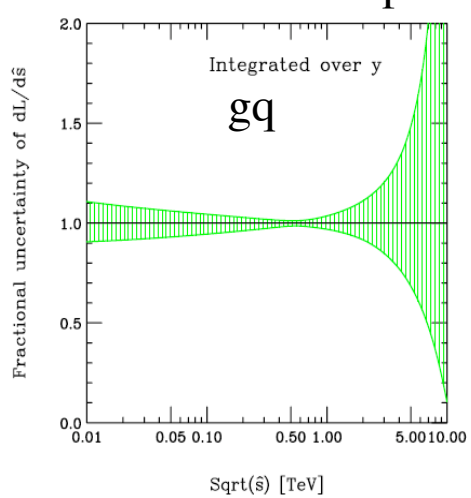

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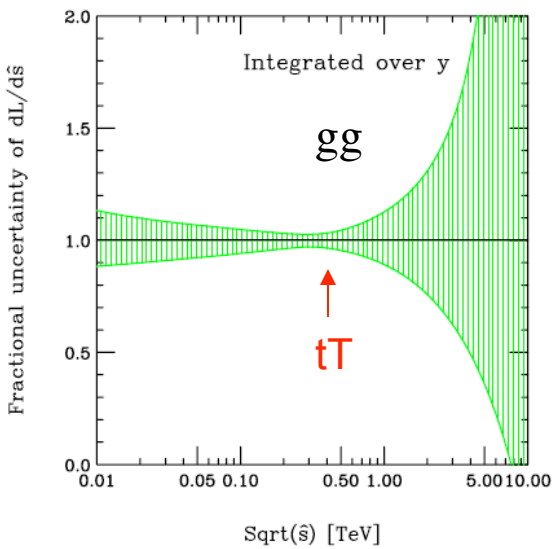
PDF uncertainties at the LHC



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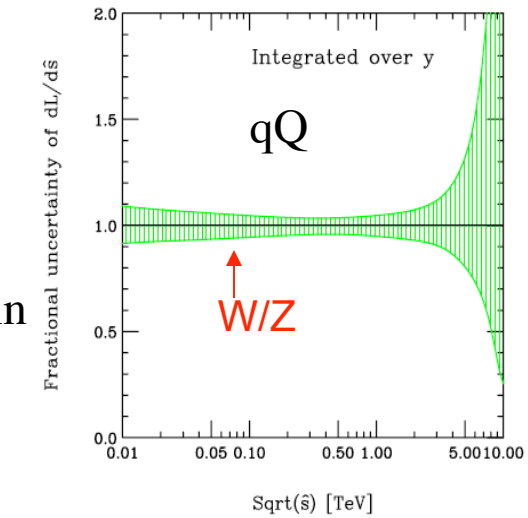

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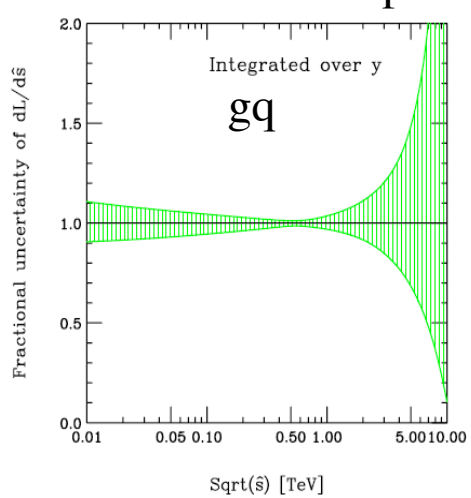

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NB II: the pdf uncertainties for W/Z cross sections are not the smallest

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

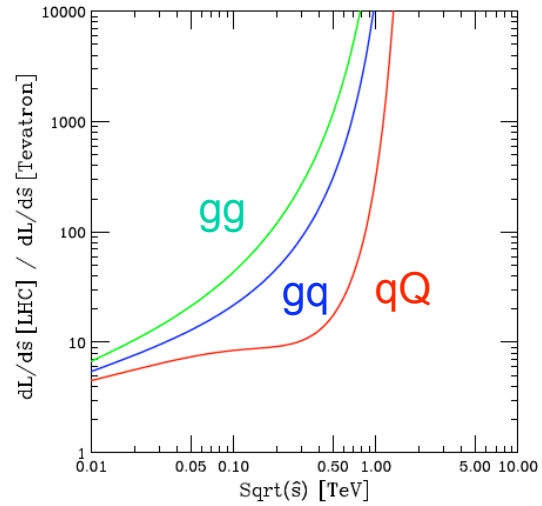


Figure 11. The ratio of parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y at the LHC and Tevatron. Green=gg (top), Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$ (middle), Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u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

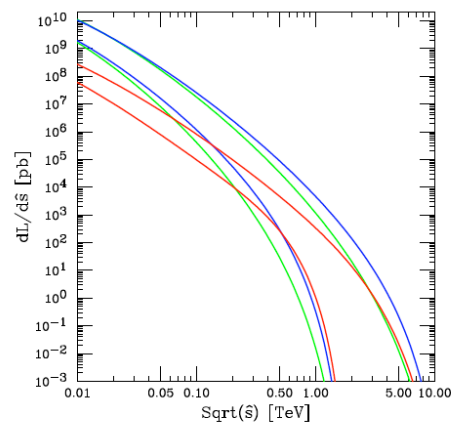


Figure 10. The parton-parton luminosity $\left[\frac{1}{\hat{s}}\frac{dL_{ij}}{d\tau}\right]$ in pb integrated over y. Green=gg, Blue=$g(d+u+s+c+b)+g(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})+(d+u+s+c+b)g+(\bar{d}+\bar{u}+\bar{s}+\bar{c}+\bar{b})g$, Red=$d\bar{d}+u\bar{u}+s\bar{s}+c\bar{c}+b\bar{b}+\bar{d}d+\bar{u}u+\bar{s}s+\bar{c}c+\bar{b}b$.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

…but wait, we're not running at 14 TeV in 2009-2010

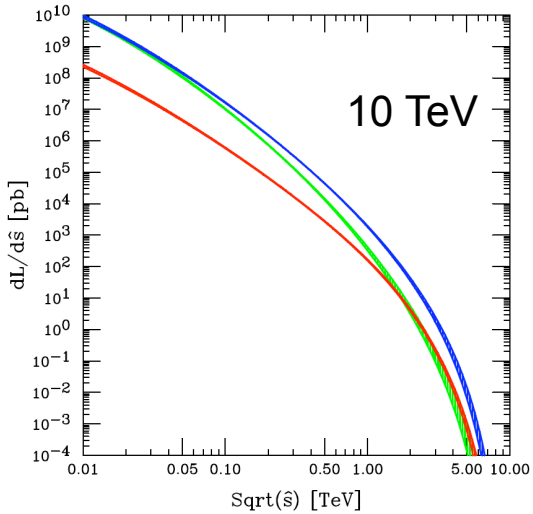


Figure 2: Luminosities integrated over y: LHC(pp) at $\sqrt{s} = 10\,\mathrm{TeV}$.
Green = gg, Blue = $gq + g\bar{q}$, Red = $u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} + b\bar{b}$.

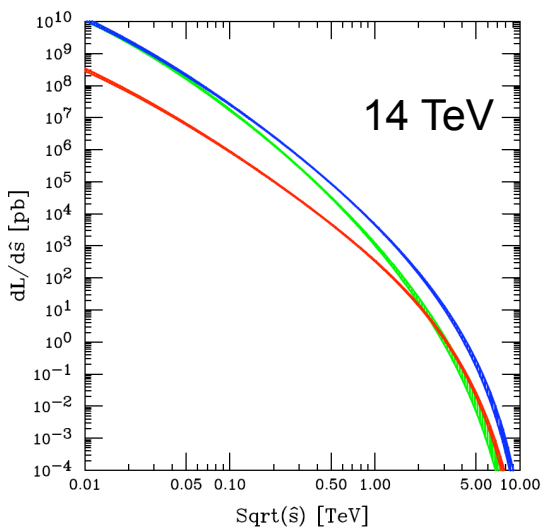


Figure 1: Luminosities integrated over y: LHC(pp) at $\sqrt{s} = 14\,\mathrm{TeV}$.
Green = $g\,g$, Blue = $gq + g\bar{q}$, Red = $u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} + b\bar{b}$.

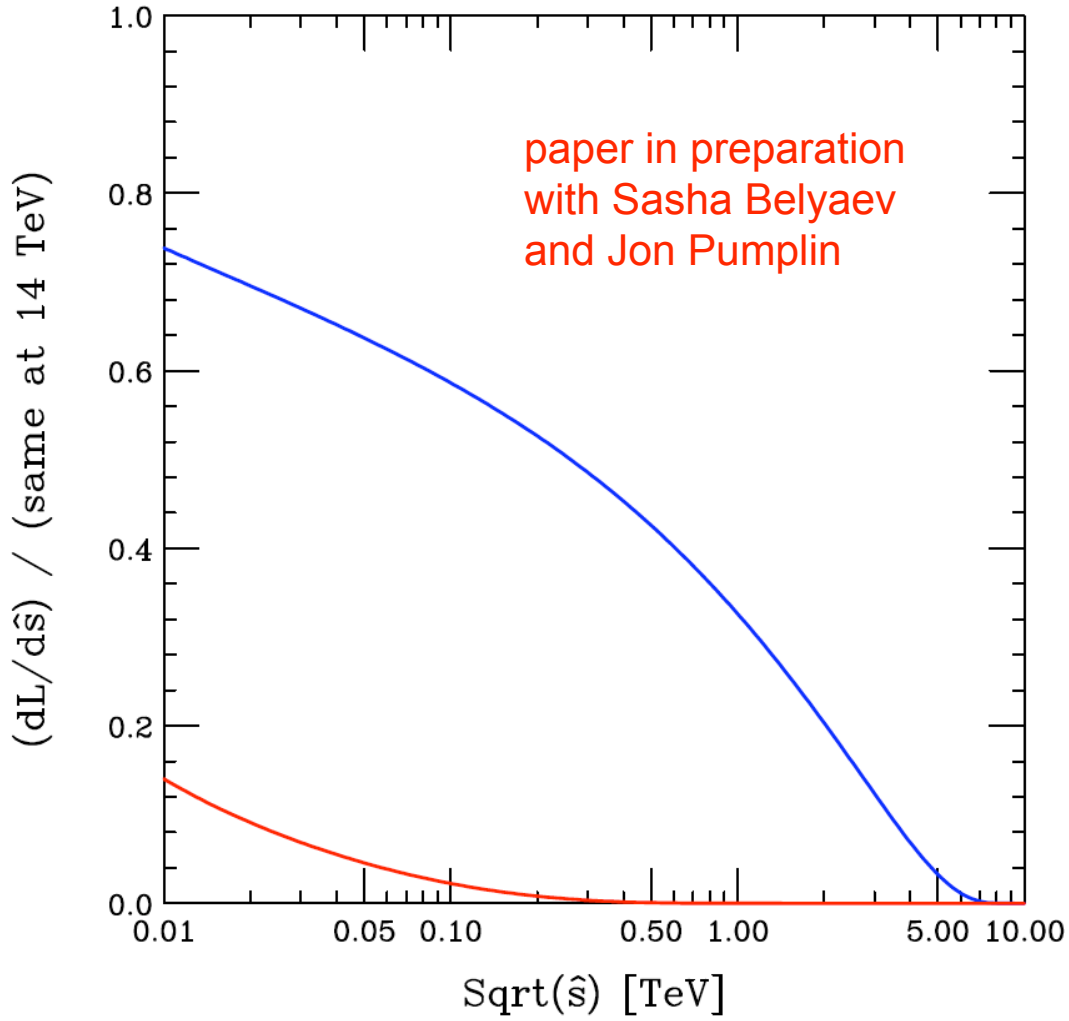


Figure 7: gg luminosity integrated over y:
Blue = (pp at 10 TeV) / (pp at 14 TeV);
Red = ($p\bar{p}$ at 1.96 TeV) / (pp at 14 TeV).

Other ratios

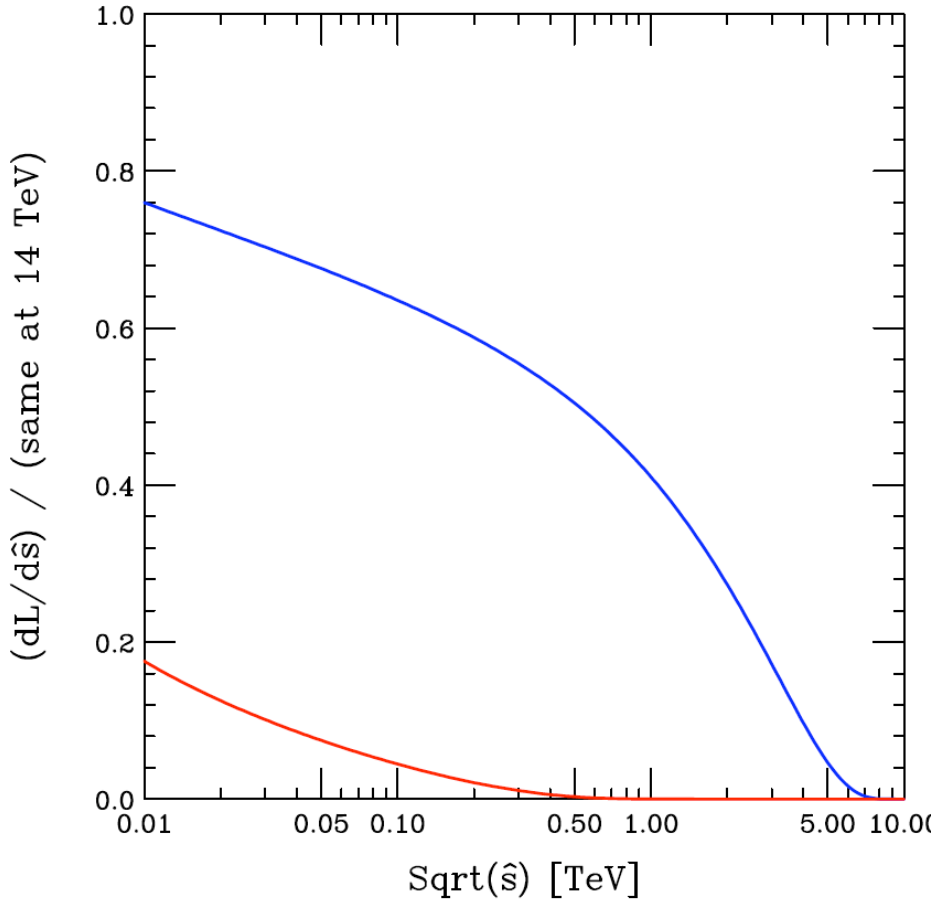


Figure 8: $gq + g\bar{q}$ luminosity integrated over y:
Blue = (pp at 10 TeV) / (pp at 14 TeV);
Red = ($p\bar{p}$ at 1.96 TeV) / (pp at 14 TeV).

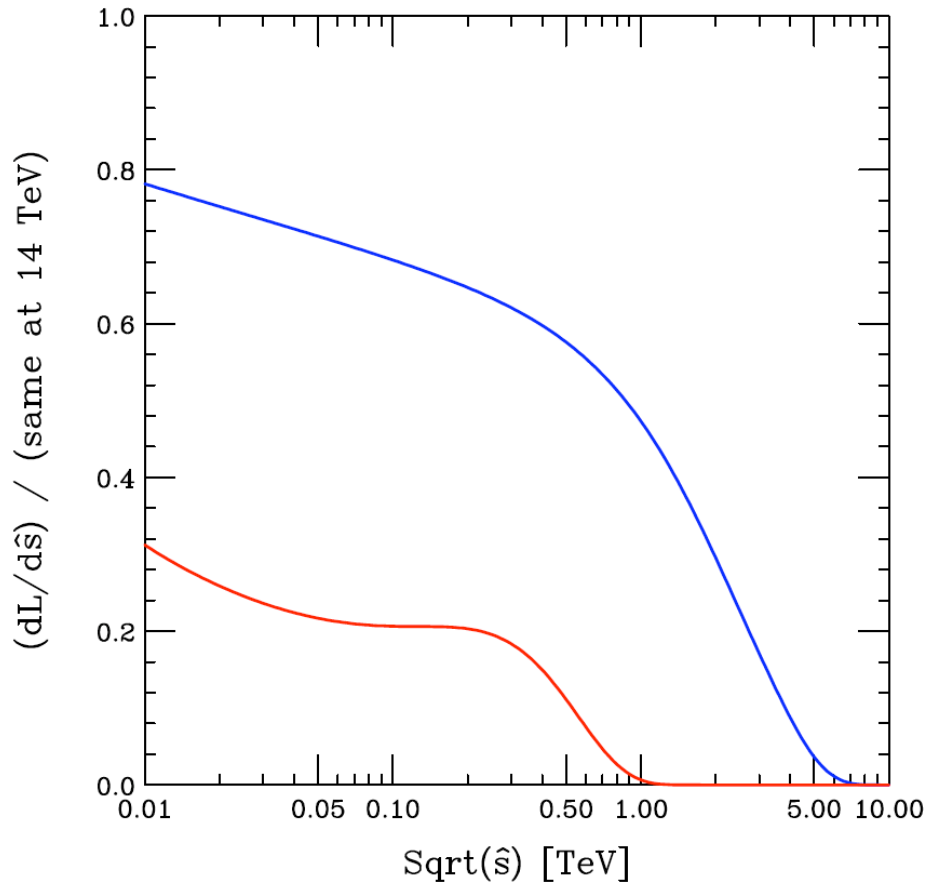


Figure 9: $u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} + b\bar{b}$:
Blue = (pp at 10 TeV) / (pp at 14 TeV);
Red = ($p\bar{p}$ at 1.96 TeV) / (pp at 14 TeV).

…but most importantly, look at ratios of qQ luminosities

- The plan is to run the LHC in 2009-2010 accumulating at least 200 pb^{-1}
- Take a discovery region (~1 TeV, say for squark pair production)
- The LHC is a factor of 50 more efficient at producing a 1 TeV object through a qQ initial state…so it would take 10 fb^{-1} at the Tevatron to equal the 200 pb^{-1} at the LHC
- …which the Tevatron will probably get (per expt)
- …with much better understood detectors and much lower backgrounds
- So don't count the Tevatron out just yet for discovery physics

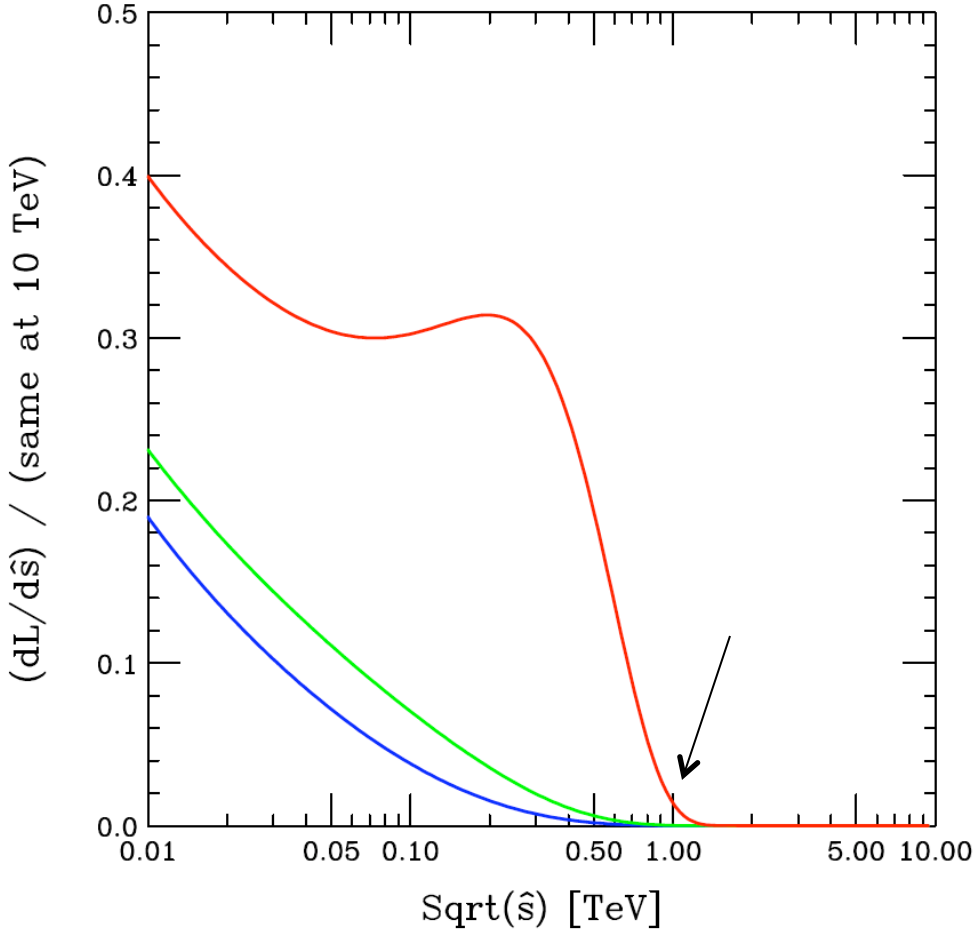
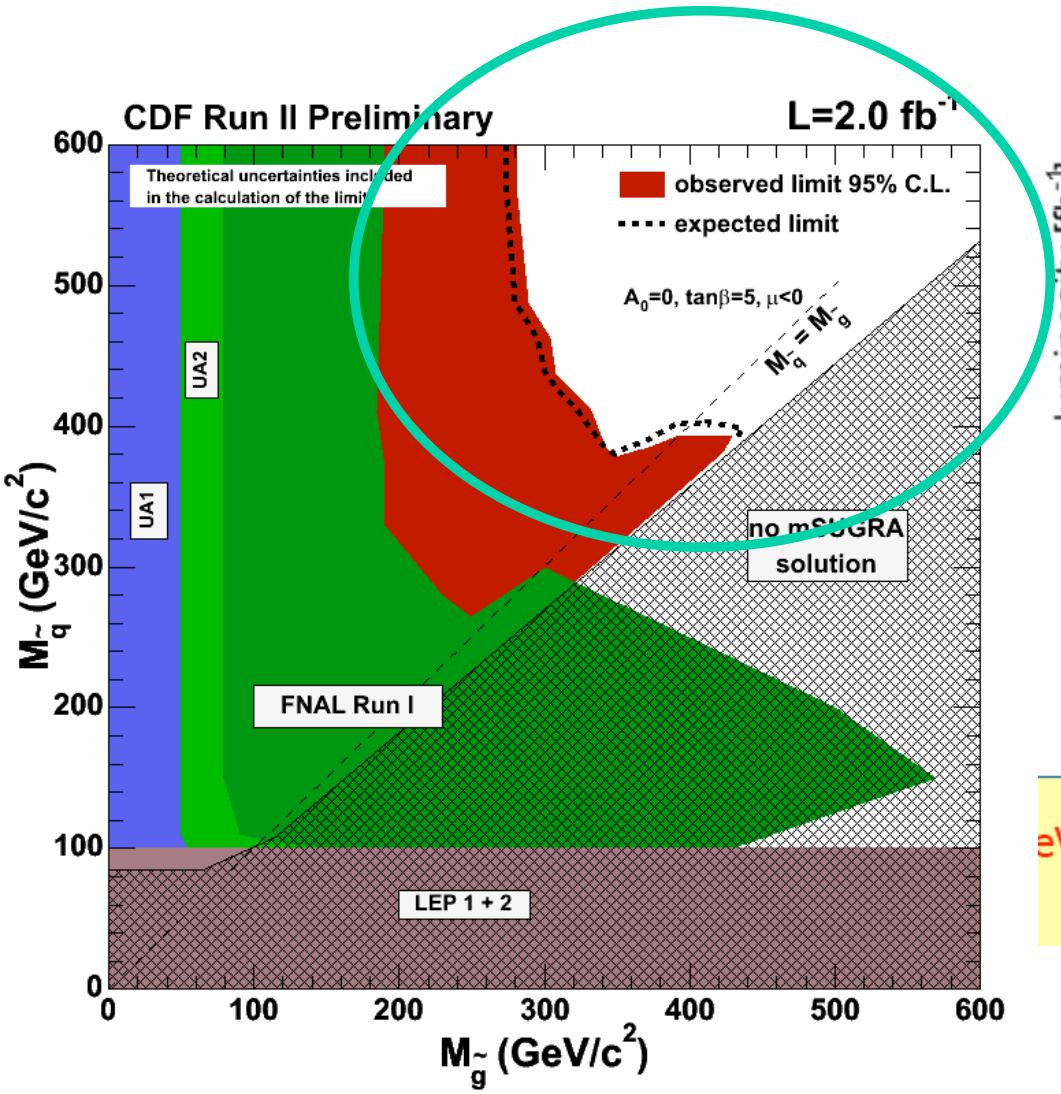
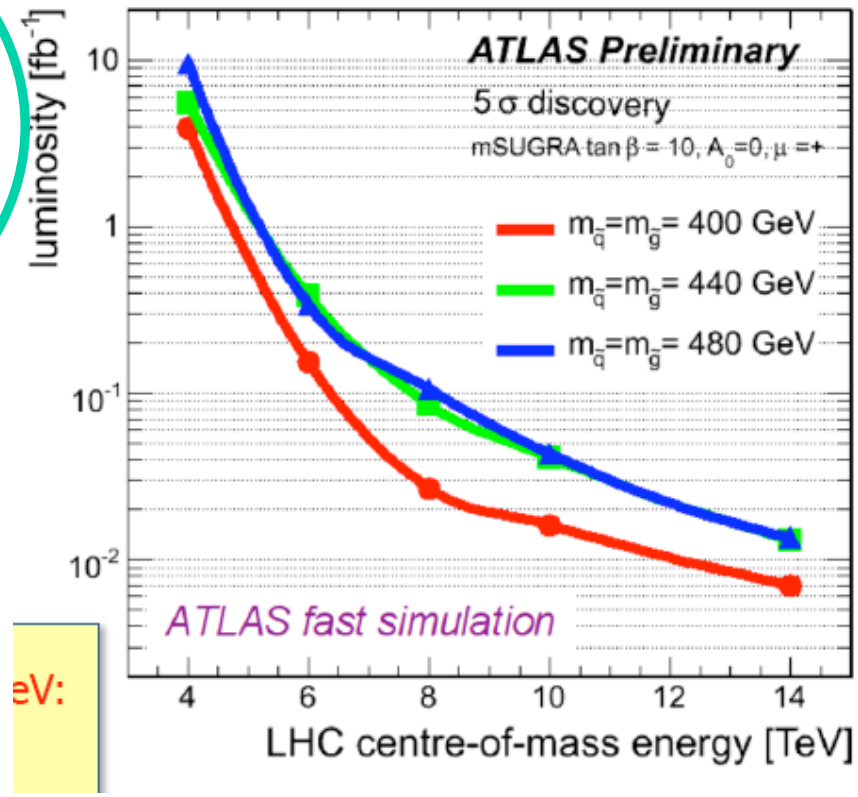


Figure 13: ($p\bar{p}$ at 1.96 TeV) / (pp at 10 TeV). luminosity integrated over y. Blue: gg; Green: $gq + g\bar{q}$; Red: $u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} + b\bar{b}$.

Tevatron limits vs LHC discovery potential





Back to the LHC: it 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
- $s_{W+3\ jets} > s_{W+2\ jets}$

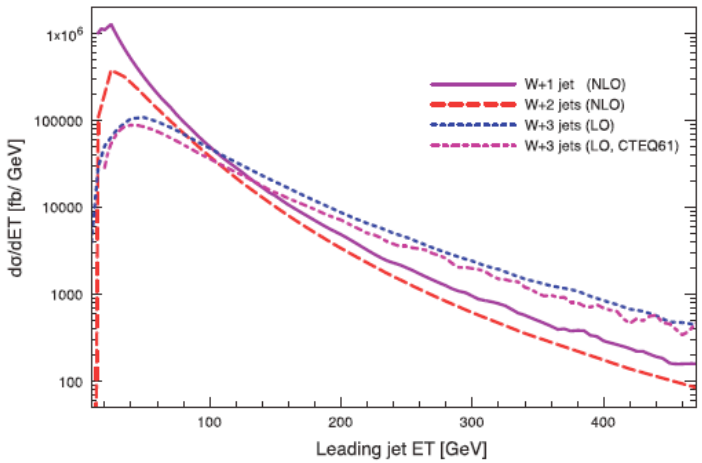


Figure 91. Predictions for the production of $W+ \geqslant 1, 2, 3$ jets at the LHC shown as a function of the transverse energy of the lead jet. A cut of 20 GeV has been placed on the other jets in the prediction.

- Indication that can expect interesting events at LHC to be very *jetty* (especially from gg initial states)
- Can also understand this from the point-of-view of Sudakov form factors

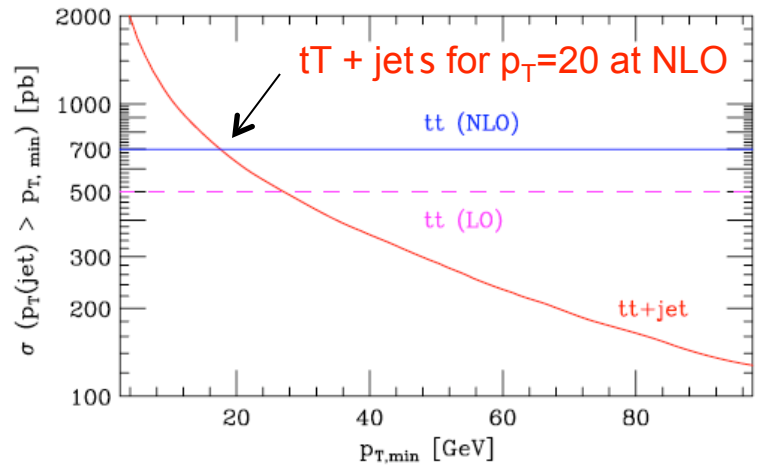


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

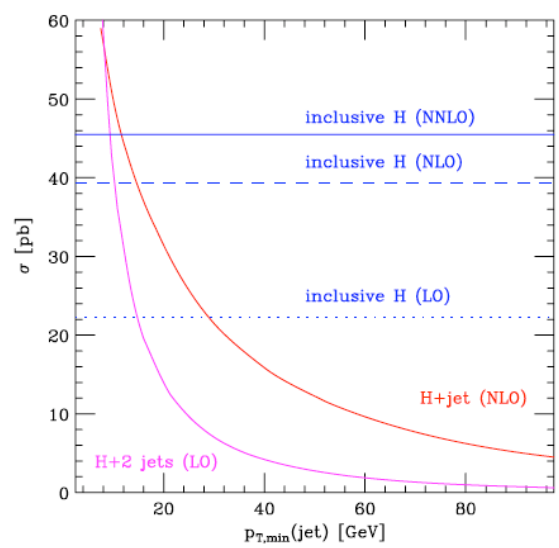


Figure 100. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

Aside: Sudakov form factors

- Sudakov form factors form the basis for both resummation and parton showering
- We can write an expression for the Sudakov form factor of an initial state parton in the form below, where *t* is the hard scale, to is the cutoff scale and *P(z)* is the splitting function

$$\Delta(t) \equiv \exp\left[-\int_{t_0}^{t} \frac{dt'}{t'} \int \frac{dz}{z} \frac{\alpha_S}{2\pi} P(z) \frac{f(x/z,t)}{f(x,t)}\right]$$

- Similar form for the final state but without the pdf weighting
- Sudakov form factor resums all effects of soft and collinear gluon emission, but does not include non-singular regions that are due to large energy, wide angle gluon emission
- Gives the probability **not** to radiate a gluon greater than some energy

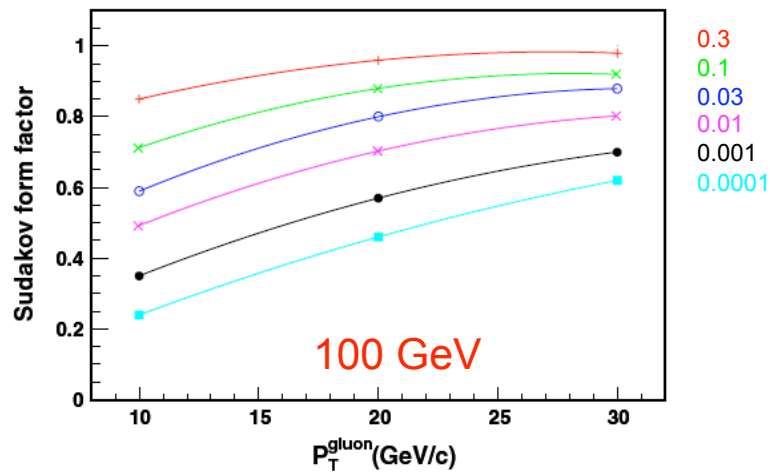


Figure 21. The Sudakov form factors for initial-state gluons at a hard scale of 100 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

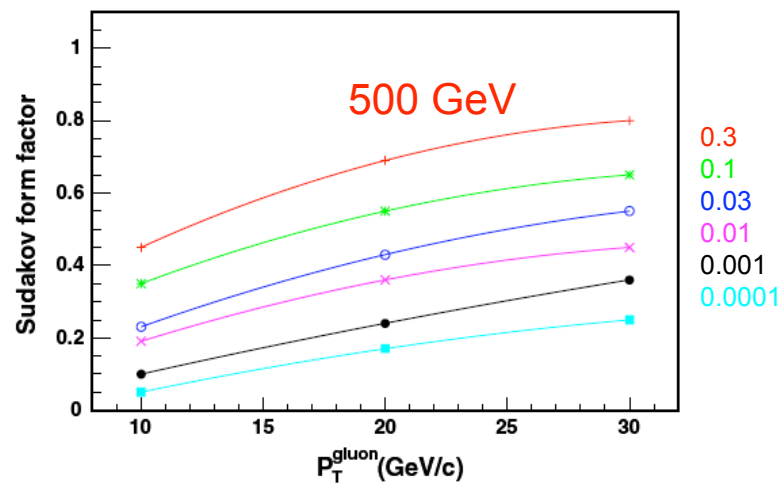


Figure 22. The Sudakov form factors for initial-state gluons at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

Sudakov form factors for tT

- tT production at the LHC dominated by gg at x values factor of 7 lower than Tevatron
- So dominant Sudakov form factor goes from
- to

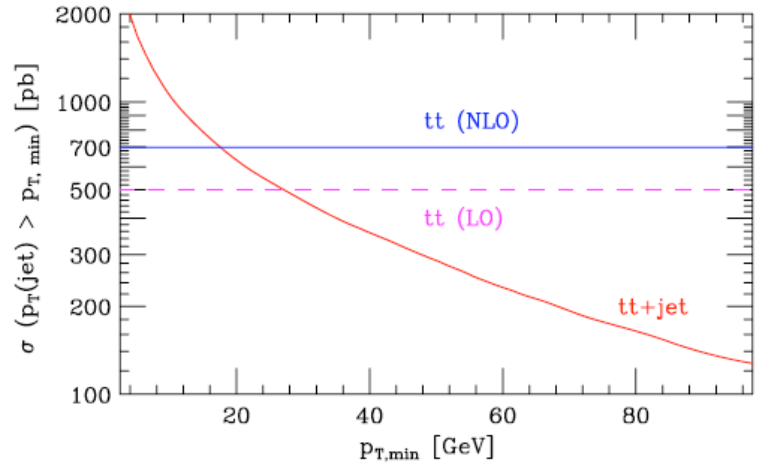


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

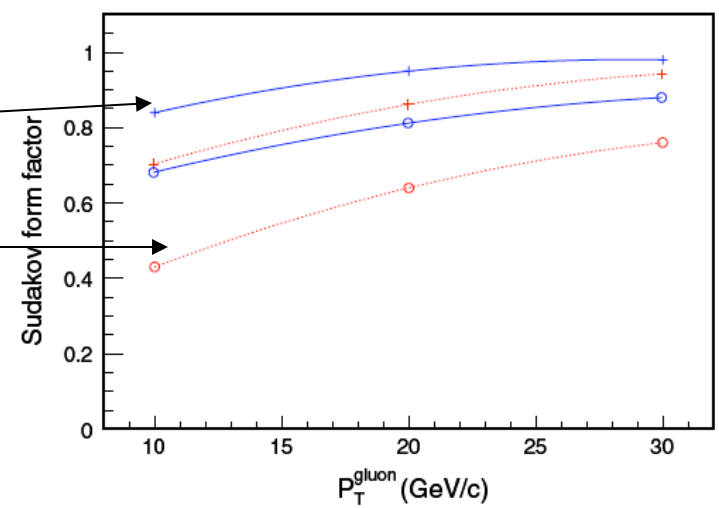


Figure 96. The Sudakov form factors for initial-state quarks and gluons at a hard scale of 200 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for quarks (blue-solid) and gluons (red-dashed) at parton x values of 0.3 (crosses) and 0.03 (open circles).

- So probability of radiating a 10 GeV gluon goes up by roughly a factor of 3

Sudakov form factors: quarks and gluons

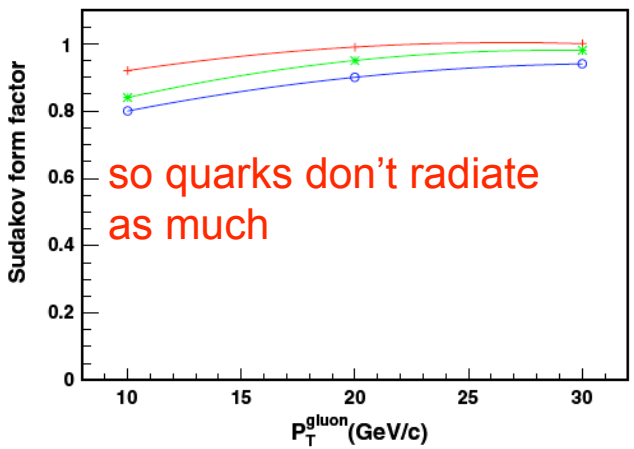


Figure 23. The Sudakov form factors for initial-state quarks at a hard scale of 100 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1 and 0.03.

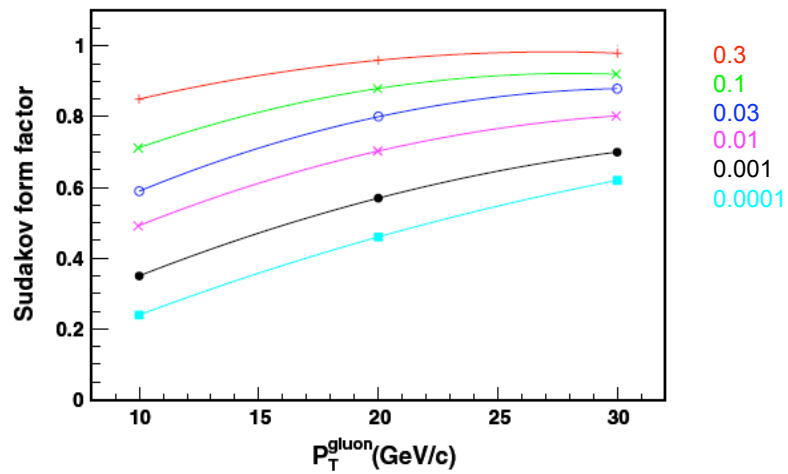


Figure 21. The Sudakov form factors for initial-state gluons at a hard scale of 100 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

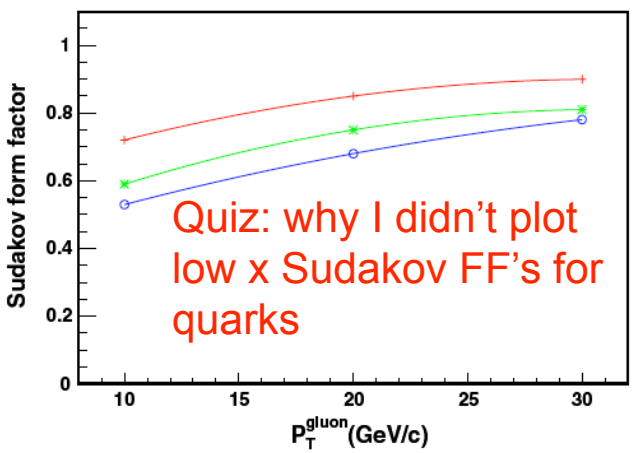


Figure 24. The Sudakov form factors for initial-state quarks at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1 and 0.03.

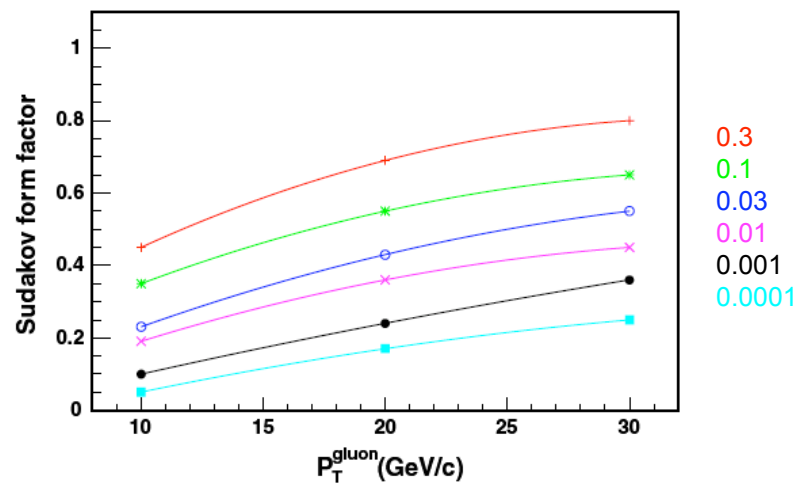
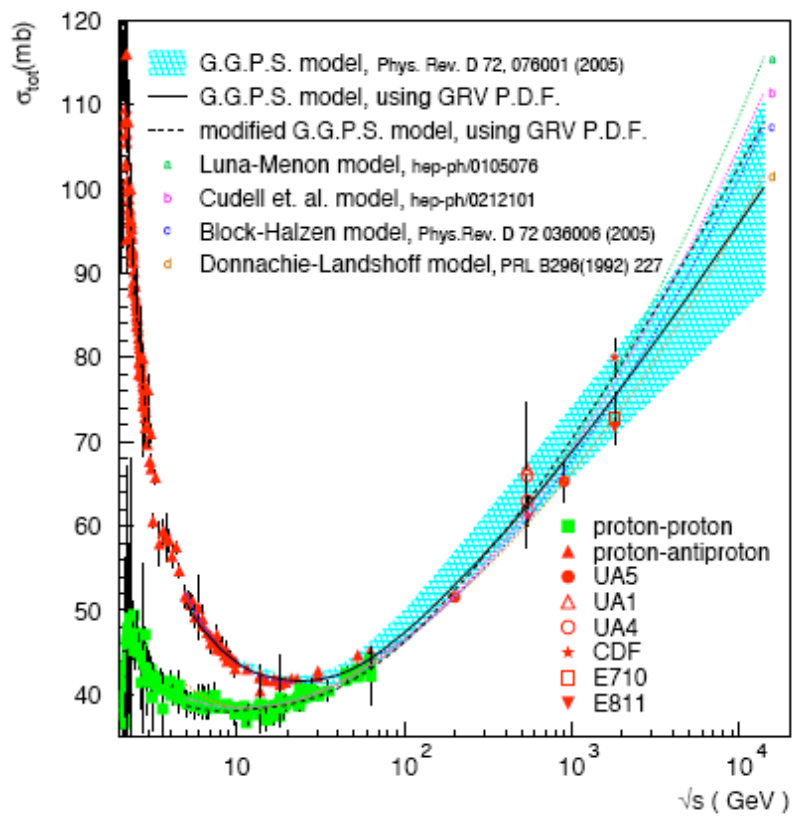


Figure 22. The Sudakov form factors for initial-state gluons at a hard scale of 500 GeV as a function of the transverse momentum of the emitted gluon. The form factors are for (top to bottom) parton x values of 0.3, 0.1, 0.03, 0.01, 0.001 and 0.0001.

Total cross section at LHC (10-14 TeV)

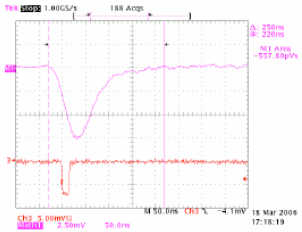
- Fair amount of uncertainty on extrapolation to LHC
  - ln(s) or $\ln^2(s)$ behavior
  - rely on Roman pot measurements
    - need 90 m optics run; sometime in 2009?
  - extrapolating measured cross section to full inelastic cross section will still have uncertainties (and may take time/analysis)
  - we'll need benchmark cross sections for normalization
- $s_{physics}$ ~ #events/luminosity
- We're not going to know the luminosity very well until we know the total inelastic cross section
- So it's useful to also have some benchmark cross sections for normalization

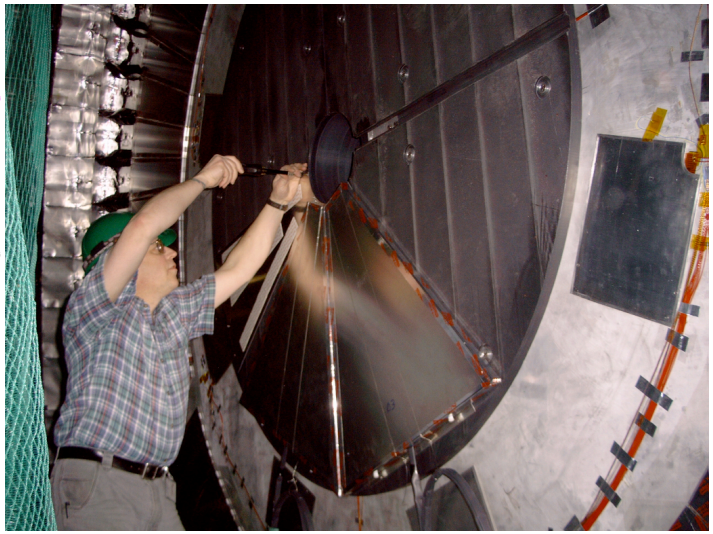


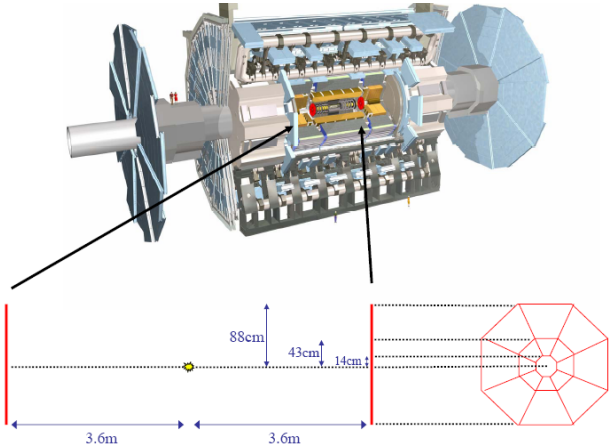
Peter Landshoff's best guess

Early triggering in ATLAS

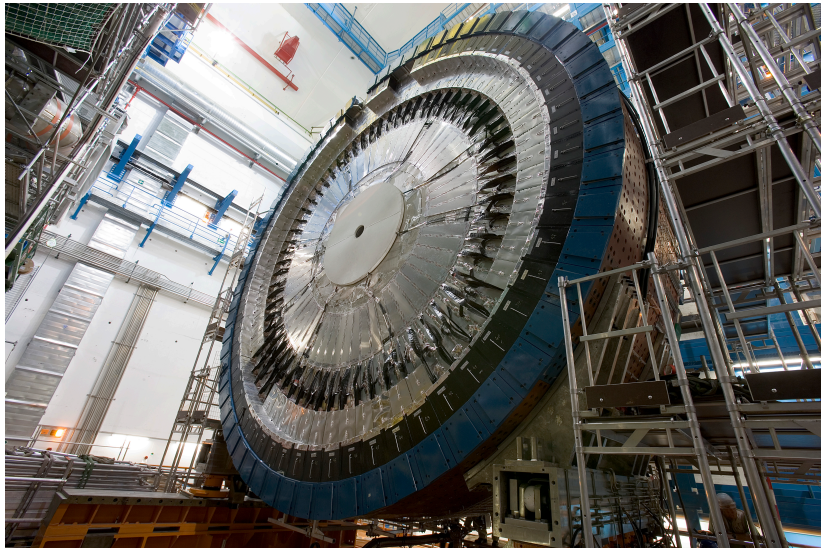
- Beam pickups will indicate which bunches are filled
- Need a fast signal from detector that an interaction has occurred
- This is the role of the MBTS counters
  - mounted on LAr cryostats and cover an h region from ~2 to 3.8





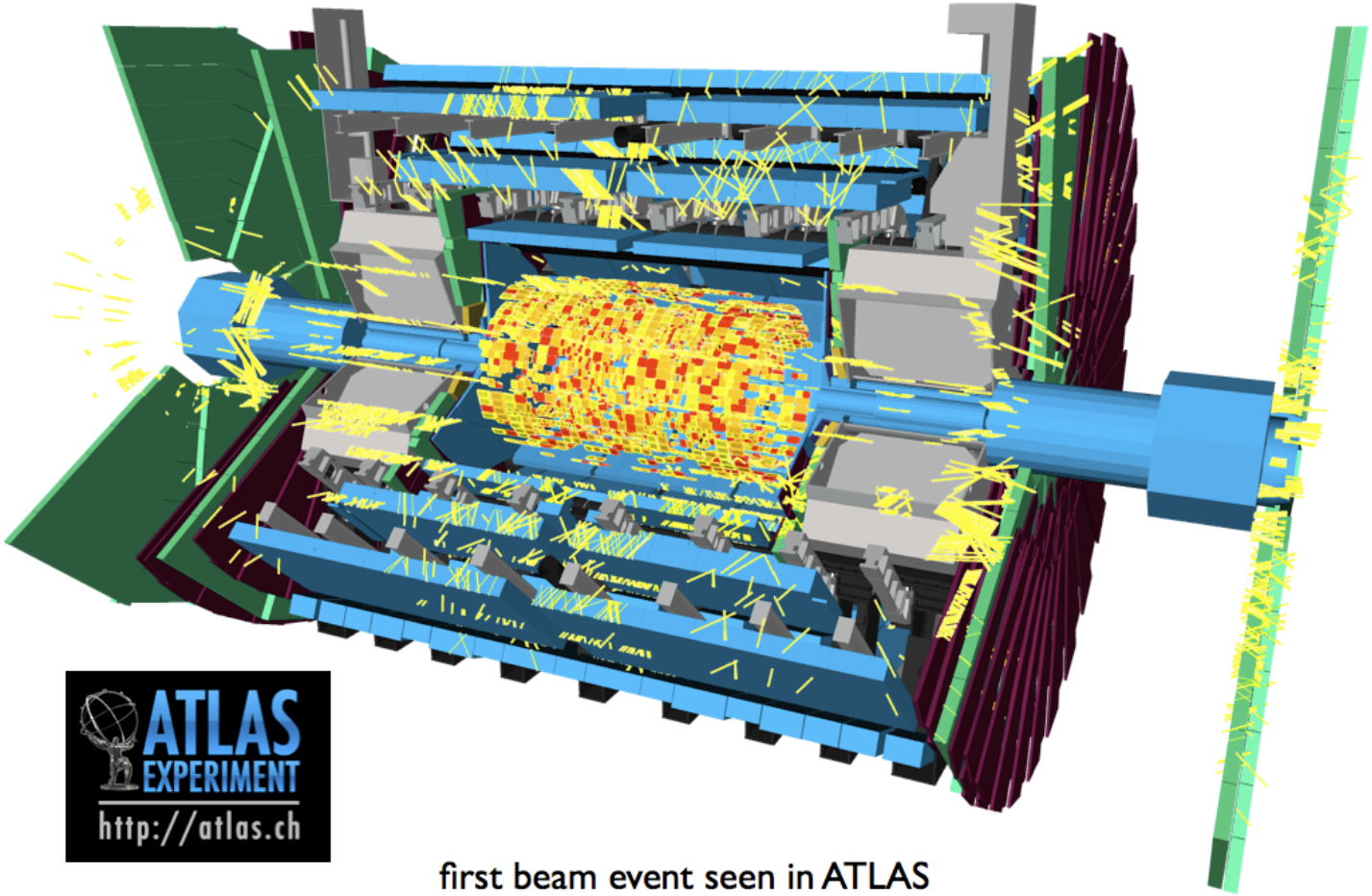


  - 8 segments in f on each side; 2 segments in h
  - single beam events from last September were triggered with MBTS



•will be first detector in ATLAS to die (but ok for year)

Commissioning with single beam



first beam event seen in ATLAS

All events triggered with MBTS

Single beam hitting an upstream collimator, proving that ATLAS can trigger on 1E5 muons. ~1000 TeV in the detector

Known unknown: underlying event at the LHC

- There's a great deal of uncertainty regarding the level of underlying event at 14 TeV, but it's clear that the UE is larger at the LHC than at the Tevatron
- Should be able to establish reasonably well with the first few pb^{-1} in 2009 (at 10 TeV)
- We will need to take the effects of the underlying event into account when comparing LHC data to theory

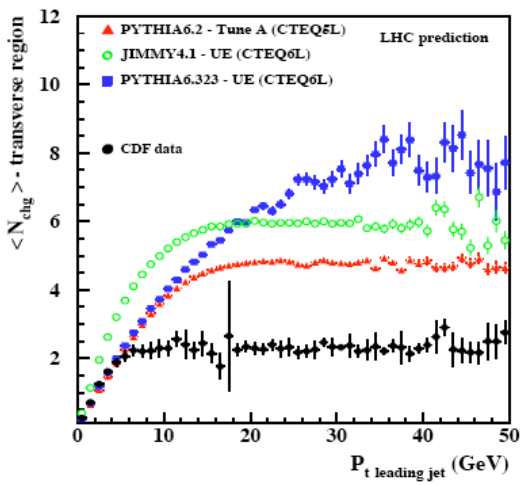
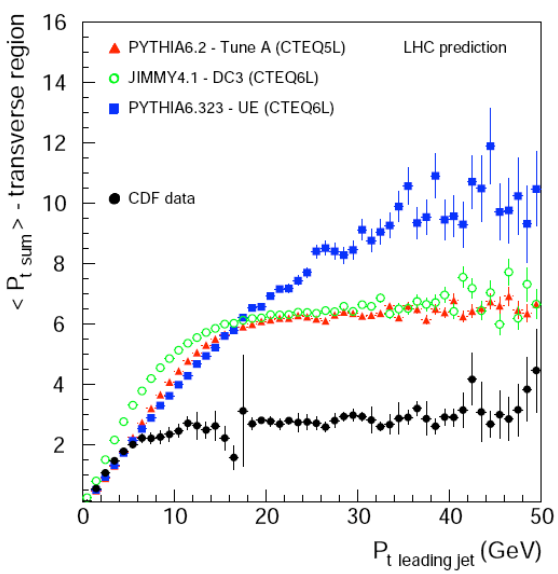
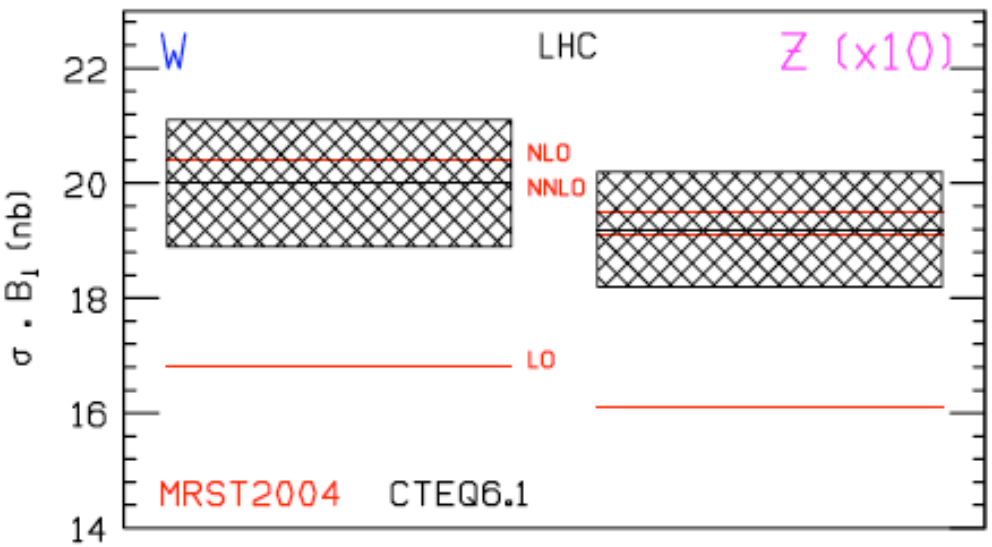


Figure 6: Pythia6.2 - Tune A, Jimmy4.1 - UE and Pythia6.323 - UE predictions for the average charged multiplicity in the underlying event for LHC pp collisions.



Precision benchmarks: W/Z cross sections at the LHC

- CTEQ6.1 and MRST NLO predictions in good agreement with each other
- NNLO corrections are small and negative
- NNLO mostly a K-factor; NLO predictions adequate for most predictions at the LHC



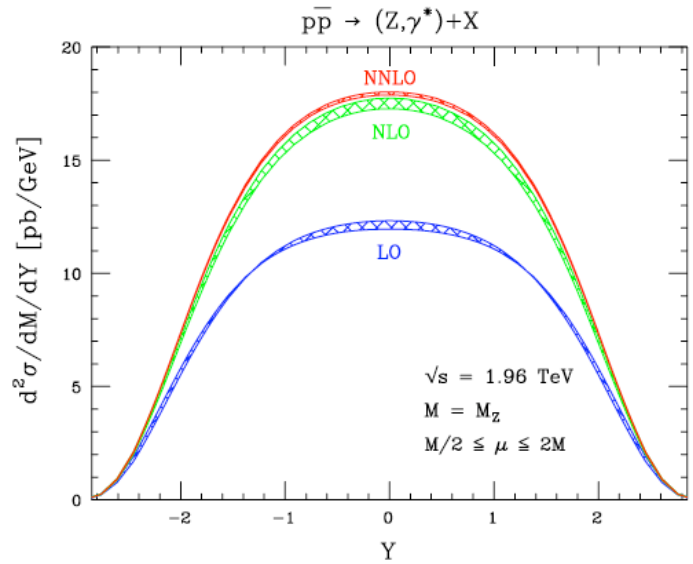
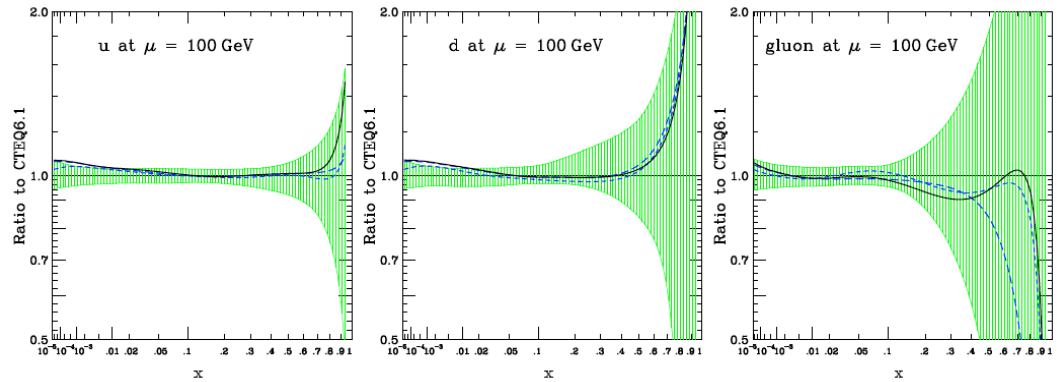


Figure 38. Predictions for the rapidity distribution of an on-shell Z boson in Run 2 at the Tevatron at LO, NLO and NNLO. The bands indicate the variation of the renormalization and factorization scales within the range $M_Z/2$ to $2M_Z$.

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.

Heavy quark mass effects in global fits

- CTEQ6.1 (and previous generations of global fits) used zero-mass VFNS scheme
- With new sets of pdf's (CTEQ6.5/6.6), heavy quark mass effects consistently taken into account in global fitting cross sections and in pdf evolution
- In most cases, resulting pdf's are within CTEQ6.1 pdf error bands
- But not at low x (in range of W and Z production at LHC)
- Heavy quark mass effects only appreciable near threshold
  - ex: prediction for F_2 at low x,Q at HERA smaller if mass of c,b quarks taken into account
  - thus, quark pdf's have to be bigger in this region to have an equivalent fit to the HERA data



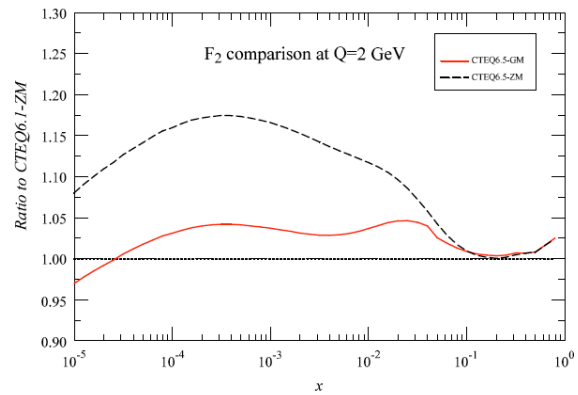
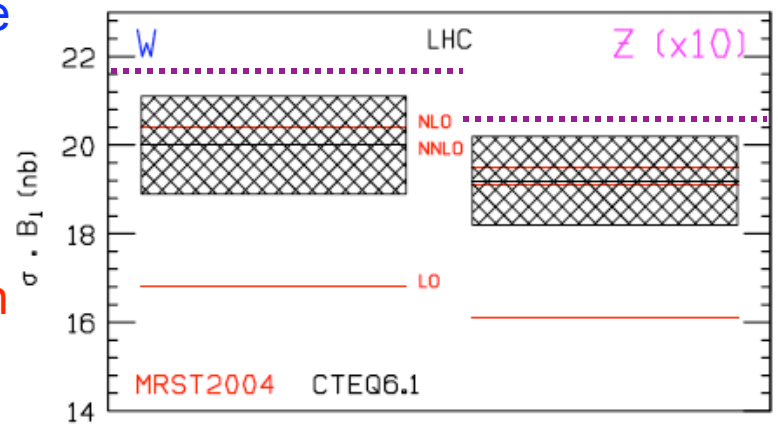


Figure 6: Comparison of theoretical calculations of F_2 using CTEQ6.1M in the ZM formalism (horizontal line of 1.00), CTEQ6.5M in the GM formalism (solid curve), and CTEQ6.5M in the ZM formalism (dashed curve).

implications for LHC phenomenology

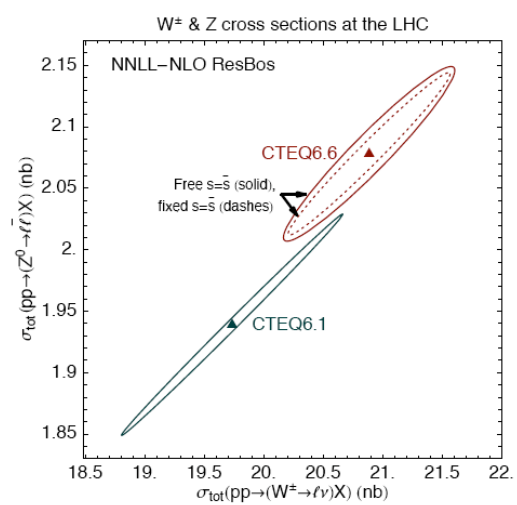
CTEQ6.5(6)

- Inclusion of heavy quark mass effects affects DIS data in x range appropriate for W/Z production at the LHC
- Cross sections for W/Z increase by 7-8%
  - now CTEQ and MRST2004 in disagreement
  - and relative uncertainties of W/Z increase
  - although individual uncertainties of W and Z decrease somewhat
- Two new free parameters in fit dealing with strangeness degrees of freedom so now have 44 error pdf's rather than 40



CTEQ6.5(6)

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.

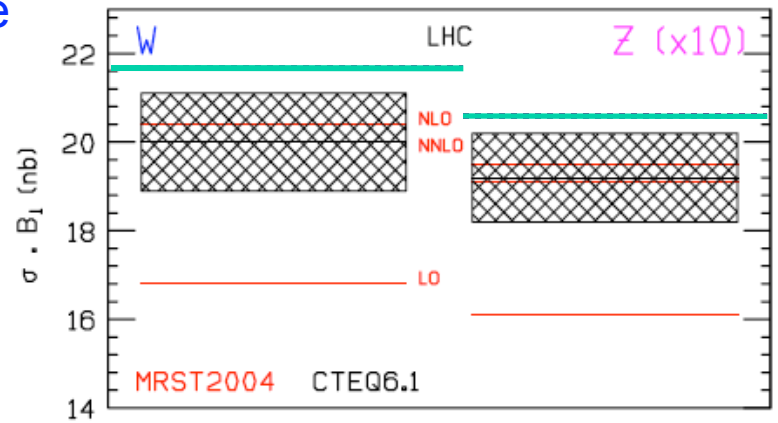


Note importance of strange quark uncertainty for ratio

Figure 8: W & Z correlation ellipses at the LHC obtained in the fits with free and fixed strangeness.

…but

- Inclusion of heavy quark mass effects affects DIS data in x range appropriate for W/Z production at the LHC
- …but MSTW2008 with improved heavy quark mass scheme has also lead to increased W/Z cross sections at the LHC
  - now CTEQ6.6 and MSTW2008 in better agreement



CTEQ6.5(6)

MSTW08

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.

CMS expectation for 10 pb^{-1}

$\Delta\sigma/\sigma$(pp-> Z+X -> ee+X) = 1.9 (stat) ± 2.3 (syst) %

$\Delta\sigma/\sigma$(pp->W+X -> e+X) = 1.2 (stat) ± ~5 (syst) %

- Identification/reconstruction efficiency: ~1% from data
- Backgrounds: 5% (e)
- Theory (including acceptance) ~2% (PDFs, ISR)

ATLAS expectation for 50 pb^{-1}

$\Delta\sigma/\sigma$(pp-> Z+X -> μμ+X) = 0.8 (stat) ± 3.8 (syst) %

$\Delta\sigma/\sigma$(pp->W+X -> μ+X) = 0.2 (stat) ± 3.1 (syst) %

- Identification/reconstruction efficiency : 2-3%
- Backgrounds: <1% (muons)
- Theory (including acceptance) ~2% (PDFs, ISR)

F. Petrucchi
Moriond09

On a longer timescale:

CMS expectation for 1 fb^{-1}

$\Delta\sigma/\sigma$(pp-> Z+X -> μμ+X) = 0.13 (stat) ± 2.3 (syst) %

$\Delta\sigma/\sigma$(pp->W+X -> μ+X) = 0.04 (stat) ± 3.3 (syst) %

ATLAS expectation for 1 fb^{-1}

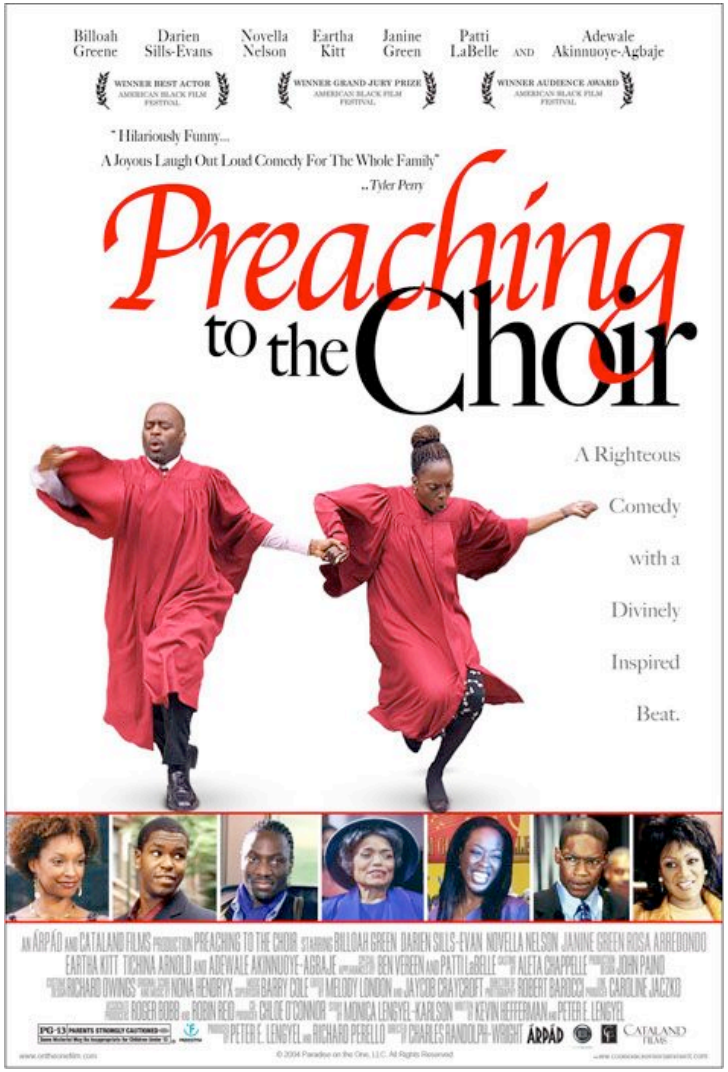
$\Delta\sigma/\sigma$(pp-> Z+X -> ee+X)= 0.20 (stat) ± 2.4 (syst) %

$\Delta\sigma/\sigma$(pp->W+X -> e+X) = 0.04 (stat) ± 2.5 (syst) %

- Eff unc. <1% with data-driven methods
- Background reduced with selections

NLO corrections

- NLO is the first order for which the normalization, and sometimes the shape, is believable
- NLO is necessary for precision comparisons of data to theory
  - for the New York theorists in the audience, this is what is known as preaching to the choir
- Sometimes backgrounds to new physics can be extrapolated from non-signal regions, but this is difficult to do for low cross section final states and/or final states where a clear separation of a signal and background region is difficult



NLO corrections

Sometimes it is useful to define a K-factor (NLO/LO). Note the value of the K-factor depends critically on its definition. K-factors at LHC (mostly) similar to those at Tevatron.

	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.

K-factors may differ from unity because of new subprocesses/ contributions at higher order **and/or differences between LO and NLO pdf's**

CHS
Les Houches 2007

NLO calculation priority list from Les Houches 2005-2007: theory benchmarks

G. Heinrich and J. Huston

process ($V \in \{Z, W, \gamma\}$)	relevant for
1. $pp \to VV$+jet	$t\bar{t}H$, new physics
2. $pp \to H + 2$ jets	H production by vector boson fusion (VBF)
3. $pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
5. $pp \to VVb\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to VV + 2$ jets	VBF$\to H \to VV$
7. $pp \to V + 3$ jets	various new physics signatures
8. $pp \to VVV$	SUSY trilepton

Table 2. The wishlist of processes for which a NLO calculation is both desired and feasible in the near future.

2007 →

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [3]; Campbell/Ellis/Zanderighi [4] and Binoth/Karg/Kauer/Sanguinetti (in progress)
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [5]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [6, 7]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [8] and WWZ by Hankele/Zeppenfeld [9]
Calculations remaining from Les Houches 2005	
4. $pp \to t\bar{t}b\bar{b}$	relevant for $t\bar{t}H$
5. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$
6. $pp \to VVb\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
7. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$
8. $pp \to V$+3jets	VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [10–12] various new physics signatures
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	Higgs and new physics signatures
Calculations beyond NLO added in 2007	
10. $gg \to W^*W^*$ $\mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
11. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
12. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
13. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

private codes only

leading color

What about time lag in going from availability of matrix elements to having a parton level Monte Carlo available? See e.g. H + 2 jets. Other processes are going to be just as complex. What about other processes for which we are theorist/time-limited? What about codes *too complex* for non-experts to run/only private codes?See CTEQ4LHC

Pushing the envelope: 7-point amplitudes

- W + 3 jets to NLO
  - (some parts to leading color)
  - arXiv:0902.2760

C. F. Berger[a], Z. Bern[b], L. J. Dixon[c], F. Febres Cordero[b], D. Forde[c], T. Gleisberg[c], H. Ita[b], D. A. Kosower[d] and D. Maître[e]

  - more than 1000 Feynman diagrams
  - LO varies by factor of 2

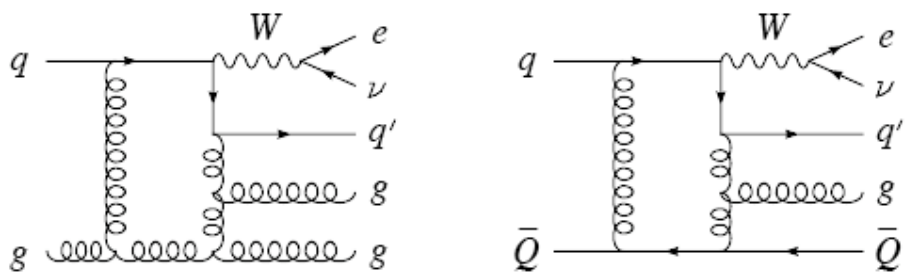
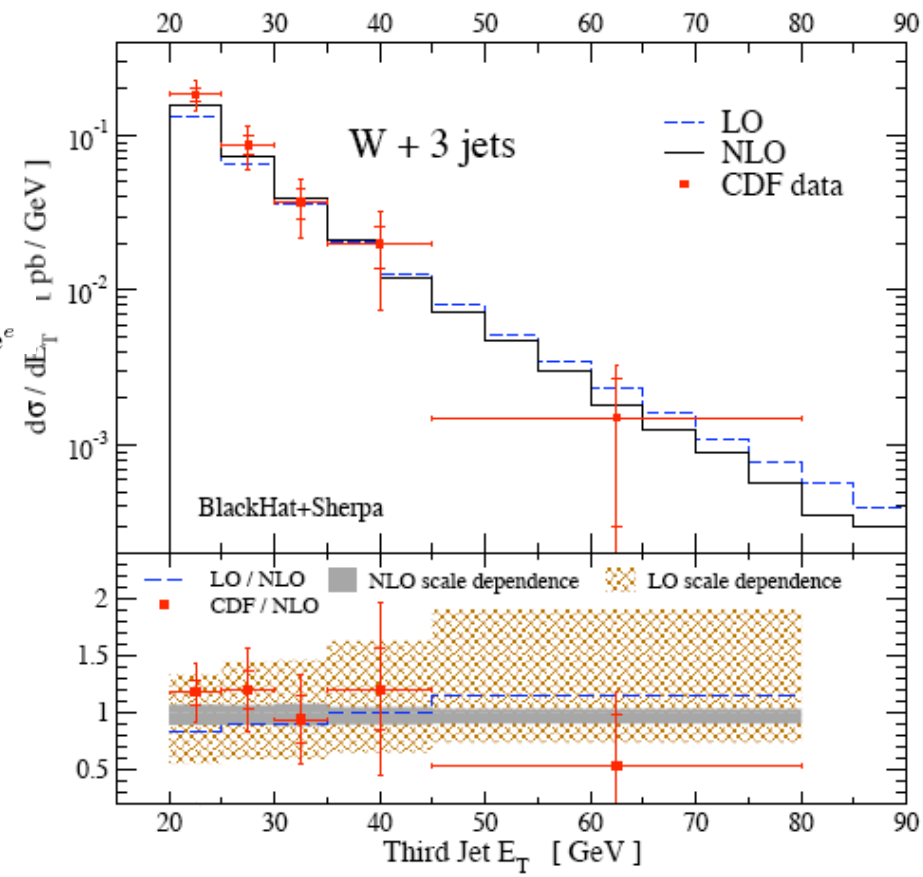


FIG. 1: Sample diagrams for the seven-point amplitudes $qg \to e\nu\, q'gg$ and $q\bar{Q} \to e\nu\, q'g\bar{Q}$. The $e\nu$ pair couples to the quarks via a W boson.



need closer look at the Tevatron with higher statistics than went into this analysis

Go back to 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->gg
  - *K*(gg->tT) > *K*(qQ -> tT)
- 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?

Table 1. 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. Jets satisfy the requirements $p_T > 15$ GeV and $|\eta| < 2.5$ (5.0) at the Tevatron (LHC). In the $W + 2$ jet process the jets are separated by $\Delta R > 0.52$, whilst the weak boson fusion (WBF) calculations are performed for a Higgs of mass 120 GeV.

	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
$W + 1$ jet	m_W	$\langle p_T^{\rm jet}\rangle$	1.42	1.20	1.43	1.21	1.32	1.42
$W + 2$ jets	m_W	$\langle p_T^{\rm jet}\rangle$	1.16	0.91	1.29	0.89	0.88	1.10
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.48
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51
Higgs via WBF	m_H	$\langle p_T^{\rm jet}\rangle$	1.07	0.97	1.07	1.23	1.34	1.09

Casimir for biggest color representation final state can be in

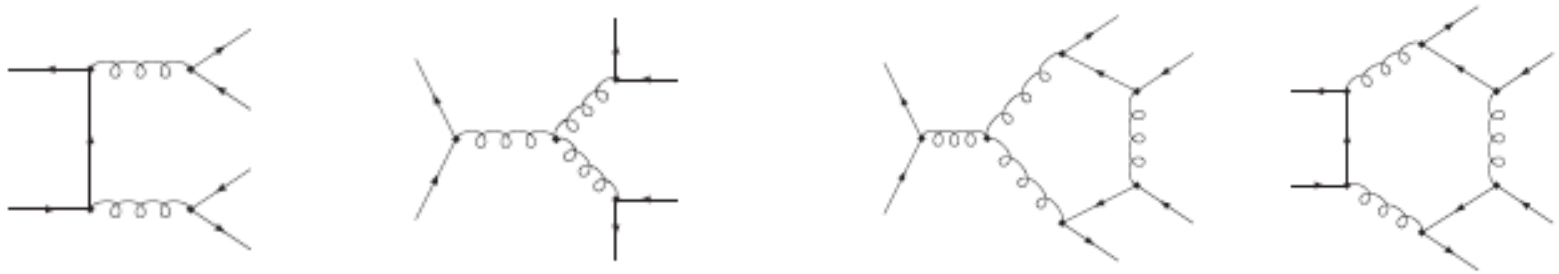
Simplistic rule

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

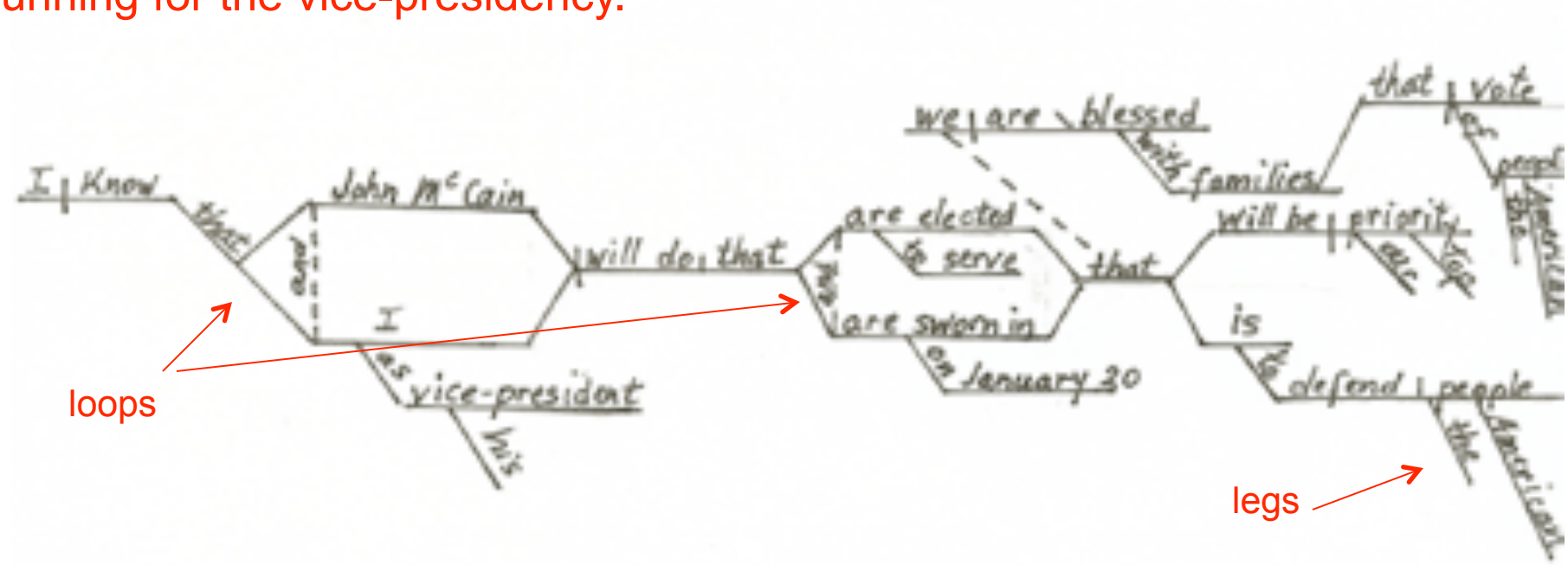
Casimir color factors for initial state

Difficult calculations

I know that the multi-loop and multi-leg calculations are very difficult



but just compare them to the complexity of the sentences that Sarah Palin when running for the vice-presidency.



Don't forget

- NNLO: we need to know some processes (such as inclusive jet production) at NNLO
  - technology is at point where NNLO pdf's are really NNLO (but would like NNLO jet production)
- Resummation effects: affect important physics signatures
  - mostly taken into account if NLO calculations can be linked with parton showering Monte Carlos

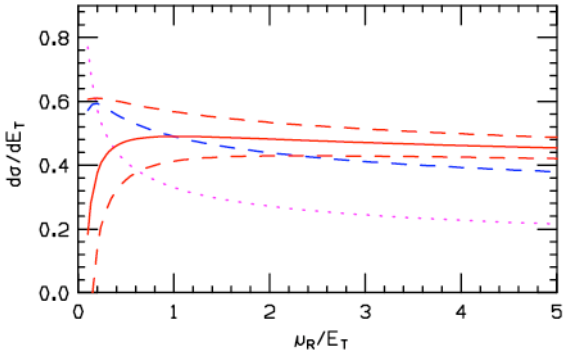


Figure 16. The single jet inclusive distribution at $E_T = 100\,\text{GeV}$, appropriate for Run I of the Tevatron. Theoretical predictions are shown at LO (dotted magenta), NLO (dashed blue) and NNLO (red). Since the full NNLO calculation is not complete, three plausible possibilities are shown.

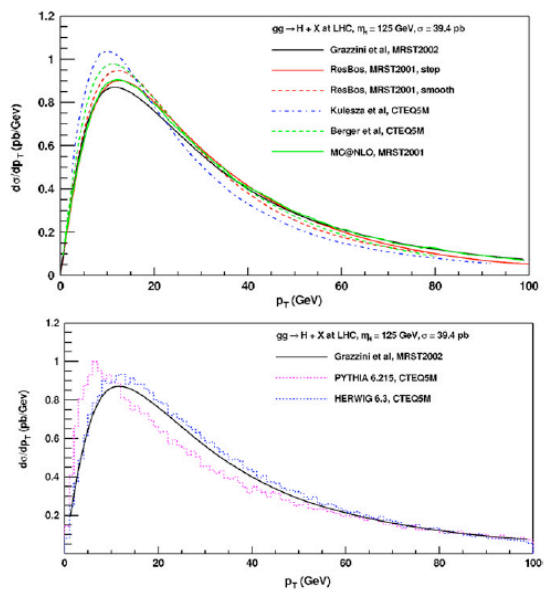


Figure 102. The predictions for the transverse momentum distribution for a 125 GeV mass Higgs boson at the LHC from a number of theoretical predictions. The predictions have all been normalized to the same cross section for shape comparisons. This figure can also be viewed in colour on the benchmark website.

…and

- BFKL logs: will we finally see them at the LHC?

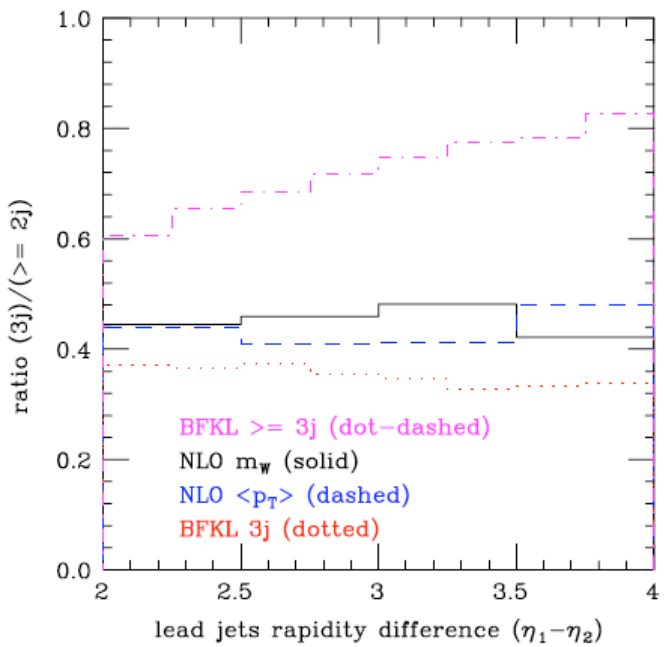


Figure 92. The rate for production of a third (or more) jet in $W+\geqslant 2$ jet events as a function of the rapidity separation of the two leading jets. A cut of 20 GeV has been placed on all jets. Predictions are shown from MCFM using two values for the renormalization and factorization scale, and using the BFKL formalism, requiring either that there be exactly 3 jets or 3 or more jets.

- EW logs: $a_W \log^2(p_T^2/m_W^2)$ can be a big number at the LHC

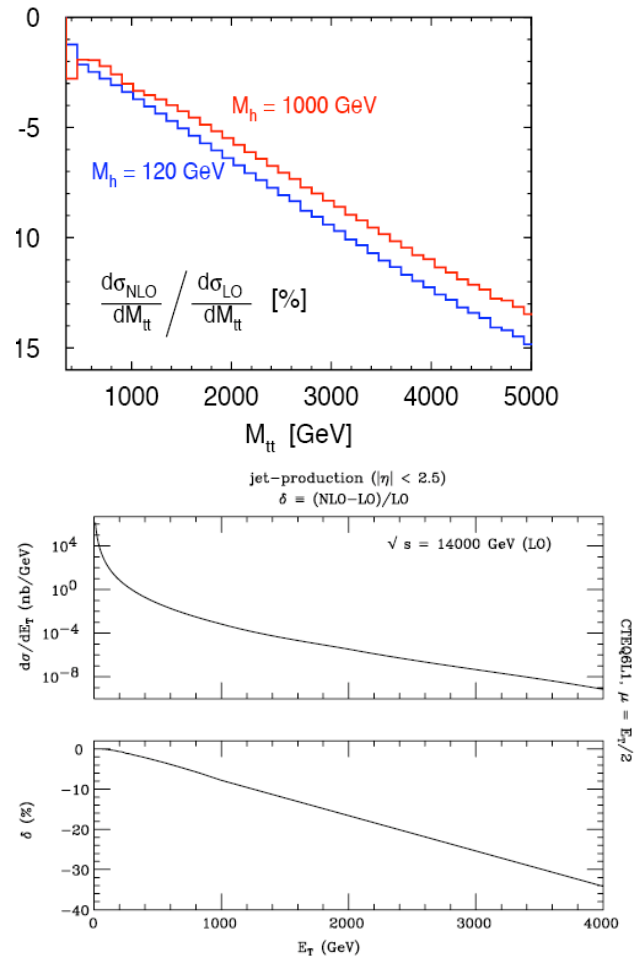
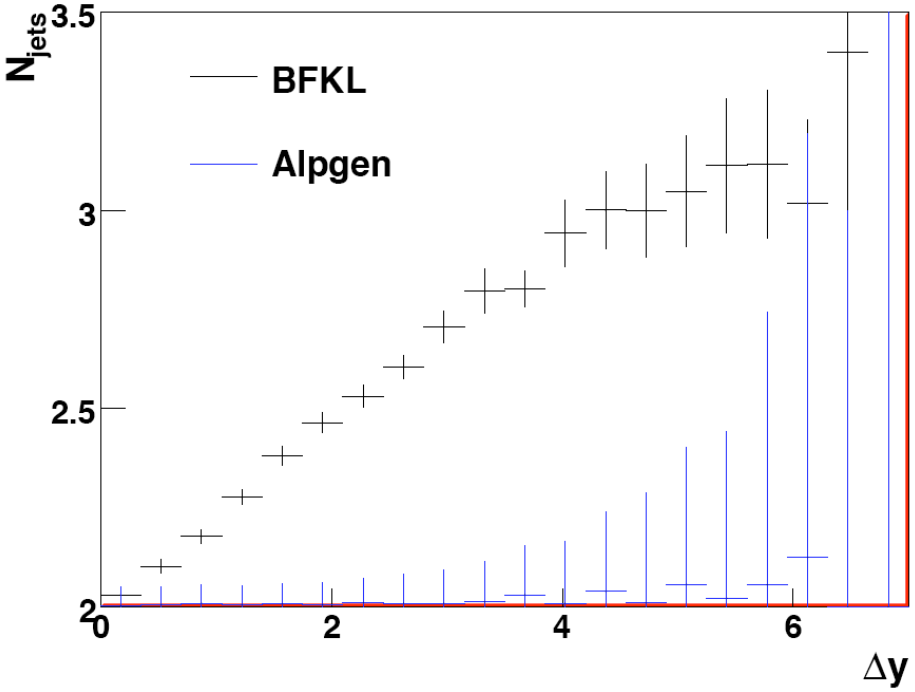


Figure 107. The effect of electroweak logarithms on jet cross sections at the LHC.

BFKL study: W + jets at the LHC

- Look at W + >= 2 jets at the LHC (40 GeV/c cut); find the largest rapidity difference between any two jets satistifying cuts
- Calculate the average jet multiplicity in the event using a (B)FKL formalism (Jeppe Andersen) and using ALPGEN(+ HERWIG)
- Basically linear increase observed in (B)FKL formalism… not present in ALPGEN +HERWIG (where ALPGEN = W + 2 partons)
  - parton shower can't produce hard radiation at the level expected (by BFKL)
- But wait…there's more

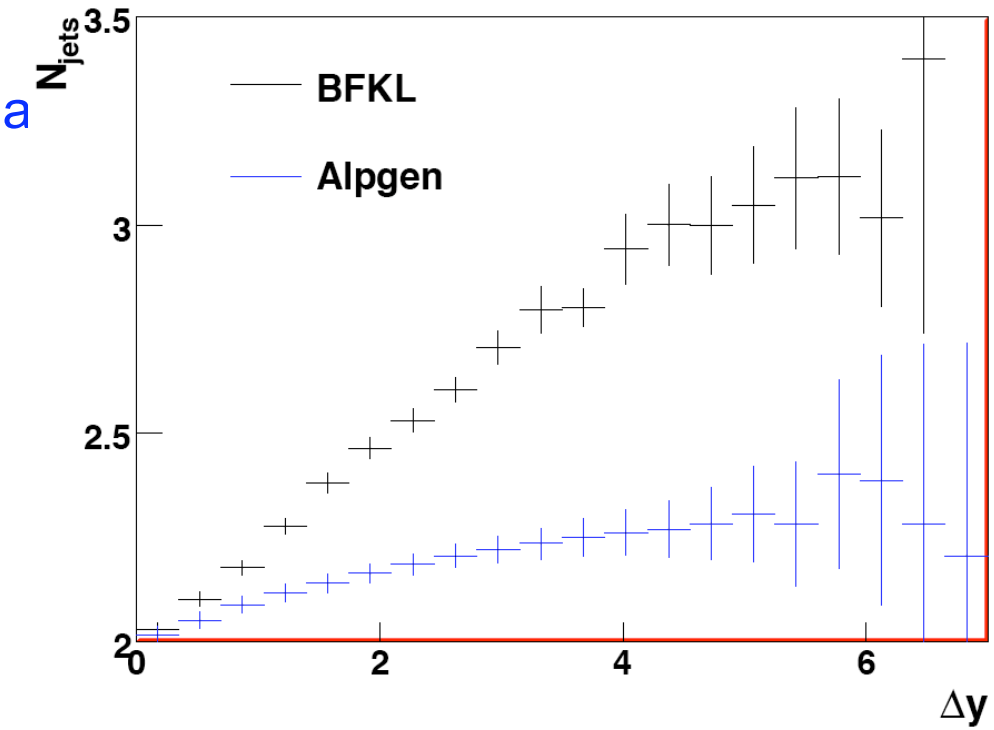
- Paper in preparation with Jeppe Andersen, Mario Campanelli, John Campbell and Rasmus Mackeprang



W + jets at the LHC

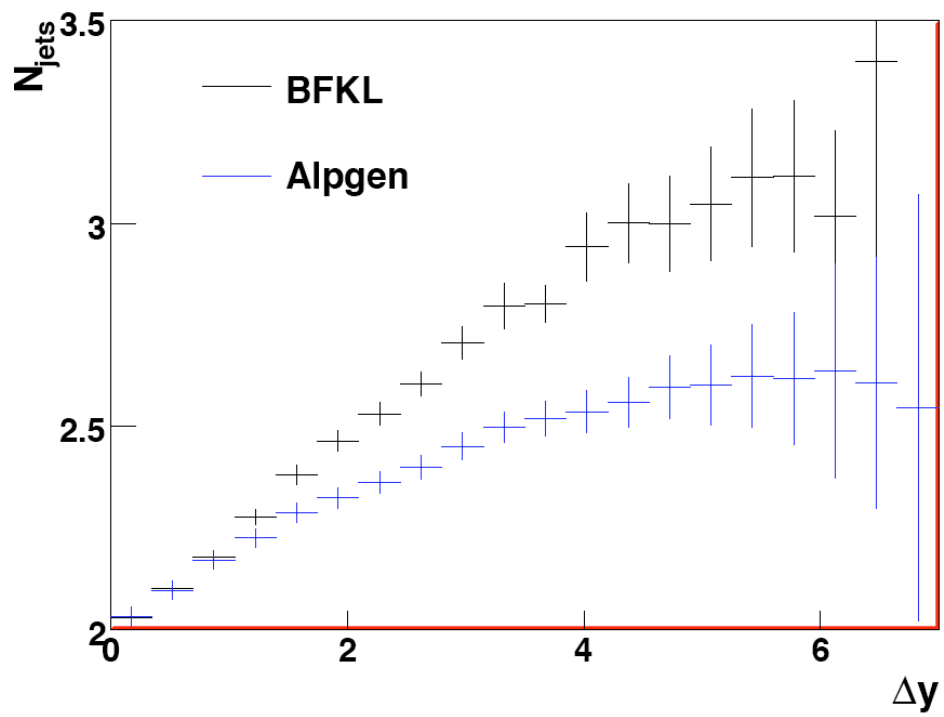
- Look at W + >= 2 jets at the LHC (40 GeV/c cut); find the largest rapidity difference between any two jets satistifying cuts
- Calculate the average jet multiplicity in the event using a (B)FKL formalism (Jeppe Andersen) and using ALPGEN(+ HERWIG)

- ALPGEN (=W + 2,3 partons) + HERWIG (mlm matching)



W + jets at the LHC

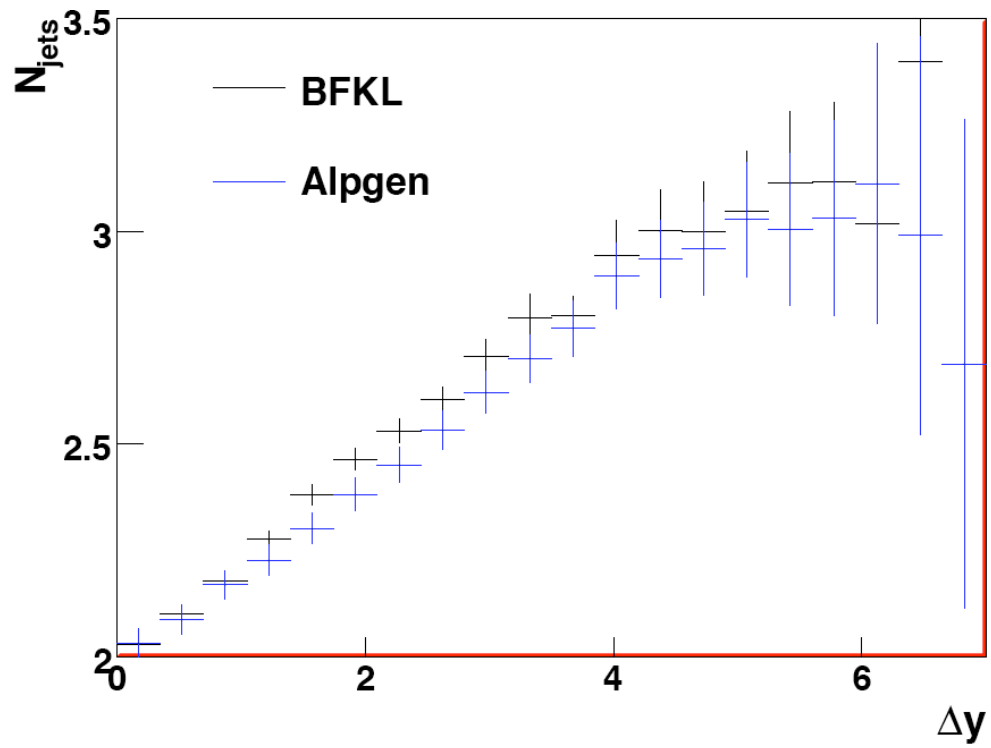
- Look at W + >= 2 jets at the LHC (40 GeV/c cut); find the largest rapidity difference between any two jets satistifying cuts
- Calculate the average jet multiplicity in the event using a (B)FKL formalism (Jeppe Andersen) and using ALPGEN(+ HERWIG)
- ALPGEN (=W + 2,3,4 partons)+HERWIG (mlm matching)



W + jets at the LHC

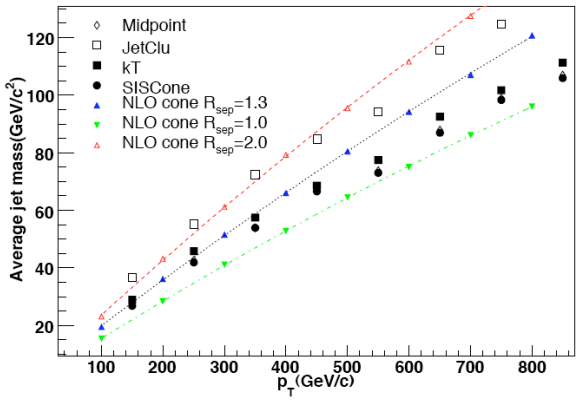
- Look at W + >= 2 jets at the LHC (40 GeV/c cut)
- Look at the average jet multiplicity using a (B)FKL formalism (Jeppe Andersen) and using ALPGEN(+ HERWIG)
- As we add more hard partons to ALPGEN, the result becomes closer to the (B)FKL prediction
- The behavior shown here should be universal for all multi-jet final states and is important to understand for/ during the early LHC data in order to understand VBF Higgs/new physics
- NLO knows about the first power of the (logarithmically) large corrections, both in the real and virtual pieces
- We are carrying out studies with W + jets (comparing to NLO W+2,3 jets) and for Higgs + jets (comparing to NLO Higgs + 2 jets and WBF Higgs) in preparation for 10 TeV data

- ALPGEN (=W + 2,3,4,5 partons)+HERWIG (mlm matching)



One slide about jets: jet masses

- It's often useful to examine jet masses, especially if the jet might be some composite object, say a W/Z or even a top quark



- For 2 TeV jets (J8 sample), peak mass (from dynamical sources) is on order of 125 GeV/c^2, but with long tail
  - Sudakov suppression for low jet masses
  - fall-off as 1/m^2 due to hard gluon emission
  - algorithm suppression at high masses
    - jet algorithms tend to split high mass jets in two

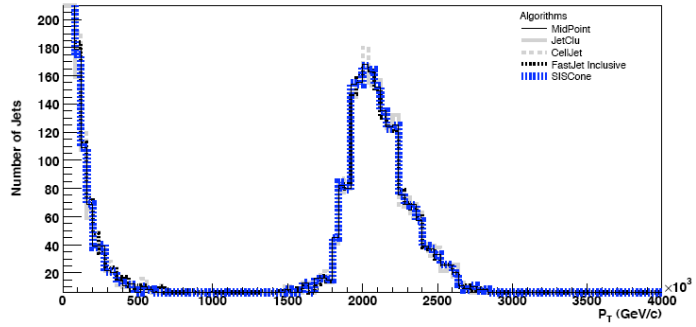


Figure 50: The inclusive jet cross section for the LHC with a $p_{T,min}$ value for the hard scattering of approximately 2 TeV/c, using several different jet algorithms with a distance scale ($D = R_{cone}$) of 0.7. The first bin has been suppressed.

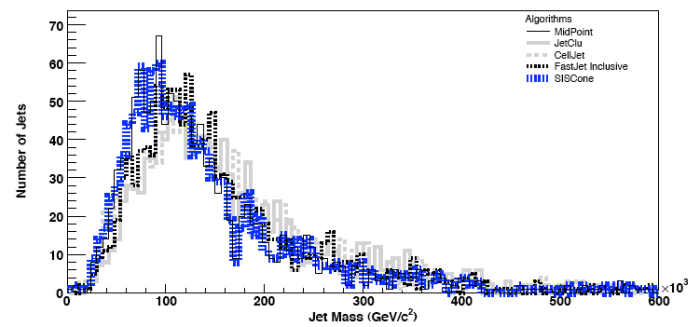


Figure 51: The jet mass distributions for an inclusive jet sample generated for the LHC with a $p_{T,min}$ value for the hard scattering of approximately 2 TeV/c, using several different jet algorithms with a distance scale ($D = R_{cone}$) of 0.7. The first bin has been suppressed.

From jet review paper

CTEQ4LHC/FROOT

- Collate/create cross section predictions for LHC
  - processes such as W/Z/ Higgs(both SM and BSM)/ diboson/tT/single top/photons/ jets…
  - at LO, NLO, NNLO (where available)
    - new: W/Z production to NNLO QCD and NLO EW
  - pdf uncertainty, scale uncertainty, correlations
  - impacts of resummation (q_T and threshold)
- As prelude towards comparison with actual data
- Using programs such as:
  - MCFM
  - ResBos
  - Pythia/Herwig/Sherpa
  - … private codes with CTEQ
- First on webpage and later as a report

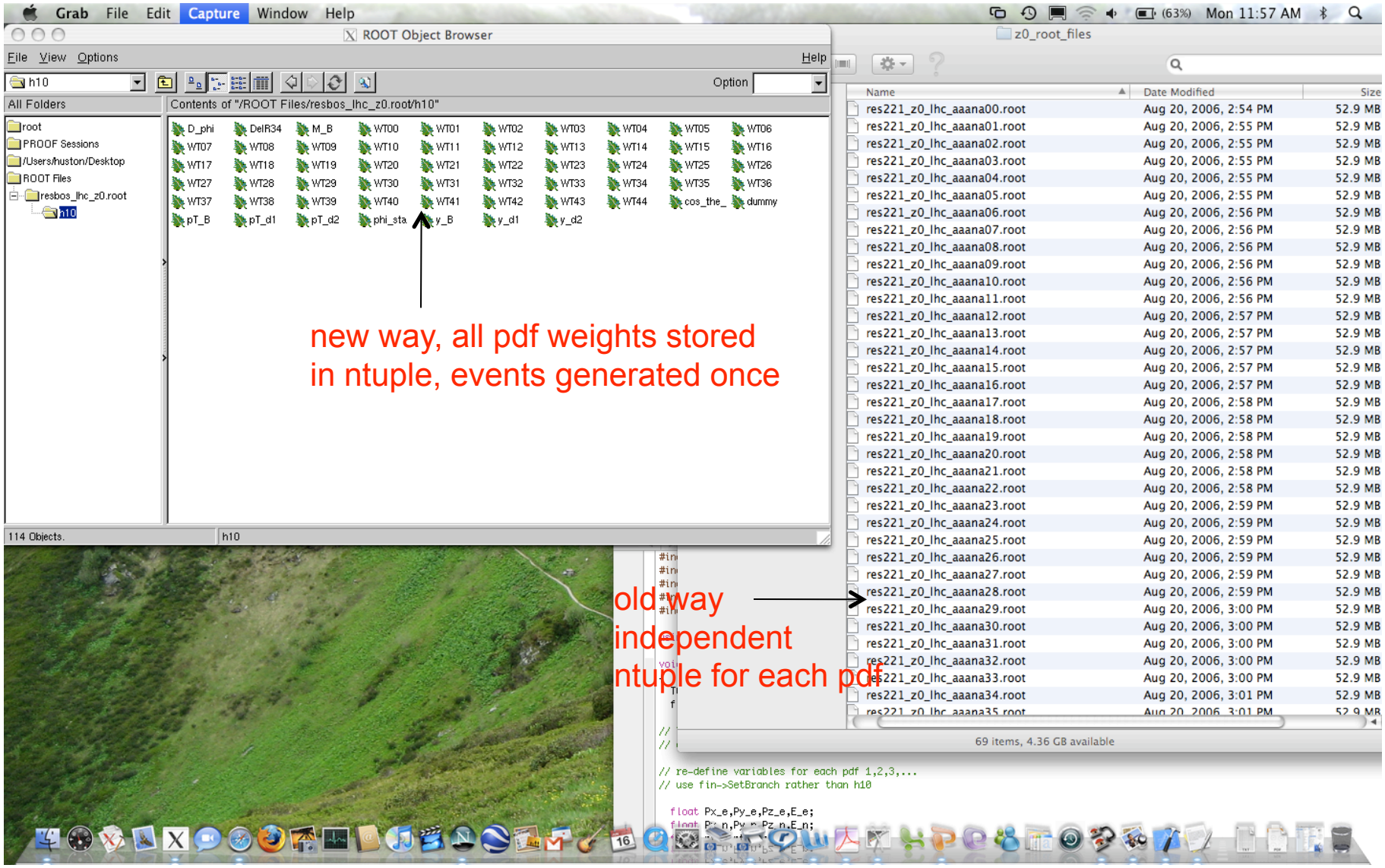
Primary goal: have all theorists (**including you**) write out parton level output into ROOT ntuples; you don't even have to learn ROOT
Secondary goal: make libraries of prediction ntuples available

- FROOT: a simple interface for writing Monte-Carlo events into a ROOT ntuple file
- Written by Pavel Nadolsky (nadolsky@physics.smu.edu)

- CONTENTS
- ========
- froot.c -- the C file with FROOT functions
- taste_froot.f -- a sample Fortran program writing 3 events into a ROOT ntuple
- taste_froot0.c -- an alternative top-level C wrapper (see the compilation notes below)
- Makefile

PDF Uncertainties and FROOT

Z production in ResBos



On the experimental side

For the maximal exploitation of physics, there are also requirements on the experimental side. We suggest that cross sections at the LHC should be quoted at the hadron level, and where possible with the estimated parton-to-hadron corrections, so that any theoretical prediction (parton or hadron level) can easily be compared after the fact to the archived data [16]. Also, the experimental data needs to be quoted only for the range of measurement, rather than extrapolated to the full cross section; for example, measurements of $W \to e\nu$ should be quoted for the range of electron transverse momentum and rapidity and of missing transverse energy actually used in the triggering and analysis, rather than performing an extrapolation to the full W cross sections. Such recommendations were the exception (CDF W+jets) rather than the rule at the Tevatron and a clear model needs to be set for the LHC.

[Les Houches NLO report '08]

Plus, experimentalists have to make more use of the theoretical information that is available, even if that information has not been incorporated into Pythia or Herwig, and is available only at the (weighted) parton level.

prototype webpage

http://www.pa.msu.edu/~huston/cteq4lhc/higgs/cteq4lhc_higgs.html

PDFs: CTEQ6.6, CTEQ6L1, CTEQ modified LO pdf's
Order of calculations: LO, NLO, NNLO, NNLO+NNLL
.
.
.

Total cross section predictions for the gg subprocess are shown in the table below, at NLO and LO, with scales of mHiggs and mHiggs/2 and with cteq6.6, cteq6l1 and modified LO pdf's. The relevant K-factor (NLO/LO is shown in parentheses next to the LO cross section. The calculations were performed with MCFM.

order	NLO	NLO	LO	LO	LO	LO	LO	LO
PDF	cteq6.6	cteq6.6	cteq6.6	cteq6.6	cteq6l1	cteq6l1	mod LO	mod LO
scale	mHiggs	mHiggs/2	mHiggs	mHiggs/2	mHiggs	mHiggs/2	mHiggs	mHiggs/2
sigma (fb) mHiggs=120 GeV	36340	42455	15830 (2.30)	18190 (2.43)				
sigma (fb) mHiggs=200 GeV	12815	15020	5865 (2.18)					
sigma (fb) mHiggs=300 GeV	5070	5955	2395 (2.12)	2925 (2.04)				
sigma (fb) mHiggs=400 GeV								

ROOT ntuples for each of the predictions above can be found below, along with a sample ROOT analysis script. Since the ntuples may be quite large, we'll have to find the best way of making them available.

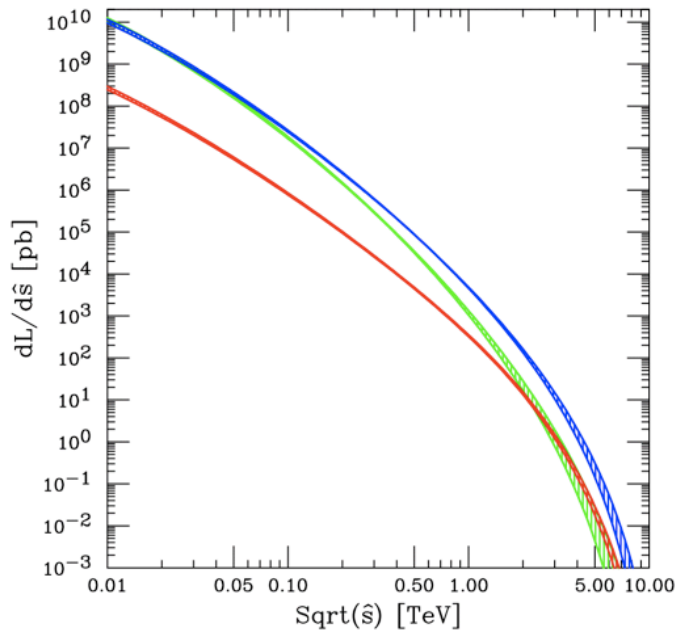
Next week I'll download these ntuples to CASTOR at CERN

order	NLO	NLO	LO	LO	LO	LO	LO	LO
PDF	cteq6.6	cteq6.6	cteq6.6	cteq6.6	cteq6l1	cteq6l1	mod LO	mod LO
scale	mHiggs	mHiggs/2	mHiggs	mHiggs/2	mHiggs	mHiggs/2	mHiggs	mHiggs/2
mHiggs=120 GeV	ntuple	ntuple	ntuple	ntuple	ntuple	ntuple	ntuple	ntuple
mHiggs=200 GeV	ntuple	ntuple	ntuple	ntuple	ntuple	ntuple	ntuple	ntuple
mHIggs=300 GeV	ntuple	ntuple	ntuple	ntuple	ntuple	ntuple	ntuple	ntuple
mHiggs=400 GeV	ntuple	ntuple	ntuple	ntuple	ntuple	ntuple	ntuple	ntuple

http://www.pa.msu.edu/~huston/cteq4lhc/higgs/cteq4lhc_higgs.html

Higgs physics on the back of an envelope

Estimating the cross sections and related quantities for Higgs production does not necessarily require running programs. Estimates accurate to within a few tens of percent should be possible with 'back-of-the-envelope' types of calculations. The pdf luminosity plots for the LHC are shown below. The gg luminosity is given by the blue curve. The LO cross section for Higgs production is shown below to the right.



$$\hat{\sigma}(gg \to H) = \frac{\pi}{\hat{s}} \delta\left(\hat{s} - m_H^{\ 2}\right) \left|M(gg \to H)\right|^2$$

$$\left|M(gg \to H)\right|^2 = \frac{\alpha_s^{\ 2}(m_H^{\ 2}) G_F M_H^{\ 4}}{288\sqrt{2}\pi^2} \left| I\left(\frac{m_t^{\ 2}}{m_H^{\ 2}}\right)\right|^2$$

$$\left|M(gg \to H)\right|^2 \sim (2.9E-9)\alpha_s^{\ 2}(m_H^{\ 2}) M_H^{\ 4} \left[1 + \frac{1}{4\left(\frac{m_t^{\ 2}}{m_H^{\ 2}}\right)}\right]^2$$

For low mass Higgs (say below 200 GeV), this can be approximated as:

$$\hat{\sigma}(gg \to H) = (1.4E-10) M_H (GeV)^2 [pb]$$

For example, for a Higgs mass of 120 GeV, the gg pdf luminosity is ~1E7pb. The Higgs sub-process cross section (at LO) at 120 GeV is 2E-06 pb, leading to a prediction for the Higgs cross section of 20 pb. The K-factor for Higgs production at

http://www.pa.msu.edu/~huston/cteq4lhc/higgs/cteq4lhc_higgs.html

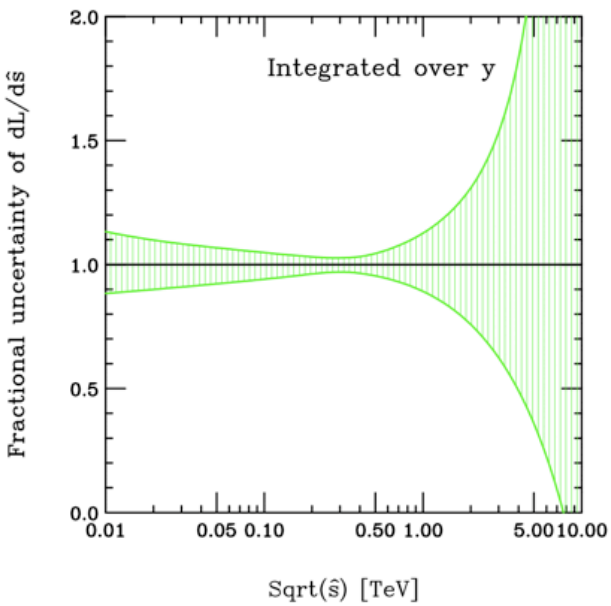
For example, for a Higgs mass of 120 GeV, the gg pdf luminosity is ~1E7pb. The Higgs sub-process cross section (at LO) at 120 GeV is 2E-06 pb, leading to a prediction for the Higgs cross section of 20 pb. The K-factor for Higgs production at the LHC can be read from the table below as 2.3 leading to a prediction at NLO as 46 pb, in agreement with the plot showon at the top of the page.

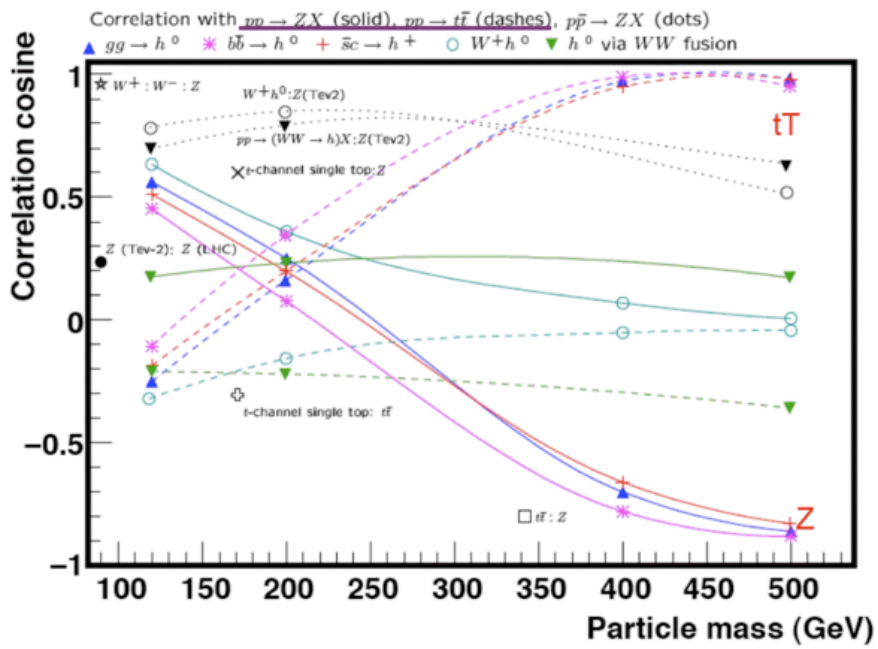
	Typical scales		Tevatron K-factor			LHC K-factor		
Process	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
W+1jet	m_W	$p_T^{\rm jet}$	1.42	1.20	1.43	1.21	1.32	1.42
W+2jets	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.

http://www.pa.msu.edu/~huston/cteq4lhc/higgs/cteq4lhc_higgs.html

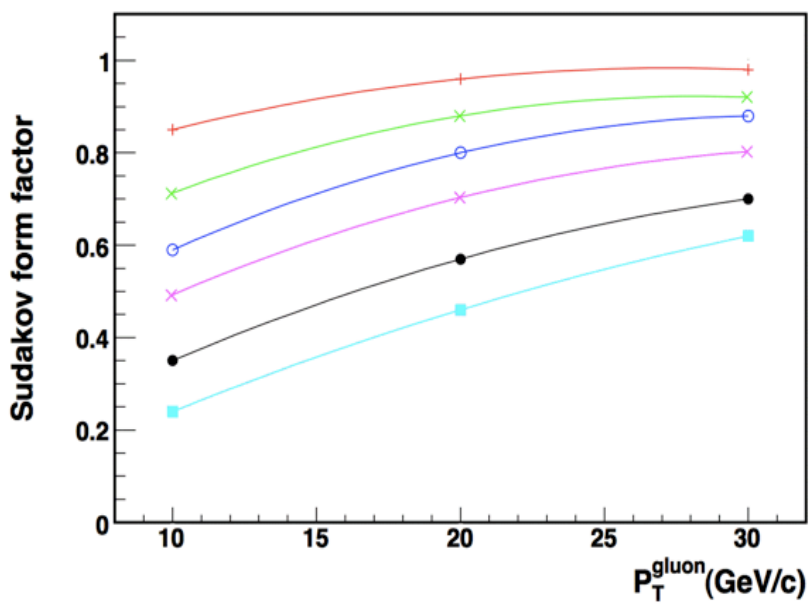
The pdf luminosity for Higgs production through gg production can be estimated from the figure below. For low mass Higgs production, the pdf uncertainty is less than 5%. The pdf correlations are shown on the lower right. Here we might also make available some pdf correlation tools.

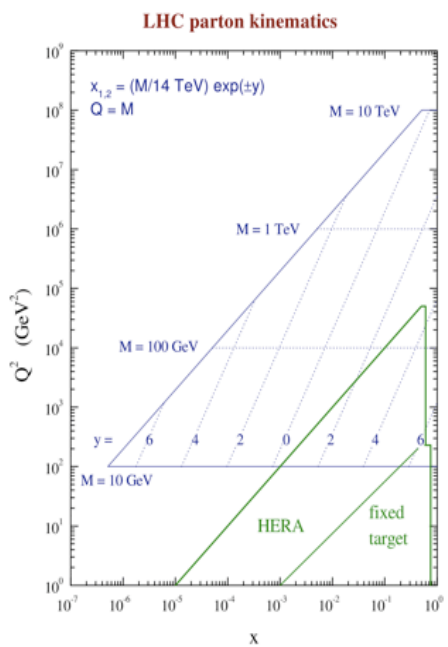




http://www.pa.msu.edu/~huston/cteq4lhc/higgs/cteq4lhc_higgs.html

The initial state Sudakov form factor for one of the gluons producing the Higgs can be read from the plot shown below. The Sudakov form factors (for Q=100 GeV) are for x values of (top to bottom) 0.3,0.1,0.03,0.01, 0.001,0.0001. Production of a low mass Higgs involves initial state gluons with x values on the order of 0.01 (the purple curve). The Sudakov form factor for emitted gluons on the order of 20 GeV is ~0.7, i.e. there is a probability of 0.3 of emitting such a gluon. The probability of neither initial state gluon emitting a gluon of 20 GeV or greater is 0.7*0.7, or ~0.5. Using Poisson statistics, the average jet multiplicity (for transverse momenta > 20 GeV) is 0.7.





Summary

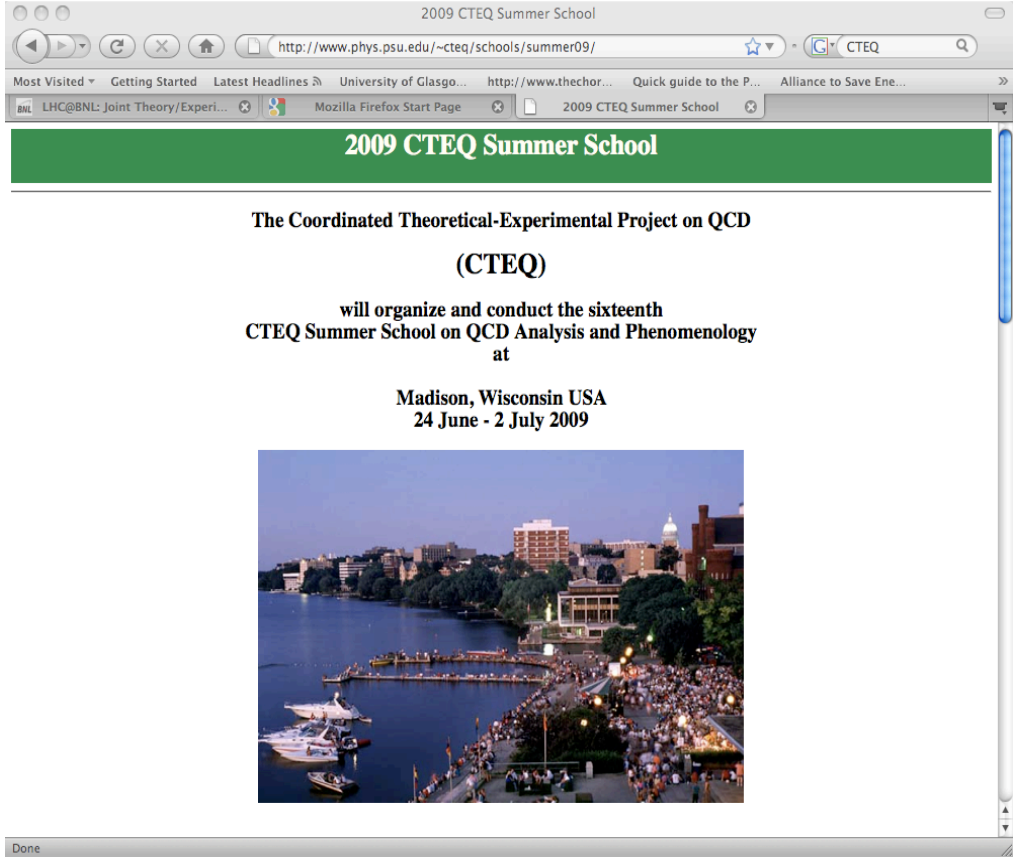
- Physics will come flying hot and heavy when LHC turns on in 2009
- Important to establish both the SM benchmarks and the tools we will need to properly understand this flood of data
- Having (only) 200 pb^{-1} of data at 10 TeV may be the best thing for us…understanding before discovery
- …but perhaps not the most exciting
- Much of the work discussed in this talk will continue at Les Houches
- June 8-26, 2009

- Plans for Les Houches
  - collecting results of completed higher order calculations
    - tables, plots and ntuples a la CTEQ4LHC
    - common format for storing parton level information in the ntuples
    - scale variations stored
  - special interest in higher order corrections of Higgs observables
  - missing processes for wishlist
  - standardization of NLO computations
    - minimal agreement on color and helicity management and on passing IR subtraction terms could lead to transportable modules for virtual corrections
  - new techniques for NLO computations
  - IR safe jet algorithms

http://www.lpthe.jussieu.fr/LesHouches09Wiki/index.php/Main_Page

Summary-2

- In the near future, CTEQ will also have
  - update to NLO pdf's
    - recent Tevatron data
  - modified LO pdf's
    - several types
  - combined (x and q_t) pdf fits
    - useful for precision measurements such as W mass
  - NNLO pdf's



Bonus feature

Now some technical stuff

- Consider a cross section X(a), a function of the Hessian eigenvectors
- i^{th} component of gradient of X is

$$\frac{\partial X}{\partial a_i} \equiv \partial_i X = \frac{1}{2}(X_i^{(+)} - X_i^{(-)})$$

- Now take 2 cross sections X and Y
  - or one or both can be pdf's
- Consider the projection of gradients of X and Y onto a circle of radius 1 in the plane of the gradients in the parton parameter space
- The circle maps onto an ellipse in the XY plane
- The angle f between the gradients of X and Y is given by

$$\cos\varphi = \frac{\vec{\nabla}X \cdot \vec{\nabla}Y}{\Delta X \Delta Y} = \frac{1}{4\Delta X\,\Delta Y}\sum_{i=1}^{N}\left(X_i^{(+)} - X_i^{(-)}\right)\left(Y_i^{(+)} - Y_i^{(-)}\right)$$

- The ellipse itself is given by

$$\left(\frac{\delta X}{\Delta X}\right)^2 + \left(\frac{\delta Y}{\Delta Y}\right)^2 - 2\left(\frac{\delta X}{\Delta X}\right)\left(\frac{\delta Y}{\Delta Y}\right)\cos\varphi = \sin^2\varphi$$

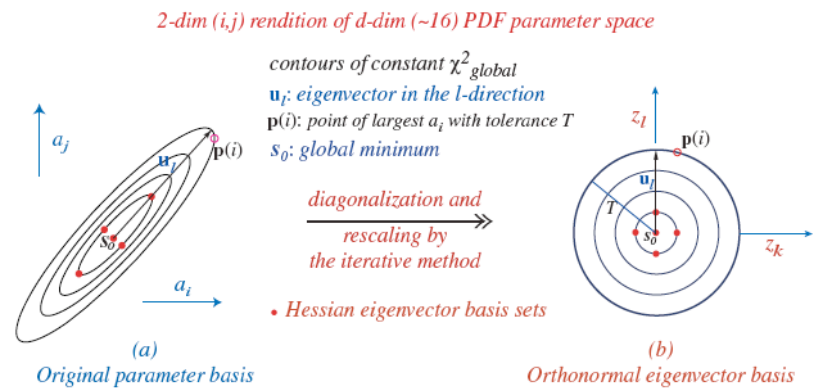


Figure 28. A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

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

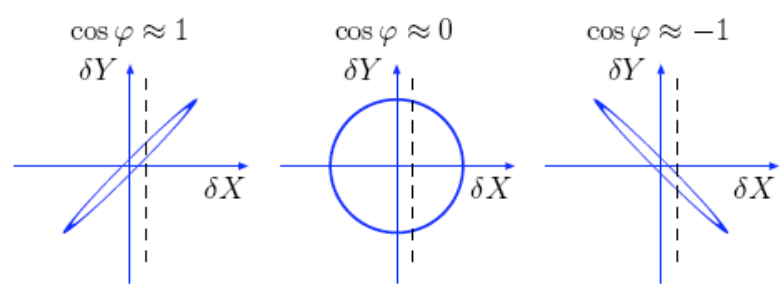


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

PDF's: correlations with Z, tT

Define a correlation cosine between two quantities

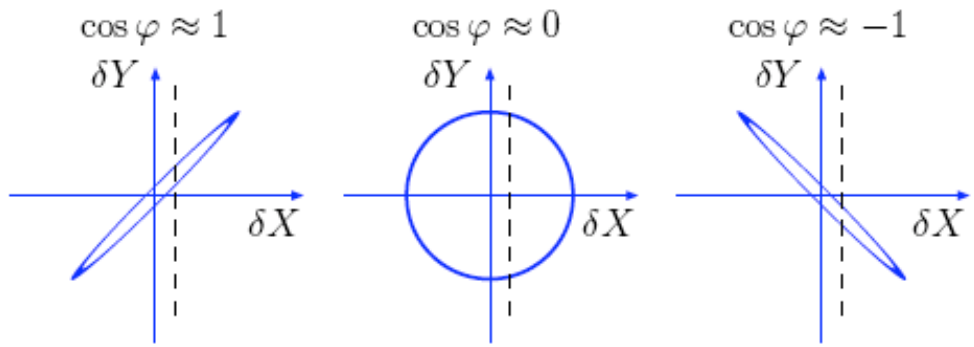


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

- If two cross sections are very correlated, then cosf~1
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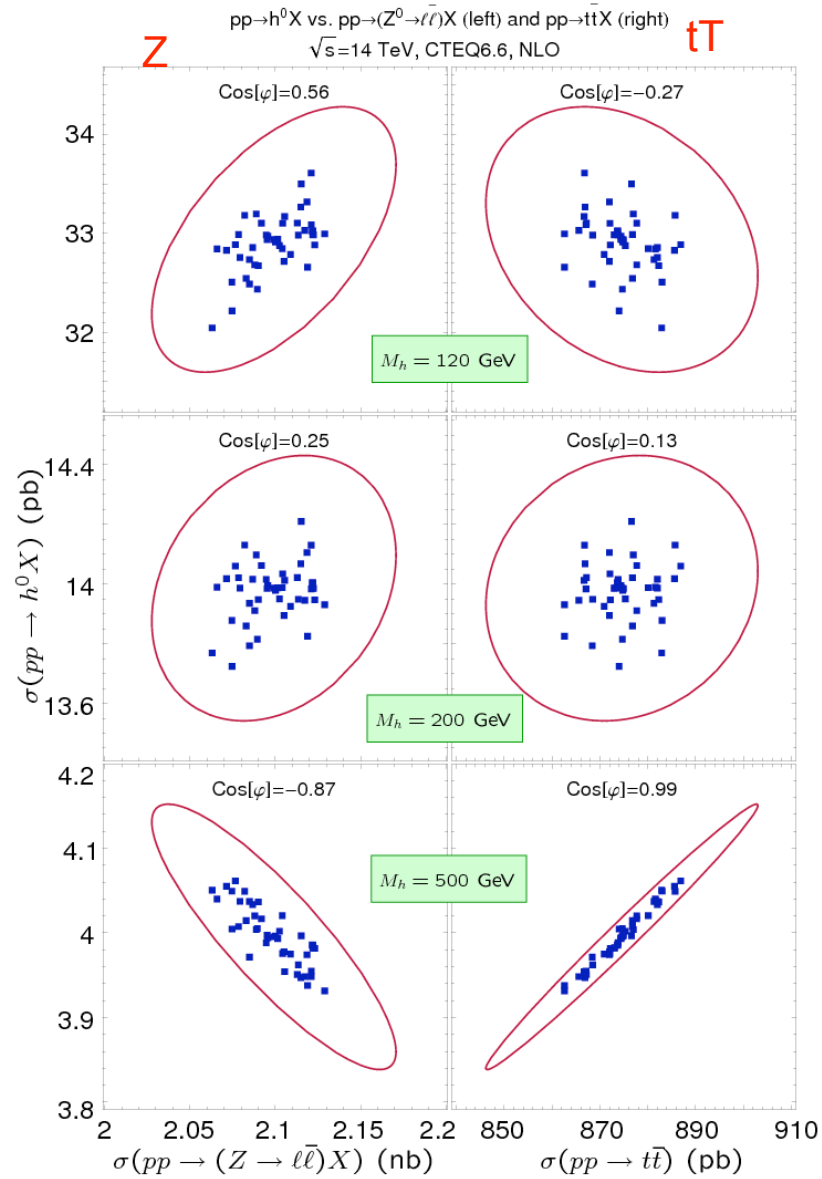


Correlations with Z, tT

Define a correlation cosine between two quantities

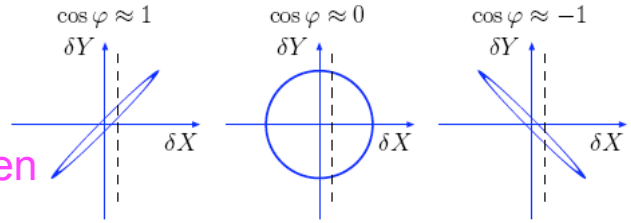
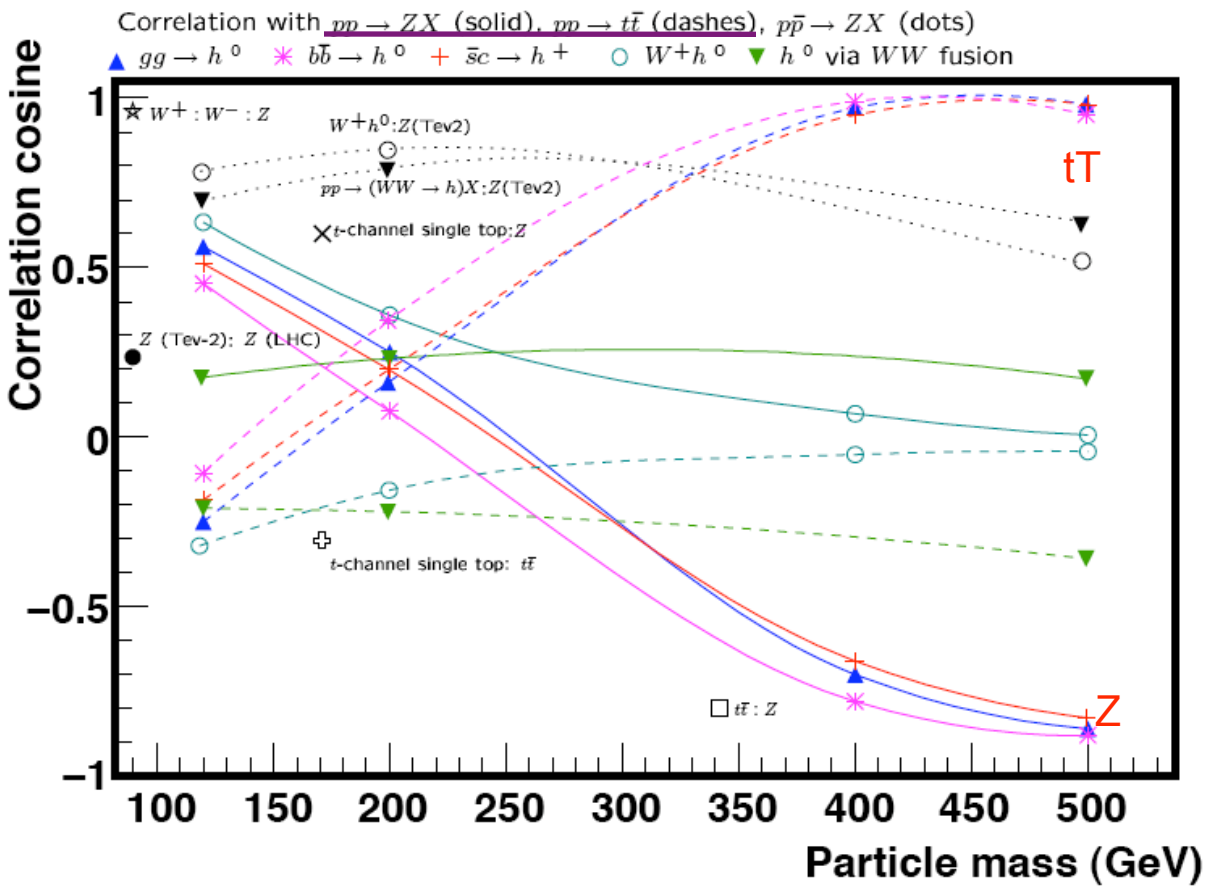


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.



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

- 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 f > 0;e.g. $D(s_{W^+}/s_Z)$~1%

- If cos f < 0, pdf uncertainty for one cross section normalized to a benchmark cross section is larger

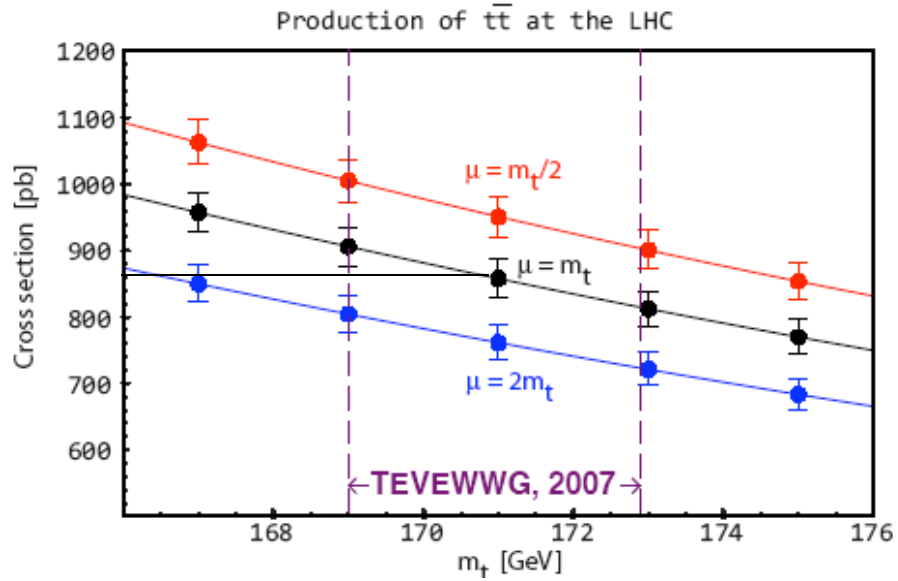
- So, for gg->H(500 GeV); pdf uncertainty is 4%; $D(s_H/s_Z)$~8%

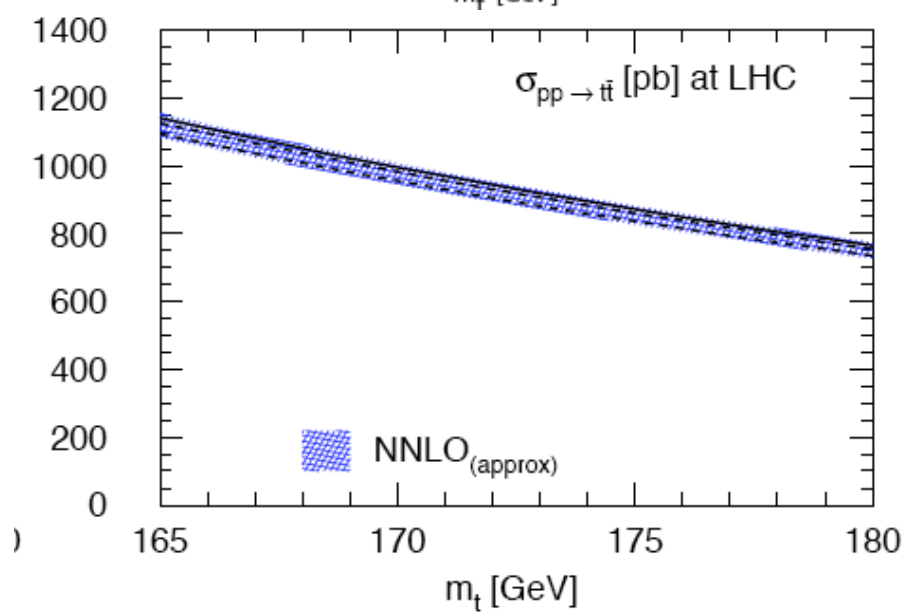
W/Z summary so far

- We will use W and Z cross sections as luminosity normalizations in early running and perhaps always
  - because integrated luminosity is not going to be known much better than 15-20% at first and maybe never better than 5-10%
- The pdf uncertainty for the ratio of a cross section that proceeds with a qQ initial state to the W/Z cross section is significantly reduced
- The pdf uncertainty for the ratio of a cross section that proceeds with a gg initial state to the W/Z cross section is significantly increased
- Would it be reasonable to use tT production as an additional normalization tool?
  - yeah, yeah I know it's difficult
  - see extra slides

Theory uncertainties for tT at LHC

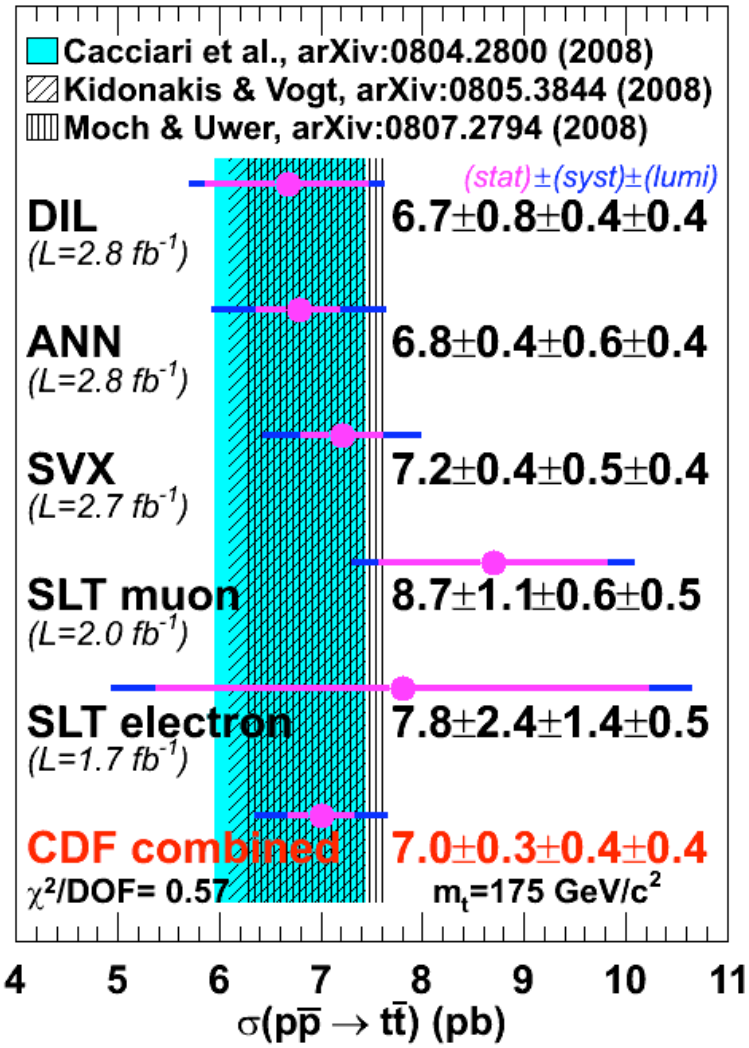
- Note that at NLO with CTEQ6.6 pdf's the central prediction for the tT cross section for $m=m_t$ is ~850 pb (not 800 pb, which it would be if the top mass were 175 GeV); ~880 pb if use effect of threshold resummation
- The scale dependence is around +/-11% and mass dependence is around +/-6%
- Tevatron plans to measure top mass to <1 GeV
  - mass dependence goes to ~+/-3%
- NNLO tT cross section will be finished in near future
  - scale dependence will drop
  - threshold resummation reduces scale dependence to ~3% (Moch and Uwer) but see recent results of Czakon and Mitov
- tT still in worse shape than W/Z, but not by too much
  - and pdf uncertainty is (a bit) smaller





What about experimental uncertainties?

- 10-15% in first year
  - unfortunately, which is where we would most like to have a precise value
- Ultimately, ~5%?
  - dominated by b-tagging uncertainty?
  - systematic errors in common with other complex final states, which may cancel in a ratio?
- Tevatron now does 8% (non-lum)



Back to LO: modified LO pdf's (LO*)

- What about pdf's for parton shower Monte Carlos?
  - standard has been to use LO pdf's, most commonly CTEQ5L/ CTEQ6L, in Pythia, Herwig, Sherpa, ALPGEN/Madgraph+…
- …but
  - LO pdf's can create LHC cross sections/acceptances that differ in both shape and normalization from NLO
    - due to influence of HERA data
    - and lack of ln(1/x) and ln(1-x) terms in leading order pdf's and evolution
  - …and are often outside NLO error bands
  - experimenters use the NLO error pdf's in combination with the central LO pdf even with this mis-match
    - causes an error in pdf re-weighting
  - predictions for inclusive observables from LO matrix elements for many of the collider processes that we want to calculate are not so different from those from NLO matrix elements (aside from a reasonably constant K-factor)

Modified LO pdf's (LO*)

- …but
  - we *like* the low x behavior of LO pdf's and rely upon them for our models of the underlying event at the Tevatron and its extrapolation to the LHC
  - as well as calculating low x cross sections at the LHC
- …and people didn't listen to me when I said to use NLO pdf's in MC's
- thus, the need for modified LO pdf's

CTEQ talking points

- LO* pdf's should behave as LO as x->0; as close to NLO as possible as x->1
- LO* pdf's should be universal, i.e. results should be reasonable run on any platform with nominal physics scales
- It should be possible to produce error pdf's with
  - similar Sudakov form factors
  - similar UE
  - so pdf re-weighting makes sense
- LO* pdf's should describe underlying event at Tevatron with a tune similar to CTEQ6L (for convenience) and extrapolate to a *reasonable* UE at the LHC

CTEQ techniques

- Include in LO* fit (weighted) pseudo-data for characteristic LHC processes produced using CTEQ6.6 NLO pdf's with NLO matrix elements (using MCFM), along with full CTEQ6.6 dataset (2885 points)
  - low mass bB
    - fix low x gluon for UE
  - tT over full mass range
    - higher x gluon
  - W^+,W^-,Z^0 rapidity distributions
    - quark distributions
  - gg->H (120 GeV) rapidity distribution

<u>Choices</u>

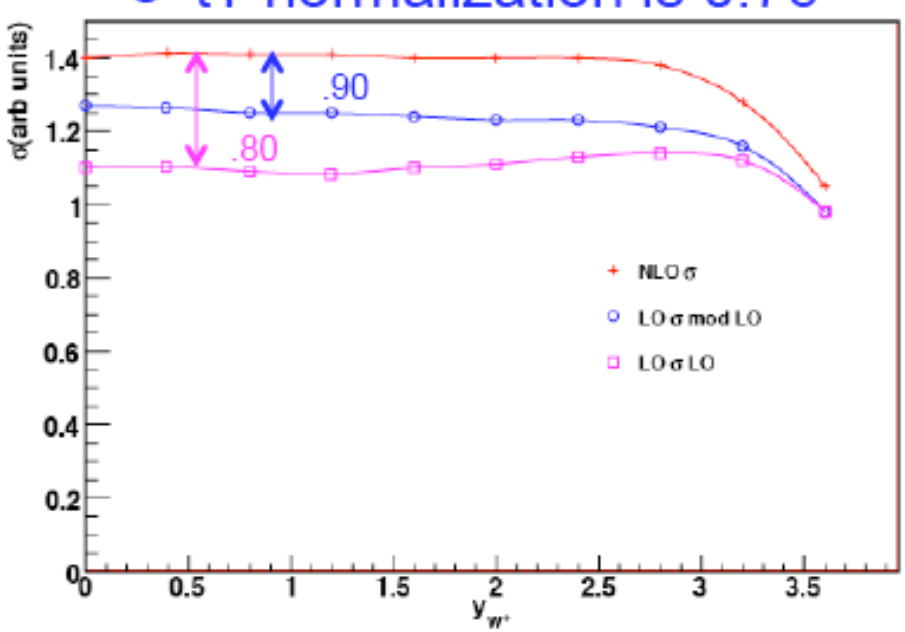
- Use of 2-loop or 1-loop a_s
  - Herwig preference for 2-loop
  - Pythia preference for 1-loop
- Fixed momentum sum rule, or not
  - re-arrange momentum within proton and/or add extra momentum
  - extra momentum appreciated by some of pseudo-data sets but not others and may lose some useful correlations
- Fix pseudo-data normalizations to K-factors expected from higher order corrections, or let float
- Scale variation within reasonable range for fine-tuning of agreement with pseudo-data
  - for example, let vector boson scale vary from 0.5 m_B to 2.0 m_B
- Will provide pdf's with several of these options for user

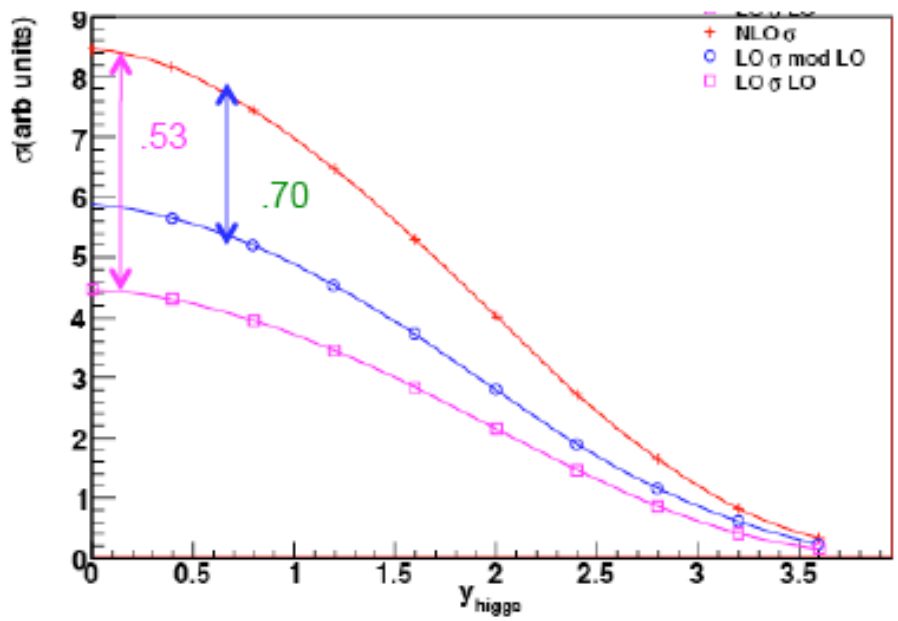
Some observations

- Pseudo-data has conflicts with global data set
  - that's the motivation of the modified pdf's
- Requiring better fit to pseudo-data increases chisquare of LO fit to global data set (although this is not the primary concern; the fit to the pseudo-data is)
  - c^2 improves with a_s free in fit
  - c^2 improves with momentum sum rule free
    - prefers more momentum, smaller a_s
    - normalization of pseudo-data (needed K-factor) gets closer to 1
    - still some conflicts with DIS data that don't prefer more momentum
  - c^2 typically improves if K-factors can vary from values given in previous slide

Some results

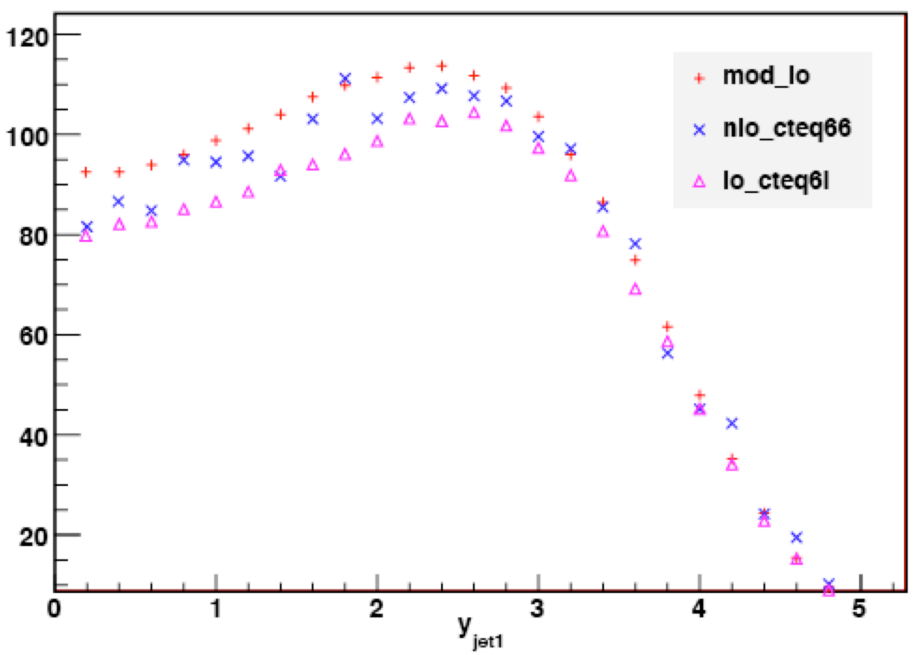
- Rapidity distributions for W^+ and Higgs from pure NLO, LO with LO pdf, LO with CTEQ modified LO pdf
- Momentum sum=1.06 for CTEQ modified LO pdf
  - why so much less than mod MSTW?
- $\alpha_s(m_Z)$=0.124 for CTEQ modified LO pdf
- tT normalization is 0.76

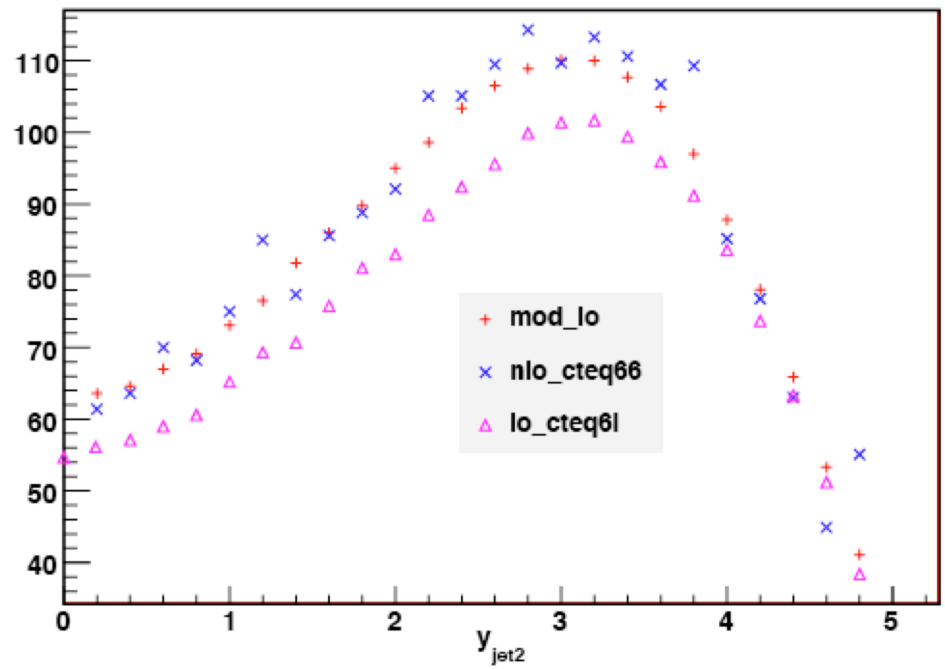




VBF Higgs

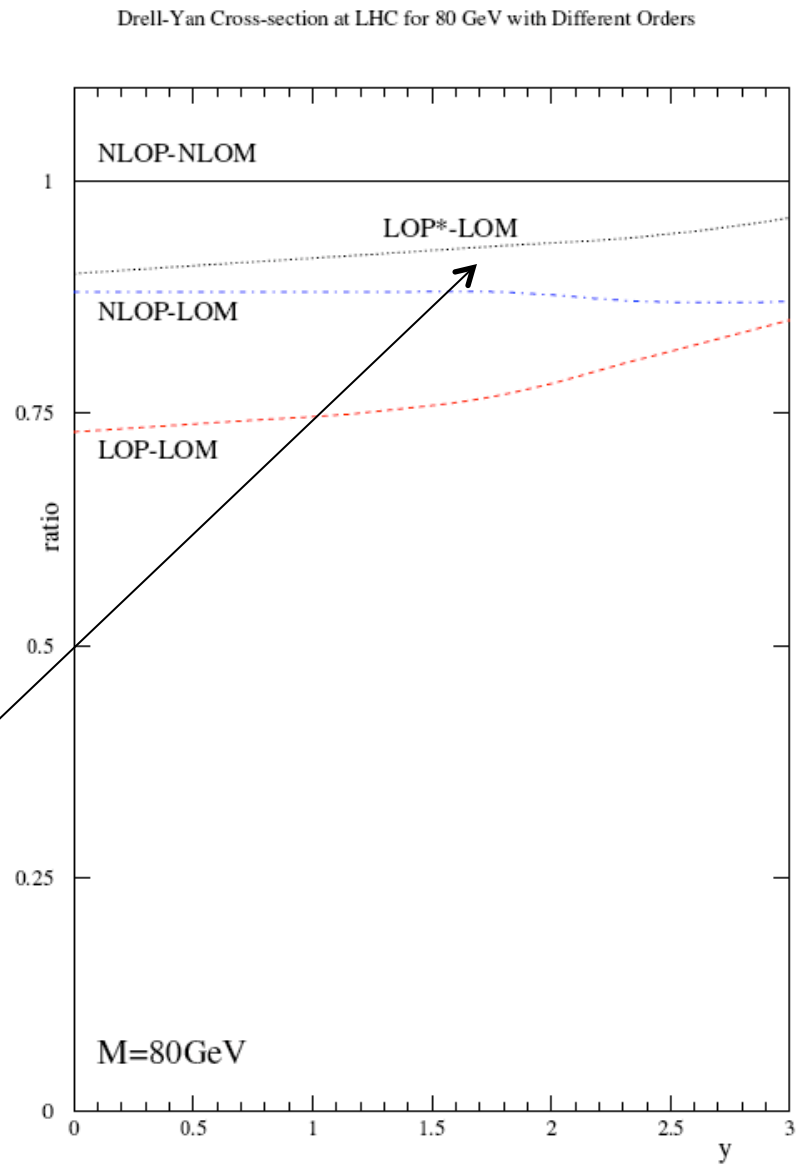
Below are the rapidity distributions for the two tagging jets in VBF production of a 120 GeV Higgs at the LHC. The modified LO pdf gives a better description of the shape of the jet rapidity distributions, especially for the 2nd jet. The NLO cross section using CTEQ6.6 is 4.1 pb. The LO cross section using CTEQ6L is 3.8 pb and using the modified LO pdf is 4.2 pb. These pseudo-data were not in the fit but are sensitive to the high x quark distributions.





MRSTLO*

- The MRST group has a modified LO pdf that tries to incorporate many of the points mentioned on the previous slides
- They relax the momentum sum rule (114%) and achieve a better agreement (than MRST LO pdf's) with some important LHC benchmark cross sections



SpartyJet

Sparty

J. Huston, K. Geerlings
Michigan State University

P-A. Delsart, LAPP

SpartyJet

What is SpartyJet?

- "a framework intended to allow for the easy use of multiple jet algorithms in collider analyses"
  - **Fast** to run, no need for heavy framework
  - **Easy** to use, basic operation is very simple
  - **Flexible**
    - ROOT-script or standalone execution
      - "on-the-fly" execution for event-by-event results
    - many different input types
    - different algorithms
    - output format

Available Algorithms

CDF - JetClu

- MidPoint (with optional second pass)

D0 - D0RunIICone

(from Lars Sonnenschein)

ATLAS - Cone

- FastKt

FastJet (from Gavin Salam and Matteo Cacciari)

- FastKt

- Seedless Infrared Safe Cone (SISCone)

Pythia 8 - CellJet

all algorithms are fully parameterizable

JetBuilder

- basically a frontend to handle most of the details of running SpartyJet
- not necessary, but makes running SpartyJet **much** simpler
- Allows options that are not otherwise accessible
  - text output
  - add minimum bias events

with JetBuilder

```
gSystem->Load("libTree.so") ;
gSystem->Load("libs/libJetCore.so");
gSystem->Load("libs/libCDFJet.so");

StdTextInput textinput("data/J1_Clusters.dat");

JetBuilder builder;
builder.configure_input((InputMaker*)&textinput);

builder.add_default_alg( new cdf::JetClustFinder("myJetClu"));
builder.set_default_cut(0,1*textinput.getGeV);

builder.configure_output
("SpartyJet_Tree","data/output/simple.root");
builder.process_events(10);
```

without JetBuilder

```
TFile f("/home/delsart/SpartyJet_v0a/libSISCone/example/data/small.root");
TTree * tree = (TTree*) f.Get("CollectionTree");

atlas::CBNTInput input;
input.init(tree);

JetAlgorithm * alg = new JetAlgorithm("MidPointJets");

JetPtSelectorTool *selec = new JetPtSelectorTool(1*GeV);
MidPoint * midpoint = new MidPoint("TOTO");

alg->addTool((JetTool*)midpoint);
alg->addTool((JetTool*)selec);

alg->init();

NtupleMaker ntg;
ntg.addJetVar("MidPointJets");
ntg.init("JetTree","out.root");

Jet::jet_list_t injets;
Jet::jet_list_t outjets;

input->fillInput(2,injets);
alg->execute(injets, outjets);

ntg.set_data("MidPointJets", outjets);
ntg.fillJets() ;

clear_jetlist(injets);
clear_jetlist(outjets);

 input->fillInput(5,injets);
alg->execute(injets, outjets);

ntg.set_data("MidPointJets", outjets);
ntg.fillJets() ;

ntg.finalize();
```

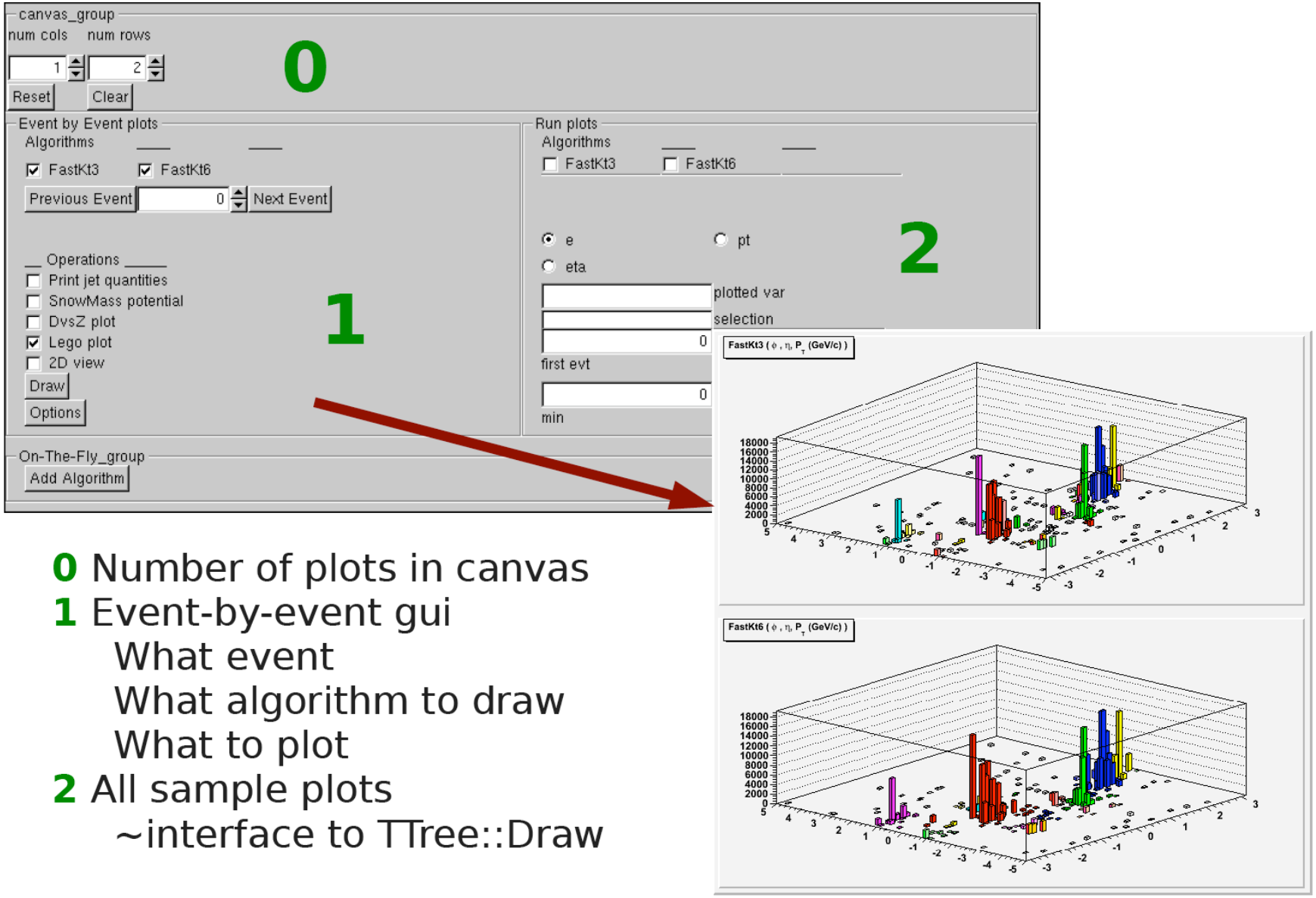
"on-the-fly" method

- no input data file, no output data file
- from other C++ programs, call a variant of jets = SpartyJet::getjets(JetTool*,data)
- Currently supported data types:

```
Jet::jet_list_t&                        SpartyJet::getjets( JetTool* tool
                                                            Jet::jet_list_t& inputJets);

std::vector<TLorentzVector>&            SpartyJet::getjets( JetTool* tool
                                                            std::vector<TLorentzVector>& input);

std::vector<TLorentzVector>&            SpartyJet::getjets( JetTool* tool
                                                            std::vector<TLorentzVector>& input,
                                                            std::vector<std::vector<int> >& constituents);

std::vector<SpartyJet::simplejet>       SpartyJet::getjets( JetTool* tool
                                                            std::vector<simplejet>& input);
```

reconstruct individual jets with new parameters in context of analysis

Gui interface



0 Number of plots in canvas

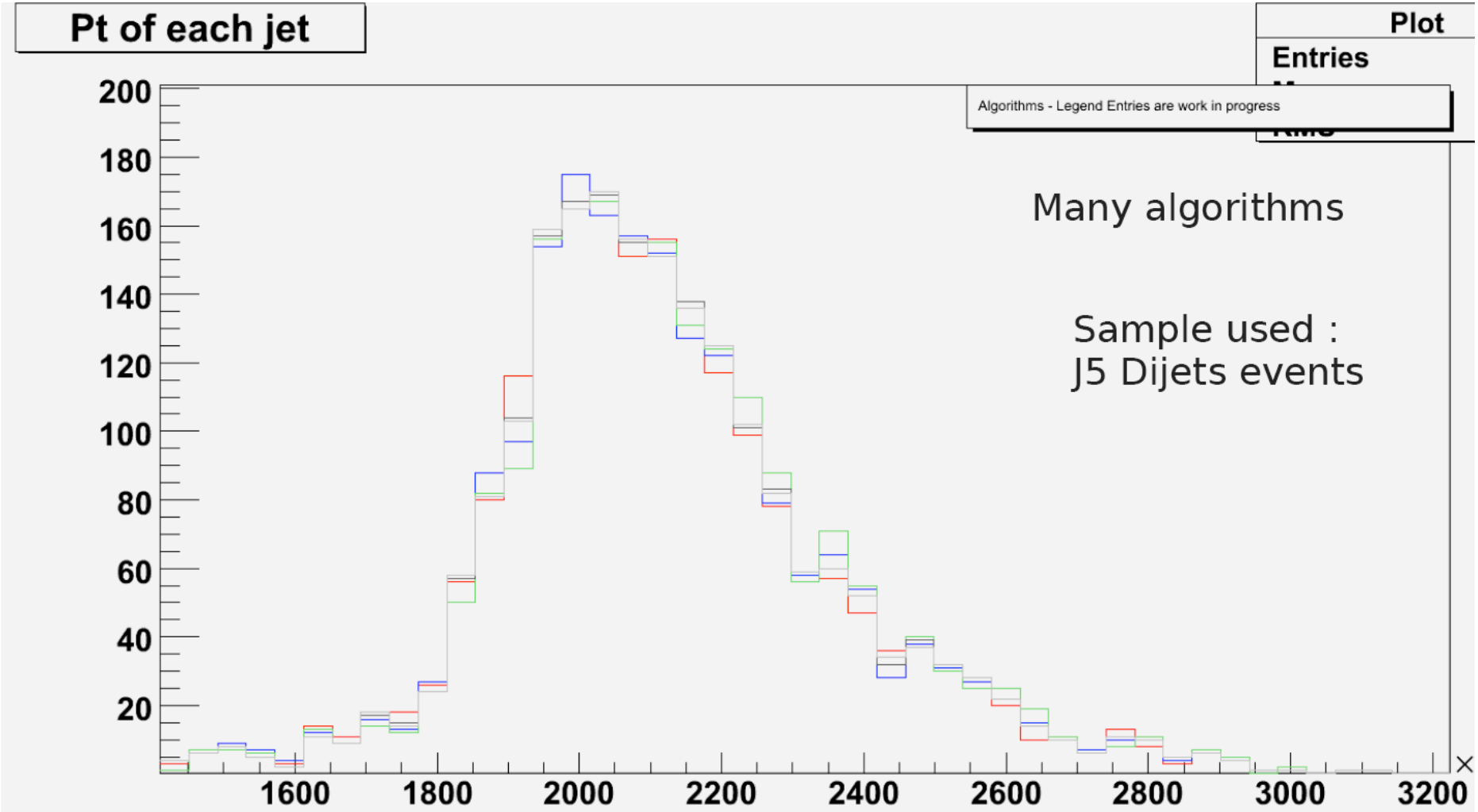
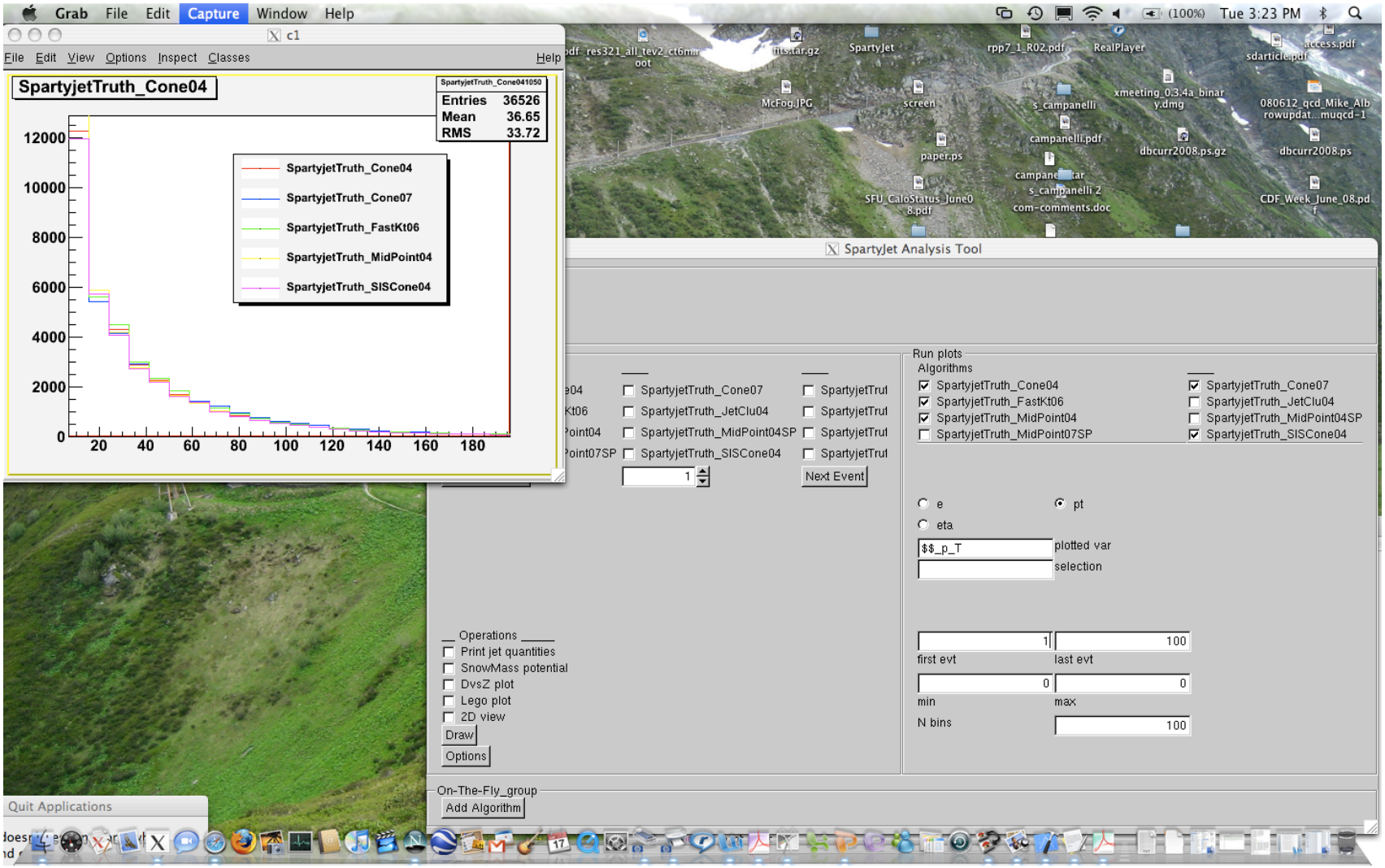
1 Event-by-event gui

- What event
- What algorithm to draw
- What to plot

2 All sample plots

- ~interface to TTree::Draw

2:Interactive plots



Laptop running