Understanding Cross Sections @ LHC

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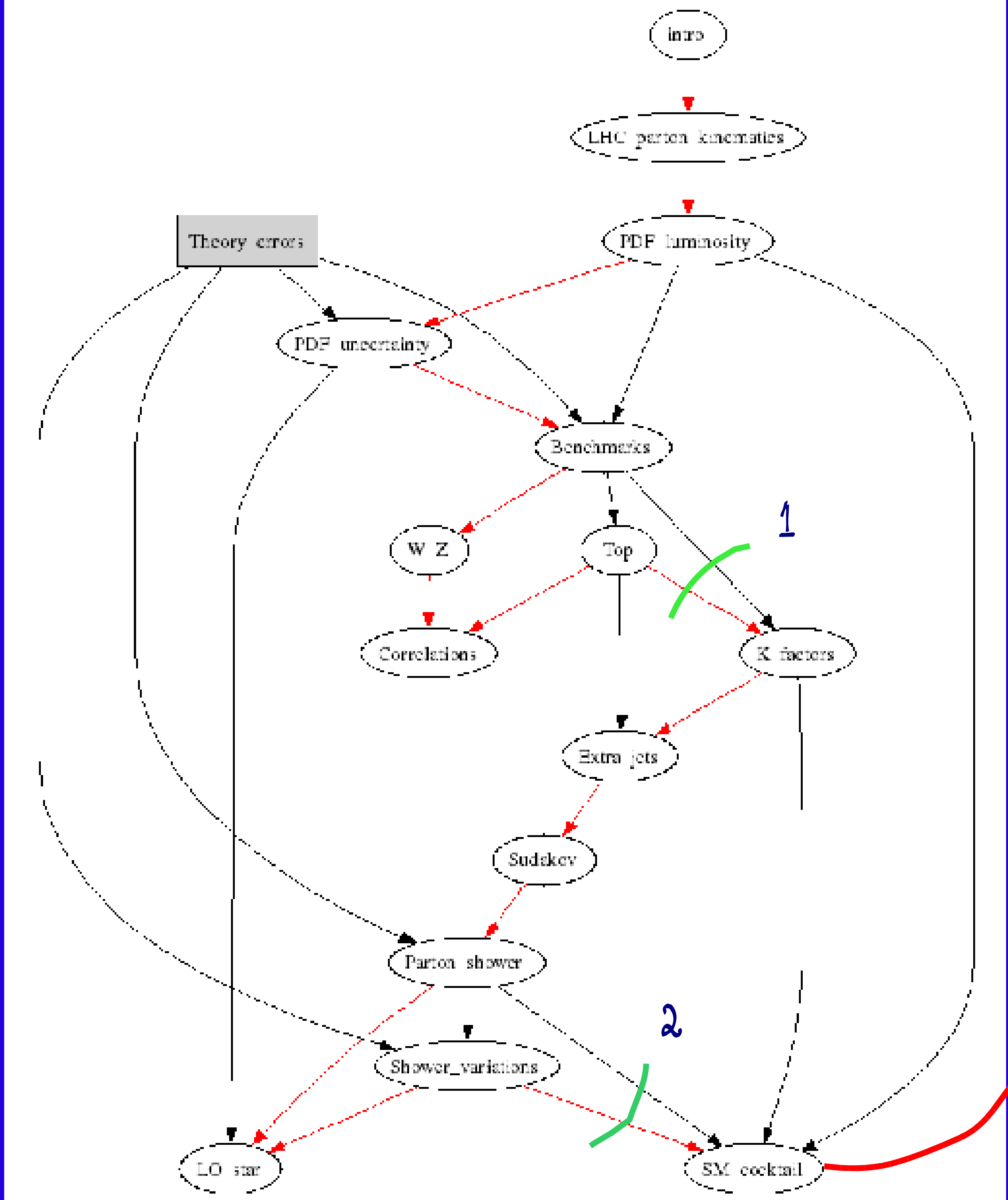
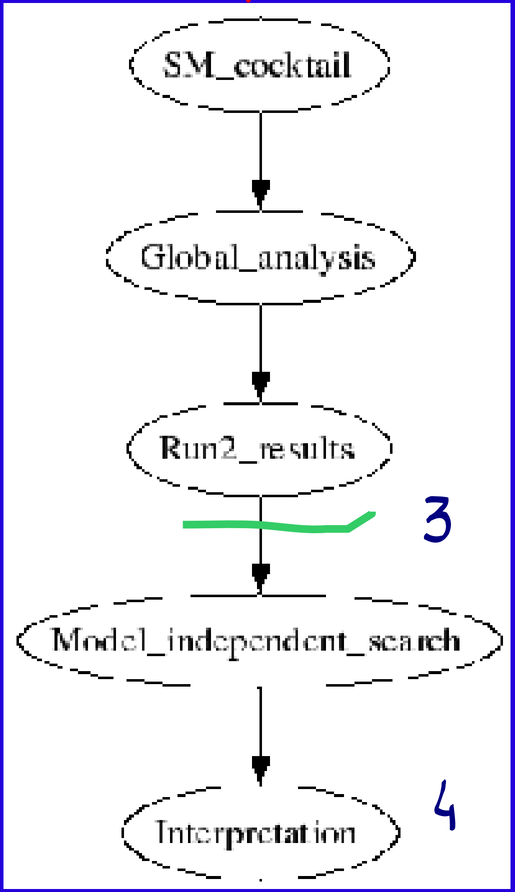
Computing Division
Fermilab

My goal is to discuss:

- How well do we understand the Standard Model (@high pT)?
- What do we need to understand?
- How will we systematically gain knowledge @ LHC?

Outline


intro
LHC parton kinematics
PDF luminosity
Theory errors
PDF uncertainty
Benchmarks
W Z
Top
Correlations
K factors
1
Extra jets
Sudakov
Parton shower
Shower_variations
2
LO star
SM cocktail

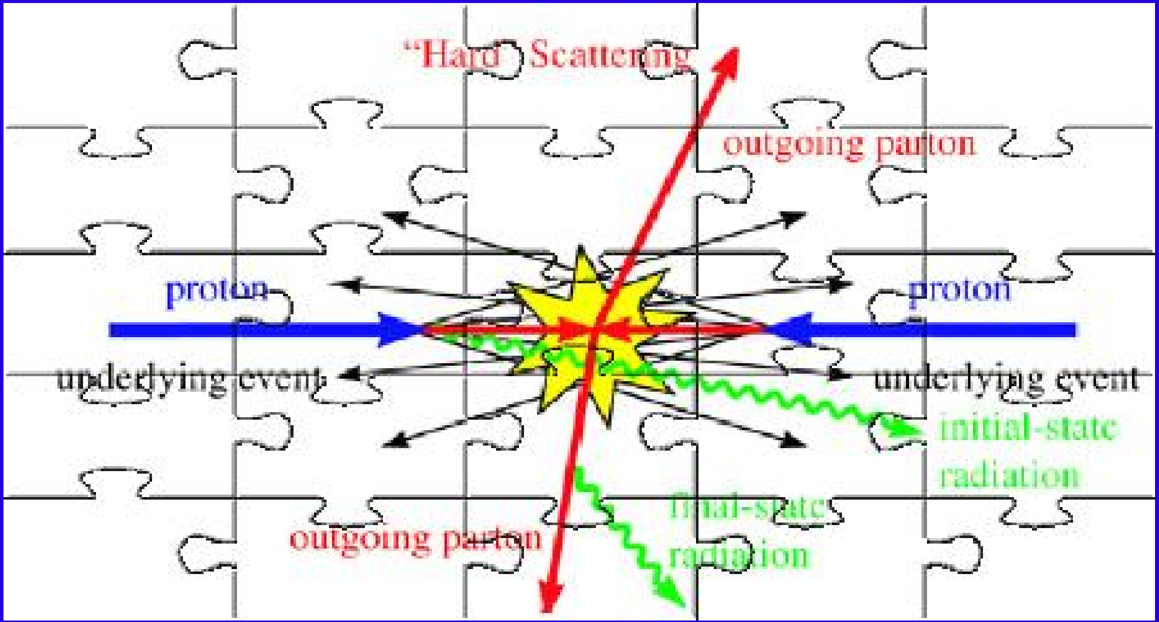

SM_cocktail
Global_analysis
Run2_results
3
Model_independent_search
Interpretation
4

Understanding Cross Sections @ LHC: many pieces to the puzzle

LO, NLO and NNLO calculations
K-factors

Benchmark cross sections and pdf correlations

PDFs with uncertainties



Underlying event and minimum bias

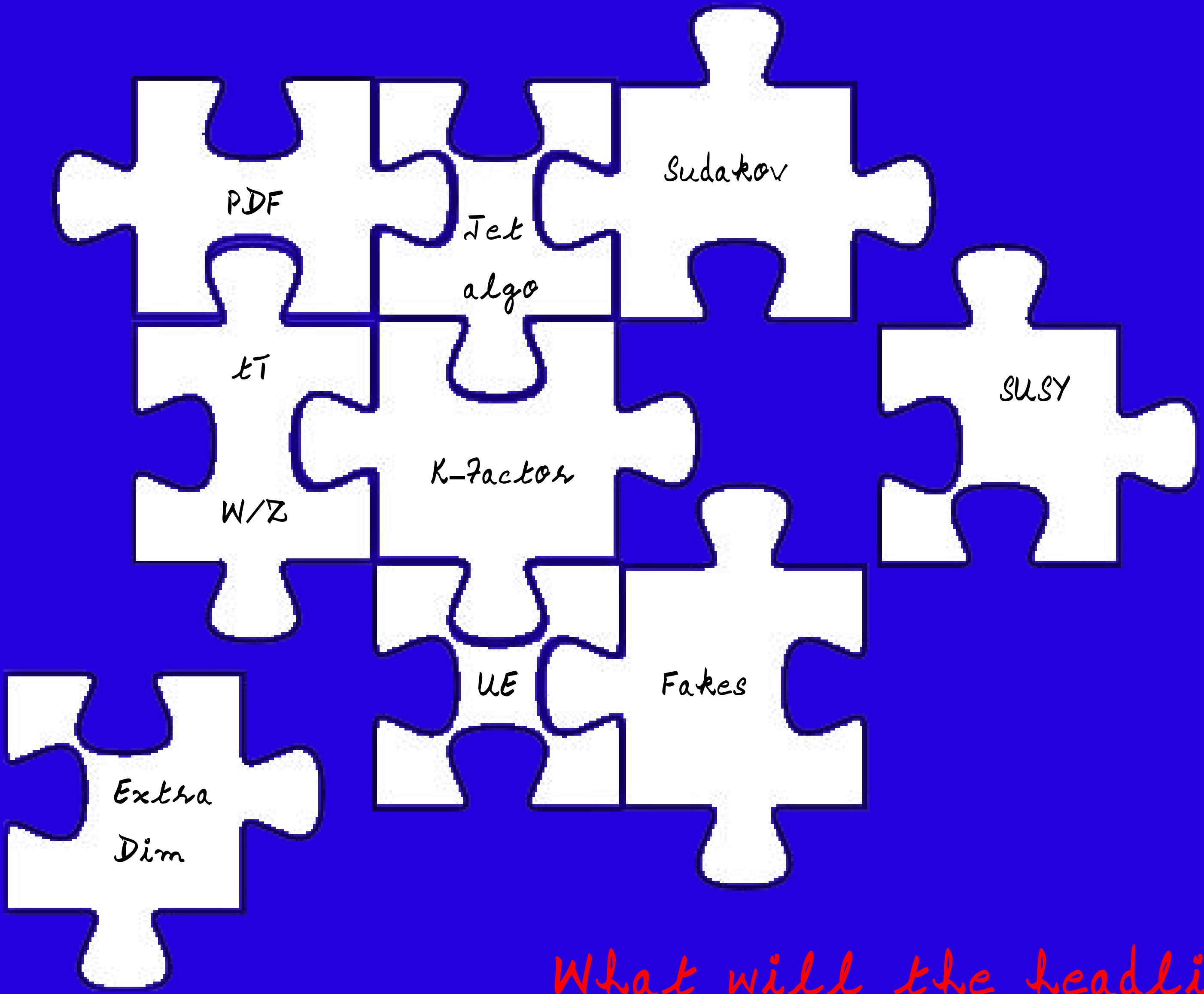
Fragmentation/Hadronization

Sudakov form factors

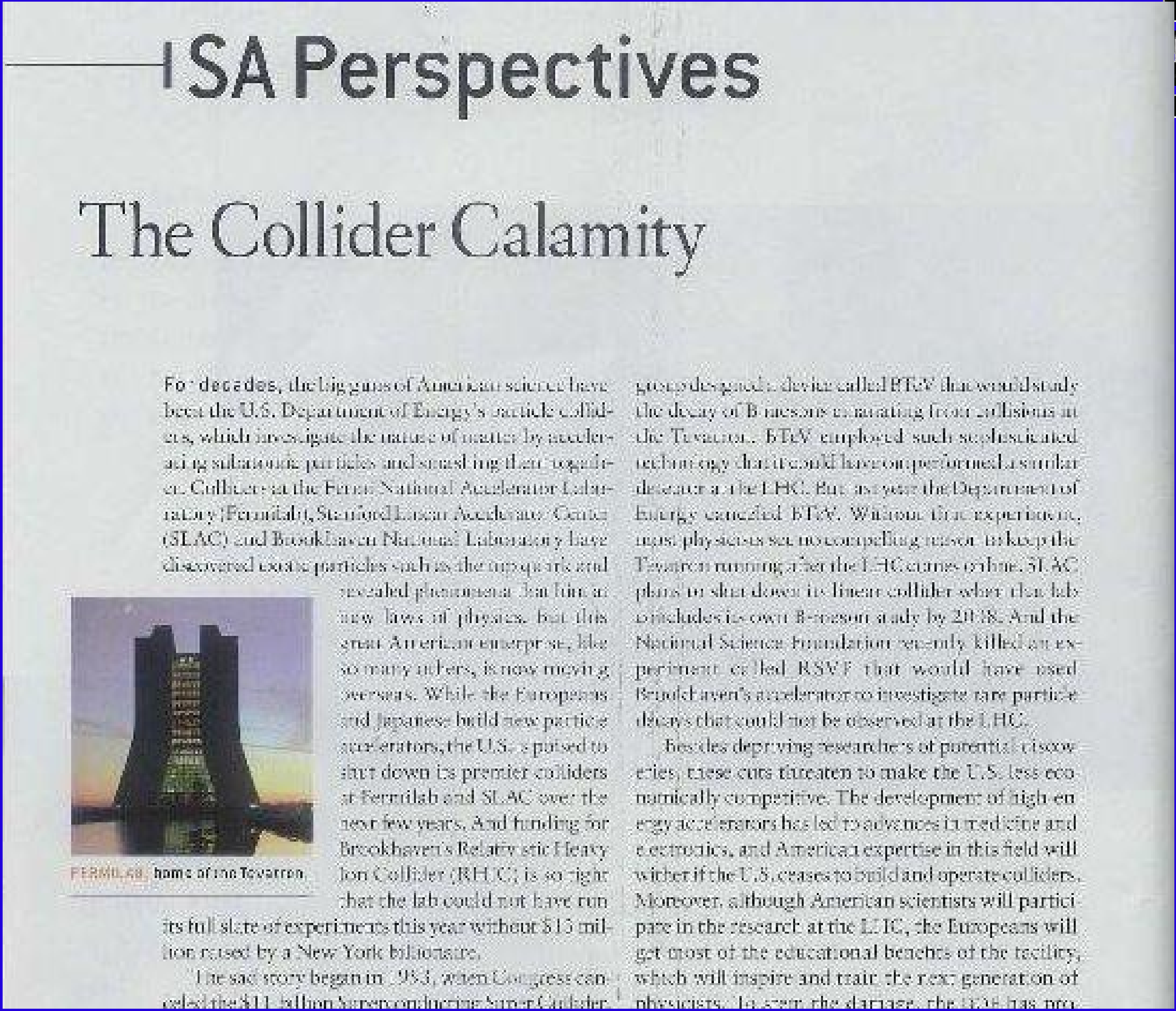
Jet algorithms and jet reconstruction

Won't discuss

(How) will the puzzle pieces fit together?



What will the headlines be?



SA Perspectives

The Collider Calamity

For decades, the big guns of American science have been the U.S. Department of Energy's particle colliders, which investigate the nature of matter by accelerating subatomic particles and smashing them together. Colliders at the Fermi National Accelerator Laboratory (Fermilab), Stanford Linear Accelerator Center (SLAC) and Brookhaven National Laboratory have discovered exotic particles such as the top quark and revealed phenomena that hint at new laws of physics. But this great American enterprise, like so many others, is now moving overseas. While the Europeans and Japanese build new particle accelerators, the U.S. is poised to shut down its premier colliders at Fermilab and SLAC over the next few years. And funding for Brookhaven's Relativistic Heavy Ion Collider (RHIC) is so tight that the lab could not have run its full slate of experiments this year without $13 million raised by a New York billionaire.

FERMILAB, home of the Tevatron.

The sad story began in 1993, when Congress canceled the $11-billion Superconducting Super Collider

group designed a device called BTeV that would study the decay of B mesons emanating from collisions in the Tevatron. BTeV employed such sophisticated technology that it could have outperformed a similar detector at the LHC. But last year the Department of Energy canceled BTeV. Without that experiment, most physicists see no compelling reason to keep the Tevatron running after the LHC comes online. SLAC plans to shut down its linear collider when that lab concludes its own B-meson study by 2008. And the National Science Foundation recently killed an experiment called RSVP that would have used Brookhaven's accelerator to investigate rare particle decays that could not be observed at the LHC.

Besides depriving researchers of potential discoveries, these cuts threaten to make the U.S. less economically competitive. The development of high-energy accelerators has led to advances in medicine and electronics, and American expertise in this field will wither if the U.S. ceases to build and operate colliders. Moreover, although American scientists will participate in the research at the LHC, the Europeans will get most of the educational benefits of the facility, which will inspire and train the next generation of physicists. To stem the damage, the DOE has pro-

The New York Times

1315 Physicists Report Failure In Search for Supersymmetry

The negative result illustrates

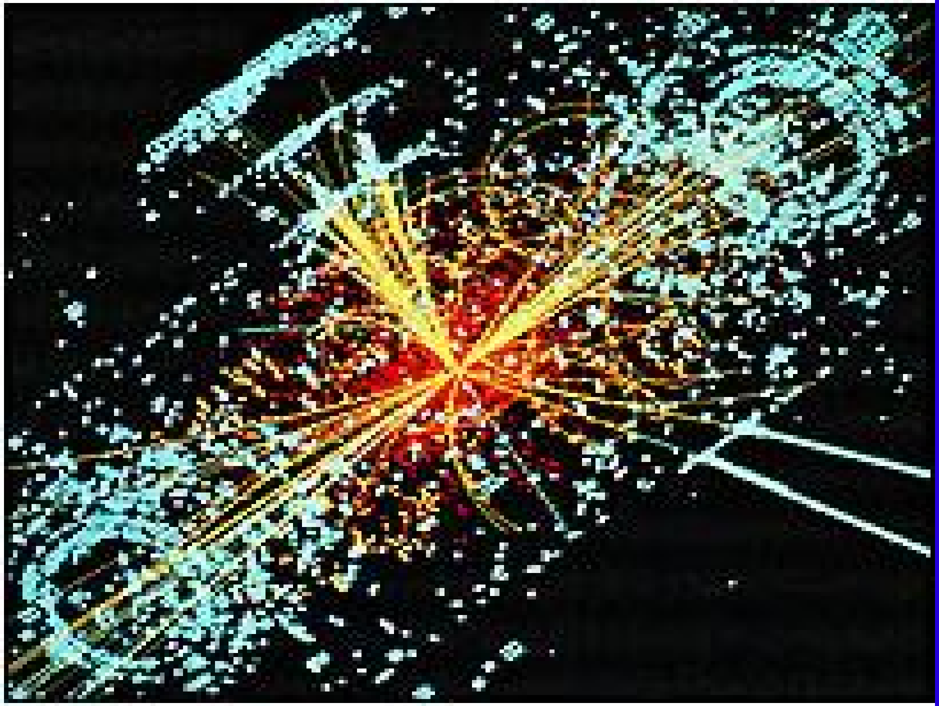
'God particle' may have been seen

... finally

By Paul Rincon

BBC News Online science staff

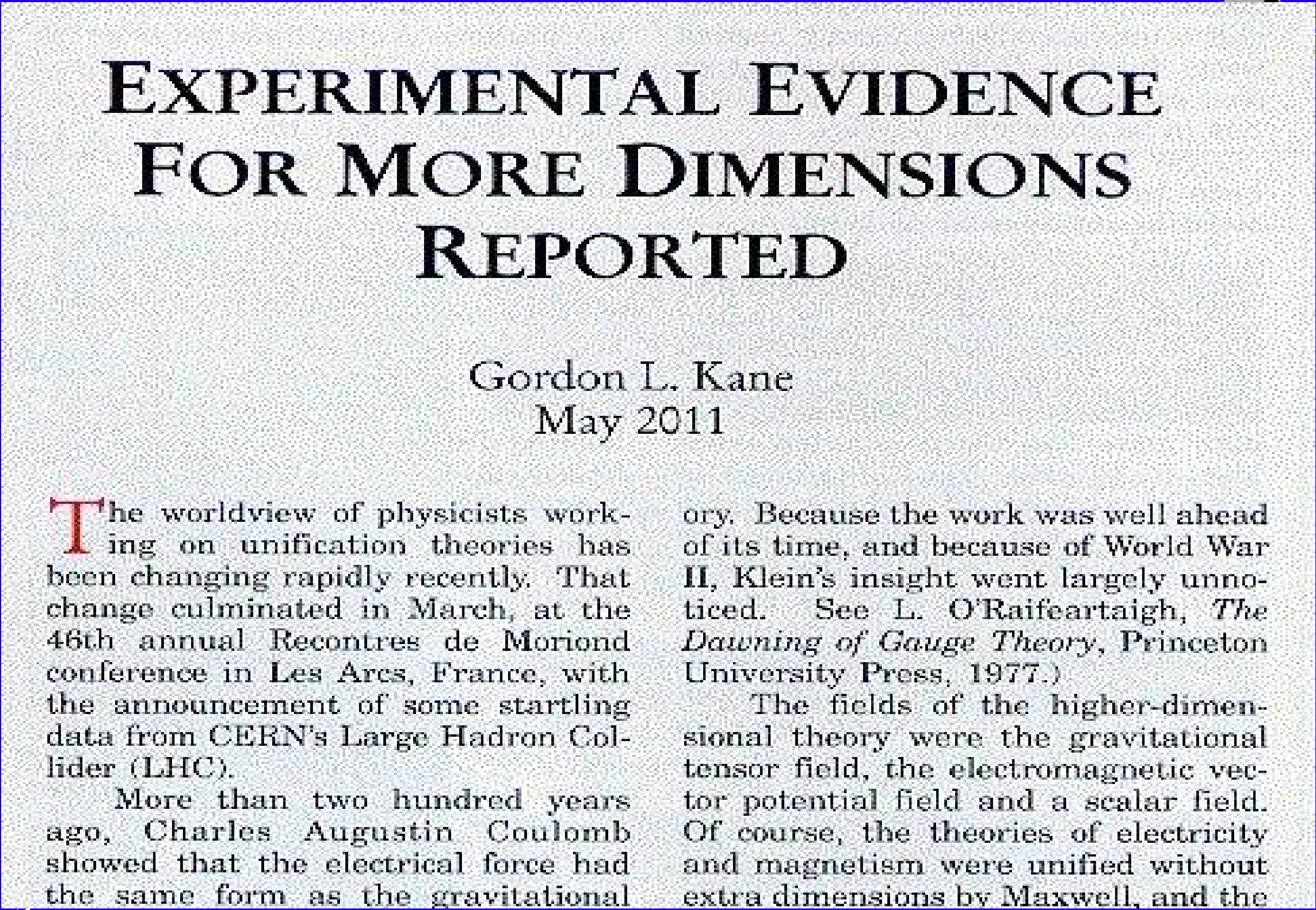
A scientist says one of the most sought after particles in physics - the Higgs boson - may have been found, but the evidence is still relatively weak.



Once produced, the Higgs boson would decay very quickly

Peter Renton, of the University of Oxford, says the particle may have been detected by researchers at an atom-smashing facility in Switzerland.

The Higgs boson explains why all other particles have mass and is fundamental to a complete understanding of matter.



EXPERIMENTAL EVIDENCE FOR MORE DIMENSIONS REPORTED

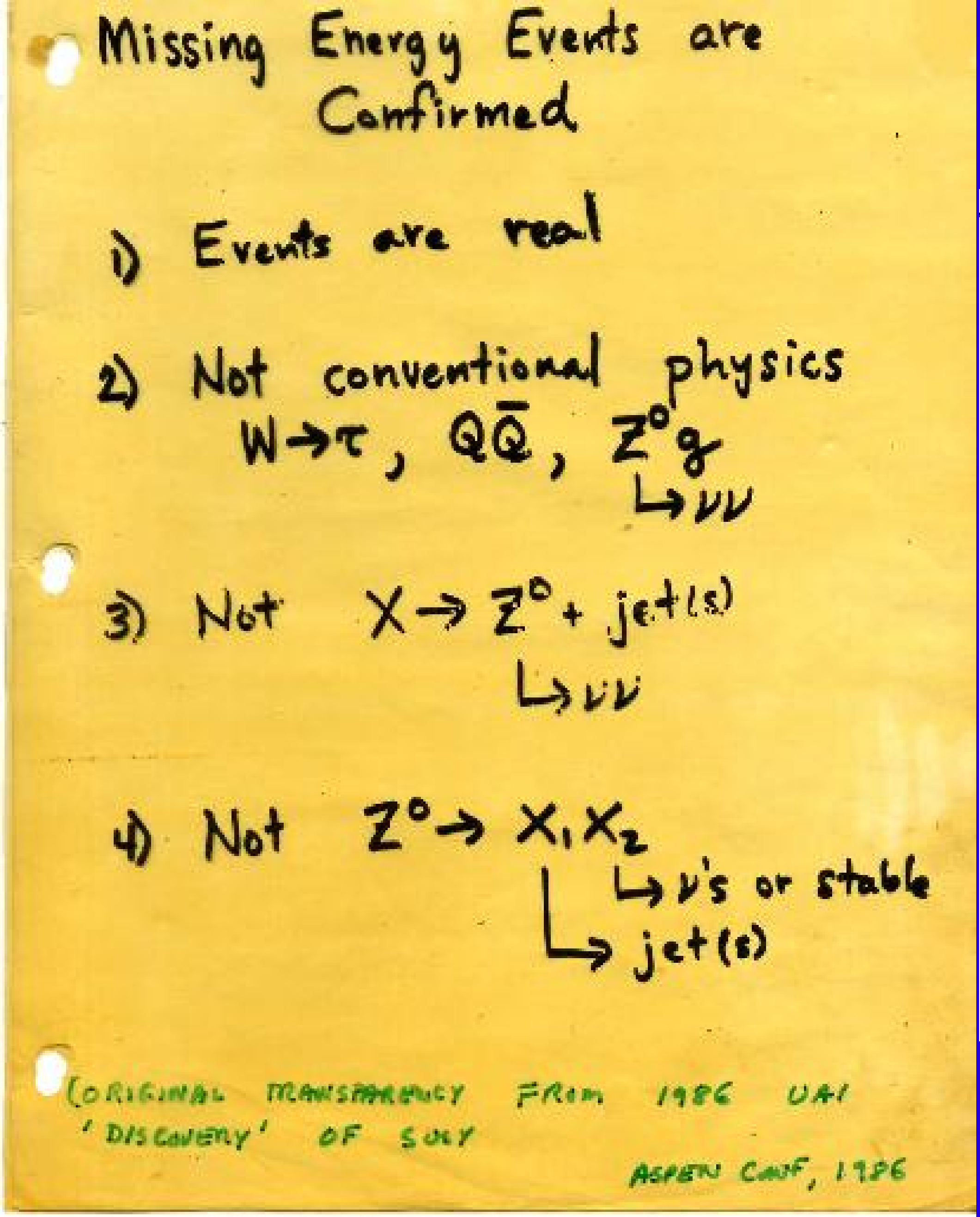
Gordon L. Kane
May 2011

The worldview of physicists working on unification theories has been changing rapidly recently. That change culminated in March, at the 46th annual Recontres de Moriond conference in Les Arcs, France, with the announcement of some startling data from CERN's Large Hadron Collider (LHC).

More than two hundred years ago, Charles Augustin Coulomb showed that the electrical force had the same form as the gravitational

ory. Because the work was well ahead of its time, and because of World War II, Klein's insight went largely unnoticed. See L. O'Raifeartaigh, *The Dawning of Gauge Theory*, Princeton University Press, 1977.)

The fields of the higher-dimensional theory were the gravitational tensor field, the electromagnetic vector potential field and a scalar field. Of course, the theories of electricity and magnetism were unified without extra dimensions by Maxwell, and the



Missing Energy Events are Confirmed

1) Events are real

2) Not conventional physics
   $W \to \tau$, $Q\bar{Q}$, $Z^0 g$
   ↳ $\nu\nu$

3) Not $X \to Z^0 + \text{jet(s)}$
   ↳ $\nu\nu$

4) Not $Z^0 \to X_1 X_2$
   ↳ ν's or stable
   ↳ jet(s)

(ORIGINAL TRANSPARENCY FROM 1986 UA1 'DISCOVERY' OF SUSY

ASPEN CONF, 1986

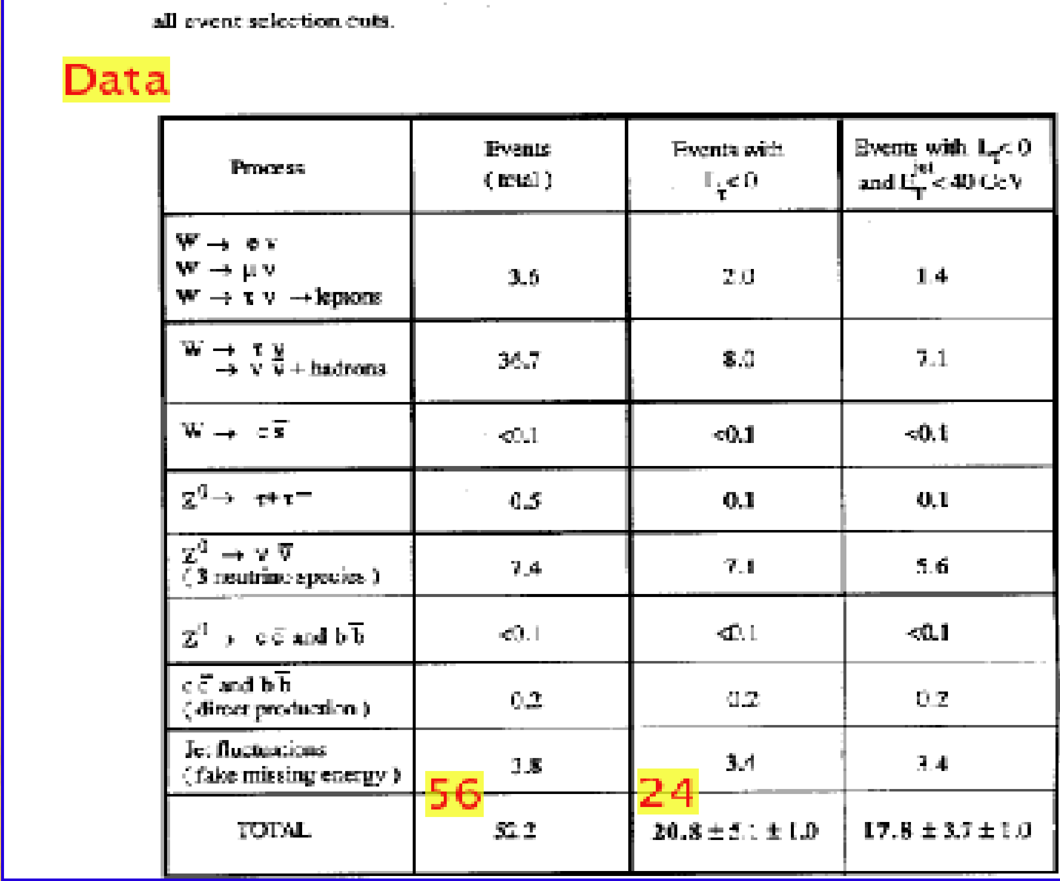
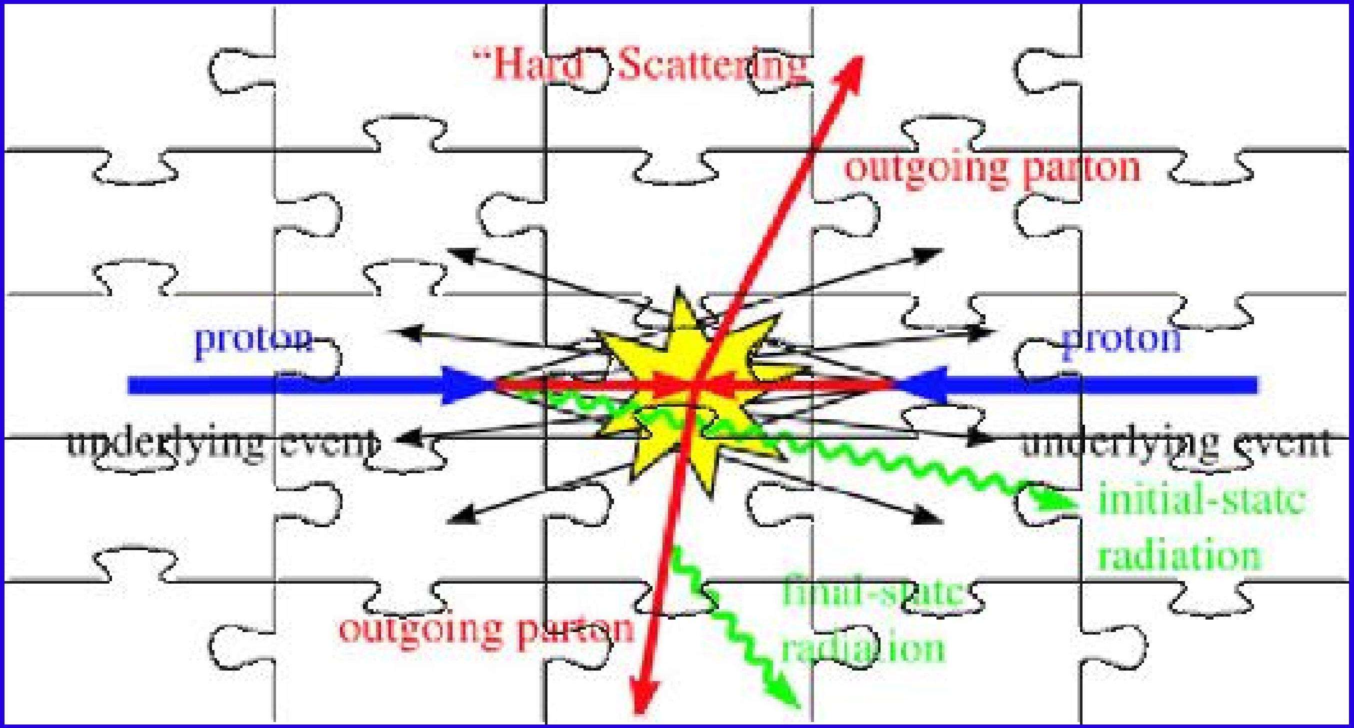


Table 1. Predicted rates for processes giving large missing transverse energy events passing all event selection cuts.

Data

Process	Events (total)	Events with $L_\tau < 0$	Events with $L_\tau < 0$ and $E_T^{jet} < 40$ GeV
$W \to e\nu$ $W \to \mu\nu$ $W \to \tau\nu \to$ leptons	3.6	2.0	1.4
$W \to \tau\nu$ $\to \nu\bar{\nu}$ + hadrons	36.7	8.0	7.1
$W \to c\bar{s}$	<0.1	<0.1	<0.1
$Z^0 \to \tau^+\tau^-$	0.5	0.1	0.1
$Z^0 \to \nu\bar{\nu}$ (3 neutrino species)	7.4	7.1	5.6
$Z^0 \to c\bar{c}$ and $b\bar{b}$	<0.1	<0.1	<0.1
$c\bar{c}$ and $b\bar{b}$ (direct production)	0.2	0.2	0.2
Jet fluctuations (fake missing energy)	3.8	3.4	3.4
TOTAL	56 52.2	24 $20.8 \pm 5.1 \pm 1.0$	$17.8 \pm 3.7 \pm 1.0$

What do we expect at the LHC?



How much does the $t\bar{t}$ cross section change from the Tevatron to the LHC?

10x

100x

500x

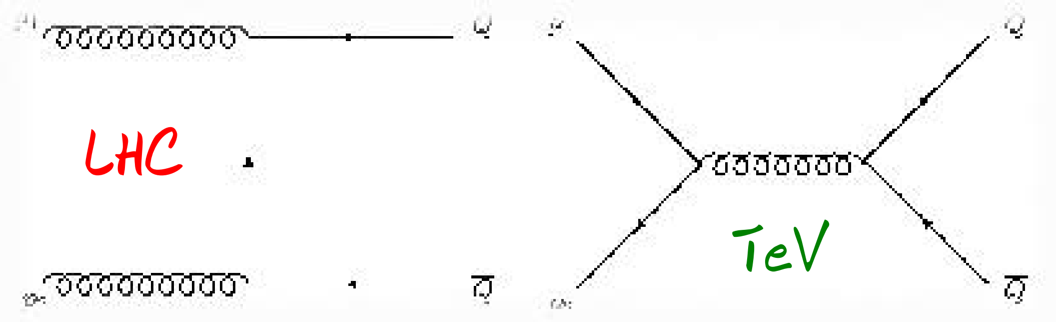
[Kidonakis]

How much does the $t\bar{t}$ cross section change from the Tevatron to the LHC?

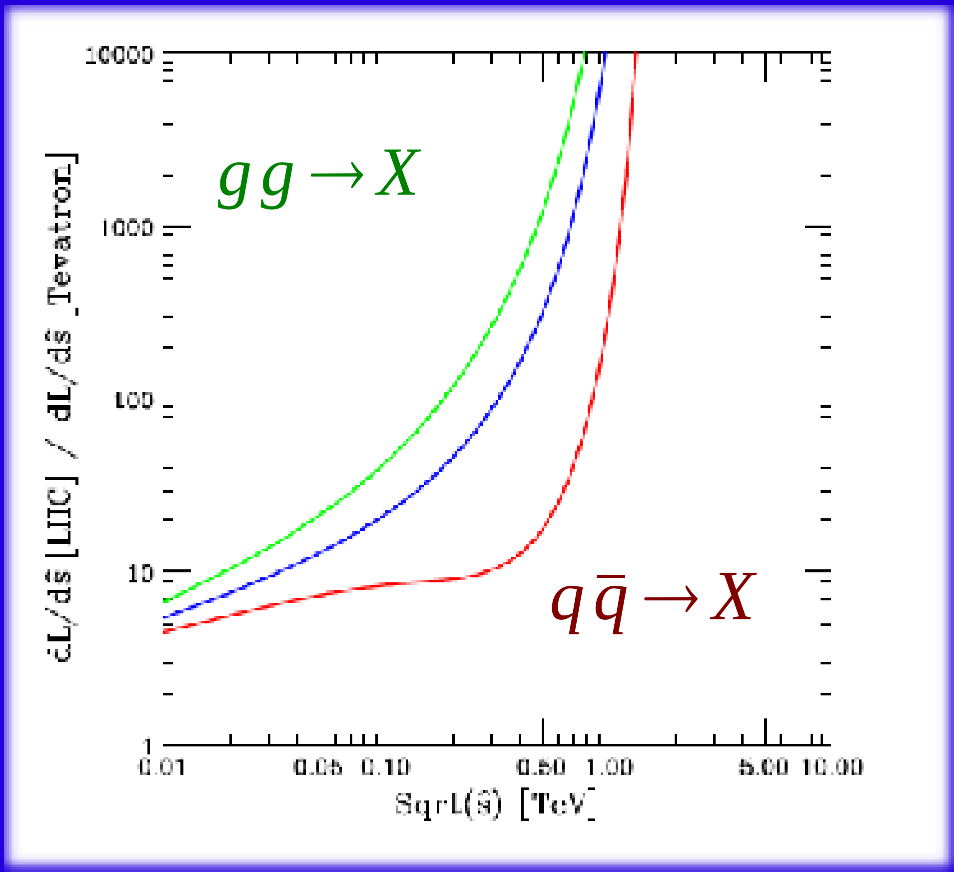
10x

100x [Kidonakis]

500x



Partonic luminosity LHC/TeV2



How much does the $\tilde{\chi}^+\tilde{\chi}^-$ (m=200 GeV) cross section change from the Tevatron to the LHC?

10x

100x

500x

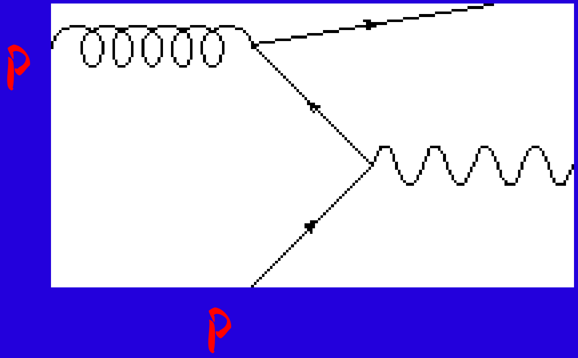
[Pythia]

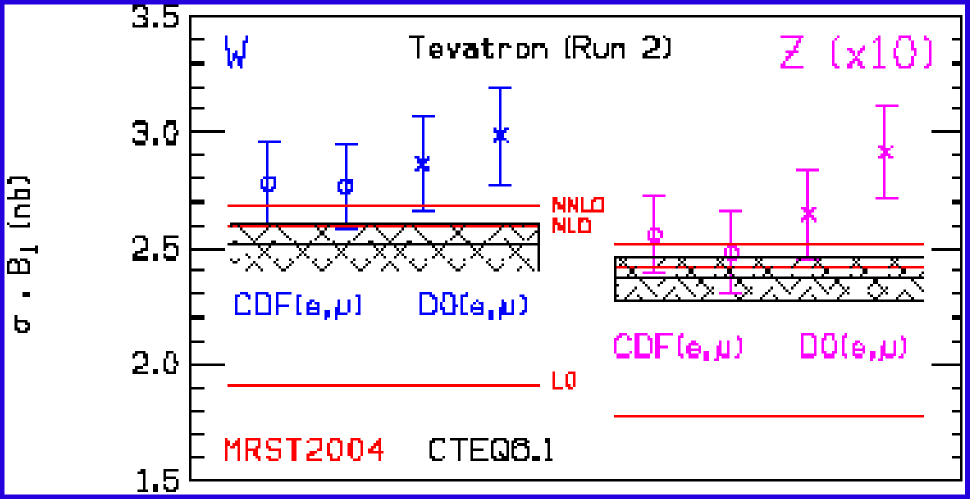
How much does the $\tilde{\chi}^+\tilde{\chi}^-$ (m=200 GeV) cross section change from the Tevatron to the LHC?

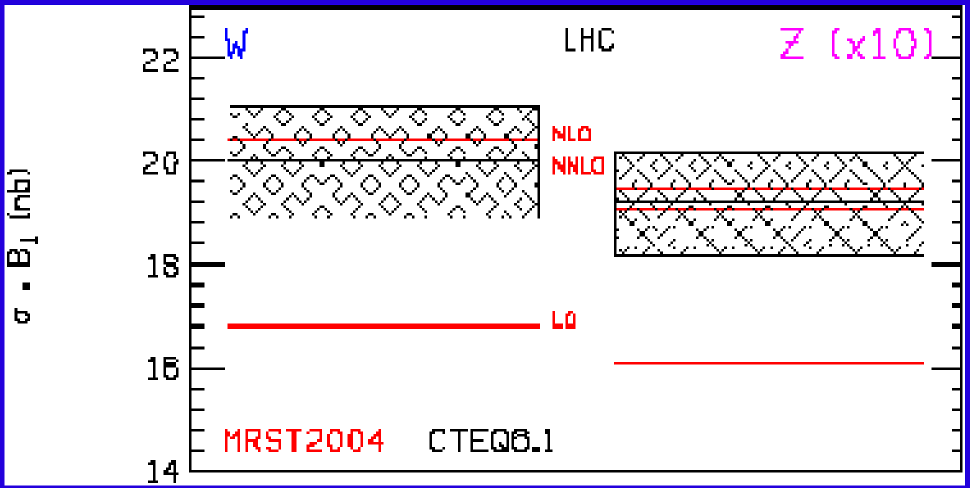
10x [Pythia]

100x

500x







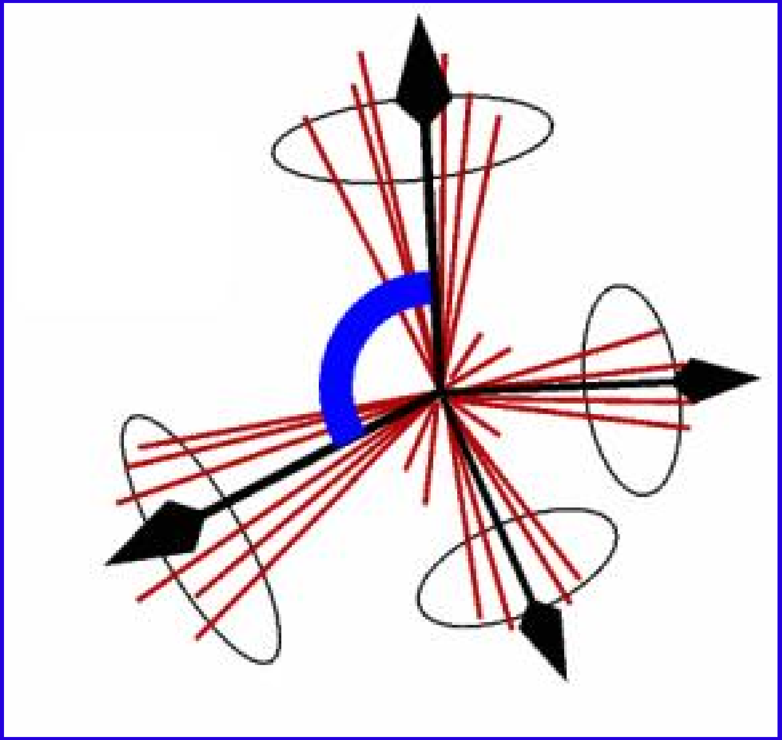
How much does the W+4j cross section change from the Tevatron to the LHC?

$$k_{Tj} > 20\, GeV$$

10x

100x

500x



[MadEvent]

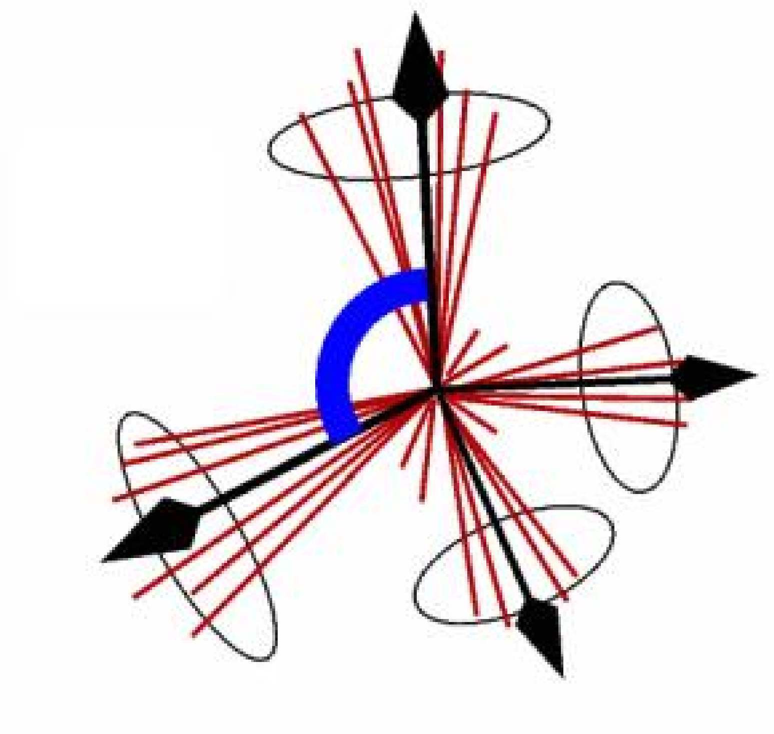
How much does the W+4j cross section change from the Tevatron to the LHC?

$$k_{Tj} > 20\,GeV$$

10x

100x

[✓ 500x]

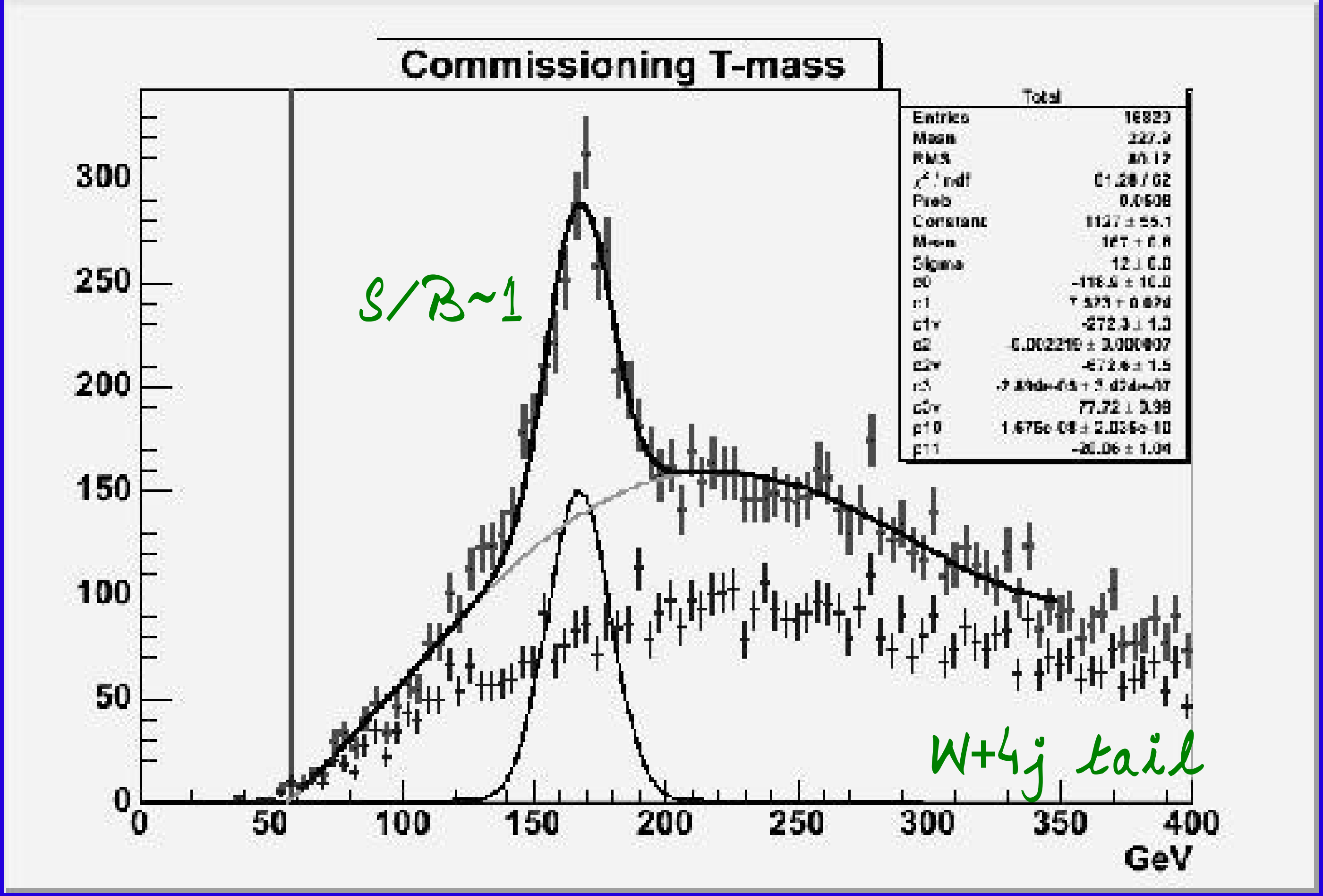


[MadEvent]

W+4 partons			
TEVATRON		**LHC**	
Graph	**Cross Sect(fb)**	**Graph**	**Cross Sect(pb)**
Sum	**1035.004**	**Sum**	**577.948**
ug_e+vedggg	112.250	gu_e+vedggg	89.815
gux_e-vexdxggg	112.040	ug_e+vedggg	89.603
uux_e-vexudxgg	112.010	gd_e-vexuggg	45.522
uux_e+veuxdgg	111.900	dg_e-vexuggg	45.342
dux_e-vexddxgg	46.423	uu_e+veudgg	34.174
udx_e+veuuxgg	46.388	dxg_e+veuxggg	15.346
dux_e-vexuuxgg	46.349	gdx_e+veuxggg	15.341
udx_e+veddxgg	46.330	uxg_e-vexdxggg	10.868
gdx_e+veuxggg	40.234	gux_e-vexdxggg	10.866
dg_e-vexuggg	40.122	gg_e+veuxdgg	9.920
udx_e+vegggg	30.906	gg_e+vescxgg	9.907
dux_e-vexgggg	30.867	gg_e-vexsxcgg	9.907
ddx_e-vexudxgg	15.189	gg_e-vexudxgg	9.842
ddx_e+veuxdgg	15.171	du_e+veddgg	8.903
...	...	...	...

Top vs W (ATLAS study)

M. Barisonzi

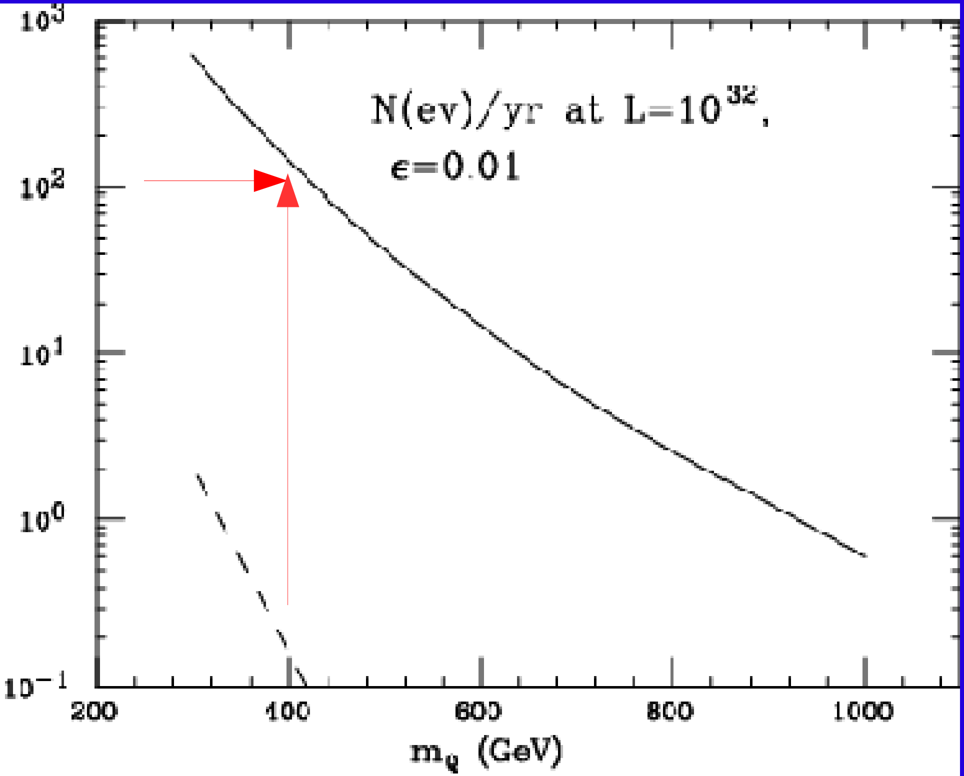


S/B~1

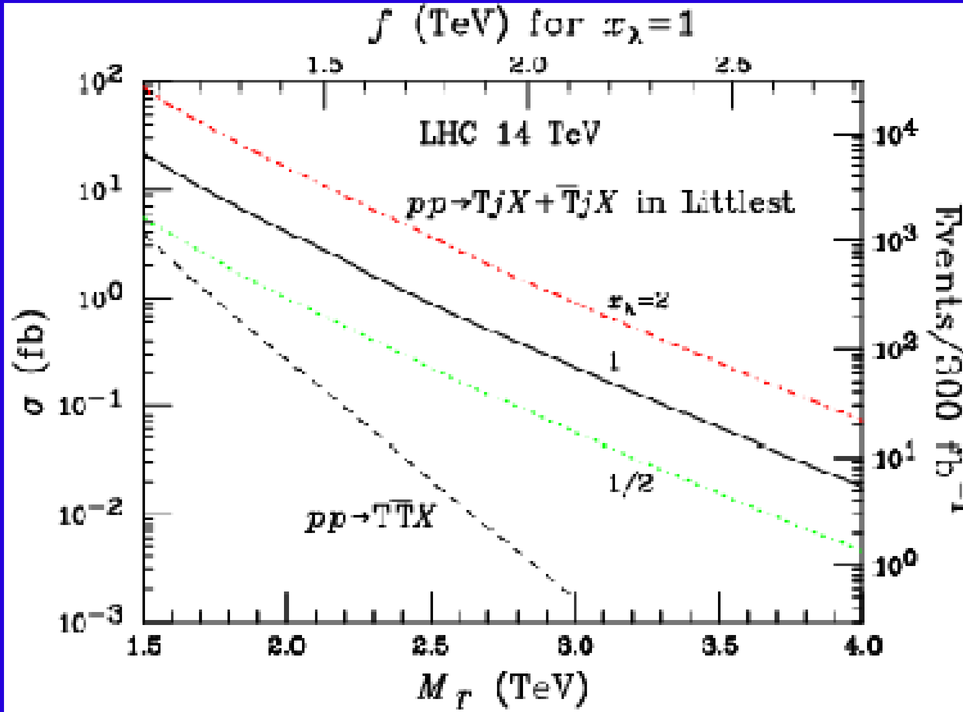
W+4j tail

Heavy Quark Production @ LHC

Huge phase space in an interesting kinematic region



MLM

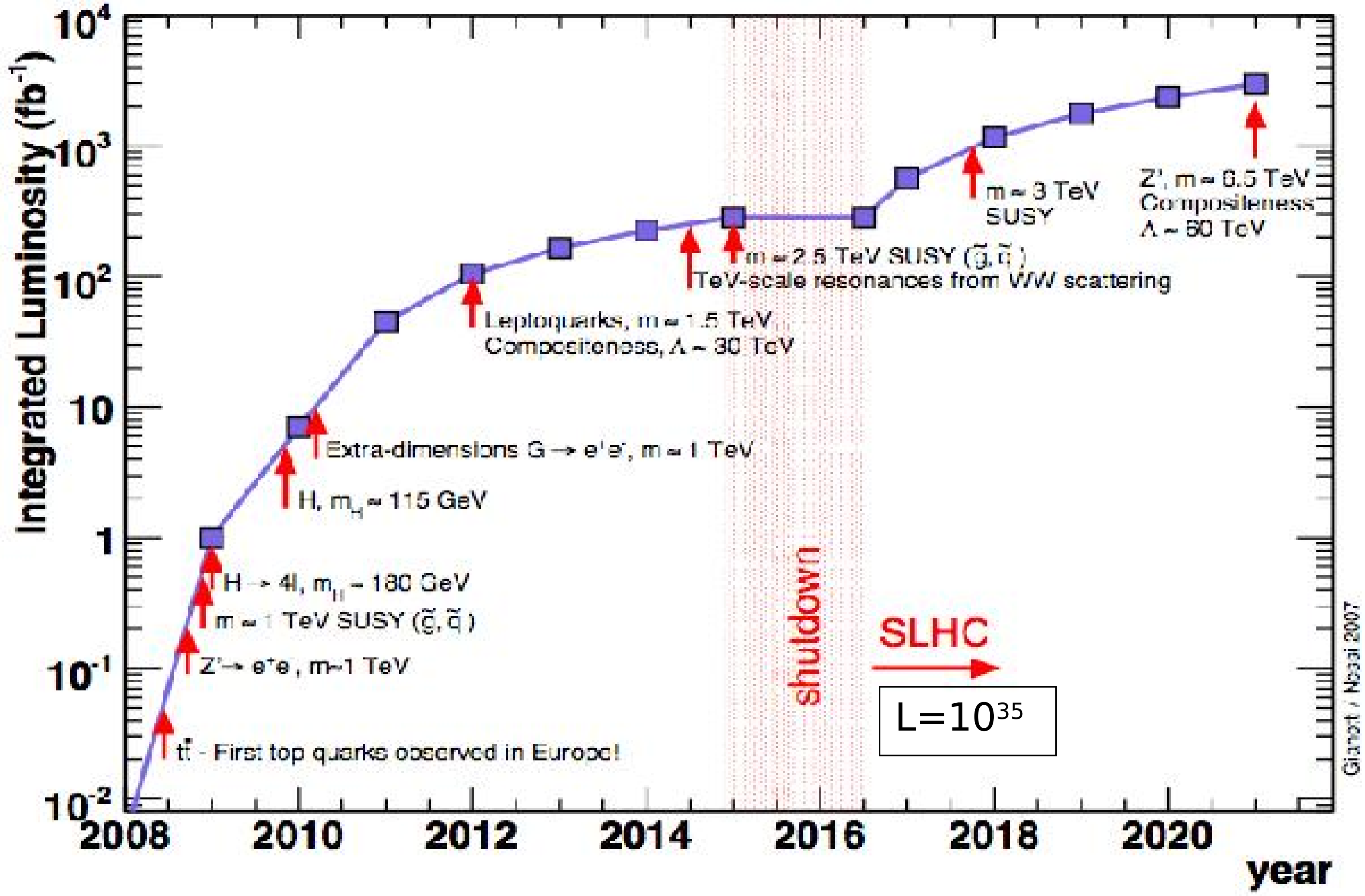


Logan, Han, Wang

Something new can appear very quickly

We’ll soon forget about early setbacks

LHC vs time: a guess …



But first we need to answer:

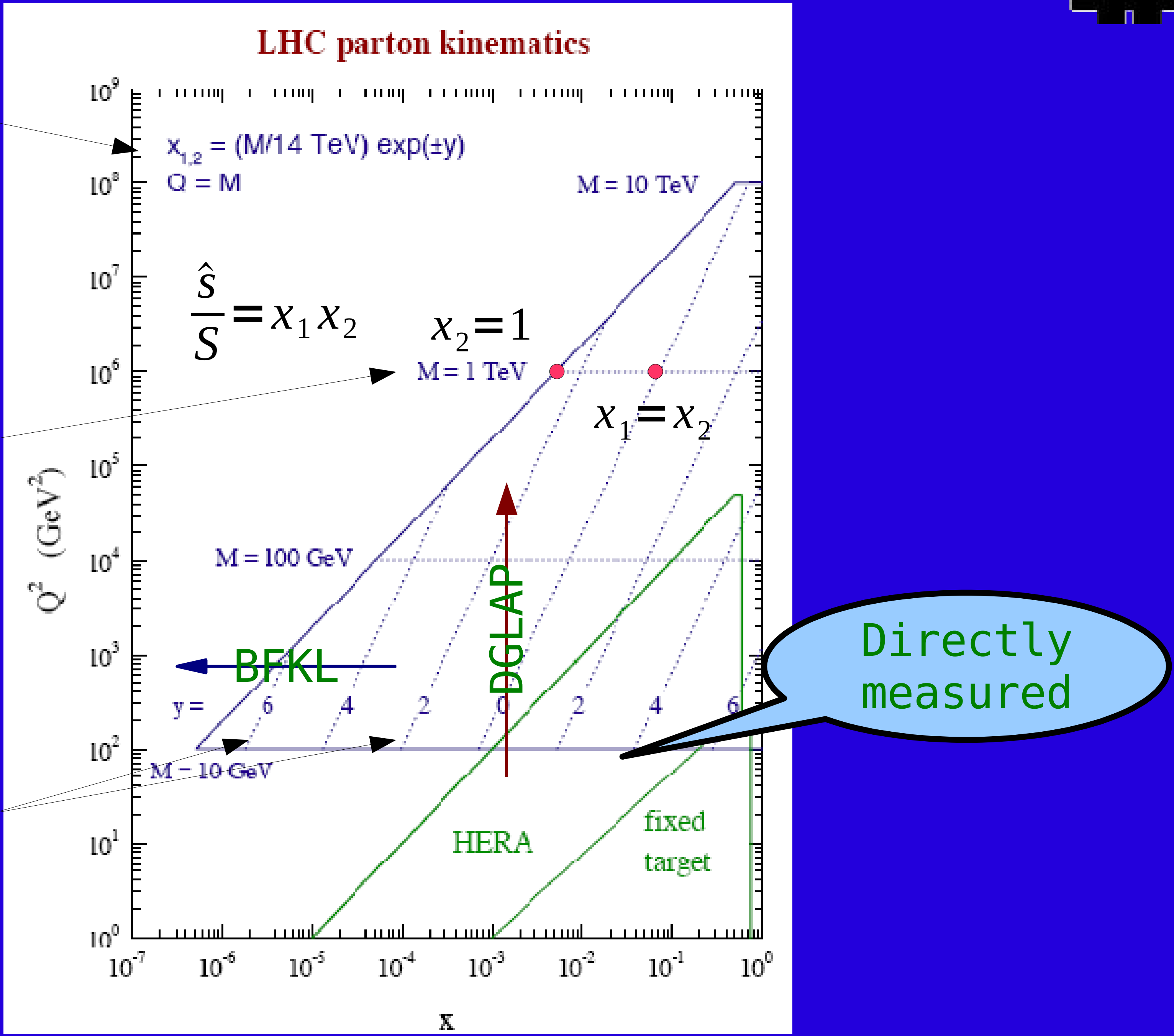
Do we understand
the Standard Model
(our data)?

Cross sections@LHC

Partonic x

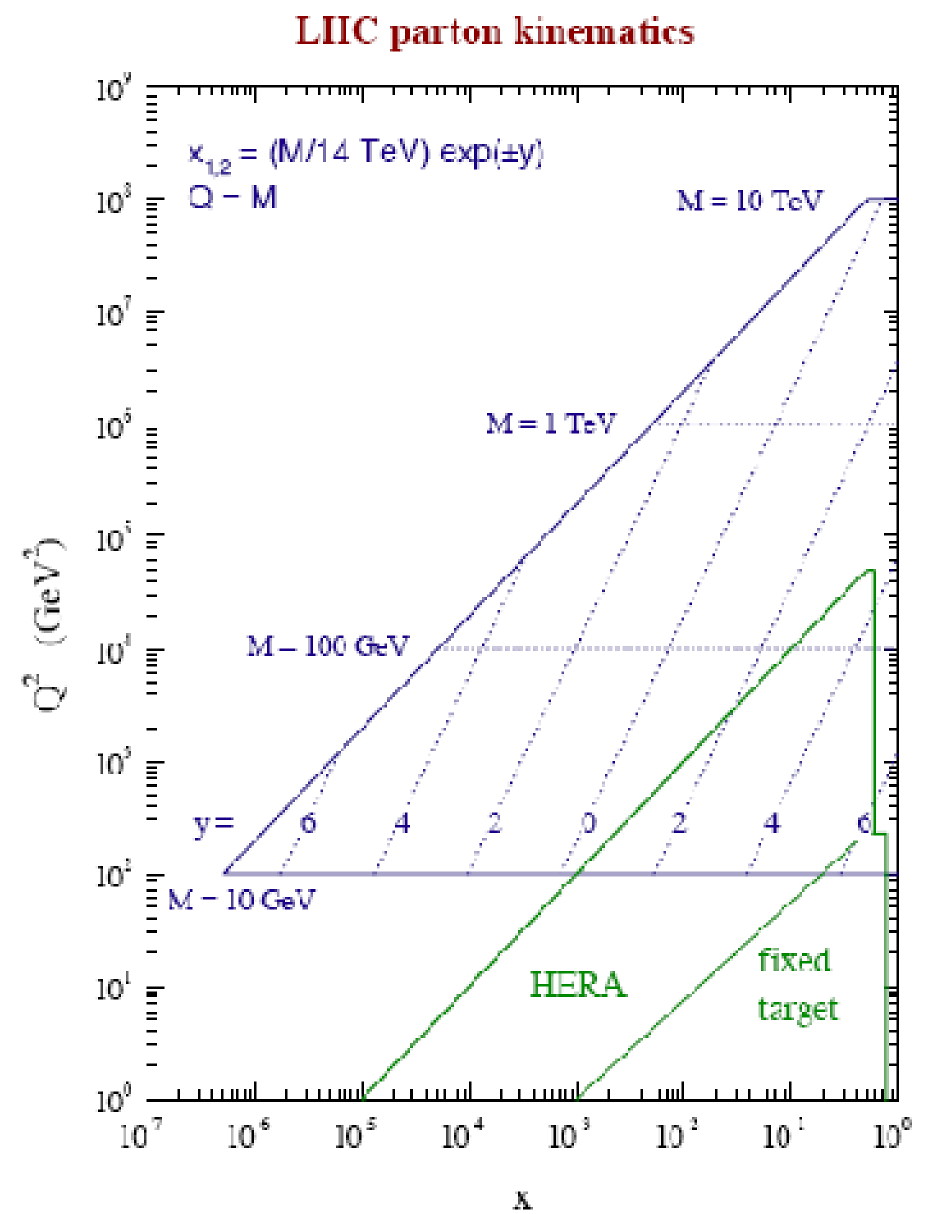
Mass of a Resonance

Rapidity of Resonance



Cross sections@LHC

- @LHC != K @TeV2
- Small x in key searches
    - Dominance of gluon and sea quark
    - Large phase space for gluon emission
- HERA/fixed target cover limited range
- Sensitive to x>1E^{-6} (crucial for the underlying event) and Q^2 up to 100 TeV^2
- Assume DGLAP evolution
    - Blindly going to very low x
    - BFKL may be important



Simple Estimates @LHC

- To serve as a handy "look-up" table, it's useful to define a parton-parton luminosity

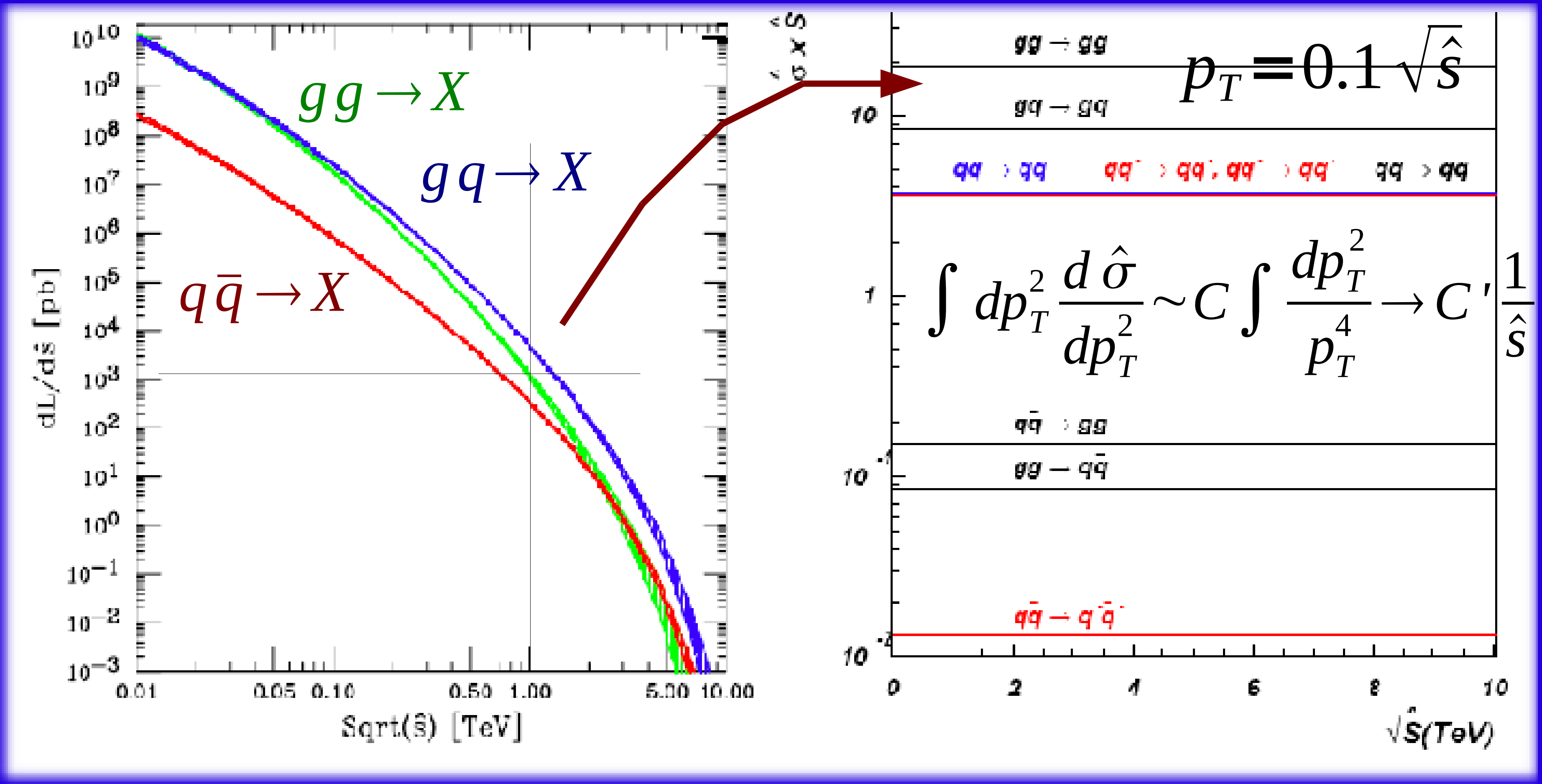
$$\frac{dL_{ij}}{d\hat{s}\,dy} = \frac{1}{\hat{s}} S_{ij}[f_i(x_{1,}\mu) f_j(x_{2,}\mu) + 1 \Leftrightarrow 2]$$

- Estimate the production rate for hard scattering at the LHC as the product of a differential parton luminosity and a scaled hard scatter matrix element

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

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

Cross section estimates for LO massless QCD



$$p_T = 0.1\sqrt{\hat{s}}$$

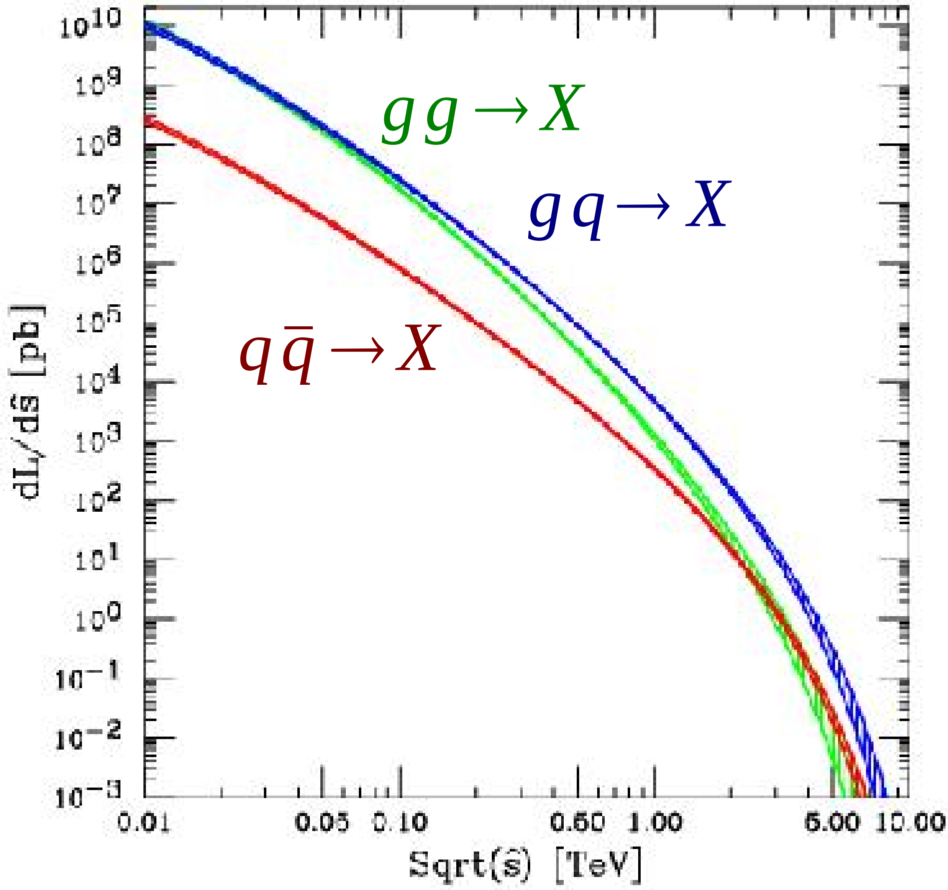
$$\int dp_T^2 \frac{d\hat{\sigma}}{dp_T^2} \sim C\int \frac{dp_T^2}{p_T^4} \to C'\frac{1}{\hat{s}}$$

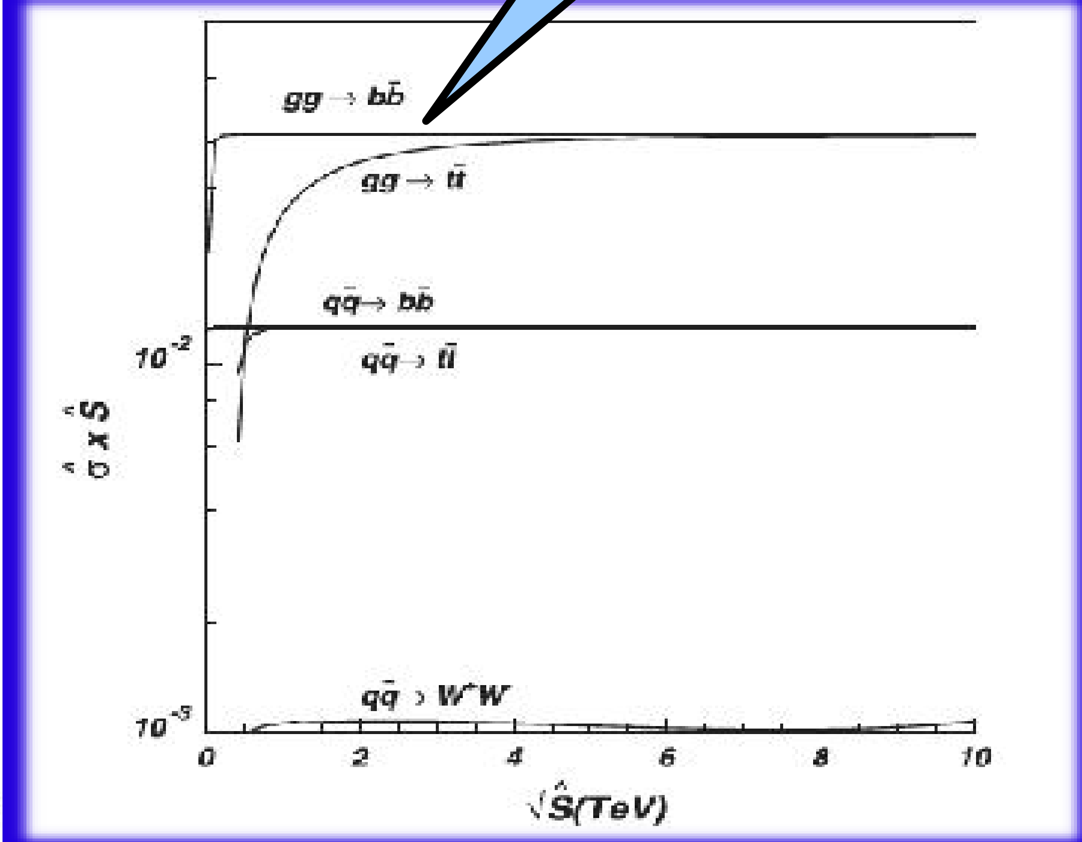
@1 TeV: $\delta\hat{s} = .01\hat{s} \to \sigma(gg \to X) = 200\,pb$

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

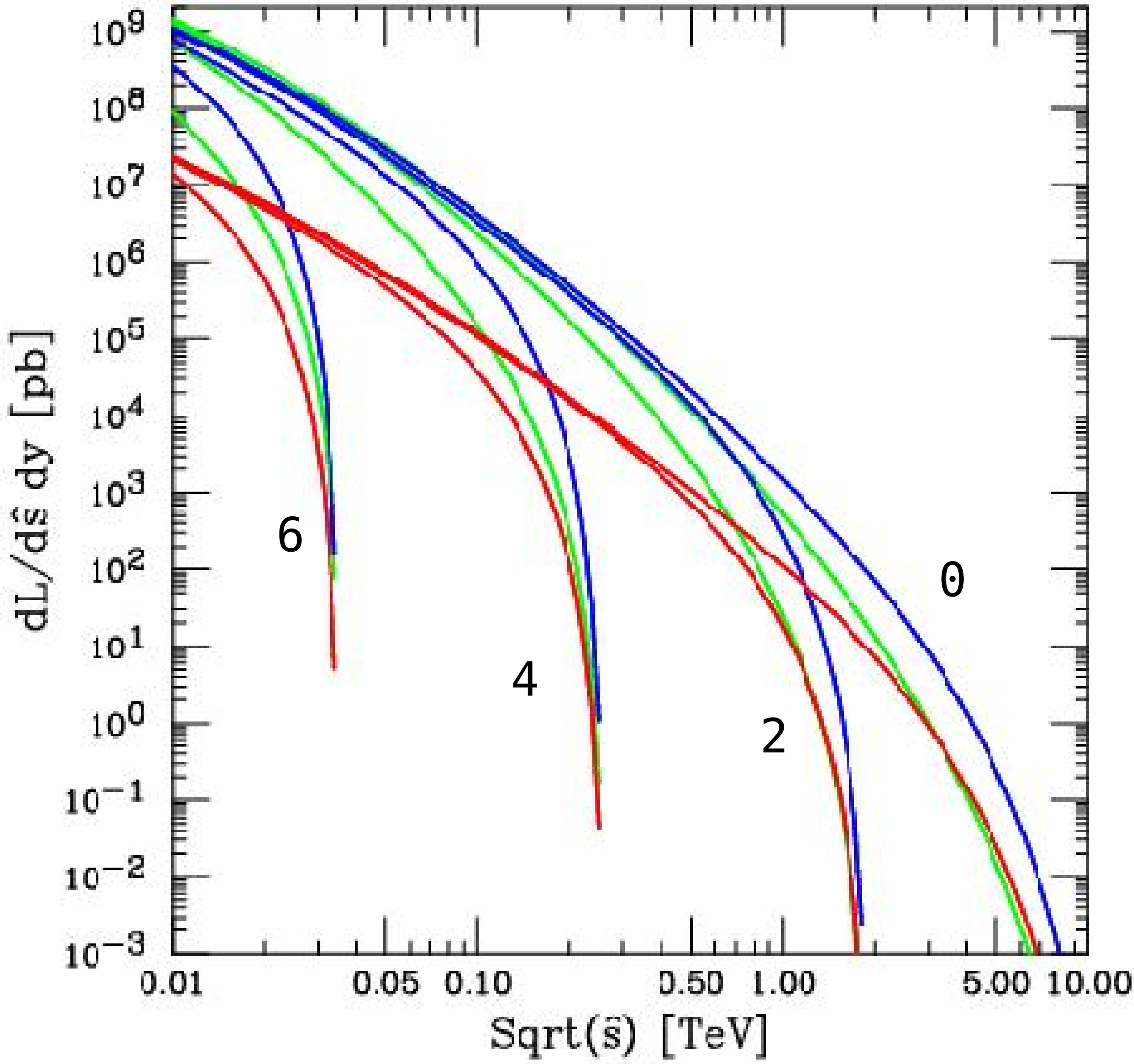
Heavy quark production

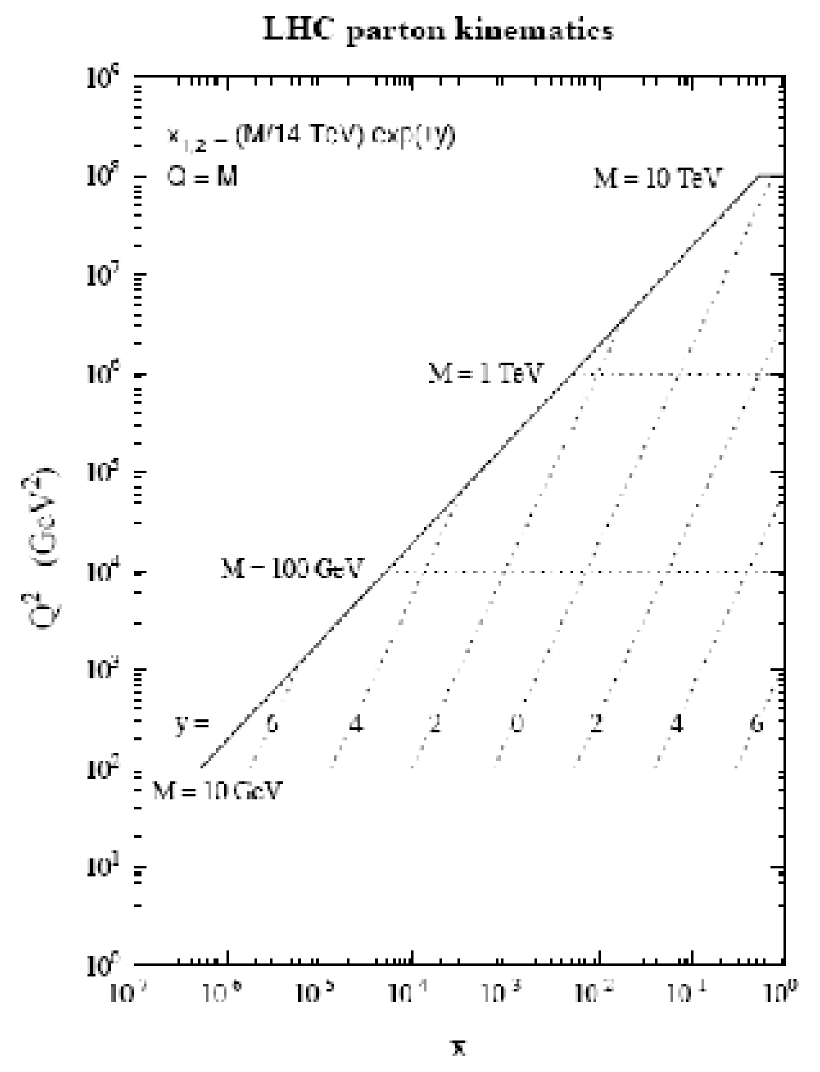
Threshold effect





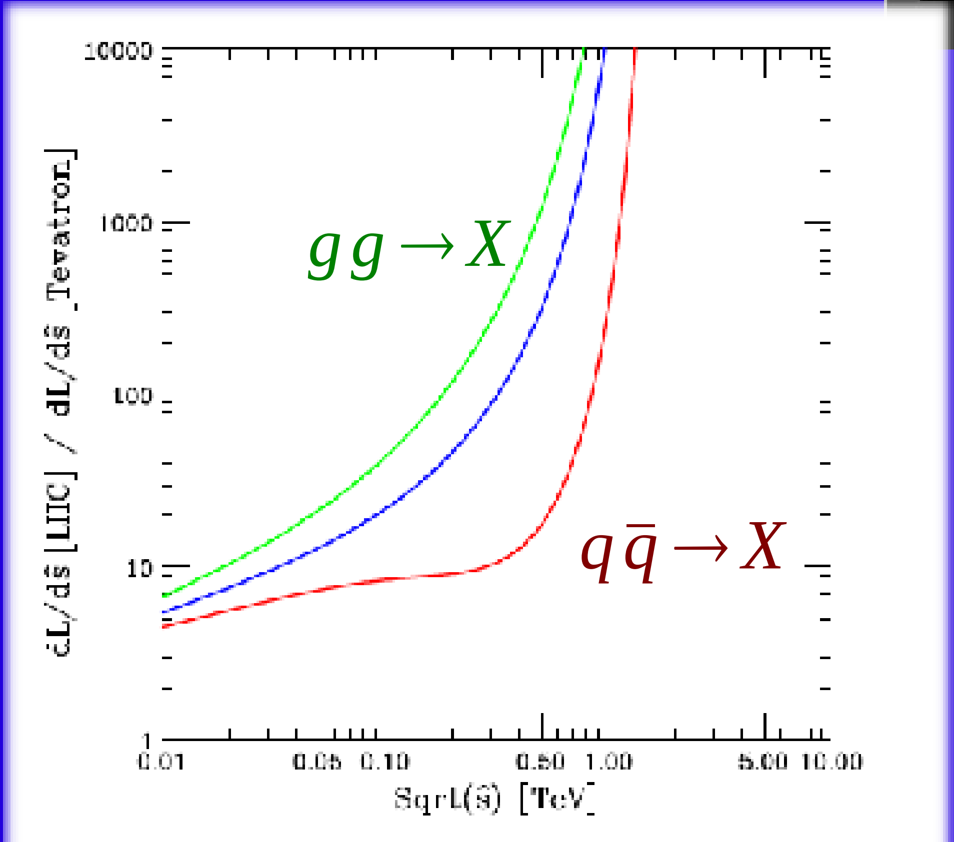
Rapidity (y) Dependence

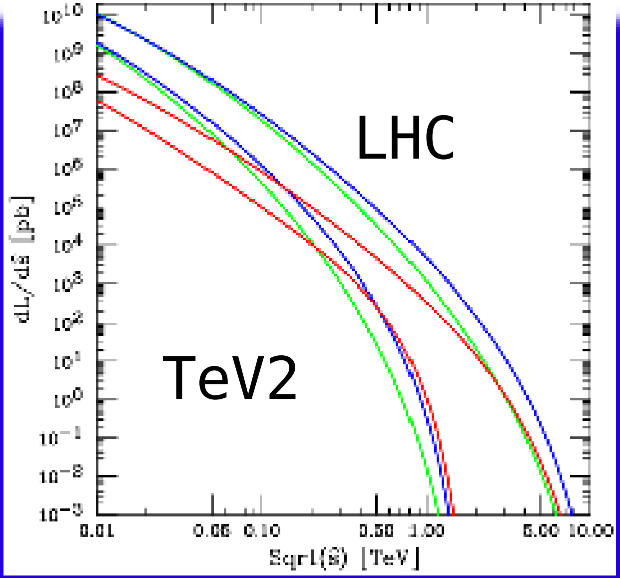




LHC/TeV2 PDF luminosities

- 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)
- W+4 jets is a background to tt~ production both @TeV2 & @LHC
- tt~ production @TeV2 is largely through qq~ initial states and qq~->tt~ has an enhancement factor at the LHC of ~10
- tt~ has a gg initial state too, so total enhancement @LHC is a factor of 100
    - but increased W + jets background means that a higher jet cut is necessary at the LHC
    - jet cuts have to be higher at LHC than at Tevatron

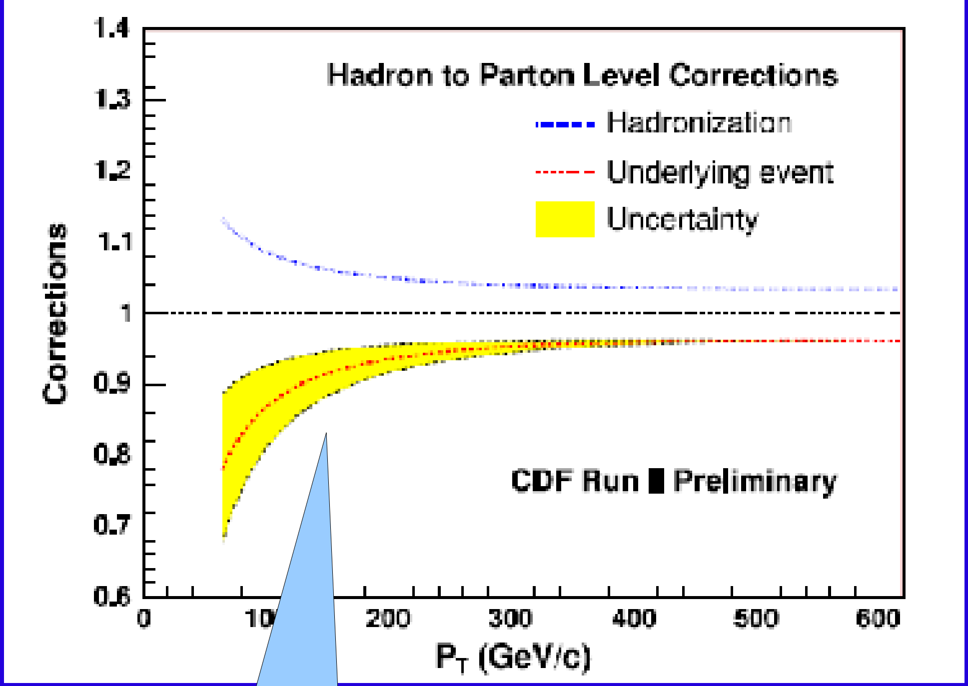


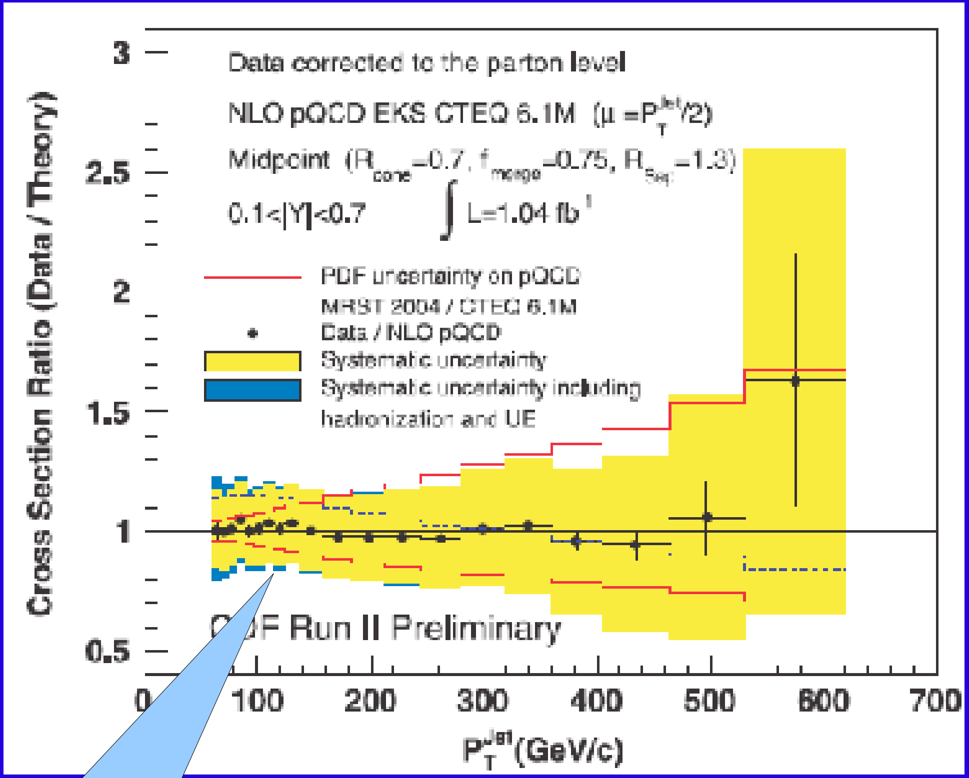


How well are the PDFs known?

Won't we just measure them?

Many systematics to overcome





Non-pert

Other systematics

Initial Lumi known to 10-20%

Error pdf's

- Central fit to PDF data does not reflect expt'l uncertainty
- Want ensembles
- Constrains parameters of chosen form:

$$F(x,Q_0)=A_0 x^{A_1}(1-x)^{A_2}P(x;A_3)$$

- Many parameters → many sets → eigenvalues

Error pdf's imply a level of precision that is inherent to NLO

- at NLO, can construct an orthonormal set of eigenvectors accompanying a level of precision corresponding to a given change of $\Delta\chi^2$ in the global fit
- that level of $\Delta\chi^2$ not well defined for LO fits

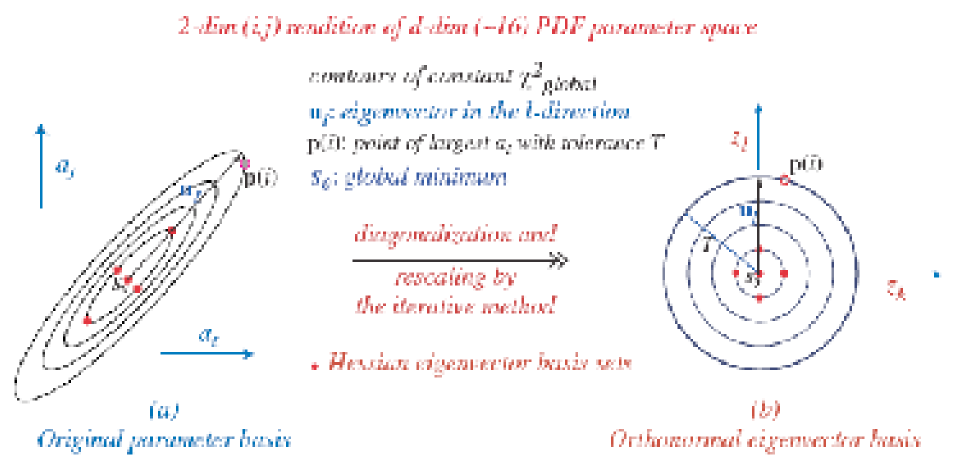
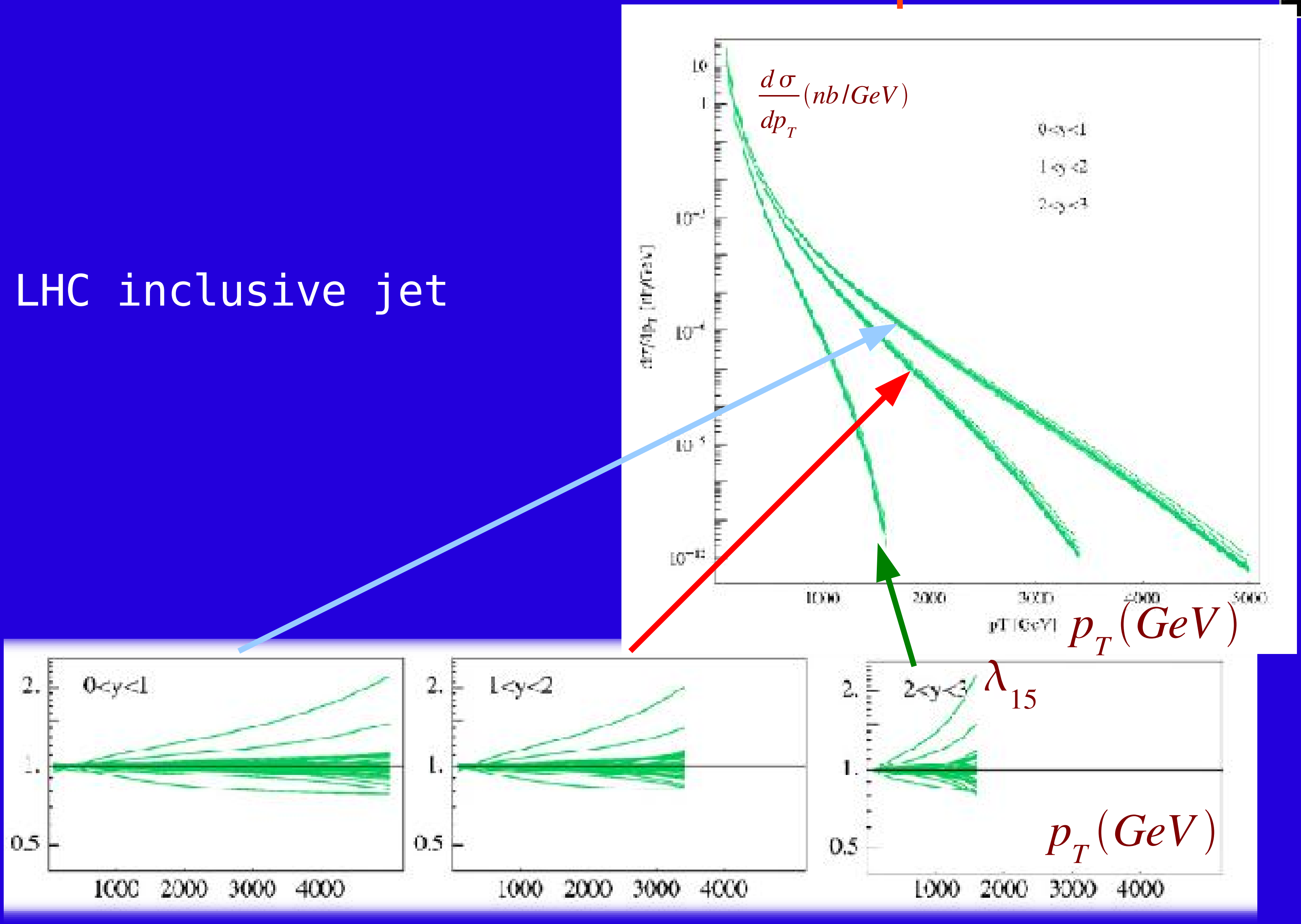


Figure 28. A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

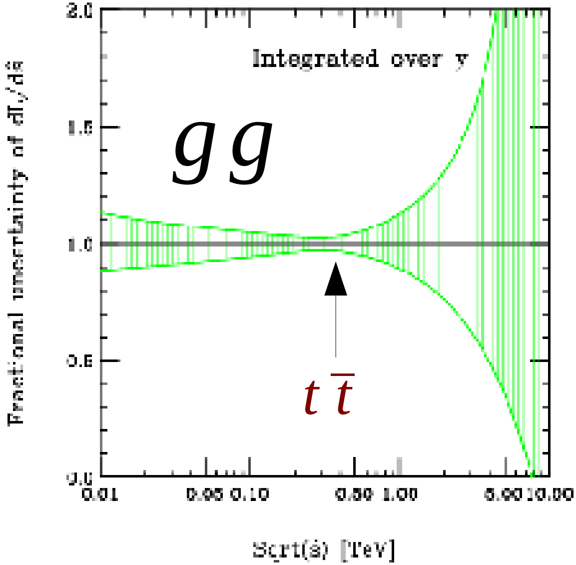
PDF errors: example

LHC inclusive jet

Ratio



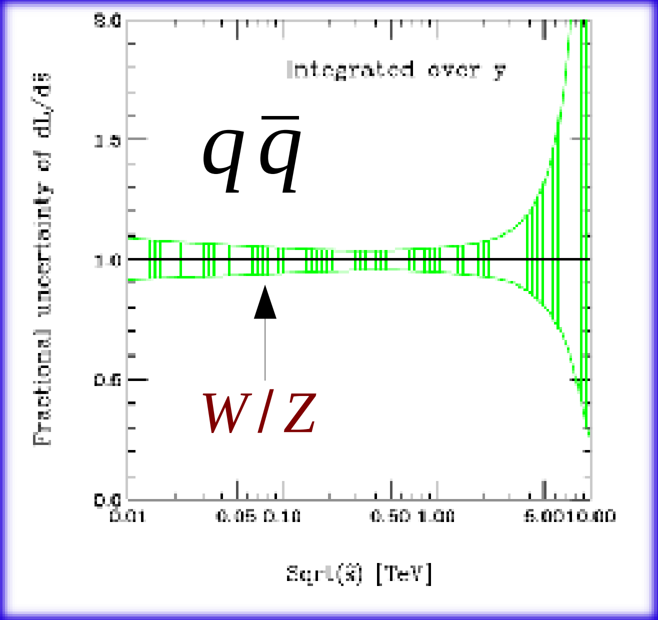
PDF uncertainties at the LHC



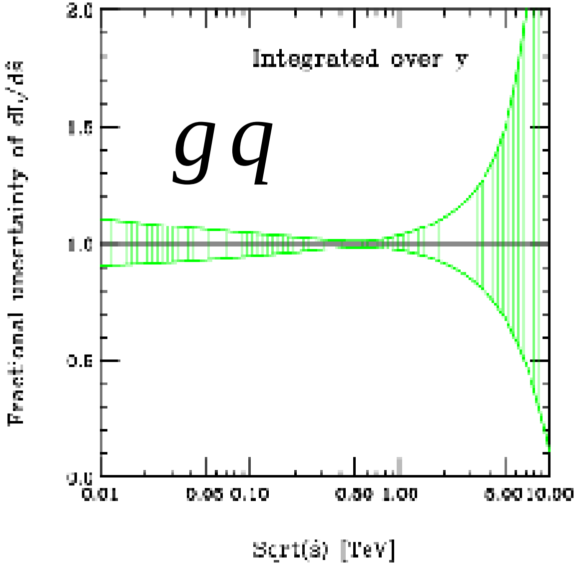
Under 1 TeV, PDF lumi known to 10%

Need similar precision in theory calculations

Limits when LHC data will impact PDF fits



Top uncertainty is of the same order as W/Z production



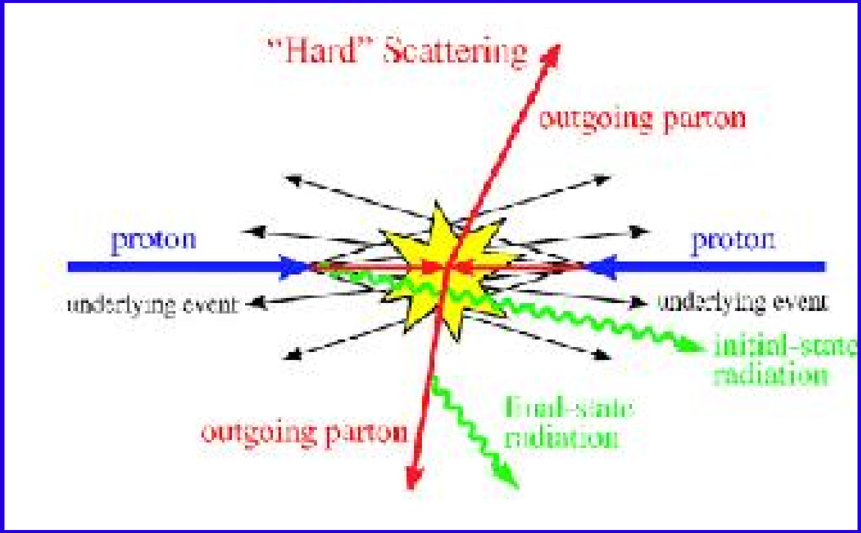
Errors are determined using the Hessian method for Chi^2 of 100 using only experimental uncertainties

Pdf uncertainties for W/Z cross sections are not the smallest

Benchmarks/cross section measurements at the LHC

Known unknown: underlying event @LHC

- Many different extrapolations
- Good LHC-Run1 measurement in 2009 @10 TeV
- Needed for comparing LHC data to theory



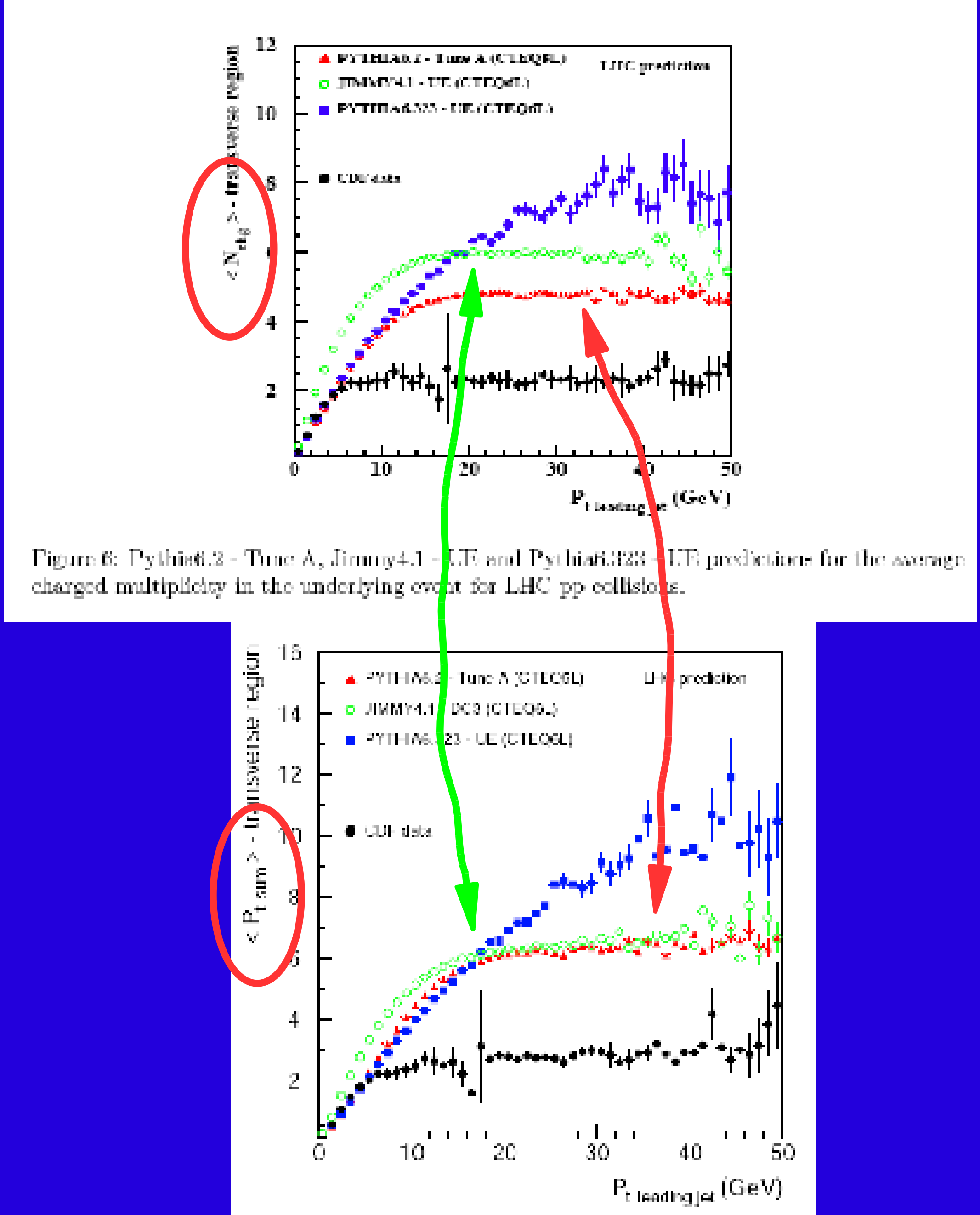
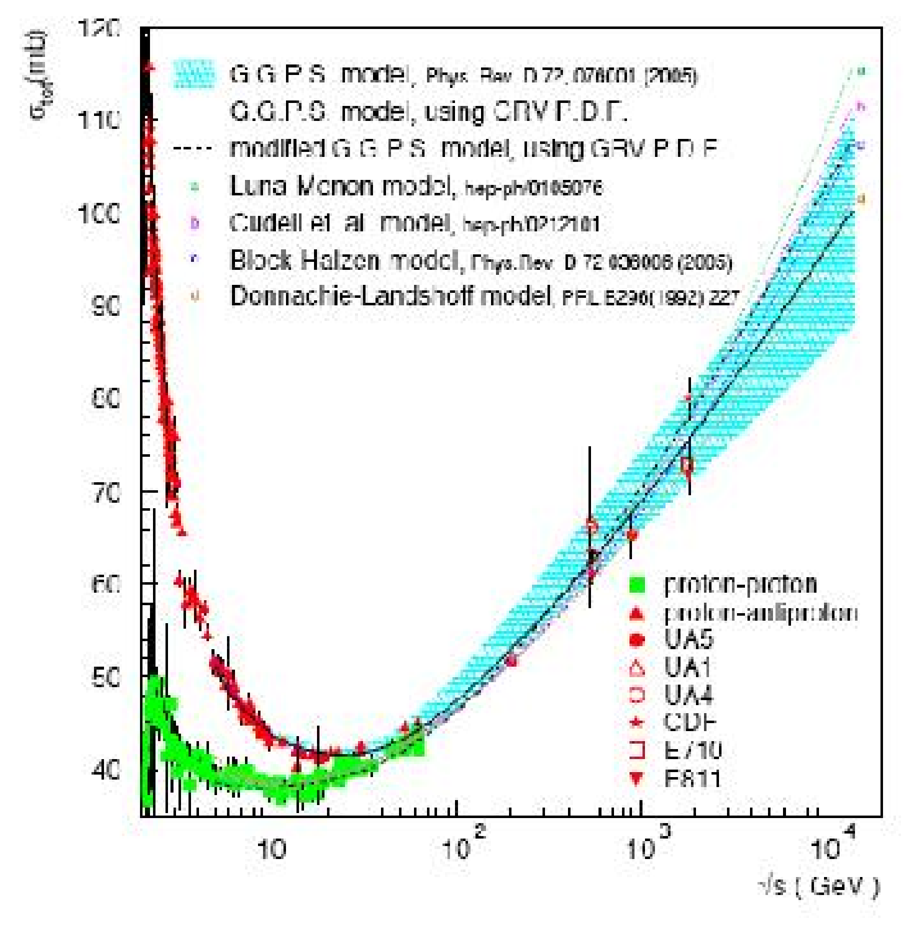


Figure 6: Pythia6.2 - Tune A, Jimmy4.1 - UE and Pythia6.323 - UE predictions for the average charged multiplicity in the underlying event for LHC pp collisions.

Total cross section @LHC (10-14 TeV)

- Fair amount of uncertainty on extrapolation to LHC
  - ln(s) or $\ln^2(s)$
  - 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
- σ_{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



Correlated with UE model!

Inclusive jet production

- Spans a very wide kinematical range, including the highest transverse momenta (smallest distance scales) of any process
- Note in the cartoon to the right that in addition to the 2->2 hard scatter that we are interested in, we also have to deal with the collision of the remaining constituents of the proton and anti-proton (the “underlying event”)
- This has to be accounted for/subtracted for any comparisons of data to pQCD predictions

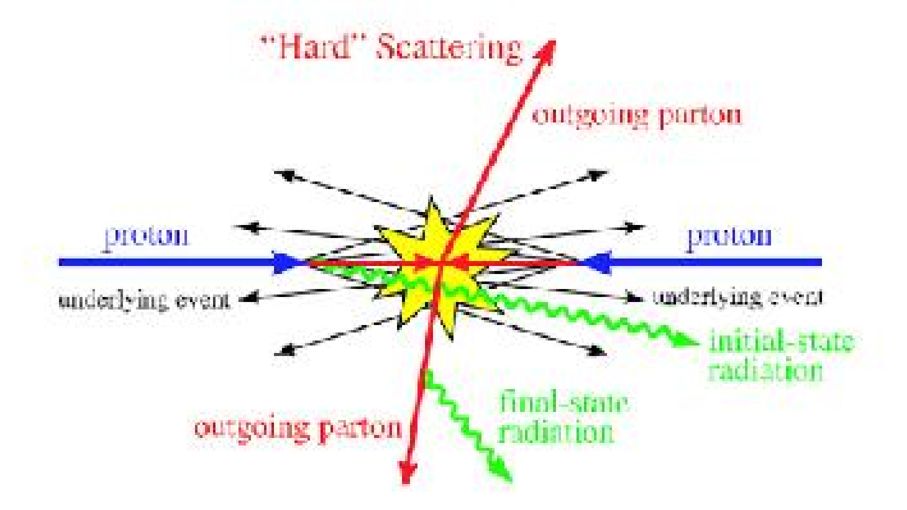
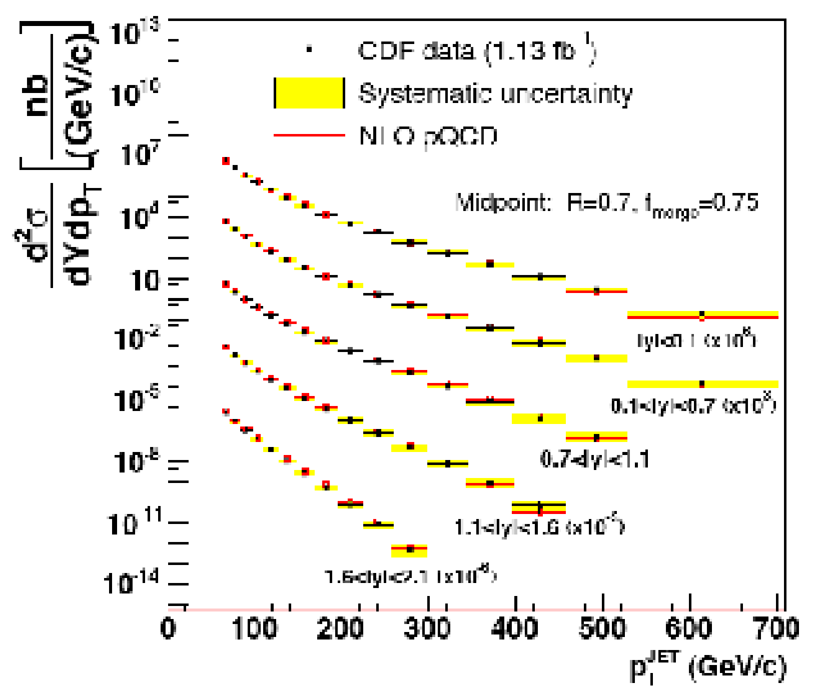
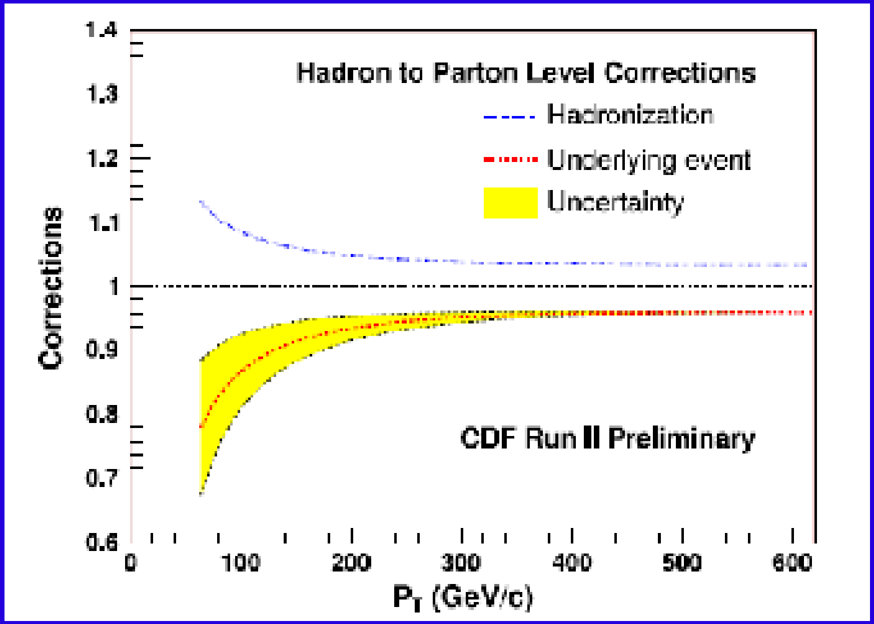


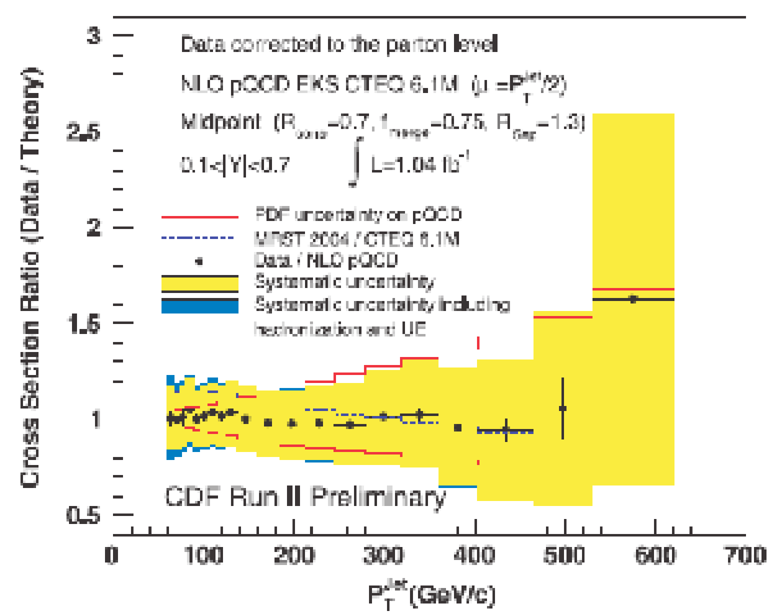
Figure 43. Schematic cartoon of a 2 → 2 hard-scattering event.



Inclusive Jet Corrections @TeV2

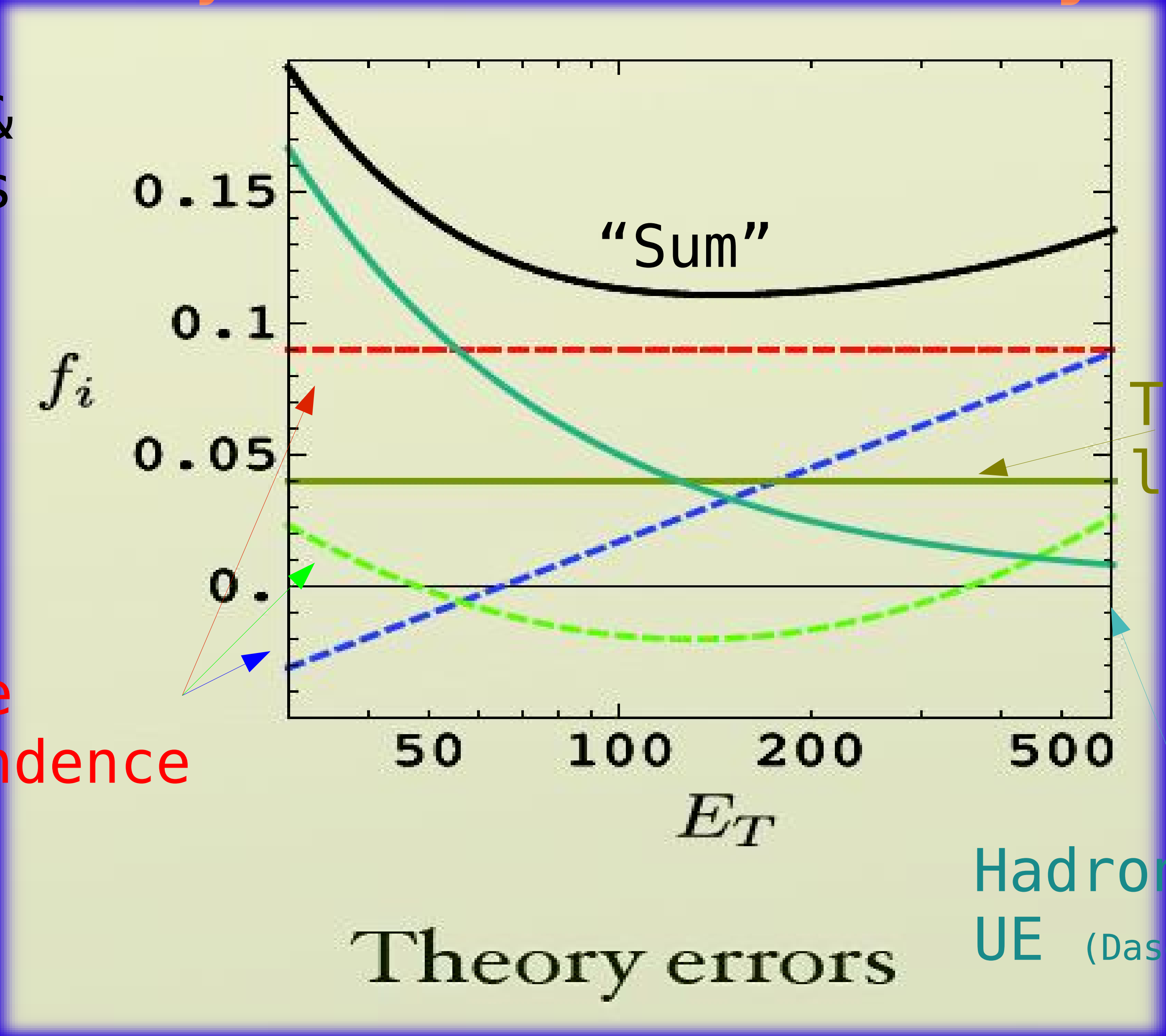
- Hadron to parton level corrections
  - subtract energy from the jet cone due to the underlying event
  - add energy back due to hadronization
    - partons whose trajectories lie inside the jet cone produce hadrons landing outside
  - the hadronization corrections will be similar at the LHC, while the UE corrections should be much larger
- Result is in good agreement with NLO pQCD predictions using CTEQ6 pdf’s
  - pdf uncertainty is similar to experimental systematic errors





“Theory error”: inclusive jets

Soper&
Olness



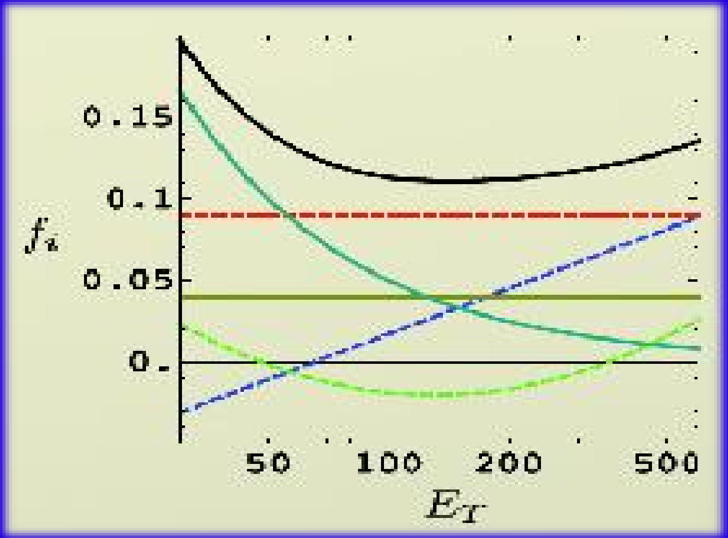
Threshold
logs

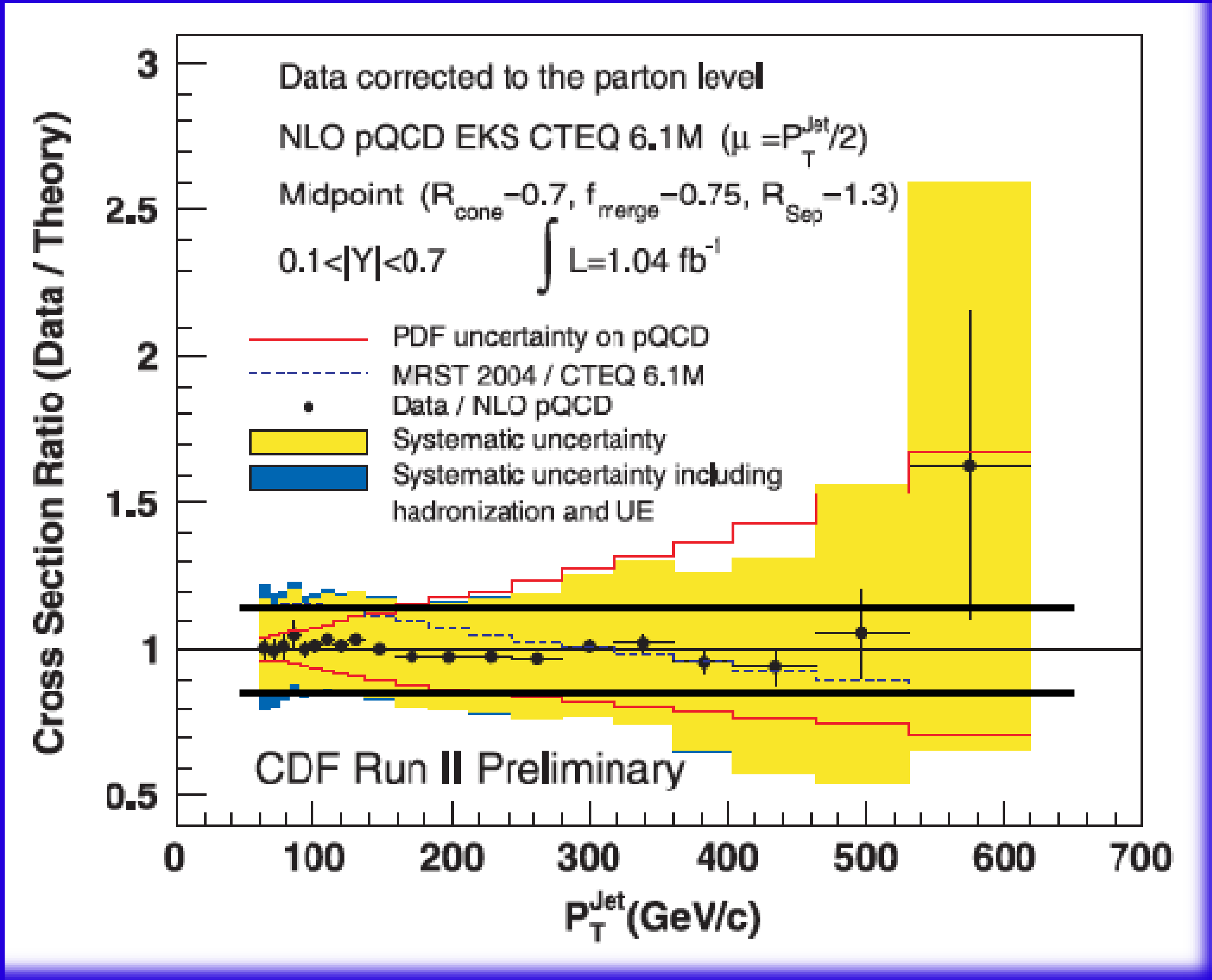
Scale
dependence

Hadronization
UE (Dasgupta et al)

Comparable to other errors

$$\frac{d\sigma}{dE_{T\,err}} = \frac{d\sigma}{dE_T}(1+f_i)$$





Intention:
add theory
error to
PDF fits

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

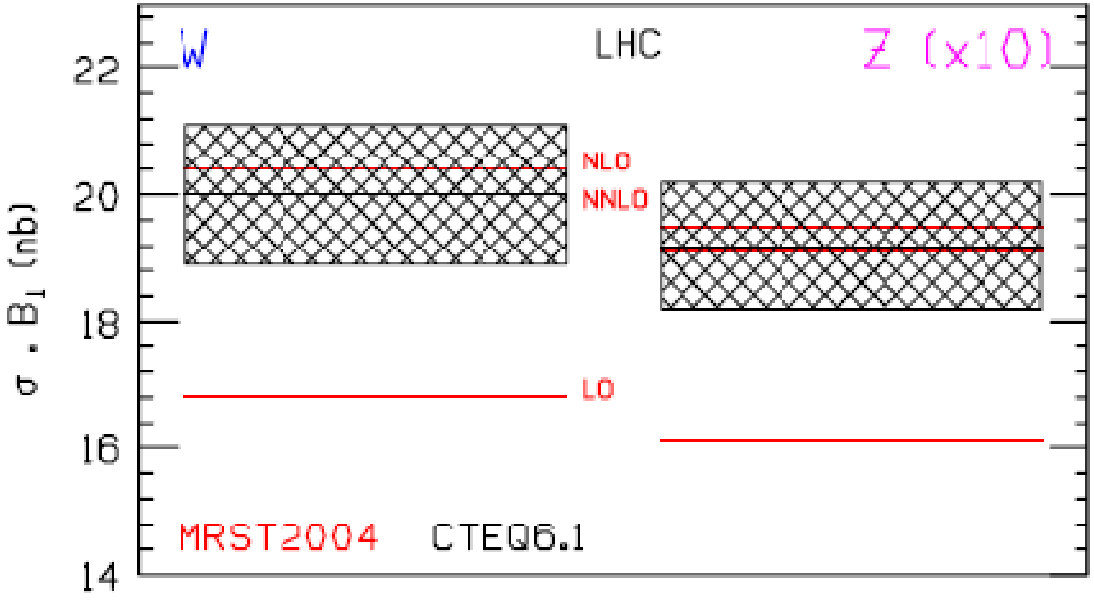


Figure 80. Predicted cross sections for *W* and *Z* production at the LHC using MRST2004 and CTEQ6.1 pdfs. The overall pdf uncertainty of the NLO CTEQ6.1 prediction is approximately 5%, consistent with figure 77.

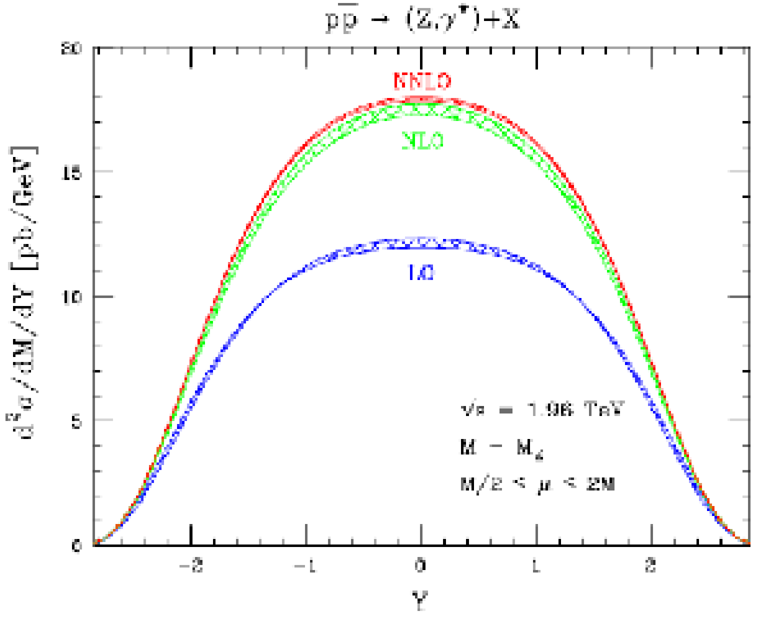


Figure 38. Predictions for the rapidity distribution of an on-shell *Z* boson in Run 2 at the Tevatron at LO, NLO and NNLO. The bands indicate the variation of the renormalization and factorization scales within the range $M_Z/2$ to $2M_Z$.

W/Z Overview

- 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 (more on this)
- Can we use Top production as an additional normalization tool?

Cross Section Correlations

$$N(t\,\bar{t}) = (lumi)\,x\,(efficiency)\,x\,((pdf)_{ij}\,x\,\sigma(ij \rightarrow t\,\bar{t}))$$

$$N(W) = (lumi)\,x\,(efficiency)\,x\,((pdf)_{ij}\,x\,\sigma(ij \rightarrow W))$$

$R = \frac{N(t\,\bar{t})}{N(W)}$ has no (lumi) uncertainty

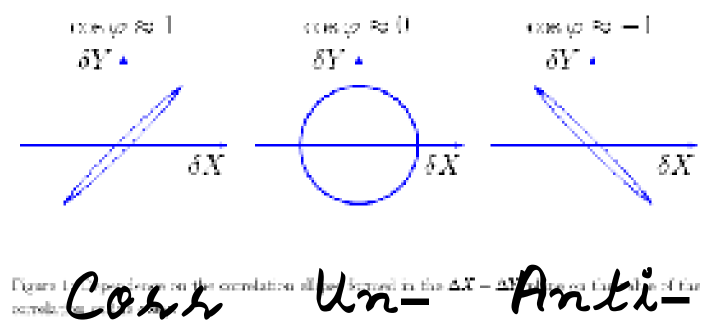
Correlation Matrix

$$\frac{\sigma_R^2}{R^2} = \frac{\delta^2(t)}{t^2} + \frac{\delta^2(W)}{W^2} - 2\frac{V_{tW}}{tW}$$

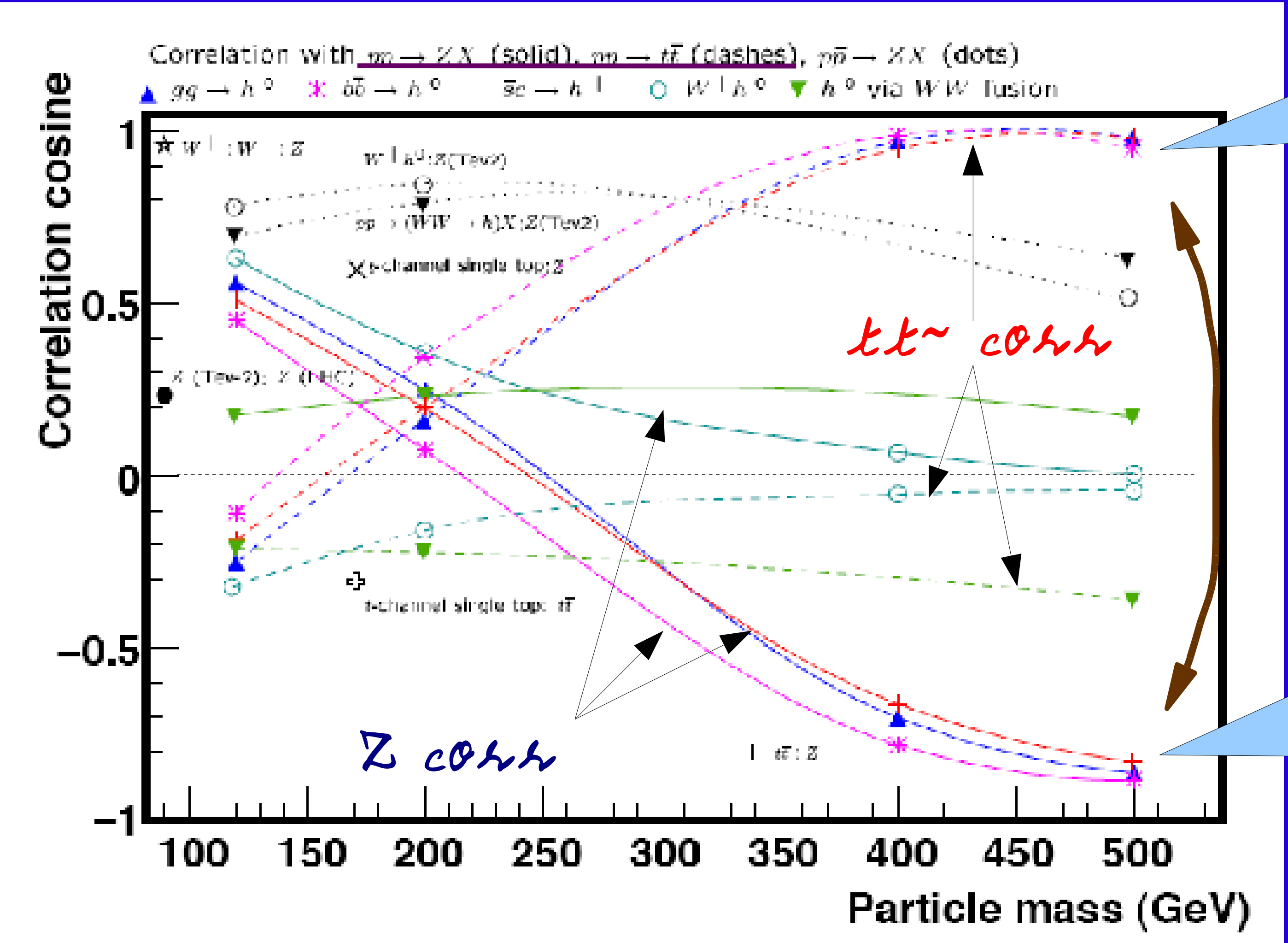
Method 2: N(Wbb+jets) = MC(Wbb+jets)/MC(W+jets)x N(W+jets)

Correlations with Z, tt~

Define a correlation cosine



gg->H(500 GeV) has 4% d-PDF

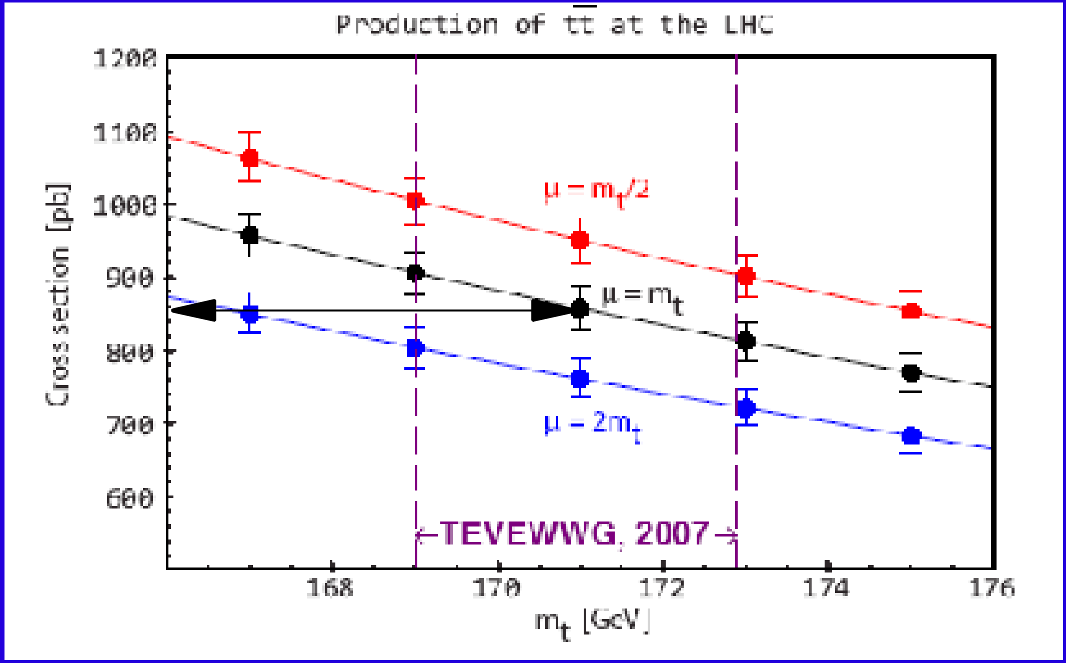


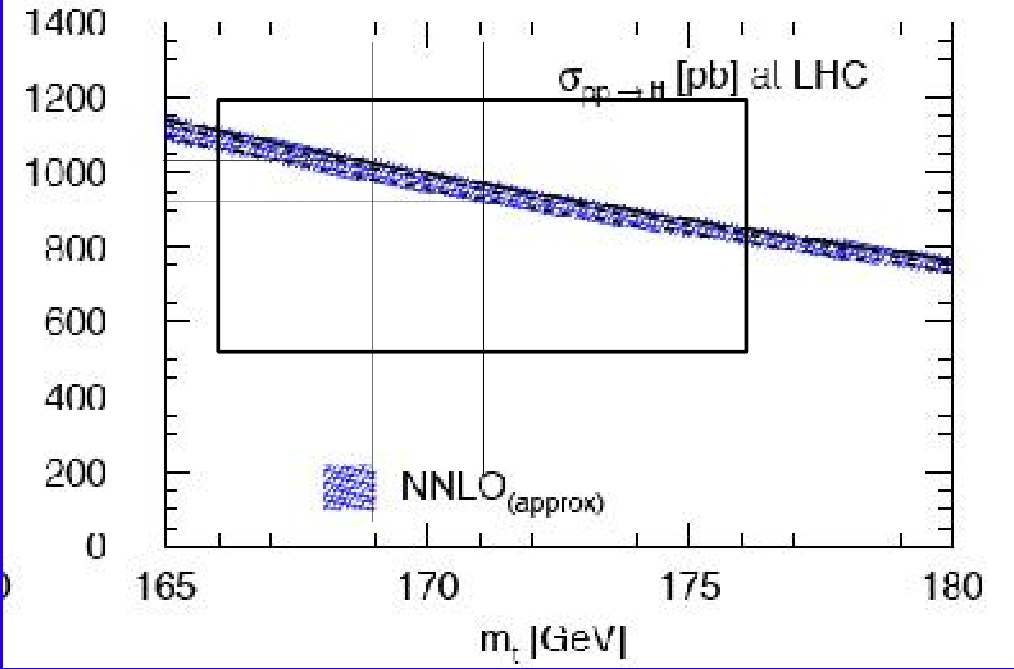
gg->H(500 GeV) has 1.5% d-PDF if using tt~

gg->H(500 GeV) has 7% d-PDF if using Z

Theoretical uncertainty on tt~

- Central value for $\mu = m_t$ is ~850 pb; ~880 pb if using 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 +/-3%
- NNLO tt~ cross section in the works
  - scale dependence will drop
  - threshold resummation reduces scale dependence to ~3% (Moch and Uwer)
- 6%?? → worse than Z
  - d-pdf is 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-lumi)