Summary and Outlook

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SLAC

KITP Conference on Collider Physics
Santa Barbara, 1/16/2004

Caveat emptor

There was a wide range of excellent talks
-- many thanks to Zvi, Zoltan, Joey and Kirill!

I could not possibly summarize them all

Try to give a flavor of some main themes,
recent progress, and outlook
for the workshop and beyond

Organizing Principles

In the words of Donald Rumsfeld:

"As we know, there are known knowns, there are things we know we know.

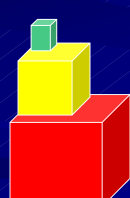
We also know there are known unknowns, that is to say we know there are some things we do not know.

But there are also unknown unknowns -- the ones we don't know we don't know."

Our science is frequently "just" about moving known unknowns into the category of known knowns -- but this work prepares us to venture into the unknown unknowns

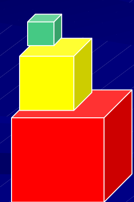
Cosmological Interpretation

known known	$\Omega_B = 5\%$
known unknown	$\Omega_M = 25\%$
unknown unknown	$\Omega_\Lambda = 70\%$



Collider Physics Interpretation

known known	Standard Model processes computed, measured, OK
known unknown	SM processes uncomputed, unmeasured, or problematic
unknown unknown	Beyond the Standard Model



Current experimental situation

Mostly known known: Overall, Standard Model in great shape

However, there are a number of 2.5-3.5σ known unknowns.
Are they statistics, experimental or theoretical systematics?
Or could one or more of them herald the unknown unknown?

Precision Electroweak

Generally good agreement, but some tension in fit.

Overall the EW precision tests support the SM and a light Higgs.

The χ^2 is not great:

χ^2/ndof=25.5/15 (4.4%)

Note: includes NuTeV and APV [not $(g-2)_\mu$]

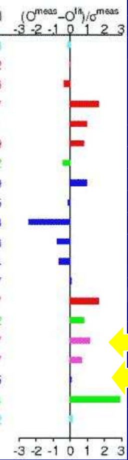
Without NuTeV:
(th. error questionable)

χ^2/ndof=16.7/14 (27.3%)
Much better!

G. Altarelli

Winter 2003

	Measurement	Pull
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	-0.16
m_Z [GeV]	91.1875 ± 0.0021	0.02
Γ_Z [GeV]	2.4952 ± 0.0023	-0.36
σ_{had}^0 [nb]	41.540 ± 0.037	1.67
R_l	20.767 ± 0.025	1.01
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.79
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.42
R_b	0.21644 ± 0.00065	0.99
R_c	0.1718 ± 0.0031	-0.15
$A_{fb}^{0,b}$	0.0995 ± 0.0017	-2.43
$A_{fb}^{0,c}$	0.0713 ± 0.0036	-0.78
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.07
A_l(SLD)	0.1513 ± 0.0021	1.67
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.82
m_W [GeV]	80.426 ± 0.034	1.17
Γ_W [GeV]	2.139 ± 0.069	0.67
m_t [GeV]	174.3 ± 5.1	0.05
NuTeV → $\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	2.94
APV → $Q_W(Cs)$	-72.83 ± 0.49	0.12



ones to watch

Tevatron Run II Data

CDF, D0 performing well.
~220 pb^{-1}/expt up to 8/03 shutdown
~100 pb^{-1}/expt shown here
Quick recovery from shutdown.

Wood, Huston, Witherell, Yao

Rich menu of energy frontier physics for next few years:

- New physics searches
- Precision electroweak: W, Z, top measurements
- Di-vector boson production
- Jets
- b and charm physics

We got the appetizers this week

Example: W production

Huston

	Sample	Back.	$\sigma \cdot B(W \to l\nu_l)$ (nb)		In 2 fb^{-1}
e	38625	6%	$2.64 \pm 0.01_{stat} \pm 0.09_{sys} \pm 0.16_{lum}$	→	~1.1M
μ	21599	11%	$2.64 \pm 0.02_{stat} \pm 0.12_{sys} \pm 0.16_{lum}$	→	~600K
τ	2346	26%	$2.62 \pm 0.07_{stat} \pm 0.21_{sys} \pm 0.16_{lum}$	→	~65K

CDF
72 pb^{-1}

- Already completely systematically limited, not even counting luminosity uncertainty
- Same true for *Z*
- Better theoretical description of lepton rapidity and p_T would surely help with acceptance systematics.

LO	LO, Γ_W=0	LO, no spin corr's	LO, PDF= CTEQ6.19
0.4890(2)	0.4971(2)	0.5259(2)	0.5245(2)

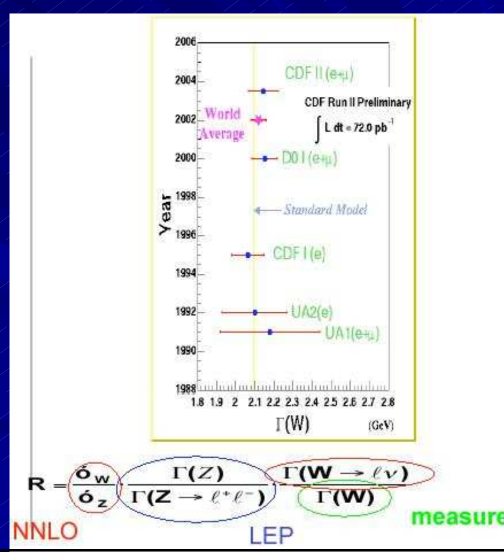
Mangano

- For luminosity uncertainty, probably must soon switch to W,Z as "luminosity monitor" (quote σ_X/σ_W)

W to Z ratio

Huston

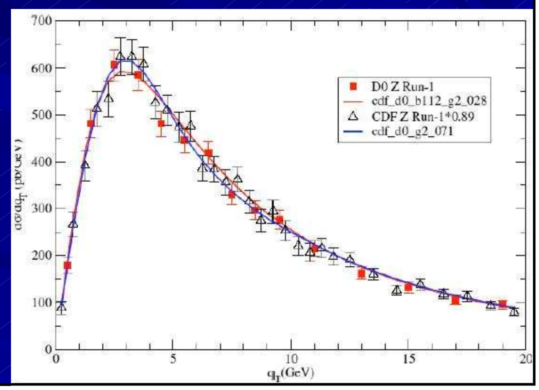
- R cancels the luminosity uncertainty
- Can also view as measurement of σ_W/σ_Z instead of $\Gamma(W)$.
- PDF test, but not very orthogonal to existing constraints.



p_T distributions and resummation

Huston

- Well measured for *Z*, tests resummation formalism and determines critical parameters for m_W measurement.
- *Z* and especially $\gamma\gamma$ p_T distribution excellent preparation for gg -> Higgs at LHC.

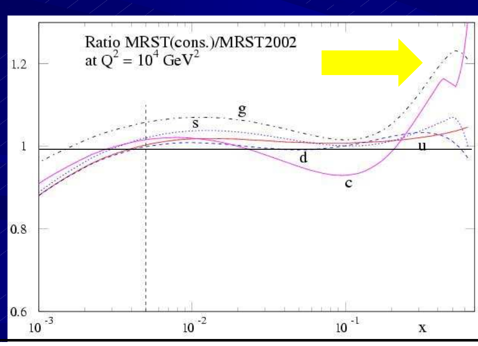


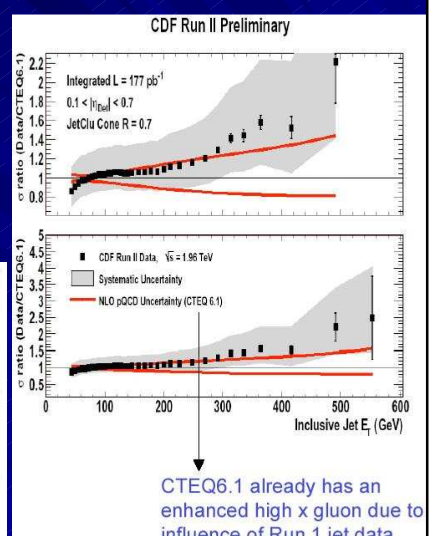
Jets

Huston

- High cross section (vs. Drell-Yan) -> most direct probe of shortest distance scales.
- Tension between high E_T jet data and pdf fits – alleviated by omitting small x, Q^2 data

Stirling





Jets

Do we need NNLO jet cross sections at hadron colliders?

- After all, jets are rather complicated objects
- Steep E_T dependence magnifies energy scale uncertainties
- Underlying event a problem (630 vs. 1800 data, energy flow studies)

Still, I think the answer is YES ---

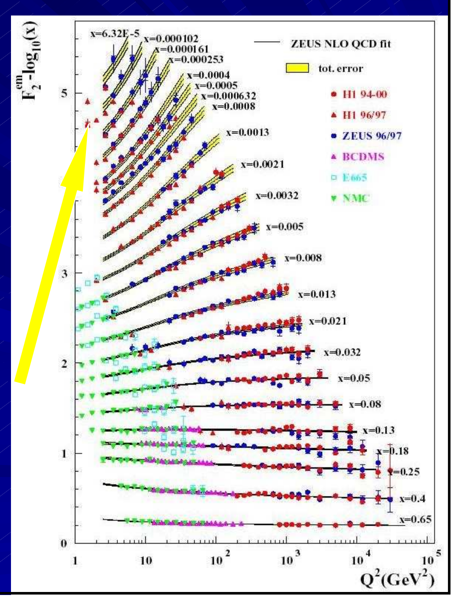
If nothing else, to focus more attention on these problems

- Less μ-dependence to hide behind
- Less worries (one hopes) about matching theoretical and experimental jet algorithms, e.g. R_{sep} parameter artificially introduced into NLO theory

QCD at HERA

Wolf

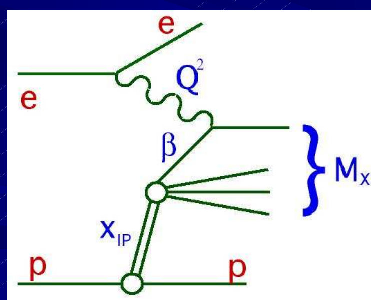
- Beautiful agreement between F_2 data and QCD evolution over a broad range of Q^2 and x
- Without these data we would be unable to make precise cross section predictions for Tevatron, LHC.
- Recall tension between Run II high E_T jet data and pdf fits – alleviated by omitting small x, Q^2 data (NLO evolution inadequate?) Stirling
- HERA2 data will improve precision further, push into fixed target region.

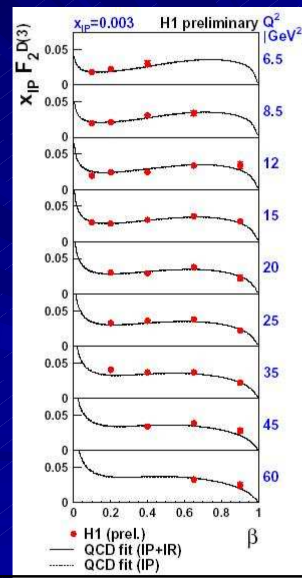


QCD at HERA

Wolf

- 10% of DIS is diffractive
- Pomeron (not just a pole in the J plane!) looks much like a gluonic proton.

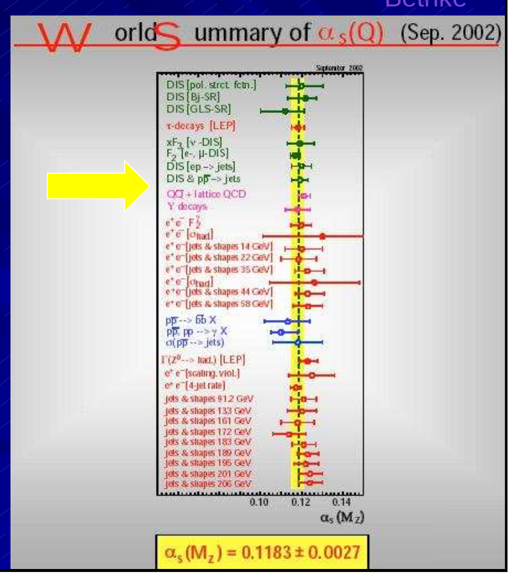




$\alpha_S(Q)$ and Jets in e^+e^- annihilation

Bethke

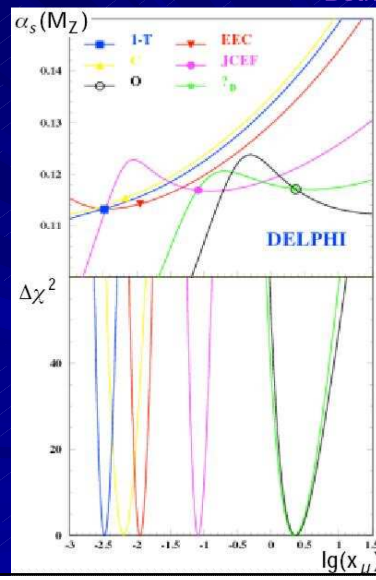
- Good agreement between many types of measurements over many decades in Q (N_c = 3.00 +- 0.10) and in t (= time) (JADE data)
- NLO theory – even resummed -- clearly limiting e^+e^- event shape extractions – eagerly awaiting NNLO
- Also eagerly awaiting imminent lattice gauge theory result! Trottier



$\alpha_S(Q)$ and Jets in e^+e^- annihilation

Bethke

- DELPHI use of experimental distributions to "determine" renormalization scale μ.
- Very interesting to re-examine when NNLO results are available.



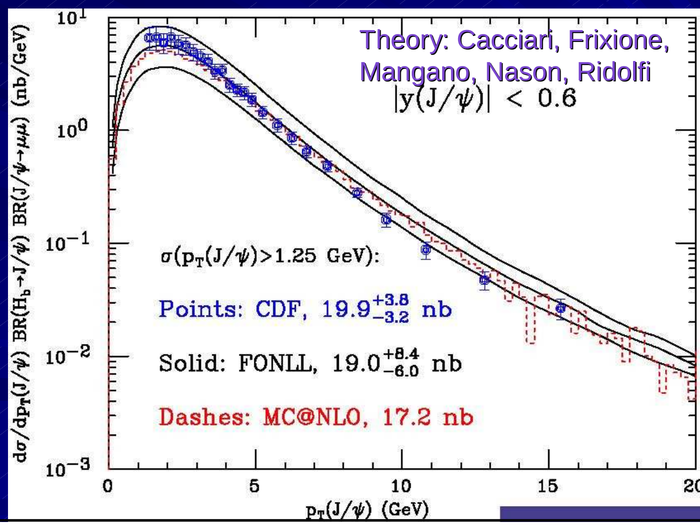
A partial list of anomalies

- Tension in EW precision fit between A^b_{FB}, A^e_{LR}, m_H > 114 GeV — Altarelli
- Muon anomalous magnetic moment — Altarelli, Marciano
- Pdf tension between small x, Q^2 DIS and Tevatron high E_T jet data — Huston, Stirling
- CP asymmetry in B -> (s penguin) (ϕK_s + …) vs. B -> (J/ψ)K_s (3.1σ)
- NuTeV measurement of $\sin^2\theta_W$ — Altarelli, Marciano, Stirling
- LSND (wait for miniBooNe!) — Witherell

anomalies, part B

- B production at Tevatron – no longer!!

Huston, Gehrmann, Frixione

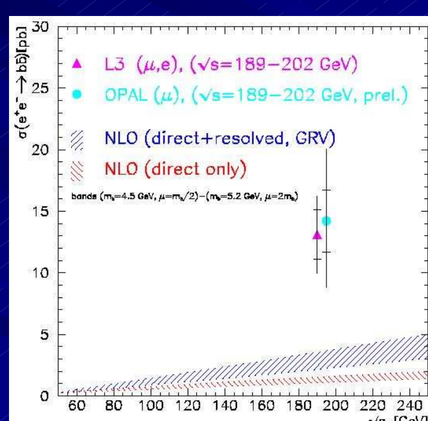


anomalies, part b

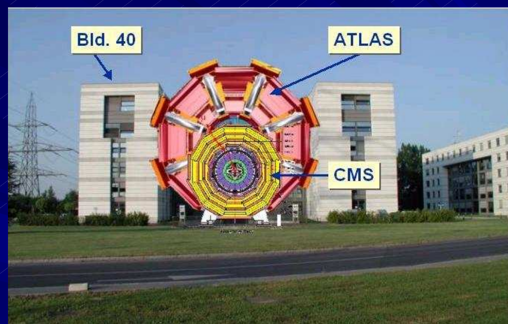
- b production in $\gamma\gamma$ collisions

Gehrmann

More theoretical attention needed? Large acceptance issues



The LHC is Coming!



Dissertori, Hinchliffe

- Promises to take us deep into the unknown unknown
- Detectors, triggers optimized for SM objects likely to appear in new physics decays:

  jets, leptons, isolated γs, missing E_T, b tagging; W,Z; top

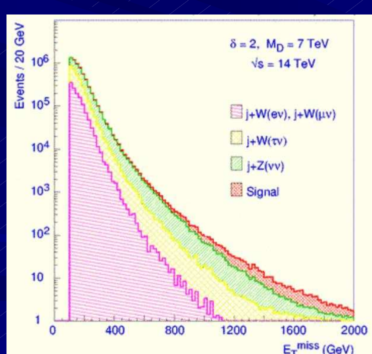
.

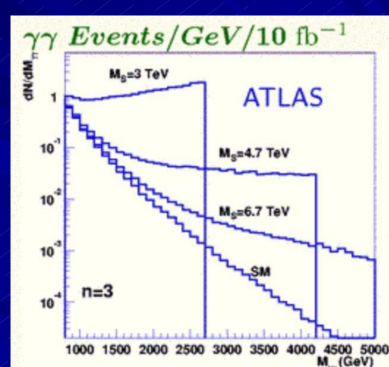
LHC ready for extra dimensions

Hinchliffe

Whether they are large and flat

Direct: $q\bar{q}$ -> graviton + γ(g) Indirect: gg -> graviton -> γγ





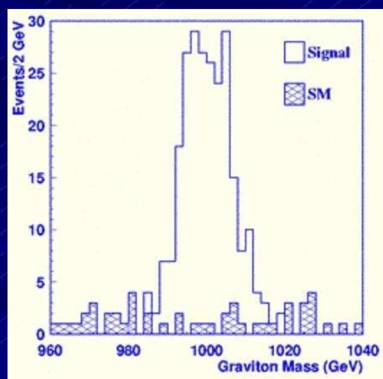
LHC ready for extra dimensions

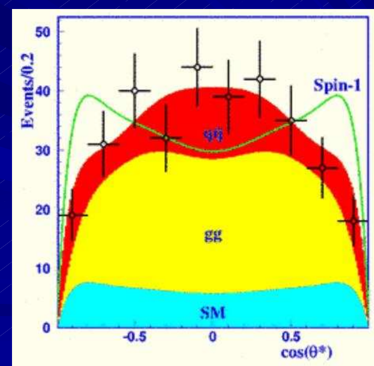
Hinchliffe

warped

resonant gg -> graviton -> e^+e^-

check it's not spin 1



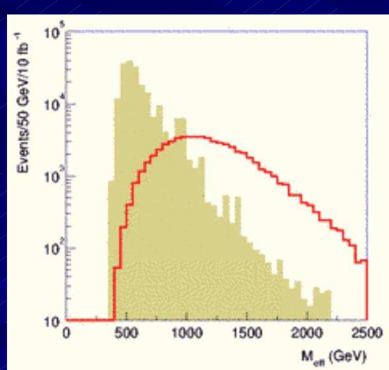


Hinchliffe

LHC ready for extra dimensions

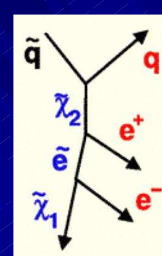
fermionic (SUSY)

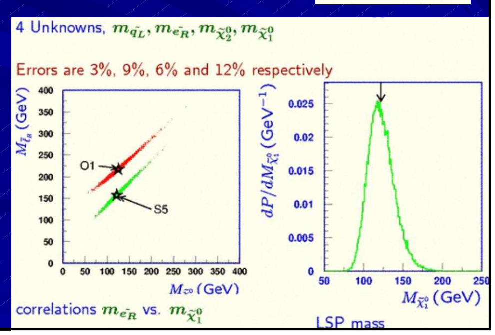
Find it and set the mass scale



$$M_{\text{eff}} = P_{t,1} + P_{t,2} + P_{t,3} + P_{t,4} + \not{E}_T$$

cascade kinematics gives several (correlated) masses





Hinchliffe

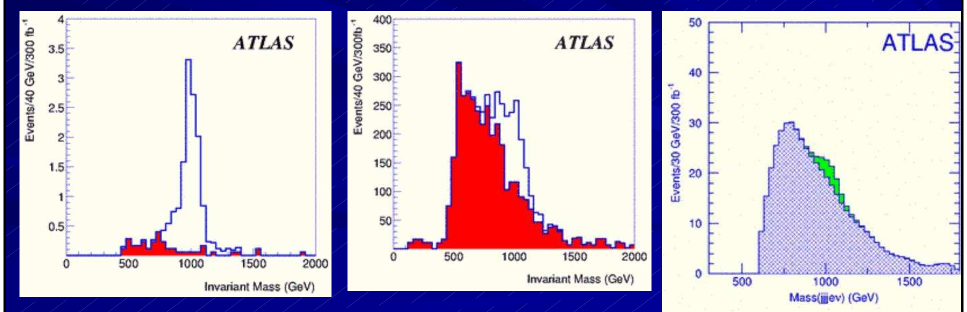
LHC ready for extra dimensions

in theory (group) space (Little Higgs)

T = top quark partner cancels $\delta m^2_H|_{top}$

observe in 3 modes, test branching ratios

$T \to Z\,t \to l^+ l^-\, b l \nu$ $T \to W\,b \to l^+ \nu\, b$ $T \to h\,t \to b\bar{b}\, b l \nu$

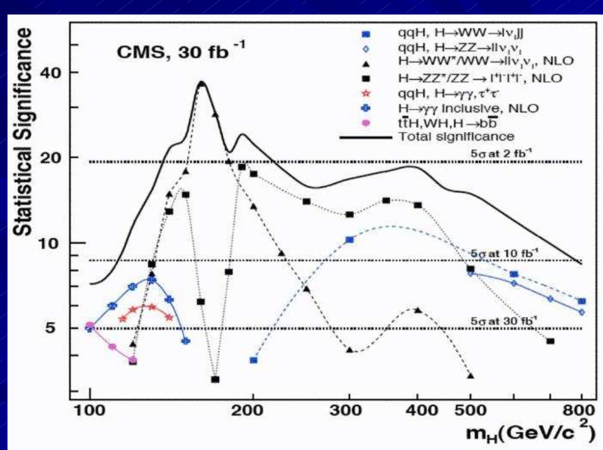


LHC also ready for the Higgs

Dissertori

- Lots of work has gone into each of these curves.
- Lots more required for many of them:
  - ttH,
  - forward jet tagging for weak boson fusion,

  etc.
- SUSY Higgs parameter space will be well covered too.



BUT NOTE : no systematic errors included!

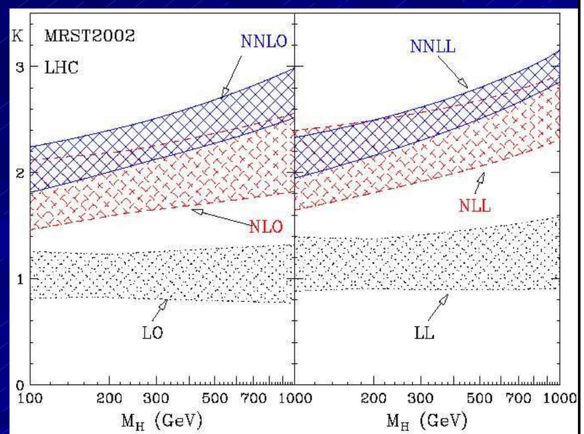
Higgs production (gluon fusion)

Kilgore

- Lots of work has gone into each of these curves too!

Harlander, Kilgore;
Anastasiou, Melnikov;
Smith, Ravindran, van Neerven;
Catani, Grazzini, De Florian, Nason

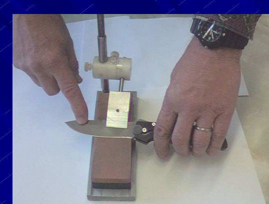
- Launched flexible new ways of doing difficult phase-space integrals.



- bb -> (MSSM) Higgs at NNLO - also important for validating b structure function approach

Harlander, Kilgore

Sharpening Our Tools



Theoretical tools span a wide range:

- Mathematical tools
- Computer algebra
- Integration/phase space techniques; analytical and numerical
- Understanding of soft and collinear behavior: resummation of large logs, semi-analytically or via parton showers
- Monte Carlos: Indispensable tool for qualitative description of exclusive events at hadron level, now becoming increasingly quantitative

Mathematical Tools

Analytic understanding of the "solution space" for Feynman integrals:

- DIS in moment (*N*) space: Harmonic sums — Moch

$$S_{m_1 \ldots m_k}(N) = \sum_{i=1}^{N} \frac{1}{i^{m_1}} S_{m_2 \ldots m_k}(i)$$

- DIS in *x* space; 2-loop integrals for multi-scale problems: Harmonic polylogarithms — Gehrmann
- Unitarity; also supersymmetry relations — Campbell

Waiting in the wings?

- Twistor space; sheaf cohomology (Witten, hep-th/0312171)

Computer Algebra Tools

Makes many other mathematical tools feasible:

- Integration by parts, Lorentz invariance identities

  ⇒ **Large** systems of linear equations (10^4 - 10^6) to solve recursively or by Gauss elimination.
- Process thousands of Feynman diagrams. — Moch, Gehrmann
- FORM, Maple, Mathematica are the slide rules of our time (for many of us)
- Yes, they will look just as quaint in 30 years (at least their user interfaces)

Integration/Phase Space Tools

Gehrmann
Kosower

- Loop integration techniques (IBP, Lorentz invariance) can be applied to phase-space integration to give analytic results for singular integrals, order by order in dim. reg. parameter ε.
- Including those for NNLO "tripole" subtraction terms — Gehrmann-De Ridder, Gehrmann, Heinrich; Weinzierl
- Sector decomposition, also invented for loop integrals, allows numerically stable direct evaluation of NNLO e^+e^- -> 2-jet observables. Anastasiou, Melnikov, Petriello
- Efficient phase-space generation also important for accurate and fast evaluation of multi-particle cross sections with multi-channel peaking behavior: Mangano

RAMBO, EXCALIBUR,…

Sector decomposition, numerically

Anastasiou, Melnikov, Petriello

- Most important lessons of this technique:
  - Not necessary (for a human) to understand the behavior of the integrand in the various singular regions.
  - Not necessary to integrate singular terms analytically to verify cancellations.
- Method looks generalizable to the NNLO 3-jet problem
  - Either directly on the 5-particle phase space (5-variables -> 8-variables)
  - Or to integrate subtraction terms over 4-particle subspaces.
- Even simpler application: NNLO W, Z, Higgs production

(Mangano, Kilgore)

Resummation Tools

Sterman

- Soft/collinear factorization of cross section -> summation of large logs inevitably encountered in QCD
- Mandatory for Q_T distributions of W, Z, Higgs
- Highly desirable for threshold production of heavy objects (or even gg -> Higgs)
- Now carried out at high accuracy (NNLL)
- Automated NLL numerical program (CAESAR) — Banfi, Salam, Zanderighi
- Also at the heart of parton showering – can this accuracy be improved too? (Marchesini)
- At amplitude level, factorization provides understanding of 1/ε poles, as well as ingredients for building general subtraction/slicing methods for NLO and now NNLO.

Gehrmann, Kosower, Sterman

Monte Carlo Tools

Mangano

Three complementary approaches

	ME MC's	X-sect evaluators	Shower MC's
Final state description	Hard partons jets. Describes geometry, correlations, etc	Limited access to final state structure	Full information available at the hadron level
Higher order effects: loop corrections	Hard to implement, require introduction of negative probabilities	Straighforward to implement, when available	Included as vertex corrections (Sudakov FF's)
Higher order effects: hard emissions	Included, up to high orders (multijets)	Straighforward to implement, when available	Approximate, incomplete phase space at large angle
Resummation of large logs	??	Possible, when available	Unitary implementation (i.e. correct shapes, but not total rates)

and their automotive analogs

Monte Carlo Tools

Mangano
Frixione

Two very interesting recent mergings of these tools:

- LO multijet MEs + shower MCs – (double count)

  (Catani, Krauss, Kuhn, Webber; Lonnblad; Mrenna, Richardson)

- Shower MCs with NLO accuracy, (Dobbs, GRACE)

  -> MC@NLO (Frixione, Webber)

and their automotive analogs are?

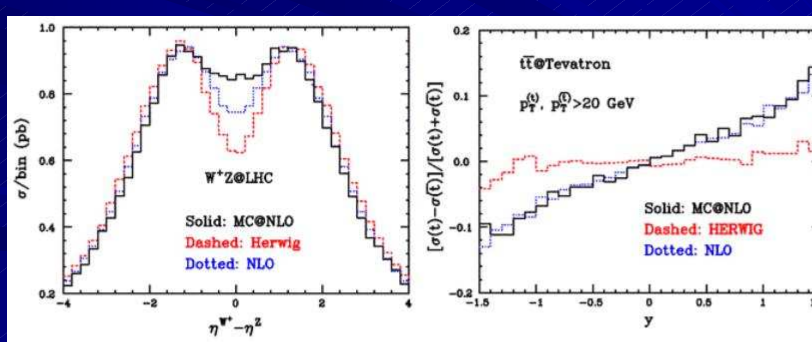
MC@NLO results

Frixione
Webber

Key NLO features retained,
plus additional soft radiation,
exclusive event structure

WZ approx. radiation zero further filled

One-loop $t\bar{t}$ charge asymmetry maintained



NLO QCD corrections

Campbell

An experimenter's wishlist

- Hadron collider cross-sections one would like to know at NLO

Run II Monte Carlo Workshop, April 2001

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

Conclusion: We do need more experiment-theory dialog after all!

NLO QCD status

Campbell

- Still, an impressive amount of recent progress (from theorist's perspective):
  - NLOJET++ (Nagy) pp -> (2,3) jets, e^+e^- -> (3,4) jets, ep -> (2,3)+1 jets
  - AYLEN/EMILIA (DeFlorian, LD, Kunszt, Signer) pp -> (W,Z)+(W,Z,γ)
  - DIPHOX/EPHOX (Aurenche, Binoth, Fontannaz, Guillet, Heinrich, Pilon, Werlen) pp -> γ + jet, pp -> $\gamma\gamma$, γp -> γ + jet
  - MCFM (Campbell, Ellis) $p\bar{p}$ -> (W,Z) + (0,1,2) jets, $p\bar{p}$ -> (W,Z) + $b\bar{b}$
  - (Mangano, Nason, Ridolfi) pp -> $Q\bar{Q}$
  - (Harris, Laenen, Phaf, Sullivan, Weinzierl) pp -> $Q\bar{q}$
  - (Dawson, Jackson, Orr, Reina, Wackeroth; Beenakker, Dittmaier, Kramer, Plumper, Spira, Zerwas) pp -> $Q\bar{Q}H$
- For a more complete list (LO, NNLO, MC, EW), and to find the codes, see: http://www.ippp.dur.ac.uk/~wjs/HEPCODE/

If your code is not there, let James know - he'll add it! Stirling

NLO QCD prospects

Campbell

- Frontier is "one more leg" [or "one more mass"]
- Virtual corrections are the bottleneck
- Probably it is time to "automate" and go numerical
- Subtraction of IR and UV divergences more or less understood (Dittmaier; Nagy, Soper)
- Issue of "when" you go numerical, before or after some reductions?
- Do you want to do lots of integrals on the fly? Or fewer, once and for all, but worry more about spurious singularities (Gram determinants)?
- Definitely a good topic for this workshop.
- Also important:
  - Prioritization of wishlist
  - Porting to MC@NLO
  - Matching to resummed calculations
  - Improvements to methods for real radiation (slicing, subtraction)

Don't forget NLO EW corrections

Sudakov effects lead to growth with Q:

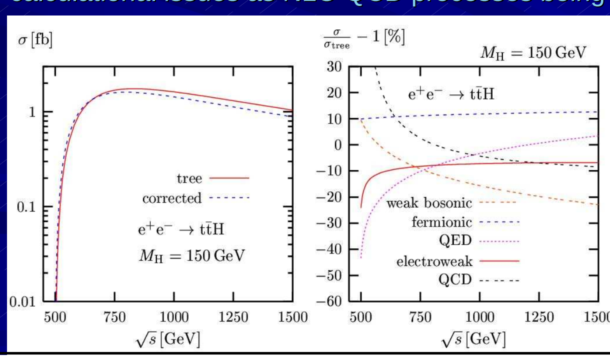
$$\delta\sigma \propto \frac{\alpha_W}{\pi}\ln^2(Q/M_W)$$

Corrections important for high mass systems

- divector-boson production
- ttH production

at LHC, LC.

Similar calculational issues as NLO QCD processes being contemplated

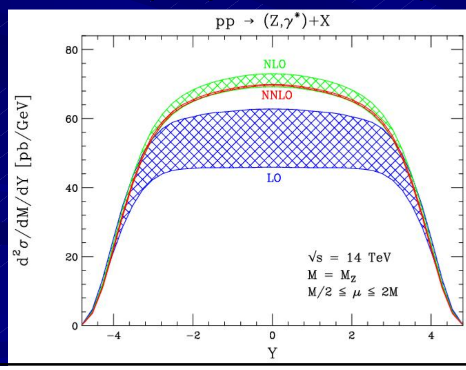


NNLO for collider processes

Gehrmann
Kosower

- Still at the "artisanal" stage, limited to special quantities:
  – Total cross sections for color singlet objects
  -- And now, rapidity distributions (one more δ-fn)

Hamberg, Matsuura, van Neerven (1991)



- But the tools are in place for rapid industrialization.

Anastasiou, LD, Melnikov, Petriello

Conclusions

- Energy frontier physics has a very bright decade ahead with the Tevatron and particularly the LHC
- Expect to step deeply into the unknown unknown in 2007-2010
- Transform it/them into at least a known unknown some time thereafter?
- Guided also by precision/rare experiments at lower energies, e.g. B CP asymmetries and rare decays, muon g-2, μ->e conversion, Z pole observables, neutrino physics, neutron EDM
- Also guided by theory:
  – models for physics beyond the Standard Model
  – increasingly refined Standard Model predictions, to nail down the experimental backgrounds and calibrate the new physics
  – same tools to directly refine the new physics signatures, once they emerge.
- For ultimate understanding, so new known unknowns -> known knowns linear collider almost certainly required.

Conclusions

If we are very lucky, new physics will soon hit us over the head

But we should prepare for more subtle possibilities too!

What can theorists do

To assist more directly in experimental analyses?

- S. Frixione: Fully employed in adding more processes to MC@NLO
- But what about the rest of us?