QCD, jets and Monte Carlo: theory

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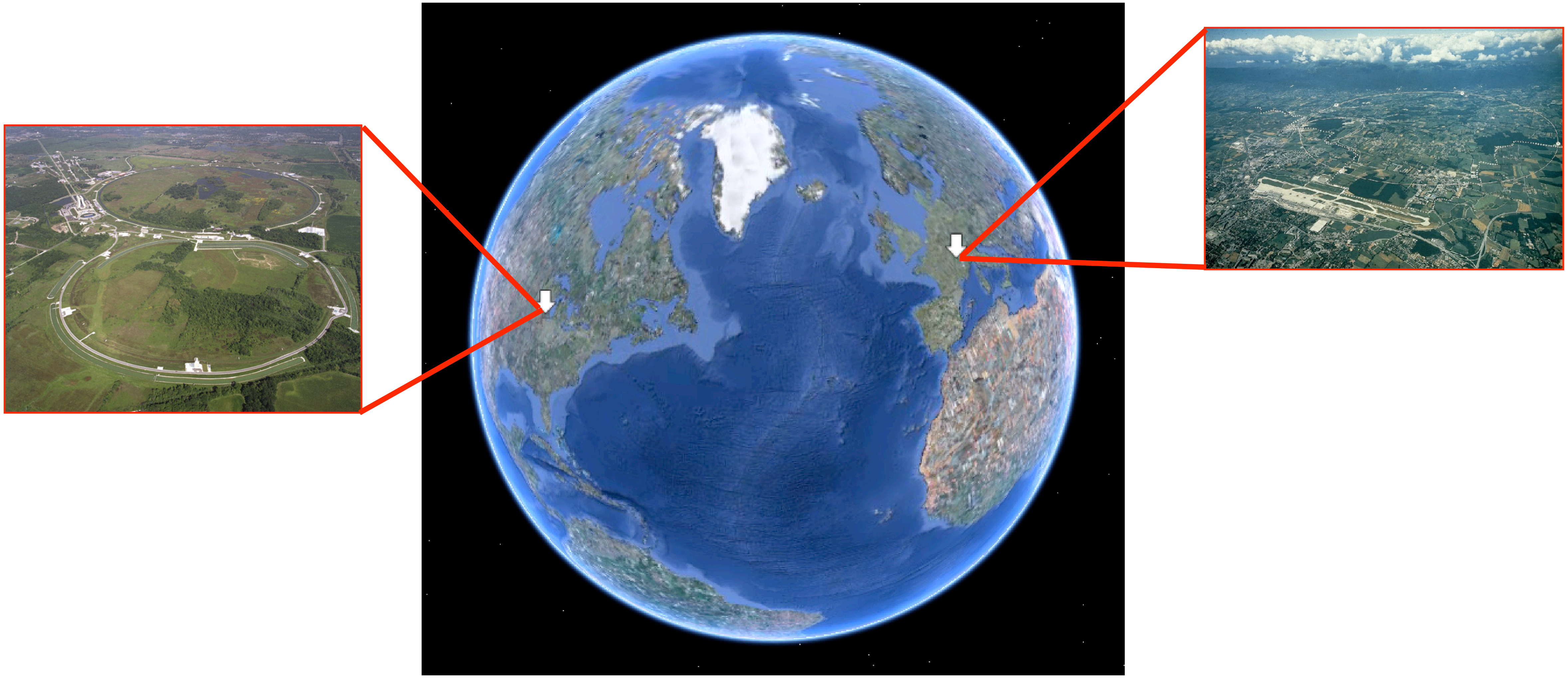
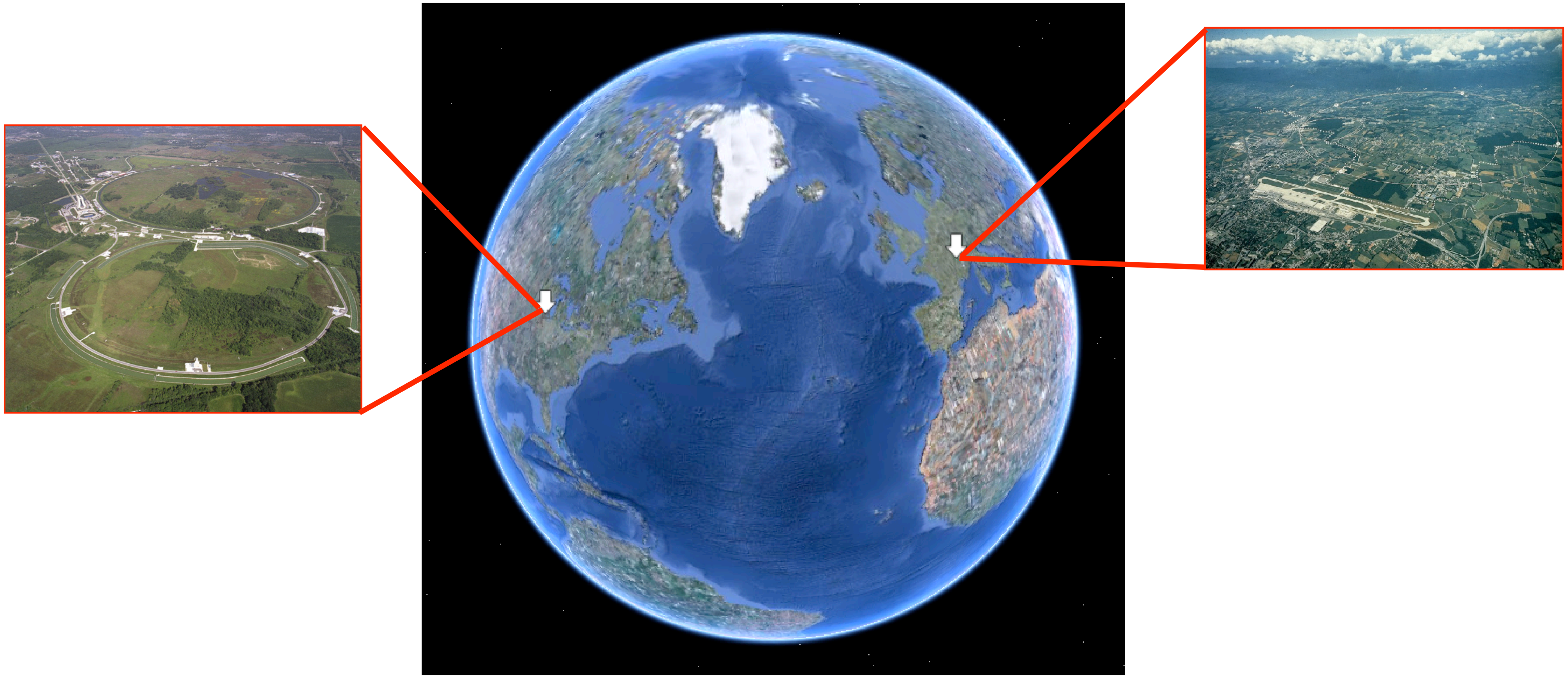
University of Glasgow

UK HEP Forum, "From the Tevatron to the LHC"
May 7 2009

From the Tevatron to the LHC ...



From the Tevatron to the LHC ...

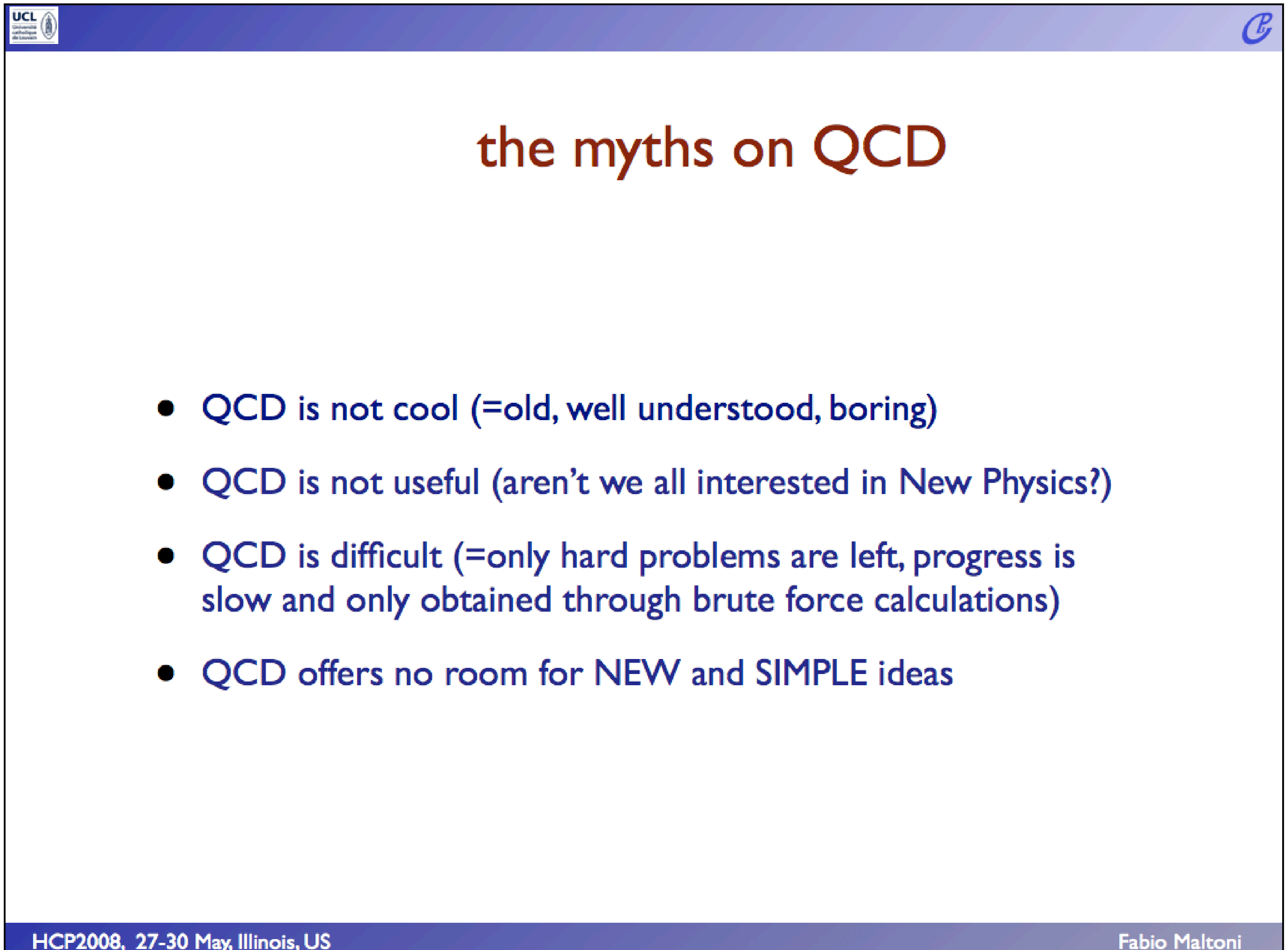


```
1960d0                  [sqrts in GeV]
+1                      [ih1 =1 for proton and -1 for antiproton]
-1                      [ih2 =1 for proton and -1 for antiproton]
```

```
14000d0                 [sqrts in GeV]
+1                      [ih1 =1 for proton and -1 for antiproton]
+1                      [ih2 =1 for proton and -1 for antiproton]
```

Setting the stage

- Standard Model physics + hadron colliders = QCD.



Setting the stage

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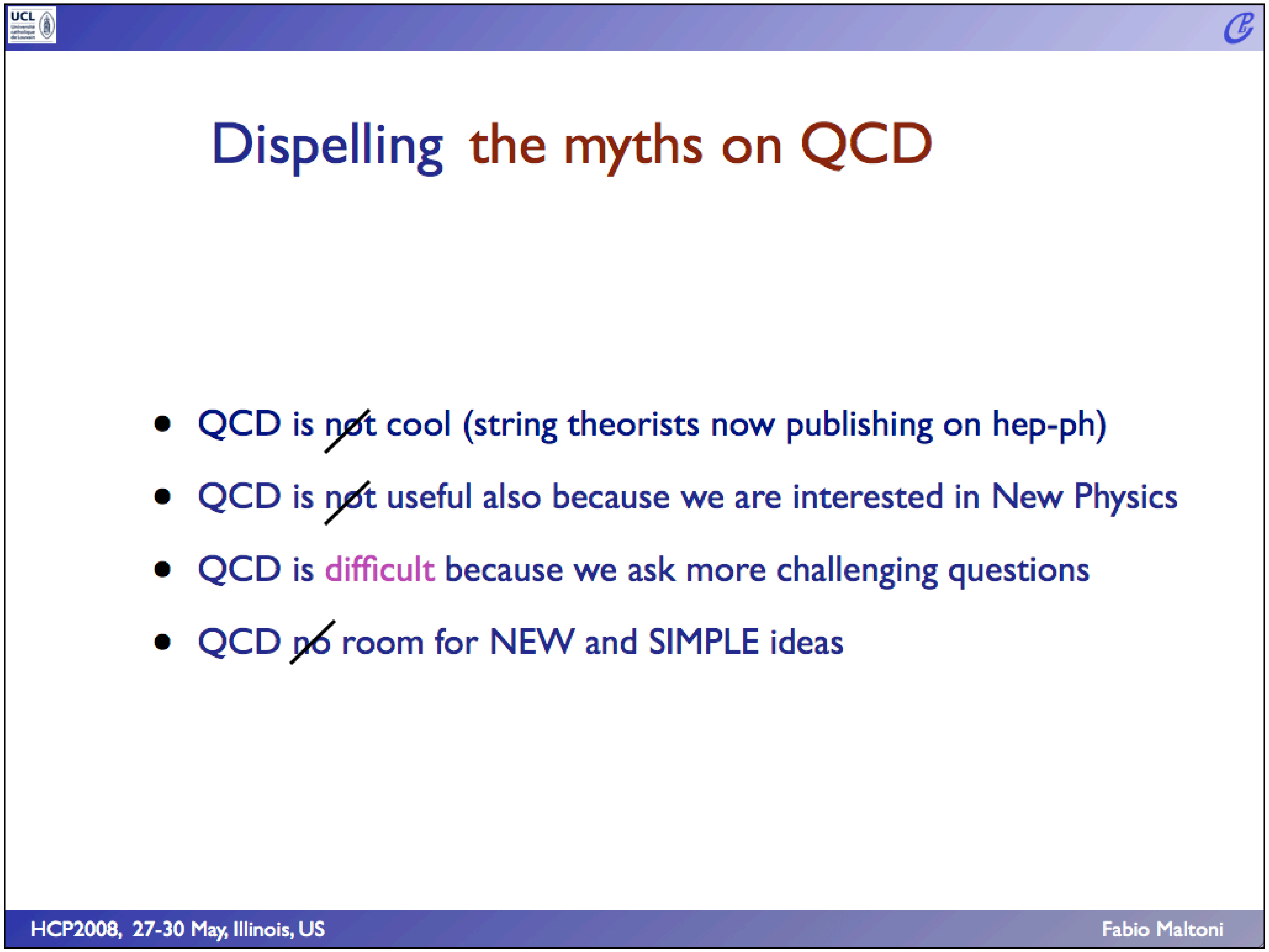
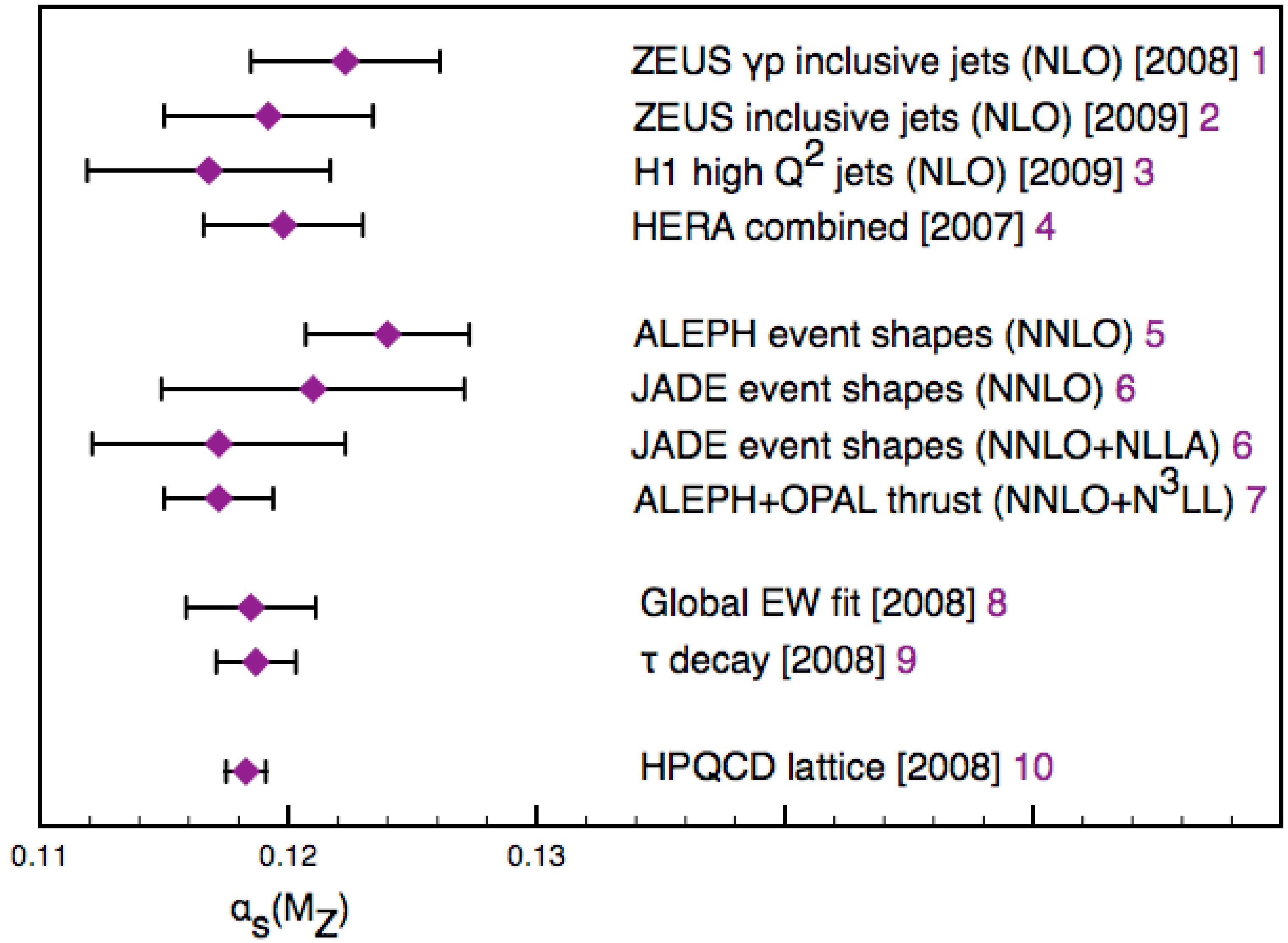


The cornerstone of QCD: α_s

experimental error tiny, dominated by NLO theory {

availability of NNLO and matching to resummed calculation improves error {

consistency between low and high energy extractions {



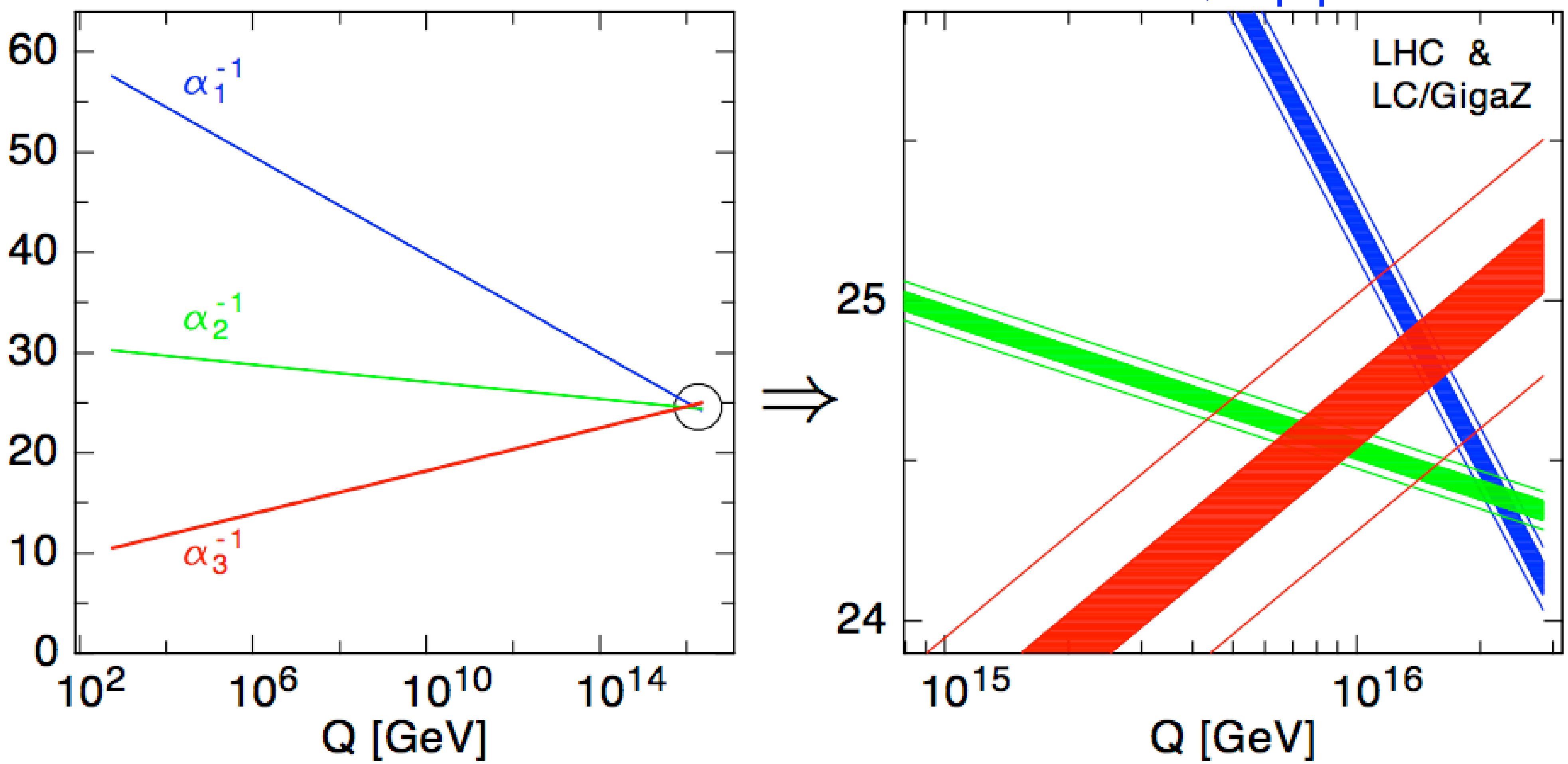
1 ZEUS collaboration, ZEUS-prel-08-008
2 ZEUS collaboration, ZEUS-prel-09-006
3 H1 collaboration, arXiv:0904.3870
4 Glasman, arXiv:0709.4426
5 Dissertori et al., arXiv:0712.0327
6 Bethke et al., arXiv:0810.1389
7 Becher, Schwartz, arXiv:0803.0342
8 EW working group, arXiv:0811.4682
9 Maltman, Yavin, arXiv:0807.0650
10 Davies et al., arXiv:0807.1687

What do we do with it?

- Consistency check of determinations from different processes and theory approximations (pQCD, NRQCD, lattice) and at different physical scales (running coupling).
- Tests of gauge coupling unification in GUT embeddings of BSM physics.

Allanach et al., hep-ph/0403133

mSUGRA (SPS1a)

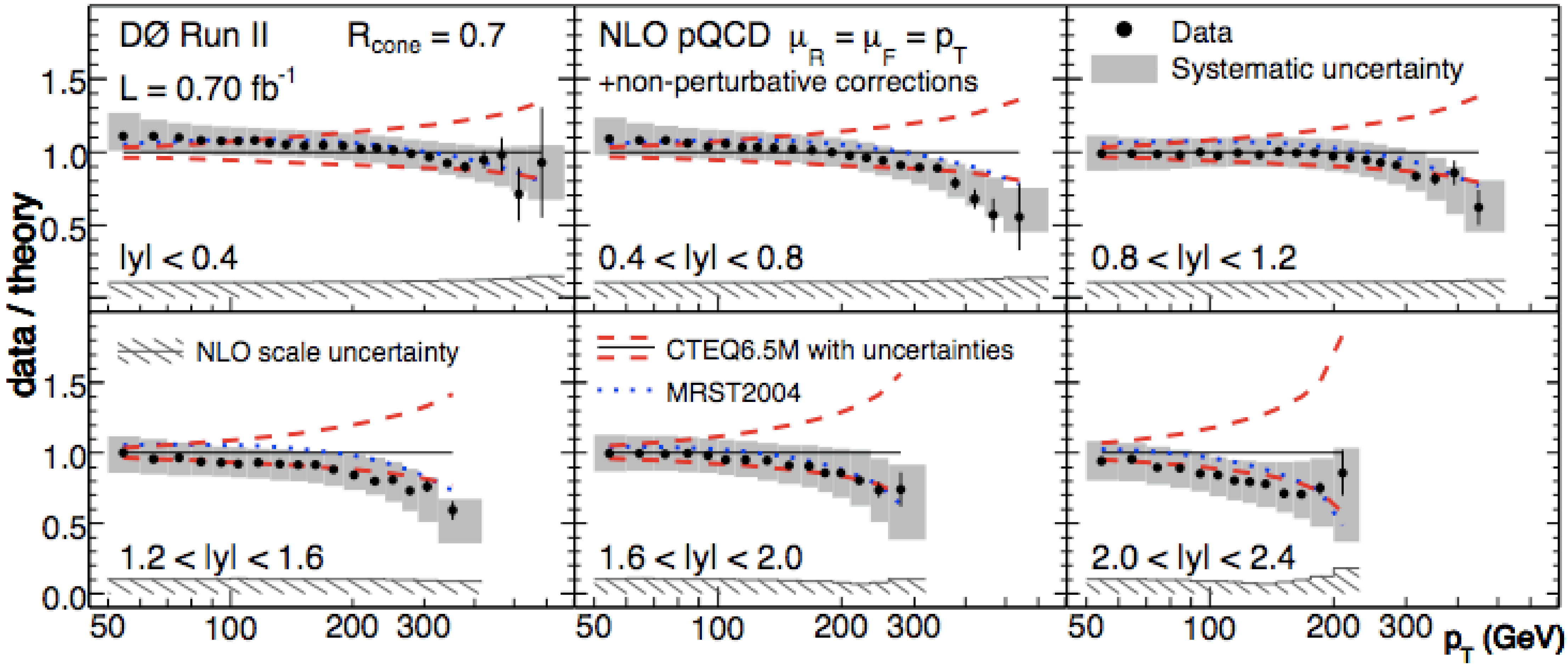


[outer band]
$\alpha_s(M_Z)$=
0.1134 ± 0.003
(PDG 2002)

[inner band]
LHC & LC
→ ± 0.001

How accurately do we need to determine α_s? ($\delta\alpha_s$(HPQCD) ≈ 4x$\delta\sin^2\theta_w$)
What do we actually learn about BSM physics?

Signatures of QCD: jets



D0 collaboration, Fermilab-Pub-08-034-E

- Classic QCD process in excellent agreement with NLO theory.
- Within PDF uncertainties over wide kinematic range.
- Systematic uncertainty at the same level, providing tight constraints on the form of the PDFs.

Jet algorithms

- Cannot talk about jets without discussing algorithms.
- Everyone knows what an ideal algorithm looks like.

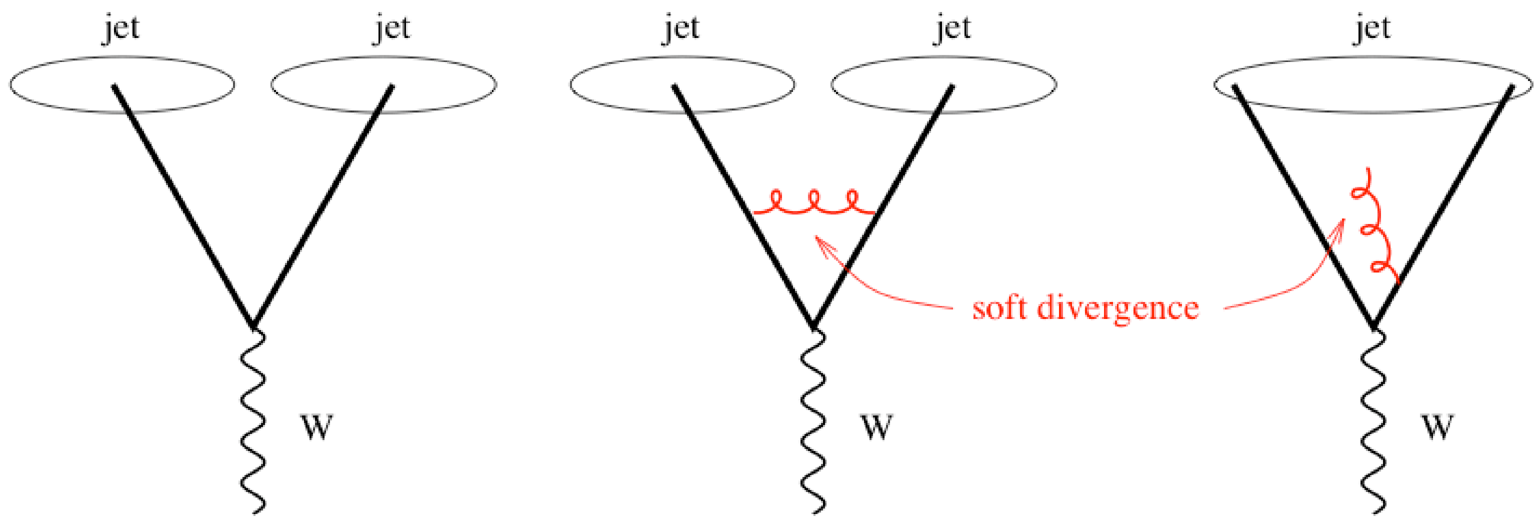
> Several important properties that should be met by a jet definition are [3]:
>
> 1. Simple to implement in an experimental analysis;
> 2. Simple to implement in the theoretical calculation;
> 3. Defined at any order of perturbation theory;
> 4. Yields finite cross section at any order of perturbation theory;
> 5. Yields a cross section that is relatively insensitive to hadronization.

"Snowmass accord"

Fermilab-Conf-90/249-E

- It is just hard to realise this in practice.
- Protracted debate between cone (exp.) and k_T (theory) proponents as a result of tension between 1. and 4.
- Point 4. fails due to a lack of infrared safety that kicks in beyond LO and/or for large jet multiplicities. Notionally ~1% error.
- Small effect + human inertia leads to adiabatic change.

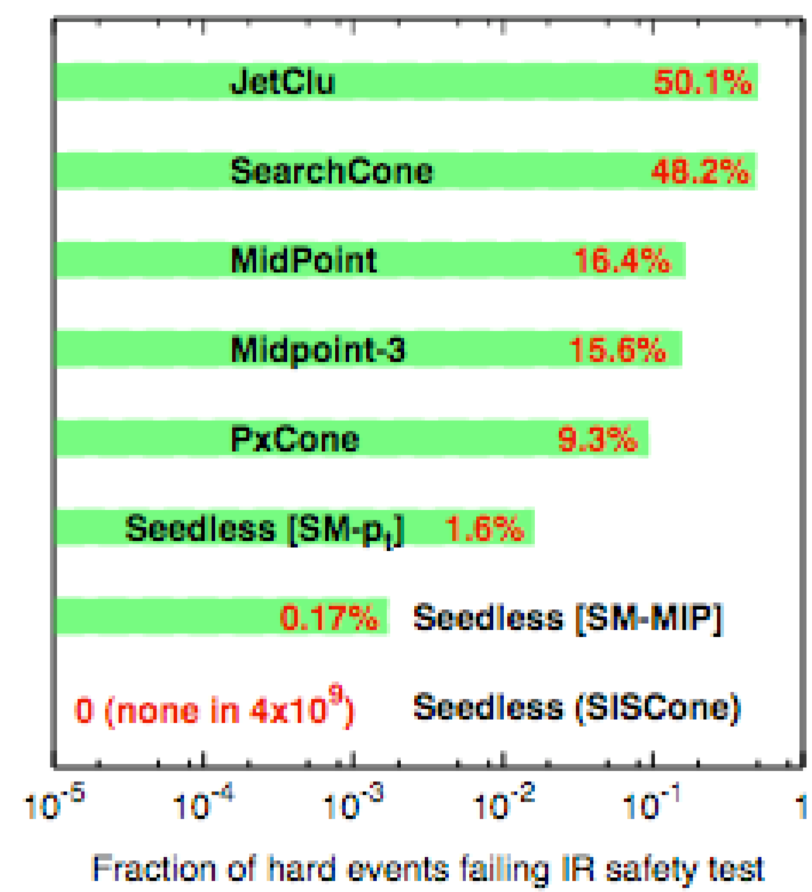
Infrared safety



	$\alpha_s^2 \alpha_{EW}$	$\alpha_s^3 \alpha_{EW}$	$\alpha_s^3 \alpha_{EW}$
1-jet			$+\infty$
2-jet	$\mathcal{O}(1)$	$-\infty$	0

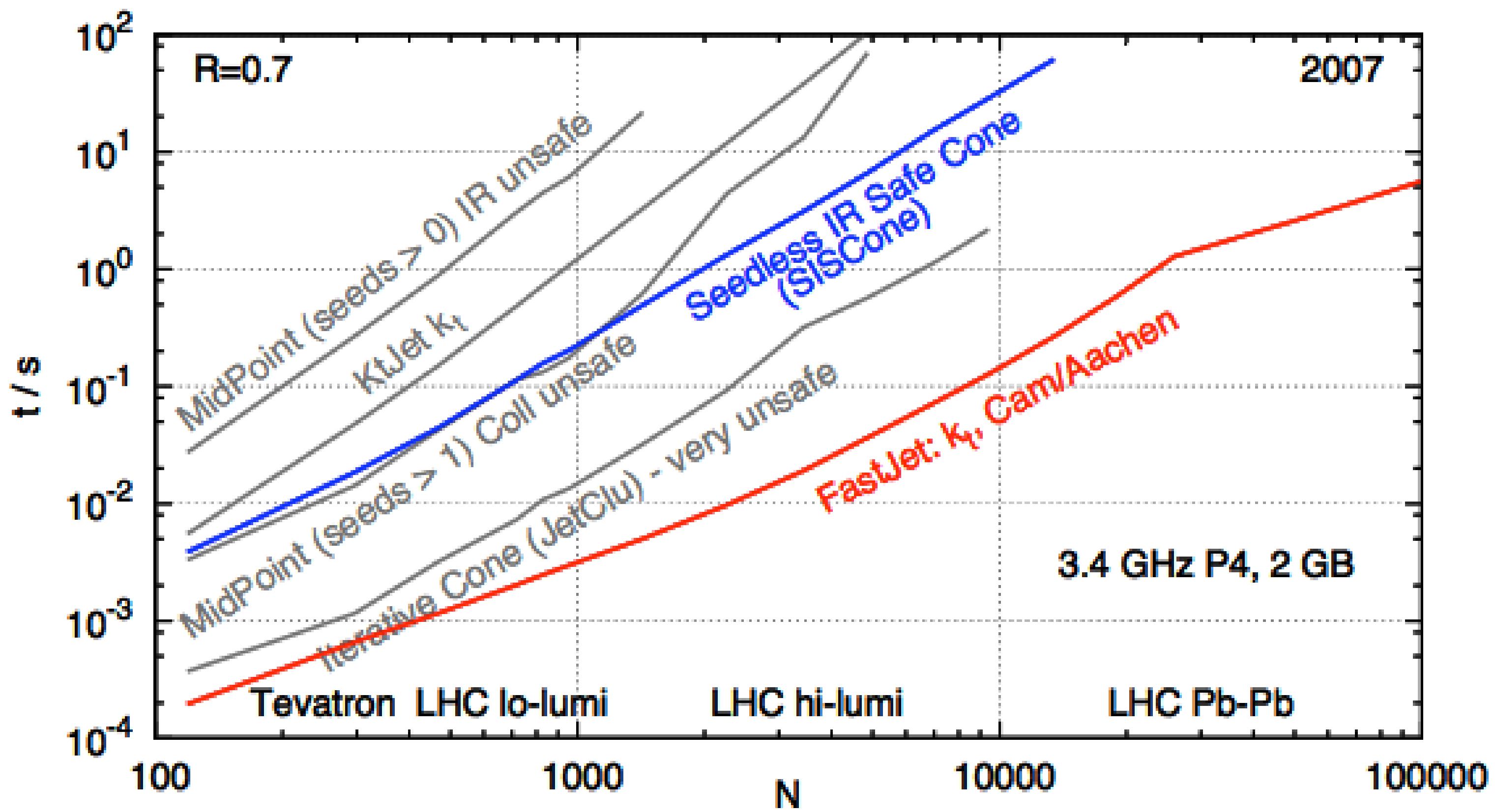
Jets at LO and NLO

- Unfortunately, "higher order effect" is in principle a fraction of an infinite contribution.
- Failure rate can be large for the usual algorithms.



New algorithms

- A show-stopper for the k_T algorithm has been its complexity - computationally, $O(N^3)$ for N towers.
- This has now been much reduced to O(N logN) by recasting the problem as one in computational geometry.



Cacciari, Salam, Soyez (2008)

Fast k_T algorithm available as part of the "Fastjet" package

Also, anti-k_T: clusters in order of decreasing k_T, looks a lot like cones

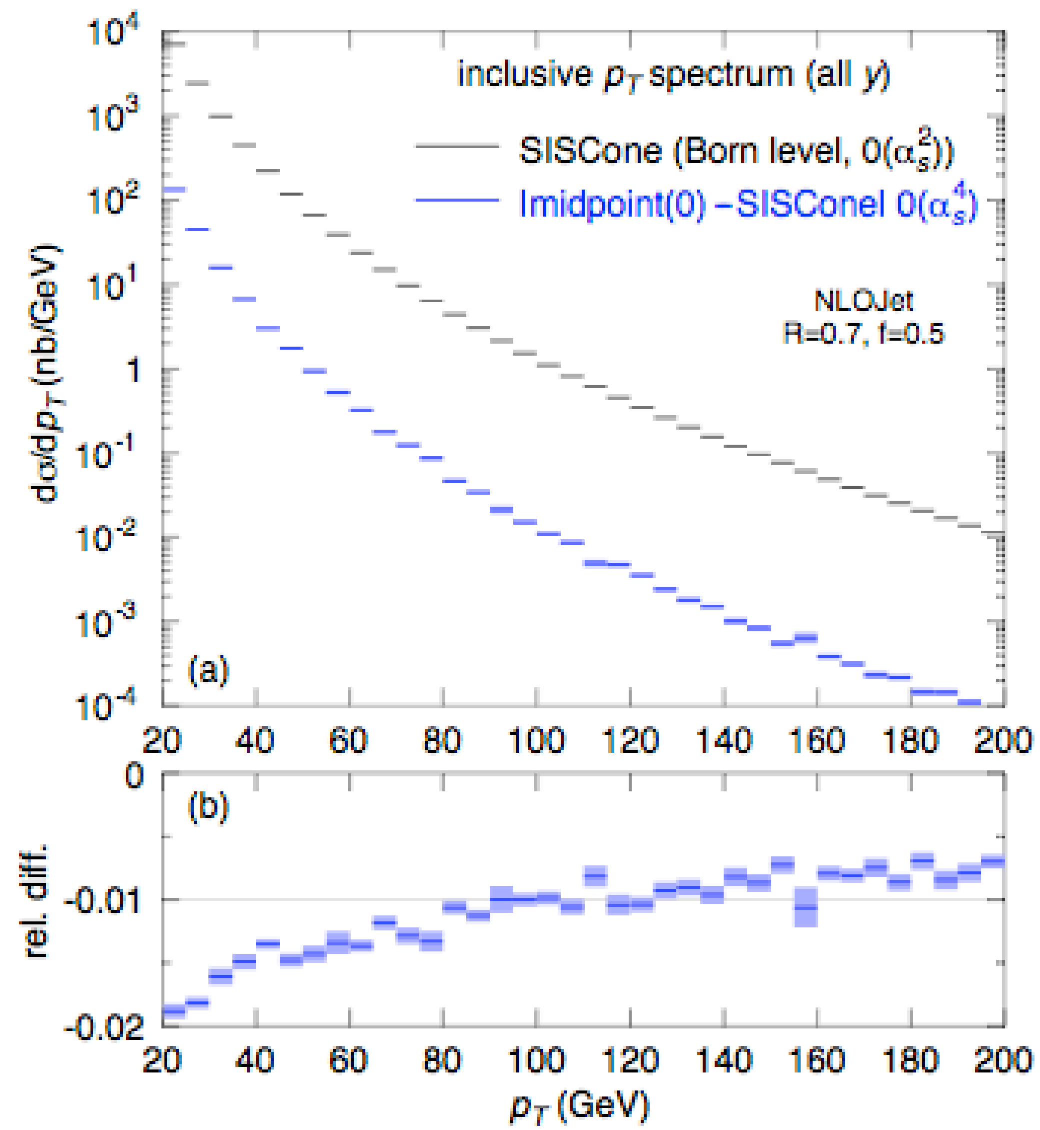
- Now even faster than the (IR unsafe) usual cone algorithm.

Cone reloaded

- IR problems with cone result from the fact that not all possible stable cones are sought. Reason: $O(N\ 2^N)$ time.
- "Thinking outside the cone" using geometrical methods reduces this to $O(N^2 \log N)$ and gives the first safe cone algorithm, SISCone.
- Slower than k_T, but the same as midpoint. Still feels like the same old cone algorithm but now theoretically well-defined.

nominal 1% justified in p_T spectrum

bigger effects expected in more exclusive observables



New jet uses at the LHC

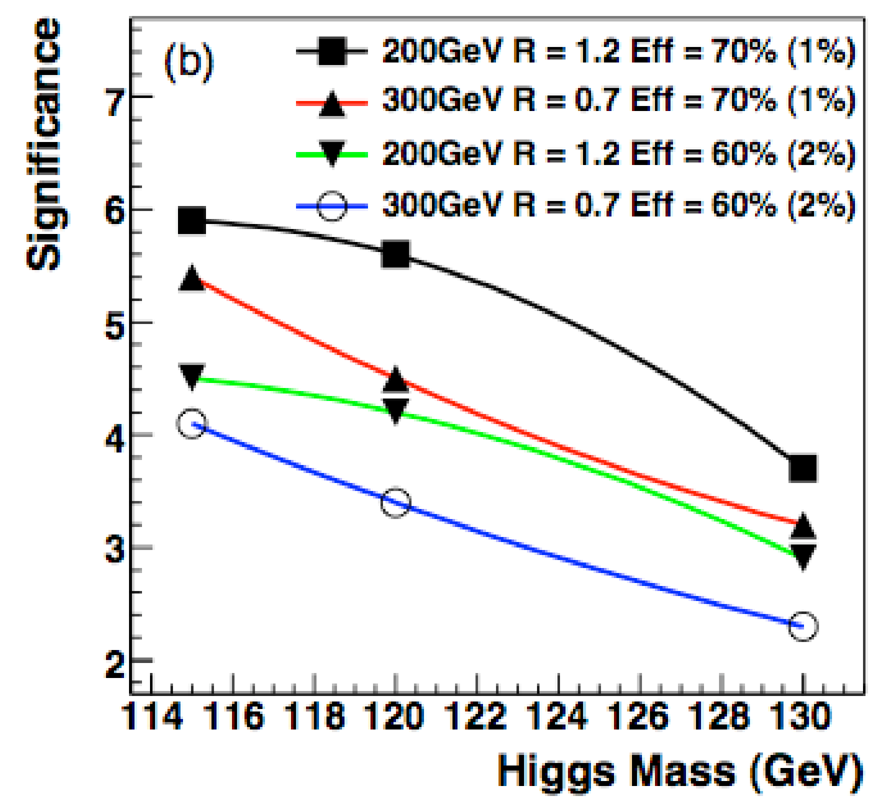
Butterworth et al., PRL 100:242001 (2008)

- Idea: resurrect Higgs search channels that utilize the decay into bottom quarks. Specifically, WH and ZH.
  - use boosted events, $p_T(V)$, $p_T(H)$ > 200 GeV;
  - smaller cross sections (by about 5%) but higher acceptance and much reduced top backgrounds;
  - Higgs candidates produce a fat jet containing two b quarks.

- Identify candidate bottom quarks by undoing steps of the clustering procedure and examining jet substructure.

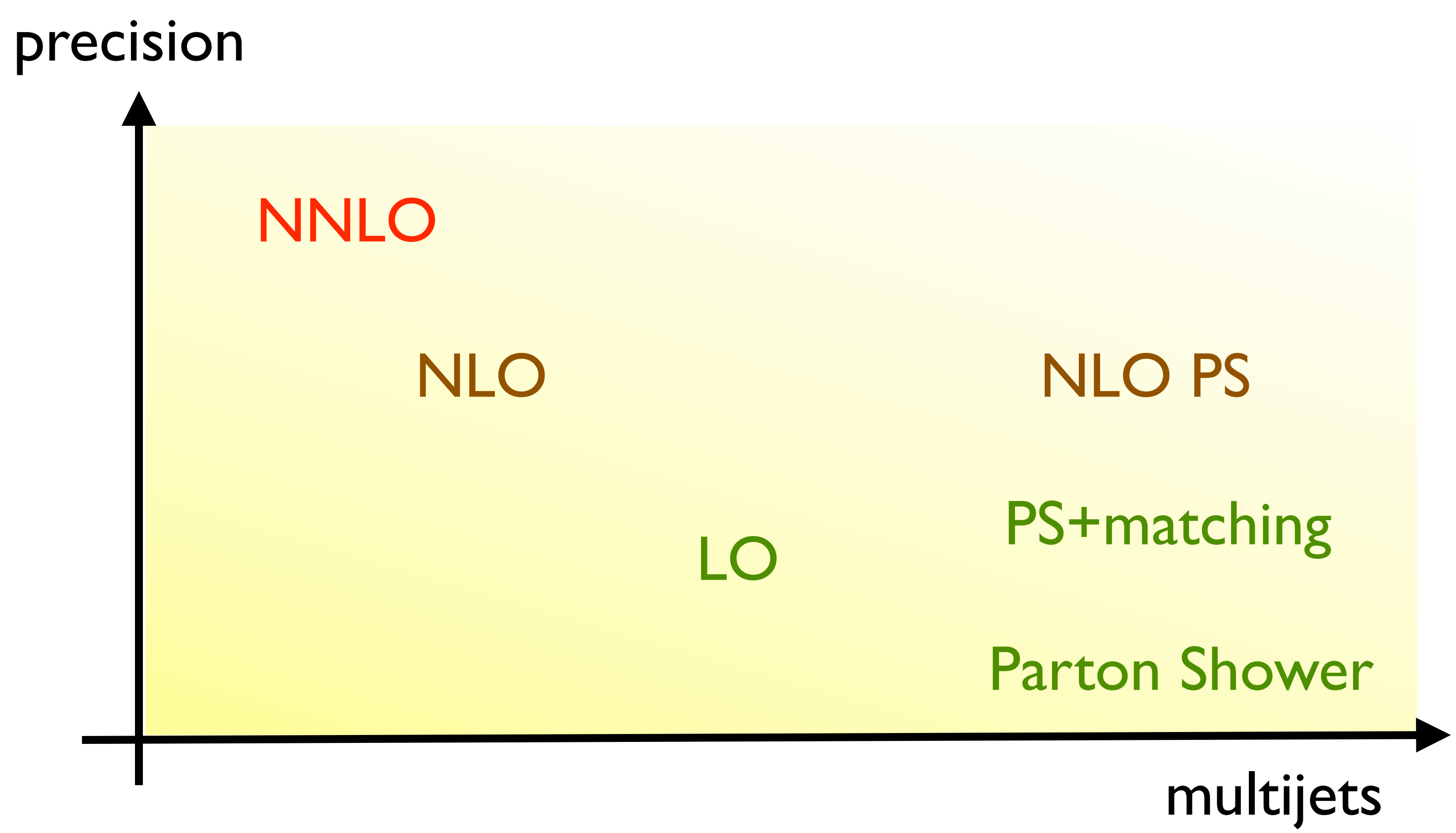
Signal significance looks promising.

Is the idea of bigger jets and substructure useful more generally at the LHC?



QCD playground: vector boson + jets

- A cradle of pQCD innovation, driven by high importance (backgrounds): e.g. generic jets+MET at LHC.
- Challenge: need both good precision and multijets.
- Progress on both fronts during lifetime of Tevatron.
- Focus first on improvements in the area of parton showers.



feature	benefits	drawbacks	solutions
approximations in matrix elements	any number of particles in total or per jet, resummed Sudakov logs good for soft region	problems at high p_T, large angles	matching prescriptions: MLM, CKKW
stochastic (independent) branchings		no quantum interference, problems with correlations	inclusion of some effects: Nagy, Soper
leading order matrix elements	solved problem	uncertain normalization	NLO parton shower, e.g. MC@NLO, POWHEG

Improved PS

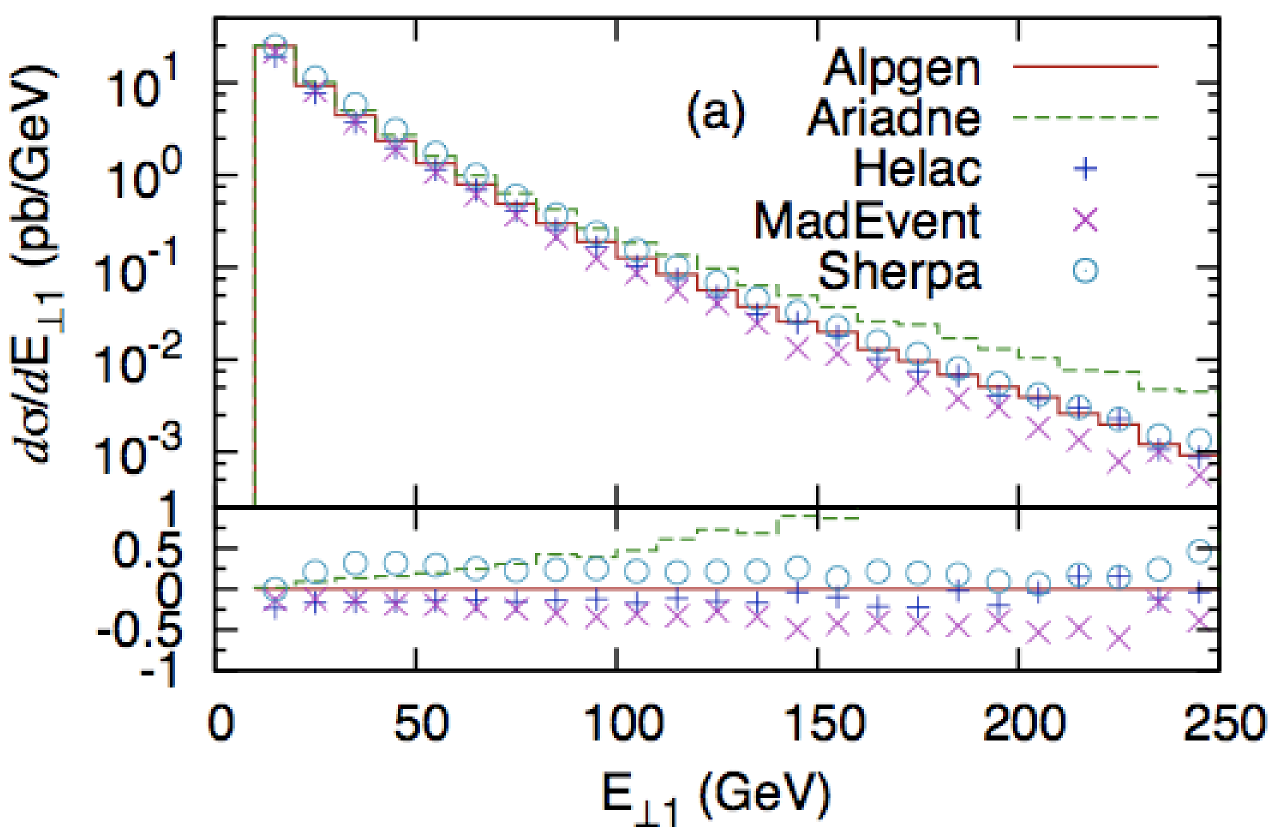
- Matching: use PS shower where it works and LO matrix elements where approximations break down.

- Formally independent of technical cut, but not in practise. Must use common sense and tuning with data.
- Variety of matching schemes to handle the issue of double-counting, mostly based on two core approaches:

CKKW	Catani, Kuhn, Krauss, Webber
MLM	Mangano

Parton shower comparison

- Good testing ground for various parton shower approaches:
  - vector boson mass sets a hard scale so pQCD good;
  - plenty of data to compare with over a large kinematic range.



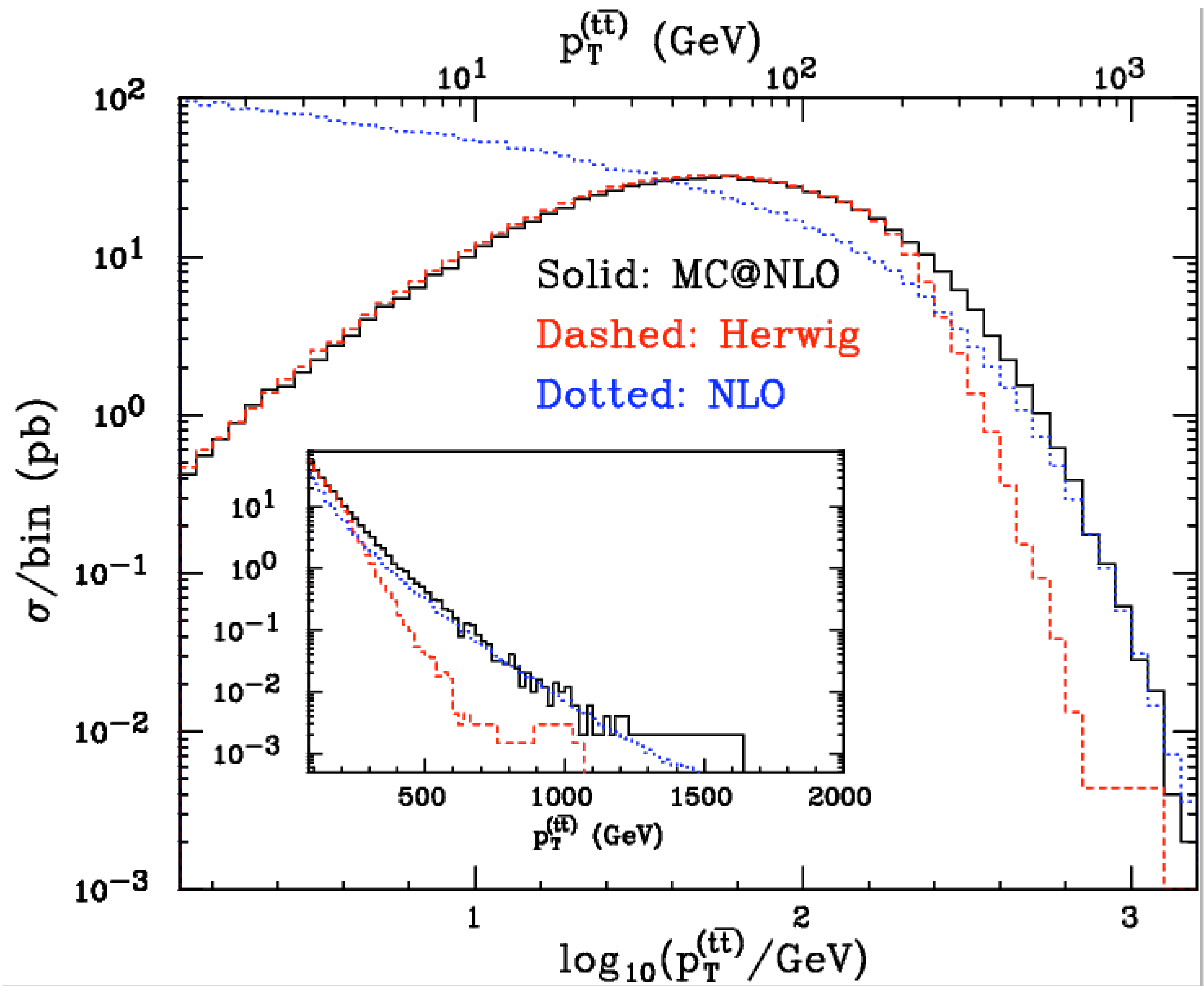
leading jet p_T in W+jet events at the Tevatron

J. Alwall et al. arXiv:0706.2569

- Differences in rates and distributions, but ...
  - variations can be accounted for by usual change of scales;
  - can tune to Tevatron data and extrapolate to LHC.

Parton Shower + NLO

- NLO PS: shower uses NLO matrix elements, including one real emission. Must take care to avoid double counting.
- First real implementation in the wild: MC@NLO.



best of both worlds:

information on the NLO normalization and scale dependence, together with all the goodness of a parton shower

Frixione and Webber, 2003

MC@NLO

S. Frixione

MC@NLO 3.3 [hep-ph/0612272]

IPROC	IV	IL_1	IL_2	Spin	Process
–1350–IL				✓	$H_1H_2 \to (Z/\gamma^* \to) l_{IL}\bar{l}_{IL} + X$
–1360–IL				✓	$H_1H_2 \to (Z \to) l_{IL}\bar{l}_{IL} + X$
–1370–IL				✓	$H_1H_2 \to (\gamma^* \to) l_{IL}l_{IL} + X$
–1460–IL				✓	$H_1H_2 \to (W^+ \to) l^+_{IL}\nu_{IL} + X$
–1470–IL				✓	$H_1H_2 \to (W^- \to) l^-_{IL}\bar{\nu}_{IL} + X$
–1396				×	$H_1H_2 \to \gamma^*(\to \sum_i f_i f_i) + X$
–1397				×	$H_1H_2 \to Z^0 + X$
–1497				×	$H_1H_2 \to W^+ + X$
–1498				×	$H_1H_2 \to W^- + X$
–1600–ID					$H_1H_2 \to H^0 + X$
–1705					$H_1H_2 \to b\bar{b} + X$
–1706		7	7	×	$H_1H_2 \to t\bar{t} + X$
–1706		i	j	✓	$H_1H_2 \to (t \to) bl^+_i\nu_i(\bar{t} \to)\bar{b}l^-_j\bar{\nu}_j + X$
–2000–IC		7		×	$H_1H_2 \to t/\bar{t} + X$
–2000–IC		i		✓	$H_1H_2 \to (t \to) bl^+_i\nu_i/(\bar{t} \to)\bar{b}l^-_i\bar{\nu}_i + X$
–2001–IC		7		×	$H_1H_2 \to \bar{t} + X$
–2001–IC		i		✓	$H_1H_2 \to (\bar{t} \to)\bar{b}l^-_i\bar{\nu}_i + X$
–2004–IC		7		×	$H_1H_2 \to t + X$
–2004–IC		i		✓	$H_1H_2 \to (t \to) bl^+_i\nu_i + X$
–2600–ID	1	7		×	$H_1H_2 \to H^0W^+ + X$
–2600–ID	1	i		✓	$H_1H_2 \to H^0(W^+ \to) l^+_i\nu_i + X$
–2600–ID	-1	7		×	$H_1H_2 \to H^0W^- + X$
–2600–ID	-1	i		✓	$H_1H_2 \to H^0(W^- \to) l^-_i\bar{\nu}_i + X$
–2700–ID	0	7		×	$H_1H_2 \to H^0Z + X$
–2700–ID	0	i		✓	$H_1H_2 \to H^0(Z \to) l_il_i + X$
–2850		7	7	×	$H_1H_2 \to W^+W^- + X$
–2850		i	j	✓	$H_1H_2 \to (W^+ \to) l^+_i\nu_i(W^- \to) l^-_j\bar{\nu}_j + X$
–2860		7	7	×	$H_1H_2 \to Z^0Z^0 + X$
–2870		7	7	×	$H_1H_2 \to W^+Z^0 + X$
–2880		7	7	×	$H_1H_2 \to W^-Z^0 + X$

Recent activities:

- Lepton spin correlations in $t\bar{t}$ and single-top production released with v3.3
- Hadron spin correlations in $t\bar{t}$ now into ATLAS and CMS software (v3.31)
- W and Z production with interface to HERWIG++
- Early stage of interface to PYTHIA
- Wt is now completed

- Large catalogue of processes, but neither inclusive jet nor V+jets.

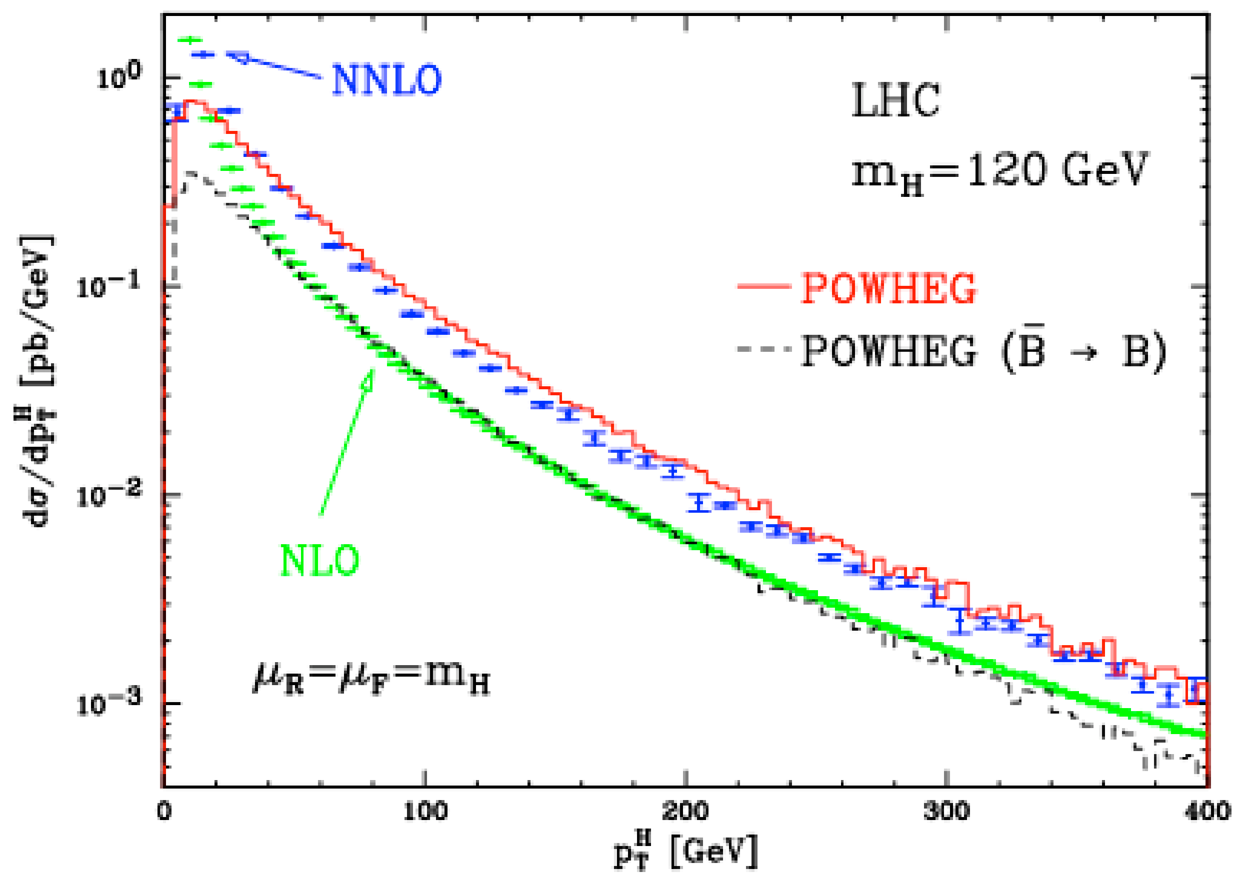
Other strategies

- This is the best known approach, but others have also been proposed:

Schwartz	based on SCET
Giele, Kosower, Skands	VINCIA
Bauer, Tackmann, Thaler	GenEvA

- POWHEG can already be used for hadronic collisions
  Nason et al., 2004, 2007
  - good for variety of predictions
  - not tied to a specific parton shower and potentially easier to use with existing NLO results
  - no negative weight events
  - differences in hard emission that are formally NNLO.

arXiv:0812.0578

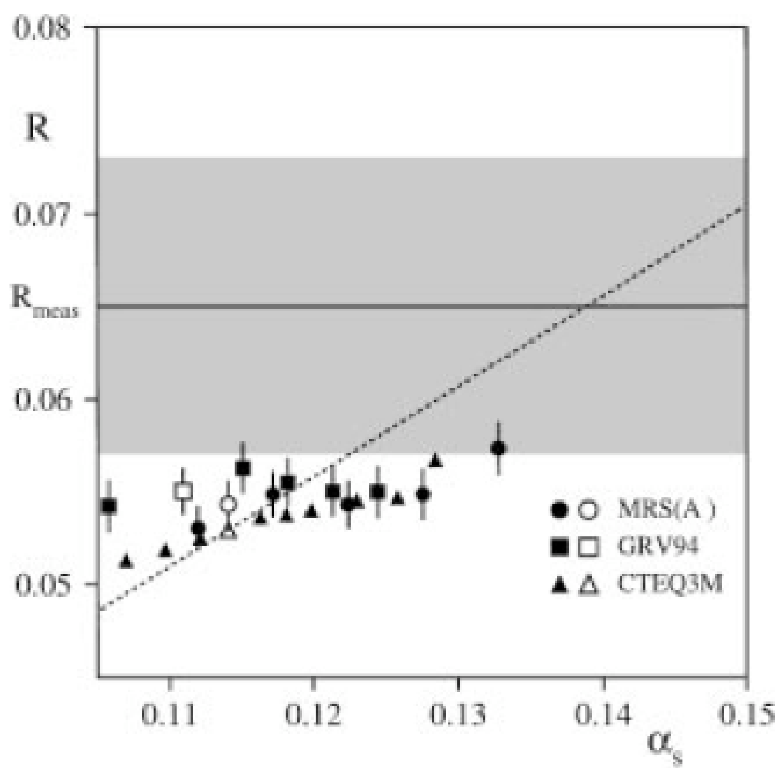


Higher orders

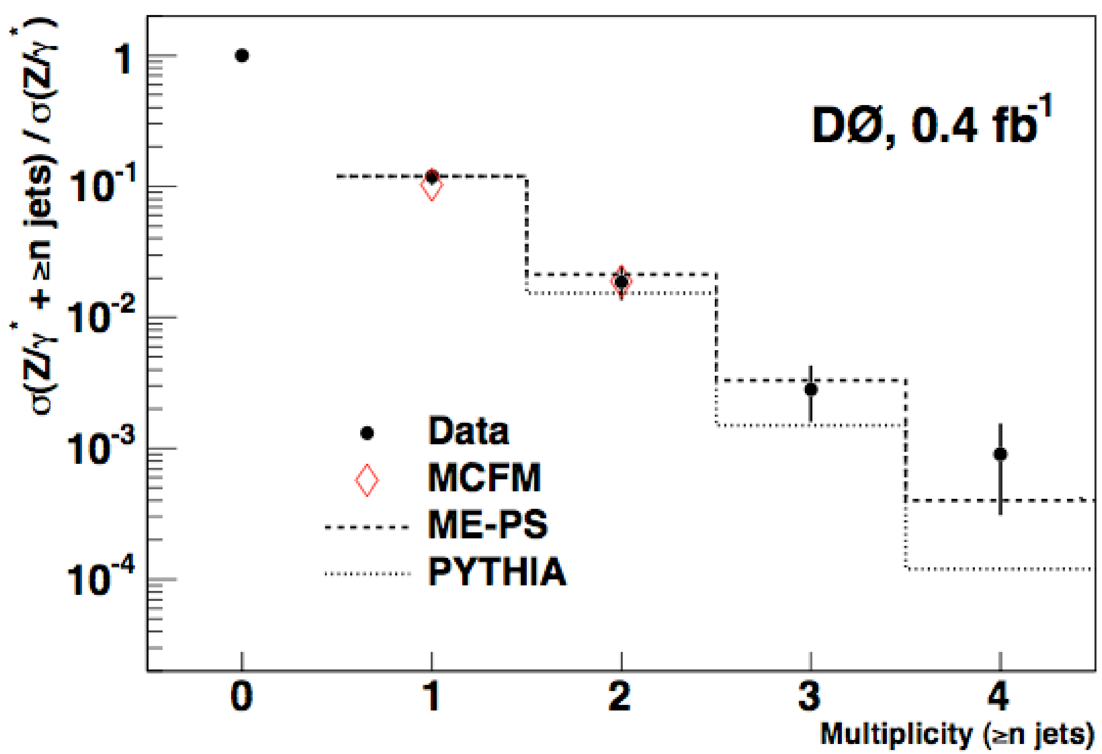
- Over the lifetime of the Tevatron, NLO has become the standard for accurate predictions - at least for small(ish) final states.
- W/Z+1 jet known at NLO for a long time, but 2 jets more recent.

Giele et al. hep-ph/9302225

JC, K. Ellis, hep-ph/0202176



PRL 75, 18 (1995)



PLB 658, 112 (2008)

- Hold-up due to growth in required computational time of brute force approaches; threshold for a long time has been 2→3 scatterings.

Loop advances

- Revolution in performing loop calculations for ~ 5 years.
- Initially, "twistor inspired" recursion relations: MHV, CSW, BCFW.
- Basic idea is to break loop amplitudes into smaller (tree level) amplitudes.
    - easily and efficiently computed analytically.
- Helicity amplitudes for all-gluon processes in SUSY are simplest.
- Now a viable method in the SM and with quarks.

D. Dunbar, 2008

The Six Gluon one-loop amplitude

	$N=4$	$N=1$	scalar C	scalar R
$A(++++++)$	-	-	-	93
$A(-+++++)$	-	-	-	93
$A(--++++)$	94	94	94	06
$A(-+-+++)$	94	94	05	06
$A(-++-++)$	94	94	05	06
$A(---+++)$	94	05	05	06
$A(--+-++)$	94	05	06	06
$A(-+-+-+)$	94	05	06	06

~14 papers

81% `B'

Berger, Bern, Dixon, Forde, Kosower

Bern, Dixon, Dunbar, Kosower

Britto, Buchbinder, Cachazo, Feng

Bidder, Bjerrum-Bohr, Dixon, Dunbar

Bern, Chalmers, Dixon, Kosower

Bedford, Brandhuber, Travaglini, Spence

Forde, Kosower

Bern, Bjerrum-Bohr, Dunbar, Ita

Xiao, Yang, Zhu

D Dunbar, IOP, Durham 08

Britto, Feng, Mastriolia

Mahlon

24/25

Recent progress

- The analytic structure of amplitudes is now much better understood.

$$\mathcal{M} = \sum_i a_i(4)\,\text{Boxes}_i + \sum_i b_i(4)\,\text{Triangles}_i + \sum_i c_i(4)\,\text{Bubbles}_i + \sum_i d_i(4)\,\text{Tadpoles}_i + R$$

- This has led to new methods that use recursion relations for amplitudes that are implemented numerically.
  - methods scale well with no. of legs, so real leap possible (necessary prerequisite to extended NLO+PS)
  - requires careful handling of numerical stability
- The 2→3 barrier has been well and truly broken.
- General solution of NLO also requires automation of other half of calculation, namely taking care of all soft and collinear divergences.
- Multiple solutions already developed.

Gleisberg and Krauss, 2007

Seymour and Tevlin, 2008

Frederix, Gehrmann, Greiner, 2008

Hasegawa, Moch, Uwer, 2008

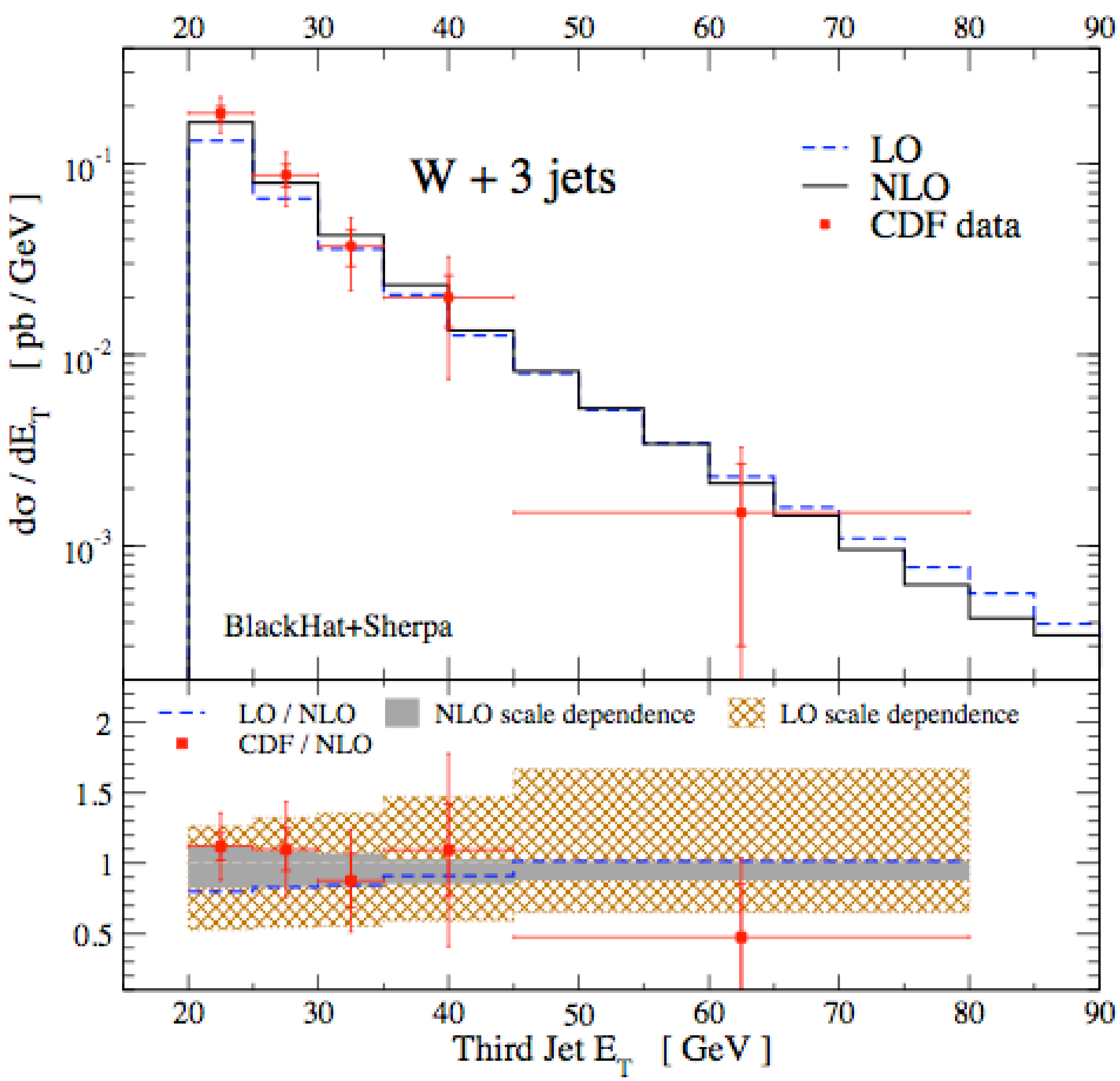
2→4 at last

- CutTools: van Hameren, Pittau, Papadopoulos, arXiv:0903.4665
  - All "Les Houches" wish-list processes at a single phase space point, i.e. ttbb, VVbb, VV+2 jets, bbbb, V+3 jets, tt+2 jets
  - no phemonenology, but impressive feat of strength.
- BlackHat: Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Maitre
  - 8 gluon amplitudes
  - W+3 jets at leading colour (i.e. throw away $1/N^2$)
  - halfway to NLO+PS already, via SHERPA implementation
- Rocket: Ellis, Giele, Kunzst, Melnikov, Zanderighi
  - 20 gluon amplitudes, V+3 jets at single phase space points
  - W+3 jets at leading colour
- arXiv:0905.0110: Bredenstein, Denner, Dittmaier, Pozzorini
  - more traditional (but just as useful!) full calculation of ttbb

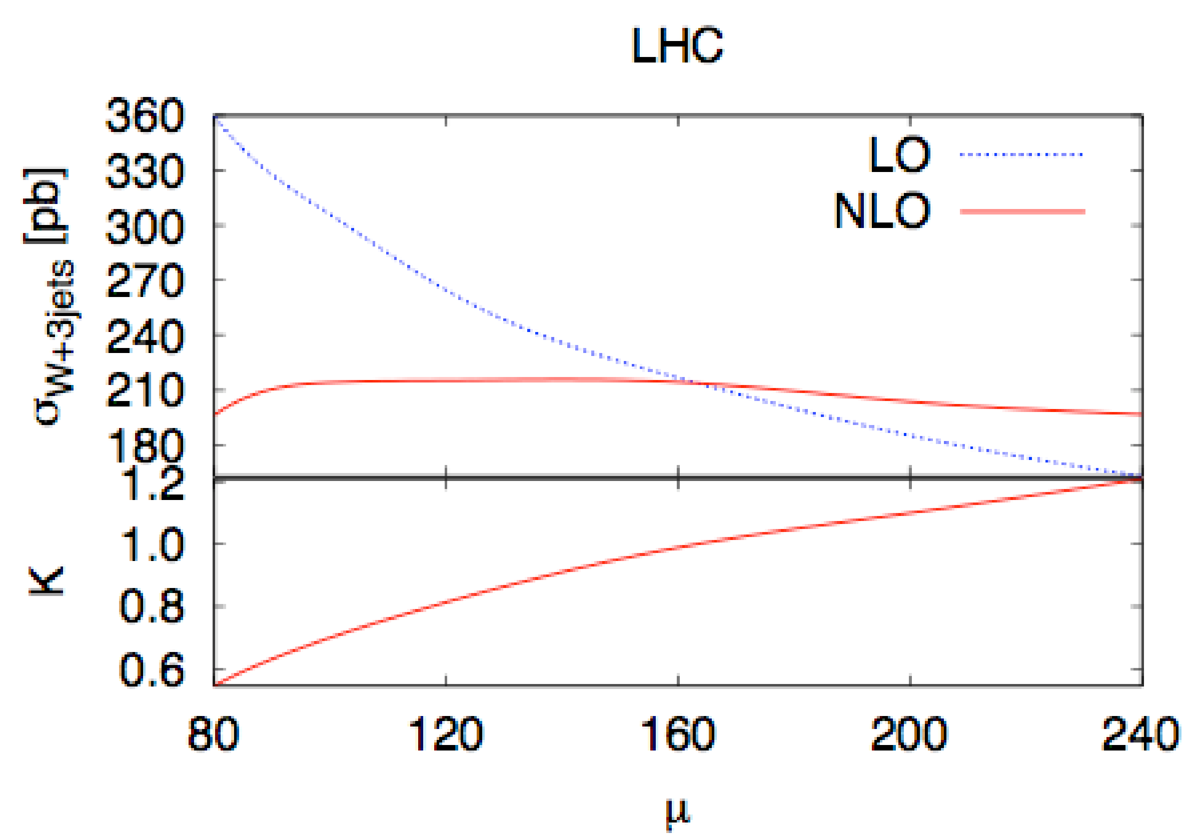
W+3 jets results

number of jets	CDF	LC NLO	NLO
1	53.5 ± 5.6	$58.3^{+4.6}_{-4.6}$	$57.8^{+4.4}_{-4.0}$
2	6.8 ± 1.1	$7.81^{+0.54}_{-0.91}$	$7.62^{+0.62}_{-0.86}$
3	0.84 ± 0.24	$0.908^{+0.044}_{-0.142}$	—

BlackHat (arXiv:0902.2760)

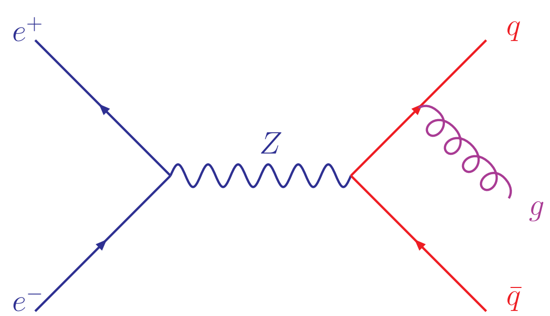


Rocket (arXiv:0901.4101)

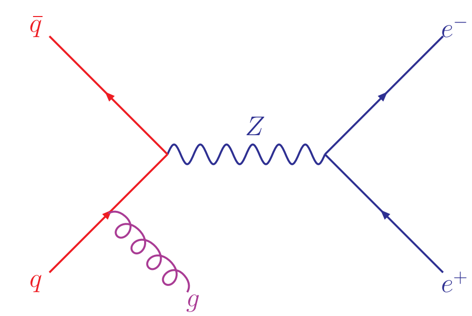


To NNLO and beyond?

- Highly non-trivial due to both two-loop diagrams and doubly-infrared singularities in real diagrams.
- Benchmark at hadron colliders: inclusive production of W, Z or Higgs.
- For jets, simplest to start at an e^+e^- machine.



non-trivial work to do crossing to hadron collider

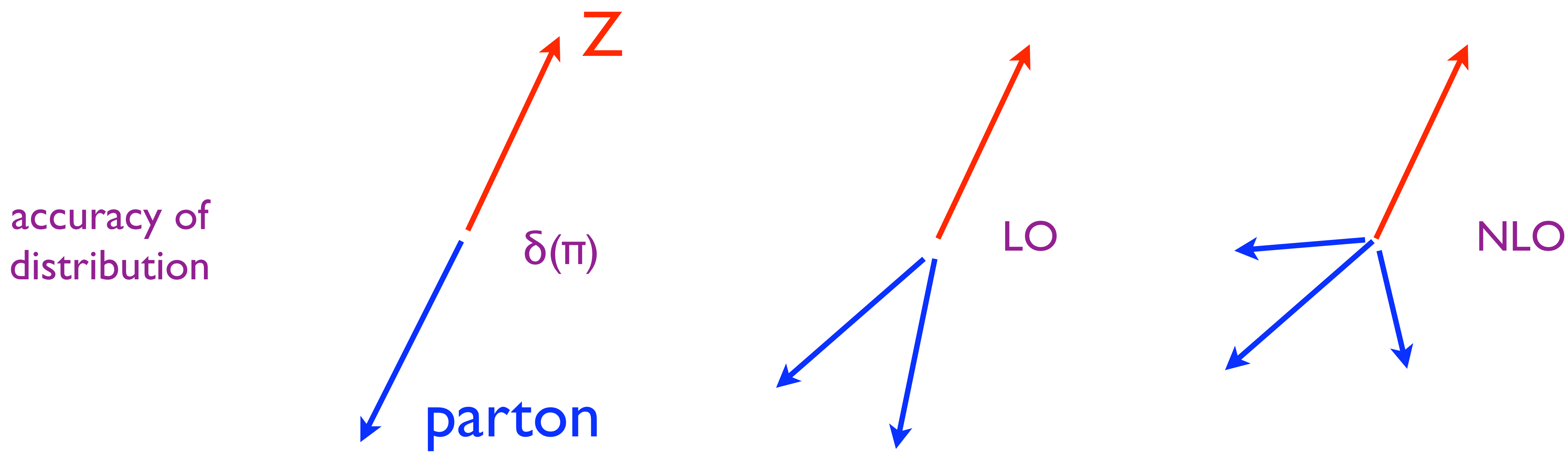


A. Gehrmann-de Ridder et al, arXiv:0711.4711

- Goal of hadroproduction of Z (or W)+1 jet at NNLO still a way off, e.g. crossing to (2+1) jet production in DIS only just completed.
  Gehrmann, Glover, arXiv: 0904:2665
- Isolating all infrared singularities in the corresponding real radiation calculation is much harder due to hadronic initial state.
- Other prospects: inclusive jet, tt, diboson (much of machinery in place now).

In the meantime ...

- Can make the best of what we do have,
  e.g. azimuthal angle between the Z and leading jet in Z+jet events.



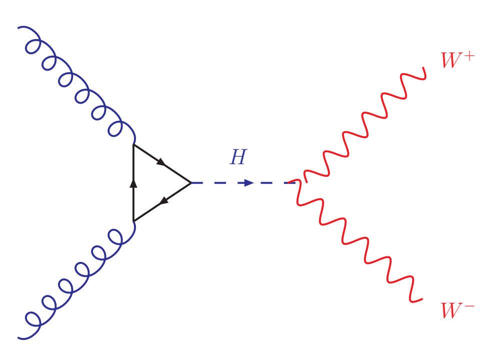
Z+1 jet calculation	LO 1-loop NLO 2-loop NNLO	+1p real NLO +1p (loop/real) NNLO	+2p real NNLO

- To get a complete NLO distribution, need to use Z+1 at NNLO.
- Except for at π, contributing diagrams are just the same ones that appear in NLO calculation of Z+2 jets → reliable prediction as long as far enough away.

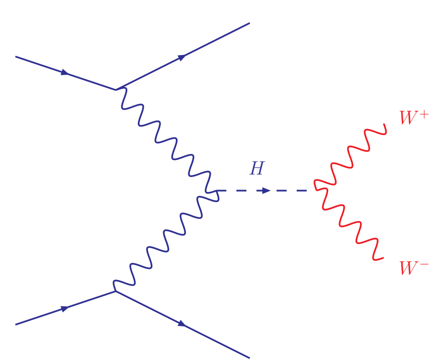
Multijets at the LHC

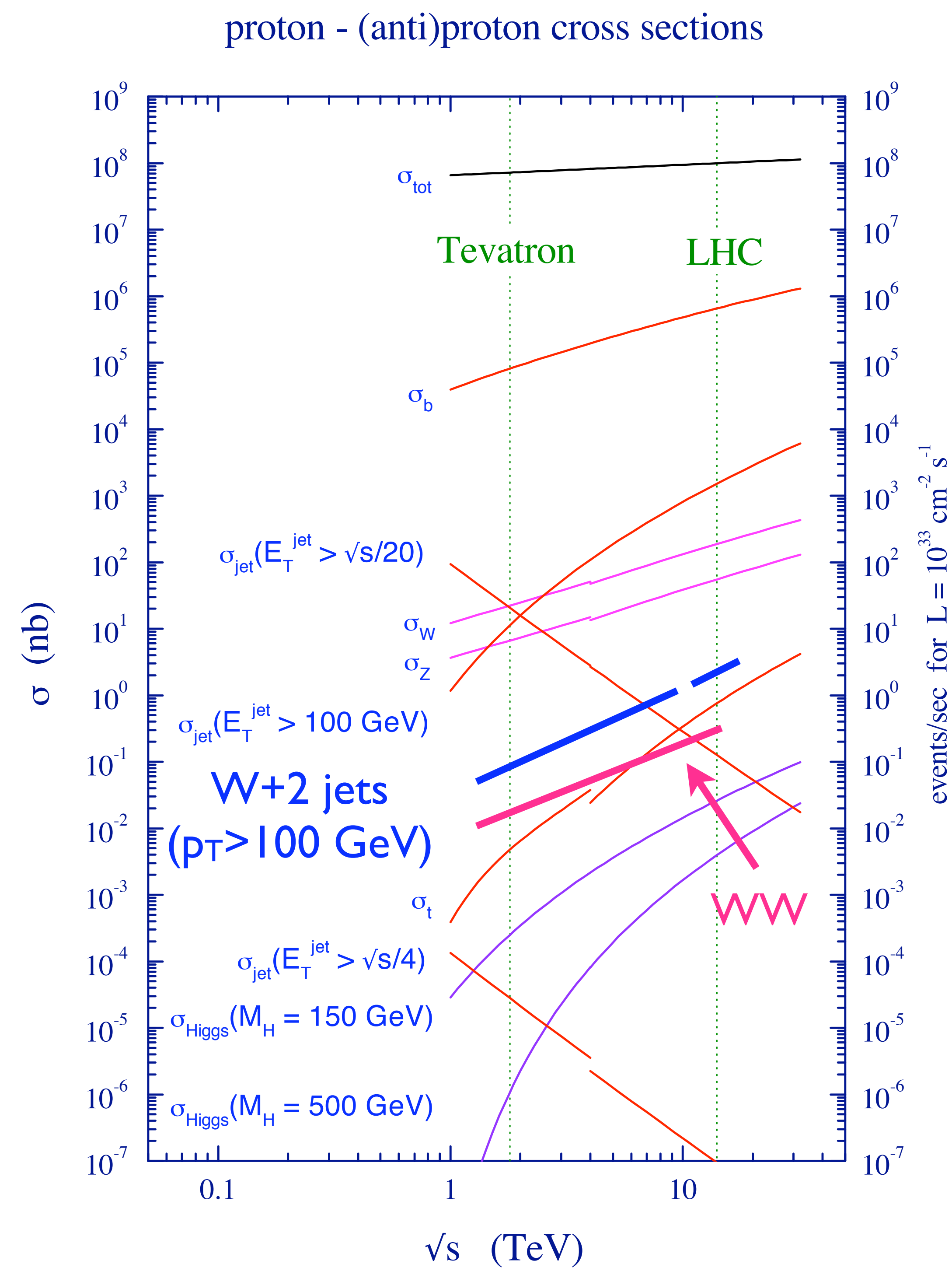
- Multijet rates become more of an issue, even for high p_T jets.
- Use Tevatron W+jets studies as a template for top+jets and diboson+jets analyses.
- Useful for e.g. Higgs search.
  Mellado et al., arXiv:0708.2507

gluon fusion → 0 jets (veto); radiation → 1 or more jets



WBF → two forward jets, one of which may be lost





- Systematic study a priority.

Heavy flavour in W/Z+jets

- Important backgrounds for many new physics searches.
- Real opportunity for significant knowledge transfer from Tevatron to LHC.

	1 C-TAG	1 B-TAG	2 C-TAG	2 B-TAG
W+1 JET	FF NLO (GKL 96, CET 05)	FF+HVQ NLO (FRW+CEMW 08)	N/A	N/A
W+2 JETS	LO ONLY	HVQ NLO (CEMW 07)	FF NLO (FRW 07)	
Z+1 JET	FF NLO (FRW 08) HVQ NLO (CEMW 03)		N/A	N/A
Z+2 JETS	HVQ NLO (CEMW 06)		FF NLO (FRW 08)	

HVQ: charm or bottom in initial state

FF: heavy quarks in final state only

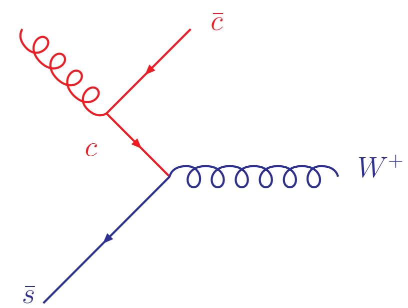
(two different theory approaches with complementary features)

GKL = Giele, Keller, Laenen
CET = JC, Ellis, Tramontano
FRW = Febres Cordero, Reina, Wackeroth
CEMW = JC, Ellis, Maltoni, Willenbrock

Theory vs. Tevatron data

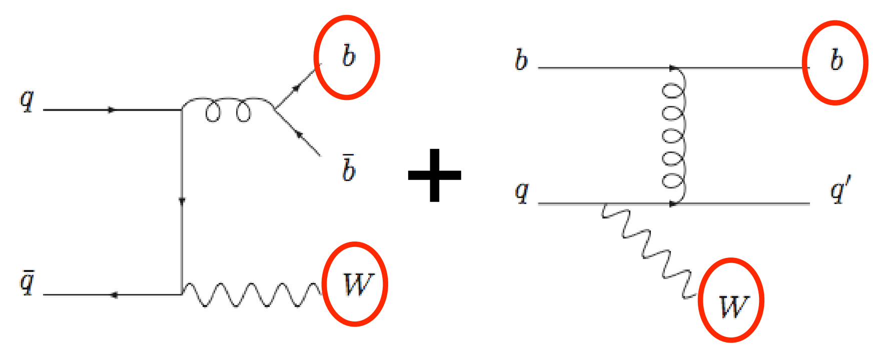
- Tevatron results on vector bosons + heavy flavour jets are hard to interpret at the moment.

W+c



CDF data and NLO consistent

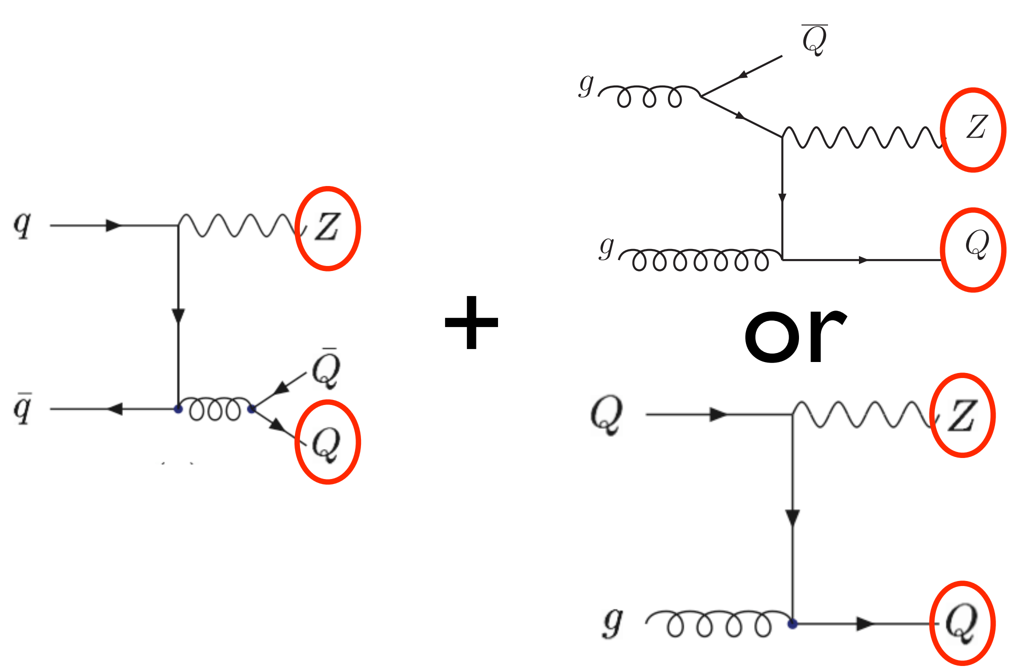
W+b+X



CDF data ~ (3-4) x LO

(but new analysis underway w/ improved NLO prediction; beware "jet" vs. "event" x-sec.)

Z+b+X

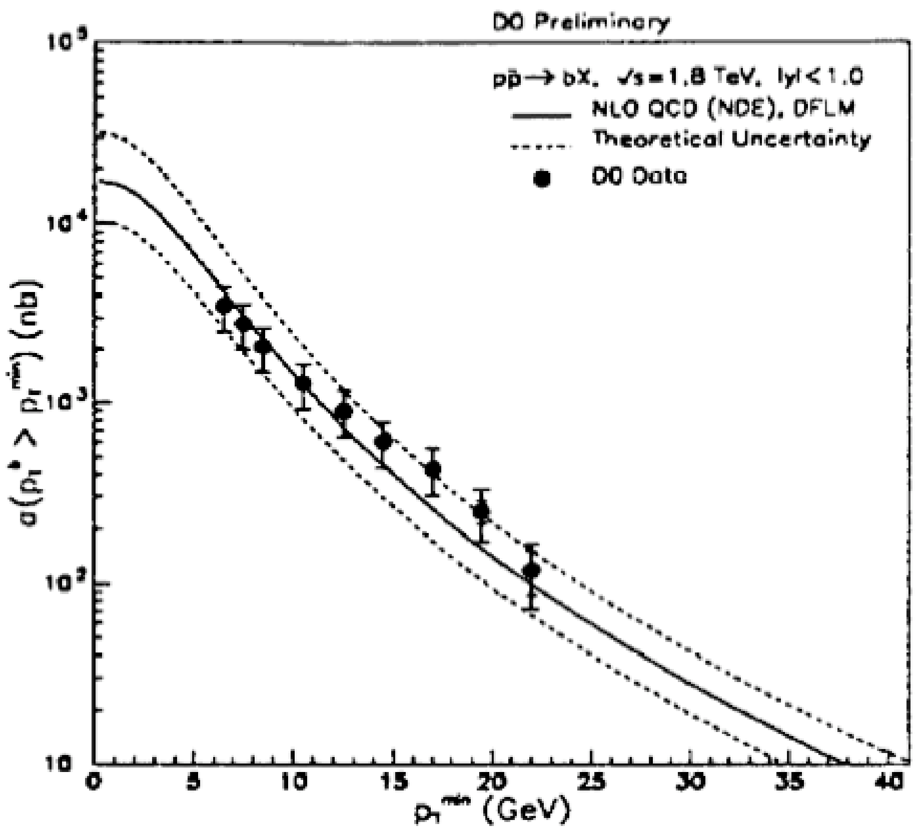


D0 data and NLO consistent

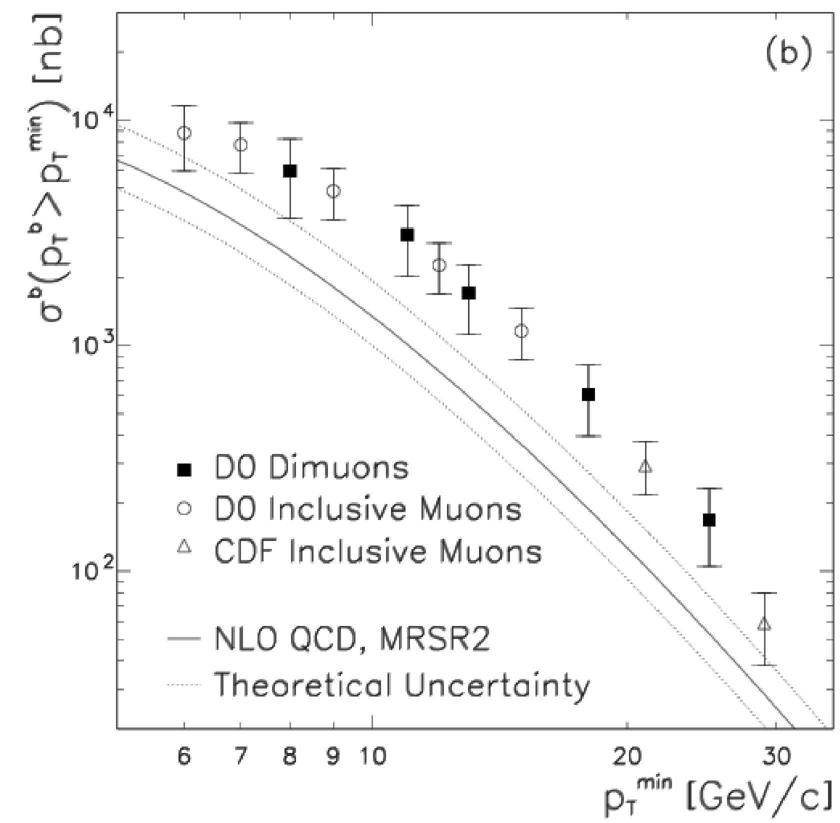
BUT the two different theory approaches give very different $p_T(Z)$ distributions → guide to understanding theory better

History repeating itself?

- The difficulty of confronting data and theory can be highlighted by tracing the evolution of this heavy flavour process.



Prelim. (Moriond, 1994)

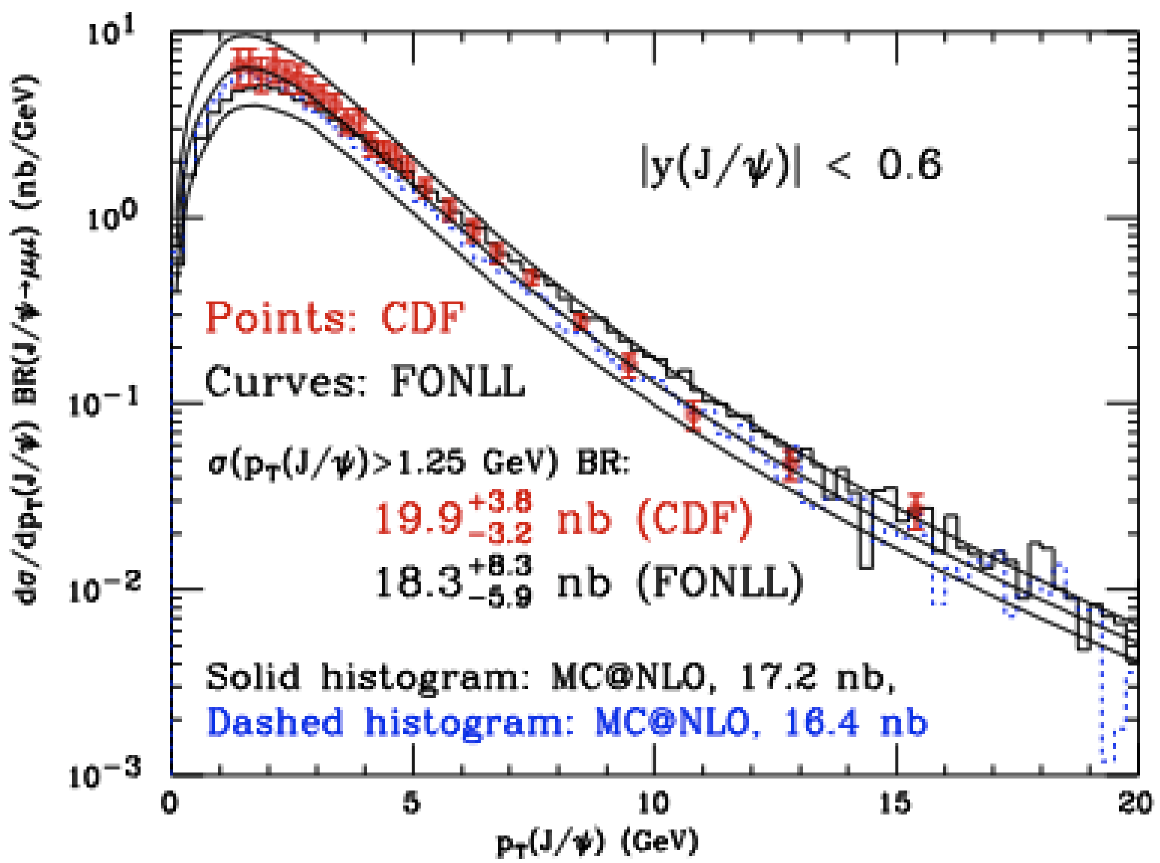


PLB 487, 264 (2000)

- Problems with both data and theory:
  - pollution with other production modes;
  - changes in the gluon PDF and α_s (thanks HERA!)

Resolution

- D0 cross section at large rapidity indicated a problem with the fragmentation function b → B, which had been extracted in e^+e^- collisions.
- This led to a reanalysis of the FF using the latest fixed order (NLO) and NLL results, "FONLL".
  - Forward discrepancy solved by a combination of ~20% effects, but an overall factor of two still remained.
- Remaining difference vanished in Run II, where data was smaller than expected and new PDFs increased the theory slightly.



Cacciari et al., JHEP 0407:033,2004

New tool MC@NLO not significantly different in this case (but good for other things!)

Conclusions

- For the most part, the Standard Model - and in particular, QCD - has held up well to scrutiny at the Tevatron.
- Measurements have taught us about the applicability of our theoretical tools and their limitations.
- You can teach an old dog new tricks: jet algorithms can be better behaved (IR safety) and do more for you (NP searches).
- Parton showers with matching to many MEs/NLO now standard for LHC.
- Huge amount of innovation in performing NLO calculations and steady progress at NNLO.
- Many of the dustier corners of pQCD, which the Tevatron is only beginning to probe, will be under scrutiny at the LHC.
- In many cases, the biggest gains have resulted from the experimental and theoretical communities continually challenging one another. Long may that continue!