QCD Theory

DPF 2009

John Campbell, University of Glasgow

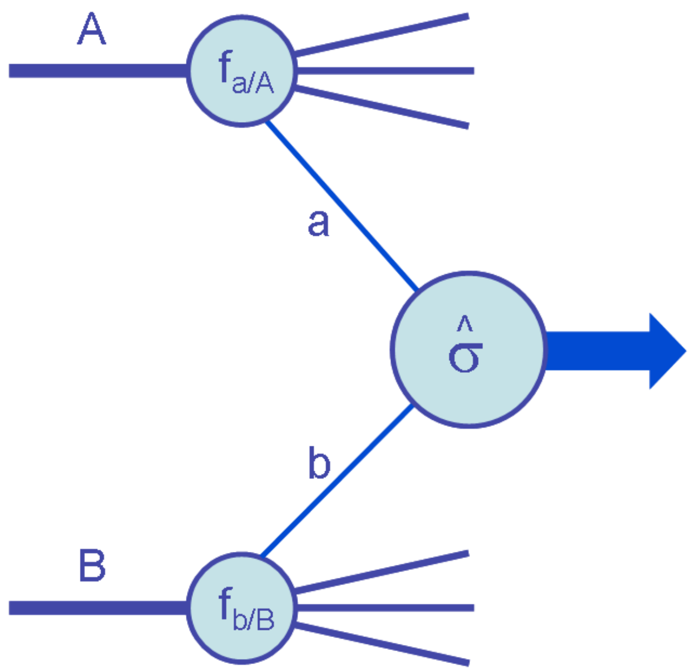
Outline

1. NLO enlightenment
2. Beyond NLO partons
3. PDF analyses
4. Jet algorithms
5. The strong coupling

Concentrate (mostly) on pQCD at hadron colliders

- see talks of Grinstein, El-Khadra, McLerran for other aspects of QCD theory
- big subject, selective review - apologies for absences

QCD at hadron colliders



- At hadron colliders phenomenology is based on appeal to factorization property of the physical process into soft and hard regions.

$$\sigma_{AB} = \int \mathrm{d}x_a \mathrm{d}x_b \; f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2) \, \hat{\sigma}_{ab \to X}$$

need to define *X*

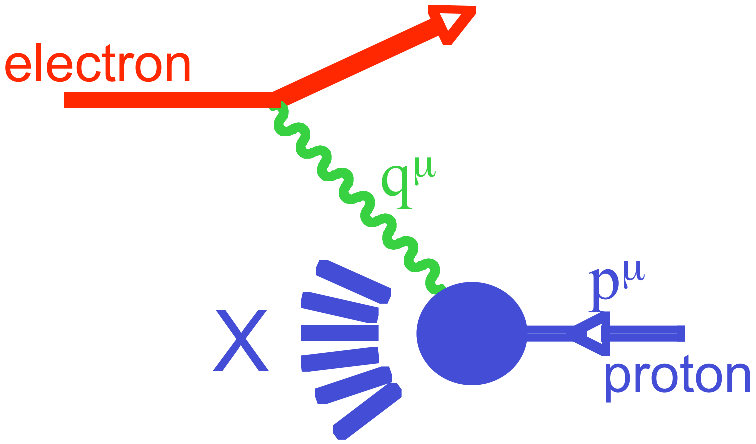
soft, non-perturbative physics

hard scattering matrix element

- Soft physics
    - encoded in parton distribution functions (PDFs)
    - cannot be calculated ab initio
    - universal, Q^2 dep. perturbative
    - stringent test of QCD at HERA.

$f_a(x, Q^2)$

probability of finding parton of type *a* carrying momentum fraction *x*, inside a fast-moving proton that is probed at scale *Q*



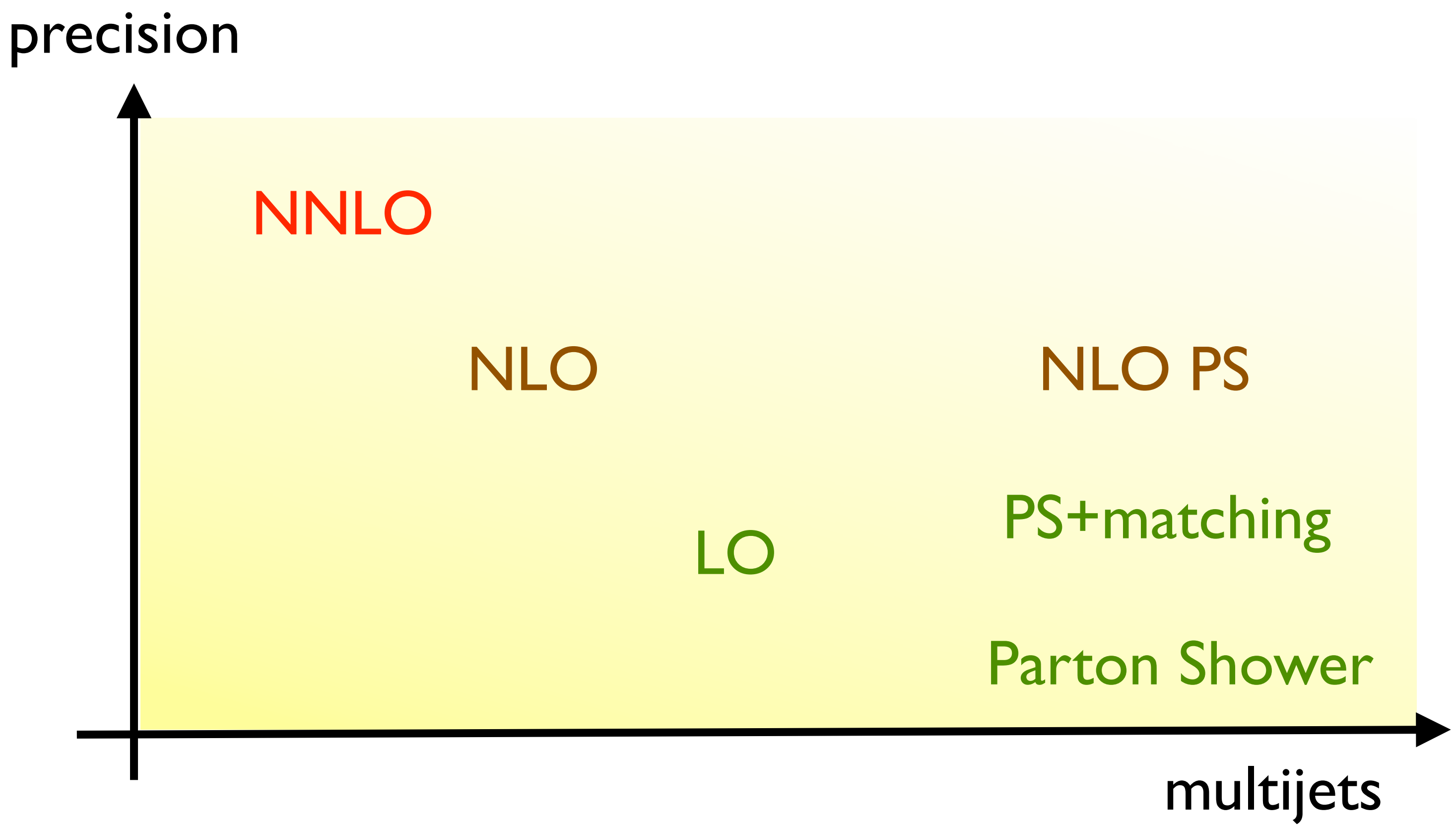
$$Q^2 = -q^2$$

$$x = \frac{Q^2}{2p.q}$$

Partons and showers

- Parton level QCD
  (exact matrix elements)
  - higher orders can be included
  - precision (~10% NLO, ~1% NNLO)
  - good in hard regions
  - small final states
  - only partons, not hadrons

- Parton shower [PS]
  (collinear approx., iterative)
  - hadrons and event simulation
  - widely applicable
  - good in soft regions
  - poor in hard regions
  - based on leading order



- Different avenues for combining:
  - PS+matching improves description in hard regions
    now relatively standard
  - NLO PS retains the benefits of the higher order calc.
    still being developed

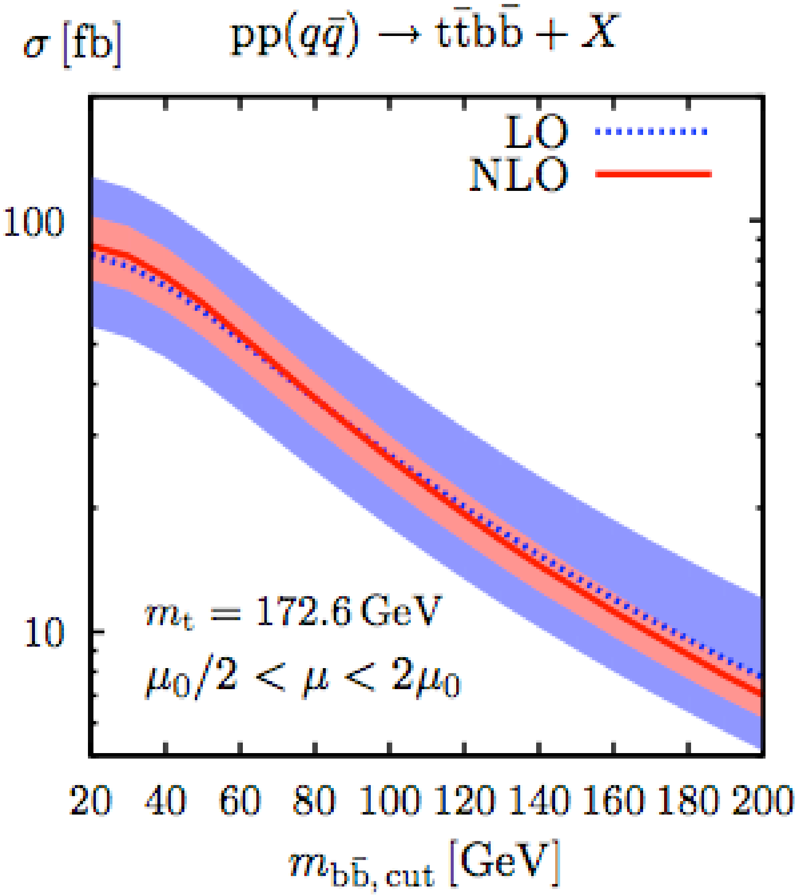
1. NLO enlightenment

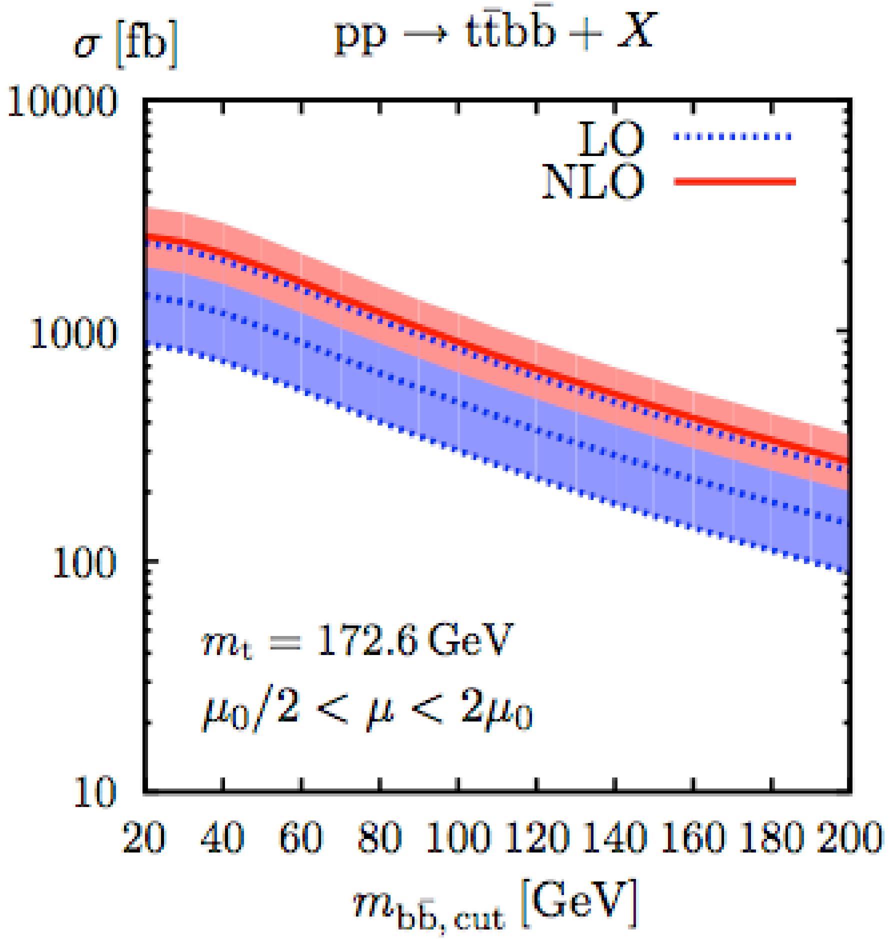
- Traditionally: many 1-loop Feynman diagrams, complicated Lorentz structure, algorithmic reduction to a basis of known integrals.
- More recently, this method has been supplemented by expansions in regions of instability and/or by implementing parts of the algorithm numerically.
- The first NLO 2→4 calculation by this method late last year: production of ttbb, a leading background to ttH(→bb) production.

Bredenstein et al., arXiv: 0807.1248

(quark-antiquark channel only)

small corrections, more stable





Bredenstein et al., arXiv: 0905.0110

(now includes gluon-gluon)

“K-factor” ~ 1.8, uncertainty halved

"OPP method" **(Ossola, Papodopoulos, Pittau)**

- Constructs 1-loop amplitudes directly from the form of the integrand.

Ossola, Papodopoulos, Pittau, hep-ph/0609007

- Algebraic reduction in a well-defined algorithm, automated by numerical implementation in public code CutTools.

Ossola, Papodopoulos, Pittau, arXiv:0704.1271

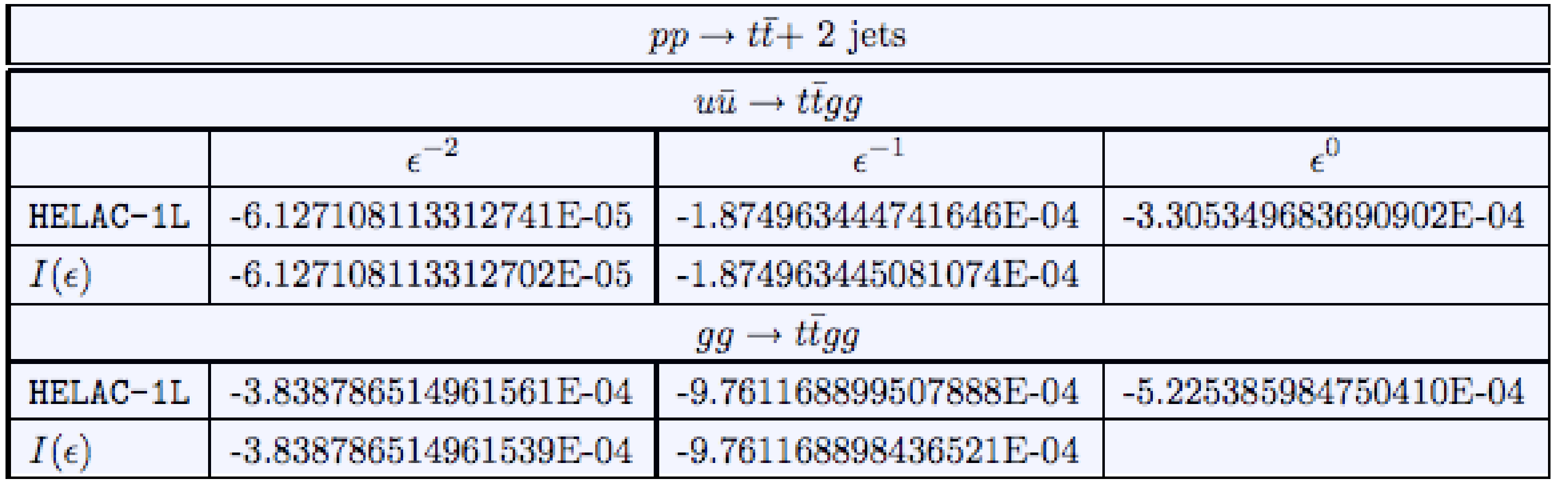
- Full NLO calculation of triple vector boson production.

Binoth, OPP, arXiv:0804.0350

- Turned into general purpose tool by extending tree level generator HELAC.

van Hameren, Papodopoulos, Pittau, OPP, arXiv:0903.4665

- All of 2007 Les Houches (prioritized) wishlist at a single point.



$pp \to t\bar{t}+$ 2 jets			
$u\bar{u} \to t\bar{t}gg$			
	ϵ^{-2}	ϵ^{-1}	ϵ^{0}
`HELAC-1L`	-6.127108113312741E-05	-1.874963444741646E-04	-3.305349683690902E-04
$I(\epsilon)$	-6.127108113312702E-05	-1.874963445081074E-04	
$gg \to t\bar{t}gg$			
`HELAC-1L`	-3.838786514961561E-04	-9.761168899507888E-04	-5.225385984750410E-04
$I(\epsilon)$	-3.838786514961539E-04	-9.761168898436521E-04	

- Impressive feat of strength, a little way off from phenomenology.

✱ See **arXiv:0907.4723** for very recent progress (ttbb)

Unitarity methods

- A breakthrough in understanding the analytic structure of amplitudes has come from (re-)considering unitarity of the S-matrix.

the same known integrals: note, nothing higher than a 4-point (box)

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

coefficients determined by cutting diagrams into tree-level (compact, well-understood) amplitudes

Britto, Cachazo and Feng, hep-th/0412103

rational term: requires much more care

- Key result: loop integration → algebra.
- Combine with recursion methods for computing tree level amplitudes
  - ➡ a plethora of powerful algorithms for computing virtual matrix elements.
- Added to algorithmic handling of real radiation → v. close to automated NLO.

Gleisberg and Krauss, arXiv: 0709.2881; Seymour and Tevlin, arXiv:0803.2331; Hasegawa et al., arXiv: 0807.3701; Frederix et al., 0808.2128

BlackHat

(Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Maitre)

- Virtual: numerical realisation of unitarity in D=4, rational part by on-shell recursion; instabilities avoided by on-the-fly use of multi-precision.

Berger, Bern, Dixon, Forde, Kosower, hep-ph/0604195

- Real: builds on SHERPA, automatic generation of (dipole) subtraction terms.

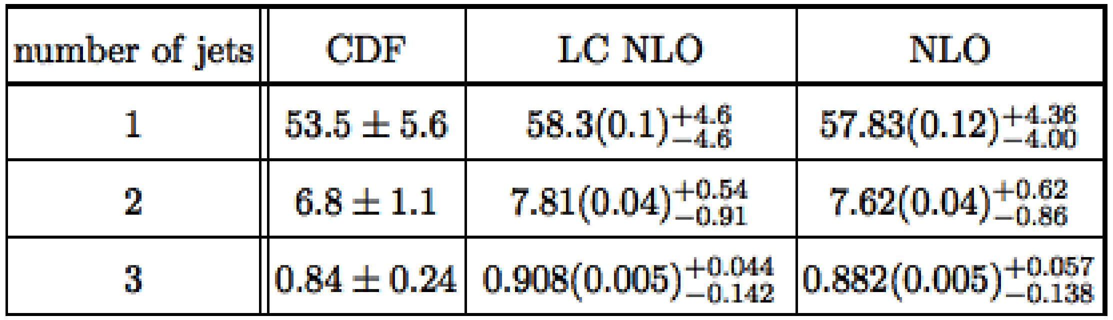
Gleisberg and Krauss, arXiv: 0709.2881

- Calculation of virtual 8-gluon amplitudes.
- Leading color approximation to W+3 jet production.

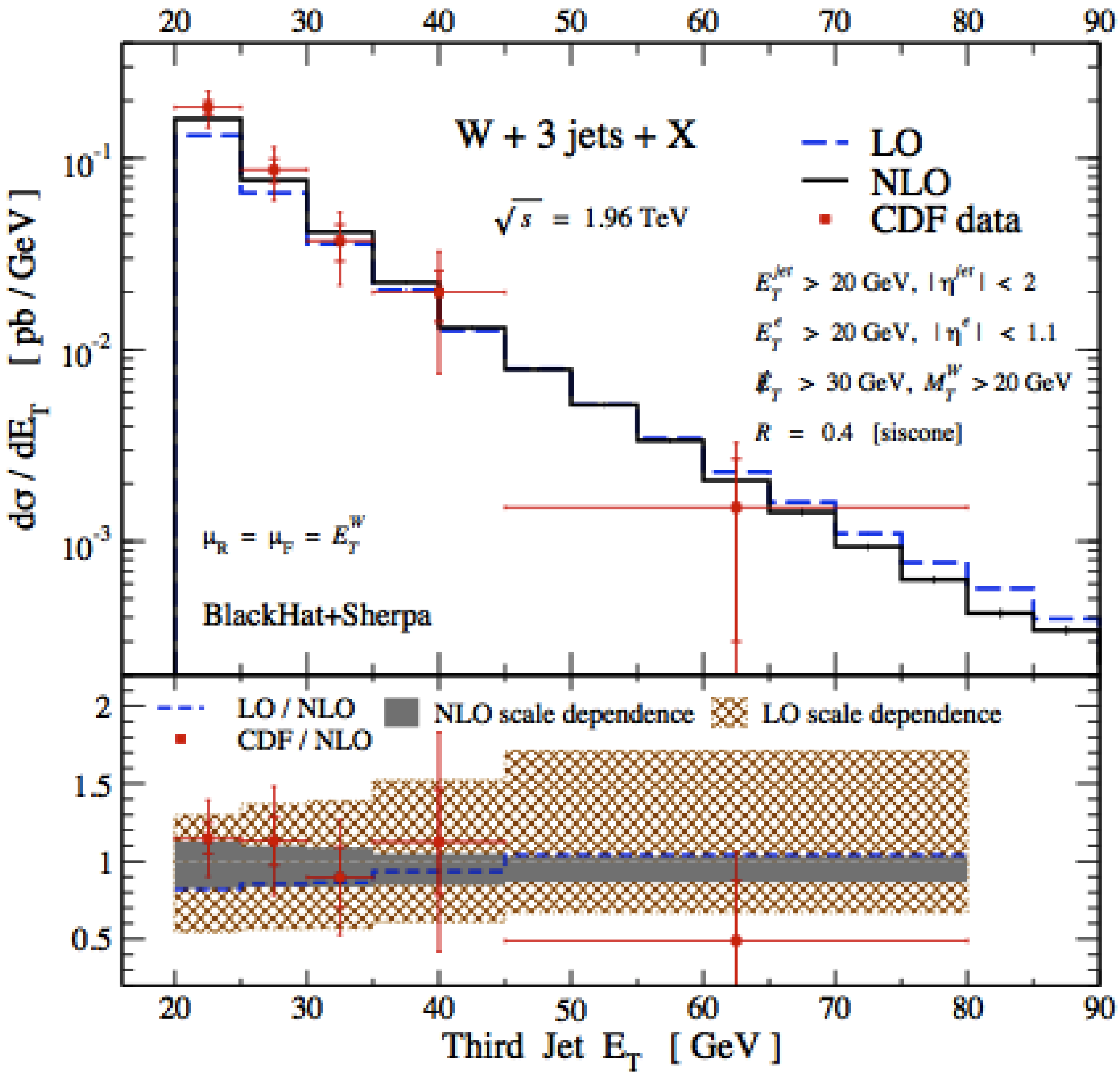
Berger et al., arXiv: 0902.2760

- Full calculation including all subleading terms.

Berger et al., arXiv: 0907.1984



number of jets	CDF	LC NLO	NLO
1	53.5 ± 5.6	$58.3(0.1)^{+4.6}_{-4.6}$	$57.83(0.12)^{+4.36}_{-4.00}$
2	6.8 ± 1.1	$7.81(0.04)^{+0.54}_{-0.91}$	$7.62(0.04)^{+0.62}_{-0.86}$
3	0.84 ± 0.24	$0.908(0.005)^{+0.044}_{-0.142}$	$0.882(0.005)^{+0.057}_{-0.138}$



Rocket

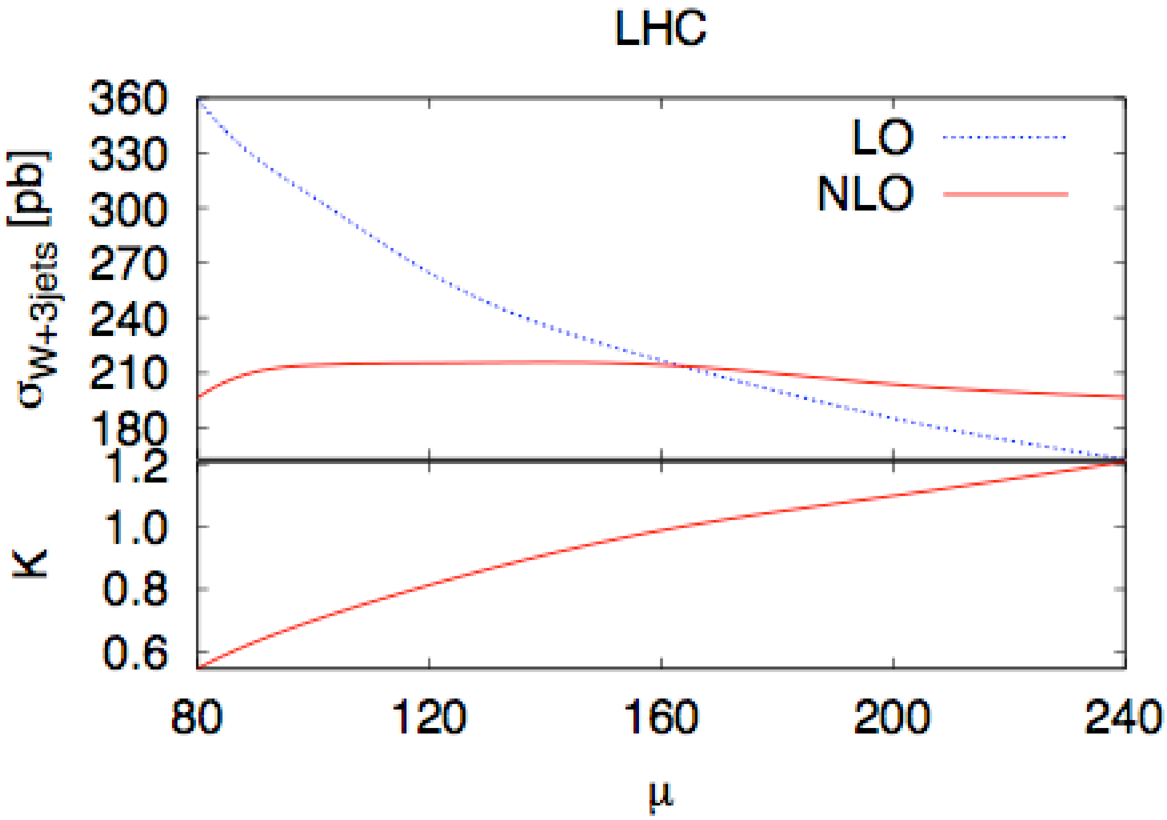
(Ellis, Giele, Kunszt, Melnikov, Zanderighi)

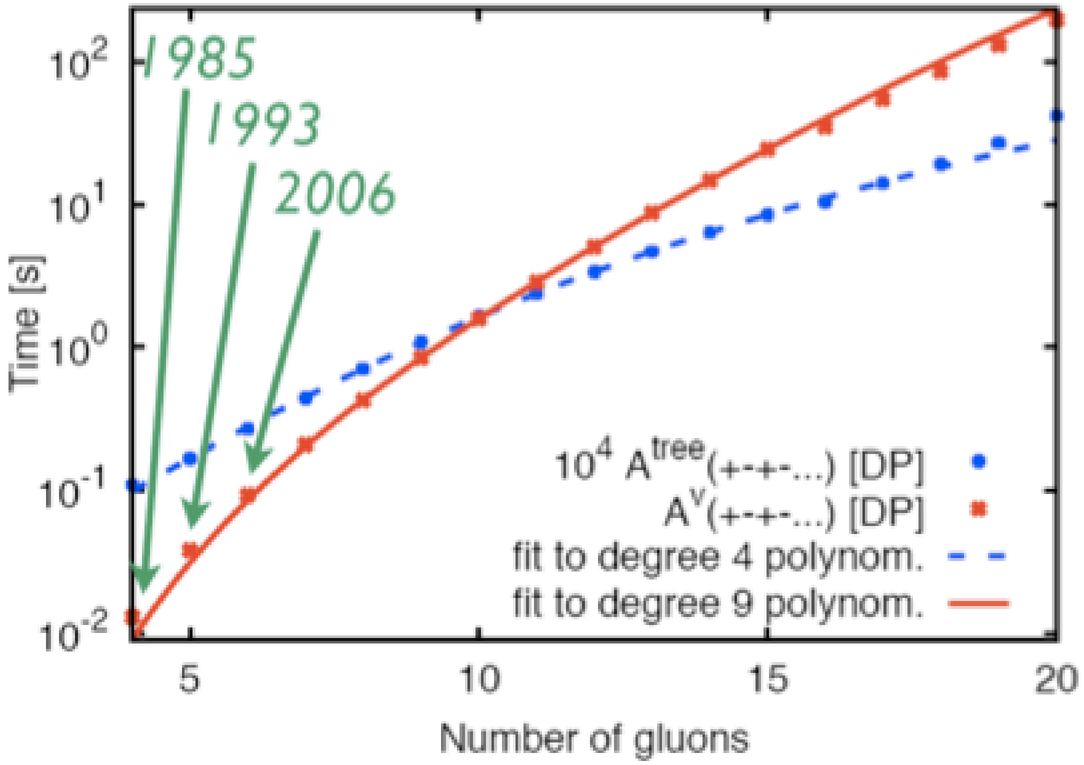
- Virtual: unitarity in D dimensions and off-shell recursion.

- Real: builds on existing MCFM implementation of dipole subtraction.

- (Slightly different) leading color approximation to W+3 jets.

Ellis, Melnikov, Zanderighi, arXiv:0901.4101, 0906.1445





- Multi-gluon scattering at a single phase space point.

Giele, Zanderighi, arXiv: 0805.2152

  - demonstrates the power of a numerical approach

Analytic Higgs + parton amplitudes

- A particular area of analytic interest has been in the calculation of H + parton amplitudes, using effective coupling of Higgs to gluons ($m_t \to \infty$).
- Structure of helicity amplitudes is very similar to pure QCD.

Dixon, Glover, Khoze, hep-th/0411092

- The particular case of Higgs+2 partons is especially interesting at the LHC: background to vector boson fusion search channel.

H+2 gluons, 2 quarks	- +	0906.008
	+ -	0906.008
	+ +	unknown
	- -	unknown
H+4 gluons	- - - -	0607139
	- - - +	unknown
	- - + +	0704.3914
	- + - +	0804.4149
	- + + +	unknown

Badger, Glover, hep-ph/0607139

Berger, del Duca, Dixon, hep-ph/0608180

Badger, Glover Risager, arXiv:0704.3914

Glover, Mastrolia, Williams, arXiv:0804.4149

Dixon, Sofianatos, arXiv: 0906.0008

- Most of these are calculations for general Higgs+n parton scattering.
- Phenomenology still relies on (slower) semi-numerical calculation.

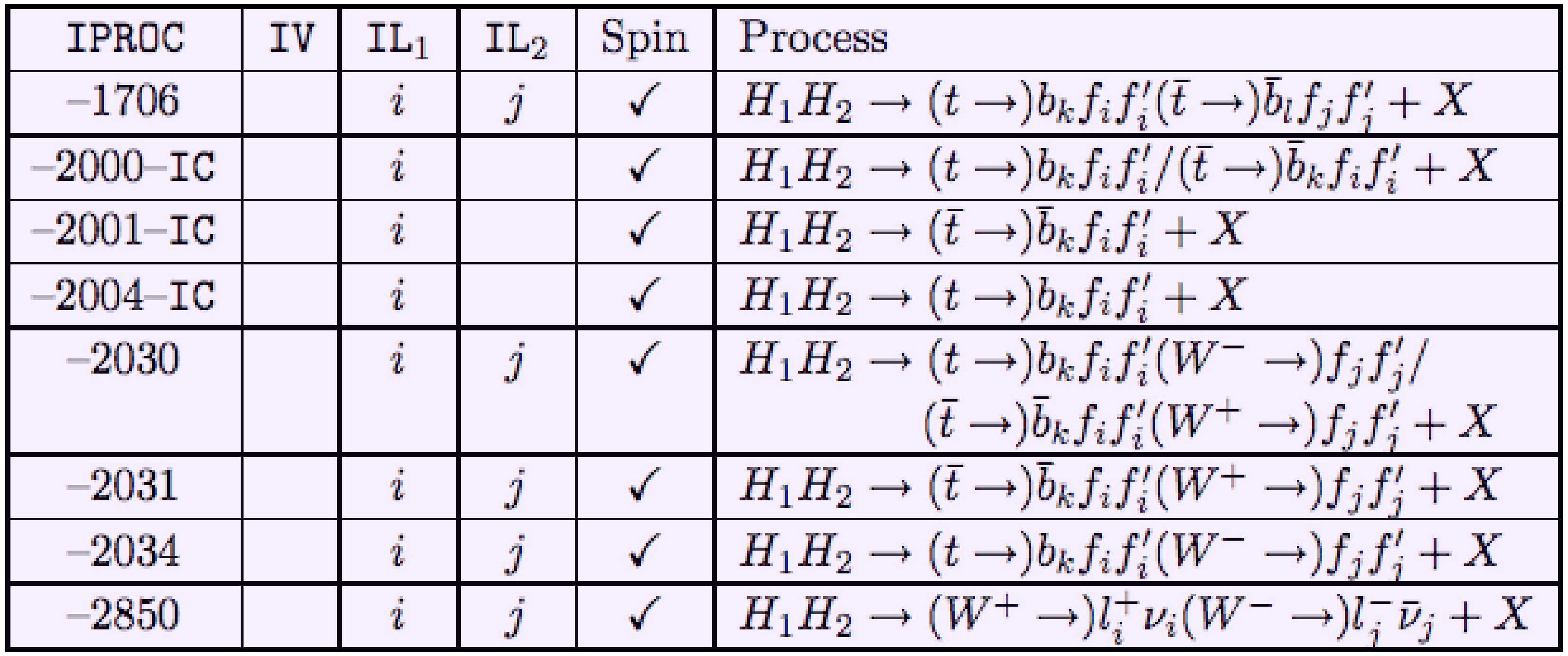
JC, Ellis, Zanderighi, hep-ph/0608194

2. Beyond the NLO parton level

- MC@NLO: first concrete implementation of a NLO parton shower, based on HERWIG Monte Carlo.

Frixione and Webber, hep-ph/0204244

- Solved the long-standing problem of double counting radiation that must be included at NLO and also generated in the shower.
- Mostly limited to final states containing no massless partons, i.e. initial state radiation and collinear radiation from massive quarks.



IPROC	IV	IL$_1$	IL$_2$	Spin	Process
−1706		i	j	✓	$H_1H_2 \to (t \to)b_k f_i f_i'(\bar{t} \to)\bar{b}_l f_j f_j' + X$
−2000−IC		i		✓	$H_1H_2 \to (t \to)b_k f_i f_i'/(\bar{t} \to)\bar{b}_k f_i f_i' + X$
−2001−IC		i		✓	$H_1H_2 \to (\bar{t} \to)\bar{b}_k f_i f_i' + X$
−2004−IC		i		✓	$H_1H_2 \to (t \to)b_k f_i f_i' + X$
−2030		i	j	✓	$H_1H_2 \to (t \to)b_k f_i f_i'(W^- \to)f_j f_j'/$ $(\bar{t} \to)\bar{b}_k f_i f_i'(W^+ \to)f_j f_j' + X$
−2031		i	j	✓	$H_1H_2 \to (\bar{t} \to)\bar{b}_k f_i f_i'(W^+ \to)f_j f_j' + X$
−2034		i	j	✓	$H_1H_2 \to (t \to)b_k f_i f_i'(W^- \to)f_j f_j' + X$
−2850		i	j	✓	$H_1H_2 \to (W^+ \to)l_i^+\nu_i(W^- \to)l_j^-\bar{\nu}_j + X$

- Most recently: Wt production.

Frixione et al., arXiv:0805.3067

- Significant production mode at the LHC, background to H→WW.

POWHEG

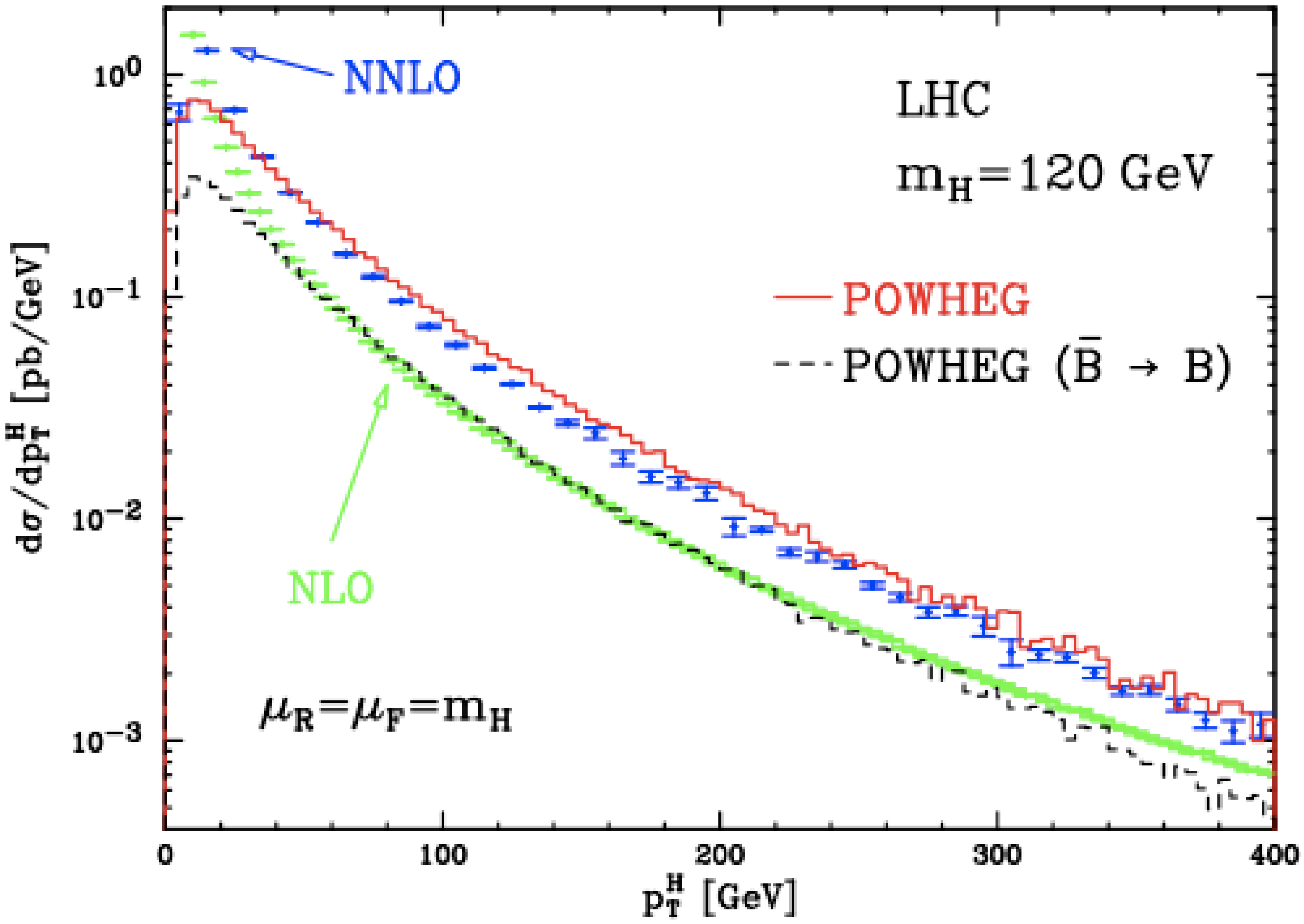
- A more recent implementation that interfaces with any shower.

Nason,hep-ph/0409146; Frixione, Nason and Oleari, arXiv:0709:2092

- Applied to heavy quark production, V, VH, single top.

Alioli et al., arXiv:0907:4076

- Upcoming diboson production, V+jet.
- Promise of a general framework for including any NLO calculation.



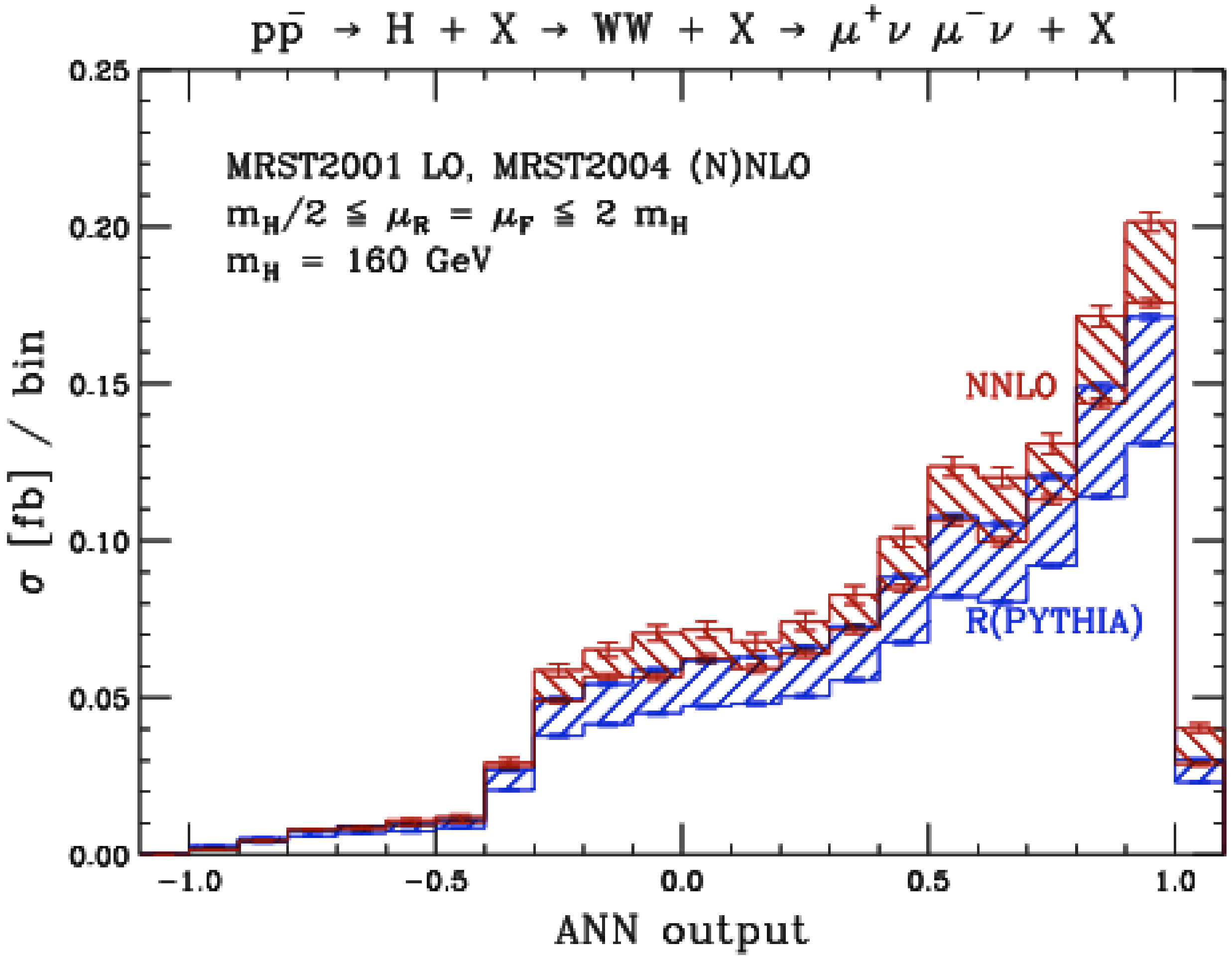
Alioli et al., arXiv:0812:0578

- Comparison with MC@NLO yields interesting differences that are formally NNLO.
- Default behavior reproduces NNLO Higgs p_T spectrum.
  - useful for phenomenology.
  - just a tuning of the shower.

NNLO: Higgs production

- One of the flagship channels for NNLO innovation (also Drell Yan).
- Highly non-trivial: 2-loop diagrams and doubly-singular real radiation.
  - 2002 fully inclusive predictions
  - 2003 resummation of (NNL) logarithms, first differential distribution
  - 2004 fully differential predictions
  - 2009 full dependence of 2-loop calculation on m_t

Harlander, Ozeren, arXiv:0907.2997; Pak, Rogal, Steinhauser, arXiv:0907.2998



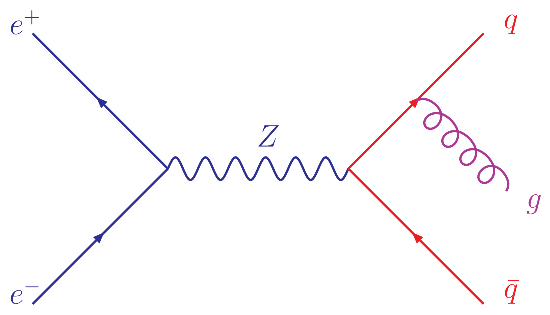
- Study of NNLO calculation directly in a neural network.

Anastasiou et al., arXiv: 0905:3529

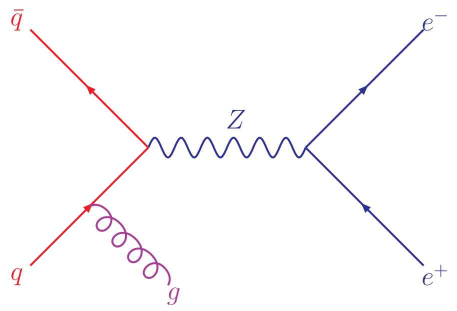
  - investigate Tevatron sensitivity
  - compare with parton shower analysis used by CDF and D0

Jets at NNLO

- Benchmark calculations so far are 2→1 scatterings.
  - Adding additional particles is tough.
  - General framework not quite worked out yet.
- For jets, simplest to start with an electron-position machine: $e^+e^- \rightarrow$ 3 jets.



non-trivial work to do crossing to hadron collider



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

- Improves extraction of α_s from event shapes, where theory error dominates.
- Goal of hadro-production of Z (or W) + 1 jet at NNLO still a way off, e.g. 2-loop amplitudes to (2+1) jet production in DIS recently completed.

Gehrmann and Glover, arXiv: 0904:2665

- Isolating all infrared singularities in the corresponding real radiation calculation is much harder due to hadronic initial state.

Higher orders: quick reference

Hadron collider final state	1-loop at a single point	NLO	NLO + shower	NNLO
V (=W/Z)	✔	✔	✔	✔
V + jet	✔	✔	★[1]	
V V	✔	✔	✔	★[2]
dijets	✔	✔		
top pair	✔	✔	✔	★[3]
t-channel single top	✔	✔	✔	
V + 2 jets	✔	✔		
V V + jet	✔	✔		
three jets	✔	✔		
top pair + jet	✔	✔[4]		
V V V	✔	✔[5,6]		
V + 3 jets	✔[7]	✔[8,9] (W)		
V V + 2 jets	✔[7]			
V V + bottom pair	✔[7]			
top pair + 2 jets	✔[7]			
top pair + bottom pair	✔[7]	✔[10]		
two bottom pairs	✔[7]			
(20-gluon scattering)	✔[11]			

1: Alioli, Nason, Oleari and Re

2: Chachamis, Czakon, Eiras

3: Czakon, Mitov, Moch;
Bonciani, Ferroglia,
Gehrmann, Studerus

4: Dittmaier, Uwer, Weinzierl,
arXiv:0810.0452

5: Binoth et al,
arXiv:0804.0350

6: Campanario et al,
arXiv:0809.0790

7: van Hameren et al.,
arXiv:0903.4665

8: C. Berger et al.,
arXiv:0902.2760

9: Ellis, Melnikov, Zanderighi
arXiv:0901.4101

10: Bredenstein et al,
arXiv:0905.0110

11: Giele and Zanderighi,
arXiv:0805.2152

A glimpse beyond NNLO

- Recent results are beginning to shed light on the structure of scattering amplitudes in gauge theories at all orders.
- A formula that predicts the infrared singularities present in any higher order QCD-like calculation has been conjectured.

Becher and Neubert, arXiv: 0901.0722; Gardi and Magnea, 0901.1091

- Formula successfully reproduces singularities in all known calculations, e.g.
    - 2-loop matrix elements
    - 3-loop quark and gluon form factor
    - 4-loop, 4-gluon amplitude in N=4 SUSY YM
- The structure of the formula is very simple; it could have been more complex, but that is not supported by these cross checks.
    - deeper organizing principle to the theory that we have not yet understood?
    - application to resummed predictions
- Extension to calculations with massive particles more complicated.

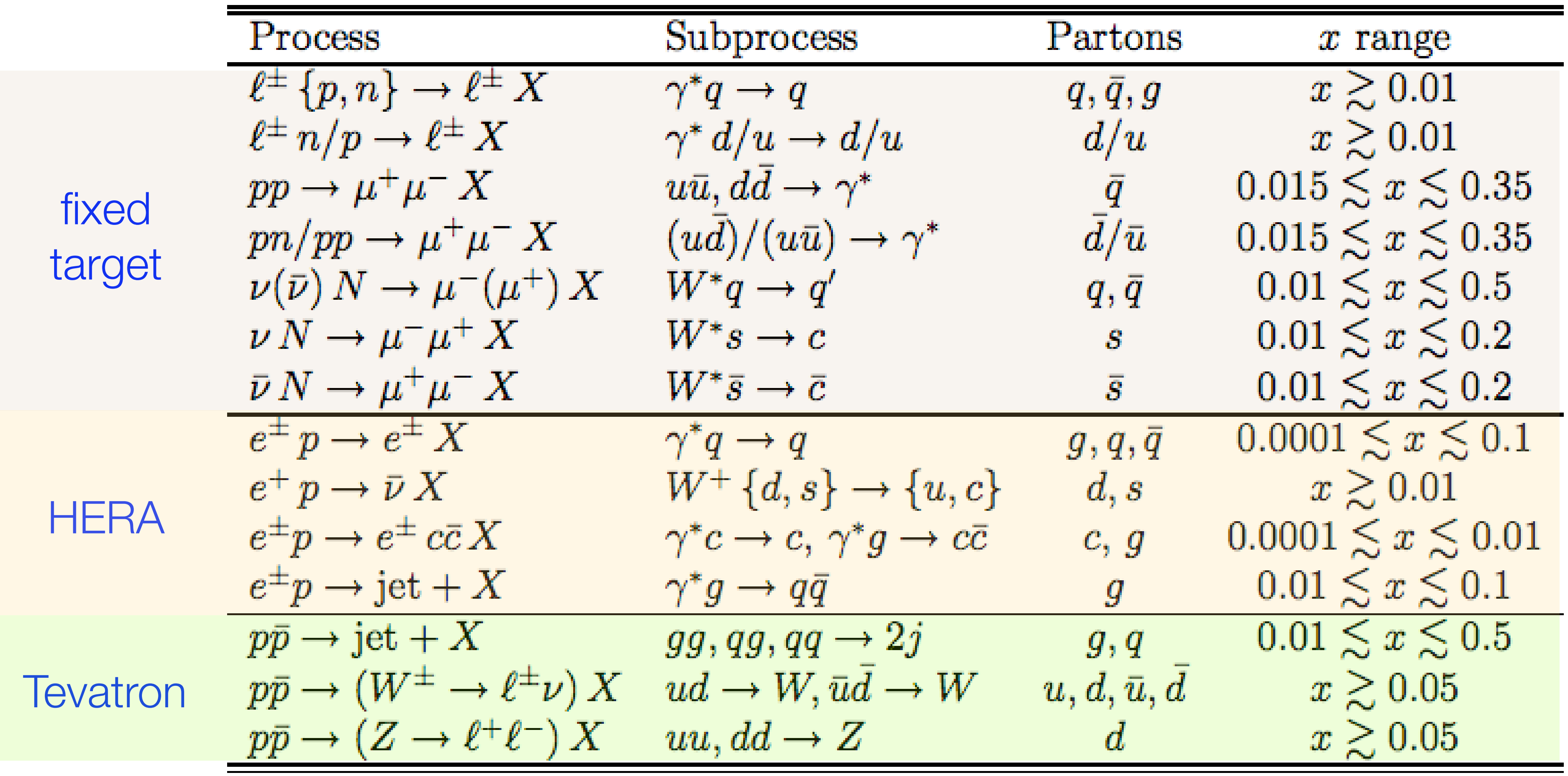
Becher and Neubert, arXiv: 0904.1021; Ferroglia et al., arXiv: 0907.4791

3. Global PDF analyses

- Historically, two collaborations providing global fits to experimental data in a similar spirit, using given functional forms of the PDFs.

CTEQ **MRS(T)/MSTW**

- Complementary information from many different sources, example: one of the most recent analyses (MSTW2008).



	Process	Subprocess	Partons	x range
fixed target	$\ell^\pm \{p,n\} \to \ell^\pm X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
	$\ell^\pm n/p \to \ell^\pm X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
	$pp \to \mu^+\mu^- X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
	$pn/pp \to \mu^+\mu^- X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
	$\nu(\bar{\nu})\, N \to \mu^-(\mu^+)\, X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
	$\nu\, N \to \mu^-\mu^+ X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
	$\bar{\nu}\, N \to \mu^+\mu^- X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
HERA	$e^\pm p \to e^\pm X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
	$e^+ p \to \bar{\nu} X$	$W^+ \{d,s\} \to \{u,c\}$	d, s	$x \gtrsim 0.01$
	$e^\pm p \to e^\pm c\bar{c}\, X$	$\gamma^* c \to c,\ \gamma^* g \to c\bar{c}$	$c,\ g$	$0.0001 \lesssim x \lesssim 0.01$
	$e^\pm p \to \text{jet} + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
Tevatron	$p\bar{p} \to \text{jet} + X$	$gg, qg, qq \to 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$
	$p\bar{p} \to (W^\pm \to \ell^\pm \nu)\, X$	$ud \to W, \bar{u}\bar{d} \to W$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
	$p\bar{p} \to (Z \to \ell^+\ell^-)\, X$	$uu, dd \to Z$	d	$x \gtrsim 0.05$

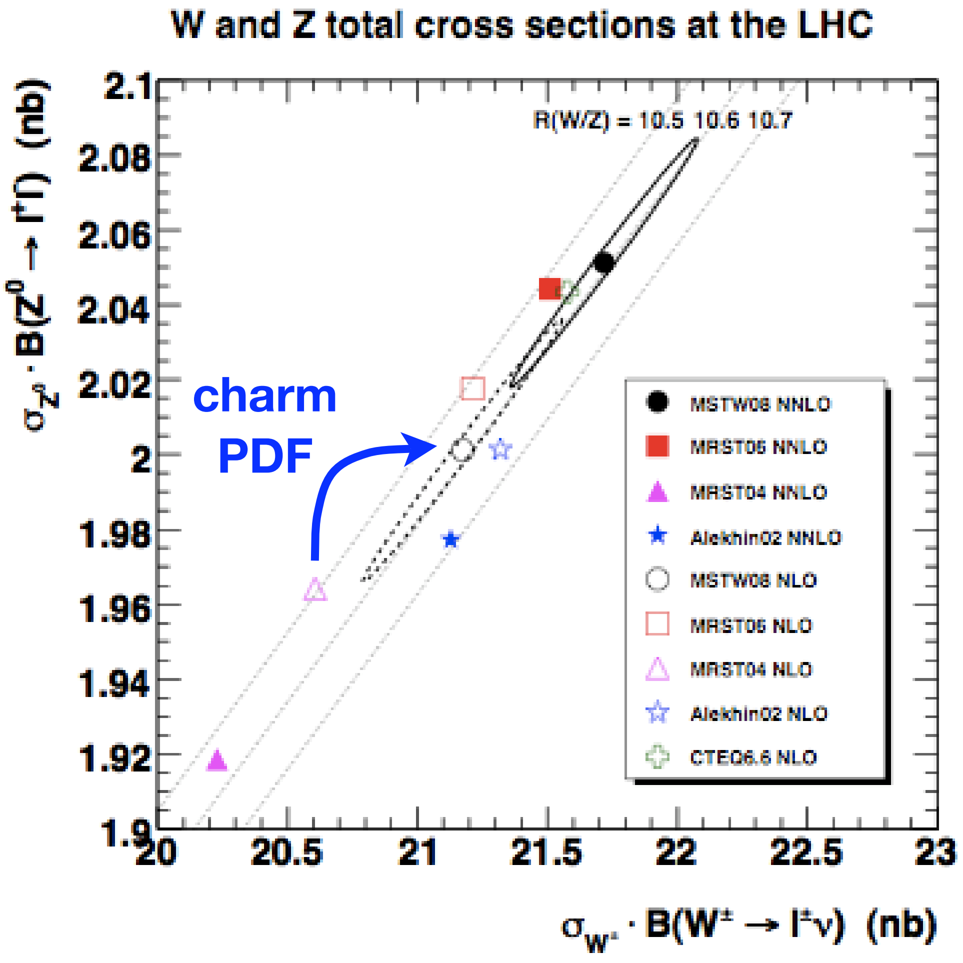
State of play: MSTW **(Martin, Stirling, Thorne, Watt)**

- New data sets: CCFR/NuTeV dimuons to determine strange distributions, Tevatron Run II inclusive jets, W lepton charge asymmetry, Z rapidity
- New method for propagating experimental errors to PDFs

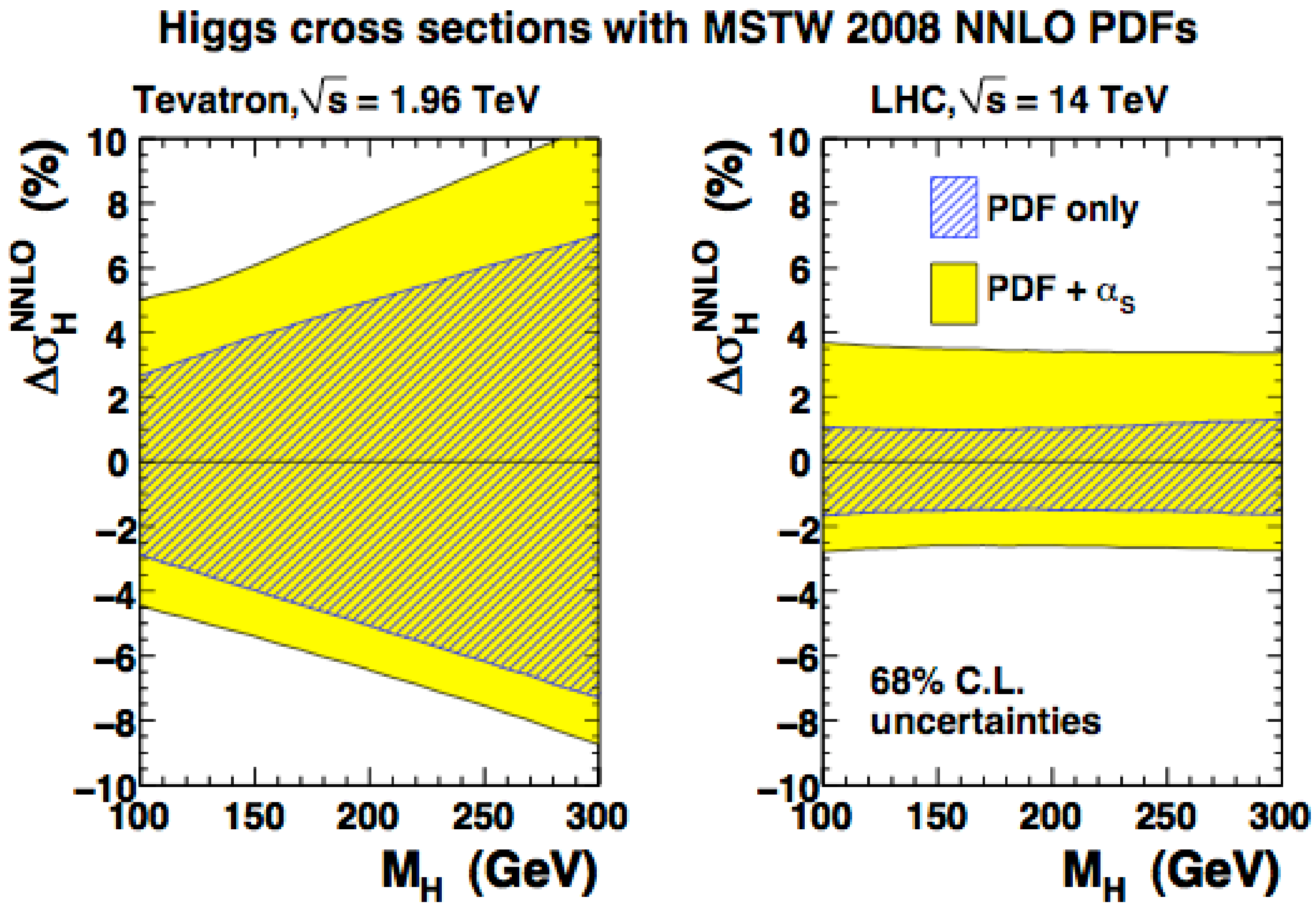
Note: unable to fit D0 Run II W→eν data

- Sets with different central values for $\alpha_s(m_Z)$, to allow for consistent variation.

arXiv: 0901.0002



arXiv: 0905.3531



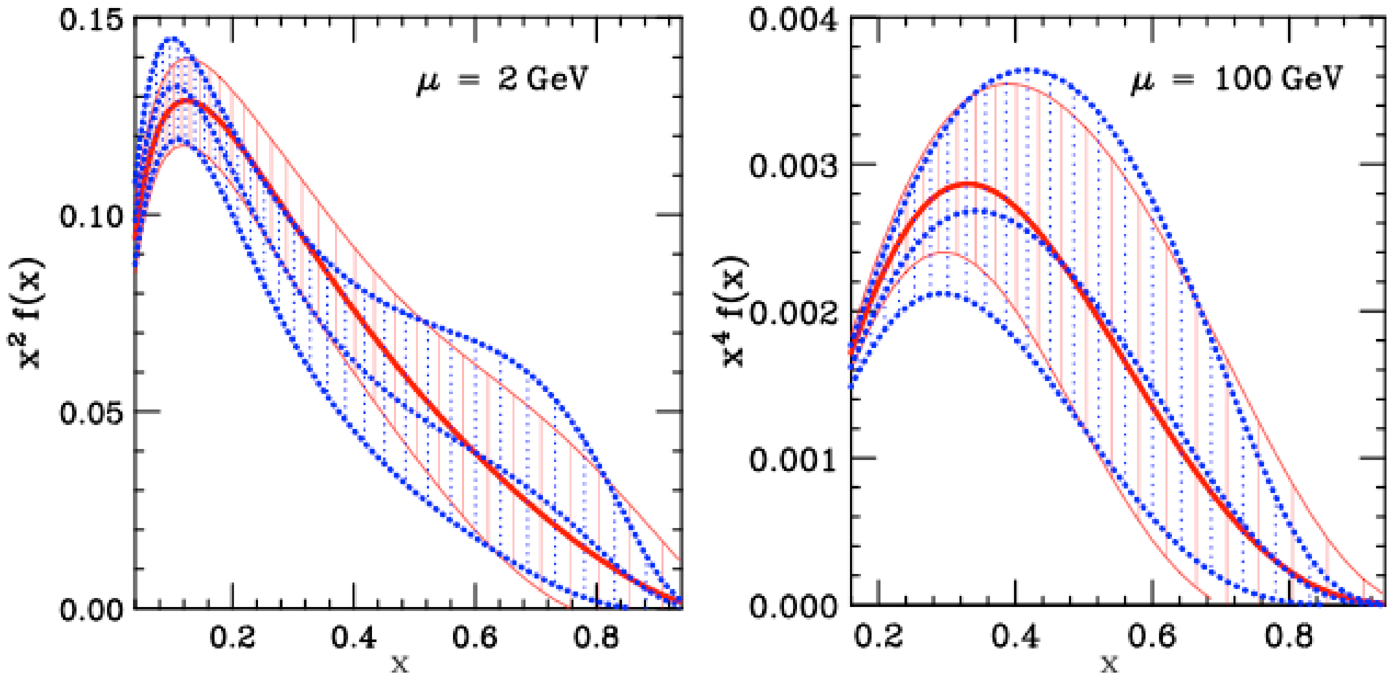
CTEQ

- Last major overhaul in 2002: CTEQ6 **(hep-ph/0201195)**.
- Plethora of updates: CTEQ6.1 (2003) → CTEQ6.5 (2006) → CTEQ6.6 (2008).
- Most recently: CT09G **(Pumplin, Huston, Lai, Tung, Yuan, arXiv:0904.2424)**
  - inclusion of Run II jet data changes only the gluon density, which is now parametrized more freely.

$$g(x, \mu_0) = a_0\, x^{a_1}\, (1-x)^{a_2}\, \exp(a_3 x\, +\, a_4 x^2\, +\, a_5 \sqrt{x})$$

CTEQ6.6: $a_2=4$, $a_5=0$

  - new method for interpreting PDF uncertainties directly in observables.



gluon dist.

CT09G

CTEQ6.6

small scale behavior most affected, small impact at high scales

NNPDF

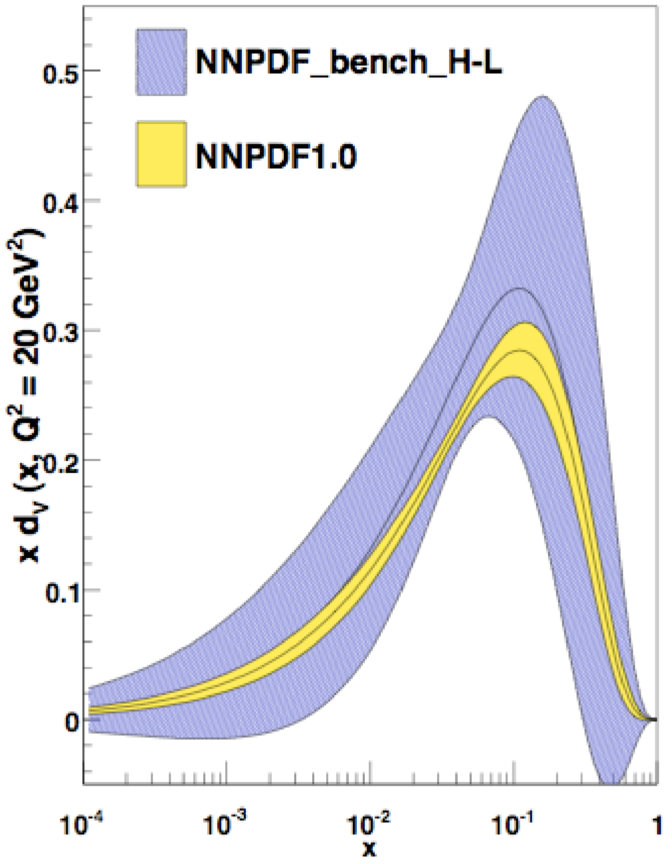
- Fits based on neural networks to fix the functional form of the PDFs with much more flexibility.

NNPDF collaboration, Ball et al., arXiv:0808.1231

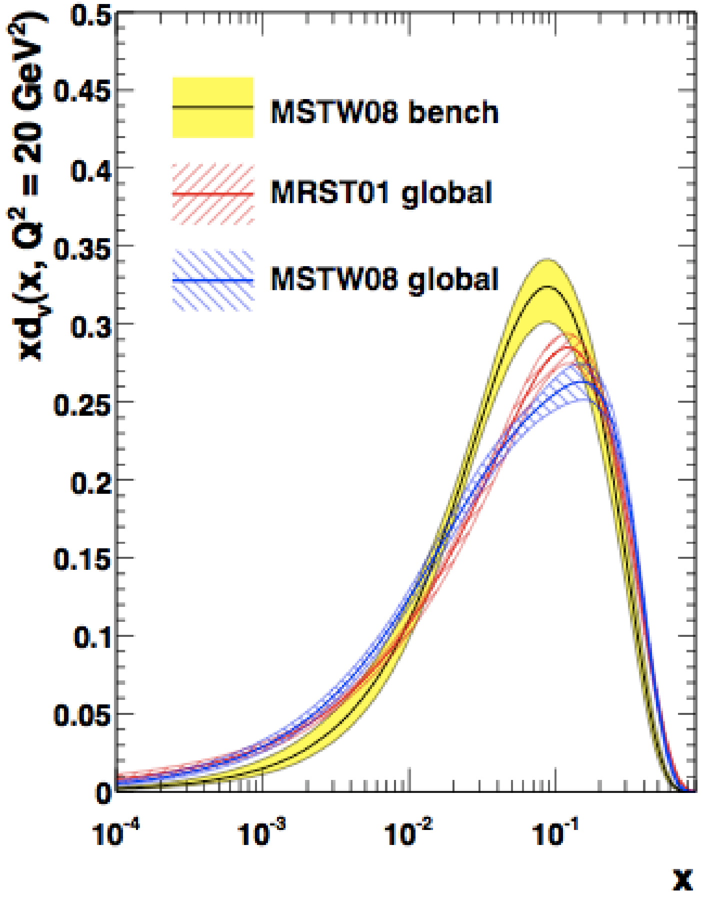
- Currently limited to fixed-target and DIS only.
- Propagate errors to the PDFs by using an ensemble of data sets representing the full experimental errors.

HERA and the LHC,
Dittmar et al.,
arXiv: 0901.2504

benchmark
= reduced
set of inputs



Down valence distribution



within errors for
NNPDF, not for
MSTW

overly
constrained
parametrisation?

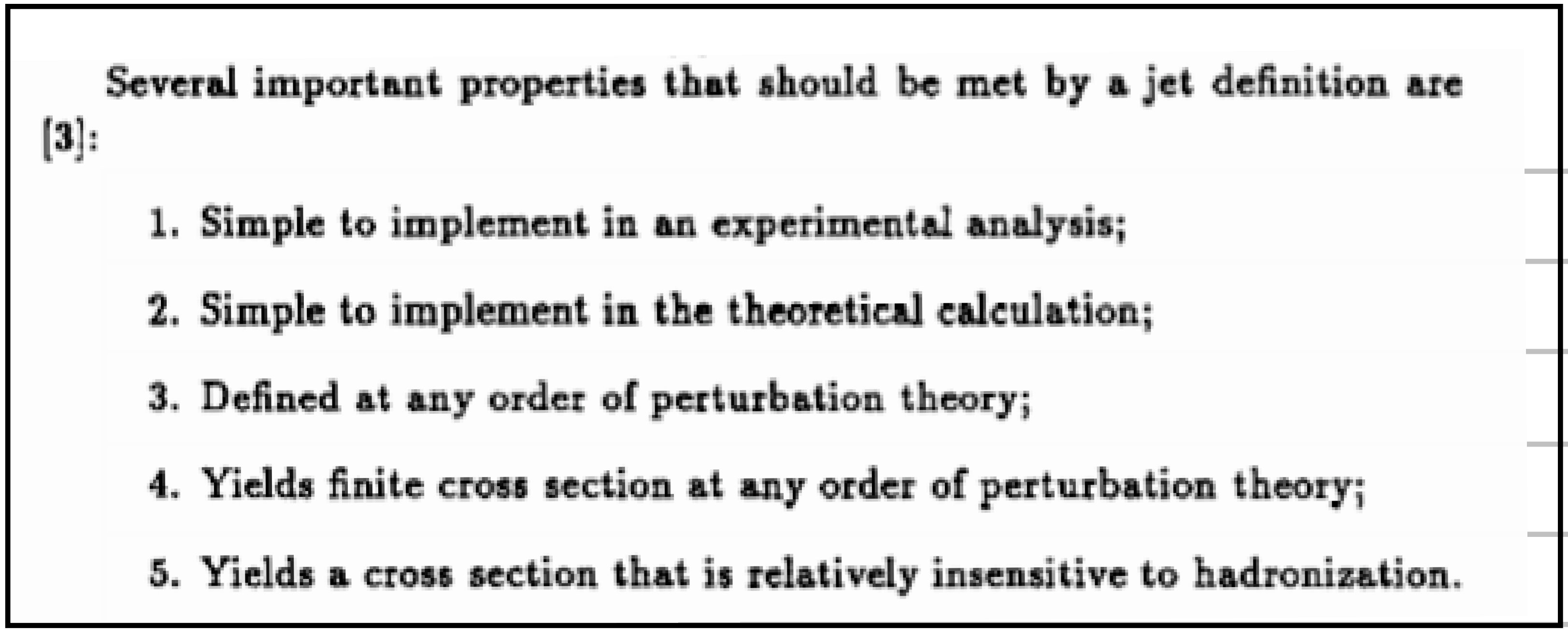
due to imposing
$\bar{u} = \bar{d}$?

4. Jet algorithms

- Over the years, many methods for sweeping hadrons (partons) into jets.

"Snowmass accord"

Fermilab-Conf-90/249-E



Several important properties that should be met by a jet definition are [3]:

	cone	k_T
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.	✓	✓

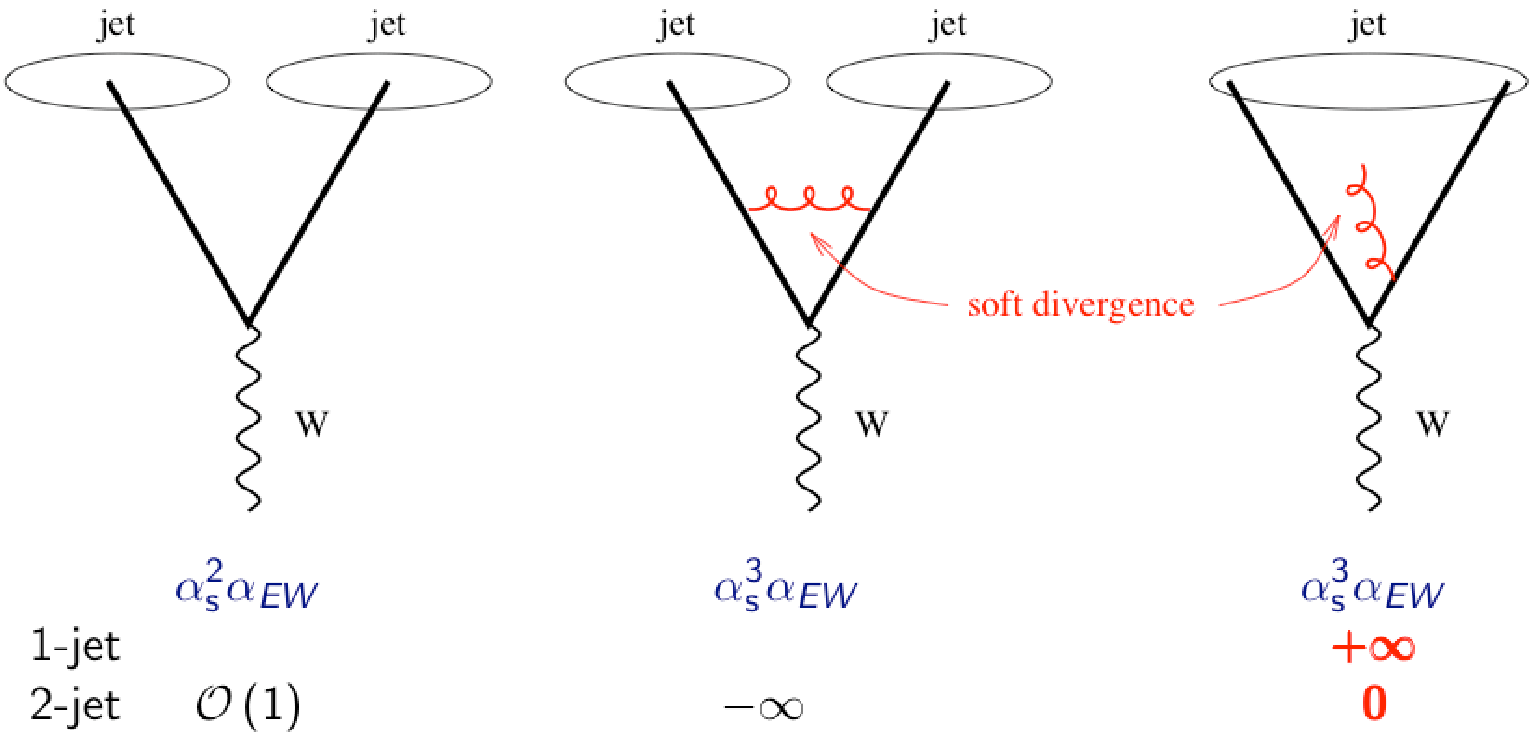
- Realising all of these in practice has been difficult.

For a recent review see: Salam, arXiv:0906.1833

- The k_T algorithm has long been criticised for producing unusual jet structures and for being hard to use because of pileup and the underlying event. Moreover, traditional implementations of it are computationally expensive.
- Cones have evolved substantially, e.g. iterative cones, midpoint algorithms, etc. and most implementations lack general collinear or infrared safety.

Infrared unsafety

- An algorithm is infrared unsafe when the addition of a soft particle changes the configuration of jets found by the algorithm.



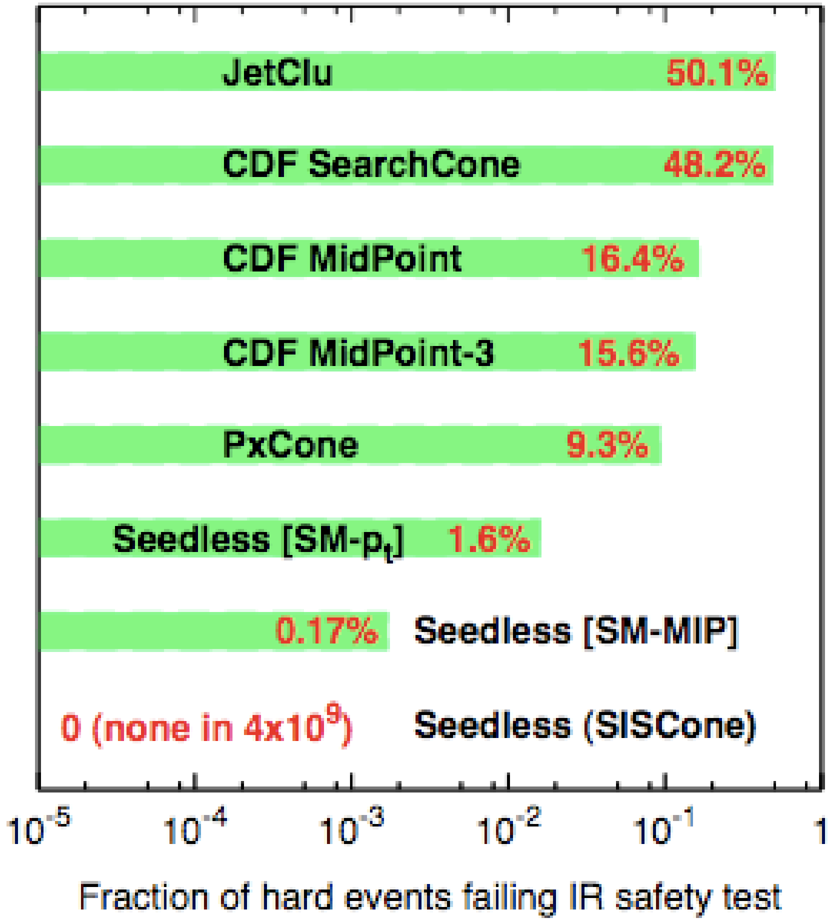
- Integrating over phase space, both 1- and 2-jet contributions are infinite.
- Detector/algorithm details are regulators → large logs instead of infinities.
    - cross sections then depend on details of the detector.
    - e.g. CDF - D0 - theory comparisons become less compelling.

Seedless cone algorithms

- The origin of the this behavior is the use of seeds, initial directions for the putative jets that are subsequently improved iteratively.
- If one considers all possible clusterings of particles into jets, the algorithm is seedless and infrared safety can be guaranteed.
  - the simplest such algorithm is expensive: $O(N\ 2^N)$ for N particles.
    (fine for fixed order calculations, not so much for data)
- Better solution using techniques from computational geometry: SISCone ("Seedless Infrared Safe").

  Salam and Soyez, arXiv: 0704.0292

  - time: $O(\varepsilon N^2 \log[\varepsilon N])$, $\varepsilon \sim 0.1\text{-}0.01$
- Infrared safety rigorously checked.
  - failure rates quoted are not from typical events, but ones that contain *very soft* momenta.

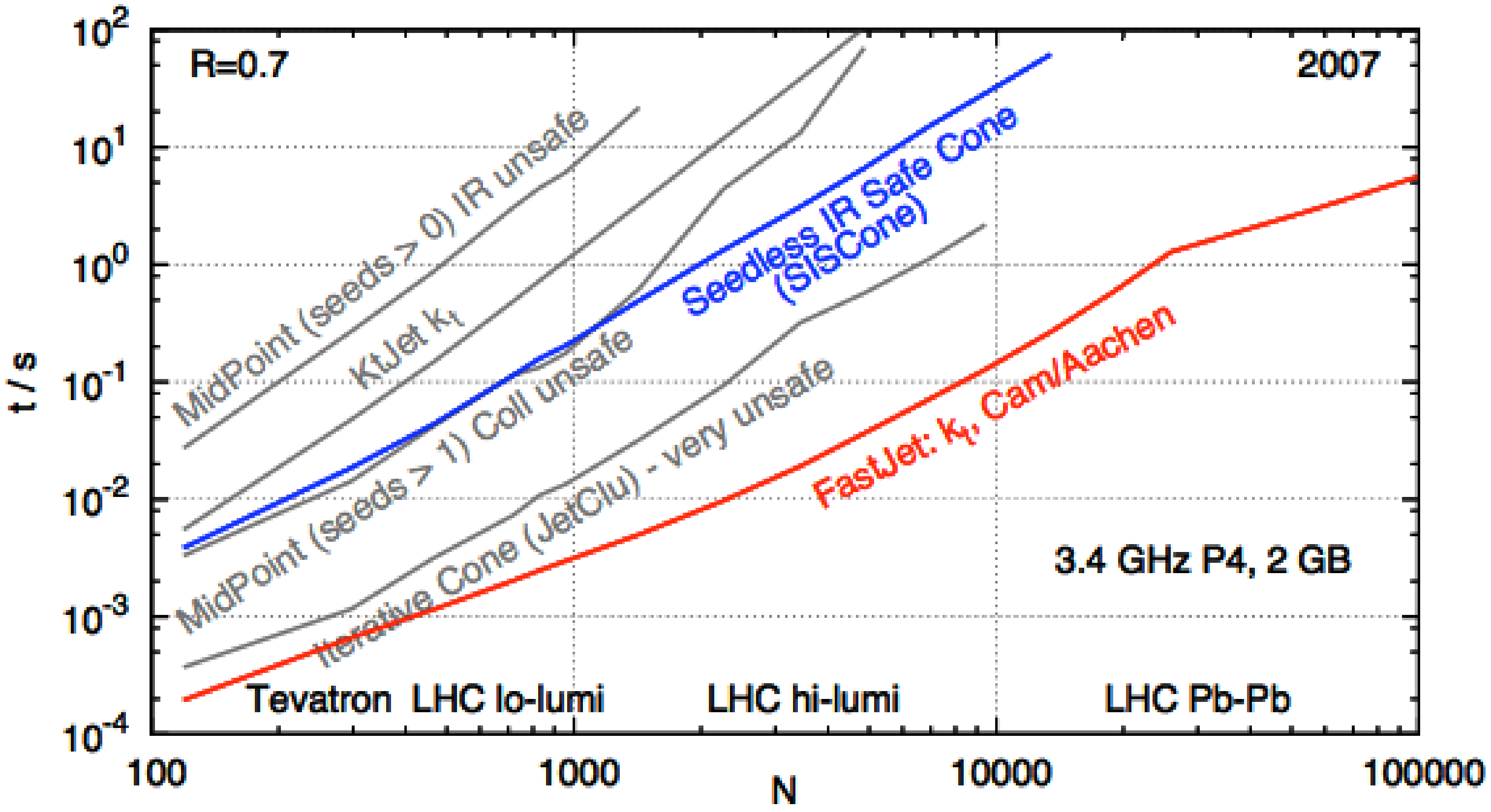


Recombination algorithms

- The k_T algorithm is just a particular example of one that proceeds by sequentially combining pairs of particles according to some measure.

$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}\,, \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

- Searching for this minimum gives such recombination algorithms a complexity $O(N^3)$, which is largely impractical at hadron colliders.
- Once again, a geometrical approach reduces this considerably, to $O(N \log N)$.



Cacciari and Salam, LPTHE-06-02

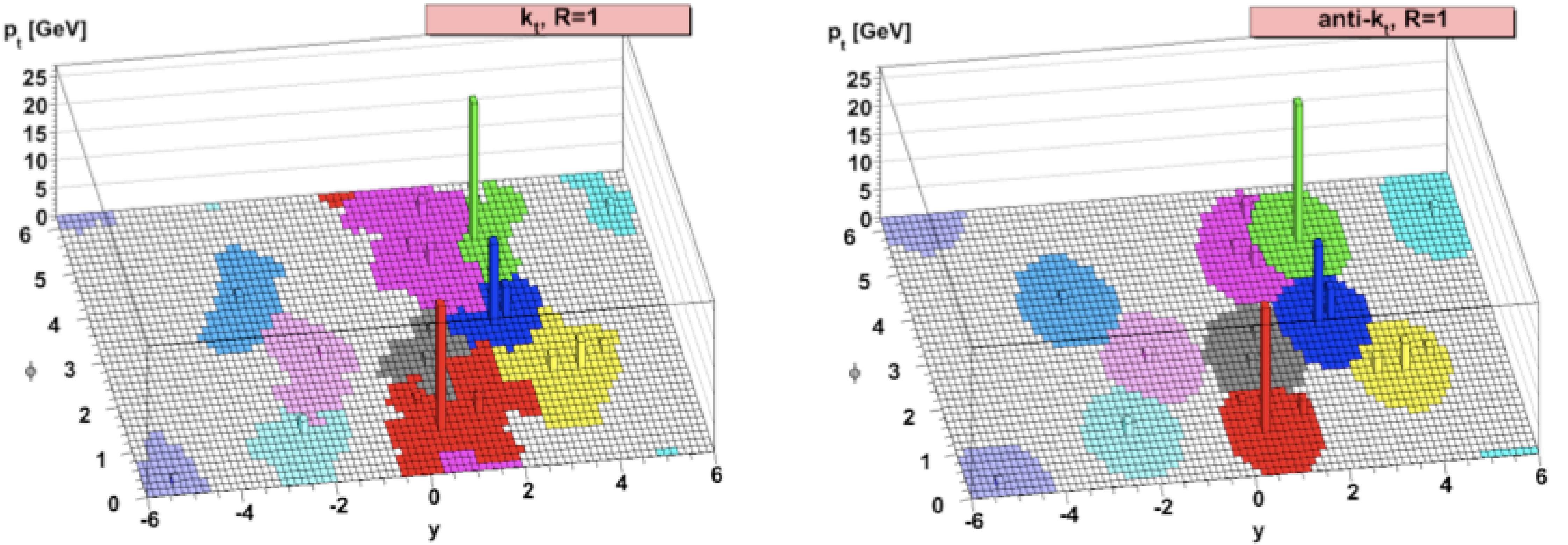
Implemented efficiently in the public package "FastJet"

http://fastjet.fr/

Cacciari, Salam, Soyez

The anti-k_T algorithm

- A lingering complaint against the k_T algorithm is that it sweeps soft particles into jets first, creating irregular ("unnatural") jet structure.



- A simple modification of the measure prevents this, instead sweeping in hard particles first.

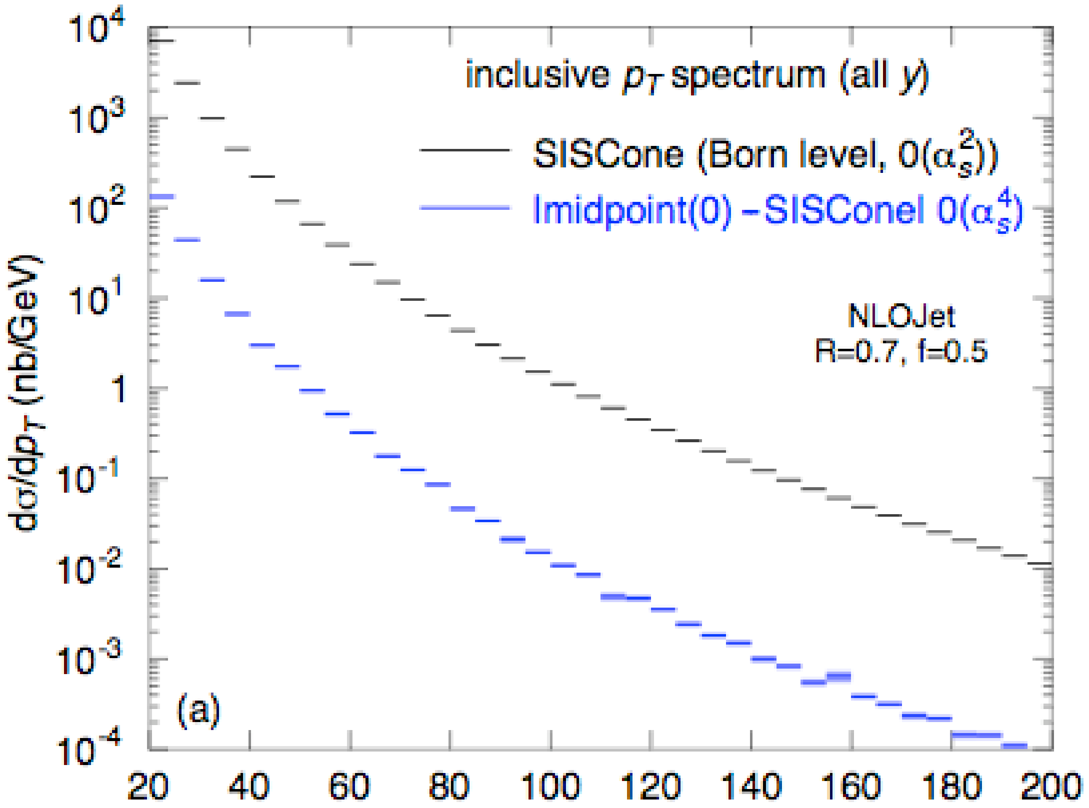
$$d_{ij} = \min\left(\frac{1}{p_{ti}^2}, \frac{1}{p_{tj}^2}\right) \frac{\Delta R_{ij}^2}{R^2}$$

Delsart
Cacciari, Salam and Soyez, arXiv:0802.1189

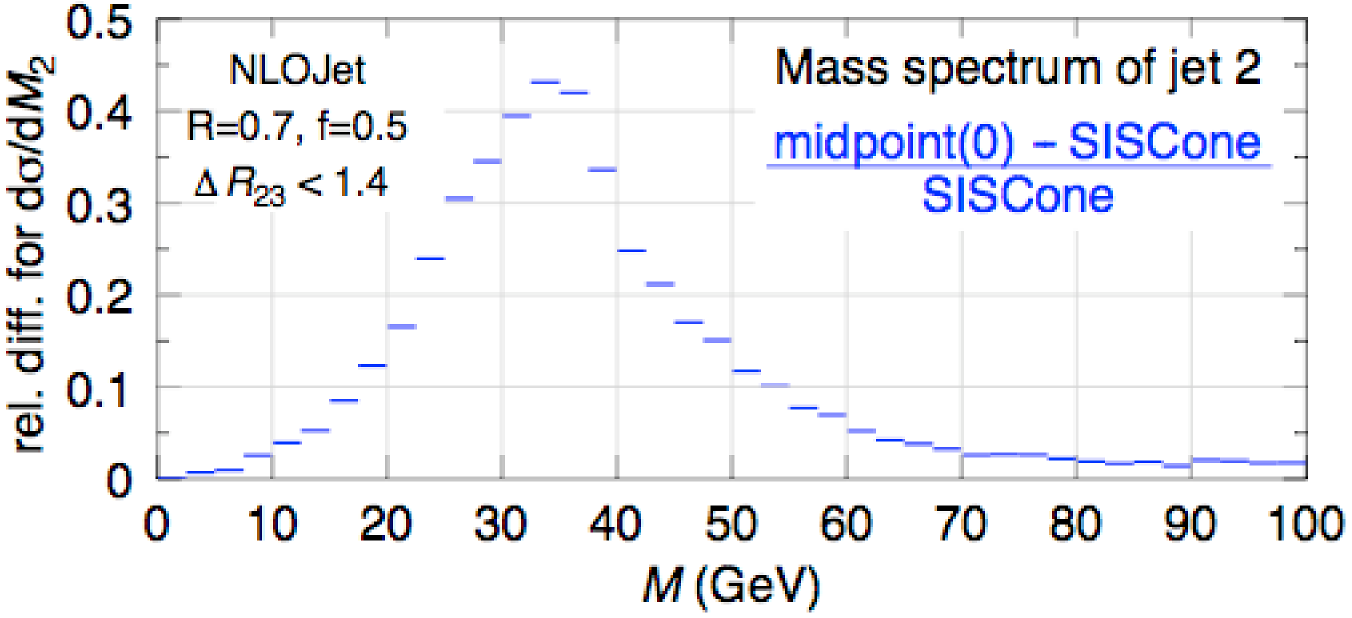
- This results in much smoother and conventional-looking (cone) jets.

Algorithm differences in practice

inclusive measurement



exclusive (jet mass)



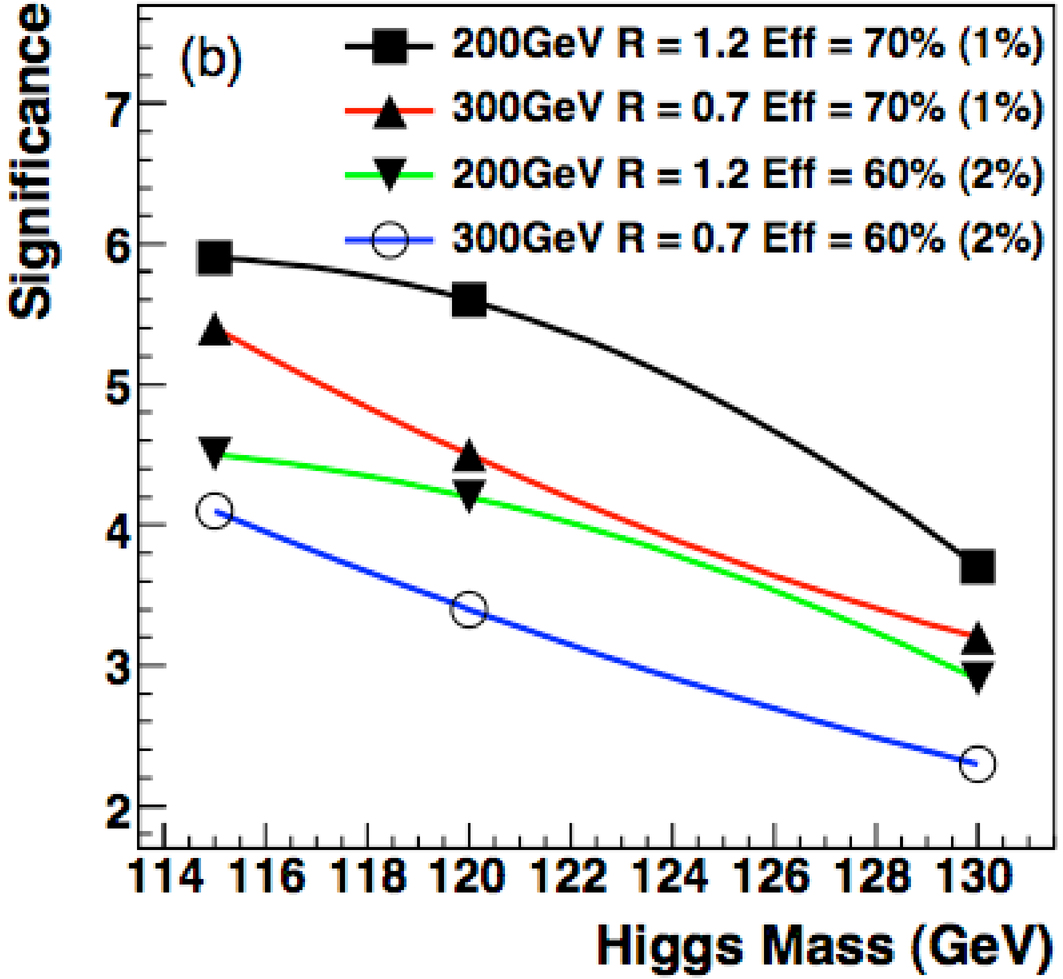
Both computed using 2→4 tree-level diagrams only

- Differences for exclusive quantities much larger than nominal (inclusive) ~ 1%.
- These contributions appear at NNLO (inclusive) and NLO (jet mass):
  - differences manifest as infrared problems → theory ill-defined for midpoint
  - existing comparisons of inclusive NLO with midpoint okay
- An IR-safe algorithm is clearly always preferred
  - otherwise, hope IR-safe predictions span results using unsafe algorithms

New jet uses at the LHC

- 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 (only about 5% of total) but much reduced top backgrounds and higher acceptance;
  - 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.
- General comment: making use of tailored jet algorithms and jet substructure will be imperative for maximum exploitation of LHC.

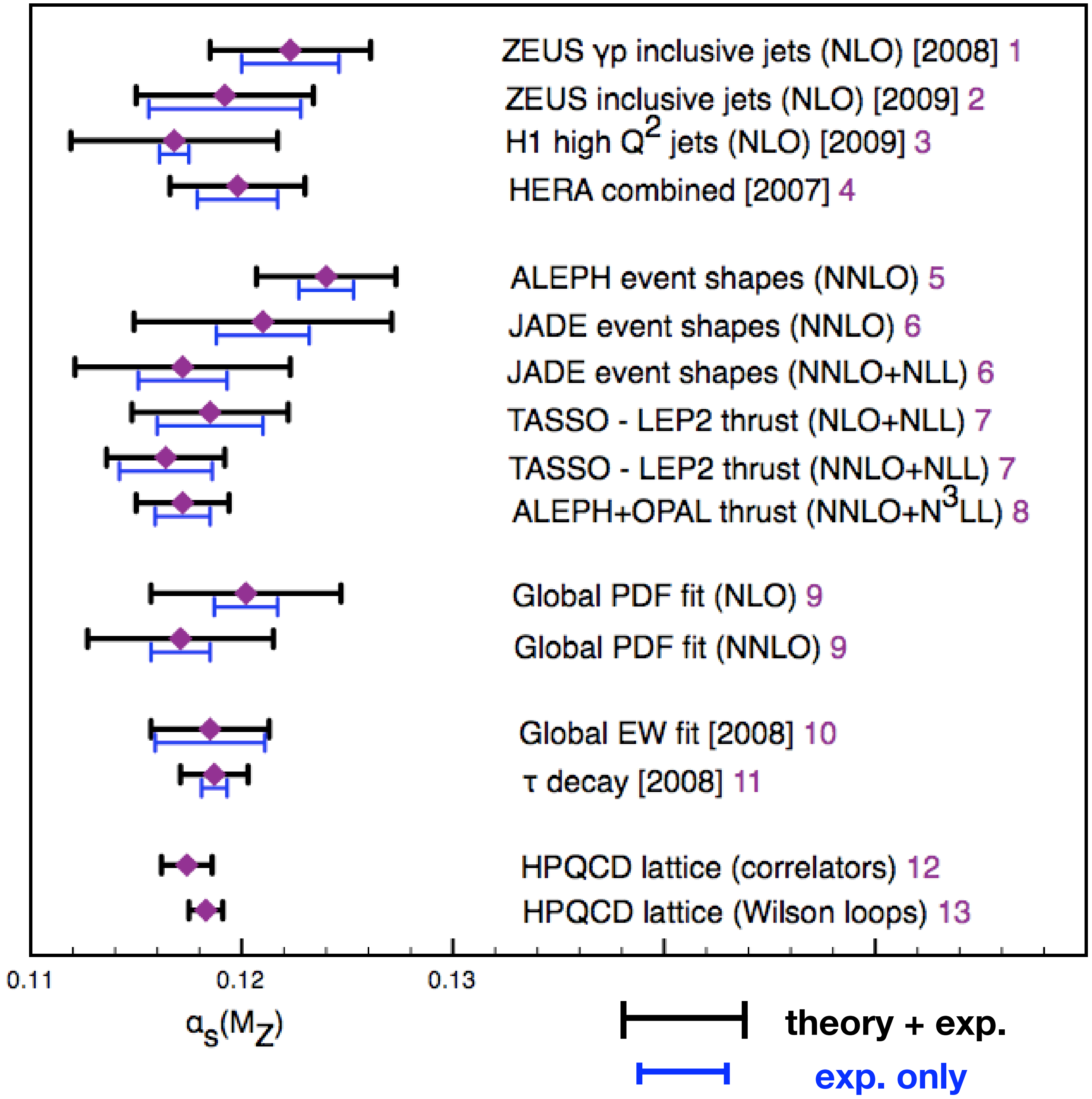
Butterworth et al., arXiv:0810.0409



5. The strong coupling

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 **Davison, Webber, arXiv:0809.3326**
8 **Becher, Schwartz, arXiv:0803.0342**
9 **Martin et al. (MSTW), arXiv:0905.3531**
10 **EW working group, arXiv:0811.4682**
11 **Maltman, Yavin, arXiv:0807.0650**
12 **Allison et al., arXiv:0805.2999**
13 **Davies et al., arXiv:0807.1687**

July 2009 - select determinations



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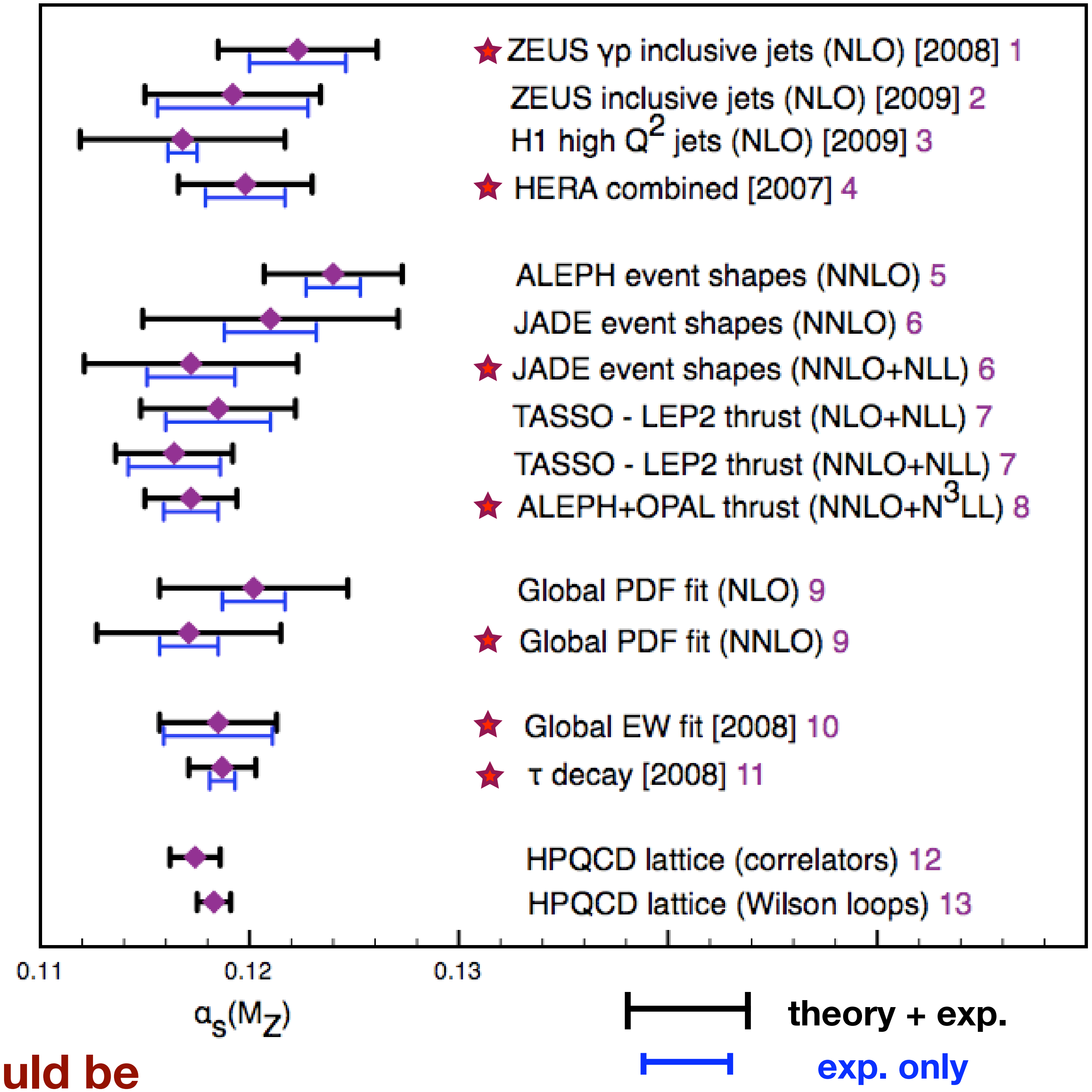


Representative averages:

★
continuum: $\alpha_s(M_Z) = 0.1186 \pm 0.0010$

lattice: $\alpha_s(M_Z) = 0.1180 \pm 0.0007$

(caution: correlations and errors should be properly combined, world needs an update)

Conclusions

- At the threshold of the LHC era, the theory of QCD at hadron colliders is well-poised to help unravel its secrets.
- The accurate theoretical predictions that we will be able to make use of are the result of progress on many different fronts ...
  - ✓ higher orders in the strong coupling (NLO, NNLO, ...)
    - ‣ conceptual breakthroughs in understanding field theory (e.g. unitarity)
    - ‣ new algorithms for efficient automation
  - ✓ better understanding of proton substructure (PDFs)
  - ✓ safe and accessible jet definitions
- Many exciting new developments emerging ...
  - ★ next generation of NLO parton shower predictions
  - ★ NNLO predictions for key LHC processes
  - ★ infrared singularities as a roadmap at two loops and beyond

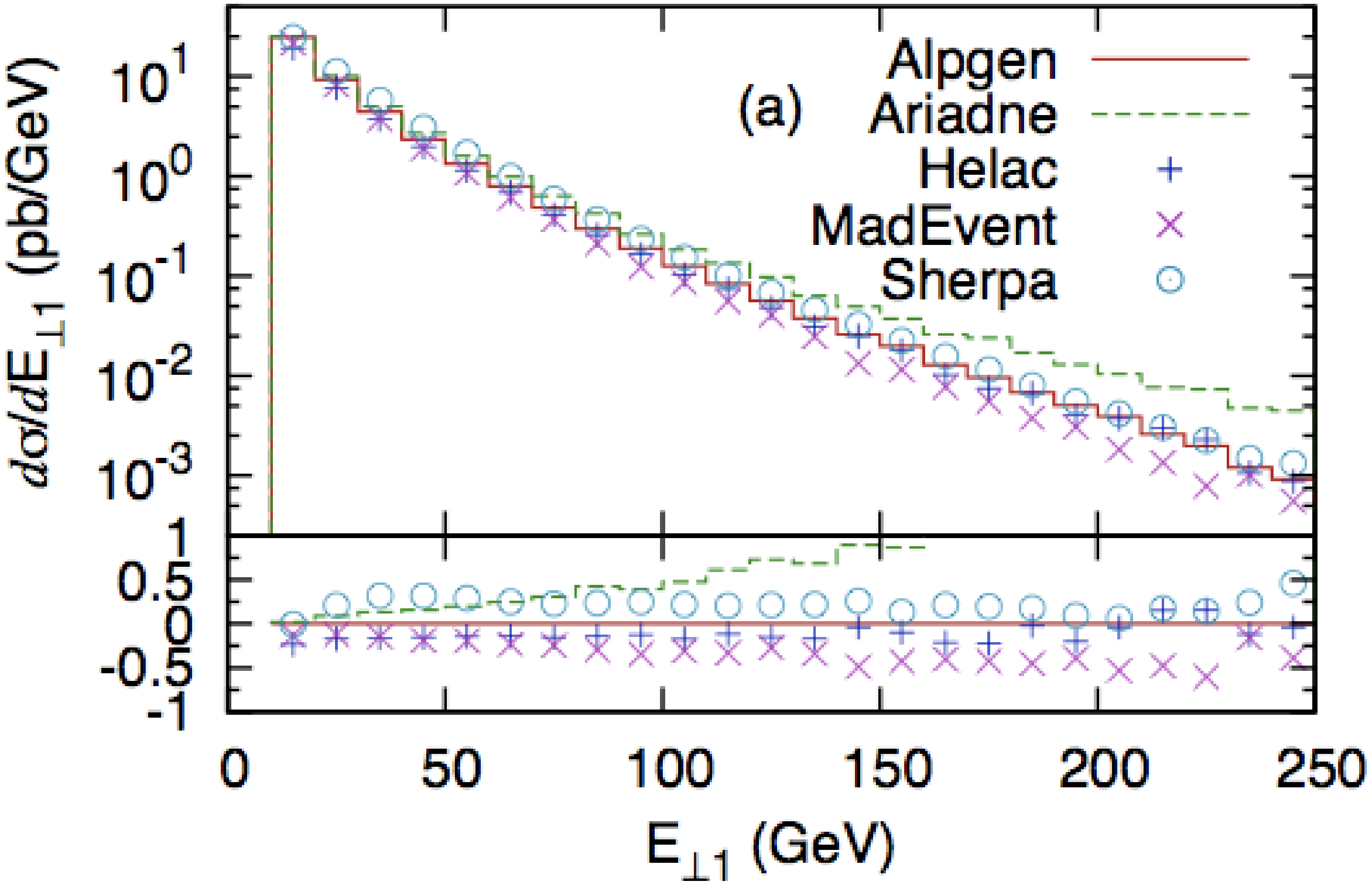
Backup slides

Matching

- Correct the collinear approximation by using information from the hard matrix elements of higher multiplicity.

Catani, Kuhn, Krauss, Webber, hep-ph/0109231; Mangano (2005)

  - a plethora of different approaches.
- Pioneered in studies of vector bosons and jets.
  - good testing ground for pQCD and a wealth of data.

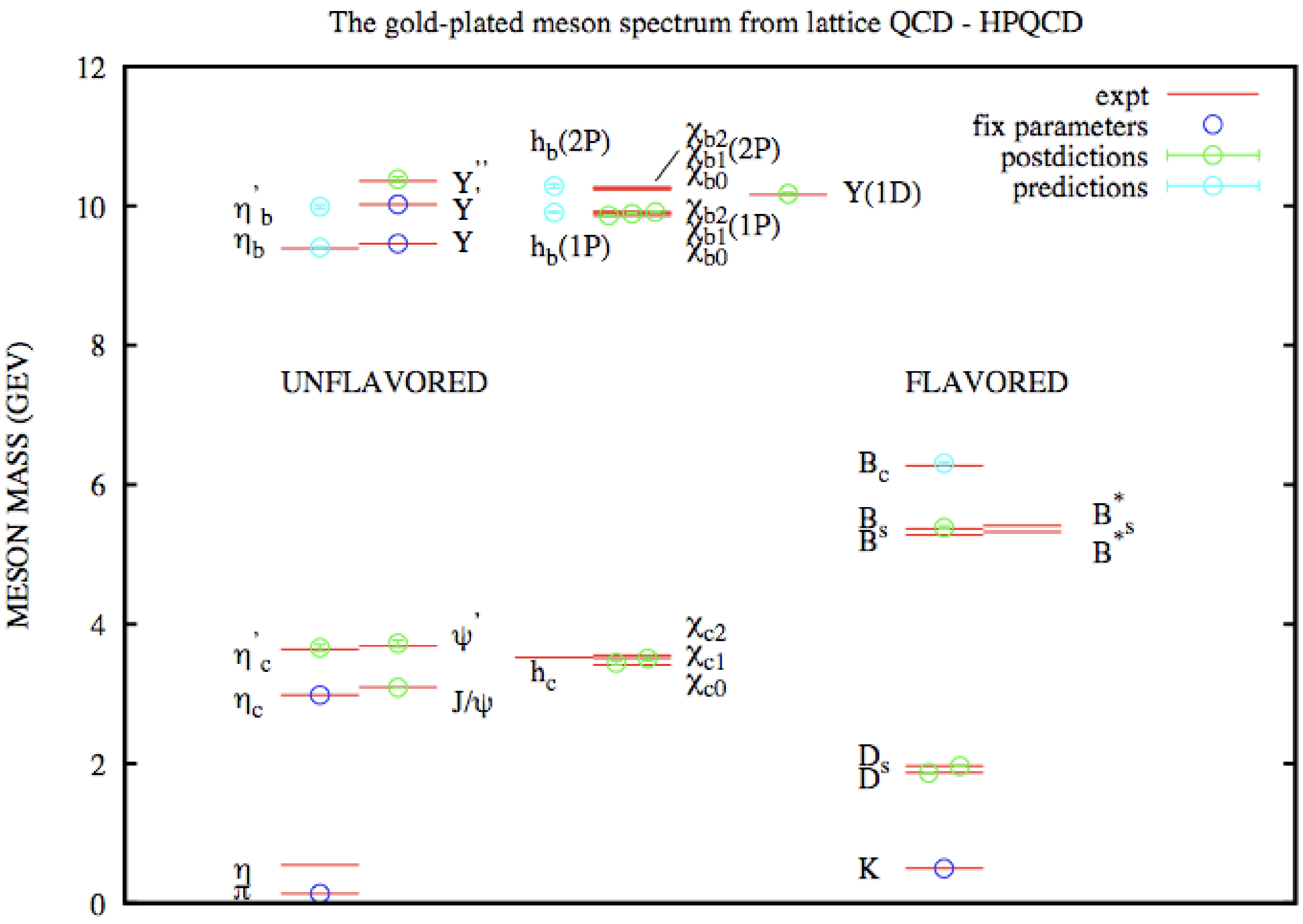


Alwall et al., arXiv:0706.2569

- Reasonable agreement between different showers and matching schemes.
- Can tune to Tevatron data and extrapolate to the LHC.
- Other final states still need to be checked systematically.

Lattice determination of α_S (HPQCD)

- Wilson loops:
  - absolute scale for strong coupling comes from mass splitting between ϒ and ϒ’
  - well known experimentally and accurately determined on the lattice



- Current-current correlators:
  - determined from moments of η_c correlator extrapolated to continuum and compared with continuum perturbation theory
  - need lattice spacing as above, plus charm mass from η_c

The strong coupling

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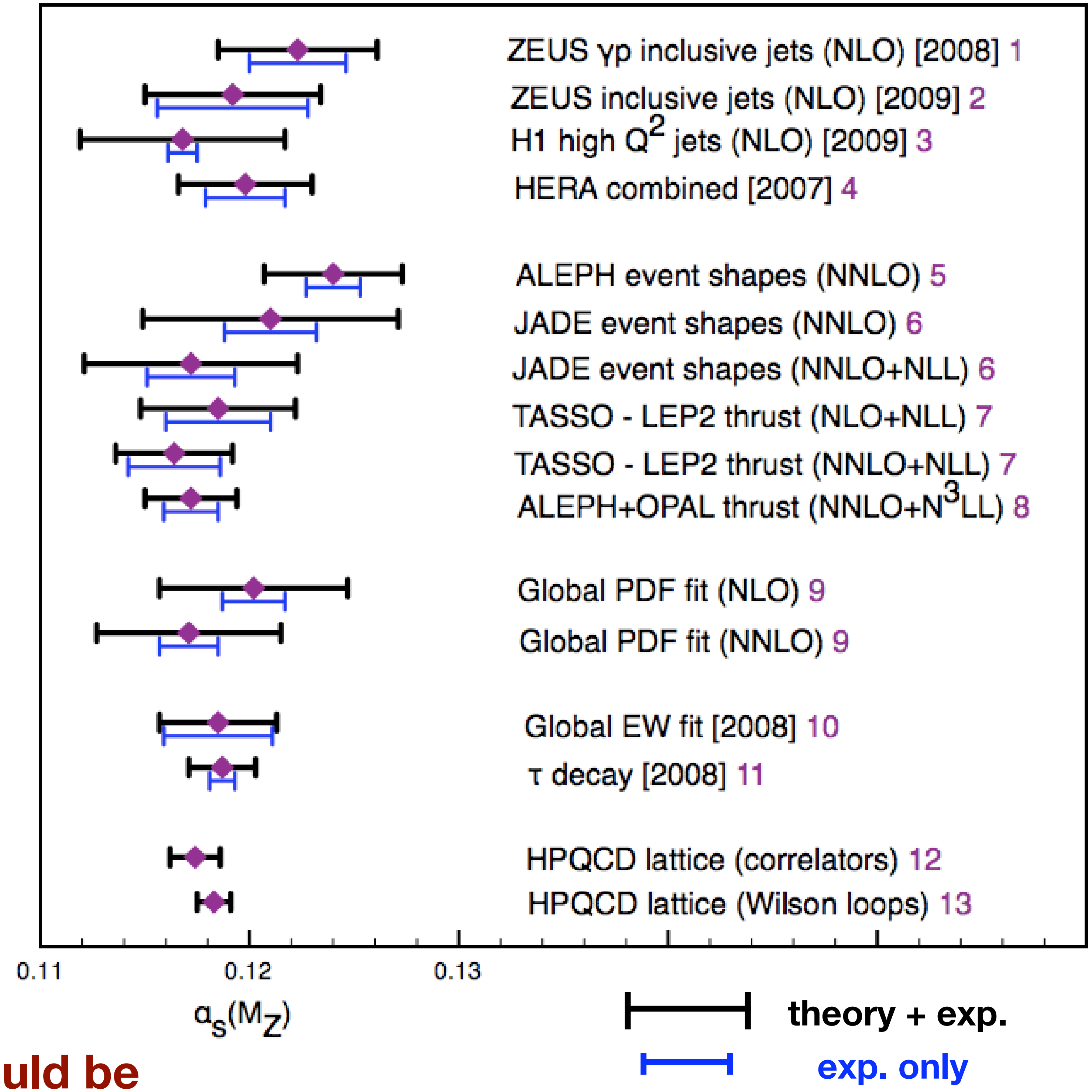


Average of all results:

continuum: $\alpha_s(M_Z) = 0.1183 \pm 0.0005$

lattice: $\alpha_s(M_Z) = 0.1180 \pm 0.0007$

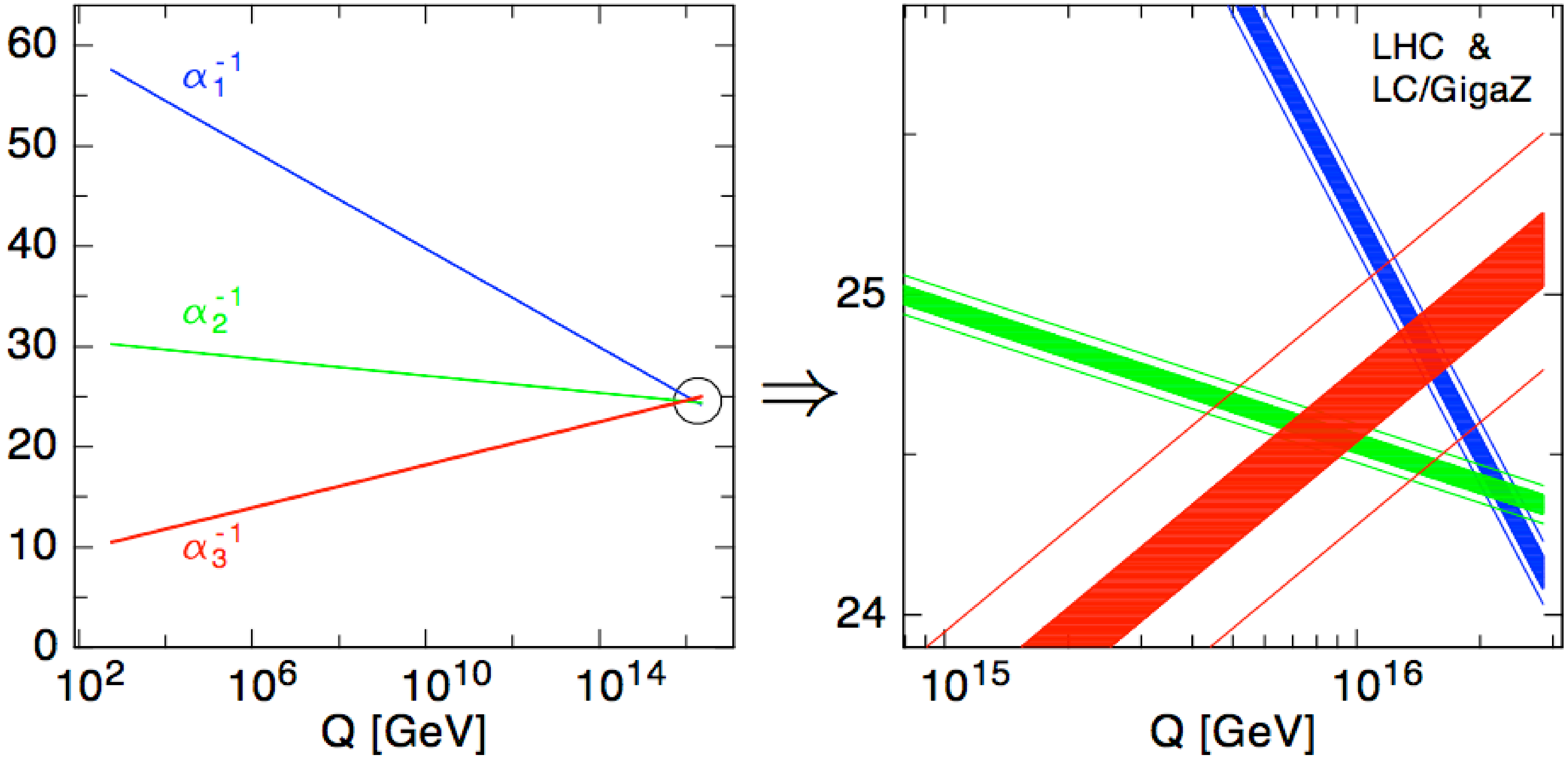
(caution: correlations and errors should be properly combined, world needs an update)

How precise do we need α_S?

- 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.

mSUGRA (SPS1a)

Allanach et al., hep-ph/0403133



[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?