Standard model at the LHC: QCD

SSP 2012, Groningen

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No LHC without understanding QCD

QCD at the LHC operates in new regime: high energy, large multiplicities. It produces interesting needles

- Higgs, top, SM, BSM, ...

and enormous amounts of hay

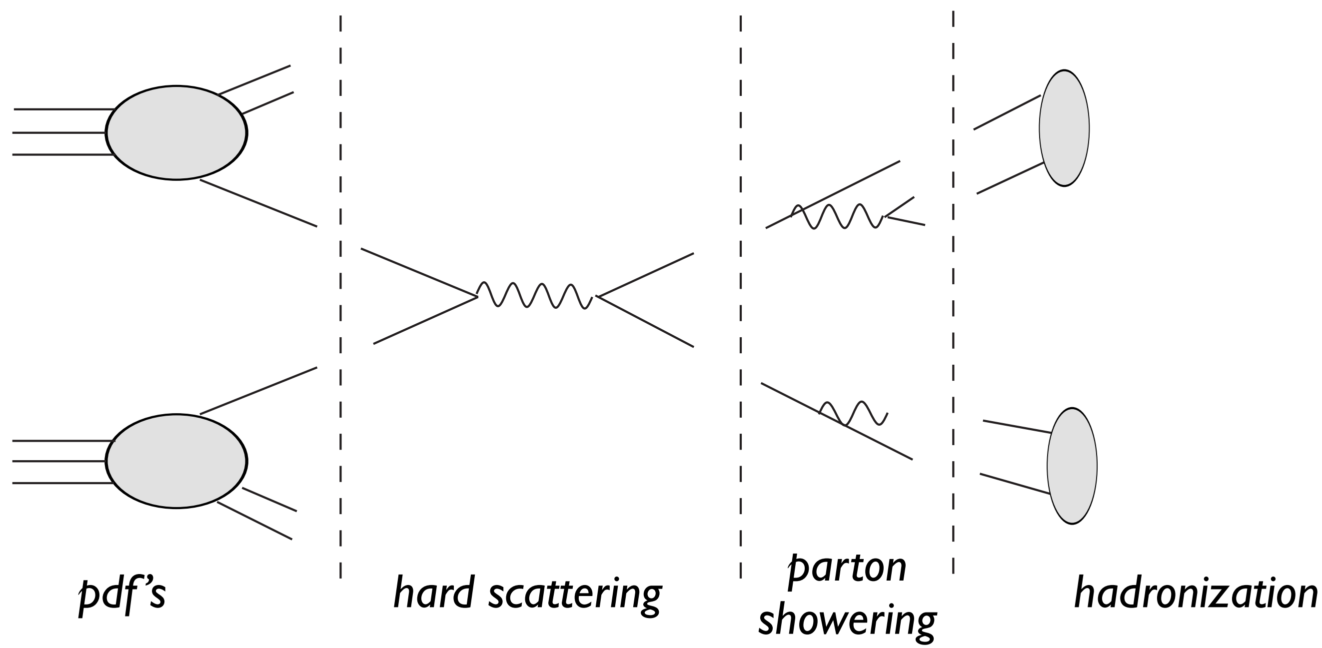
- Jets, b's, underlying events, multi-parton scattering

How to separate?

- Develop/use the best theoretical tools available
- Much interaction among theorists and experimenters

LHC poses a daunting challenge to QCD theorists

QCD predictions at the LHC



Factorization theorem

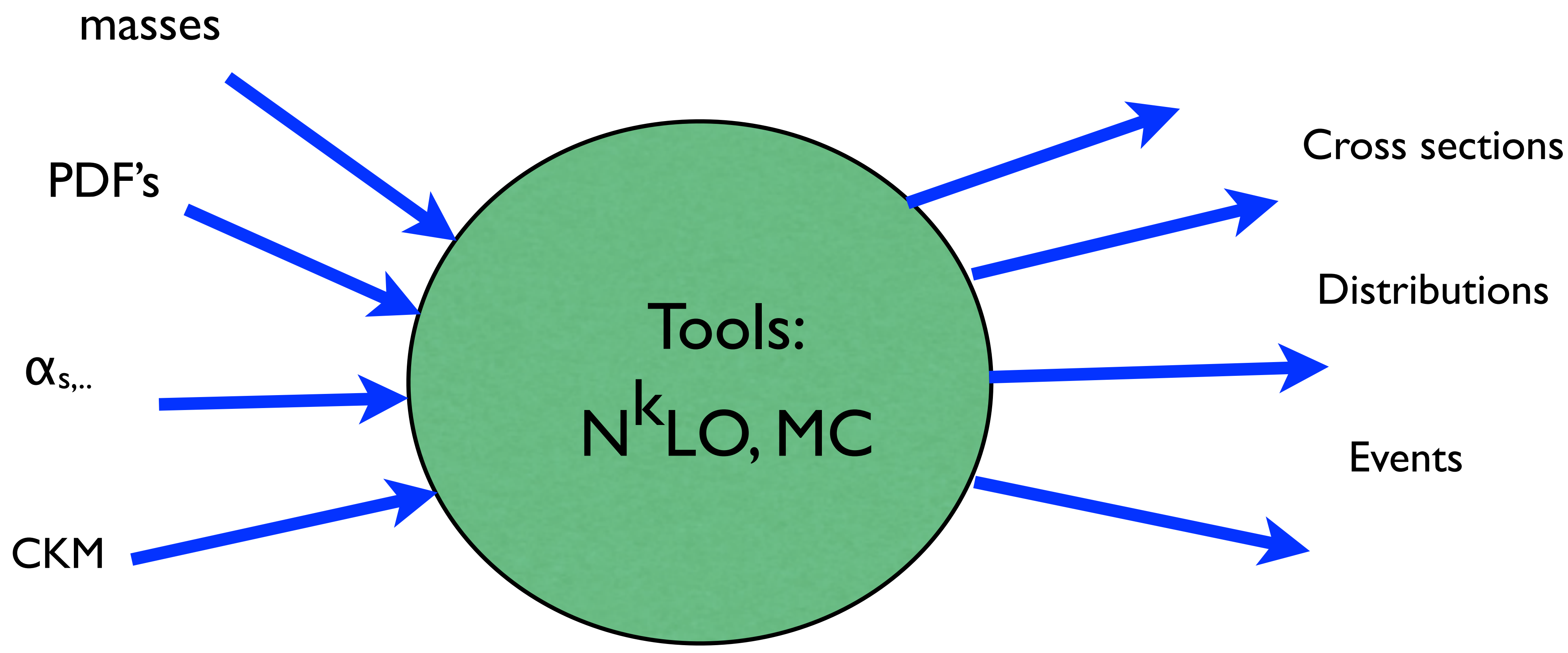
Collins, Soper, Sterman; Bodwin

pdf's *initial state spin etc averaging*

$$\langle O \rangle \;=\; \frac{1}{2s}\int dx_1 f(x_1)\int dx_2 f(x_2)\;\frac{1}{(2s_1+1)(2s_2+1)n_1 n_2}$$
$$\times \sum_n \int d\phi_{n-2}\, O(p_1,\ldots,p_n)\,|A(n)|^2 \quad + \sum_{p=1} c_p \left(\frac{\Lambda}{Q}\right)^p$$

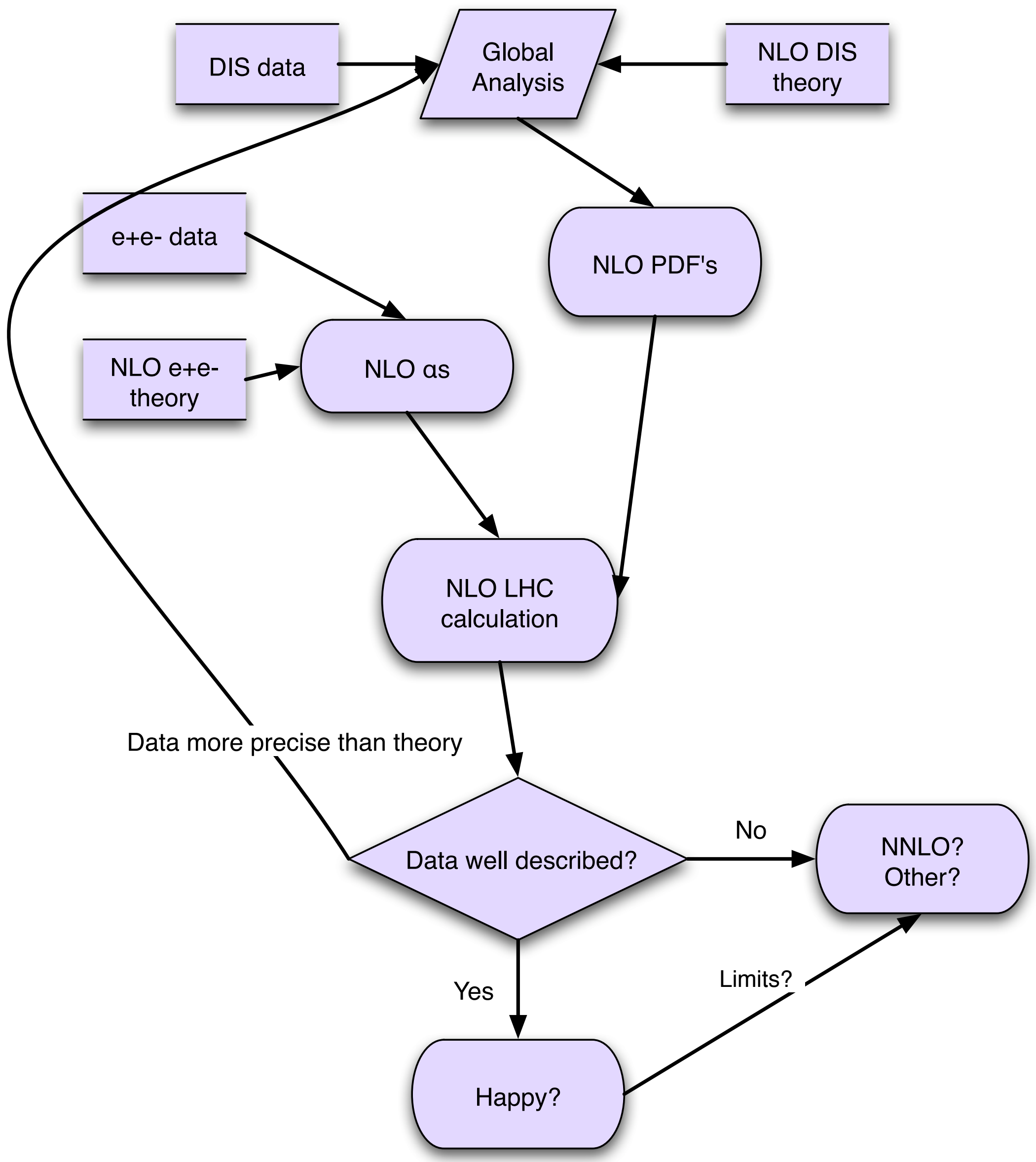
phase space integral *observable* *amplitude* *power corrections*

QCD predictions, simplified



- Each input has uncertainty
- Tools have intrinsic accuracy

QCD predictions, less simplified



This talk

Flavor of state-of-the-art in

- LO, NLO, NNLO
- Resummation
- Monte Carlo

with some recent applications and present challenges

Disclaimer: vastly incomplete referencing

Higher order QCD

LO, NLO cross sections

Multi-differential hadronic NLO cross section

NLO PDF's

$$\frac{d\sigma^{pp\to X}}{d^3p_1\dots d^3p_n} = \sum_{a,b}\int dx_1 dx_2 f_a(x_1,\mu_F) f_b(x_2,\mu_F)$$

$$\times\ \hat{\sigma}_{ab}(p_a + p_b \to p_X, \alpha_s(\mu_R), \mu_R, \mu_F) + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)$$

Multi-differential parton-level NLO cross section

Power corrections

Renormalization and Factorization scale

For NNLO, add "N" in all the right places..

Parton distribution functions

$$f_{i/P}(x, \mu_F)$$

Probability for parton of type “i” inside proton P
to interact having momentum fraction “x”

- ✓ There are 13.
- ✓ Universal, and crucial for accurate predictions at LHC
- ✓ Sophisticated approaches, various groups, publicly available
- ✓ No time to do justice..

Status of Higher Order

Order	$2 \to 1$	$2 \to 2$	$2 \to 3$	$2 \to 4$	$2 \to 5$	$2 \to 6$
1	LO					
α_s	NLO	LO				
α_s^2	NNLO	NLO	LO			
α_s^3	NNNLO	NNLO	NLO	LO		
α_s^4				NLO	LO	
α_s^5					NLO	LO
						NLO

- LO well-understood, now more efficient than ever
- NLO: a flood of new developments
- NNLO 2→2 starting now..
  - ✓ Show now also start including NLO QCD + EW
- NNNLO: for $F_2(x,Q)$, from same (Nikhef) foundry as NNLO splitting functions

Moch, Vermaseren, Vogt

Need for computer algebra!!

FORM Vermaseren

Result of a brute force calculation (actually only a small part of it):

$$k_1 \cdot k_4 \, \varepsilon_2 \cdot k_1 \, \varepsilon_1 \cdot \varepsilon_3 \, \varepsilon_4 \cdot \varepsilon_5$$

NLO: all it took was a wish...

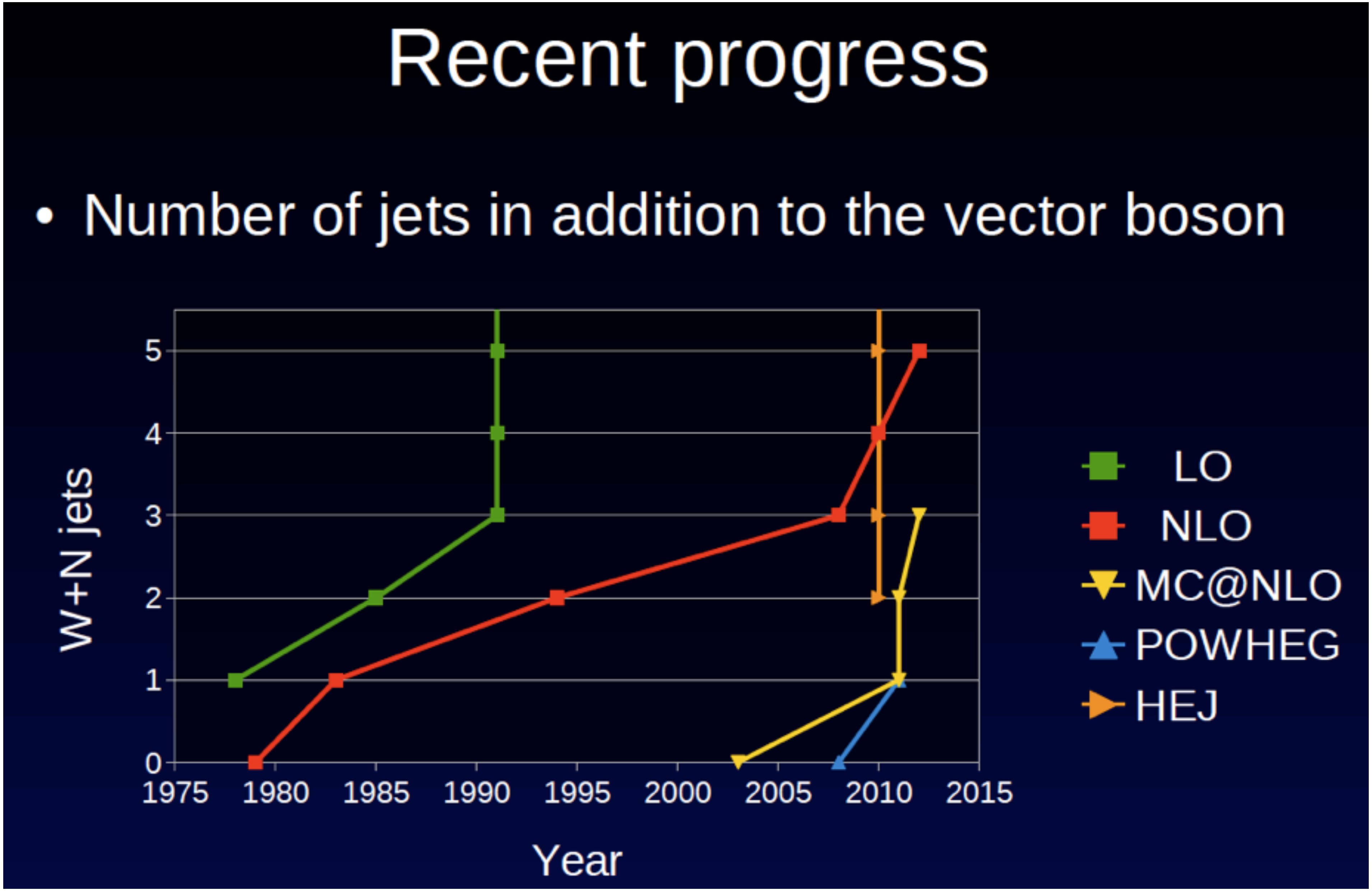
- First composed in Les Houches in 2005, added to in 2007,2009 by Joey Huston
- List of "doable" calculations needed for LHC
- They have now all been done
  - (except tttt)

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$ jet	WW jet completed by Dittmaier/Kallweit/Uwer [27, 28]; Campbell/Ellis/Zanderighi [29]. ZZ jet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [30] WZ jet, $W\gamma$ jet completed by Campanario et al. [31, 32]
2. $pp \to$ Higgs+2 jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [33]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [34, 35] Interference QCD-EW in VBF channel [36, 37]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [38] and WWZ by Hankele/Zeppenfeld [39], see also Binoth/Ossola/Papadopoulos/Pittau [40] VBFNLO [41, 42] meanwhile also contains $WWW, ZZW, ZZZ, WW\gamma, ZZ\gamma, WZ\gamma, W\gamma\gamma, Z\gamma\gamma, \gamma\gamma\gamma, W\gamma\gamma j$ [43, 44, 45, 46, 47, 21]
4. $pp \to t\bar{t}b\bar{b}$	relevant for $t\bar{t}H$, computed by Bredenstein/Denner/Dittmaier/Pozzorini [48, 49] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [50]
5. $pp \to V$+3 jets	W+3 jets calculated by the Blackhat/Sherpa [51] and Rocket [52] collaborations Z+3jets by Blackhat/Sherpa [53]
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$, computed by Bevilacqua/Czakon/Papadopoulos/Worek [54, 55]
7. $pp \to VV\,b\bar{b}$,	Pozzorini et al. [25], Bevilacqua et al. [23]
8. $pp \to VV$+2jets	W^+W^++2jets [56], W^+W^-+2jets [57, 58], VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [59, 60, 61]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	Binoth et al. [62, 63]
NLO calculations added to list in 2009	
10. $pp \to V$ +4 jets	top pair production, various new physics signatures Blackhat/Sherpa: W+4jets [22], Z+4jets [20] see also HEJ [64] for $W + n$jets
11. $pp \to Wb\bar{b}j$	top, new physics signatures, Reina/Schutzmeier [11]
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
also completed:	
$pp \to W\gamma\gamma$ jet	Campanario/Englert/Rauch/Zeppenfeld [21]
$pp \to 4$ jets	Blackhat/Sherpa [19]

..and a revolution in calculational methods

Nonlinear progress in W+n jets

D. Maitre, Talk at SM@LHC workshop, NBI



Berger, Bern, Dixon, Febres-Cordero, Forde Ita, Kosower, Maitre

Leading order

The problem here is not handling divergences, but handling complexity. For gg $\to$ng number of diagrams grows factorially

n	2	3	4	5	6	7	8
diagrams	4	25	220	2485	34300	559405	1.05E+07

Nowadays routinely handled:

- Madgraph/Madevent (helicity amplitudes), Sherpa/Amegic++, Helac/Phegas, Alpgen (recursion), Comphep (matrix elements)
  - ✓ after many inventions

LO scattering: know your quantum numbers

Color-decomposition

$$\mathcal{A}_n(1,..,n) = g^{n-2} \sum_{\sigma} \mathrm{Tr}(T^{a_{\sigma(1)}} \cdots T^{a_{\sigma(n)}})\, A_n(\sigma(1),..,\sigma(n))$$

Color-ordered amplitudes

For n=6: 34300 → 501 color-ordered amplitudes

Specify all helicities → can use efficient spinor techniques

helicity

$$A(1^{\pm}, 2^{\pm}, \ldots, n^{\pm})$$

$$u_+(p) = |p+\rangle, \quad \overline{u}_- = \langle p-|$$

$$\langle pq \rangle \equiv \langle p - | q + \rangle, \quad [pq] \equiv \langle p + | q - \rangle$$

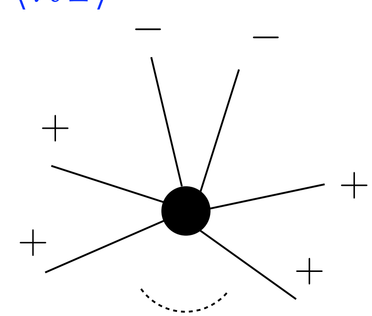
MHV amplitude

$$A_n^{tree}(1^+, \ldots, j^-, \ldots, k^-, \ldots, n^+) = i(\sqrt{2})^{n-2} \frac{\langle jk \rangle^4}{\langle 12 \rangle \ldots \langle n1 \rangle}$$

Parke, Taylor

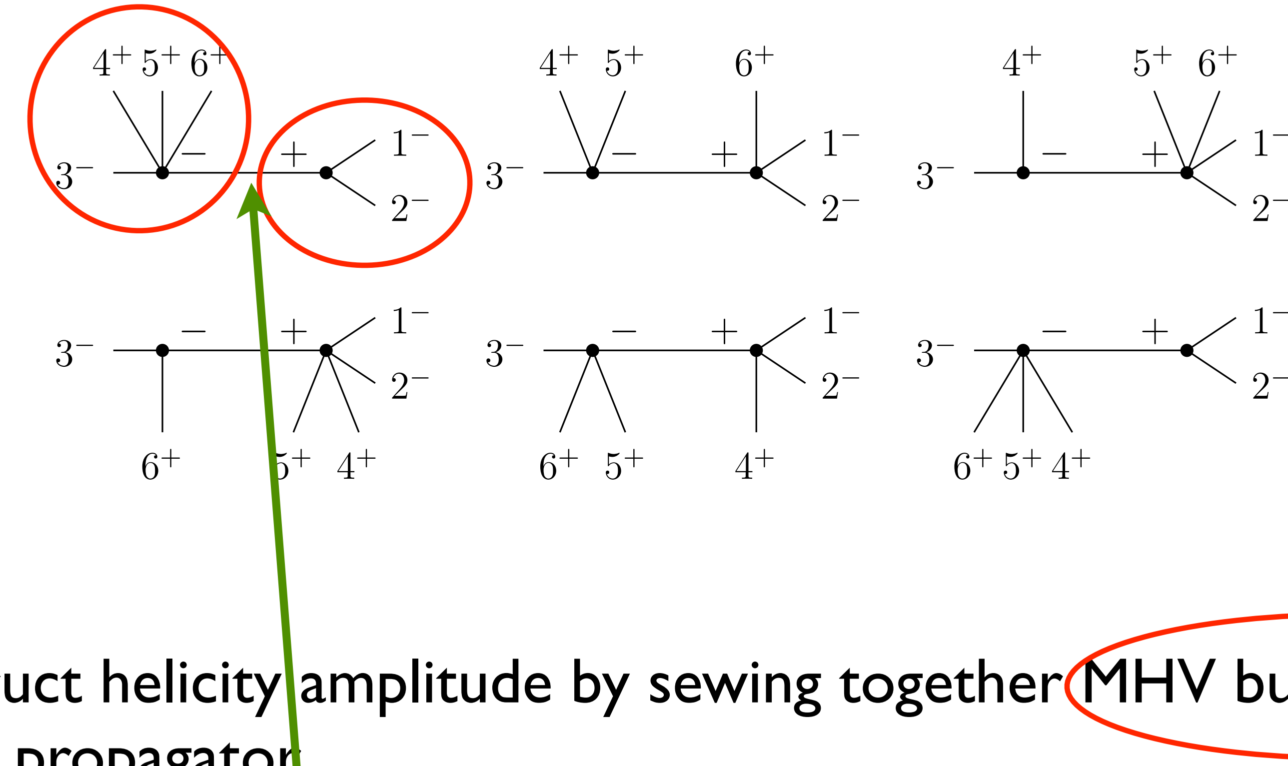
But what about more minuses?

From twistor approach (Witten): use these as building blocks



Twistor: spinor with half its components Fourier-transformed

Post-twistor recursion



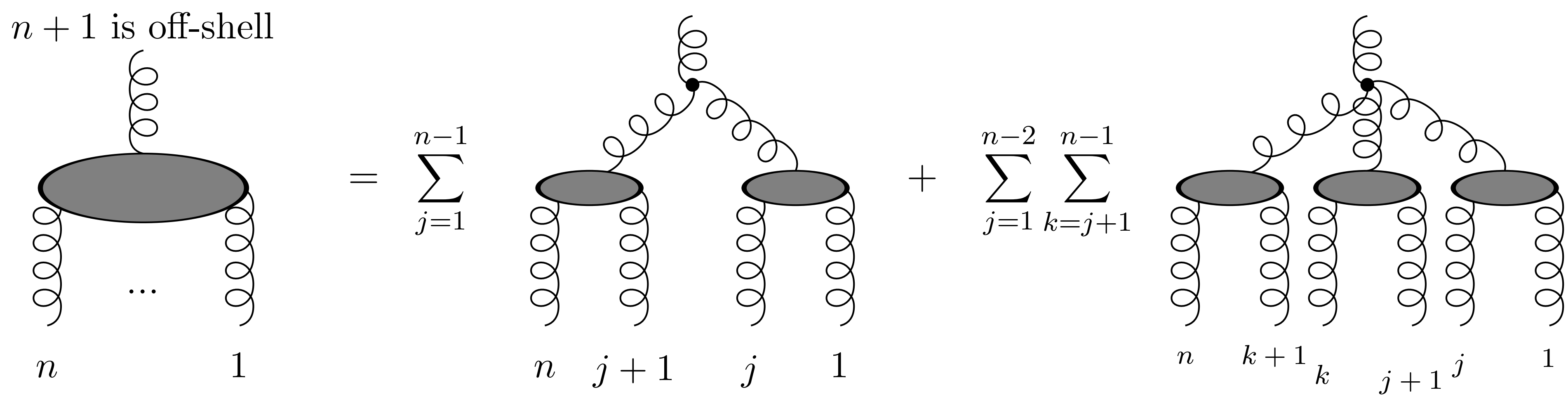
Construct helicity amplitude by sewing together MHV building blocks using 1 propagator.

Cachazo, Svrcek, Witten

Six diagrams only! (Was 220 in this case..)

Pre-twistor recursion (Leiden, 1980's and 90's)

Berends, Giele



- Define "currents": one gluon off-shell, n off-shell. Obey "obvious" recursion.
- Analytically elegant, numerically efficient, was important for top-quark discovery (VECBOS: Berends, Kuijf, Tausk, Giele)

What is faster, the old or the new?

Speed

Duhr, Hoche, Maltoni

Final State	BG		BCF		CSW	
	CO	CD	CO	CD	CO	CD
$2g$	0.24	0.28	0.28	0.33	0.31	0.26
$3g$	0.45	0.48	0.42	0.51	0.57	0.55
$4g$	1.20	1.04	0.84	1.32	1.63	1.75
$5g$	3.78	2.69	2.59	7.26	5.95	5.96
$6g$	14.2	7.19	11.9	59.1	27.8	30.6
$7g$	58.5	23.7	73.6	646	146	195
$8g$	276	82.1	597	8690	919	1890
$9g$	1450	270	5900	127000	6310	29700
$10g$	7960	864	64000	-	48900	-

Dinsdale, Ternick, Weinzier

n	4	5	6	7	8	9	10	11	12
Berends-Giele	0.00005	0.00023	0.0009	0.003	0.011	0.030	0.09	0.27	0.7
Scalar	0.00008	0.00046	0.0018	0.006	0.019	0.057	0.16	0.4	1
MHV	0.00001	0.00040	0.0042	0.033	0.24	1.77	13	81	—
BCF	0.00001	0.00007	0.0003	0.001	0.006	0.037	0.19	0.97	5.5

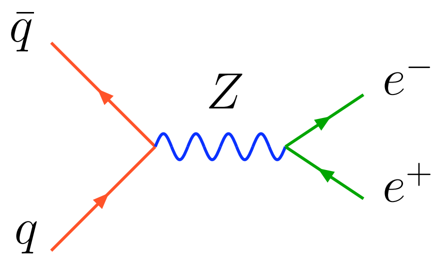
The old is still faster (except for MHV)...

Badger, Biedemann, Hackl, Plefka, Schuster, Uwer

LO, NLO, etc

LO

$\hat{\sigma}^{(0)}$

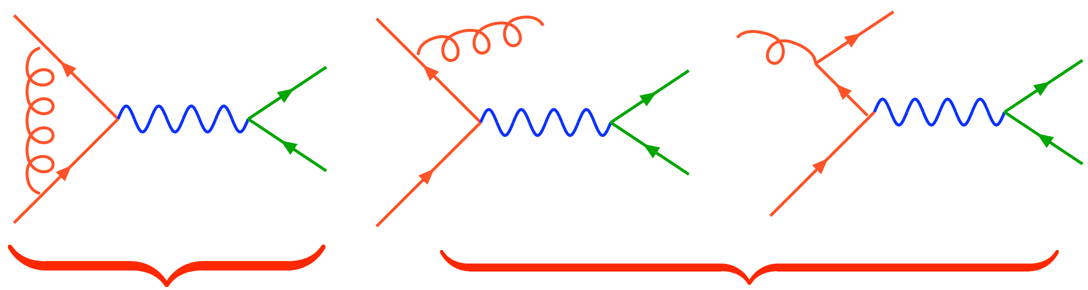


Combine with PDF's, put in MC integrator, apply cuts etc

Calculate in D=4-2ε dimensions

NLO

$\hat{\sigma}^{(1)}$



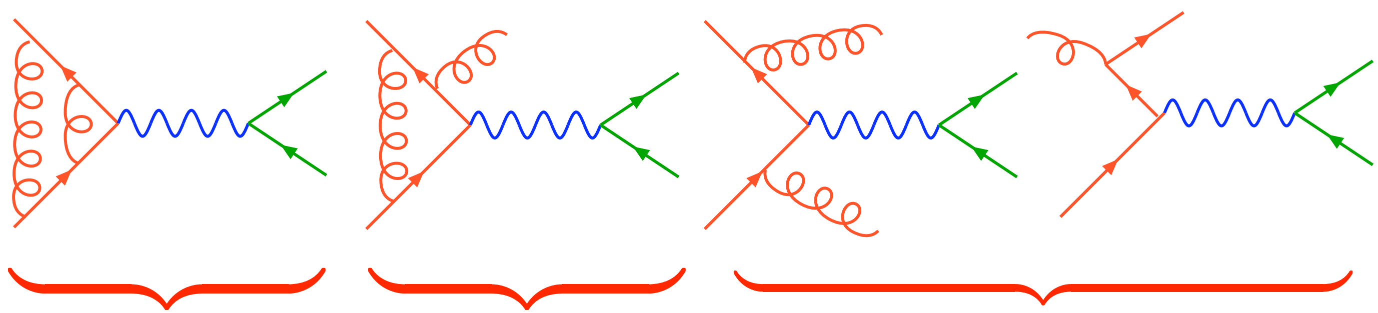
1 loop

1 extra parton

Cancel IR poles $1/\varepsilon^2$ before anything else

NNLO

$\hat{\sigma}^{(2)}$



2 loop

1 loop +
1 extra parton

2 extra partons

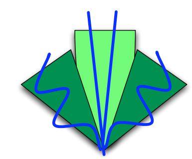
Cancel IR poles $1/\varepsilon^4$ etc before anything else; hard!

Handling intermediate IR divergences

$$d\sigma_{NLO} = \int_{d\Phi_{n+1}} \left(d\sigma^R_{NLO} - d\sigma^S_{NLO} \right) + \left[\int_{d\Phi_n} d\sigma^V_{NLO} + \int_{d\Phi_n} \left(\int_{d\Phi_1} d\sigma^S_{NLO} \right) \right]$$

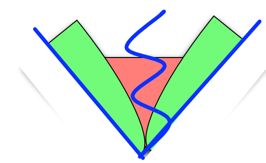
Subtraction schemes (Ellis, Ross, Terrano): find clever $d\sigma^S_{NLO}$

- Dipole (Catani, Seymour): emitter + spectator + soft-collinear parton



  - ✓ Color-charge operators; collinear split + half of soft

- Antenna (Kosower): 2 radiators + soft-collinear parton



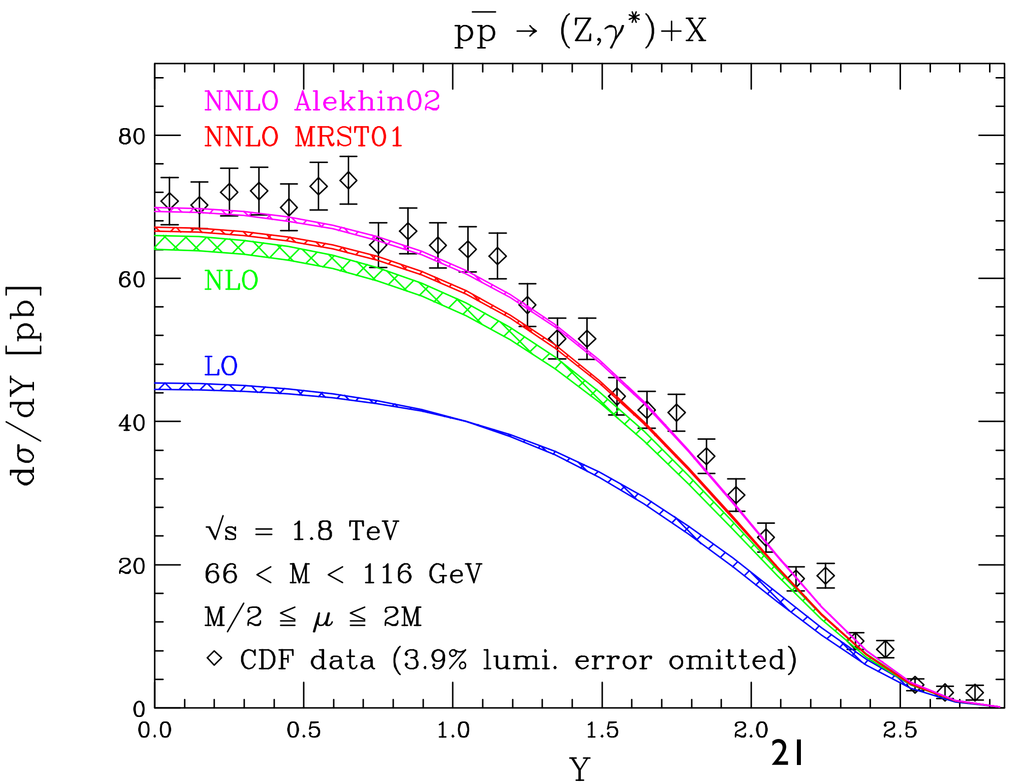
  - ✓ Color-ordering; soft + half collinear splits

- FKS (Frixione, Kunszt, Signer): isolate each singularity with projectors. Use plus prescriptions to define IR-finite part.

Why go beyond LO?

Precision!

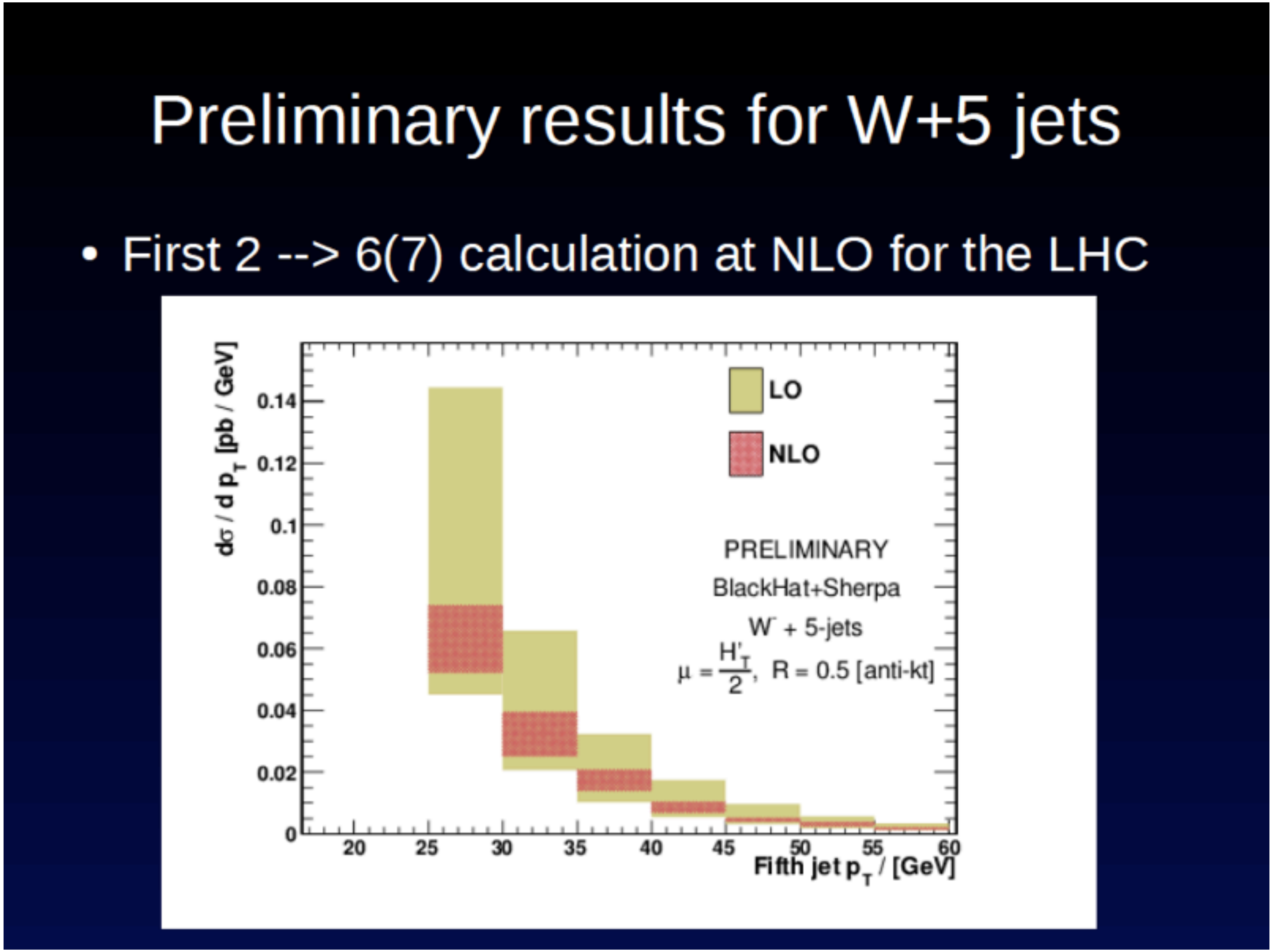
- Accurate prediction of production rates
- Better modelling of distribution shapes due to extra partons
- Self-diagnostics of PT
- New channels open up beyond LO, not necessarily small



Anastasiou, Petriello, Melnikov

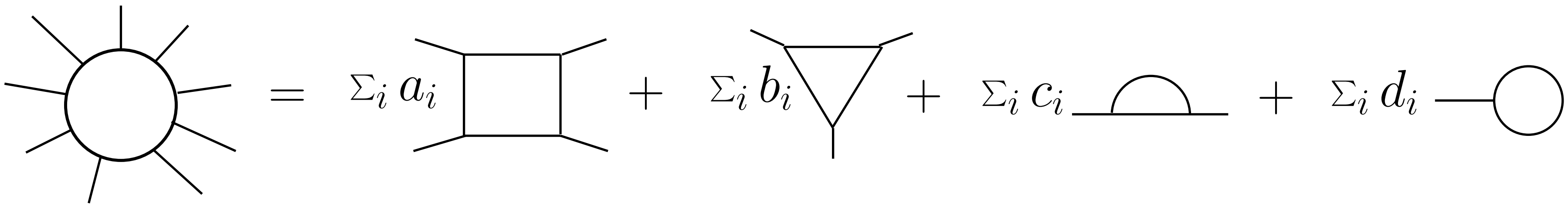
NLO benefit

D. Maitre, Talk at SM@LHC
workshop, NBI, April 2012



One-loop revolution

Vermaseren, van Neerven; Bern, Dixon, Kosower,...

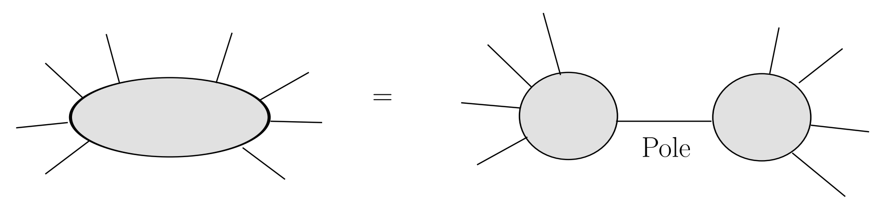


$$\mathcal{M} = \sum_i a_i(D)\text{Boxes}_i + \sum_i b_i(D)\text{Triangles}_i + \sum_i c_i(D)\text{Bubbles}_i + \sum_i d_i(D)\text{Tadpoles}_i$$

Since boxes, triangles etc are standard basis: *find coefficients*

Many ideas based on unitarity: construct a function from its poles and branch cuts

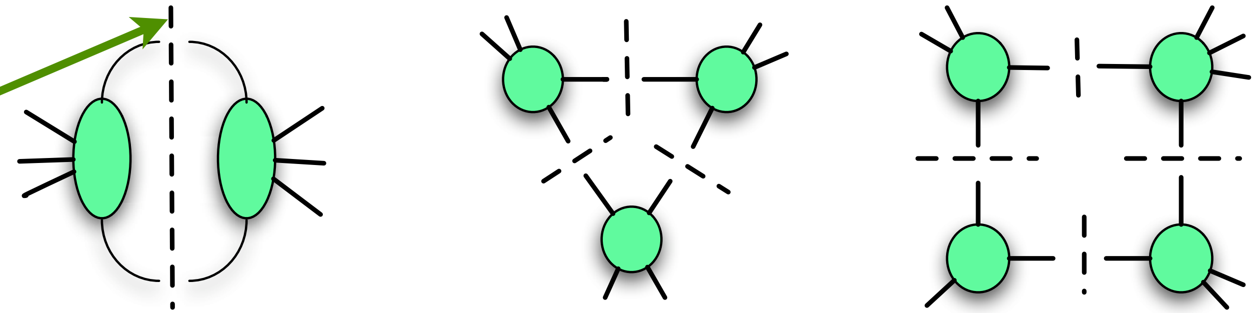
- poles: lower # of external lines
- branch cuts: lower # of loops



Generalized unitarity

$$\frac{1}{p^2 + i\epsilon} \longrightarrow -i2\pi\delta_+(p^2)$$

Replace propagator by cut one, as in phase space



$$\mathcal{M} = \sum_i a_i(4)\mathrm{Boxes}_i + \sum_i b_i(4)\mathrm{Triangles}_i + \sum_i c_i(4)\mathrm{Bubbles}_i + \sum_i d_i(4)\mathrm{Tadpoles}_i + \mathrm{Rational\ term}$$

Basis set of integrals

- ✓ Calculate cuts of M on left
- ✓ Cut on right only in Boxes etc
- ✓ Match, find coefficients a,b,c,d
- ✓ Use other methods to find Rational term

Bern, Dixon, Dunbar, Kosower, Britto, Cachazo, Feng, Anastasiou, Kunszt, Mastrolia

More one-loop ideas

- ✓ Numerical loop integration — Nagy, Soper
- ✓ Numerical solution to BG recursions — Ellis, Giele, Zanderighi

$$I_{\mu_1\mu_2\ldots\mu_n} = \int \frac{d^D l}{(2\pi)^D} \frac{l_{\mu_1}\cdots l_{\mu_n}}{D_0 D_1 \cdots D_N}$$

Tensor integral

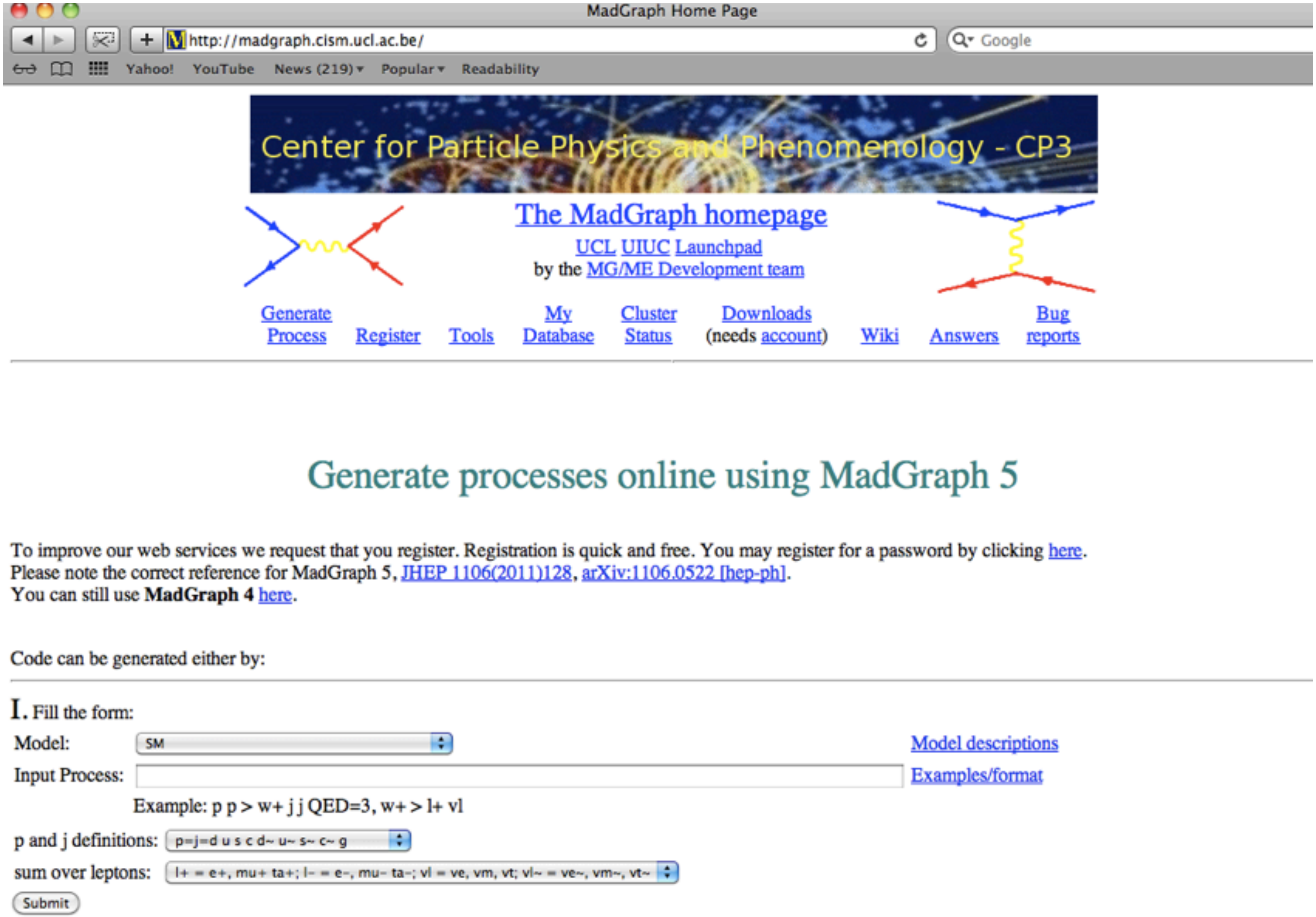
- ✓ Better Passarino-Veltman — Denner, Dittmaier; Binoth, Guillet, Pilon, Heinrich, Schubert

$$\int d^D l \frac{1}{D_1 D_2 D_3} = \int d^D l \int_0^1 dx \int_0^{1-x} dy \frac{1}{[xD_1 + yD_2 + (1-x-y)D_3]^3}$$

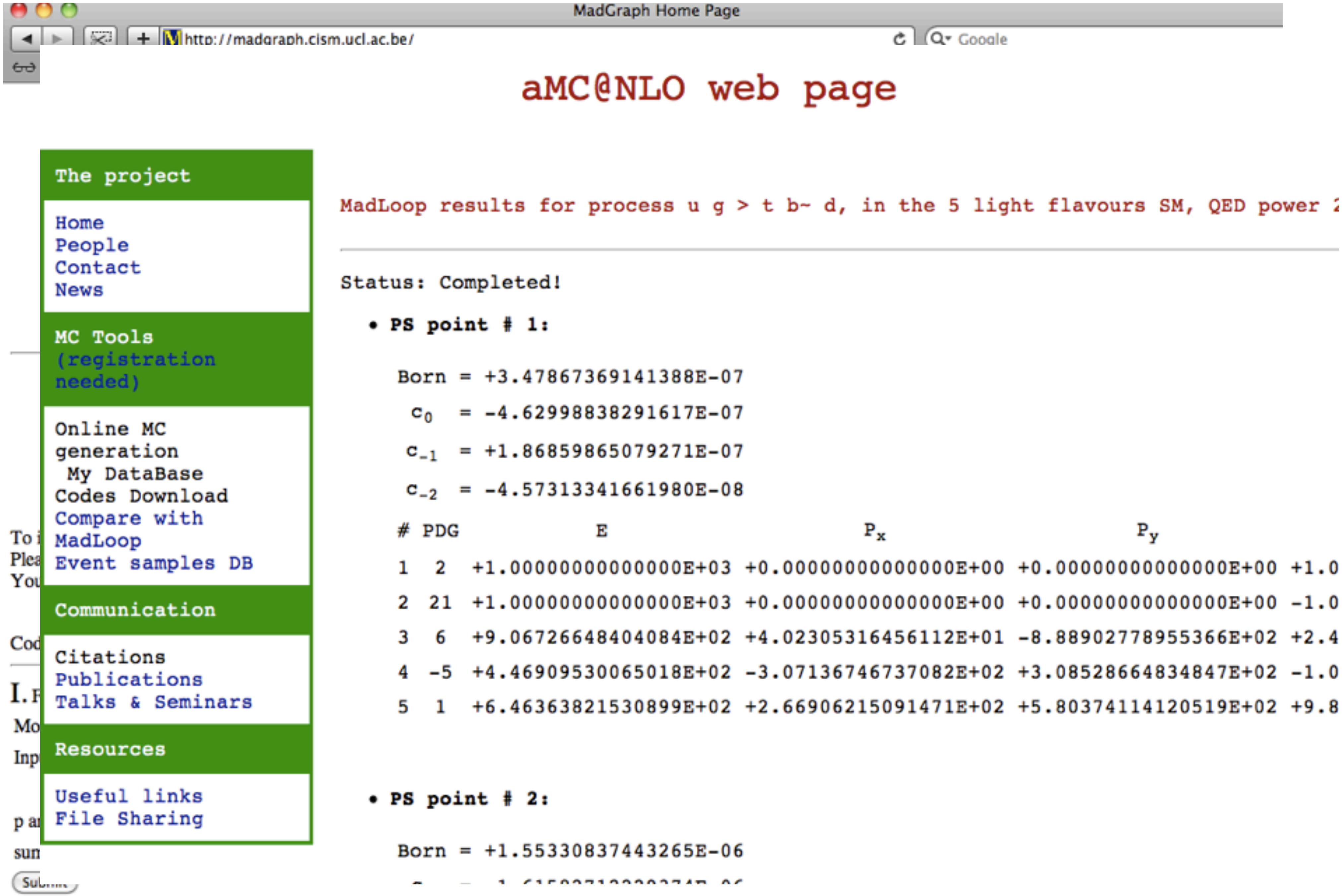
- ✓ Sector decomposition of multiple Feynman parameter integrals plus contour deformation — Anastasiou, Beerli, Daleo
- ✓ Algebraic inversion of coefficients of scalar integrals at integrand level, using unitarity conditions, and partial fractioning (pp→ VVV) — Ossola, Papadopoulos, Pittau; Ellis, Giele, Kunszt; Melnikov

Lively marketplace of ideas, now settling on a few vendors

Web tools: MadGraph, aMC@NLO



Web tools: MadGraph, aMC@NLO



MadGraph Home Page

http://madgraph.cism.ucl.ac.be/

aMC@NLO web page

The project

Home
People
Contact
News

MC Tools (registration needed)

Online MC generation
My DataBase
Codes Download
Compare with MadLoop
Event samples DB

Communication

Citations
Publications
Talks & Seminars

Resources

Useful links
File Sharing

MadLoop results for process u g > t b~ d, in the 5 light flavours SM, QED power 2

Status: Completed!

- **PS point # 1:**

Born = +3.47867369141388E-07

c_0 = -4.62998838291617E-07

c_{-1} = +1.86859865079271E-07

c_{-2} = -4.57313341661980E-08

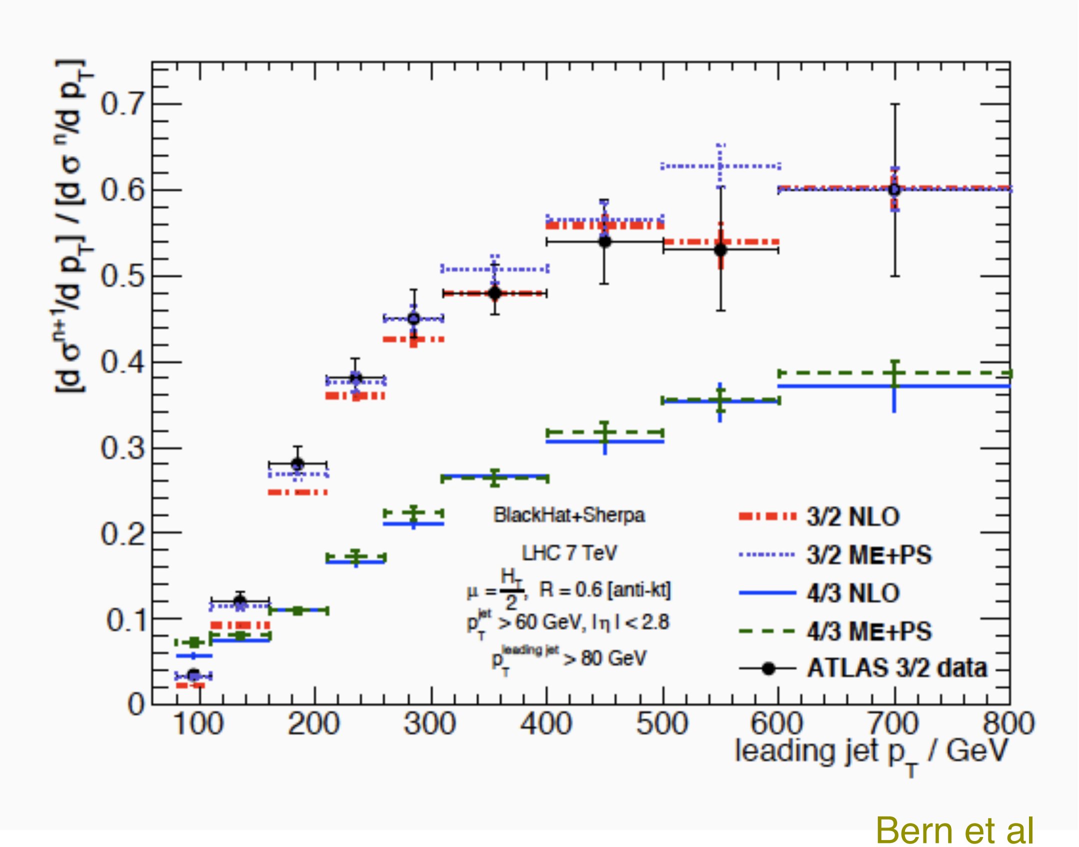
#	PDG	E	P_x	P_y	
1	2	+1.00000000000000E+03	+0.00000000000000E+00	+0.00000000000000E+00	+1.0
2	21	+1.00000000000000E+03	+0.00000000000000E+00	+0.00000000000000E+00	-1.0
3	6	+9.06726648404084E+02	+4.02305316456112E+01	-8.88902778955366E+02	+2.4
4	-5	+4.46909530065018E+02	-3.07136746737082E+02	+3.08528664834847E+02	-1.0
5	1	+6.46363821530899E+02	+2.66906215091471E+02	+5.80374114120519E+02	+9.8

- **PS point # 2:**

Born = +1.55330837443265E-06

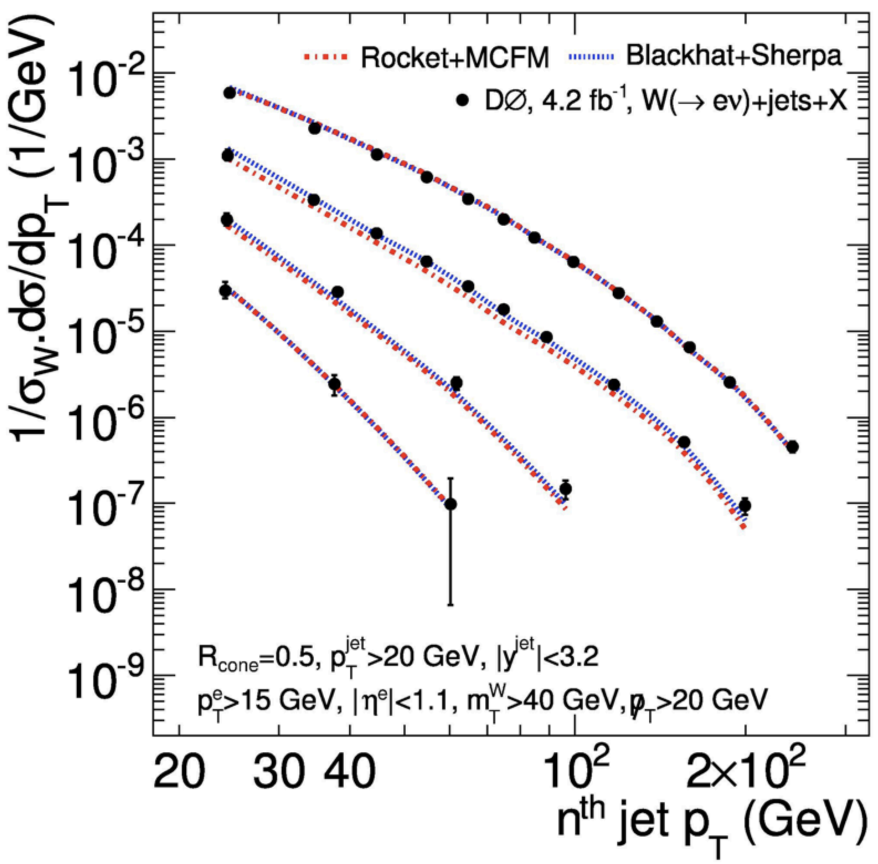
NLO, does it work?

pp → 4 jets



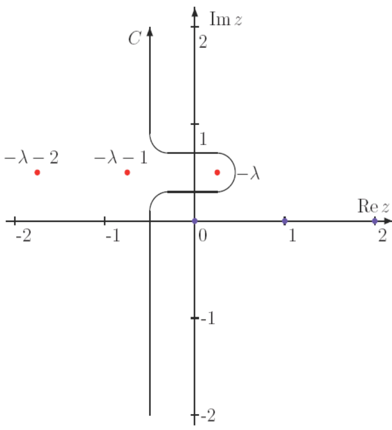
Bern et al
[Blackhat]

W+n jets



Yes

Two-loop methods



Laporta algorithm: reduce all tensor integrals to basis of scalar integrals.

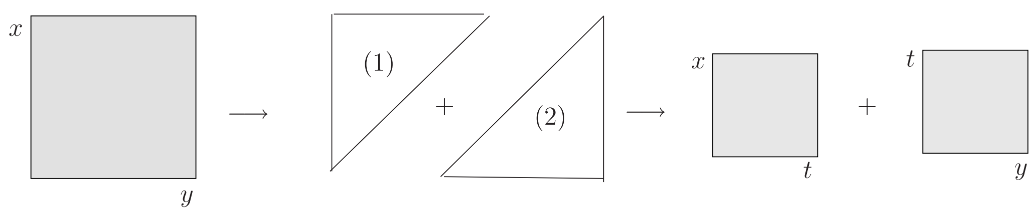
Mellin-Barnes transform: $\frac{1}{(A+B)^\nu} = \frac{1}{\Gamma(\nu)}\frac{1}{2\pi i}\int_C dz \frac{A^z}{B^{\nu+z}}\Gamma(-z)\Gamma(\nu+z)$

Smirnov; Tausk

- Inverse Feynman parameter trick. Can do FP integrals now easily. Contour integrals automatized (AMBRE) Czakon

Sector decomposition: Binoth, Heinrich; Roth, Denner

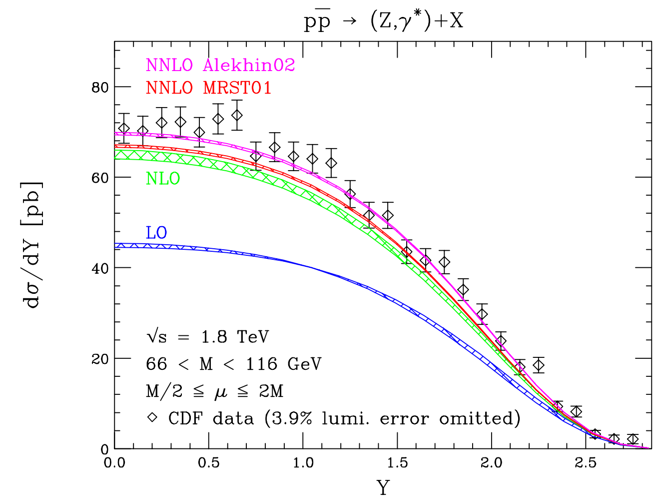
- Hack up multi-dimensional FP parameter space, such that 1 singularity per region.



NNLO

Why/when NLO not enough?

- ✓ When uncertainties at NLO are still large
- ✓ For extracting precise values from data
- ✓ When NLO corrections are large

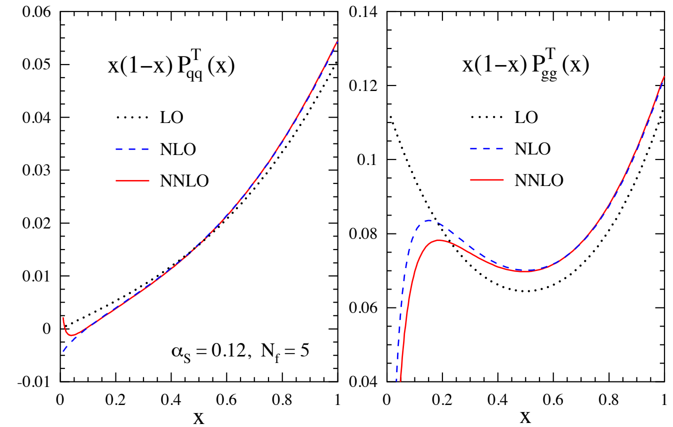


We have now for hadron colliders:

van Neerven, Harlander, Kilgore, Anastasiou, Melnikov, Ravindran, Smith, Dixon, Petriello

- ✓ Inclusive W,Z and H cross sections, and rapidity distributions
- ✓ Fully differential V and H production — Anastasiou, Melnikov, Petriello; Catani, Grazzini
- ✓ Spacelike, and diagonal time-like, splitting functions

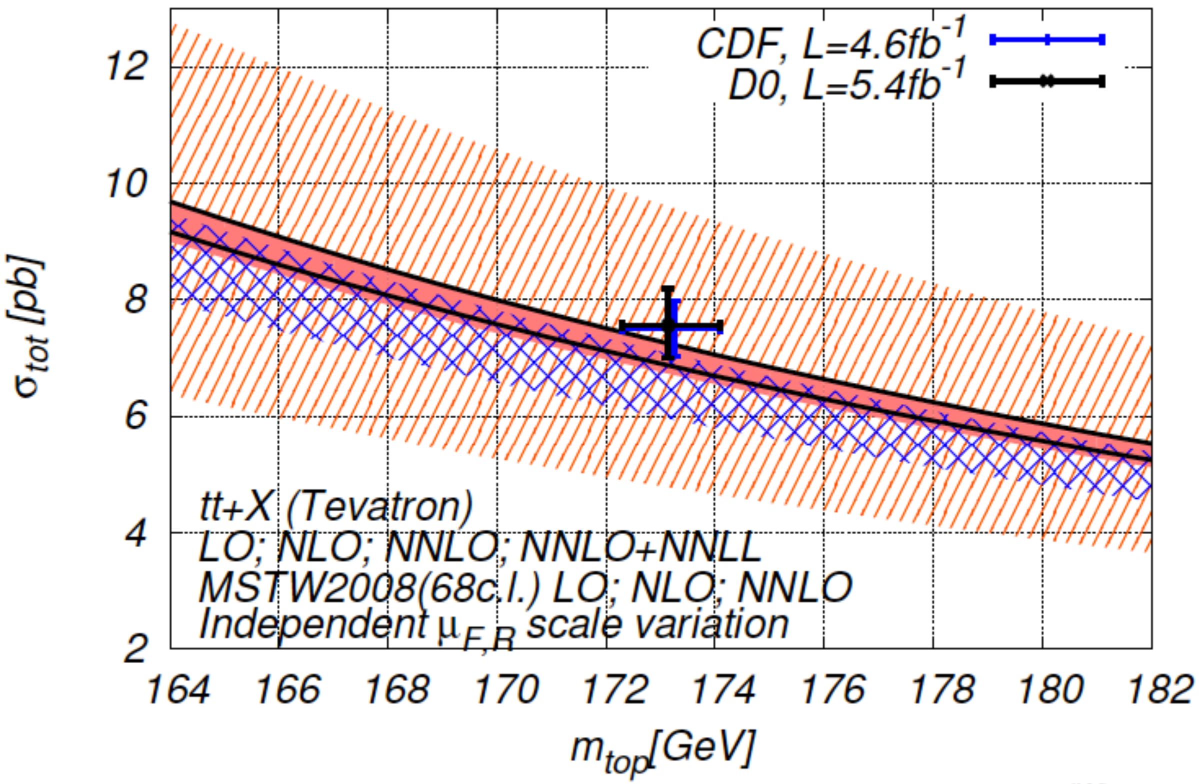
Moch, Vermaseren, Vogt



Excitement: NNLO top cross section finally here

(at least for qq->QQ)

Baernreuther, Mitov, Czakon
[spring 2012]



$$\sigma_{\rm tot}^{\rm res} = 7.067 \; {}^{+0.143\,(2.0\%)}_{-0.232\,(3.3\%)} \; [\text{scales}] \; {}^{+0.186\,(2.6\%)}_{-0.122\,(1.7\%)} \; [\text{pdf}]$$

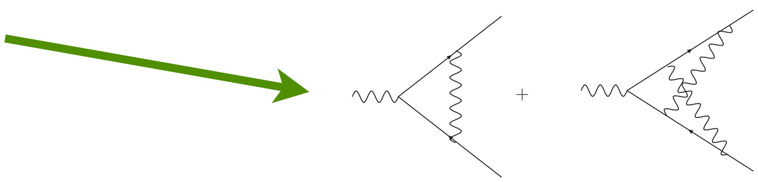
Best prediction at NNLO+NNLL

- ✓ Uncertainty now only a few % at NNLO.
- ✓ First NNLO calculation with initial hadrons and full color structure

All order QCD: resummation

- ✓ Effects of soft gluons can be summed to all orders
- ✓ Many ways to derive exponential form
- ✓ Algebraic: PT is exponent of "webs", after eikonal approximation Gatheral; Frenkel, Taylor; Sterman
- ✓ Webs: subset of diagrams, with modified color factors
- ✓ For Higgs/Drell-Yan inclusive cross section:

$$\begin{aligned} \hat{O} &= 1 + \alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \ldots \\ &= \exp\left(\underbrace{\underbrace{L g_1(\alpha_s L)}_{LL} + g_2(\alpha_s L)}_{NLL} + \alpha_s g_3(\alpha_s L) + \ldots \right) \underbrace{C(\alpha_s)}_{\text{constants}} \\ &+ \text{ suppressed terms} \end{aligned}$$



$$\hat{\sigma}_i(N) = C(\alpha_s) \times \exp\left[\int_0^1 dz \frac{z^{N-1} - 1}{1 - z} \left\{ 2 \int_{\mu_F^2}^{(1-z)^2 Q^2} \frac{d\mu^2}{\mu^2} A_i(\alpha_s(\mu^2)) + D_i(\alpha_s(1 - z)Q^2) \right\} \right]$$

Sterman; Catani, Trentadue, Grazzini, de Florian, Forte, Ridolfi, Vogelsang, Kidonakis, EL, Magnea, Stavenga, White, Ridolfi, Moch, Vogt, Eynck, Ravindran, Becher, Neubert, Ji, Idilbi,...

WEBS FOR QCD AMPLITUDES

Gardi, EL, Stavenga, White

Mitov, Sterman, Sung

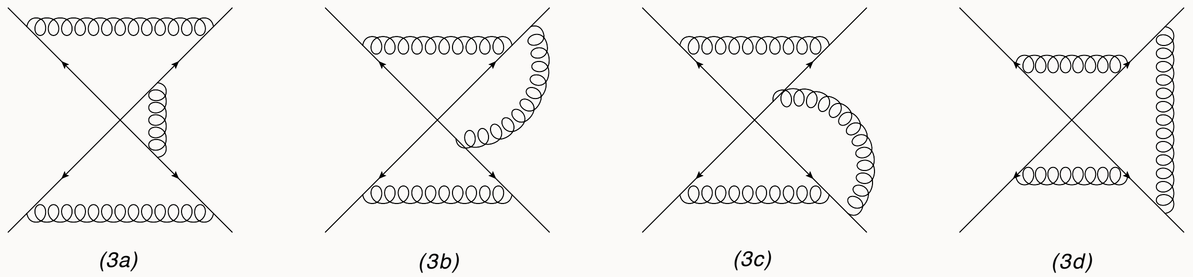
- Found purely exponential structure
- $$\sum \mathcal{F}(D)C(D) = \exp[\sum_{d,d'} \mathcal{F}(d) R_{dd'} C(d')]$$

$$\sum_{d'} R_{dd'} = 0$$

Eigenvalues 0 or 1

Projector matrix

- multi-parton webs are "closed sets" of diagrams, with modified color factors



= Web

- $$\frac{1}{6}\Big[C(3a) - C(3b) - C(3c) + C(3d)\Big] \times \Big[M(3a) - 2M(3b) - 2M(3c) + M(3d)\Big]$$

Resummation

✓ State of the art NNLL

✓ Different approaches, healthy competition

✓ Much progress in analytical understanding:

- Approaching all order knowledge of IR structure of QCD amplitudes

Monte Carlo simulation of QCD

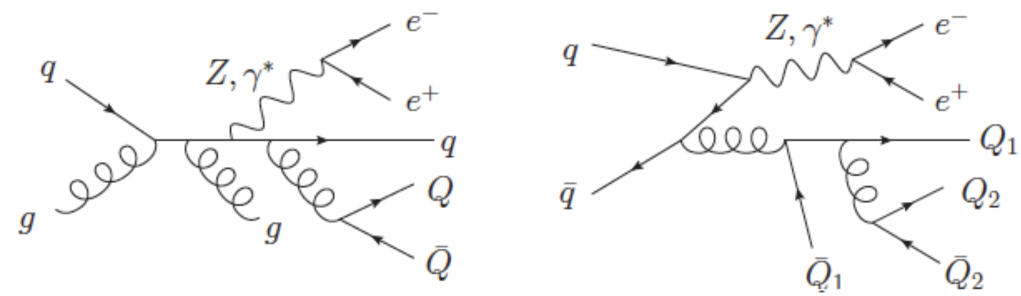
Monte Carlo

Great advances in Monte Carlo in recent years

- Multipurpose: PYTHIA 8 (C++), HERWIG++, SHERPA
- Matrix element based: Alpgen, Madgraph/Madevent, Comphep, Helac
- NLO combined with parton showers: MC@NLO, POWHEG,
- Renaissance after many theorists entered field recently, many new ideas
  - ✓ ..but it don't really count when there ain't code.

Matrix element generators

Good description when no two partons are too collinear, or one is soft

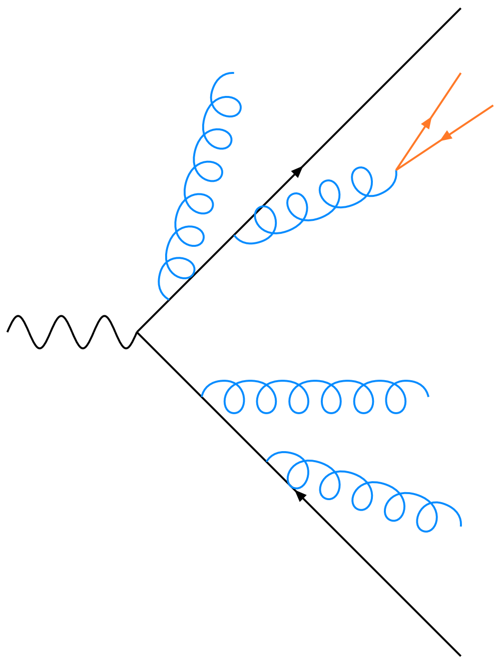


Calculate full tree-level matrix element using

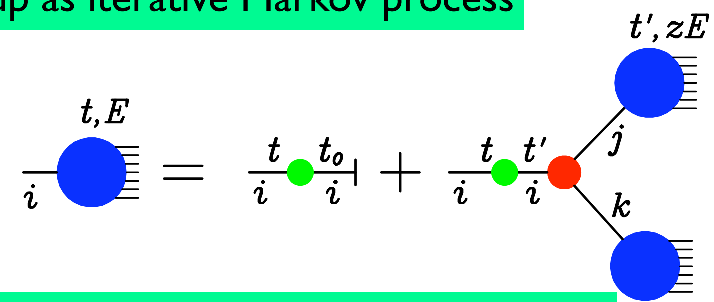
- Diagrams
  - ✓ Helicity amplitudes (MadEvent, Amegic++), squared amplitudes (Comphep)
- Leiden recursion relations (Alpgen, Helac/Phegas)
- Always fixed number of partons
  - ✓ MadEvent: 2 → 6, HELAC, Alpgen, Amegic++ 2 → 8

Parton showers

Approximate description of matrix element when radiation is mostly collinear and soft



Set up as iterative Markov process



based on factorization of matrix element and phase

Sudakov form factor: probability of no emission between two emissions (virtual graphs)

$$\Delta_i(t_1, t_2) = \exp\left[-\sum_{(jk)} \int_{t_2}^{t_1} \frac{dt}{t} \frac{\alpha_S(t)}{2\pi} \int dz\, P_{i,jk}(z) \int \frac{d\varphi}{2\pi} \right]$$

Number of partons per event not fixed

How to combine best of both?

Matching ME to PS

CKKW Catani, Krauss, Kuhn, Webber

- ✓ Small (large) angles: use PS (ME)
- ✓ Define matching angle (scale)
- ✓ Above: dress up ME with Sudakov form factors
- ✓ Below: use PS, but don't allow pT above matching scale

MLM Mangano

- ✓ Generate N-jet with ME.
- ✓ Define matching angle (scale) and start PS
- ✓ Demand hard jets have original parton, otherwise reject
- ✓ For each N the shower cannot increase N

Matching NLO to PS

Match to avoid double counting again

- emission from NLO and PS should be counted once
- virtual part of NLO and Sudakov should not overlap
- two main approaches:

  Frixione, Webber; Nason

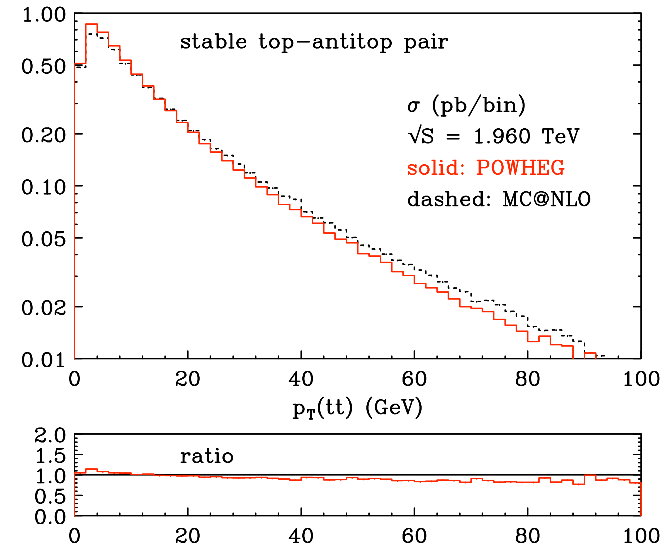
  ✓ MC@NLO exact to NLO, no overshoot, some negative weights

  Nason; Frixione, Oleari

  ✓ POWHEG insists on having positive weights, exponentiates complete real matrix element.

Match both to NLO and ME: Vincia

Effective theory based: GenEvA



Giele, Kosower, Skands

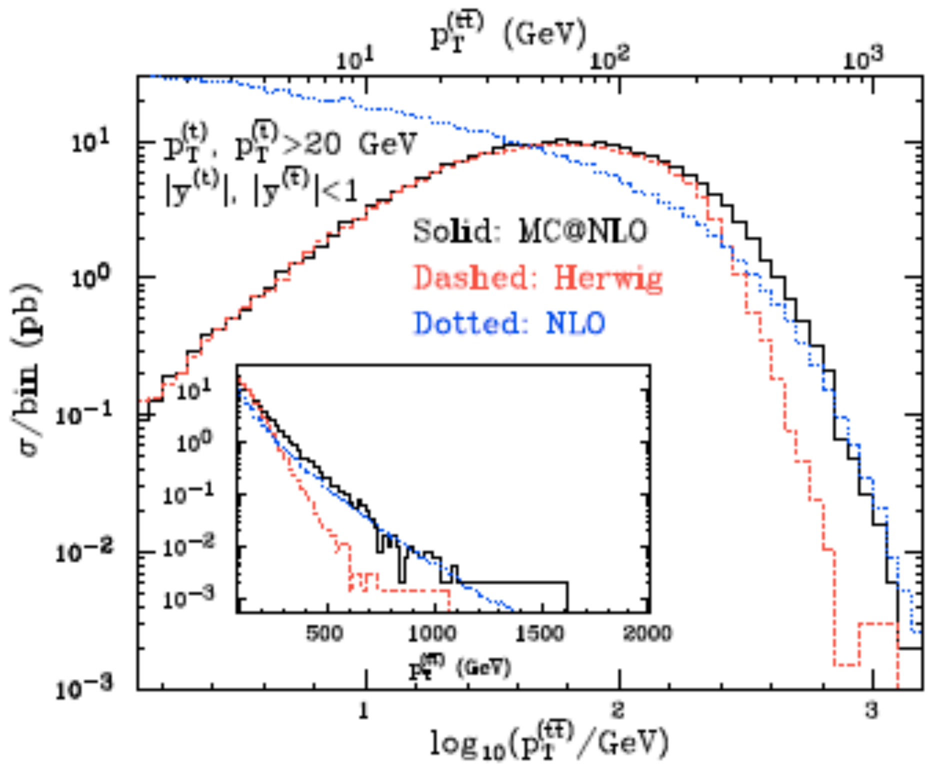
Bauer, Tackmann, Thaler

MC@NLO and $t\bar{t}$

Frixione, Nason, Webber

- First process in MC@NLO with final state colored partons, multiple color flows
- Interpolates well between NLO and parton showers

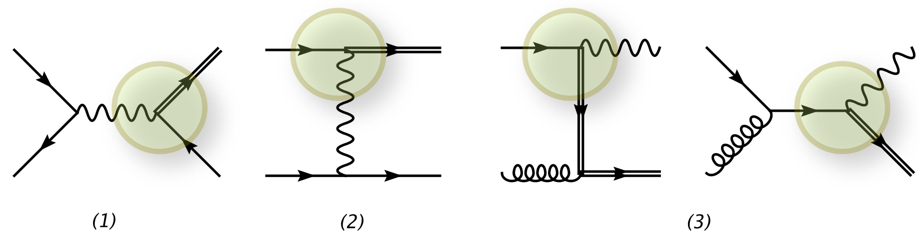
Combine the best parts of MC and Feynman-diagram approach



Automatic NLO + PS

- Is well-underway
  - POWHEG Box
  - aMC@NLO
- Mashups:
  - POWHEG + Madgraph4
  - Sherpa + MC@NLO
  - ...

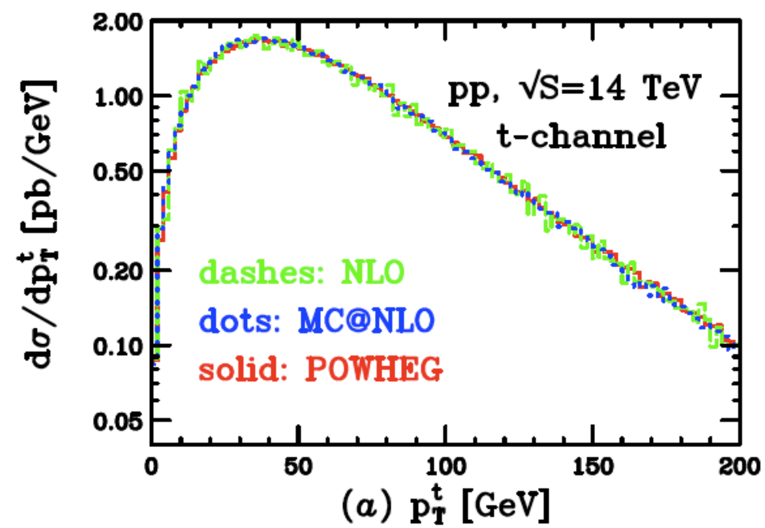
Single top at NLO



s-channel: timelike W

t-channel: spacelike W

Wt channel: real W



Included in MC@NLO & POWHEG

Frixione, EL, Motylinski, Webber

Important process for LHC

- Allows measurement of V_{tb} per channel
- Easier check of chiral structure of Wtb vertex than
- Infer the b-density
- Sensitive to FCNC's (t-channel), or W' resonances (s-channel)

Harris,EL,Phaf,Sullivan, Weinzierl; Cao, Schwienhorst, Yuan; Zhu; Campbell, Ellis, Tramontano

Challenges, an incomplete (wish)list

- Near: Complete full NLO automation
  - ✓ fast, accurate, flexible, easy code
  - ✓ matched to LL parton showers
- Far-ish: begin NNLO wishlist, leading to automation
  - ✓ also NLO QCD + NLO EW corrections
- Near-ish: NLL parton showers, and matching
- Near: Full NNLL resummation for QCD processes
  - ✓ including next-to-eikonal corrections

Conclusions

- Remarkable developments in perturbative QCD
  - ✓ higher order calculations, Monte Carlo's, and their combinations
  - ✓ with some remarkable engineering
- Due to young and experienced researchers alike

QCD theorists are up to the LHC challenge