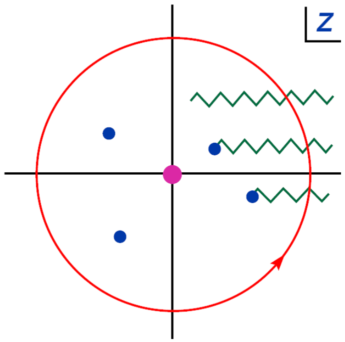
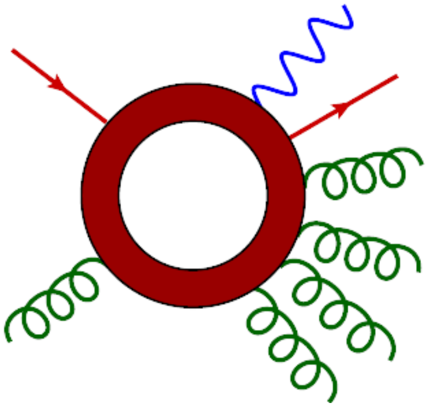
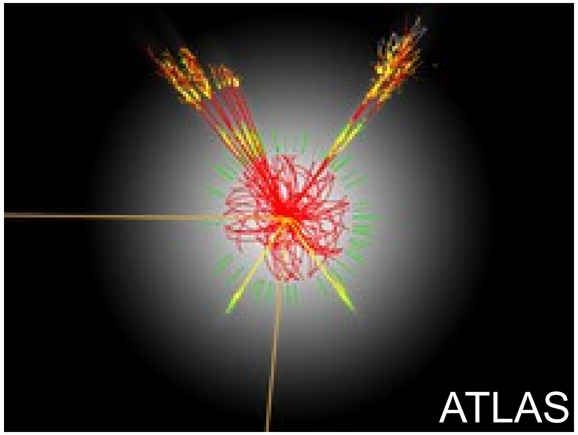
New Tools for Forecasting Old Physics at the LHC



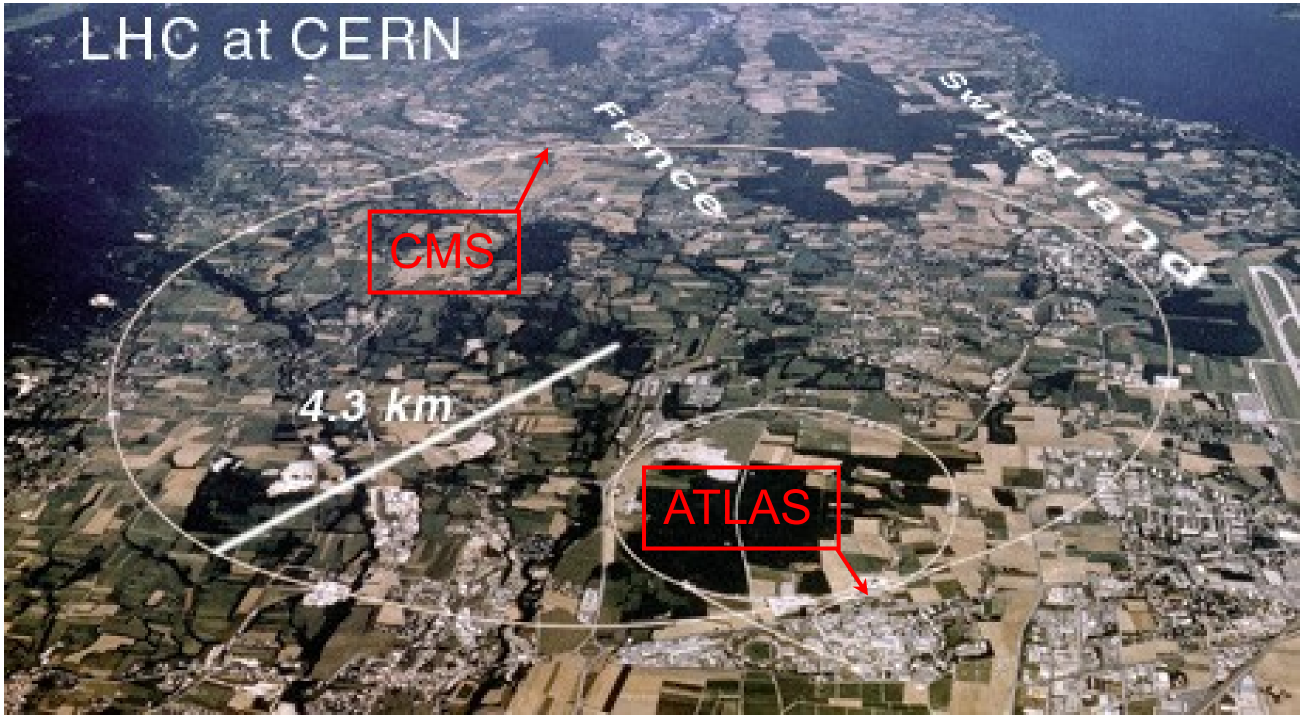




Lance Dixon (CERN & SLAC)

CERN Colloquium
20 January, 2011

The Large Hadron Collider



- Proton-proton collisions at **7 → 14 TeV** center-of-mass energy, 3.5 → 7 times greater than previous (Tevatron)
- Luminosity (collision rate) → 10—100 times greater
- New window into physics at shortest distances – opening now!

New Physics around the Corner

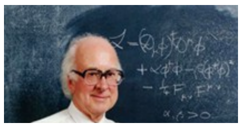
Expect new physics at the 100 GeV – 1 TeV mass scale, associated with electroweak symmetry breaking. At least, a Higgs boson (or similar)

- Many theories predict a host of new massive particles in this mass range, including a **dark matter candidate**
  - **supersymmetry**
  - **new dimensions of space-time**
  - **new forces**
  - etc.

- Most new massive particles decay rapidly to old, ~massless particles:
  quarks, gluons, charged leptons, neutrinos, photons

- **How to distinguish new physics from old (Standard Model)?**
- **From other types of new physics?**

Signals vs. Backgrounds

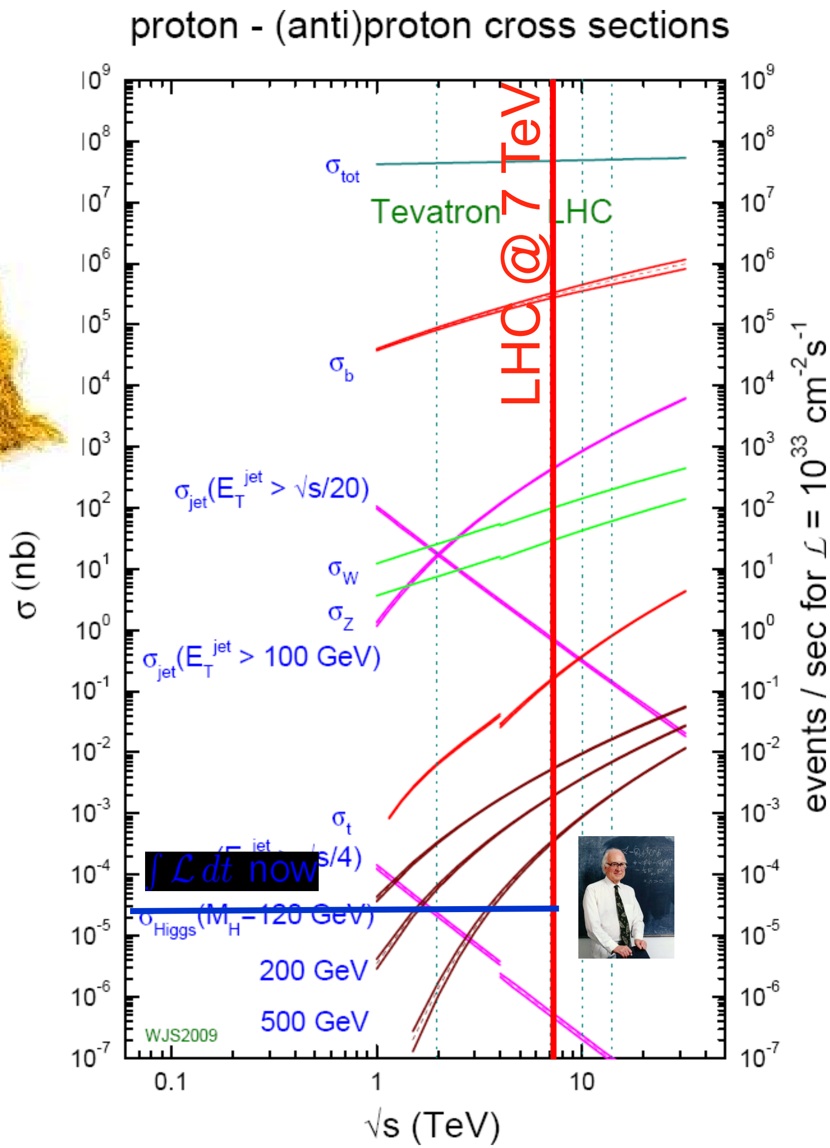


electron-positron colliders
– small backgrounds

vs.

hadron colliders
– large backgrounds

LHC Data Dominated by Jets



new physics →

Jets come from quarks and gluons.

- *q,g* from decay of new particles?
- Or from old QCD?

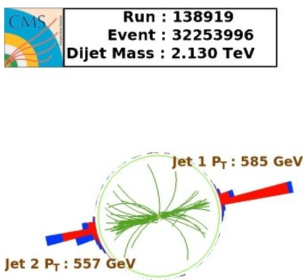
- Every process shown also comes with one more jet at ~ 1/5 the rate
- Should understand Standard Model production of

  X + 1,2,3,… jets

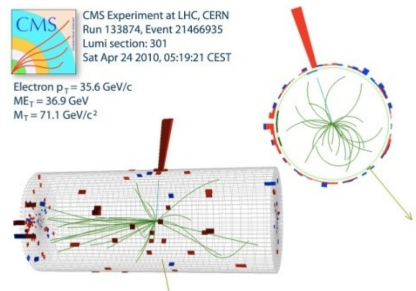
  where

  X = W, Z, tt, WW, H, …

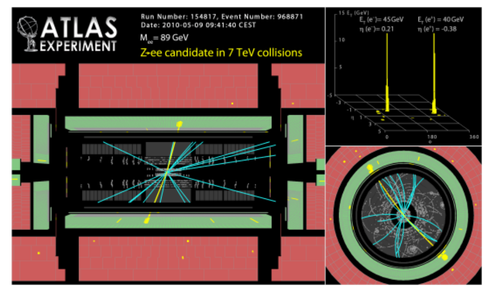
A Few Postcards from the Frontier



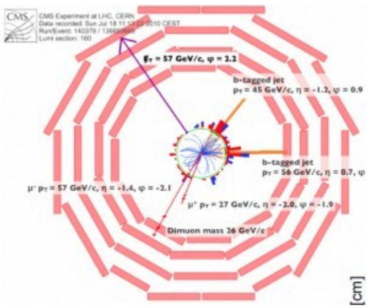
2 jets



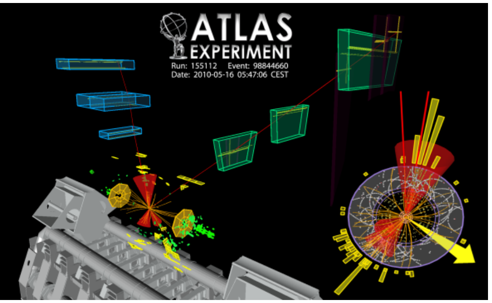
W



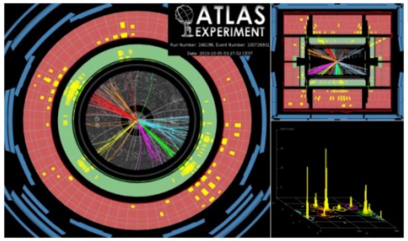
Z



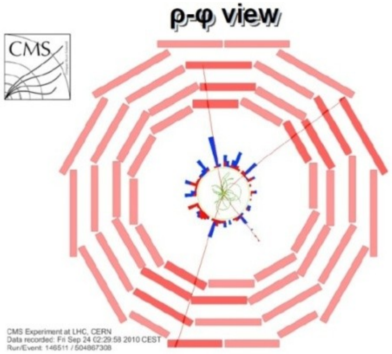
top



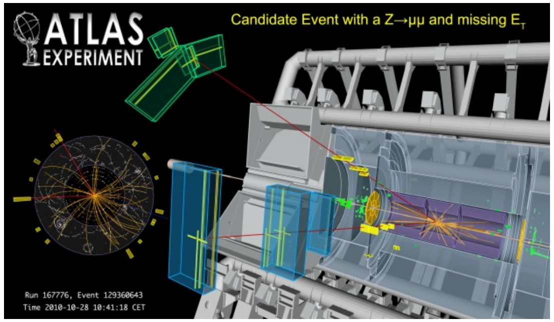
W + 3 jets



8 jets

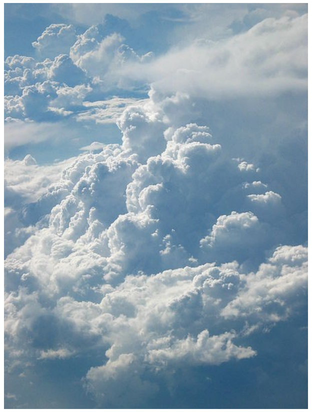


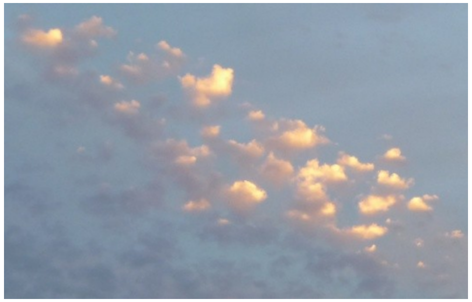
ZZ



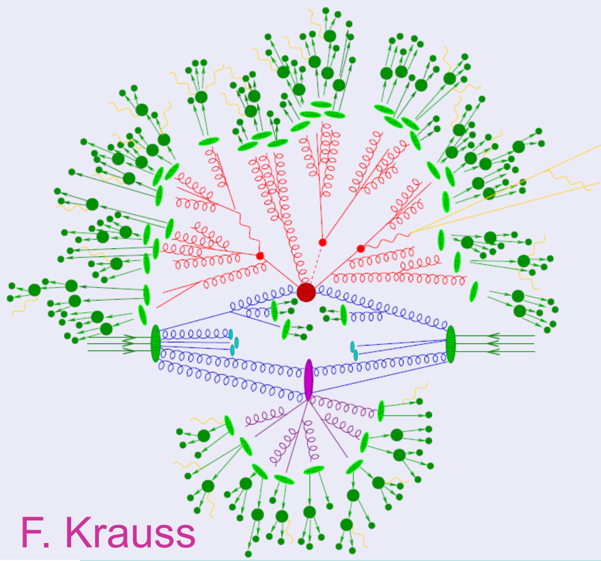
ZZ?

Now let's talk about the weather…

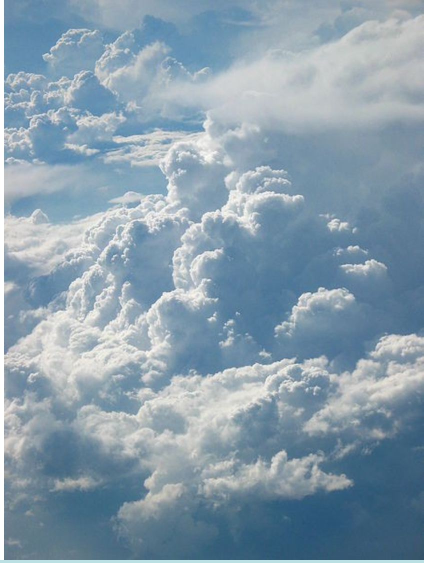






LHC events and clouds



- **Both have fractal properties**
- **Cannot predict individual events**
  - Clouds: unpredictable turbulence, etc., on small distance scales
  - LHC: quantum mechanics, plus unpredictable QCD (strongly coupled) at long distances
- **All about predicting suitable ensembles**
  - weather, or climate, using global circulation models (large distances)
  - cross sections or probabilities that (ideally) are only sensitive to short distances (infrared safe) using perturbative QCD
  - new physics ~ climate change

Asymptotic Freedom

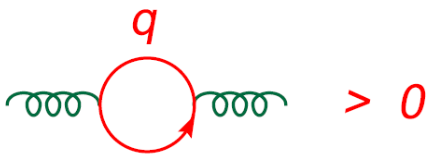
Gross, Wilczek, Politzer (1973)

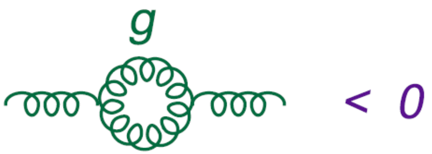
Gluon self-interactions make quarks almost free, and make QCD calculable at short distances (high energies)

Quantum fluctuations of massless virtual particles polarize vacuum

QED: electrons screen charge (e larger at short distances)

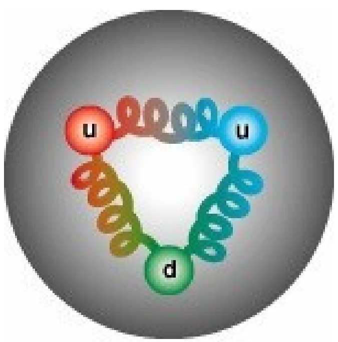
QCD: gluons anti-screen charge (g_s smaller at short distances)

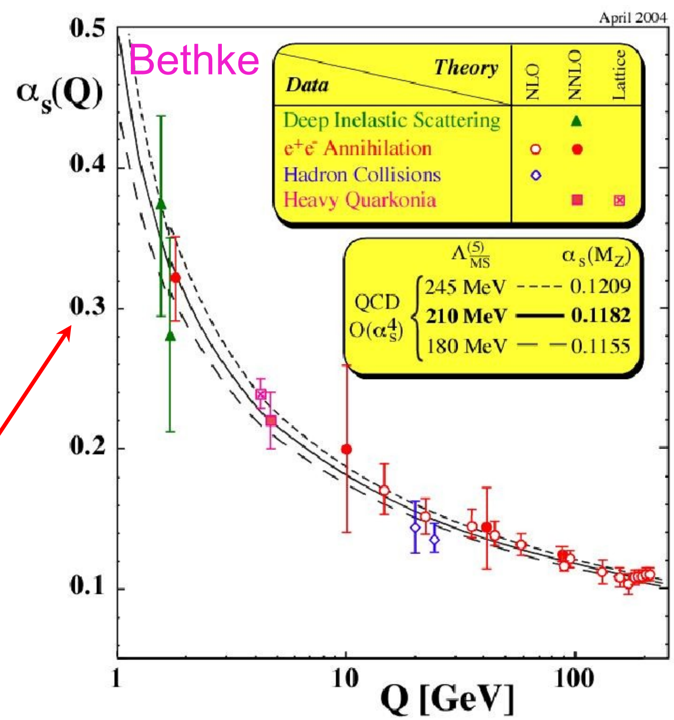


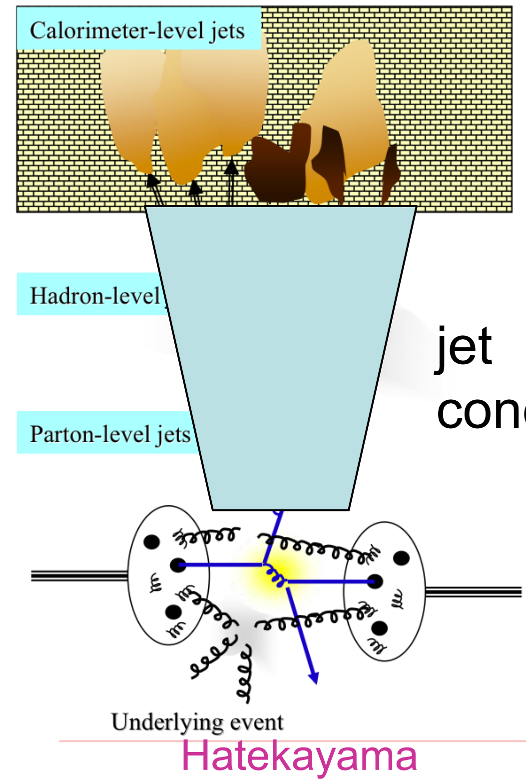


Asymptotic Freedom (cont.)

Running of α_s is *logarithmic*, *slow* at short distances (large Q)







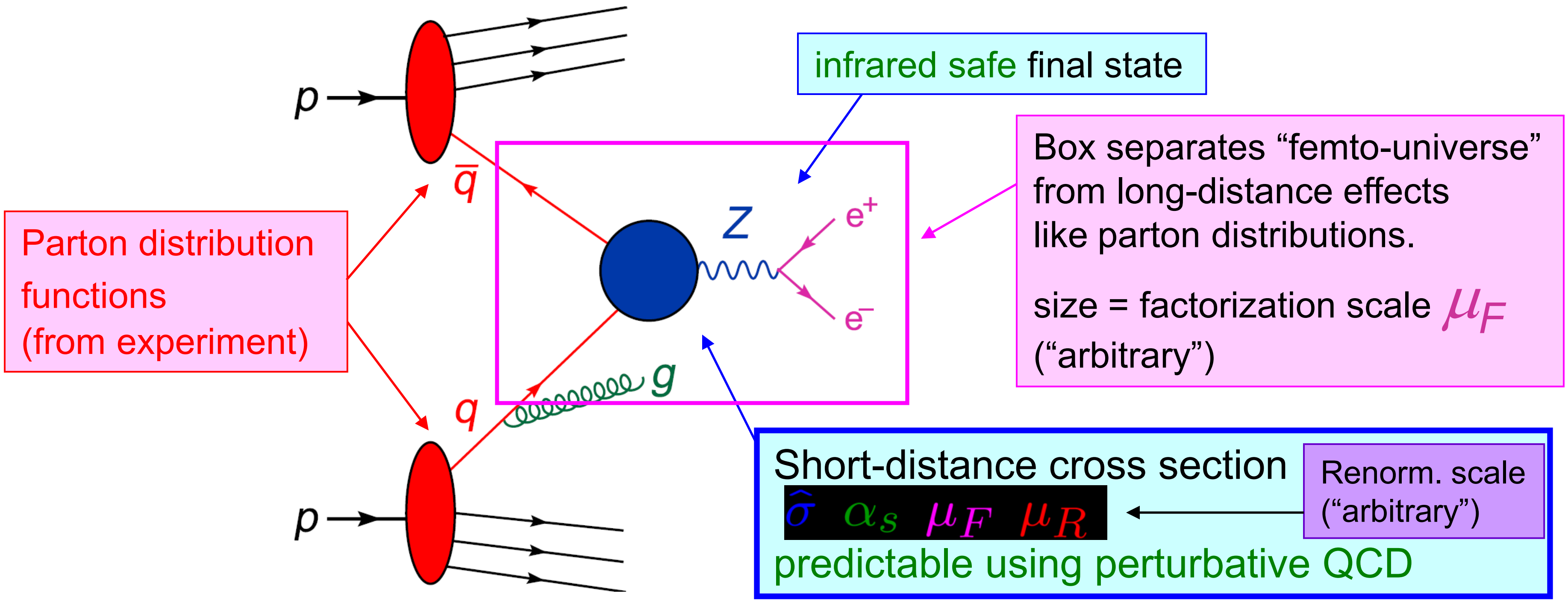
jet cone

confining

calculable

QCD Factorization & Parton Model

Asymptotic freedom: At short distances, quarks and gluons (partons) in proton are almost free, and are sampled "one at a time"



Short-Distance Cross Section in Perturbation Theory

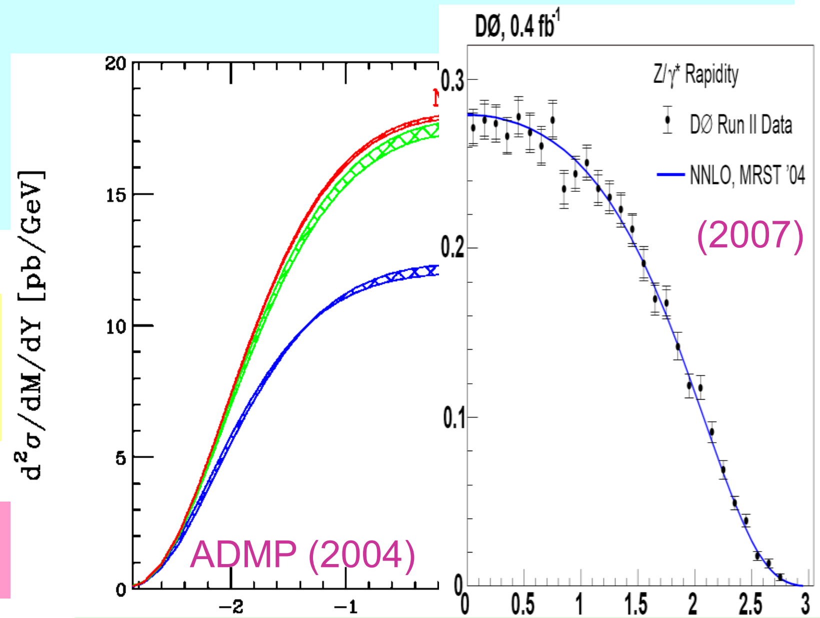
$$\hat{\sigma}(\alpha_s,\mu_F,\mu_R) \;=\; [\alpha_s(\mu_R)]^{n_\alpha}\left[\hat{\sigma}^{(0)} + \frac{\alpha_s}{2\pi}\hat{\sigma}^{(1)}(\mu_F,\mu_R) + \left(\frac{\alpha_s}{2\pi}\right)^2\hat{\sigma}^{(2)}(\mu_F,\mu_R) + \cdots\right]$$

LO NLO NNLO

Problem: Leading-order (LO) predictions only qualitative due to **poor convergence** of expansion in α_s μ (setting $\mu_R = \mu_F = \mu$)

Example: Z production at Tevatron
- Distribution in rapidity Y

~50% corrections, LO → NLO

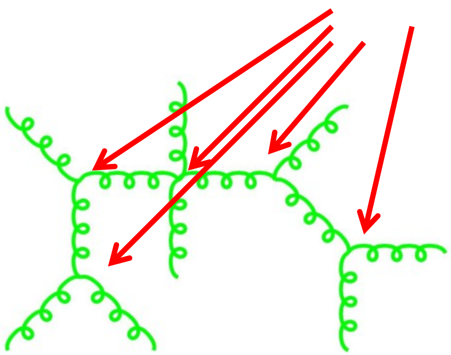


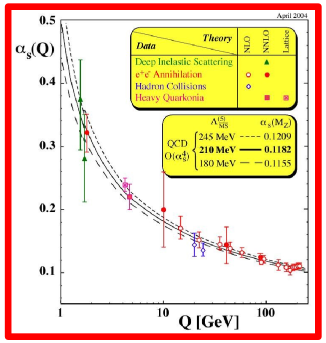
by NNLO, a precision observable

LO uncertainty increases with n_{jets}

$$\hat{\sigma}(\alpha_s, \mu_F, \mu_R) = [\alpha_s(\mu_R)]^{n_\alpha}\left[\hat{\sigma}^{(0)} + \frac{\alpha_s}{2\pi}\hat{\sigma}^{(1)}(\mu_F, \mu_R) + \left(\frac{\alpha_s}{2\pi}\right)^2 \hat{\sigma}^{(2)}(\mu_F, \mu_R) + \cdots\right]$$

LO NLO NNLO



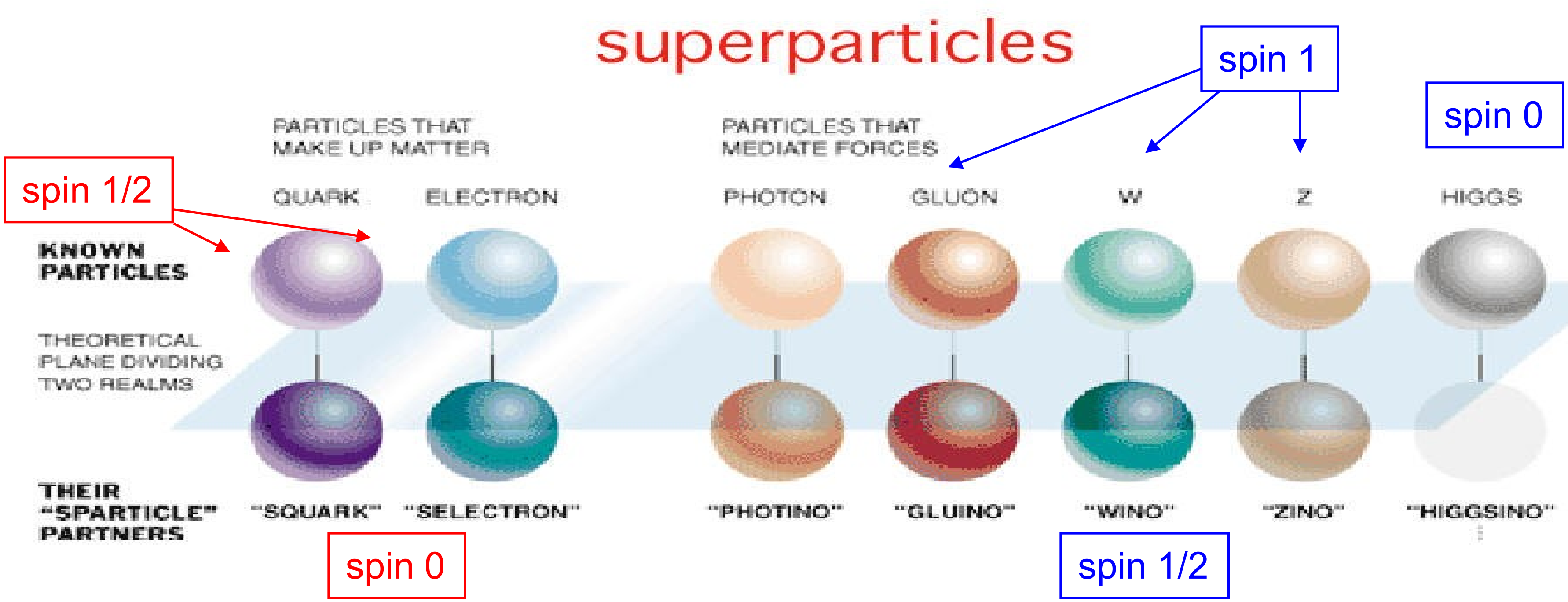


Uncertainty brought under much better control with NLO corrections: ~ 50% or more → ~ 15-20%

NLO really required for quantitative control of multi-jet final states

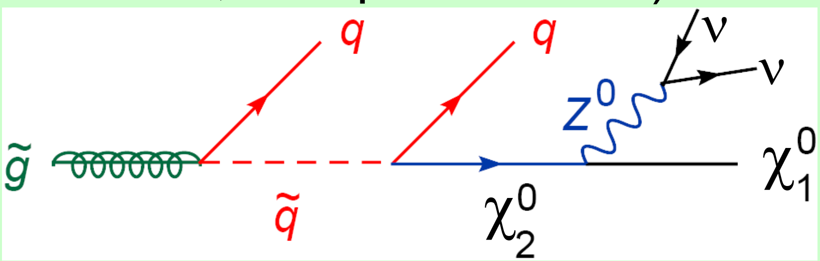
New Physics Example: Supersymmetry

• Symmetry between fermions (matter) and bosons (forces)
• Very elegant, also solves theoretical puzzles
• Lightest supersymmetric particle can be **dark matter**
• For every elementary particle already seen, another one should show up soon at LHC!

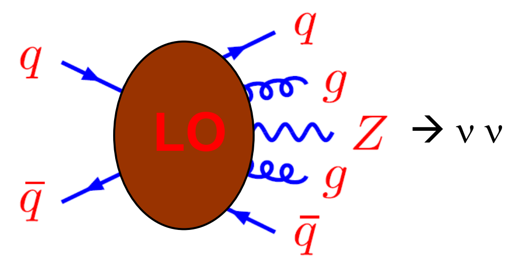


Backgrounds to Supersymmetry at LHC

- **Decay from gluino to neutralino** (dark matter, escapes detector)



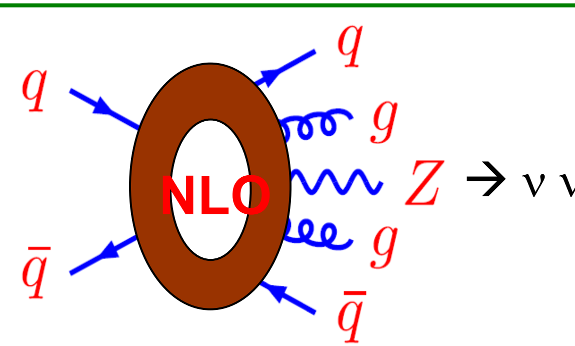
- **2 gluinos in event →**
  Signal: missing energy (MET) + 4 jets
- SM background: Z + 4 jets, Z → neutrinos



Current state of art for Z + 4 jets based on **LO approximation** → normalization still quite uncertain

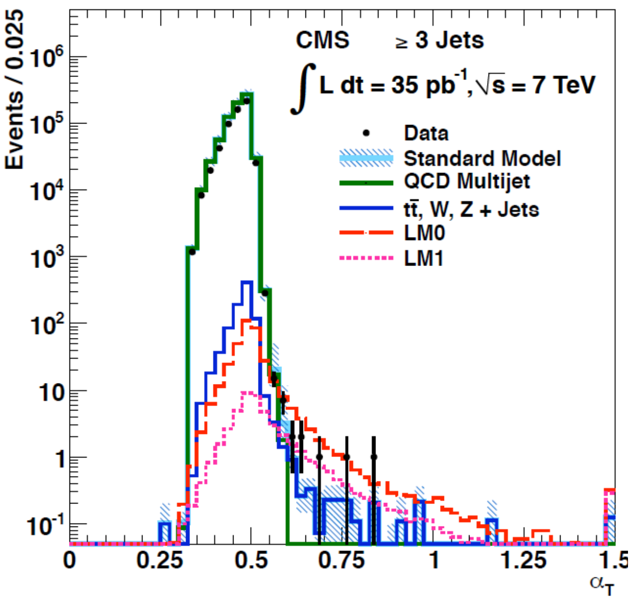
- Motivates goal of

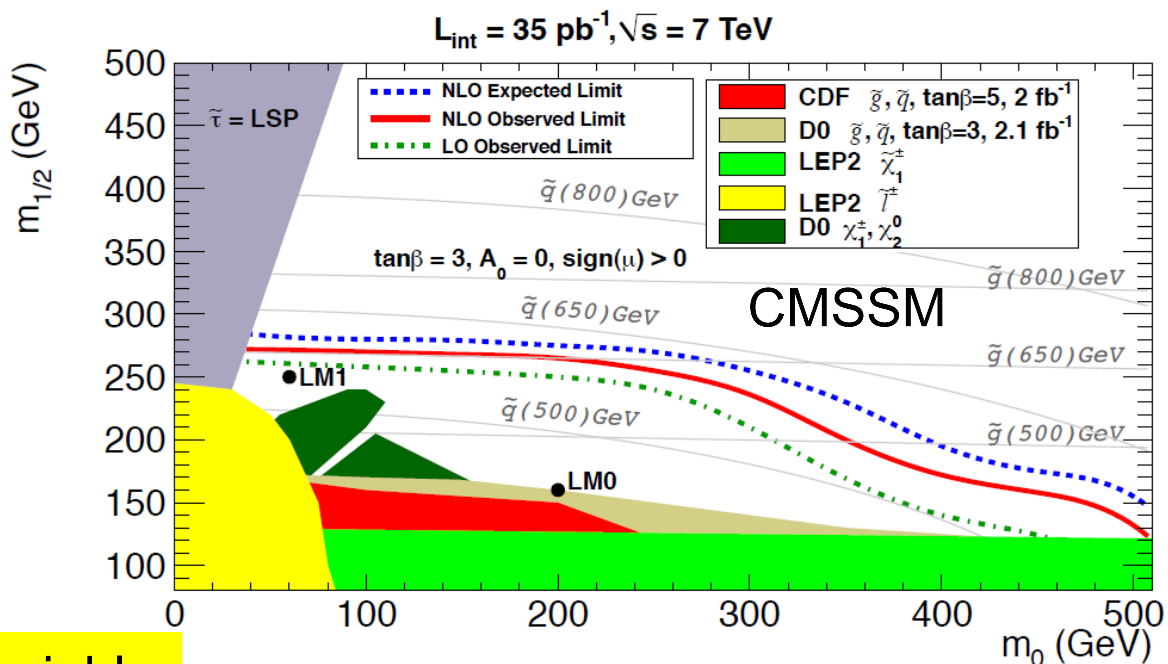
$pp \to Z + 4$ jets
at NLO in QCD



New Limits on Supersymmetry from LHC

CMS, 1101.1628



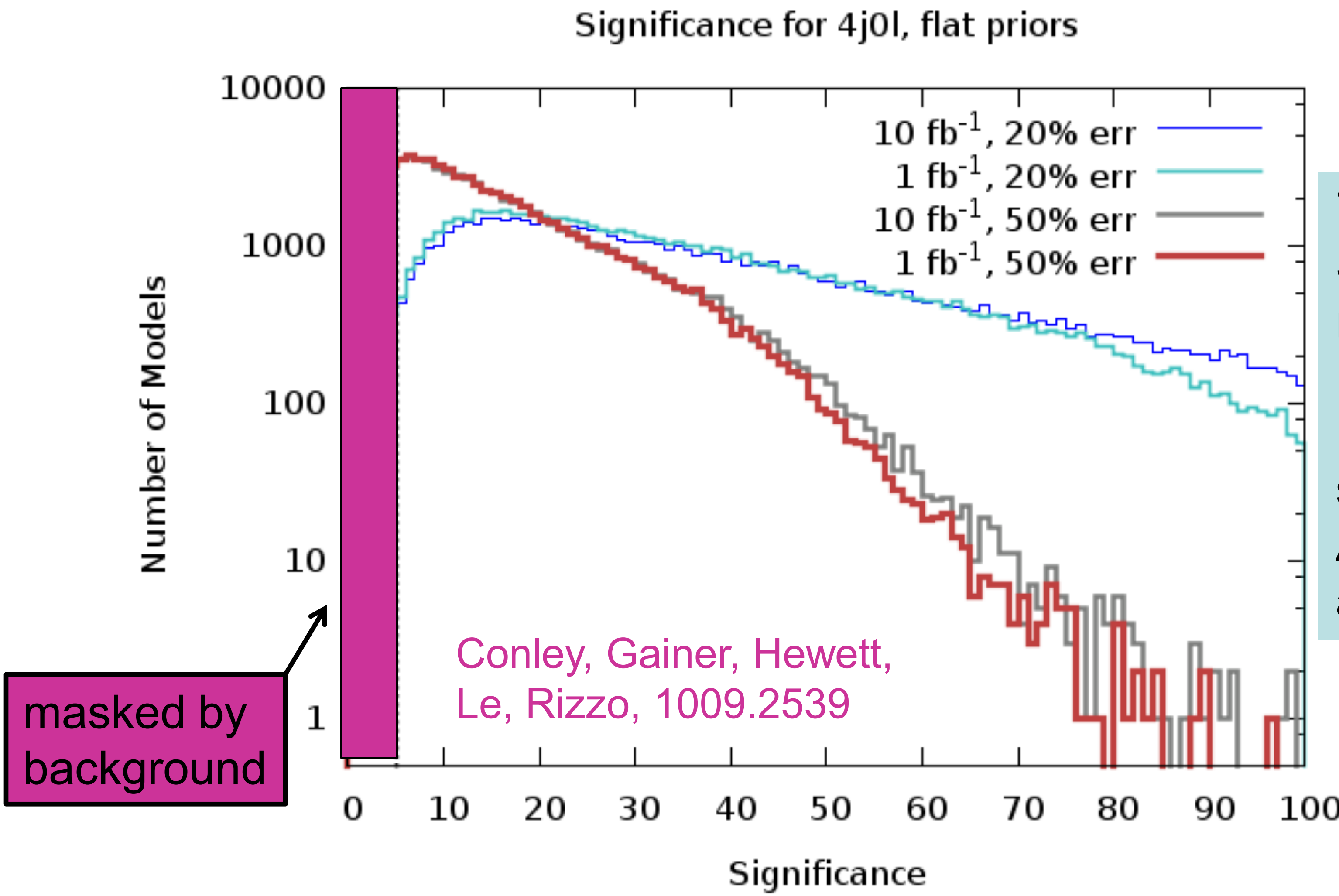


α_T = MET + jets shape variable

- LHC off to an extremely promising start!

- As data increases rapidly this year, better SM theory can help

Reducing Background Systematics Improves SUSY Search Sensitivity



70,000 SUSY models

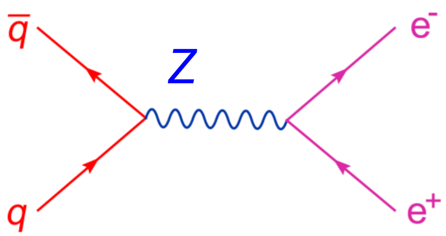
MET + 4 jet search, ATLAS-style analysis

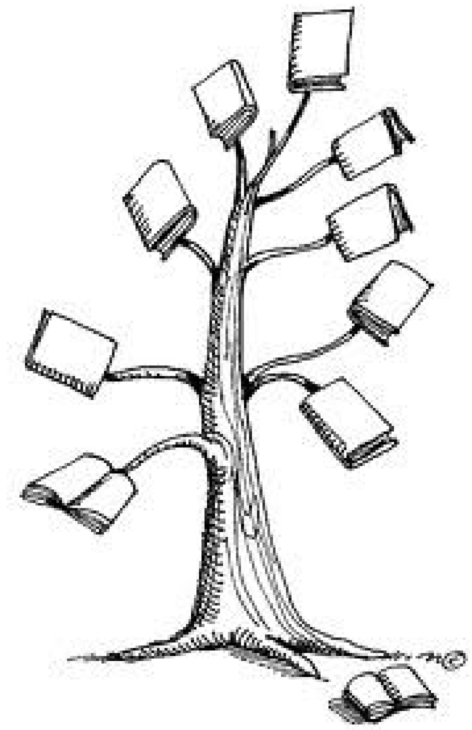
LO = Trees

LO cross section can be computed using only Feynman diagrams with no closed loops – called tree diagrams.
Here is a very simple one:

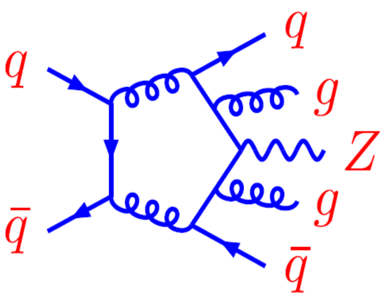
$\hat{\sigma}^{(0)}$

LO





Although there are many kinds of trees, some harder than others, "textbook" methods often suffice



NLO = Loops

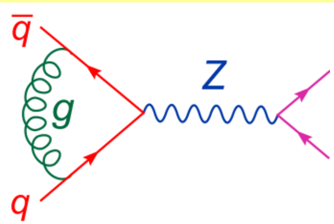
NLO cross section needs Feynman diagrams with exactly one closed loop

Where the fun really starts – textbook methods quickly fail, even with very powerful computers

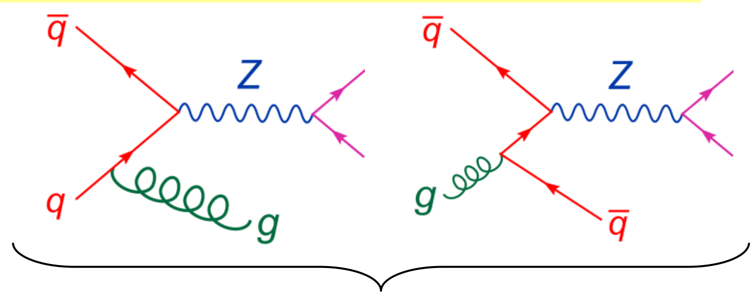
- NLO also needs tree-level amplitudes with one more parton
- Both terms infinite(!) – combine them to get a finite result

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

NLO



1 loop



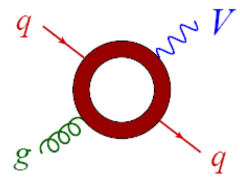
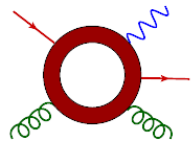
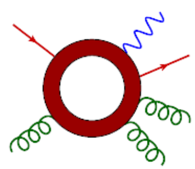
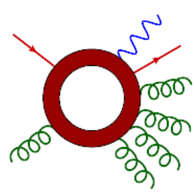
tree + 1 parton

- One-loop amplitudes were the bottleneck for a long time

– focus today just on this part of the problem

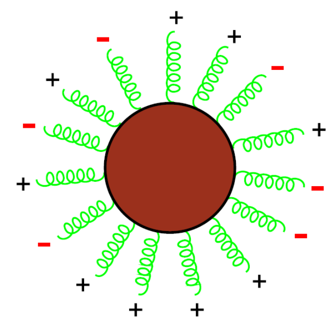
Loops get difficult quickly!

For $pp \to W + n$ **jets** (maximum number of external gluons only)

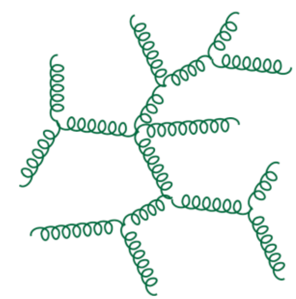
# of jets		# 1-loop Feynman diagrams
1		11
2		110
3		1,253
5		256,265

A Better Way to Compute?

- Backgrounds (and many signals) require detailed understanding of scattering amplitudes for many ultra-relativistic ("massless") particles – especially quarks and gluons of QCD



- Long ago, **Feynman** told us how to do this – in principle



+ …

- However, **Feynman diagrams**, while very general and **powerful**, are not optimized for these processes
- There are more efficient methods for multi-jet processes!

Remembering a Simpler Time...

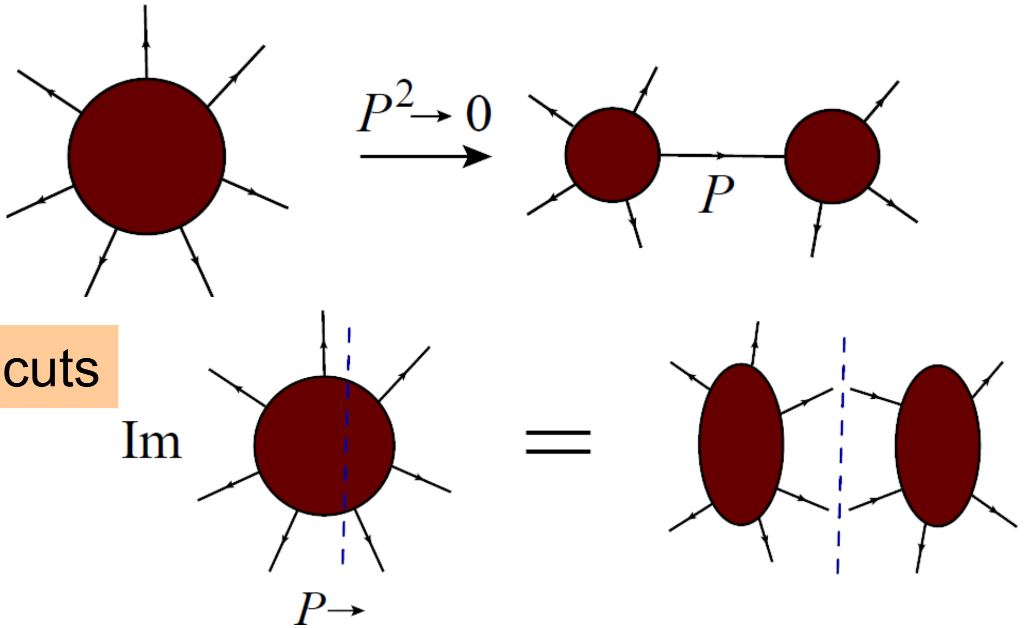
- In the 1960s there was no QCD, no Lagrangian or Feynman rules for the strong interactions

The Analytic *S*-Matrix

Bootstrap program for strong interactions: Reconstruct scattering amplitudes **directly** from **analytic properties: "on-shell" information**

- Poles

- Branch cuts



Landau; Cutkosky;
Chew, Mandelstam;
Eden, Landshoff,
Olive, Polkinghorne;
Veneziano;
Virasoro, Shapiro;
… (1960s)

Analyticity fell out of favor in 1970s with the rise of QCD & Feynman rules

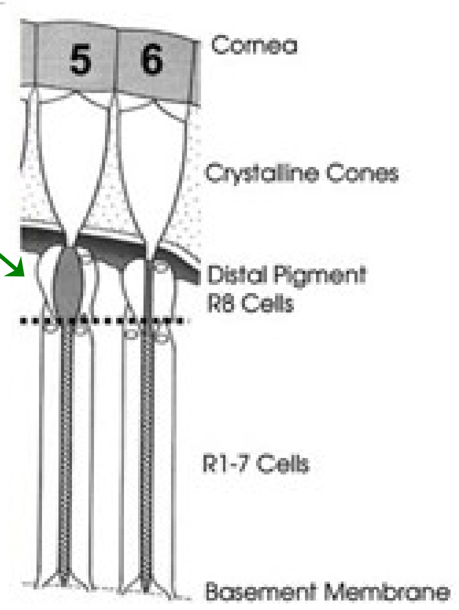
Now **resurrected** for computing amplitudes in **perturbative** QCD – as **alternative to Feynman diagrams!**
Perturbative information now assists analyticity.

The Tail of the Mantis Shrimp

- Reflects left and right circularly polarized light differently

- Led biologists to discover that its eyes have differential sensitivity
- It communicates via the helicity formalism

λ/4 plate



"It's the most private communication system imaginable. No other animal can see it."

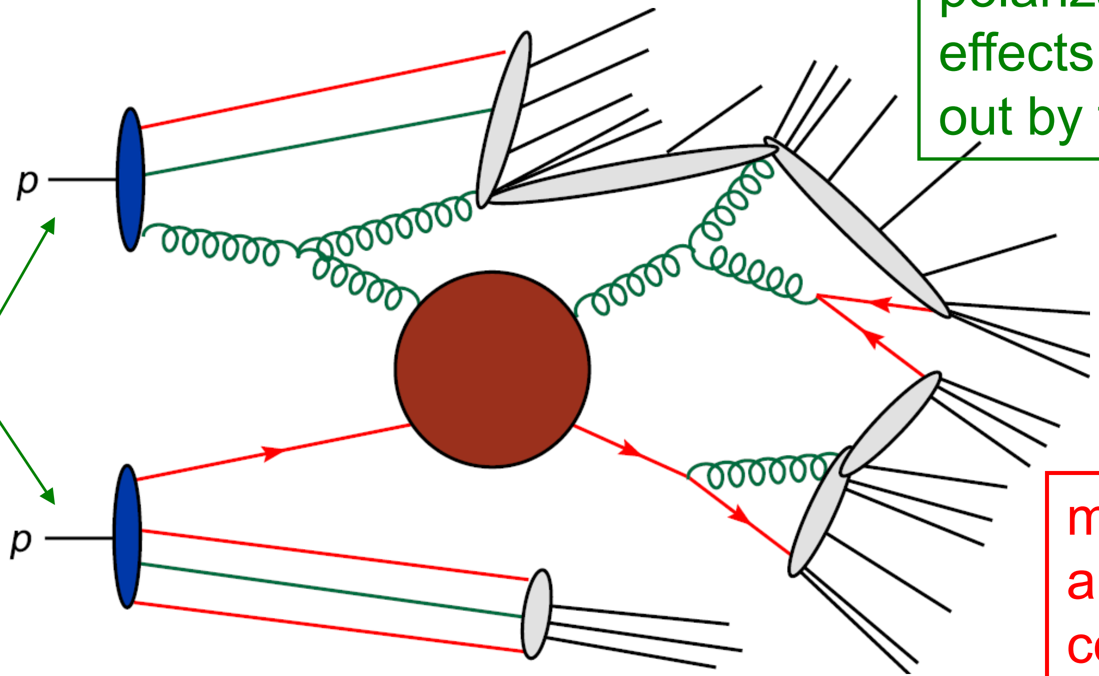
- Roy Caldwell (U.C. Berkeley)

What the Biologists Didn't Know

Particle theorists have also evolved capability to communicate results via helicity formalism

LHC experimentalists are blind to it

almost all final-state polarization effects washed out by fragmentation

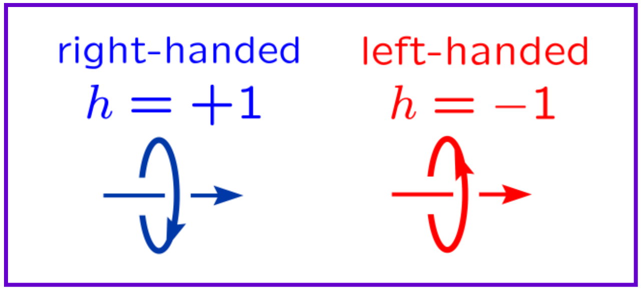


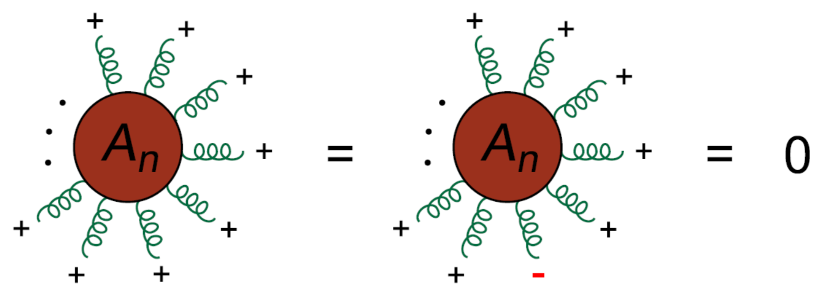
unpolarized

must sum over all helicity configurations

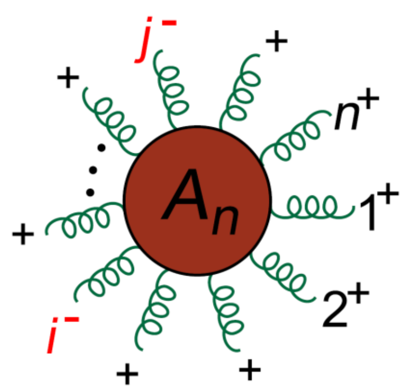
Helicity Formalism Exposes Tree-Level Simplicity in QCD

Many helicity amplitudes either vanish or are very short





Analyticity makes it possible to recycle this simplicity into loop amplitudes



$$= \frac{\langle i\, j \rangle^4}{\langle 1\, 2 \rangle \langle 2\, 3 \rangle \cdots \langle n\, 1 \rangle}$$

Parke-Taylor formula (1986)

For Efficient Computation

Reduce
the number of "diagrams"

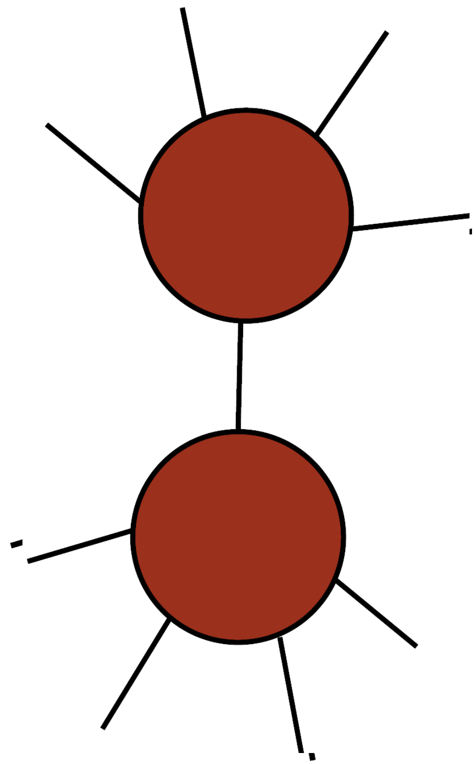
Reuse
building blocks over & over

Recycle
lower-point (1-loop) & lower-loop (tree)
on-shell amplitudes

Recurse

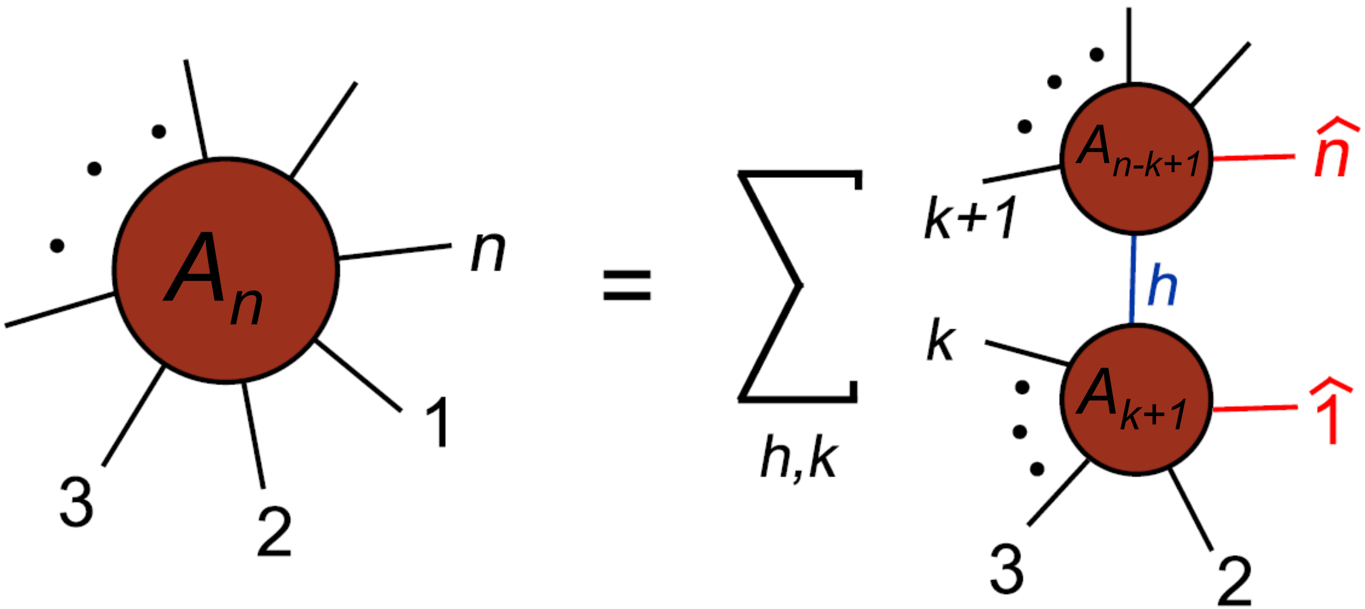
Recycling “Plastic” Amplitudes

Amplitudes fall apart into simpler ones in special limits – pole information



Pole information
→ BCFW (On-shell) Recursion Relations

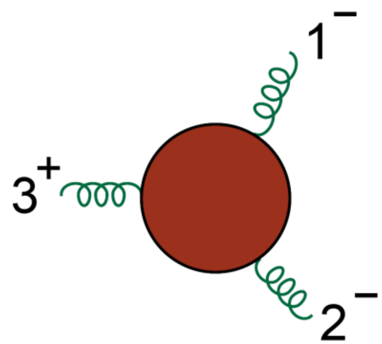
Britto, Cachazo, Feng, Witten, hep-th/0501052



A_{k+1} and A_{n-k+1} are **on-shell** tree amplitudes with **fewer** legs, and with momenta shifted by a **complex** amount

Trees recycled into trees

All Gluon Tree Amplitudes Built From:



$$= \frac{\langle 1\,2\rangle^4}{\langle 1\,2\rangle\langle 2\,3\rangle\langle 3\,1\rangle}$$

In contrast to Feynman vertices, it is on-shell, completely physical

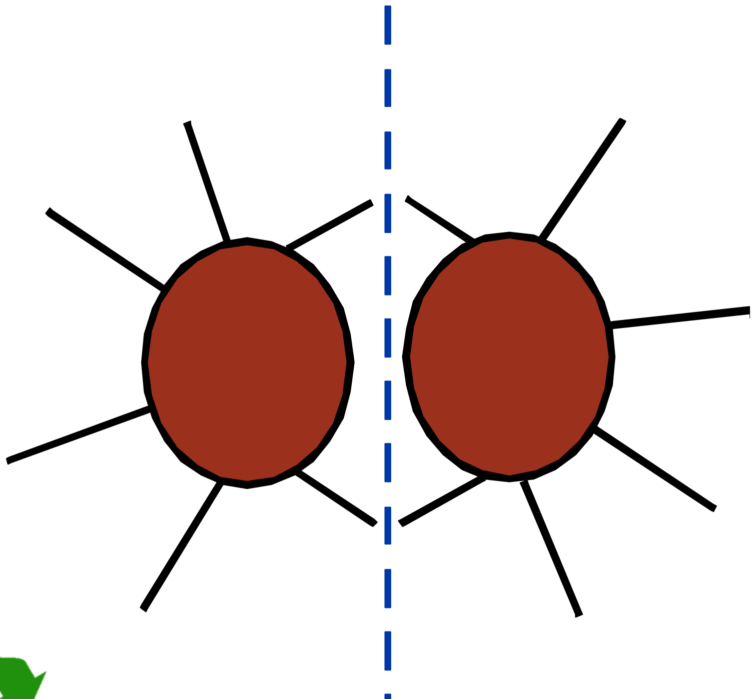
- On-shell recursion leads to very compact analytic formulae, and fast numerical implementation.
- Can do same sort of thing at loop level.

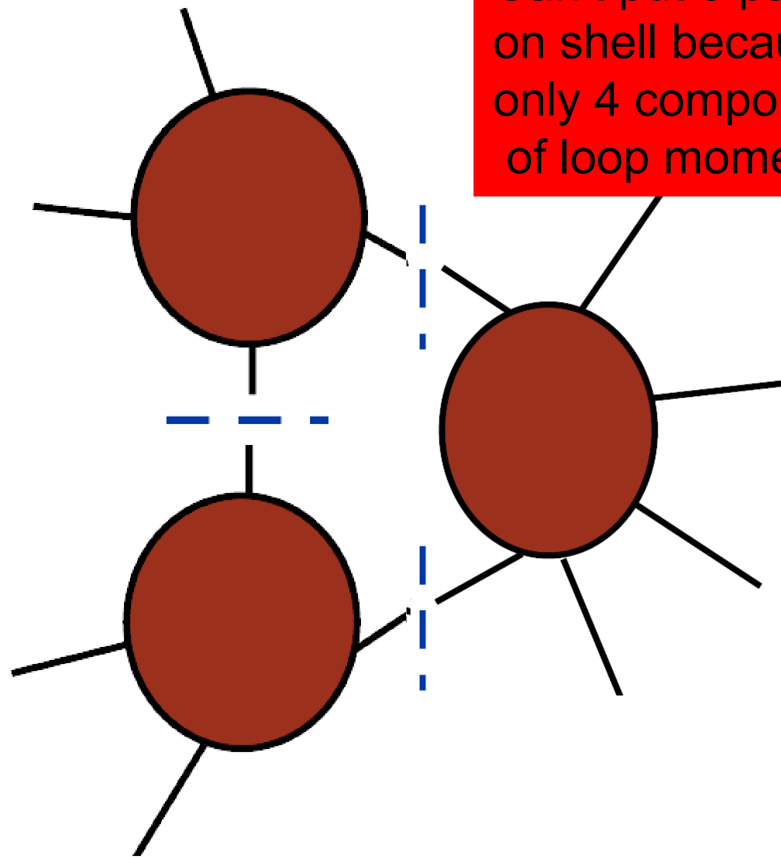
Branch cut information → Generalized Unitarity (One-loop Plasticity)

Ordinary unitarity:
put 2 particles on shell

Generalized unitarity:
put 3 or 4 particles on shell

Can't put 5 particles on shell because only 4 components of loop momentum





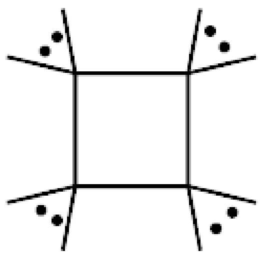
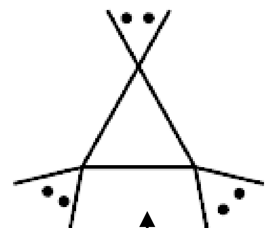
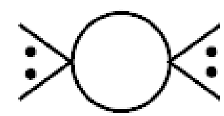
Trees recycled into loops!

One-Loop Amplitude Decomposition

Bern, LD, Dunbar, Kosower (1994)

• **Missing from the old, nonpertubative analytic *S*-matrix**

coefficients can be determined from products of trees using (generalized) unitarity

$A^{1\text{-loop}} = \sum_i d_i$  $+ \sum_i c_i$  $+ \sum_i b_i$ 

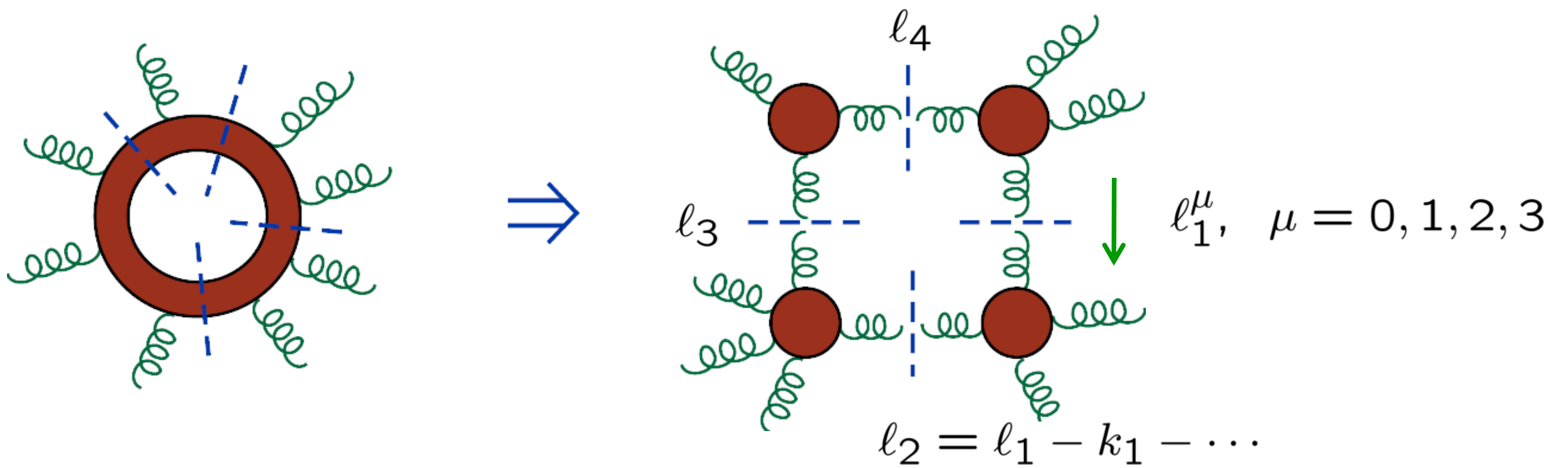
$+ R + \mathcal{O}(\epsilon)$

Known functions (integrals), same for all amplitudes

rational part; from D-dimensional trees, or recursively

Generalized Unitarity for Box Coefficients d_i

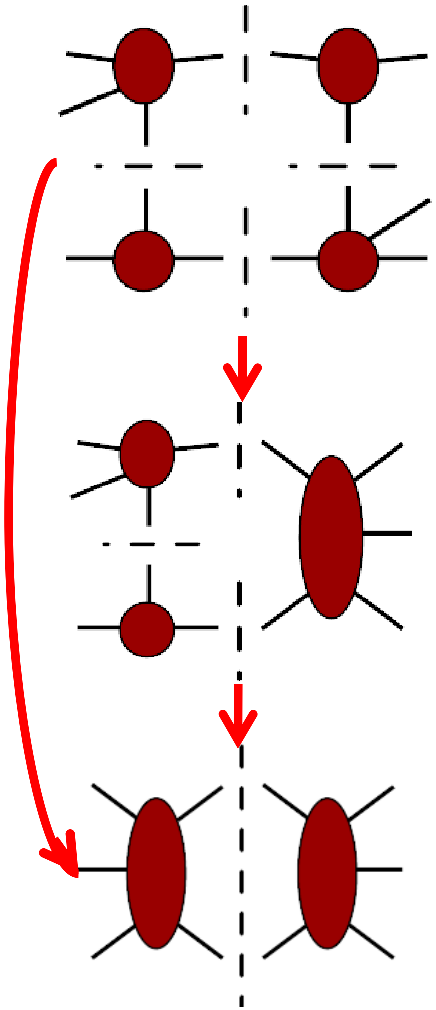
Britto, Cachazo, Feng, hep-th/0412103



Just multiply together 4 different tree amplitudes, evaluated at 2 different loop momenta that solve simple “quadruple cut” equations:

$$
\begin{aligned}
d_i &= A^{1-\text{loop}}(\ell_i)|_{\ell_i^2 = m_i^2,\ i=1,2,3,4} \\
&= \sum_{\pm} A_1^{\text{tree}}(\ell_0^{\pm}) A_2^{\text{tree}}(\ell_0^{\pm}) A_3^{\text{tree}}(\ell_0^{\pm}) A_4^{\text{tree}}(\ell_0^{\pm}) \\
&= d_i^{+} + d_i^{-}
\end{aligned}
$$

Rest of amplitude determined hierarchically



Each box coefficient comes uniquely from 1 “quadruple cut”

Ossola, Papadopolous, Pittau, hep-ph/0609007; Mastrolia, hep-th/0611091; Forde, 0704.1835; Ellis, Giele, Kunszt, 0708.2398; Berger et al., 0803.4180;…

Each triangle coefficient from 1 triple cut, but “contaminated” by boxes

Each bubble coefficient from 1 double cut, removing contamination by boxes and triangles

Bottom Line:

Trees recycled into loops!

Similar methods work for multiple loops
– especially in theories with lots of supersymmetry like N=4 super-Yang-Mills and N=8 supergravity

Automated On-Shell Programs at One Loop

CutTools: Ossola, Papadopolous, Pittau, 0711.3596

NLO *WWW, WWZ*, ... Binoth+OPP, 0804.0350

NLO $t\bar{t}b\bar{b}$, $t\bar{t}$ + 2 jets,… Bevilacqua, Czakon, Papadopoulos, Pittau, Worek, 0907.4723; 1002.4009; now going into MadGraph (Frederix,Frixione,...)

Blackhat: Berger, Bern, LD, Febres Cordero, Forde, H. Ita, D. Kosower, D. Maître; T. Gleisberg, 0803.4180, 0808.0941, 0907.1984, 1004.1659, 1009.2338

+ **Sherpa** → NLO *W,Z* + 3,4 jets

Rocket: Giele, Zanderighi, 0805.2152

Ellis, Giele, Kunszt, Melnikov, Zanderighi, 0810.2762

NLO *W* + 3 jets (large N_c), W^+W^+ + 2 jets

EMZ, 0901.4101, 0906.1445; Melia, Melnikov, Rontsch, Zanderighi, 1007.5313

SAMURAI: Mastrolia, Ossola, Reiter, Tramontano, 1006.0710

NGluon: Badger, Biedermann, Uwer, 1011.2900

As a result…

Dramatic increase recently in rate of NLO predictions for new processes!

Les Houches Experimenters' Wish List

2010

process wanted at NLO	background to
1. $pp \to VV +$ jet	$t\bar{t}H$, new physics Dittmaier, Kallweit, Uwer; Campbell, Ellis, Zanderighi
2. $pp \to H + 2$ jets	H in VBF BCDEGMRSW; Campbell, Ellis, Williams Campbell, Ellis, Zanderighi; Ciccolini, Denner Dittmaier
3. $pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$ Bredenstein, Denner Dittmaier, Pozzorini; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$ Bevilacqua, Czakon, Papadopoulos, Worek
5. $pp \to VVb\bar{b}$	VBF $\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to VV + 2$ jets	VBF $\to H \to VV$ Melia, Melnikov, Rontsch, Zanderighi VBF: Bozzi, Jäger, Oleari, Zeppenfeld
7. $pp \to V + 3$ jets	new physics Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre; Ellis, Melnikov, Zanderighi
8. $pp \to VVV$	SUSY trilepton Lazopoulos, Melnikov, Petriello; Hankele, Zeppenfeld; Binoth, Ossola, Papadopoulos, Pittau
9. $pp \to b\bar{b}b\bar{b}$	Higgs, new physics GOLEM

Feynman diagram methods

now joined by

on-shell methods based on analyticity (unitarity)

table courtesy of C. Berger

Top Quark Pairs + Jets

- Like (W,Z) + jets, a very important class of backgrounds
- Jets can boost the $t\bar{t}$ system, increasing missing E_T, and provide jets to pass various signal cuts.
- Cross sections large – no electroweak couplings
- State of art:

- **NLO *tt* + 1 jet:** Dittmaier, Uwer, Weinzierl, hep-ph/0703120,…
- **+ top decays:** Melnikov, Schulze, 1004.3284
- **+ NLO parton shower:** Kardos, Papadopoulos, Trócsányi, 1101.2672

- **NLO *tt* + *bb*:** Bredenstein, Denner, Dittmaier, Pozzorini, 0905.0110, 1001.4006; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek, 0907.4723
- **NLO *tt* + 2 jets:** Bevilacqua, Czakon, Papadopoulos, Worek, 1002.4009

NLO $pp \to t\bar{t}\,b\bar{b}$ at LHC

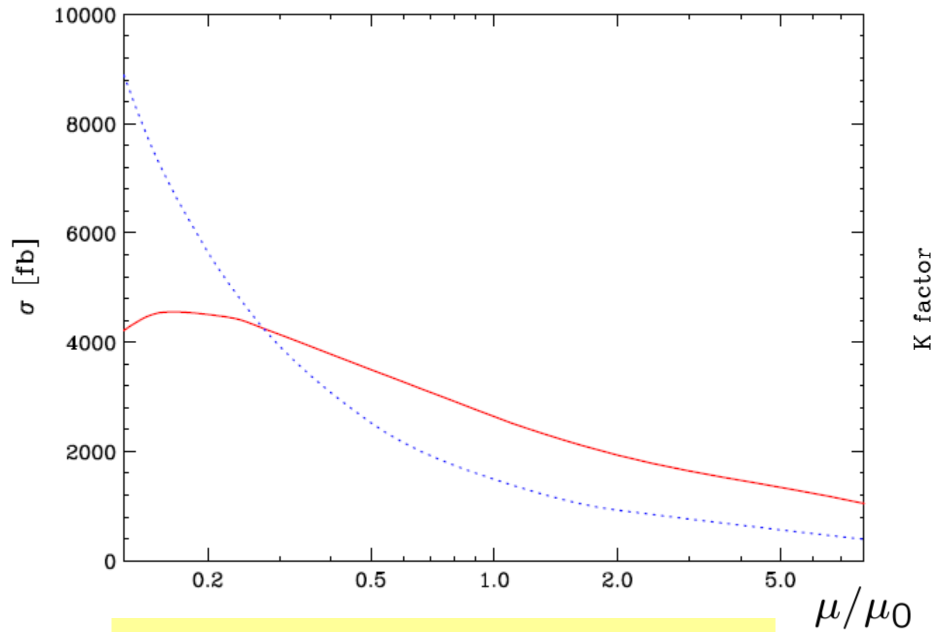
Background to $t\,\bar{t}$ + *Higgs*, $H \to b\bar{b}$ at LHC (for λ_t)

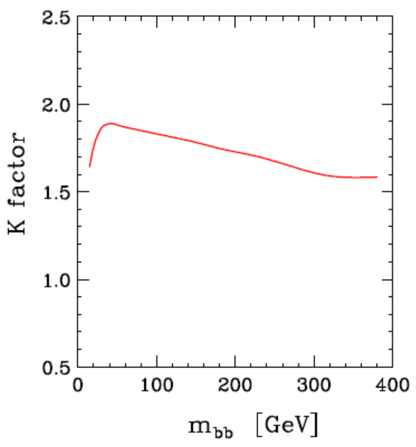
First done using Feynman diagrams

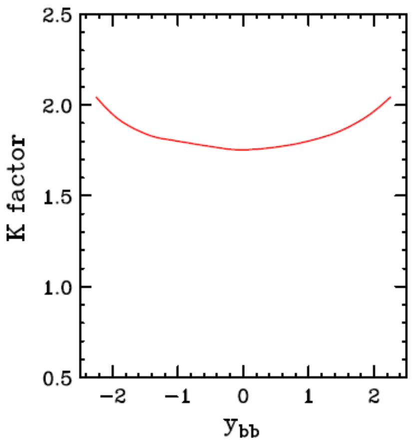
Recomputed using unitarity (**CutTools**)

Bredenstein et al., 0807.1248, 0905.0110

Bevilacqua et al., 0907.4723







much improved
scale uncertainties at NLO

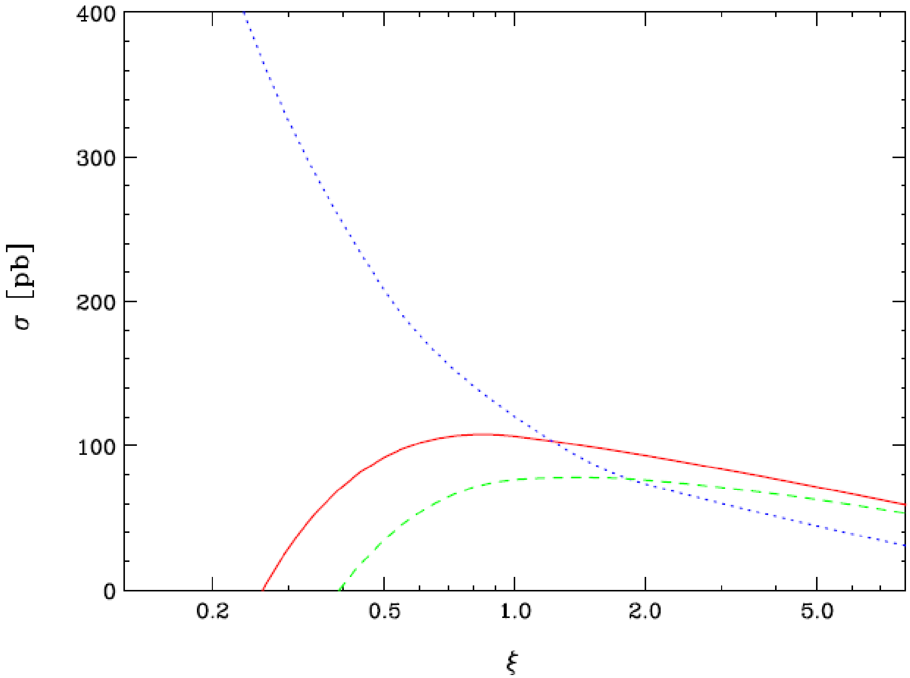
shape changes in *bb* distributions from LO to NLO (K=NLO/LO)

[redacted]

Like [redacted], a background to [redacted]

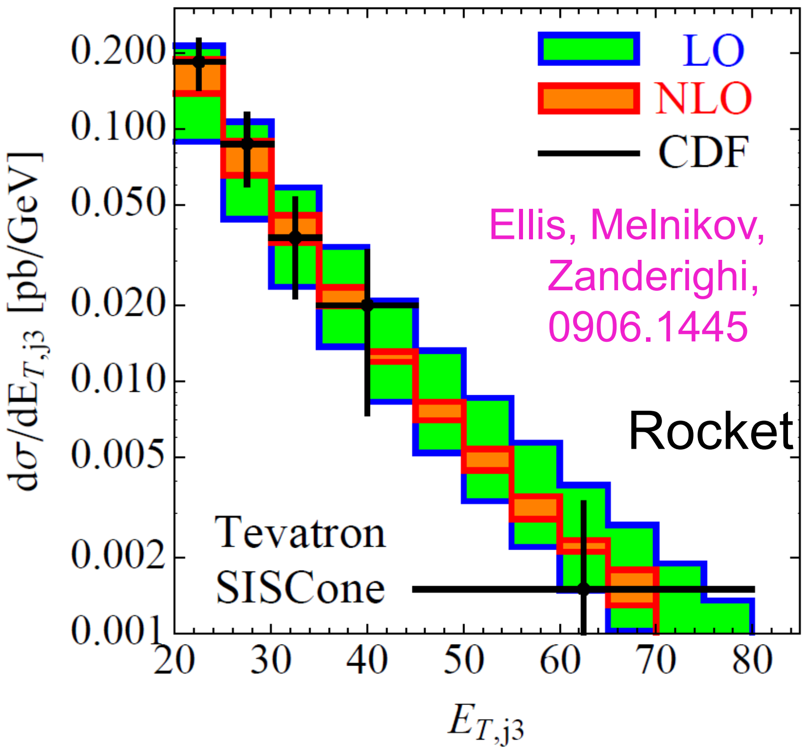
Only computed via unitarity (**CutTools**)

Bevilacqua, Czakon, Papadopoulos, Worek, 1002.4009

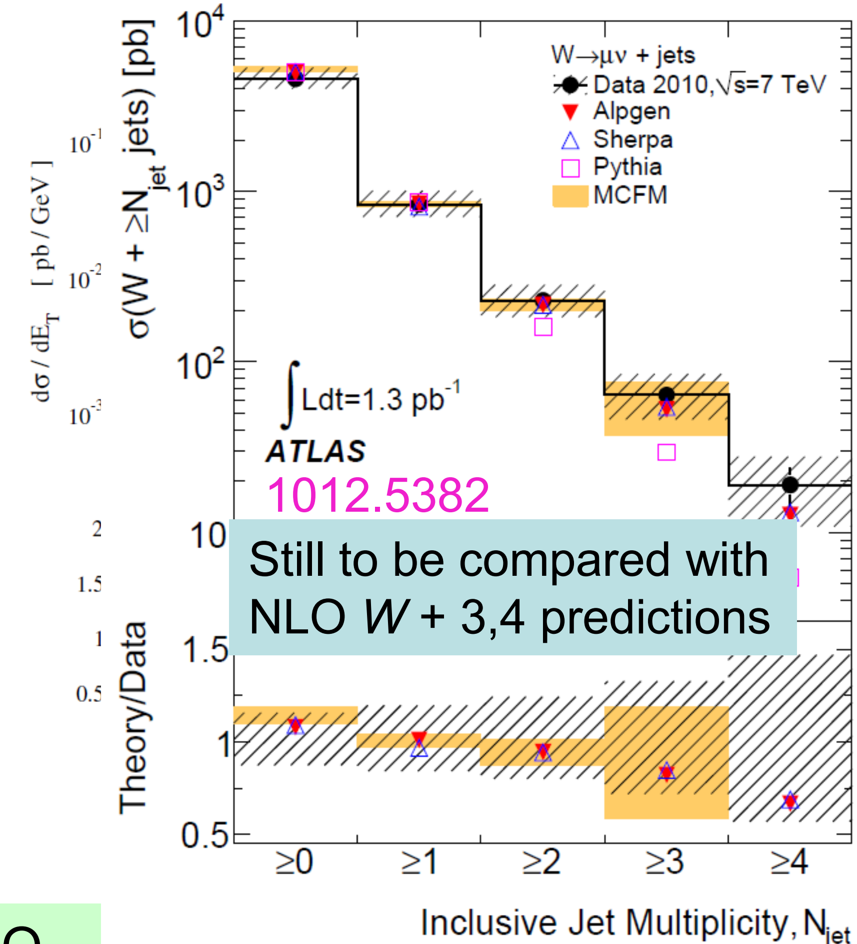


Again large reduction in scale dependence from LO → NLO

W + 3 jets at Tevatron → LHC



Leading-color adjustment procedure



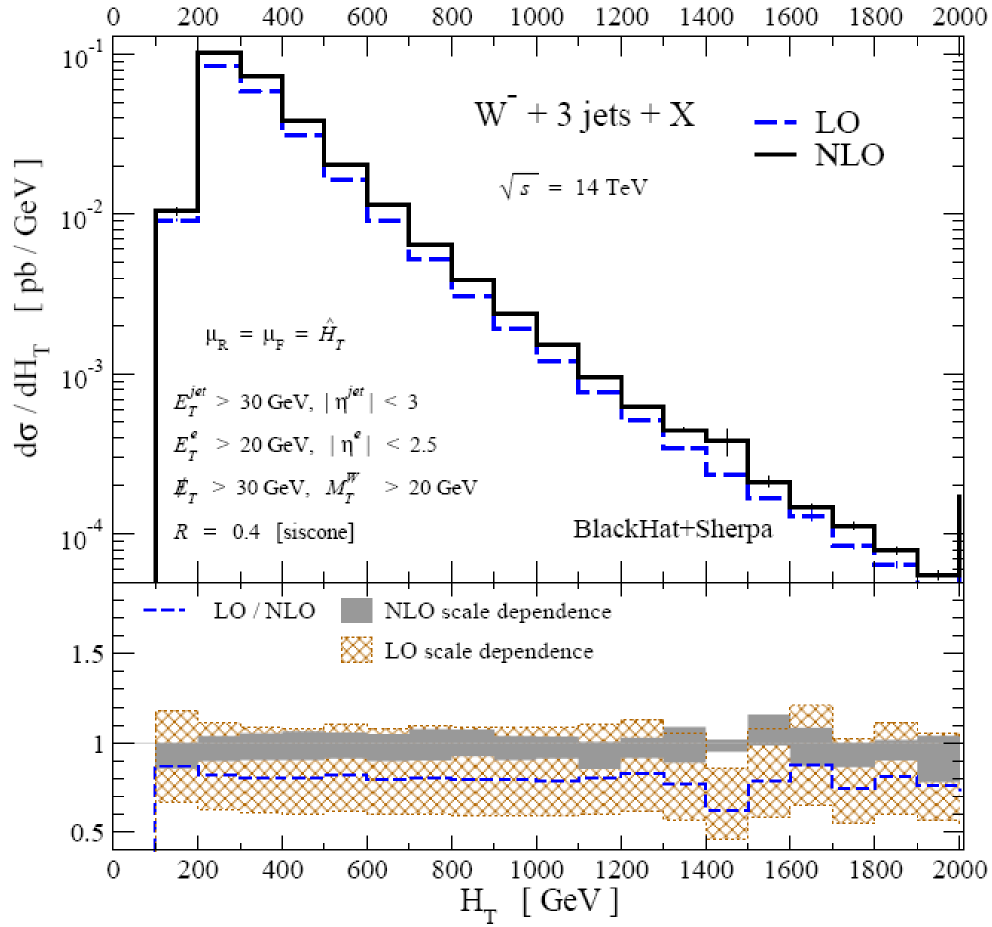
Still to be compared with NLO W + 3,4 predictions

- Much smaller uncertainties than at LO.
- Agrees well with data; more data available now from Tevatron and LHC

Total Transverse Energy H_T at LHC

$$H_T = \sum_j E_{T,j}^{\text{jet}} + E_T^e + E_T^\nu$$

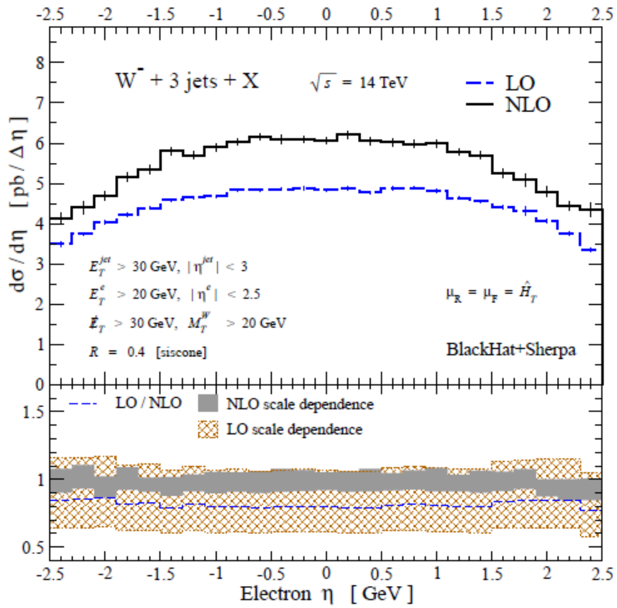
often used in supersymmetry searches

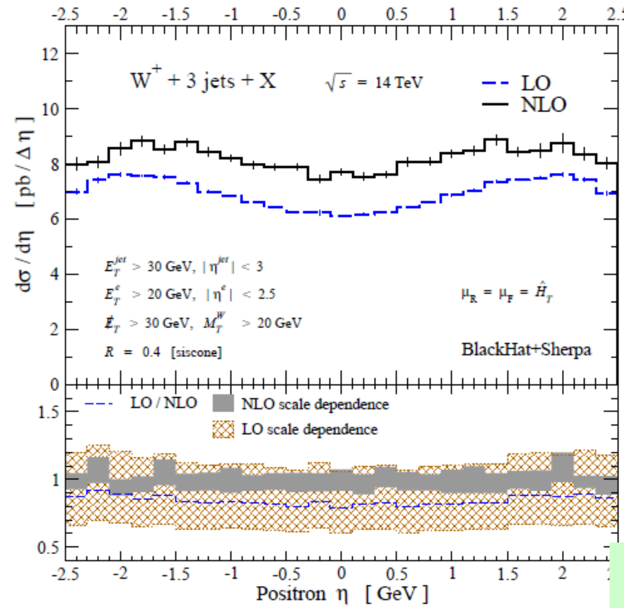


0907.1984

flat LO/NLO ratio due to good choice of scale $\mu = H_T$

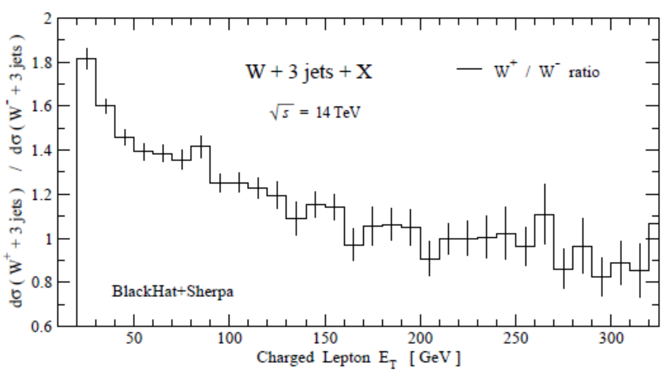
Positrons Differ from Electrons in $W^{\pm}$ + 3 jets at LHC (pp)

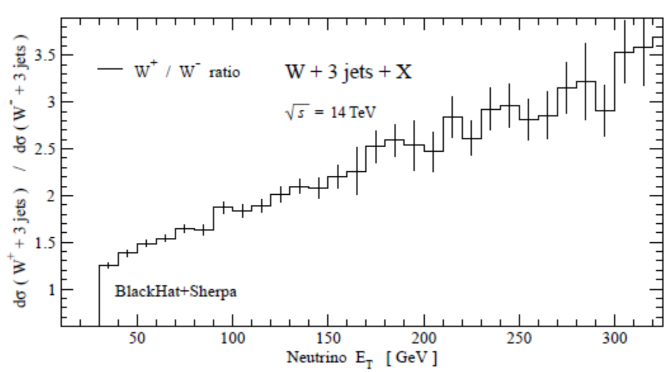




rapidity distributions remember *u(x)/d(x)* large as $x \rightarrow 1$

0907.1984

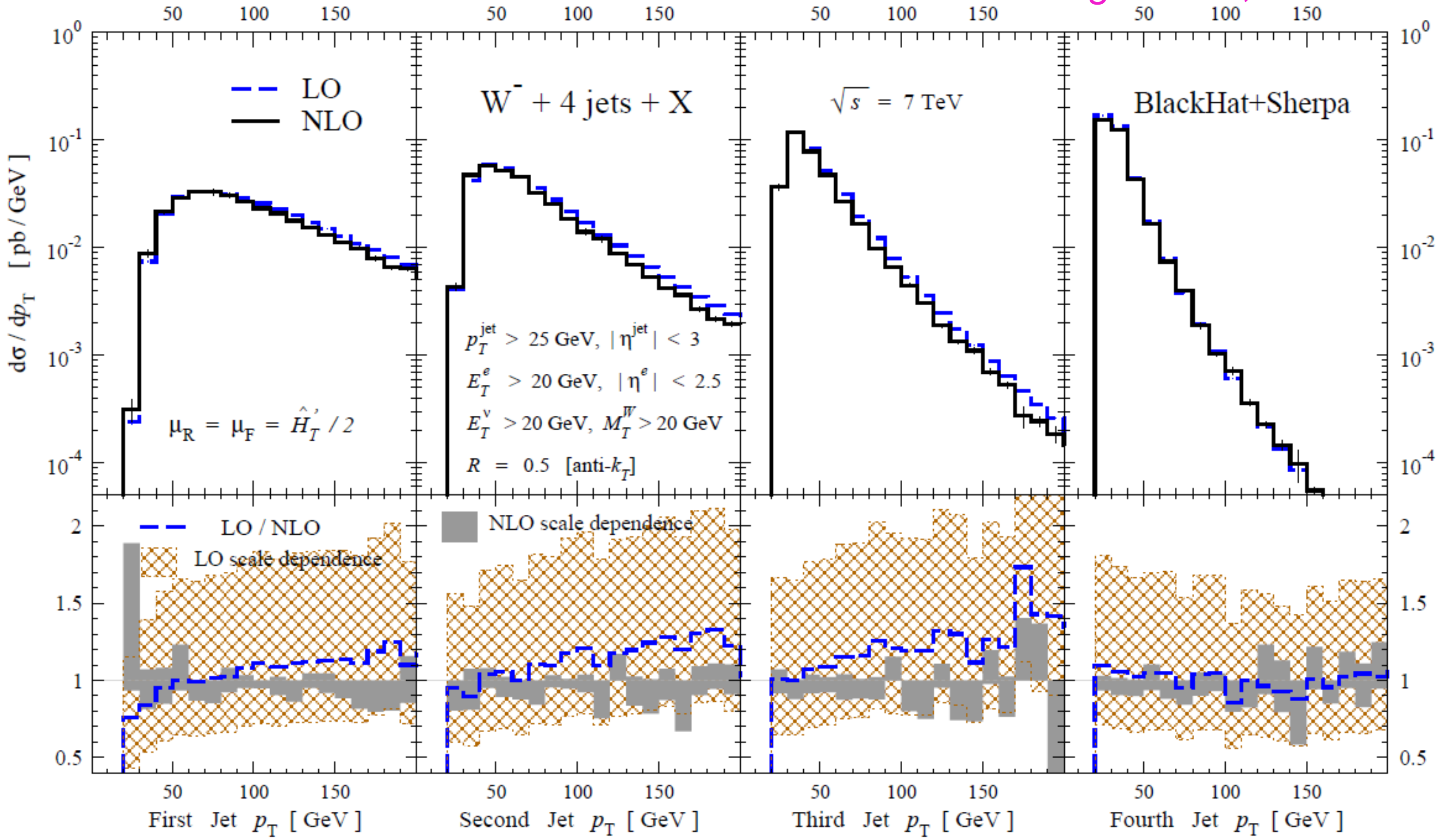




W^+/W^- transverse ratios trace a remarkably large left-handed *W* polarization – may be useful to separate it from top, new physics

NLO $pp \rightarrow W + 4$ jets

Berger et al., 1009.2338



First hadron collider process known at NLO with 5 objects in final state.
Also important SUSY background.

One indicator of NLO progress

pp → W + 0 jet	1978	Altarelli, Ellis, Martinelli
pp → W + 1 jet	1989	Arnold, Ellis, Reno
pp → W + 2 jets	2002	Campbell, Ellis
pp → W + 3 jets	2009	BH+Sherpa Ellis, Melnikov, Zanderighi
pp → W + 4 jets	2010	BH+Sherpa

Conclusions

- New and efficient computational approaches to one-loop QCD amplitudes now used to forecast important Standard Model backgrounds at the LHC
  - exploit **analyticity/unitarity**: build loop amplitudes out of trees
  - implemented **numerically** in several programs: **BlackHat**, **CutTools**, **NGluon, Rocket, Samurai, …**
- Long and growing list of complex processes computed at NLO with these techniques:
- *VVV (V=W or Z)*
- *ttbb, ttj, ttjj*
- W^+W^+jj
- *Wjjj, Zjjj, Wjjjj*
- Also very important to incorporate into NLO Monte Carlos, a la MC@NLO & POWHEG (no time to discuss here)
- Success will assist in optimal exploitation of LHC data!