

# Summary and Outlook

LoopFest 2012

May 12, 2012

Zvi Bern, UCLA



*LoopFest XI*  
*Radiative corrections for the LHC and beyond*

May 10-12, 2012  
University of Pittsburgh

Organizers:  
Sally Dawson    Frank Petriello  
Ayres Freitas    Ira Rothstein  
Ambar Jain    Doreen Wackeroth  
Adam Leibovich

<http://indico.cern.ch/event/loopfest11>  
Sponsored by University of Pittsburgh Particle physics, Astrophysics and Cosmology Center (Pitt-PACC)  
and Carnegie-Mellon University

Photo credit: © Marc O. Rieger

The poster features a scenic view of the Pittsburgh skyline with the city's bridges and buildings reflected in the river. In the foreground, a red trolley is visible. The University of Pittsburgh and Carnegie Mellon University logos are also present.

## Outline

**Today our field is arguably the most important area of theoretical particle physics.**

**At this conference we have seen a large number of very impressive advances.**

**Here I want to talk about what we need to do to keep our field strong in the long term.**

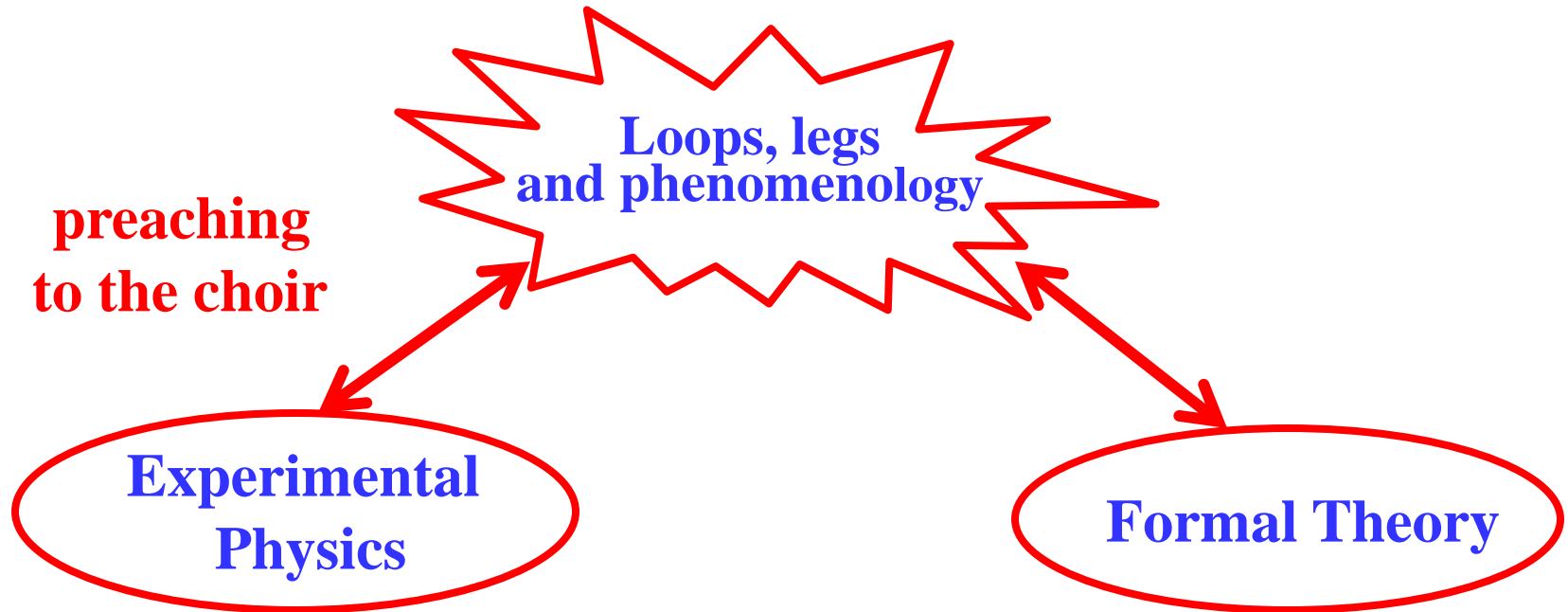
**This will not be a usual summary.**

**I will draw examples that fit my theme from elsewhere as well as from talks at this conference.**

# Links to other fields

**A healthy field should have links to other fields.**

**It must have important input into other fields.**



- Important to learn from other subfields.
- Future health of our field demands that we produce explicit results of direct interest to people outside our subfield.

## **Fads come and go**

- **Ringwaldmania (1989) .**
- **M theory as a matrix model (1996).**
- **Dijkgraaf –Vafa (2002).**
- **String based model building (1986-1989).**  
**etc.**

**Some disappear completely and some have tails that fade in time**

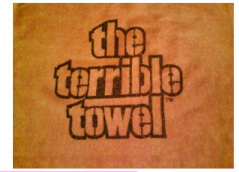
### **Question:**

**What should we do to ensure that we have a long-lasting impact?**

**Answer: When people look back in 10 years they should say:**

- 1) A great discovery was made at the LHC because of what we did.**
- 2) Fundamental theoretical breakthroughs emerged from work in collider phenomenology.**

## **The need to link to experiments**



# Editorial Comment

- Once we have the calculations, how do we (experimentalists) use them?
- If a theoretical calculation is done, but it can not be used by any experimentalists, does it make a sound?
- Best perhaps is inclusion in parton shower Monte Carlos: but what is the learning curve to get new processes added
- Oftentimes, the fixed-order program is too complex (/non-public) to be run by non-authors
- In that case, ROOT ntuples may be the best solution
  - ◆ ...or at least a useful stop-gap measure

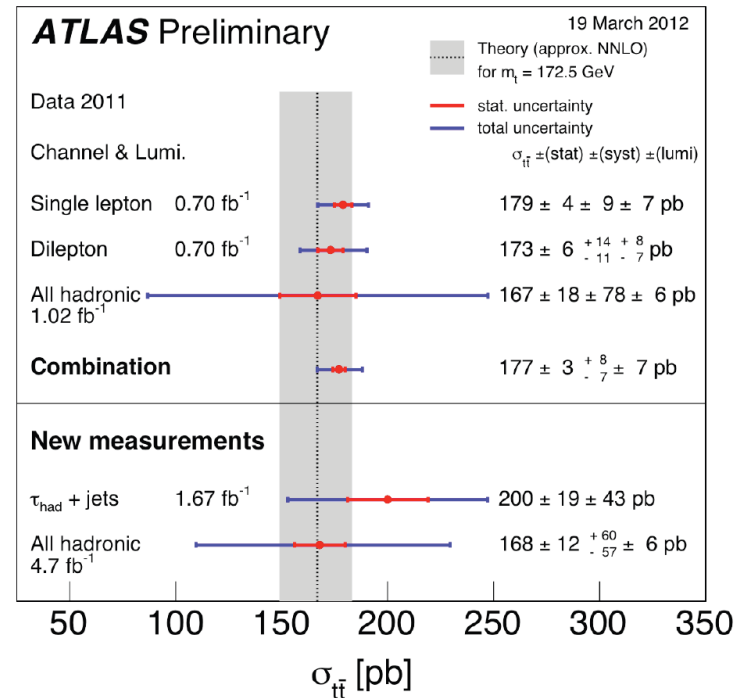
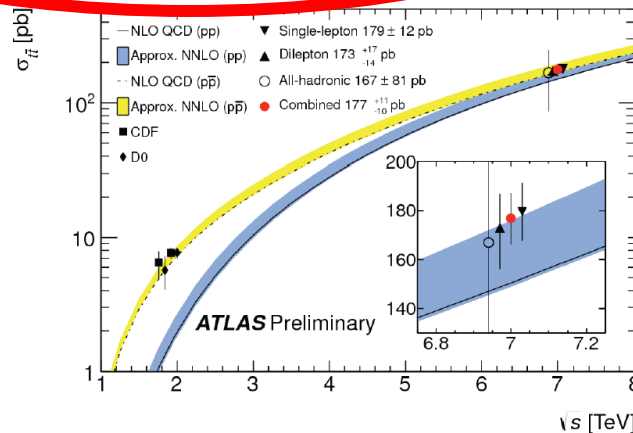




# Summary of cross-section measurements

All ATLAS measurements of  $\sigma_{t\bar{t}}$  are consistent with each other.

NNLO prediction of  $\sigma_{t\bar{t}}$  is consistent with measurement, albeit with larger uncertainty.



**NEW: e/ $\mu$  +  $\tau$  jets** **arXiv:1205.2067** **/L = 2.05 fb<sup>-1</sup>**

**$\sigma_{t\bar{t}} = 186.0 \pm 13(\text{stat}) \pm 20(\text{syst}) \pm 7(\text{lumi})$  pb**

James A. Mueller

Loop Fest 2012

# Top Production at Tevatron

People in the audience are doing something about this.

(Barnreuther, Czakon and Mitov, (arXiv:1204.5201))

$$\bar{q}q \rightarrow t\bar{t} + X$$

contributions at NNLO  
Sufficient for Tevatron

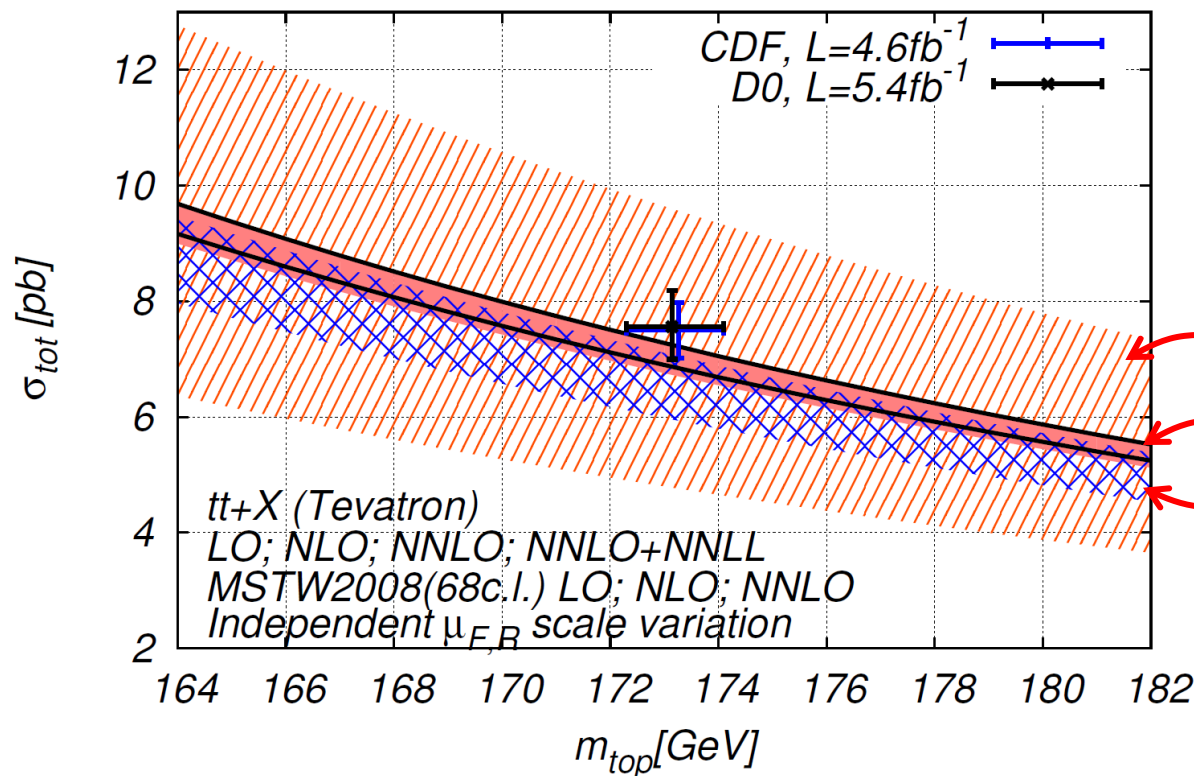
First complete NNLO  
calculation with four  
colored partons

LO

NNLO

NLO

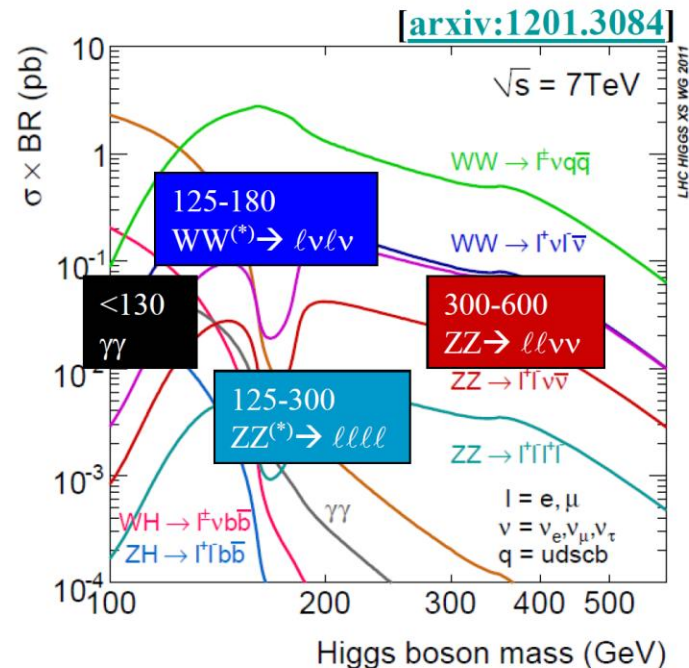
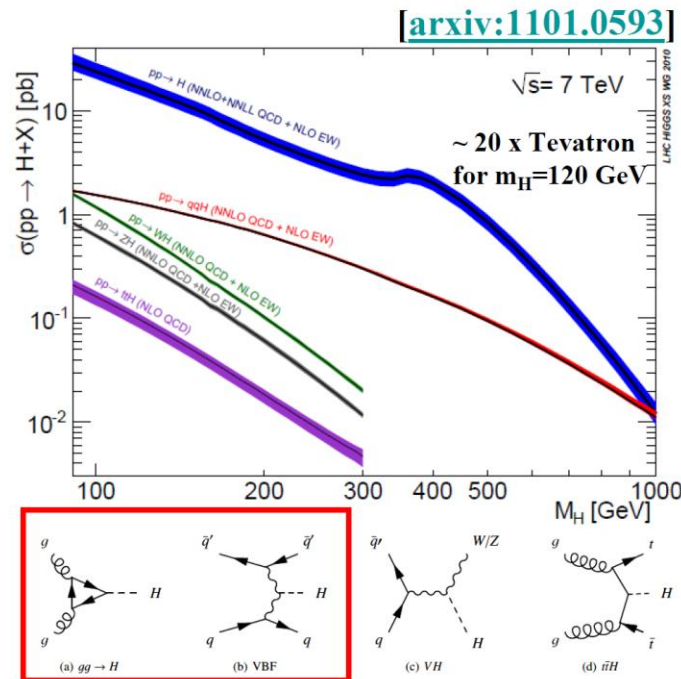
See Alexander Mitov's  
talk



Also many other advances in top physics background and signal:  
Talks from Dittmaier, Schultze, Bevilacqua, Kosower, Ozeren

“continue reducing the uncertainties for Higgs cross sections”

# Higgs Production & Decay



- Mostly NNLO Cross-sections  $\Rightarrow$  theory uncertainties  $< 20\%$
- Progress in theoretical predictions of numerous and complex backgrounds
- Working group for high-mass Higgs ( $> 600 \text{ GeV}$ ) started

Many talks on Higgs signal or background: Dittmaier, Frederix, Hoeche, Riena, Stewart, Kuhn, Zeppenfeld, etc

# Example of Focus on Experiments

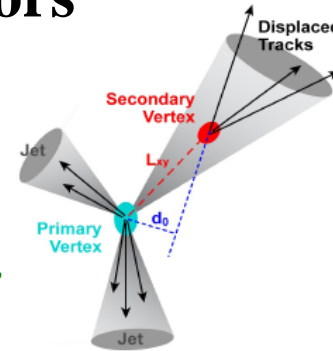
From Walter Giele's talk

## NLO forward branching phase-space generators

### What changes:

For a given exclusive jet event we calculate the scattering probability:

- Just one Born and one Virtual event contributes.
- Generate limited set of bremsstrahlung events:
  - These events do *not* change the observed jet final state.
  - We obtain a positive definite probability for the NLO jet event.
  - Unweighted NLO!
- In words: we integrate out all physics (partonic configurations) below the jet resolution scale.



**A very nice theoretical formulation. What is their first application?**

# Example: NLO Matrix Element Method

See Ciaran Williams talk

## What was first application of new way to do NLO?

### The Matrix Element Method (MEM)

- All measurements of SM parameters and searches for new physics rely on matrix elements at some level.
- The Matrix element contains the maximal amount of theoretical information available (for the hard scattering process).
- The goal of the MEM is to perform a measurement using the matrix element to create a probability distribution function.

$$\mathcal{P}(\mathbf{x}|\Omega) = \frac{1}{\sigma_{\Omega}^{LO}} \int dx_a dx_b d\mathbf{y} \sum_{ij} \frac{f_i(x_a) f_j(x_b)}{x_a x_b s} \mathcal{B}_{\Omega}^{ij}(p_a, p_b, \mathbf{y}) W(\mathbf{x}, \mathbf{y}) .$$

- Then this can be used to build a Likelihood for the model ( $\Omega$ ) under investigation.

$$\mathcal{L}(\mathbf{x}|\Omega) = f(N) \prod_{i=1, N} \mathcal{P}(\mathbf{x}_i|\Omega).$$

**Matrix element method is *a technique developed by experimenters* to squeeze as much information as possible out of data.**

# Example: Matrix Element Method

See Ciaran Williams' final slide

## Future study

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We are keen to extend the method to other measurements, in particular....

- Measurement of the top mass at the LHC and Tevatron (flagship application of the MEM).
- Higgs in other channels, associated production, two photons etc. Confirming SM properties, BR, spin etc. WW....
- Measurement of/Limits on triple anomalous gauge couplings.

• We gladly welcome experimental input! Beta code of NLOME is available, first release expected in May/June. BIG Thank you to experimentalists who have helped so far!



**A good attitude!**

# Example: Matrix Element Method at NLO



**Rainer Wallny led single top analysis at CDF using the matrix element method**

*“It would really be wonderful if we could use the matrix element method at NLO!”*



**Rainer after feeding him a diet of NLO MEM steroids?**

# Example: Uses of ROOT ntuples

Running BlackHat+Sherpa for state of the art  $W+4,5$  jets not so simple. How do we get it to the experimenters?



## ROOT ntuples



Joey Huston's talk

- More complex to use than MCFM
  - ♦ no manual for example
  - ♦ and you don't produce the events yourself
- ntuples produced separately by Blackhat + Sherpa for →
  - ♦ so TB's of disk space
- No jet clustering has been performed; that's up to the user
  - ♦ a difference from MCFM, where the program has to be re-run for each jet size/algorithm
- What algorithms/jet sizes that can be run depends on how the files were generated
  - ♦ i.e. whether the right counter-events are present
- For the files on the right at 7 TeV (for  $W^+ + 3$  jets), one can use kT, antikT, siscone ( $f=0.75$ ) for jet sizes of 0.4, 0.5, 0.6 and 0.7
- bornLO (stands alone for pure LO comparisons; not to be added with other contributions below)
  - 20 files, 5M events/file, 780 MB/file
- Born
  - 18 files, 5M events/file, 750 MB/file
- loop-lc (leading color loop corrections)
  - 398 files, 100K events/file, 19 MB/file
- loop-fm1c (needed for full color loop corrections)
  - 399 files, 15K events/file, 3 MB/file
- real (real emission terms)
  - 169 files, 2.5 M event/file, 5 GB/file
- vsub (subtraction terms)
  - 18 files, 10M events/file, 2.8 GB/file

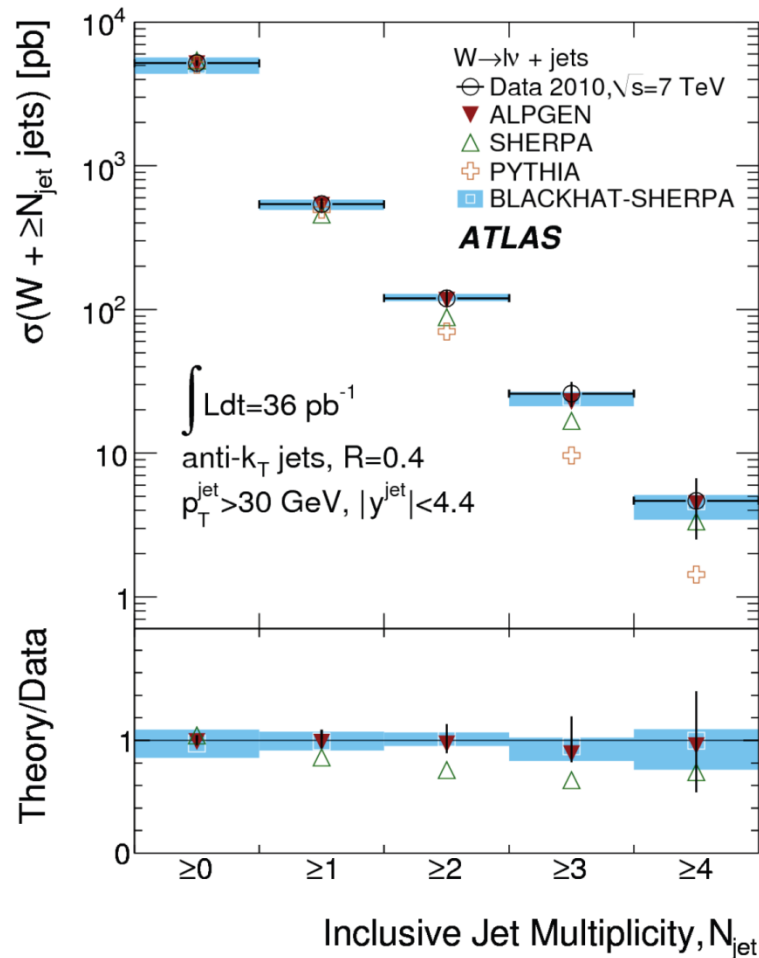
Joey is happy because he can carry out NLO QCD studies of  $W, Z+1,2,3,4$  jets and compare to ATLAS data.

Also a good way for theorist to exchange results.

# Example: Uses of ROOT ntuples

From Ozeren's talk

## ROOT ntuples in Action



## ATLAS W+jets [1201.1276]

- ntuples created with BlackHat +Sherpa [1009.2338]
- experimenters perform their own analysis of the NLO results
- see also Z+4j [ATLAS 1111.2690]

... we look forward to similar comparisons of our W+5jet NLO results with data!

# Merging NLO with Parton Showers

Important progress on getting NLO into an experimenter friendly form. Equivalent to adding NLO to Pythia.

See talk from Stefan Hoeche

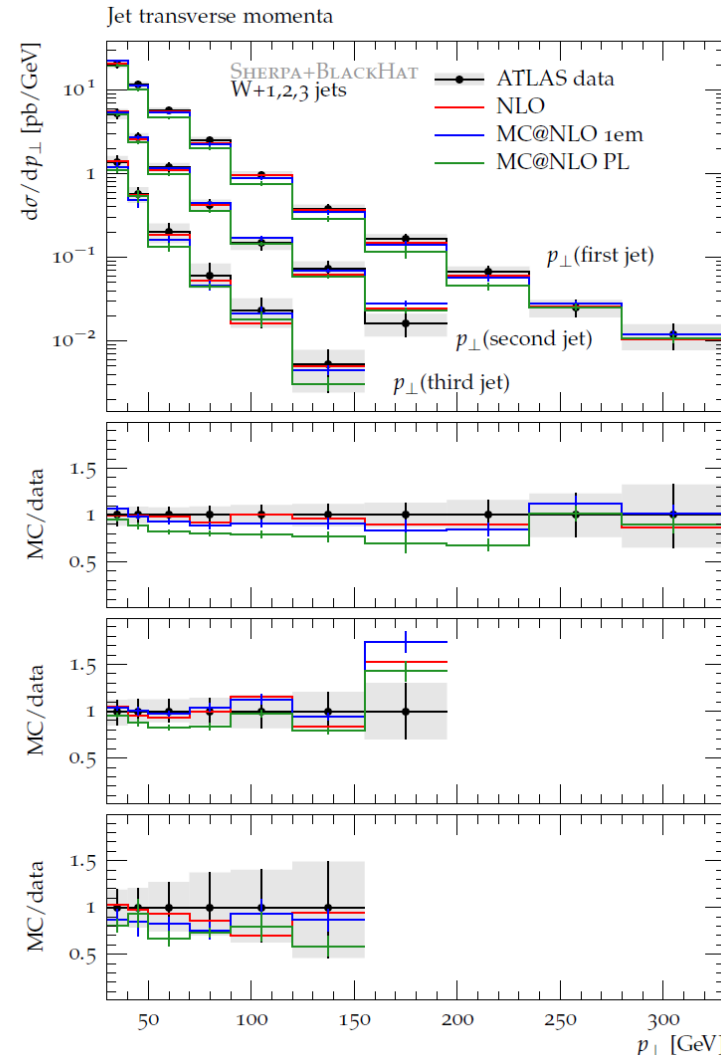
MC@NLO shown to work well in  $W+n$  jets, where  $n \leq 3$  at present

[Frederix,Frixione,Hirschi,Maltoni,Pittau,Torrielli]  
arXiv:1110.5502 [SH,FK,MS,FS] arXiv:1201.5882

Most general color structures already present in  $W+3$  jets

Any more complications unlikely  
... but keep your fingers crossed !

Probably fair to say that current bottleneck in MC is *not* matching of NLO & PS at fixed multiplicity



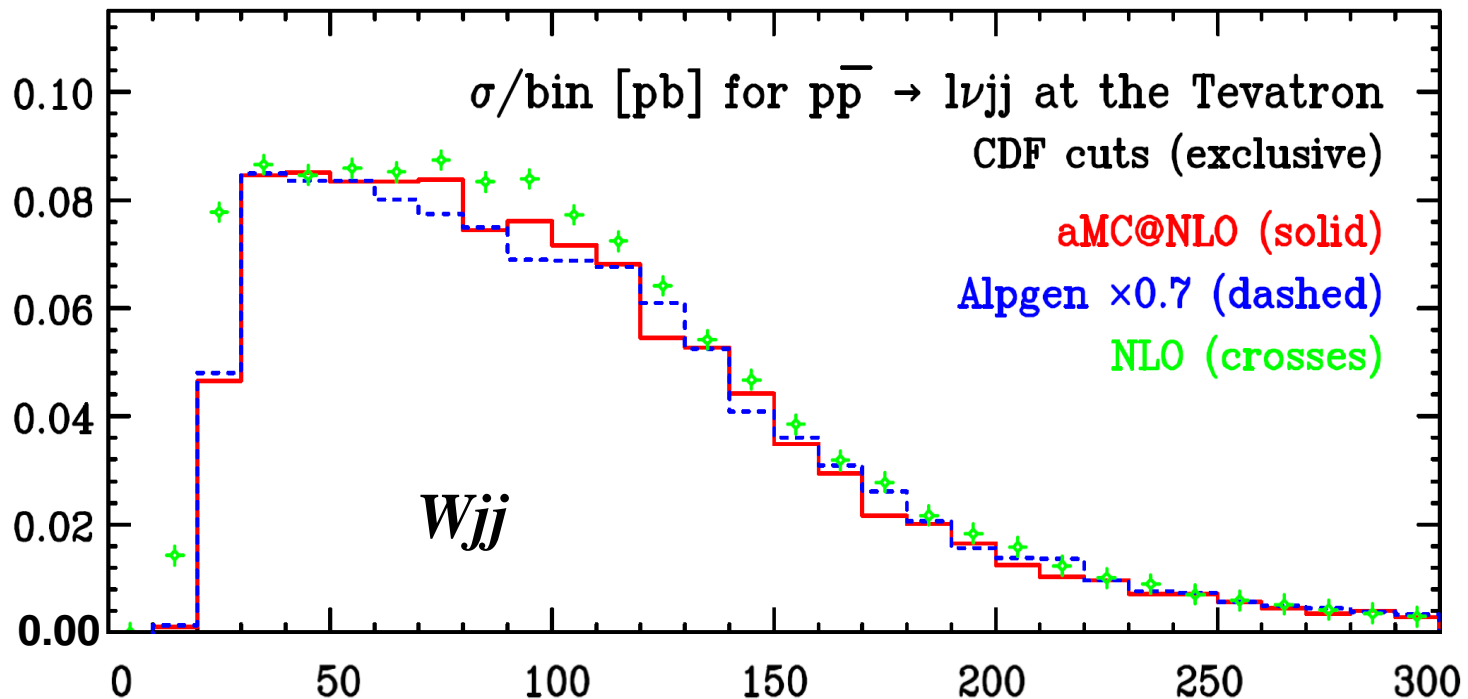
$W+1,2,3$   
jets

# Merging NLO with Parton Showers

Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli (arXiv:1110.5502)

An application of NLO + parton showers has been to look at CDF dijet anomaly.

From talk from Frederix



- CMS used Alpgen (scaled). NLO has a slightly different shape.
- aMC@NLO is close to Alpgen, so it looks that QCD is under good control.

# Data Driven Background Estimation

CMS uses photons to estimate Z background to susy searches.

See Kosower's talk

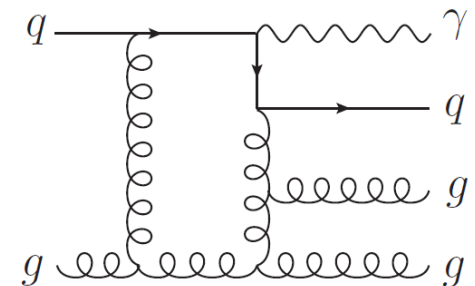
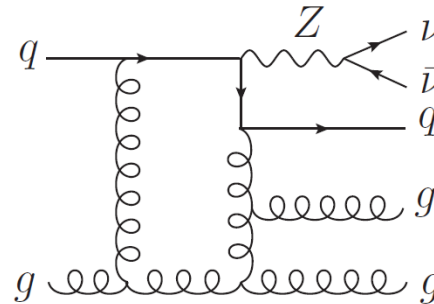
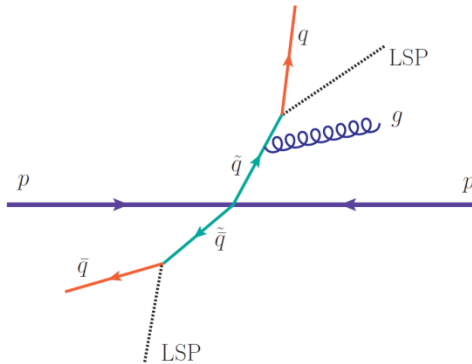
CMS PAS SUS-08-002; CMS PAS SUS-10-005; arXiv:1106.4503

$$\sigma(pp \rightarrow Z(\rightarrow \nu\bar{\nu}) + \text{jets}) = \sigma(pp \rightarrow \gamma + \text{jets}) \times R_{Z/\gamma}$$

↑  
irreducible background

↑  
measure this

↑  
ratio is  
theory input



Task of theorist assigned by experimenters was to understand conversion and give theoretical uncertainty to CMS.

ZB, Diana, Dixon, Febres Cordero, Hoche, Ita, D.A. Kosower, D. Maitre, Ozeren (arXiv:1106.1423); Ask, Parker, Sandoval, Shea, Stirling (arXiv:1107.2803)

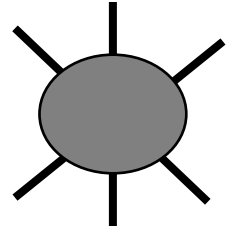
## **Links to formal theory**

- **Examples where phenomenology calculations help formal theory.**
- **Examples where formal theory can help us with phenomenology calculations.**

## Connections to Formal Areas

**Parke-Taylor (MHV) amplitude:**

$$A(1^-, 2^-, 3^+ \dots, n^+) = i \frac{\langle 12 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \dots \langle n1 \rangle}$$



- **Original observation: simple pattern for 4,5,6 points.**
- **Relatively minor observation led to important advances because structure generalizes.**

**Laid the ground for many more advances:**

- 1) **Unitarity method.**
- 2) **Connection to Witten's twistor string.**
- 3) **On-shell recursion.**
- 4) **Explosion of interest in  $N = 4$  sYM and  $N = 8$  supergravity amplitudes.**

# How is QCD Connected to $N = 4$ sYM?

$N = 4$  sYM plays central role in AdS/CFT and string theory

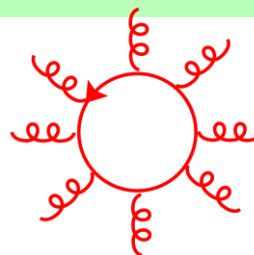
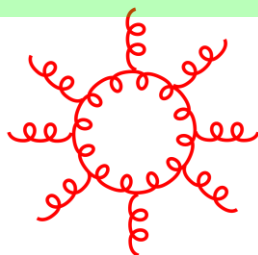
Connection to QCD is trivial.

At any loop order to get  $N = 4$  sYM from QCD:

- Replace quarks with 1 adjoint fermion.
- Place all states in  $D = 10$  (equivalent to 4 fermion flavors in  $D = 4$ ).
- Put all loop momenta in  $D = 4 - 2\epsilon$ .

Dimensional reduction of  $D = 10$ ,  $N = 1$  susy

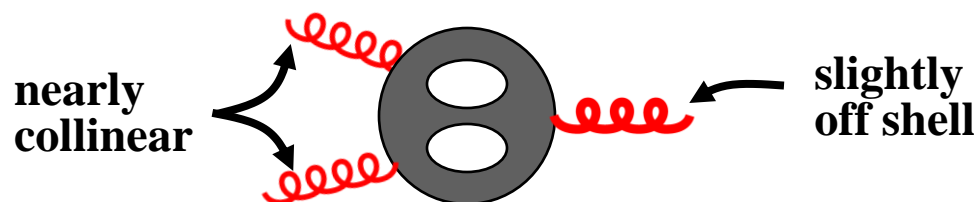
If you have a QCD computation,  $N = 4$  sYM is essentially free.



# Connections to $N = 4$ sYM Theory

Anastasiou, ZB, Dixon and Kosower; ZB, Dixon and Smirnov

**We were calculating the 2 loop splitting amplitude in QCD  
Needed for checking computations of 2 loop amplitudes  
and also connected to AP splitting functions.**



**While calculating QCD we decided to have a look at  $N = 4$  sYM.**

**Strange curiosity: the  $N = 4$  sYM splitting amplitude iterates**

$$r_S^{(2), \mathcal{N}=4}(\epsilon; z, s) = \frac{1}{2} \left( r_S^{(1), \mathcal{N}=4}(\epsilon; z, s) \right)^2 + f(\epsilon) r_S^{(1), \mathcal{N}=4}(2\epsilon; z, s) + \mathcal{O}(\epsilon)$$

2 loop splitting amplitude      1 loop splitting amplitude      **It iterates!**

**Who ordered that?**

# $N = 4$ sYM Amplitudes

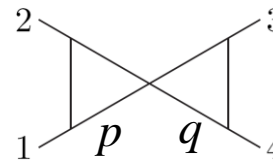
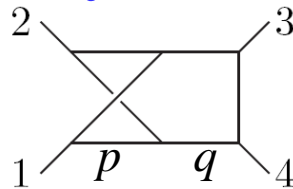
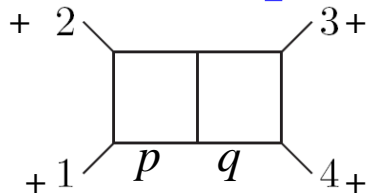
- Led to *all-order* resummation of 4, 5 point planar  $N = 4$  sYM amplitude. Agrees with string theory via AdS/CFT.
- Many theorists are currently extending this to higher points.
- Goal is to solve planar  $N = 4$  sYM theory.

*Explicit* QCD computations can provide the key stimulus to a formal development in areas such as AdS/CFT and  $N = 4$  sYM theory.

# A Two-Loop Hint

From 2006 HP<sup>2</sup>  
(Zurich) summary talk

Consider the four gluon all-positive helicity amplitude in QCD.  
This is the simplest example. If we can't find simplicity here  
there is no hope for any other QCD amplitudes.



$$p^2 = p_{[4]}^2 - \lambda_p^2$$

$$q^2 = q_{[4]}^2 - \lambda_q^2$$

If you expand it in polylogs it is some moderate mess.

Instead let's write it in a special basis of integrals

$$D_s = 4 - 2\epsilon\delta_R$$

$$A_{1234}^P = i \frac{[12][34]}{\langle 12 \rangle \langle 34 \rangle} \left\{ s_{12} \mathcal{I}_4^P \left[ (D_s - 2)(\lambda_p^2 \lambda_q^2 + \lambda_p^2 \lambda_{p+q}^2 + \lambda_q^2 \lambda_{p+q}^2) + 16((\lambda_p \cdot \lambda_q)^2 - \lambda_p^2 \lambda_q^2) \right] (s_{12}, s_{23}) \right. \\ \left. + 4(D_s - 2) \cancel{\mathcal{I}_4^{\text{bow-tie}}} [(\lambda_p^2 + \lambda_q^2)(\lambda_p \cdot \lambda_q)](s_{12}) \right. \\ \left. + \frac{(D_s - 2)^2}{s_{12}} \cancel{\mathcal{I}_4^{\text{bow-tie}}} [\lambda_p^2 \lambda_q^2 ((p+q)^2 + s_{12})] (s_{12}, s_{23}) \right\}.$$

Bern, Dixon, Kosower  
hep-th/0001001

planar

non-planar

$$A_{12;34}^{\text{NP}} = i \frac{[12][34]}{\langle 12 \rangle \langle 34 \rangle} s_{12} \mathcal{I}_4^{\text{NP}} \left[ (D_s - 2)(\lambda_p^2 \lambda_q^2 + \lambda_p^2 \lambda_{p+q}^2 + \lambda_q^2 \lambda_{p+q}^2) + 16((\lambda_p \cdot \lambda_q)^2 - \lambda_p^2 \lambda_q^2) \right] (s_{12}, s_{23})$$

Why do the planar and non-planar double boxes  
look the same? I believe this is a clue.

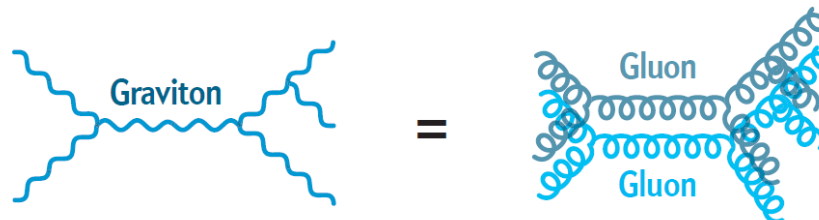
## A Hint of What?

ZB, Carrasco, Johansson (2010)

The answer or even the connection to the above was not clear until much later and came from investigating other curiosities at four loops in  $N = 4$  sYM theory.

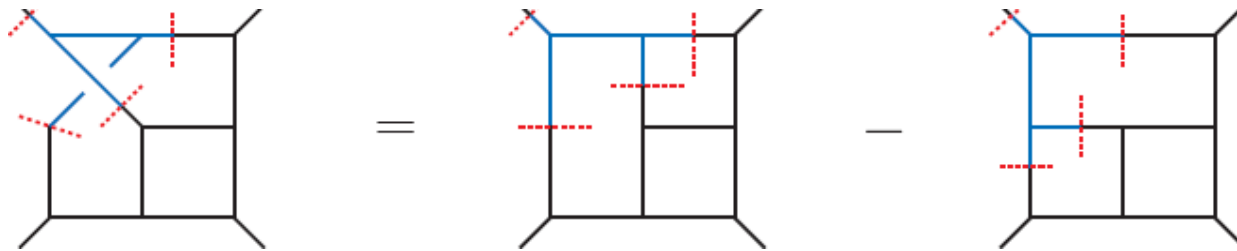
Answer is rather surprising:

- A hint for a general *all-loop* duality between color and kinematics, even with no susy. Same algebraic structure.
- A hint for perturbative quantum gravity as a double-copy of gauge theory.
- An extremely powerful means for computing gravity amplitudes and studying their UV behavior.



# Consequence: Gravity as a Double Copy of Gauge Theory

BCJ



assume this:

$$c_k = c_i - c_j$$

$$n_k = n_i - n_j$$

If you have a set of duality satisfying numerators.  
To get:

**gauge theory  $\longrightarrow$  gravity theory**

simply take

**color factor  $\longrightarrow$  kinematic numerator**

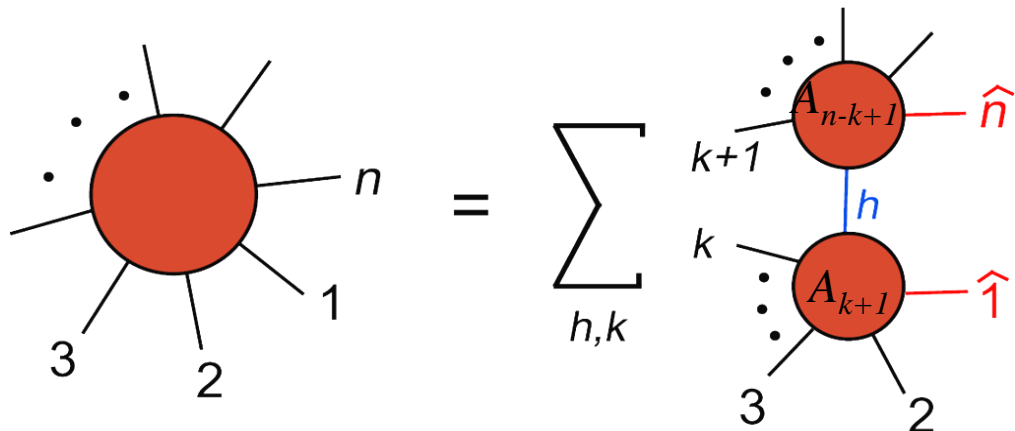
**Gravity loop integrands are free!**

Today our most powerful means of investigating UV properties of (super)gravity theories uses this.

# Input from $N = 4$ Community

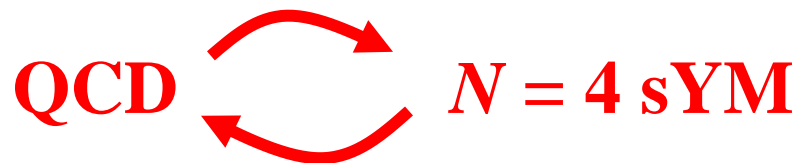
## Tree-level on-shell recursion

Britto, Cachazo, Feng and Witten



**Building blocks are on-shell amplitudes**

- Understanding of IR divergences developed for QCD played key role in finding recursion relations.
- Generalized unitarity in  $N = 4$  amplitude suggested recursion.
- Led to on-shell recursion applicable to any Standard Model process at tree level.



Used to generate compact analytic QCD amplitudes.

BlackHat tree amplitudes, for example, derived using this. 27

# Input from $N = 4$ sYM Community

Symbols introduced to  $N=4$  sYM by Goncharov, Spradlin, Vergu, Volovich

## Symbols

From C. Duhr's Loops and Legs 2012 talk

- Assume you have a function  $F(x_1, \dots, x_n)$  that satisfies

$$dF(x_1, \dots, x_n) = \sum_i F_i(x_1, \dots, x_n) d \ln R_i$$

Then the symbol of  $F$  is defined by

$$\mathcal{S}(F) = \sum_i \mathcal{S}(F_i) \otimes R_i$$

- Multiple polylogarithms satisfy the differential equation (for generic arguments):

$$dG(a_{n-1}, \dots, a_1; a_n) = \sum_{i=1}^{n-1} G(a_{n-1}, \dots, \hat{a}_i, \dots, a_1; a_n) d \log \left( \frac{a_i - a_{i+1}}{a_i - a_{i-1}} \right)$$

- Some care is needed though for non generic arguments!

**Go learn about symbols if you deal with polylogs!**

# Input $N = 4$ sYM Community

From Claude Duhr's Loops and Legs 2012 talk

## Higgs + 3 gluons

- There is a remarkable relation between 3 a priori unrelated objects:

[Brandhuber, Gang,  
Travaglini]

- H + 3 gluons @ 2 loops. **in QCD**
- 2 loop 3 gluon form factor in  $N=4$  SYM.
- 6-point 2 loop remainder function in  $N=4$  SYM.

**QCD** H + 3 gluons

Remainder  **$N = 4$**

Maximal  
Transcendentality

Special  
kinematics

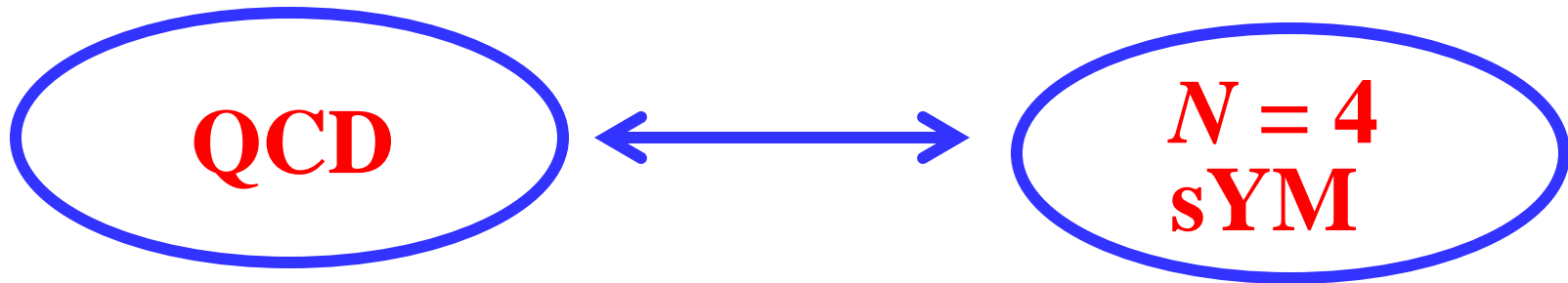
**$N = 4$**  Form factor

**Claude found it!**

- A simpler representation of the Higgs amplitudes in terms of classical polylogarithms only should exist.

## Summary

- Pay careful attention to what the experimenters *actually* need!
- It is clear the  $N = 4$  and collider phenomenology communities can learn from each other.



We can look forward to an exciting future

**Let's thank the organizers  
for this great conference**

**Sally Dawson  
Ayres Frietas  
Ambar Jain  
Adam Leibovich  
Frank Petriello  
Ira Rothstein  
Doreen Wackerroth**

