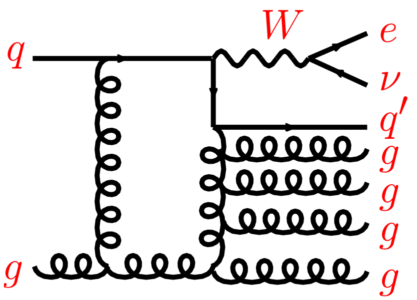
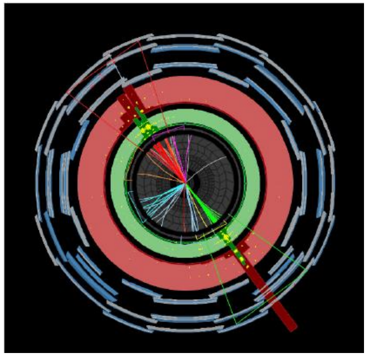
Higher Order QCD for the LHC

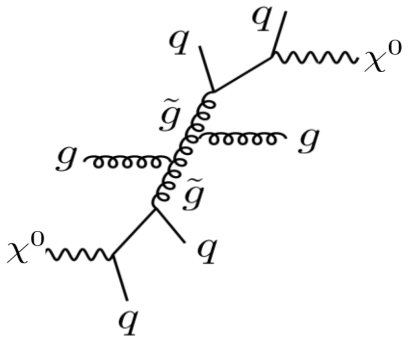
SLAC Summer Institute

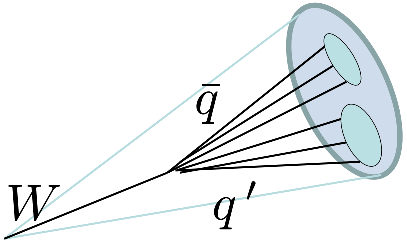
SLAC, June 25, 2012

Zvi Bern, UCLA









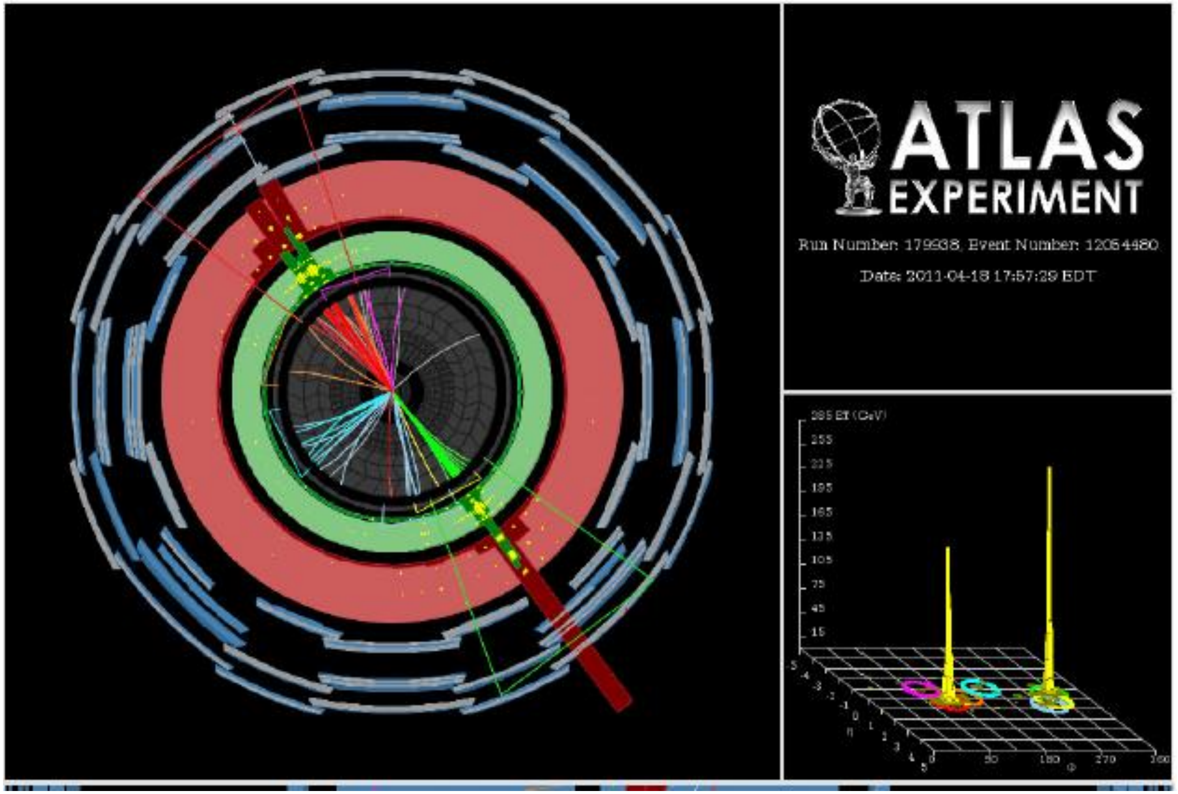
Outline

- **Some new developments in QCD for understanding LHC physics.**
- **Examples of QCD in results such as susy exclusions and Higgs boson.**

Vast field. Impossible to cover everything in a half an hour, so I will just show a few examples of recent progress.

Apologies to the many whose important work I will gloss over or skip.

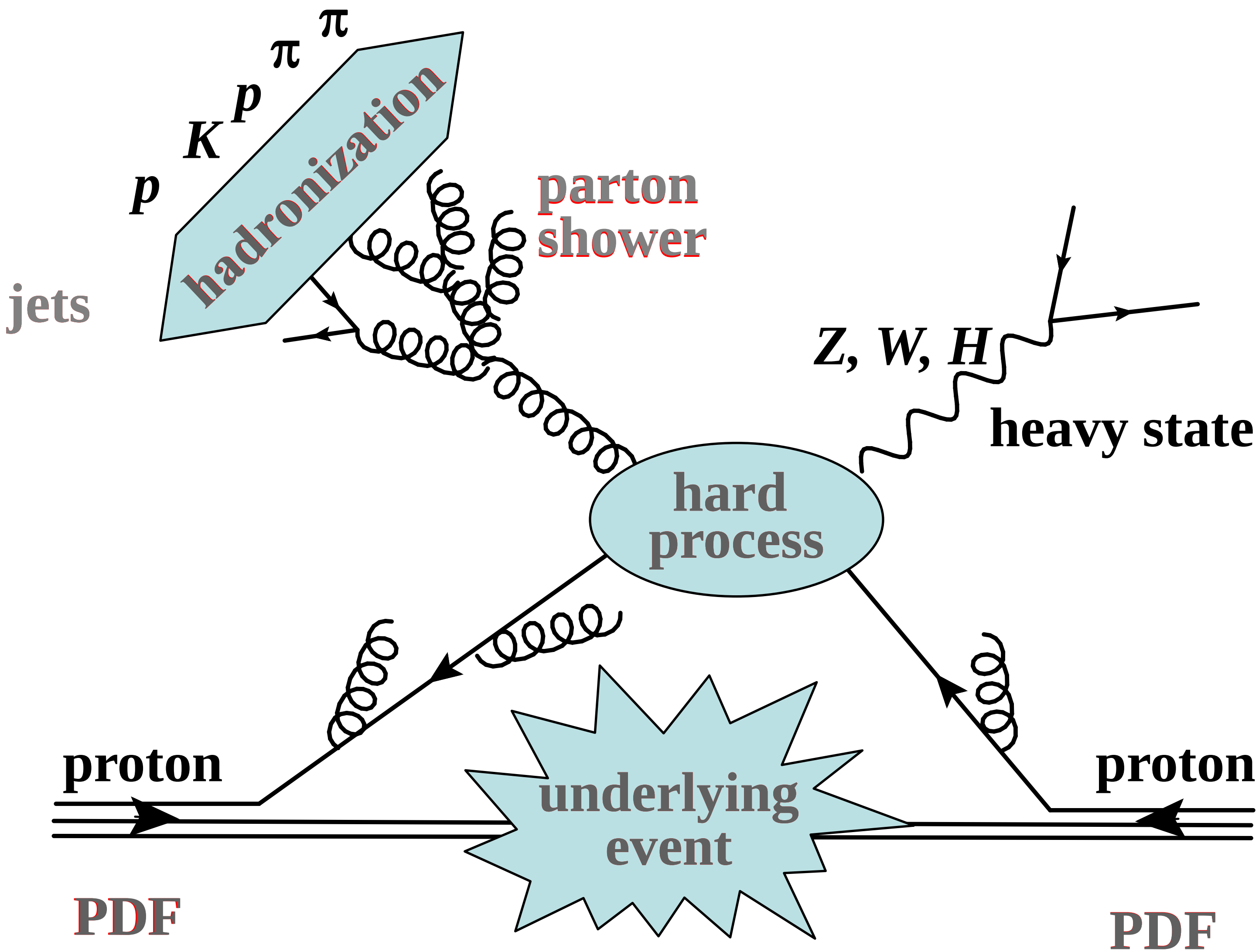
Experimenter's View of LHC Collision



Note jets

To properly interpret we need QCD

Theorist's View of LHC Collision



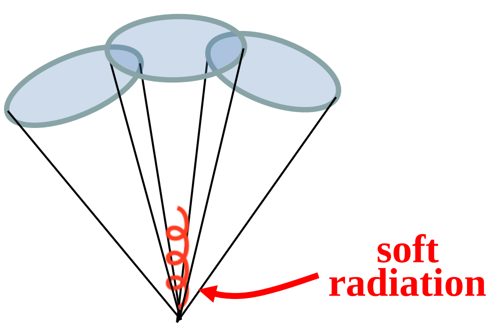
Complicated environment: many aspects of QCD must be understood

Standard QCD Tools for Experimenters

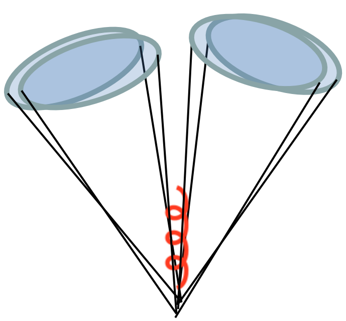
Many important theoretical tools used by experimenters: Pythia, Herwig, Alpgen, Madgraph, Sherpa, MC@NLO, POWHEG, etc. Many important improvements in recent years.

In this talk I will focus on recent examples of *precision QCD calculations* for hadron colliders, especially examples aiding the search for new physics.

An important ingredient underlying precision physics with jets at the LHC are *infrared safe* jet algorithms used by both CMS and ATLAS. Without these, problematic to compare to QCD.



not infrared safe



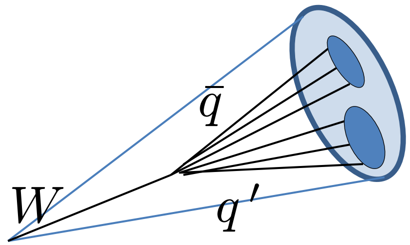
infrared safe

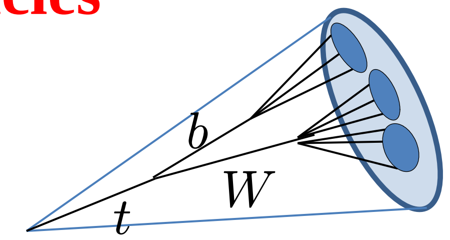
FastJet package supplies IR safe algorithms

Cacciari, Salam, Soyez

Boosted Objects and Jet Substructure

Use jet substructure to identify heavy particles





Clean up jets to expose heavy particles in jet substructure:

- **Filtering: undo last recombinations and keep main subjets.**

  Butterworth, Davison, Rubin, Salam (arXiv:0802.2470)

- **Trimming: remove regions in a jet with too little energy.**

  Krohn, Thaler and Wang (arXiv:0912.1342)

- **Pruning: take a jet and recluster it removing asymmetric wide angle recombinations**

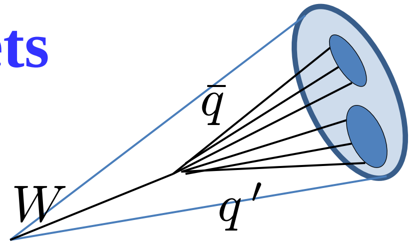
  Ellis , Vermilion, Walsh (arXiv:0903.5081, arXiv:0912.0033)

Improves resolution by removing soft, large-angle particles from jet

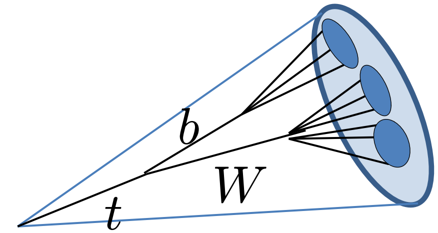
Many others have contributed: Almeida, Cacciari, Chen, Erdogan, Falkowski, Han, Hook, Jankowiak, Juknevich, Katz, Kim, Kribs, Larkoski, Lee, Martin, Nojiri, Perez, Plehn, Raklev, Rehermann, Roy, Rojo, Shelton, Sreethawong, Son, Soyez, Sung, Tweedie, Schwartz, Seymour, Soper, Spannowsky, Sterman, van Tilburg, Virzi, Wacker, Wang, Zhu, etc.

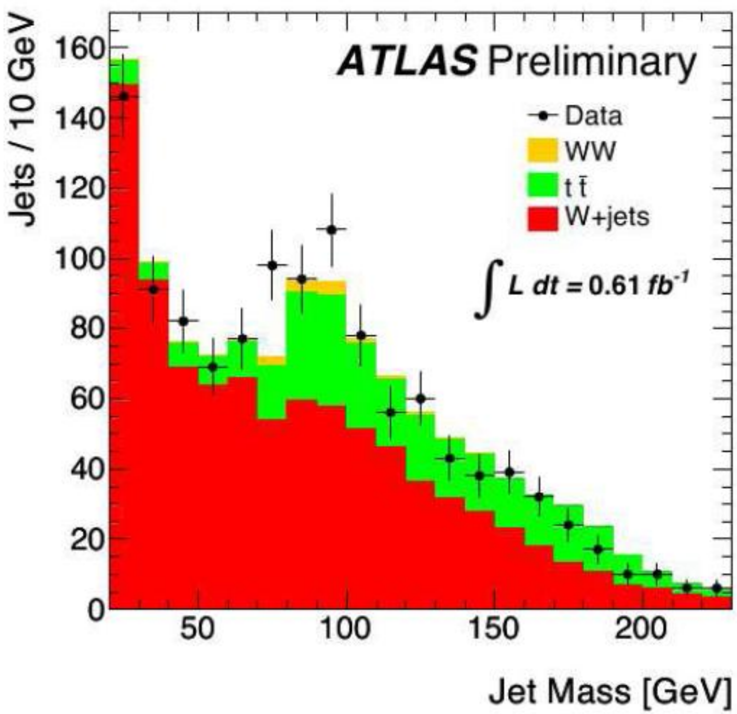
Experimental Progress on Boosted Objects and Jet Substructure

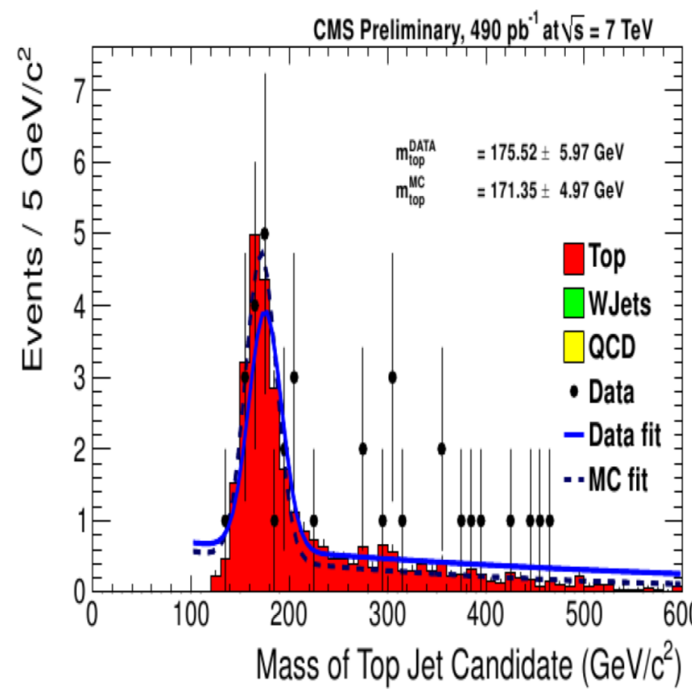
***W* jets**



top jets





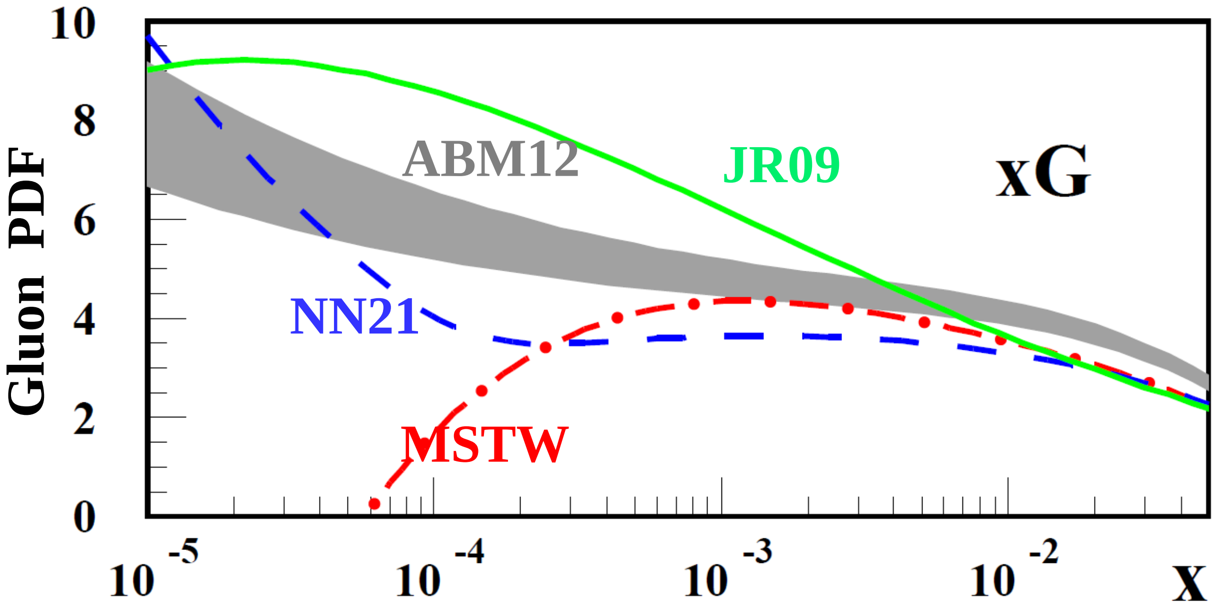


Offers a new window to search for new heavy mass states decaying into jets, previously thought to be inaccessible due to QCD background.

PDF Issues and Higgs

What's up with the gluons?

Alekhin, Blumlein, Moch (arXiv:1202.2281)



carried out in NNLO QCD

disagreement outside quoted errors

The discrepancy due to use of different data sets and treatment of power corrections. α_s low for ABM

m_H	ABM11	ABKM09	JR09	MSTW	NN21
125	$16.99\ {}^{+1.69}_{-1.63}\ {}^{+0.37}_{-0.37}$	$16.87\ {}^{+1.68}_{-1.63}\ {}^{+0.47}_{-0.47}$	$16.53\ {}^{+1.54}_{-1.44}\ {}^{+0.53}_{-0.53}$	$18.36\ {}^{+1.92}_{-1.82}\ {}^{+0.21}_{-0.28}$	$19.30\ {}^{+2.09}_{-1.89}\ {}^{+0.26}_{-0.26}$

Up to 15% effect on the Higgs cross section at 8 TeV

Illustrates the crucial importance of getting the PDFs right.

Why We Do Higher-Order QCD Calculations

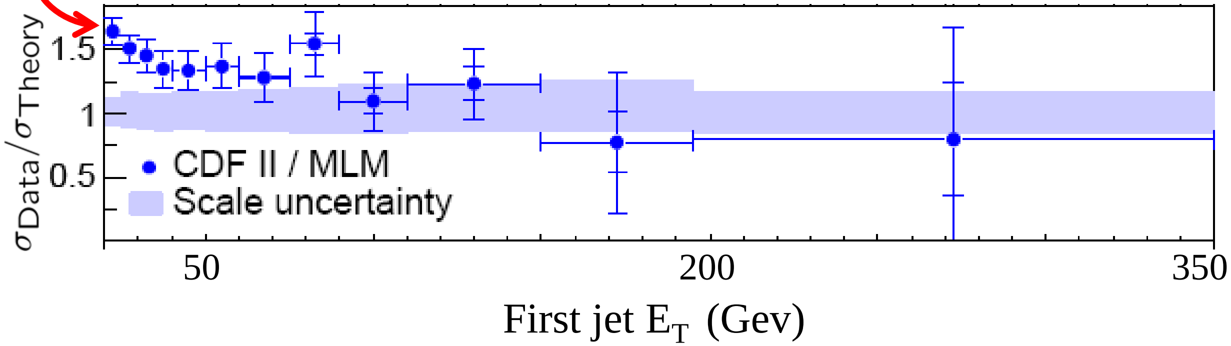
Classic example of the use of higher order QCD

note disagreement

CDF collaboration
arXiv: 0711.4044

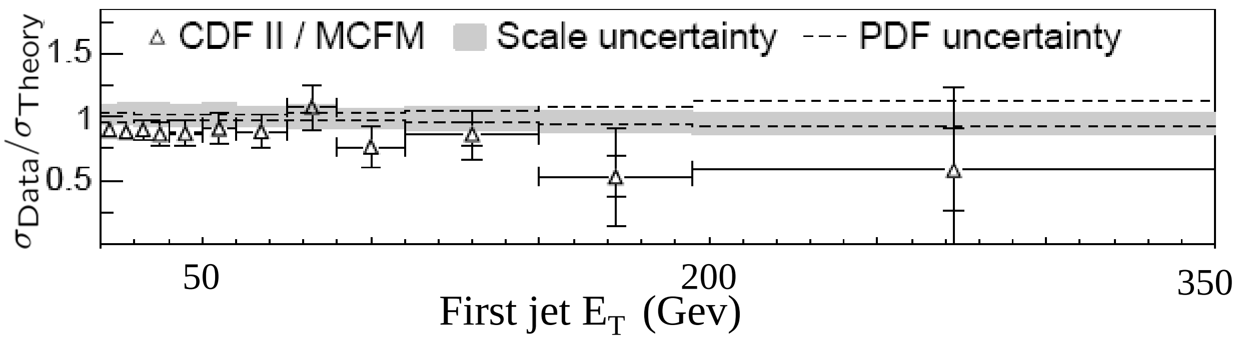
***W* + 2 jets at the Tevatron**

LO



leading order + parton showering

NLO QCD



NLO does better, smallest theoretical uncertainty

Higher-order QCD can resolve discrepancies between theory and experiment and help in the search for new physics.

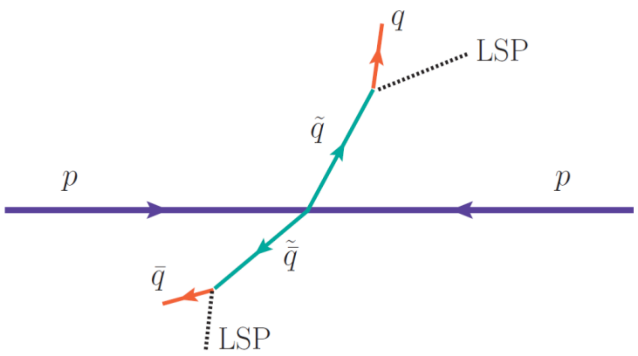
Data Driven Background Estimation

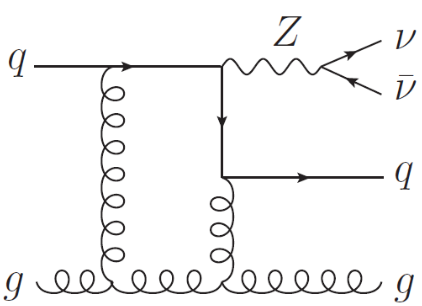
CMS uses photons to estimate Z background to susy searches.

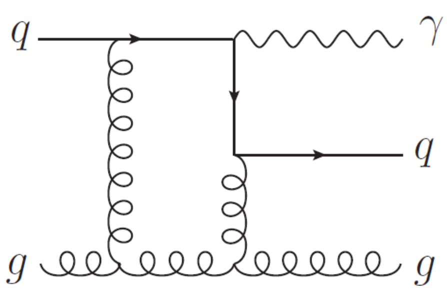
CMS PAS SUS-08-002; CMS PAS SUS-10-005; arXiv:1106.4503

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

irreducible background **measure this** **ratio is theory input**







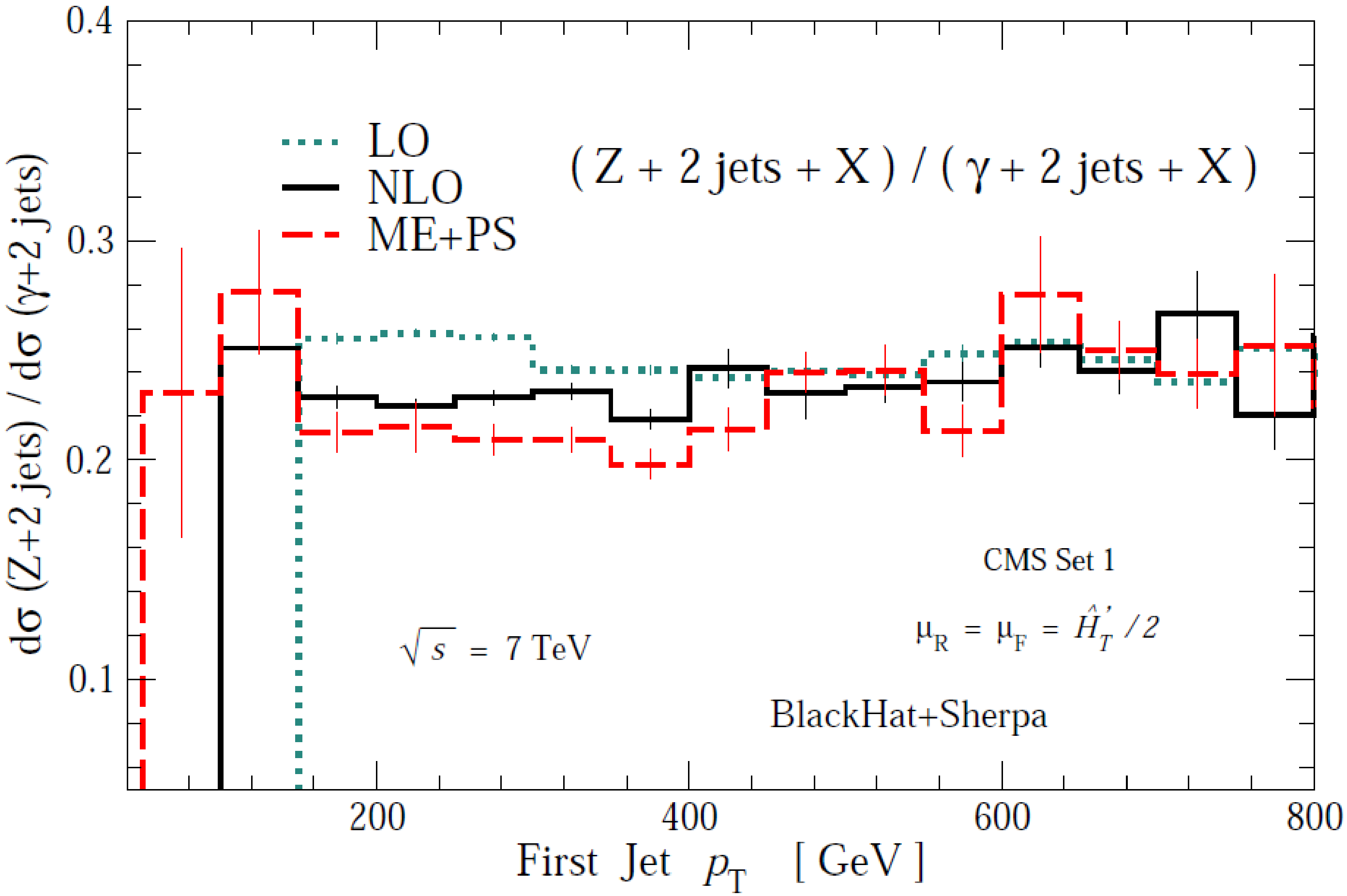
Photons have 6 times the rate compared to $Z \to \mu\bar{\mu}$

Task of theorists 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 and arXiv:1206.6064) ; Ask, Parker, Sandoval, Shea, Stirling (arXiv:1107.2803)

Z/γ ratio

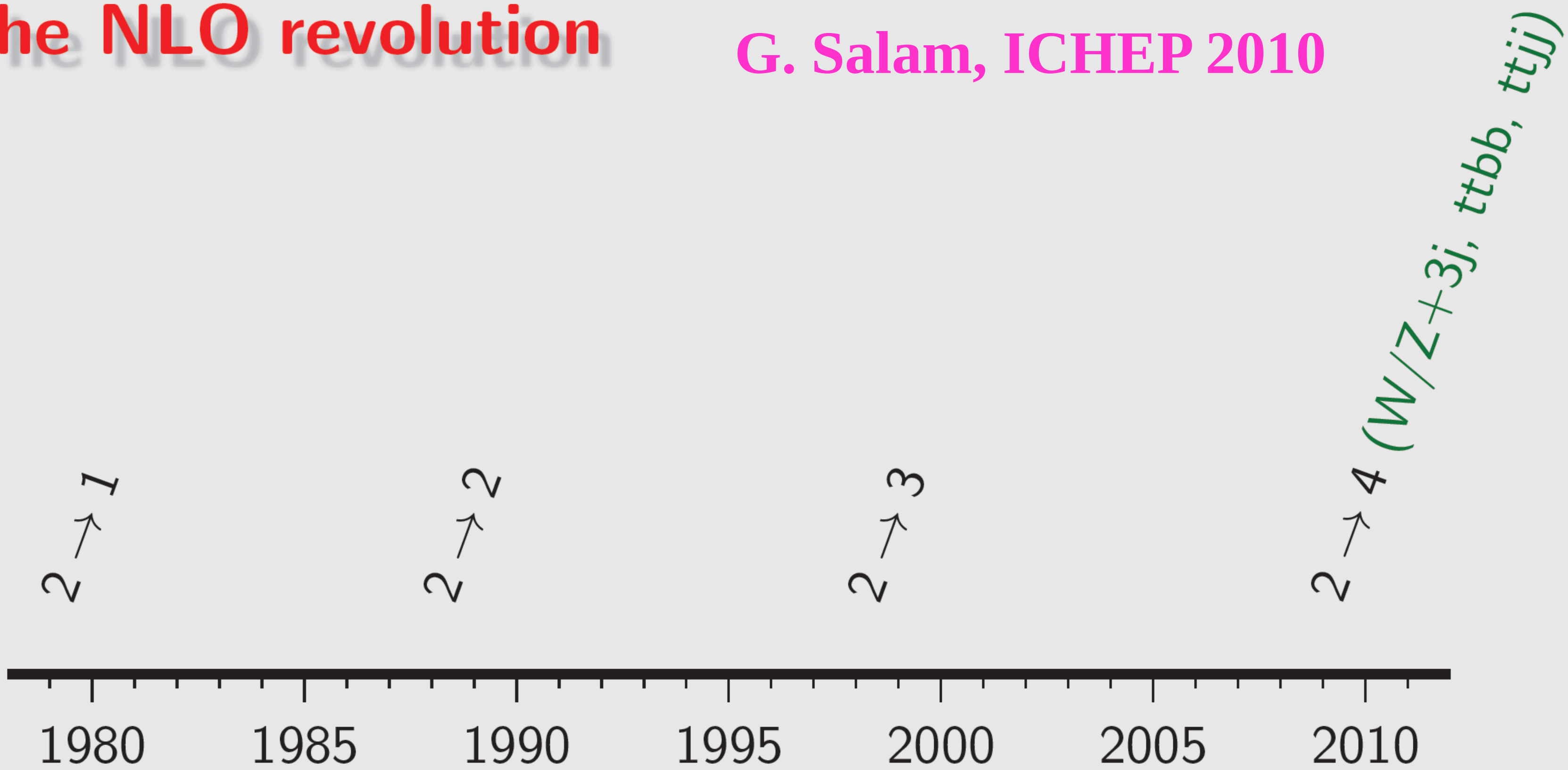
BlackHat Collaboration



Different theoretical predictions track each other.
This conversion directly used by CMS in their estimate of theory uncertainty in susy search.

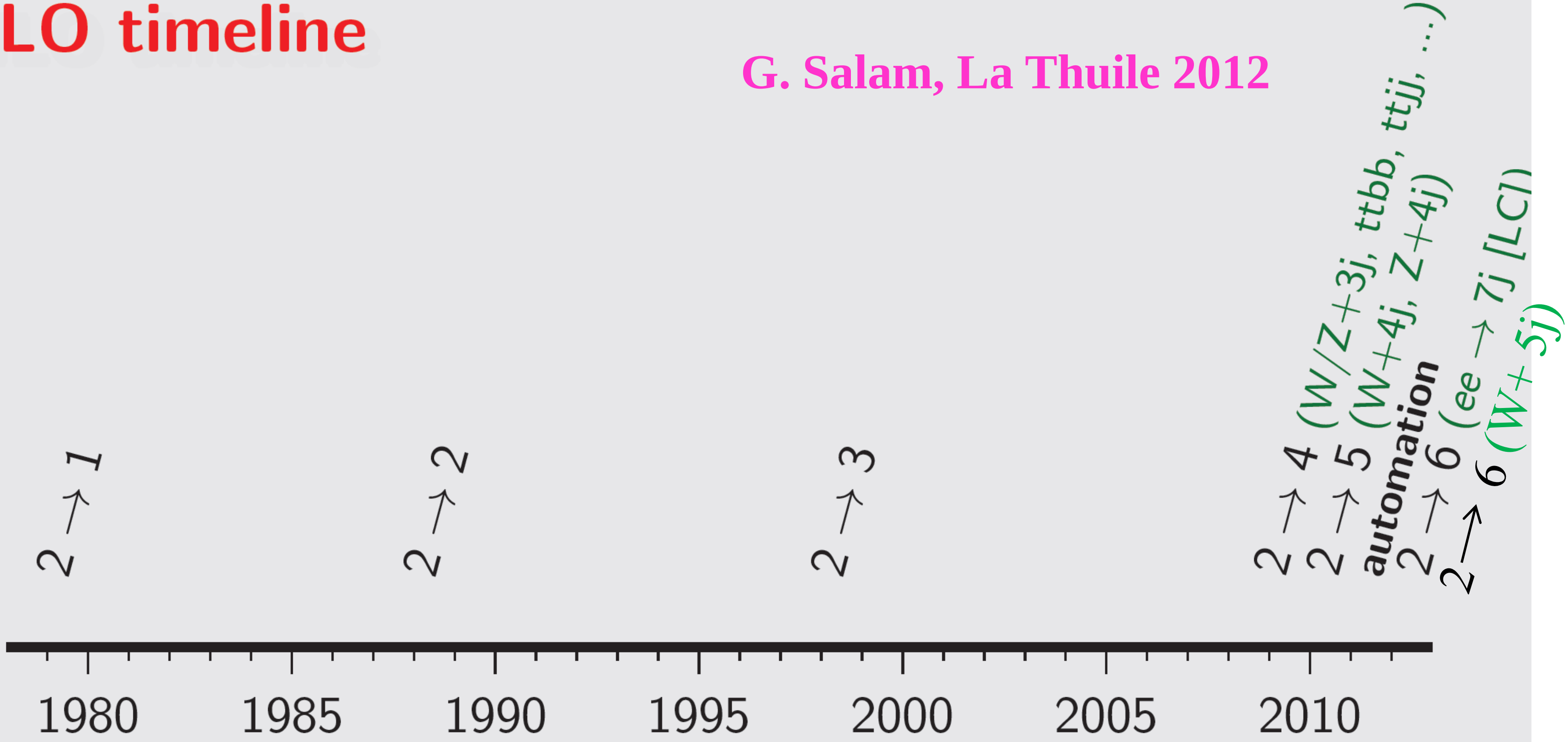
The NLO revolution

G. Salam, ICHEP 2010



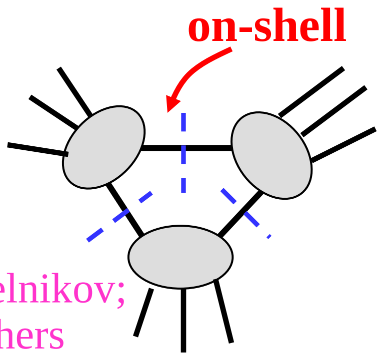
2009: NLO $W+3j$ [Rocket: Ellis, Melnikov & Zanderighi] [unitarity]
2009: NLO $W+3j$ [BlackHat: Berger et al] [unitarity]
2009: NLO $t\bar{t}b\bar{b}$ [Bredenstein et al] [traditional]
2009: NLO $t\bar{t}b\bar{b}$ [HELAC-NLO: Bevilacqua et al] [unitarity]
2009: NLO $q\bar{q} \to b\bar{b}b\bar{b}$ [Golem: Binoth et al] [traditional]
2010: NLO $t\bar{t}jj$ [HELAC-NLO: Bevilacqua et al] [unitarity]
2010: NLO $Z+3j$ [BlackHat: Berger et al] [unitarity]

NLO timeline



2010: NLO $W+4j$ [BlackHat+Sherpa: Berger et al] [unitarity]
2011: NLO $WWjj$ [Rocket: Melia et al] [unitarity]
2011: NLO $Z+4j$ [BlackHat+Sherpa: Ita et al] [unitarity]
2011: NLO $4j$ [BlackHat+Sherpa: Bern et al] [unitarity]
2011: first automation [MadNLO: Hirschi et al] [unitarity + feyn.diags]
2011: first automation [Helac NLO: Bevilacqua et al] [unitarity]
2011: first automation [GoSam: Cullen et al] [feyn.diags(+unitarity)]
2011: $e^+e^- \to 7j$ [Becker et al, leading colour] [numerical loops]
2012: NLO W+5j [BlackHat+Sherpa, preliminary] [unitarity]

Some Advances



- **On-Shell Revolution. A different way to do QFT.**

  ZB, Dixon, Dunbar, Kosower ; ZB, Morgan; ZB, Dixon, Kosower;
  Britto, Cachazo and Feng; Anastasiou, Britto, Feng, Kunszt, Mastrolia;
  Giele, Kunszt, Melnikov; Badger; Ossola, Papadopoulos, Pittau; Giele, Kunszt, Melnikov;
  Forde; Berger, ZB, Kosower, Forde, Gleisberg, Hoeche, Ita, Maitre, Ozeren; & others

- **Improved efficiency in Feynman diagram methods.**

  Bredenstein, Denner, Dittmaier, Pozzorini; Cascioli , Maierhofer, and Pozzorini.

- **New purely numerical approach.** Becker, Goetz, Reuschle, Schwan, Weinzierl

Some of the new packages using modern ideas:

— **Helac-NLO** Bevilacqua, Czakon, Garzelli, van Hameren, Kardos, Ossola, Papadopoulos, Pittau, Worek

— **CutTools** Ossola, Papadopoulos, Pittau

— **BlackHat** ZB, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre, Ozeren

— **Rocket** Ellis, Giele, Kunszt, Melnikov, Zanderighi

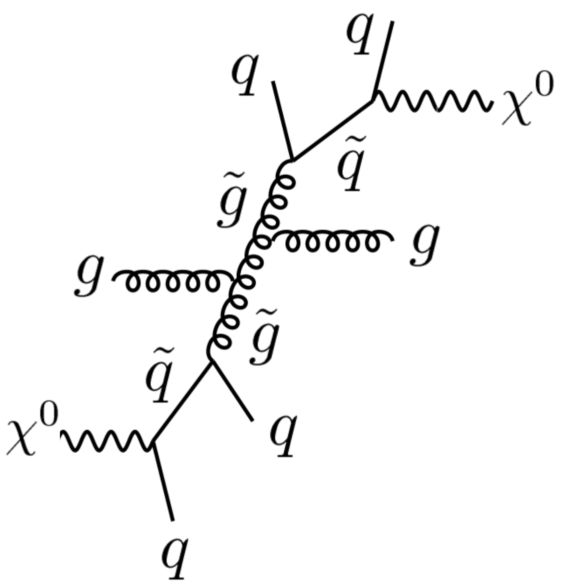
— **SAMURAI** Mastrolia, Ossola, Reiter, Tramontano

— **MadLoop** Hirchi, Maltoni, Frixione, Frederix, Garzelli, Pittau

— **GoSam** Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano

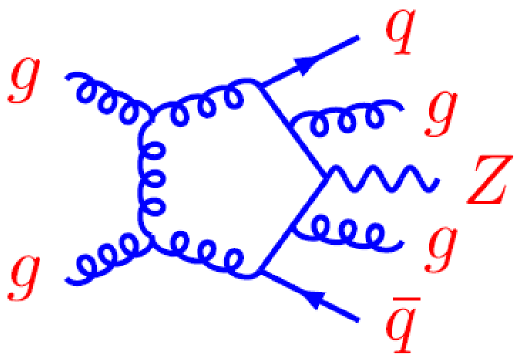
— **Ngluon** Badger, Biedermann, Uwer

Example: Susy Search



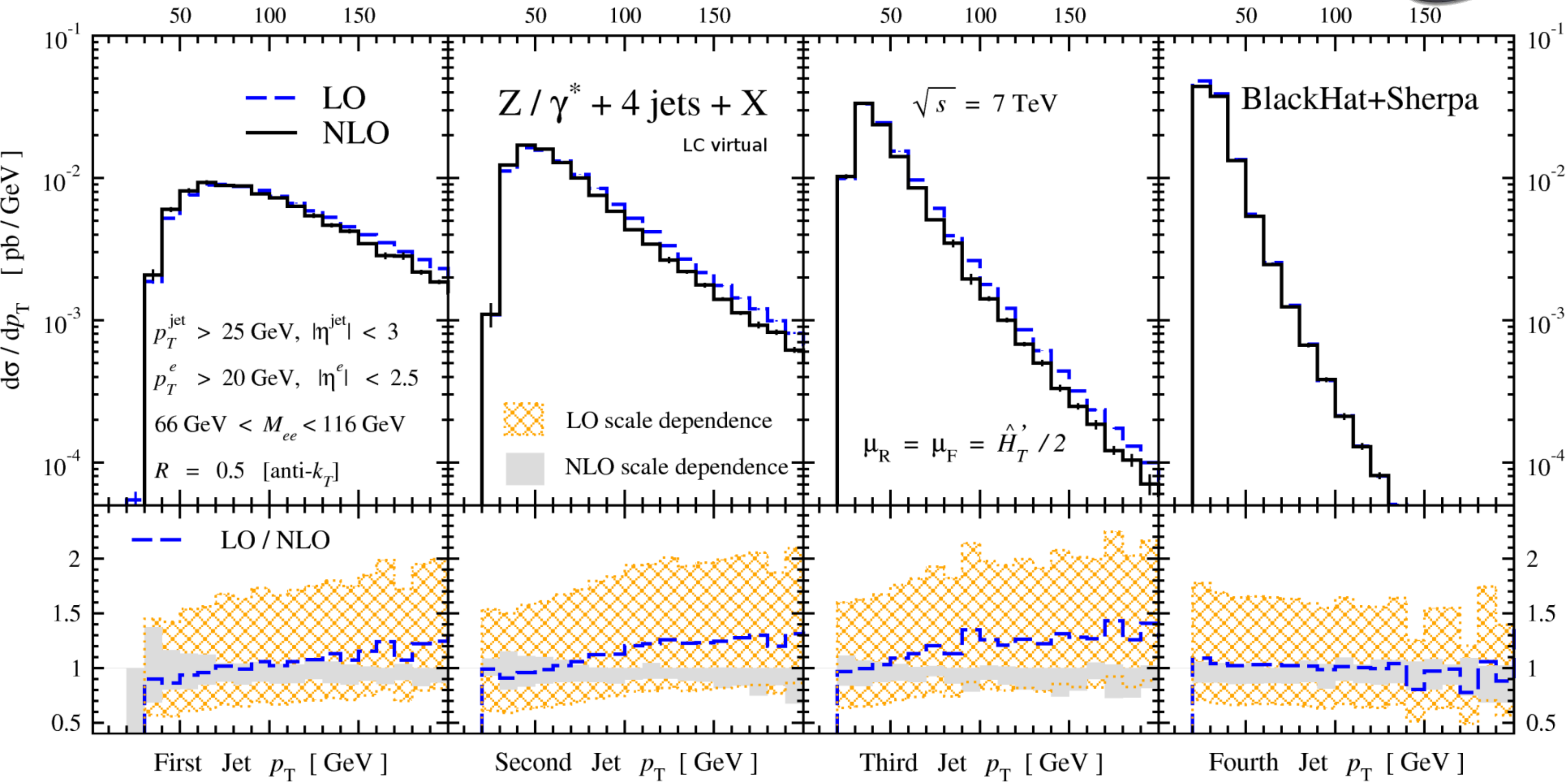
- **Cascade from gluino to neutralino (escapes detector)**
- **Signal: missing energy + 4 jets**
- **SM background from *Z* + 4 jets, *Z* → neutrinos**

To improve understanding of background we want $pp \to Z + 4$ jets in at least NLO QCD

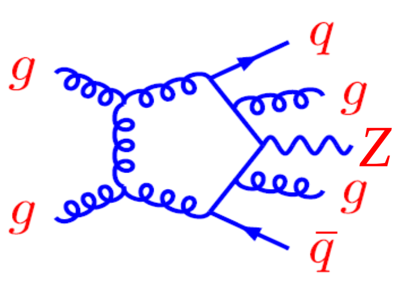


Z+4 Jets at NLO

[BlackHat] Ita, ZB, Febres Cordero, Dixon, Kosower, Maitre (2011)

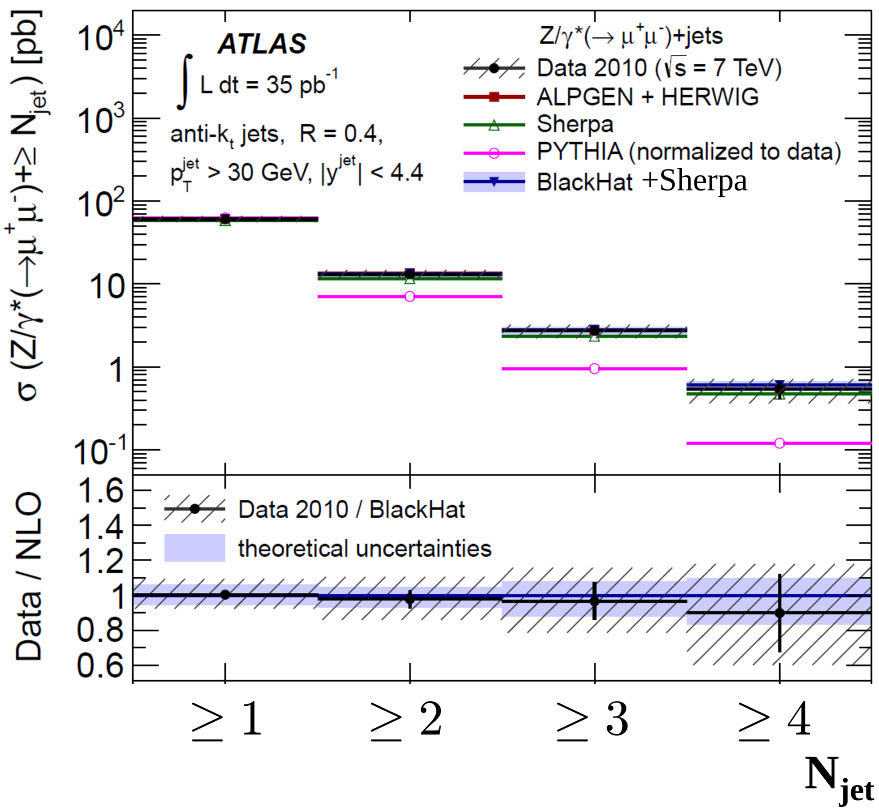


- Big improvement in scale stability.
- Best available theoretical predictions.



ATLAS Comparison Against NLO QCD

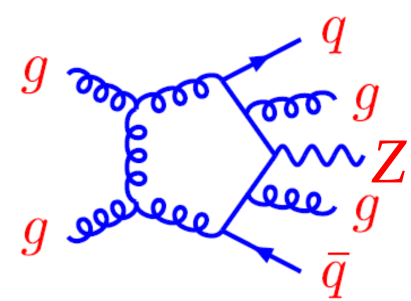
***Z* +1, 2, 3, 4 jets inclusive**



Powerful experimental confirmation of NLO approach. With these experimental cuts no new physics is expected.

We look forward to higher precision data.

very good agreement

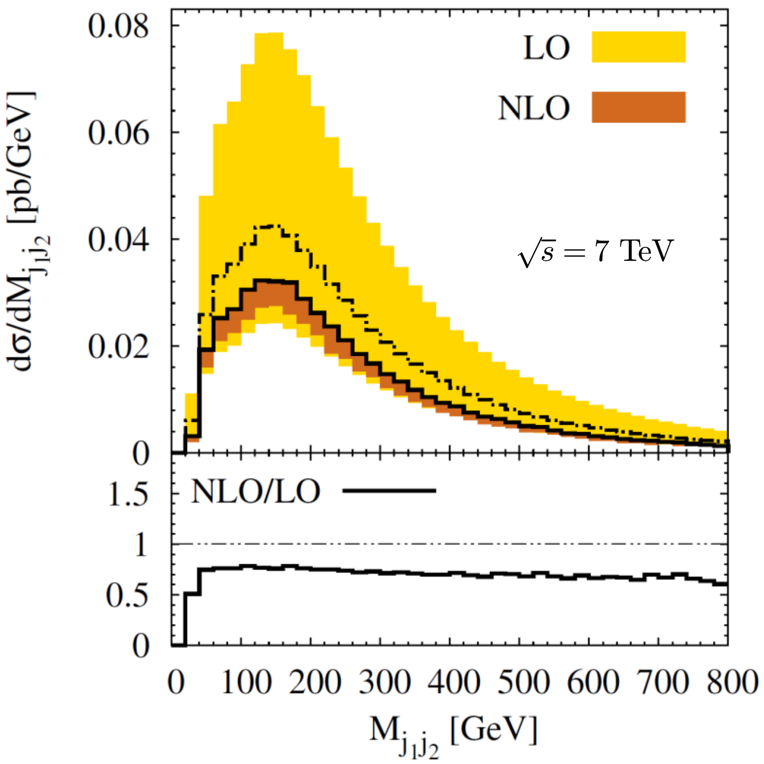


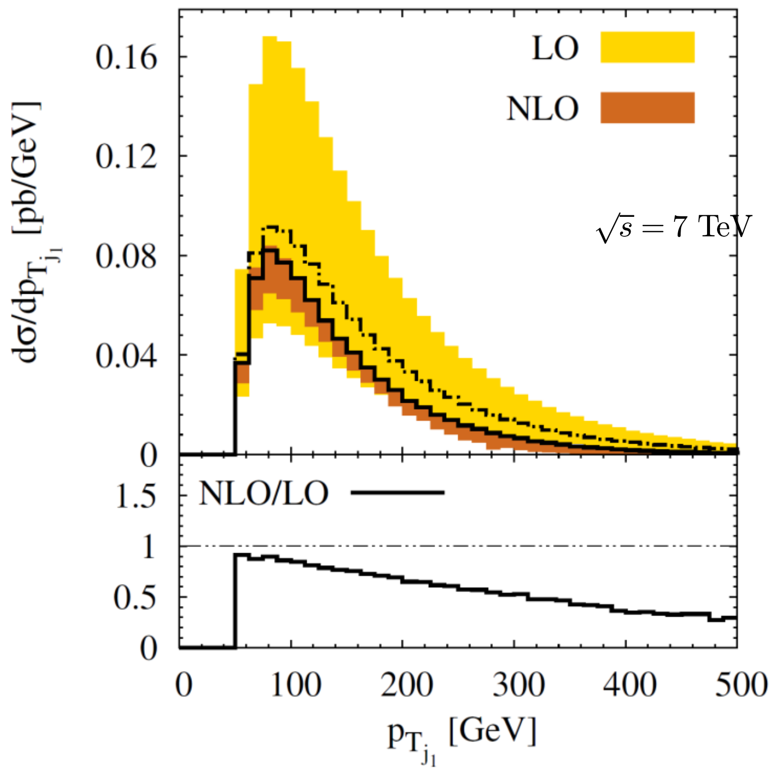
- **Even *W*+5 jets at NLO nearly complete.** see K. Ozeren's talk at LoopFest 2012
- **Serious advance in our ability to do NLO calculations.**

Recent Advances in NLO

Bevilacqua, Czakon, Papadopoulos, Worek (arXiv: 1108.2851)

A very nice example from HELAC-NLO: $t\bar{t}$ + 2 jet production



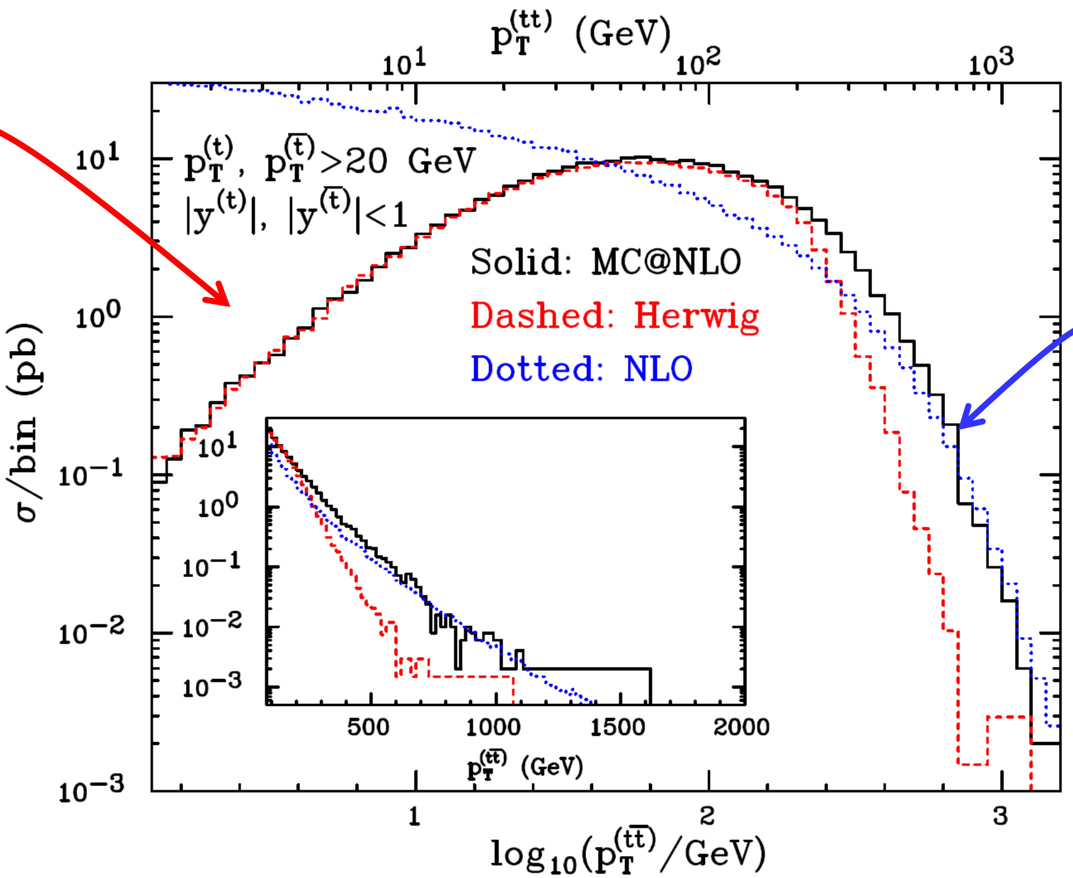


Besides the enormous reduction in scale uncertainty, large changes in shape between LO and NLO are evident for some distributions.

Merging NLO with Parton Showers

Frixione, Nason and Webber (hep-ph/0305252)

matches shower at low p_T



matches NLO at high p_T

MC@NLO uses Herwig

Classic example of utility of NLO + parton showers

By merging NLO with parton showers we get advantages of both

Merging NLO with Parton Showers

- **Want to simultaneously have advantages of both NLO and parton showers.**
- **Nontrivial technical issues, e.g must remove double counting.**

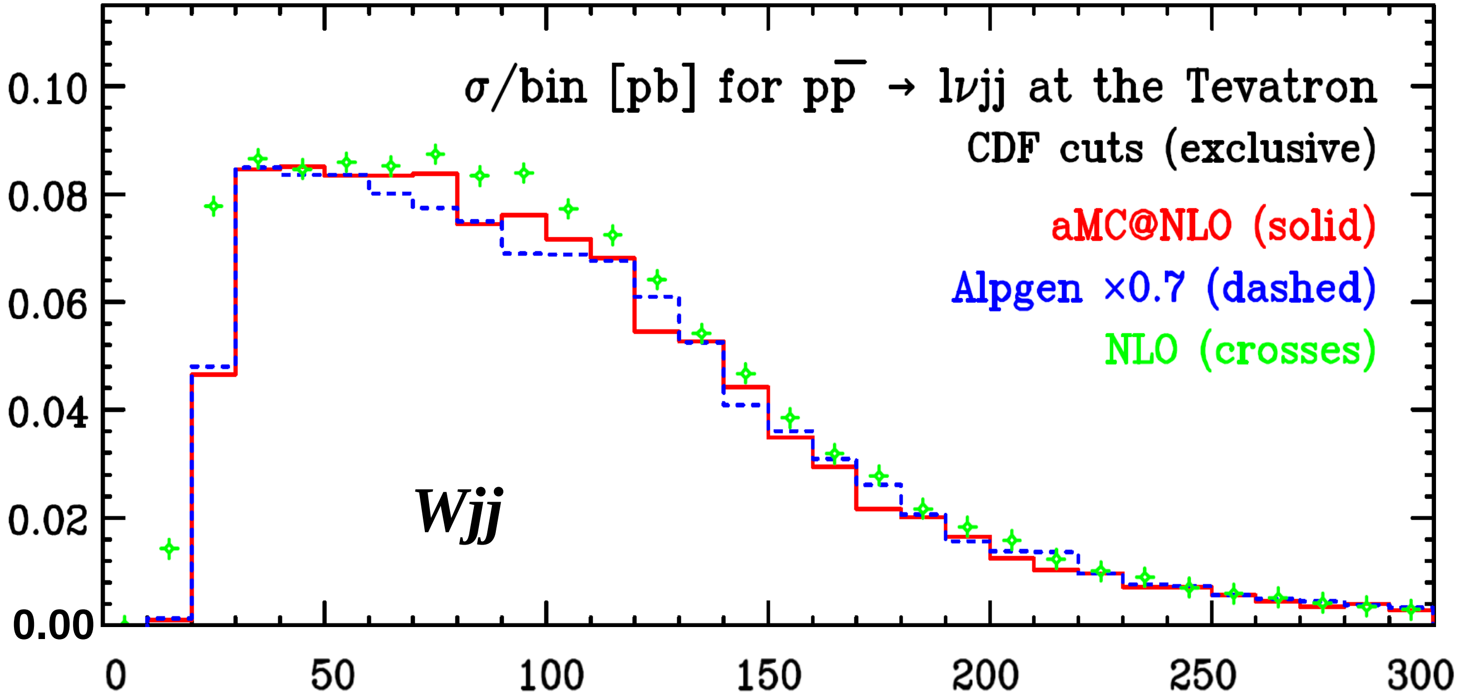
Impressive new progress from many groups

• **MC@NLO**	Frixione, Webber, et al
• **POWHEG**	Frixione, Nason, Oleari, Alioli, Re. Melia, Nason, Rontsch, Zanderighi
• **SHERPA**	Hoeche, Krauss, Schoenherr, Siegert
• **VINCIA**	Giele, Kosower, and Skands, et al.
• **GENeVa**	Bauer, Tackman, Thaler, et al,.
• **aMC@NLO**	Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli
• **KRKMC**	Skrzypek, Jadach, Kusina, Placzek, Slawinska, Gituliar

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.



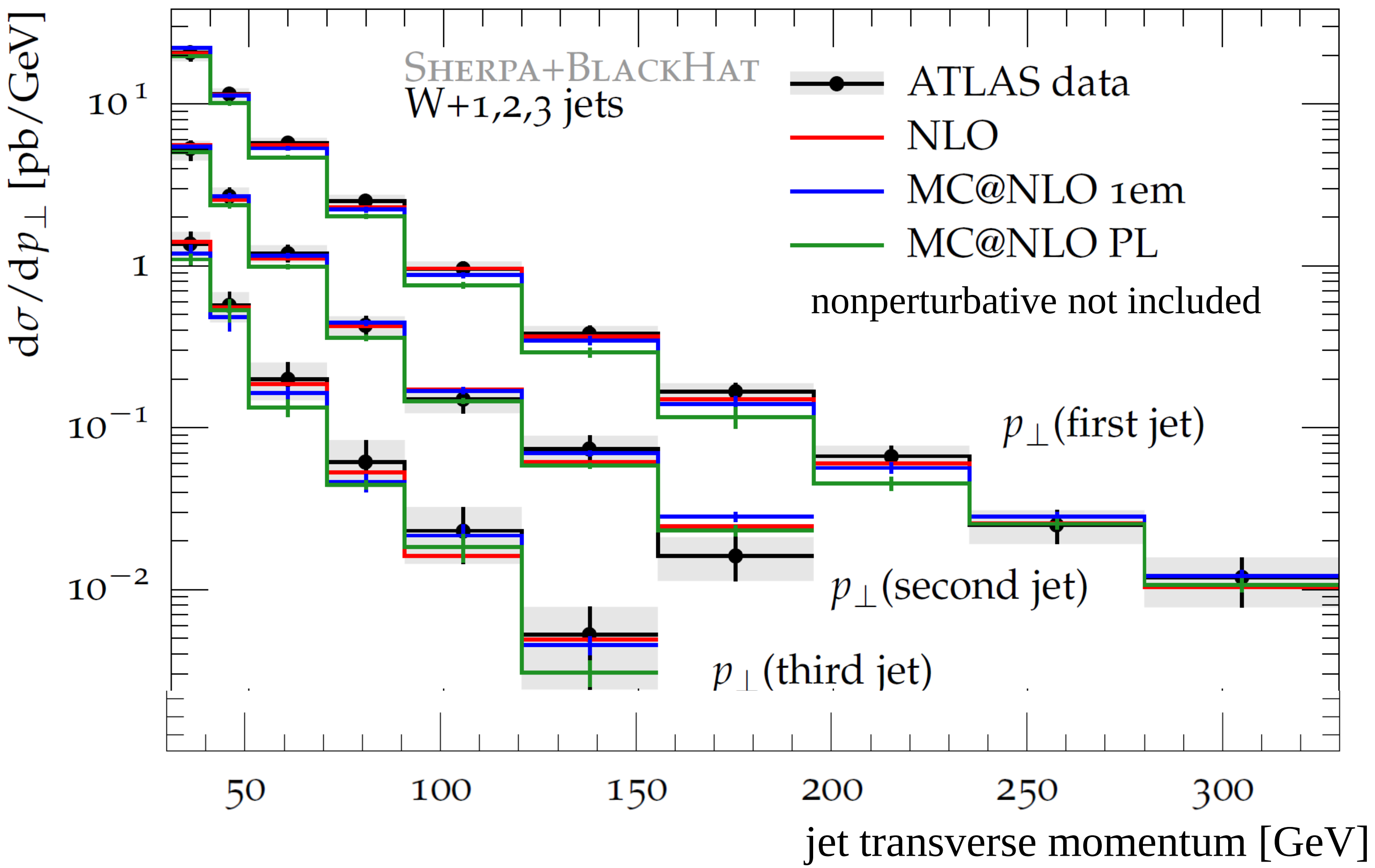
- **CMS used Alpgen (scaled). NLO has a slightly different shape.**
- **aMC@NLO is close to Alpgen, so it looks that QCD is under good control.**

Merging NLO with Parton Showers

Recent state-of-the-art example

Hoeche, Krauss, Schoenherr, Siegert

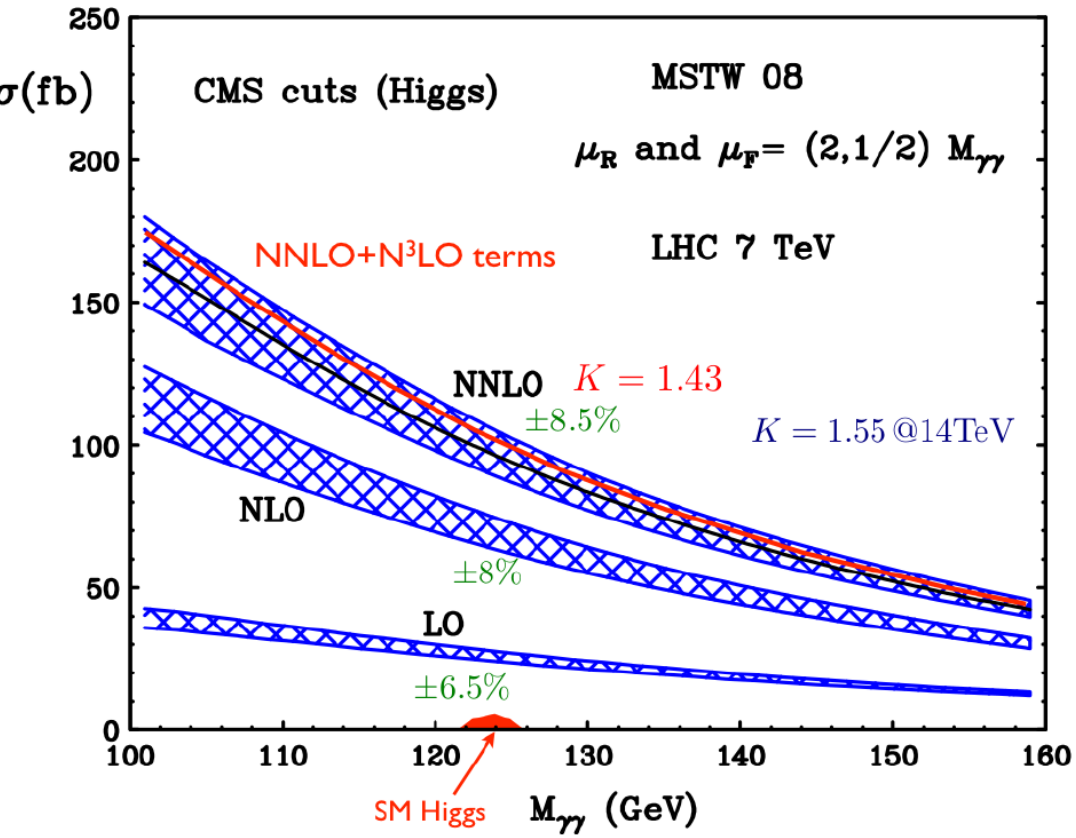
Jet transverse momenta



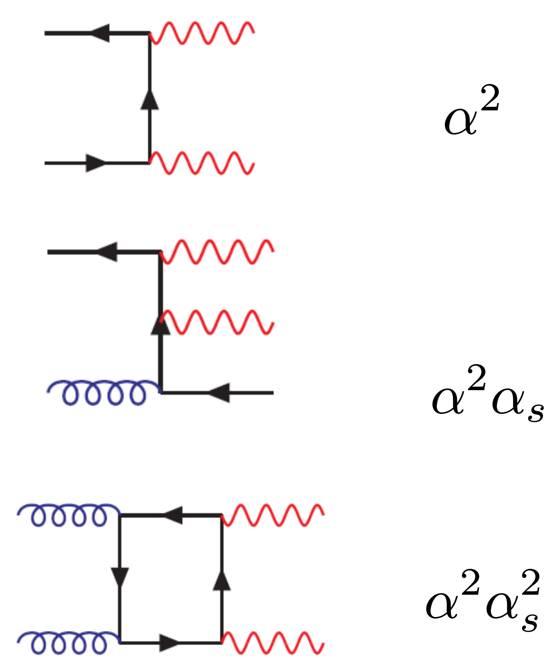
Nontrivial example of *W*+3 jets based on MC@NLO framework

NNLO QCD: γγ Background to Higgs

Catani, Cieri, de Florian, Ferrera, Grazzini



When new large luminosity channels open at high orders, low-order predictions will be unreliable.



LHC is glue factory so box contribution is same order as born

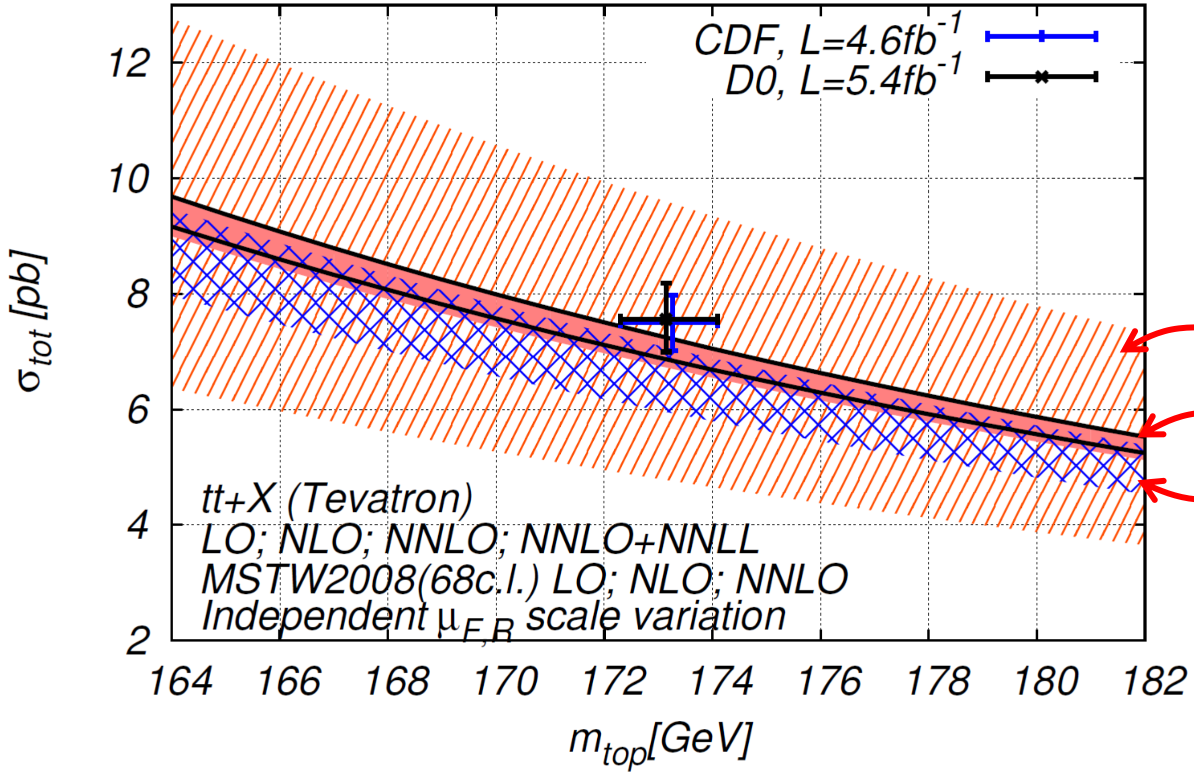
- **Example where NNLO is very useful.**
- **By NNLO all channels open.**
- **Known N³LO terms don't cause large shift.**

ZB, Dixon, Schmidt

Top Production at Tevatron

Recent paper demonstrates the remarkable power of NNLO (here combined with NNLL resummation).

Barnreuther, Czakon and Mitov (arXiv:1204.5201)



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

contributions at NNLO
Sufficient for Tevatron

First complete NNLO calculation with four colored partons

LO

NNLO

NLO

May be helpful for understanding A_{FB}

Theoretical uncertainties smaller than experimenal ones.
~ 3% perturbative uncertainty

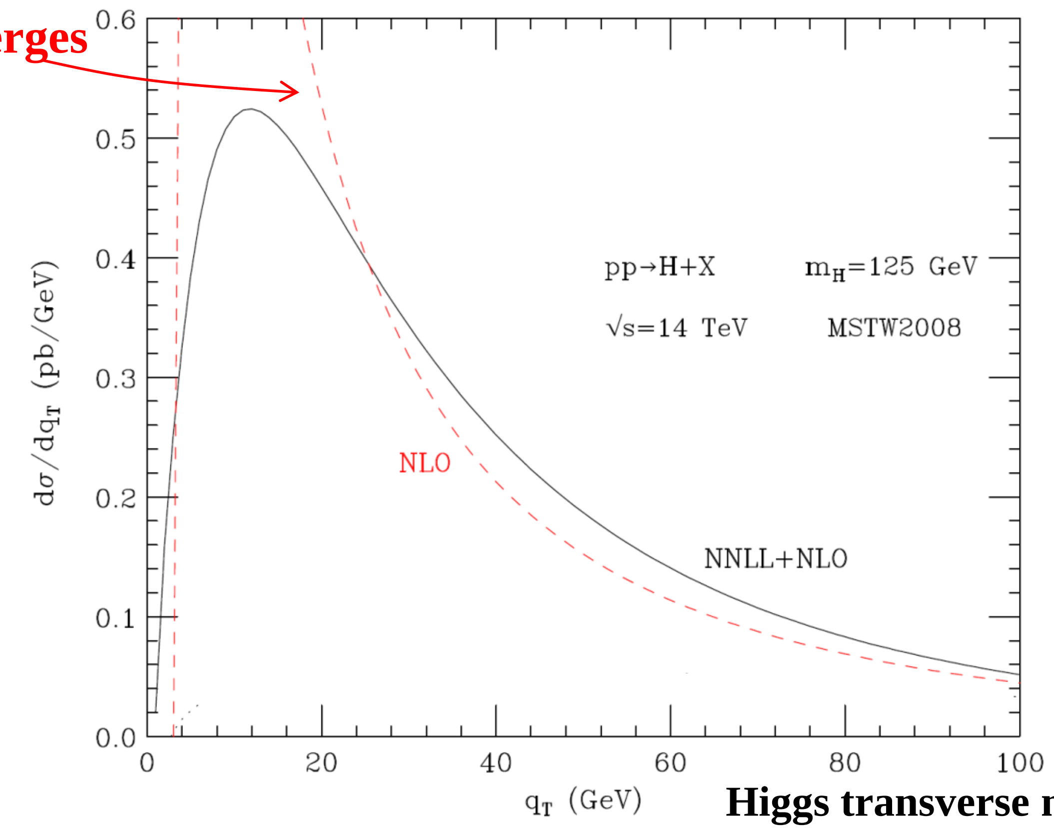
Resummation Application to Higgs

Large logs for small transverse momentum, q_T, of Higgs: $\mathrm{Log}(q_T^2/M_H^2)$

Either use parton shower program or carry out resummation of logs.

de Florian, Ferrera, Grazzini, Tommasini (arXiv: 1109.2109)

fixed order diverges



Higgs transverse momentum

Recent example of NNLL resummation matched to NLO QCD

See also Ahrens, Becher, Neubert and Yang (arXiv:1008.3162) with N^3LL

Summary

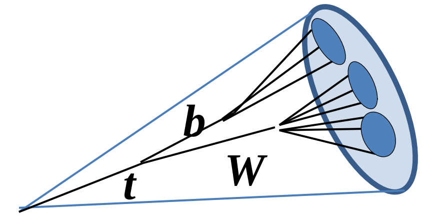
- QCD is providing crucial input to collider experiments in the hunt for new physics.
- New ideas for using information from inside jets to study heavy particles.
- Enormous progress in higher multiplicities and/or loops.
- Merging of different techniques and approaches.

Reviewed examples with vector bosons, Higgs, top, susy and generic heavy particle searches.

The tools and advances described here are essential for getting the most out of the LHC and for making an exciting future.

Extra Slides

New Search Strategies



•*N*-subjetiness

Thaler and van Tilburg (arXiv:1011.2268,1108.2701), Kim (arXiv:1011.1493)

$$0 \cdot \tau_N \cdot 1$$

$$\tau_N = \frac{\sum_k p_{T,k} \left(\min\left\{\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\right\}\right)^\beta}{\sum_k p_{T,k} (R_0)^\beta}$$

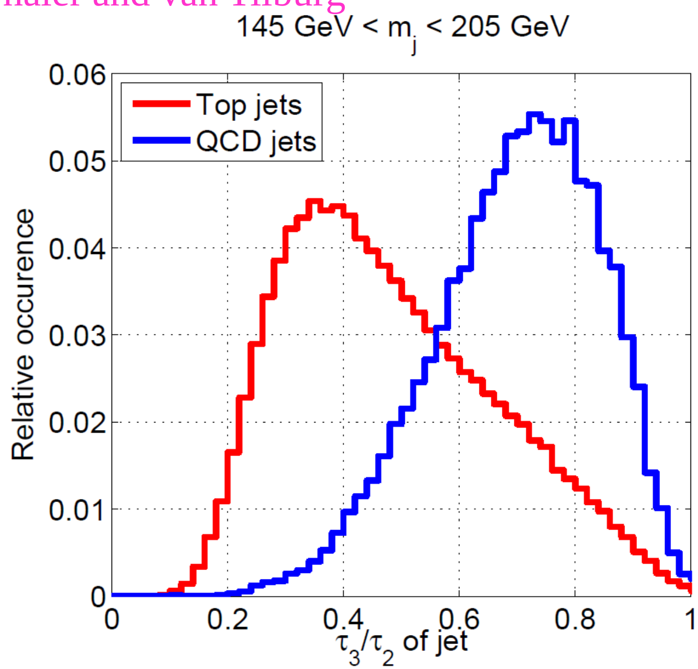
$\beta = 1$ good choice

$\Delta R^2 = \Delta\phi^2 + \Delta\eta^2$

R_0 jet radius

τ_N / τ_{N-1} provides strong discriminating power for *N*-pronged objects

Thaler and van Tilburg



Many other ideas, e.g.:

- **Dipolarity color flow observable**

  Hook, Jankowiak, Wacker

- **Substructure via angular correlations**

  Jankowiak and Larkoski

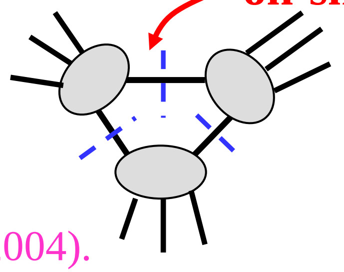
- **Template overlap method**

  Almeida, Erdogan, Juknevich, Lee, Perez, Sterman

- **Shower deconstruction**

  Soper and Spannowsky

Some NLO QCD Theoretical Developments



- **Unitarity method.** ZB, Dixon, Dunbar, Kosower (1994,1998).
- **Complex momenta in generalized cuts.**

  Britto, Cachazo, Feng (2004).

- ***D* dimensional unitarity to capture rational pieces of loops.**

  ZB, Morgan (1995); ZB, Dixon, Dunbar, Kosower (1996), ZB, Dixon, Kosower (2000);
  Anastasiou, Britto, Feng, Kunszt, Mastrolia (2006); Giele, Kunszt, Melnikov (2008); Badger (2009)

- **Efficient on-shell reduction of integrals compatible with on-shell**

  Ossola, Papadopoulos, Pittau (OPP) (2006);); Giele, Kunszt, Melnikov (2008);
  Forde (2007); Berger et al [BlackHat] (2008)

- **Improved efficiency in Feynman diagram methods.**

  Bredenstein, Denner, Dittmaier, Pozzorini (2008)

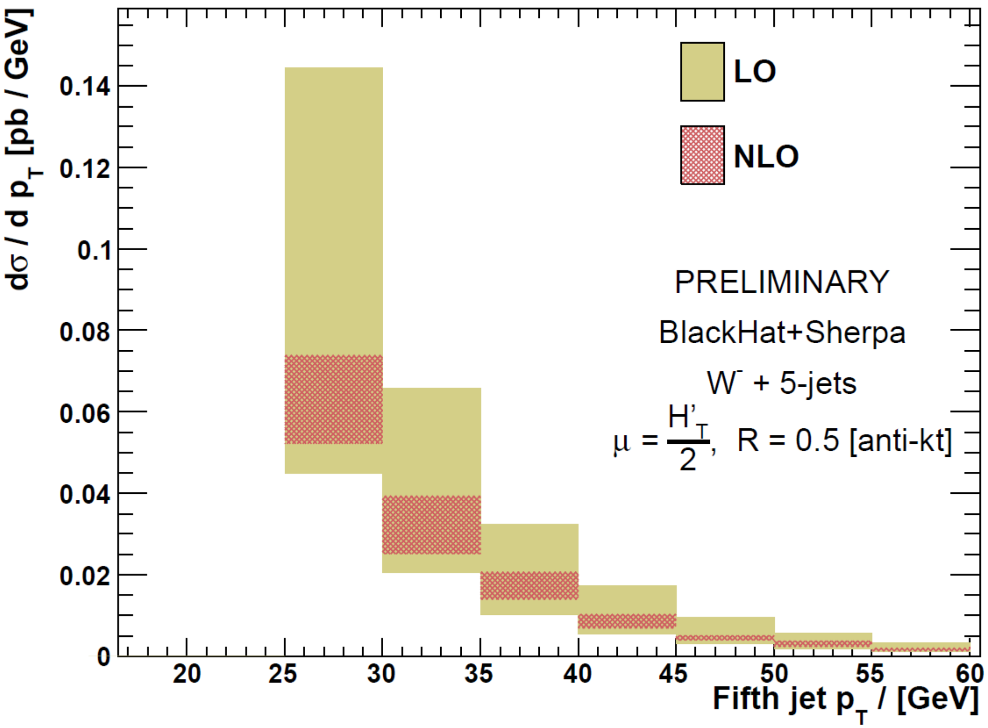
- **New efficient purely numerical approach.**

  Becker, Goetz, Reuschle, Schwan, Weinzierl (2011)

Preliminary W + 5 Jets in NLO QCD

ZB, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre, Ozeren [BlackHat collaboration]

P_T spectrum of 5[th] jet



Variations of renormalization and factorization scales by factors of 2 are shown

As expected, enormous scale dependence reduced by NLO

- **A new level for "state of the art".**
- **First NLO QCD 2→6 process for the LHC!**
- **People at ATLAS promise to immediately compare to data when complete. Particularly important background to *top* production.**

Advances in NLO Automation

There has been a lot of recent work on automating recent NLO advances.

2 → 2,3 and some 2→4 processes automated

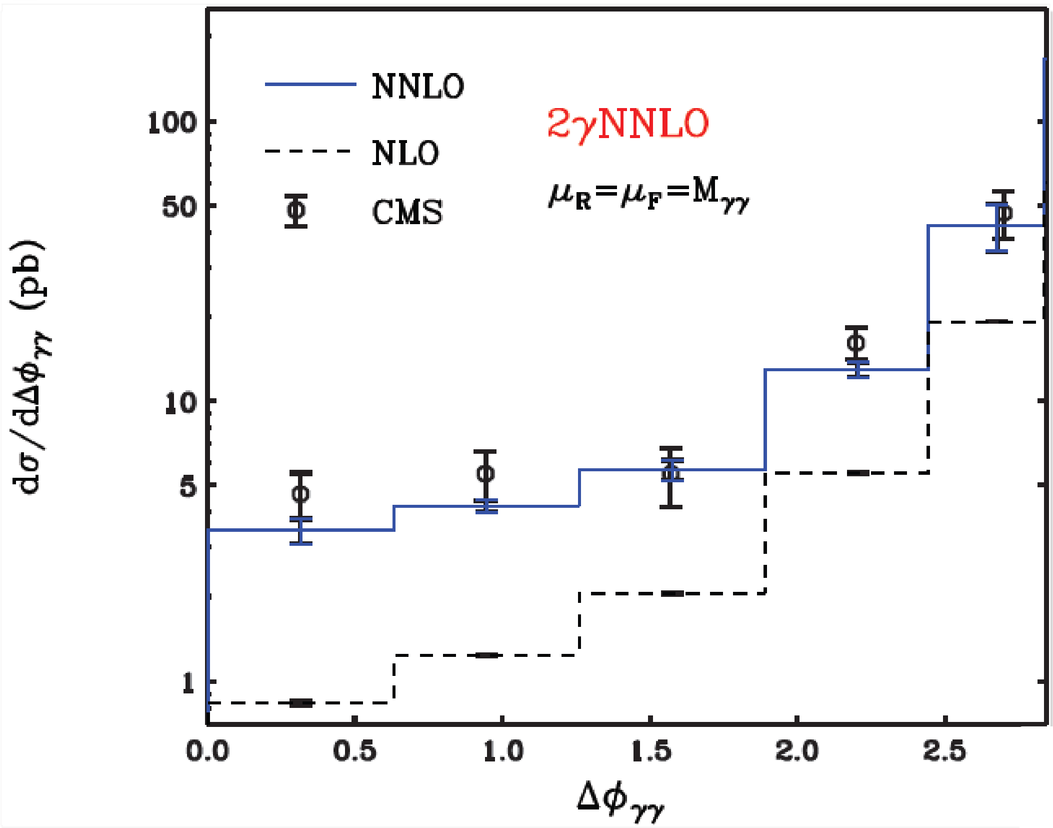
- **Helac-NLO:** Bevilacqua, Czakon, Ossola, Papadopoulos, Pittau, Worek
- **MadLoop:** Hirchi, Maltoni, Frixione, Frederix, Garzelli, Pittau
- **GoSam:** Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano

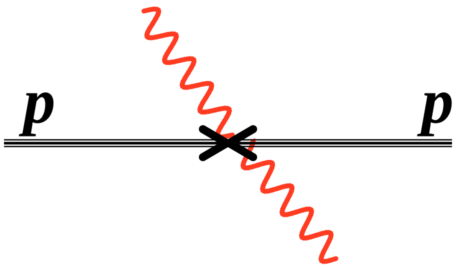
Example from MadLoop arXiv:1103.0621

	Process	μ	n_{lf}	Cross section (pb) LO	Cross section (pb) NLO
a.1	$pp \to t\bar{t}$	m_{top}	5	123.76 ± 0.05	162.08 ± 0.12
a.2	$pp \to tj$	m_{top}	5	34.78 ± 0.03	41.03 ± 0.07
a.3	$pp \to tjj$	m_{top}	5	11.851 ± 0.006	13.71 ± 0.02
a.4	$pp \to t\bar{b}j$	$m_{top}/4$	4	25.62 ± 0.01	30.96 ± 0.06
a.5	$pp \to t\bar{b}jj$	$m_{top}/4$	4	8.195 ± 0.002	8.91 ± 0.01
b.1	$pp \to (W^+ \to)e^+\nu_e$	m_W	5	5072.5 ± 2.9	6146.2 ± 9.8
b.2	$pp \to (W^+ \to)e^+\nu_e\, j$	m_W	5	828.4 ± 0.8	1065.3 ± 1.8
b.3	$pp \to (W^+ \to)e^+\nu_e\, jj$	m_W	5	298.8 ± 0.4	300.3 ± 0.6
b.4	$pp \to (\gamma^*/Z \to)e^+e^-$	m_Z	5	1007.0 ± 0.1	1170.0 ± 2.4
b.5	$pp \to (\gamma^*/Z \to)e^+e^-\, j$	m_Z	5	156.11 ± 0.03	203.0 ± 0.2
b.6	$pp \to (\gamma^*/Z \to)e^+e^-\, jj$	m_Z	5	54.24 ± 0.02	56.69 ± 0.07
c.1	$pp \to (W^+ \to)e^+\nu_e b\bar{b}$	$m_W + 2m_b$	4	11.557 ± 0.005	22.95 ± 0.07
c.2	$pp \to (W^+ \to)e^+\nu_e t\bar{t}$	$m_W + 2m_{top}$	5	0.009415 ± 0.000003	0.01159 ± 0.00001
c.3	$pp \to (\gamma^*/Z \to)e^+e^- b\bar{b}$	$m_Z + 2m_b$	4	9.459 ± 0.004	15.31 ± 0.03
c.4	$pp \to (\gamma^*/Z \to)e^+e^- t\bar{t}$	$m_Z + 2m_{top}$	5	0.0035131 ± 0.0000004	0.004876 ± 0.000002
c.5	$pp \to \gamma t\bar{t}$	$2m_{top}$	5	0.2906 ± 0.0001	0.4169 ± 0.0003
d.1	$pp \to W^+W^-$	$2m_W$	4	29.976 ± 0.004	43.92 ± 0.03
d.2	$pp \to W^+W^- j$	$2m_W$	4	11.613 ± 0.002	15.174 ± 0.008
d.3	$pp \to W^+W^+ jj$	$2m_W$	4	0.07048 ± 0.00004	0.1377 ± 0.0005
e.1	$pp \to HW^+$	$m_W + m_H$	5	0.3428 ± 0.0003	0.4455 ± 0.0003
e.2	$pp \to HW^+ j$	$m_W + m_H$	5	0.1223 ± 0.0001	0.1501 ± 0.0002
e.3	$pp \to HZ$	$m_Z + m_H$	5	0.2781 ± 0.0001	0.3659 ± 0.0002
e.4	$pp \to HZ j$	$m_Z + m_H$	5	0.0988 ± 0.0001	0.1237 ± 0.0001
e.5	$pp \to Ht\bar{t}$	$m_{top} + m_H$	5	0.08896 ± 0.00001	0.09869 ± 0.00003
e.6	$pp \to Hb\bar{b}$	$m_b + m_H$	4	0.16510 ± 0.00009	0.2099 ± 0.0006
e.7	$pp \to Hjj$	m_H	5	1.104 ± 0.002	1.036 ± 0.002

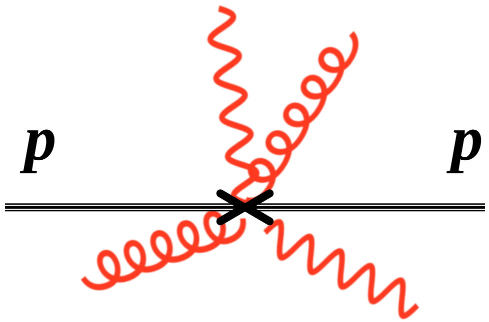
NNLO QCD: $\gamma\gamma$ Background to Higgs

Catani, Cieri, de Florian, Ferrera, Grazzini (arXiv: 1110.2375)





In LO QCD $\Delta\phi_{\gamma\gamma} = \pi$



In NLO and NNLO QCD $\Delta\phi_{\gamma\gamma} \leq \pi$

- **With NNLO QCD excellent agreement with experiment.**
- **No surprise here. Perturbative QCD is working exactly as expected. This is quantity where it is clear NLO should really behave like LO and NNLO like NLO.**