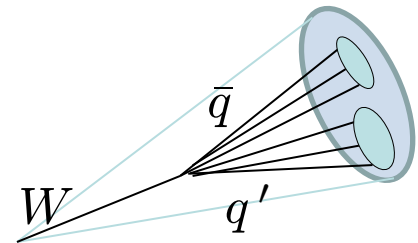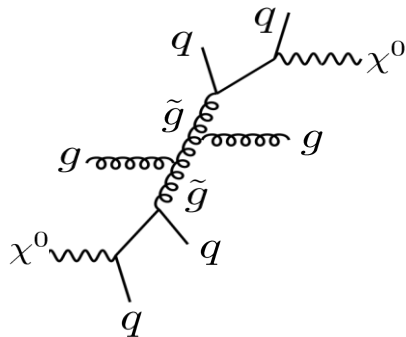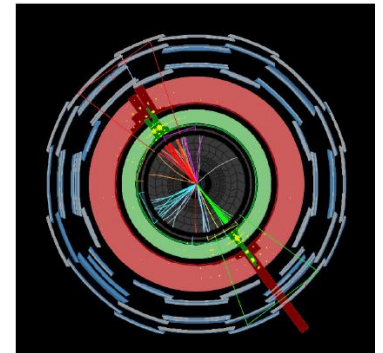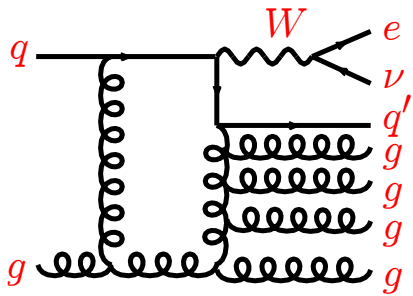# Higher Order QCD for the LHC

SLAC Summer Institute

SLAC, June 25, 2012

Zvi Bern, UCLA

- **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.

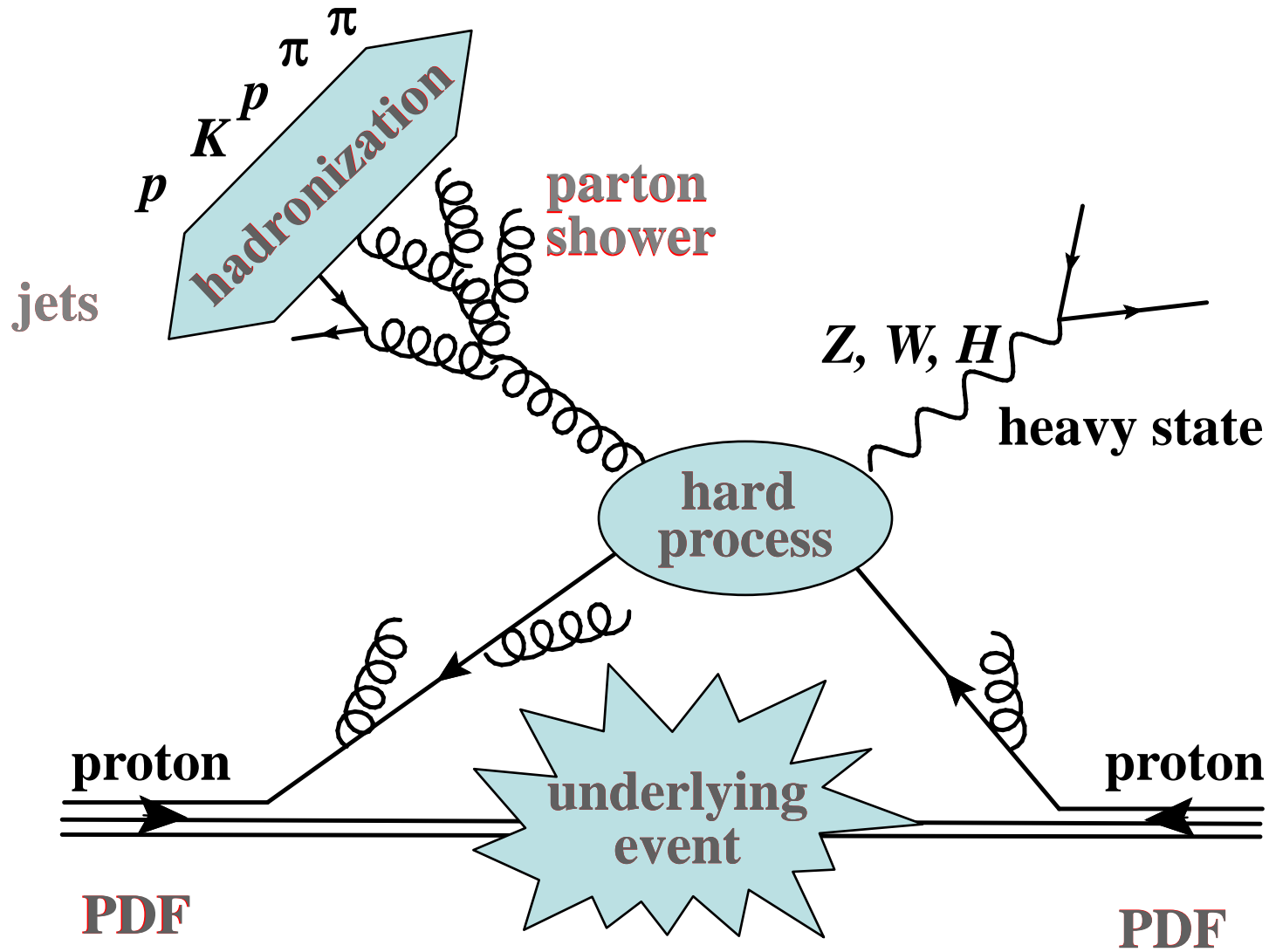# Experimenter's View of LHC Collision
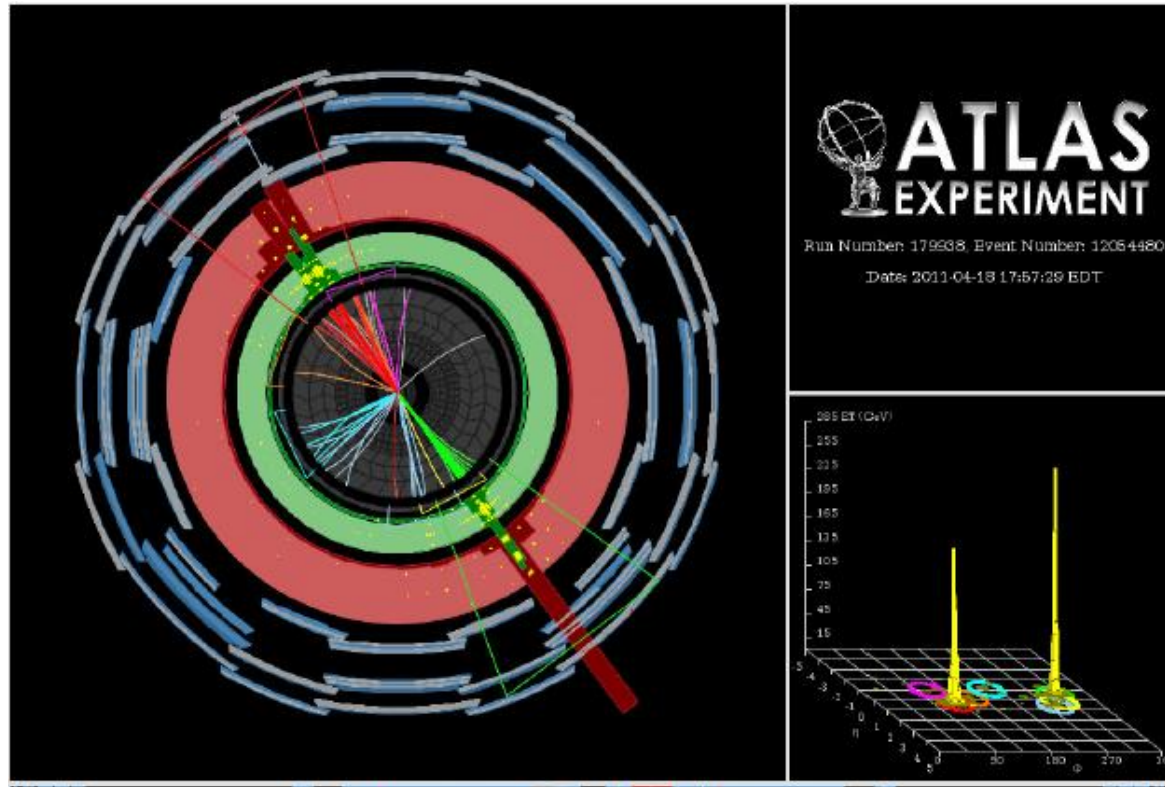
Note jets

To properly interpret we need QCD

3

Theorist's View of LHC Collision

jets

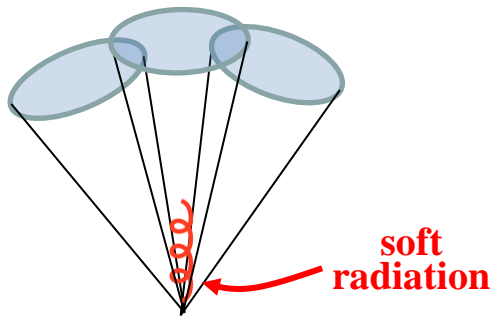π π
p π
K p
p

hadronization

parton shower

Z, W, H

heavy state

hard process

underlying event

proton

proton

PDF

PDF

**Complicated environment: many aspects of QCD must be understood**

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.
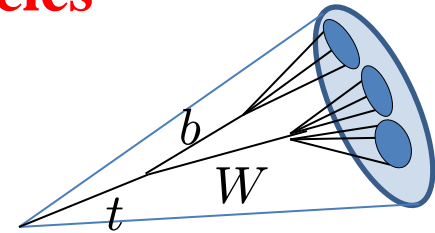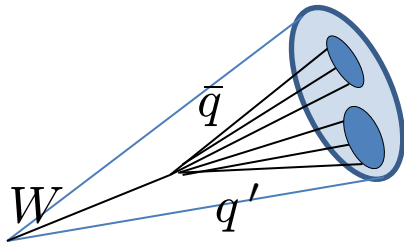
soft radiation
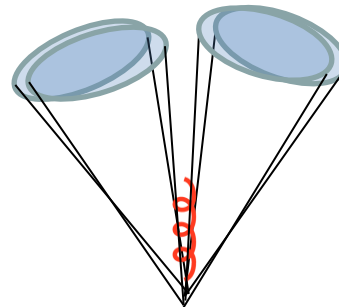
FastJet package supplies IR safe algorithms

Cacciari, Salam, Soyez

not infrared safe

infrared safe

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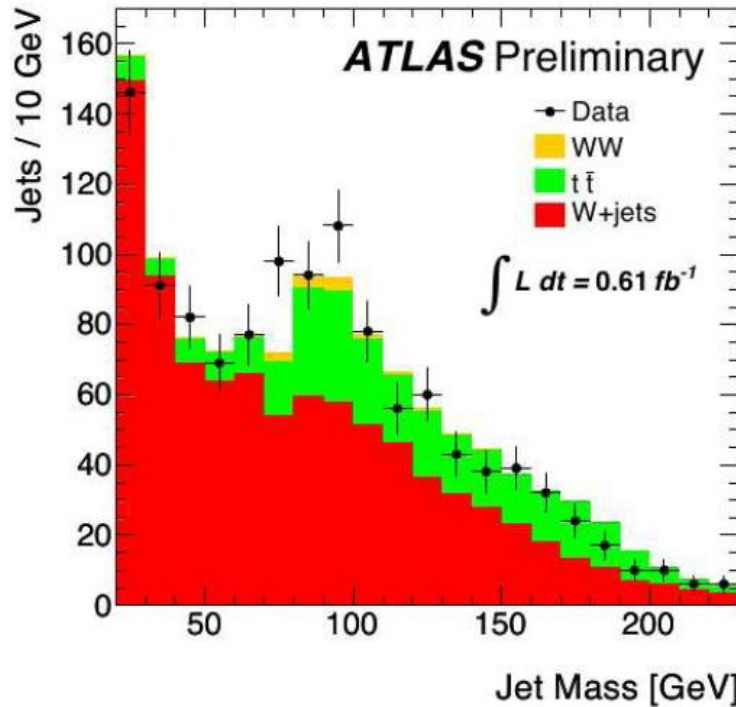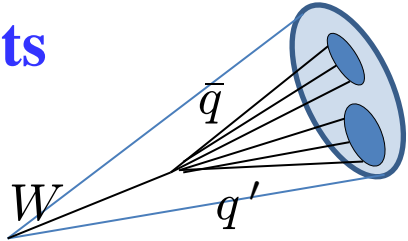
top jets
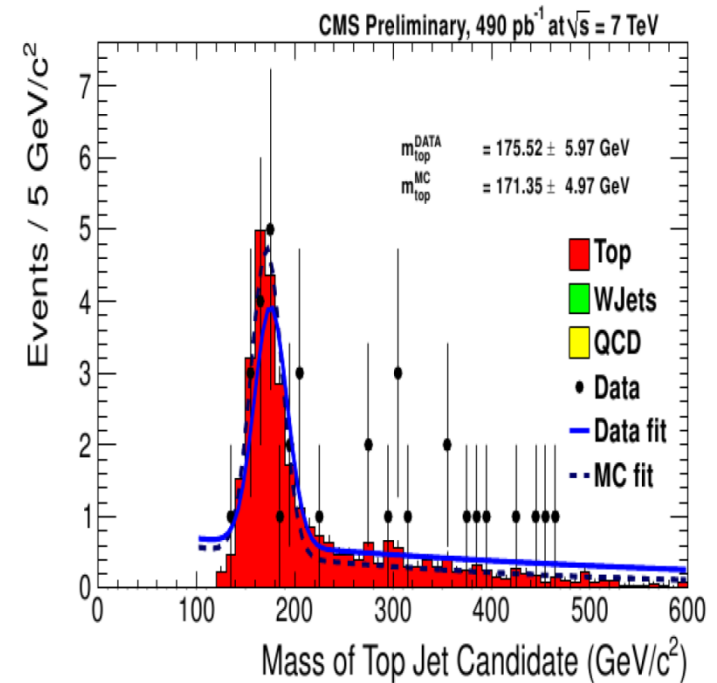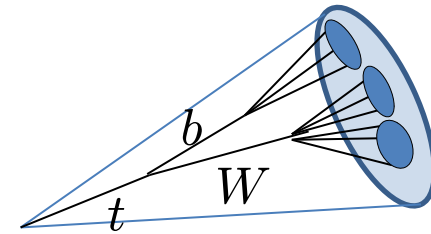
Offers a new window to search for new heavy mass states decaying into jets, previously thought to be inaccessible due to QCD background.

PDF Issues and Higgs

What's up with the gluons? Alekhin, Blumlein, Moch (arXiv:1202.2281)
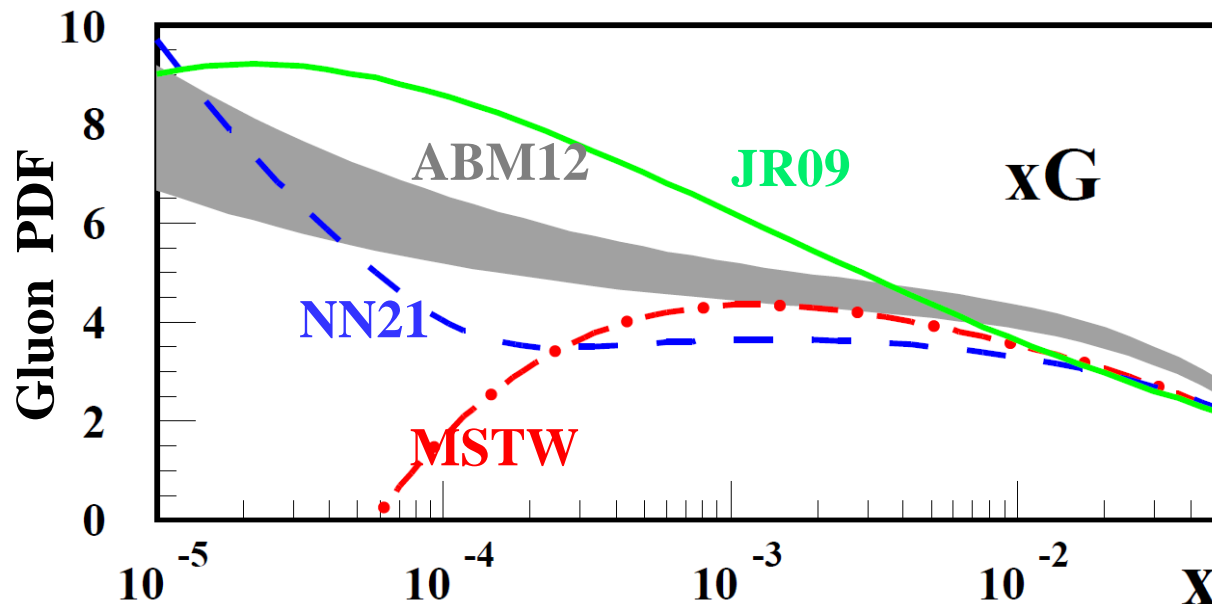
carried out in NNLO QCD

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

W + 2 jets at the Tevatron

CDF collaboration
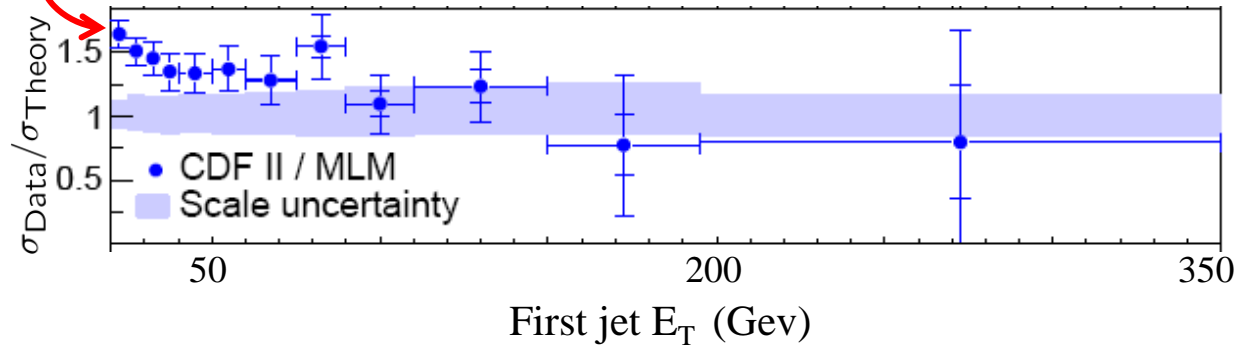arXiv: 0711.4044

LO

leading order + parton showering

NLO QCD
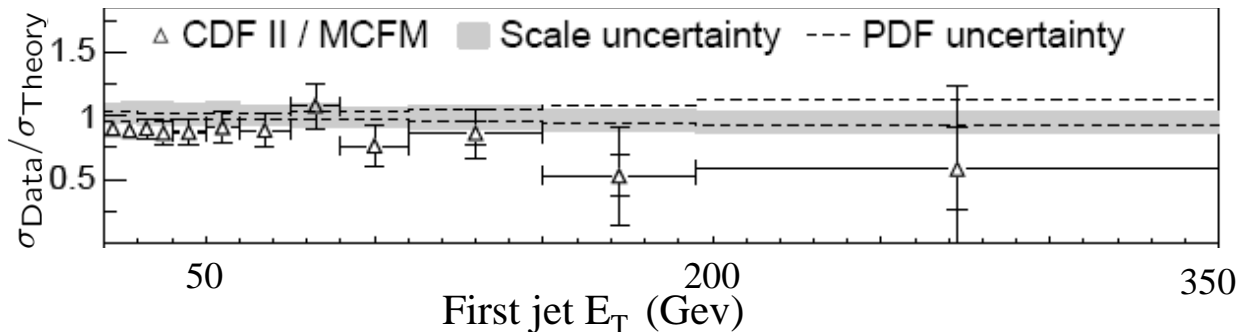
NLO does better, smallest theoretical uncertainty

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

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**
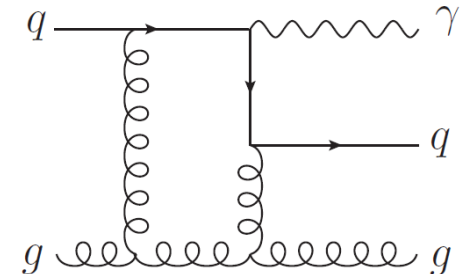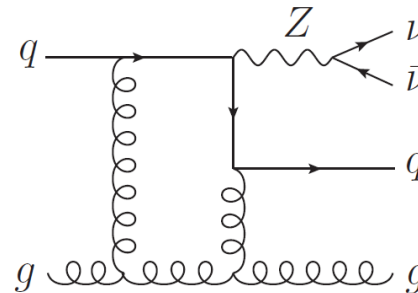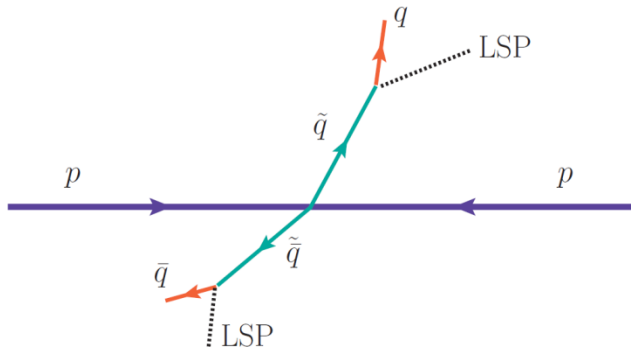
Photons have higher rate compared to $Z \to \mu\bar{\mu}$

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)

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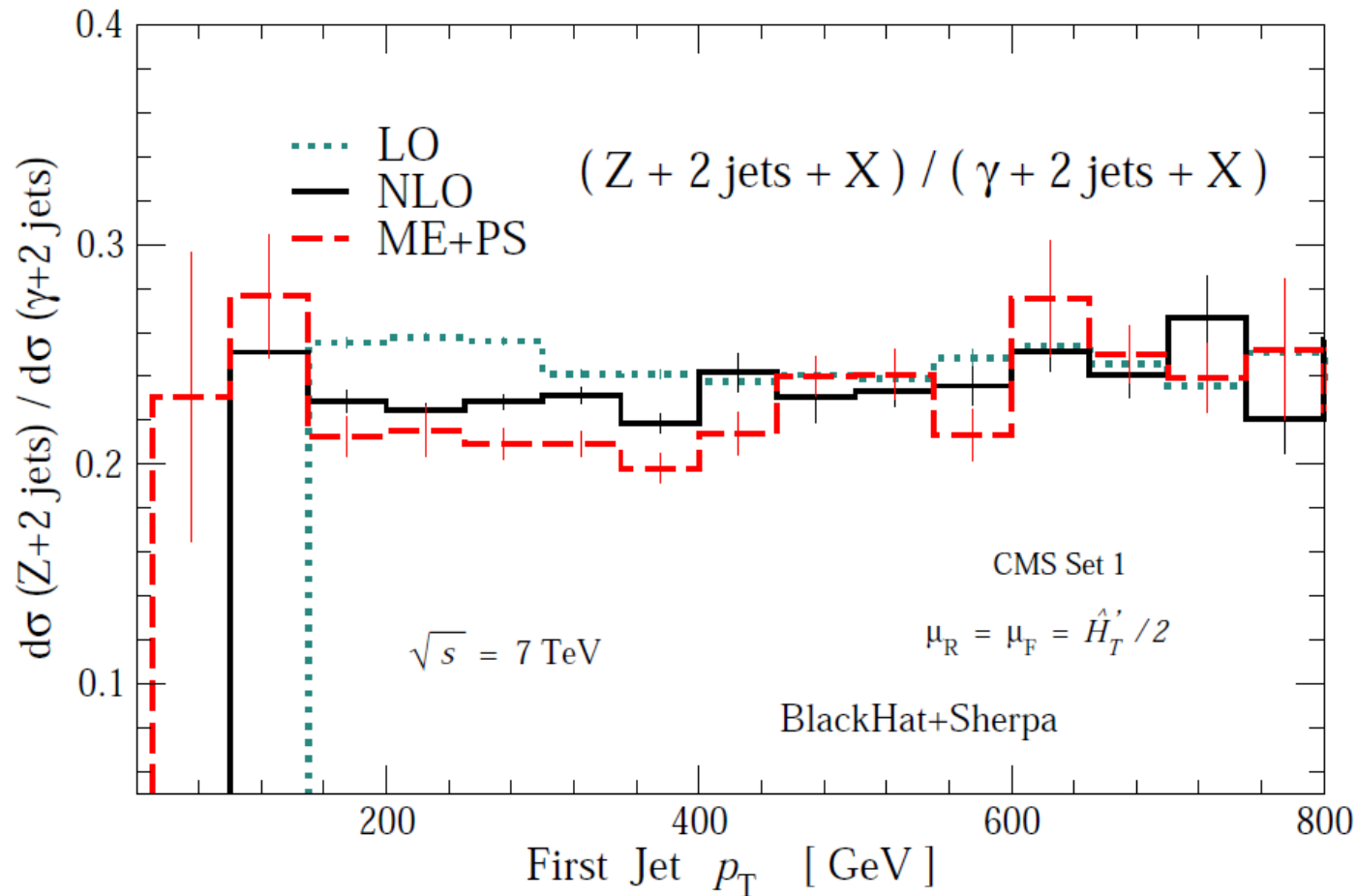
Different theoretical predictions track each other.
This conversion directly used by CMS in their estimate
of theory uncertainty in susy search.

11

The NLO revolution

2 → 1

2 → 2

2 → 3

2 → 4 (W/Z+3j, ttbb, ttjj)

1980   1985   1990   1995   2000   2005   2010
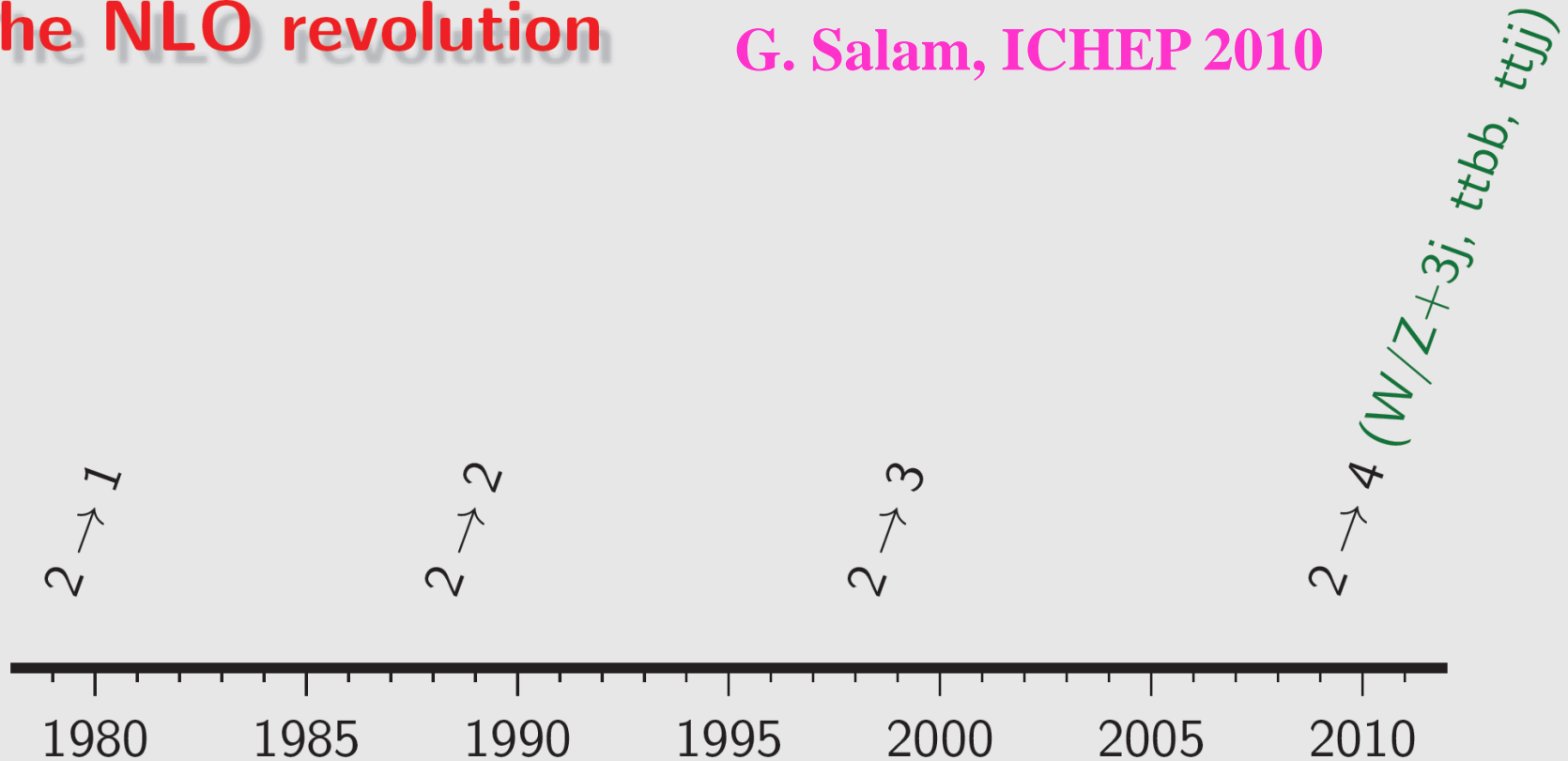
2009: NLO $W+3j$ [Rocket: Ellis, Melnikov & Zanderighi]   [unitarity]
2009: NLO $W+3j$ [BlackHat: Berger et al]   [unitarity]
2009: NLO $t\bar{t}b\bar{b}$ [Bredenstein et al]   [traditional]
2009: NLO $t\bar{t}b\bar{b}$ [HELAC-NLO: Bevilacqua et al]   [unitarity]
2009: NLO $q\bar{q} \to b\bar{b}b\bar{b}$ [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

G. Salam, La Thuile 2012

2 → 1   2 → 2   2 → 3   2 → 4 (W/Z+3j, ttbb, ttjj, ...)
                           2 → 5 (W+4j, Z+4j)
                           automation
                           2 → 6 (ee → 7j [LC])
                           2 → 6 (W+ 5j)

```
1980    1985    1990    1995    2000    2005    2010
```
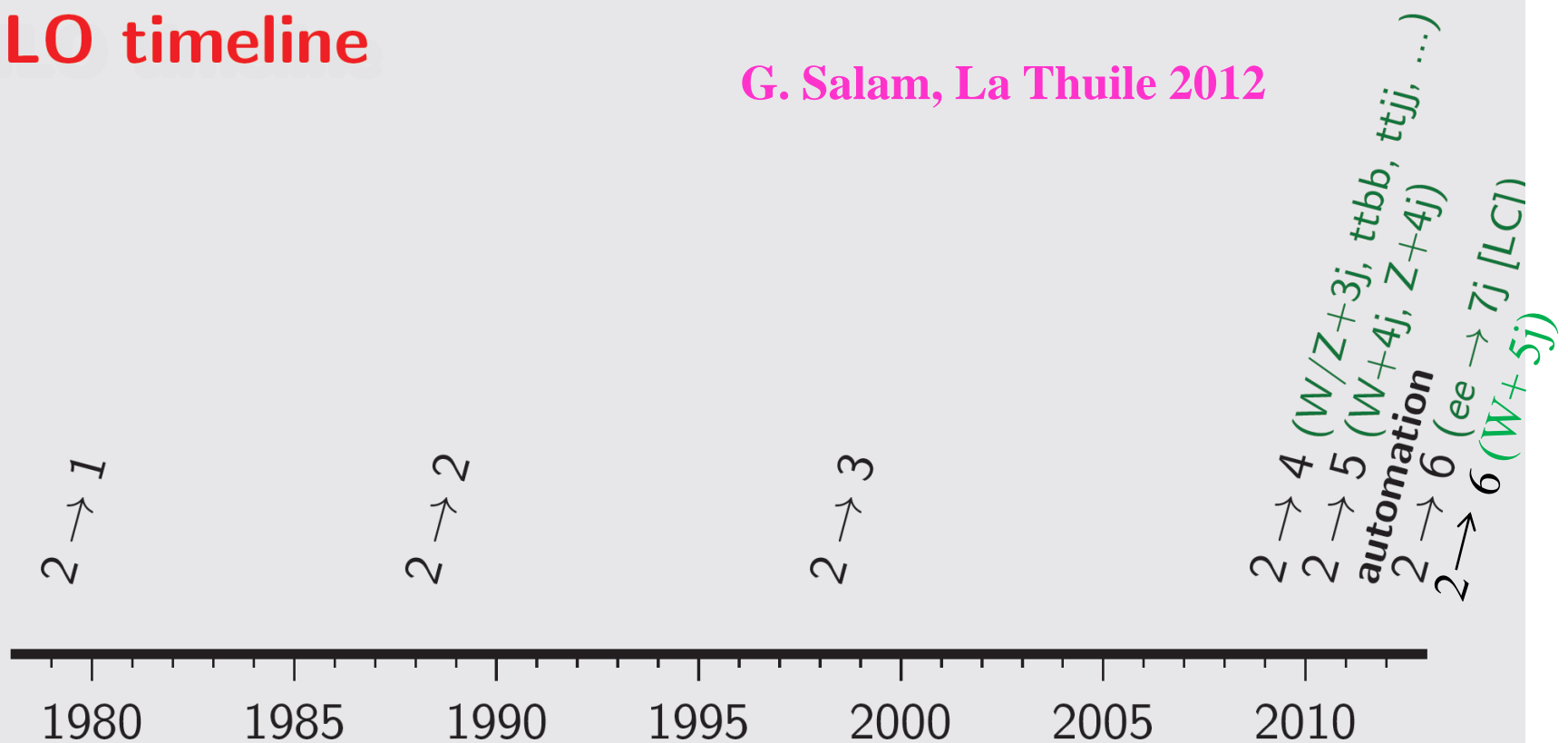
2010: NLO W+4j [BlackHat+Sherpa: Berger et al]   [unitarity]
2011: NLO $WWjj$ [Rocket: Melia et al]   [unitarity]
2011: NLO Z+4j [BlackHat+Sherpa: Ita et al]   [unitarity]
2011: NLO 4j [BlackHat+Sherpa: Bern et al]   [unitarity]
2011: first automation [MadNLO: Hirschi et al]   [unitarity + feyn.diags]
2011: first automation [Helac NLO: Bevilacqua et al]   [unitarity]
2011: first automation [GoSam: Cullen et al]   [feyn.diags(+unitarity)]
2011: $e^+e^- \rightarrow 7j$ [Becker et al, leading colour]   [numerical loops]
2012: NLO W+5j [BlackHat+Sherpa, preliminary]   [unitarity]

Some Advances

on-shell

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

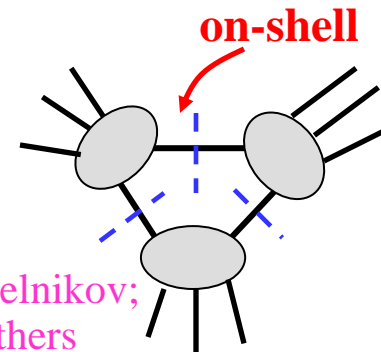 ZB, Dixon, Dunbar, Kosower ; ZB, Morgan; ZB, Dixon, Kosower;
  Britto, Cachazo and Feng; Anastasiou, Britto, Feng, Kunszt, Mastrolia;
  Giele, Kunszt, Melnikov; Badger; Ossola, Papadopoulos, Pittau; Giele, Kunszt, Melnikov;
  Forde; Berger, ZB, Kosower, Forde, Gleisberg, Hoeche, Ita, Maitre, Ozeren;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

14

Example: Susy Search
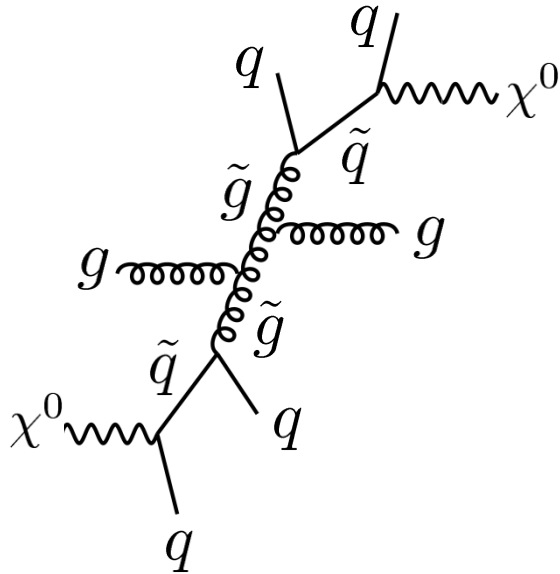
- **Cascade from gluino to neutralino (escapes detector)**
- **Signal: missing energy + 4 jets**
- **SM background from Z + 4 jets, $Z \rightarrow$ neutrinos**

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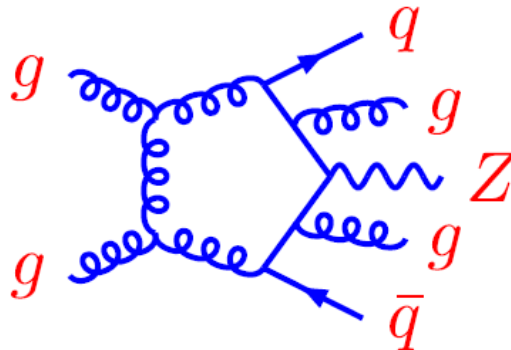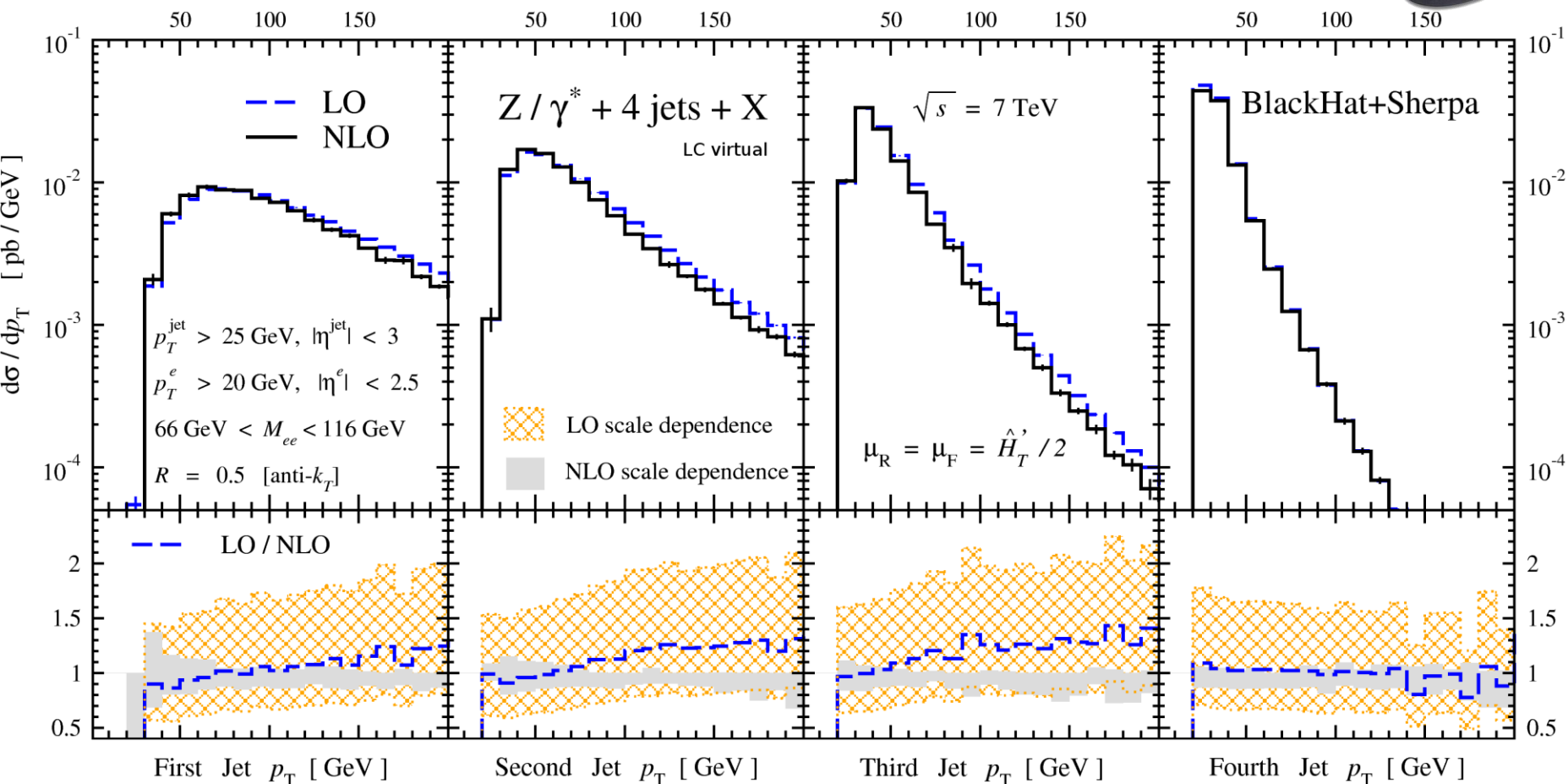
Z+4 Jets at NLO

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

- Big improvement in scale stability.
- Best available theoretical predictions.
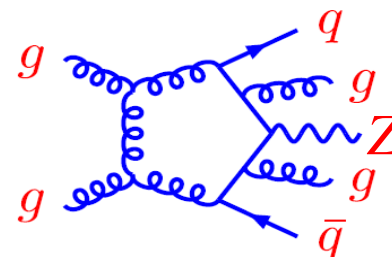
ATLAS Comparison Against NLO QCD

Z +1, 2, 3, 4 jets inclusive
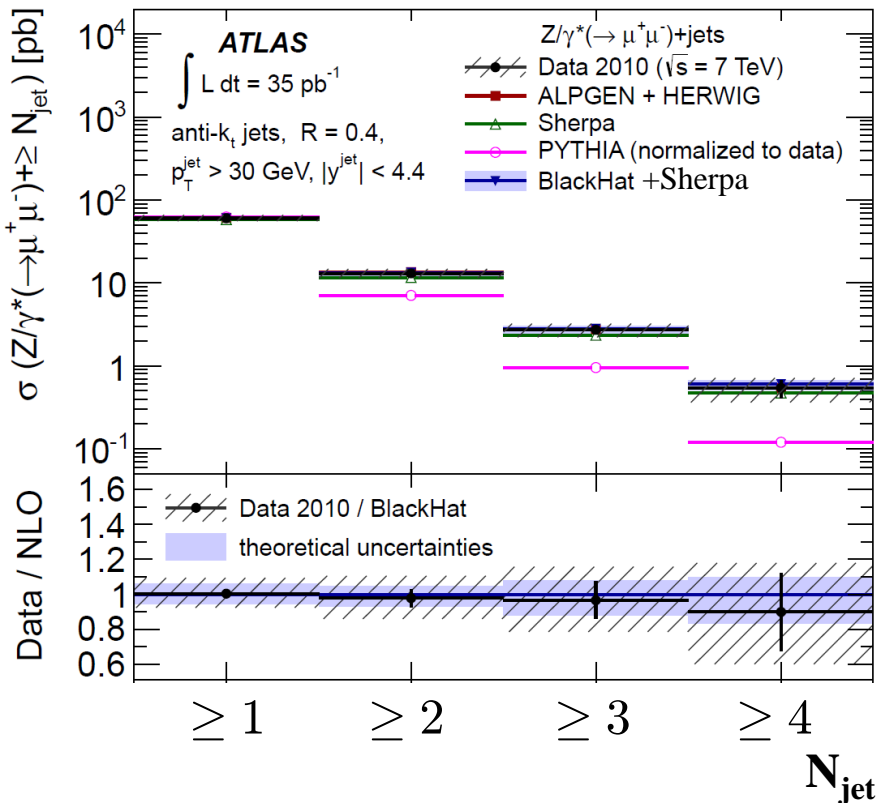
Powerful experimental confirmation of NLO approach. With these experimental cuts no new physics is expected.

We look forward to higher precision data.

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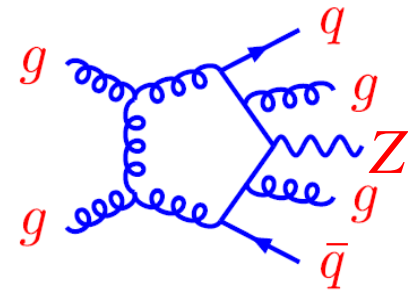
- **Even *W*+5 jets at NLO nearly complete.** **see K. Ozeren's talk at LoopFest 2012**
- **Serious advance in our ability to do NLO calculations.**

17

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

A very nice example from HELAC-NLO: $t\bar{t} + 2$ jet production
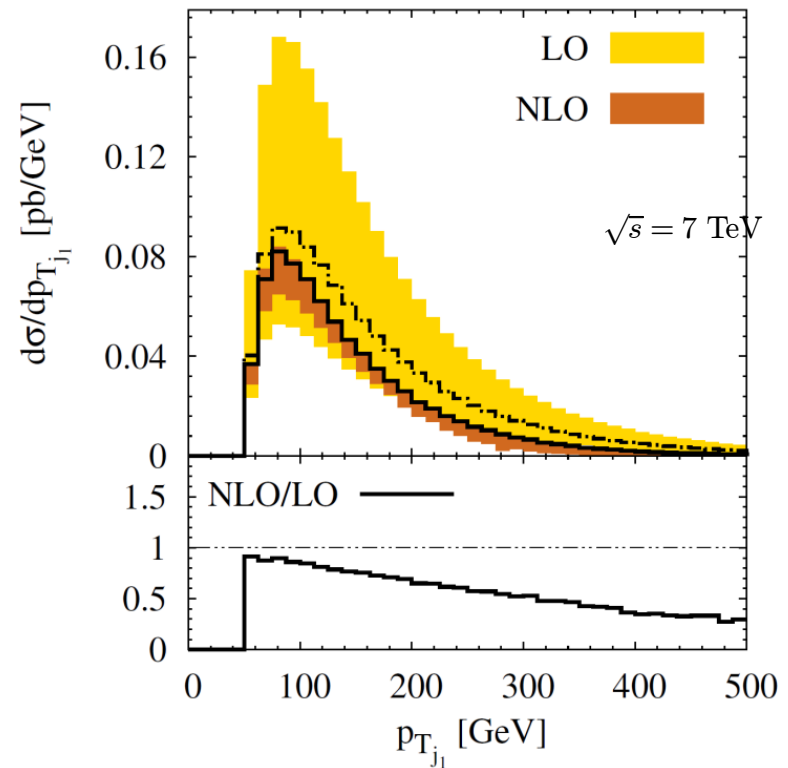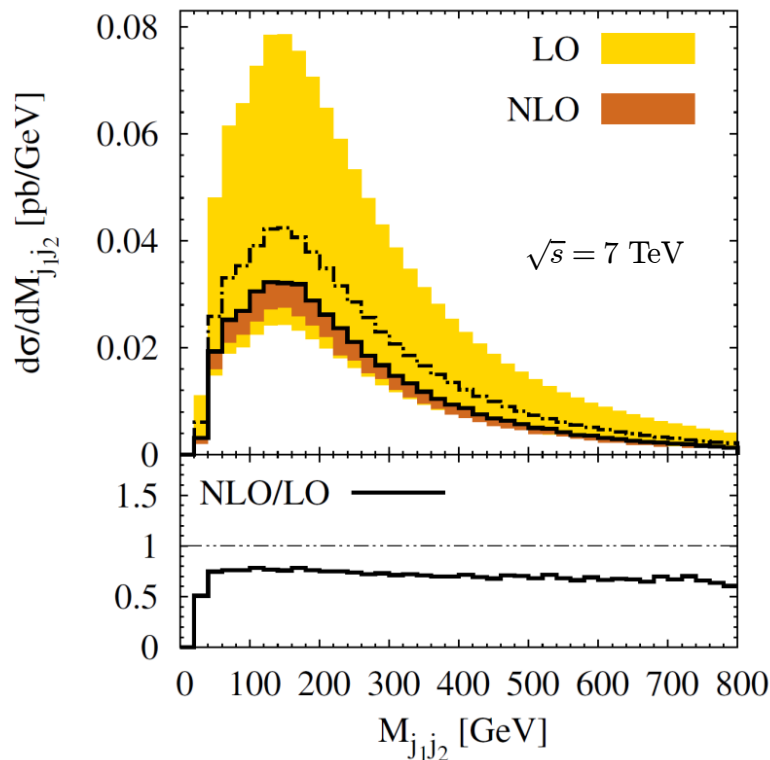
Besides the enormous reduction in scale uncertainty, large changes in shape between LO and NLO are evident for some distributions.

18

Merging NLO with Parton Showers

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

matches shower at low p_T
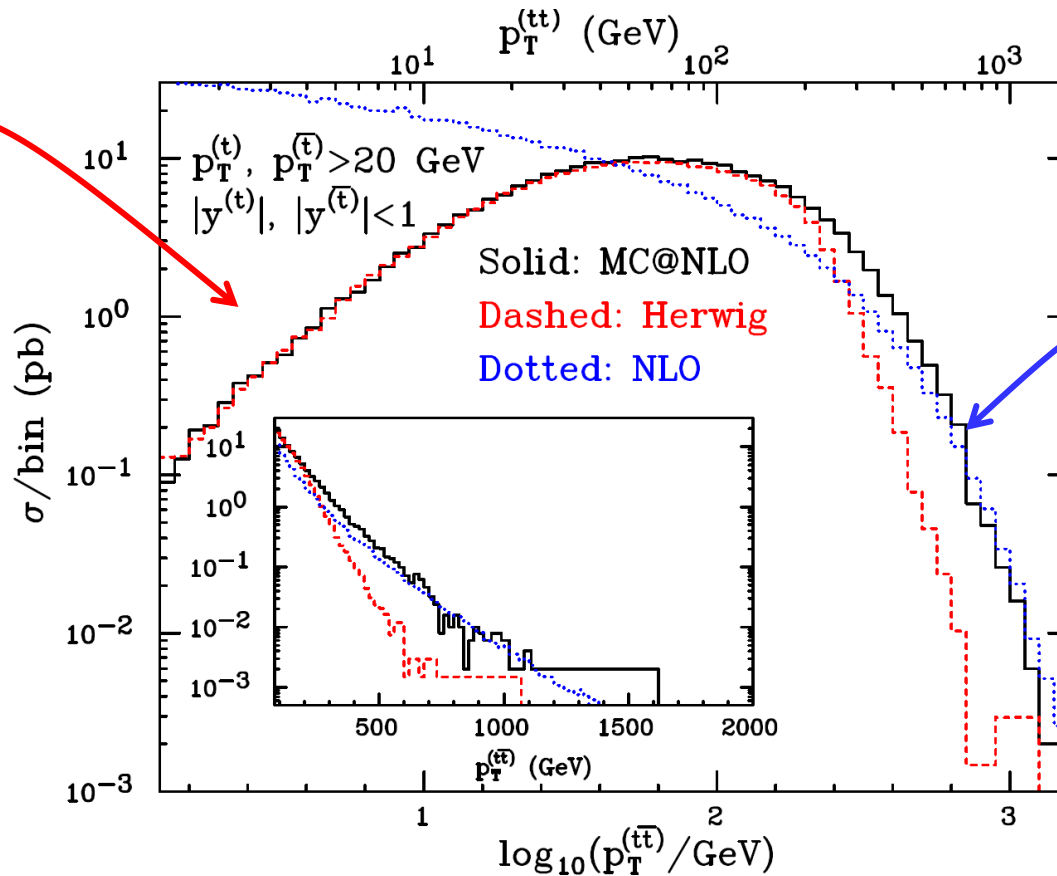
matches NLO at high p_T

MC@NLO uses Herwig

Solid: MC@NLO
Dashed: Herwig
Dotted: NLO

$p_T^{(t)}$, $p_T^{(\bar{t})} > 20$ GeV
$|y^{(t)}|$, $|y^{(\bar{t})}| < 1$

$p_T^{(t\bar{t})}$ (GeV)

σ/bin (pb)

$\log_{10}(p_T^{(t\bar{t})}/\mathrm{GeV})$

$p_T^{(t\bar{t})}$ (GeV)

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

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

An application of NLO + parton showers has been to look at CDF dijet anomaly.
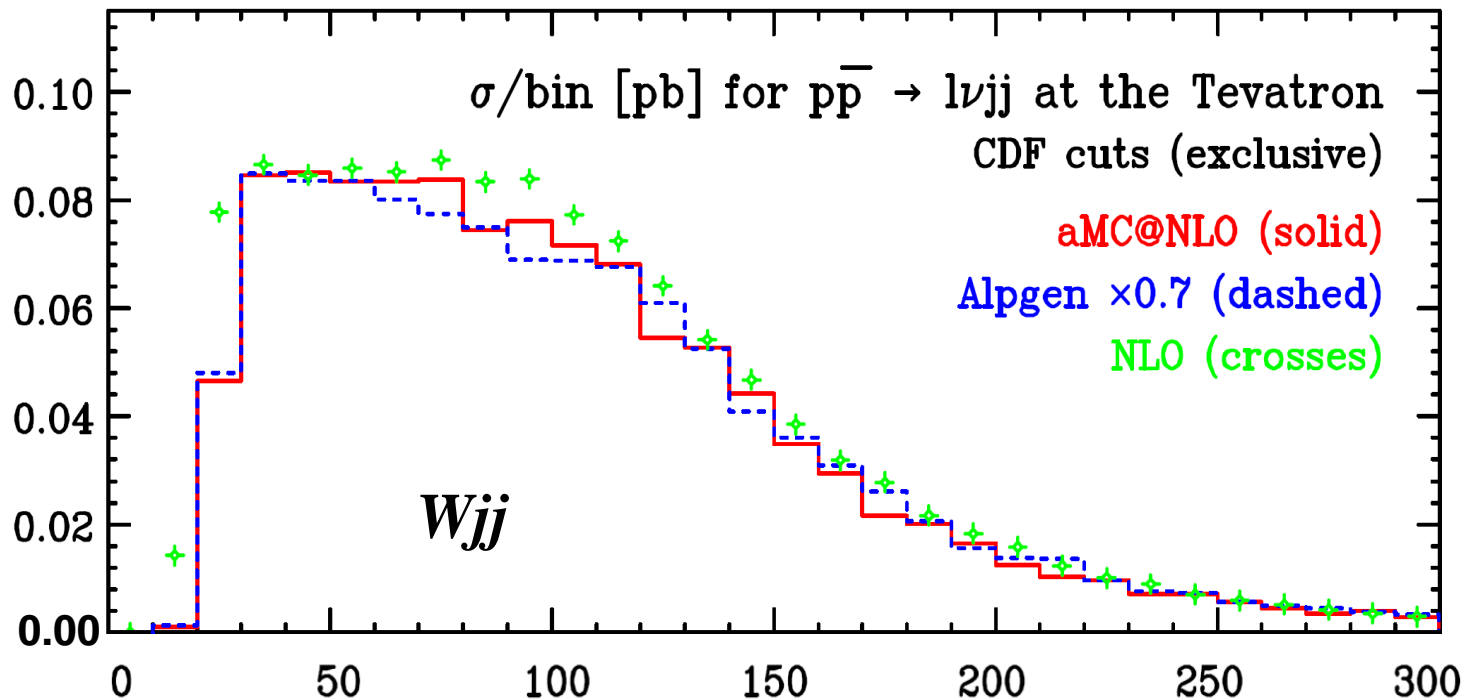
- **CMS used Alpgen (scaled). NLO has a slightly different shape.**
- **aMC@NLO is close to Alpgen, so it looks that QCD is under good control.**

Recent state-of-the-art example

Hoeche, Krauss, Schoenherr, Siegert

Jet transverse momenta

SHERPA+BLACKHAT
W+1,2,3 jets

- ATLAS data
- NLO
- MC@NLO 1em
- MC@NLO PL

nonperturbative not included

$p_\perp$(first jet)

$p_\perp$(second jet)

$p_\perp$(third jet)

jet transverse momentum [GeV]

$d\sigma/dp_\perp$ [pb/GeV]
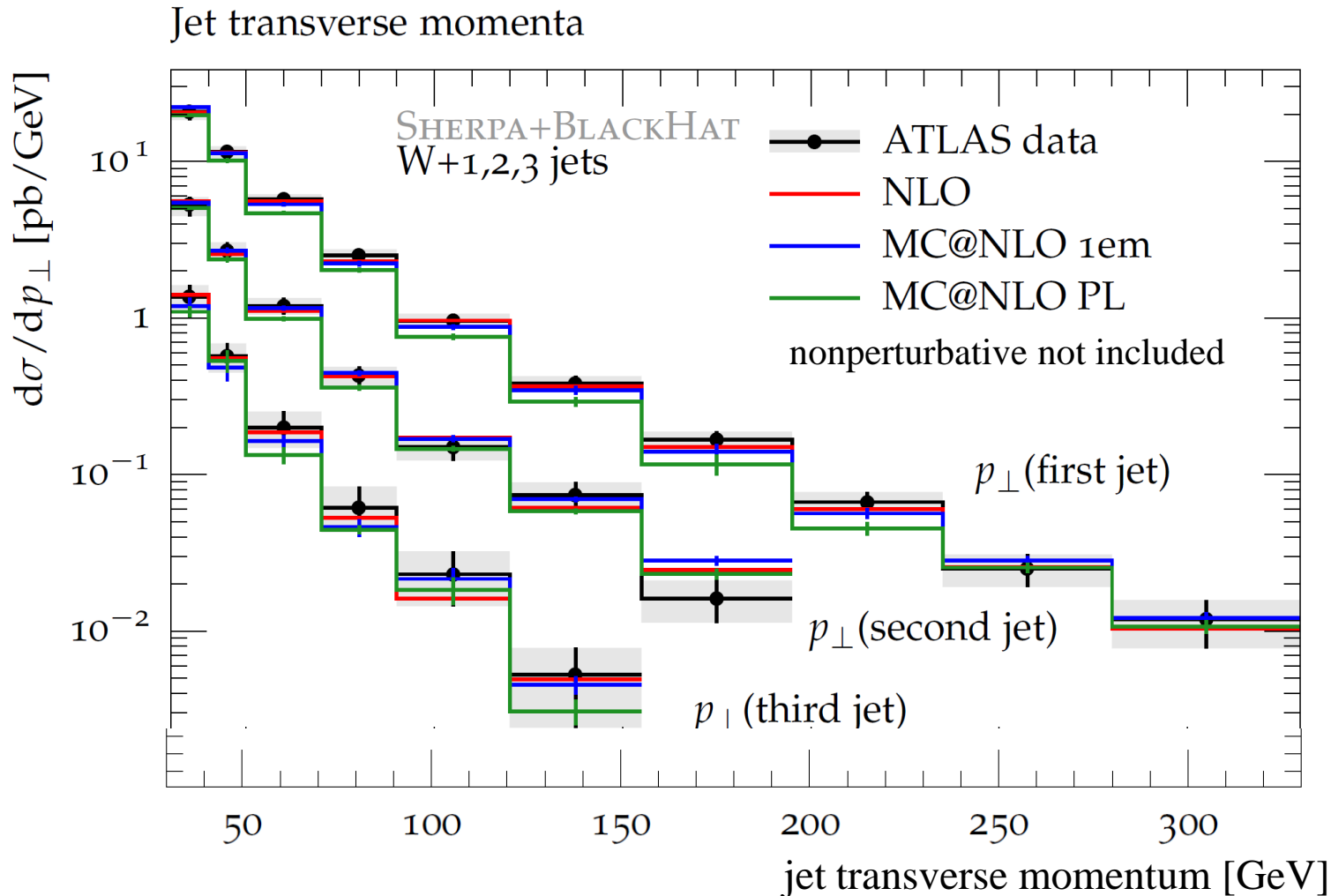
Nontrivial example of $W+3$ jets based on MC@NLO framework

Catani, Cieri, de Florian, Ferrera, Grazzini

σ(fb)

CMS cuts (Higgs) MSTW 08

μ_R and $\mu_F = (2, 1/2) M_{\gamma\gamma}$

NNLO+N³LO terms

LHC 7 TeV

NNLO $K = 1.43$
±8.5%

$K = 1.55$ @14TeV

NLO

±8%

LO

±6.5%

SM Higgs $M_{\gamma\gamma}$ (GeV)

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

α^2

$\alpha^2 \alpha_s$

$\alpha^2 \alpha_s^2$
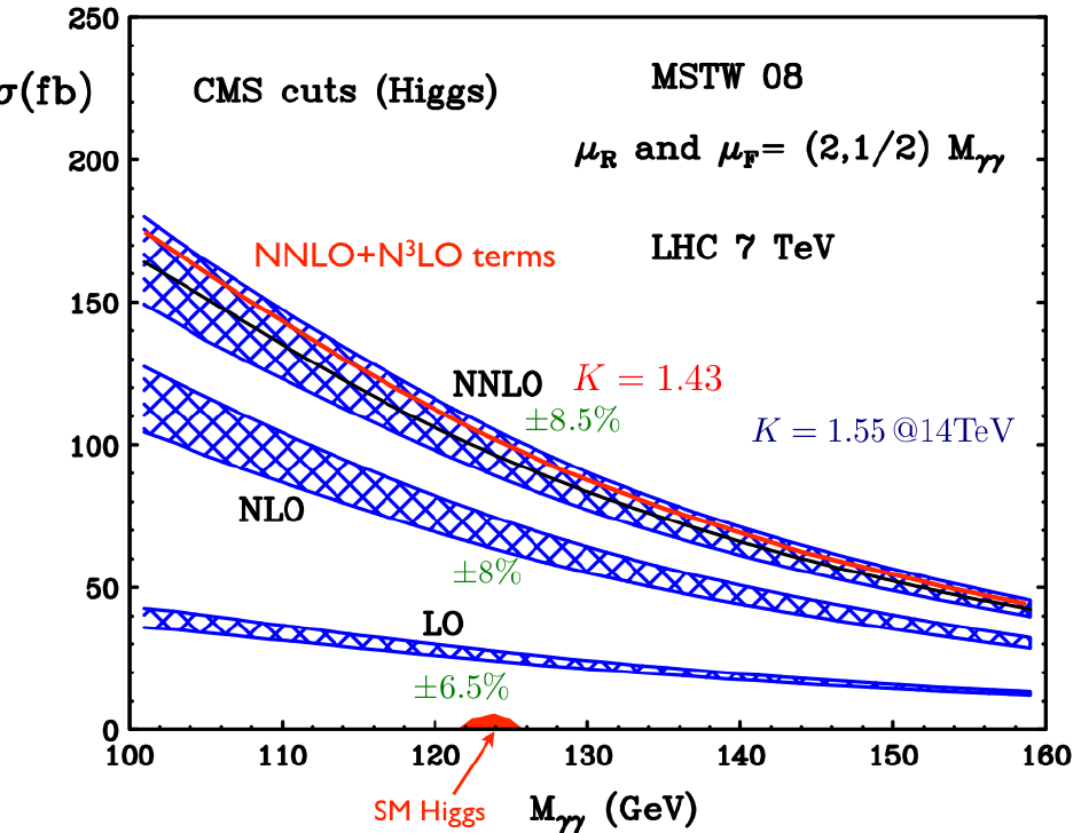
- **Example where NNLO is very useful.**
- **By NNLO all channels open.**
- **Known N³LO terms don't cause large shift.**
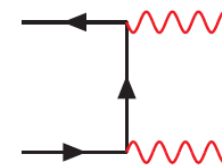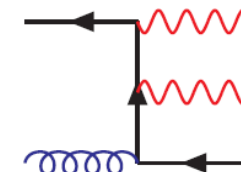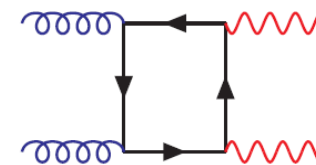
LHC is glue factory so box contribution is same order as born

ZB, Dixon, Schmidt

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

Barnreuther, Czakon and Mitov (arXiv:1204.5201)

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

contributions at NNLO Sufficient for Tevatron
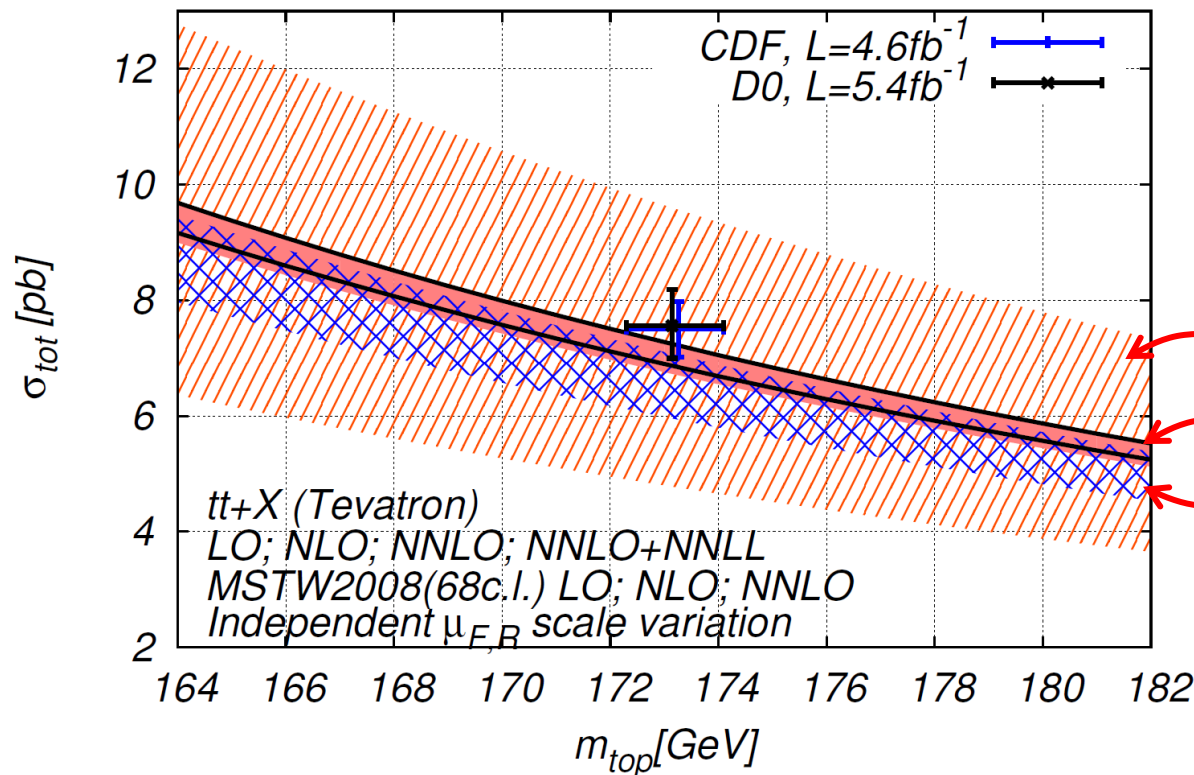
First complete NNLO calculation with four colored partons

LO

NNLO

NLO

May be helpful for understanding A_{FB}

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

24

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

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

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

fixed order diverges

$pp \rightarrow H+X$ $m_H=125$ GeV

$\sqrt{s}=14$ TeV   MSTW2008

NLO

NNLL+NLO

$d\sigma/dq_T$ (pb/GeV)

q_T (GeV)   **Higgs transverse momentum**
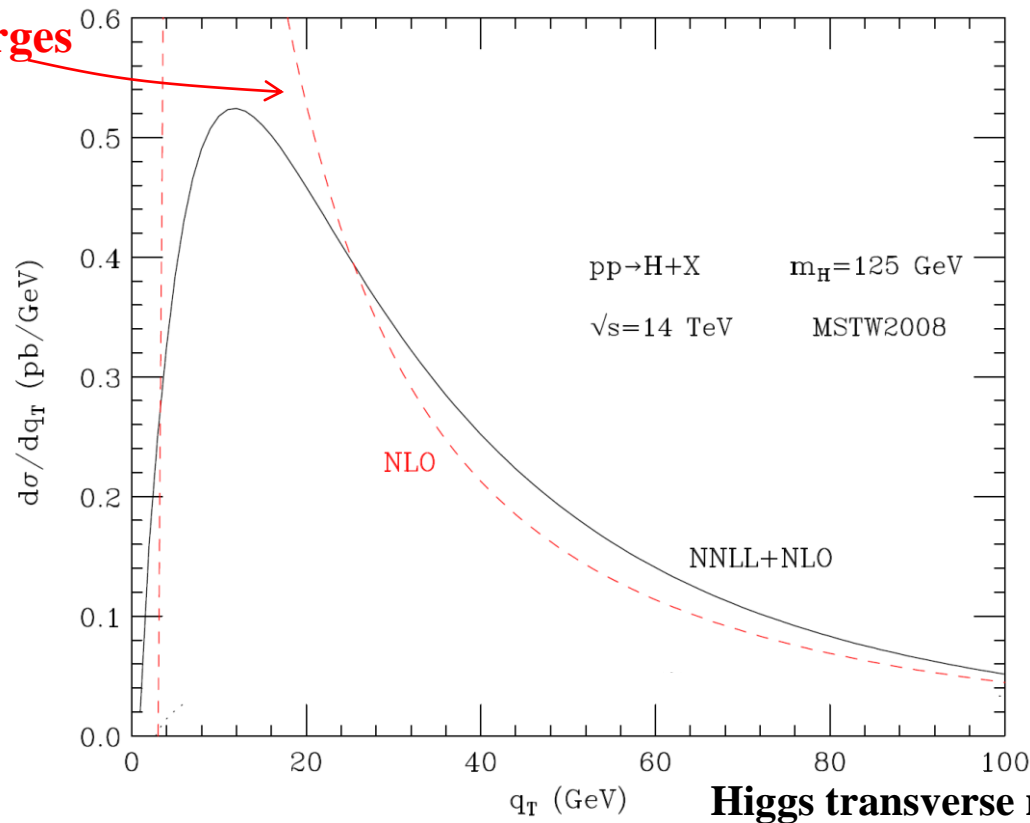
Recent example of NNLL resummation matched to NLO QCD

See also Ahrens, Becher, Neubert and Yang (arXiv:1008.3162) with N³LL

25

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
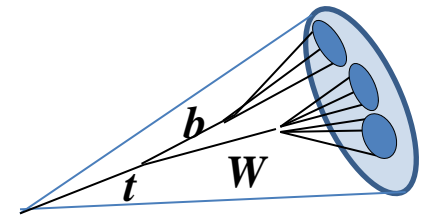
• **N-subjetiness**   Thaler and van Tilburg (arXiv:1011.2268,1108.2701), Kim (arXiv:1011.1493)

$$0 \leq \tau_N \leq 1$$

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

$\beta = 1$ 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

145 GeV < m_j < 205 GeV
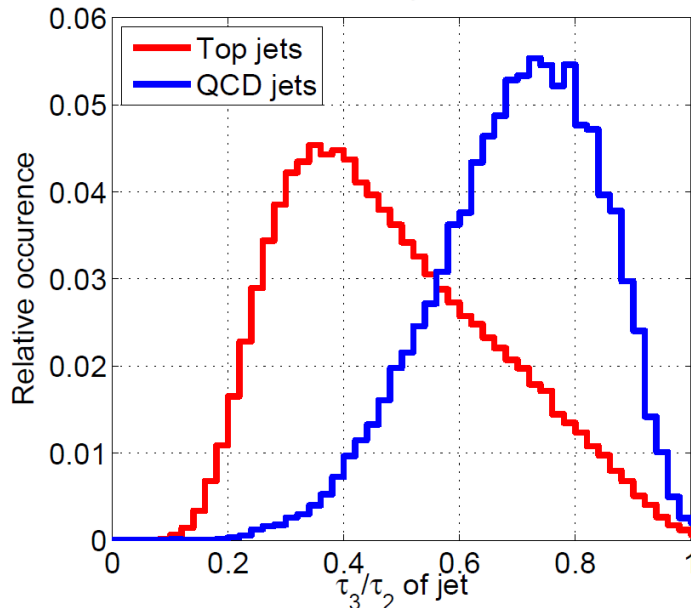
Many other ideas, e.g.:

• **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   28

Some NLO QCD Theoretical Developments

on-shell

- **Unitarity method.**   ZB, Dixon, Dunbar, Kosower (1994,1998).

- **Complex momenta in generalized cuts.**

  Britto, Cachazo, Feng (2004).

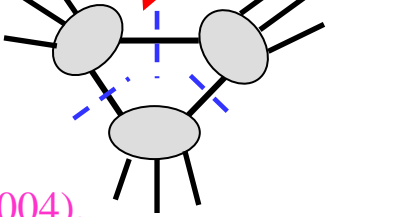- ***D* dimensional unitarity to capture rational pieces of loops.**
  ZB, Morgan (1995); ZB, Dixon, Dunbar, Kosower (1996), ZB, Dixon, Kosower (2000); Anastasiou, Britto, Feng, Kunszt, Mastrolia (2006); Giele, Kunszt, Melnikov (2008); Badger (2009)

- **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)

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

P_T spectrum of 5th jet
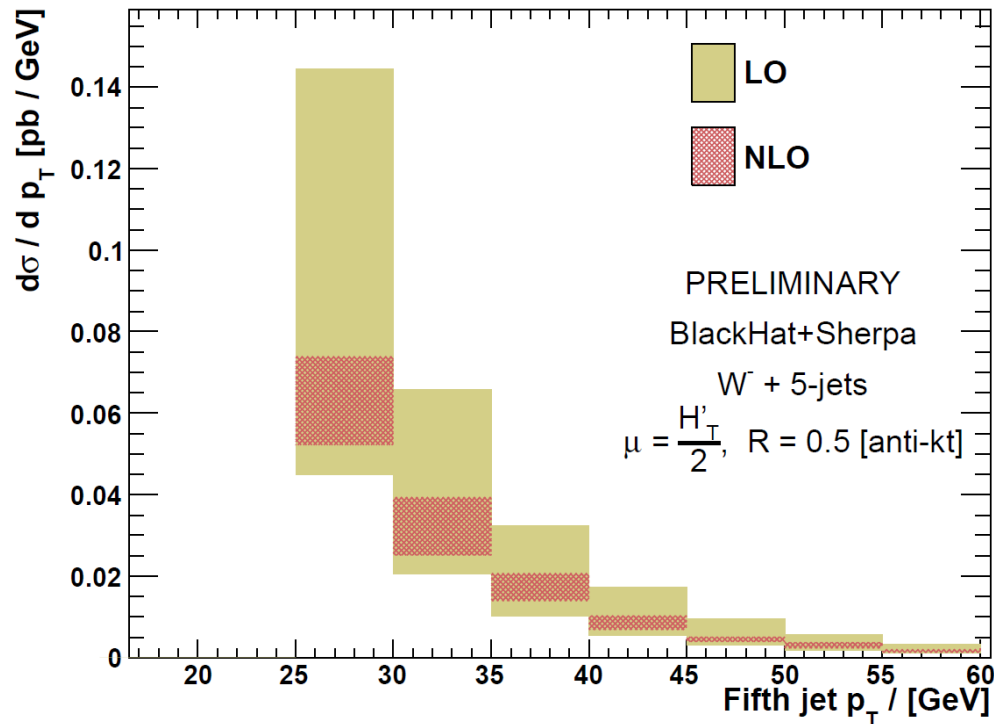
Variations of renormalization and factorization scales by factors of 2 are shown

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.**

30

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

Catani, Cieri, de Florian, Ferrera, Grazzini (arXiv: 1110.2375)
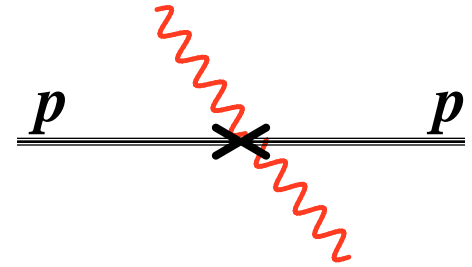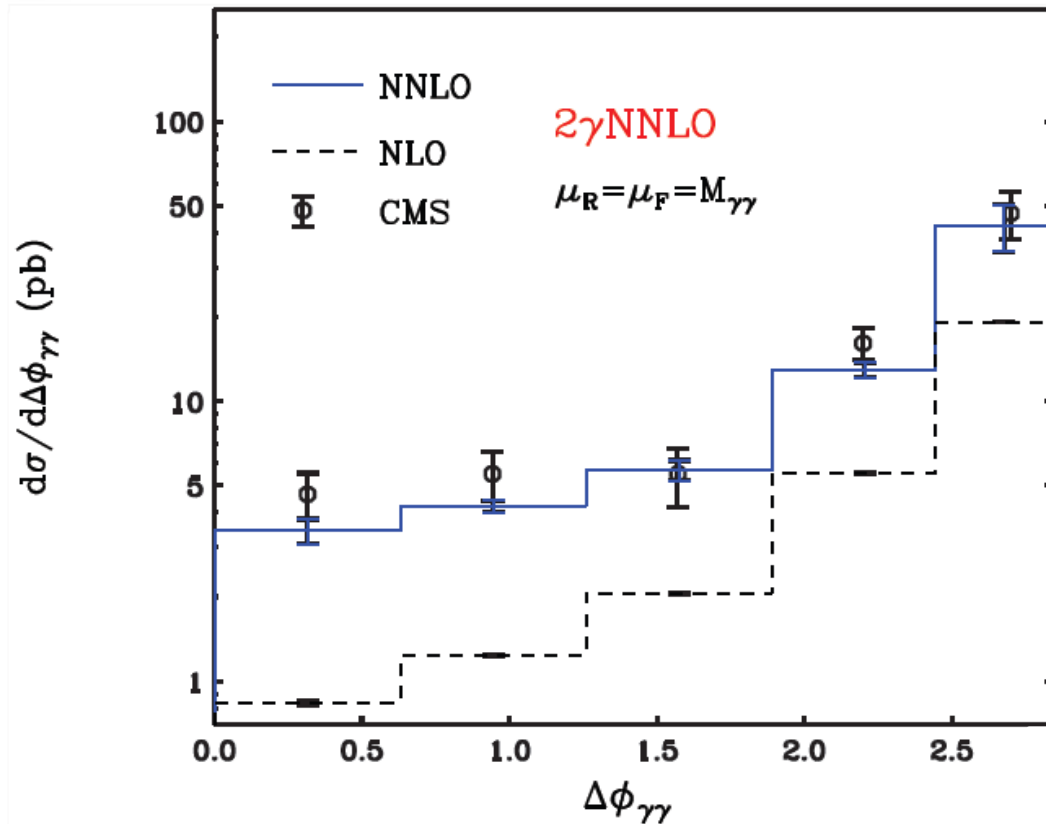
In LO QCD $\Delta\phi_{\gamma\gamma} = \pi$
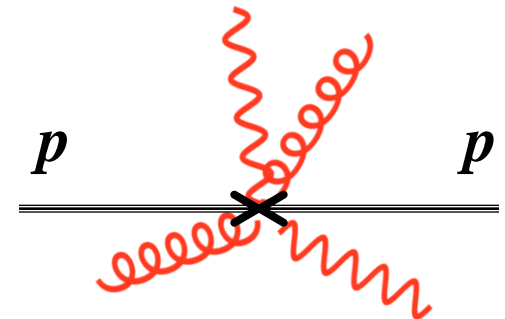
In NLO and NNLO QCD
$\Delta\phi_{\gamma\gamma} \leq \pi$

- **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.**

32