Developments in (p)QCD

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Present Status of QCD

✓ Thanks to LEP, HERA and the TEVATRON
QCD now firmly established theory of strong interactions

✓ We have gained a lot of confidence in comparing theoretical predictions with experimental data

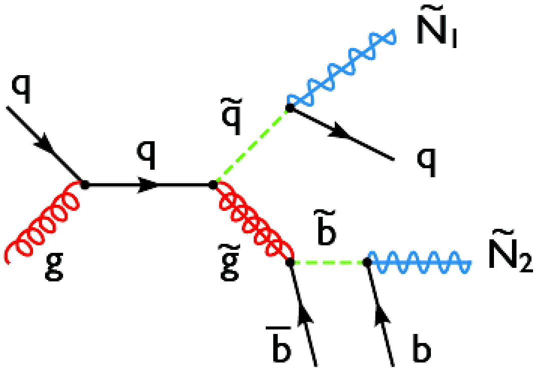
✓ No major areas of discrepancies

?? But LHC brings new frontiers in energy and luminosity

?? typical SM process is accompanied by multiple radiation to form multi-jet events

?? most BSM signals involve pair-production and subsequent chain decays

SUSY:



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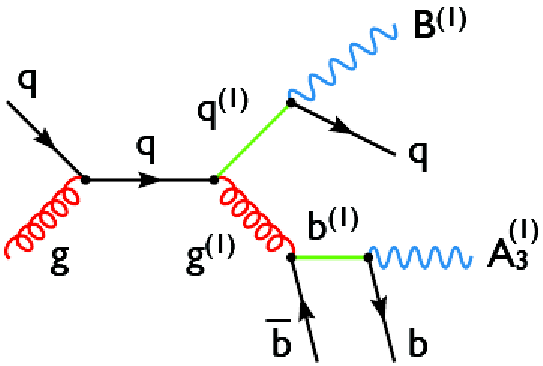
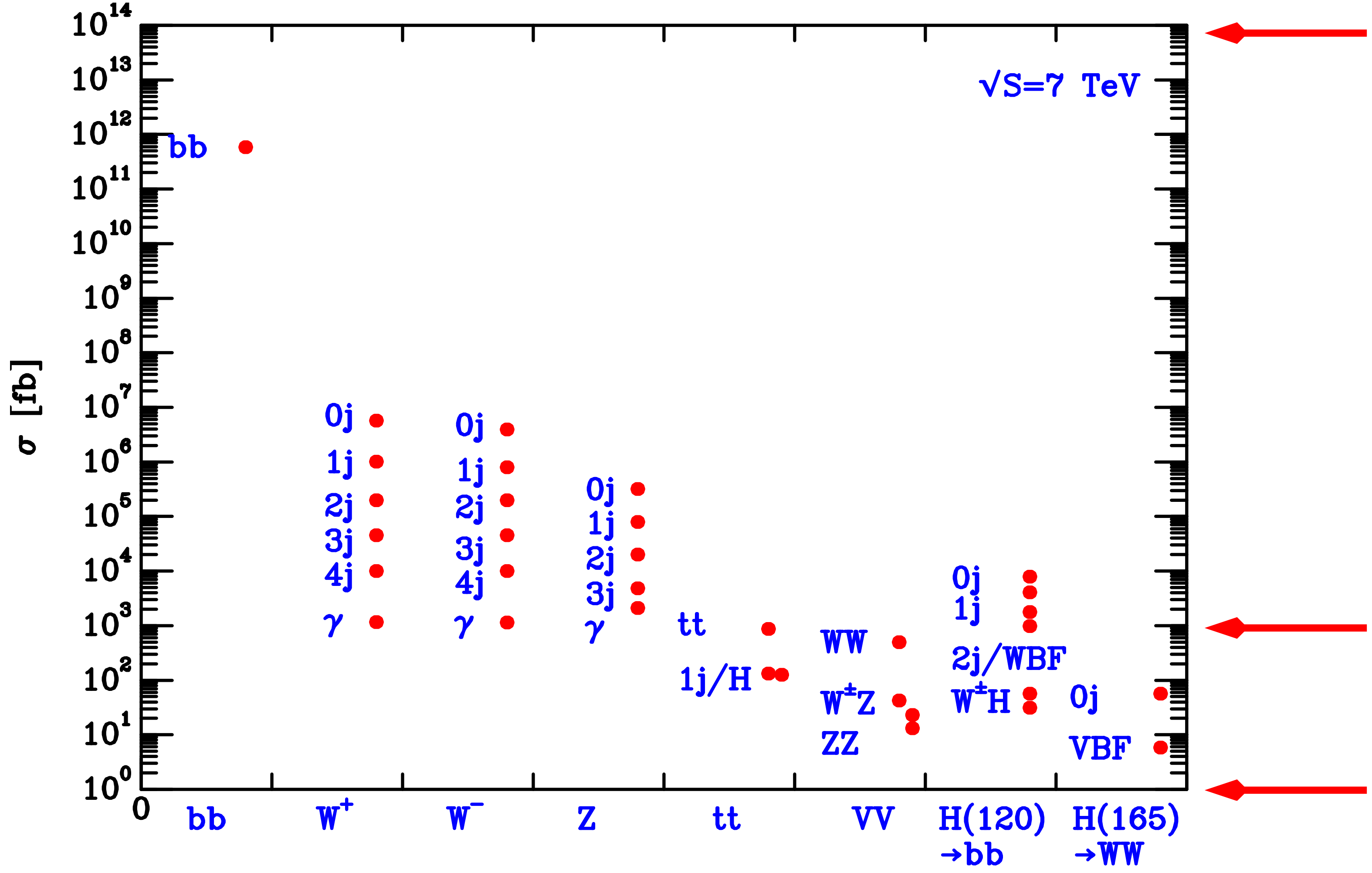


Key question

- ?? Do we have the necessary theoretical understanding about QCD to face up to the challenge that is the LHC?
- !! Hard emission is less suppressed at LHC energies
  Previously, three effects ensured the suppression of hard radiative corrections:
  - !! increasing powers of the coupling
  - !! rapid decrease of pdfs at higher values of x
  - !! limit on available phase space when E_{object} (M_W or jet E_T cut) is not significantly smaller than $\sqrt{s}$
- !! New problem in the LHC-era where multiparticle final states are the signal for new physics

SM cross sections at the LHC Ellis (10)



✓ Includes decay of W/Z to one species of charged lepton and semi-leptonic decay of top ($t \to b\ell\nu$) (where applicable) and jets, $E_T > 25$ GeV

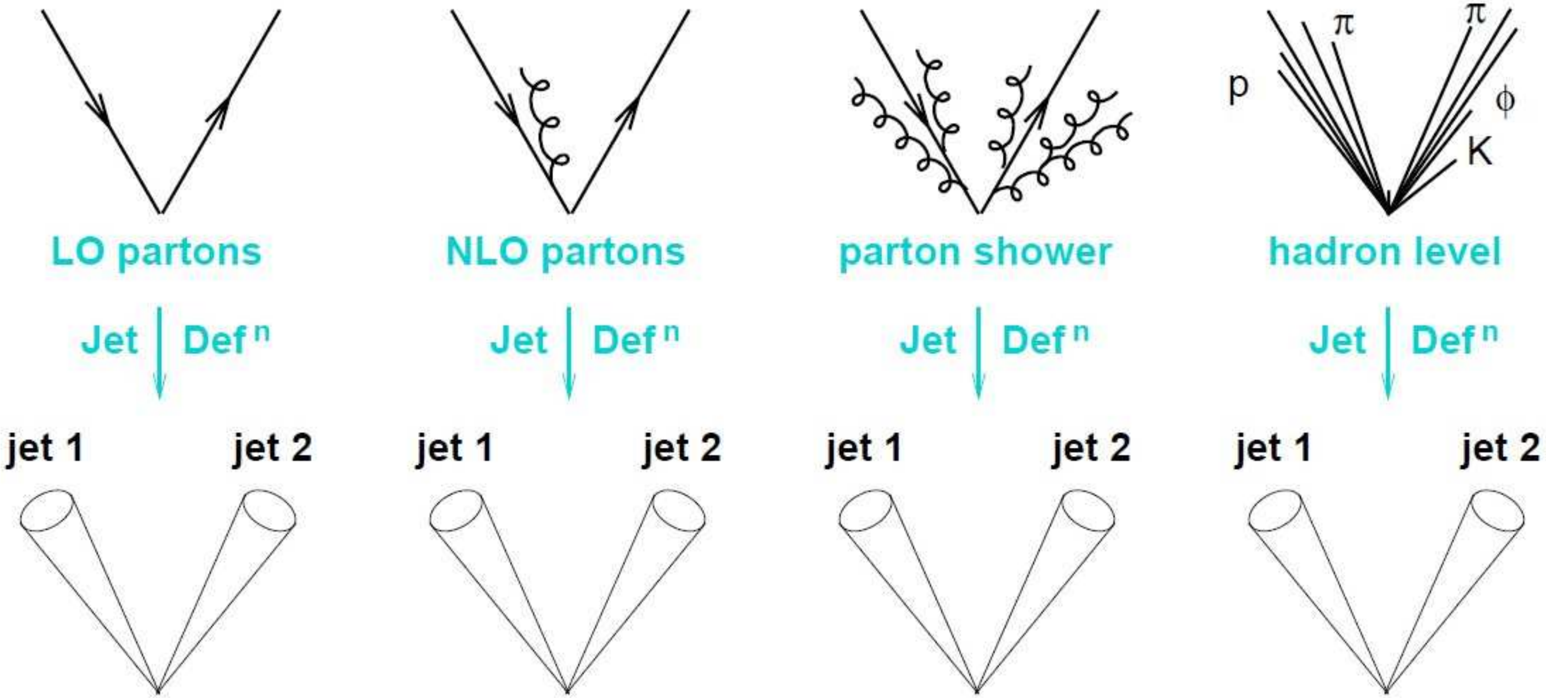
What is covered in this talk

1. Jets
2. NLO multiparticle production
3. NNLO precision observables
4. Parton density functions

1. Jets

Jets

- ✓ Final-state signature of quark and gluon production
- ✓ Defined through a jet algorithm



- ✓ Project any number of particles onto finite number of jets

  \- but must be insensitive to collinear and soft radiation

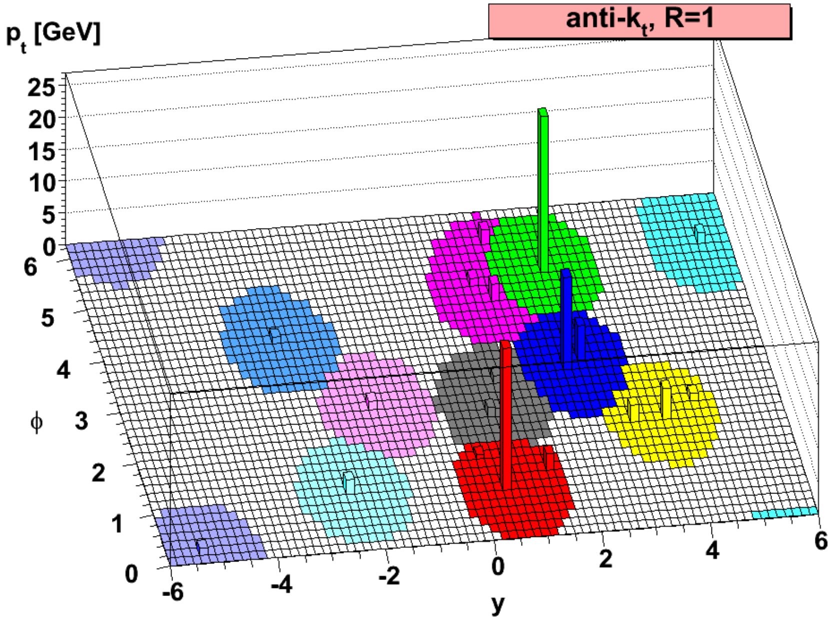
A new general-purpose jet algorithm - anti-kT

Compute the smallest "distance" d_{ij} or d_{iB} and either cluster i and j together or identify i as a jet

Cacciari, Salam, Soyez (08)

$$d_{ij} = \frac{\Delta R_{ij}^2}{R^2} \frac{1}{\max\{k_{Ti}^2, k_{Tj}^2\}}, \qquad d_{iB} = \frac{1}{k_{Ti}^2}$$

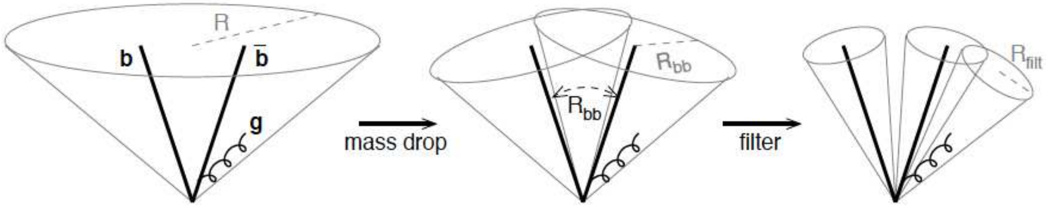
- ✓ clusters hardest particles first,
- ✓ shape of jet insensitive to soft particles
- ✓ cone-shaped jets
- ✓ may be easier to get jet energy scale right



- ✓ ATLAS and CMS have used anti-k$_{\mathrm{T}}$ for their first data.
- ✓ **For the first time ever**, a hadron-collider will carry out measurements that can be consistently compared with theoretical (perturbative QCD) calculations!

Jet substructure

- ✓ The LHC is the first place where heavy ($\sim$ 100 GeV) particles will be copiously produced well above threshold.
- ✓ They will often be boosted, and will often decay to hadrons.
- ✓ The decay products will often appear in a single jet.
- ✓ e.g. high p_T Higgs production with decay to $b\bar{b}$, looks like a single massive jet
- ✓ need to examine the substructure of massive jets to get the physics out.



What next - Jetography!

Salam

What next - Jetography!

Salam

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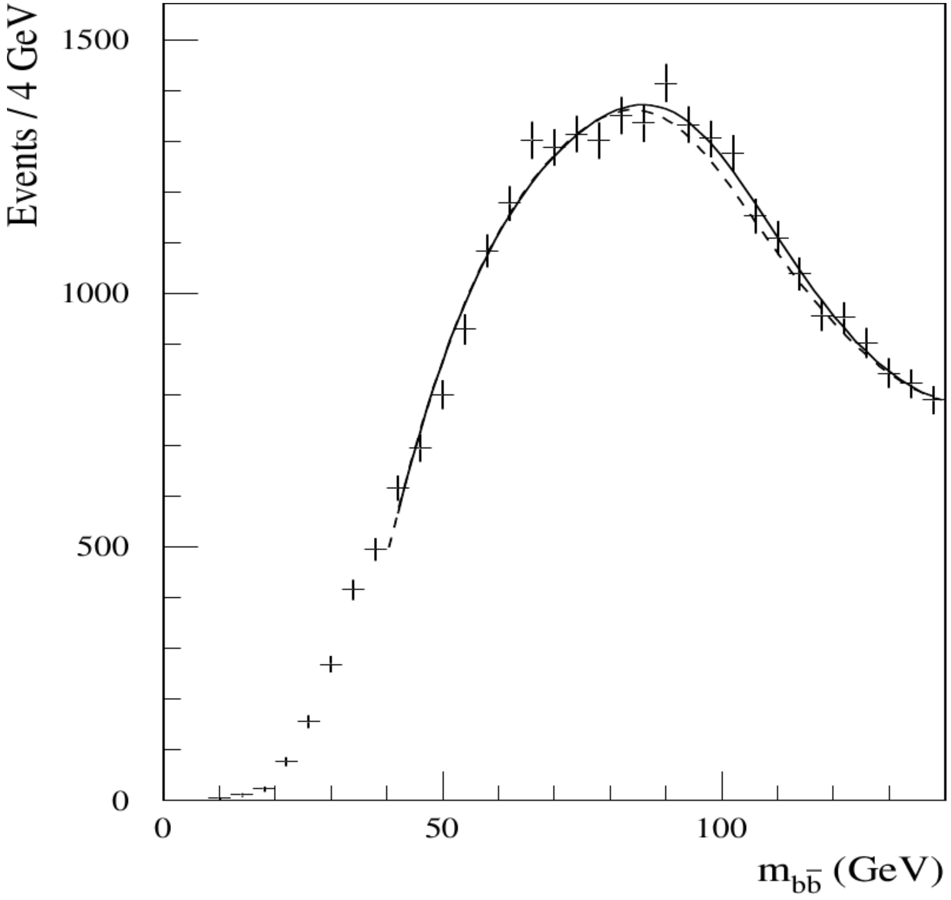
1330	LOS ANGELES	AF 072 DL 8508		CLOSED	
		AZ 354			
1330	TOKYO-NARITA	AF 276		CLOSED	
1330	BOSTON	AF 332 DL 8604	6-7	EXPECTED 15:30	E73
1330	DAMASCUS	AF 510	5	BOARDING	E56
1340	MEXICO	AF 438 AM 8038		CLOSED	
		AZ 369			
1350	ABIDJAN	AF 702 AZ 3594		CLOSED	
		KL 227 NW 4306			
		DL 857			
1355	RIYADH	AF 534	8-9	EXPECTED 15:30	E60
1440	LONDON HEATHROW	AF 1580	5	BOARDING	E21
				LAST CALL	
1525	EDINBURGH	AF 5052 MK 9374	5	ON TIME	E30
		AZ 363 UX 3611			
1530	ABERDEEN	AF 5558 UX 3563	5	ON TIME	E26
		AZ 360			
1535	DUBLIN	AF 5014 UX 3575	5	ON TIME	E22
		AZ 358			
1535	NEWCASTLE	AF 5853 AZ 3584	5	ON TIME	E21
		UX 351			
1545	MANCHESTER	AF 2568 UX 3505	5	ON TIME	E23
		AZ 271			

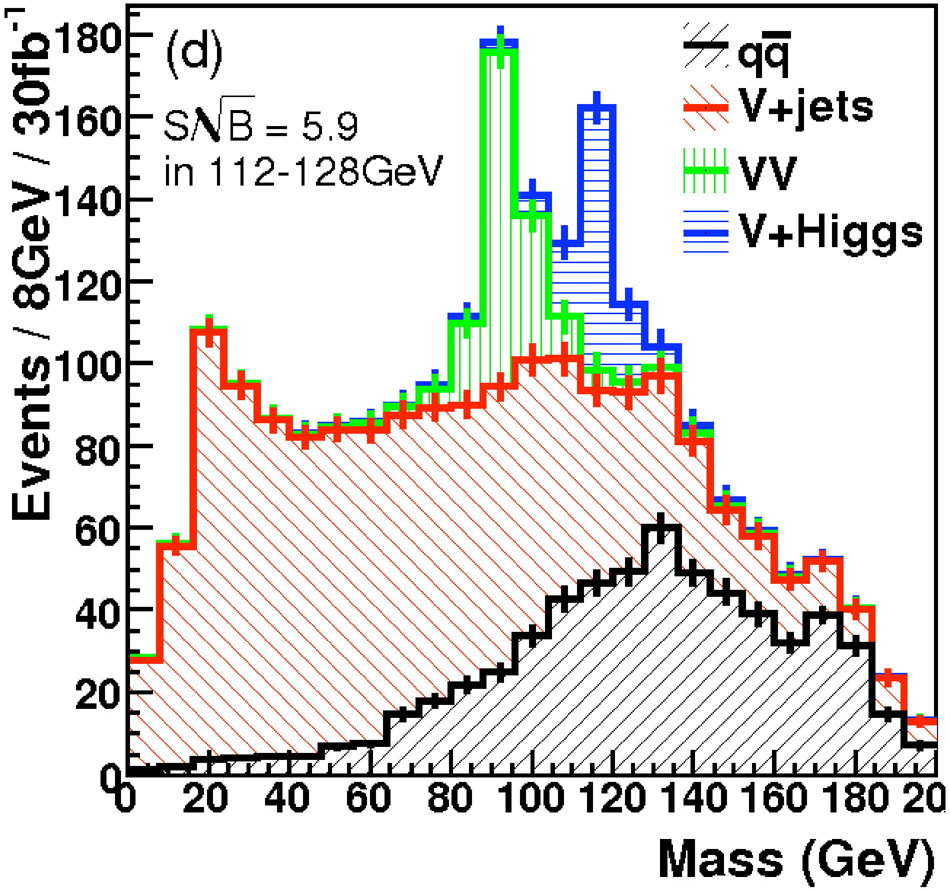
in analogy with photography [autofocus etc]

Potential of Jetography

VH with H → bb rescued as one of the best discovery channels for light Higgs at LHC

Butterworth, Davison, Rubin, Salam (08)





2. NLO multiparticle production

State of the Art - at a glance

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

LO Automated and under control, even for multiparticle final states

NLO Well understood for $2 \to 1$ and $2 \to 2$ in SM and beyond

NLO $2 \to 3$ SM calculations becoming routine, see Les Houches wish list

NLO Some $2 \to 4$ processes e.g. $pp \to t\bar{t}b\bar{b},\ t\bar{t}jj,\ V+3j,\ WWjj$

NLO Very first $2 \to 5$ LHC cross section in 2010 $pp \to Wjjjj$

NNLO Inclusive and exclusive Drell-Yan and Higgs cross sections

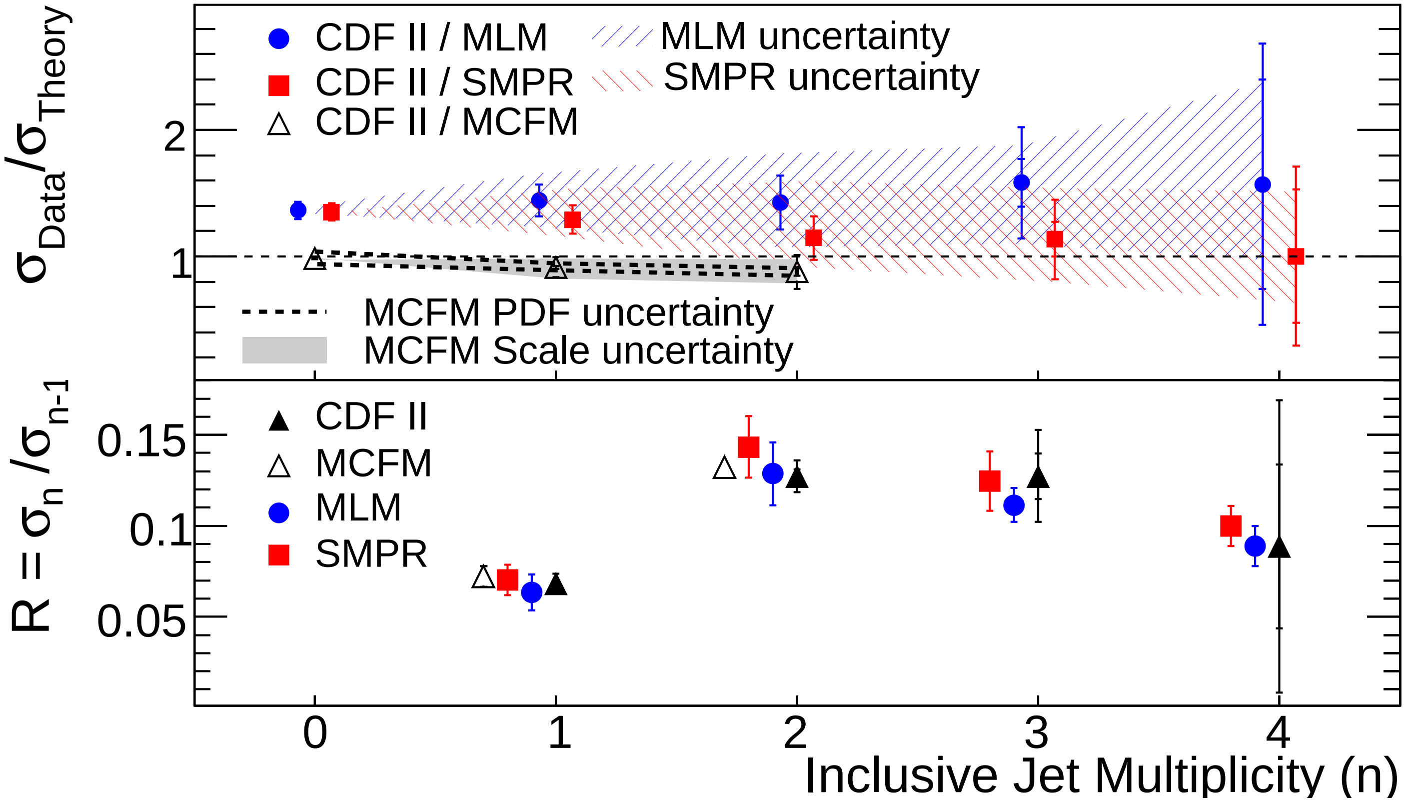
NNLO $e^+e^- \to 3$ jets, but still waiting for $pp \to \mathrm{jets},\ W+\mathrm{jet},\ t\bar{t}, VV$

Limitations of Tree Level

Very large uncertainty for multiparticle final states

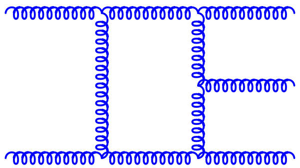
- ✗ Large renormalisation scale uncertainty, magnified by the large amount of radiation e.g. a $\pm 10\%$ uncertainty in α_s leads to a $\pm 30\%$ uncertainty for $W + 3$ jets
- ✗ Large factorisation scale uncertainty
  higher factorisation scales deplete partons at large x - may increase or decrease cross section
- ✗ Both of these effects change the shapes of distributions
- ✓ Partly stabilised by going to NLO
- ✓ New channels open up at higher orders qg + large gluon PDF
- ✓ Increased phase space allows more radiation
- ✓ Large π^2 coefficients in s-channel $\Rightarrow$ large NLO corrections 30% - 100%

W + n-jet rates from CDF

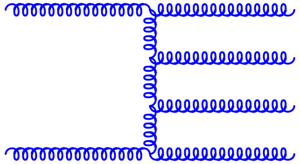


- ✗ Large uncertainty at LO - increasing with number of jets
- ✗ Normalisation not good at LO
- ✓ Normalisation better at NLO
- ✓ Reduced theory error at NLO

Anatomy of a NLO calculation e.g. $pp \to 3j$



- ✓ one-loop matrix elements
  - ✓ explicit infrared poles from loop integral
  - ✓ current frontier $2 \to 4$: major challenge



- ✓ tree-level real radiation process
  - ✓ implicit poles from soft/collinear emission
- ✓ plus method for combining the infrared divergent parts
  - ✓ dipole subtraction Catani, Seymour; Dittmaier, Trocsanyi, Weinzierl, Phaf
  - ✓ residue subtraction Frixione, Kunszt, Signer
  - ✓ antenna subtraction Kosower; Campbell, Cullen, NG; Daleo, Gehrmann, Maitre

LHC priority NLO wish list, Les Houches 2005/7*

process	background	status - mostly from Feynman diagram approach
$pp \to VV + 1$ jet	WBF $H \to VV$	WWj (07), ZZj (09)
$pp \to t\bar{t} + b\bar{b}$	$t\bar{t}H$	$q\bar{q} \to t\bar{t}b\bar{b}$ (08), $gg \to t\bar{t}b\bar{b}$ (09)
$pp \to t\bar{t} + 2$ jets	$t\bar{t}H$	$t\bar{t}j$ (07), $t\bar{t}Z$ (08), $t\bar{t}jj$ (10)
$pp \to VV + b\bar{b}$	WBF $H \to VV$, $t\bar{t}H$, NP	
$pp \to VV + 2$ jets	WBF $H \to VV$	WBF $pp \to VVjj$ (07), $pp \to WWjj$ (10)
$pp \to V + 3$ jets	NP	$W + 3$ jets (09), $Z + 3$ jets (10), $W^- + 4$ jets (10)
$pp \to VVV$	SUSY trilepton	ZZZ (07), WWZ (07), WWW (08), ZZW (08)
$pp \to b\bar{b}b\bar{b}^*$	Higgs and NP	$b\bar{b}b\bar{b}$ (partial 09)

- ✓ $pp \to H + 2$ jets via gluon fusion (06)
- ✓ $pp \to H + 2$ jets via WBF, electroweak and QCD corrections (07)
- ✓ $pp \to H + 3$ jets via WBF, (07)

Many contributors Badger, Berger, Bern, Bevilacqua, Binoth, Bozzi, Bredenstein, Campanario, Campbell, Ciccolini, Czakon, Denner, Dittmaier, Dixon, Ellis, FebresCordero, Figy, Forde, Gleisberg, Glover, Greiner, Guffanti, Guillet, Hankele, Heinrich, Ita, Kallweit, Karg, Kauer, Kosower, Lazopoulos, Maitre, Mastrolia, Melia, Melnikov, Ossola, Papadopoulos, Petriello, Pittau, Pozzorini, Reiter, Reuter, Rontsch, Sanguinetti, Uwer, Williams, Worek, Zanderighi, Zeppenfeld,

NLO: multi-leg one-loop amplitudes

- ✓ Challenges of one-loop multileg-amplitude
  - ✓ complexity: number of diagrams, number of scales
  - ✓ stability: linear dependence among external momenta
- ✓ General structure

$$\mathcal{A} = \sum_i d_i \mathrm{Box}_i + \sum_i c_i \mathrm{Triangle}_i + \sum_i b_i \mathrm{Bubble}_i + \sum_i a_i \mathrm{Tadpole}_i \quad (+R)$$

- ✓ Enormous recent progress
  - ✓ tensor reduction and form factor decomposition

    Denner, Dittmaier; Binoth, Guillet, Heinrich, Pilon, Schubert
  - ✓ unitarity and multiparticle cuts to fix coefficients

    Bern, Dixon, Dunbar, Kosower; Britto, Cachazo, Feng; Mastrolia; Forde; Badger
  - ✓ reduction at the integrand level Ossola, Papadopoulos, Pittau
  - ✓ numerical D-dimensional unitarity Ellis, Giele, Kunszt, Melnikov

Automating NLO calculations

Real radiation: based on LO event generators

- ✓ Based on Dipole subtraction
  - ✓ SHERPA Gleisberg, Krauss
  - ✓ AutoDipole Hasegawa, Moch, Uwer
  - ✓ MadDipole Frederix, Gehrmann, Greiner
  - ✓ TeVJet Seymour, Tevlin
  - ✓ Helac/Phegas Czakon, Papadopoulos, Worek
- ✓ Based on Dipole subtraction
  - ✓ MadFKS Frederix, Frixione, Maltoni, Stelzer
- ✓ extensive libraries in existing NLO packages
  - ✓ MCFM Campbell, Ellis
  - ✓ NLOJET++ Nagy, Trocsanyi

Automating NLO calculations

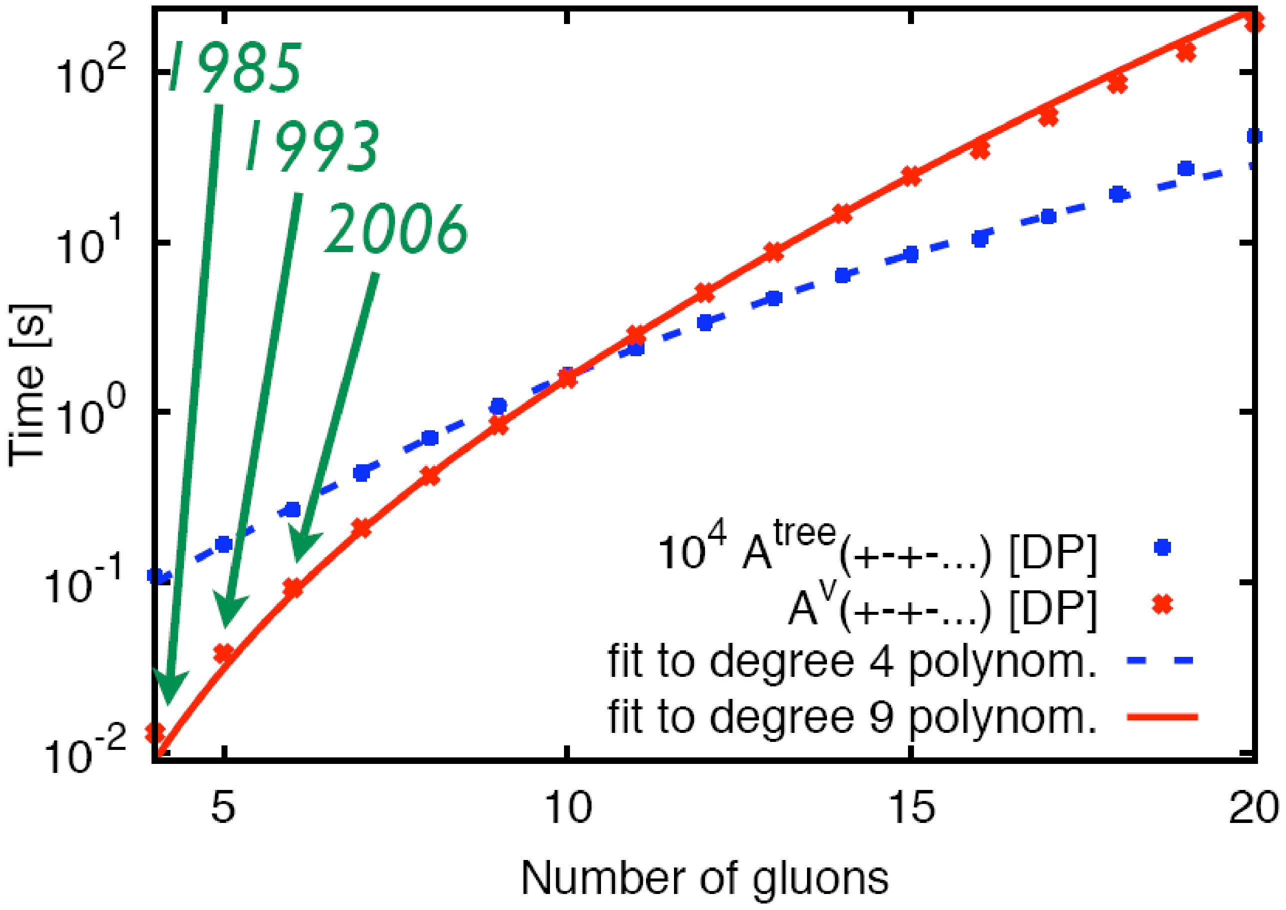
Virtual corrections: implementations

- ✓ semi-numerical form factor decomposition: GOLEM Binoth, Guillet, Heinrich, Pilon, Reiter
- ✓ unitarity and multi-particle cuts: BlackHat Berger, Bern, Dixon, Febres Cordero, Forde, Ita, Kosower, Maitre
- ✓ reduction at integrand level: CutTools Ossola, Papadopoulos, Pittau
- ✓ generalized D-dimensional unitarity: Rocket Giele, Ellis, Kunszt, Melnikov, Zanderighi
- ✓ generalized D-dimensional unitarity: Samurai Mastrolia, Ossola, Reiter, Tramontano
- ✓ several more packages in progress Lazopoulos; Giele, Kunszt, Winter; Melnikov, Schulze; . . .

Most recently: combine virtual (CutTools) and real (MadFKS) contributions into automated NLO package: MadLoop

Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau

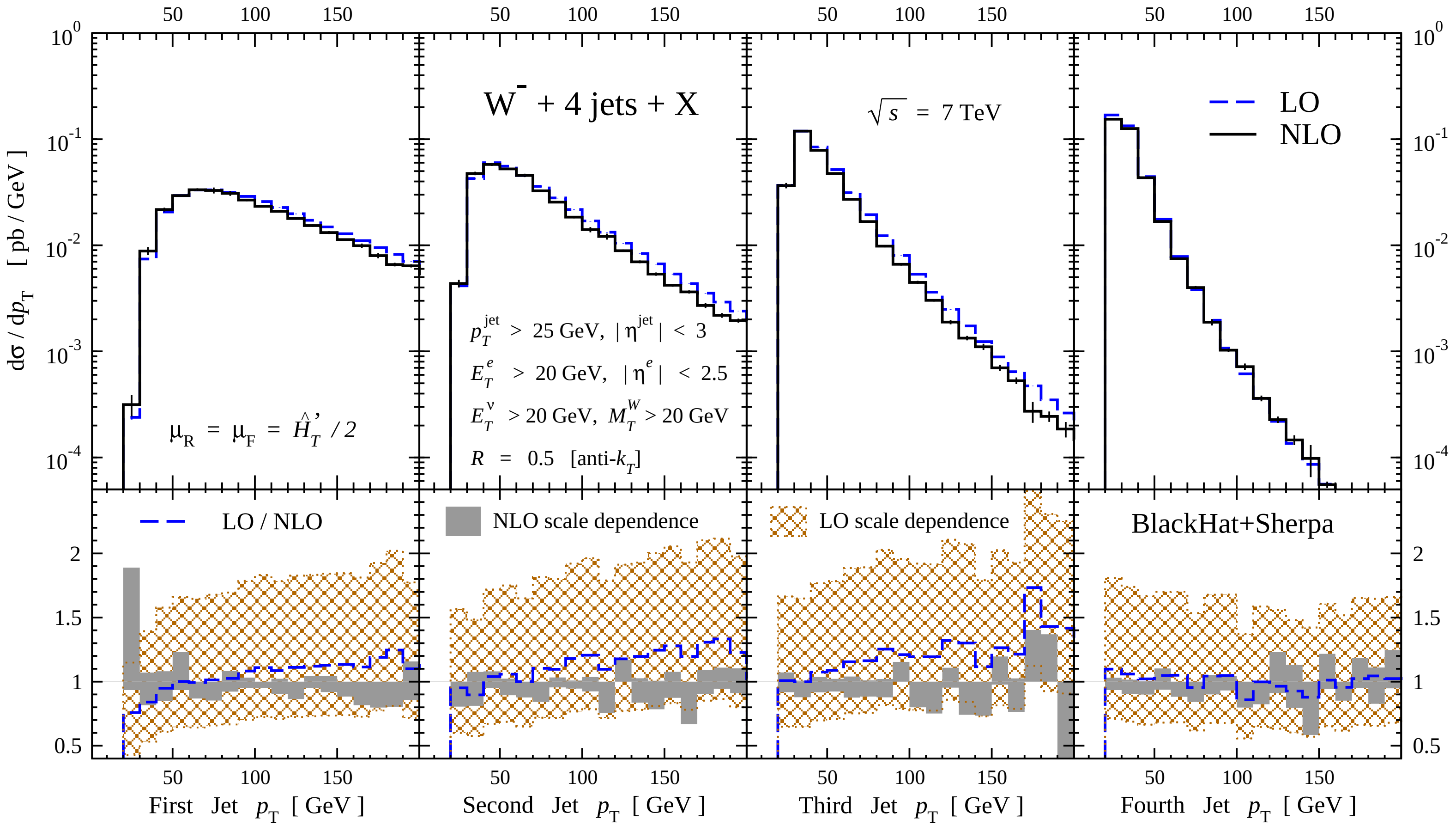
Massive leap forward: gg → (N-2)g at 1-loop



✓ single colour ordering, single phase space point — Giele, Zanderighi (08)

other numerical programs by Lazopoulos (08) and Giele, Winter (09)

Massive leap forward: W+4 jet at NLO

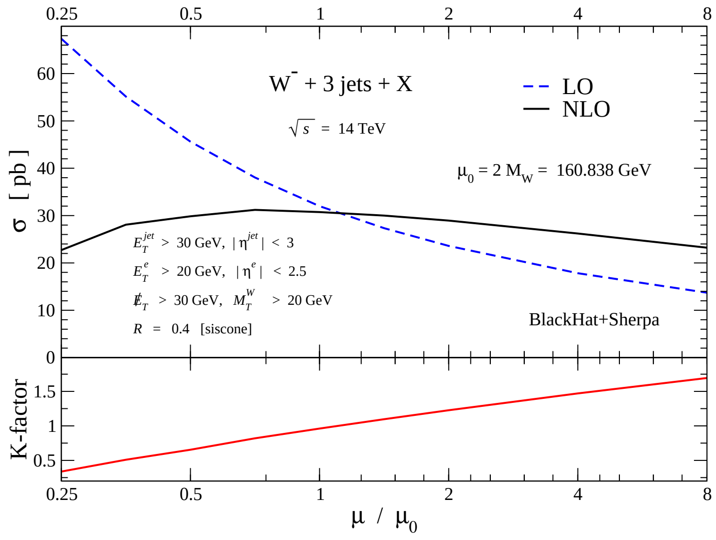


Here for W^- and in leading colour approximation

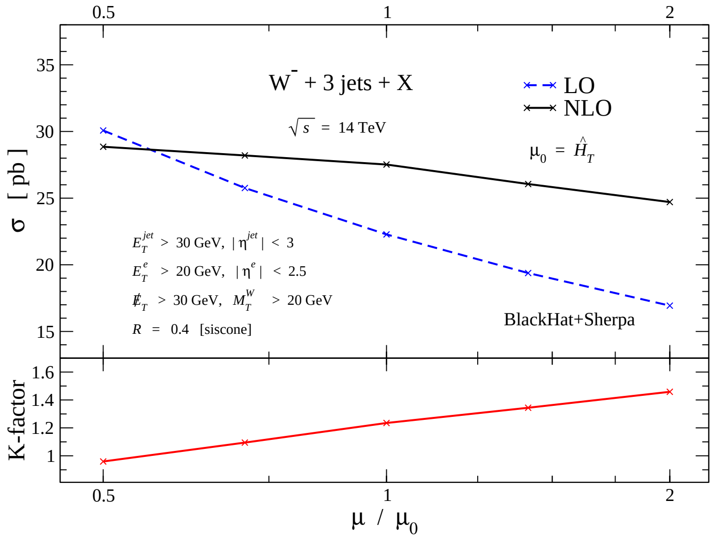
Berger et al. (10)

Scale dependence of observables

- ✓ Traditionally LO uncertainty estimated by varying scale around global scale like M_W or E_T^W
- ✓ At high energy, there are more complicated event structures and other kinematic scales are possible, that can dramatically affect the LO contribution and hence the K-factor



Fixed scale $\mu_0 = 2M_W$



Dynamical scale $\mu_0 = \hat{H}_T$

Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre, (09)

What can we hope for at NLO?

- ✓ Les Houches accord on standardisation of NLO computations and how to efficiently combine new virtual results with existing real radiation packages
  `http://www.lpthe.jussieu.fr/LesHouches09Wiki/index.php/Draft`

  Cannot do better than tree calculations..., at the moment processes with 7 or 8 particles in the final state.
- ✓ All 2 to 4 processes with both Feynman diagrammatic and newer unitarity/OPP based methods
- ✓ 2 to 5 and perhaps 2 to 6 processes with unitarity/OPP based methods
- ✓ hope for a better understanding of how to choose scale - possibly including more dynamic variables that depend on the event structure??

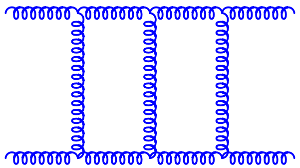
3. NNLO precision observables

Precision observables at NNLO

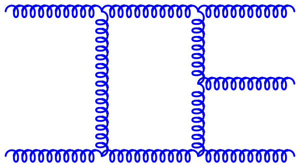
When is NNLO needed?

- ✓ Processes measured to few per cent accuracy
  - ✓ $e^+e^- \rightarrow 3$ jets
  - ✓ $2+1$ jet production in deep inelastic scattering
  - ✓ jet production at hadron colliders
  - ✓ vector boson (single, plus jet, pair) production at hadron colliders
  - ✓ Higgs production at hadron colliders
  - ✓ top quark pair production at hadron colliders
- ✓ Processes with potentially large perturbative corrections
  - ✓ Higgs production at hadron colliders
  - ✓ vector boson production at hadron colliders
- ✓ Require NNLO corrections for
  - ✓ meaningful interpretation of experimental data
  - ✓ precise determination of fundamental parameters

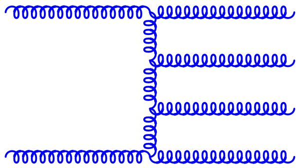
Anatomy of a NNLO calculation e.g. $pp \to 2j$



- ✓ two-loop matrix elements
  - ✓ explicit infrared poles from loop integral
  - ✓ known for massless $2 \to 2$
  - ✗ major challenge to include more mass scales



- ✓ one-loop matrix elements
  - ✓ explicit infrared poles from loop integral
  - ✓ implicit poles from soft/collinear emission



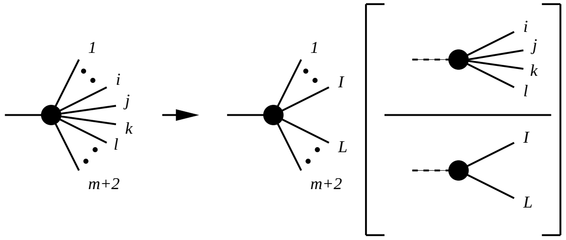
- ✓ double real radiation matrix elements
  - ✓ implicit poles from double unresolved emission

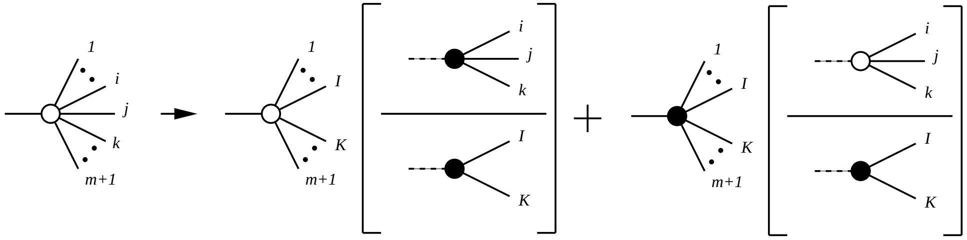
- ✗ need method to extract implicit poles

NNLO calculations: real radiation

- ✓ Technical challenge: real radiation for arbitrary final state cuts
  - ✓ two unresolved partons at tree level, one parton at one loop
  - ✓ infrared limits are process-independent
- ✓ Solutions
  - ✓ sector decomposition: expansion in distributions, numerical integration Binoth, Heinrich; Anastasiou, Melnikov, Petriello
  - ✓ subtraction: approximation in all unresolved limits, analytical integration
    - ✓ several well-established methods at NLO
    - ✓ q_T subtraction for $2 \to 1$ processes

      Catani, Grazzini
    - ✓ antenna subtraction Gehrmann, Gehrmann-De Ridder, NG





Precision observables at NNLO – What is known?

- ✓ $e^+e^- \to 3$ jets and event shapes

  Gehrmann, Gehrmann-De Ridder, NG, Heinrich; Weinzierl

- ✓ Inclusive cross sections for W, Z and H production

  van Neerven, Harlander, Kilgore, Anastasiou, Melnikov, Ravindran, Smith.

- ✓ Semi-inclusive $2 \to 1$ distributions - W, Z and H rapidity distributions

  Anastasiou, Dixon, Melnikov, Petriello

- ✓ Fully differential $pp \to H, W, Z + X$

  Anastasiou, Melnikov, Petriello; Catani, Cieri, Ferrera, de Florian, Grazzini

  including decays and allowing arbitrary cuts

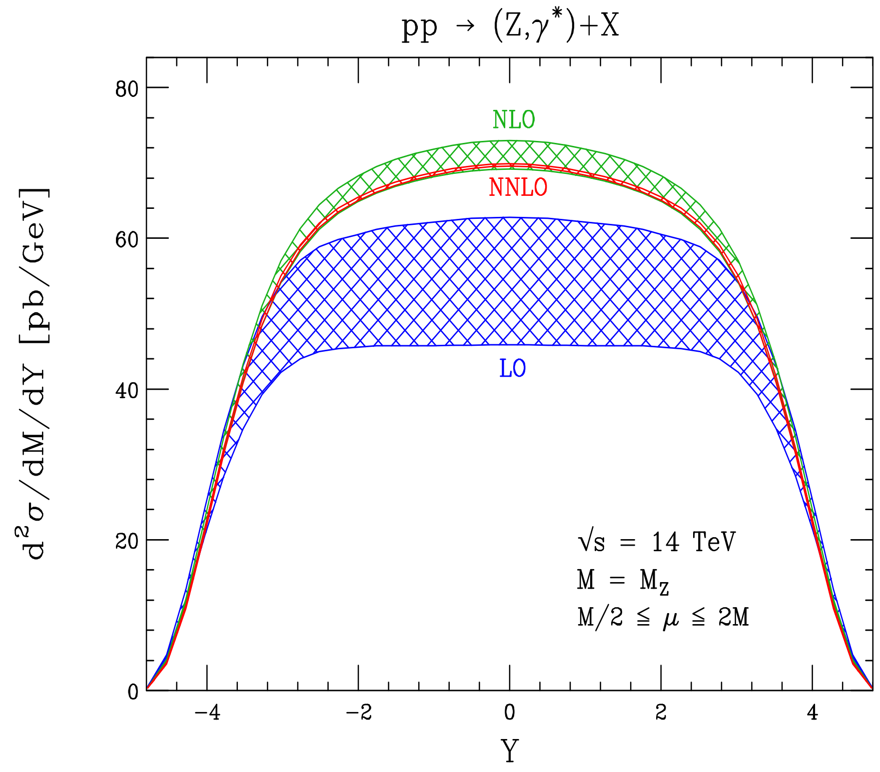
- \+ mixed QCD/EW corrections to Higgs production

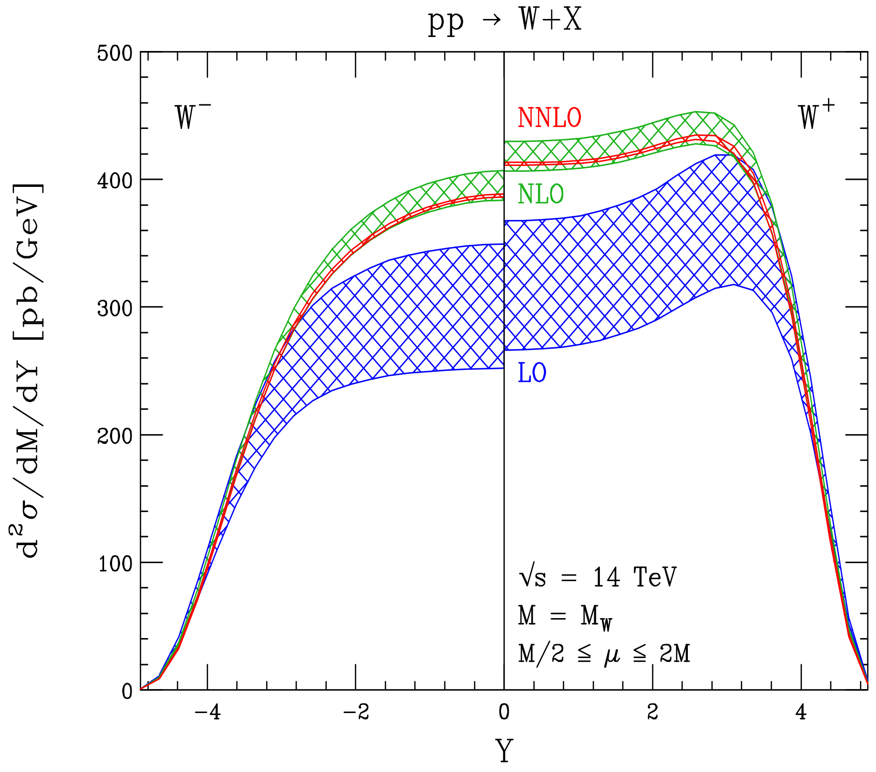
  Anastasiou, Boughezal, Petriello

- ✓ factorizable NNLO corrections to Higgs production via vector boson fusion

  Bolzoni, Maltoni, Moch, Zaro

Gauge boson production at the LHC





Gold-plated process

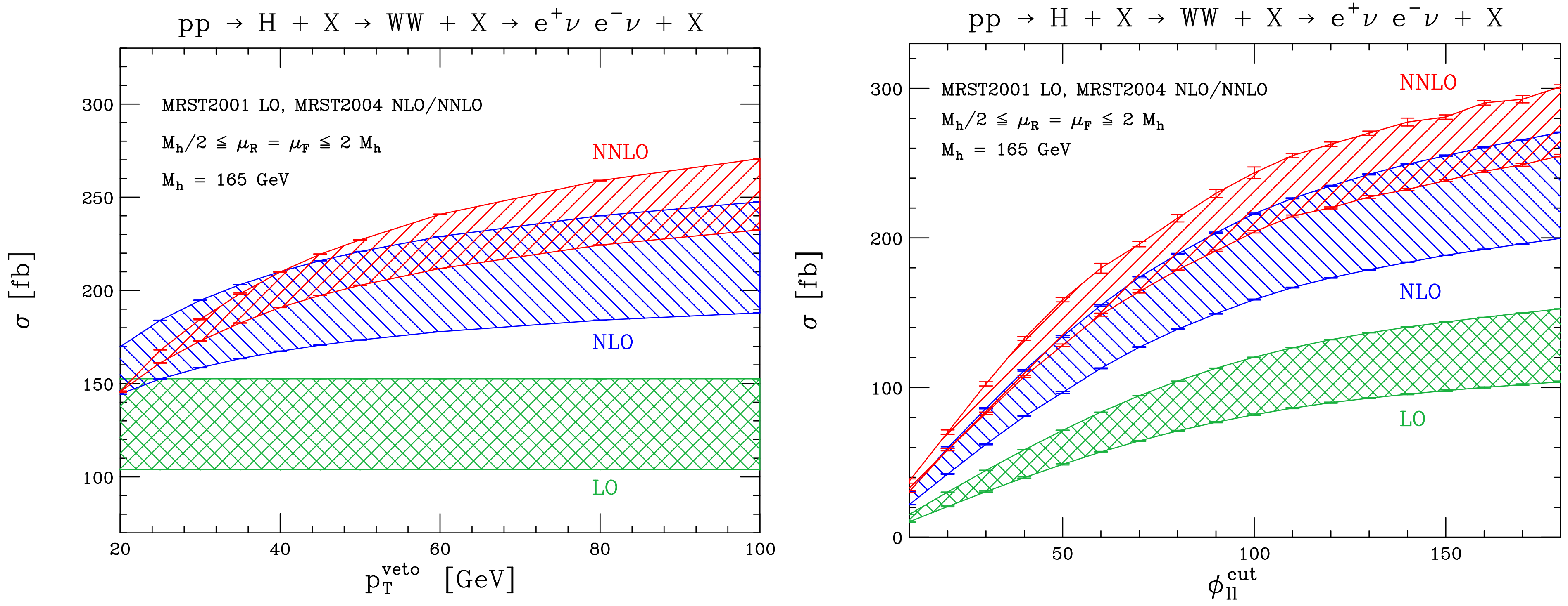
Anastasiou, Dixon, Melnikov, Petriello (04)

At LHC NNLO perturbative accuracy better than 1%

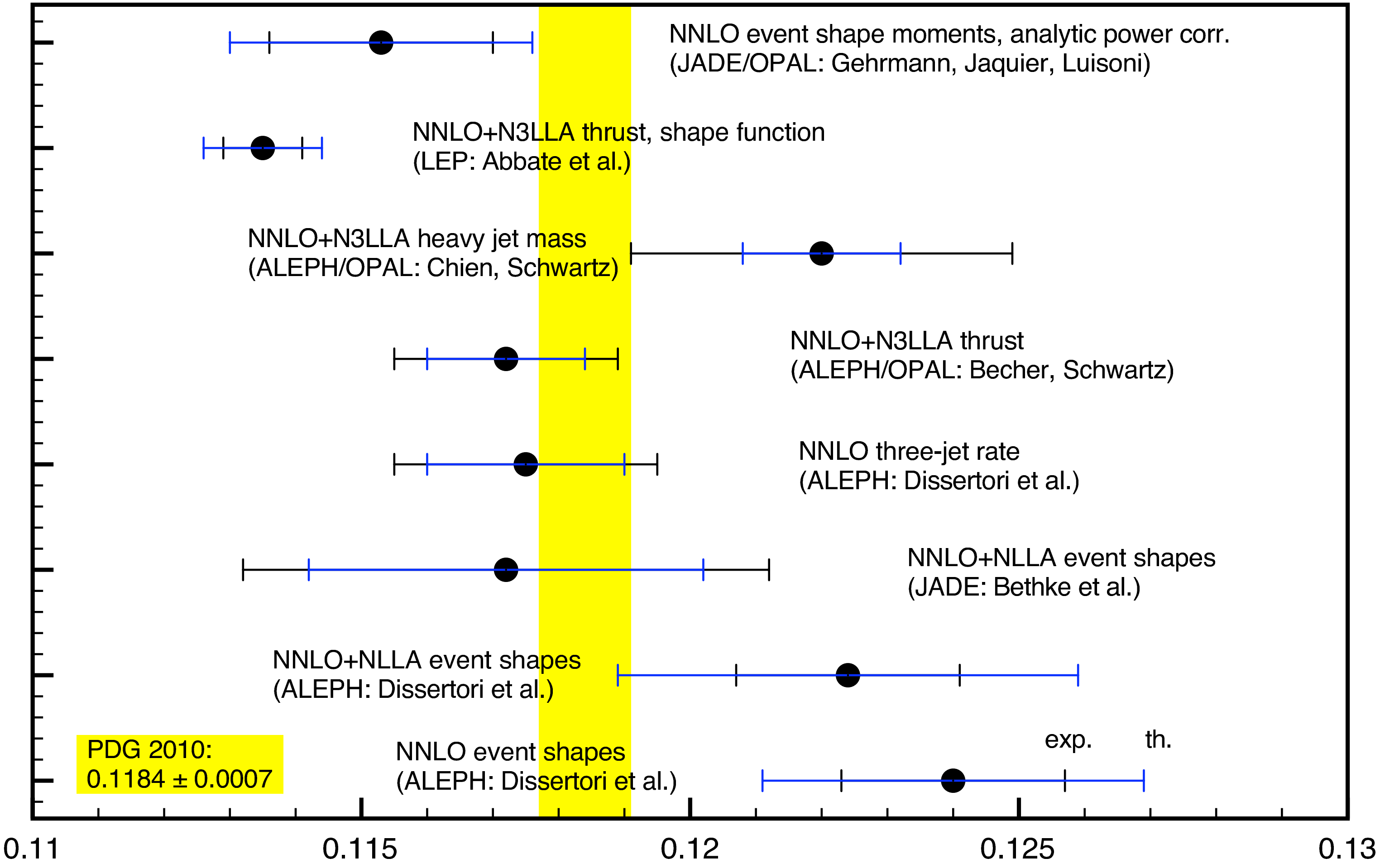
Higgs boson production at the LHC

- ✓ Fully exclusive $pp \to H \to WW \to \ell\nu\ell\nu$ Anastasiou, Dissertori, Stöckli, (07) Catani, Grazzini (07)
- ✓ Experimental cuts to reduce backgrounds affect LO/NLO/NNLO cross sections differently e.g. jet-veto suppresses additional radiation,

$\Longrightarrow$ importance of including cuts and decays in realistic studies



$\alpha_s(M_Z)$ from NNLO 3-jets in e^+e^-



Other NNLO calculations for LHC on horizon

✓ $pp \to jet$ +X

- needed to constrain gluon PDF at large x and fix strong coupling
- matrix elements known for some time — Anastasiou et al, Bern et al
- NNLO antenna subtraction terms partially known

Daleo, Gehrmann, Luisoni, Maitre; Boughezal, Gehrmann-De Ridder, Ritzmann; NG, Pires

✓ $pp \to t\bar{t}$

- necessary for $\sigma_{t\bar{t}}$ and m_t determination
- matrix elements partially known

Czakon, Mitov, Moch; Bonciani, Ferroglia, Gehrmann, Studerus, Maitre

✓ $pp \to VV$

- signal: to study the gauge structure of the Standard Model
- background: for Higgs boson production and decay in the intermediate mass range
- large NLO corrections — Chachamis, Czakon, Eiras

4. Parton density functions

Parton distributions

Parton distributions determined from global fit to collider data

- ✓ data sets
  - ✓ DIS (fixed target, HERA)
  - ✓ heavy quark production in DIS (HERA)
  - ✓ Drell-Yan (fixed target, Tevatron)
  - ✓ vector boson production (Tevatron)
  - ✓ jet production (HERA, Tevatron)
- ✓ at LO, NLO, NNLO
- ✓ require DGLAP splitting functions
  - ✓ known to NNLO Moch, Vermaseren, Vogt
- ✓ require hard coefficient functions
  - ✓ known to NNLO for DIS, Drell-Yan, heavy quarks in DIS van Neerven et al.; Anastasiou, Dixon, Melnikov, Petriello; Bierenbaum, Blümlein, Klein
  - ✓ known to NLO for jet production
- ✓ must incorporate experimental and theoretical errors

Parton distributions: global fits

MSTW :LO/NLO/NNLO Martin, Stirling, Thorne, Watt (09)

- ✓ error propagation through eigenvectors of covariance matrix
- ✓ allow systematic comparison of different orders

CTEQ : LO/NLO Pumplin, Huston, Lai, Nadolsky, Tung, Yuan (09)

- ✓ special focus on Tevatron jet data
- ✓ also provide effective LO* distributions for event generators

GJR : NNLO Gluck, Jiminez-Delgado, Reya (08)

- ✓ based on radiative parton model (valence-like partons at low scales)

NNPDF : NLO Ball, Del Debbio, Forte, Guffanti, Latorre, Rojo, Ubiali (10)

- ✓ fully flexible initial distributions through neural network parametization
- ✓ error treatment through multiple fits to data replicas

ABKM : NNLO Alekhin, Blümlein, Klein, Moch (09)

- ✓ extensive comparison of different heavy quark prescriptions

Parton distributions: global fits

	MSTW08	CTEQ6.6	NNPDF2.0	ABKM09	GJR08
HERA DIS	✓	✓	✓	✓	✓
Fixed Target DIS	✓	✓	✓	✓	✓
Fixed Target Drell-Yan	✓	✓	✓	✓	✓
Tevatron W/Z	✓	✓ (Run 1)	✓	✗	✗
Tevatron Jets	✓	✓ (Run 1)	✓	✗	✓
GM-VFNS	✓	✓	✗	✗	✗
NNLO	✓	✗	✗	✓	✓

✓ quark distributions determined precisely at large x

✓ gluon distribution uncertain by about 10% at large x

✓ large differences for $x < 10^{-3}$

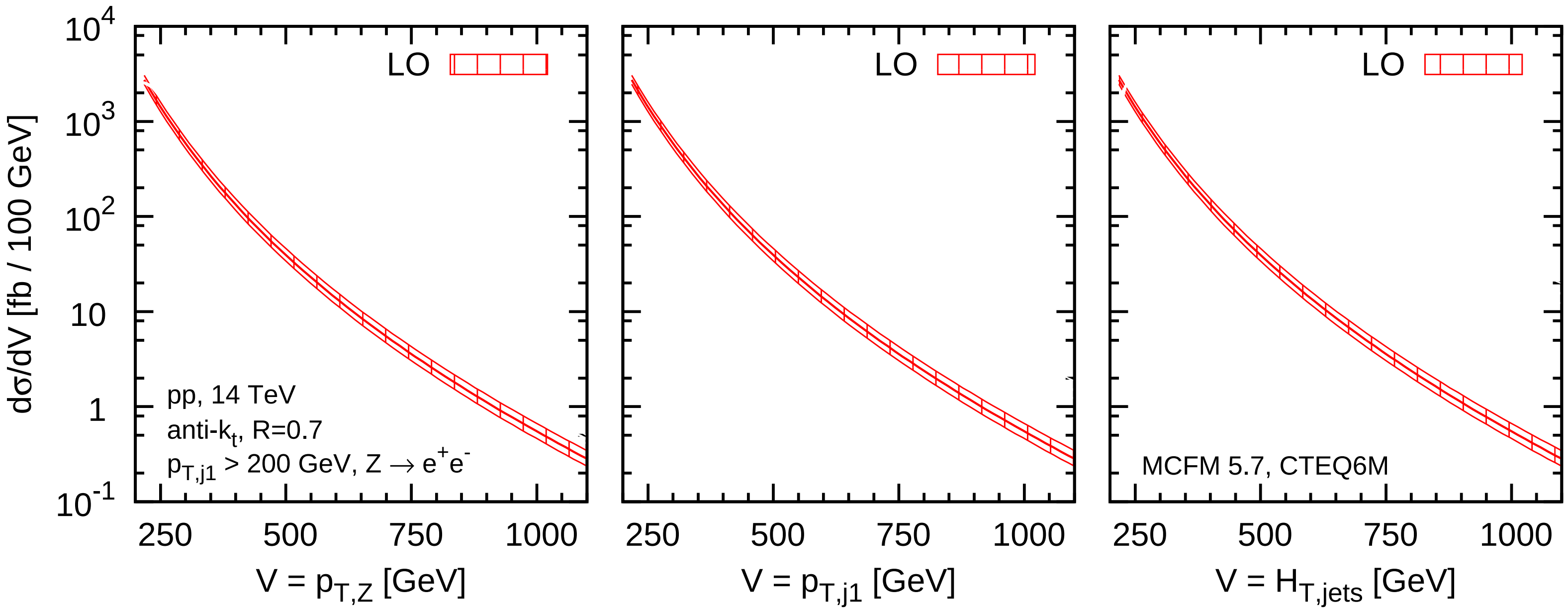
✓ consistency within errors

✓ tendency towards low α_s, e.g. $\alpha_s(M_Z) = 0.11350.0014$ (ABKM)

Summary

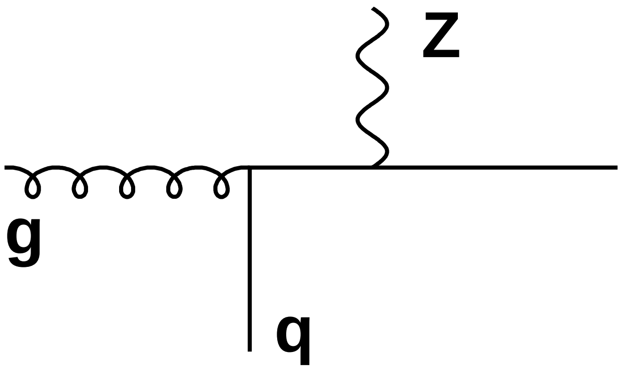
- ✓ driven by the LHC needs, there has been a remarkable development of theoretical tools
  - ✓✓ new theoretically sound jet definition - anti-k_T
    $\Rightarrow$ Jetography - extract more information from internal jet structure
  - ✓✓ first signs of automated multiparticle NLO cross sections
  - ✓✓ first NNLO calculations for precision observables
  - ✓✓ more choice of PDF's - and trying to understand differences
- ✓ ready to take on the challenge of finding new physics at the LHC

Need for caution



Consider three observables, $p_{T,Z}$, $p_{T,j1}$ and $H_{T,jets}$, that are equivalent at LO

Rubin, Salam, Sapeta, (10)



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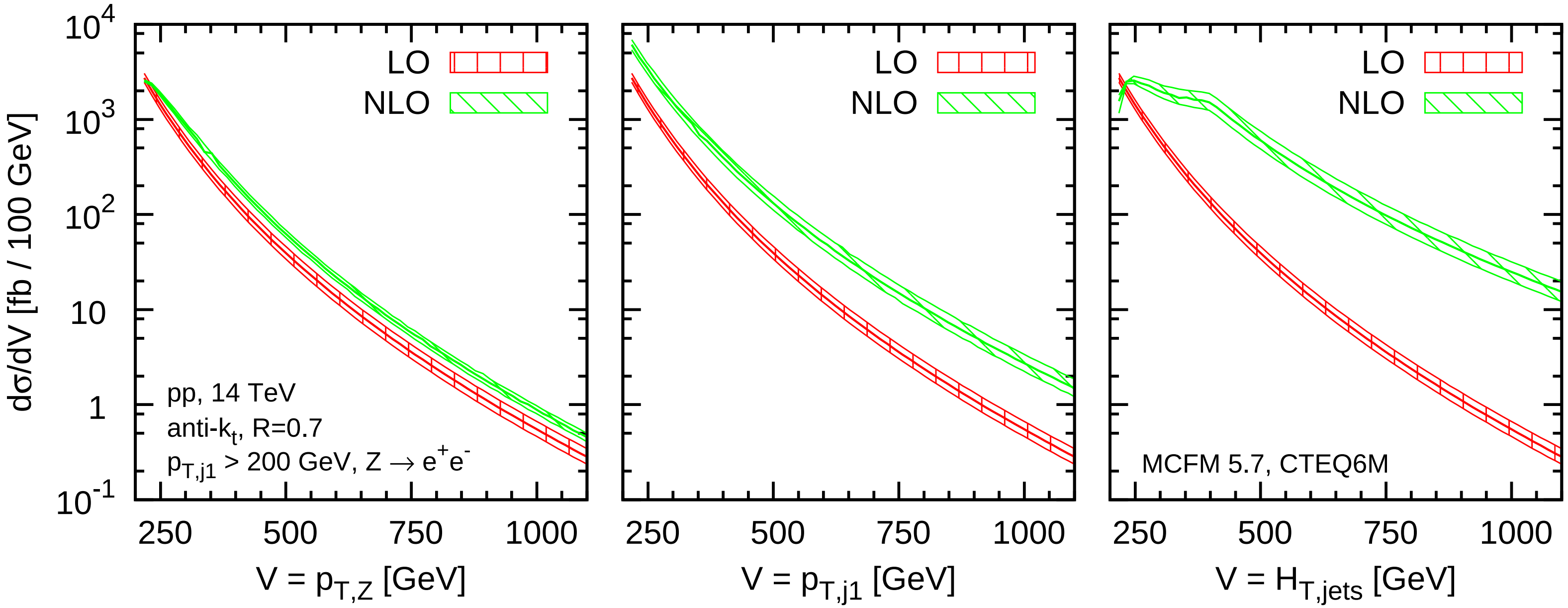
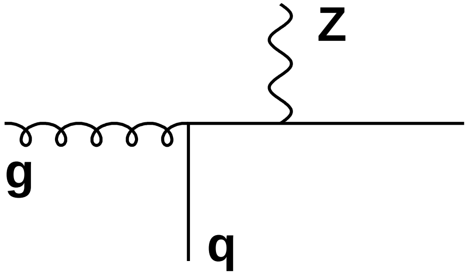


Rubin, Salam, Sapeta, (10)

- ✓ The $p_{T,Z}$ observable is rather typical: a NLO K-factor of about 1.5, fairly independently of $p_{T,Z}$ and scale dependence reduced with respect to LO.
- ✓ The $p_{T,j1}$ distribution is more unusual: K-factor grows noticeably with $p_{T,j1}$, reaching values of about 4 to 6.
- ✓ The $H_{T,jets}$ observable is even more striking, with K-factors approaching 100.

What is going on?

Appearance of diagrams with new kinematic topologies at NLO!!



at LO the only event topology is that of a Z-boson recoiling against a quark or gluon jet. gluon radiation from this basic topology gives modest corrections to all three observables.

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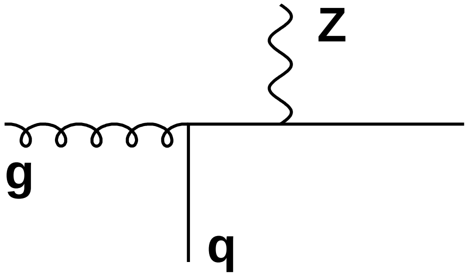

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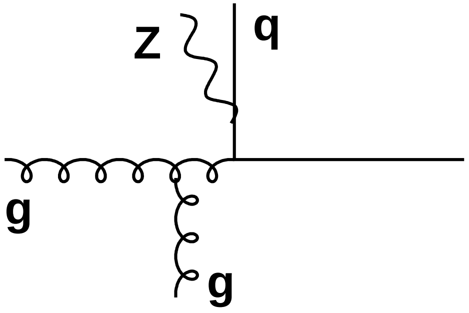
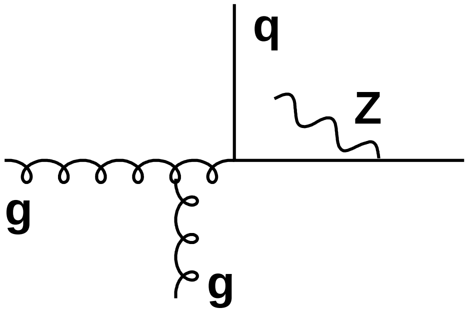


some NLO diagrams have the topology is that of a dijet event, in which a soft or collinear Z-boson is radiated from outgoing or incoming legs. These diagrams do not contribute significantly to the high $p_{T,Z}$ distribution, because the Z-boson carries only a moderate fraction of the total pt.

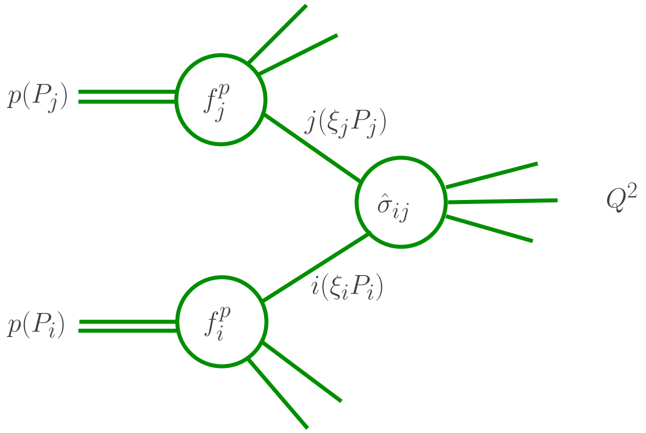


However for $p_{T,j1}$, it is irrelevant whether the Z boson is soft or not. This leads to a contribution of

$$\mathcal{O}\left(\alpha_s \alpha_W \ln^2\left(\frac{p_{T,j1}}{M_Z}\right)\right)$$

so the K-factor grows with increasing p_T.

Hard processes in perturbative QCD



Understanding of QCD is mandatory for

- ✓ Interpretation of collider data
- ✓ Precision Studies
- ✓ Searches for New Physics

$$\sigma(Q^2) = \sum_{i,j} \left[\hat{\sigma}_{ij}(\alpha_s(\mu^2), \mu^2/Q^2) \otimes f_i^p(\mu^2) \otimes f_j^p(\mu^2)\right]$$

✓ Key elements: the parton distributions, the description of the hard cross section, and the link between partons and hadrons - the jet algorithm