Perturbative QCD and Jets

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Lecture 3

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The NLO revolution

Why revolution?

Enormous progress in the last few years in the calculation of NLO corrections for high-multiplicity final states (i.e. beyond 2 → 2 scattering)

- driven to a large extent by the development of unitarity inspired (numerical) methods
- lead to large efforts (and achievements) in the **automation** of NLO corrections
- merging of NLO with **parton showers** is well on its way

Why NLO?

(already saw a few examples in the last lectures)

- reduction of scale uncertainties (first reliable error estimate)
- corrections can be quite large (e.g. Higgs)
- more accurate predictions for normalisation and shapes of distributions
- new partonic channels can open up
- large sensitivity to cuts at LO as extra radiation is not taken into account well enough

Progress monitor

Les Houches NLO wishlist for LHC backgrounds, Status 2007 (May)

process ($V \in \{Z, W, \gamma\}$)	status
1. $pp \to V\,V$ jet	Dittmaier, Kallweit, Uwer; Campbell, Ellis, Zanderighi; Binoth, Guillet, Karg, Kauer, Sanguinetti
2. $pp \to V\,V\,V$	Lazopoulos, Melnikov, Petriello (ZZZ)
3. $pp \to t\bar{t}\,b\bar{b}$	
4. $pp \to t\bar{t} + 2$ jets	
5. $pp \to V\,V\,b\bar{b}$	
6. $pp \to V\,V + 2$ jets	
7. $pp \to V + 3$ jets	
8. $pp \to b\bar{b}b\bar{b}$	
9. $pp \to 4$ jets	
10. EW corr. to W,Z prod.	

(red means "done")

Status Les Houches 2009

$pp \to W\,W\,\text{jet}$	Dittmaier/Kallweit/Uwer; Campbell/Ellis/Zanderighi
	Binoth/Guillet/Karg/Kauer/Sanguinetti
$pp \to Z\,Z\,\text{jet}$	Binoth/Gleisberg/Karg/Kauer/Sanguinetti; Dittmaier/Kallweit
$pp \to t\bar{t}\,b\bar{b}$	Bredenstein/Denner/Dittmaier/Pozzorini;
	Bevilacqua/Czakon/Papadopoulos/Pittau/Worek
$pp \to t\bar{t} + 2\,\text{jets}$	Bevilacqua/Czakon/Papadopoulos/Worek
$pp \to Z\,Z\,Z$	Lazopoulos/Melnikov/Petriello; Hankele/Zeppenfeld
$pp \to V\,V\,V$	Binoth/Ossola/Papadopoulos/Pittau; Zeppenfeld et al.
$pp \to V\,V\,b\bar{b}$	
$pp \to W\,\gamma\,\text{jet}$	Campanario/Englert/Spannowsky/Zeppenfeld
$pp \to V\,V + 2\,\text{jets}$	VBF: Bozzi/Jäger/Oleari/Zeppenfeld, VBFNLO coll.
$pp \to W + 3\,\text{jets}$	BlackHat coll.; Ellis/Giele/Kunszt/Melnikov/Zanderighi*
$pp \to Z + 3\,\text{jets}$	BlackHat collaboration
$pp \to b\bar{b}b\bar{b}$	Binoth/Greiner/Guffanti/Guillet/Reiter/Reuter

● done ● partial results * leading colour only

Status 2011

- $pp \to W^+W^- b\bar{b}$ Denner, Dittmaier, Kallweit, Pozzorini '10 ; Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '11
- $pp \to W/Z + 4$ jets, $W + 5$ j BlackHat coll. '10/'11/'12
- $pp \to W/Z/\gamma + 3$ jets BlackHat collaboration '09/'10
- $pp \to t\bar{t}$ +2 jets Bevilacqua, Czakon, Papadopoul., Worek '10
- $pp \to t\bar{t}\, b\bar{b}$ Bredenstein, Denner, Dittmaier, Pozzorini '09; Bevilacqua, Czakon, Papadopoulos, Worek '09
- $pp \to W\gamma\gamma j$ Campanario, Englert, Rauch, Zeppenfeld '11
- $pp \to W^+W^+ j\, j$ Melia, Melnikov, Rontsch, Zanderighi '10;
- $pp \to W^+W^- j\, j$ Melia, Melnikov, Rontsch, Zanderighi '11; GoSam '12
- $pp \to 4\, b$ Binoth et al '09; GoSam '11
- NGluon ($N <\sim 14$) Badger, Biedermann, Uwer '11 (public)
- $e^+e^- \to 5$ jets Frederix, Frixione, Melnikov, Zanderighi '10
- $e^+e^- \to \leq 7$ jets Weinzierl et al '11
- also: BIG advances in automation

Les Houches NLO wishlist today

Not quite true!

(fulfilled wished generate bigger ones)

Les Houches fixed order NLO wishlist has been replaced by something much better (and much larger)

NNLO QCD+NLO EW wishlist

Process	known	desired	details
H	dσ @ NNLO QCD dσ @ NLO EW finite quark mass effects @ NLO	dσ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	dσ @ NNLO QCD (g only) dσ @ NLO EW finite quark mass effects @ LO	dσ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD dσ(gg) @ NLO QCD dσ(VBF) @ NLO EW	dσ @ NNLO QCD + NLO EW	H couplings
H + V	dσ @ NNLO QCD dσ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
t$\bar{\text{t}}$H	dσ(stable tops) @ NLO QCD	dσ(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	dσ @ LO QCD (full m_t dependence) dσ @ NLO QCD (infinite m_t limit)	dσ @ NLO QCD (full m_t dependence) dσ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Table 1: Wishlist part 1 – Higgs (V = W, Z)

add a column here for current exp precision and that expected at 14 TeV

N. Glover, S. Dittmaier

Joey Huston, Les Houches '13 summary talk

NNLO QCD + NLO EWK wishlist

Process	known	desired	details
$t\bar{t}$	σ_{tot} @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW	precision top/QCD, gluon PDF, effect of extra radiation at high rapidity, top asymmetries
$t\bar{t} + j$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW	precision top/QCD top asymmetries
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD (t channel)	precision top/QCD, V_{tb}
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO weak	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: incl. jets, dijet mass $\rightarrow$ PDF fits (gluon at high x) $\rightarrow \alpha_s$ CMS http://arxiv.org/abs/1212.6660
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: $R3/2$ or similar $\rightarrow \alpha_s$ at high scales dom. uncertainty: scales CMS http://arxiv.org/abs/1304.7498
$\gamma + j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD +NLO EW	gluon PDF $\gamma + b$ for bottom PDF

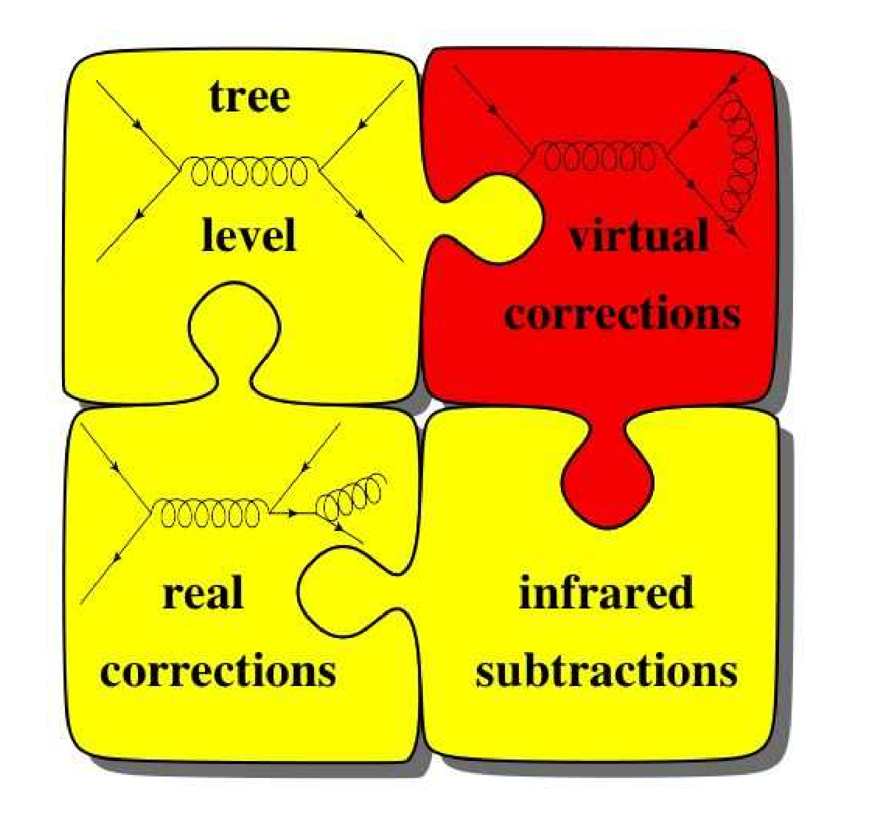
Table 2: Wishlist part 2 – jets and heay quarks

NNLO QCD + NLO EWK wishlist

Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
$V + j$	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	$Z + j$ for gluon PDF $W + c$ for strange PDF
$V + jj$	$d\sigma$(lept. V decay) @ NLO QCD	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of $H + jj$ final state
VV'	$d\sigma$(V decays) @ NLO QCD $d\sigma$(stable V) @ NLO EW	$d\sigma$(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
$gg \to VV$	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
$V\gamma$	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW	TGCs
$Vb\bar{b}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for $VH \to b\bar{b}$
$VV'\gamma$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs
$VV'V''$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$VV' + j$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	bkg. to H, BSM searches
$VV' + jj$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\gamma\gamma$	$d\sigma$ @ NNLO QCD		bkg to $H \to \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons ($V = W, Z$)

NLO in a cartoon

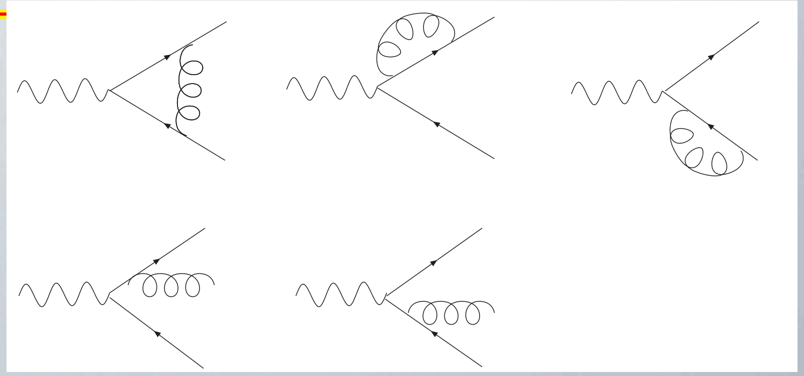


exploit modular structure

Tree Modules	One-Loop Module	IR Modules
$\lvert\mathcal{A}^{LO}\rvert^2$ $\oplus$	$2\,Re(\mathcal{A}^{LO\,\dagger}\mathcal{A}^{NLO,virt})$ $\oplus$	integrated IR subtraction terms
$\lvert\mathcal{A}^{NLO,real}\rvert^2$	$\ominus$	soft/collinear subtraction terms

has been bottleneck
for a long time

ingredients for m-particle observable at NLO



virtual part (one-loop integrals):

$$\mathcal{A}^V_{NLO} = A_2/\epsilon^2 + A_1/\epsilon + A_0^{(v)}$$

$$d\sigma^V \sim Re\left(\mathcal{A}^\dagger_{LO}\,\mathcal{A}^V_{NLO}\right)$$

real radiation part: soft/collinear emission of massless particles

$\Rightarrow$ need subtraction terms

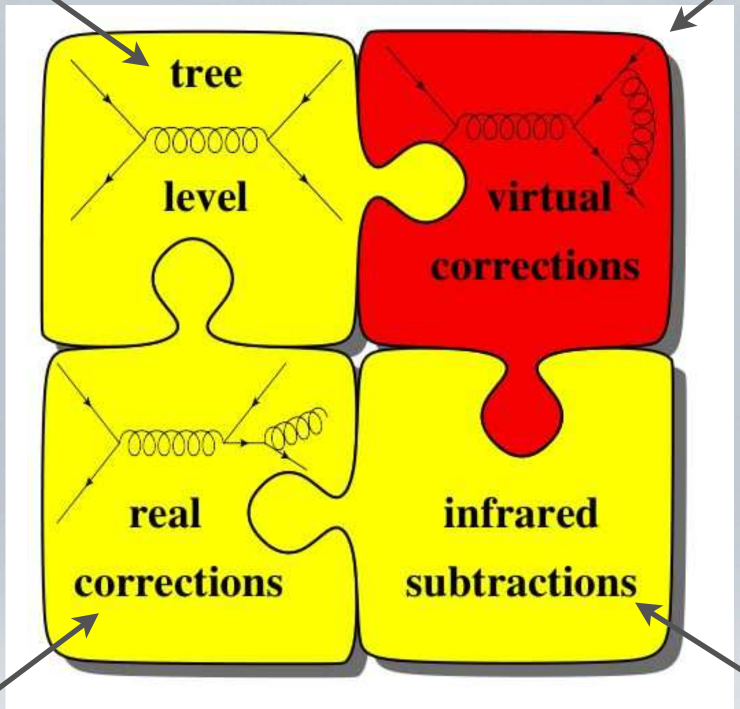
$$\Rightarrow \int_{\text{sing}} d\sigma^S = -A_2/\epsilon^2 - A_1/\epsilon + A_0^{(r)}$$

$$\sigma^{NLO} = \underbrace{\int_{m+1}\left[d\sigma^R - d\sigma^S\right]_{\epsilon=0}}_{\text{numerically}} + \underbrace{\int_m\left[\underbrace{d\sigma^V}_{\text{cancel poles}} + \underbrace{\int_{\text{s}} d\sigma^S}_{\text{analytically}}\right]_{\epsilon=0}}_{\text{numerically}}$$

modular structure of pieces entering an NLO calculation ⇒ **divide into sub-tasks:**

Monte Carlo Program (MC)

"One Loop Provider" (OLP)



Monte Carlo Program (MC)

Monte Carlo Program (MC)

Note: MC may also provide other nice tools, e.g. for plotting, link to Rivet analysis, event files, ...

for cross-talk between MC and OLP: need standards

Monte Carlo tool (MC) | One-Loop-Provider (OLP)

initialisation:

process info
CH summed
model parameters
fix scheme
. . .

order →

copy/confirm

← contract

runtime:

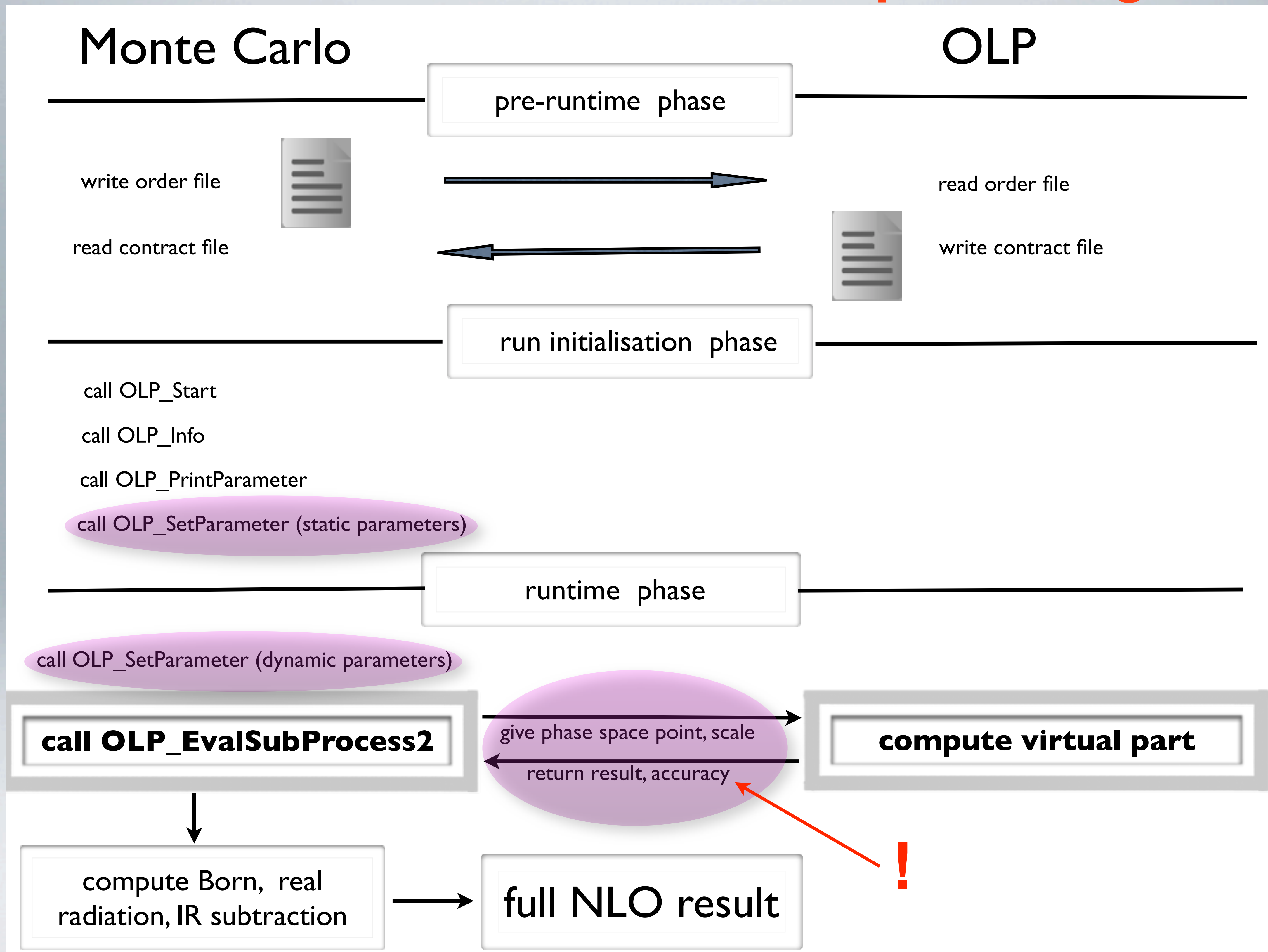
events ⇄ $A_2, A_1, A_0, |Born|^2$

standard interface

Binoth Les Houches Accord (BLHA)

(worked out at Les Houches 2009)

BLHA has been used by several groups meanwhile ⇒ **update August 2013**



OLP: distinguish two approaches:

- generate one-loop amplitude "on the fly" or
- hard coded library of pre-generated processes

MC: needs to be able to provide subtraction terms for NLO real radiation

commonly used methods (at NLO):

- phase space slicing Giele, Glover, Kosower '93
- FKS subtraction Frixione, Kunszt, Signer '96
- Catani-Seymour dipole subtraction Catani, Seymour '96
- antenna subtraction Kosower, A.Gehrmann, T.Gehrmann, Glover '98, '05

automation of subtraction for IR divergent real radiation:

- MadDipole (public) Frederix, Greiner, Gehrmann 08
- Dipole subtraction in Sherpa (public) Gleisberg, Krauss 08
- TevJet (public) Seymour Tevlin 08
- AutoDipole (public) Hasegawa, Moch, Uwer 08,09
- Helac-Phegas (public) Czakon, Papadopoulos, Worek 09; polarized
- MadFKS Frederix, Frixione, Maltoni, Stelzer 09

examples for OLPs:

- FeynArts/FormCalc/LoopTools (public) Thomas Hahn et al
- GRACE Fujimoto et al.
- **B**lack**H**at Bern et al
- Rocket Zanderighi et al
- Helac-NLO (public) Bevilacqua, Czakon, van Hameren, Papadopoulos, Pittau, Worek
- MadLoop/ aMC@NLO Hirschi,Frederix,Frixione,Garzelli,Maltoni,Pittau
  uses CutTools (public) [Ossola, Papadopoulos, Pittau] and MadFKS
- GoSAM (public) Cullen, Greiner, GH, Luisoni, Mastrolia, Ossola, Reiter, Tramontano, uses
  Samurai (public) [Mastrolia, Ossola, Reiter, Tramontano], golem95 (public) [Binoth et al]
- NJET Badger, Biedermann, Uwer, Yundin (public)
- OpenLoops Pozzorini, Maierhöfer, Cascioli
- Recola Denner et al

- POWHEG-Box Alioli, Nason, Oleari, Re et al
- MCFM Campbell et al
- VBFNLO Zeppenfeld et al

Advantage of the interface: OLP can team up with different MCs (and vice versa)

- GoSam + MadDipole/MadGraph4 [Frederix, Gehrmann, Greiner, Maltoni et al]
  - NLO QCD corrections to $pp \to W^+W^-+2\,$jets [Greiner, GH, Mastrolia, Ossola, Reiter, Tramontano '12]
  - SUSY QCD corrections to $pp \to \tilde{\chi}_1^0\tilde{\chi}_1^0$+jet [Cullen, Greiner, GH '12]
  - QCD corrections to $pp \to \gamma\gamma$+1,2 jets [Gehrmann, Greiner, GH '13]
  - $pp \to H+3\,$jets (gluon fusion) [Cullen, van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano '13]
  - $pp \to t\bar{t}H\,$jet [van Deurzen, Luisoni, Mastrolia, Mirabella, Ossola, Peraro '13]
  - QCD corrections to graviton ($\to \gamma\gamma$)+1 jet (ADD) [Greiner, GH, Reichel, von Soden-Fraunhofen '13]
- GoSam + Sherpa
  - $pp \to H+2\,$jets (gluon fusion) [van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, von Soden-Fraunhofen, Tramontano '13]
  - $pp \to W^+W^-\, b\bar{b}$ [GH, Schlenk, Winter, to appear]
  - $pp \to t\bar{t}$+0,1 jet [Hoeche, Huang, Luisoni, Schoenherr, Winter '13]
- GoSam + Powheg [Luisoni, Nason, Oleari, Tramontano '13]
  - $pp \to HW/HZ$+0,1 jet

Merging NLO with Parton Showers

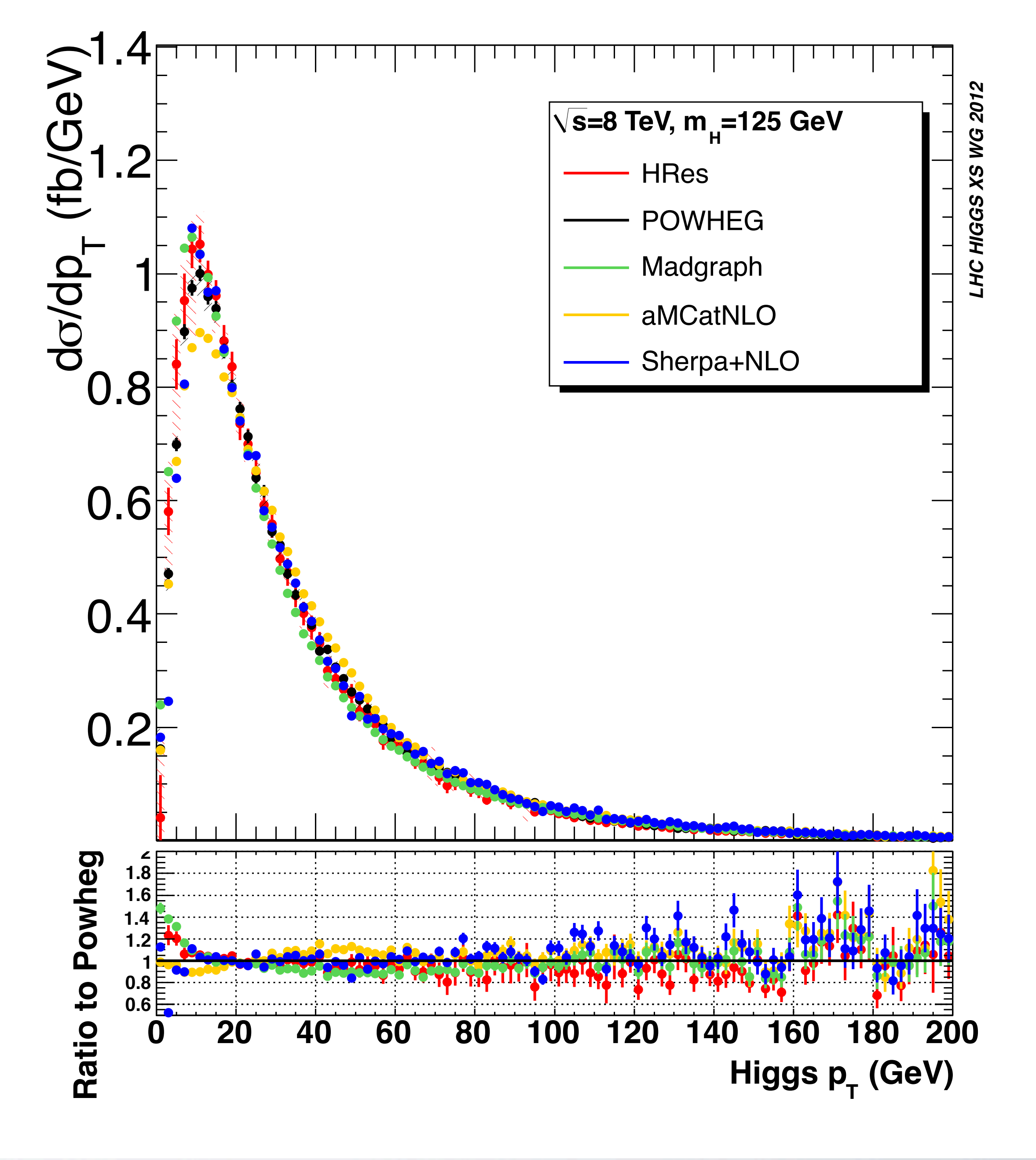
Allows to carry NLO precision to full chain of experimental analysis

two **methods**

MC@NLO Frixione, Webber **POWHEG** Nason, Frixione, Oleari, Re

- can be interfaced to Pythia, Herwig, Sherpa

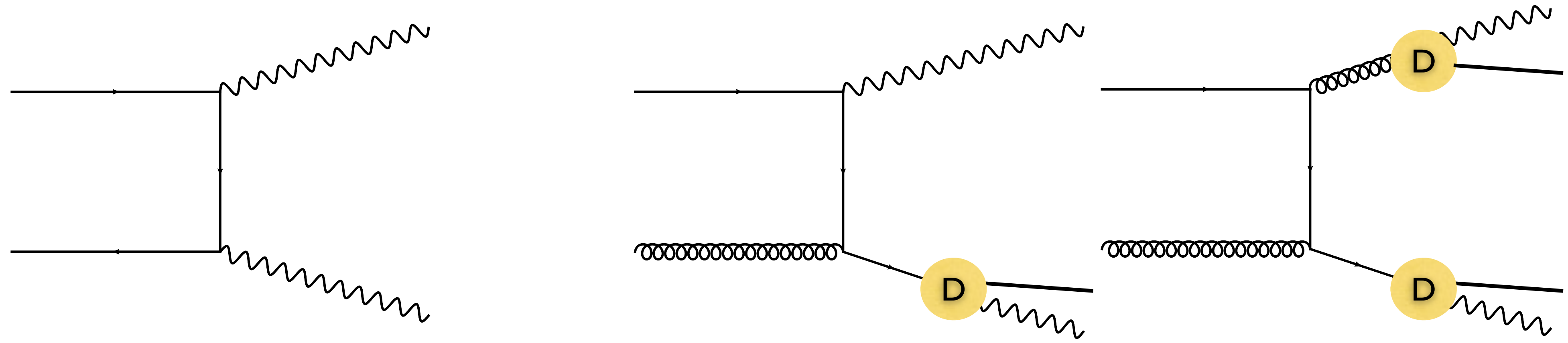
- formally same logarithmic accuracy (but some numerical differences)



N.Chanon

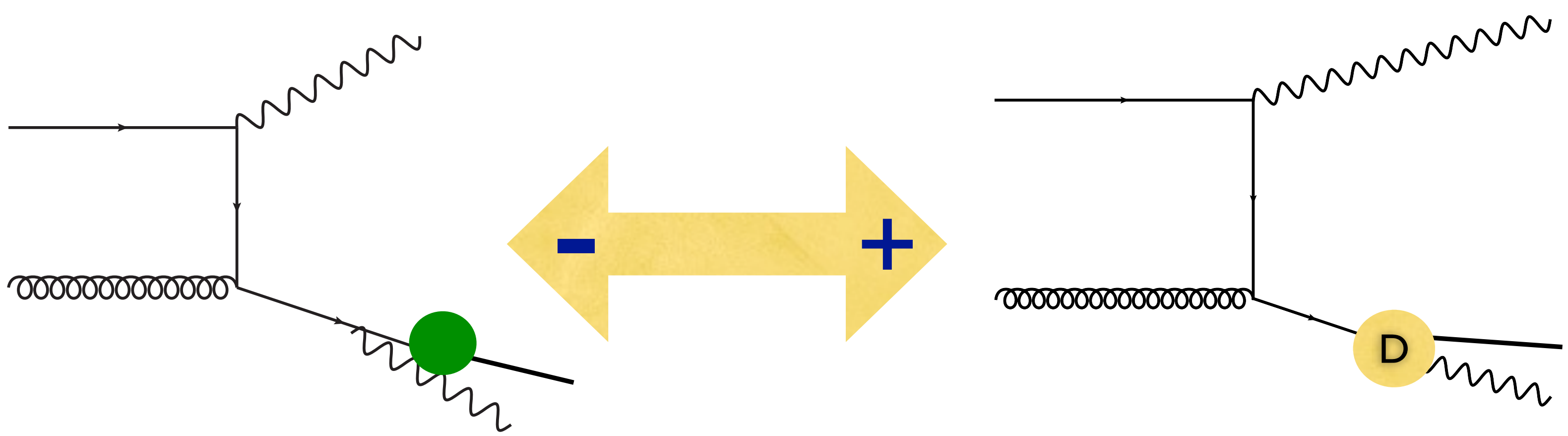
Prompt photons (= high-pt photons)

Two mechanisms for photon production



Direct (point-like) Single and double resolved (collinear fragmentation)

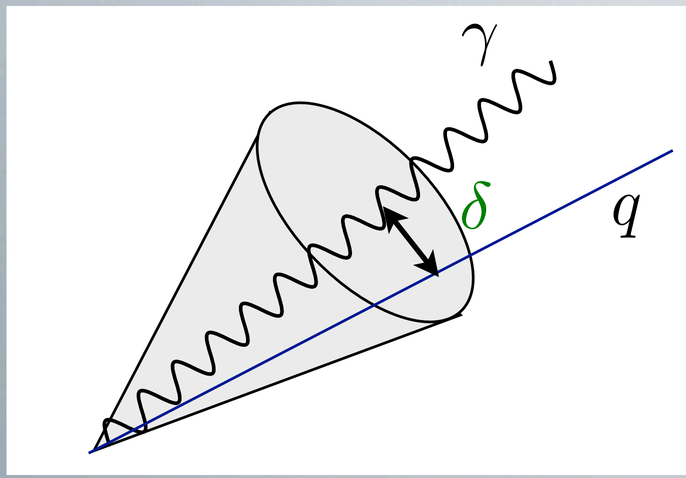
Separation between them NOT physical in general (beyond LO)



collinear divergence → Cancelled by fragmentation

fragmentation: described by convolution with non-perturbative fragmentation function (analogous to PDFs, but in final-state), not well constrained at high z

try to suppress fragmentation component by **photon isolation**



two categories of isolation prescriptions:

standard cone isolation

$$(\eta - \eta^\gamma)^2 + (\phi - \phi^\gamma)^2 \leq \delta^2$$

$$E_T^{had}(\delta) \leq E_{T\,max}^{had}$$

(e.g. $E_{T\,max}^{had} = \epsilon_c\, p_T^\gamma$)

(or fixed energy in the cone)

good for experimentalists!

they will always have some hadronic energy near the photon

smooth isolation (Frixione)

$$E_T^{had}(\delta) \leq E_{T\,max}^{had}\ \chi(\delta)$$

$$\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R_0)}\right)^n$$

no quark-photon collinear divergences

$\Rightarrow$ no fragmentation component

good for theorists!

they do not have to calculate this component at higher orders

Photon isolation

Comparing the two isolation criteria (on theory level) with a program that has implemented both criteria and contains fragmentation at NLO:

Diphox

CMS cuts, 7 TeV

$$R_0 = 0.4$$

$$n = 1$$

$E_{T\,max}^{had}$	standard/smooth
2 GeV	< 1%
3 GeV	< 1%
4 GeV	1%
5 GeV	3%
0.05 p_T	< 1%
0.5 p_T	11%

Daniel de Florian,
Leandro Cieri,
Les Houches 2013

if isolation is very tight, difference between standard and smooth cone is small

Check less inclusive observables: any significant difference?

Diphoton production $\sqrt{s} = 8\,\mathrm{TeV}$ CTEQ6M $\mu_F = \mu_R = M_{\gamma\gamma}$

$p_T^{\gamma\, hard} \geq 40\,\mathrm{GeV}$

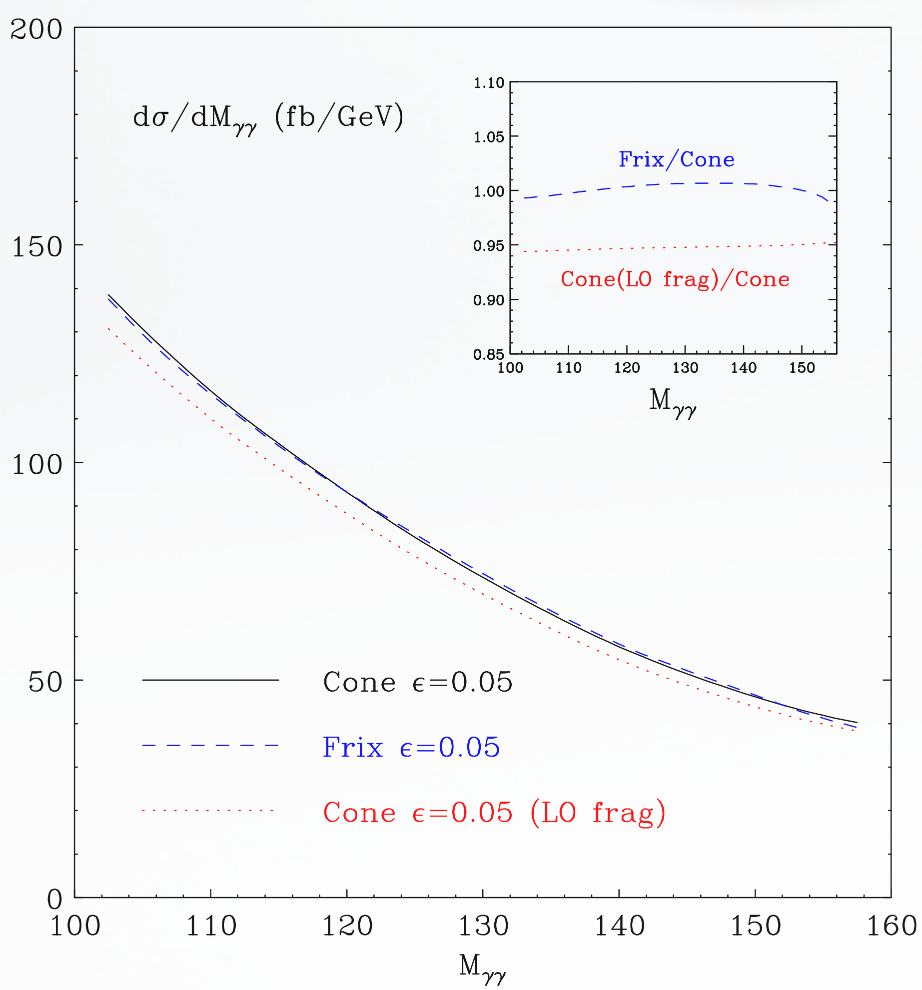
$p_T^{\gamma\, soft} \geq 30\,\mathrm{GeV}$

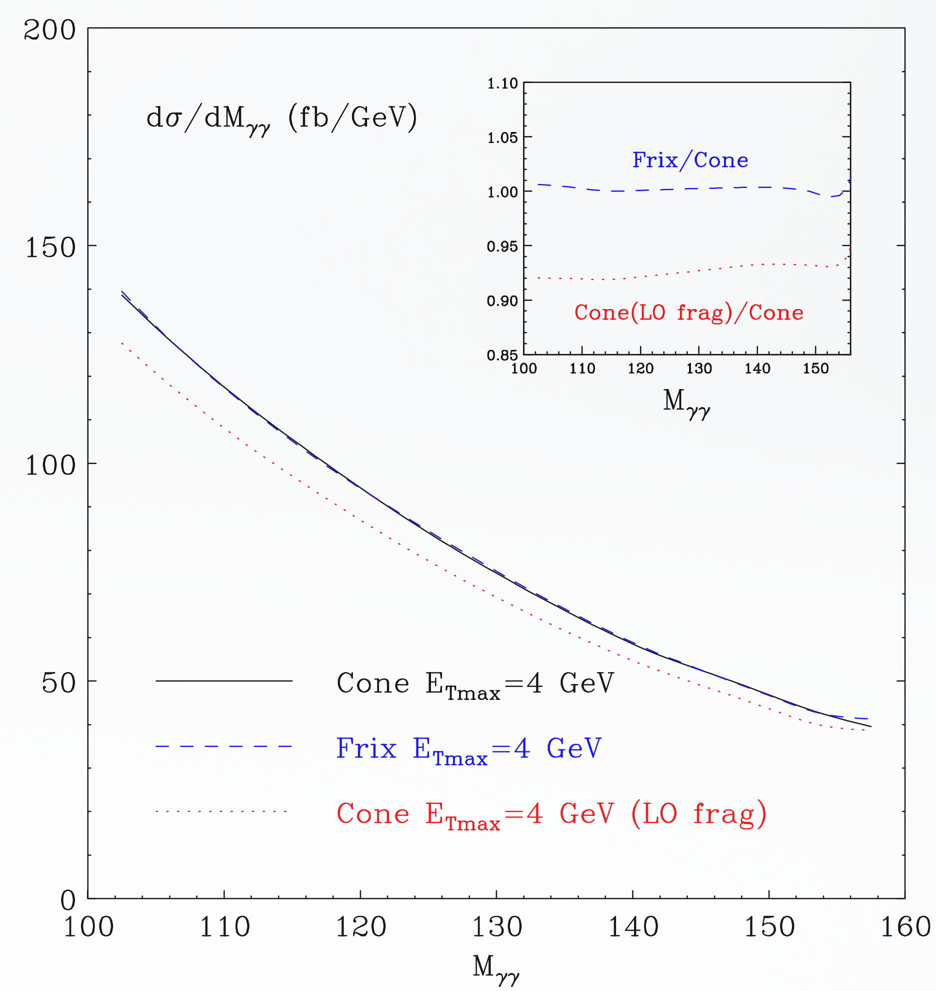
$100\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 160\,\mathrm{GeV}$ $|\eta^\gamma| \leq 2.5$ $R_{\gamma\gamma} \geq 0.45$

full NLO Cone (DIPHOX) vs Cone with LO fragmentation vs NLO Smooth

$E_{T\,max}^{had} = \epsilon\, p_T^\gamma$ $\epsilon = 0.05$

$E_{T\,max}^{had} = 4\,\mathrm{GeV}$





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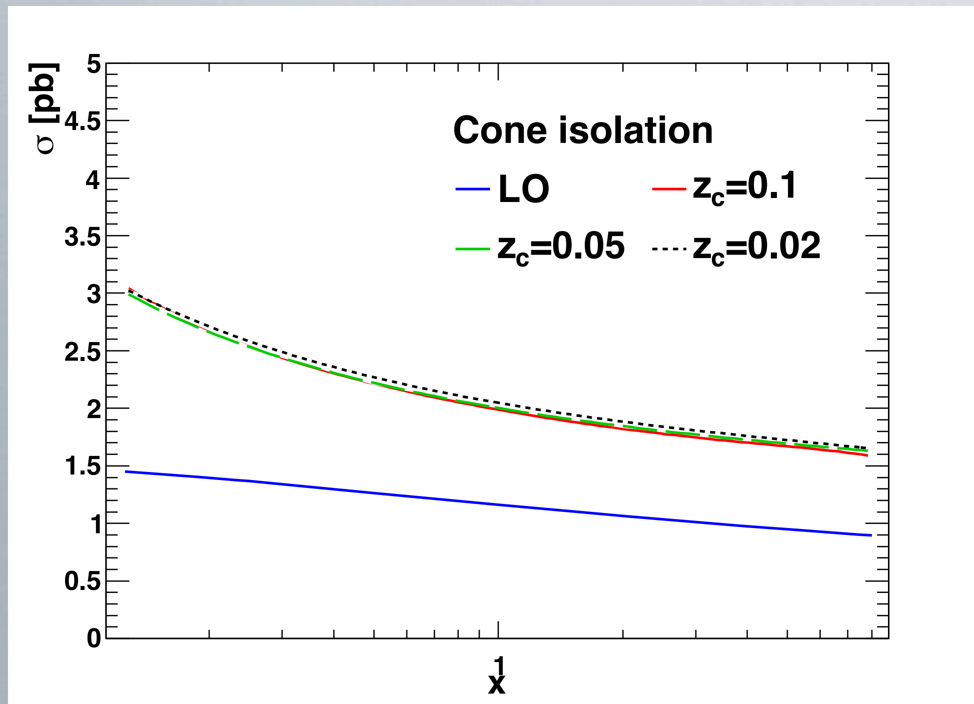
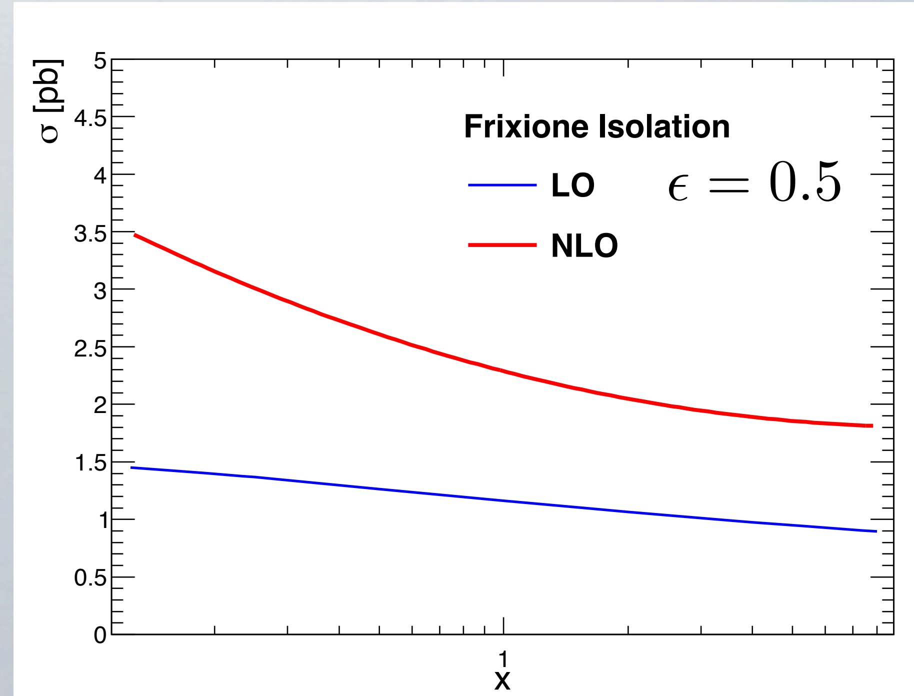
however, very tight isolation can have pitfalls

- can generate large logarithms log(R) which would be cancelled (partially) only by the fragmentation component at NLO
- can interfere with jet clustering
- mismatch theory-experiment larger because relative importance of underlying event becomes larger

$\gamma\gamma + 1$ jet   inclusive

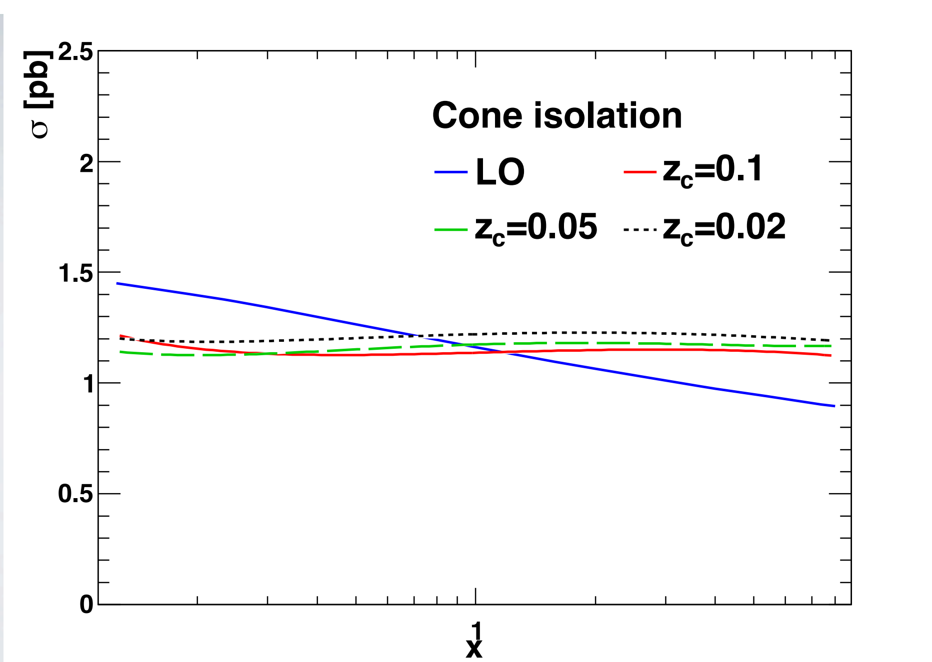


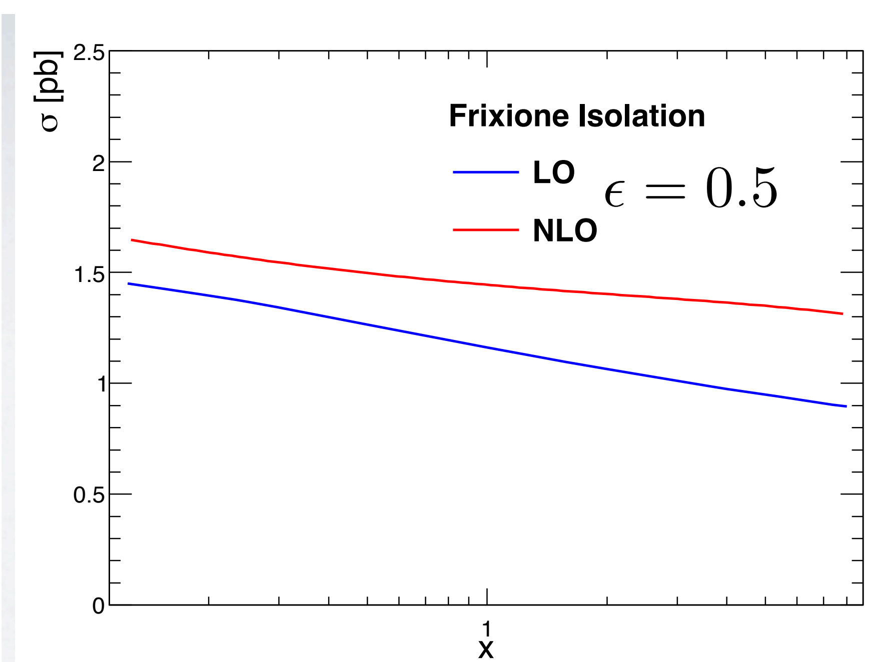


$$z_c = \frac{|\vec{p}^{\,\mathrm{had}}_{T,\mathrm{cone}}|}{|\vec{p}^{\,\gamma}_T + \vec{p}^{\,\mathrm{had}}_{T,\mathrm{cone}}|}$$

scale uncertainty larger with smooth cone isolation

exclusive cuts: veto on second jet $p_{T,j2} \leq 30$ GeV



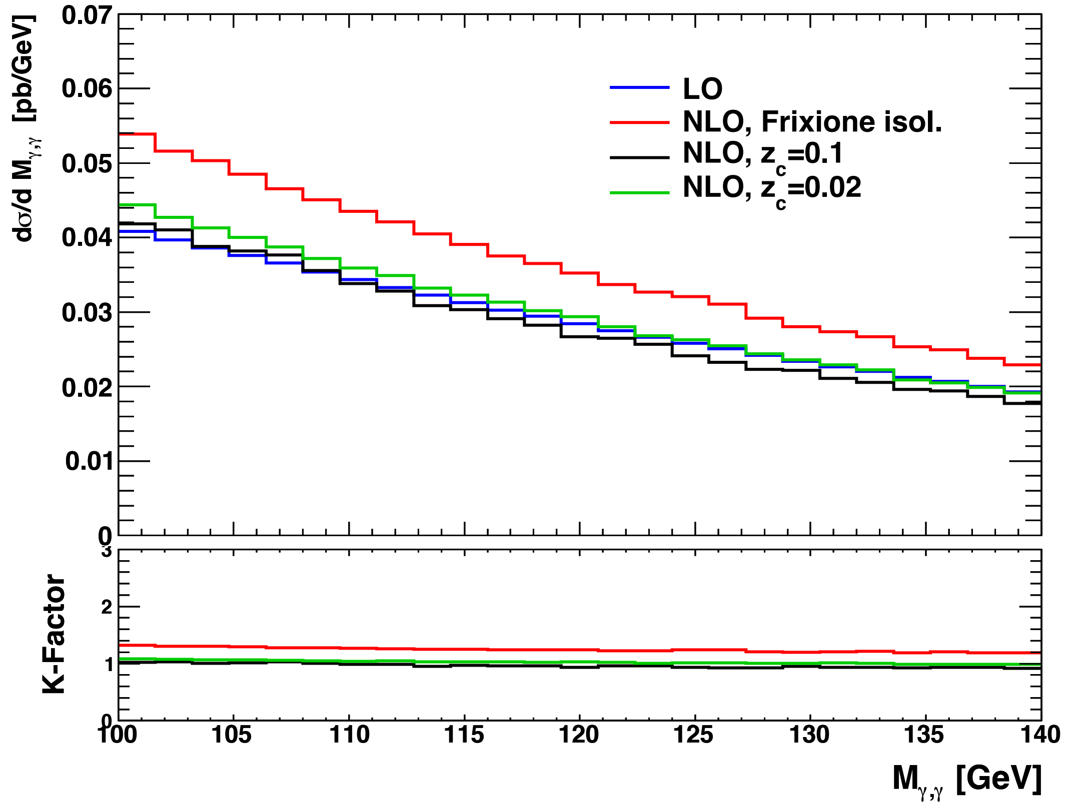


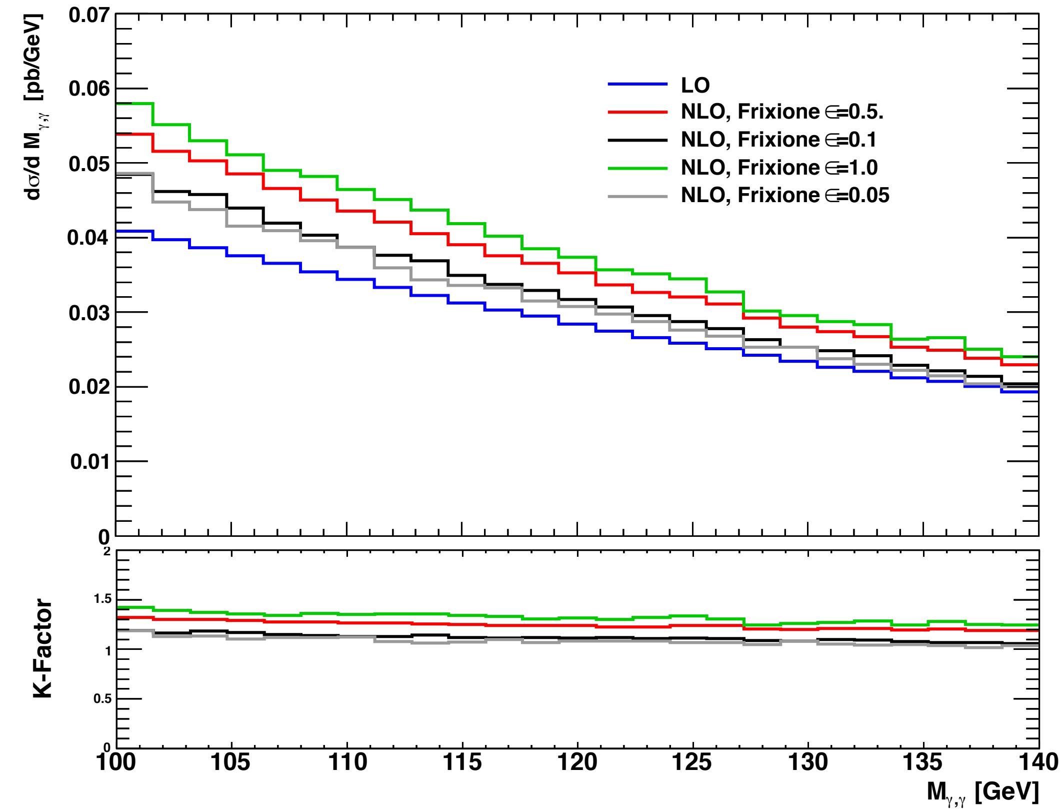
Greiner, Gehrmann, GH 2013

$\gamma\gamma +$ jet

comparison of isolation parameters for $\gamma\gamma$ invariant mass $M_{\gamma,\gamma}$

exclusive cuts



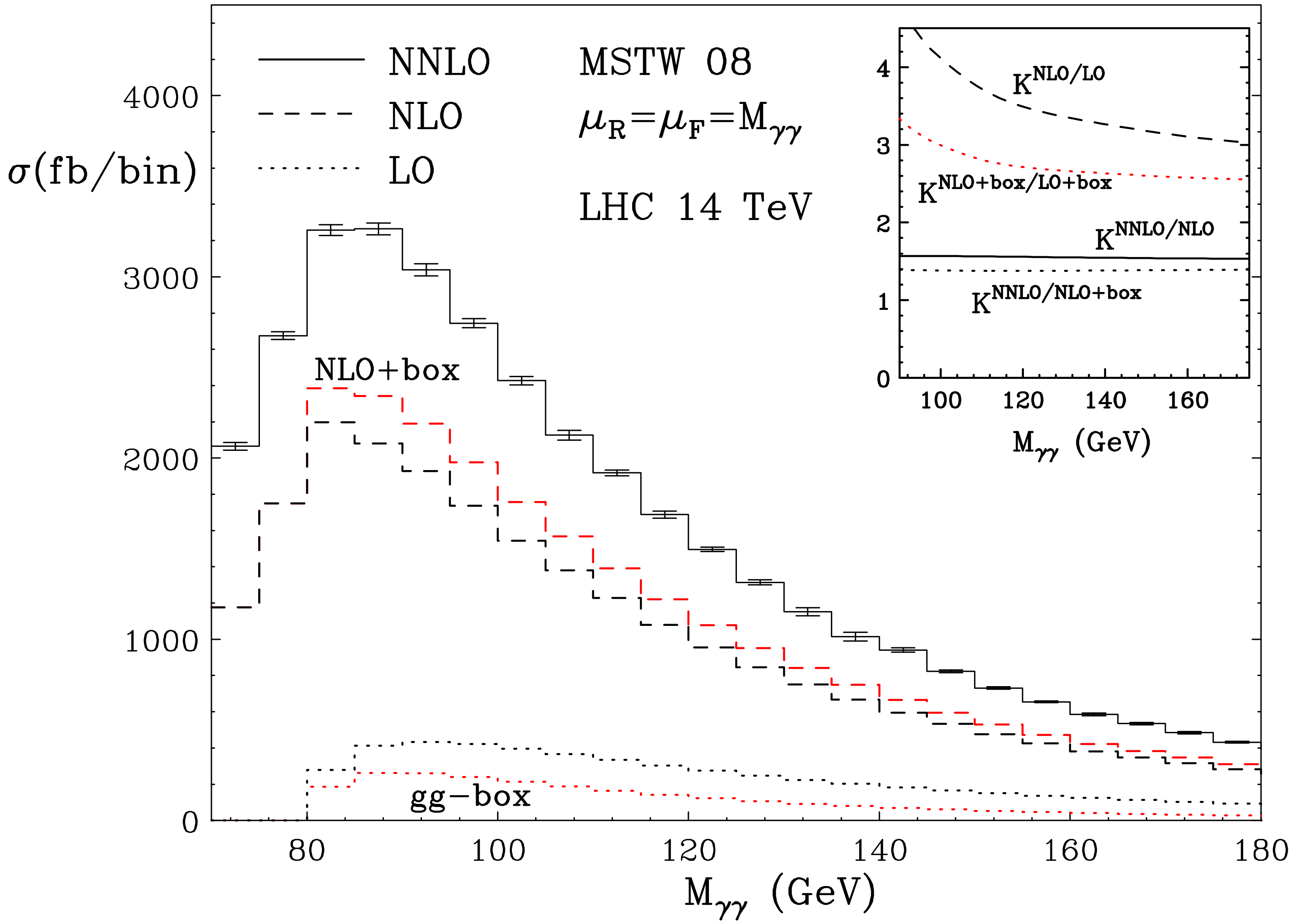


differences between standard cone isolation and Frixione isolation decrease for decreasing z_c resp. ϵ

but are sizable for moderate isolation parameters

Greiner, Gehrmann, GH 2013

$pp \to \gamma\gamma$ at NNLO



$\sqrt{S} = 14\,\text{TeV}$

$p_T^{\gamma\, hard} \geq 40\,\text{GeV}$

$p_T^{\gamma\, soft} \geq 25\,\text{GeV}$

$|\eta^\gamma| \leq 2.5$

$20\,\text{GeV} \leq M_{\gamma\gamma} \leq 250\,\text{GeV}$

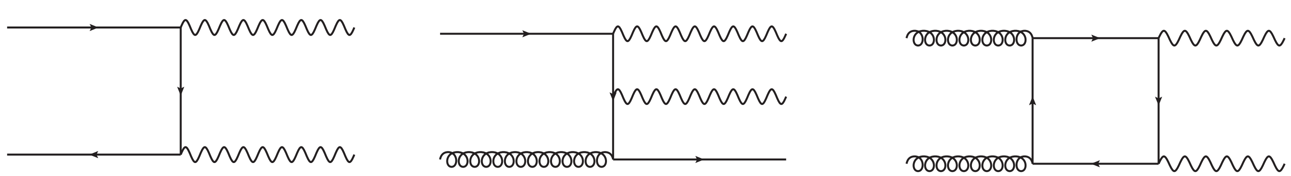
Frixione isolation

Catani, Cieri, De Florian, Ferrera, Grazzini, 2012

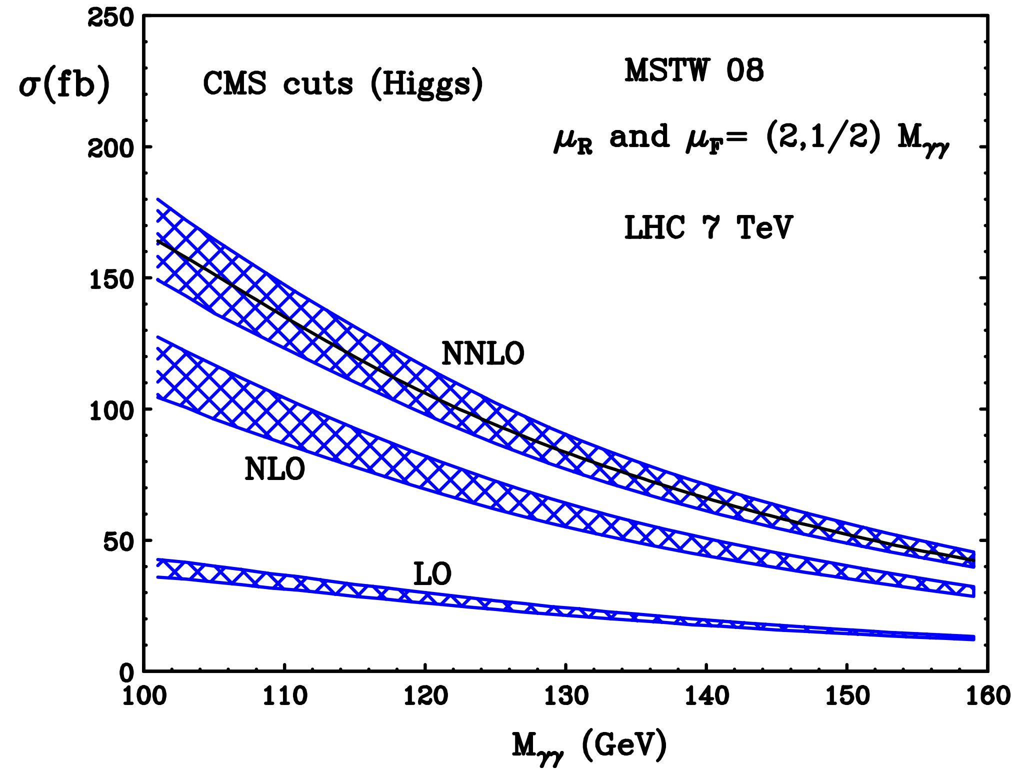
$pp \to \gamma\gamma$

S.Catani, L.Cieri, DdeF, G.Ferrera, M.Grazzini (2012)

- Invariant mass : 40-50 % corrections



$q\bar{q}$	qg	gg
α_s^0	α_s^1	α_s^2

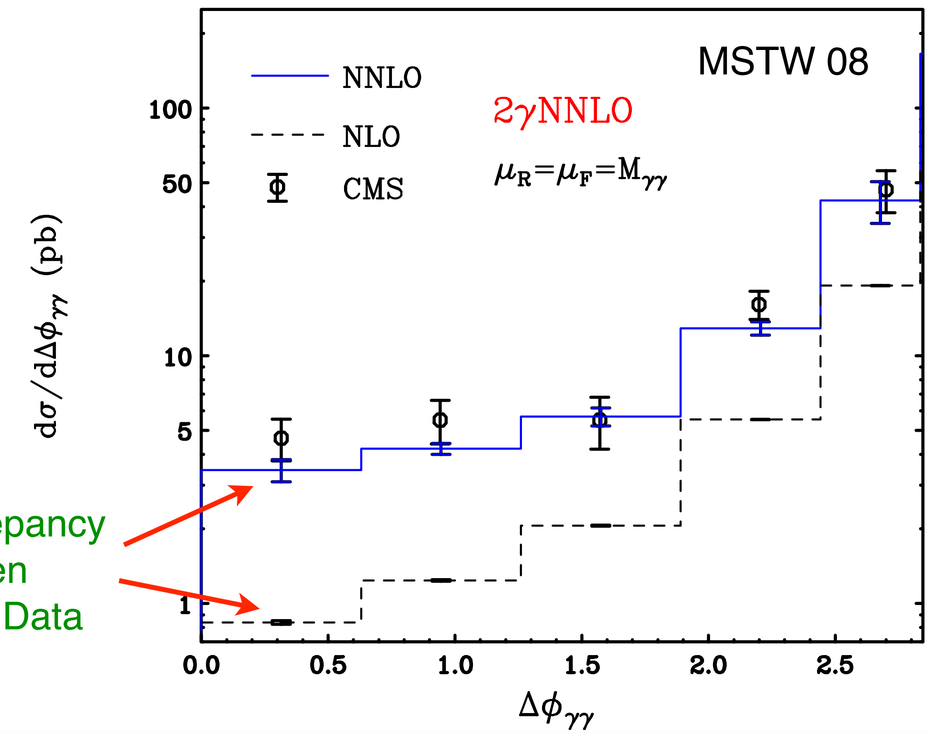


Open new channel at NLO,NNLO

- Azimuthal difference

α_s^2 Needed to understand LHC data

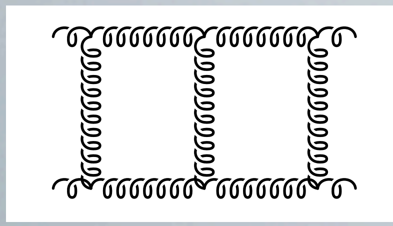
(effectively NLO)



large discrepancy
between
NLO and Data

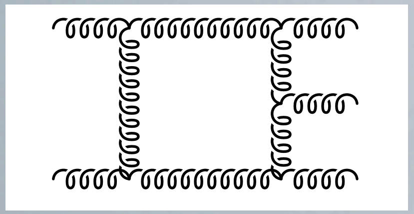
NNLO calculations

what are the different types of ingredients?



two-loop matrix elements (2→2)

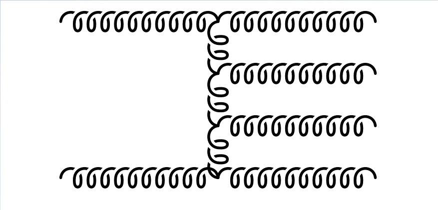
contain explicit infrared poles from two-loop virtual integrals



one-loop matrix elements (2→3)

contain explicit infrared poles from one-loop virtual integrals
and implicit infrared poles from singly unresolved real emission

will show up upon integration over the phase space



tree level matrix elements (2→4)

contain implicit infrared poles from **doubly** unresolved real emission

main difficulties:

- isolate and subtract implicit infrared poles (real radiation)
- calculate two-loop virtual integrals

Structure of NNLO cross sections

$$
\begin{aligned}
\mathrm{d}\hat{\sigma}_{NNLO} = &\int_{\mathrm{d}\Phi_{m+2}} \left(\mathrm{d}\hat{\sigma}^{RR}_{NNLO} - \mathrm{d}\hat{\sigma}^{S}_{NNLO}\right) \\
&+ \int_{\mathrm{d}\Phi_{m+1}} \left(\mathrm{d}\hat{\sigma}^{RV}_{NNLO} - \mathrm{d}\hat{\sigma}^{VS}_{NNLO} + \mathrm{d}\hat{\sigma}^{MF,1}_{NNLO}\right) \\
&+ \int_{\mathrm{d}\Phi_{m}} \left(\mathrm{d}\hat{\sigma}^{VV}_{NNLO} + \mathrm{d}\hat{\sigma}^{MF,2}_{NNLO}\right) + \int_{\mathrm{d}\Phi_{m+2}} \mathrm{d}\hat{\sigma}^{S}_{NNLO} + \int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\hat{\sigma}^{VS}_{NNLO}
\end{aligned}
$$

- Real and virtual contributions: $\mathrm{d}\hat{\sigma}^{RR}_{NNLO}$, $\mathrm{d}\hat{\sigma}^{RV}_{NNLO}$, $\mathrm{d}\hat{\sigma}^{VV}_{NNLO}$
- Subtraction term for double real radiation: $\mathrm{d}\hat{\sigma}^{S}_{NNLO}$
- Subtraction term for one-loop single real radiation: $\mathrm{d}\hat{\sigma}^{VS}_{NNLO}$
- Mass factorization counter-terms: $\mathrm{d}\hat{\sigma}^{MF,1}_{NNLO}$, $\mathrm{d}\hat{\sigma}^{MF,2}_{NNLO}$

remember NLO:

$$
\sigma^{NLO} = \underbrace{\int_{m+1} \left[d\sigma^{R} - d\sigma^{S}\right]_{\epsilon=0}}_{\text{numerically}} + \underbrace{\int_{m} \left[\underbrace{d\sigma^{V}}_{\text{cancel poles}} + \underbrace{\int_{\mathrm{s}} d\sigma^{S}}_{\text{analytically}} \right]_{\epsilon=0}}_{\text{numerically}}
$$

Real radiation at NNLO: methods

- Sector decomposition
  (T. Binoth, G. Heinrich; C. Anastasiou, K. Melnikov, F. Petriello)
  - $pp \to H$, $pp \to V$, including decays
    (C. Anastasiou, K. Melnikov, F. Petriello; S. Bühler, F. Herzog, A. Lazopoulos, R. Müller)
- Sector-improved subtraction schemes
  (M. Czakon; R. Boughezal, K. Melinkov, F. Petriello)
  - $pp \to t\bar{t}$ (M. Czakon, P. Fiedler, A. Mitov)
  - $pp \to H+j$ (R. Boughezal, F. Caola, K. Melnikov, F. Petriello, M. Schulze)
- q_T-subtraction (S. Catani, M. Grazzini)
  - $pp \to H$, $pp \to V$, $pp \to \gamma\,\gamma$, $pp \to VH$
    (S. Catani, L. Cieri, D. de Florian, G. Ferrera M. Grazzini, F. Tramontano)
- Antenna subtraction (T. Gehrmann, E.W.N. Glover, AG)
  - $e^+e^- \to 3j$ (T. Gehrmann, E.W.N. Glover, G. Heinrich, AG; S. Weinzierl)
  - $pp \to 2j$ (T. Gehrmann, E.W.N. Glover, J. Pires, AG)

NNLO: what is available or in the pipeline?

- Some measurements to few percent accuracy

✓ $e^+e^- \to 3\,\text{jets}$

$e^-p \to (2+1)\,\text{jets}$

✓ $pp \to V$

$pp \to \text{jets}$ partial

$pp \to V + \text{jets}$

✓ $pp \to t\bar{t}$

$\mathcal{O}(\alpha_s^2)$

Match experimental accuracy
Extract accurate information

- Some processes with still (potentially) large NNLO corrections

✓ $pp \to H$

✓ $pp \to \gamma\gamma$

$pp \to VV$

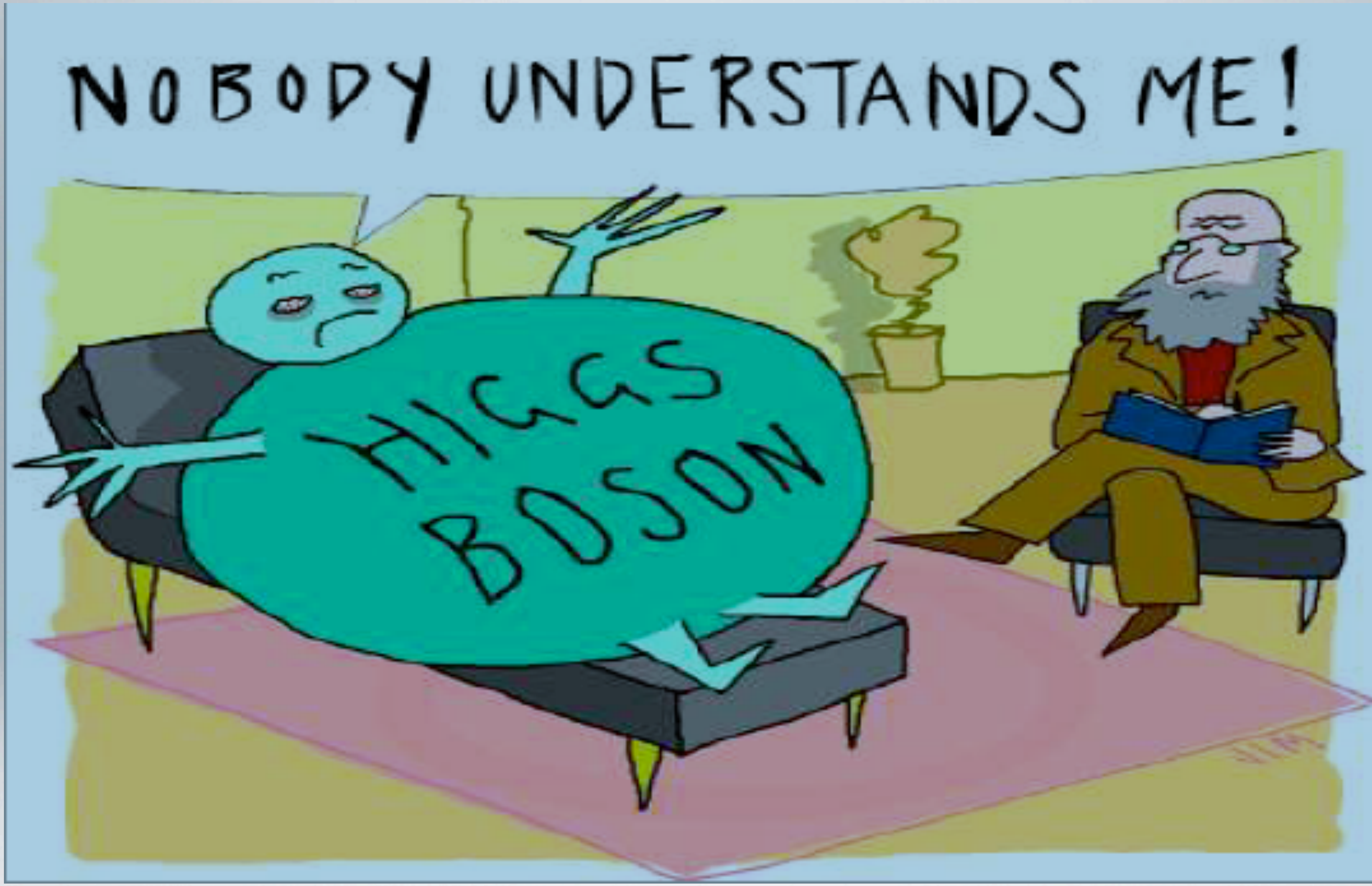
$pp \to H + \text{jets}$ partial

meaningful comparison
solid estimate of uncertainties

Daniel de Florian,
EPS 2013

Conclusions

- understanding QCD effects is crucial at hadron colliders
- precision measurements require at least NLO accuracy
- a lot of progress has been achieved in recent years (fixed higher orders, matching to parton showers, resummation, all-orders infrared structure of massless Yang-Mills theories, ...)
- nonetheless let us keep the hopes up that QCD (+EW/Higgs) is not all we will see in the next LHC run!



understanding QCD better will also help him ...