Status and prospects in higher order calculations and MC tools

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12th August 2014

Physics at the LHC and Beyond 2014, Quy-Nhon, Vietnam

outline

Precision SM predictions for LHC physics

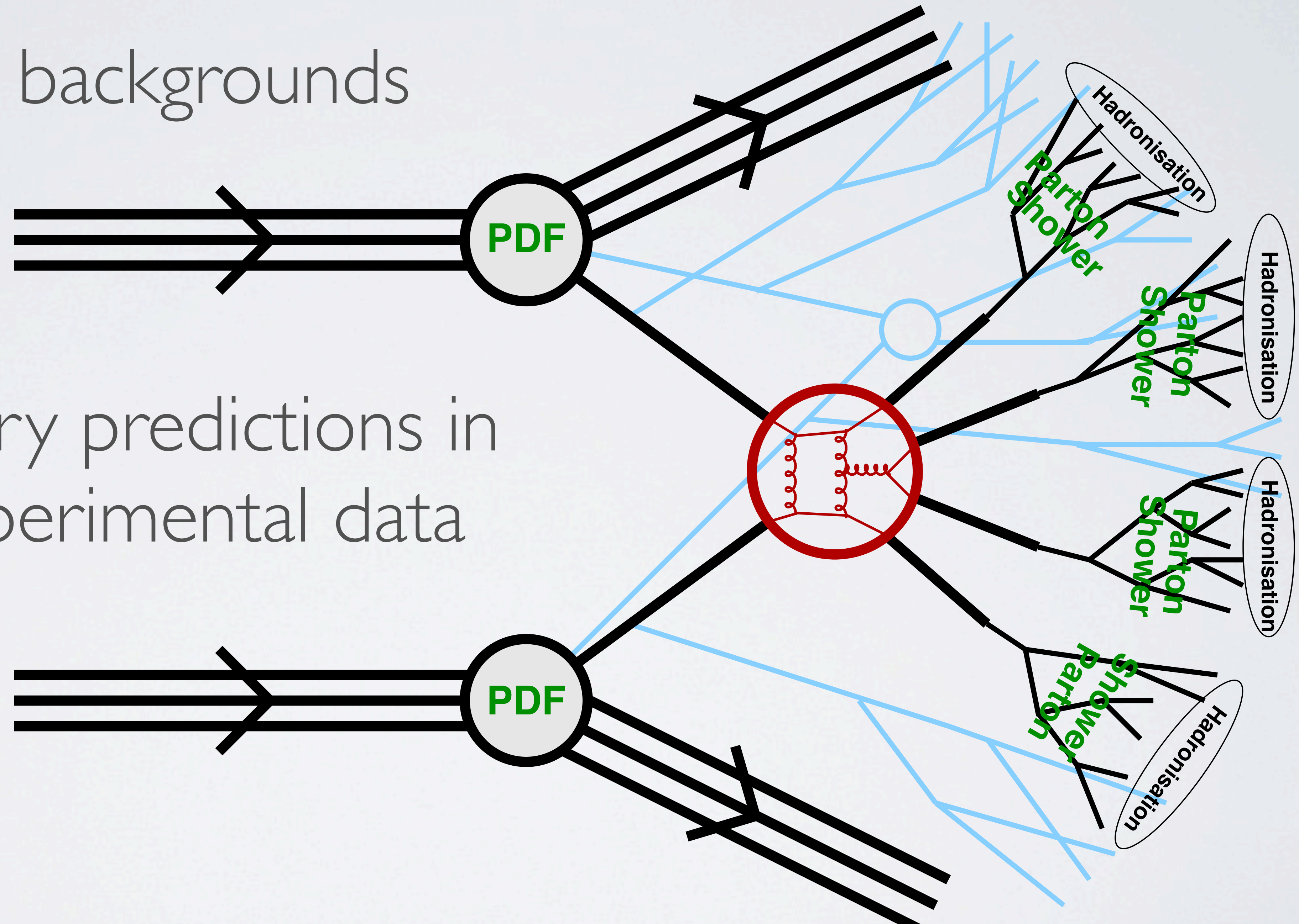
- higher order calculations
  - automated NLO: technology now available!
  - theoretical methods for NNLO predictions: IR subtraction, loop integral methods etc.
- Monte Carlo tools and simulations
  - shower matching at NLO, multi-jet merging techniques
  - phenomenological results and implications

modelling hadron collisions

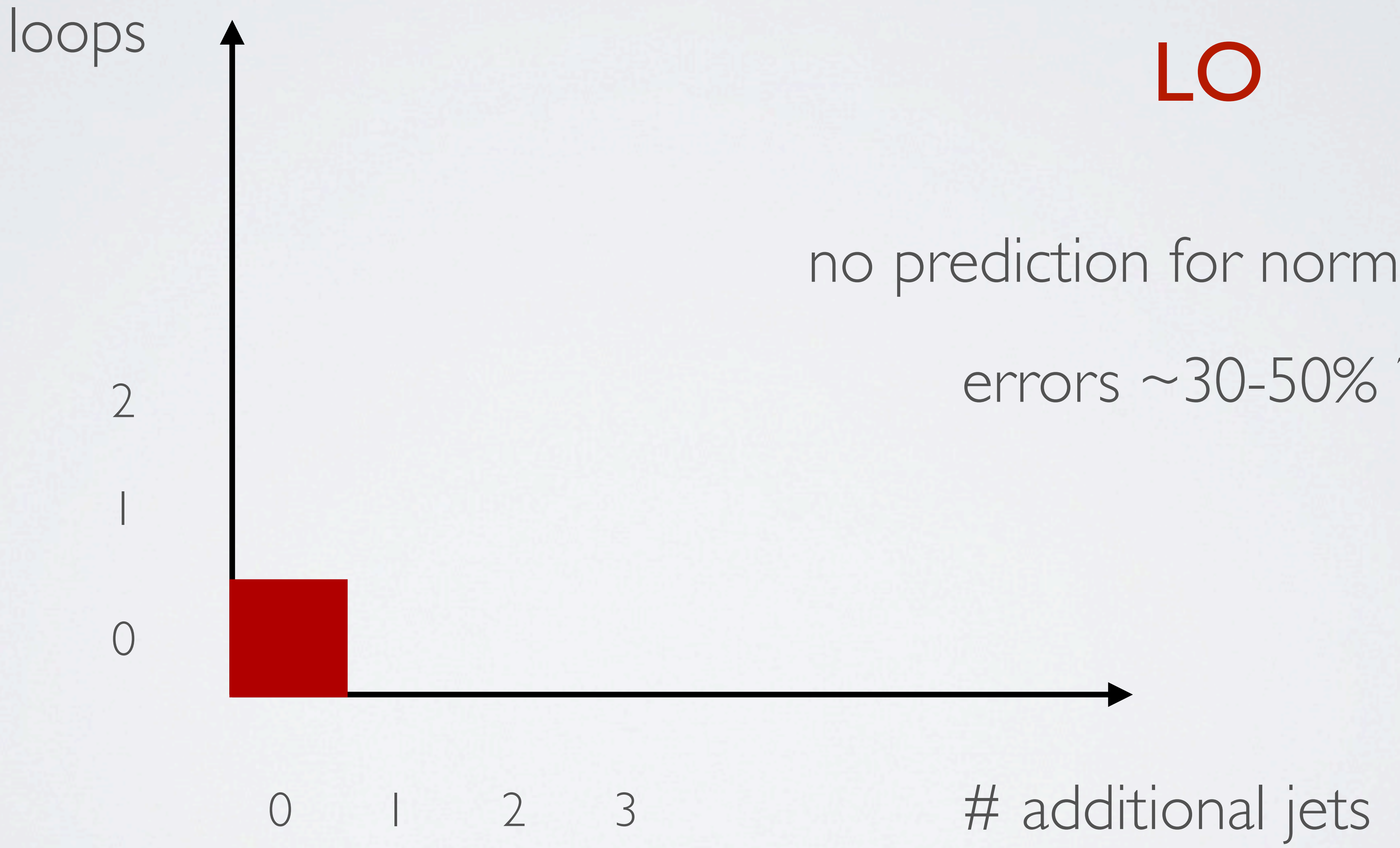
New physics backgrounds

Keeping theory predictions in line with experimental data

Determination of SM parameters



ingredients for precision

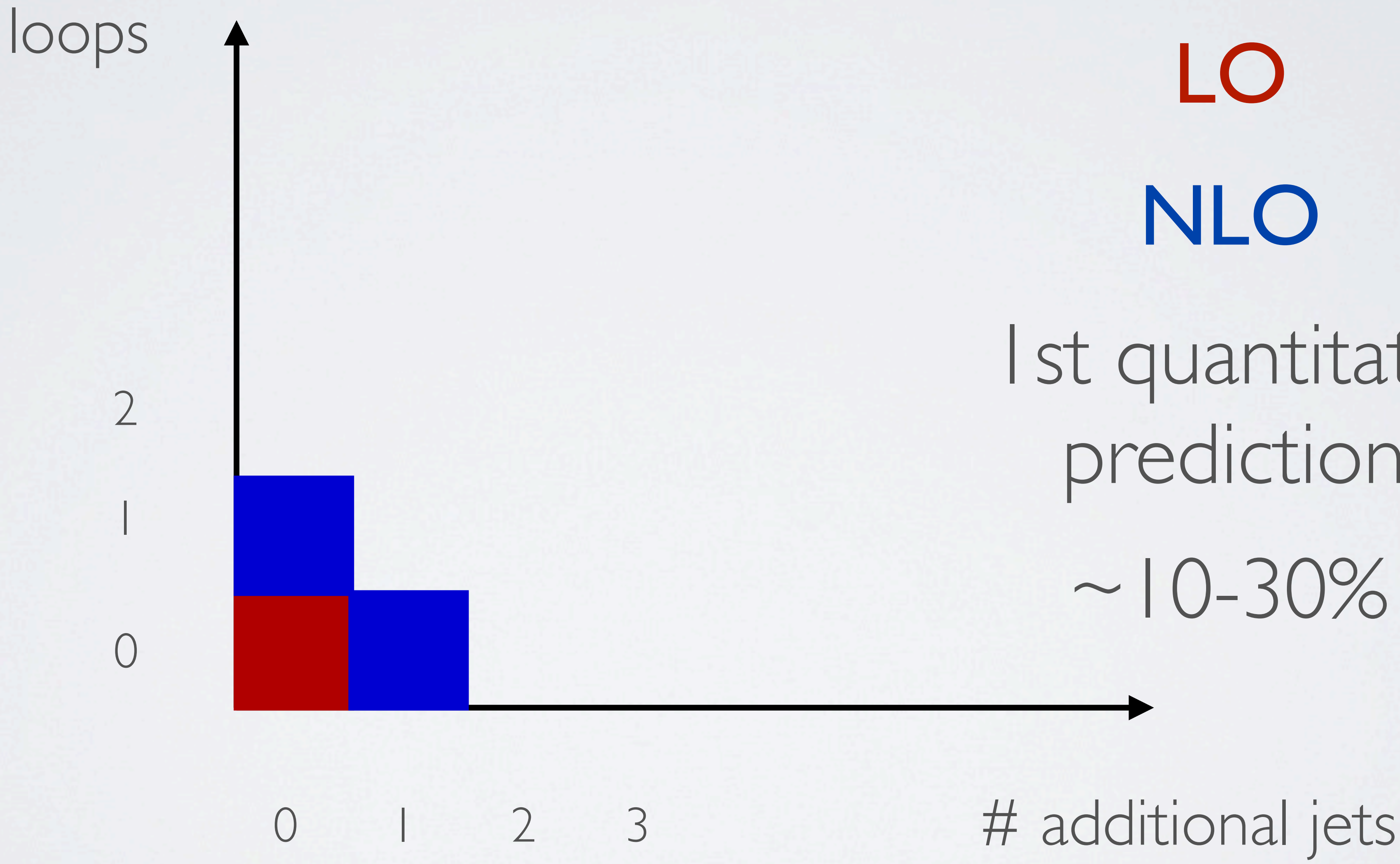


LO

no prediction for normalization

errors ~30-50% ???

ingredients for precision



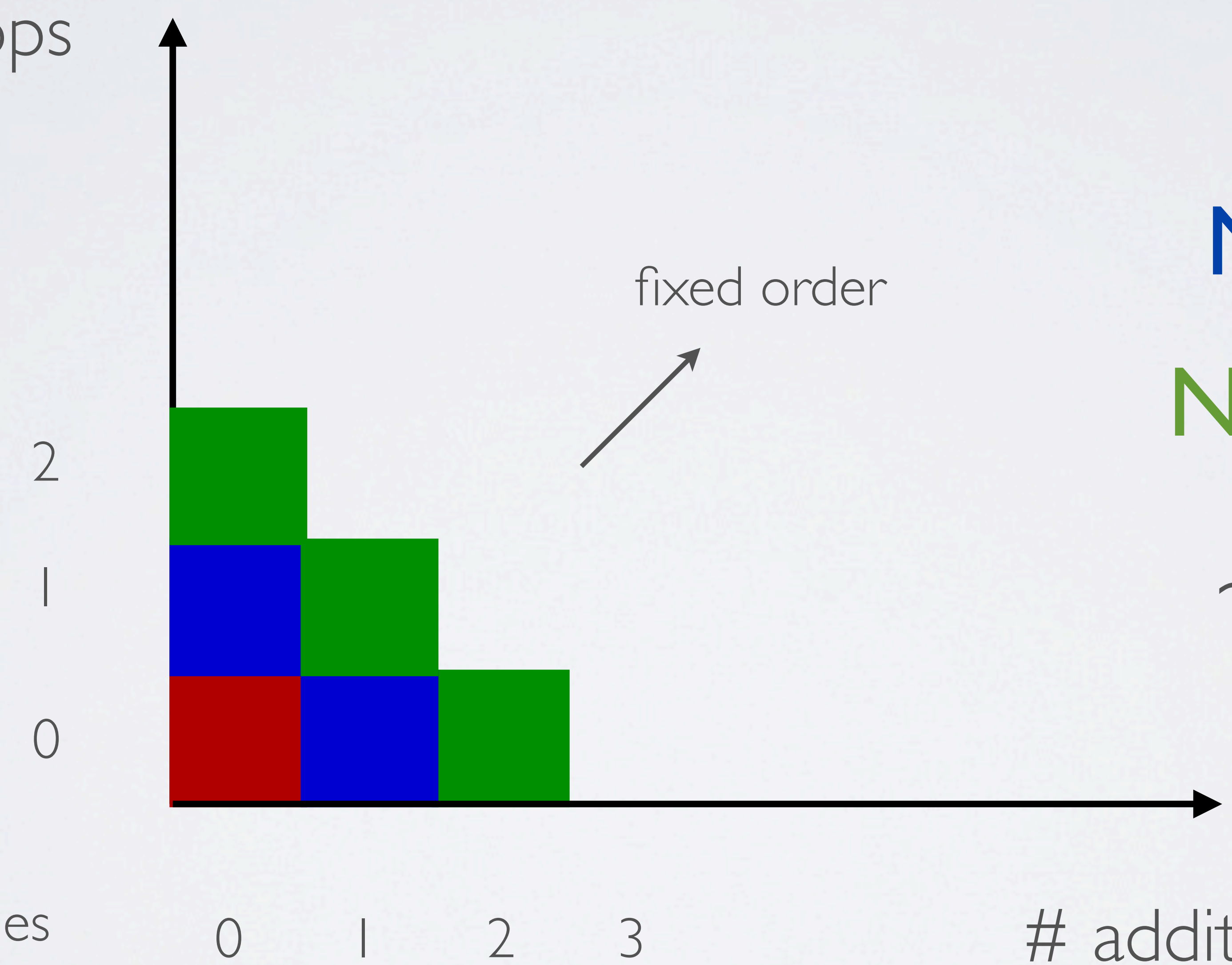
LO

NOLO

1st quantitative predictions

~10-30%

ingredients for precision



LO

NLO

NNLO

~5%

pdf uncertainties
becoming bottleneck

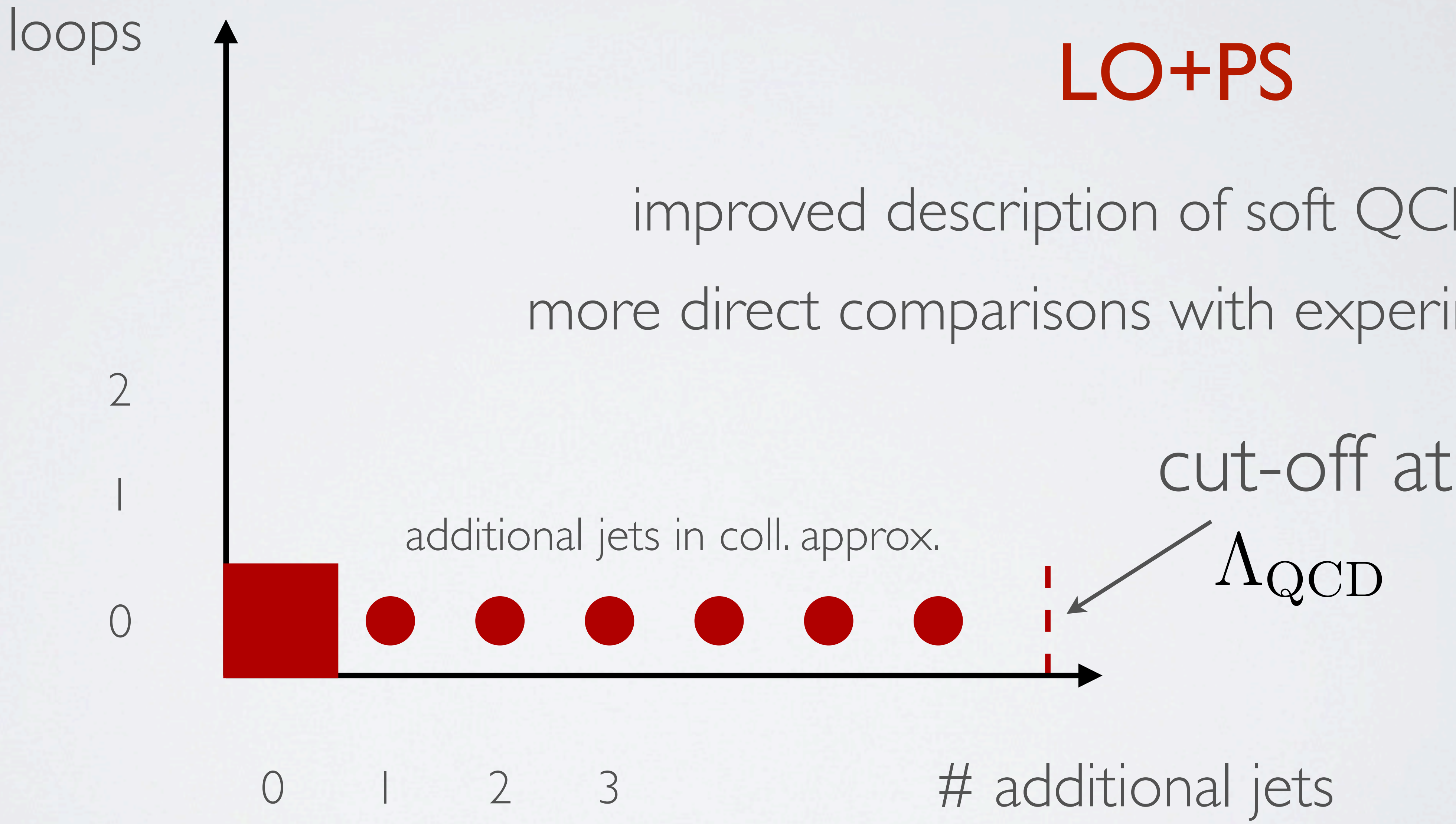
ingredients for precision

fixed order not good for all regions

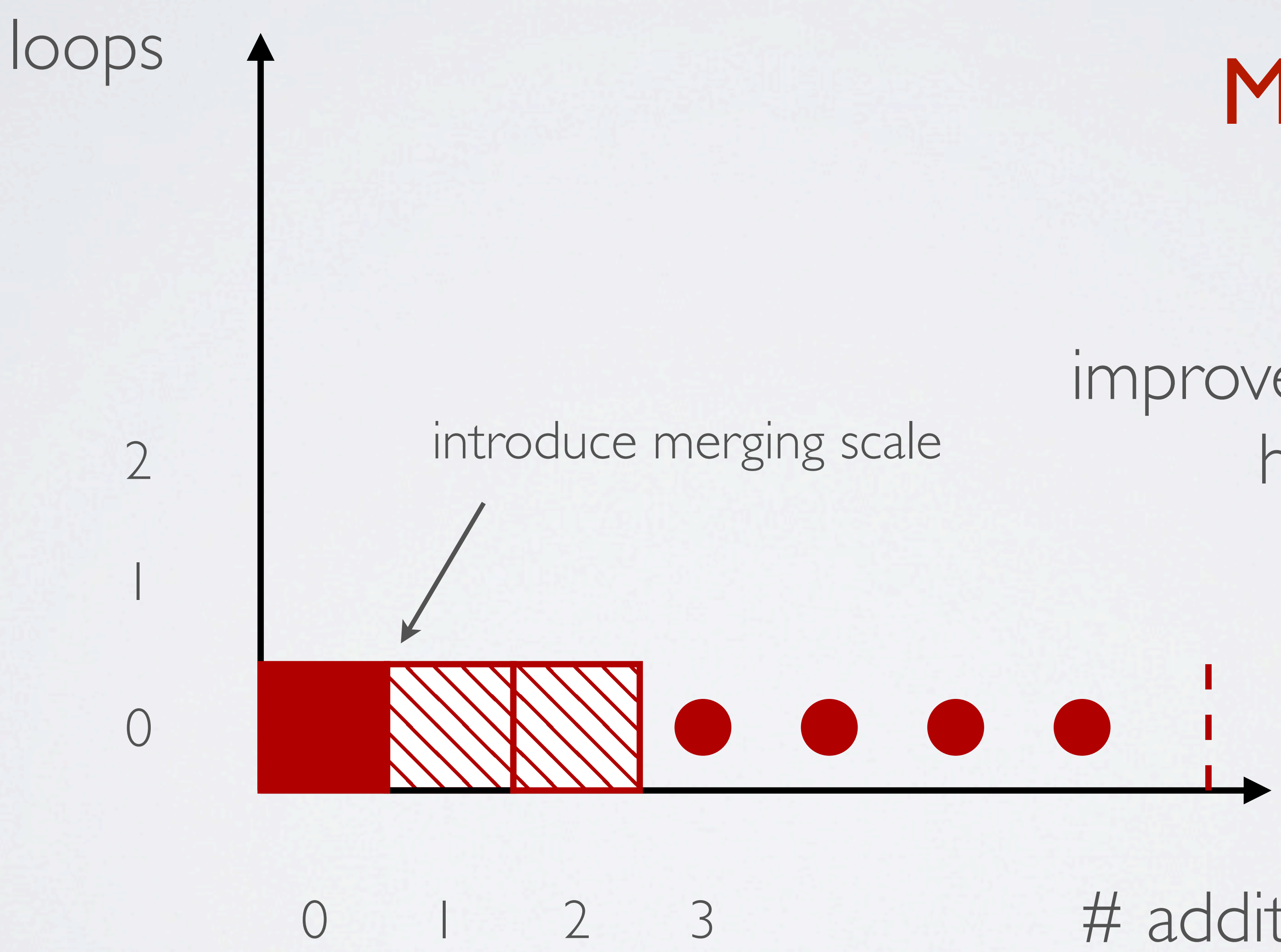
LO+PS

improved description of soft QCD

more direct comparisons with experiments



ingredients for precision

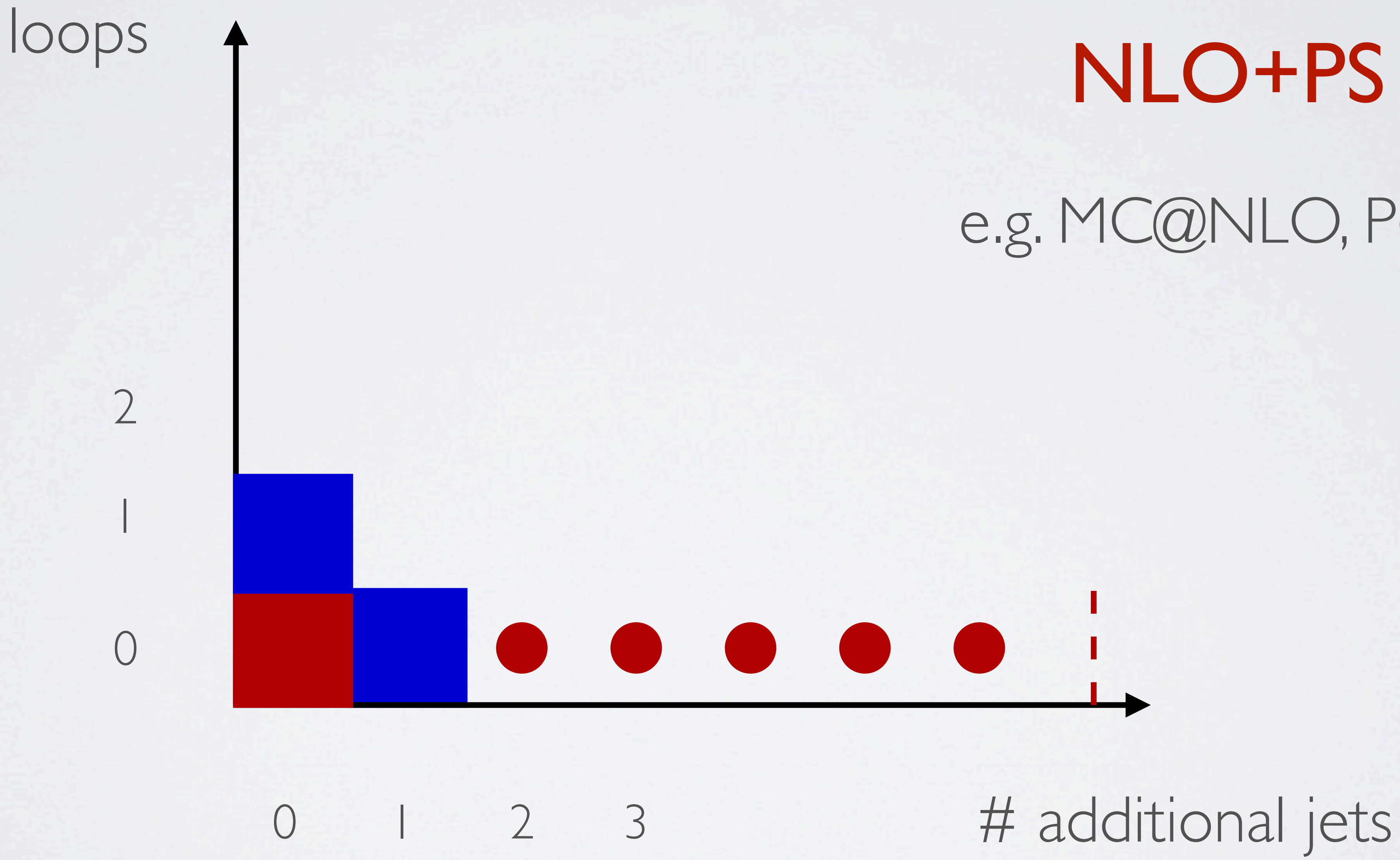


ME+PS

e.g. CKKW-L, MLM

improved description of hard QCD

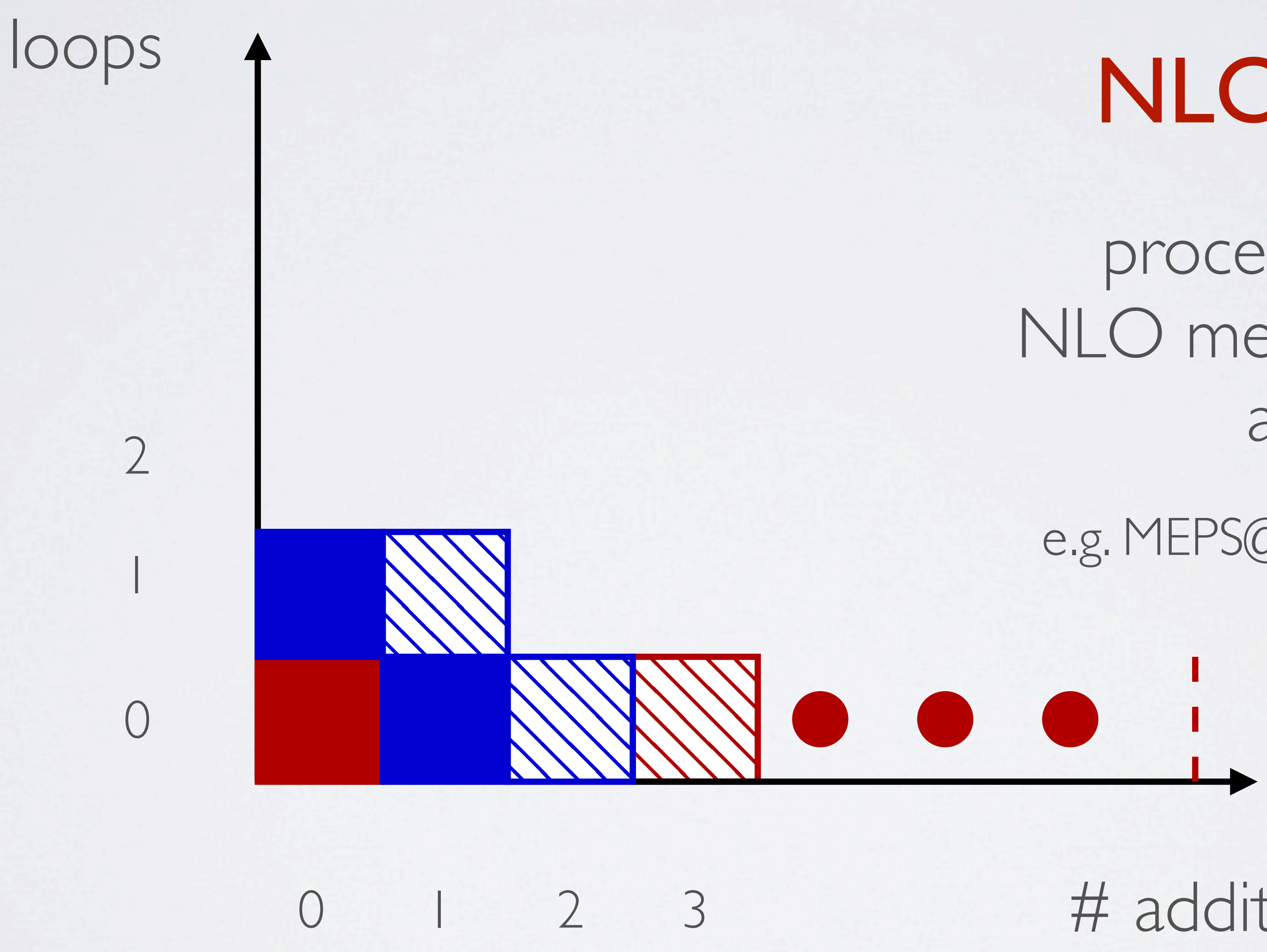
ingredients for precision



NLO+PS

e.g. MC@NLO, POWHEG

ingredients for precision



NLO ME+PS

procedures for full NLO merging becoming available

e.g. MEPS@NLO, UNLOPS, FxFx, ...

ingredients for precision

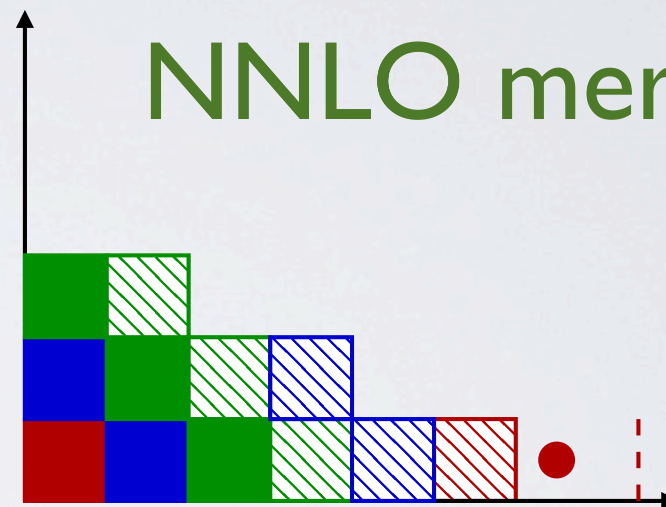
NNLO+PS

recent attempts
for DY and Higgs

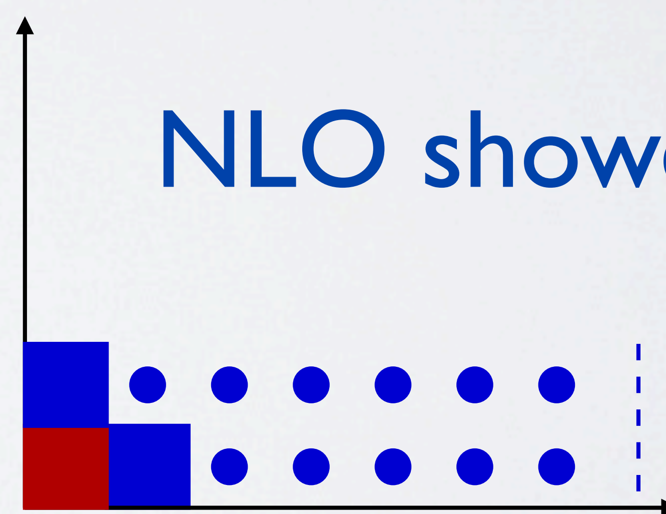
UN^{2}LOPS DY [Hoeche, Li, Prestel (2014)]

MiNLO Higgs [Nason, Re, Zanderighi (2014)]

MiNLO DY [Karlberg, Re, Zanderighi (2014)]



NNLO merging?

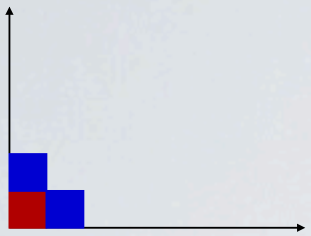


NLO showers?

not quite yet...

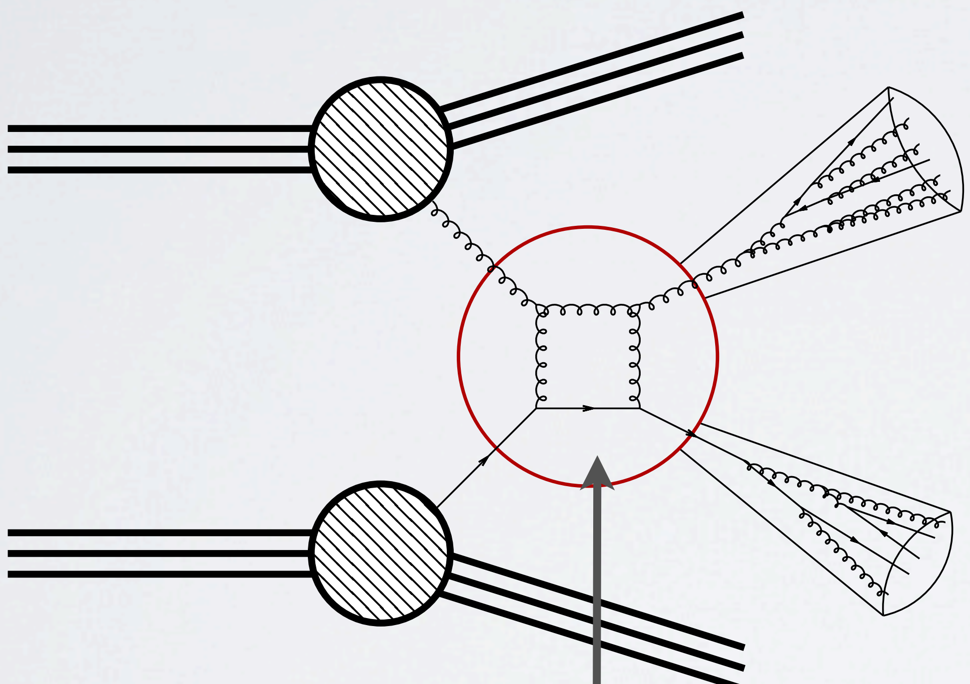
Part I: Hard processes and theoretical methods

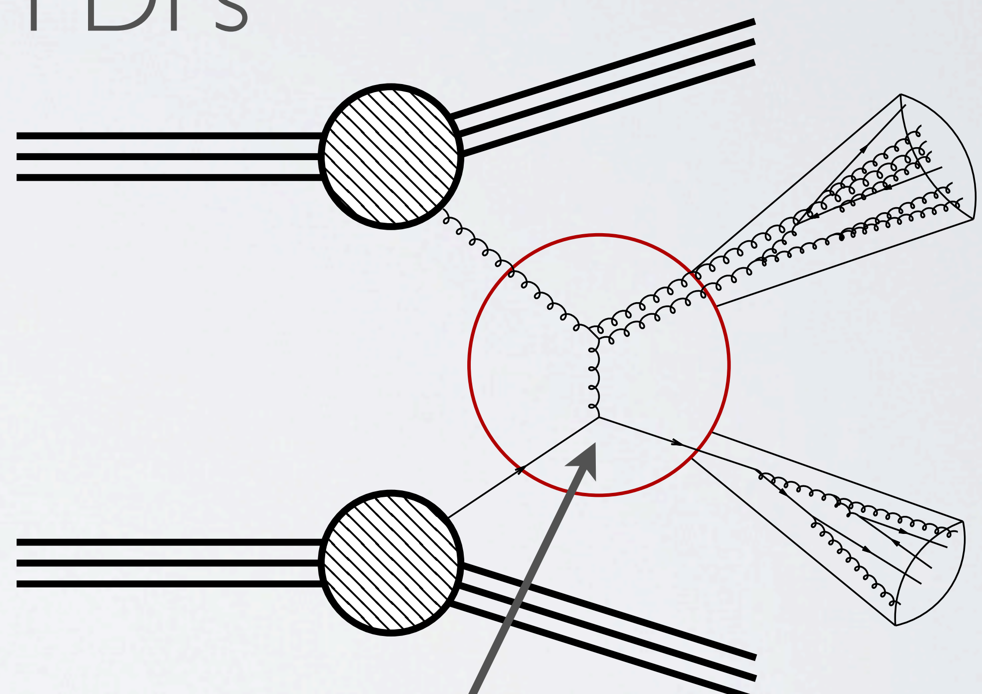
QCD at NLO



$$\sigma_{pp\to X} = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, Q)\, f_j(x_2, Q)\, \widehat{\sigma}^{NLO}_{ij\to n}$$

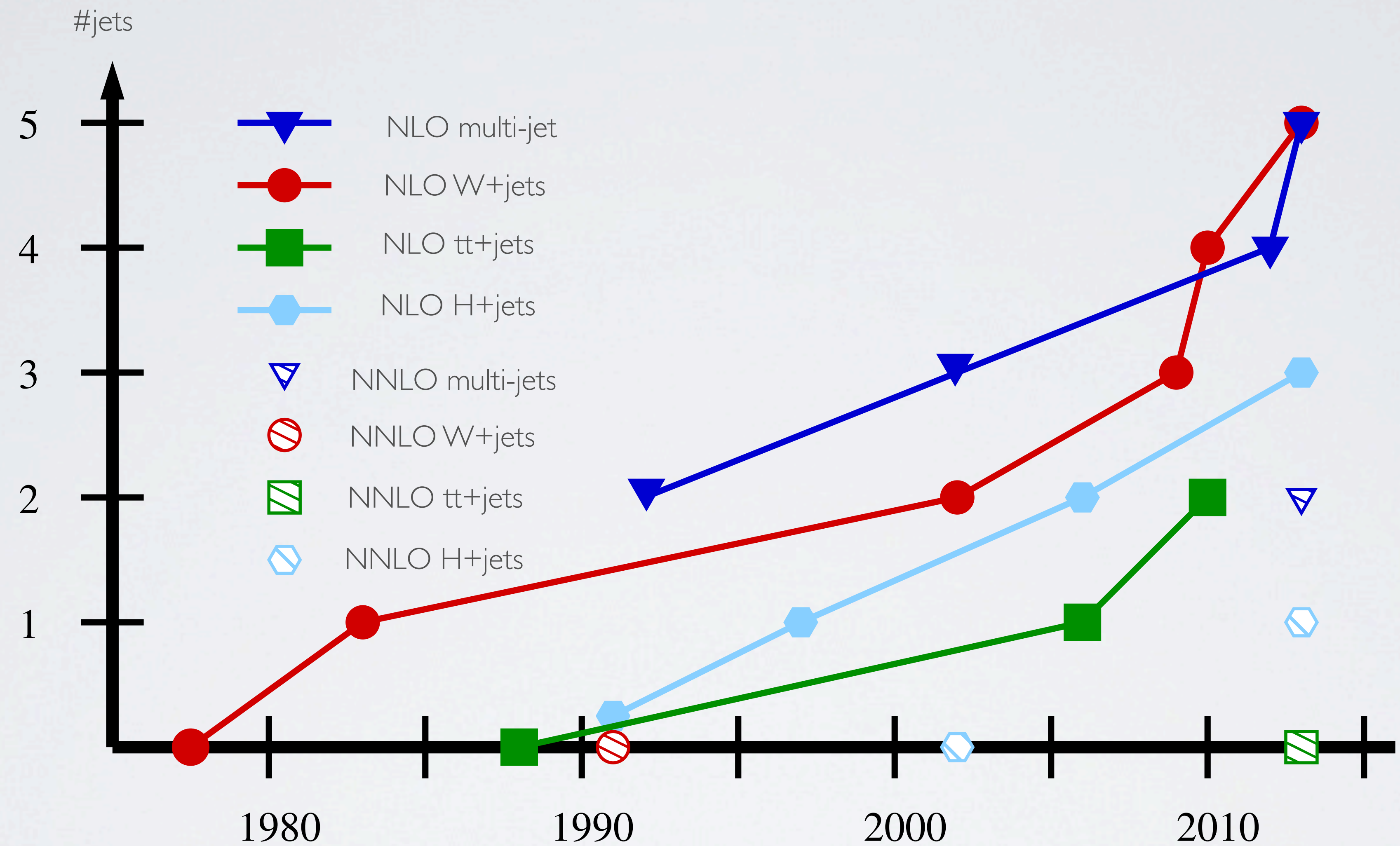
PDFs





$$\widehat{\sigma}^{\delta NLO}_{ij\to n} = \int_n \left(d\sigma^V + \int_1 d\sigma^{S_1(R)} \right) + \int_{n+1} \left(d\sigma^R - d\sigma^{S_1(R)} \right)$$

recent progress: NLO revolution!



automated IR subtraction

Frixione-Kunszt-Signer

Nagy-Soper

Catani-Seymour

new amplitude methods

(generalized)unitarity [Bern et al. (1994)] [Britto et al. (2004)]

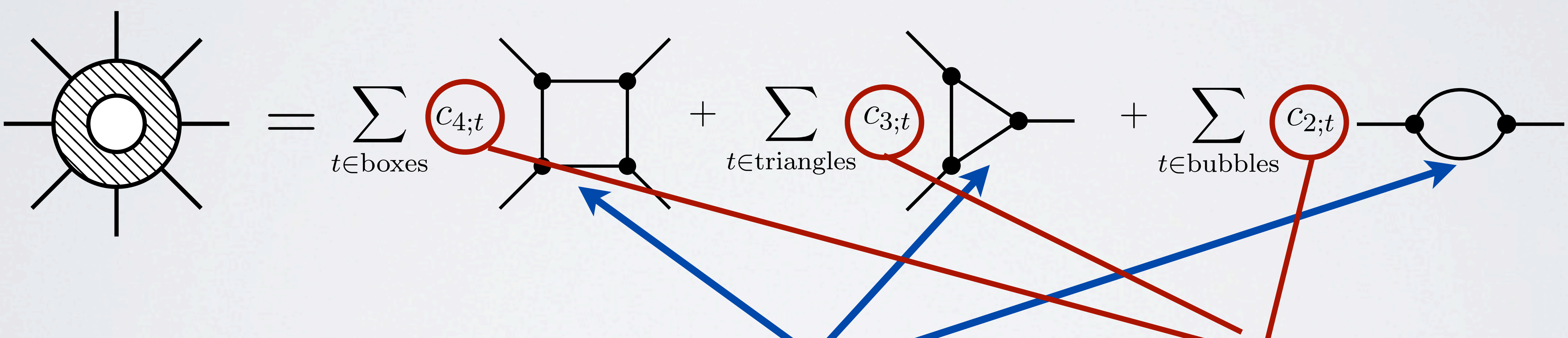
integrand reduction [Ossola et al. (2005)]

loop amplitudes

Efficient tree level generators well established

e.g. MadGraph, Alpgen, Comix, Helac,...

Tree Methods
- Feynman diagrams
- off-shell recursion
- on-shell recursion (BCFW)



integral basis separates **analytic** and **algebraic** parts

known functions at one-loop
process independent

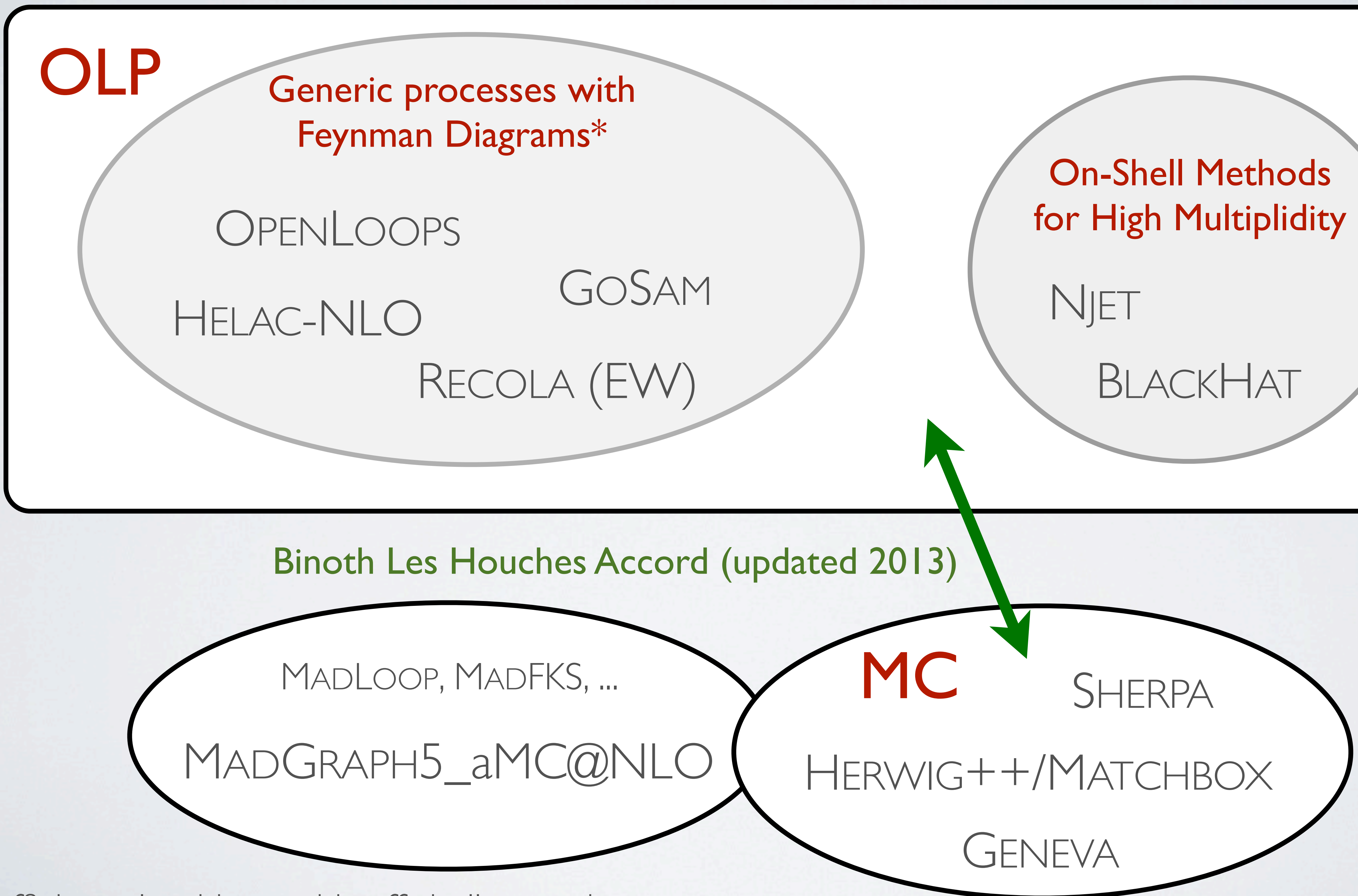
e.g. QCDLoop, OneLoop

tree-like

complex momenta

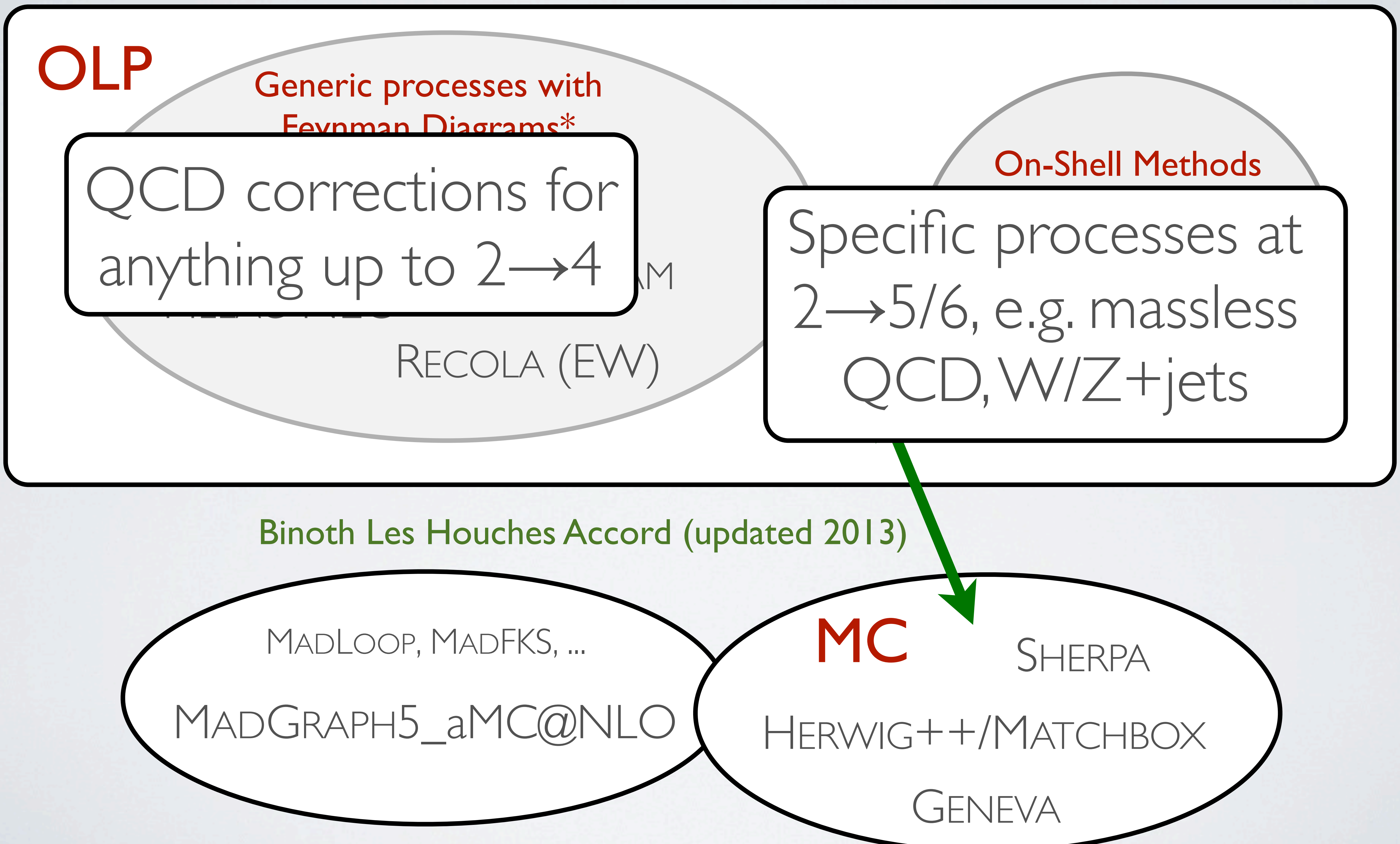
calculate numerically

automated NLO



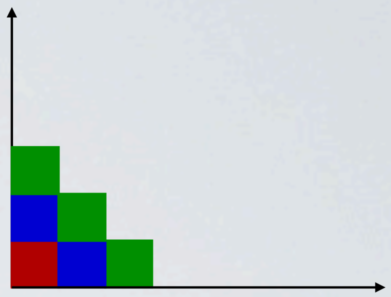
* efficient algorithms with off-shell recursion

automated NLO



* efficient algorithms with off-shell recursion

QCD at NNLO



two-loop amplitudes

$$\widehat{\sigma}_{ij\to n}^{\delta NNLO} = \int_n \left(d\sigma^{VV} + \int_1 d\sigma^{S_1(RV)} + \int_2 d\sigma^{S_2(RR)} \right) + \int_{n+1} \left(d\sigma^{RV} - d\sigma^{S_1(RV)} + \int_1 d\sigma^{S_1(RR)} \right) + \int_{n+2} \left(d\sigma^{RR} - d\sigma^{S_1(RR)} - d\sigma^{S_2(RR)} \right)$$

	analytic	FS colour	IS colour	local
antenna subtraction	✓	✓	✓	✗
STRIPPER	✗	✓	✓	✓
q_T subtraction	✓	✗	✓	✓
reverse unitarity	✓	✗	✓	-
Trócsányi et al	✗	✓	✗	✓

Infra-red subtraction

[taken from J. Currie LoopFest 2014]

recent NNLO progress

$pp \to \gamma\gamma$	[Catani, Cieri, de Florian, Ferrera, Grazzini (2011)]
$pp \to WH$	[Ferrera, Grazzini, Tramontano (2011)]
$gg \to gg$	[Currie, Gehrmann de Ridder, Gehrmann, Glover, Pires (2013)]
$pp \to t\bar{t}$	[Czakon, Fiedler, Mitov (2013)]
$gg \to Hg$	[Boughezal, Caola, Melnikov, Petriello, Schulze (2013)]
$pp \to Z\gamma$	[Grazzini, Kallweit, Rathlev, Torre (2013)]
$pp \to tj$	[Bruchseifer, Caola, Melnikov (2014)]
$pp \to ZZ$	[Cascioli, Gehrmann, Grazzini, Kallweit, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs (2014)]
$pp \to HH$	[de Florian, Mazzitelli (2014)]
$pp \to ZH$	[Ferrera, Grazzini, Tramontano (2014)]

year

loop integrals only recently available: new approach to DE [Henn (2013)]

di-jets at NNLO

gluons only, leading colour [Gehrmann de Ridder, Gehrmann, Glover, Pires arXiv:1301.7310]

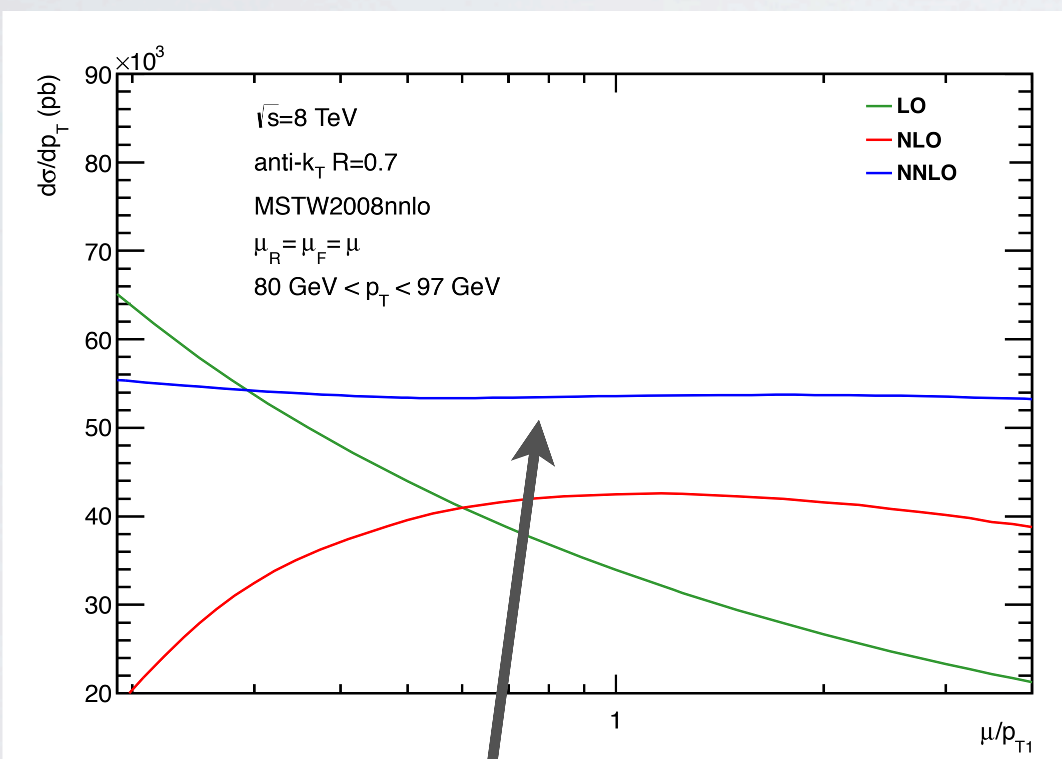
gluons only, full colour [Currie, Gehrmann de Ridder, Glover, Pires arXiv:1310.3993]

quark channels on the way...

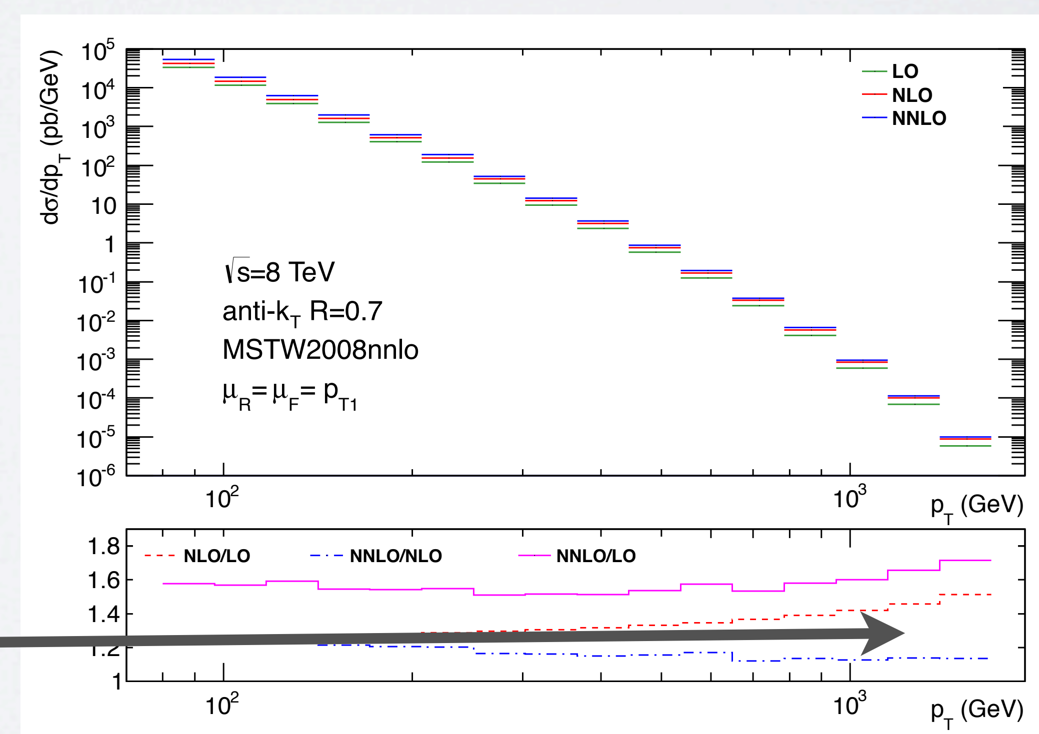
IR subtractions: antennas

two-loop amplitudes

[Anastasiou, Glover, Oleari, Tejeda-Yeomans (2000-2003)]



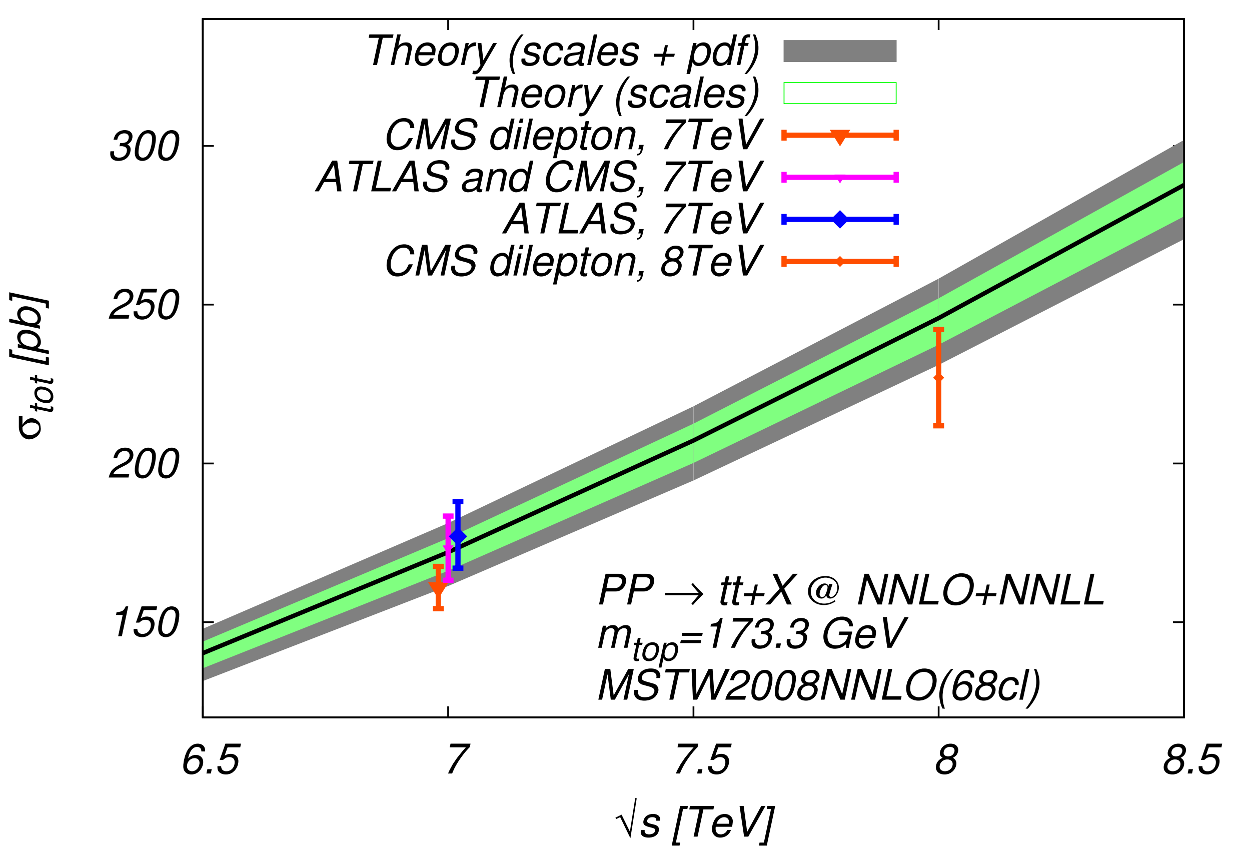
flat scale dependence



corrections over NLO up 40% at high p_T

top pair production at NNLO

[Czakon, Fielder, Mitov (2013)]



STRIPPER - sector improved phase space for real radiation

[RV and RR in qq channel with Antenna subtraction: Abelof, Gehrmann de Ridder, Maierhofer, Pozzorini (2014)]

differential distributions on the way

loop integral basis still not known analytically

constraining PDFs

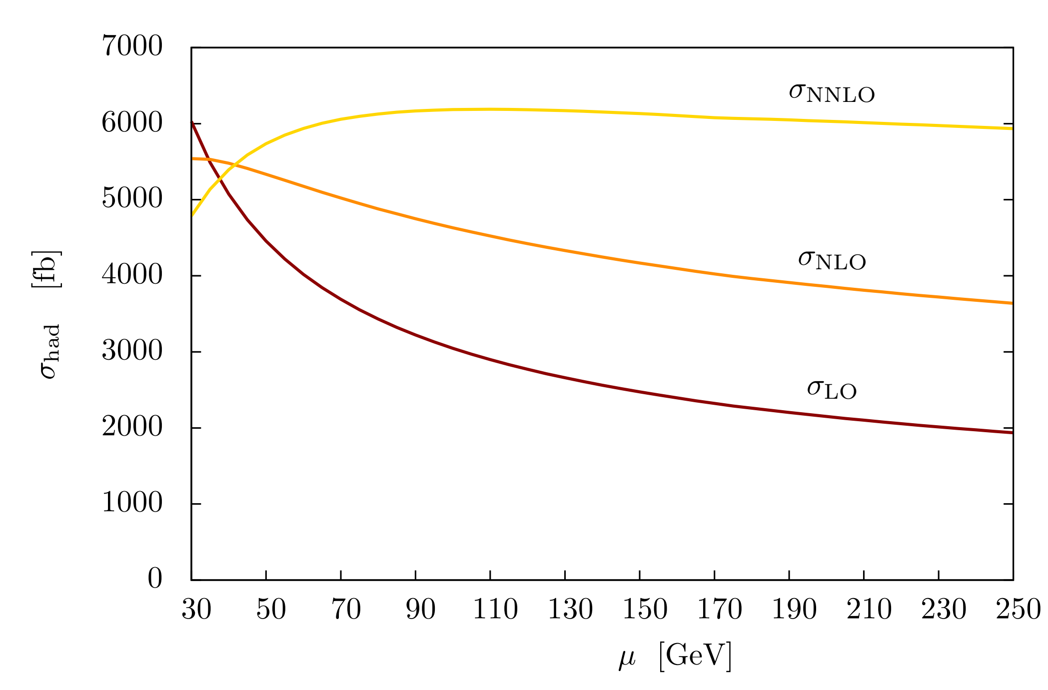
top mass measurements

significant deviations from previous approximate resummations

pp→H+j at NNLO

$$\frac{\sigma_{pp\to H+1j}}{\sigma_{pp\to H}} \sim 0.3$$

gg→Hg [Boughezal, Caola, Melnikov, Petriello, Schulze (2013)]



IR subtractions with sector decomposition (c.f. STRIPPER)

again: scale variations around order of PDF uncertainties

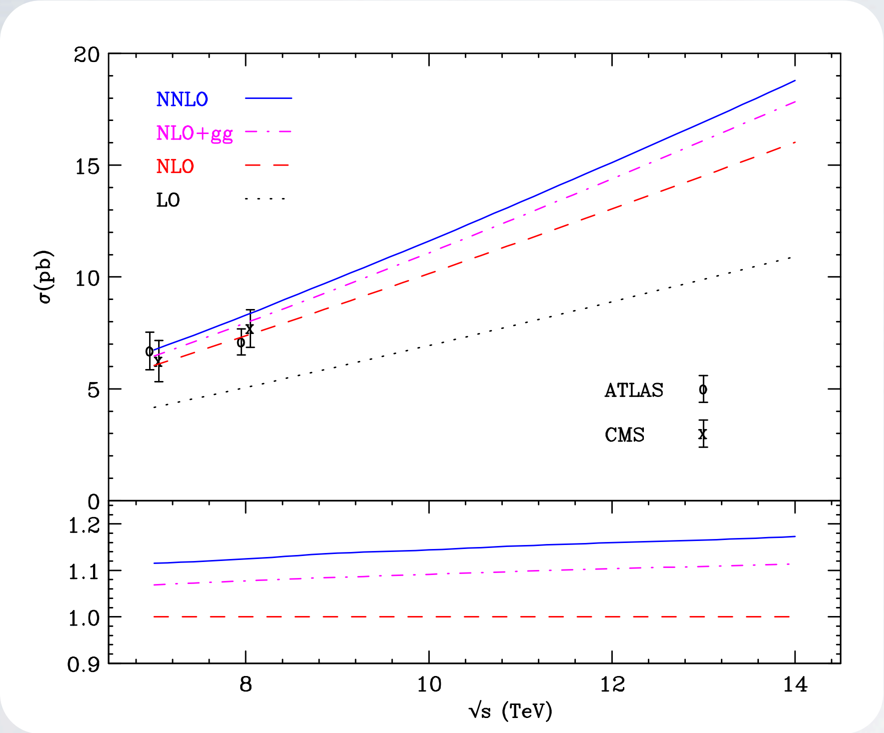
[more details in talk by Boughezal]

Higgs cross section at N^3LO [see talk by Duhr]

also with antenna sub. gg→Hg [Chen, Gehrmann, Glover, Jaquier, (in prep.)]

pp→ZZ at NNLO

[Cascioli, Gehrmann, Grazzini, Kallweit, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs arXiv:1405.2219]



IR with q_T subtraction

recently completed loop integrals using new DE method

[Gehrmann, von Manteuffel, Tancredi, Weihs arXiv:1404.4853]

[Caola, Henn, Melnikov, Smirnov arXiv:1402.7078, arXiv:1404.5590]

NNLO ~ 11-17% over NLO
(4-6% over NLO+gg initial state)

may suggest small corrections also in WW

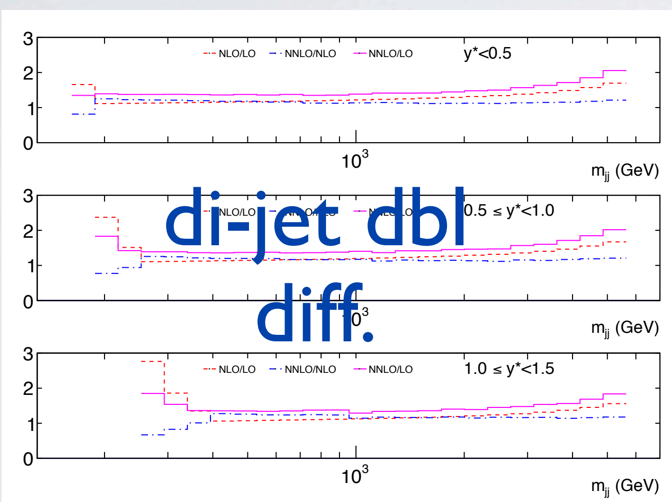
need to wait and see...

2→2 at NNLO: towards differential distributions

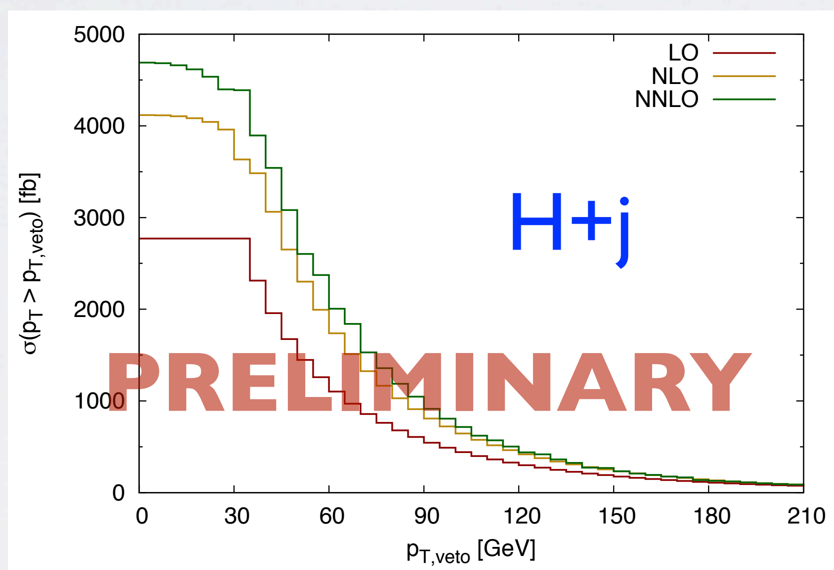
most experimental analyses need differential distributions

coloured final states at the limit of subtraction methods

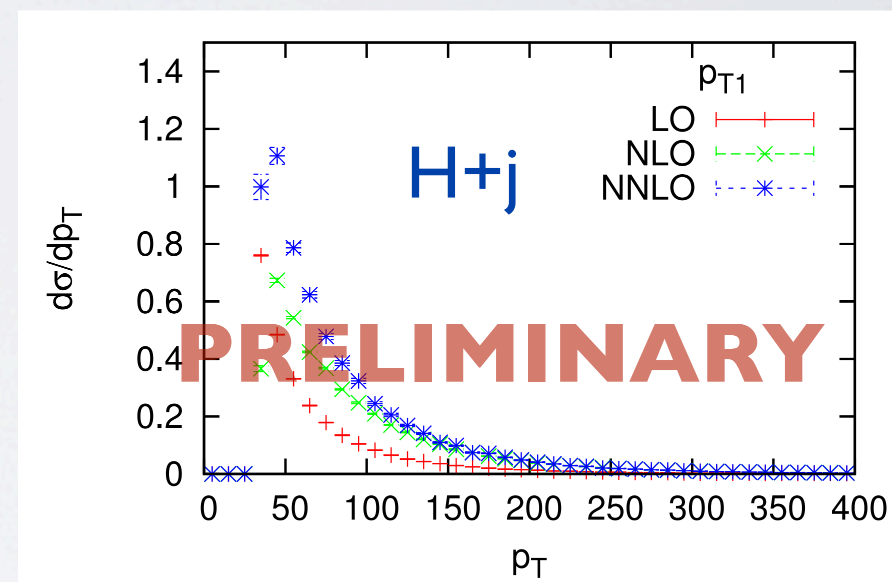
highly CPU intensive



[Currie et al. (2013)]



talk by F. Caola LoopFest 2014



talk by M. Jaquier LoopFest 2014

progress being made: full distributions coming soon

beyond 2→2 at NNLO?

measurements from Run II likely to reach % level precision

particularly ratios e.g. 3j/2j for α_s

2→3 QCD needs new theoretical methods

unknown loop integrals

highly non-trivial kinematics

reduction algorithms

reduction algorithms

integration-by-parts identities:

[Tkachov, Chetyrkin (1981)]

very difficult with large numbers of scales

powerful codes: Reduze, FIRE, ...

maximal unitarity

[Kosower, Larsen (2011)]

on-shell reduction computation of master integral coefficients via contour integration

4-D studies with complicated kinematics

Kosower, Larsen, Caron-Huot, Johansson, Sogaard, Zhang

integrand reduction

[Mastrolia, Ossola (2011)] [SB, Frellesvig, Zhang (2012)]

generalized OPP method without IBPs using computational algebraic geometry

valid in d-D

not (yet) to minimal basis of integrals

Mastrolia, Mirabella, Ossola, Peraro, SB, Frellesvig, Zhang, Huang, Feng

five-gluon all-plus helicity amplitude [SB, Frellesvig, Yang (2013)]

loop integrals

Much improved understanding of integration methods and basis of functions

still more needed for full set of NNLO integrals

cross talk between physics and mathematics

canonical basis for differential equations [Henn]

direct integration methods [Brown][Panzer]

technology already playing leading role in N^3LO computations [see talk by Duhr]

Part II: Monte-Carlo and precision phenomenology

new methods for MC simulations

NLO is the new standard precision for SM predictions

shower matching

MC@NLO, POWHEG

Frixione, Webber, Nason

multi-jet merging

MEPS@NLO,
FxFx, UNLOPS,
MiNLO, Geneva

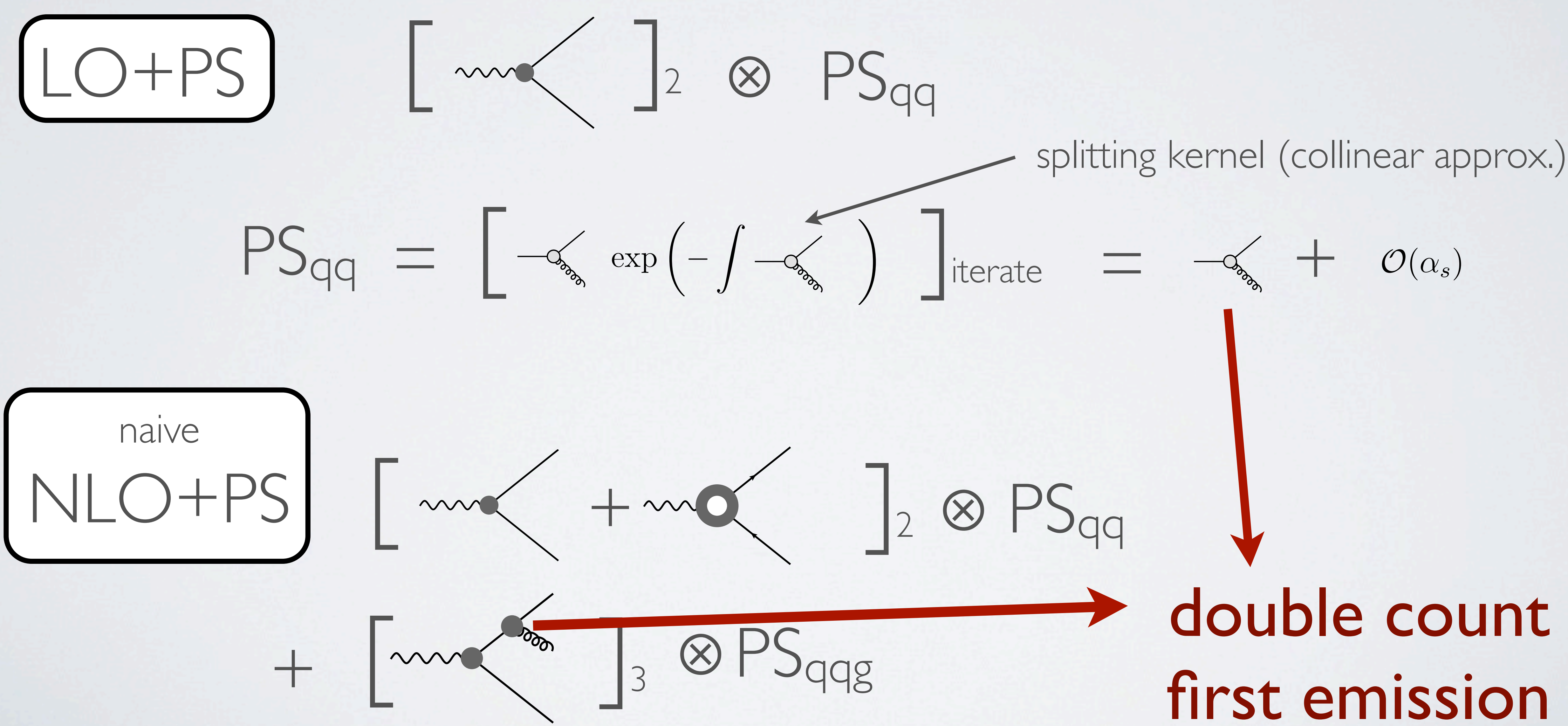
Hoeche, Krauss, Schoenherr, Siegert, Frixione, Frederix, Lonnblad, Prestel, Platzer, Hamilton, Nason, Oleari, Zanderighi, Alioli, Baur, Berggren, Hornig, Tackmann, Vermilion, Walsh, Zuberi

now being implemented into MCs

SHERPA, HERWIG++/MATCHBOX, POWHEG-BOX,
GENEVA, MADGRAPH5_aMC@NLO,...

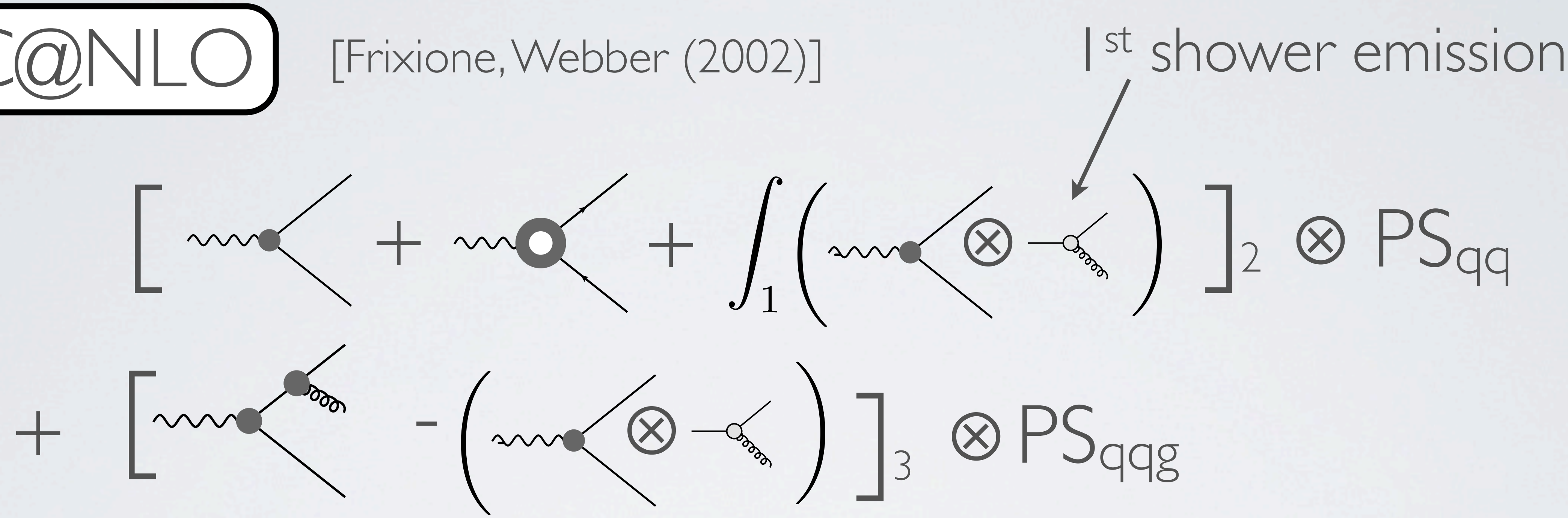
sketch of PS matching

NLO+PS merging must avoid double counting

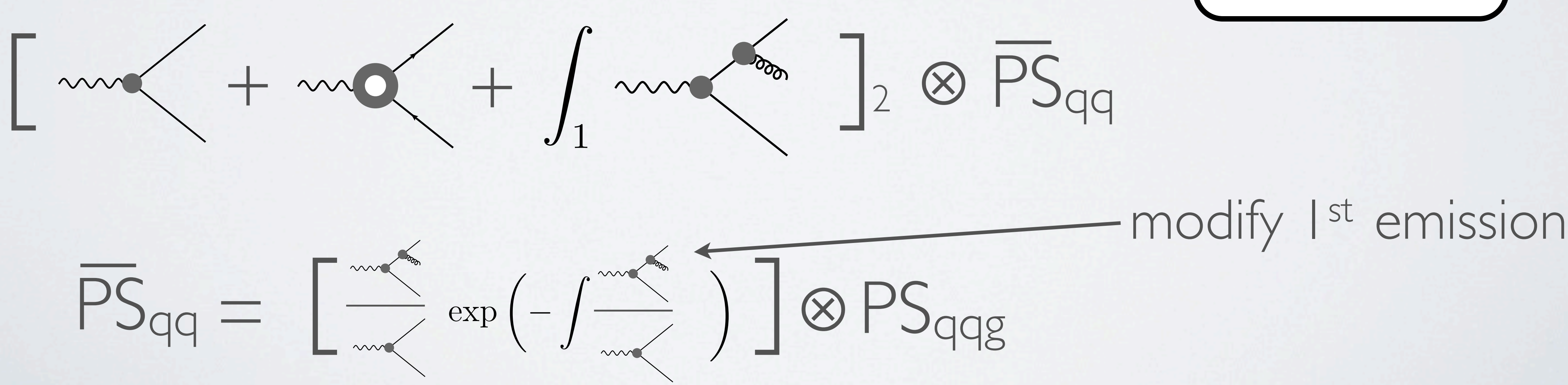


sketch of PS matching

MC@NLO [Frixione, Webber (2002)]

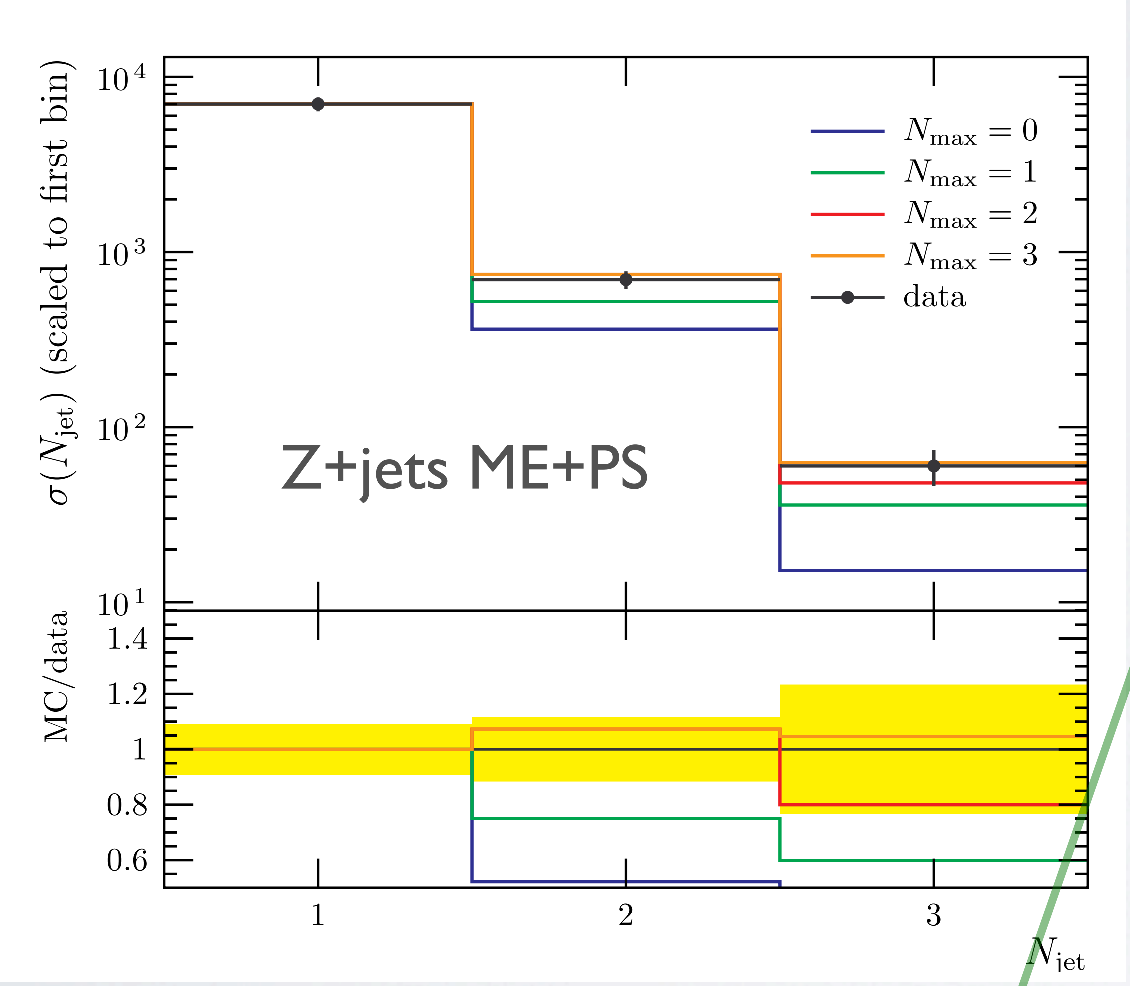


[Nason (2004)] POWHEG



multi-jet merging

LO example



[Hoeche, Krauss, Schumann, Siegert (2009)]

mild dependence on merging scale

unitary

LO methods

CKKW-L [Catani et al (2001)] [Lonnblad (2002)]

MLM [Mangano]

UMEPS [Prestel, Lonnblad (2012)]

NLO methods

FxFx [Frederix, Frixione (2012)]

UNLOPS [Prestel, Lonnblad (2012)] [Platzer (2012)]

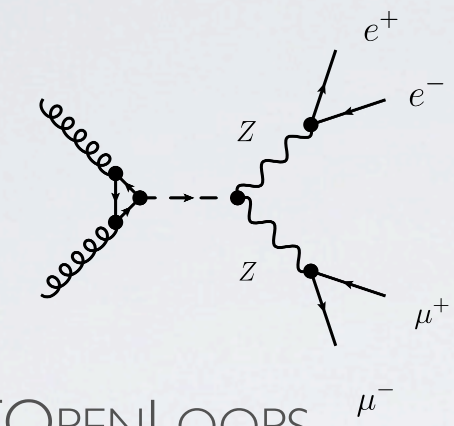
MEPS@NLO [Hoche et al. (2012)]

MiNLO [Hamilton et al. (2012)]

GENEVA [Alioli et al. (2013)]

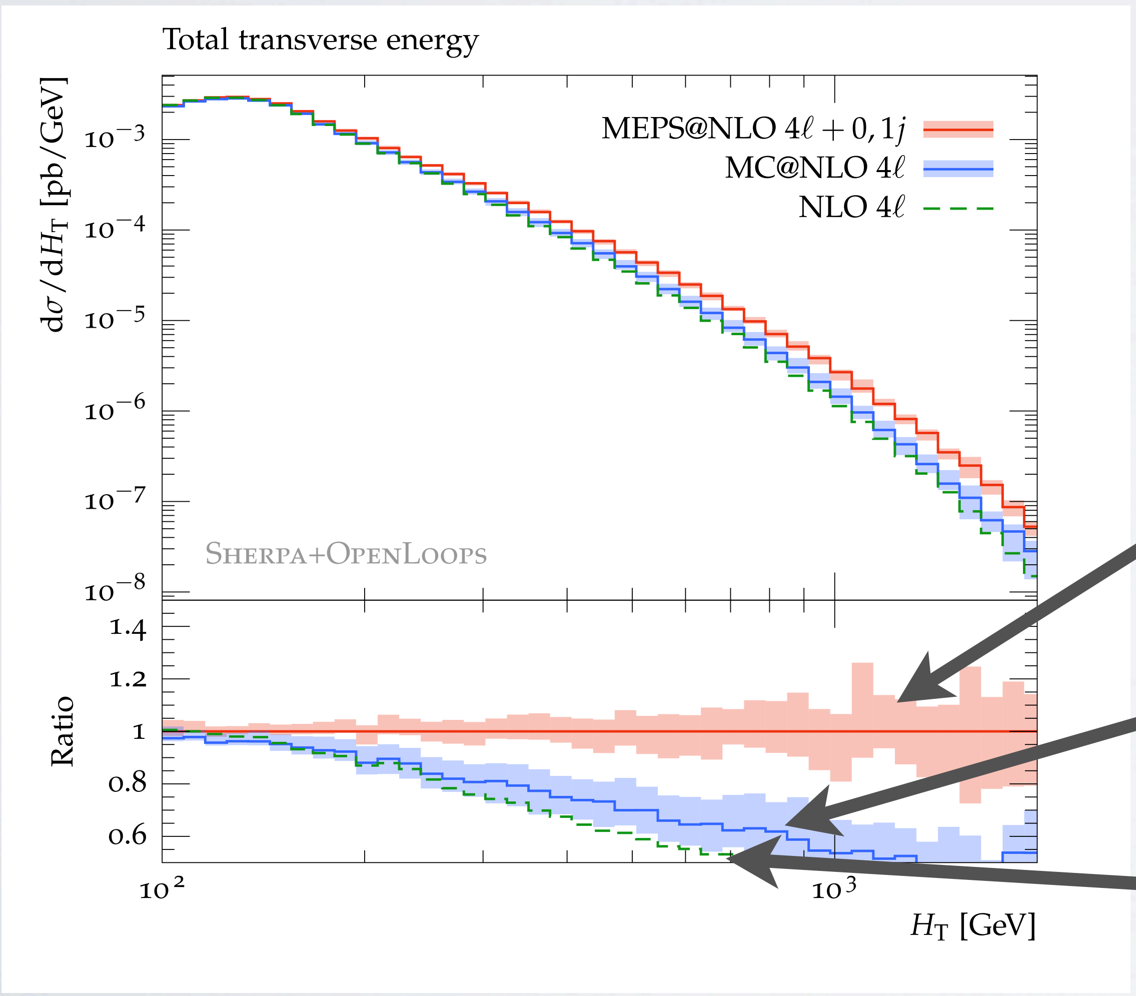
precise SM backgrounds

$$pp \to H \to 4l$$



ME+PS see [aMC@NLO: Hirschi et al. arXiv:1110.4738]

MEPS@NLO + 0,1 jets [OPENLOOPS +SHERPA: Cascioli et al. arXiv:1309.0500]

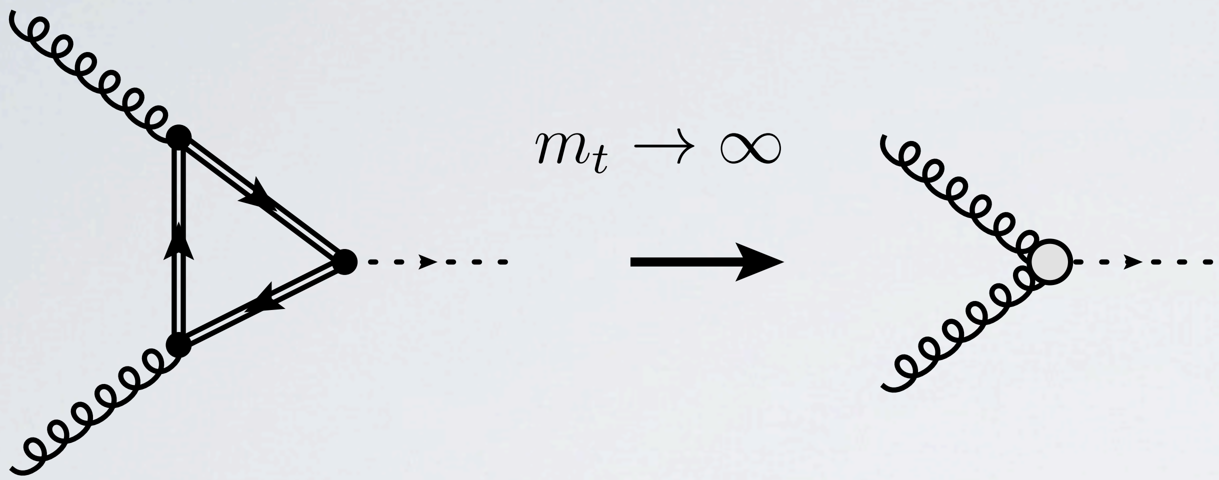


Scale choices

dynamical choices often give more stable NLO predictions e.g H_T

multi-scale choices: e.g. MiNLO [Hamilton, Nason, Zanderighi (2012)]

Higgs + jets



one-loop corrections in the heavy top quark effective theory

H+2j @ NLO

[Campbell, Ellis, Zanderighi (2006)]

[MCFM: Campbell, Ellis, Williams (2010)]

[GoSam+Sherpa: Cullen et al. (2012)]

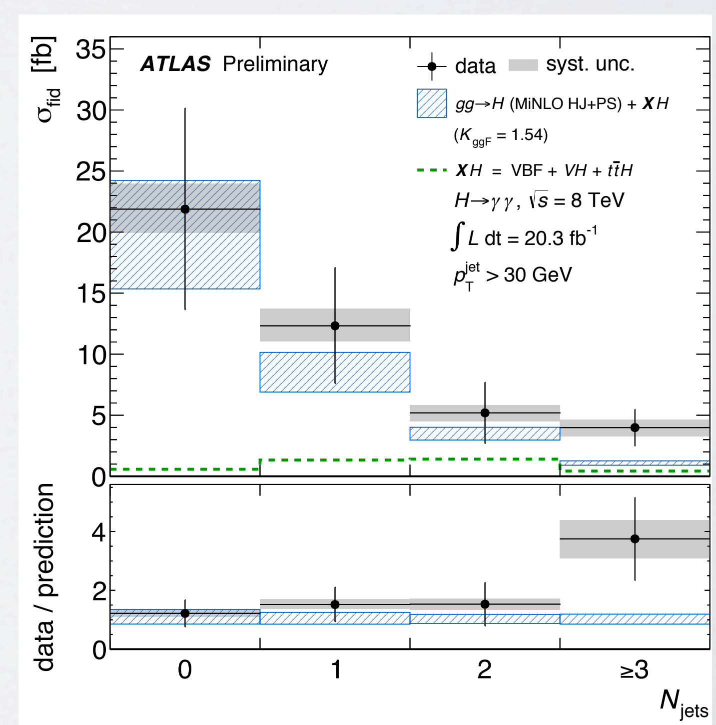
H+3j @ NLO

[GoSam+Sherpa: Cullen et al. (2013)]

VBF H+3j @ NLO

[VBFNLO: Camapanrio et al. (2013)]

fast analytic amplitudes with on-shell methods: Berger, Dixon, Del Duca, SB, Glover, Risager, Mastrolia, Williams, Sofianatos, Ellis, Campbell

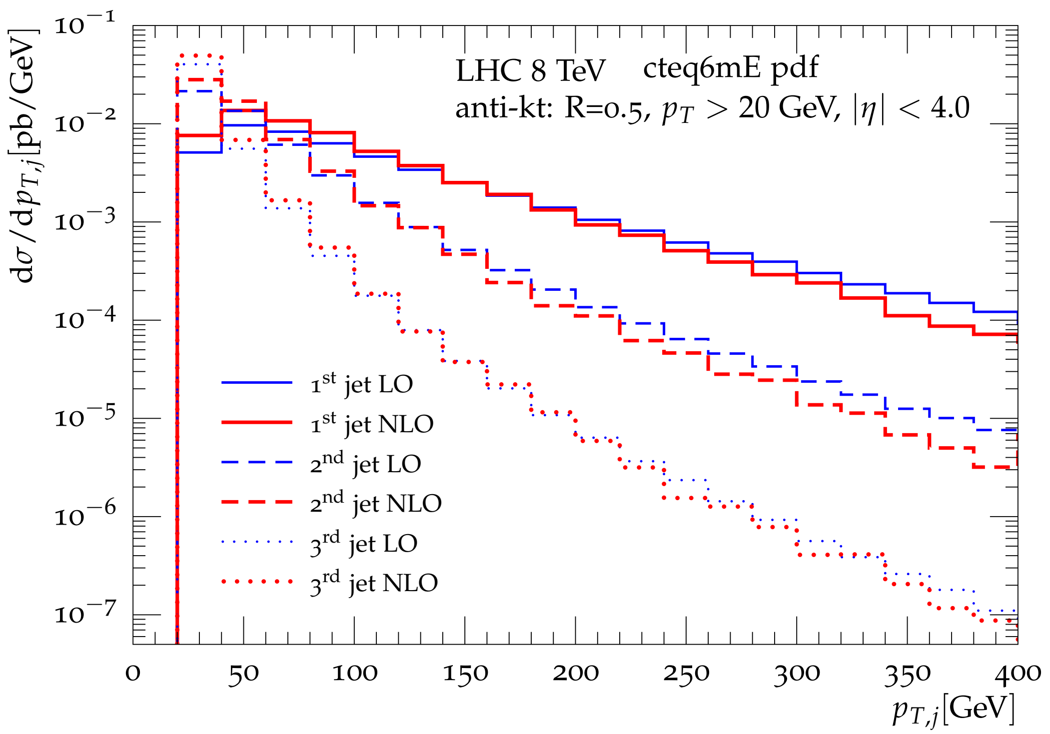


likely very important for Run II

Higgs + jets

H+3j @ NLO

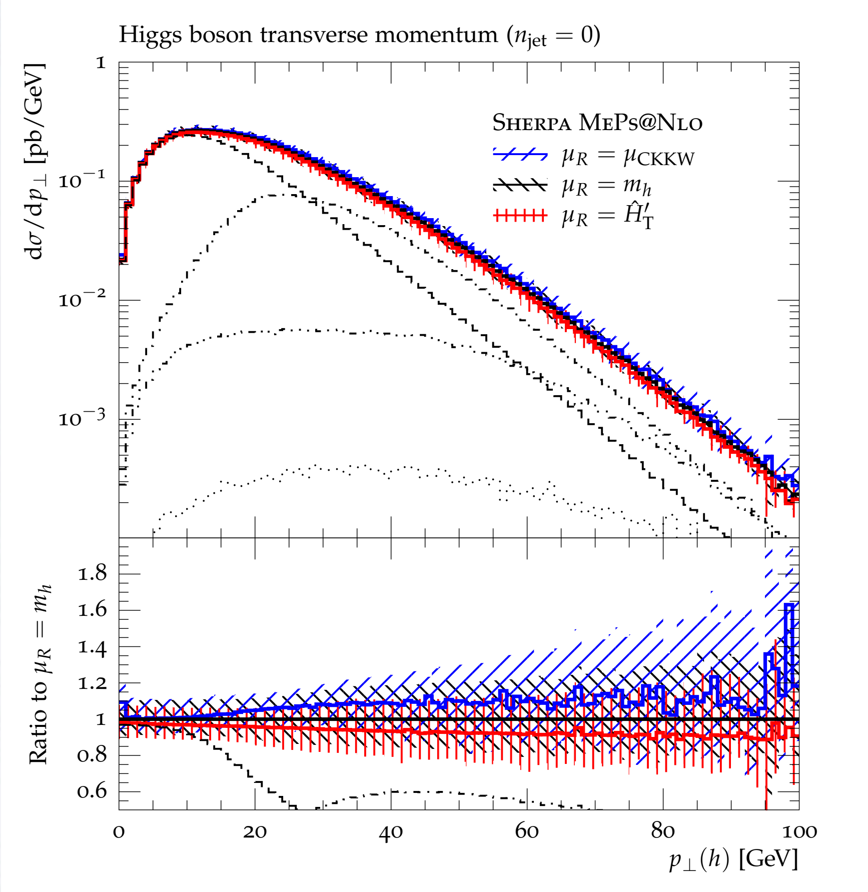
[GoSam+Sherpa: Cullen et al. (2013)]



$$\sigma_{\mathrm{LO}}[\mathrm{pb}] = 0.962^{+0.51}_{-0.31}\,, \quad \sigma_{\mathrm{NLO}}[\mathrm{pb}] = 1.18^{+0.01}_{-0.22}$$

H+1j,2j @ NLO+PS

[MCFM+Powheg+MadGraph4: Campbell et al. (2012)]



H+0,1,2 j MEPS@NLO

[MCFM+Sherpa: Hoeche, Krauss, Schoenherr (2014)]

SM backgrounds: $pp \to H \to \gamma\gamma$

Significant higher order corrections

need a consistent description of hard photons

- Frixione isolation cone
- Fragmentation functions

experimental comparisons: "tight isolation accord"

Cieri, de Florian [Les Houches WG report 1405.1067]

$$pp \to \gamma\gamma$$

+0j @ NNLO [Cieri et. al (2011)]

$$pp \to \gamma\gamma + j$$

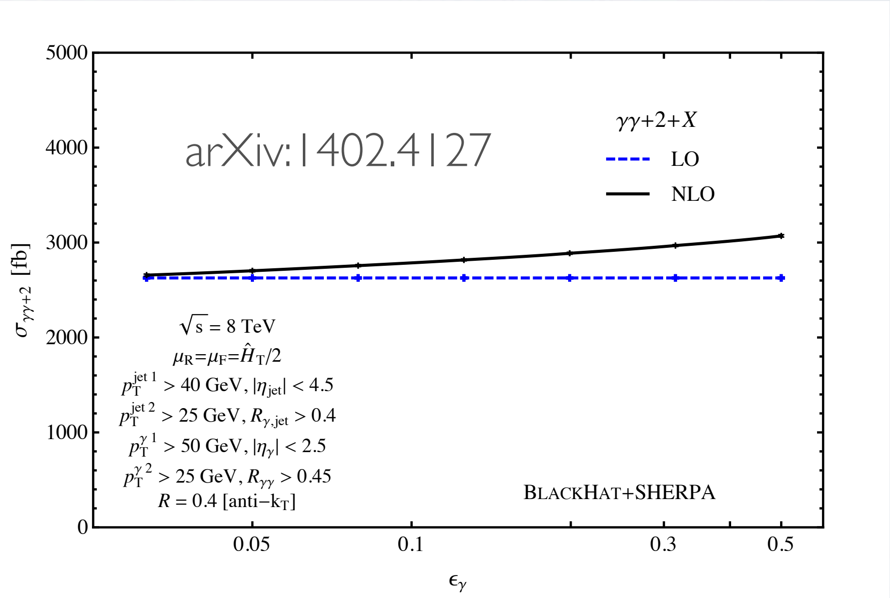
incl. fragmentation
[GoSam: Gehrmann, Greiner, Heinrich (2013)]

$$pp \to \gamma\gamma + 2j$$

[GoSam: Gehrmann, Greiner, Heinrich (2013)]
[NJet+Sherpa: SB, Guffanti, Yundin (2013)]
[BlackHat+Sherpa: Bern et al. (2014)]

$$pp \to \gamma\gamma + 3j$$

[NJet+Sherpa: SB, Guffanti, Yundin (2013)]

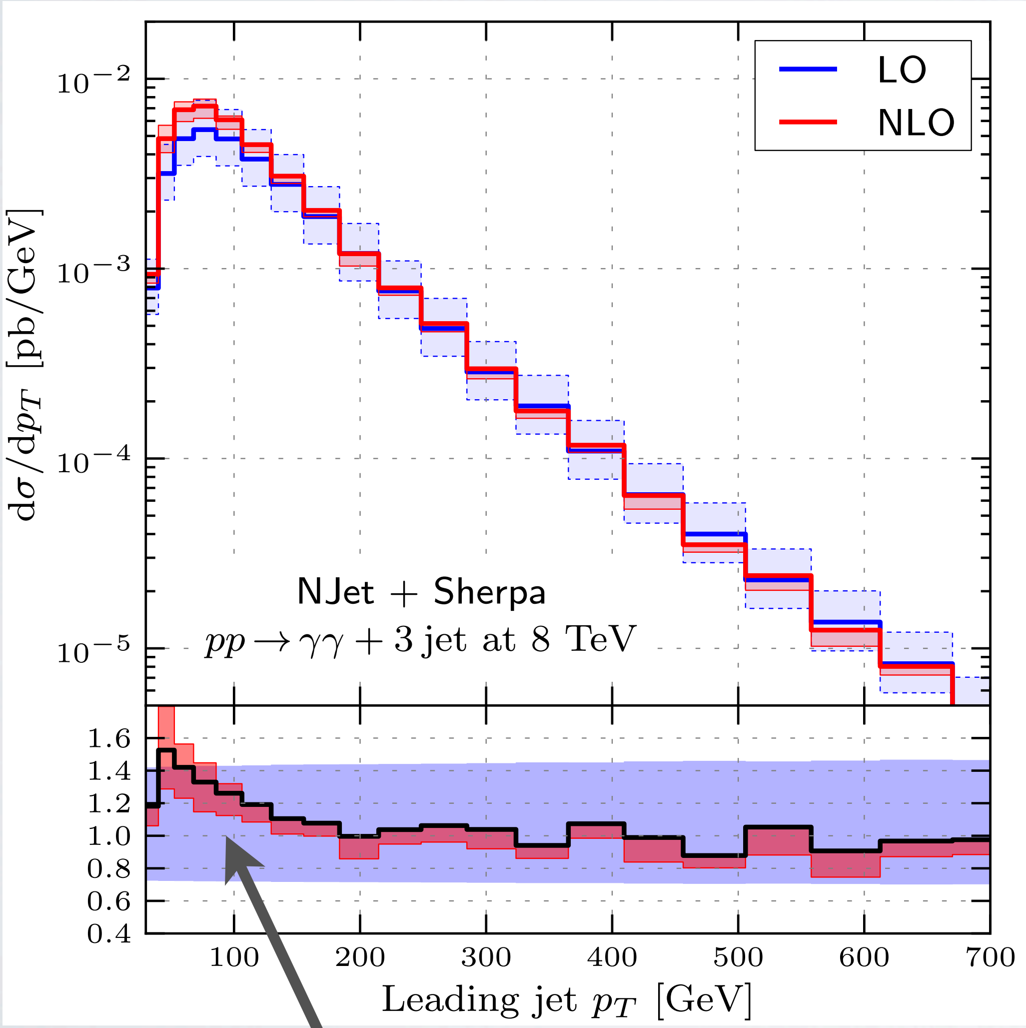


mild dependence on smooth isolation cone parameters

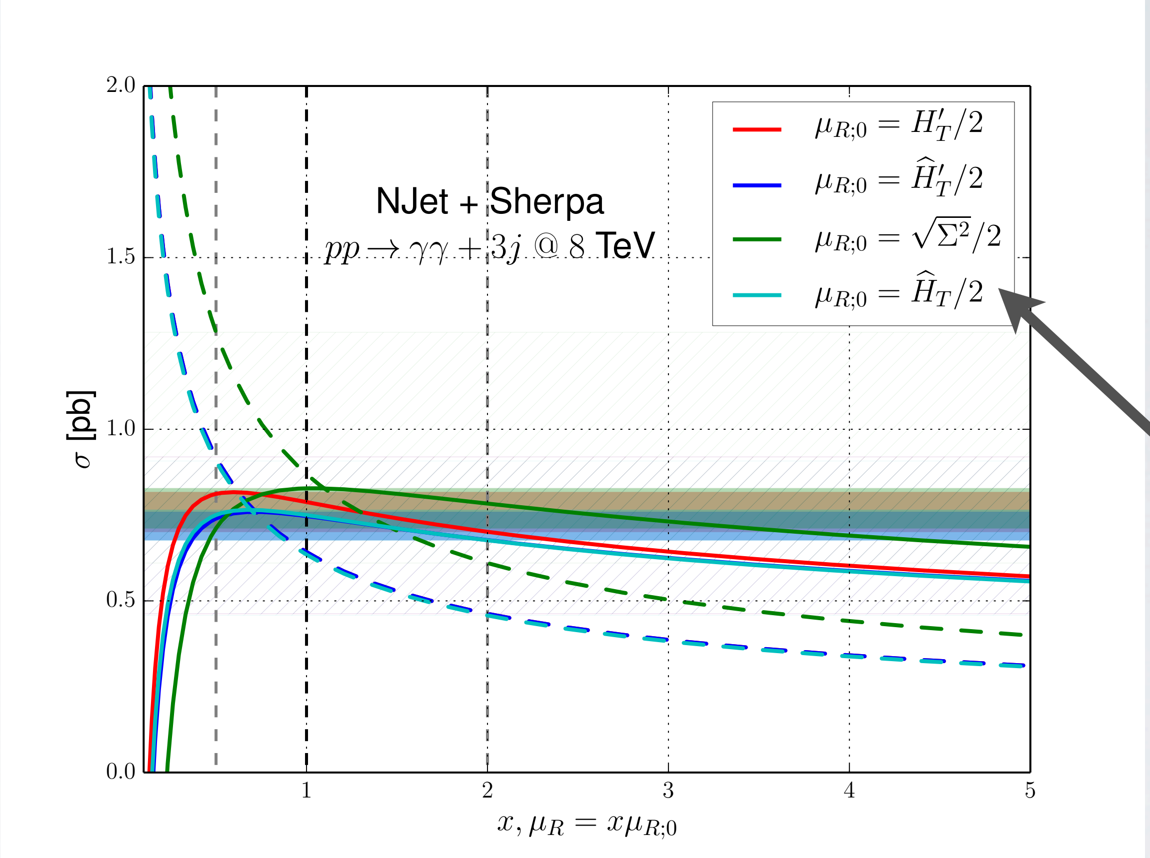
SM backgrounds: $pp \to H \to \gamma\gamma$

$pp \to \gamma\gamma + 3j$

[NJET+SHERPA: SB, Guffanti, Yundin (2013)]



large NLO corrections in some regions



different dynamical scales

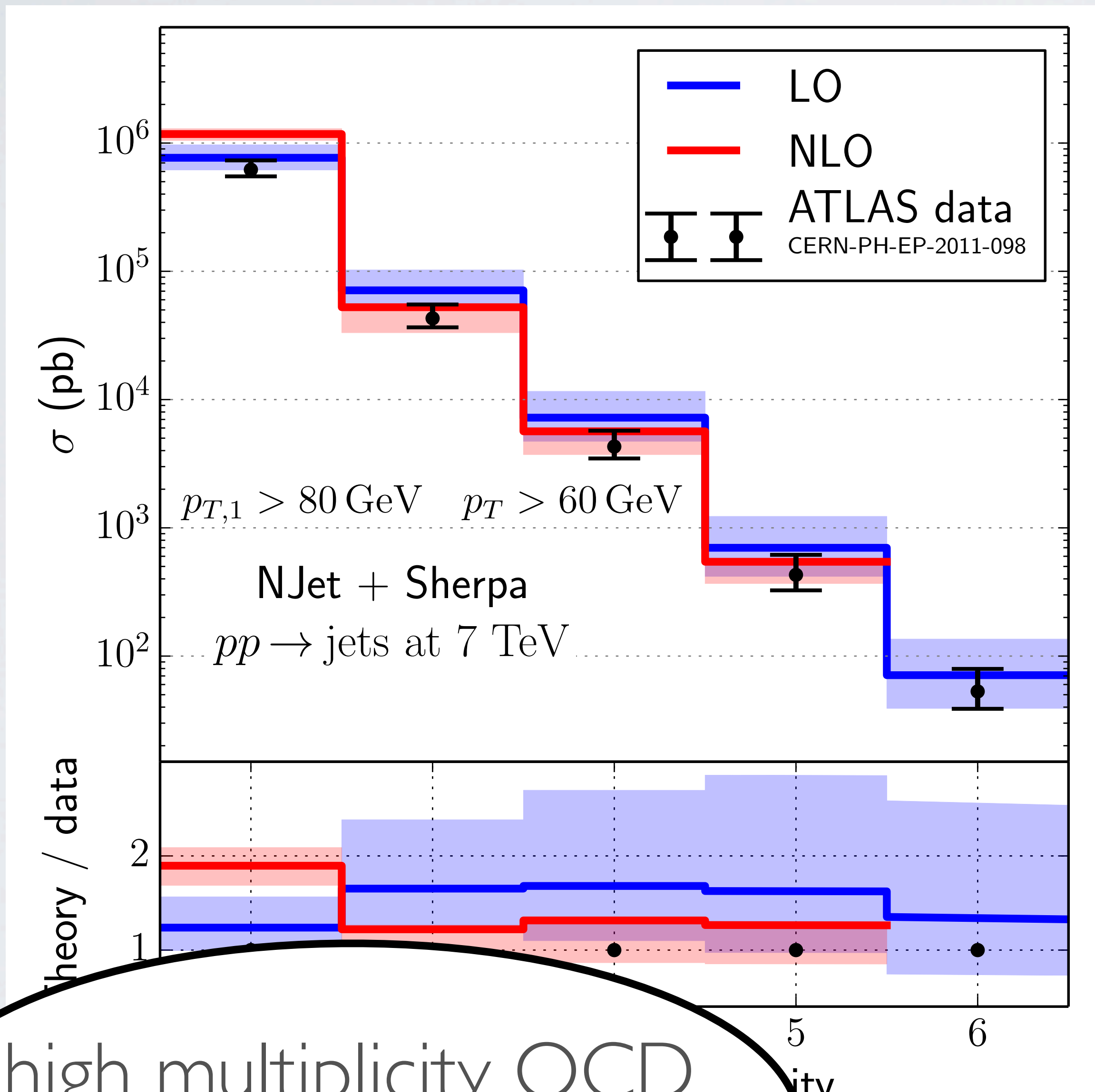
LO→NLO: reduction of scale dependence

fairly large variations outside standard range

scale variations may under-estimate theoretical uncertainties

multi-jets at NLO

asymmetric cuts



high multiplicity QCD
using on-shell techniques

4 jets @ NLO

[BLACKHAT+SHERPA: Bern, Dixon, Hoeche, Ita, Kosower, Ozeren, (2011)]

[NJET+SHERPA: SB, Biedermann, Uwer, Yundin (2012)]

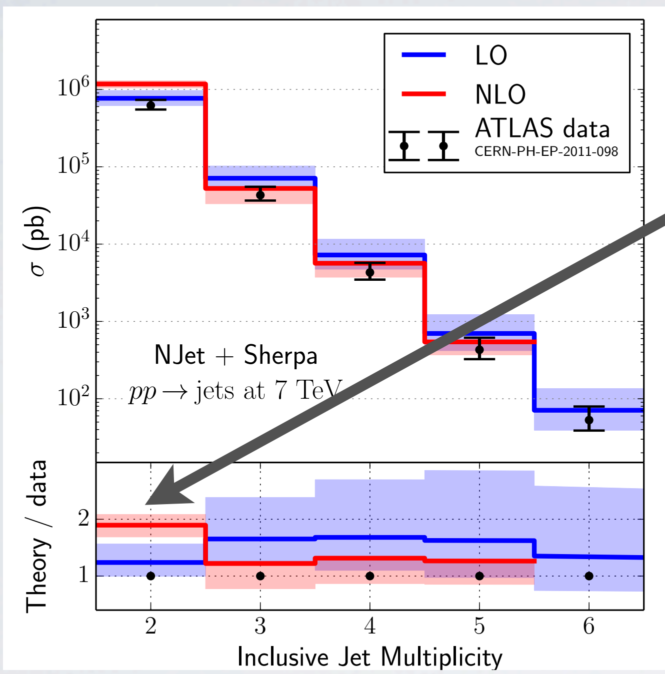
5 jets @ NLO

[NJET+SHERPA: SB, Biedermann, Uwer, Yundin (2013)]

3 jets @ NLO+PS

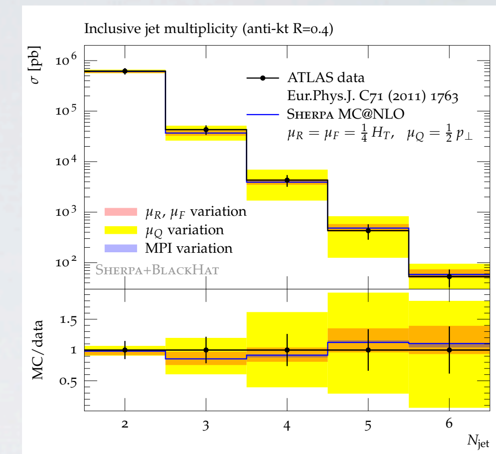
POWHEG+NLOJET++ [Kardos, Nason, Oleari (2014)]

di-jet cross sections



di-jet total cross section doesn't agree that well with the data

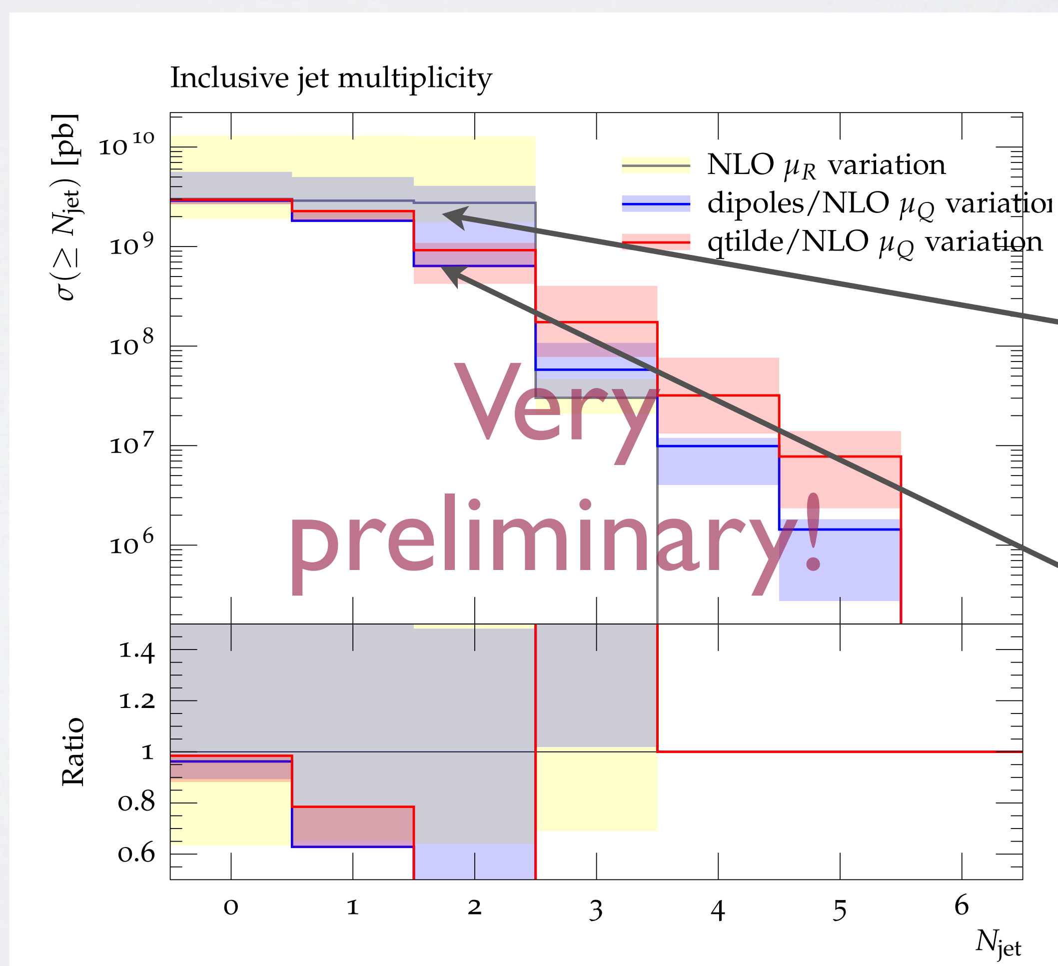
much better agreement with PS matched simulation



[BLACKHAT+SHERPA: Hoeche, Schoenherr (2012)]

comparison with HERWIG++ shower in progress

[HERWIG++/MATCHBOX: Bellm, Fischer, Gieseke, **Plätzer,** Rauch, Reuschle, Wilcock, Richardson]



NLO

NLO+PS

NJET+MADGRAPH
+COLORFULL(Sjödahl)
+HERWIG/MATCHBOX

optimizing high multiplicty

Extract the most information from a single run

Flexible analysis with Root Ntuples

Factorization scale, Renormalization scale and PDF re-weighting

BLACKHAT+SHERPA: public Ntuples

$$pp \to W^{[\to l\nu]}/Z^{[\to l^+l^-]} + \leq 4j$$

$$pp \to \leq 4j$$

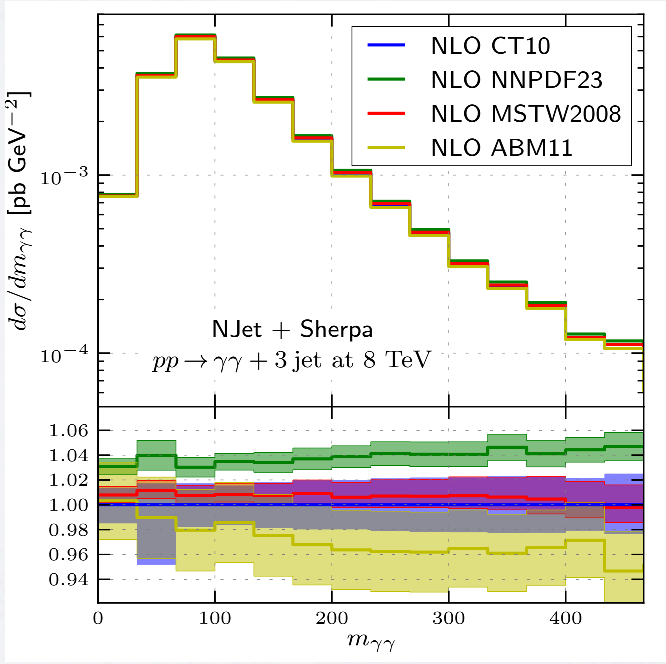
$$pp \to \gamma\gamma + \leq 2j$$

[NTUPLEREADER: Bern et. al arXiv:1310.7439]

PDF errors still intensive (e.g. 100 sets for NNPDF)

FASTNLO v2 [Britzger et al. (2012)]

APPLGRID [Carli et al. (2009)]



PDF uncertainties ~ 3-5%

also applications for NNLO distributions

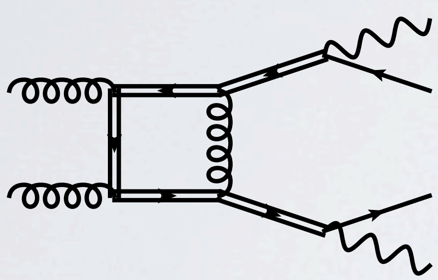
off-shell effects in top pair production

$$pp \rightarrow W^+W^-b\bar{b}$$

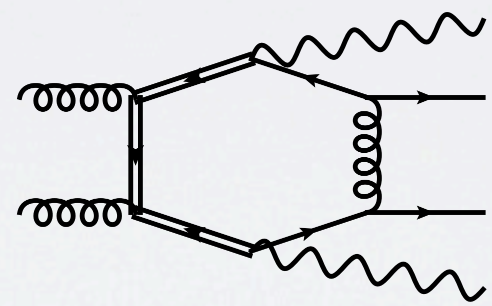
[Bevilacqua et al. (2011)] [Denner et al.(2011)]
[Frederix arXiv:1311.4893 [Cascoli et al. arXiv:1312.0546]

[Heinrich, Maier, Nisius, Schlenk, Winter arXiv:1312.6659]

factorized (NWA)



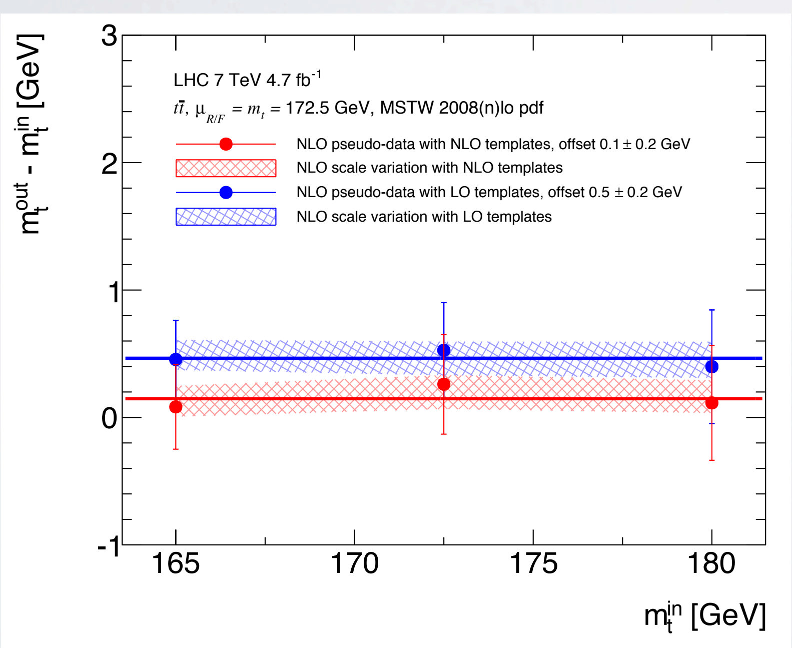
non-factorized (off-shell)

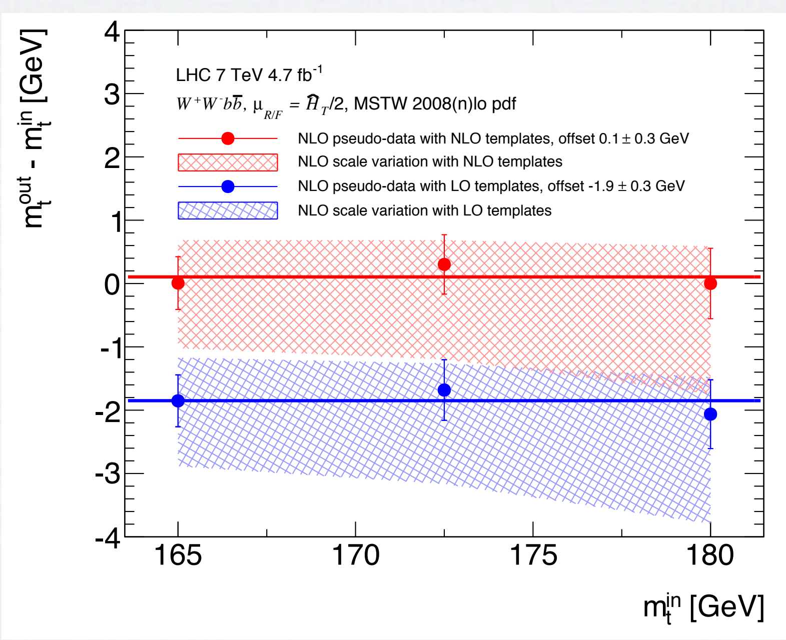


GoSam+Sherpa

factorized approx. underestimates error using template method mass extraction from m_{lb}

effects O(1GeV)





off-shell effects in top pair production

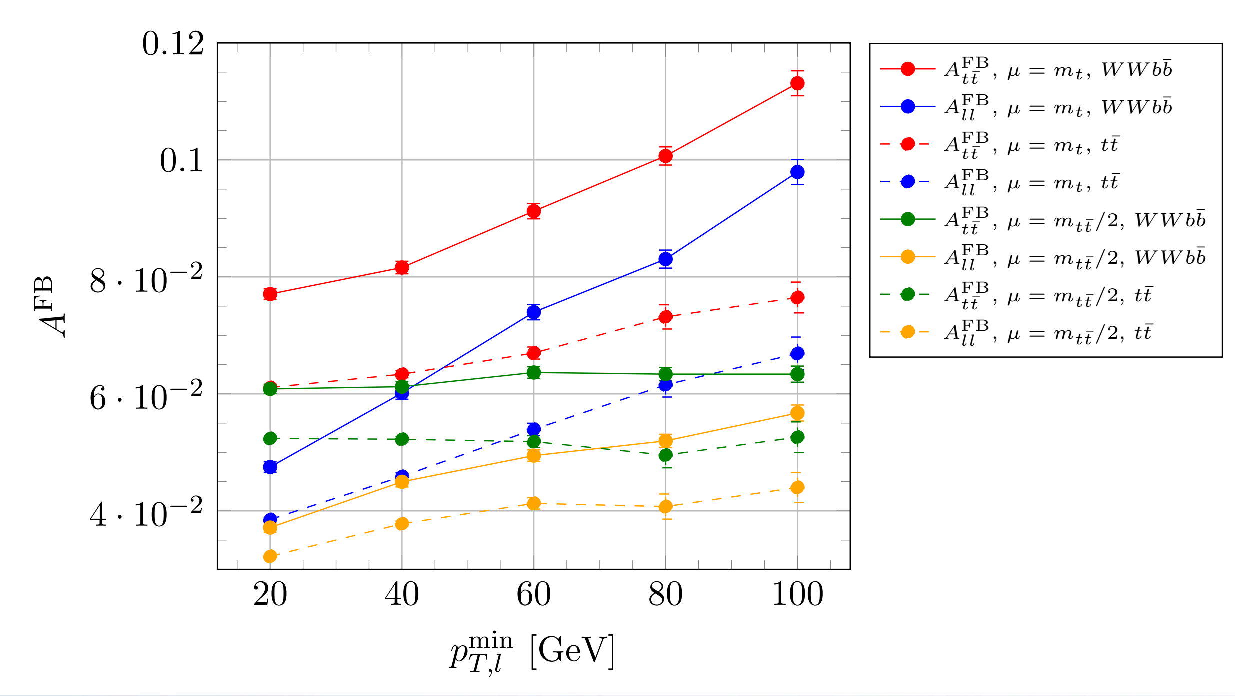
$$pp \rightarrow W^+W^-b\bar{b}$$

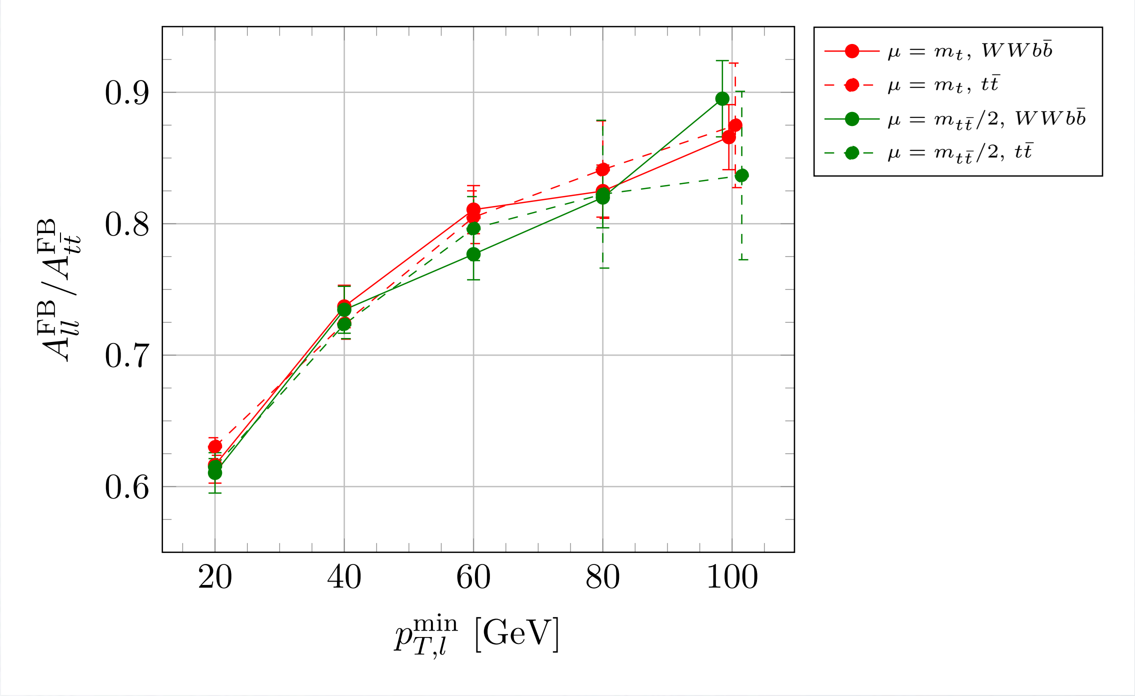
[Heinrich, Maier, Nisius, Schlenk, Winter arXiv:1312.6659]

GoSam+Sherpa

small effects in **charge** and **forward/backward** asymmetries

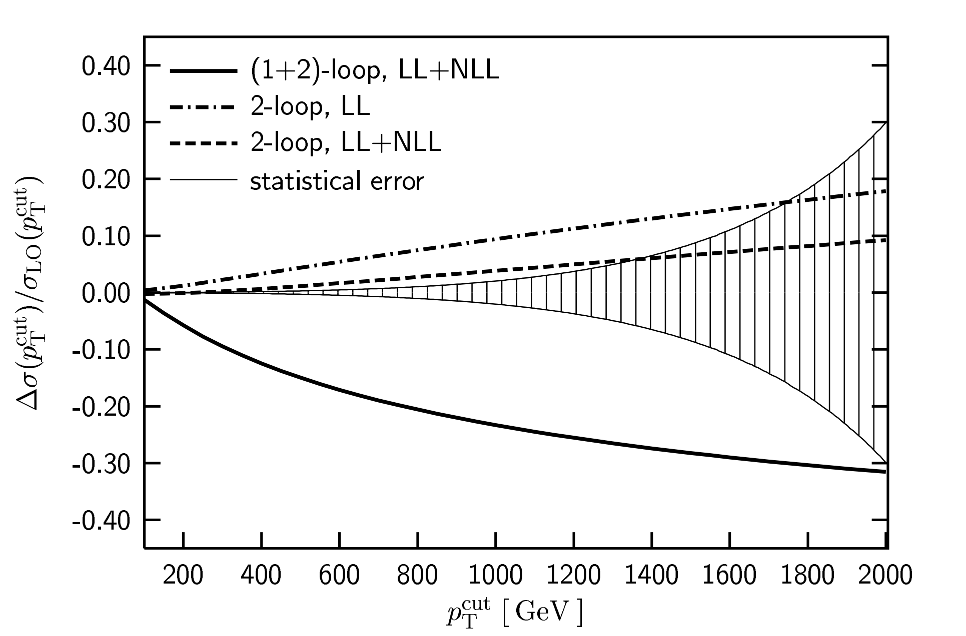
ratio A^{FB}_{ll} / A^{FB}_{tt} more stable to NLO effects (scale variations, off-shell...)





QCD+EW

mixed EW+QCD effects can be large at high pT



Kuhn, Kulesza, Schulze, Pozzorini (2005)

e.g. ~30-50% at LHC-14 for pT~1-2 TeV in Z+j

Largely known for 2→2 processes

Nearly ready for production in automated codes

see Z+2j [RECOLA: Actis, Denner, Hofer, Scharf, Uccirati]

problem: book-keeping all interference terms between g and g_s

e.g. GOSAM, RECOLA, OPENLOOPS, aMC@NLO

Outlook

- NLO: new standard accuracy for modelling SM backgrounds
  - wide range of phenomenological tools now available
  - 2⟶5/6 processes now possible
  - detailed theory uncertainty estimates with ME+PS @ NLO
  - NNLO precision for 2⟶2 processes [di-jets, H+j, tt, VV]
  - beyond 2⟶2? automated NNLO? [more theory needed here]

Backup slides

Vector bosons at NNLO

state-of-the-art in high multiplicity → W+5 jets @ NLO [BLACKHAT+SHERPA: Bern at al. arXiv:1304.1253]

Some recent updates:

VBFNLO: [v2.7.0: Baglio et. al (2014)]

$pp \to VV$ $pp \to W\gamma\gamma + j$

$pp \to VV + 2j$

backgrounds to $pp \to VH$ with MEPS@NLO

$pp \to WZ, ZZ, WWW, ZWW, WZZ, ZZZ$

[OPENLOOPS+SHERPA: Hoeche et al. (2014)]

recent updates in MCFM : [v6.8]

constraining Higgs width → $pp \to ZZ \to e^+e^-\mu^+\mu^-$ incl. gg inital states [Campbell, Ellis, Williams (2013)]

$pp \to \gamma\gamma\gamma$ and $\gamma\gamma j$ [Campbell, Williams (2014)]

POWHEG-BOX: (new V2)

$pp \to WW, WZ, ZZ$ [Melia et al. (2011)]

$pp \to WW + 2j$ EW and QCD [Jager, Zanderighi (2012)]

$pp \to ZZ + 2j$ EW and dim 6 CP viol. [Jager, Karlberg, Zanderighi (2013)]

Recent top studies at NLO

$pp \to t\bar{t} + 2j$ NLO

[HELAC-NLO: Bevilacqua et al. (2010)]

$pp \to t\bar{t}b\bar{b}$ NLO+PS

POWHEL: Garzelli et al. (2013)

$pp \to t\bar{t} + W^{\pm}/Z/\gamma$ NLO+PS

POWHEL: Garzelli et al. (2012)

POWHEL: Kardos, Trócsányi (2014)

$pp \to W^+W^-b\bar{b}$ NLO+PS

POWHEL: Garzelli et al. (2014)

POWHEL = HELAC-NLO+POWHEG-BOX

$pp \to t\bar{t}t\bar{t}$ NLO

[HELAC-NLO: Bevilacqua, Worek (2012)]

full mass effects $pp \to b\bar{b}b\bar{b}$ NLO

[HELAC-NLO: Bevilacqua, et al. (2013)]

$pp \to t\bar{t} + j$ NLO+PS

POWHEL: Kardos et al. (2011)

[Alioli, Moch, Uwer (2011)]

$pp \to t\bar{t} + 0, 1, 2j$ MEPS@NLO

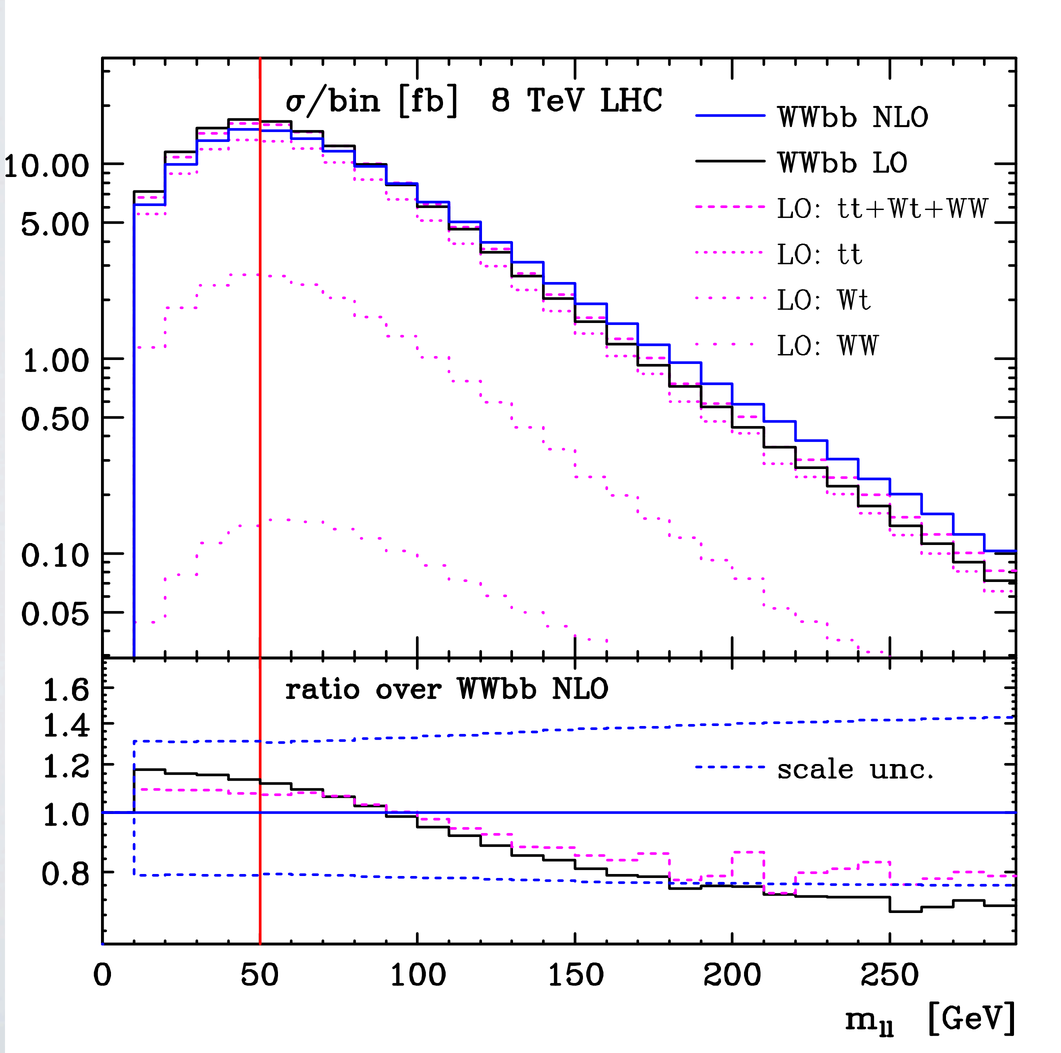
[OPENLOOPS+SHERPA: Hoeche et al. (2014)]

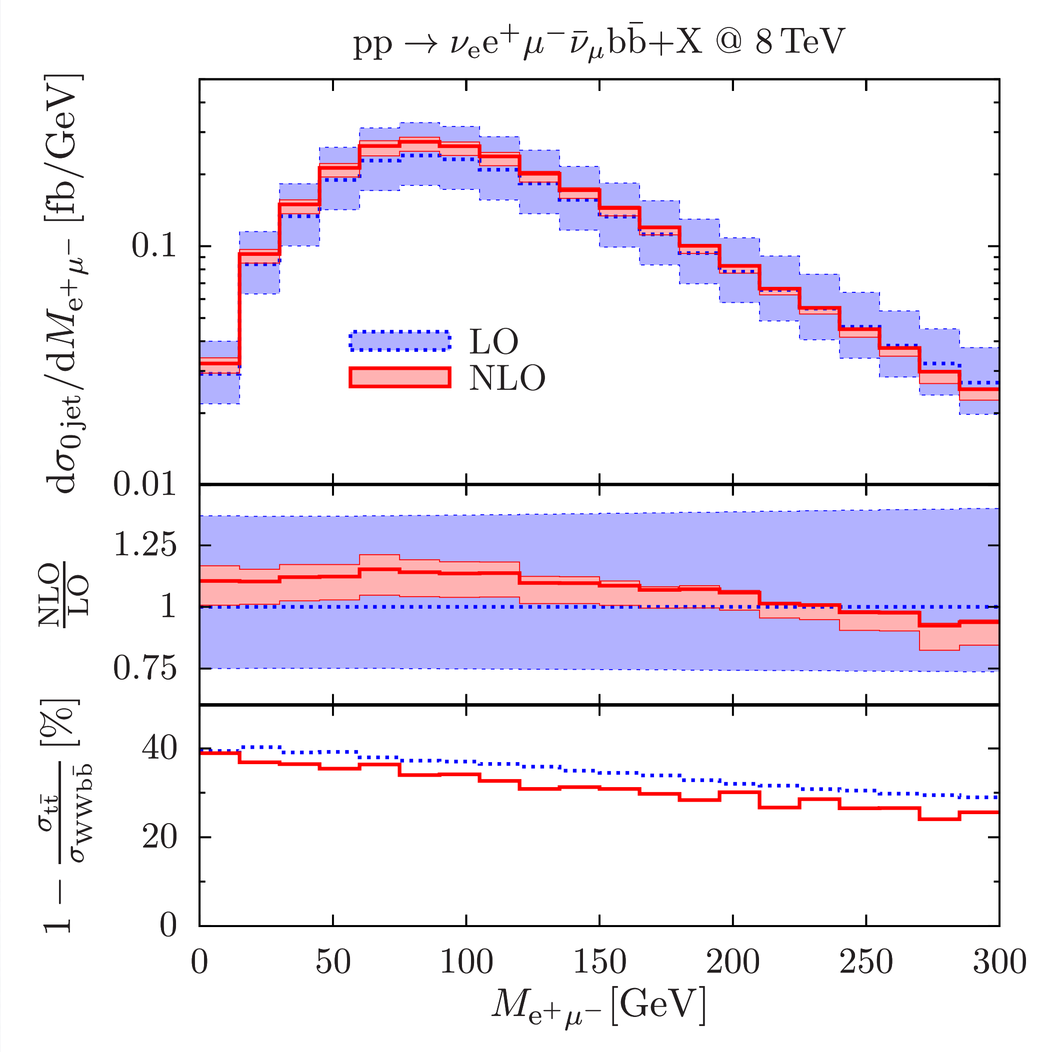
precise SM backgrounds

top backgrounds: off-shell with full b-quark mass effects

$$pp \to H \to l^+ \nu l^- \bar{\nu} b \bar{b}$$

[aMC@NLO: Frederix arXiv:1311.4893] [OpenLoops+Sherpa: Kallweit et al. arXiv:1312.0546]

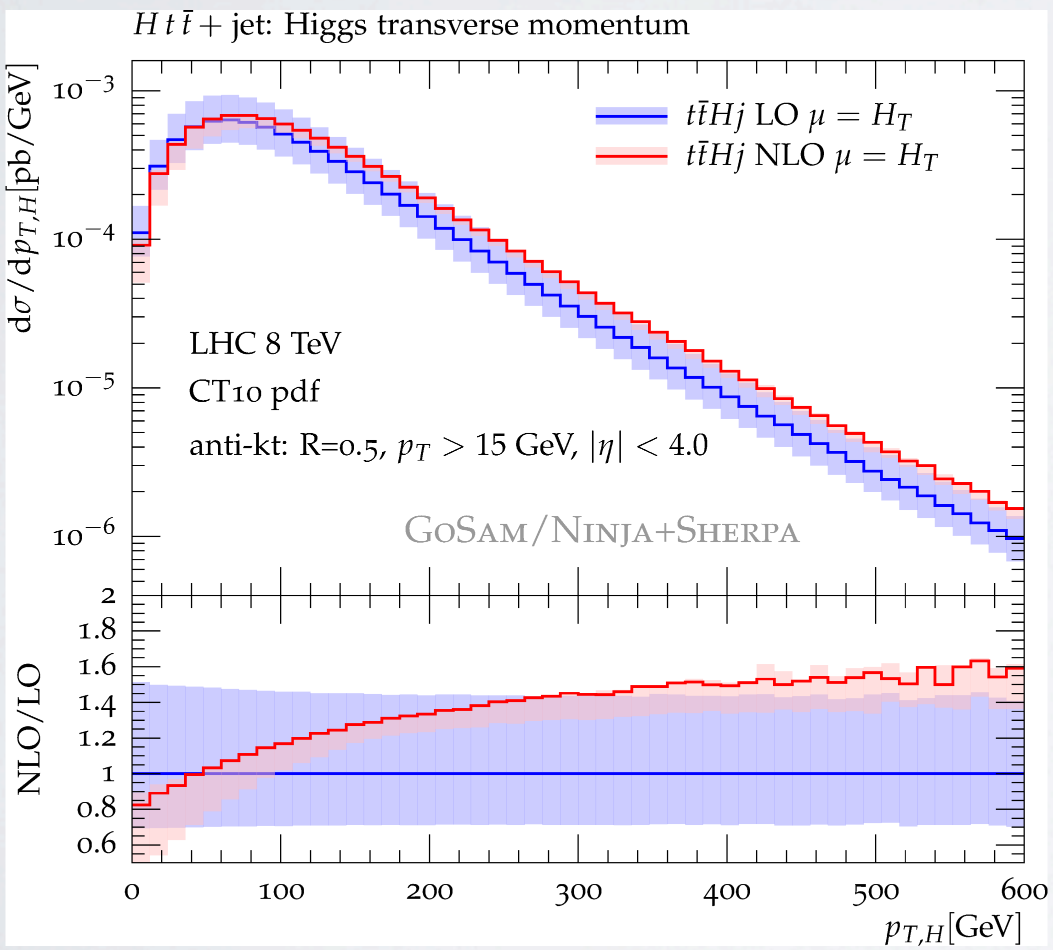




top coupling measurements

probes for ttH coupling
at NLO accuracy

$$pp \to t\bar{t}H + j \quad \text{NLO}$$



[GoSam+Sherpa: van Deurzen et al. arXiv: 1307.8437]

constraining ttZ couplings
at NLO accuracy

[Schulze, Rontsch arXiv:1404.1005]