Les Houches 2017:
SM N^xLO, NLO (multi-legs+EW) WG

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Les Houches, June 6, 2017

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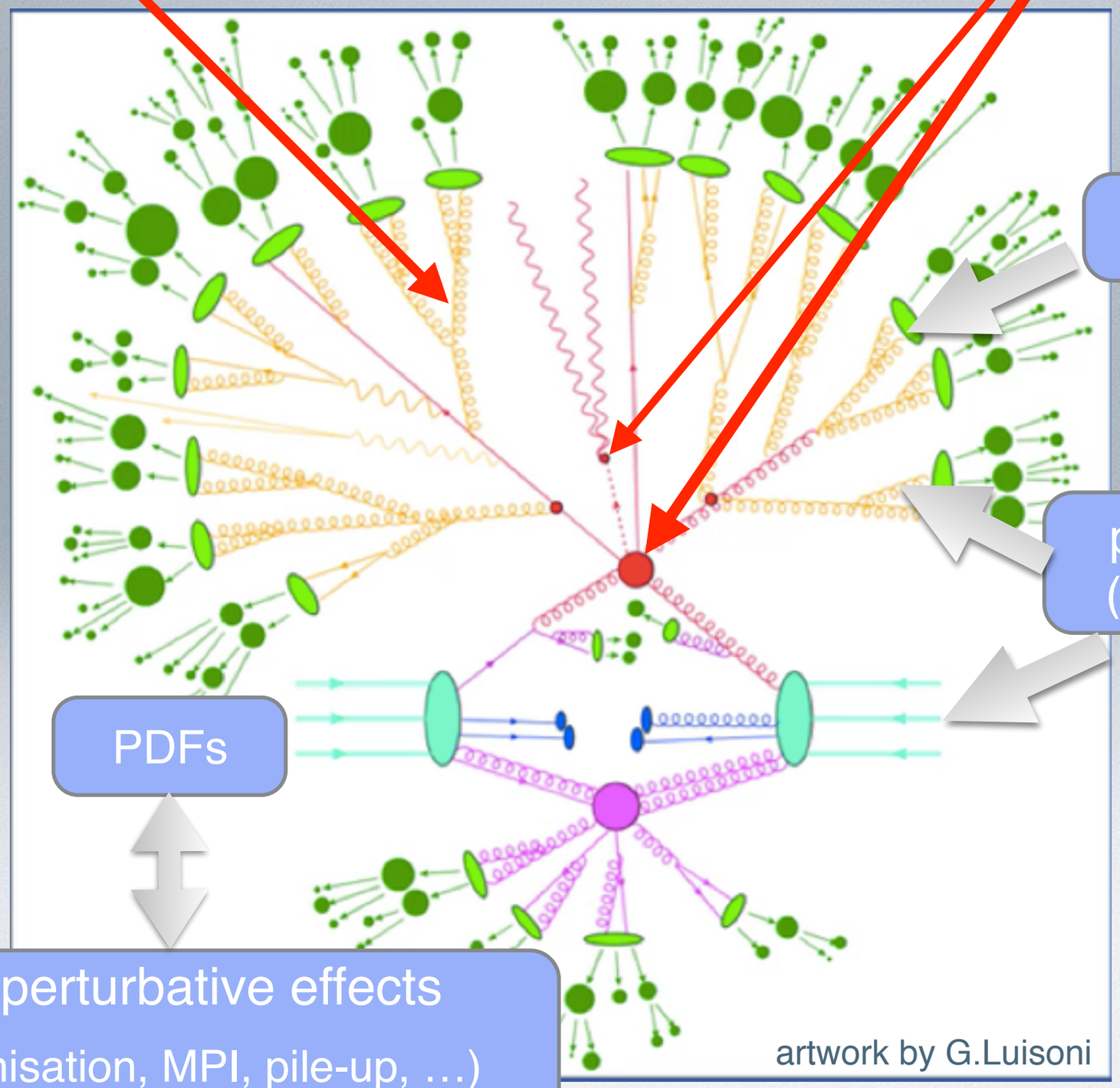
The precision frontier

parton shower

resummation

fixed order calculations
NLO (QCD+EW), NNLO, …



quark mass effects

parametric uncertainties
(e.g. couplings, masses)

PDFs

non-perturbative effects
(hadronisation, MPI, pile-up, …)

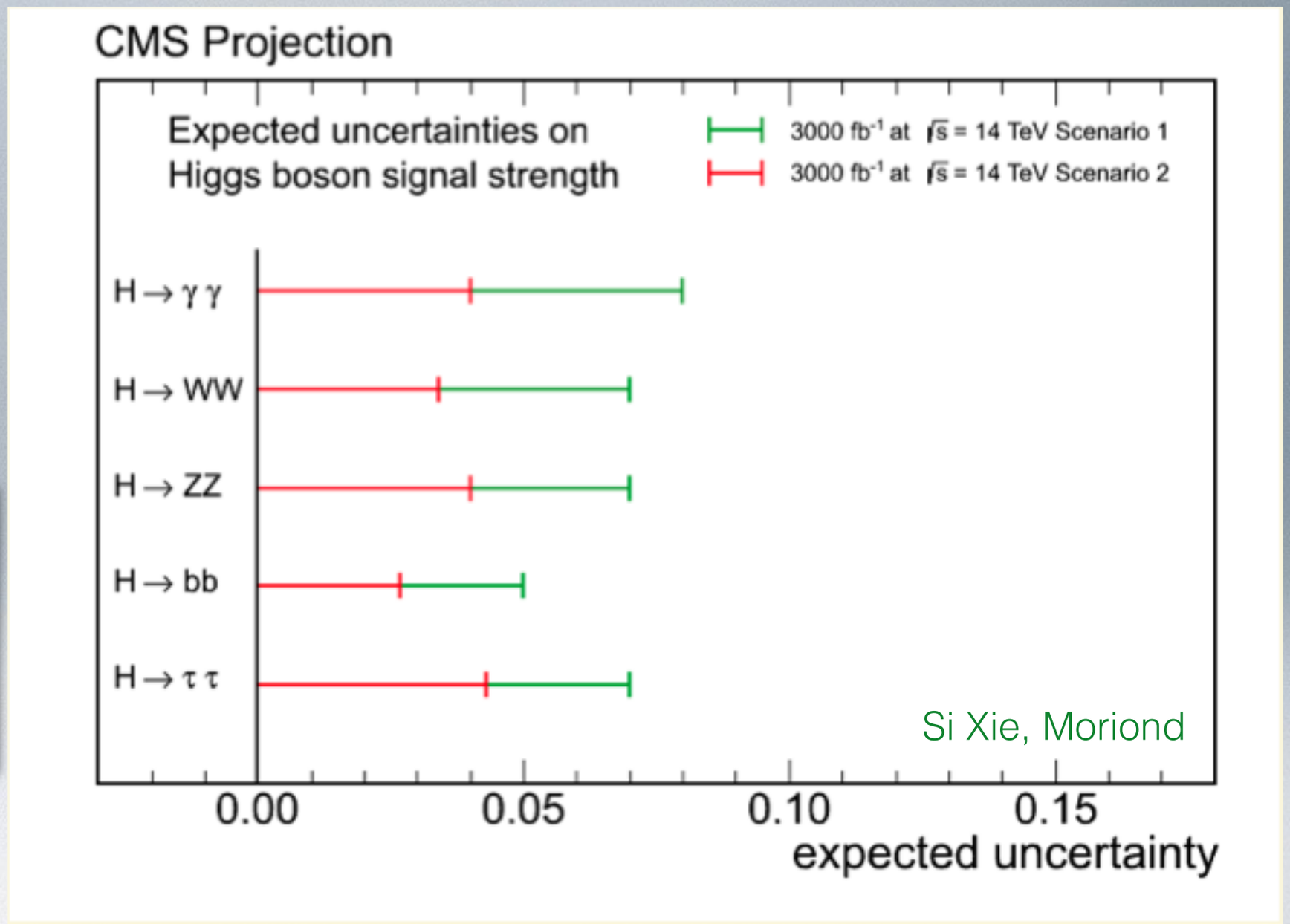
expected uncertainties at HL-LHC

scenario 1:

use current systematic uncertainties

scenario 2:

assume theory systematics improve by 50%,
scale exp. systematics by luminosity



Si Xie, Moriond

topics

not covered:

- Higgs
- parton showers
- PDFs
- jets

what's left?

topics

not covered:

- Higgs
- parton showers
- PDFs
- jets

what's left?

- wishlist
- NNLO
- quark mass effects
- scale choices (at N^xLO)
- improvements to fixed order (resummation, power corrections)
- EW corrections
- photons
- EFT $\otimes$ NLO QCD
- new methods

progress since Les Houches 2015

- available processes
  - available in which form? (public/private program, grids, Ntuples, …)
  - differential?
  - decays?
  - parton shower?
- methods
  - NNLO IR subtraction schemes
  - unitarity-based methods at 2 loops
  - 2-loop master integrals with several mass scales
    (quark mass effects, EW, mixed EW-QCD corrections, …)
  - 4-dimensional instead of D-dim (various methods)

wishlist

to be updated

process		known (May 2016)		desired
$pp \to H$	σ	$\mathrm{N^3LO_{HEFT}+N^2LO_{QCD}}\left(\frac{1}{m_t^6}\right)$	$\mathrm{d}\sigma$	$\mathrm{N^3LO_{HEFT}+N^2LO_{QCD}}$ $\mathrm{+NLO_{EW}+N^{(1,1)}LO_{QCD\times EW}}$
	$\mathrm{d}\sigma$	$\mathrm{NLO_{EW}}$		
	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{HEFT}+NLO_{QCD}+PS}$		
$pp \to H + j$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{HEFT}}$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{HEFT}+NLO_{QCD}+NLO_{EW}}$
	$\mathrm{d}\sigma$	$\mathrm{NLO_{EW}}$		
$pp \to H + 2j$	$\mathrm{d}\sigma$	$\mathrm{NLO_{HEFT}+LO_{QCD}}$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{HEFT}+LO_{QCD}+NLO_{EW}}$
	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}(VBF^*)}$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}(VBF)+NLO_{EW}(VBF)}$
	$\mathrm{d}\sigma$	$\mathrm{NLO_{EW}(VBF)}$		
$pp \to H + 3j$	$\mathrm{d}\sigma$	$\mathrm{NLO_{HEFT}}$	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}+LO_{QCD}+NLO_{EW}}$
	$\mathrm{d}\sigma$	$\mathrm{NLO_{EW}}$		
$pp \to H + V$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}}$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO}_{gg\to HV} + \mathrm{NLO_{EW}}$
$pp \to HH$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{HEFT}}$	$\mathrm{d}\sigma$	$\mathrm{N^2LO_{HEFT}+NLO_{QCD}+NLO_{EW}}$
	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}}$		
$pp \to H + t\bar{t}$	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}}$	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}+NLO_{EW}}$
	$\mathrm{d}\sigma$	$\mathrm{NLO_{EW}}$		
$pp \to H + t/H + \bar{t}$	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}}$	$\mathrm{d}\sigma$	$\mathrm{NLO_{QCD}+NLO_{EW}}$

Table I.1: Precision wish list: Higgs boson final states

focus still is on “differential”, combination with EW, quark mass effects

wishlist

to be updated

process		known (May 2016)		desired
$pp \to V$	σ	$\mathrm{N^3LO_{QCD}}(z \to 0)$	$d\sigma$	$\mathrm{N^3LO_{QCD}} + \mathrm{N^2LO_{EW}}$
	$d\sigma$	$\mathrm{N^2LO_{QCD}}$		$+ \mathrm{N^{(1,1)}LO_{QCD\times EW}}$ + decays
	$d\sigma$	$\mathrm{NLO_{EW}}$		
	$d\sigma$	$\mathrm{N^{(1,1)}LO_{QCD\times EW}}$		
$pp \to VV'$	$d\sigma$	$\mathrm{N^2LO_{QCD}}$ + decays	$d\sigma$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$+ decays
	$d\sigma$	$\mathrm{NLO_{EW}}$		
$pp \to V + j$	$d\sigma$	$\mathrm{N^2LO_{QCD}}$	$d\sigma$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$+ decays
$pp \to V + 2j$	$d\sigma$	$\mathrm{NLO_{QCD}}$+ decays	$d\sigma$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$+ decays
	$d\sigma$	$\mathrm{NLO_{EW}}$+ decays		
$pp \to VV' + 2j$	$d\sigma$	$\mathrm{NLO_{QCD}}$+ decays	$d\sigma$	$\mathrm{NLO_{QCD}}$+ $\mathrm{NLO_{EW}}$+ decays
	$d\sigma$	$\mathrm{NLO_{EW}}$		
$pp \to VV'V''$	$d\sigma$	$\mathrm{NLO_{QCD}}$	$d\sigma$	$\mathrm{NLO_{QCD}}$+ $\mathrm{NLO_{EW}}$+ decays
	$d\sigma$	$\mathrm{NLO_{EW}}$		
$pp \to \gamma\gamma$	$d\sigma$	$\mathrm{N^2LO_{QCD}}$	$d\sigma$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to \gamma\gamma + j$	$d\sigma$	$\mathrm{NLO_{QCD}}$	$d\sigma$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$

Table I.2: Precision wish list: Vector boson final states

focus is on “differential”, combination with EW, decays

wishlist

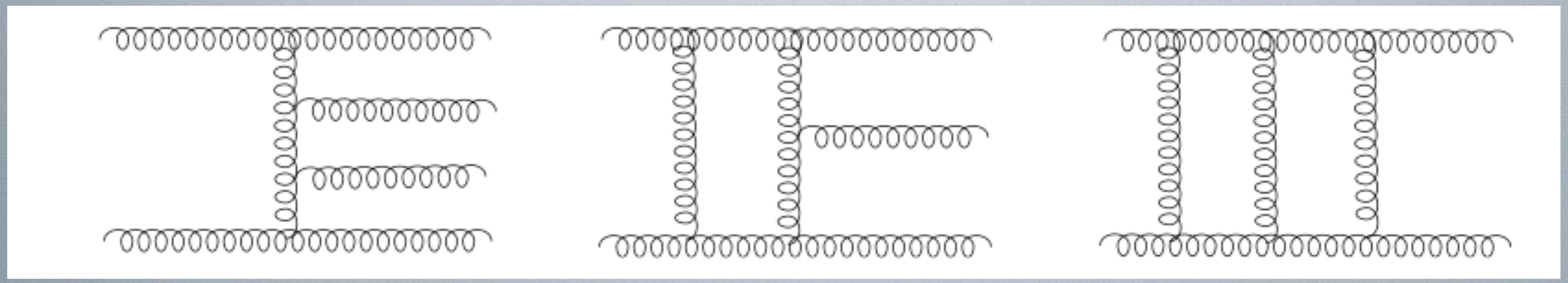
to be updated

process	known (May 2016)		desired	
$pp \to t\bar{t}$	$d\sigma$	N^2LO_{QCD}	$d\sigma$	N^2LO_{QCD} + NLO_{EW}+ decays
	$d\sigma$	NLO_{EW}		
$pp \to t\bar{t} + j$	$d\sigma$	NLO_{QCD}+ decays	$d\sigma$	N^2LO_{QCD} + NLO_{EW}+ decays
	$d\sigma$	NLO_{EW}		
$pp \to t\bar{t} + 2j$	$d\sigma$	NLO_{QCD}+ on-shell decays	$d\sigma$	NLO_{QCD}+ NLO_{EW}+ decays
$pp \to t\bar{t} + V$	$d\sigma$	NLO_{QCD}	$d\sigma$	NLO_{QCD}+ NLO_{EW}+ decays
	$d\sigma$	NLO_{EW}		
$pp \to t/\bar{t}$	$d\sigma$	N^2LO_{QCD} (t-channel)	$d\sigma$	N^2LO_{QCD} + NLO_{EW}+ decays
$pp \to 2j$	$d\sigma$	N^2LO_{QCD}(gg,qq)	$d\sigma$	NLO_{QCD}+ NLO_{EW}
	$d\sigma$	NLO_{EW}		
$pp \to j + \gamma$	$d\sigma$	NLO_{QCD}	$d\sigma$	NLO_{QCD}+ NLO_{EW}
	$d\sigma$	NLO_{EW}		
$pp \to 3j$	$d\sigma$	NLO_{QCD}	$d\sigma$	NLO_{QCD}+ NLO_{EW}

Table I.3: Precision wish list: top quark and jet final states

focus is on “differential”, combination with EW, decays

NNLO QCD corrections: building blocks



double real

1-loop virtual
$\otimes$ single real

2-loop virtual

implicit IR poles (PS integration)

explicit and implicit poles

explicit poles $1/\epsilon^{2L}$

bottlenecks: IR subtraction

two-loop integrals

harder with more massless particles
(intricate IR singularity structure)

harder with more massive/off-shell particles
(more scales → more complicated
analytic structure)

NNLO real radiation subtraction methods

- antenna subtraction analytically integrated subtraction terms

  [Gehrmann-DeRidder, Gehrmann, Glover '05]

- qt "subtraction" slicing, (colourless final states)

  [Catani, Grazzini '07]

- N-jettiness slicing

  [Gaunt, Stahlhofen, Tackmann, Walsh '15]

  [Boughezal, Focke, Liu, Petriello '15]

- sector-improved residue subtraction

  [Czakon, Heymes, Mitov '10; Czakon, Heymes '14] numerically integrated subtraction terms

  [Boughezal et al. '11] [Caola, Melnikov, Röntsch '17]

- projection to Born/ structure function approach only special kinematics

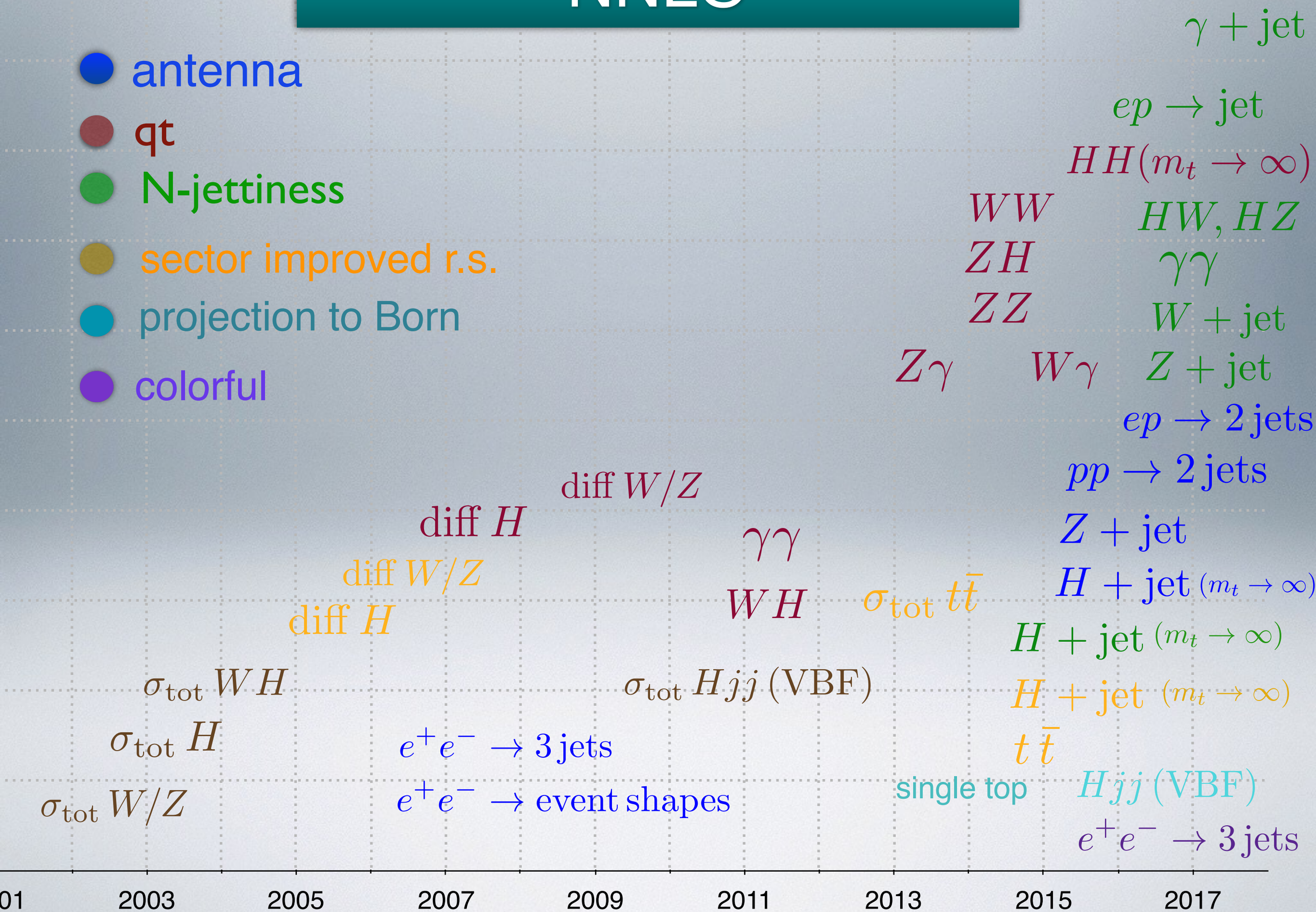
  [Goa, Li, Zhu '12] [Brucherseifer, Caola, Melnikov '14] [Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15]

- colorful only final state colour

  [Del Duca, Somogyi, Trocsanyi '05]

NNLO

- antenna
- qt
- N-jettiness
- sector improved r.s.
- projection to Born
- colorful



NNLO

topics at this workshop:

- pro's and con's of various subtraction schemes
  (in particular in view of automation)

  maybe tuned comparison for Drell-Yan?

- how to make results available to non-authors
  and allow for easy variation of scales and PDFs
  (e.g. via grids, Ntuples)

- NNLO + parton shower

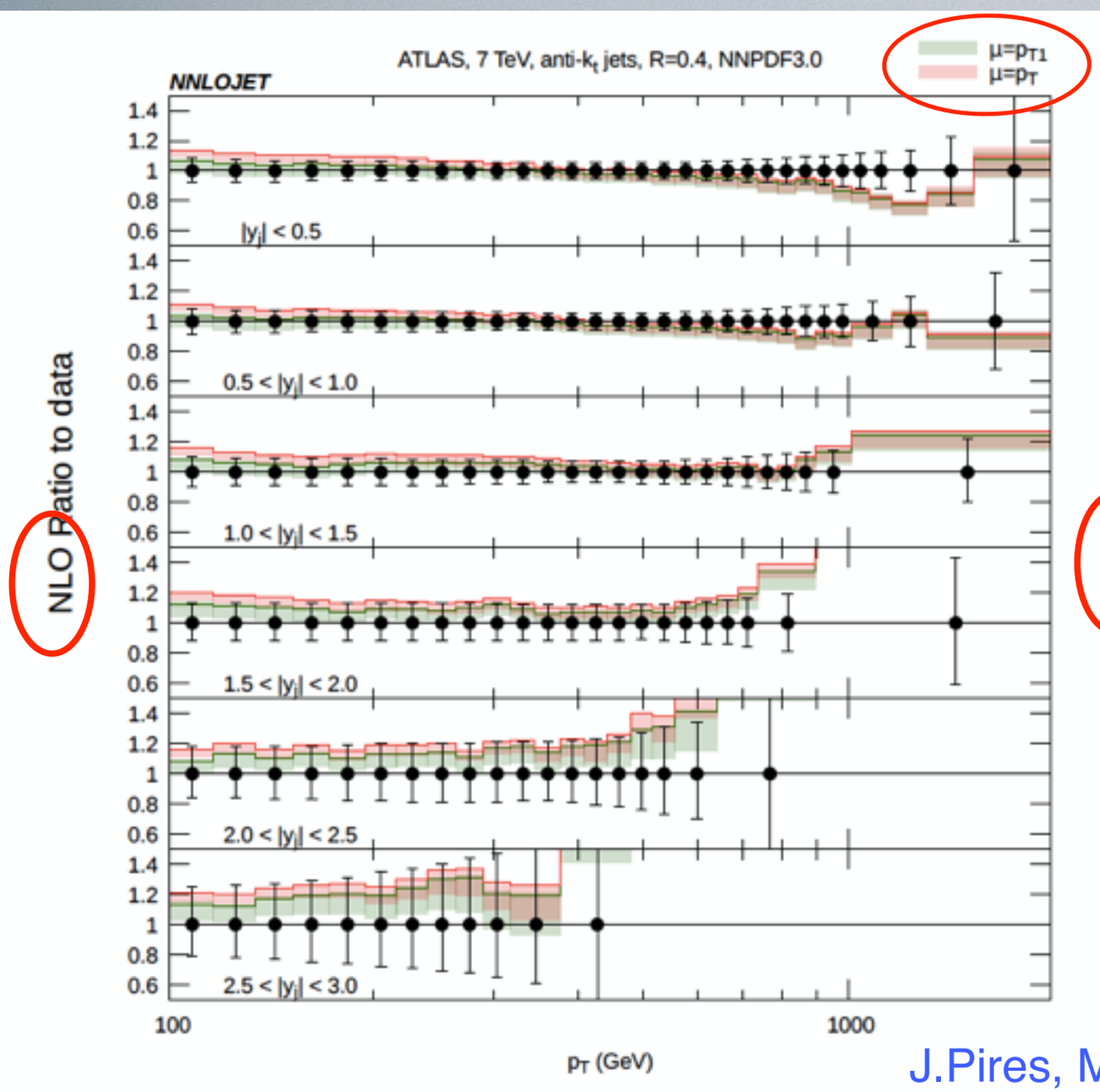
scale choices

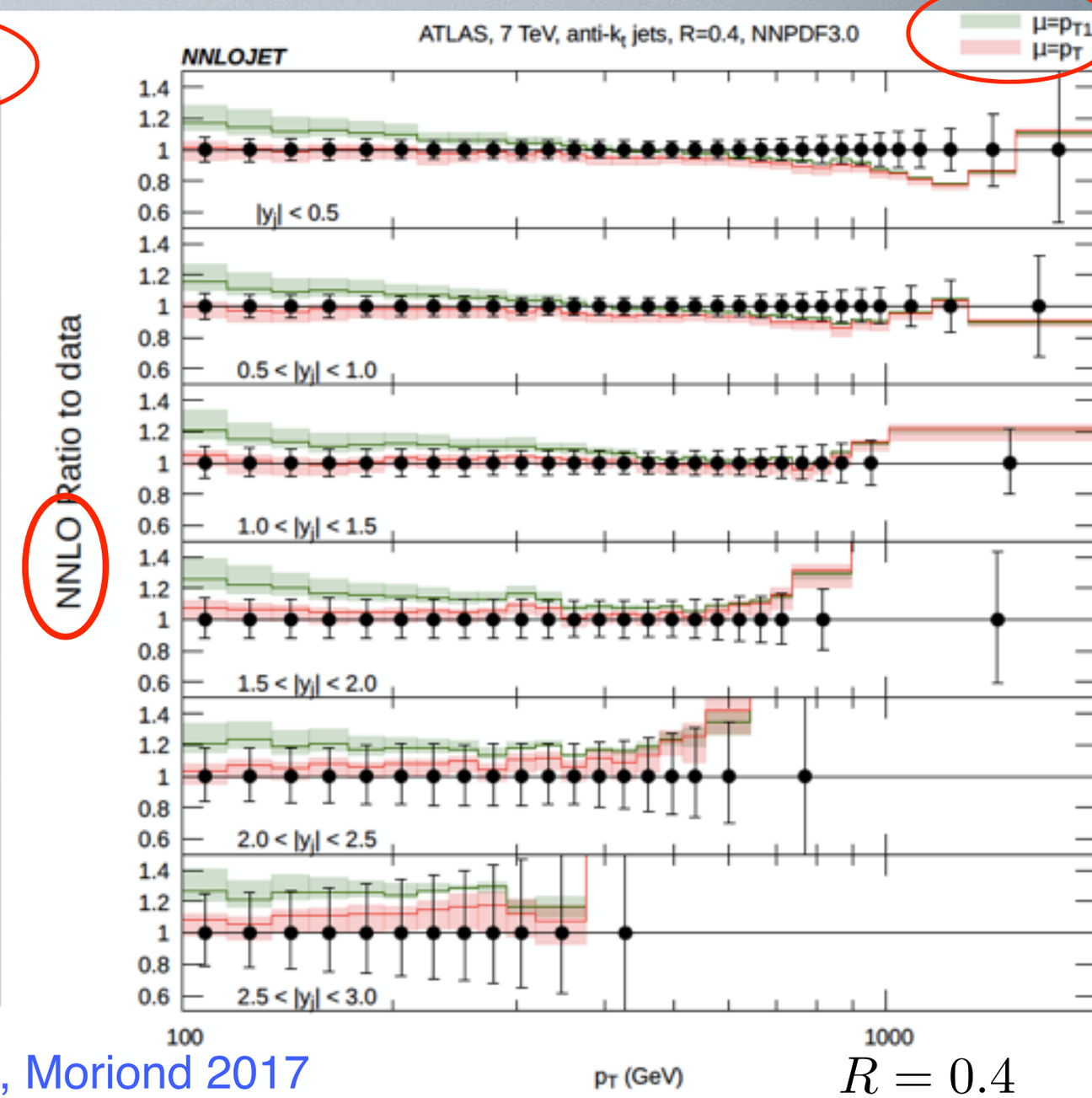
$pp \to 2\,\text{jets}$ available at NNLO

[Currie, Gehrmann-DeRidder, Gehrmann, Glover, Pires '14; Currie, Glover, Pires '16]

$\mu = p_{T1}$ leading jet pT

$\mu = p_T$ individual jet pT





J.Pires, Moriond 2017

$R = 0.4$

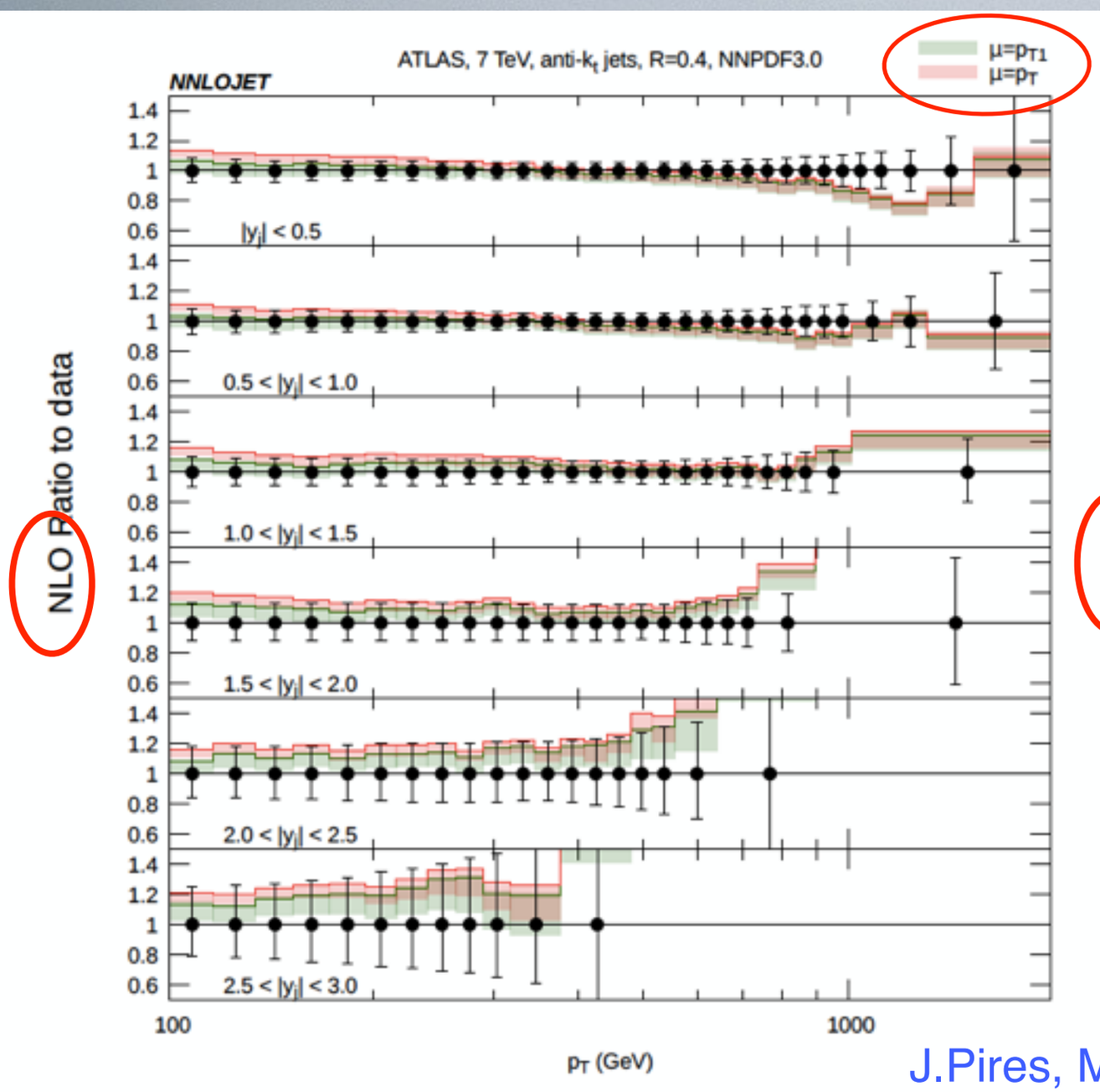
scale choices

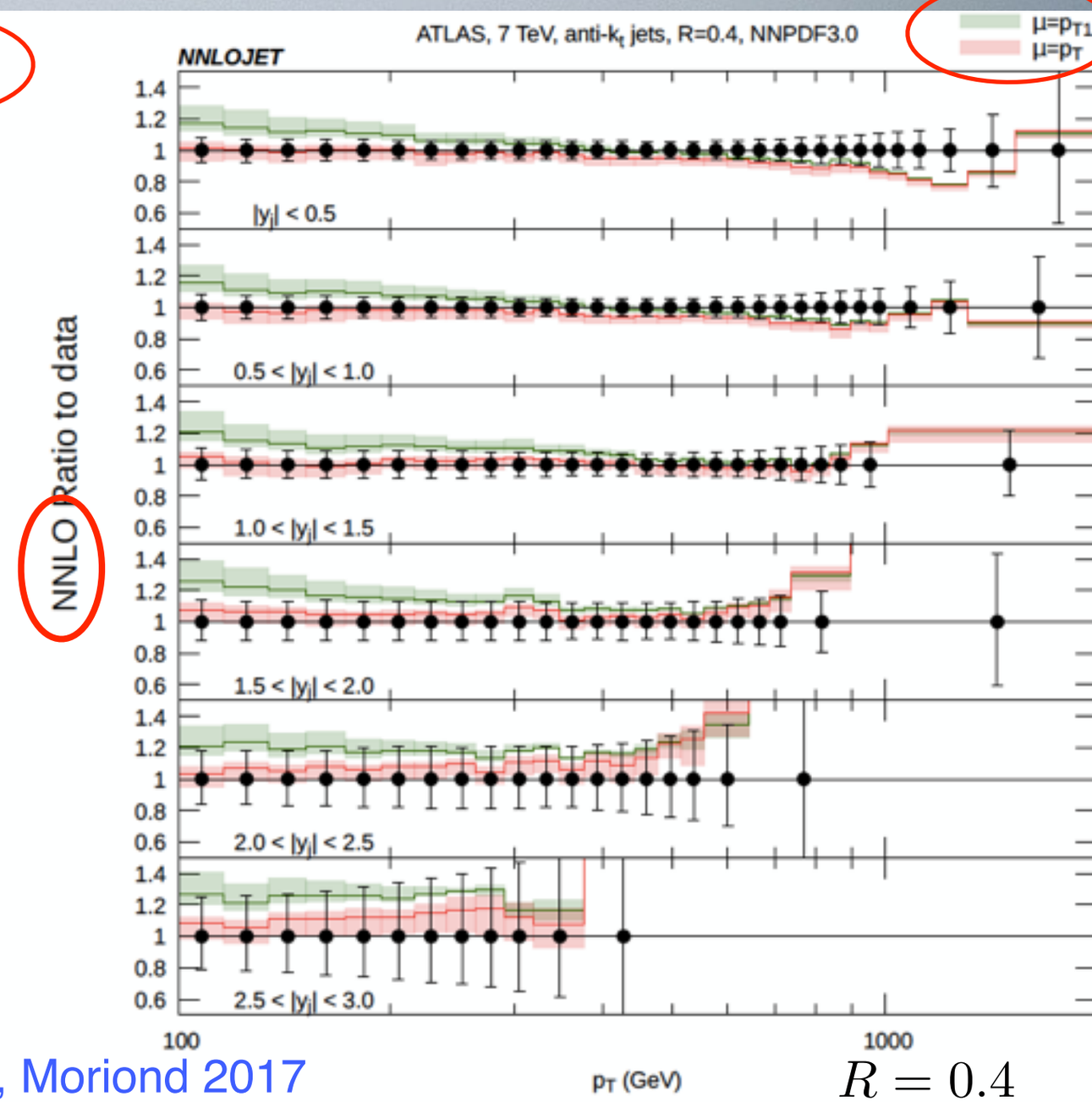
$pp \to 2\,\text{jets}$ available at NNLO

[Currie, Gehrmann-DeRidder, Gehrmann, Glover, Pires '14; Currie, Glover, Pires '16]

$\mu = p_{T1}$ leading jet pT

$\mu = p_T$ individual jet pT





J.Pires, Moriond 2017

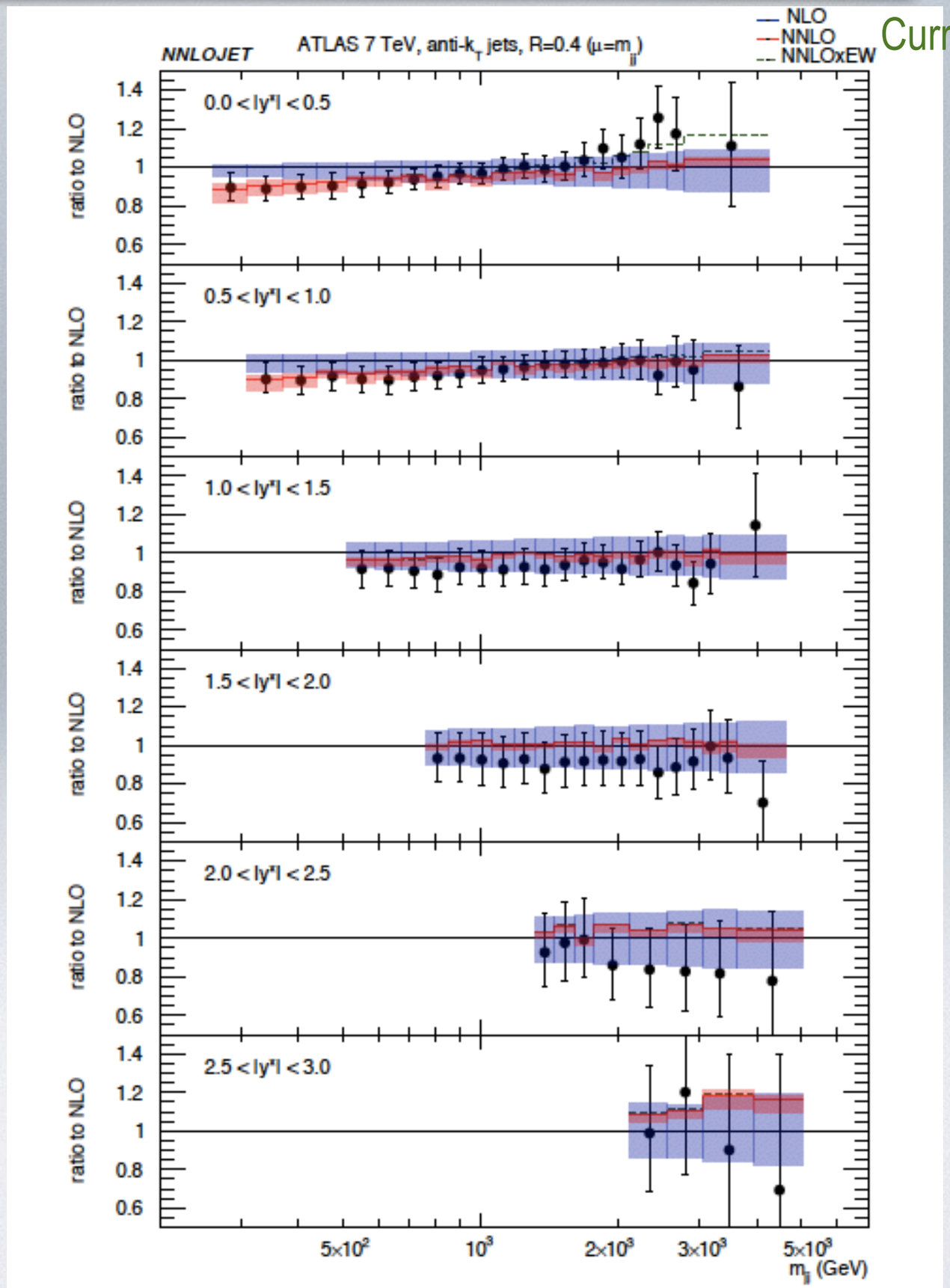
$R = 0.4$

scale choice matters!

difference larger than scale uncertainty

scale choices

$$\mu = m_{jj}$$

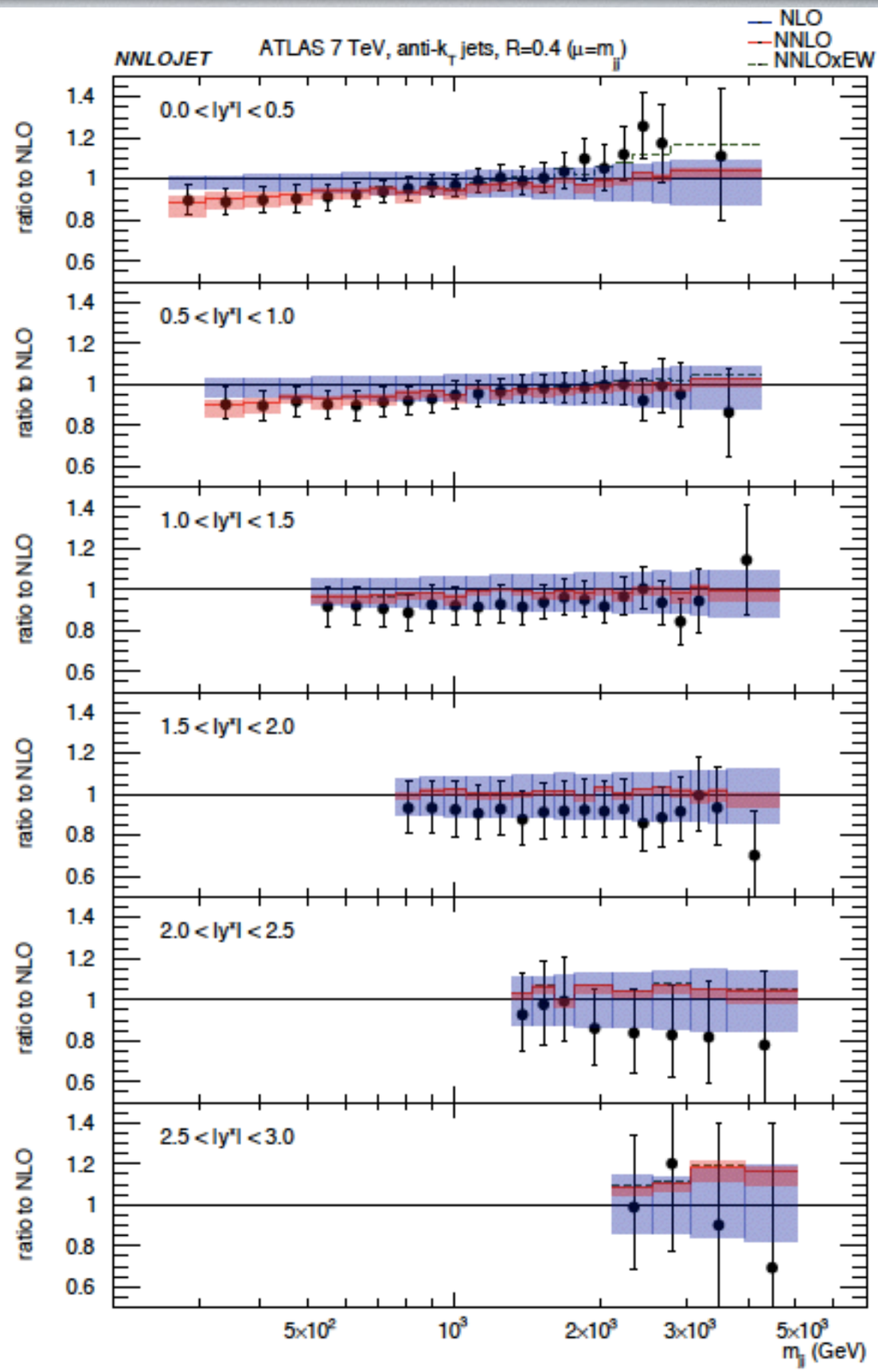


Currie, Gehrmann-DeRidder, Gehrmann, Glover, Huss, Pires '17

scale choices

$$\mu = m_{jj}$$

at NNLO:
scale uncertainty usually small, therefore it is important to assess the systematic uncertainty related to the choice of the central scale!



Currie, Gehrmann-DeRidder, Gehrmann, Glover, Huss, Pires '17

improvements to fixed order

- include power corrections to improve N-jettiness method
- numerical evaluation of soft functions, beam functions
- analytic resummation vs. parton shower (comparisons)
- include leading NNLO EW effects via EW Sudakov factors

. . .

EW corrections

- aim: **complete automation at NLO**, incl. matching to parton showers

  intense work within

  Sherpa, Powheg, Herwig7 with OLPs Recola, OpenLoops, GoSam

  and within MG5_aMC@NLO

  recent results e.g.

  dijet full NLO QCD+EW Frederix, Frixione, Hirschi, Pagani, Shao, Zaro '16

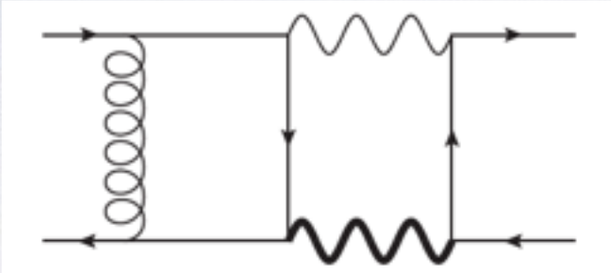
  Z+j, Z+jj, W+j, ZZ, ttH Biedermann, Bräuer, Denner, Pellen, Schumann, Thompson '17

  WW, ZZ, yZ (diboson including non-resonant) Kallweit, Lindert, Pozzorini, Schönherr '17

  top pair NNLO QCD + NLO EW Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro '17

- mixed QCD-EW corrections

  e.g. Drell-Yan



Bonciani, Di Vita, Mastrolia, Schubert '16;

von Manteuffel, Schabinger '17

- how to combine N(N)LO QCD with NLO EW

  (additive, multiplicative)

more topics in overlap region to MC & tools

- top quark physics

  off-shell effects

  resonance aware matching

  Jezo, Nason '15; Jezo, Lindert, Nason, Oleari, Pozzorini '16 (Powheg+OpenLoops bb4l)

  Frederix, Frixione, Papanastasiou, Prestel, Torielli '16 (MG5_aMC@NLO single top)

- photons

  how well does smooth cone isolation match experimental isolation

  democratic clustering (photon as a QCD parton)

  see e.g. dijet full NLO QCD+EW Frederix, Frixione, Hirschi, Pagani, Shao, Zaro '16

- EFT $\otimes$ NLO QCD

. . .

status multi-loop integrals/amplitudes

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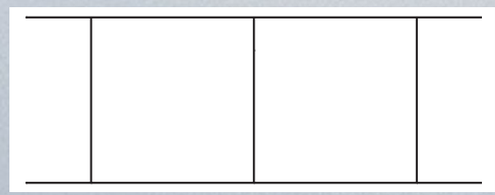
two-loop integrals/amplitudes

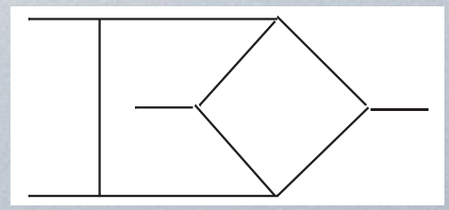
2-loop 4-point:

(black lines are massless)

- all massless:

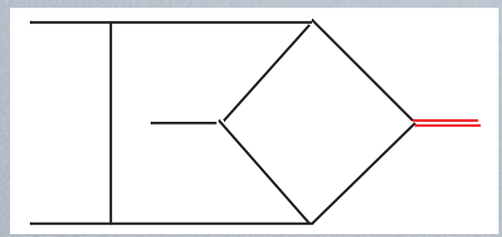


planar: Smirnov '99



non-planar: Tausk '99

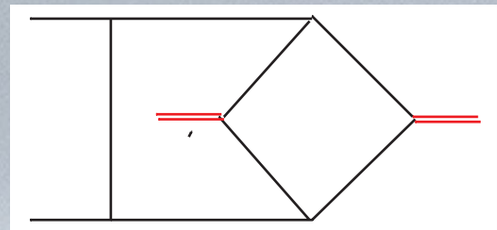
- one massive leg:
  e.g. pp to V+jet



Gehrmann and Remiddi '00-'02

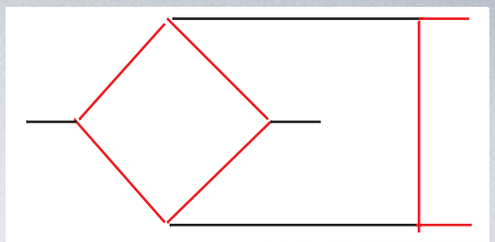
Moch, Uwer, Weinzierl '02

- two massive legs:
  e.g. pp to VV



Gehrmann, Tancredi, Weihs '13
Gehrmann, von Manteuffel, Tancredi, Weihs '14
Caola, Henn, Melnikov, Smirnov '14
Papadopoulos, Tommasini, Wever '14

- massive propagators (also massive on-shell legs) e.g. $t\bar{t}$

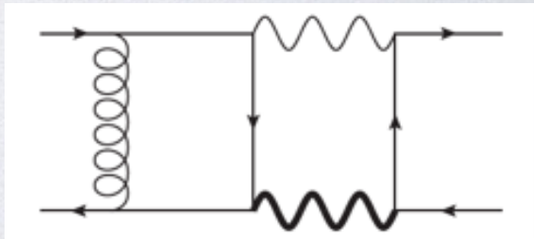


Czakon '07 (**numerically**)

Bonciani, Ferroglia, Gehrmann, von Manteuffel, Studerus '10, '13 (analytic, partial, tT)

Henn, Smirnov '13 (analytic, planar, Bhabha)

- massive propagators (one mass)
  e.g. mixed QCD-EW corrections to Drell-Yan

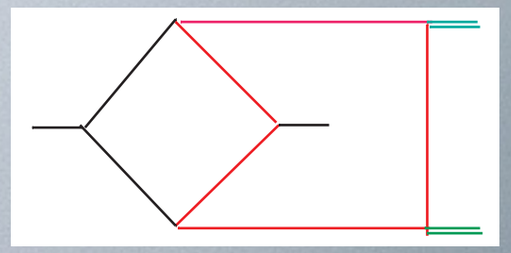


Bonciani, Di Vita, Mastrolia, Schubert '16;

von Manteuffel, Schabinger '17

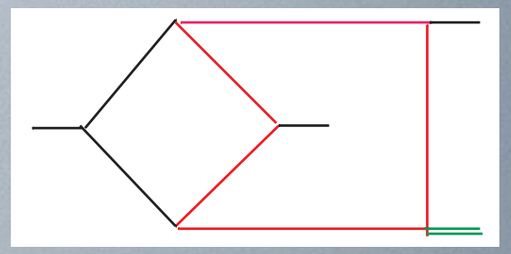
two-loop integrals/amplitudes

- massive propagators + massive legs with different mass (two additional mass scales) e.g. $gg \to HH$



Borowka, Greiner, GH, Jones, Kerner, Schlenk, Schubert, Zirke '16 **numerically**

- same number of scales e.g. H+jet:



lots of work on elliptic functions, some integrals still unknown

Tancredi, Remiddi '16; Adams, Bogner, Weinzierl '15,'16

Bonciani, Del Duca, Henn, Frellesvig, Moriello, Smirnov '16

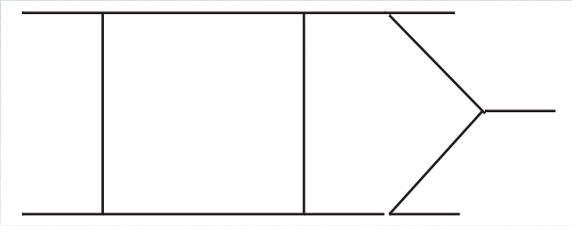
Tancredi, Primo '16,'17

b-mass dependence: Melnikov, Tancredi, Wever '16,'17

2-loop 5-point:

- all massless, planar:

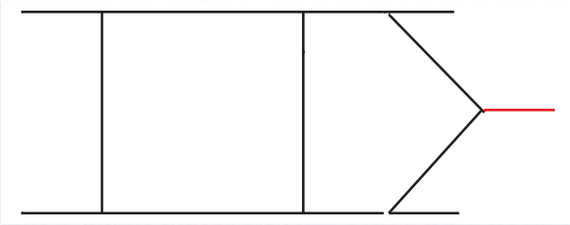
  e.g. pp to 3jets



Gehrmann, Henn, Lo Presti '15

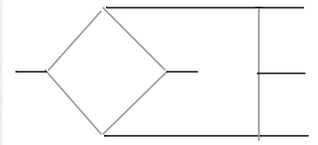
- one off-shell leg, planar:

  e.g. pp to V+2jets



Papadopoulos, Tomassini, Wever '15

- non-planar still unknown



two-loop amplitudes

analytic results based on unitarity approach:

- 5-gluon all-plus helicity amplitude

  Badger, Mogull, Ochirov, O'Connell '15; Badger, Mogull, Peraro'16

  Gehrmann, Henn, Lo Presti '15

  Dunbar, Perkins '16

- 6-gluon all-plus helicity amplitude

  Dunbar, Jehu, Perkins '16

remarkable result based on numerical unitarity:

- 4-gluon amplitude (leading colour, all helicities)

  Abreu, Febres Cordero, Ita, Jaquier, Page, Zeng '17

  result known [Glover, Oleari, Tejeda-Yeomans '01; Bern De Freitas, Dixon '02]

  but method seems suitable for automation
  (similar to what caused the "NLO revolution") ?

Les Houches 2013

Les Houches 2015

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