Pushing the precision frontier in Collider Physics

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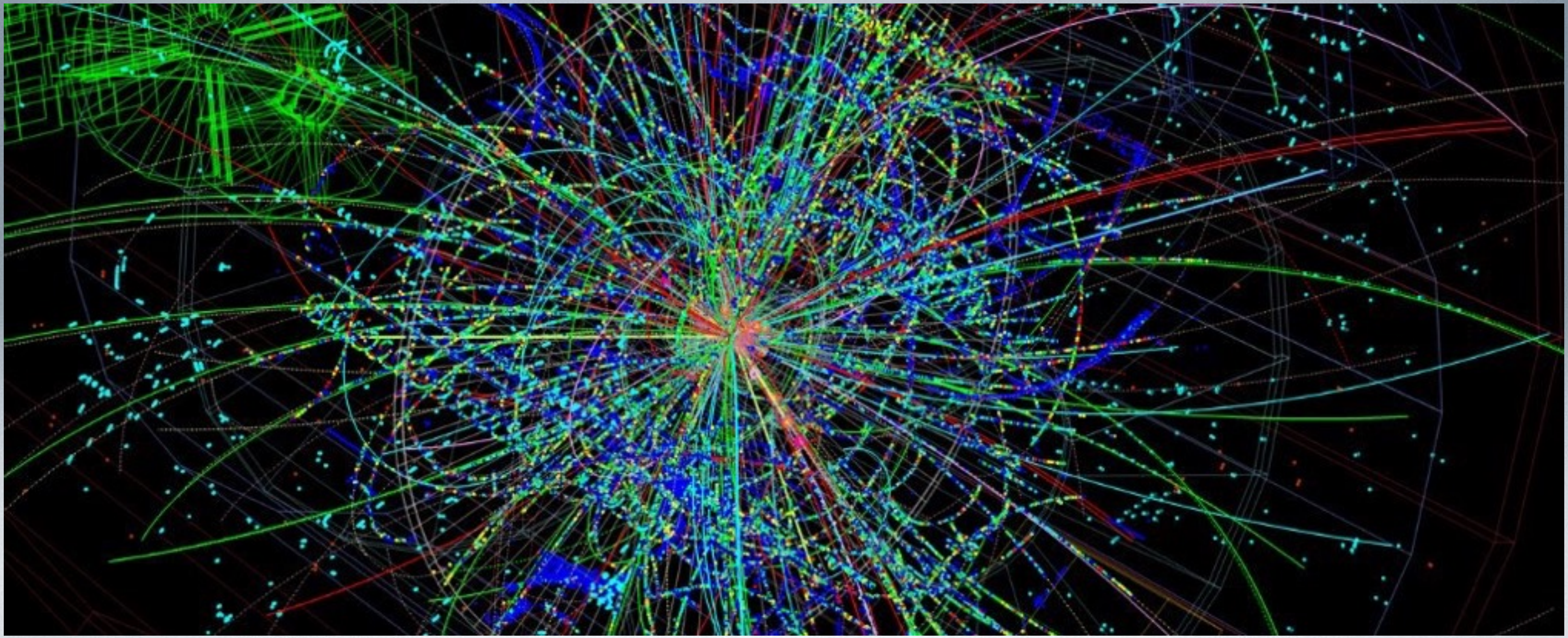

IMPRS Young Scientists workshop
Castle Ringberg, December 2018

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Outline

- Motivation: Why to push the precision further?

- Basic building blocks of precision calculations

- Overview of recent developments:
  methods and phenomenology

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Motivation

if the Standard Model is an effective theory
valid up to a scale Λ

$$\text{data} = \text{SM} + \mathcal{O}(v^2/\Lambda^2) \simeq \text{SM} + \mathcal{O}(6\% \times 1\text{TeV}^2/\Lambda^2)$$

so New Physics at the TeV scale is not excluded yet

need to reach this level of precision!

Status of the Standard Model today

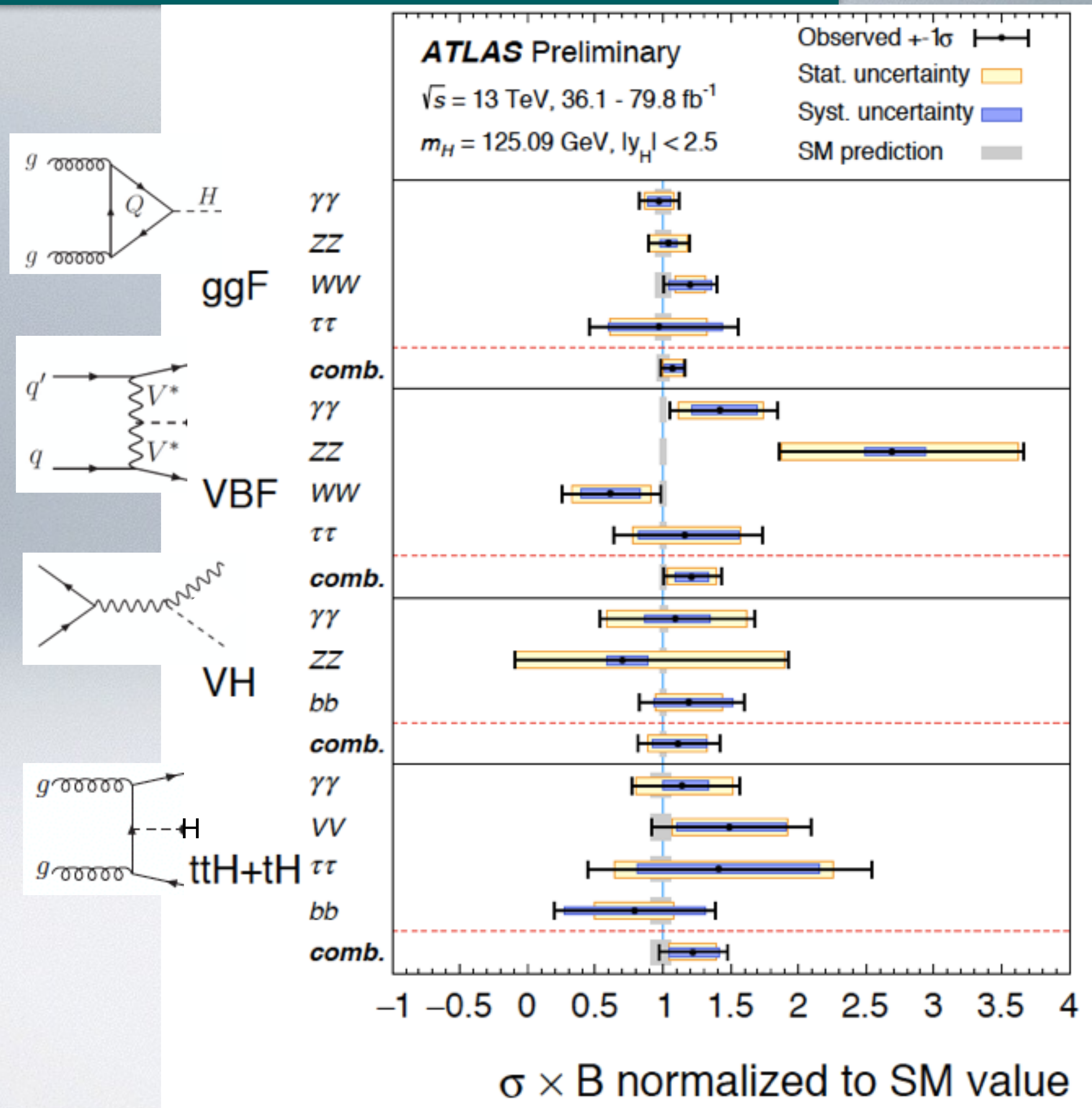
ATLAS-CONF-2018-031

Higgs production and decay

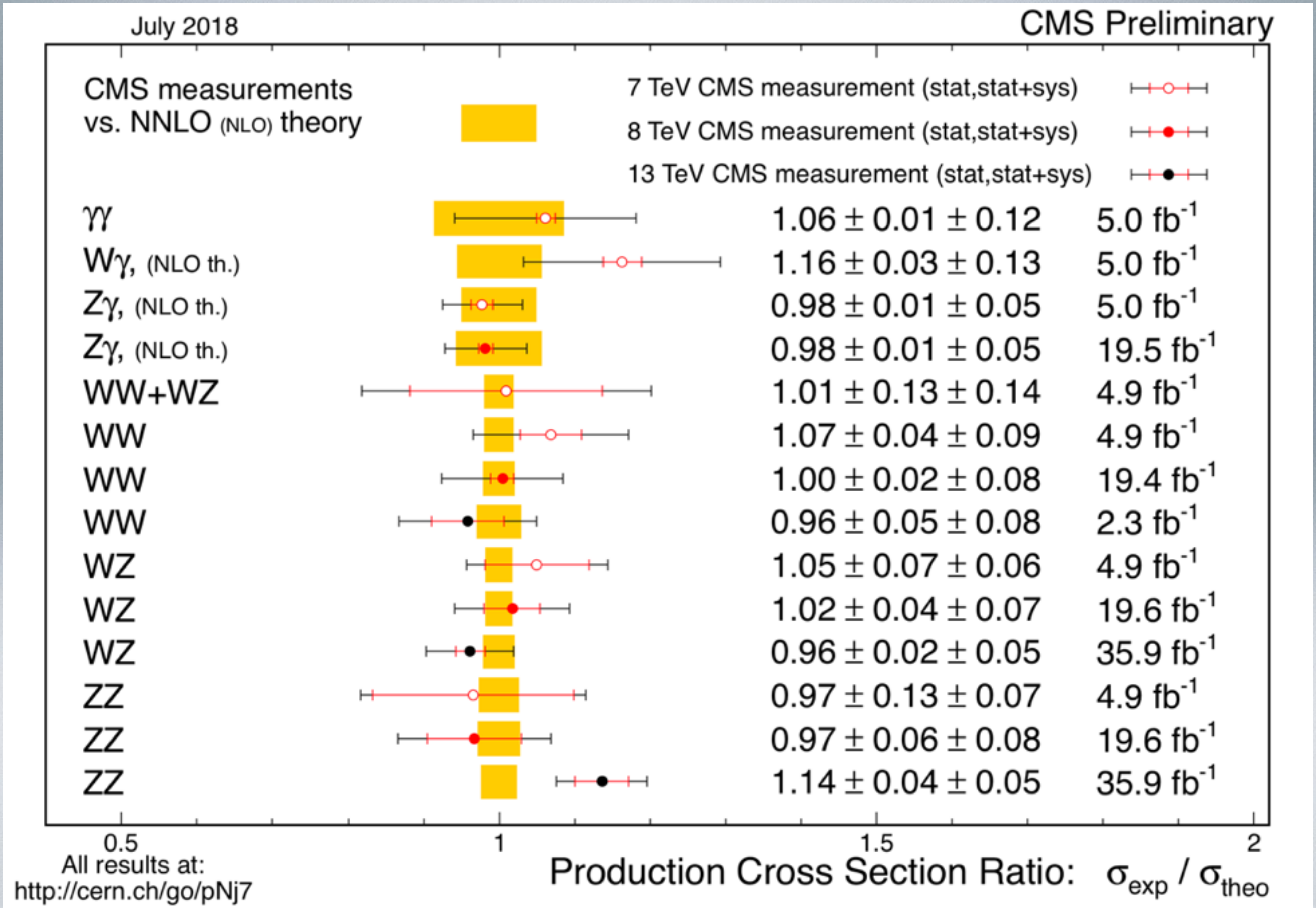
most uncertainties not below 10% level

statistics will improve

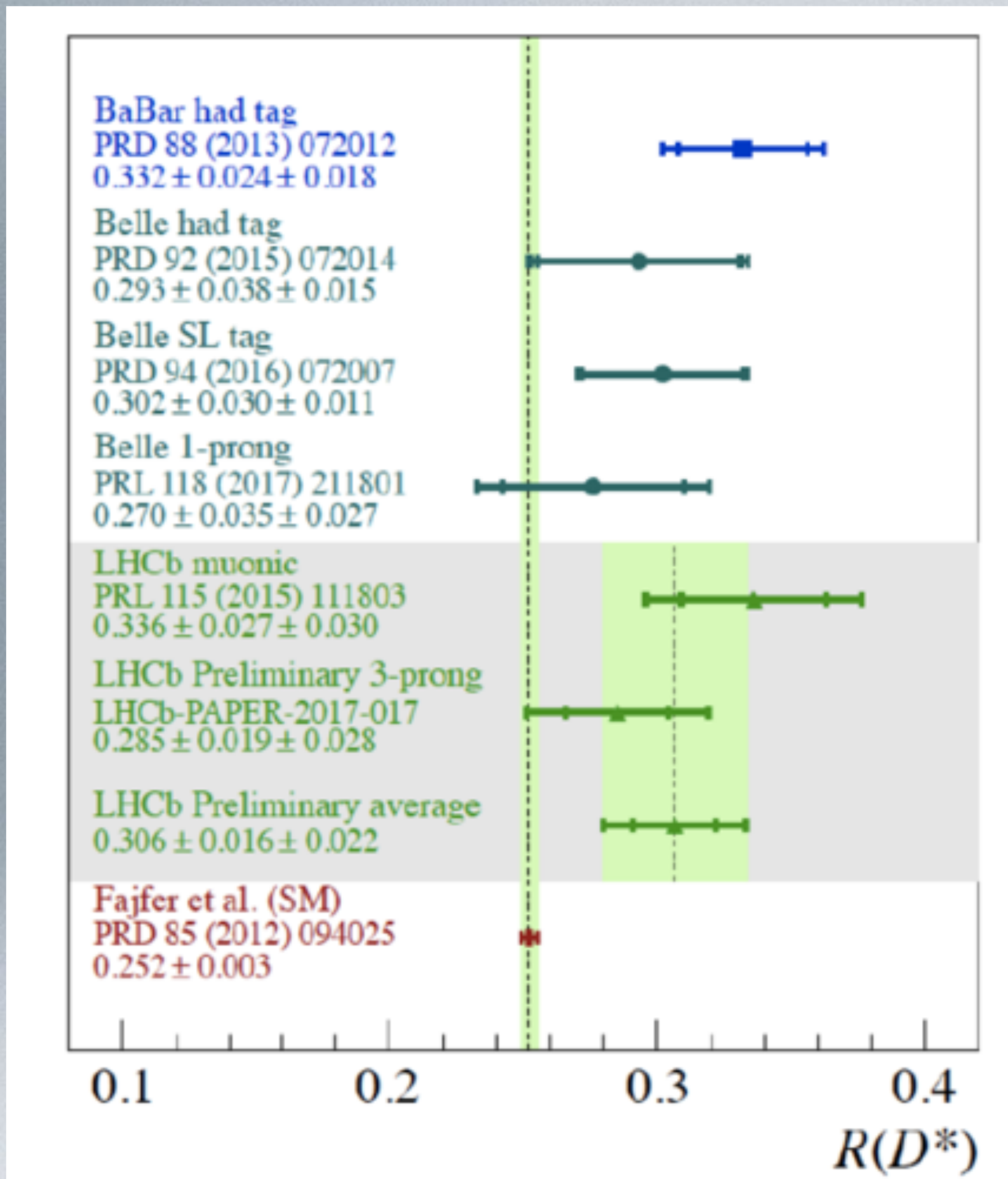
systematic uncertainty contains theory uncertainty!

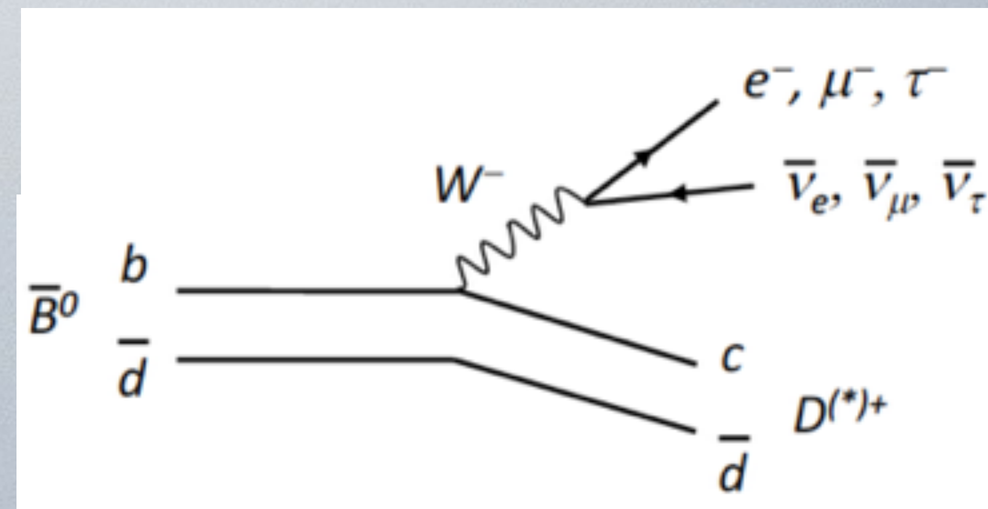


Status of the Standard Model today



some “anomalies”





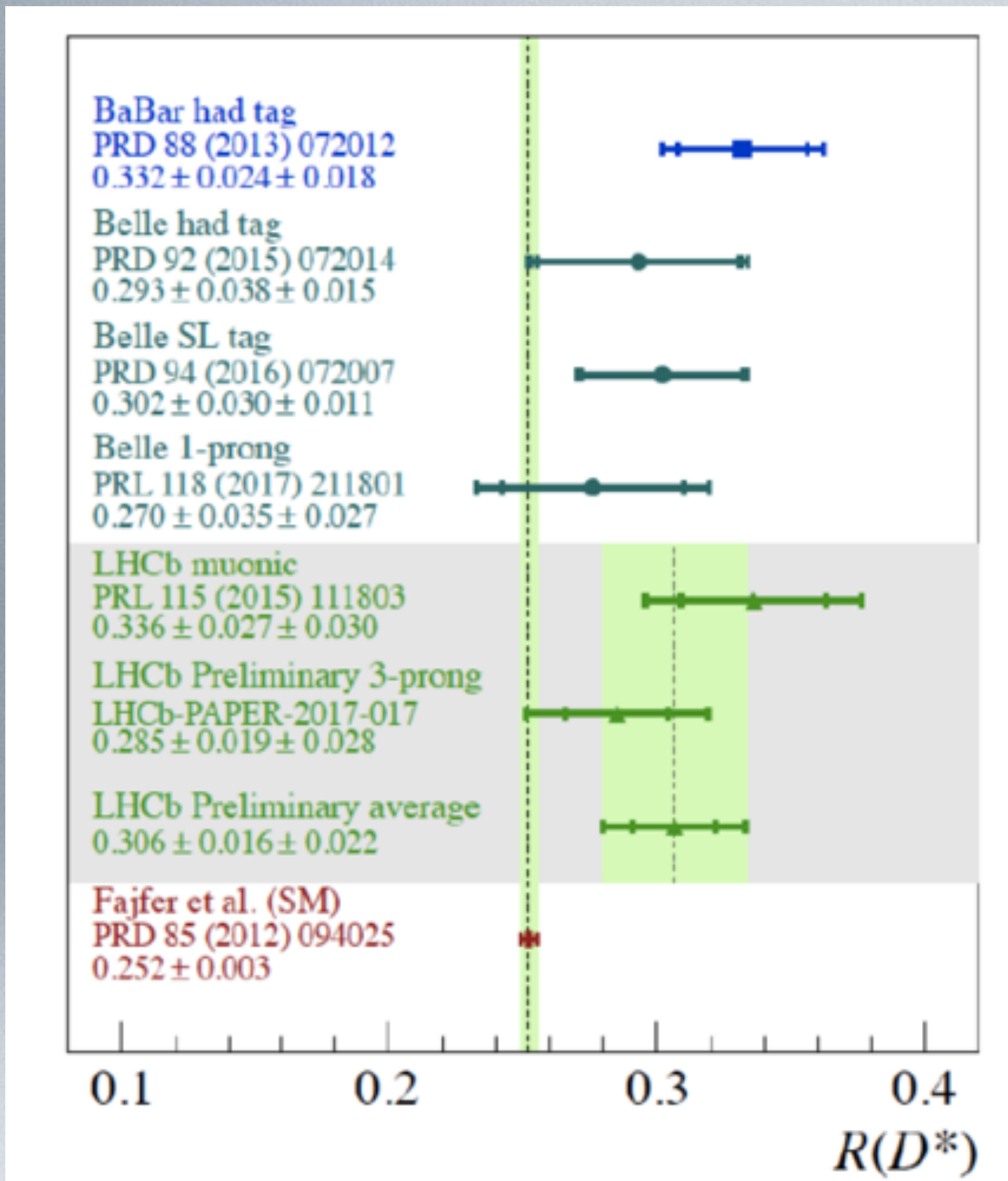
$$R_{D^*} = \frac{BR(B^0 \rightarrow D^{*+}\tau^-\overline{\nu})}{BR(B^0 \rightarrow D^{*+}\mu^-\overline{\nu})}$$

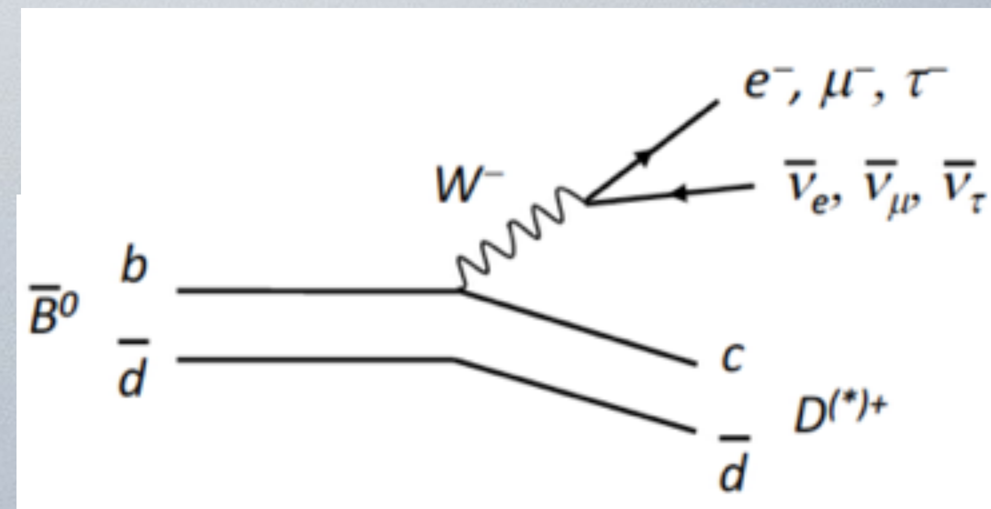
J.Albrecht, Moriond 2018

combination of R(D) and R(D*) about 4 sigma deviation from SM prediction

lepton flavour universality violated?

some “anomalies”





$$R_{D^*} = \frac{BR(B^0 \to D^{*+}\, \tau^- \overline{\nu})}{BR(B^0 \to D^{*+}\, \mu^- \overline{\nu})}$$

combination of R(D) and R(D*) about 4 sigma deviation from SM prediction

J.Albrecht, Moriond 2018

lepton flavour universality violated?

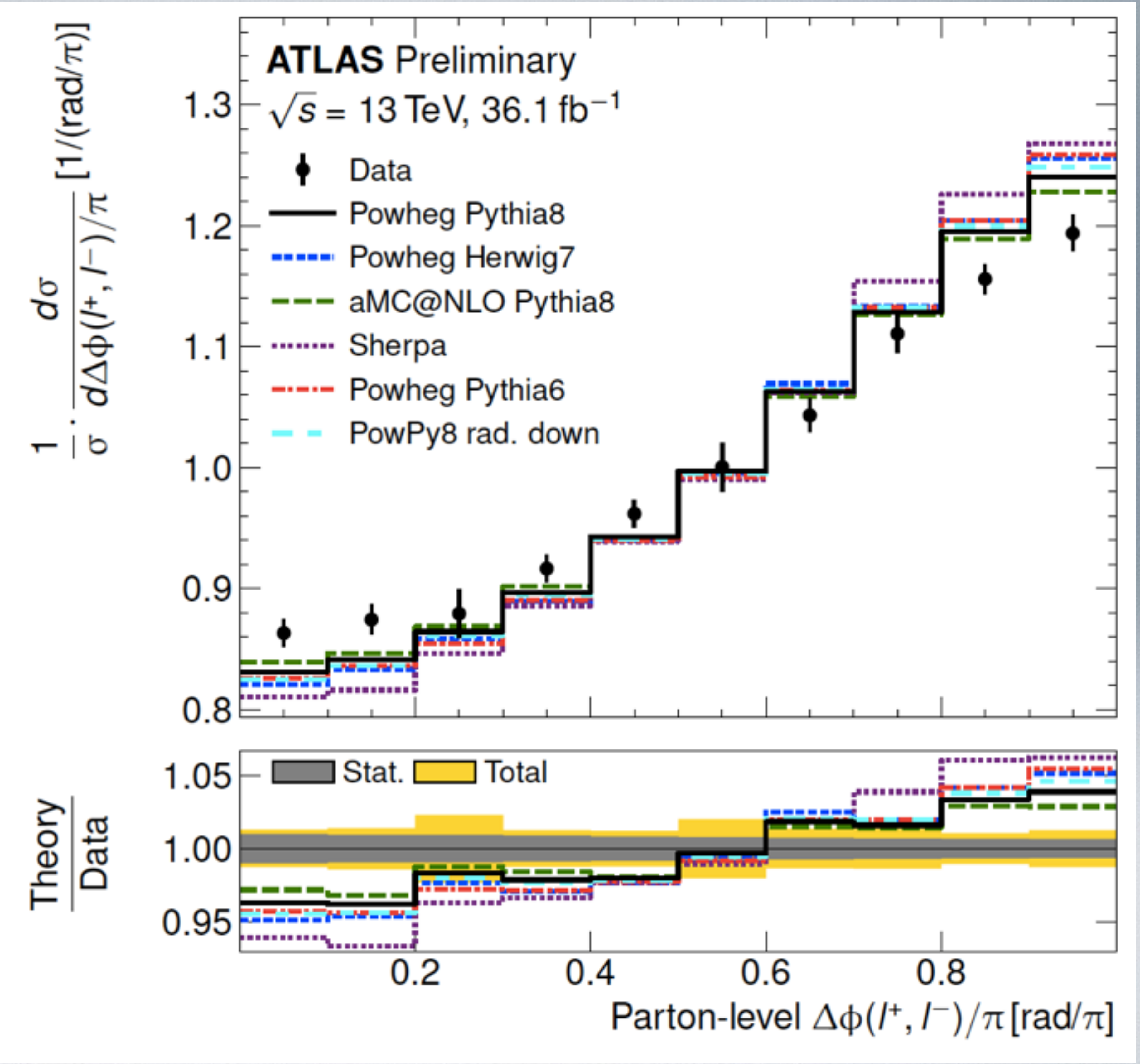
theory predictions very well under control

some “anomalies”

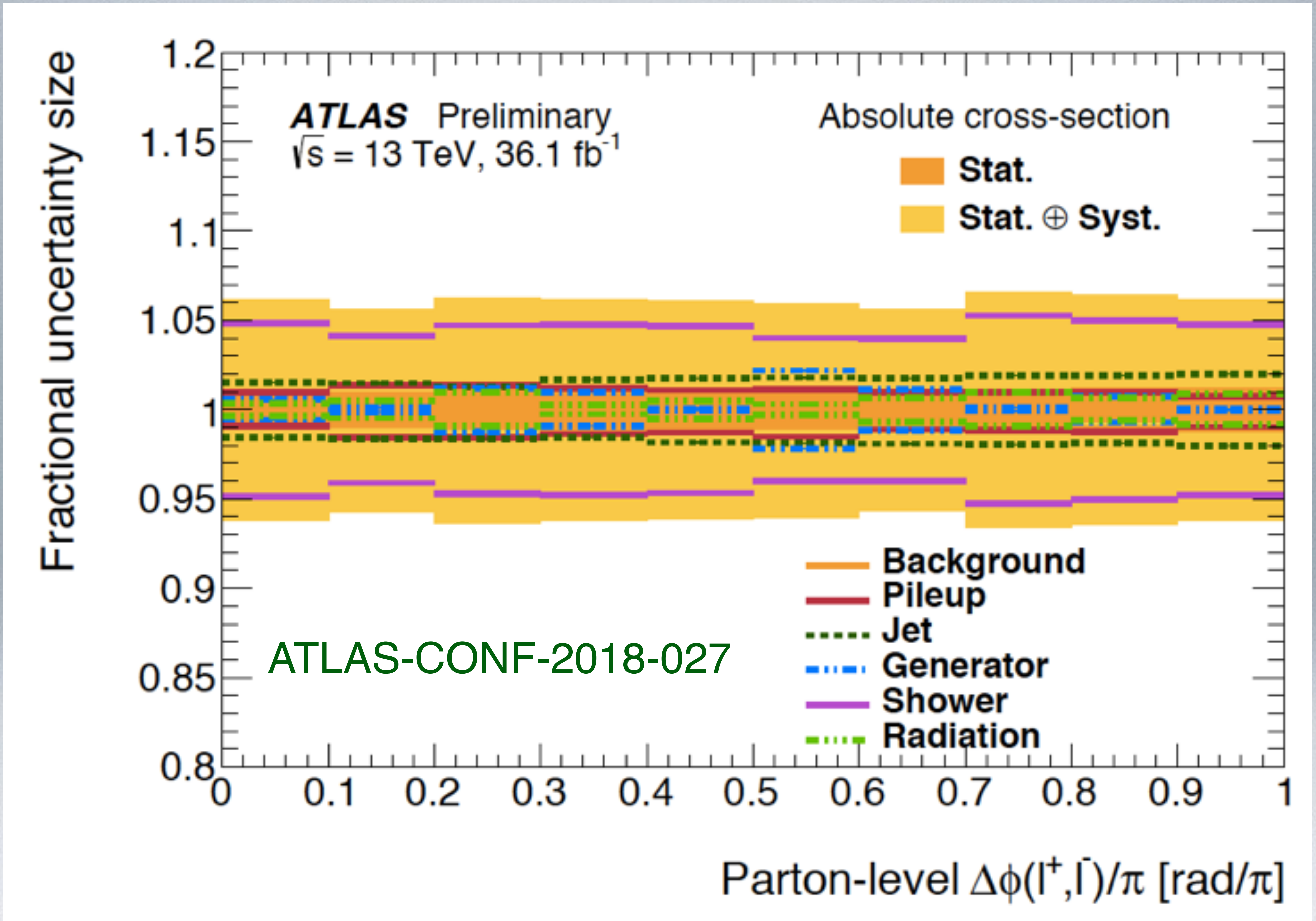
ATLAS-CONF-2018-027

spin correlations in top pair production with leptonic decays

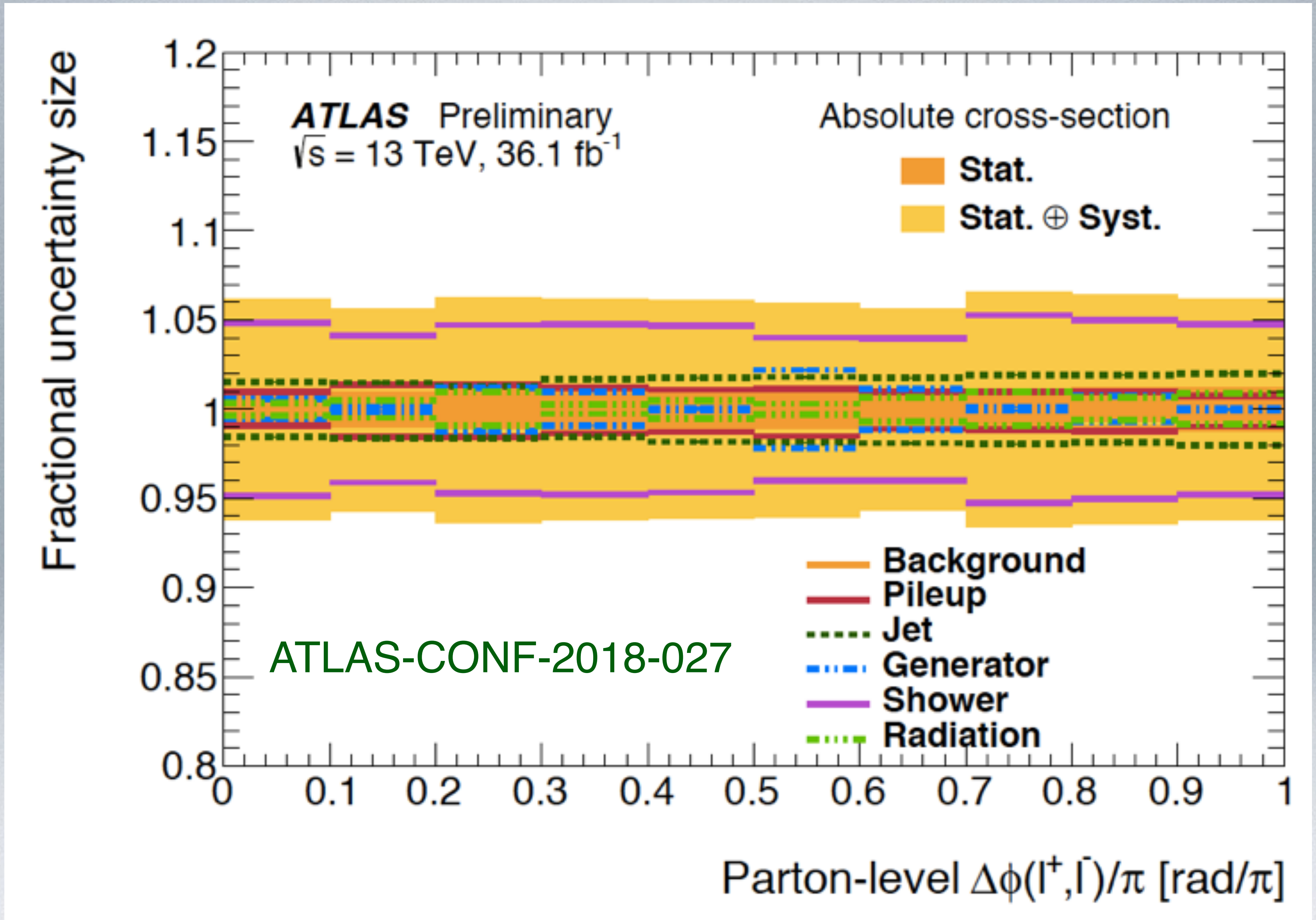
3.2 sigma deviation from SM prediction



some “anomalies”



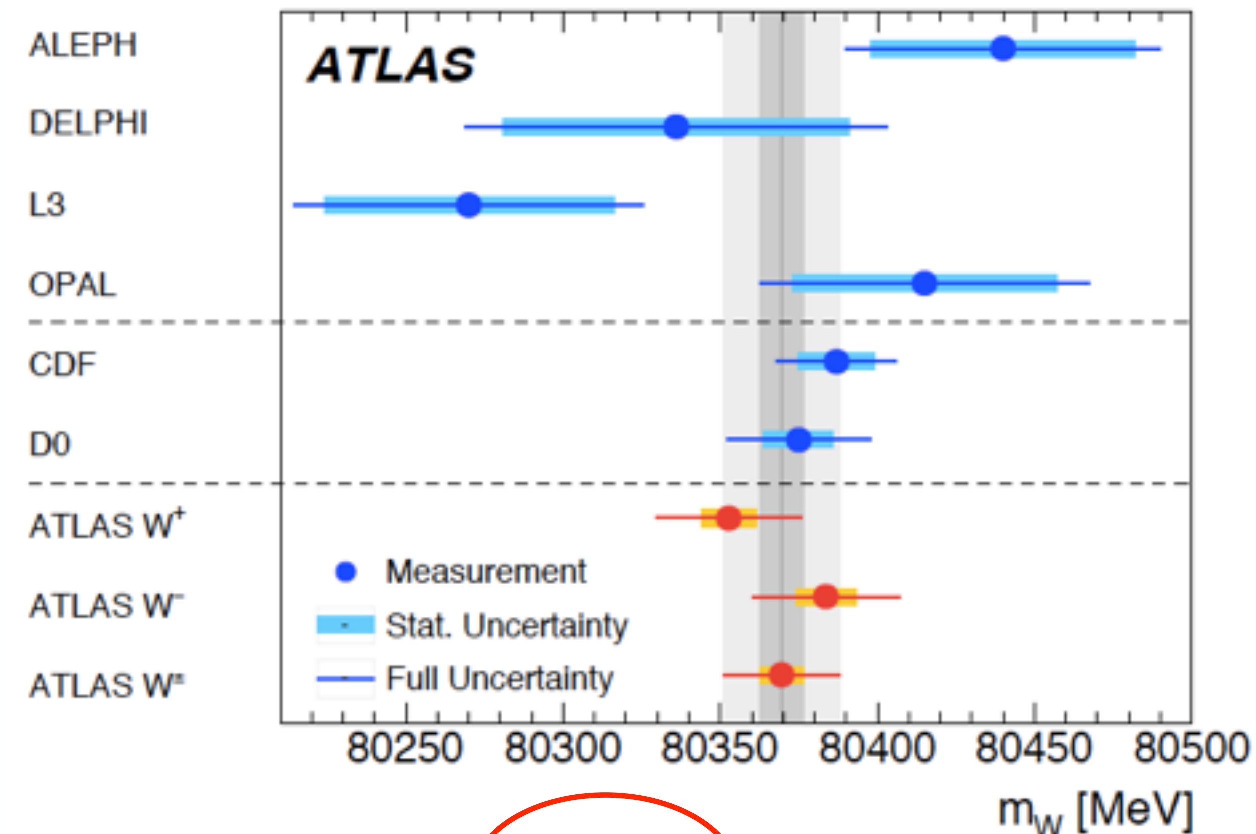
some “anomalies”



need better control of
theory predictions

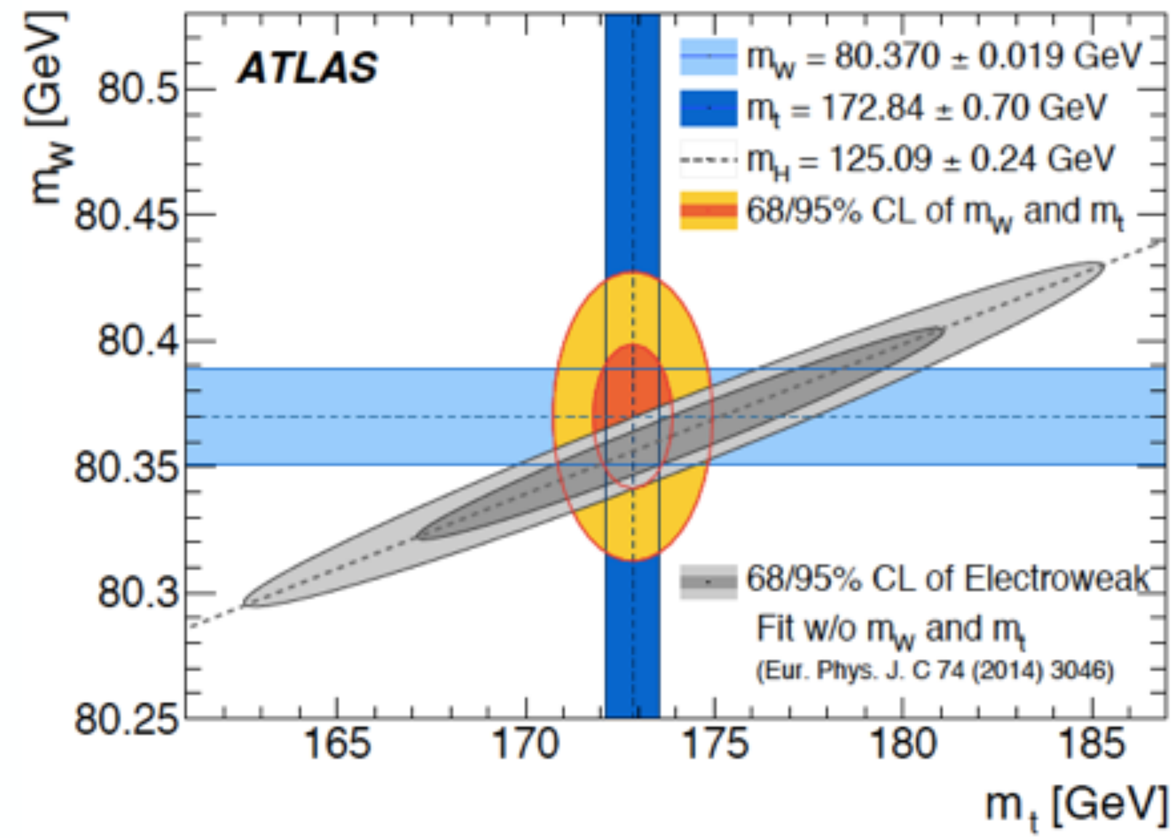
Precision measurements: W boson mass

MW experimental values



$m_W = 80370 \pm 19\ \mathrm{MeV}$ ATLAS arXiv:1701.07240

Global EW fit compared to ATLAS results



$m_W = 80356 \pm 8\ \mathrm{MeV}$

A. Vicini, LHCP 2017

extraction of M_W from **shape** of p_T^l distribution

distortion of shape at permil level leads to $\mathcal{O}(10\,\mathrm{MeV})$ shift in mass

$\Rightarrow$ control of radiative corrections distorting the shape extremely important!

The precision frontier

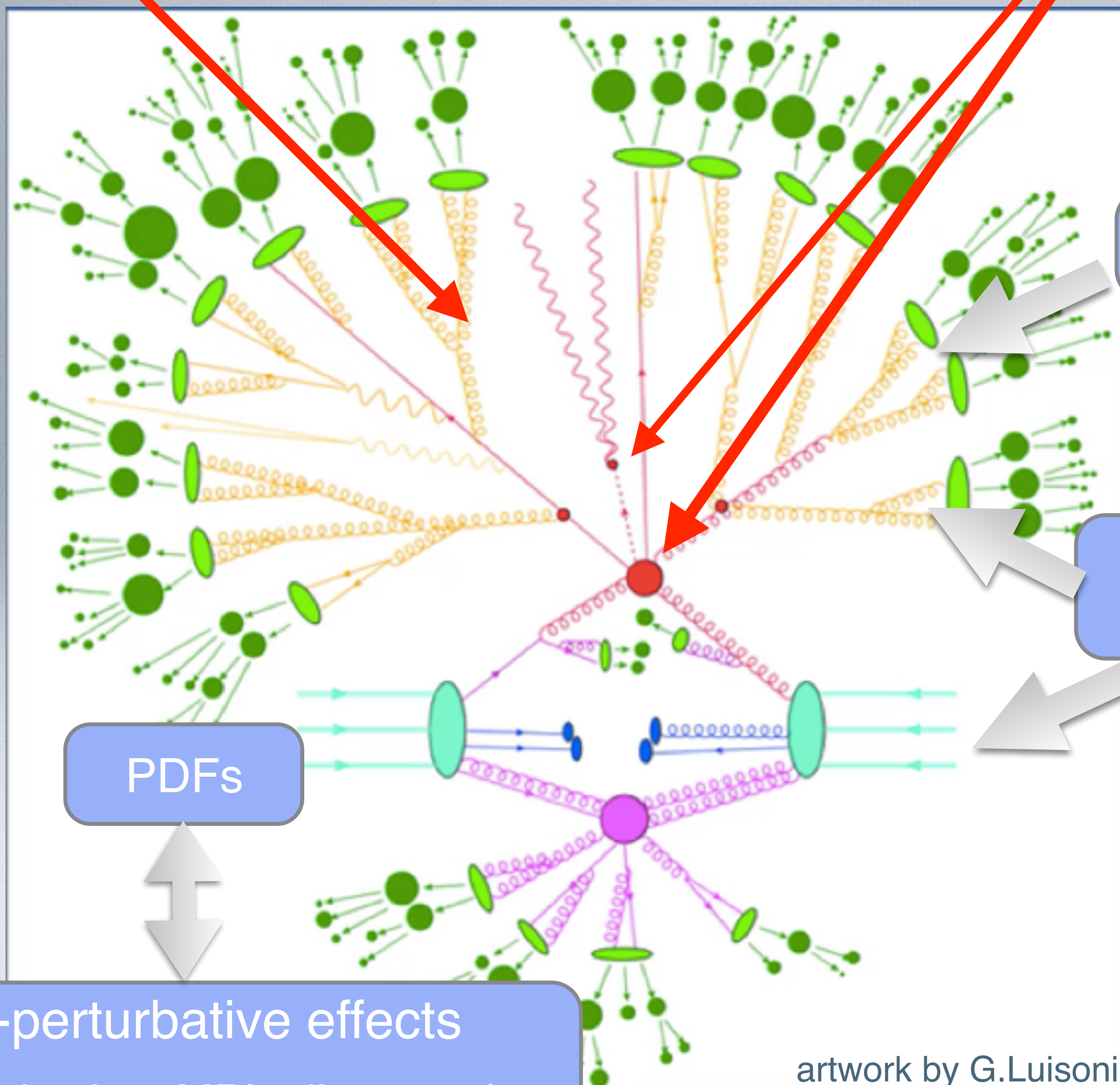
parton shower ⟷ resummation ⟷ fixed order calculations NLO (QCD+EW), NNLO, …

quark mass effects

parametric uncertainties (e.g. couplings, masses)

PDFs

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



artwork by G.Luisoni

Theorist's basic toolbox

- local gauge invariance $SU(2) \times U(1) \times SU(3)_c$
- renormalizability
- perturbative expansions, e.g.

$$\hat{\sigma} = \alpha_s^k(\mu) \, [\hat{\sigma}^{\rm LO} + \alpha_s(\mu)\, \hat{\sigma}^{\rm NLO}(\mu) + \alpha_s^2(\mu)\, \hat{\sigma}^{\rm NNLO}(\mu) + \ldots]$$

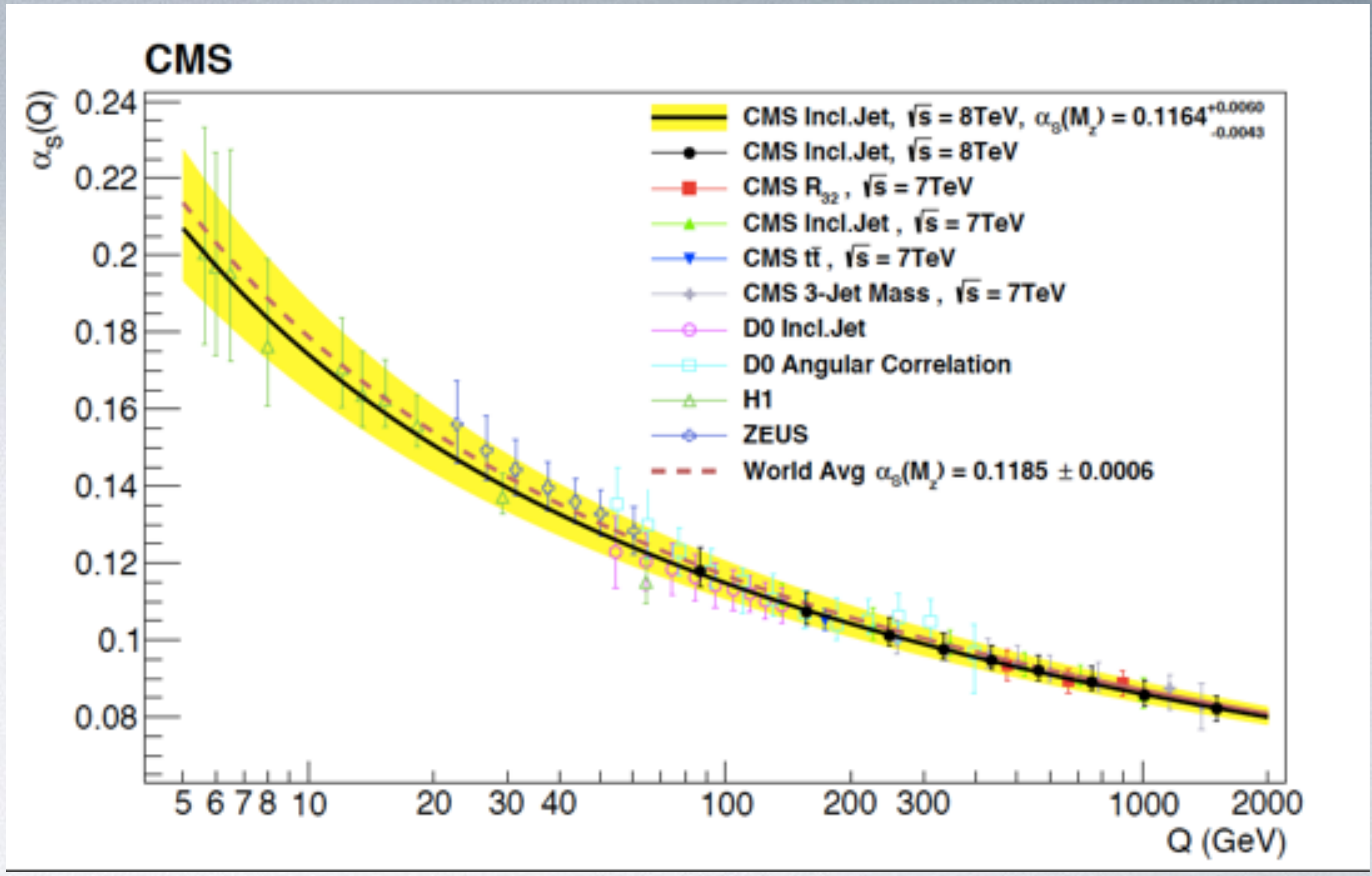
important principles of QCD:

- asymptotic freedom

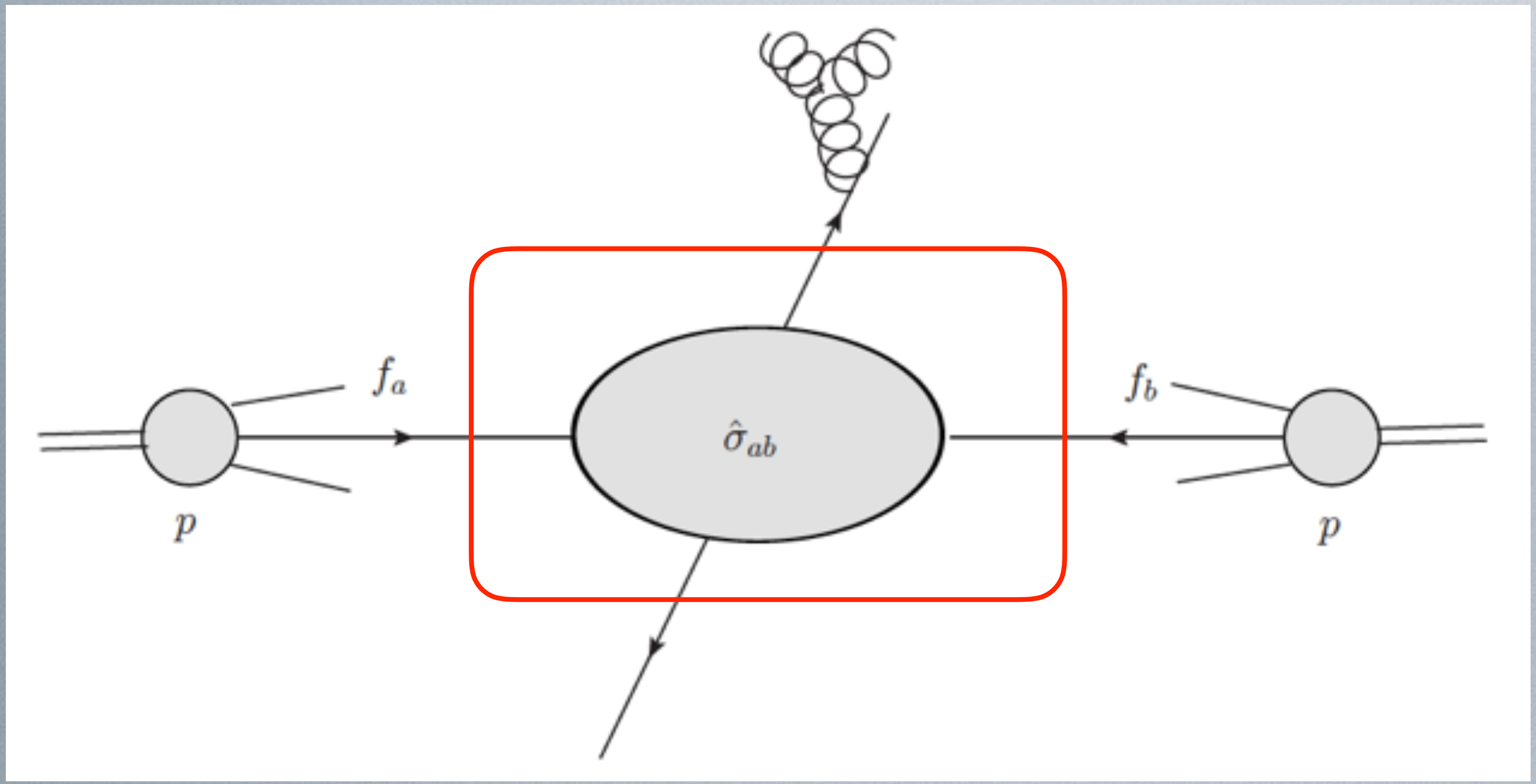
  quarks and gluons almost free particles at large energy scales

- factorisation

  short- and long distance effects can be separated



Factorisation



separate long-distance from short-distance dynamics

parton distribution functions (PDFs)

factorisation scale

$$d\sigma_{pp} = \sum_{a,b} \int_0^1 dx_1\, f_{a/p_1}(x_1, \alpha_s, \mu_f) \int_0^1 dx_2\, f_{b/p_2}(x_2, \alpha_s, \mu_f)$$
$$\times\, d\hat{\sigma}_{ab}(x_1, x_2, \alpha_s(\mu_r), \mu_r, \mu_f) \;+\; \mathcal{O}\left(\frac{\Lambda}{Q}\right)^b$$

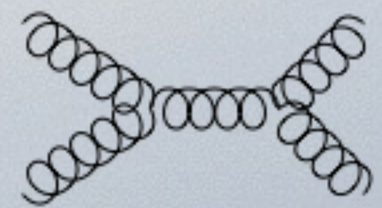
partonic cross section
(calculable in perturbation theory)

power corrections

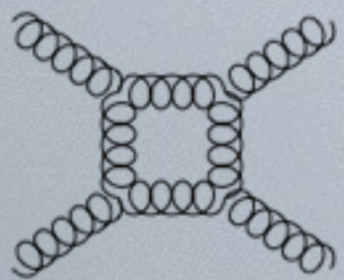
Perturbative expansion (in QCD)

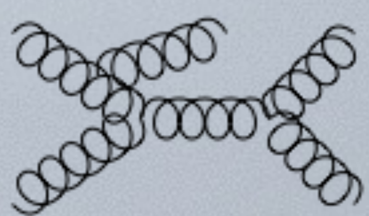
example 2 to 2 scattering

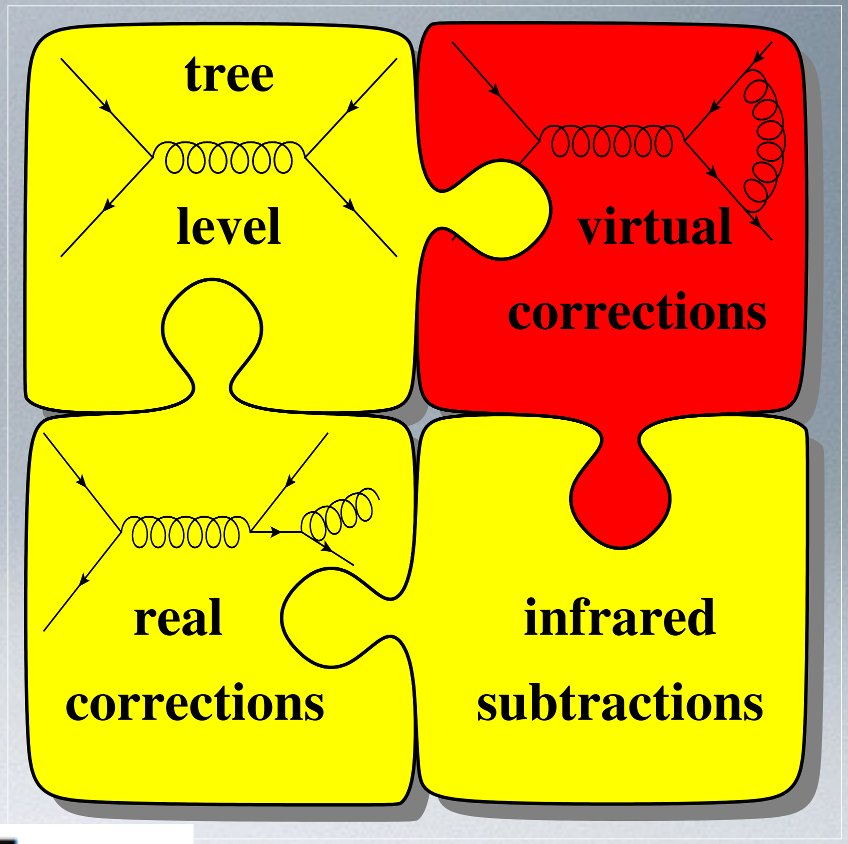
LO: usually tree level diagrams



NLO: one loop (virtual) + extra real radiation + subtraction terms







individual contributions are divergent

- requires the isolation of the singularities
  dimensional regularisation: $D = 4 - 2\epsilon$
- need a good subtraction method for

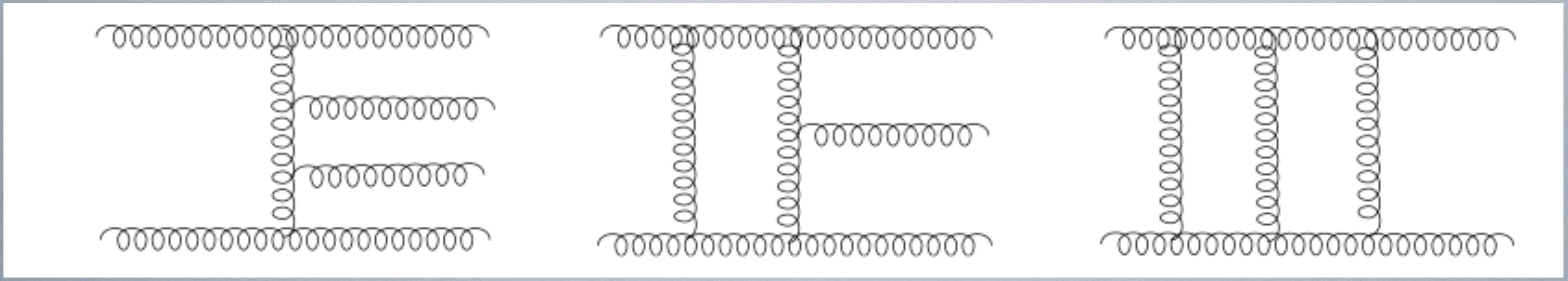
singularities of individual contributions

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

cancel poles analytically

QCD corrections: building blocks

NNLO:



double real

1-loop virtual

$\otimes$ single real

2-loop virtual

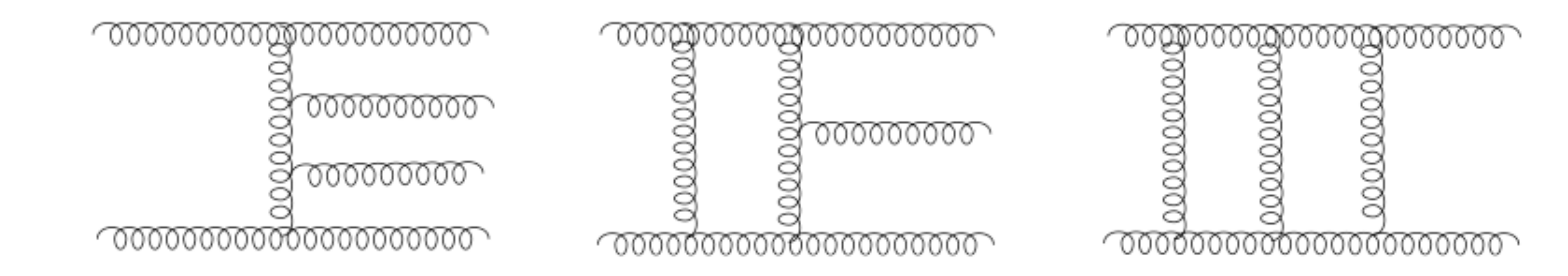
↓ implicit IR poles (PS integration)

↓ explicit and implicit poles

↓ explicit poles $1/\epsilon^{2L}$

QCD corrections: building blocks

NNLO:



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

↑

harder with more massless particles
(intricate IR singularity structure)

two-loop integrals

↑

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

Status

- NLO automation:

  phase after

  "industrial revolution"

  - various automated tools
  - NLO QCD matched to parton shower is state of the art

- NNLO: (partial) automation starts to become reality

- NNNLO: some results availabe!

What caused the NLO revolution?

- automation of subtraction methods for IR divergent real radiation

  Frixione, Kunszt, Signer '95; Catani, Seymour '96 → MadDipole, AutoDipole, FxFx, …

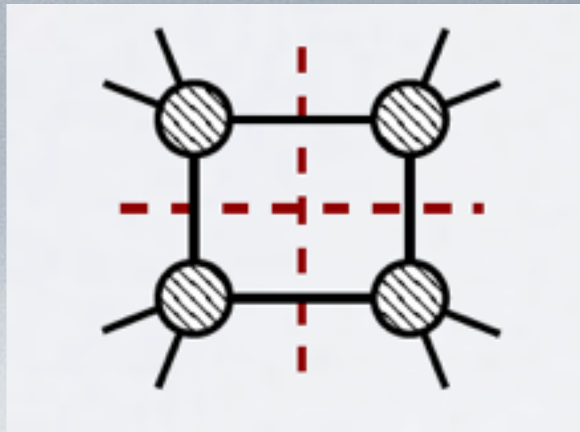
- unitarity-inspired methods for virtual corrections

  gauge dependent off-shell states introduce "spurious" terms

  → try to use on-shell quantities as building blocks

- construct N-point one-loop amplitudes from tree amplitudes

  Bern, Dixon, Dunbar, Kosower '94



- use complex momenta in generalised cuts

  Britto, Cachazo, Feng '04

- numerical reduction at integrand level

  Ossola, Papadopoulos, Pittau '06

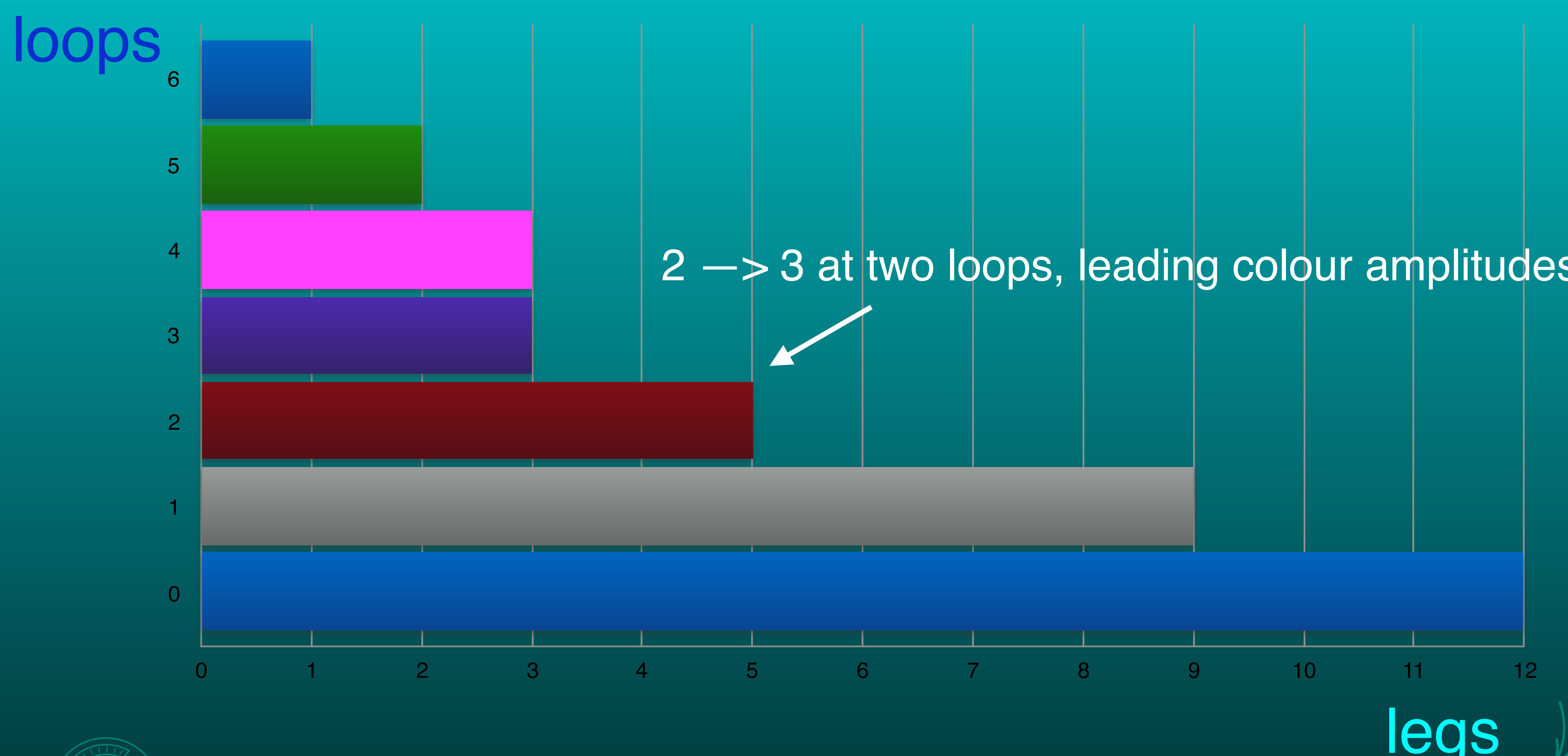
- D-dimensional unitarity

  Anastasiou, Britto, Feng, Kunszt, Mastrolia '06;
  Forde '07; Giele, Kunszt, Melnikov '08

measure of complexity

#loops + #legs + **#scales (masses, off-shellness)**

complexity does not scale linearly!



(refers to physical results, not individual integrals)

Calculations beyond one loop

typical procedure and corresponding tools

1. automated amplitude generation

public **tools** e.g. QGRAF [P.Nogueira], FeynArts [T.Hahn et al.]

saturation of Lorentz/spin indices: helicity amplitudes or projectors to form factors

2. reduction of the loop amplitudes to coefficients $\otimes$ master integrals

reduction highly non-trivial; master integrals not known before reduction

multi-purpose **tools** e.g. Reduze [C.Studerus, A.v.Manteuffel], FIRE [A.V.Smirnov], LiteRed [R.N.Lee], KIRA [Maierhöfer, Usovitsch, Uwer '17]

mostly based on integration by parts (IBP) relations

$\Rightarrow$ solve large linear systems

$$\int d^D k \frac{\partial}{\partial k^\mu} v^\mu f(k, p_i) = 0$$

two-loop **integrand** reduction:

very interesting new developments, but not ready for automation yet (?)

Mastrolia, Ossola '11; Badger, Frellesvig, Zhang '12; Kosower, Larsen '12,
Mastrolia, Mirabella, Ossola, Peraro '12; Feng, Huang '12;
Papadopoulos et al.'12; Ita '15; Larsen, Zhang '16; Mastrolia, Peraro, Primo '16,
Peraro '16; Larsen, Rietkerk '17, Badger et al '17,'18, Abreu et al '17, Boels et al '18,
Chawdry, Lim, Mitov '18, …

Development of new methods is very important!

typical procedure for multi-loop processes

3. calculation of the master integrals

- analytically? may not always be possible

  most efficient method: **differential equations**

  Kotikov '91; Remiddi '97, Gehrmann, Remiddi '00 **, ...**

  J.Henn '13: canonical form, caused "2-loop revolution" $d\vec{f}(x,\epsilon) = \epsilon\, dA(x)\, \vec{f}(x,\epsilon)$

- numerically? may not always be accurate/fast enough

  also lots of recent progress

4. subtraction of IR divergent real radiation

   interesting recent NNLO developments (see later)

5. stable and fast Monte Carlo program

   (or if not fast: how to make results available in a flexible format)

typical procedure for multi-loop processes

3. calculation of the master integrals

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most efficient method: **differential equations** see talk of Leila Maestri

Kotikov '91; Remiddi '97, Gehrmann, Remiddi '00 , ...

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(or if not fast: how to make results available in a flexible format)

multi-loop integrals

processes not (yet) known precisely enough typically involve

- several mass scales (EW corrections, quark masses, BSM particles)
- more than two loops

analytic results for multi-scale two-loop integrals are sparse

numerical evaluation:

- often considered as "poor man's solution"
  as long as analytic results are not available
- but easier extendible to many mass scales

pro's and con's

	analytic	numerical
pole cancellation	exact	with numerical uncertainty
fast evaluation	☑ (mostly)	depends
control of integrable singularities	☑ control of analytic regions	difficult
extension to more scales	difficult	less difficult
automation	difficult	promising

pro’s and con’s

	analytic	numerical
pole cancellation	exact	with numerical uncertainty
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see talk of Stephan Jahn

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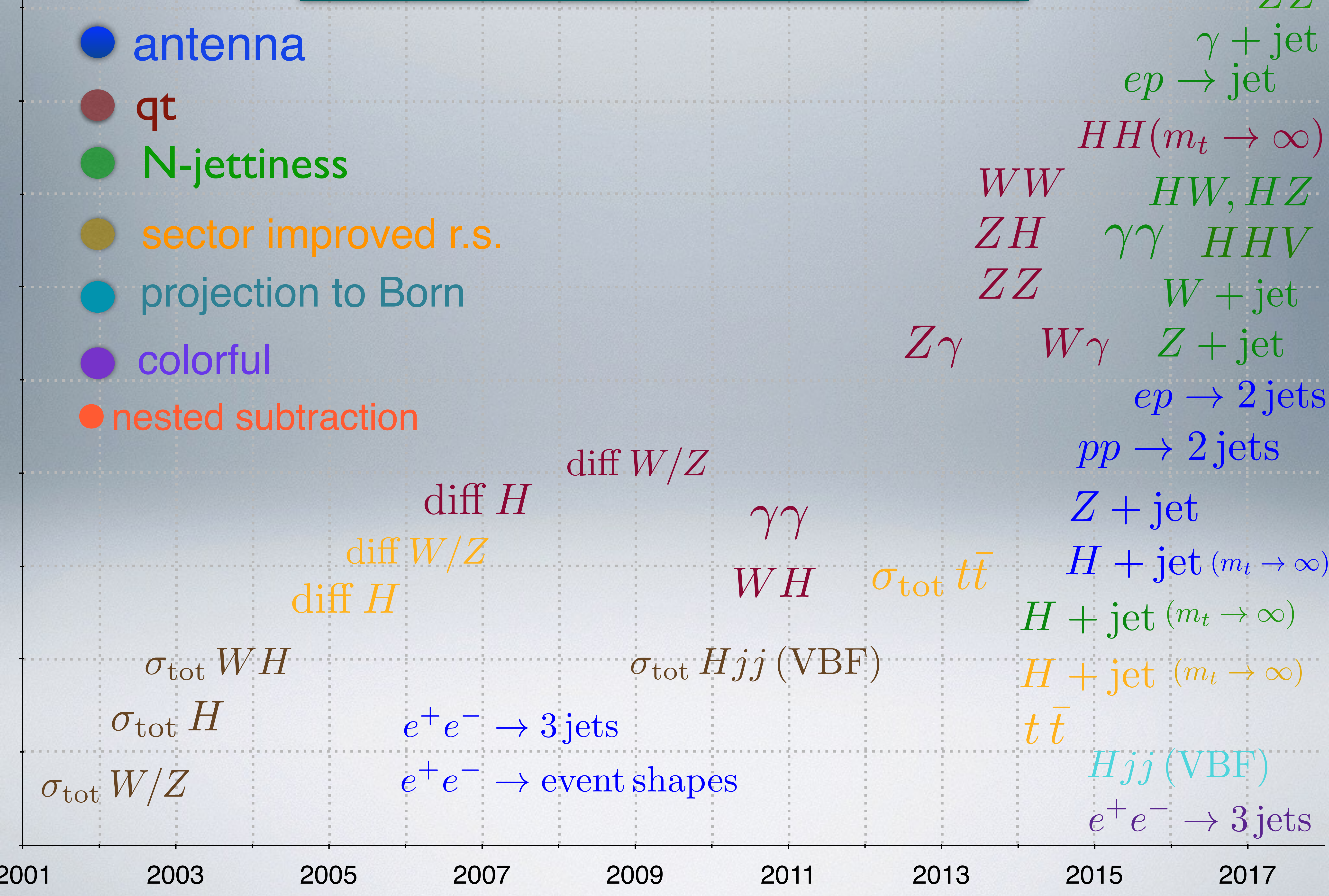
NNLO real radiation subtraction methods

- **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] [Boughezal et al. ’11]
- **nested subtraction** [Caola, Melnikov, Röntsch ’17]

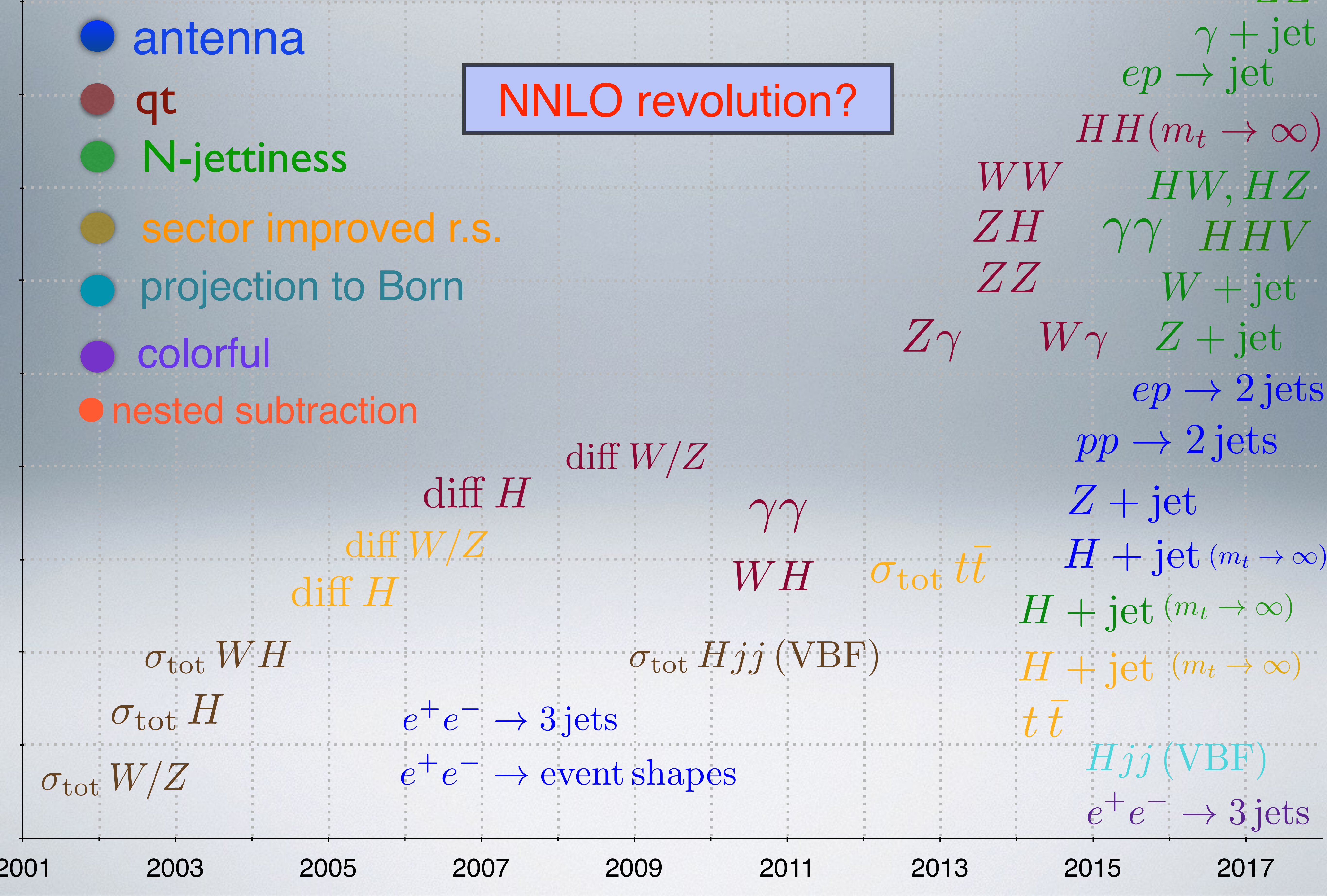
numerically integrated subtraction terms

- **projection to Born / structure function approach** only special kinematics
  [Gao, Li, Zhu ’12] [Brucherseifer, Caola, Melnikov ’14] [Cacciari, Dreyer, Karlberg, Salam, Zanderighi ’15]
- **colorful** only final state colour so far [Del Duca, Somogyi, Trocsanyi et al ’05, ‘16]
- **local analytic sector subtraction**
  [Magnea, Maina, Pellicioli, Signorile-Signorile, Torricelli, Uccirati ’18]
- **geometric subtraction** (slicing so far)
  [Herzog ’18]

NNLO results

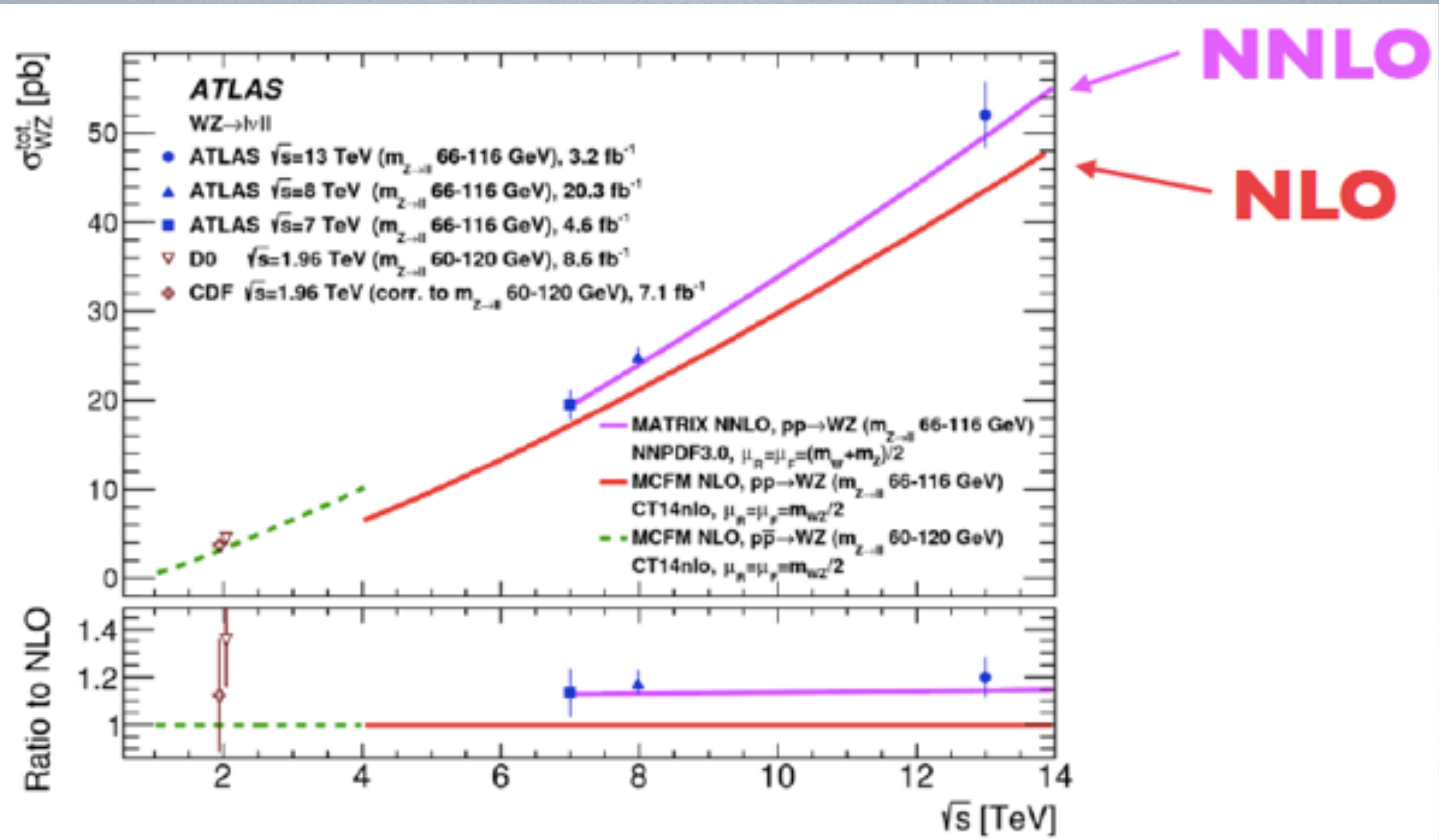


NNLO results



Precision phenomenology: some recent results

- N^3LO
- mixed QCD-EW corrections
- NNLO
- NLO for loop-induced processes



M.Wiesemann et al.

Higgs production in gluon fusion

status before 2018: N3LO in $m_t \to \infty$ limit

expansion around soft limit Anastasiou et al. 1602.00695

E_{CM}	σ	δ(theory)	δ(PDF)	$\delta(\alpha_s)$
13 TeV	48.58 pb	$^{+2.22\text{pb}}_{-3.27\text{pb}}\left(^{+4.56\%}_{-6.72\%}\right)$	$\pm$ 0.90 pb ($\pm$ 1.86%)	$^{+1.27\text{pb}}_{-1.25\text{pb}}\left(^{+2.61\%}_{-2.58\%}\right)$

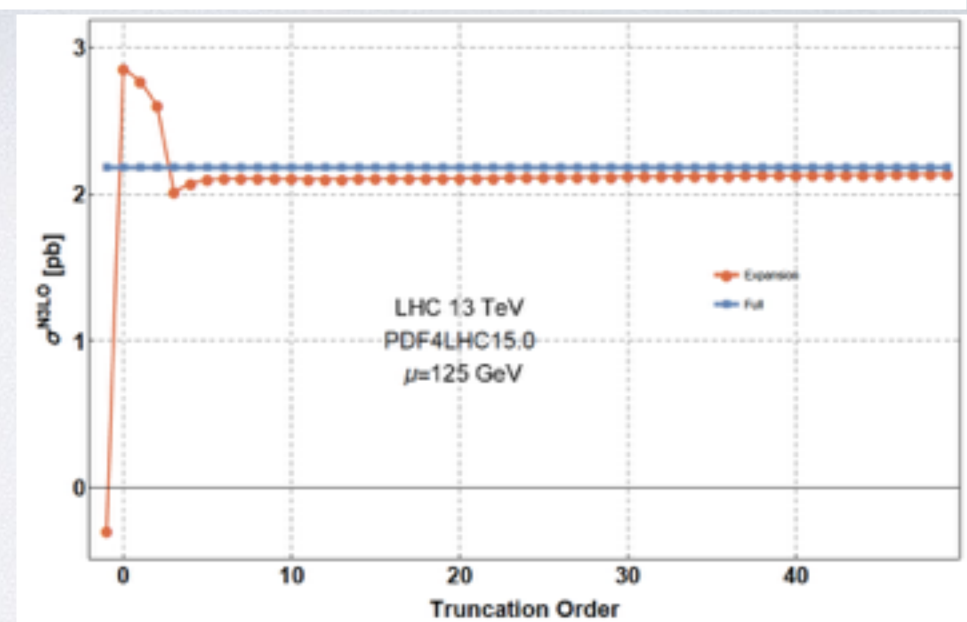
δ(theory)

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	$\pm$0.18 pb	$\pm$0.56 pb	$\pm$0.49 pb	$\pm$0.40 pb	$\pm$0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm$0.37%	$\pm$1.16%	$\pm$1%	$\pm$0.83%	$\pm$1%

gone

no expansion around soft limit anymore

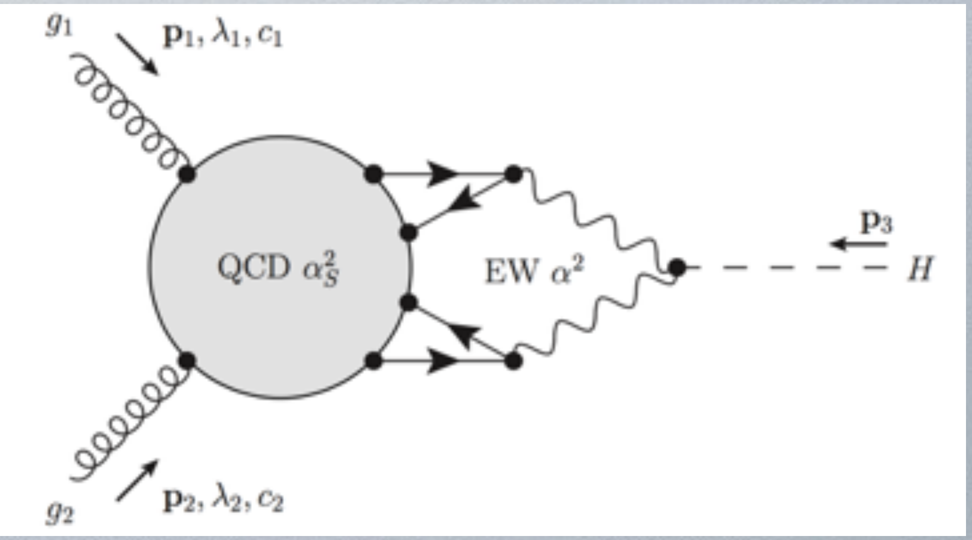
B.Mistlberger 1802.00833

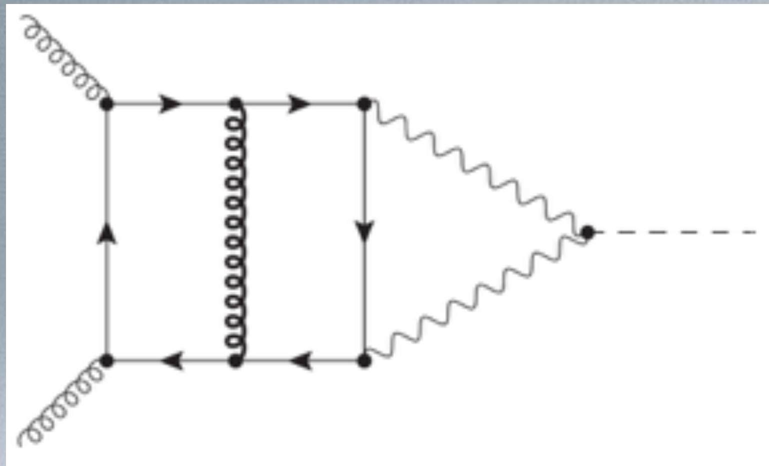


Higgs production in gluon fusion

calculation of NLO QCD corrections to mixed QCD-EW corrections

Bonetti, Melnikov, Tancredi
1711.11113, 1801.10403





multi-scale 3-loop diagrams

corresponding real radiation contribution
very challenging ⟶ soft approximation

$$\delta\sigma^{\rm NLO}_{\rm QCD-EW}/\sigma^{\rm NLO}_{\rm QCD,full} \sim (4.7 - 5.5) \times 10^{-2}$$

confirming previous estimates

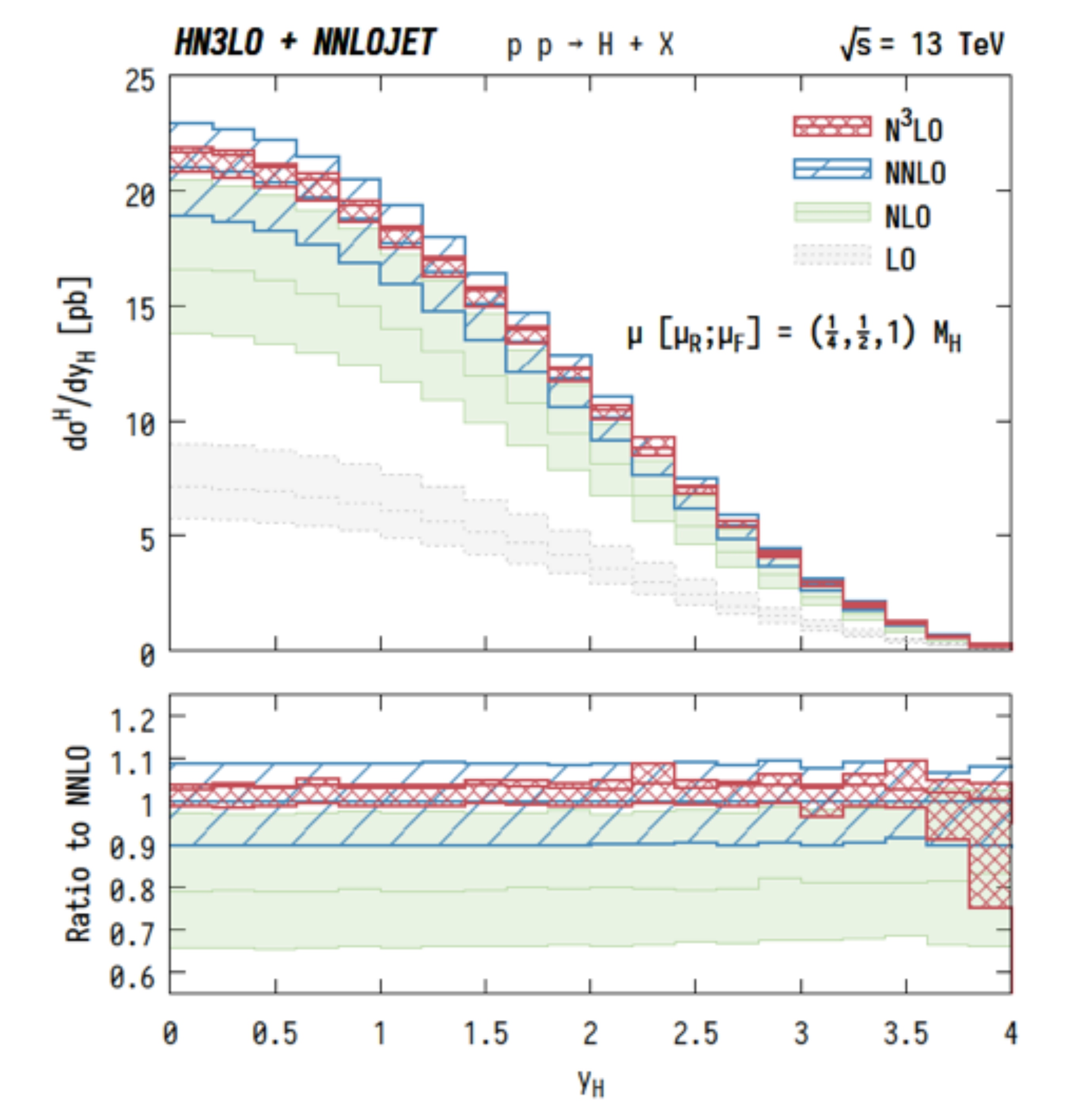
see also Anastasiou et al. 1811.11211

Higgs production in gluon fusion

differential N3LO Higgs boson production

Cieri, Chen, Gehrmann, Glover, Huss 1807.11501

(see also Dulat, Mistlberger, Pelloni '17 for partial results)



qT subtraction extended to N3LO

collinear subtraction term extracted numerically

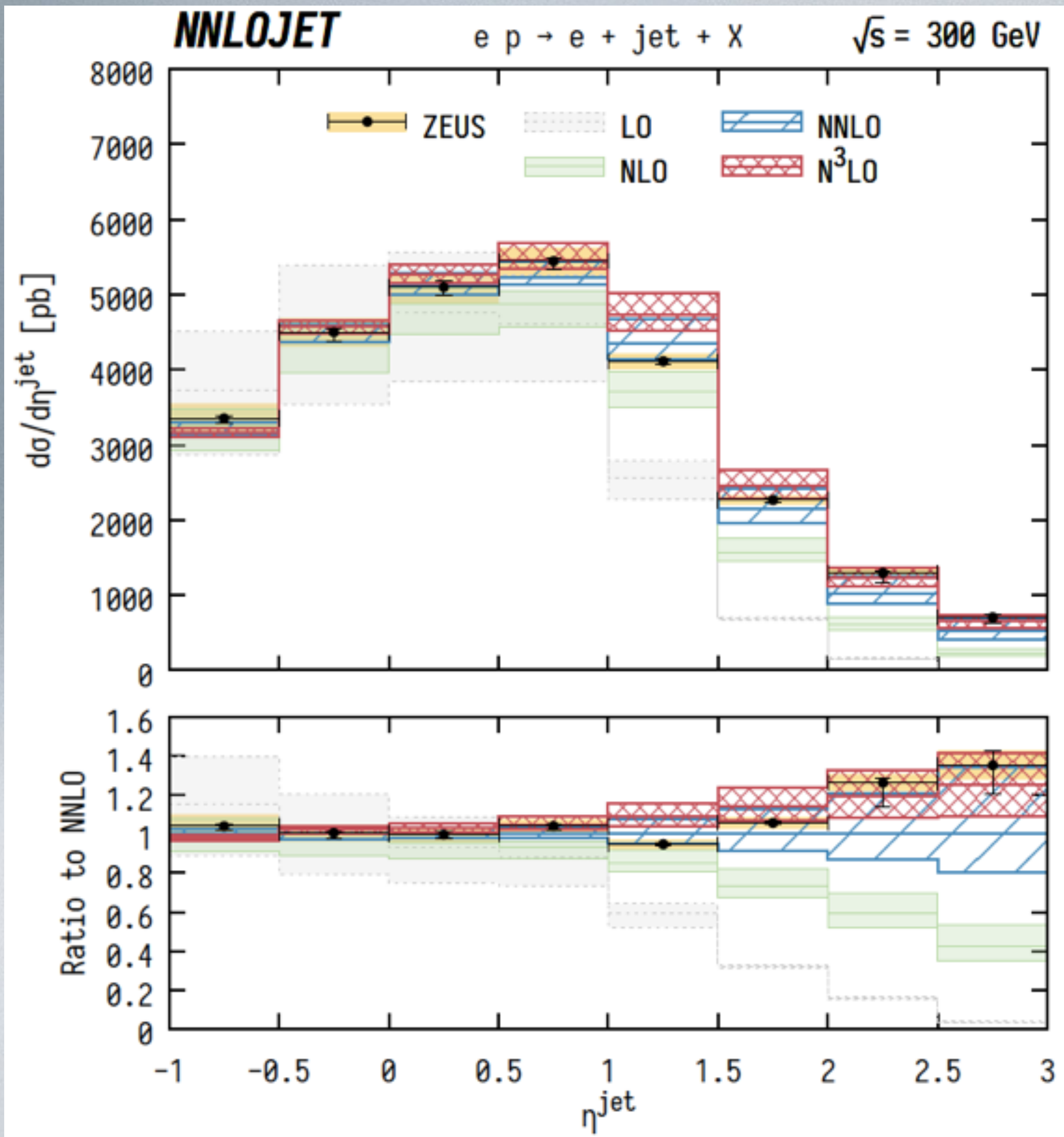
used some results from ihixs2

Dulat, Lazopoulos, Mistlberger 1802.00827

substantial reduction of scale uncertainties

Differential N3LO jet production in DIS

Currie, Gehrmann, Glover, Huss, Niehues, Vogt 1803.09973



subtraction scheme: projection to Born

Brucherseifer, Caola, Melnikov '14,

Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15

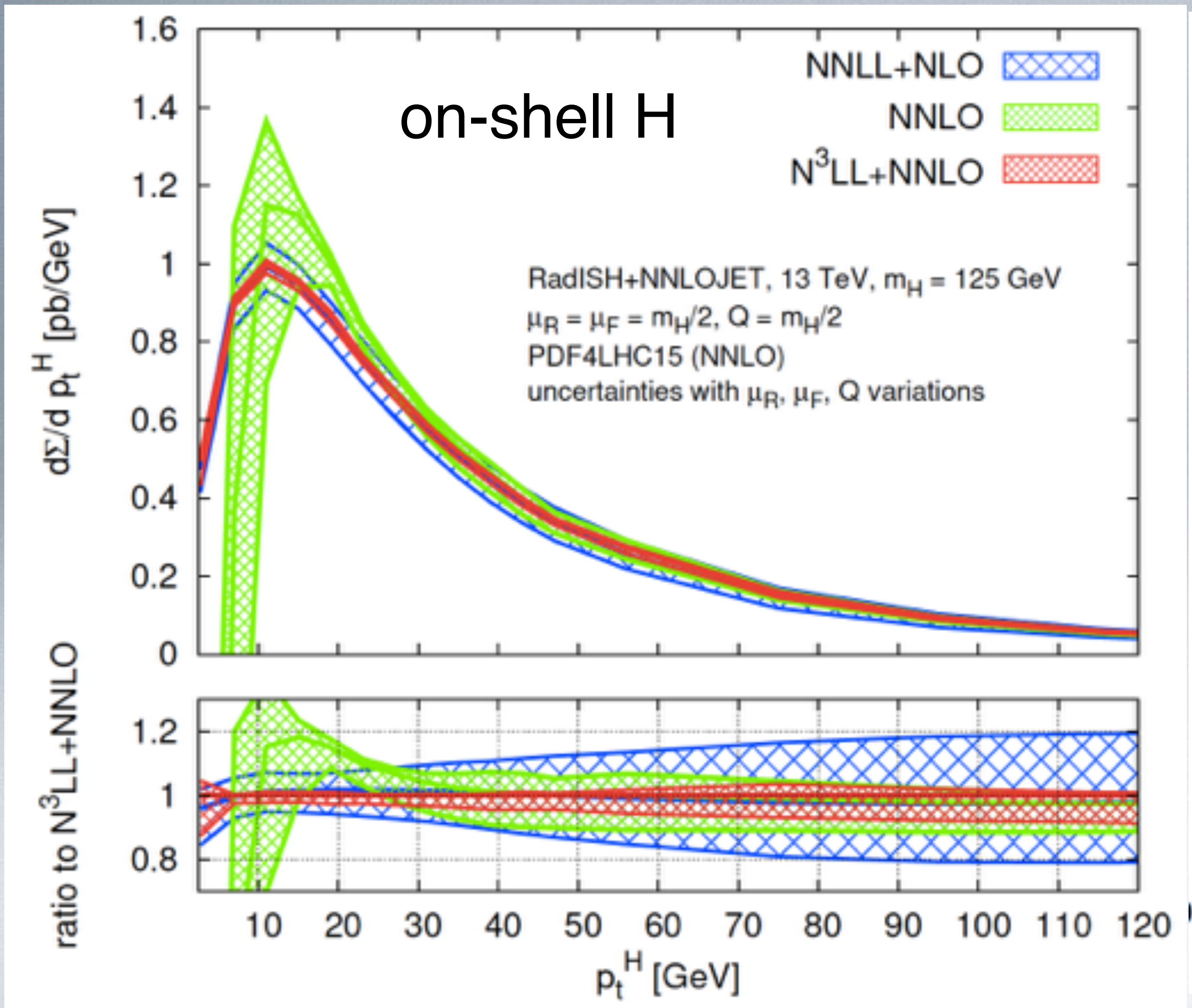
showpiece of perturbation theory

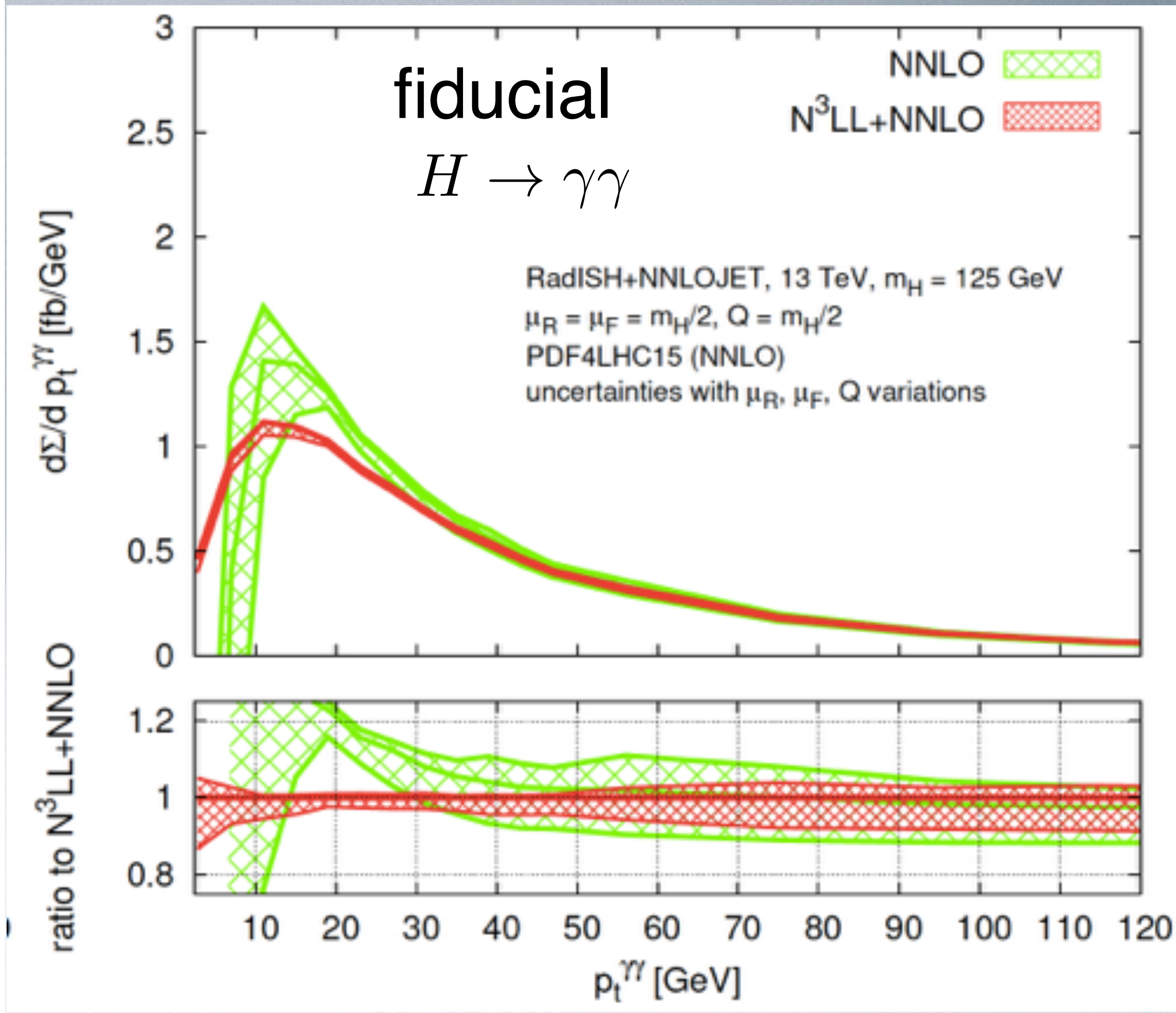
agreement with data improved

Higgs pT spectrum

Higgs pT and fiducial distributions at N3LL+NNLO in $m_t \to \infty$ limit

Bizon, Chen, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Torrielli 1805.05916



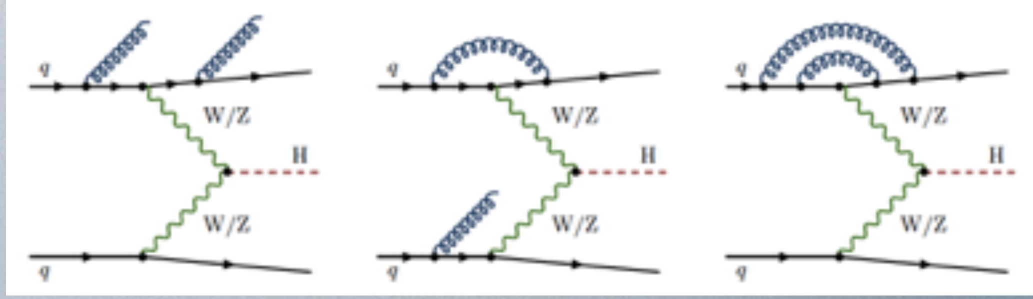


perturbative uncertainties now at a level where other effects (quark masses) become equally important in whole pT range

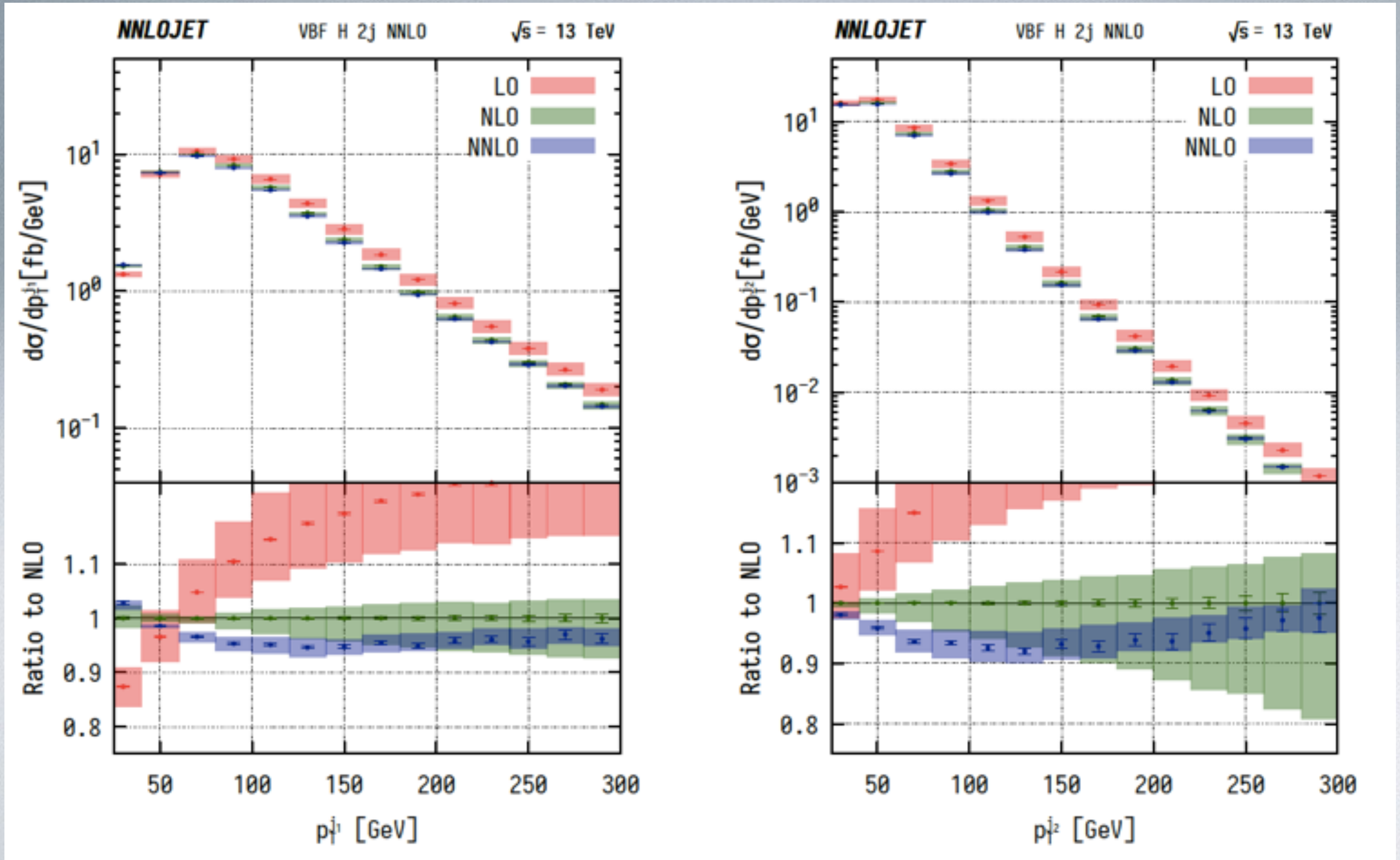
Higgs production in Vector Boson Fusion

- fully differential NLO : VBFNLO **A**rnold-**Z**eppenfeld '08-'18
- N3LO total cross section Dreyer, Karlberg '16
- differential NNLO (in "DIS-approximation")

Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15



Cruz-Martinez, Gehrmann, Glover, Huss '18 → revision of previous calculations



impact on efficiency of VBF cuts

NNLO

- enormous progress in the last few years
- caused mainly by development of IR subtraction schemes and improved techniques for loop integrals
- automation possible to some extent

  → collections of processes in same framework available

  - NNLOJet Durham/Uni Zurich++
  - MCFM v8 Campbell, Ellis, Giele, Neumann, Williams et al.
  - MATRIX Grazzini, Kallweit, Wiesemann et al.

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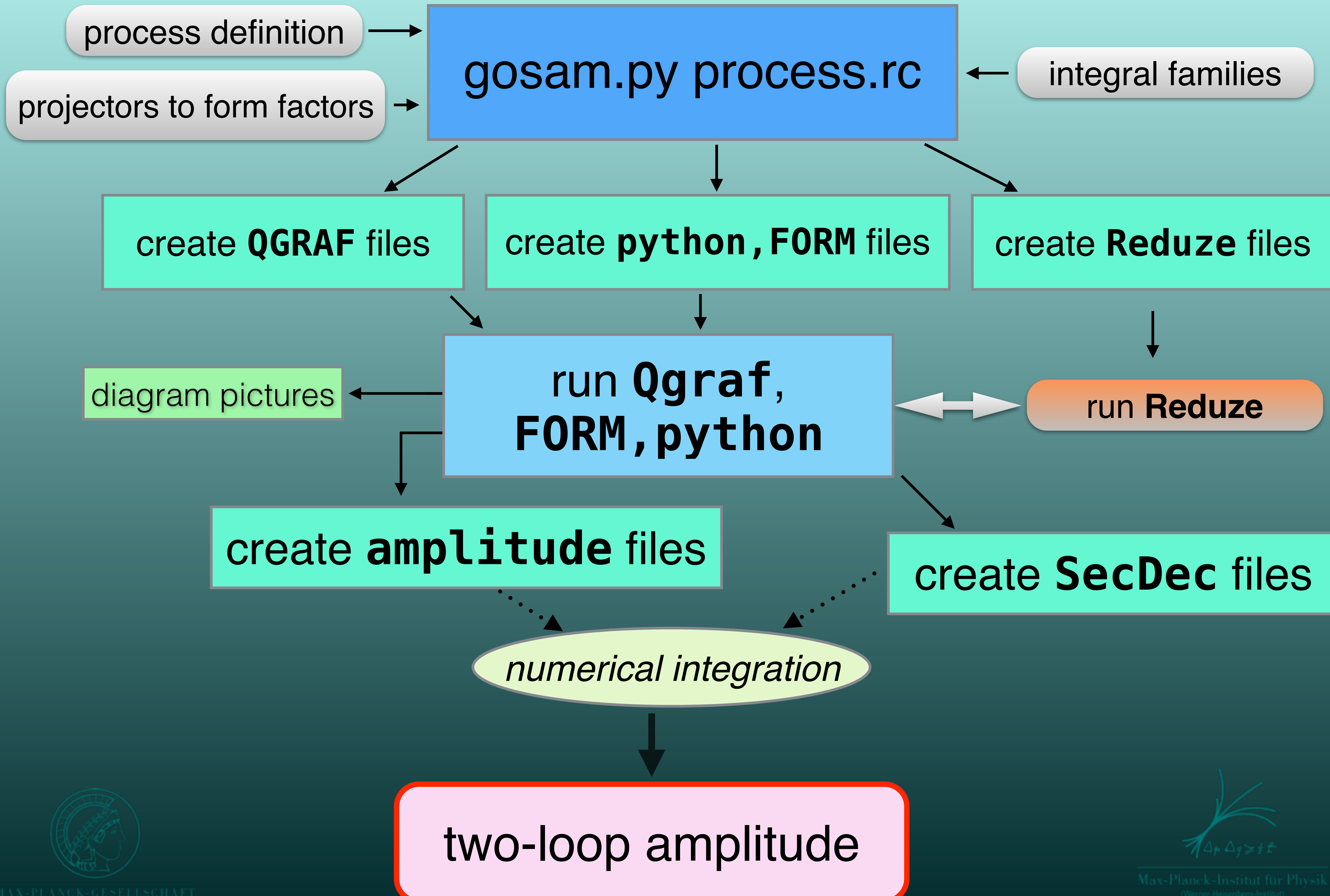
  → collections of processes in same framework available

  - NNLOJet — Durham/Uni Zurich++
  - MCFM v8 — Campbell, Ellis, Giele, Neumann, Williams et al.
  - MATRIX — Grazzini, Kallweit, Wiesemann et al.

our plan: automated generation of 2-loop amplitudes “on the fly”

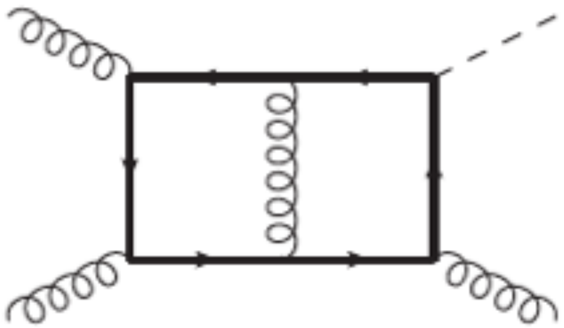
automated 2-loop amplitudes: GoSam @ 2 loops



Loop induced processes at NLO

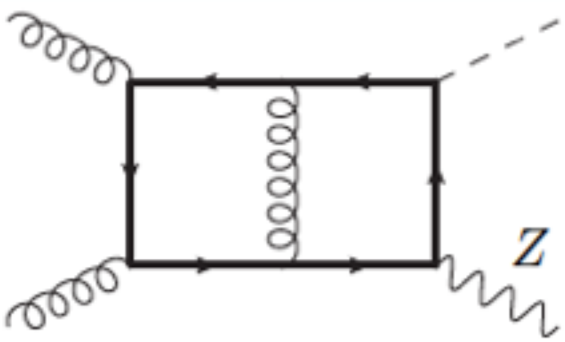
Stephen Jones, QCD@LHC '18

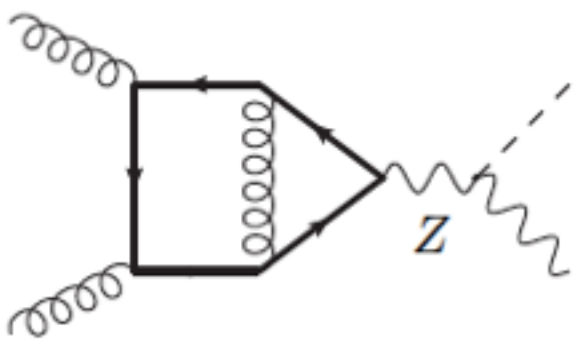
HJ Production



Contributes to Higgs p_T distribution
Important for large $p_T \gtrsim m_T$
At large p_T can "probe inside the loop", distributions can be modified by heavy BSM particles

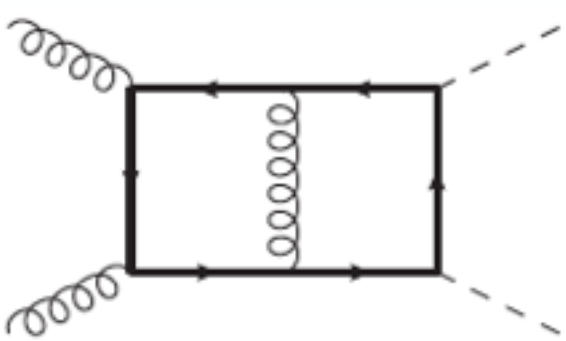
HZ Production

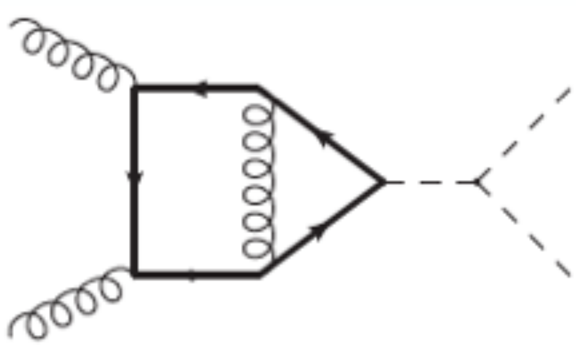




Measurement of ZH coupling
$gg \to ZH$ channel formally NNLO
Contributes ~10% @ 14 TeV

HH Production





Sensitive to Higgs self coupling, probe of EW symmetry breaking

$$\frac{m_H^2}{2} H^2 + \boxed{\frac{m_H^2}{2v} H^3} + \frac{m_H^2}{8v^2} H^4$$

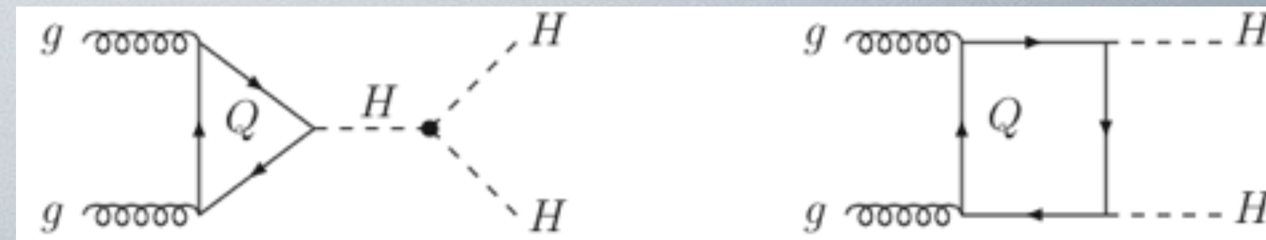
Top-quark mass corrections to e.g. $gg \to \gamma\gamma,\ gg \to ZZ$

hard due to several mass scales

HH in gluon fusion

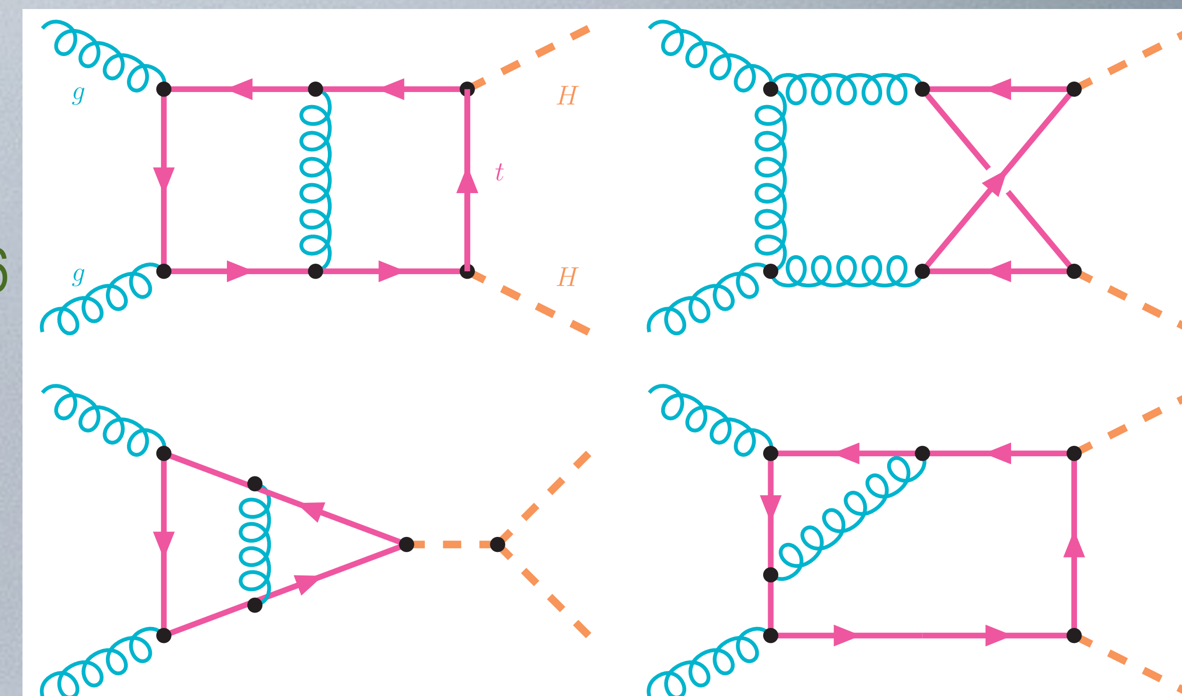
LO with full heavy quark mass dependence

Glover, van der Bij '88, Plehn, Spira, Zerwas '96



NLO with full top quark mass dependence

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



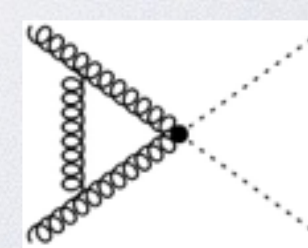
approximations:

$m_t \to \infty$ limit:

"Higgs Effective Field Theory" (HEFT)

"Born-improved NLO HEFT": rescale by $\mathcal{M}^{LO}(m_t)/\mathcal{M}^{LO}_{\mathrm{HEFT}}$

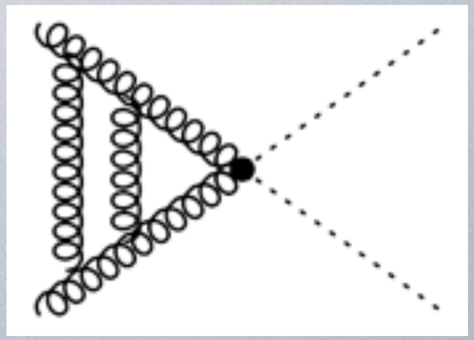
NLO in Born-improved HEFT Dawson, Dittmaier, Spira '98 (**HPAIR**)



rescaled

HH in gluon fusion

NNLO in $m_t \to \infty$ limit:



- **total xs NNLO** De Florian, Mazzitelli '13
- **NNLO including all matching coefficients** Grigo, Melnikov, Steinhauser '14
- **differential NNLO** De Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev '16

Note:

HEFT strictly valid only for $\sqrt{\hat{s}} \ll 2m_t$

HH production threshold: $2m_H < \sqrt{\hat{s}}$

$\Rightarrow$ validity of HEFT limited to $250\,\mathrm{GeV} < \sqrt{\hat{s}} < 340\,\mathrm{GeV}$

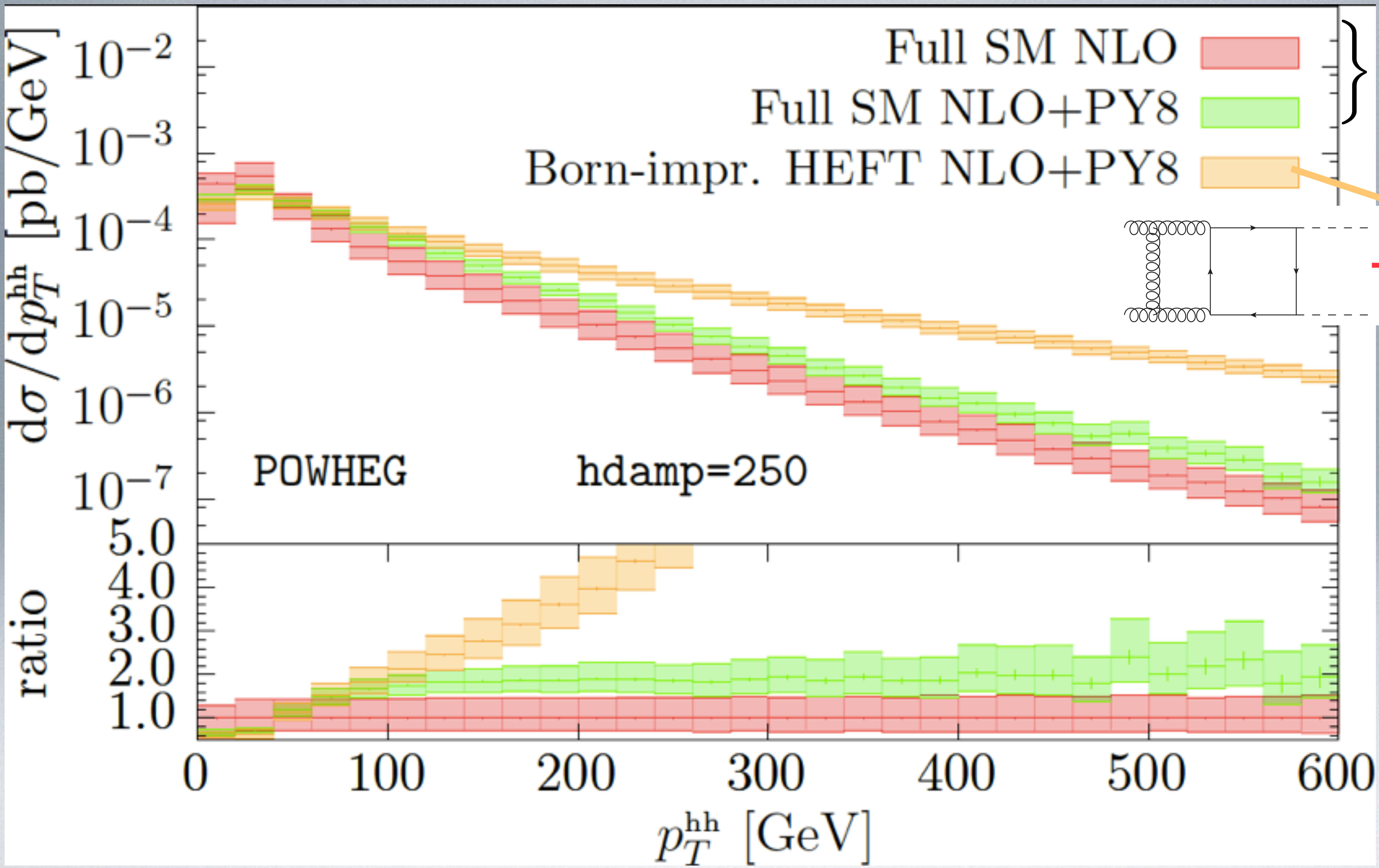
"best" approximation:

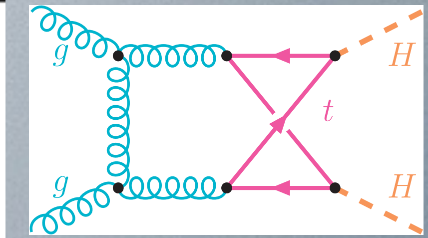
"approximate Full Theory" **(FTapprox)**

- **full mass dependence in NLO real radiation**
  Frederix, Hirschi, Mattelaer, Maltoni, Torrielli, Vryonidou, Zaro '14;
  Maltoni, Vryonidou, Zaro '14
- **NNLO_FTapprox** Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli '18

mass effects versus parton shower effects

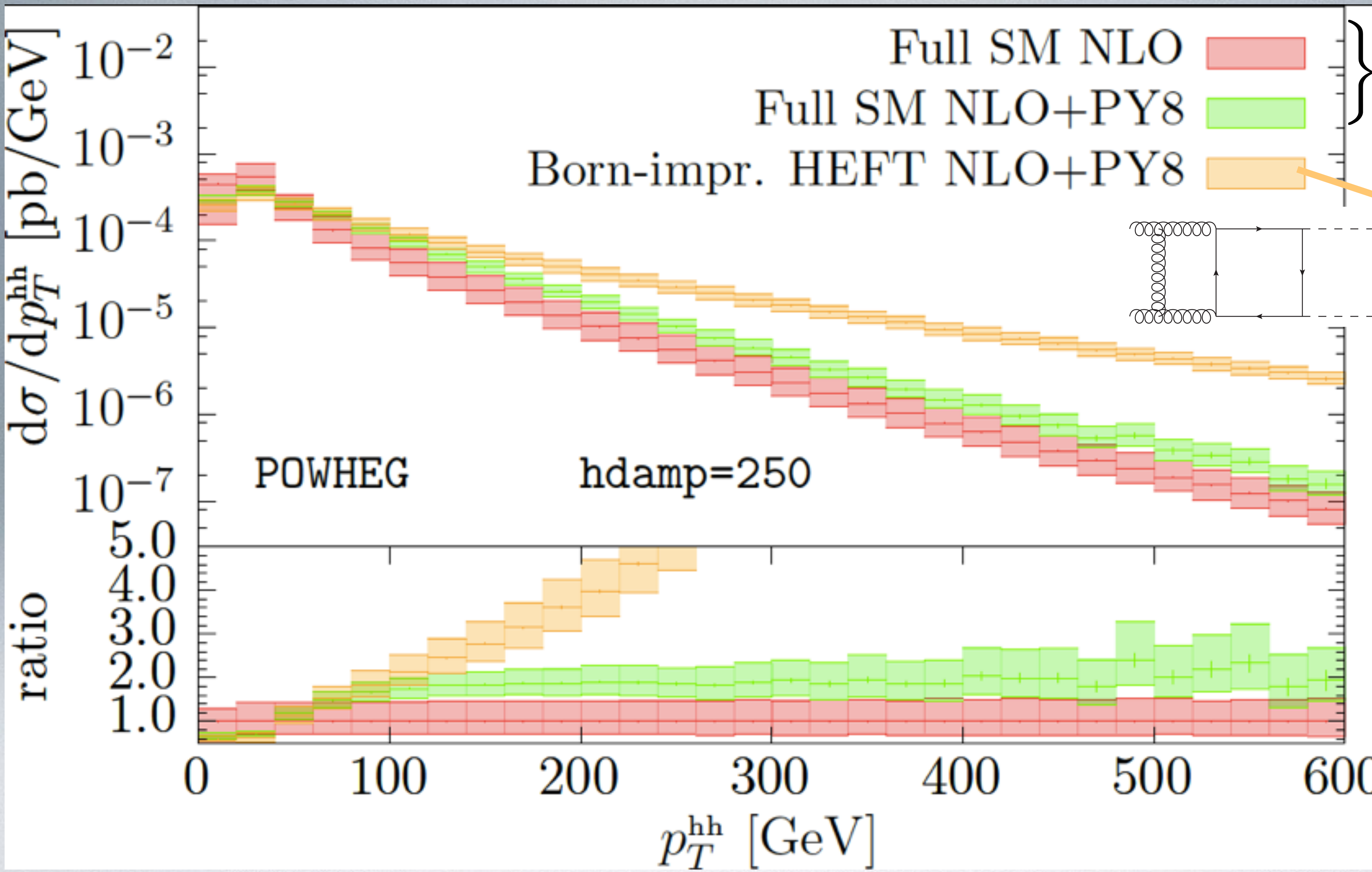
GH, S.Jones, M.Kerner, G.Luisoni, E.Vryonidou 1703.09252

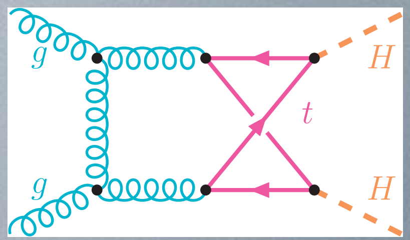


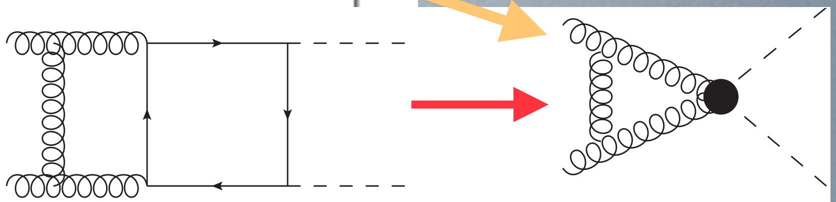


mass effects versus parton shower effects

GH, S.Jones, M.Kerner, G.Luisoni, E.Vryonidou 1703.09252





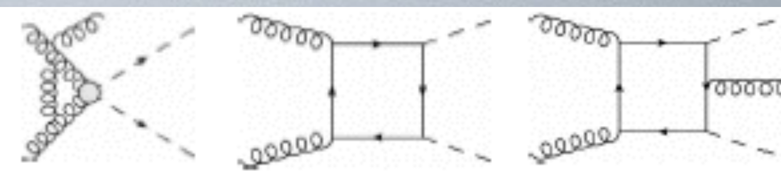


shower effects large but order(s) of magnitude smaller than difference to Born-improved HEFT

HH production: combination of full NLO with NNLO

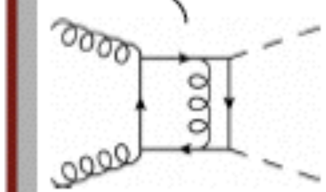
Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli; 1803.02463

Technical ingredients

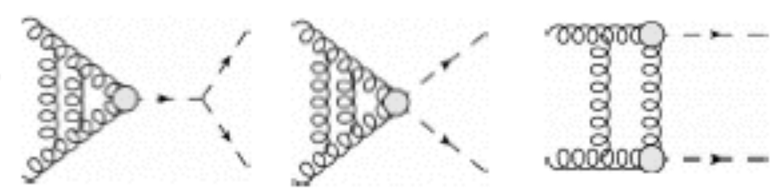


Tree-level and one-loop amplitudes (HEFT and full-M_t) → OpenLoops
[Cascioli, Lindert, Maierhofer, Pozzorini]

Full NLO (two-loop) virtual corrections → two dimensional grid + interpolation
[Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke, '16]



Analytical results for NNLO two-loop corrections in the HEFT
[de Florian, JM, '13]

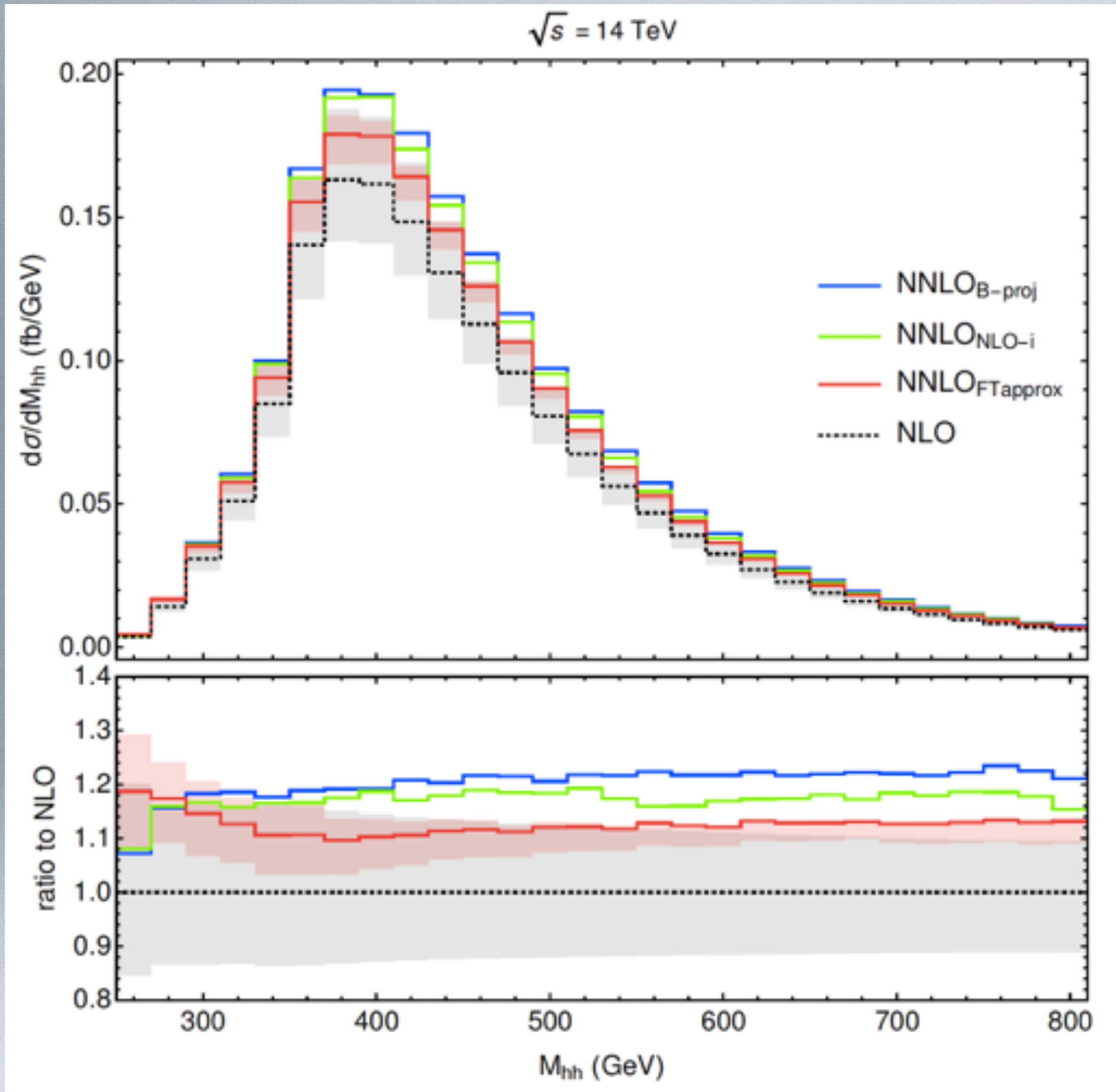


NNLO subtraction formalism: q_T-subtraction
[Catani, Grazzini, '07]

Implementation based on public code MATRIX
[Kallweit, Grazzini, Wiesemann, '17]

Javier Mazzitelli

HH production



NNLO_FTapprox:

$\mathcal{O}(\alpha_s^4)$ part: at n-loops in HEFT,

X=2-n extra partons:

reweight $\mathcal{A}^{(n)}_{\rm HEFT}(ij \to HH + X)$

with

$$\mathcal{R}(ij \to HH + X) = \frac{\mathcal{A}^{\rm Born}_{\rm Full}(ij \to HH + X)}{\mathcal{A}^{(0)}_{\rm HEFT}(ij \to HH + X)}$$

considerable reduction of scale uncertainties

remaining mt uncertainty estimated to be ~5%

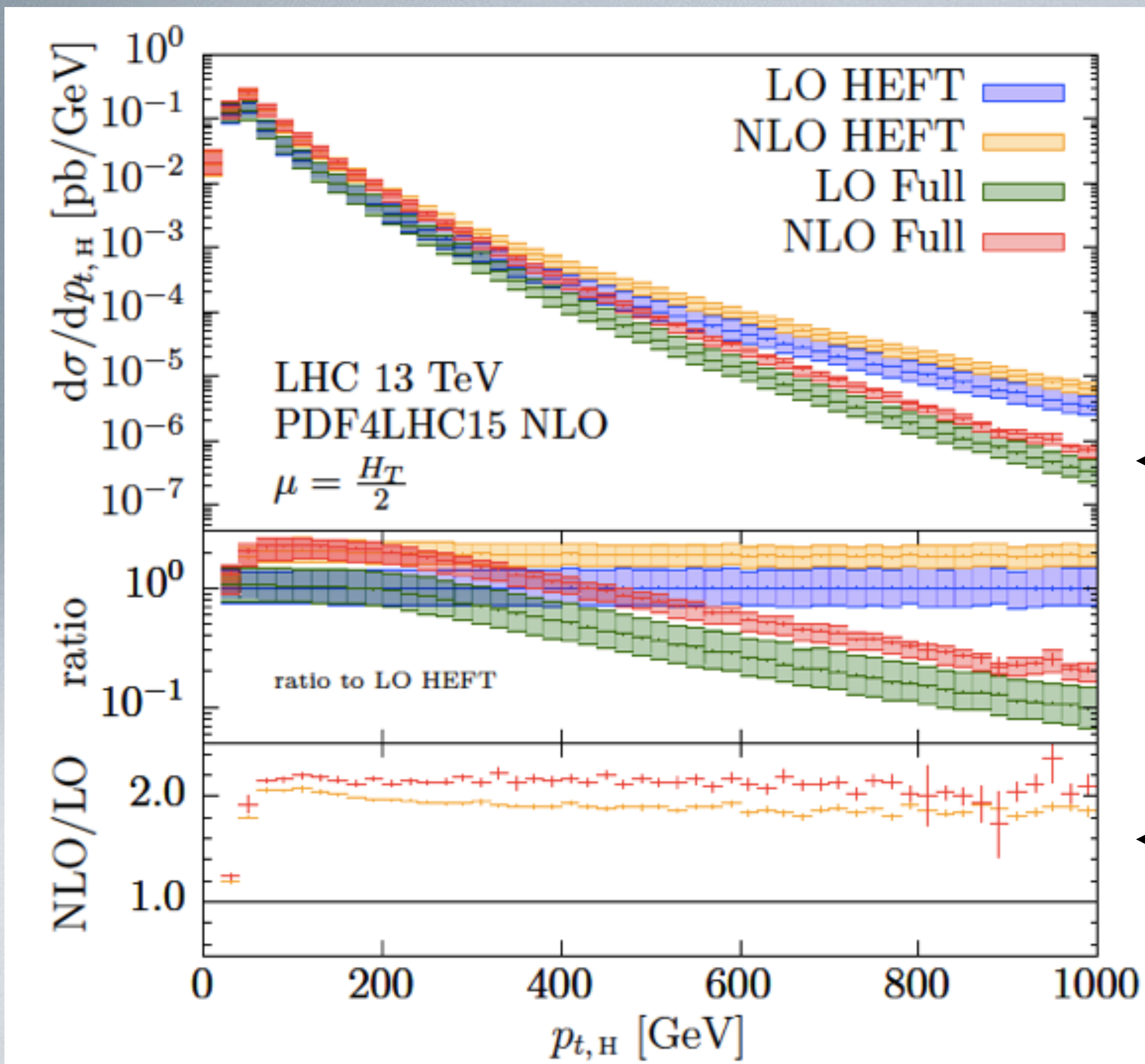
soft gluon resummation on top of NNLO_FTapprox also available

De Florian, Mazzitelli 1807.03704 resummation effects below 1% for $\mu = m_{hh}/2$

gluon fusion: Higgs pT spectrum

H+jet at NLO including full top quark mass dependence

Jones, Kerner, Luisoni, 1802.00349



settles a longstanding question about the uncertainties due to unknown top mass effects at NLO

← full NLO: different scaling behaviour at large pT

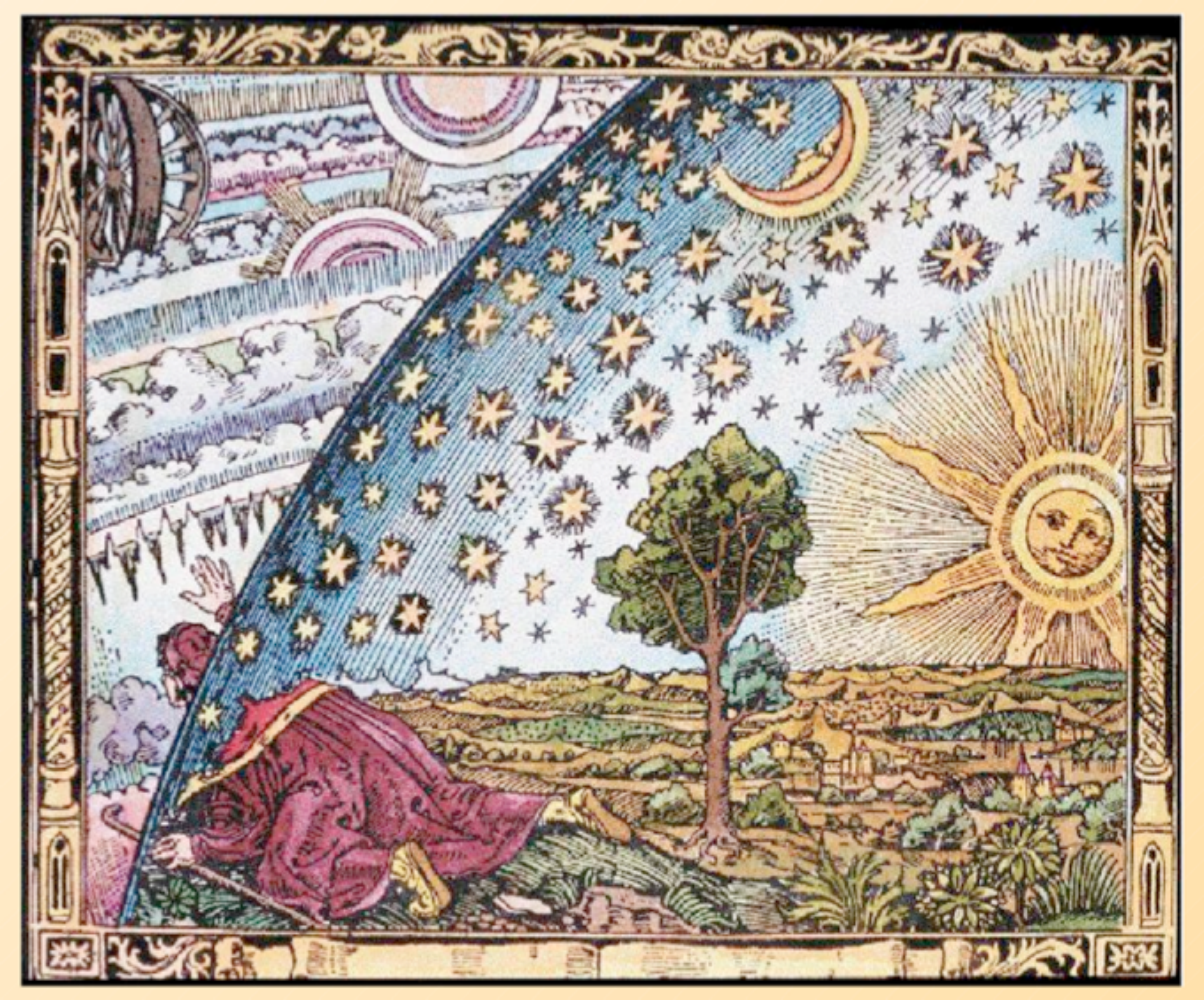
← K-factors full vs HEFT: similar shape for $\mu = H_T/2$ …

Summary

- the Higgs sector is just starting to get explored
- it is likely that New Physics is hiding in small deviations
- precision calculations and -measurements become vital

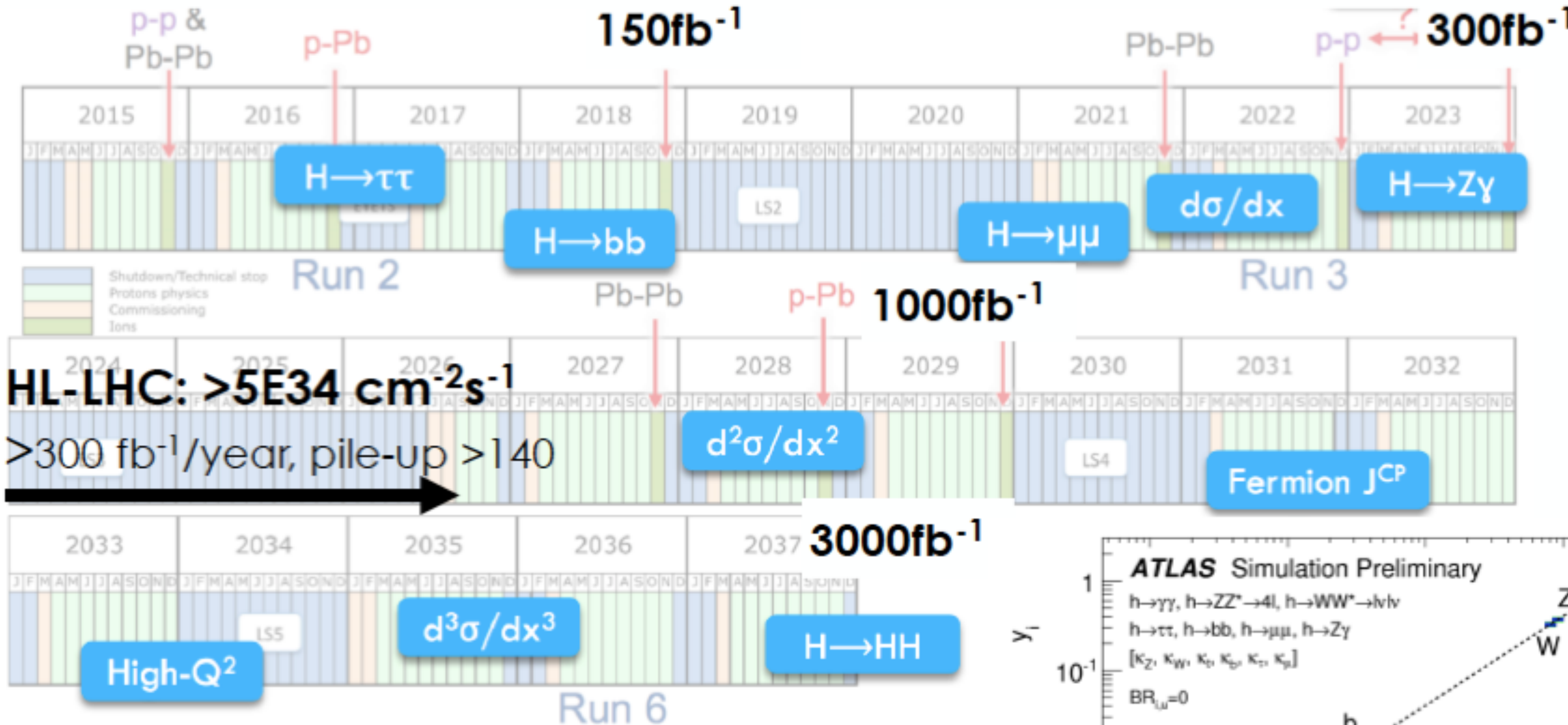
- the calculation of higher order predictions saw an amazing boost **due to**
  - new ideas how to calculate
    - loop integrals
    - IR divergent real radiation

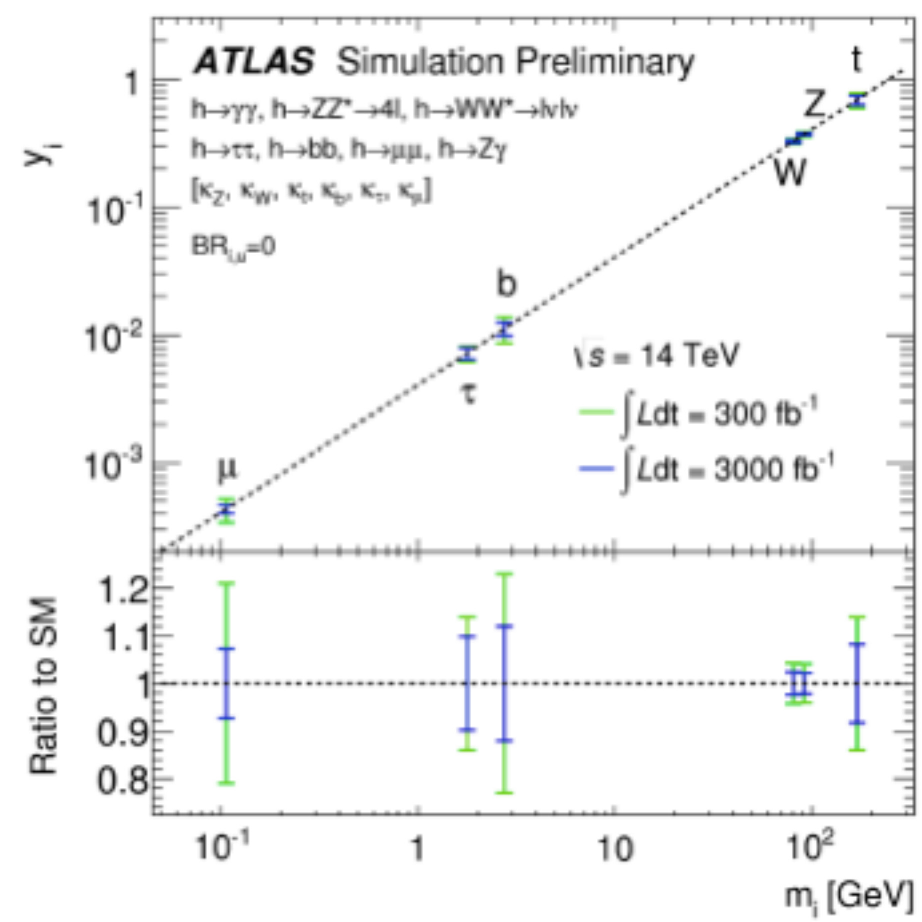
    both **analytically** and **numerically**
  - deeper insights into the structure of scattering amplitudes



TIMELINE BEYOND RUN2

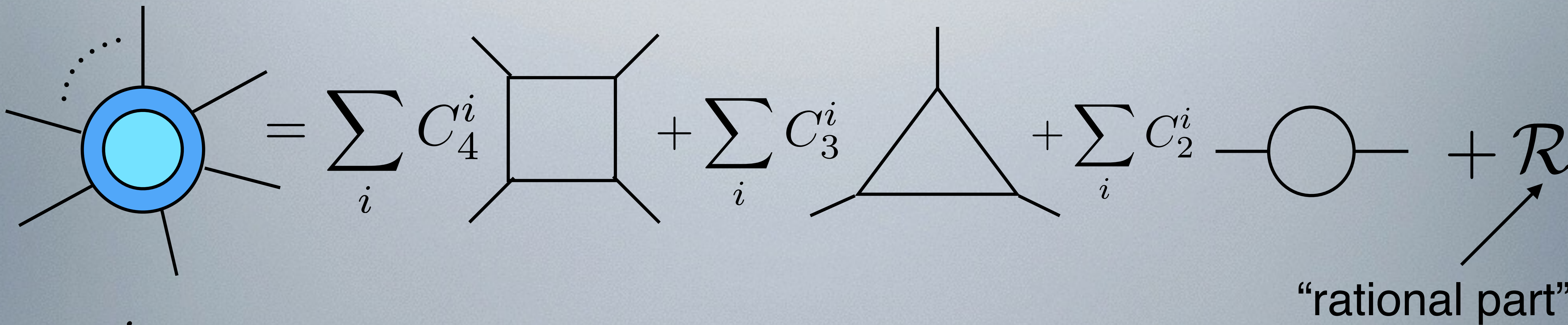
Credits: A. David @ GRC 2017





P.Meridiani, EPS 2017

One-loop n-point amplitudes



C_n^i can be obtained by numerical reduction at integrand level

“master integrals”: boxes, triangles, bubbles, tadpoles

most complicated functions are dilogarithms

very different at two loops (and beyond)!

master integrals not a priori known

NLO automation

Monte Carlo program
- tree amplitudes
- infrared subtractions
- phase space integration/ event generation
- parton shower (optional)

BLHA or custom made

One-loop provider
- virtual amplitude

- Powheg
- Sherpa
- Herwig7/Matchbox
- Geneva
- Vincia

- Blackhat
- FeynArts
- GoSam
- Madloop
- NJet
- OpenLoops
- Recola

all in one:
- MG5_aMC@NLO
- Helac-NLO
- Grace

collection of pre-computed processes:
- MCFM
- VBFNLO

NNLO real radiation subtraction methods

two main categories: "subtraction" and "slicing"

subtraction:

subtract piece which leads to IR divergences and add it back in integrated form (analytic integration over factorized phase space)

$$\begin{aligned} d\hat{\sigma}_{ab,NNLO} &= \int_{n+2} \left[d\hat{\sigma}^{RR}_{ab,NNLO} - d\hat{\sigma}^{S}_{ab,NNLO} \right] \\ &+ \int_{n+1} \left[d\hat{\sigma}^{RV}_{ab,NNLO} - d\hat{\sigma}^{T}_{ab,NNLO} \right] \\ &+ \int_{n} \left[d\hat{\sigma}^{VV}_{ab,NNLO} - d\hat{\sigma}^{U}_{ab,NNLO} \right] \end{aligned}$$

$$\begin{aligned} d\hat{\sigma}^{T}_{ab,NNLO} &= d\hat{\sigma}^{V,S}_{ab,NNLO} - d\hat{\sigma}^{MF,1}_{ab,NNLO} - \int_1 d\hat{\sigma}^{S}_{ab,NNLO}, \\ d\hat{\sigma}^{U}_{ab,NNLO} &= -d\hat{\sigma}^{MF,2}_{ab,NNLO} - \int_1 d\hat{\sigma}^{V,S}_{ab,NNLO} - \int_2 d\hat{\sigma}^{S}_{ab,NNLO} \end{aligned}$$

$$\begin{aligned} d\hat{\sigma}_{ab,NNLO} &= \int_{n+2} d\hat{\sigma}^{RR}_{ab,NNLO} + \int_{n+1} \left[d\hat{\sigma}^{RV}_{ab,NNLO} + d\hat{\sigma}^{MF,1}_{ab,NNLO} \right] \\ &+ \int_{n} \left[d\hat{\sigma}^{VV}_{ab,NNLO} + d\hat{\sigma}^{MF,2}_{ab,NNLO} \right], \end{aligned}$$

NNLO real radiation subtraction methods

slicing: define a cut parameter to separate IR sensitive part and split cross section into contributions above and below the cut

$$\begin{aligned}\sigma_{NNLO} &= \int d\Phi_N \, |\mathcal{M}_{VV}|^2 + \int d\Phi_{N+1} \, |\mathcal{M}_{RV}|^2 \, \theta_0^< \\ &+ \int d\Phi_{N+2} \, |\mathcal{M}_{RR}|^2 \, \theta_0^< + \int d\Phi_{N+1} \, |\mathcal{M}_{RV}|^2 \, \theta_0^> \\ &+ \int d\Phi_{N+2} \, |\mathcal{M}_{RR}|^2 \, \theta_0^> \\ &\equiv \sigma_{NNLO}(\mathcal{T}_0 < \mathcal{T}_0^{cut}) + \sigma_{NNLO}(\mathcal{T}_0 > \mathcal{T}_0^{cut}) \, .\end{aligned}$$

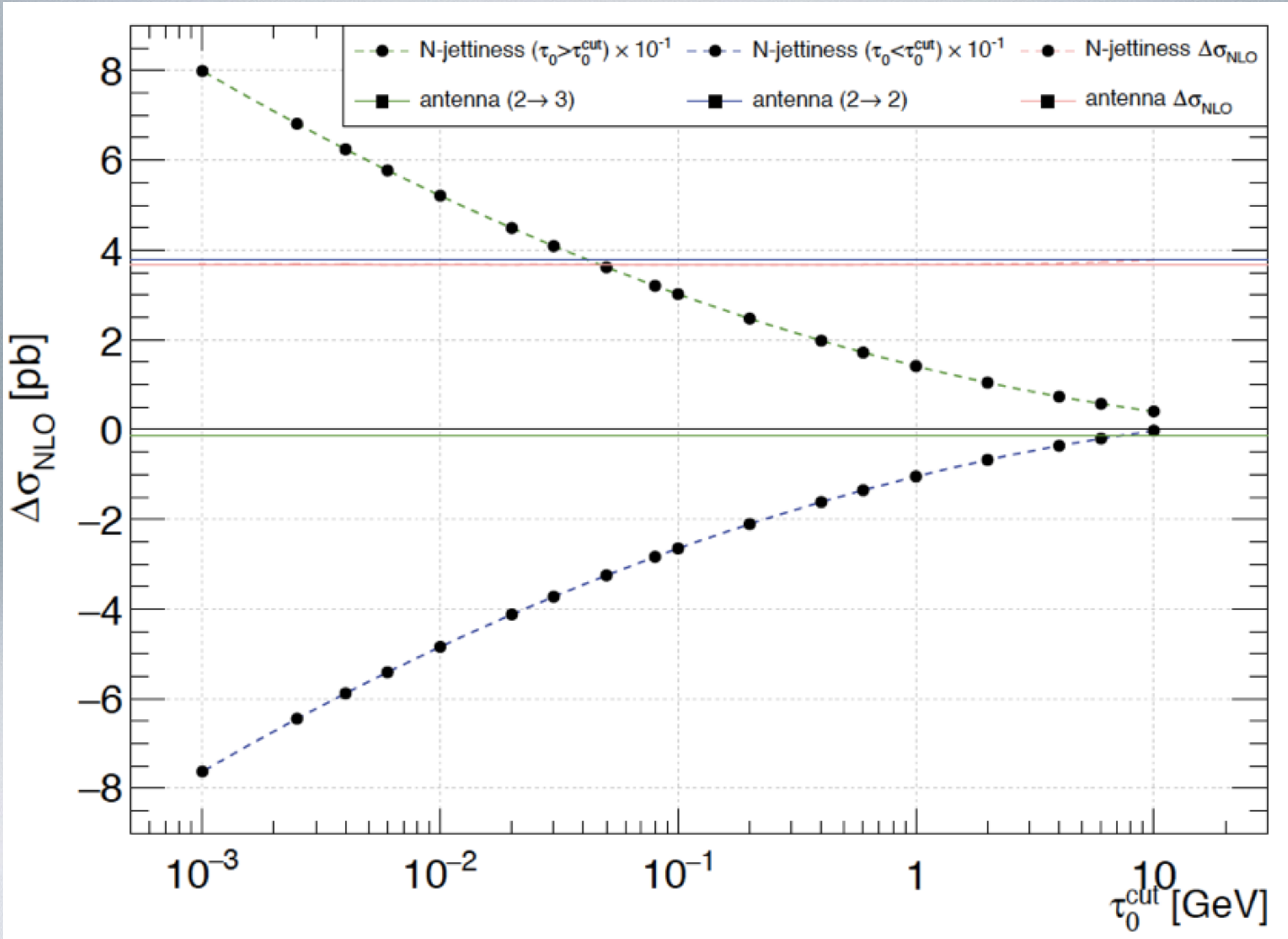
$$\theta_0^< = \theta(\mathcal{T}_0^{cut} - \mathcal{T}_0)$$

below τ^{cut} : cross section can be obtained from universal IR behaviour (SCET, resummation)

note: both parts depend logarithmically on τ^{cut} $\Rightarrow$ large cancellations

residual cutoff dependence

comparison local vs non-local subtraction method



example ZZ production GH, Jahn, Jones, Kerner, Pires ’17

MATRIX

process	status	comment
pp→Z/γ*(→ℓℓ/νν)	✓	validated analytically + FEWZ
pp→W(→ℓν)	✓	validated with FEWZ, NNLOjet
pp→H	✓	validated analytically (by SusHi)
pp→γγ	✓	validated with 2γNNLO
pp→Zγ→ℓℓγ	✓	[Grazzini, Kallweit, Rathlev '15]
pp→Zγ→ννγ	✓	[Grazzini, Kallweit, Rathlev '15]
pp→Wγ→ℓνγ	✓	[Grazzini, Kallweit, Rathlev '15]
pp→ZZ	✓	[Cascioli et al. '14]
pp→ZZ→ℓℓℓℓ	✓	[Grazzini, Kallweit, Rathlev '15]
pp→ZZ→ℓℓℓ'ℓ'	✓	[Grazzini, Kallweit, Rathlev '15]
pp→ZZ→ℓℓν'ν'	✓	[Kallweit, MW '18]
pp→ZZ/WW→ℓℓνν	✓	[Kallweit, MW '18]
pp→WW	✓	[Gehrmann et al. '14]
pp→WW→ℓνℓ'ν'	✓	[Grazzini, Kallweit, Pozzorini, Rathlev, MW '16]
pp→WZ	✓	[Grazzini, Kallweit, Rathlev, MW '16]
pp→WZ→ℓνℓℓ	✓	[Grazzini, Kallweit, Rathlev, MW '17]
pp→WZ→ℓ'ν'ℓℓ	✓	[Grazzini, Kallweit, Rathlev, MW '17]
pp→HH	(✓)	not in public release yet

Marius Wiesemann, QCD@LHC '18

NNLOJet

NNLOJET

The method of antenna subtraction is implemented in the NNLOJET program, a semi-automated Monte Carlo for NNLO phenomenology.

Processes

Many processes are already included at NNLO:

- pp→H + 0,1 jets [arXiv:1408.5325],
- pp→Z(l^+l^-) + 0,1 jets [arXiv:1607.01749],
- pp→W(l^+l^-) + 0,1 jets [arXiv:1712.07543],
- NC & CC DIS single/dijets [arXiv:1606.03991],
- NC DIS single jet (N^3LO) [arXiv:1803:09973],
- pp→dijets [arXiv:1611.01460] (Joao tomorrow).
- $e^+e^- \to 3$ jets [arXiv:1709.01097],
- VBF at NNLO [arXiv:1802.02445]

Jan Niehues, QCD@LHC ‘18

MCFM version 8

Development and optimization of MCFM

Downloadable from **mcfm.fnal.gov**

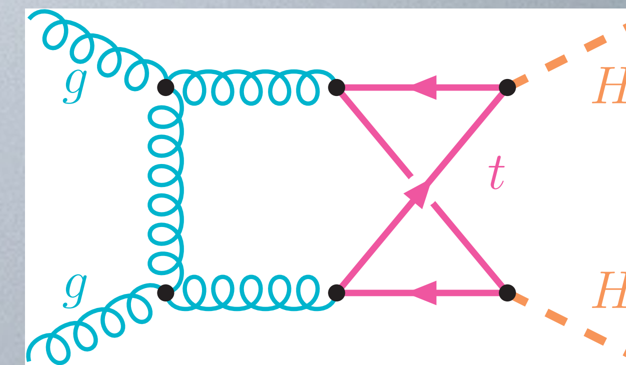
- A Multi-Threaded Version of MCFM, J.M. Campbell, R.K. Ellis, W. Giele, 2015
- Color singlet production at NNLO in MCFM,
  R. Boughezal, J.M. Campbell, R.K. Ellis, C. Focke, W. Giele, X. Liu, F. Petriello, C. Williams, 2016

The publicly available code MCFM 8.0 provides predictions for color singlet production at Next-to-Next-to Leading Order. The code runs in parallel using a hybrid openMP/MPI version of Vegas enabling MCFM to get accurate distributions in a few hours of runtime on moderate clusters of a few hundred computing cores. Included processes in this version are *W, Z, H, WH, ZH* and *di-photon* production. In the next releases more processes will be included*: Z-photon, WW, ZZ, W-jet, Z-jet, H-jet* and *photon-jet*.

Walter Giele, ACAT 2017

some details on virtual 2-loop diagrams

- amplitude reduction with **Reduze** [C. Studerus, A. v.Manteuffel]
- non-planar integrals computed mostly without reduction
- all integrals calculated numerically with **SecDec** [S.Borowka et al.]

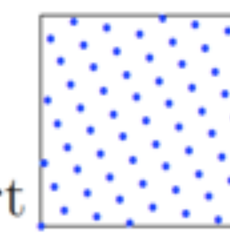


- total number of integrals after decomposition 11244, 3086 non-planar
- integration with quasi Monte Carlo method ($\mathcal{O}(1/n)$ scaling of integration errors)
  [Dick, Kuo, Sloan ’13] [Li, Wang, Yan, Zhao ’15]
- implemented in OpenCL, evaluated on GPUs [S. Jones, M. Kerner]
- number of sampling points dynamically set for each integral [M. Kerner]

QMC rank-1 lattice rule

$$I = \int d\vec{x}\, f(\vec{x}) \approx I_k = \frac{1}{n}\sum_{i=1}^{n} f(\vec{x}_{i,k})$$

$$\vec{x}_{i,k} = \left\{ \frac{i \cdot \vec{g}}{n} + \vec{\Delta}_k \right\}$$



$\{\ldots\}$ = fractional part

$\vec{g}$ = generating vector

$\vec{\Delta}_k$ = randomized shift

m different estimates $I_1 \ldots I_m$
$\rightarrow$ error estimate

combination with NNLO

three approximations:

- NLO-improved NNLO HEFT **NNLO$_{\text{NLO-i}}$**

$$\frac{d\sigma^{\mathrm{NLO-i.NNLO\,HEFT}}}{dm_{hh}} = \frac{d\sigma_{\mathrm{NLO}}}{dm_{hh}} \times \frac{d\sigma^{\mathrm{HEFT}}_{\mathrm{NNLO}}/dm_{hh}}{d\sigma^{\mathrm{HEFT}}_{\mathrm{NLO}}/dm_{hh}}$$

bin-by-bin rescaling at observable level by NNLO HEFT K-factor

- Born-projected **NNLO$_{\text{B-proj}}$**

only piece where mt dependence enters

reweight each NNLO event by the ratio $\mathrm{Born}^{\mathrm{full}}/\mathrm{Born}^{\mathrm{HEFT}}$

different final state multiplicities in single/double real part ⟶ need projection (not unique)

use qT recoil method Catani, De Florian, Ferrera, Grazzini 1507. 06937

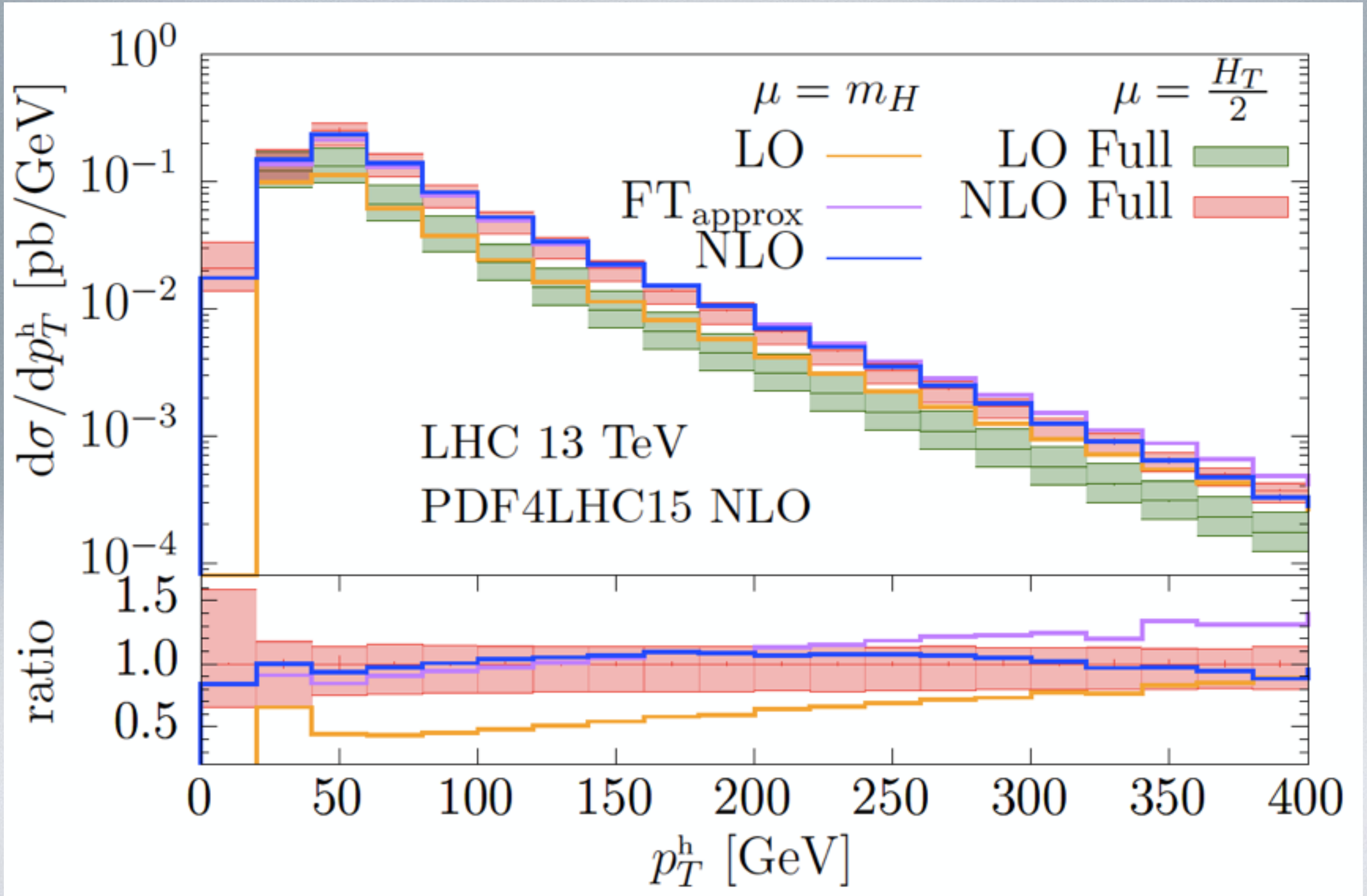
- "approximate Full Theory" **NNLO$_{\text{FTapprox}}$**

$\mathcal{O}(\alpha_s^4)$ part: at n-loops in HEFT, X=2-n extra partons: reweight $\mathcal{A}^{(n)}_{\mathrm{HEFT}}(ij \to HH + X)$

with $$\mathcal{R}(ij \to HH + X) = \frac{\mathcal{A}^{\mathrm{Born}}_{\mathrm{Full}}(ij \to HH + X)}{\mathcal{A}^{(0)}_{\mathrm{HEFT}}(ij \to HH + X)}$$

H+jet at NLO including full top quark mass dependence

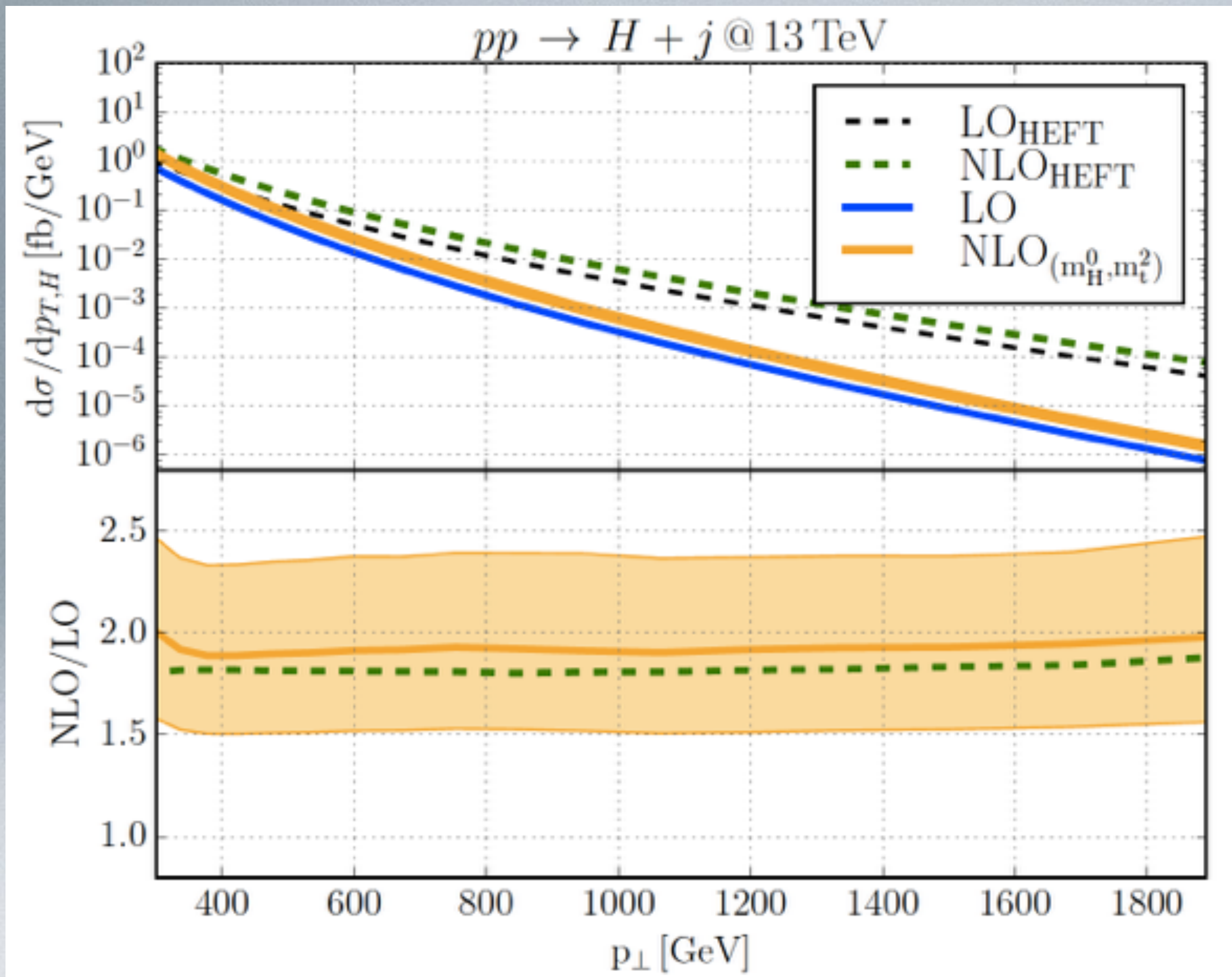
Jones, Kerner, Luisoni, 1802.00349



… but K-factors not flat for fixed scale choice $\mu = m_H$

Higgs pT spectrum

large transverse momentum expansion:



Lindert, Kudashkin, Melnikov, Wever 1801.08226

full mass dependence in real radiation

$$\mu = H_T/2$$

[see also Neumann1802.02981] (MCFM)

similar behaviour of K-factors full vs HEFT (HEFT: $m_t \to \infty$ limit)
(but not of distribution!)

Higgs pT spectrum

- Top-bottom interference effects in Higgs boson production

  Lindert, Melnikov, Tancredi, Wever '17

- b-quark effects in Higgs production at intermediate pT(H):

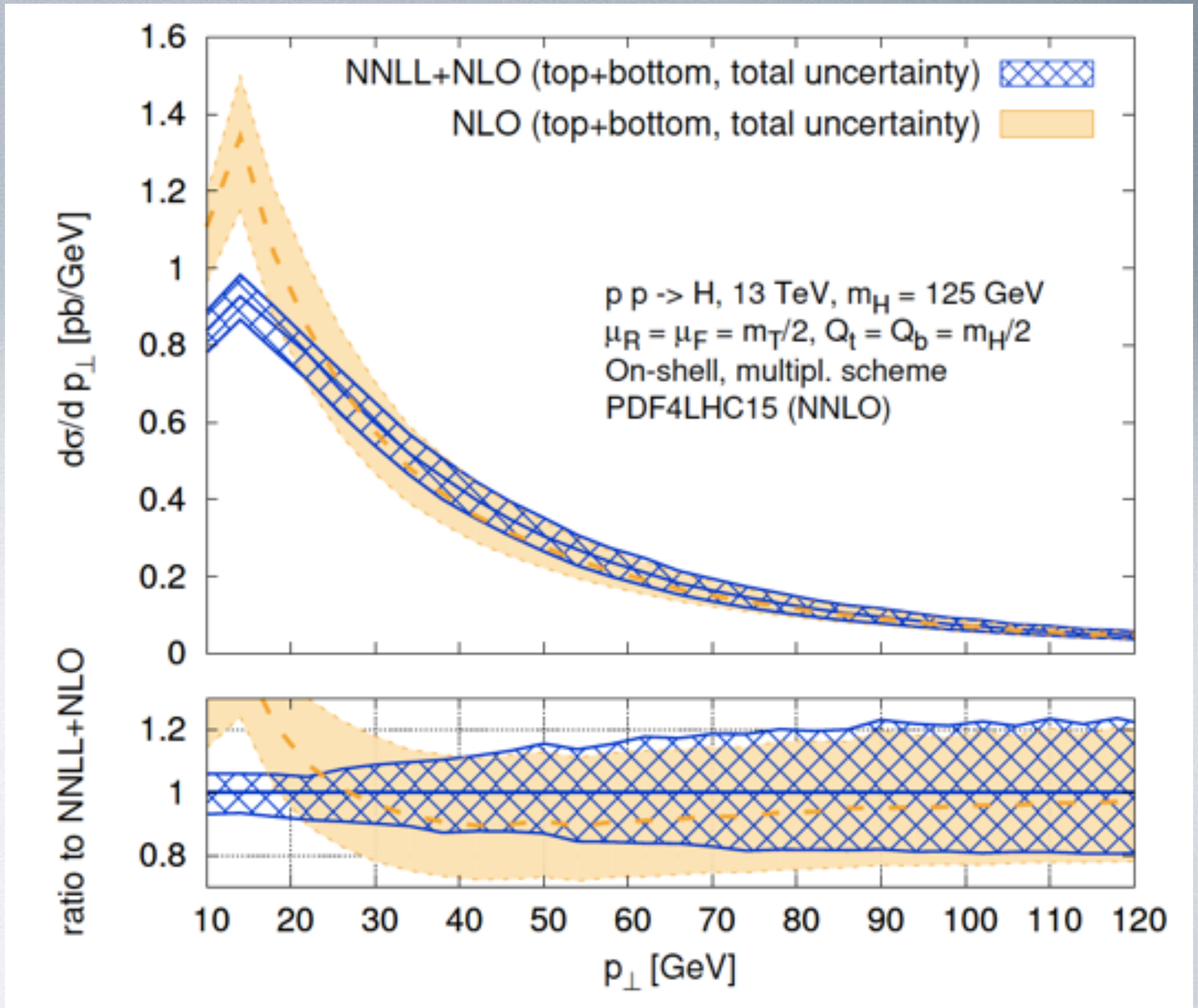
  resummation in region $m_b \lesssim p_{T,H} \lesssim m_H$

  Caola, Lindert, Kudashkin, Melnikov, Monni, Tancredi, Wever 1804.07632

  see also Grazzini, Sargsyan '13

current uncertainty in top-bottom interference contribution to pT(H) spectrum estimated to be O(20%)

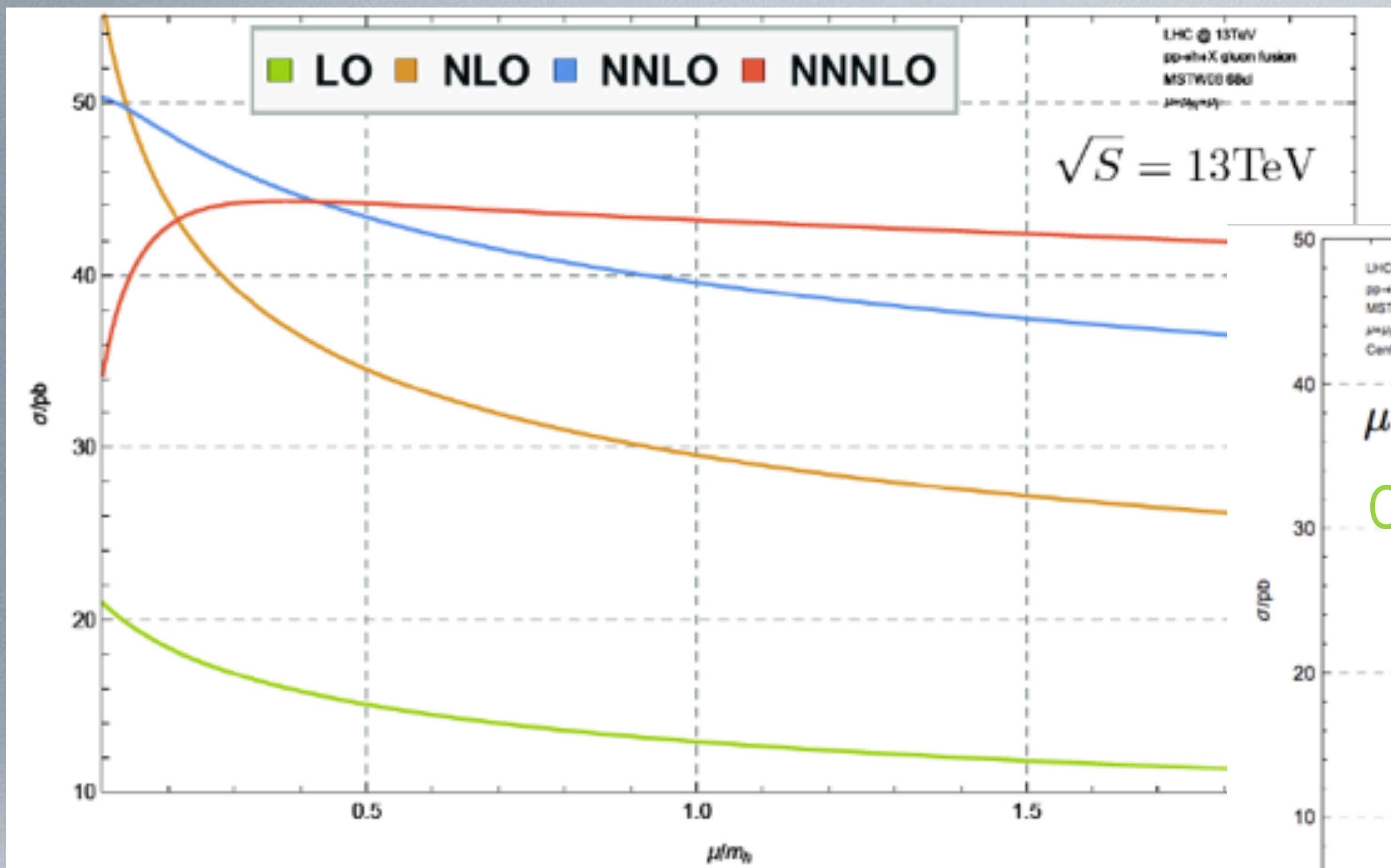
(scales, matching scheme, b-mass scheme)

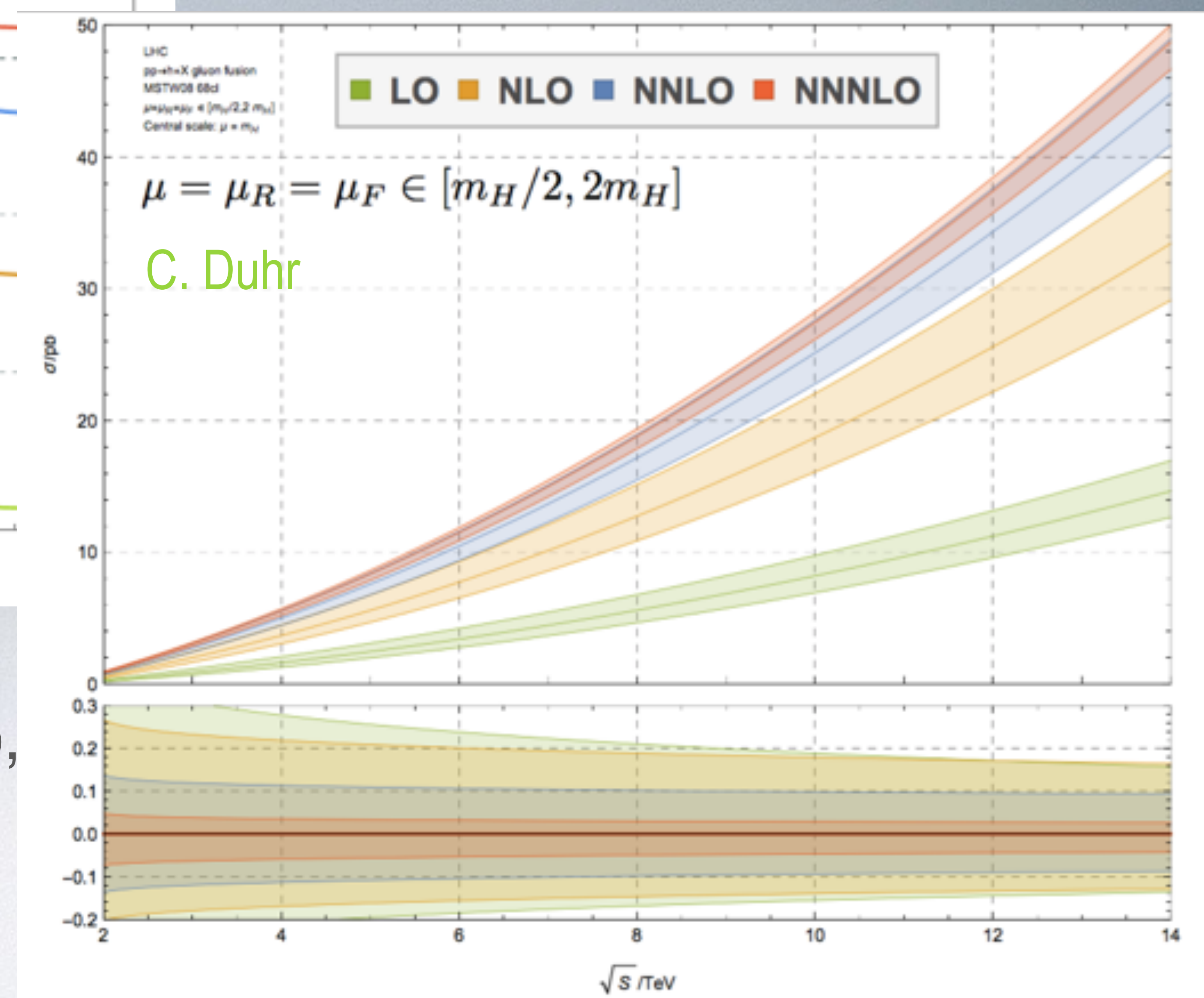


Higgs production at N3LO

$gg \to H$ inclusive

Anastasiou, Dulat, Duhr, Mistlberger ’15;
Anastasiou, Dulat, Duhr, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger ‘16





note:
NLO and NNLO bands do not overlap,
NNLO and N^3LO do

also: $qq' \to H + X$

Anzai, Hasselhuhn, Höschele, Hoff, Kilgore, Steinhauser, Ueda ’15

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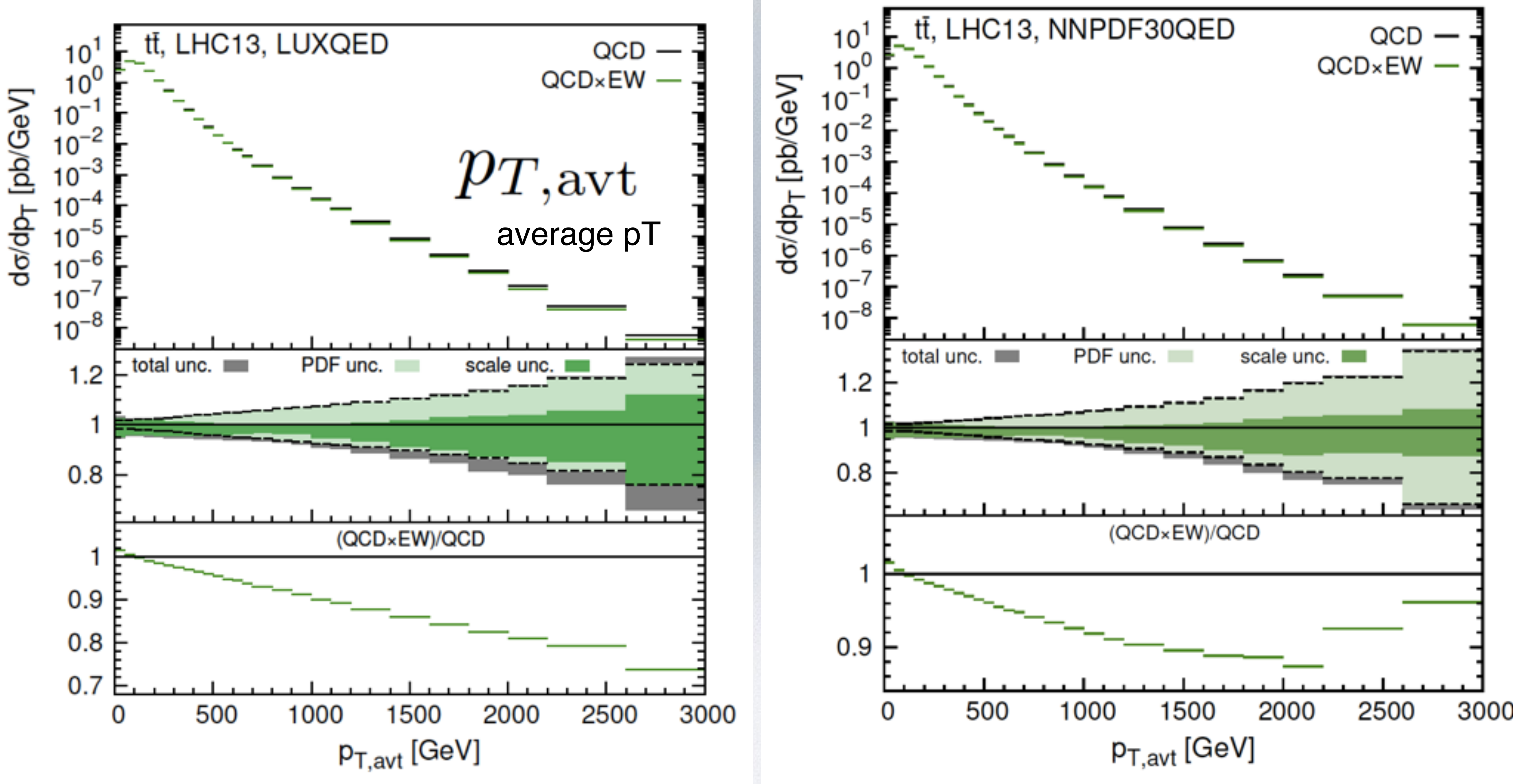
top quark pair production

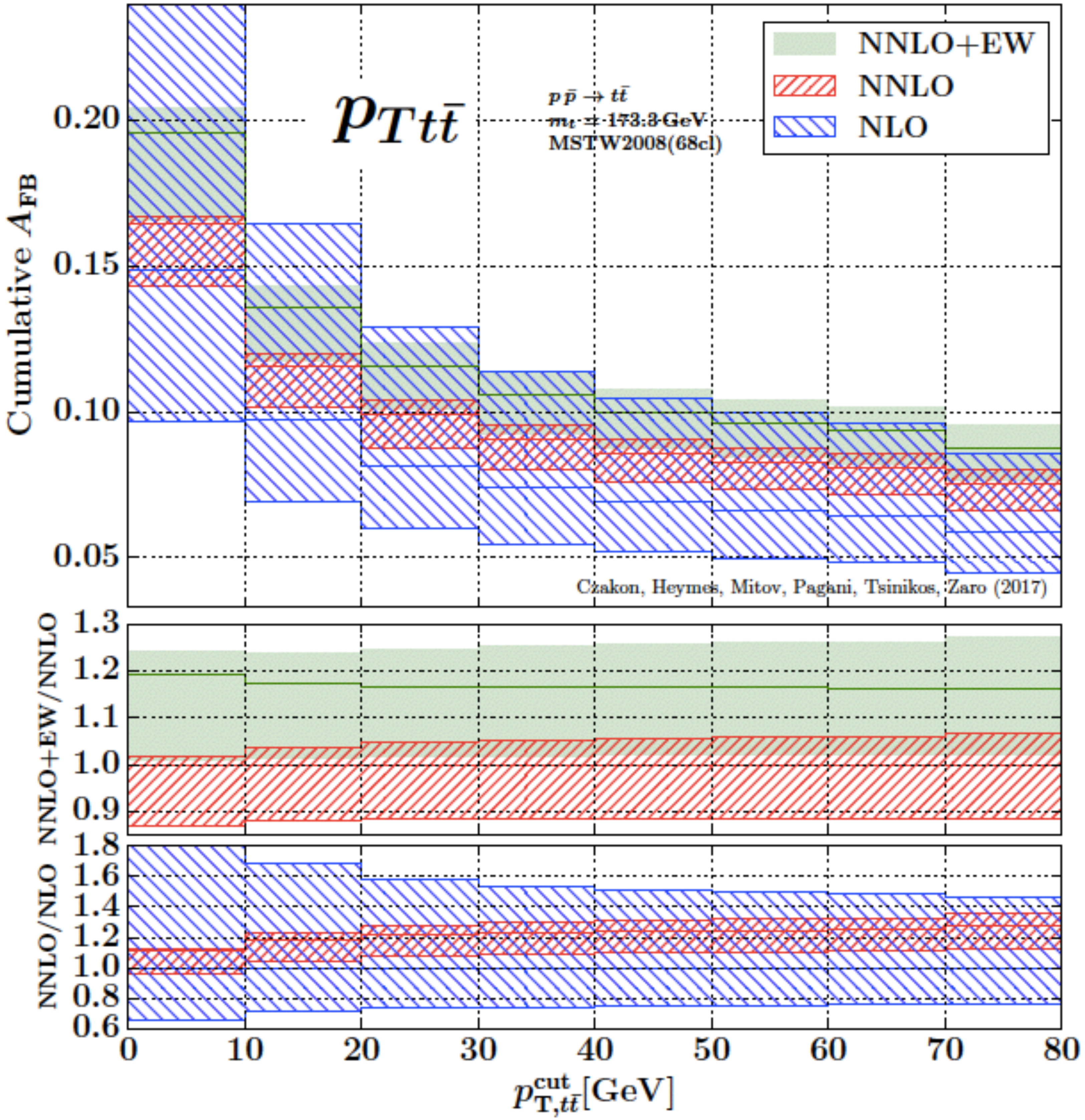
NNLO QCD and NLO EW

Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro ’17



significant role of QED PDFs

top quark A_FB



back to

Tevatron

NNLO accuracy is present in all bins.

EW corrections are large. They are **outside** the NNLO scale uncertainty band.

$$A_{FB}(p_{T,t\bar{t}} < p_{T,t\bar{t}}^{cut})$$

Davide Pagani