Novel computational techniques in particle physics

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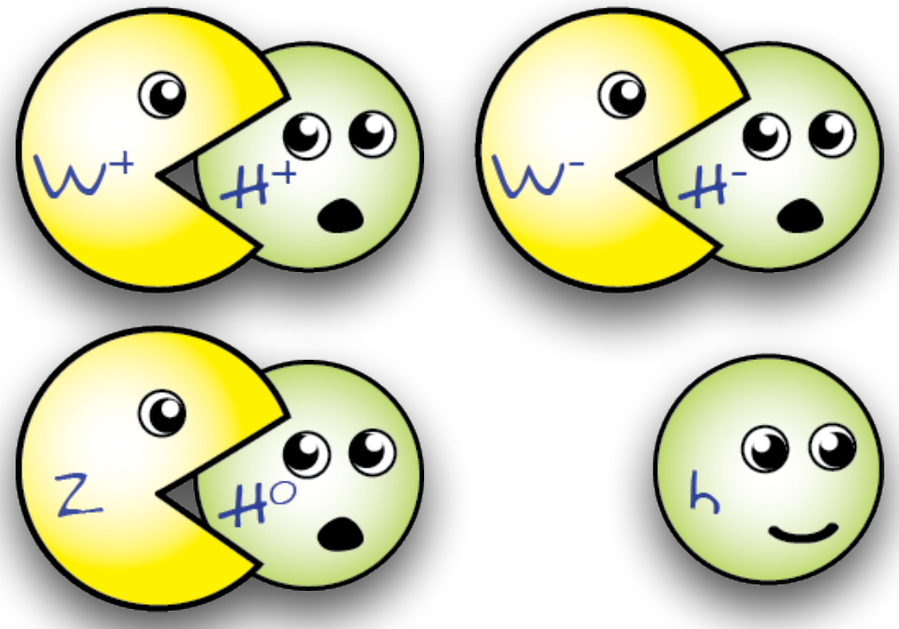
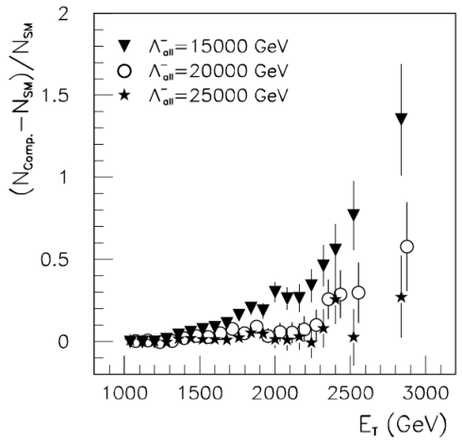
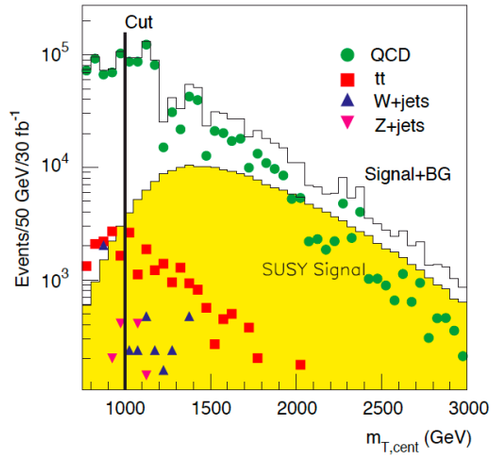


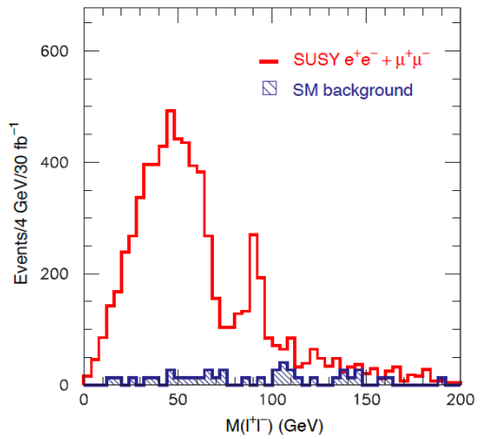
MPP Project Review 2020

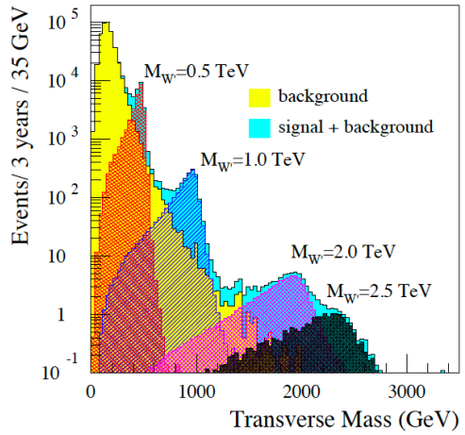
Munich (Germany), December 14-15th, 2020

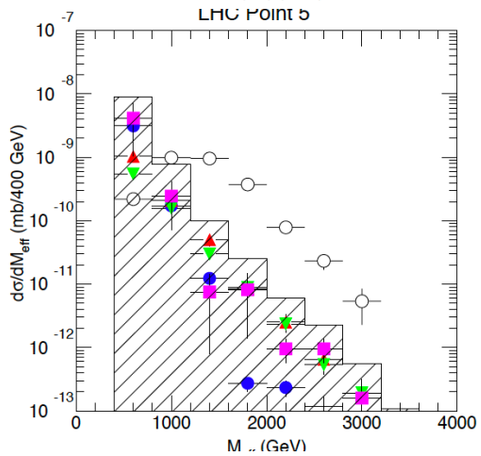
Novel computational techniques in particle physics

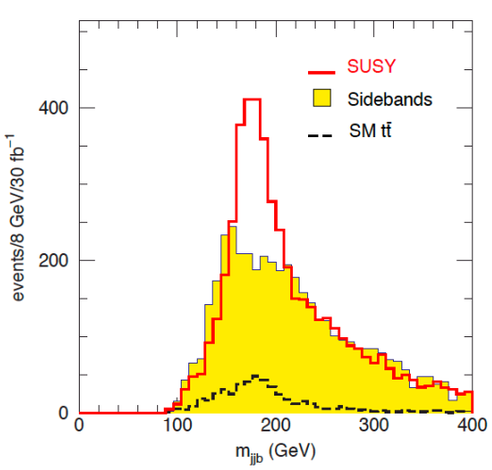

Λ^-_{all}=15000 GeV
Λ^-_{all}=20000 GeV
Λ^-_{all}=25000 GeV
$(N_{Comp.}-N_{SM})/N_{SM}$
E_T (GeV)

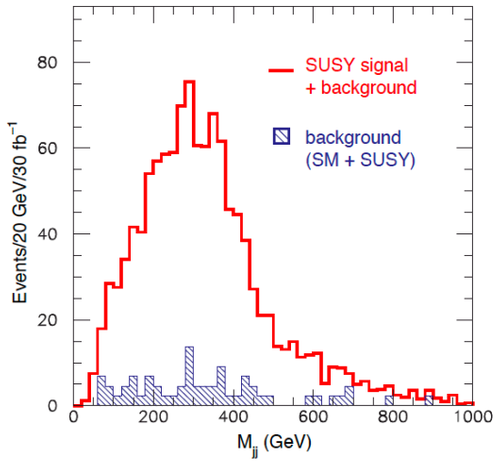

Cut
QCD
tt
W+jets
Z+jets
Signal+BG
SUSY Signal
Events/50 GeV/30 fb^{-1}
$m_{T,cent}$ (GeV)

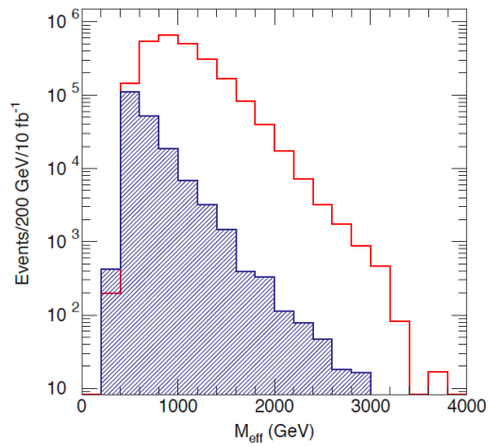

SUSY $e^+e^- + \mu^+\mu^-$
SM background
Events/4 GeV/30 fb^{-1}
M(l$^+$l$^-$) (GeV)


$M_{W'}$=0.5 TeV
background
signal + background
$M_{W'}$=1.0 TeV
$M_{W'}$=2.0 TeV
$M_{W'}$=2.5 TeV
Events/ 3 years / 35 GeV
Transverse Mass (GeV)

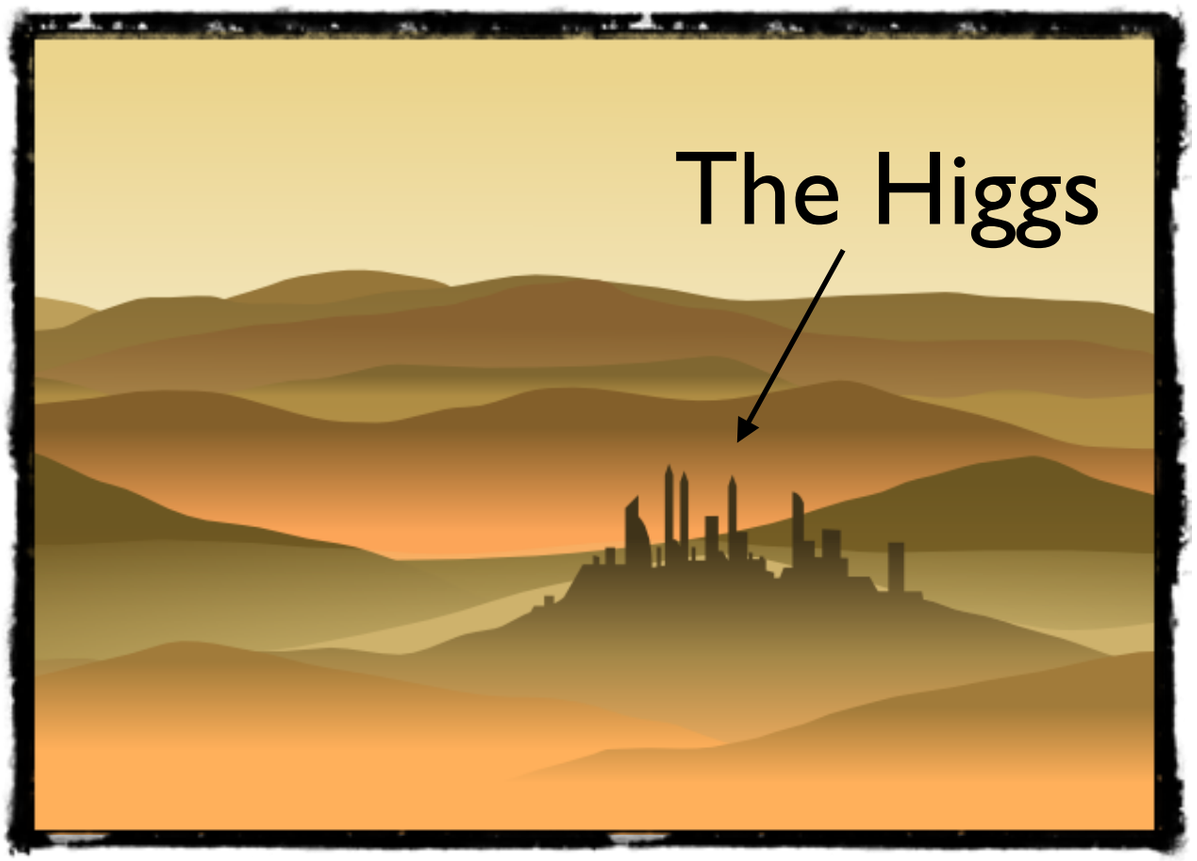

LHC Point 5
$d\sigma/dM_{eff}$ (mb/400 GeV)


SUSY
Sidebands
SM tt
events/8 GeV/30 fb^{-1}
m_{jjb} (GeV)


SUSY signal
+ background
background
(SM + SUSY)
Events/20 GeV/30 fb^{-1}
M_{jj} (GeV)


Events/200 GeV/10 fb^{-1}
M_{eff} (GeV)

Expectation vs. Reality



After more than 100 fb^{-1} no *direct evidence* of New Physics

...slide borrowed from Fabio Maltoni

...slide borrowed from Fabio Maltoni

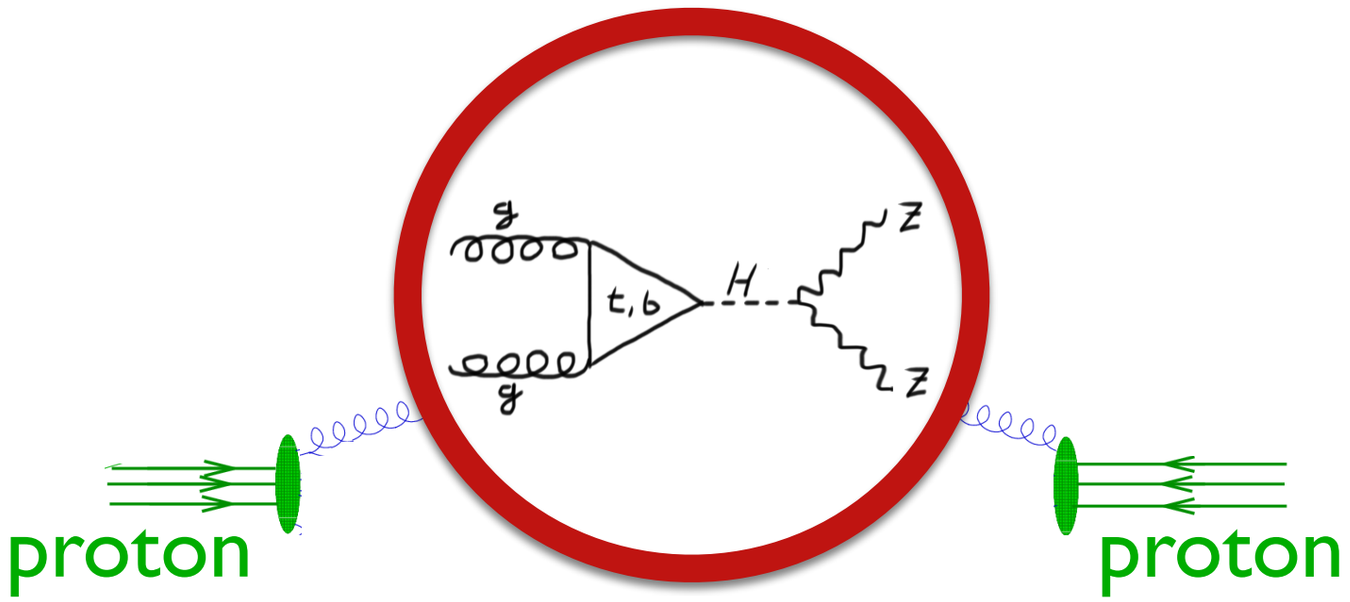
Why Happy?

Why Happy?

- ★ Optimist: New Physics around the corner.
- ★ SM tested with incredible scrutiny
- ★ Possibility to make big discovery by small group of people
- ★ Creativity: New ideas what to look for/how to make use of what we have might make a huge impact
- ★ Lots of room for New Physics in small deviations from SM
- ★ High precision calculations and simulations crucial

LHC Master formula

$$\sigma_{\text{had}} = \sum_{ij} \int \mathrm{d}x_1\, \mathrm{d}x_2\, f_i(x_1, \mu_\text{F})\, f_j(x_2, \mu_\text{F}) \times \sigma_{ij}(x_1 P_1, x_2 P_2, \mu_F) + \mathcal{O}(\Lambda/Q)$$

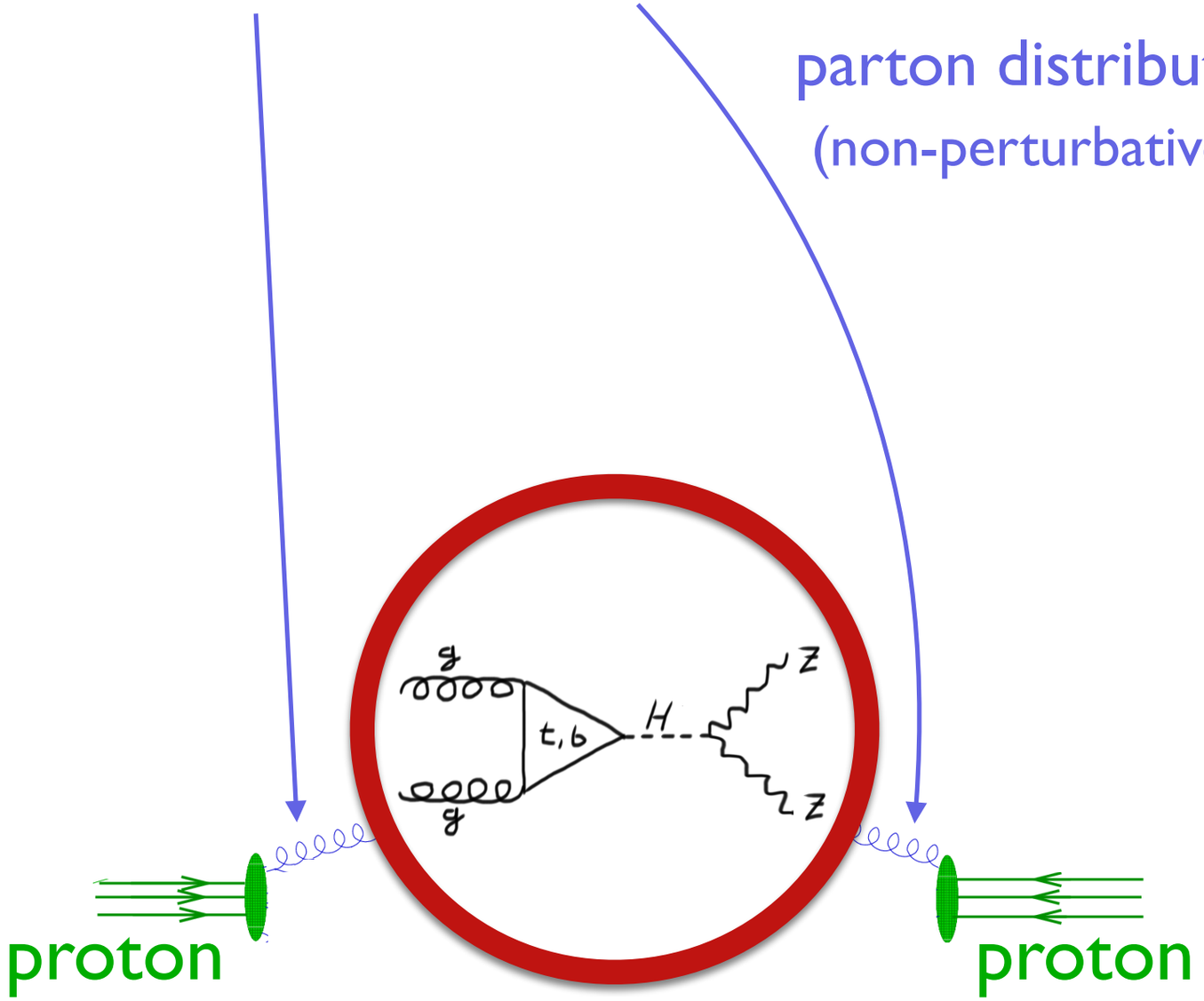


Hard Process

LHC Master formula

$$\sigma_{\text{had}} = \sum_{ij} \int \mathrm{d}x_1\, \mathrm{d}x_2 \, f_i(x_1, \mu_\text{F})\, f_j(x_2, \mu_\text{F}) \times \sigma_{ij}(x_1 P_1, x_2 P_2, \mu_F) + \mathcal{O}(\Lambda/Q)$$

parton distribution functions
(non-perturbative effects in proton)



Hard Process

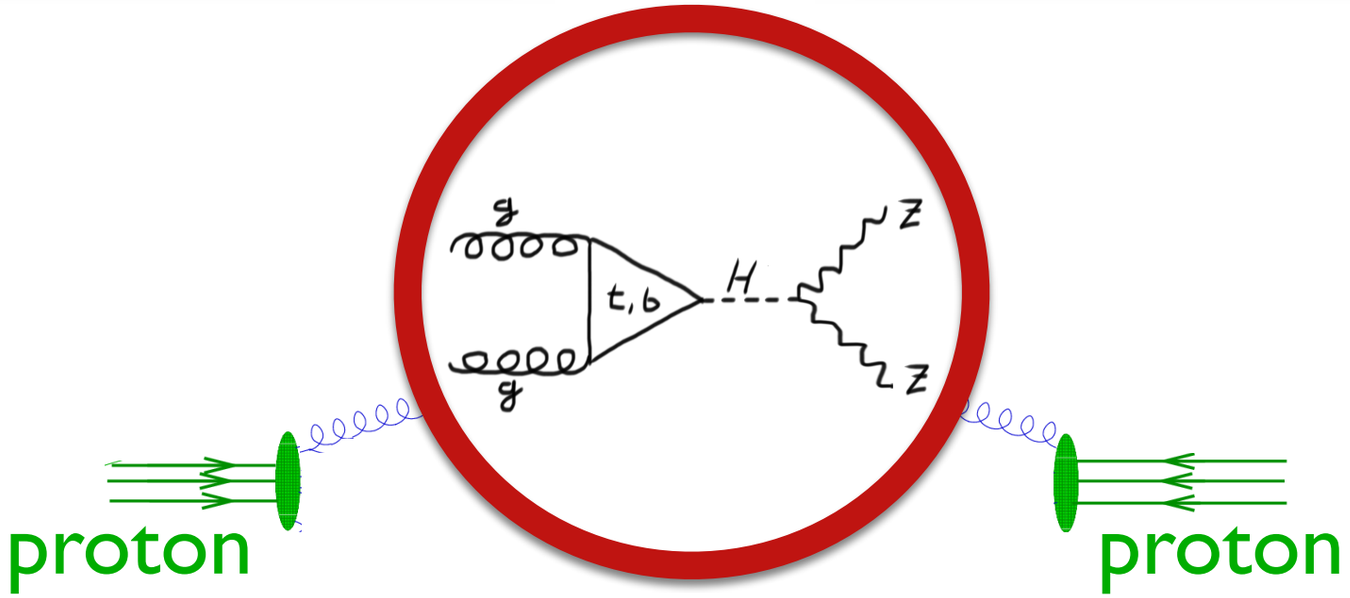
LHC Master formula

$$\sigma_{\text{had}} = \sum_{ij} \int \mathrm{d}x_1\, \mathrm{d}x_2\, f_i(x_1, \mu_F)\, f_j(x_2, \mu_F) \times \sigma_{ij}(x_1 P_1, x_2 P_2, \mu_F) + \mathcal{O}(\Lambda/Q)$$

$$\sigma_{ij} \sim \underbrace{\sigma_{\text{LO}} \cdot (1 + \underbrace{\alpha}_{\text{NLO}} + \alpha^2 + \ldots)}_{\text{NNLO}}$$

Uncertainties:
(α ~ 0.118)

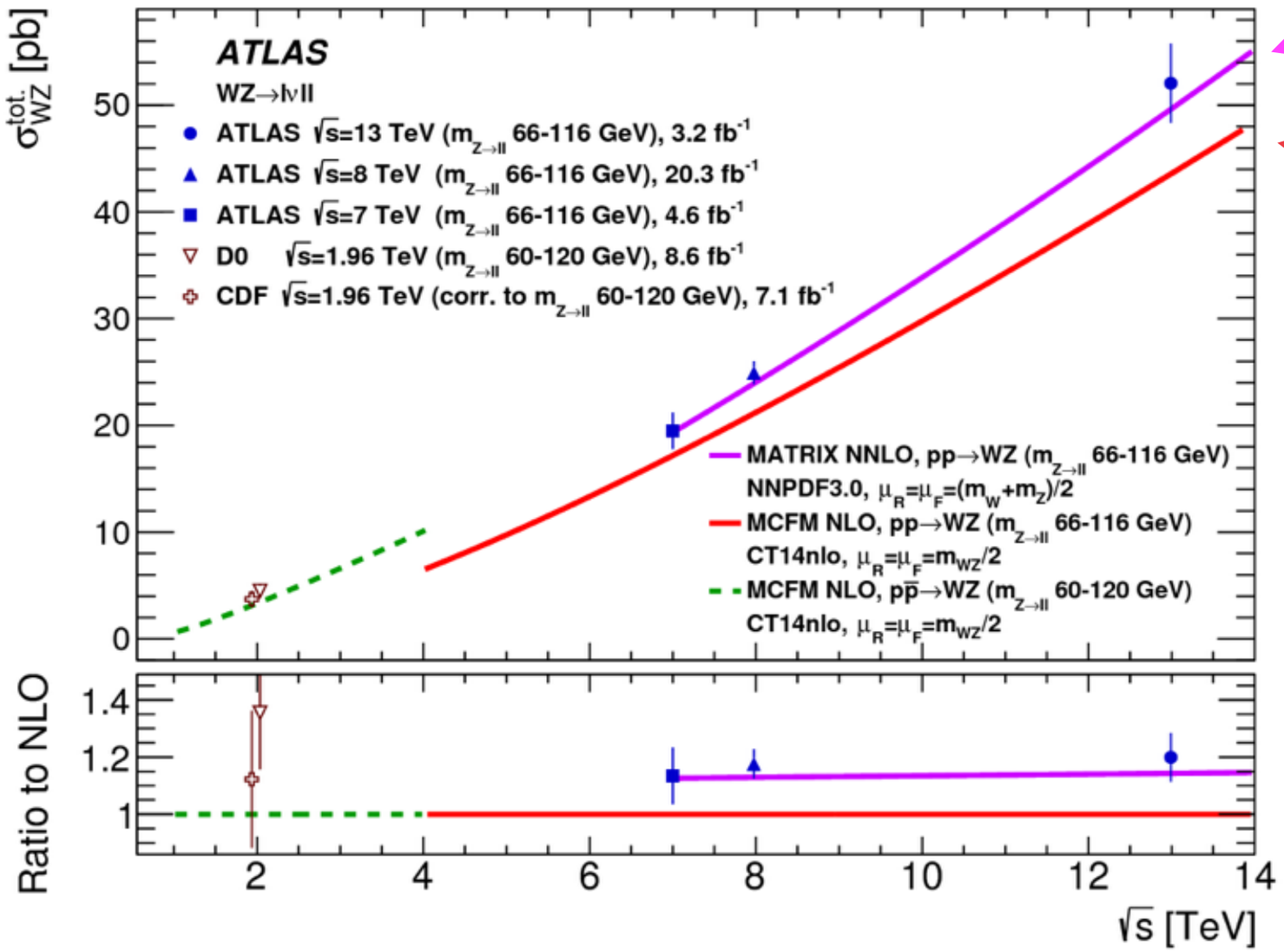
LO ~ $\mathcal{O}$(100%)
NLO ~ $\mathcal{O}$(10%)
NNLO ~ $\mathcal{O}$(1%)



Hard Process

Importance of QCD corrections
(example WZ)

[Grazzini, Kallweit, Rathlev, MW '16]



NNLO

NLO

NNLO crucial for accurate description of data

Explosion of NNLO results

...slide borrowed from Gavin Salam

NNLO corrections

✦ All 2→1 and 2→2 colour-singlet processes known

process		status	comment
pp→Z/γ*(→ℓℓ/νν)	single boson processes	✓	validated analytically + FEWZ
pp→W(→ℓν)		✓	validated with FEWZ, NNLOjet
pp→H		✓	validated analytically (by SusHi)
pp→γγ	photon processes	✓	validated with 2γNNLO
pp→Zγ→ℓℓγ		✓	[Grazzini, Kallweit, Rathlev '15]
pp→Zγ→νγγ		✓	[Grazzini, Kallweit, Rathlev '15]
pp→Wγ→ℓνγ		✓	[Grazzini, Kallweit, Rathlev '15]
pp→ZZ	massive diboson processes	✓	[Cascioli et al. '14]
pp→ZZ→ℓℓℓℓ		✓	[Grazzini, Kallweit, Rathlev '15], [Kallweit, **MW** '18]
pp→ZZ→ℓℓℓ'ℓ'		✓	[Grazzini, Kallweit, Rathlev '15], [Kallweit, **MW** '18]
pp→ZZ→ℓℓν'ν'		✓	[Kallweit, **MW** '18]
pp→ZZ/WW→ℓℓνν		✓	[Kallweit, **MW** '18]
pp→WW		✓	[Gehrmann et al. '14]
pp→WW→ℓν ℓ'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

MATRIX

[Grazzini, Kallweit, MW '17]

Public, automated NNLO framework

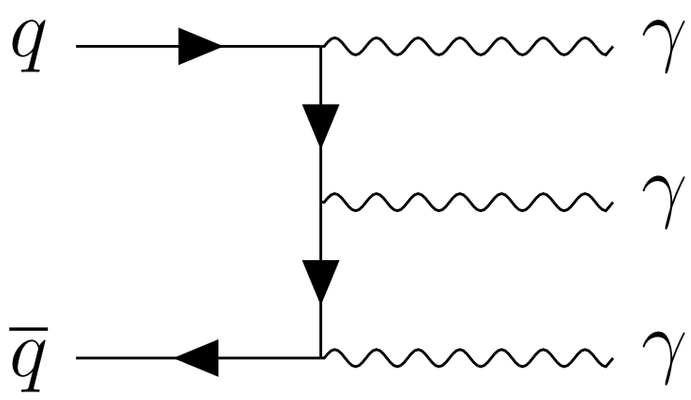
`https://matrix.hepforge.org/`

→ ***actively developed at MPP, e.g.:***

$t\bar{t}$, $b\bar{b}$, HH by Javier Mazzitelli; v2 release: NLO EW, NLO gg, VH, ...; resummation; ...

✦ other processes: $t\bar{t}$, $b\bar{b}$, single-top, H/V/γ+jet, VBF (factorized), dijet, ...

3γ at NNLO



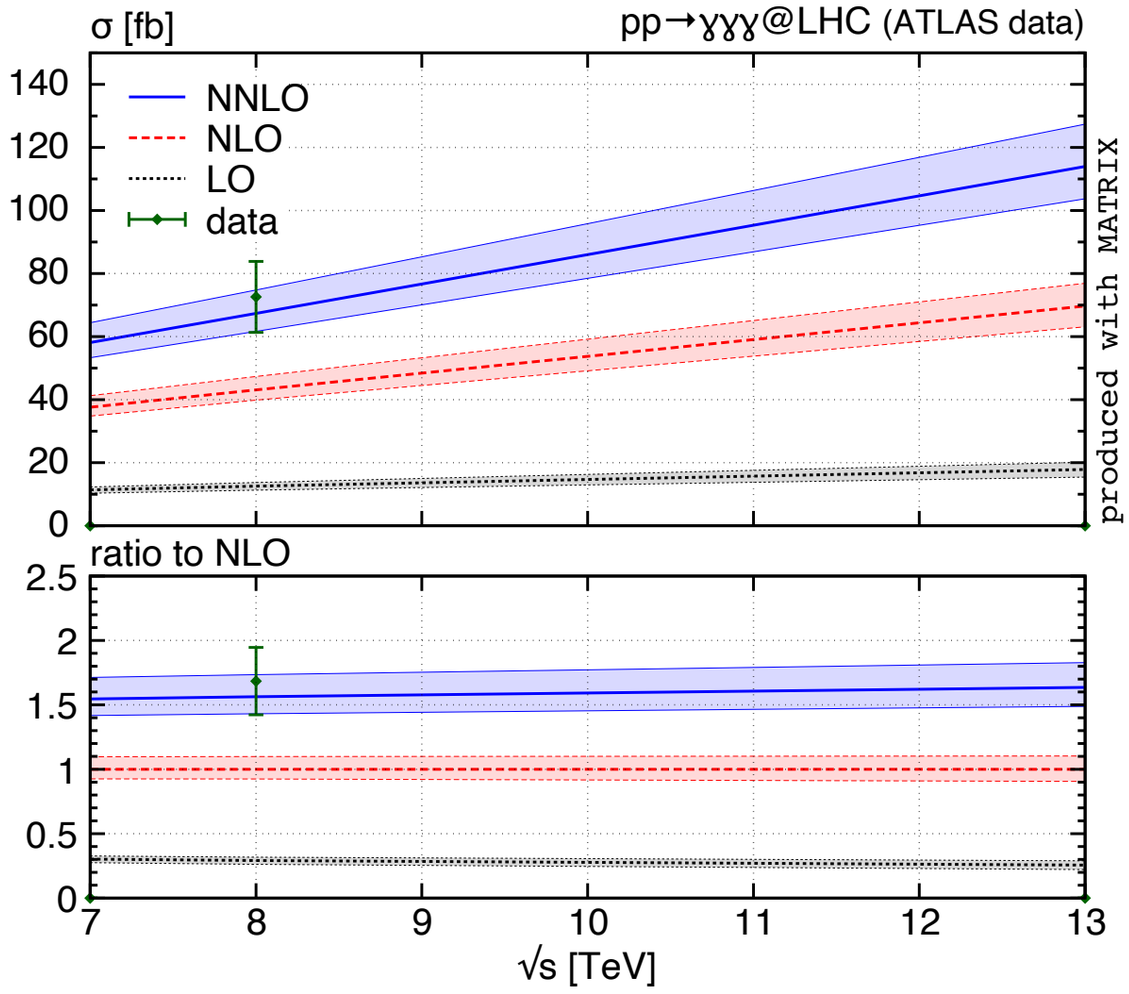
First (only) 2→3 process computed at NNLO QCD

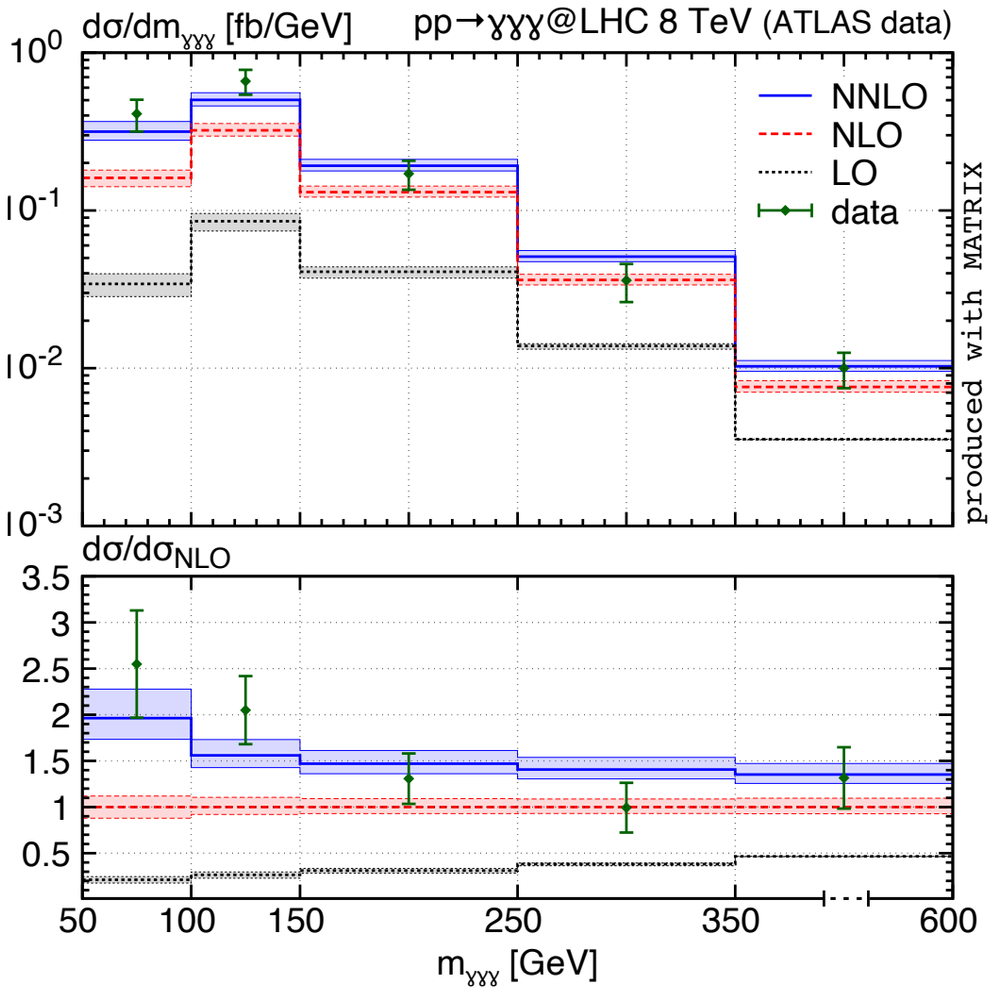
[Kallweit, Sotnikov, MW, '20]

in full agreement with [Chawdhry, Czakon, Mitov, Poncelet '19]

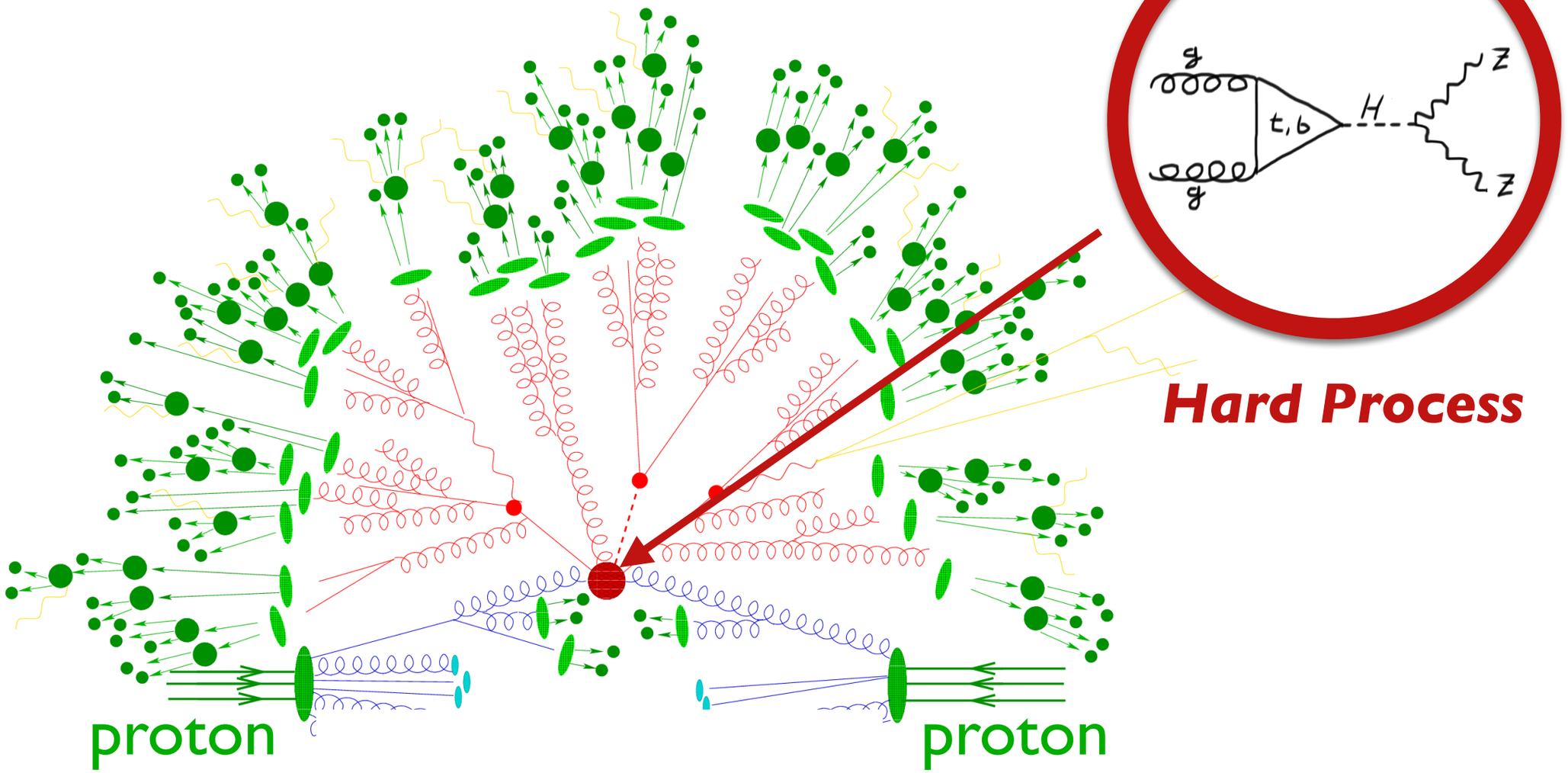
- ✦ two-loop five-point function [Abreu, Page, Pascual, Sotnikov '20]
- ✦ fast and efficient on-the-fly evaluation

➙ ***implemented in MATRIX (to be released)***



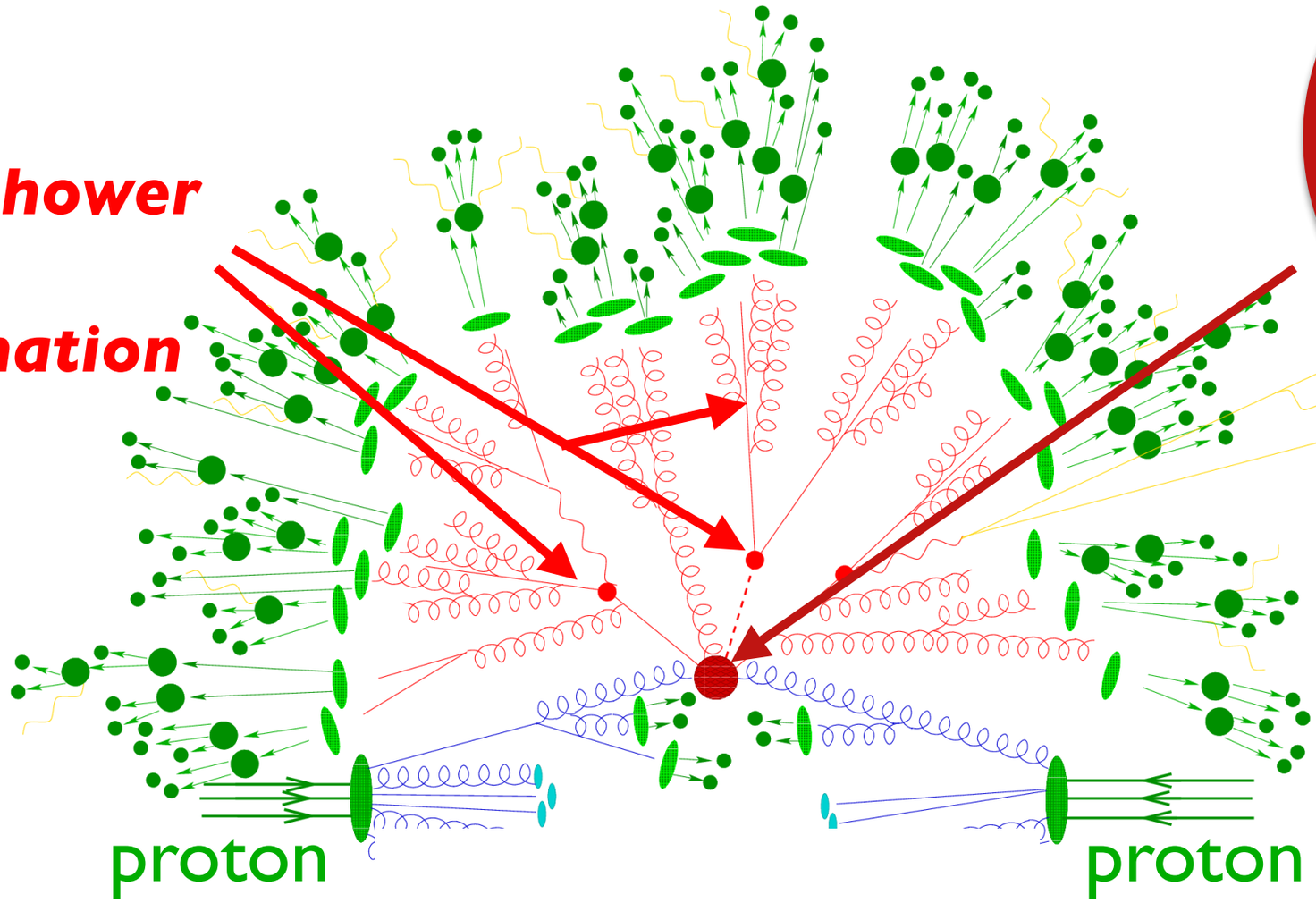


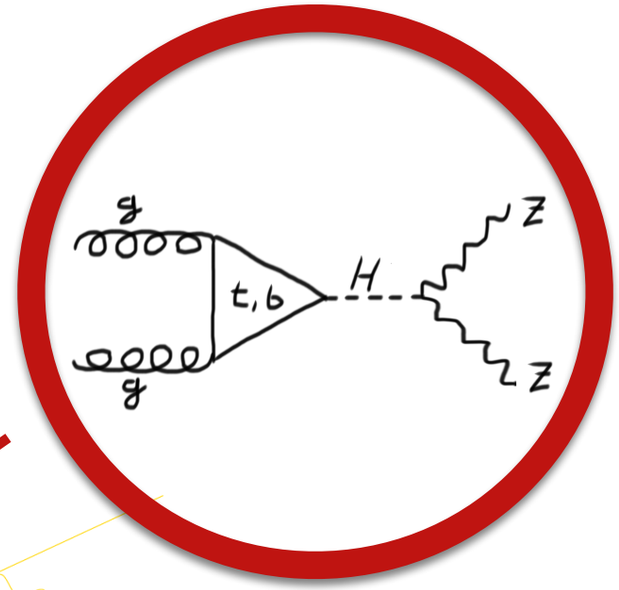
LHC event



LHC event

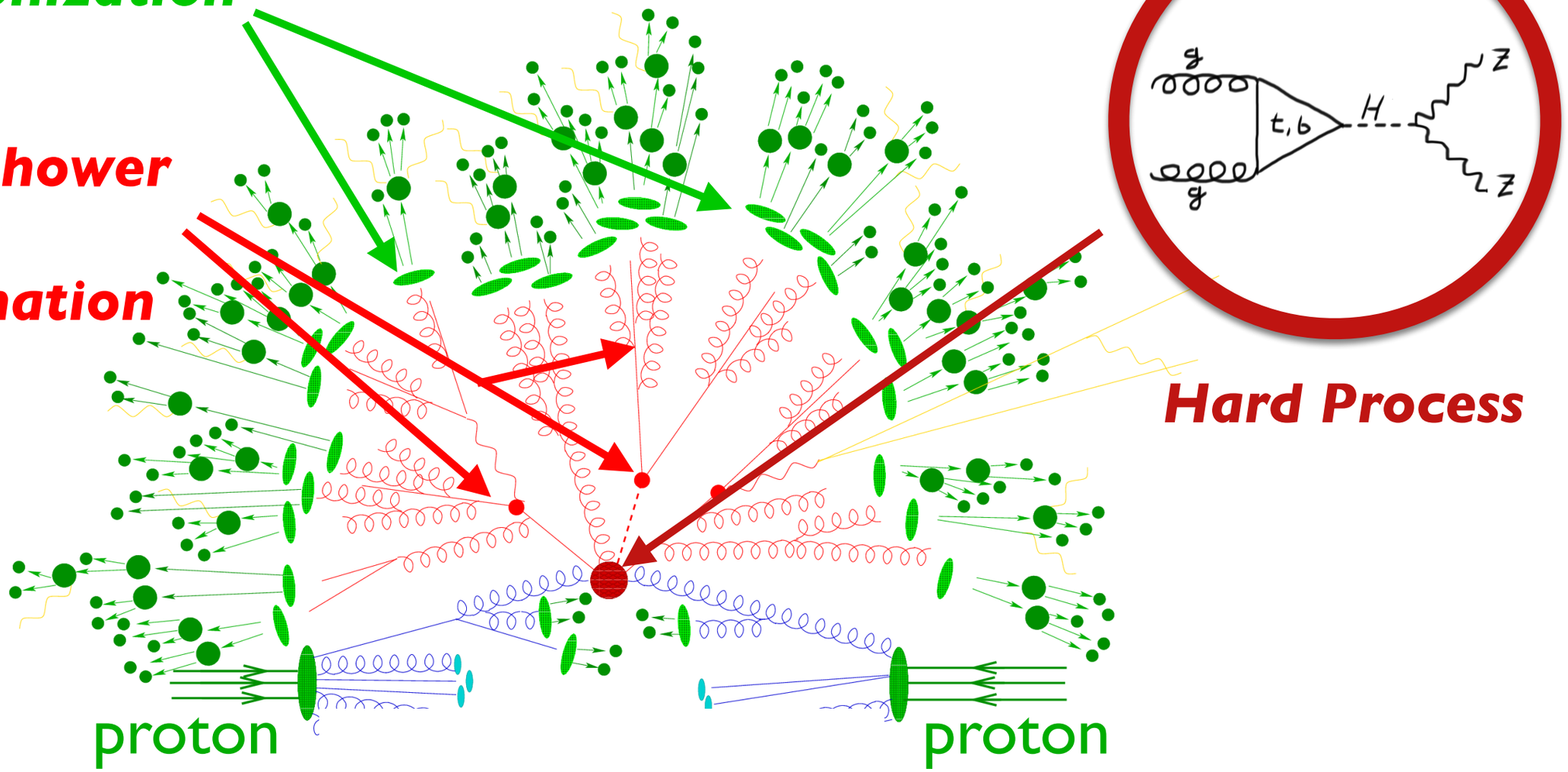
Parton Shower
or
Resummation



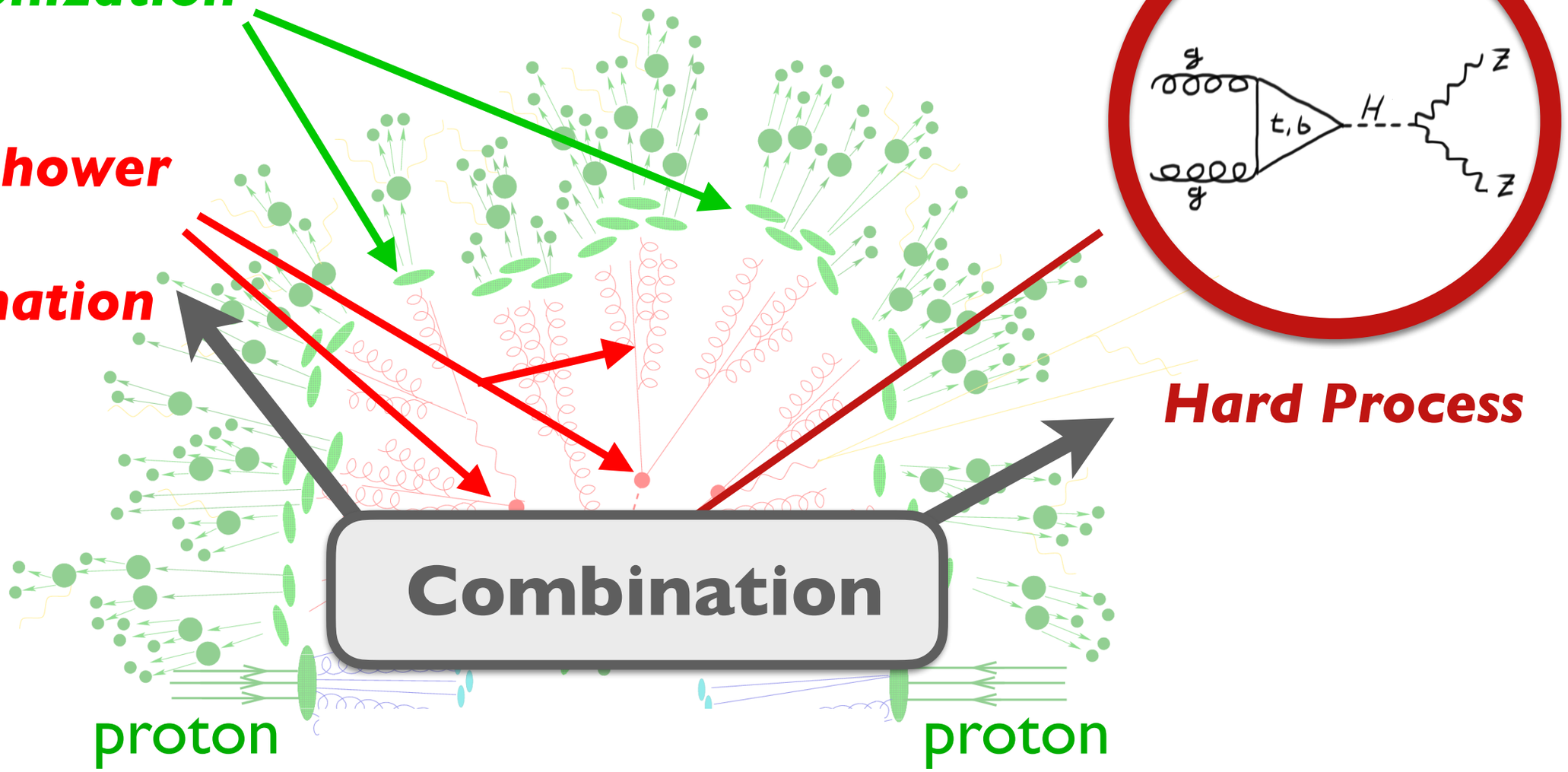


Hard Process

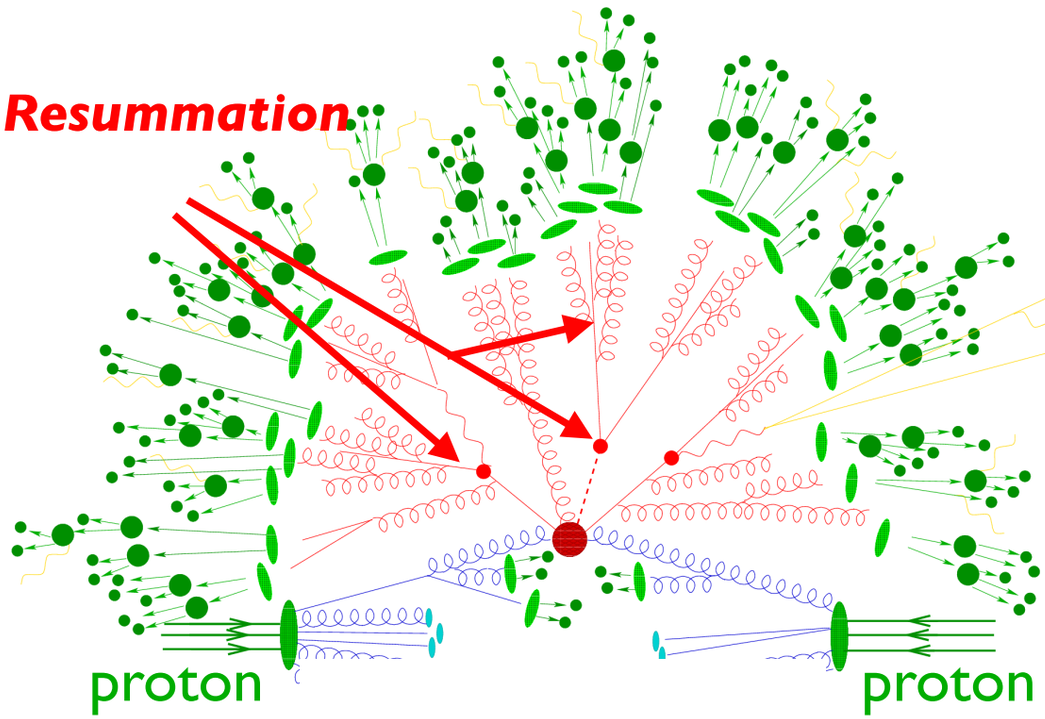
LHC event


Hadronization
Parton Shower
or
Resummation
g
g
t, b
H
Z
Z
Hard Process
proton
proton

LHC event


Hadronization
Parton Shower
or
Resummation
g
g
t, b
H
Z
Z
Hard Process
Combination
proton
proton

Resummation



$$\alpha_s L \sim 1 \Rightarrow \text{expansion in } \alpha_s \text{ not valid}$$

$$L = \log(p_T/Q)$$

$$\exp[-S_c] = \exp[\underbrace{L g_1(\alpha_s L)}_{\text{LL}} + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots]$$

LL

NLL

NNLL

$$d\sigma^{(\text{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \boxed{\exp\left[-S_c(b)\right]} \times \left[HC_1C_2\right]_{c\bar{c};a_1a_2} \times f_{a_1} f_{a_2}$$

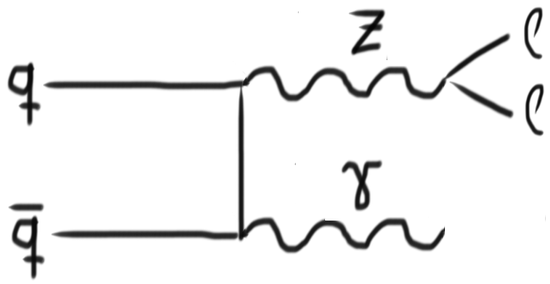
factorization formula (symbolic)

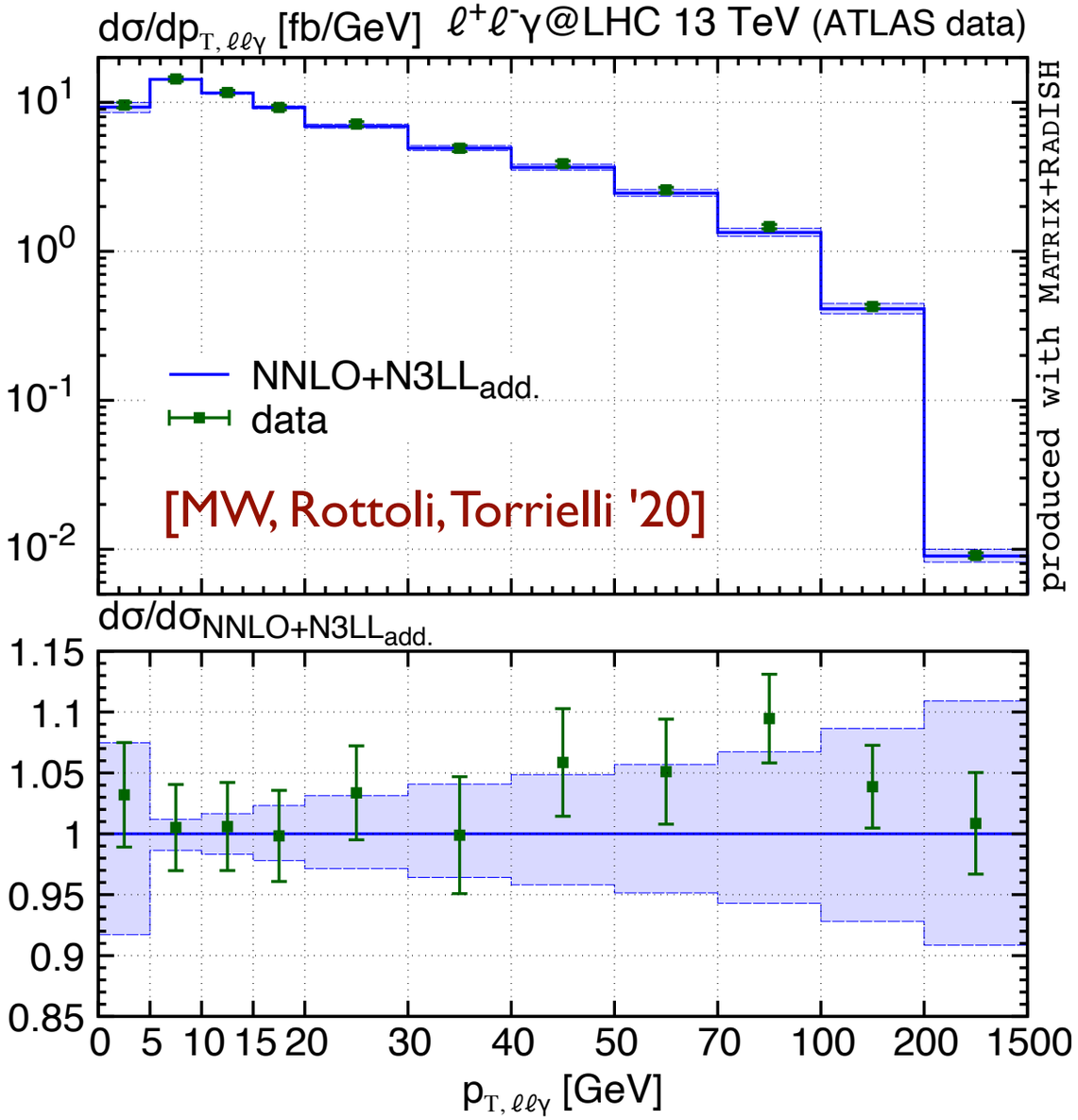
NNLO+Resummation

MATRIX+RadISH *https://matrix.hepforge.org/matrix+radish.html*

[Kallweit, Re, Rottoli, MW '20]

- ✦ automated for colour-singlet (all 2→1 and 2→2)
- ✦ state-of-the-art accuracy for various observables:
  - ❖ p_T of colour singlet at NNLO+N³LL
  - ❖ p_T of jet (jet-veto) at NNLO+NNLL
  - ❖ 2-D p_T-singlet & p_T-jet at NNLO+NNLL
- ✦ remarkable agreement with data from almost non-perturbative region to high p_T of Zγ

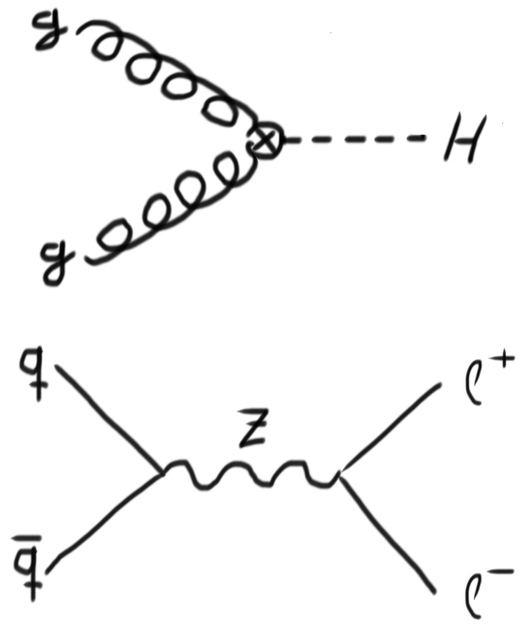




NNLO+PS

- seminal approaches for NLO+PS many years ago (POWHEG, MC@NLO)

- first NNLO+PS for simple 2→1 processes
  - ***MiNLO+reweighting*** [Hamilton, Nason, Zanderighi '12, + Re '13], [Karlberg, Hamilton, Zanderighi '14]
  - ***Geneva*** [Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '13], [Alioli, Bauer, Berggren, Tackmann, Walsh '15]
  - ***UNNLOPS*** [Höche, Prestel '14]



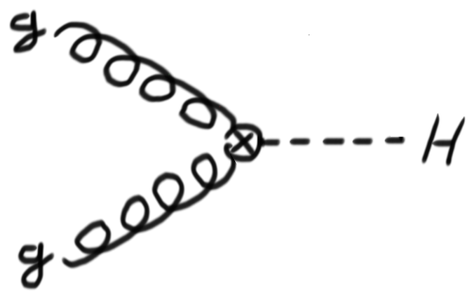
- ***MiNNLO$_{PS}$***: new approach with enormous potential

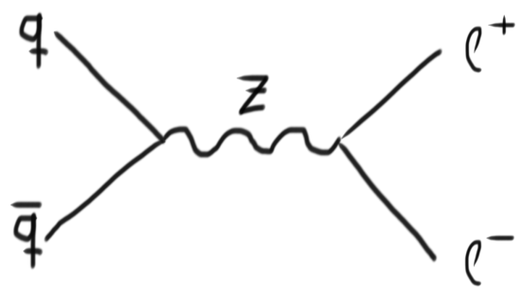
  [Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]
  - NNLO corrections extracted from analytic resummation formula

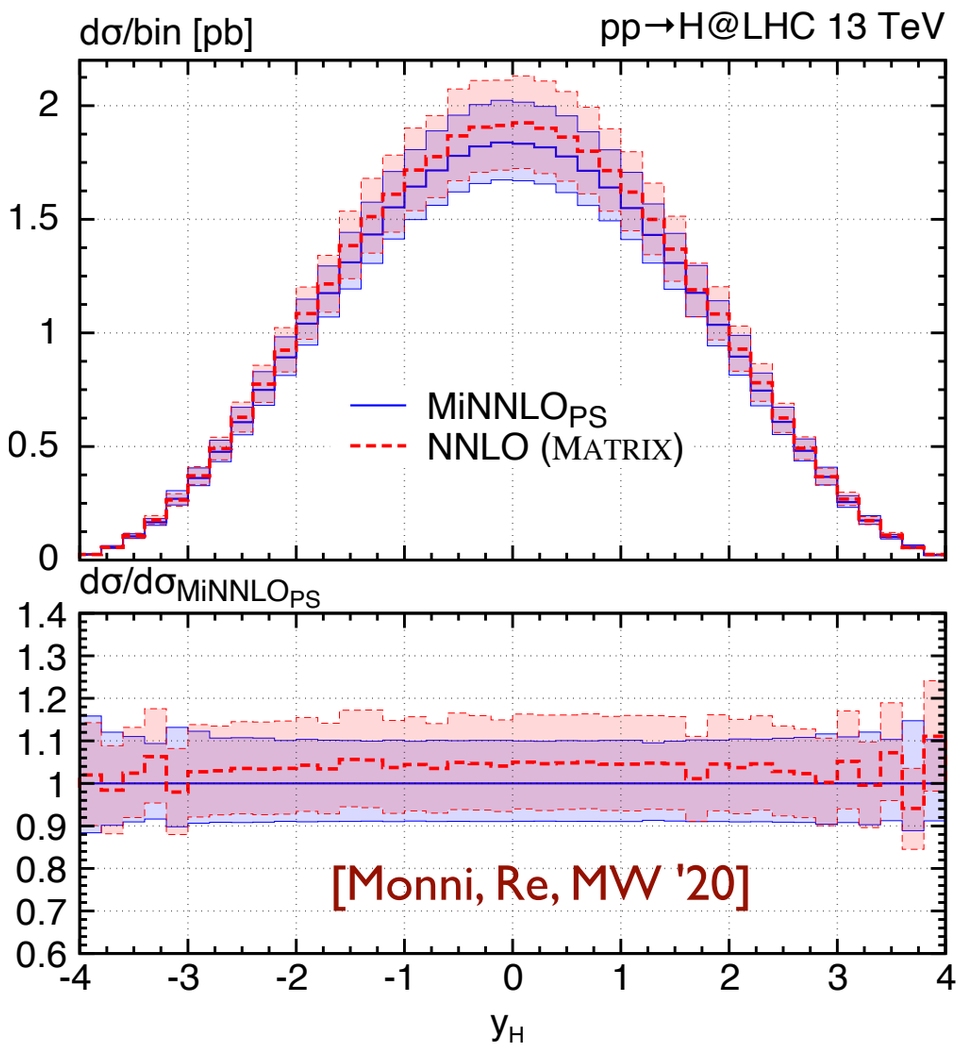
$$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left[-S_c(b)\right] \times \left[HC_1C_2\right]_{c\bar{c};a_1a_2} \times f_{a_1} f_{a_2}$$

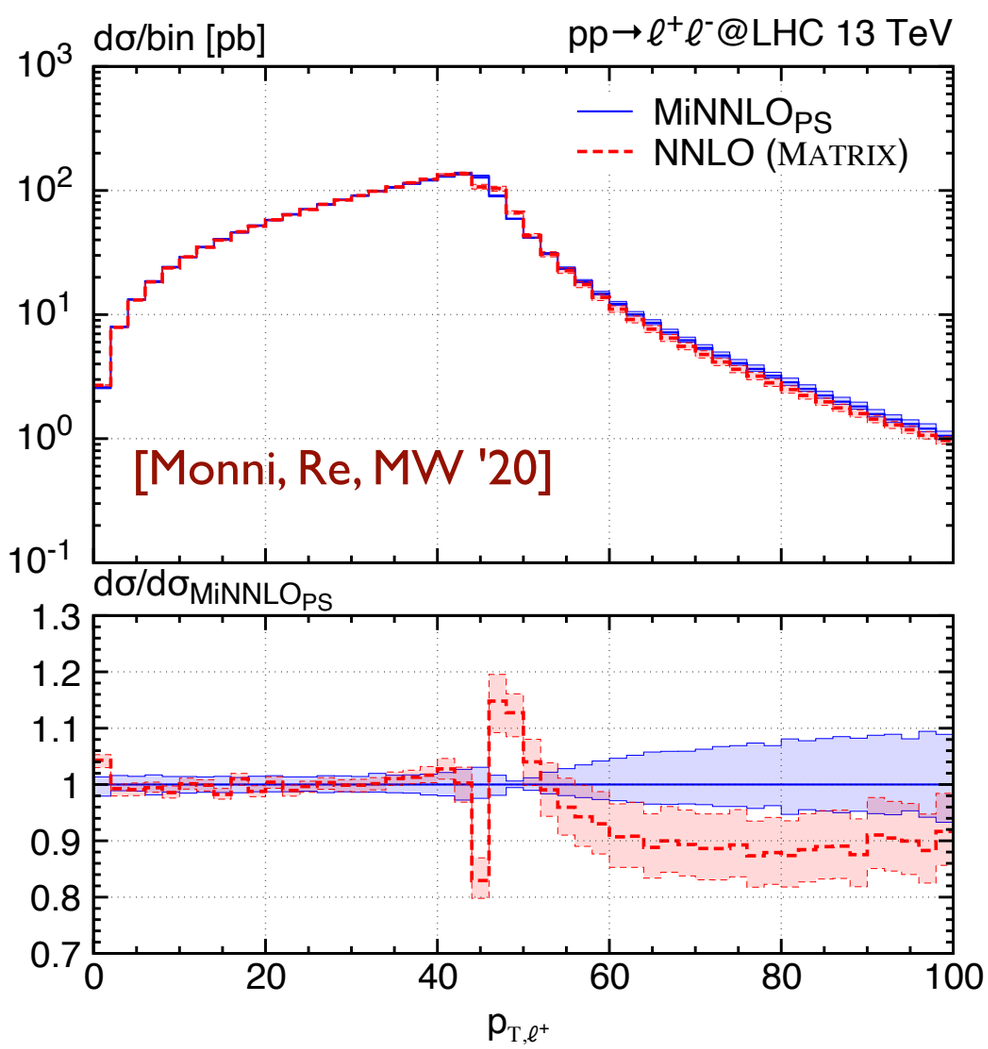
  - physically sound (no new unphysical scale)
  - applicable beyond 2→1 processes (even beyond colour-singlet)
  - numerically efficient

MiNNLO$_{PS}$ for $2 \to 1$ (color singlet)

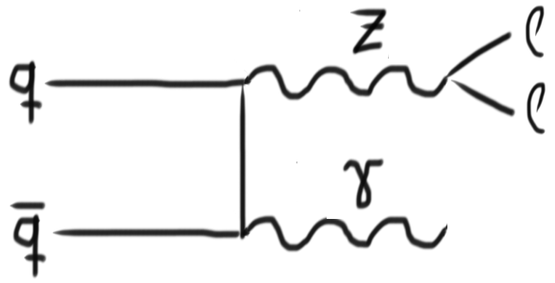


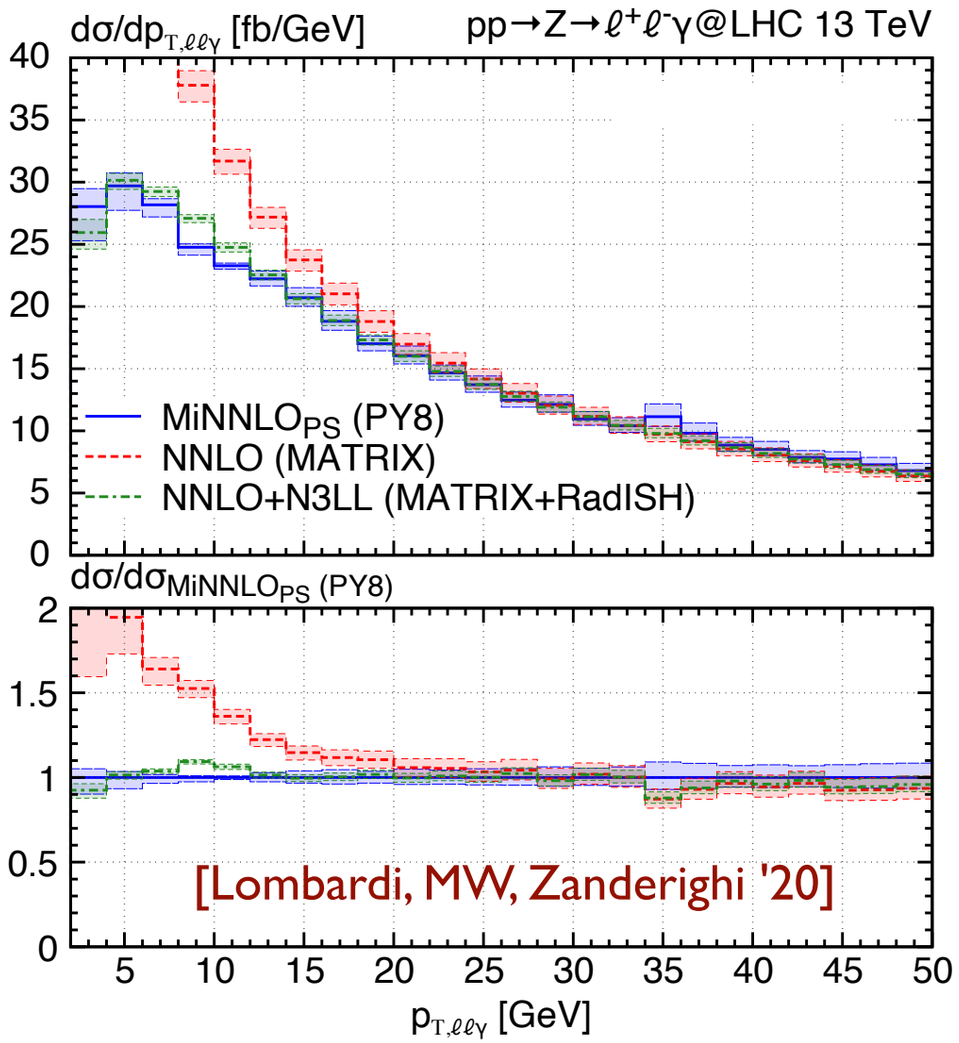


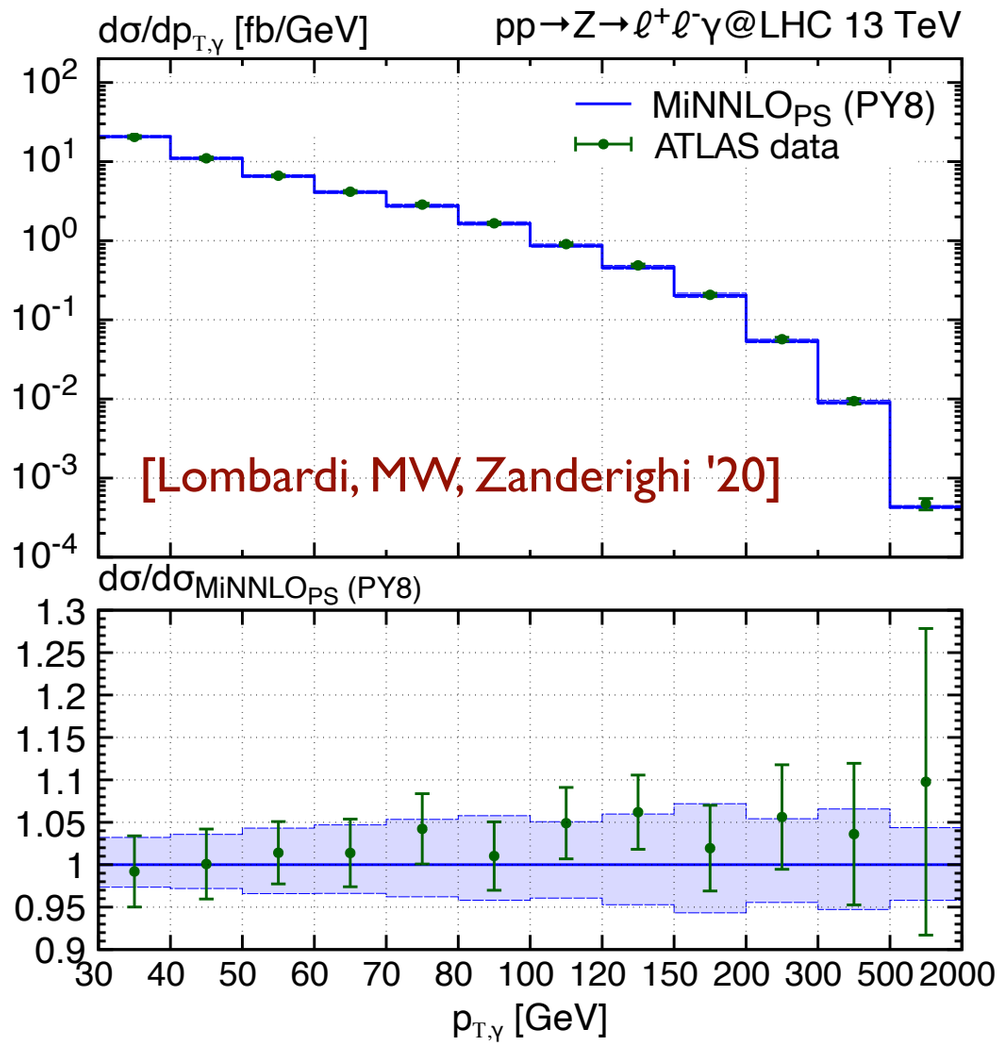




MiNNLO$_{PS}$ extension to 2→2 (Zγ)

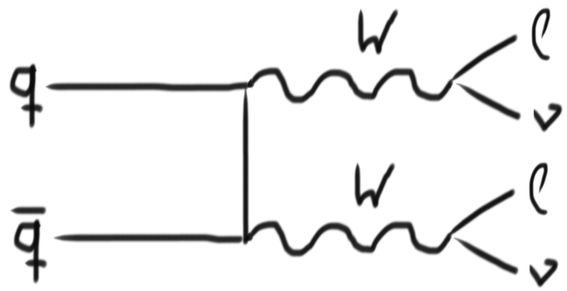




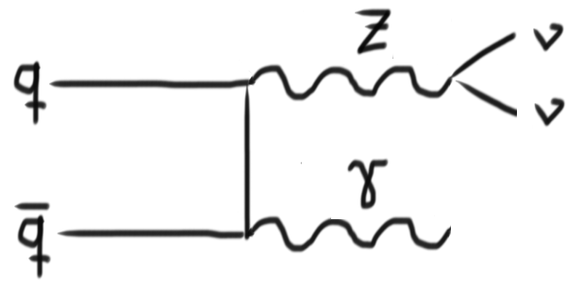


→ PhD project of Daniele Lombardi (first on-the-fly 2→2 NNLO+PS computation)

MiNNLO$_{PS}$ ongoing 2→2 campaign

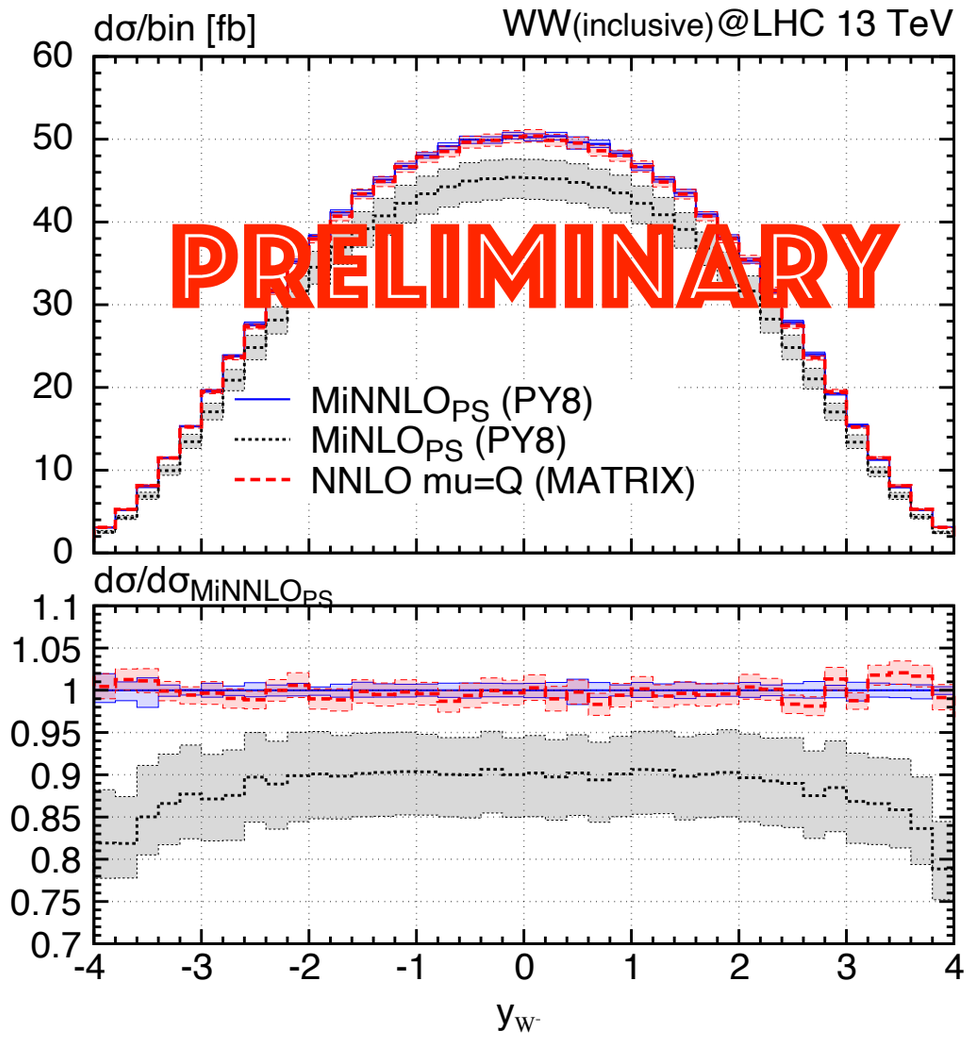


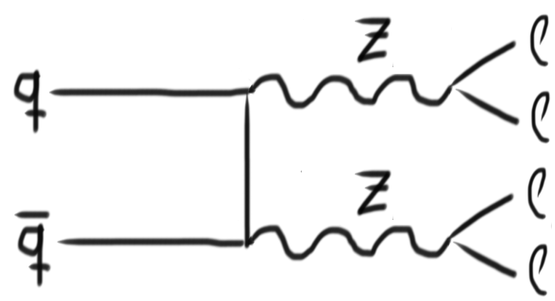
[Lombardi, MW, Zanderighi 'in preparation]



DM?

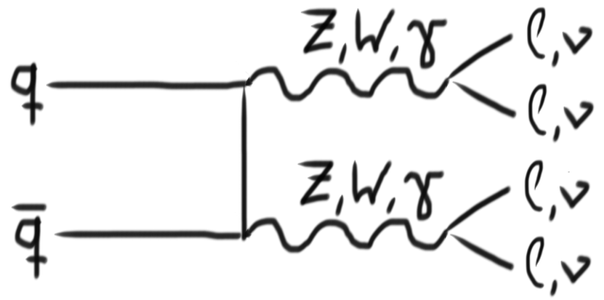
[Lombardi, MW, Zanderighi 'in preparation]





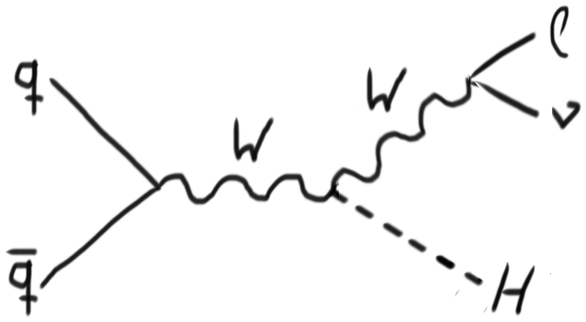
[Buonocore, Lombardi, Rottoli, MW, Zanderighi 'started]

eventually

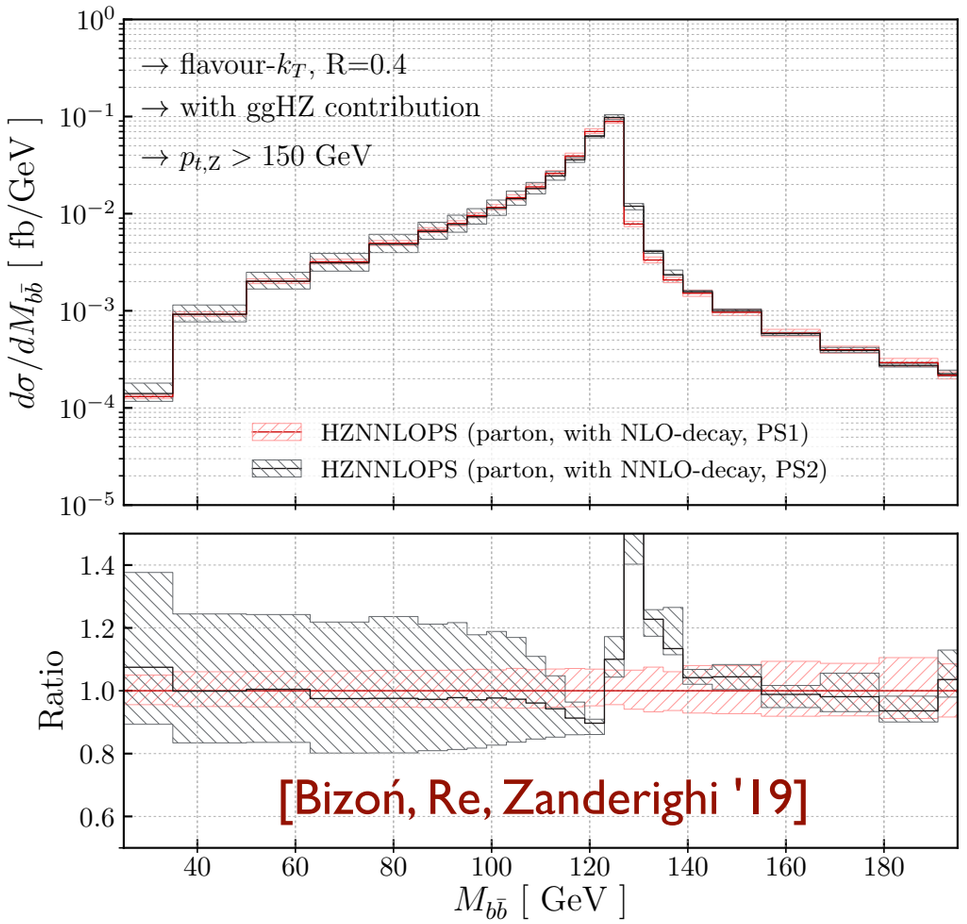


MiNNLO$_{PS}$ Higgstrahlung & SMEFT

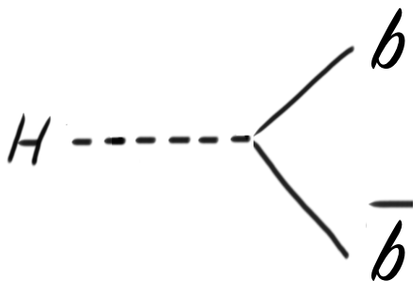
➙ ***new PhD student Silvia Zanoli implemented Higgstrahlung***



[MW, Zanderighi, Zanoli 'ongoing]



➙ ***combination with H→bb decay at NNLO+PS***

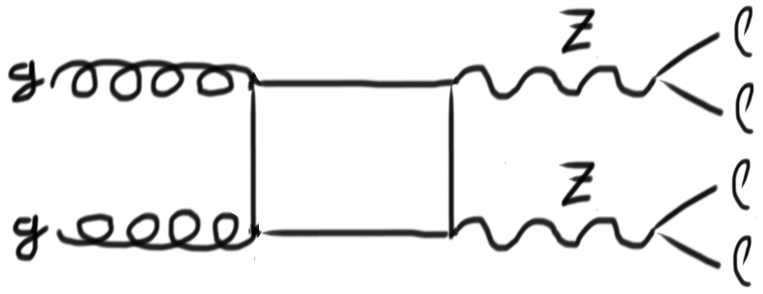


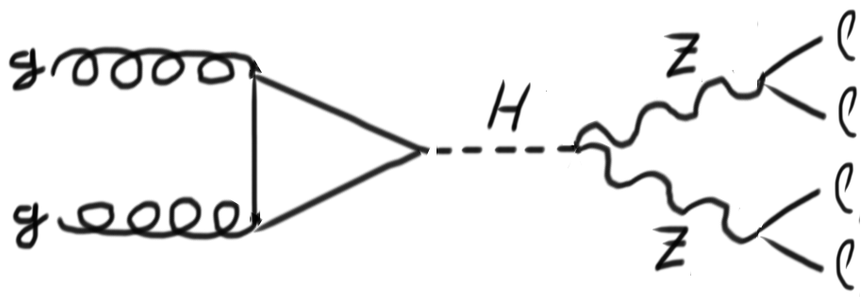
[Bizoń, Re, Zanderighi '19]

➙ ***inclusion of SMEFT effects with new PostDoc Darren Scott:***

- ❖ ***in H→bb decay at NNLO+PS (computed at NLO*** [Cullen, Pecjak, Scott '19]***)***
- ❖ ***in all diboson processes***

NLO+PS for loop-induced





➙ ***started with Gabriel Koole (shared PhD student with BSM Group of Uli Haisch)***

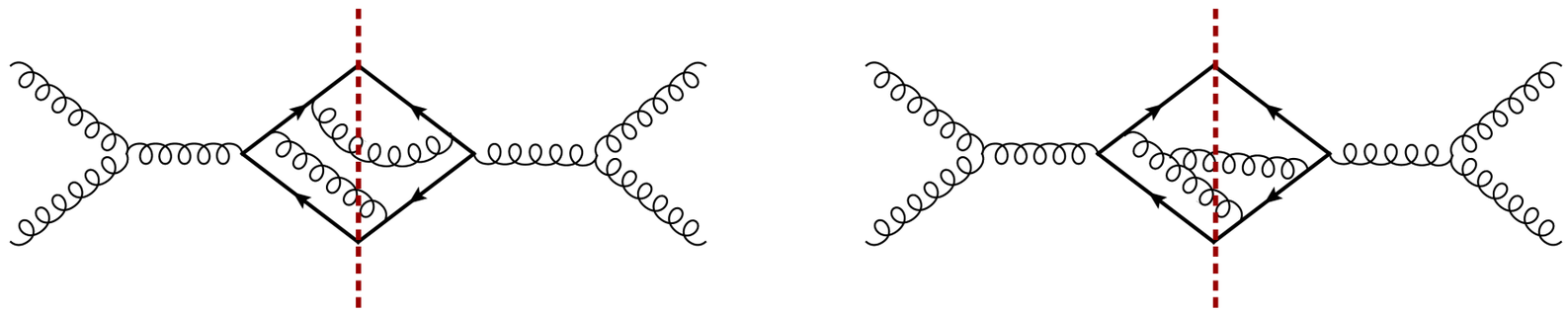
- formally NNLO (α_s^2) correction, but enhanced by gluon luminosities
- effectively only LO accurate, NLO correction (α_s^3) very large [Grazzini, Kallweit, MW, Yook '18]
- $q\bar{q} \to 4\ell$ NNLO+PS generator must be supplemented by $gg \to 4\ell$ NLO+PS generator
- include BSM/SMEFT effects (in particular in the Higgs diagram ➙ see talk by Uli !)

MiNNLO$_{PS}$ extension to heavy quarks

➙ ***started about one year ago with PostDoc Javier Mazzitelli***

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi 'in preparation]

- Extension to tt production more complicated due to final state radiation!

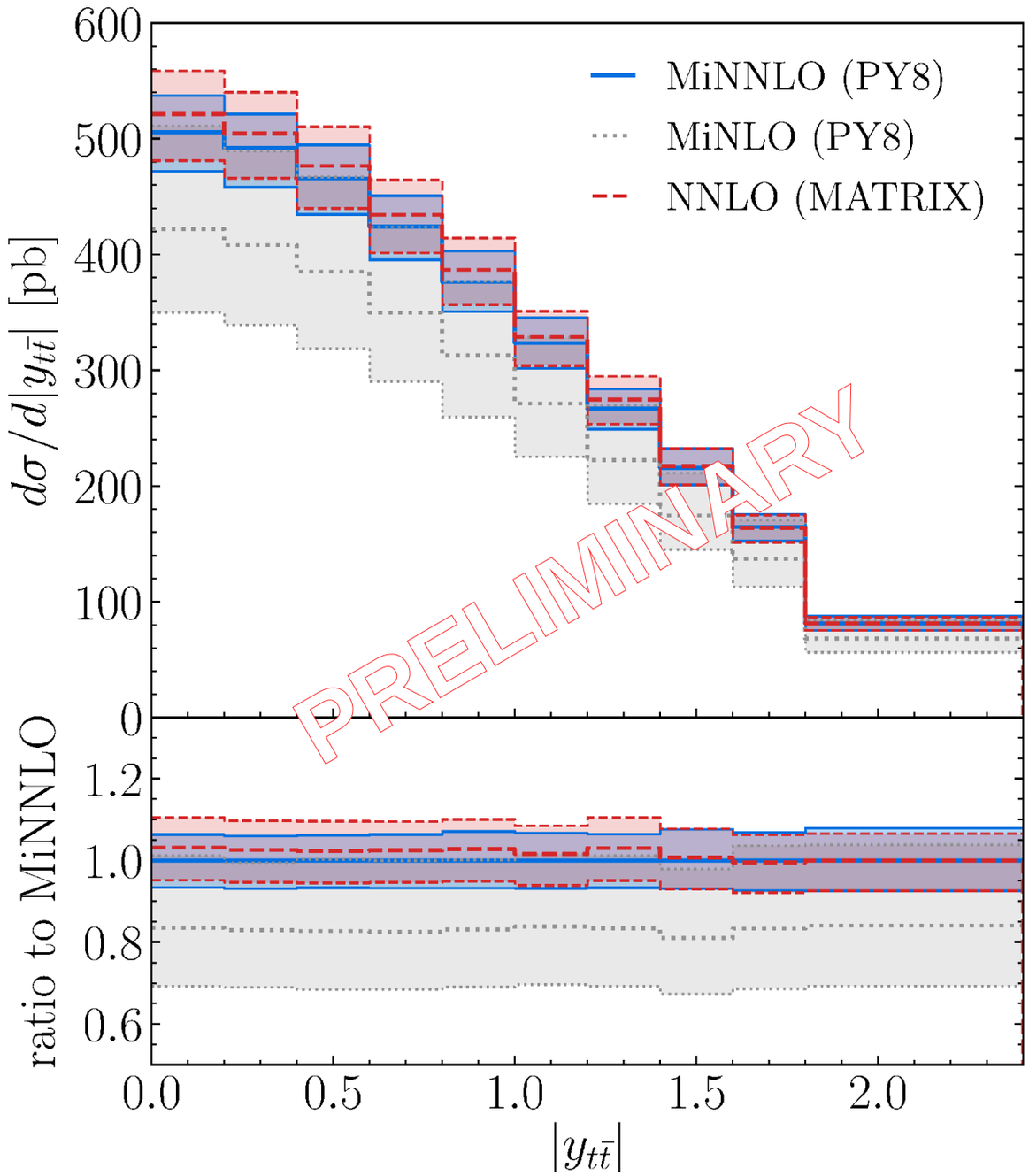


Colour singlet: $$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left[-S_c(b)\right] \times \left[HC_1C_2\right]_{c\bar{c};a_1a_2} \times f_{a_1} f_{a_2}$$

$t\bar{t}$ production: $$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left[-S_c(b)\right] \times \left[\mathrm{Tr}(\mathbf{H\Delta})C_1C_2\right]_{c\bar{c};a_1a_2} \times f_{a_1} f_{a_2}$$

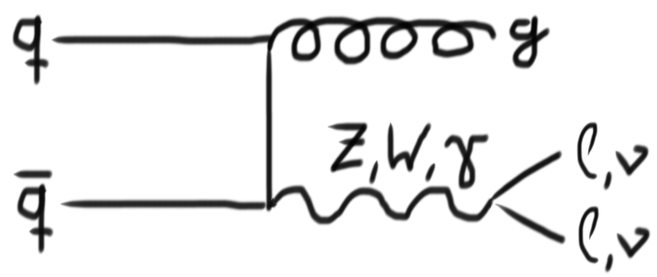
Effects coming from soft emissions from the FS contained in operator **Δ**

MiNNLO$_{PS}$ extension to heavy quarks



[Mazzitelli, Monni, Nason, Re, MW, Zanderighi 'in preparation]

MiNNLO$_{PS}$ extension to jets



➙ ***planned with new PostDoc Markus Ebert, who is an expert in Soft Collinear Effective Theory (SCET)***

➙ ***exploit SCET factorization formula of jet resolution variable (N-jettiness)***

➙ ***various important processes (H+jet, Z+jet, W+jet, γ+jet)***

➙ ***path towards N^{3}LO+PS matching***

Summary

★ with the completion of SM, particle physics entered new era: the SM is a beautiful theory that works spectacularly at colliders, but is incomplete

★ vast progress in SM predictions within our group; new members will further push activities; development of cutting-edge technologies:

- ❖ NNLO 2→3
- ❖ analytic resummation
- ❖ NNLO+PS
- ❖ ...

★ we live in data driven times (progress from experiment), but theory crucial to interpret data and to enhance sensitivity to anomalies

FREE YOUR MIND.

```
[wiesemann:~/different-branch-munich/MATRIX] ./matrix

            /---------------------------------------------------------------------\
            | MATRIX: A fully-differential NNLO(+NNLL) process library            |
            |                                                                     |
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            |         | \/ |    / _ \  |____|  / _ \  ||   \\  //                |
            |         || \/ ||  | |_| |   ||    ||_||  ||    \\ //               |
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            |                                                                     |
            |          Version: 1.0.0.release_candidate4      Aug 2017            |
            |                                                                     |
            | Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision --   |
            | Automates qT-subtraction and Resummation to Integrate X-sections    |
            |                                                                     |
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            | /          /         /          /         /          /              |
            |                                                                     |
            | M. Grazzini                              (grazzini@physik.uzh.ch)   |
            | S. Kallweit                          (stefan.kallweit@cern.ch)      |
            | M. Wiesemann                        (marius.wiesemann@cern.ch)      |
            |---------------------------------------------------------------------|
            | MATRIX is based on a number of different computations and tools     |
            | from various people and groups. Please acknowledge their efforts    |
            | by citing the list of references which is created with every run.   |
            \---------------------------------------------------------------------/

<<MATRIX-MAKE>> This is the MATRIX process compilation.
<<MATRIX-READ>> Type process_id to be compiled and created. Type "list" to show
                available processes. Try pressing TAB for auto-completion. Type
                "exit" or "quit" to stop.
|============>> list
-------------------------------------------------------------------------------------
process_id   ||   process                          ||   description
-------------------------------------------------------------------------------------
pph21         >>   p p --> H                        >>   on-shell Higgs production
ppz01         >>   p p --> Z                        >>   on-shell Z production
ppw01         >>   p p --> W^-                      >>   on-shell W- production with CKM
ppwx01        >>   p p --> W^+                      >>   on-shell W+ production with CKM
ppeex02       >>   p p --> e^- e^+                  >>   Z production with decay
ppnenex02     >>   p p --> v_e^- v_e^+              >>   Z production with decay
ppenex02      >>   p p --> e^- v_e^+                >>   W- production with decay and CKM
ppexne02      >>   p p --> e^+ v_e^-                >>   W+ production with decay and CKM
ppaa02        >>   p p --> gamma gamma              >>   gamma gamma production
ppeexa03      >>   p p --> e^- e^+ gamma            >>   Z gamma production with decay
```

Back Up