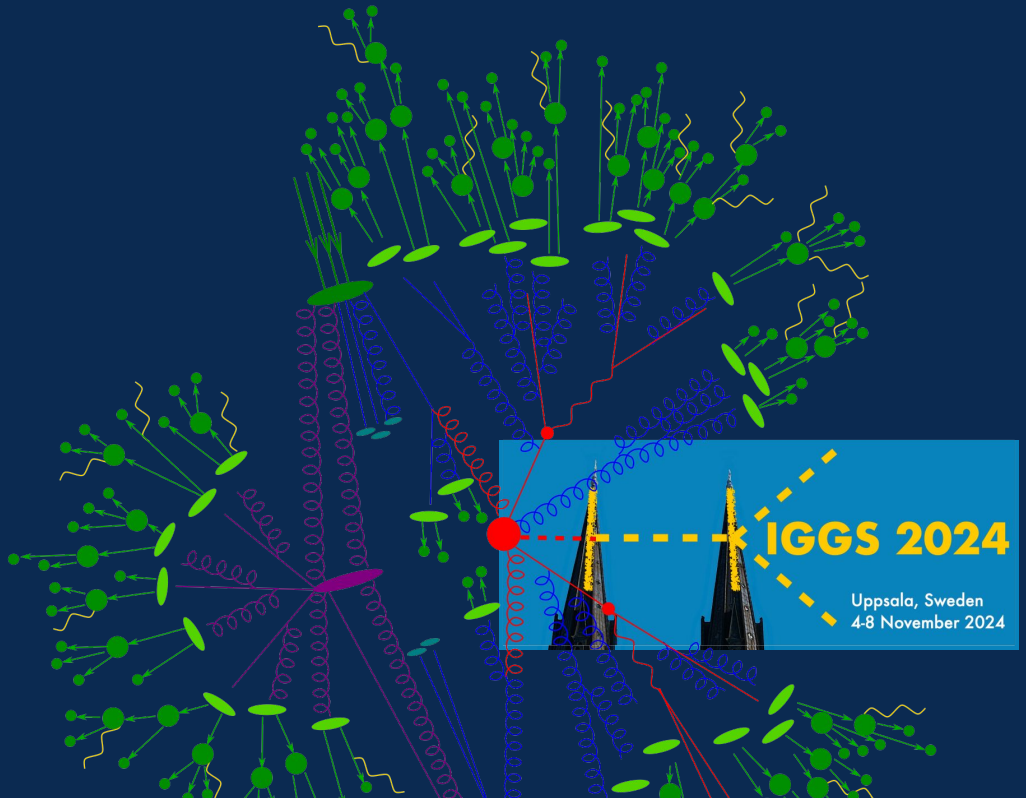
TECHNISCHE UNIVERSITÄT DRESDEN
INSTITUT FÜR KERN- UND TEILCHENPHYSIK

Monte Carlo matters for Higgs backgrounds

Frank Siegert


IGGS 2024
Uppsala, Sweden
4-8 November 2024

Outline

- Is anything **not** a Higgs background!? Plan for this talk:

"Mainstream backgrounds"
- **V+jets**
- **VV+jets**
- **$t\bar{t}$+jets**

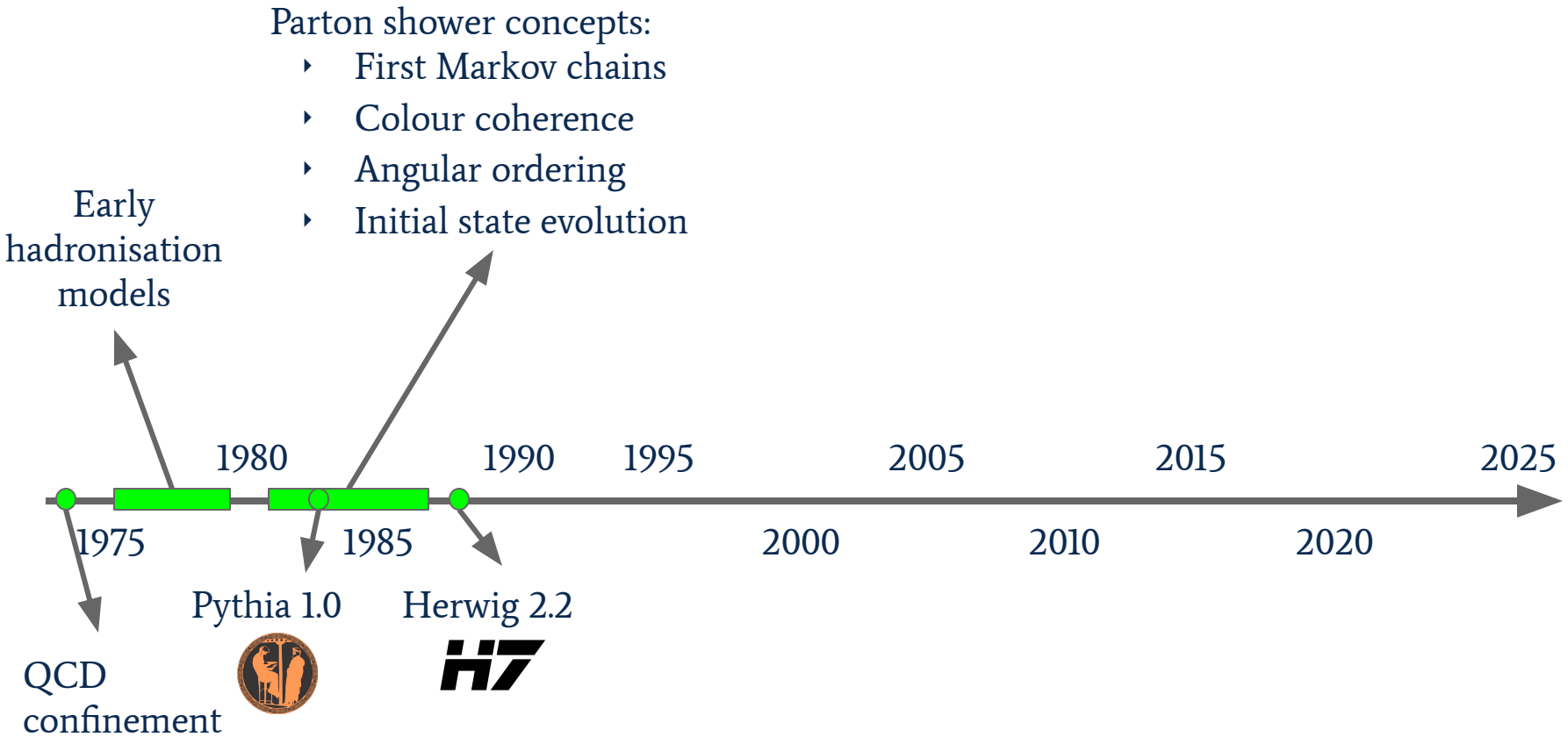
= basically full history of LHC event generation!
→ allow me 5 mins for 3 interesting aspects

"Specific (and tricky)"
- **Diphoton production**
- **Associated heavy flavour production**
- **Higgs as background**

→ the rest of the talk

Mainstream backgrounds

History of LHC event generation



History of LHC event generation

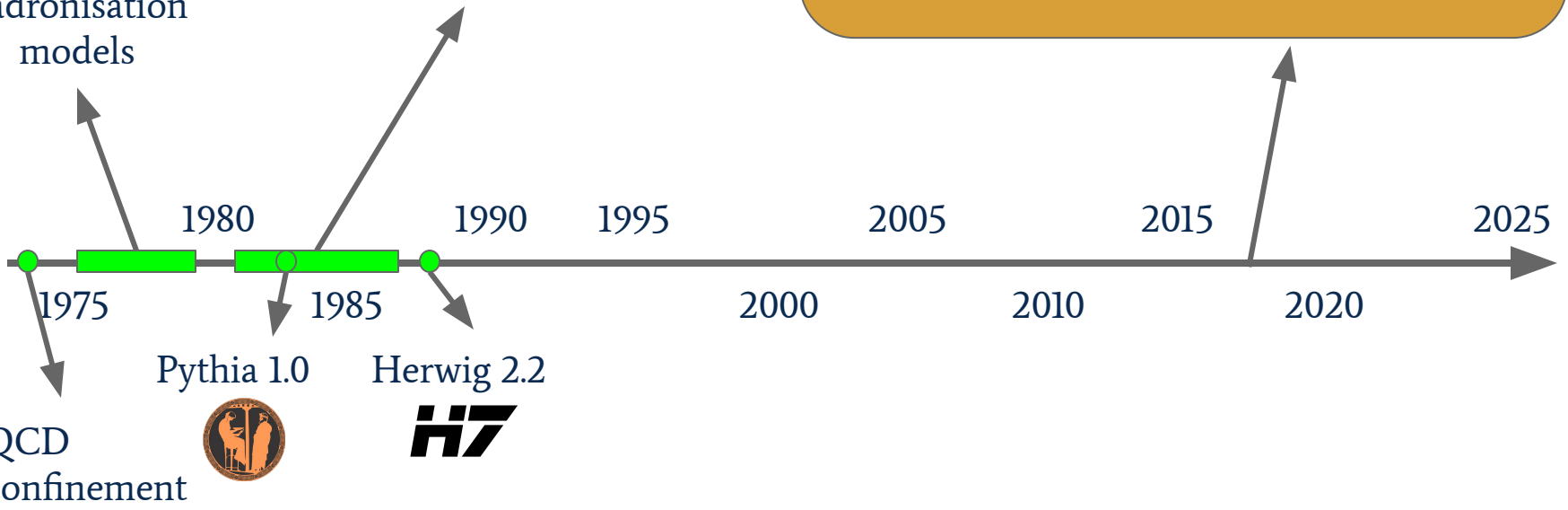
Parton shower concepts:

- First Markov chains
- Colour coherence
- Angular ordering
- Initial state evolution

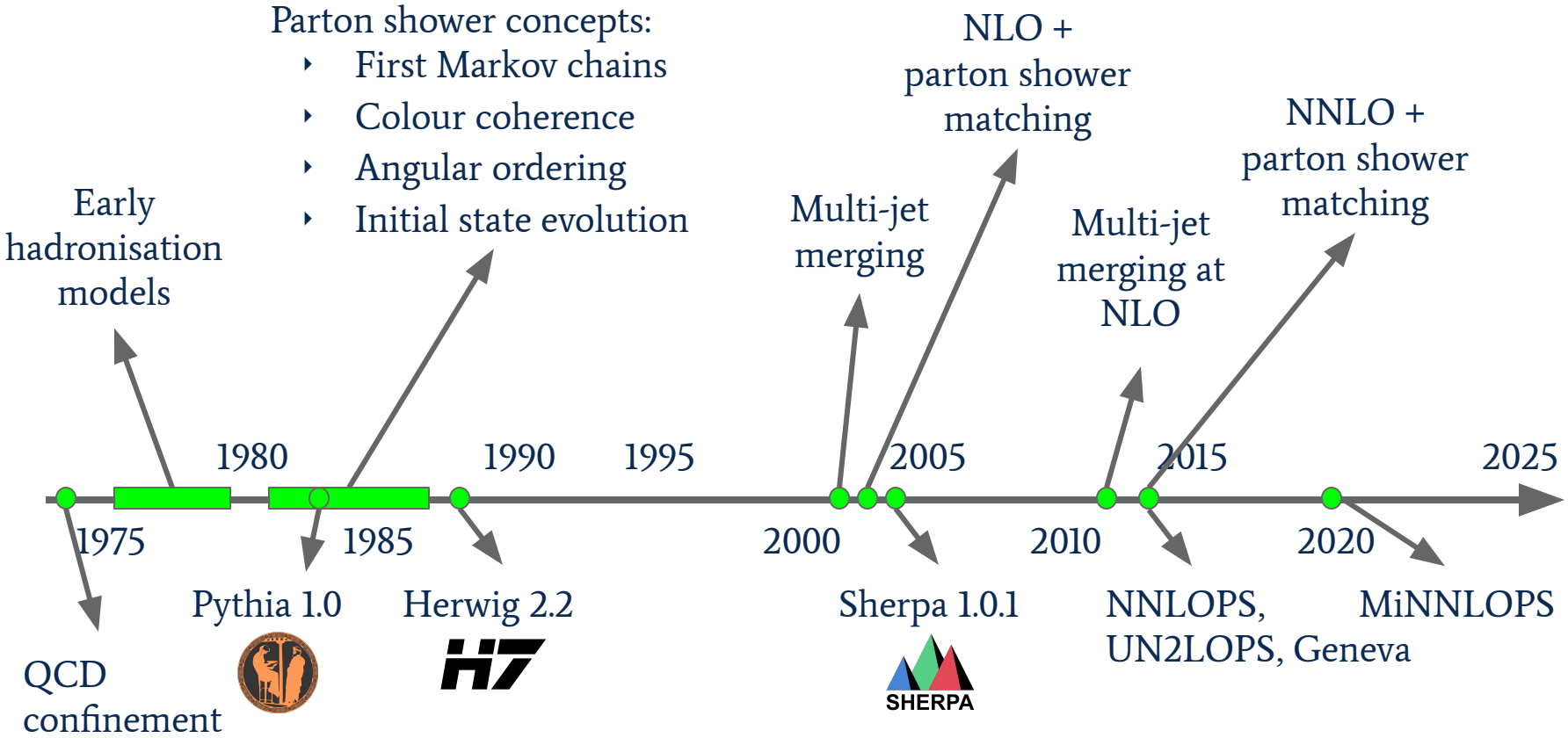
Recent efforts:
Higher formal accuracy of shower algorithms in collinear approximation

→ Silvia's talk

Early hadronisation models



History of LHC event generation



History of LHC event generation

Beyond the collinear approximation using higher-order calculations!

NLO+PS matching

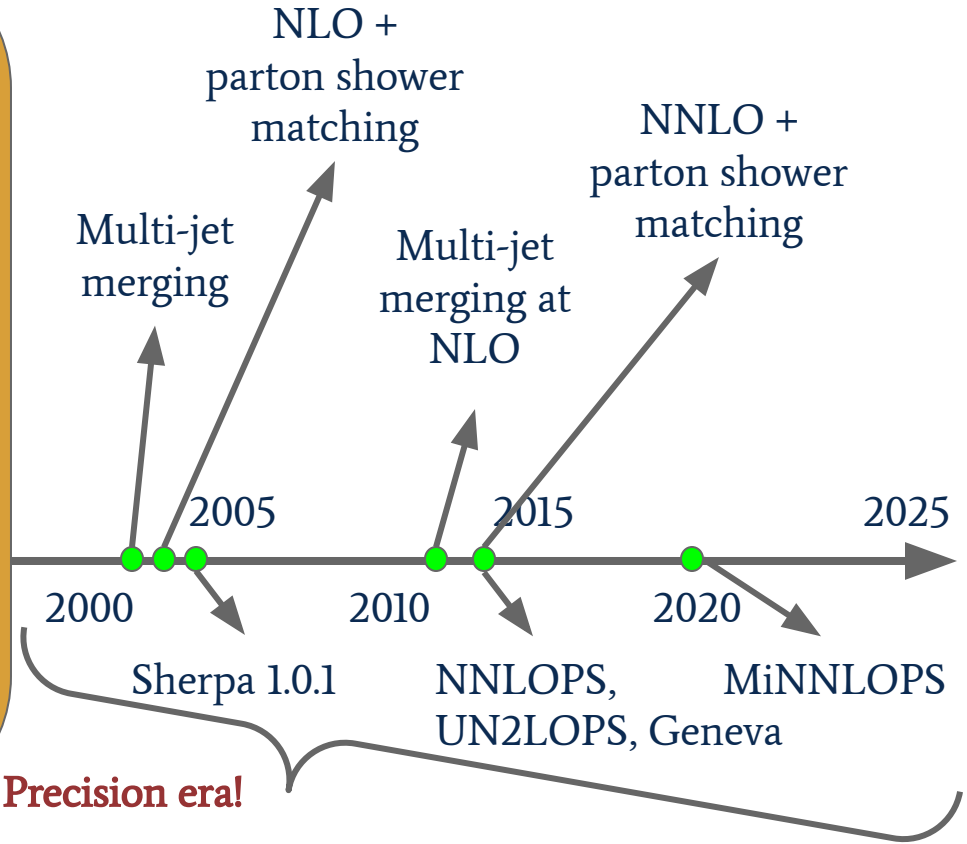
- MC@NLO, Powheg

NNLO+PS matching

- MiNNLOPS, UN^{2}LOPS, Geneva

Multi-jet merging

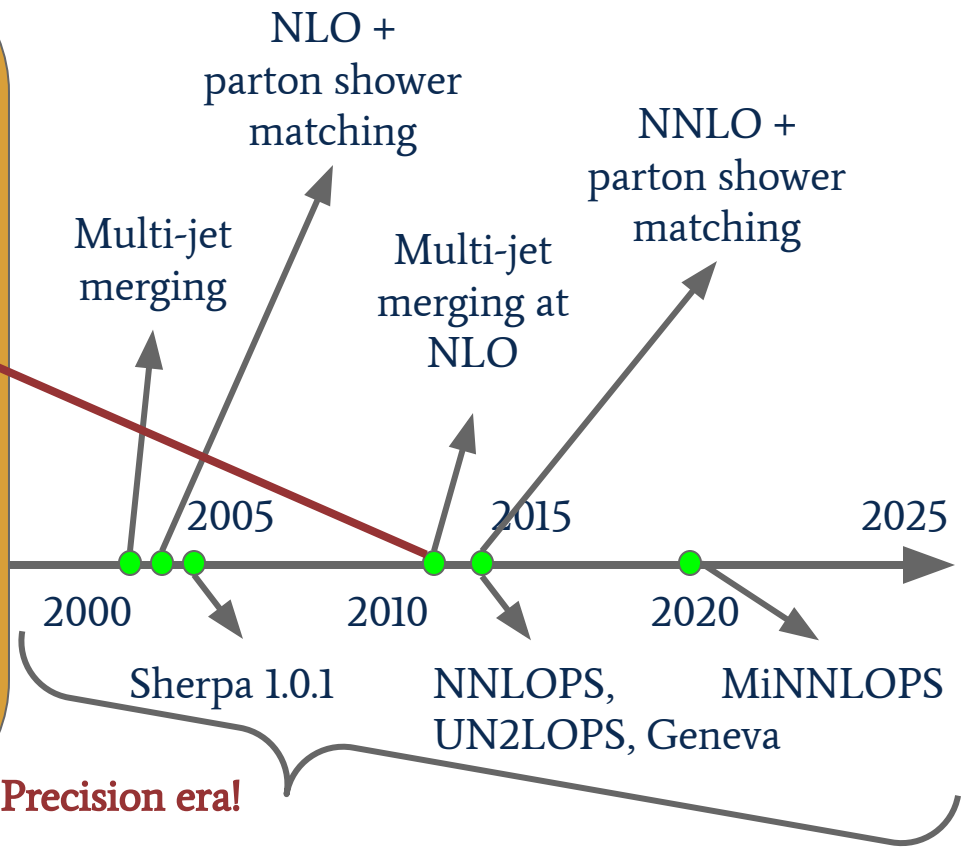
- MEPS@NLO, FxFx, ...



History of LHC event generation

Beyond the collinear approximation using higher-order calculations!

2012 - Year of the Higgs



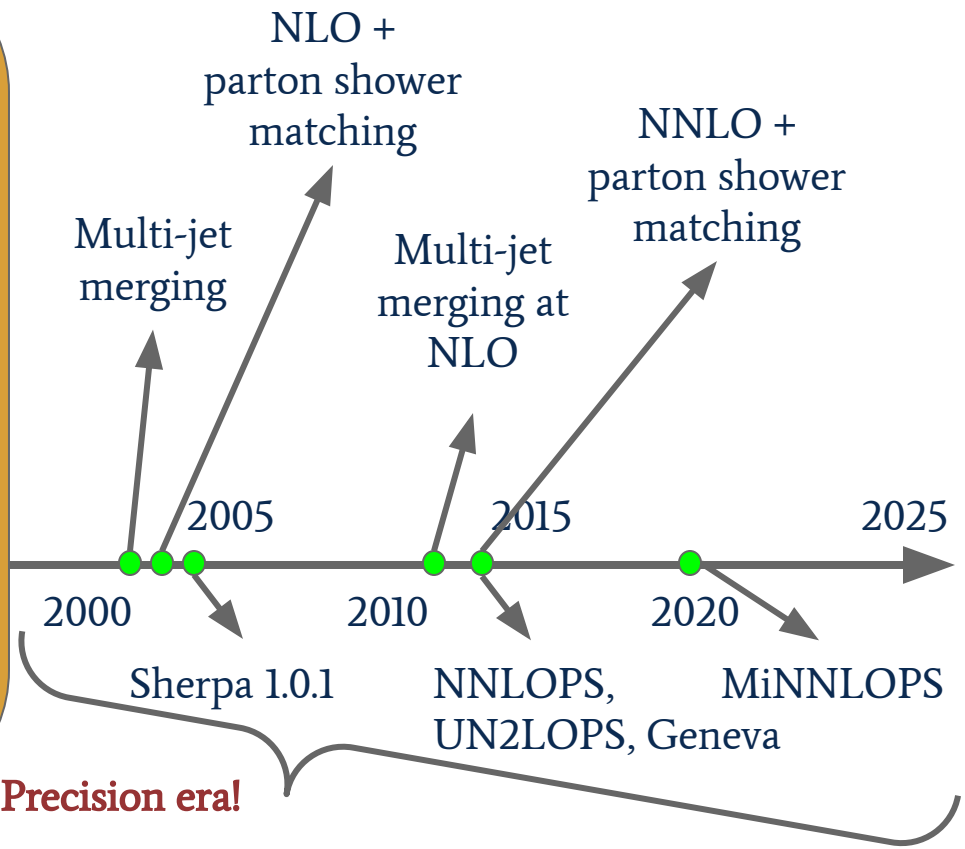
History of LHC event generation

Beyond the collinear approximation using higher-order calculations!

2012 - Year of ~~the Higgs~~ NLO multi-jet merging

Lavesson, Lönnblad (2008)
Höche, Krauss, Schönherr, FS (2012)
Frederix, Frixione (2012)
Plätzer (2012)
Alioli et al. (2012)
Lönnblad, Prestel (2012)
Hamilton, Nason, Oleari, Zanderighi (2012)

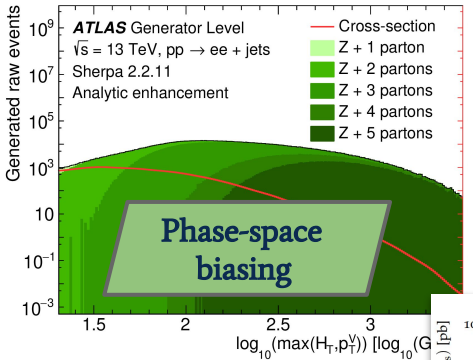
To date:
Work horse of LHC event generation!

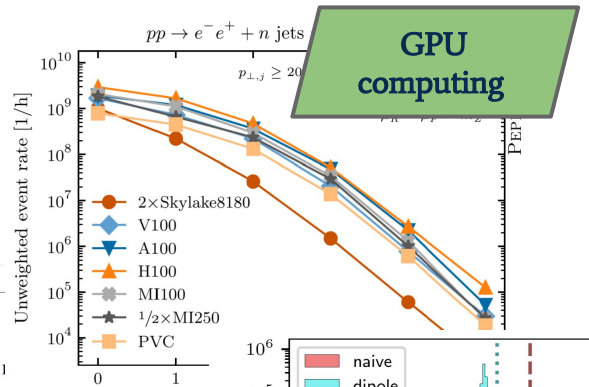


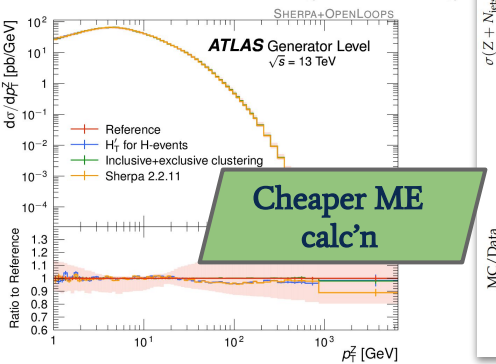
V+jets: CPU efficiency

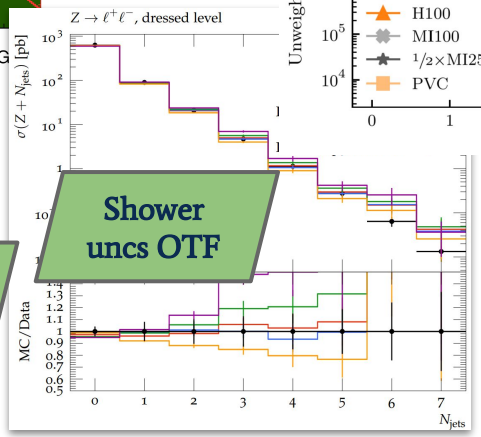
- V+jets with multi-jet merging = bulk of LHC event generation
  Does not scale to HL-LHC needs (and kills the environment)
  → Recent efforts for reducing CPU consumption

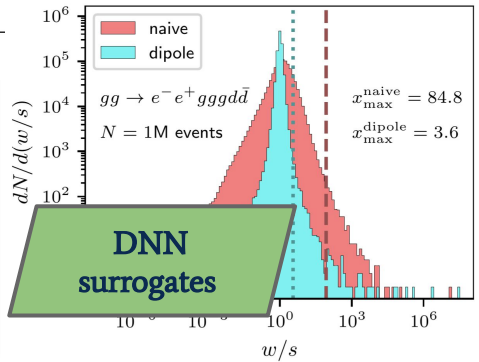
[2112.09588]
[2209.00843]
[2301.13562]
[2309.13154]
[2311.06198]
...

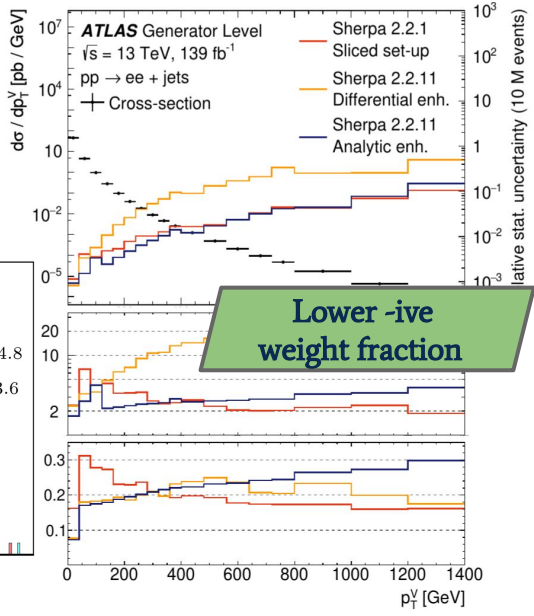






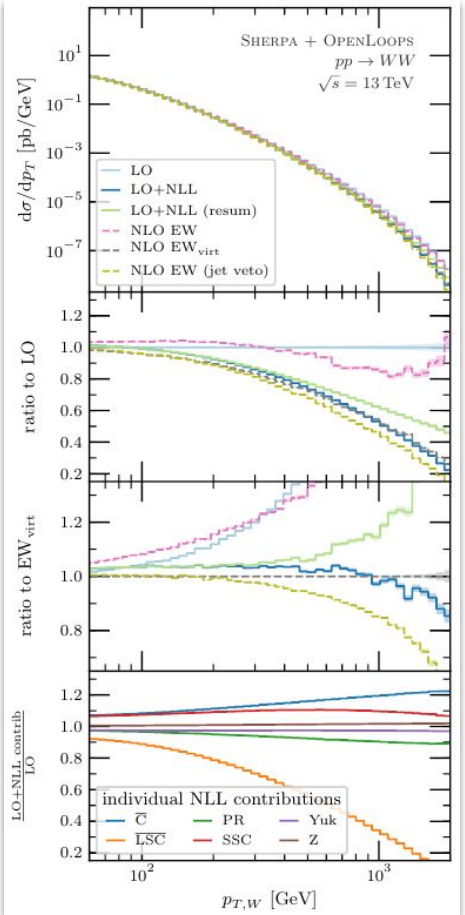






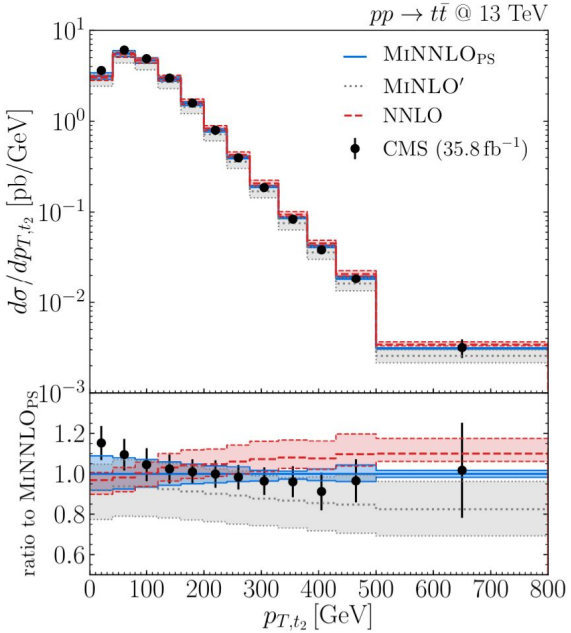
VV+jets: EW corrections

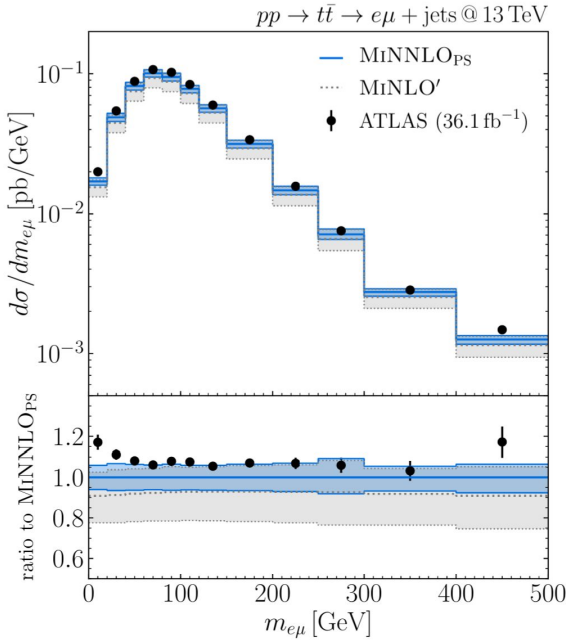
- NLO EW corrections needed for precision targets
  - Logarithmically enhanced for energies above EW scale
    → Large contributions in tails of kinematic distributions
  - But: Full NLO EW **not available in MC samples**
- **Solution I** : EW_{virt} [1511.08692]
  - **Full virtual** matrix elements, integrate out real emissions
  - Implemented in Sherpa with virtuals from OpenLoops, Recola
- **Solution II** : EW Sudakov approximation [hep-ph/0010201]
  - Further approximation: double/single logs from virtuals
  - Captures rough effects, **process independent**
  - Automated in MG5_aMC@NLO [2110.03714, 2309.00452] and Sherpa [2006.14635, 2111.13453]



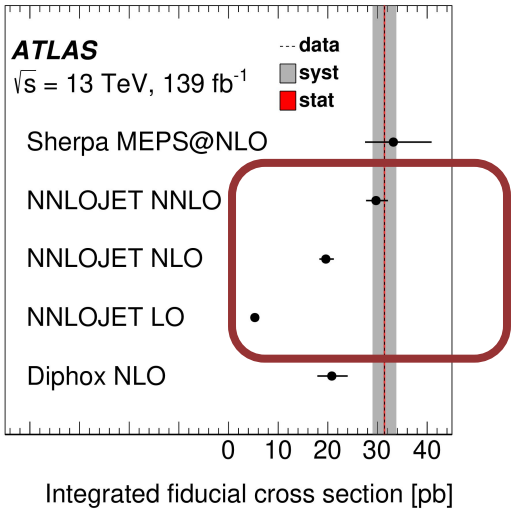
$t\bar{t}$+jets: First NNLO+PS matching with colour

- Multi-jet merging captures many components of the perturbative series
- Sometimes not enough → want full NNLO+PS accuracy
  - Available for >10 years in colour-singlet final states [1309.0017, 1405.3607]
  - **Real challenge: pp →$t\bar{t}$** First results in MiNNLO$_{PS}$+Pythia8 [2112.12135]



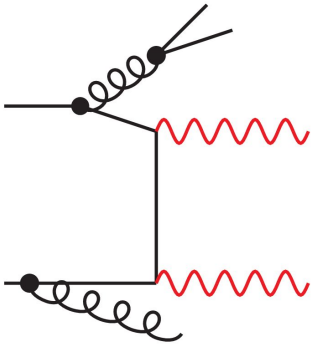


Diphoton production



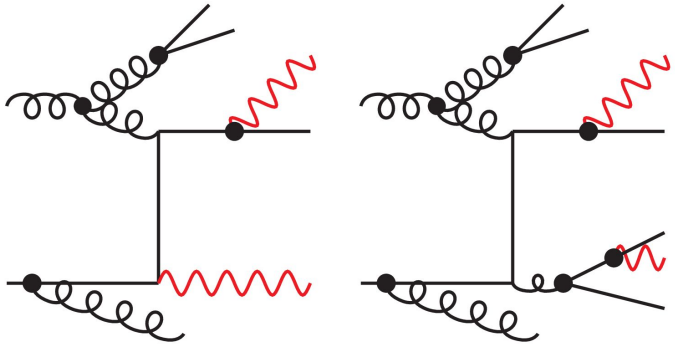
Photon production in traditional parton showers

Direct Photons



- LO matrix elements for **photon** production
- Dressed with **softer** **QCD** shower emissions

Fragmentation

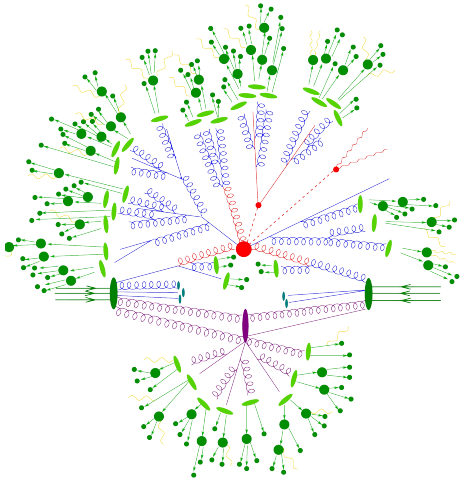


- LO matrix elements for **jet** production
- Dressed with **softer** **QED** shower emissions

$$\Delta(\mu_0^2, Q^2) = \Delta^{\mathrm{QCD}}(\mu_0^2, Q^2)\, \Delta^{\mathrm{QED}}(\mu_0^2, Q^2)$$

$$\Delta^{\mathrm{QED}}(\mu_0^2, Q^2) = \exp\left\{ -\int_{\mu_0^2}^{Q^2} \frac{\mathrm{d}t}{t} \int \mathrm{d}z \sum_i \frac{1}{2} \mathcal{K}_i^{\mathrm{QED}}(z,t) \right\}$$

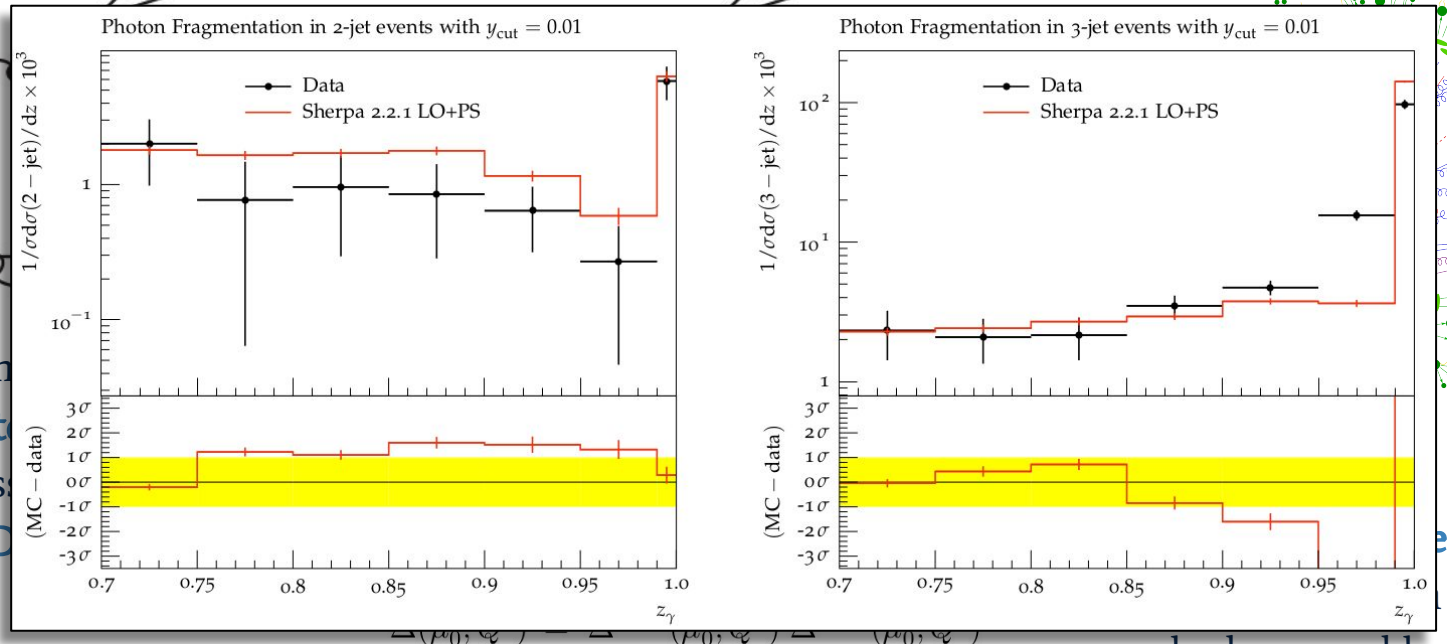
Non-prompt



- Hadron decays ($\pi^0 \to \gamma\gamma$)
- **QED final state radiation** from charged hadrons and leptons

Photon production in traditional parton showers

Direct Photons **Fragmentation** **Non-prompt**



- LO n… phot…
- Dres… QCD…

($\pi^0 \to \gamma\gamma$)

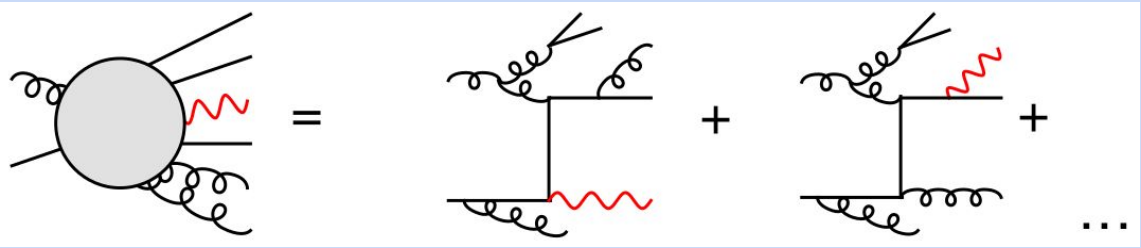
… charged hadrons and leptons

$$\Delta^{\mathrm{QED}}(\mu_0^2, Q^2) = \exp\left\{ -\int_{\mu_0^2}^{Q^2} \frac{\mathrm{d}t}{t} \int \mathrm{d}z \sum_i \frac{1}{2} \mathcal{K}_i^{\mathrm{QED}}(z,t) \right\}$$

Prompt photons via QCD multi-jet merging

Direct Photons

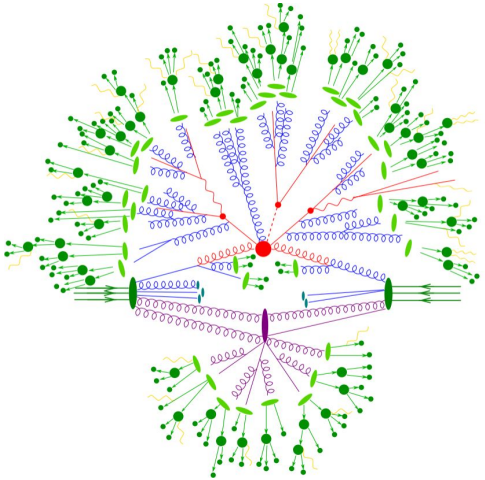
- QCD multi-jet merging (and NNLO+PS): [1611.07226]
  - Hard QCD emissions from higher-order MEs
  - Soft QCD emissions from shower
- **Relevant for photon production:**
  Multi-jet matrix elements contain direct and fragmentation-like configurations!



- Introduces dependence on photon isolation

Fragmentation

Non-prompt



- Hadron decays ($\pi^0 \to \gamma\gamma$)
- **QED final state radiation** from charged hadrons and leptons

Diphoton production in MEPS@NLO

- **State-of-the-art I:** $\gamma\gamma$ + 0,1(,2) jets @NLO + 3, ... jets @ LO
  - Highest accuracy crucial even for basic shapes
  - Shower resummation crucial for p_T related quantities
  - Multi-jet configurations especially tricky for $m_{\gamma\gamma} < p_{T1}+p_{T2}$
    → fortunately not so critical for (SM) Higgs analyses

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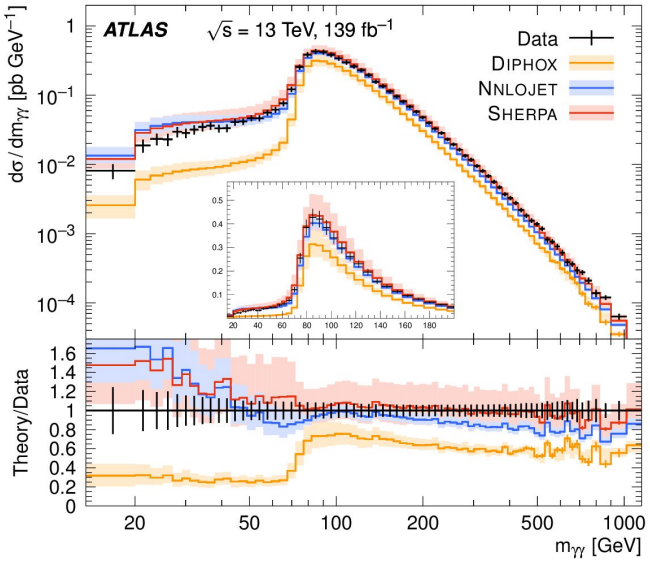
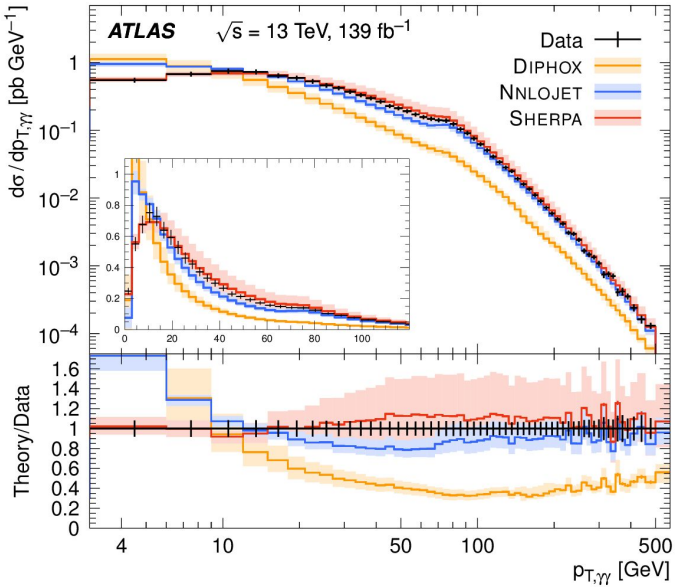
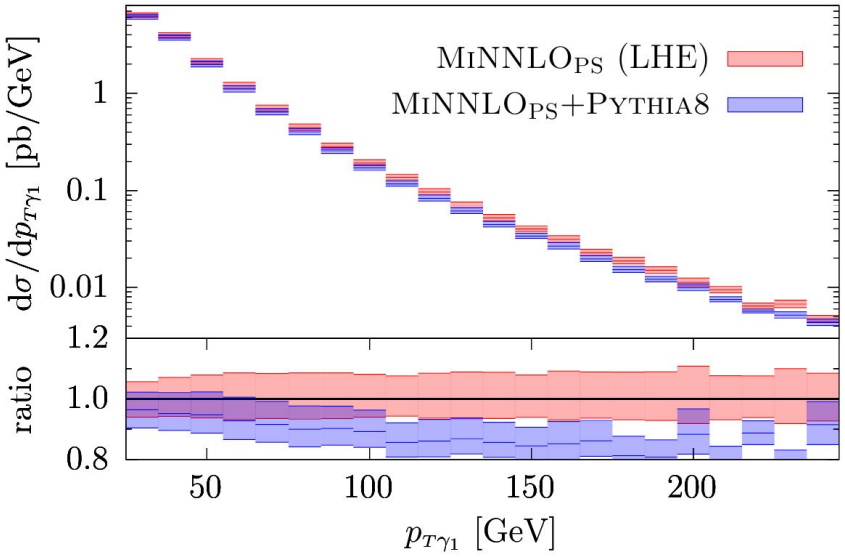
[2107.09330]

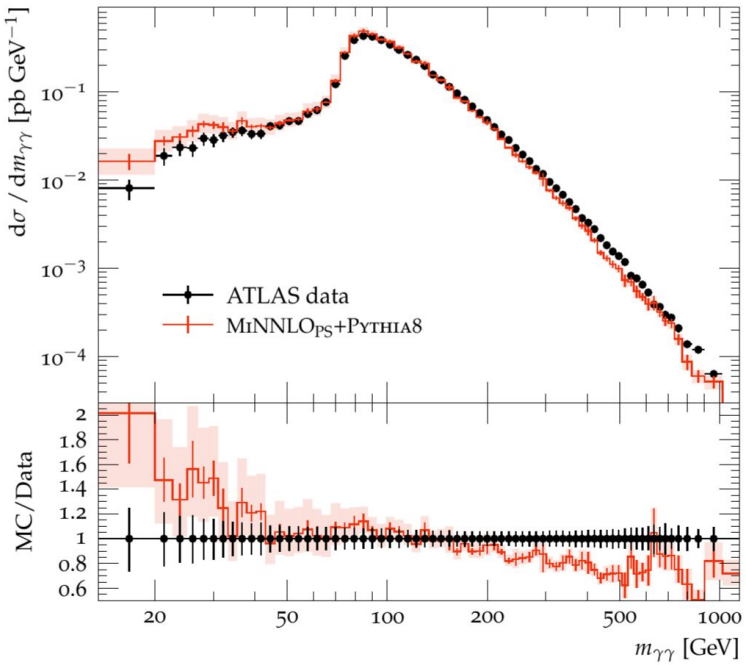




Diphoton production in NNLO+PS

- **State-of-the-art II:** NNLO+PS for photon pair production [2204.12602]
  - $\text{MiNNLO}_{\text{PS}}$ with Pythia8 → good description of data
  - Scale uncertainties still not small, perturbative series converges slowly
  - Non-negligible impact of parton shower even despite NNLO matching!





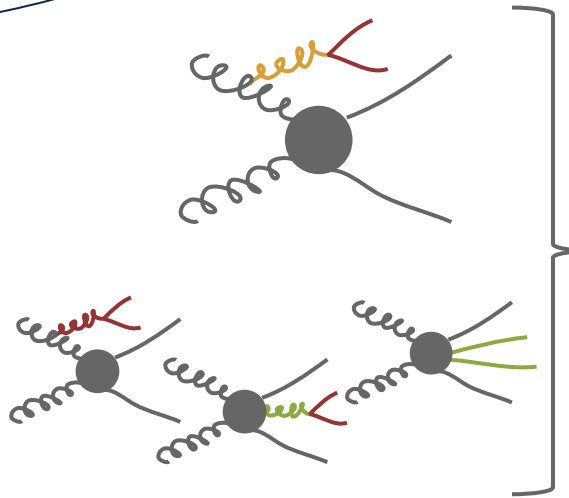
Associated heavy flavour production

Heavy-flavour associated final states

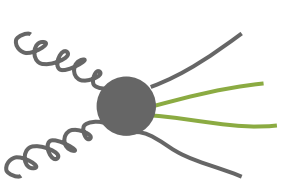
Traditional approaches for X+b(b) MC predictions:

X = Z, W, tt, γγ...

- "Inclusive" NLO+PS sample with HF production from **parton shower g →bb**
  - e.g. {Powheg,aMC@NLO}+{Pythia,Herwig}
- Multi-leg merged sample with HF from **higher-order MEs** (hard b's) or **parton shower g →bb** (soft/collinear b's)
  - e.g. MG5_aMC+Pythia, Sherpa+OpenLoops
- NLO+PS Xbb using **matrix elements** with **massive** b-quarks
  - e.g. Powheg+OpenLoops+Pythia8, Sherpa+OpenLoops



"5-flavour" schemes

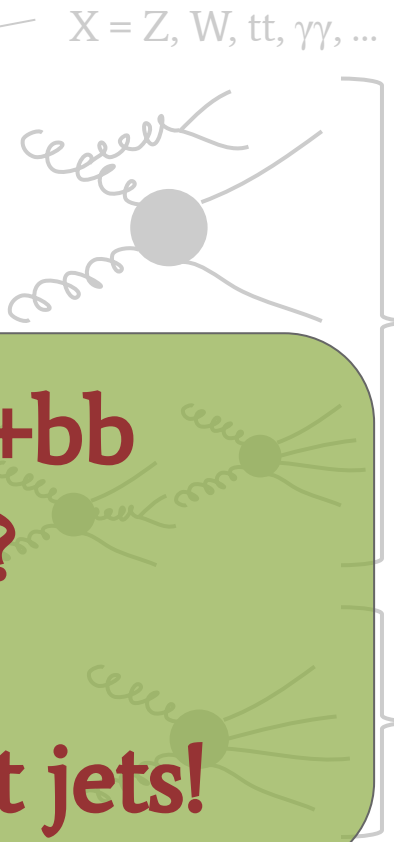


"4-flavour" schemes

Heavy-flavour associated final states

Traditional approaches for X+b(b) MC predictions:

- "Inclusive" NLO+PS sample with HF production from **parton shower g →bb**
  - e.g. {Powheg,aMC@NLO}+{Pythia,Herwig}
- Multi-leg merged sample with HF from **higher-order MEs** (hard b's) or **parton shower** (soft/collinear b's)
  - e.g. MG5_aMC+Pythia, Sherpa+OpenLoops
- NLO+PS X+bb using **matrix elements** with **massive** b-quarks
  - e.g. Powheg+OpenLoops+Pythia8, Sherpa+OpenLoops



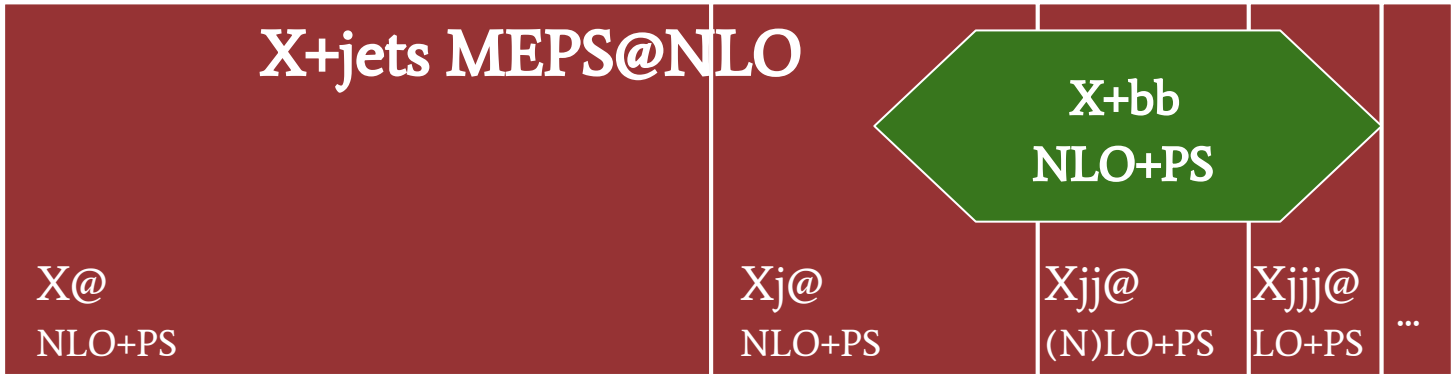
Combining 4-flavour X+bb and 5-flavour X+jets?

→ b-mass included

→ still inclusive wrt light jets!

Fusing X+bb and X+jets in the Sherpa MC

aka “Multi-jet merging in a variable flavour number scheme”



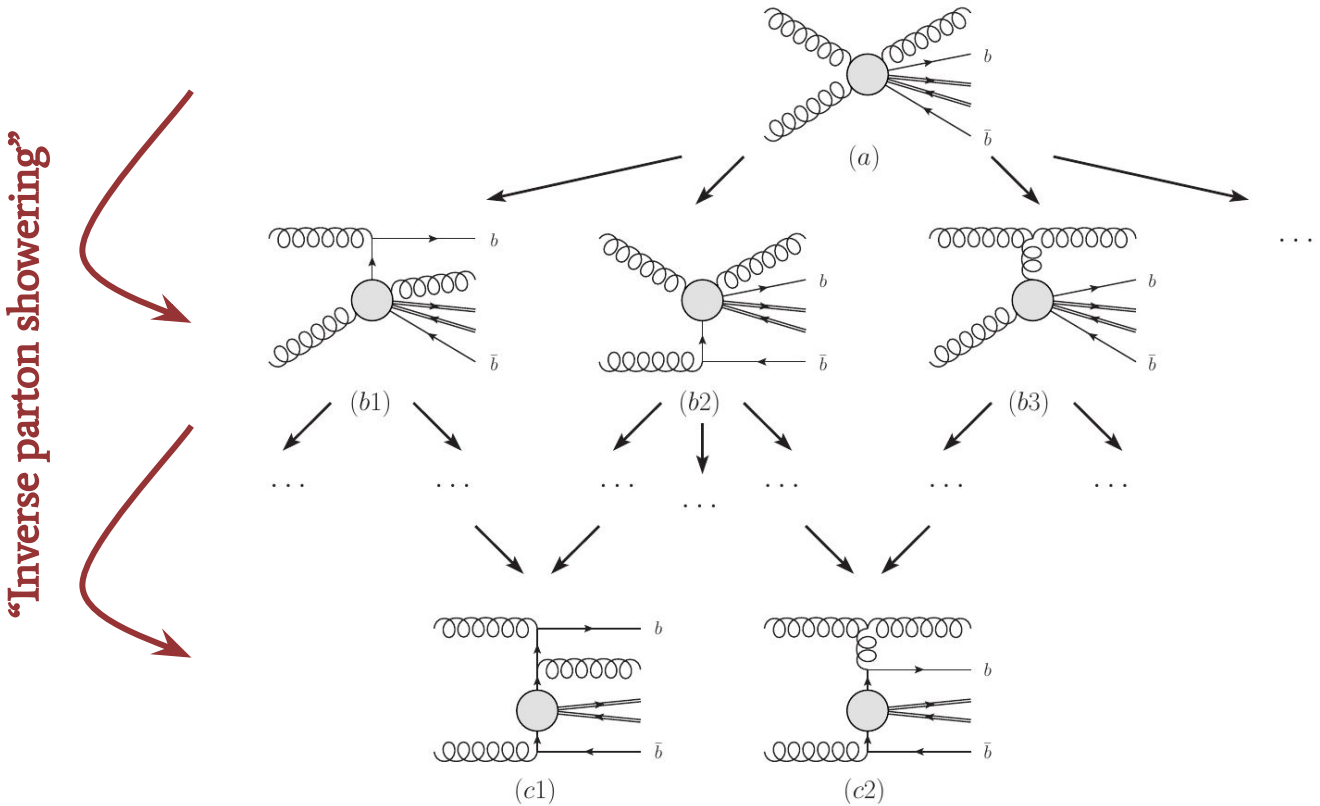
Three main ingredients:

1. Interpreting X+bb as merged contribution
2. Overlap removal
3. Matching 4F/5F in PDFs and α_s

Can be applied for LO and NLO merging!

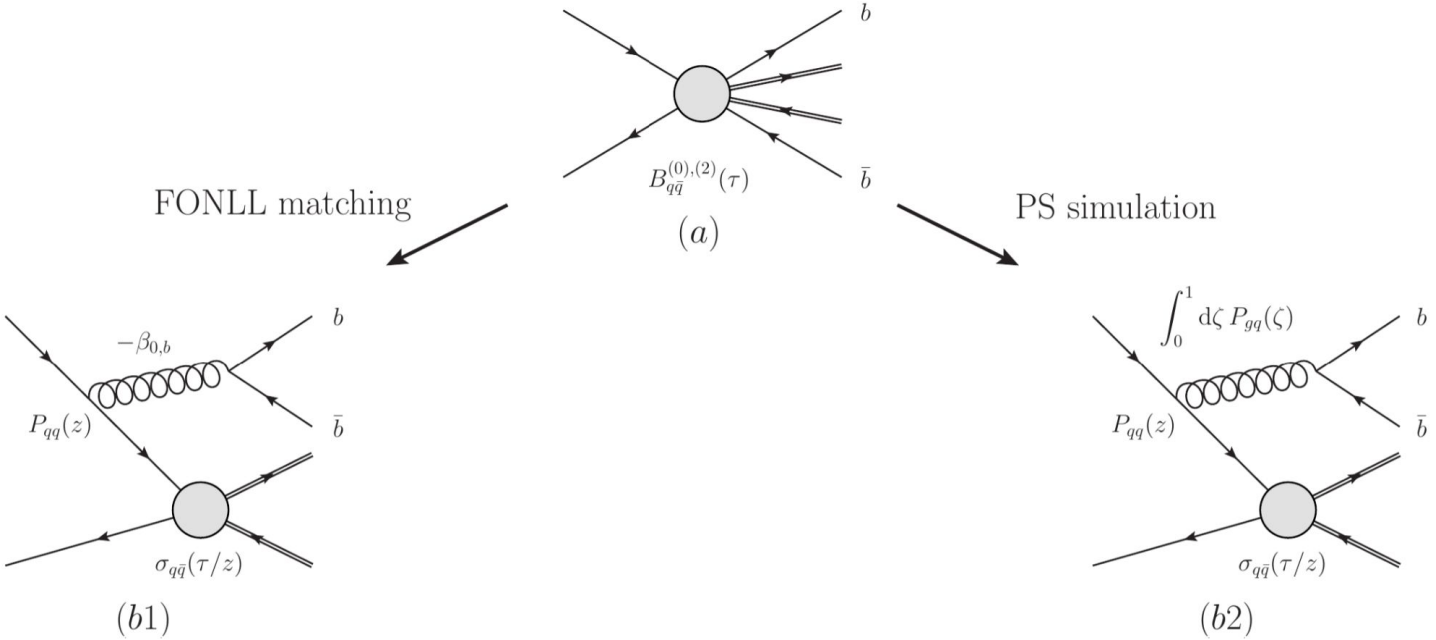
Organisation of contributions

- Implementation through **cluster histories** , e.g. for gg→ttbbg:



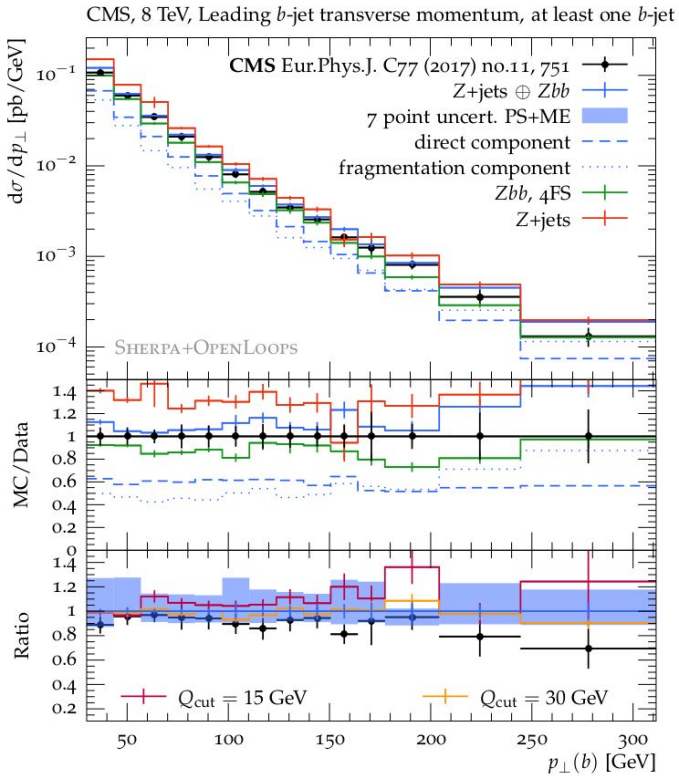
Matching massive b's and the 5FS

- Includes corrections analogous to FONLL matching in analytical calculations [2402.15497]

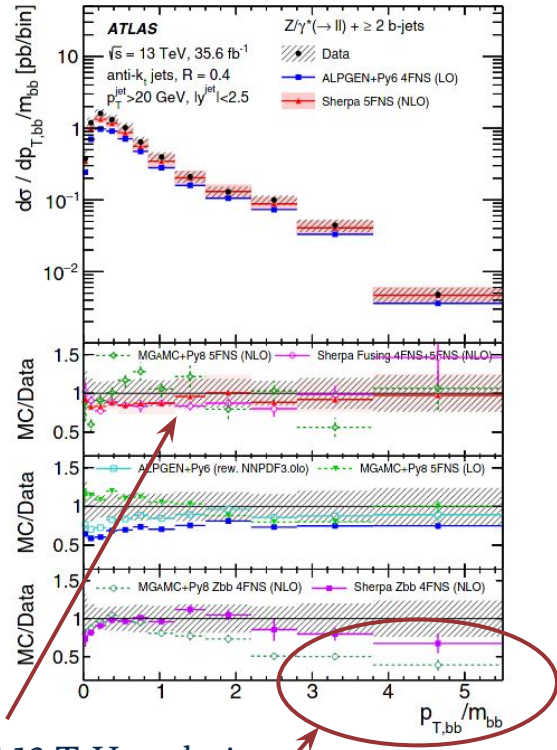


V+HF production

- Implementation in Sherpa & validation in Z+HF vs. CMS data [1904.09382]



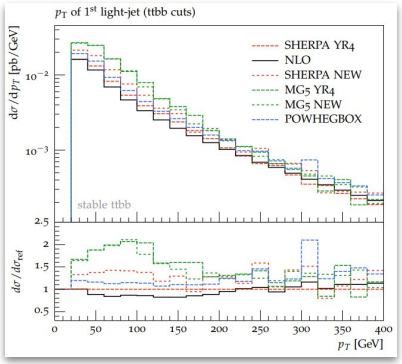
[2003.11960]

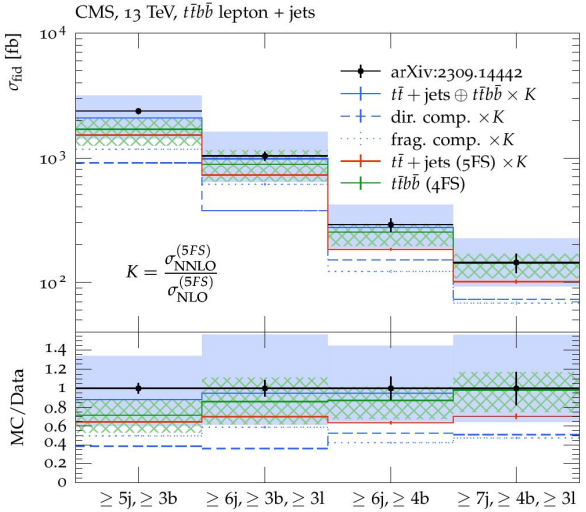


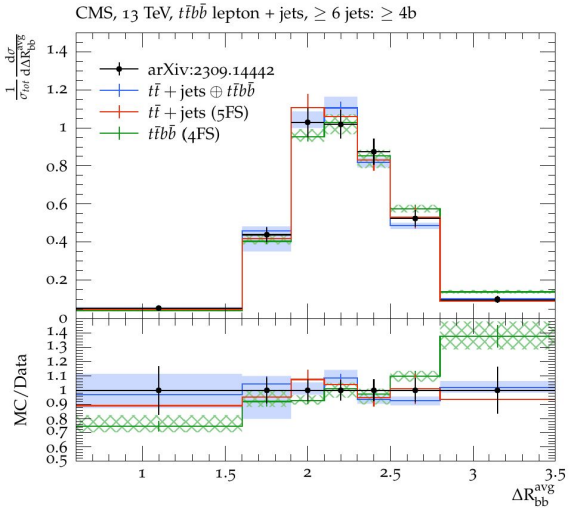
- Comparison to ATLAS 13 TeV analysis
  - particularly interesting: "inverse" hierarchies

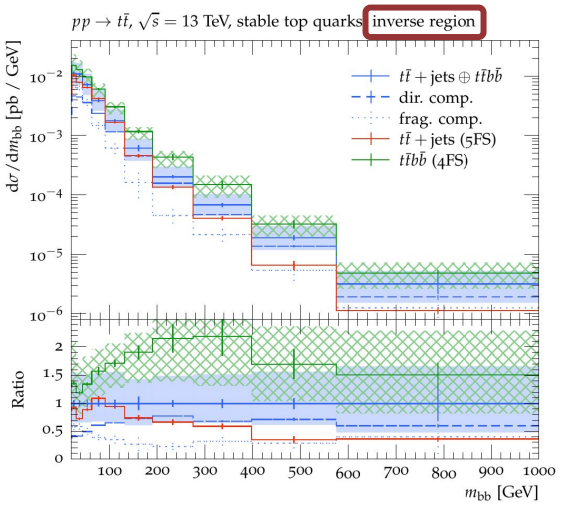
$t\bar{t}$+HF production

- More tricky case: $t\bar{t}b\bar{b}$
  - complex NLO calculations, NLO+PS differences:
  - interesting scale hierarchies
- Recent study with Sherpa [2402.15497]
  - good agreement with CMS ttbb measurement
  - "inverse hierarchy" phase space → 4FS insufficient









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Sneak preview: γγ+HF in fusing

Brand-new!

- Obvious background for H(γγ)H(bb) analyses: SM γγ+HF production
  - Data-driven modelling ($m_{\gamma\gamma}$ sidebands) with MC input (spurious signal, …)
    → still need good description of yy+HF and yy+jets → **fusing**?
- WIP: γγ + 0,1,2jets@NLO + 3jets@LO fused with massive γγbb@NLO
  [Höche, Kolay, FS 250x.yyyy]

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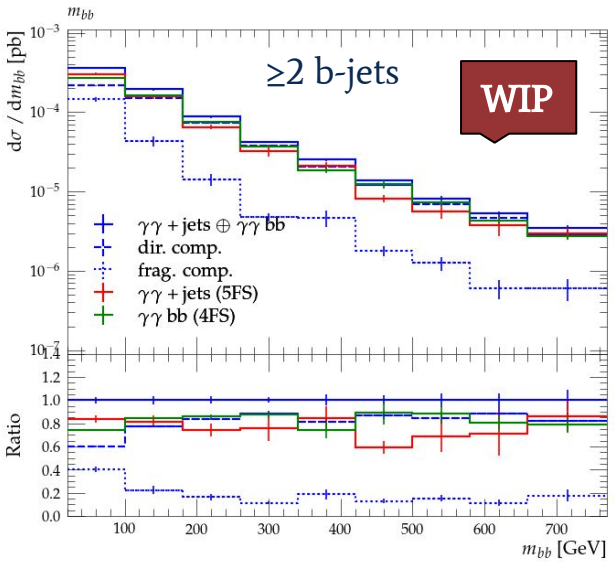
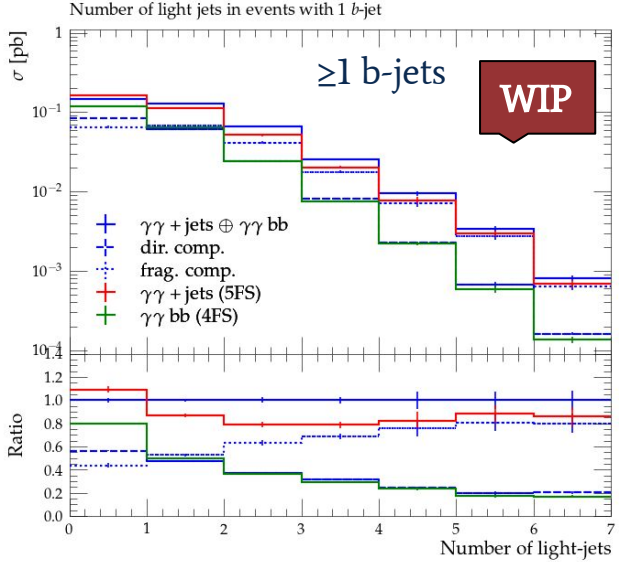
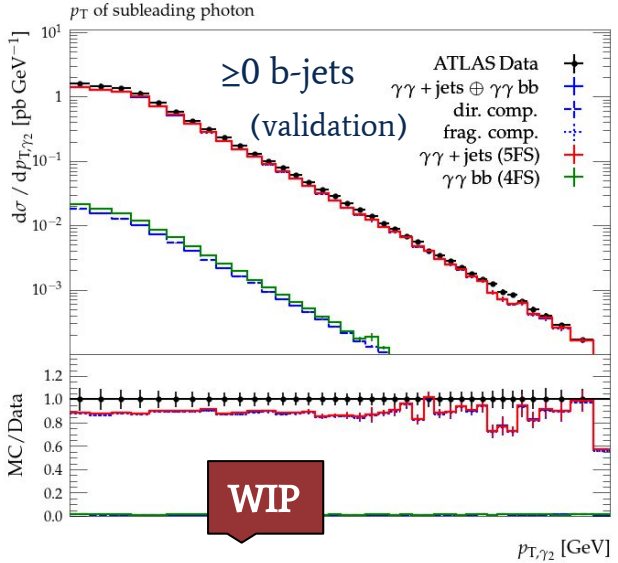


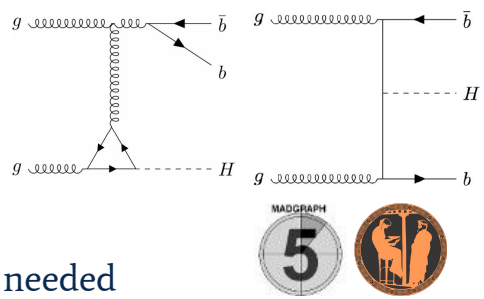


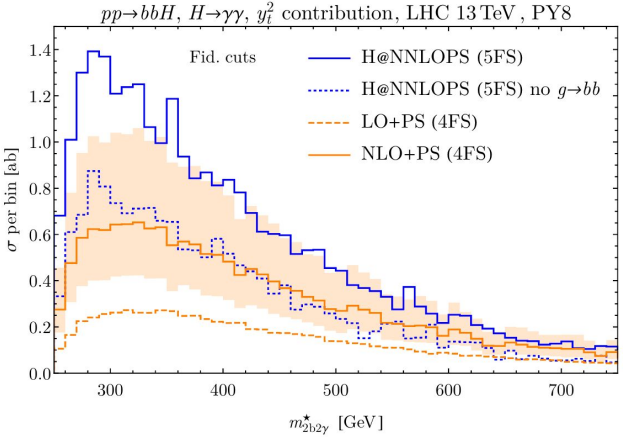


Higgs as background

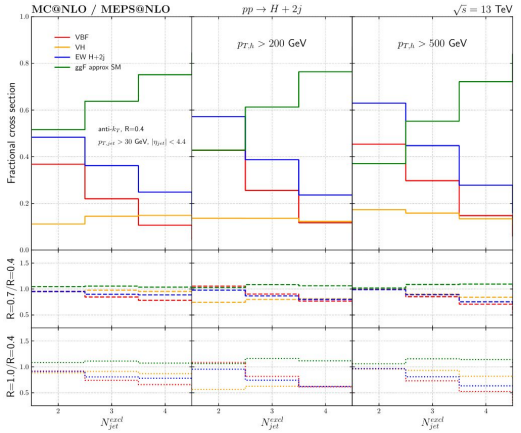
Yesterday's signal...

- pp→bbH(γγ) as background for H(bb)H(γγ) [2307.09992]
  - 4FS NLO+PS implementation for y_t and y_b diagrams
  - Aim: reduce the 100% unc's on this bkg in HH analyses (H@NNLO+PS)
  - Significant reduction in predicted rate and in unc's
  - Drawback: Perfect b-tagging needed





- gg→H+jets as background to VBF [2105.11399]
  - even with p_T(H) cut significant gg→H contribution
  - gg → H + 0,1,2j@NLO MEPS@NLO state-of-the-art (gg → H + 3j@NLO not feasible yet in MC → WIP)
  - beyond capabilities of NNLO+PS (or NLL) efforts

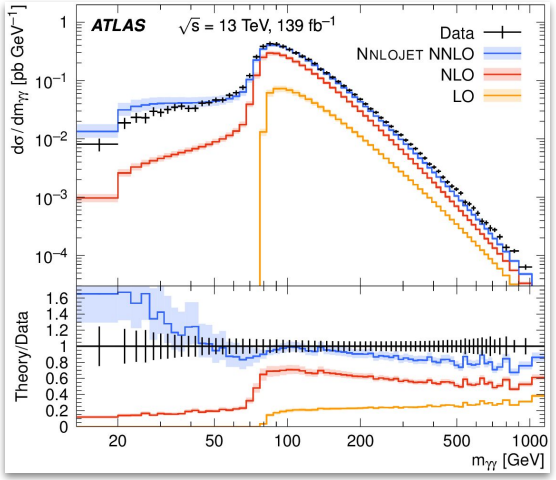


Random rumbling instead of conclusions
(in the unlikely case I still have time)

Theoretical uncertainties in analyses

Meaning of scale uncertainties

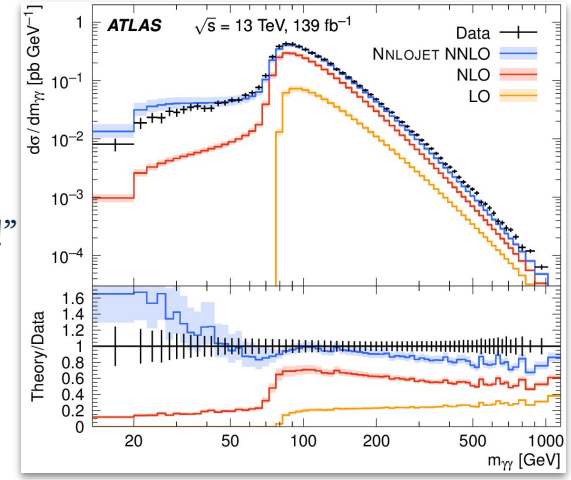
- Only estimate of missing higher-orders, sometimes **not reliable** !

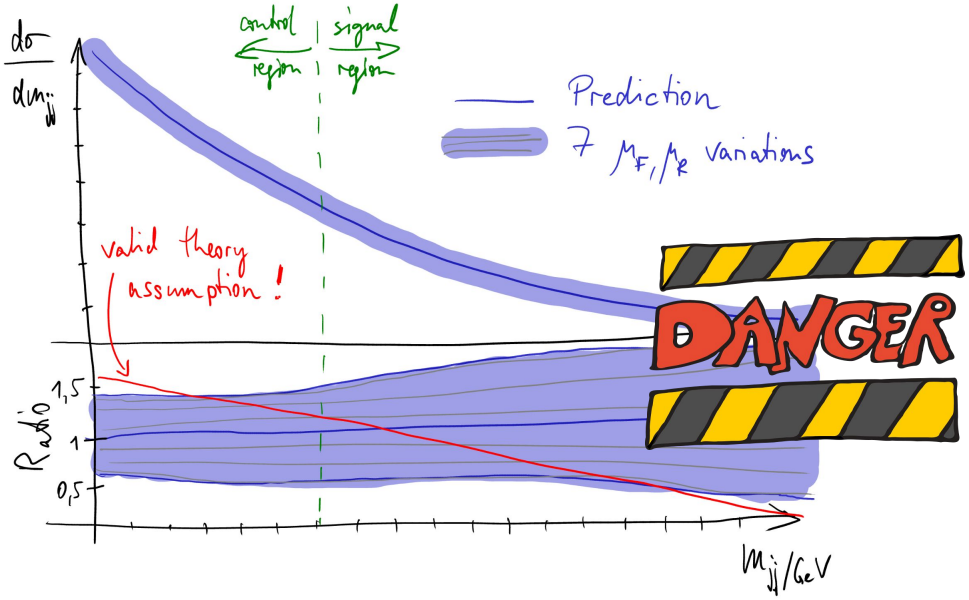


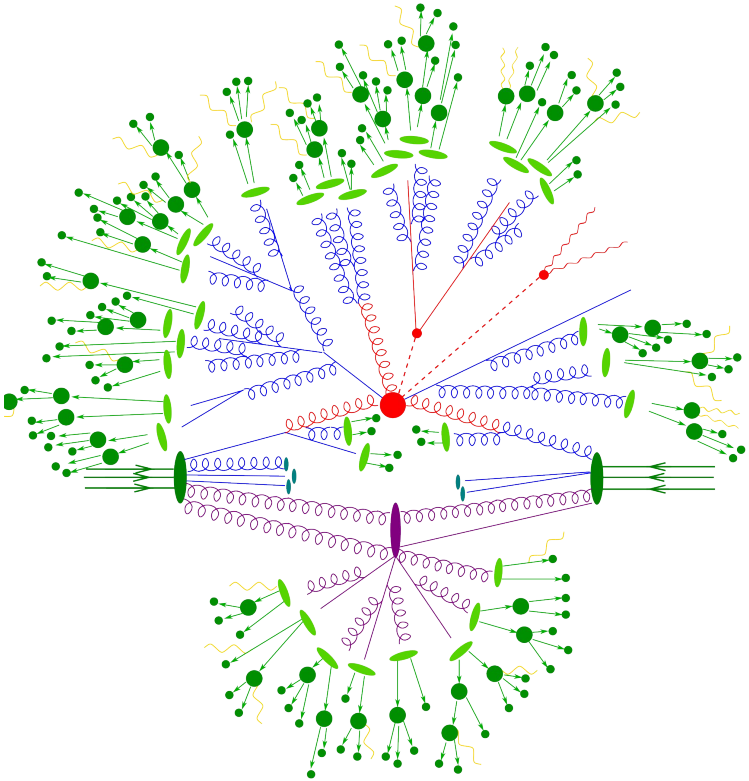
Theoretical uncertainties in analyses

Meaning of scale uncertainties

- Only estimate of missing higher-orders, sometimes **not reliable** !
- More importantly: Only envelope meaningful, not each variation
  → Tricky in likelihood fit analyses
  → "Test **different decorrelation schemes** (between regions, bins)!"







Thank you for your attention!