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$\gamma\gamma b\bar{b}$ in a variable flavor number scheme

DPG Spring Meeting, Göttingen, April 3, 2025

Introduction

- $\gamma\gamma b\bar{b}$ is one of the golden channel for HH searches
  - $b\bar{b} \longrightarrow$ high branching ratio
  - $\gamma\gamma \longrightarrow$ clean signal
- Extremely rare signal with a huge background
  - **Rate($\gamma\gamma$)** $\approx 10^3$ x rate($H \to \gamma\gamma$) $\approx 10^6$ x rate($HH \to \gamma\gamma b\bar{b}$)

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Image credit: J. Veatch

		Relative impact of the systematic uncertainties [%]	
Source	Type	Nonresonant analysis HH	Resonant analysis $m_X = 300$ GeV
Experimental			
Photon energy resolution	Norm. + Shape	0.4	0.6
Jet energy scale and resolution	Normalization	<0.2	0.3
Flavor tagging	Normalization	<0.2	0.2
Theoretical			
Factorization and renormalization scale	Normalization	0.3	<0.2
Parton showering model	Norm. + Shape	0.6	2.6
Heavy-flavor content	Normalization	0.3	<0.2
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	Normalization	0.2	<0.2
Spurious signal	Normalization	3.0	3.3

Phys. Rev. D 106, 052001 (2022)

Introduction

- **Rate($\gamma\gamma$)** → Continuum background is the focus of the talk!

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- Extremely rare signal with a huge background
  - **Rate($\gamma\gamma$)** $\approx 10^3$ x rate($H \rightarrow \gamma\gamma$) $\approx 10^6$ x rate($HH \rightarrow \gamma\gamma b\bar{b}$)
- Signal and sideband regions in $m_{\gamma\gamma}$ spectrum are used to model:
  - **Continuum** (non-resonant) background
  - **Misidentified** photons
- A well-modelled continuum background could help to resolve ambiguities

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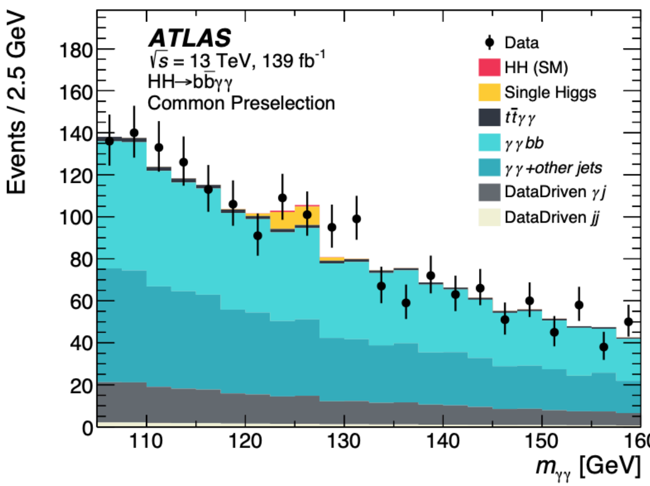
Current modeling of the backgorund

- In the continuum spectrum, two predictions used to model the background:
  - $\gamma\gamma + HF \; (\gamma\gamma b\bar{b})$
    - 4-flavor scheme (4FS)
    - **b-quarks are massive** in Matrix Elements (ME)
  - $\gamma\gamma + light\ jets$
    - 5-flavor scheme (5FS)
    - **Multi-leg merging** at various QCD accuracy
    - Statistics can be problematic!
- $100\,\%$ **overlap** between two predictions!
- The aim is to benefit from **the advantages of both predictions** by eliminating overlap



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Fusing both for better modeling

- **Combination** of both is called **fusing**!
- Predictions in the study:
  - $\underline{\gamma\gamma b\bar{b}@NLO}$ ⟶ Matching at NLO QCD in 4FS with PS
    - **Accuracy** of massive NLO calculations
  - $\underline{\gamma\gamma + 0{,}1{,}2 jets@NLO + 3 jets@LO}$ ⟶ Multi-leg merging
    - **Logarithmic accuracy** of higher order corrections in the MEs
    - **Inclusiveness** of the 5FS, important for fake heavy flavor jets

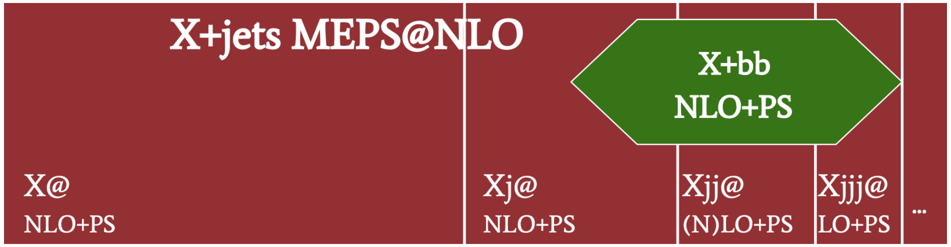
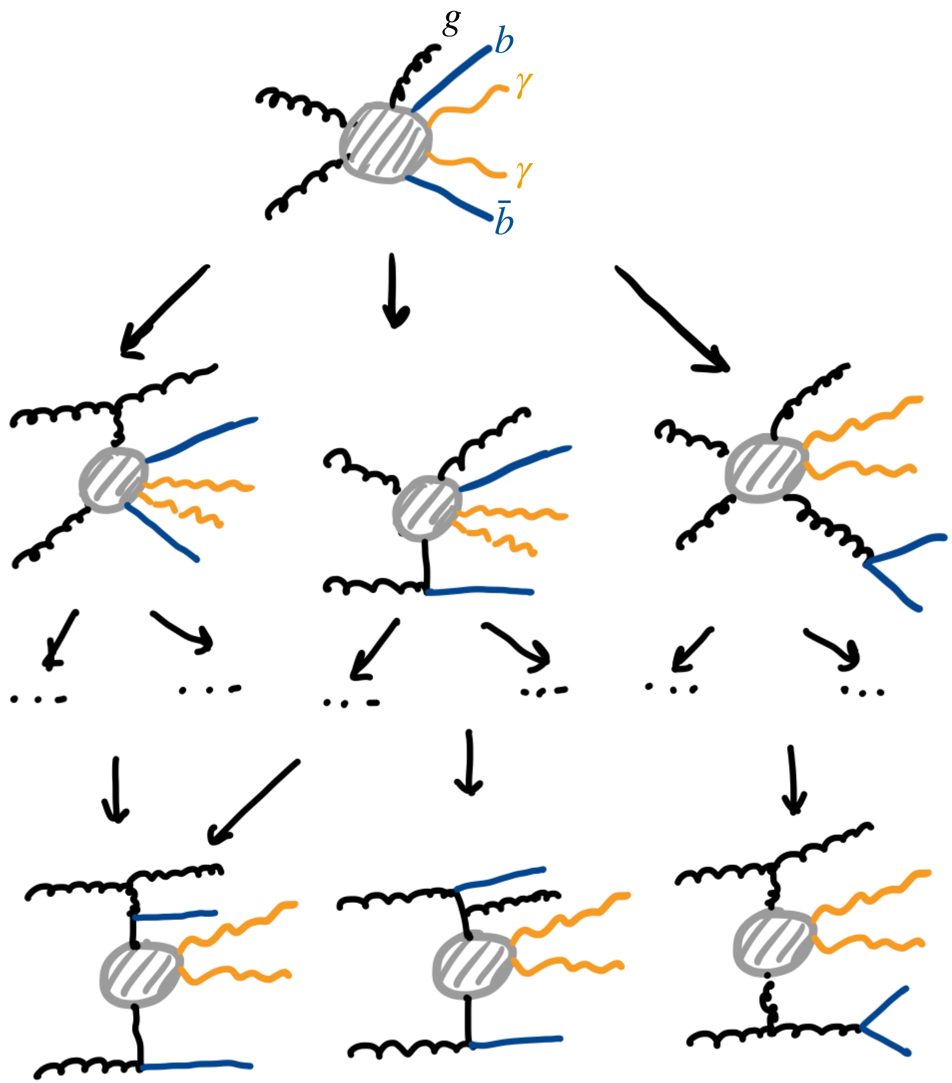


Image credit: F. Siegert

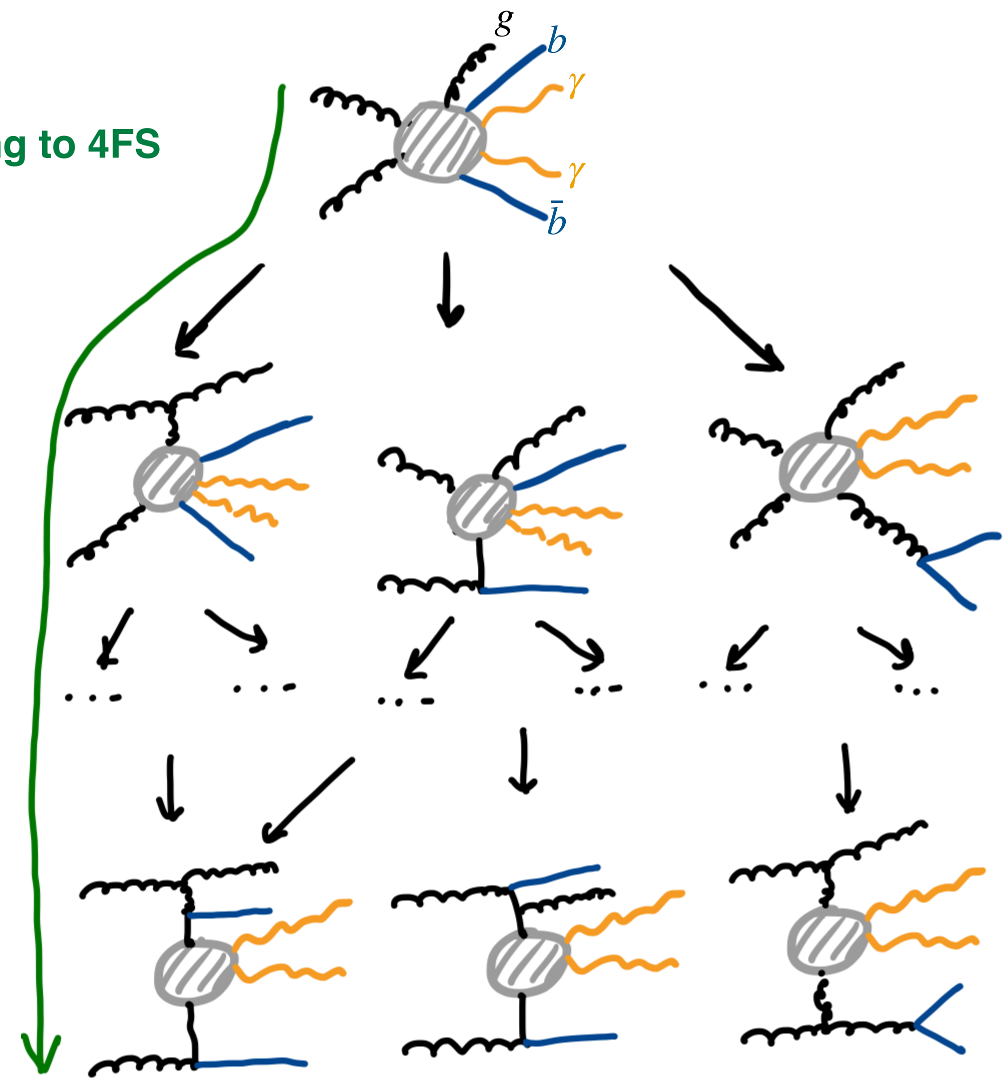
- The method is implemented in **Sherpa**, a general purpose event generator
  - Previously applied to $Z + HF$ and $t\bar{t} + HF$
  - **New** for $\gamma\gamma + HF$

$\gamma\gamma b\bar{b}$ as a part of multi-leg merging - Fusing



$\gamma\gamma b\bar{b}$ as a part of multi-leg merging - Fusing

- Apply **jet clustering to 4FS**



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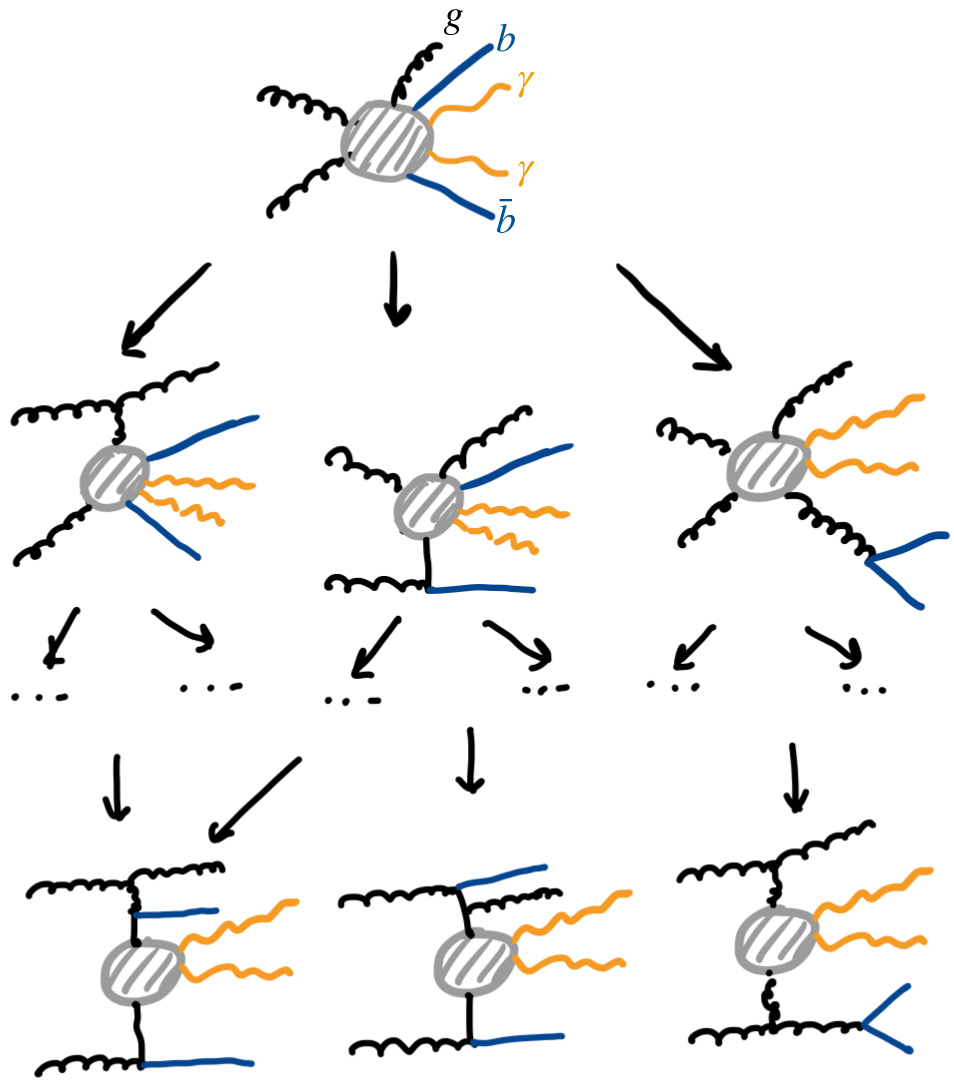
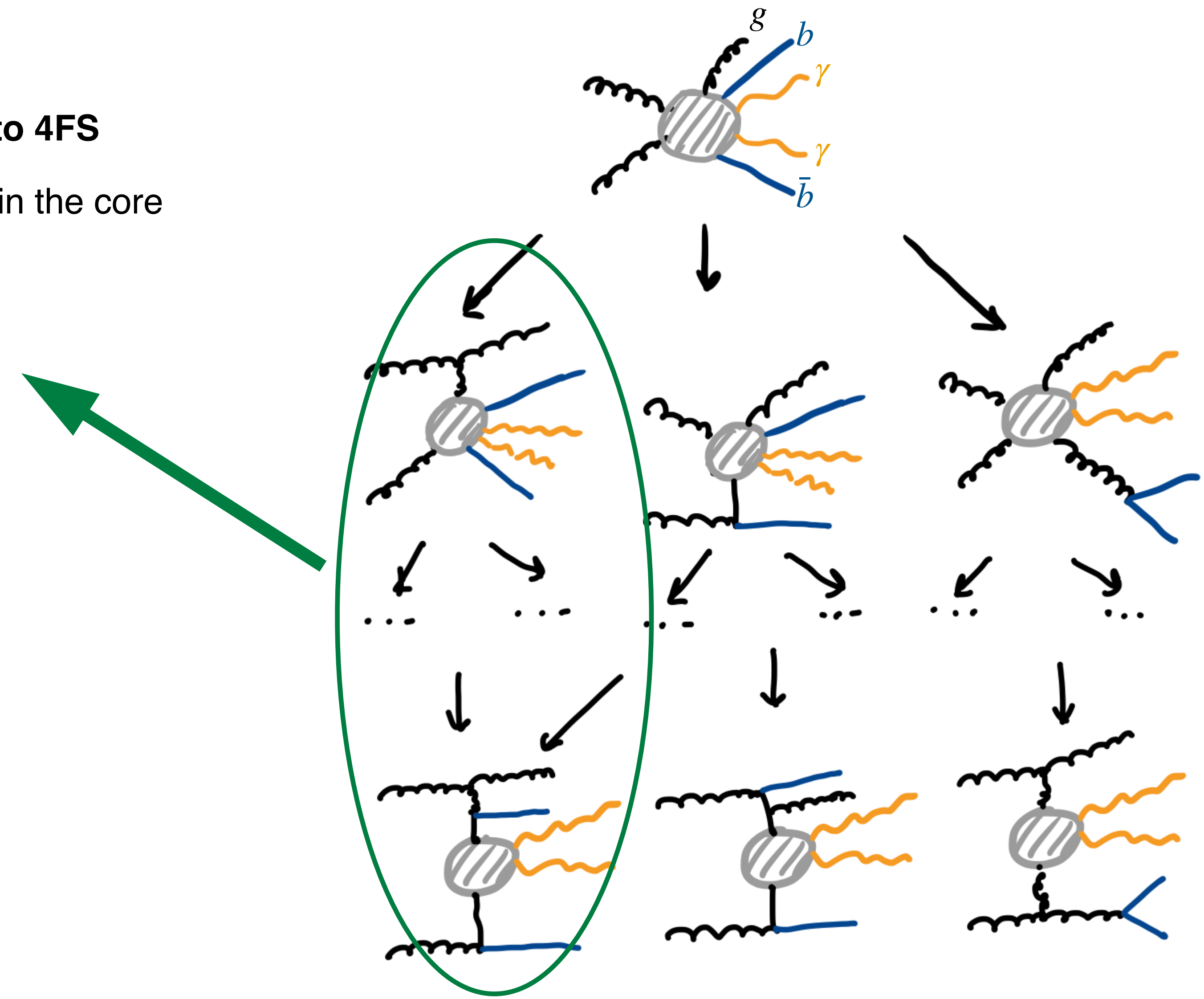
- Apply **jet clustering to 4FS**
- Find the first $b\bar{b}$**-pair** in the core process



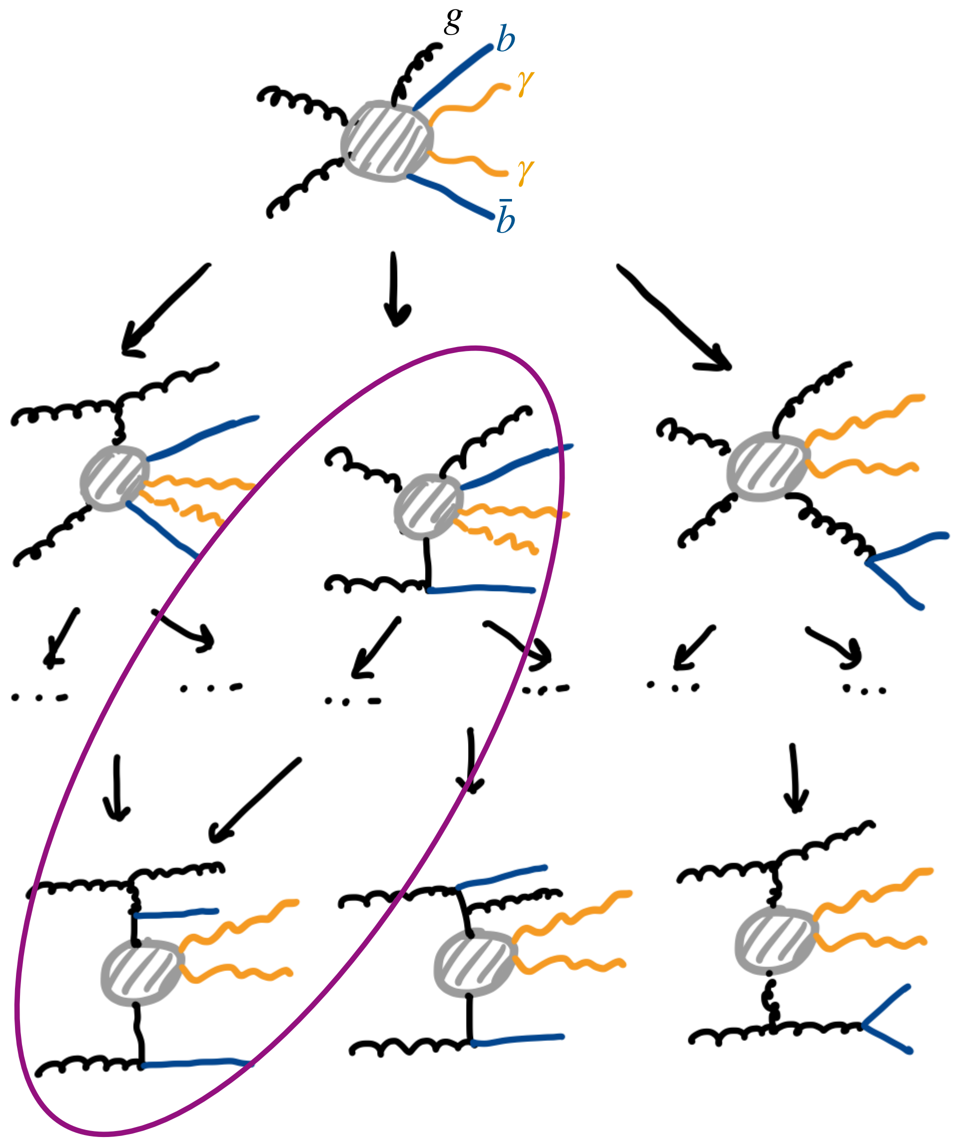
$\gamma\gamma b\bar{b}$ as a part of multi-leg merging - Fusing

- Apply **jet clustering to 4FS**
- Find the first $b\bar{b}$**-pair** in the core process
    - Keep the event!



$\gamma\gamma b\bar{b}$ as a part of multi-leg merging - Fusing

- Apply **jet clustering to 4FS**
- Find the first $b\bar{b}$**-pair** in the core process
  - Discard the event!



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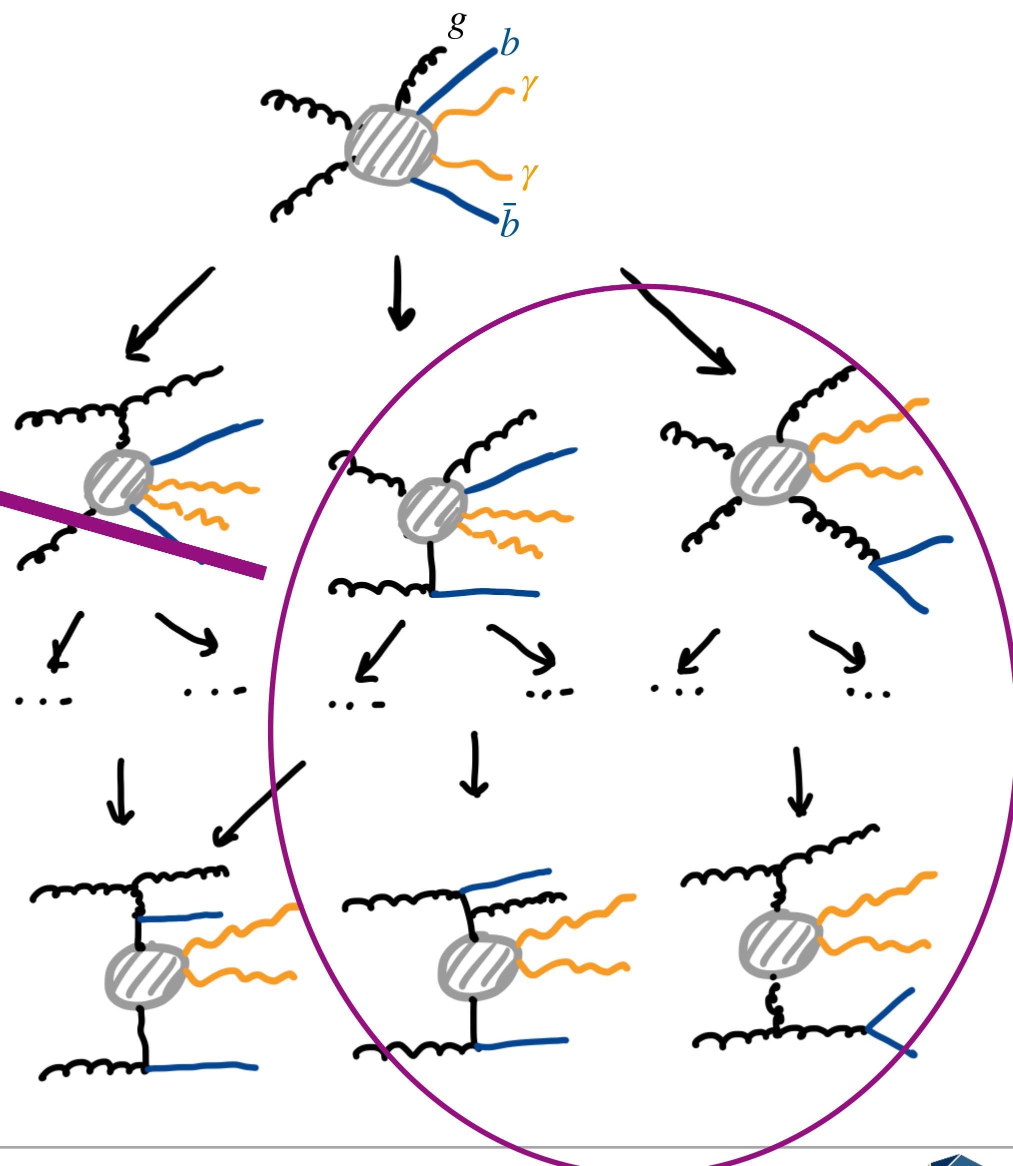
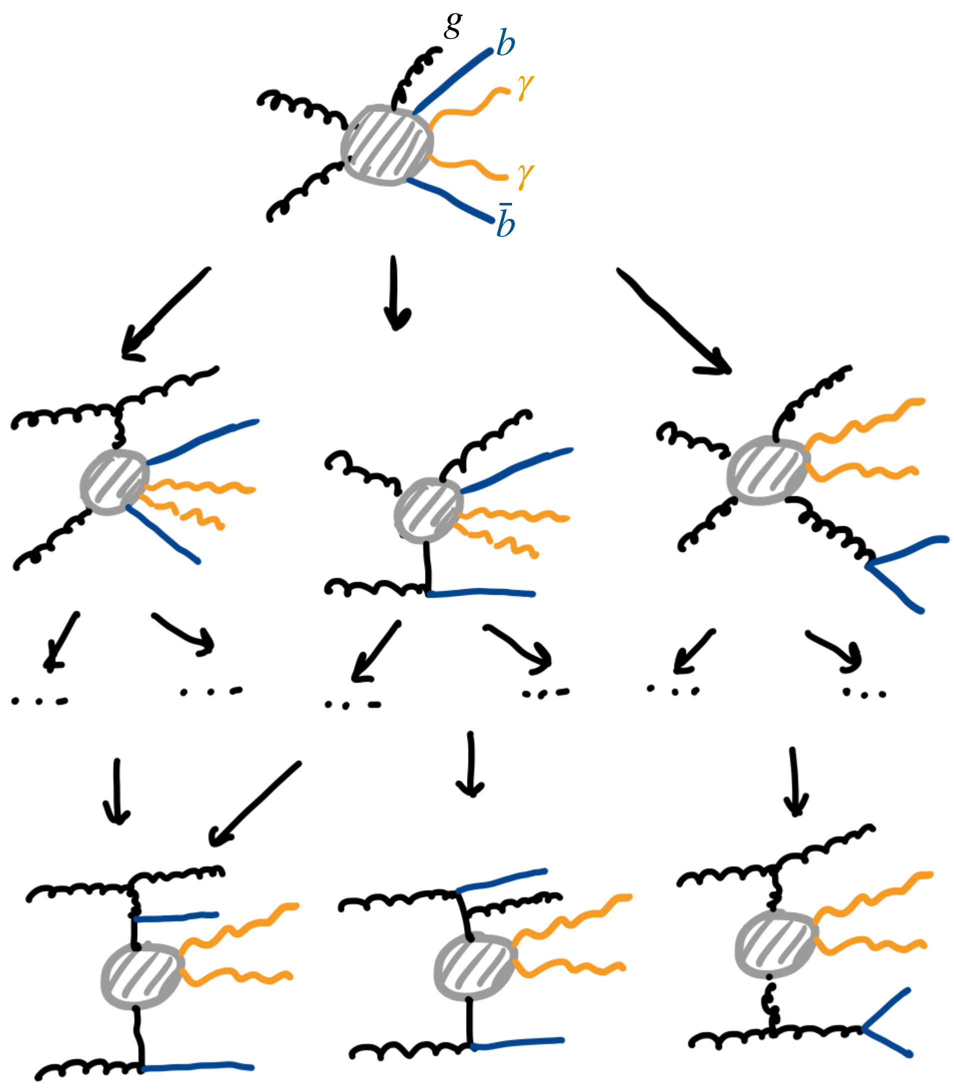


$\gamma\gamma b\bar{b}$ as a part of multi-leg merging - Fusing

- Apply **jet clustering to 4FS**
- Find the first $b\bar{b}$**-pair** in the core process
- Apply to modify ME:
  - α_s**-reweighting**
  - **Sudakov reweighting**



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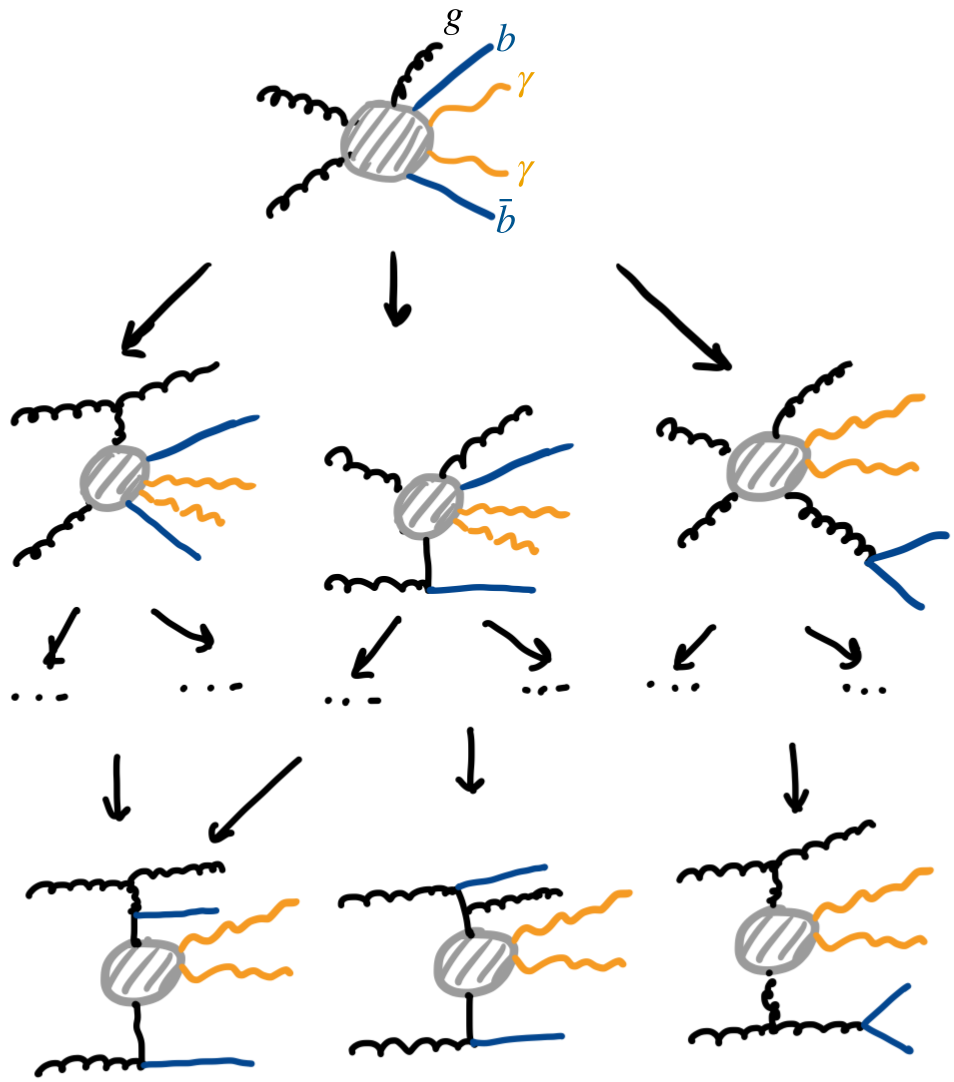
- This part is called **direct component**



$\gamma\gamma b\bar{b}$ as a part of multi-leg merging - Fusing

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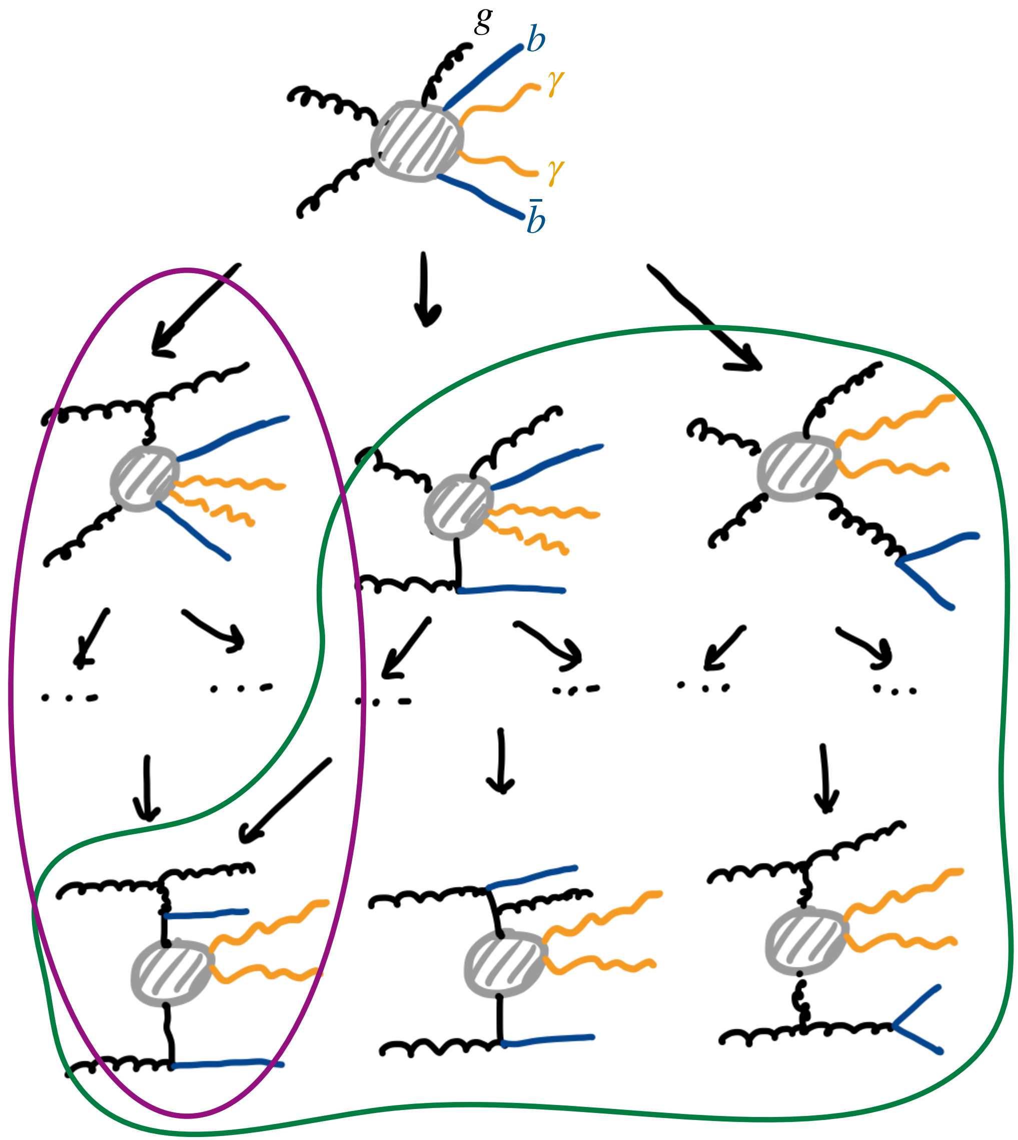
- This part is called **direct component**
- On top of the multi-leg merging in 5FS:
  - Apply the complement of the rejection procedure



$\gamma\gamma b\bar{b}$ as a part of multi-leg merging - Fusing

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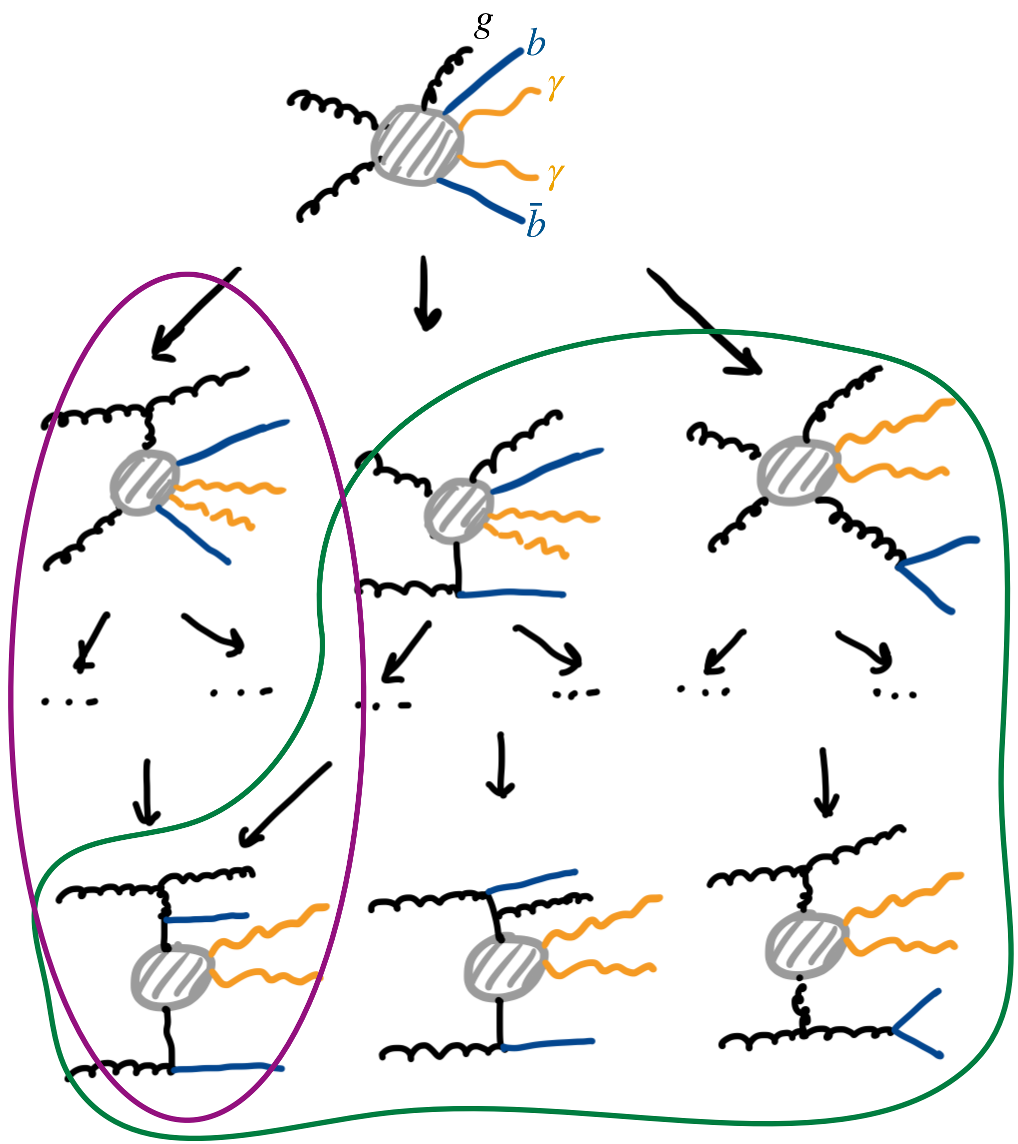
- This part is called **direct component**
- On top of the multi-leg merging in 5FS:
  - Apply the complement of the rejection procedure
- This part is **the fragmentation component**



$\gamma\gamma b\bar{b}$ as a part of multi-leg merging - Fusing

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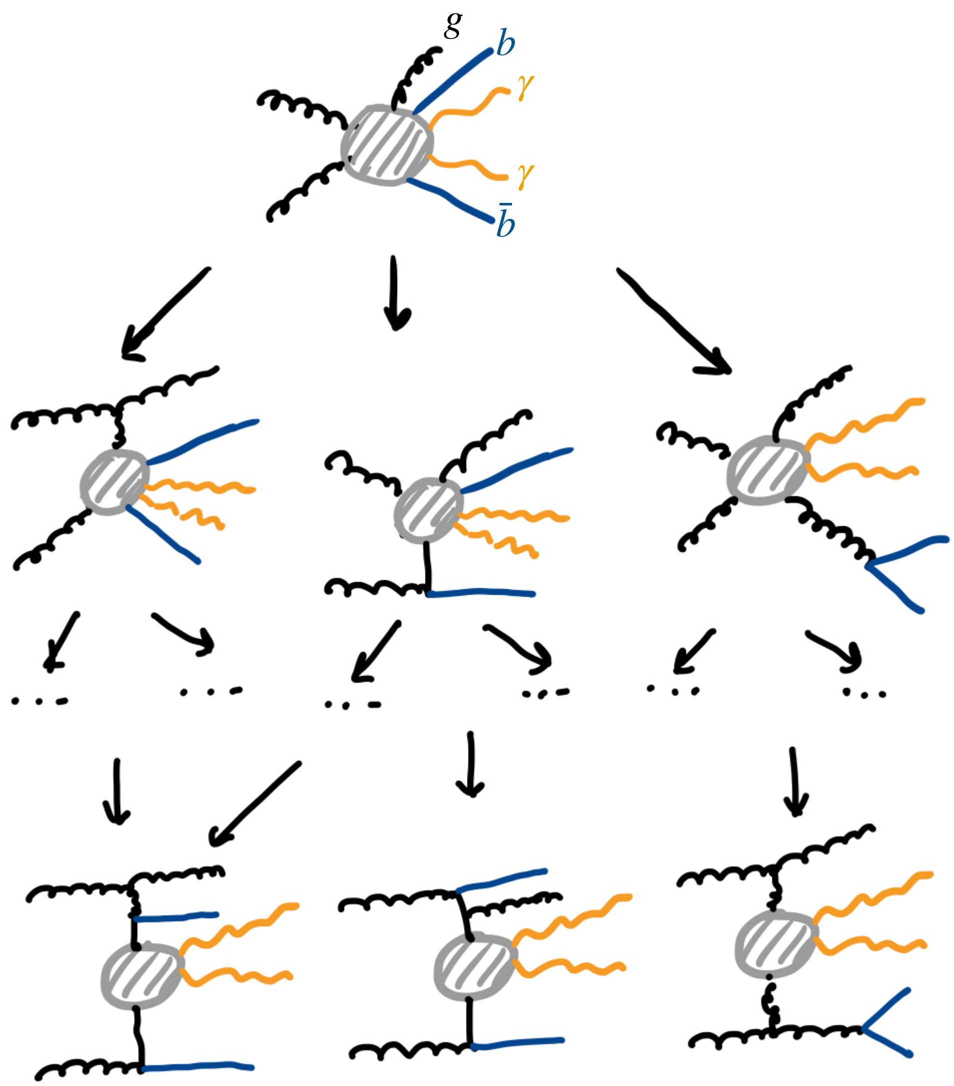
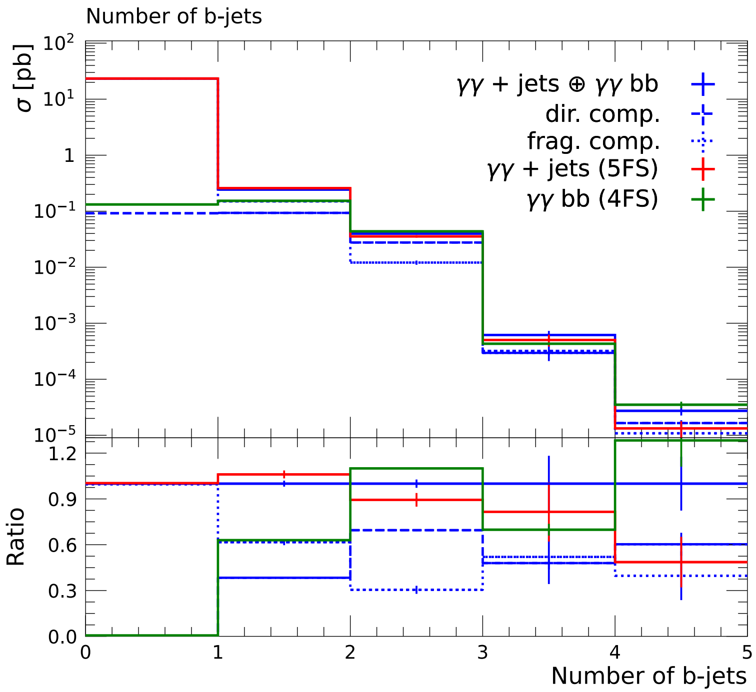
- Find the first $b\bar{b}$**-pair** in the core process
- Apply to modify ME:
    - α_s**-reweighting**
    - **Sudakov reweighting**
- This part is called **direct component**
- On top of the multi-leg merging in 5FS:
    - Apply the complement of the rejection procedure
- This part is **the fragmentation component**
- **Fused = direct + fragmentation**



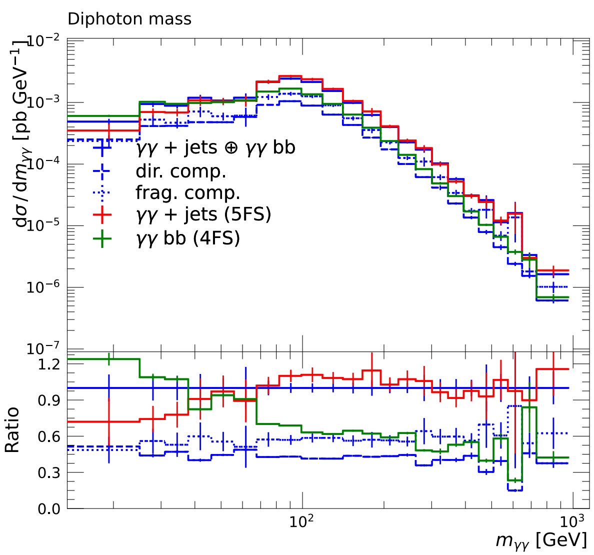
Results in $N_b \geq 0$

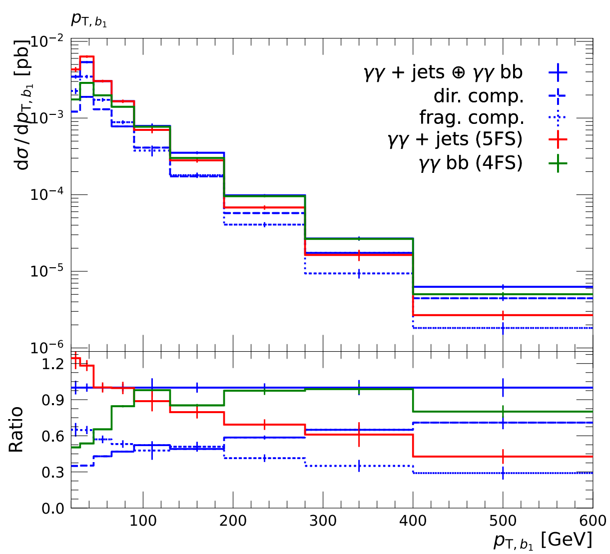
- The fusing is consistent with the 5FS and 4FS predictions in the relevant regions!

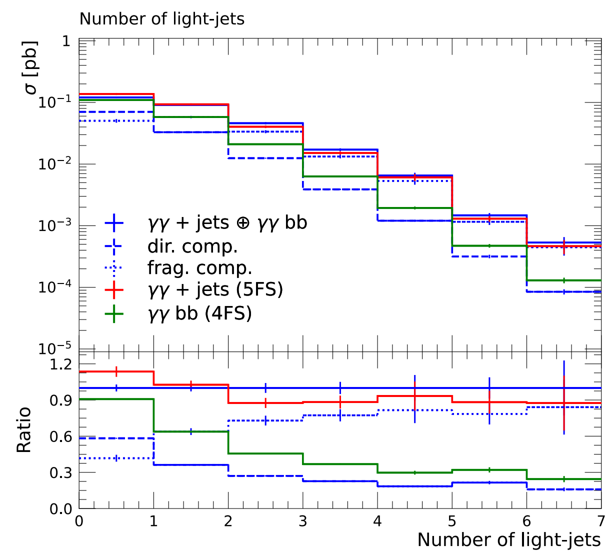


Results in $N_b \geq 1$

- Direct component is dominant in the high $p_{T,bjet}$ region.
- The fragmentation component becomes dominant with a larger number of light jets.

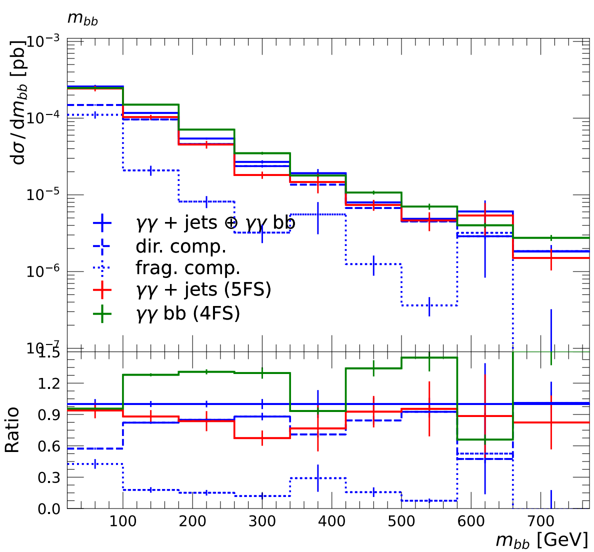


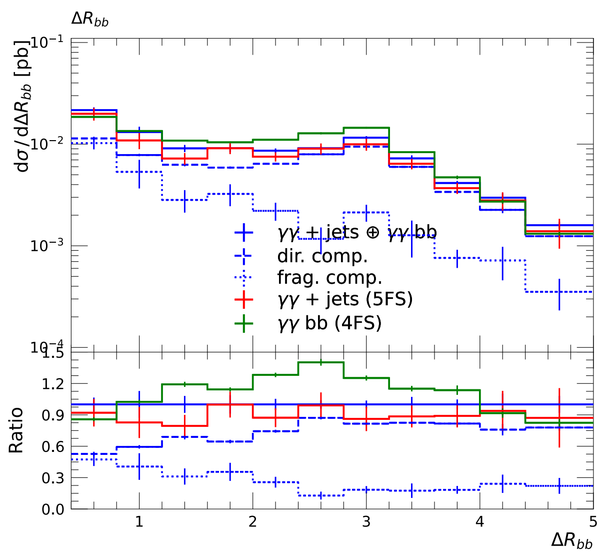


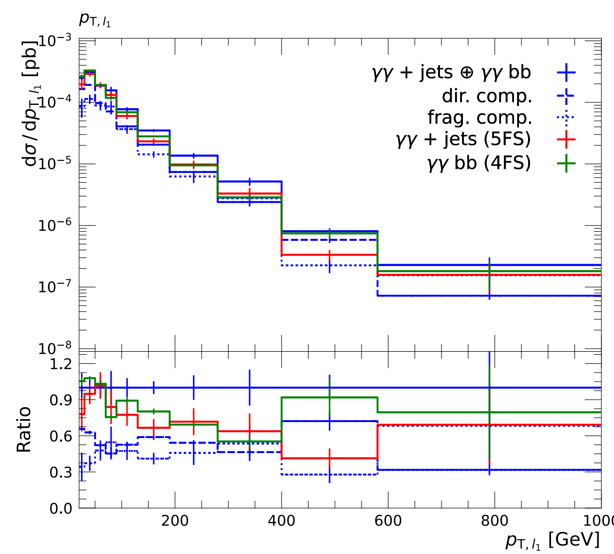


Results in $N_b \geq 2$

- 4FS and 5FS are consistent with fusing in m_{bb} and ΔR_{bb}
- The direct component dominates in this phase space!
  - except when the $b - jet$ pairs are collimated or soft.
- The fragmentation component gets important in high $p_{T,lightjet}$ region
- The fused prediction has a significantly smaller statistical uncertainty than the 5FS







Conclusion

- $\gamma\gamma + light\ jets$ and $\gamma\gamma + HF$ predictions combined for the first time!
- This could help with HH continuum background modelling
- The fused results are mostly compatible with 4FS and 5FS in the relevant regions

- The plan is to complete the work this year!
- The next step would be the modelling of Hbb background for the signal region of HH

Backup

Multi-jet merging in 5FS

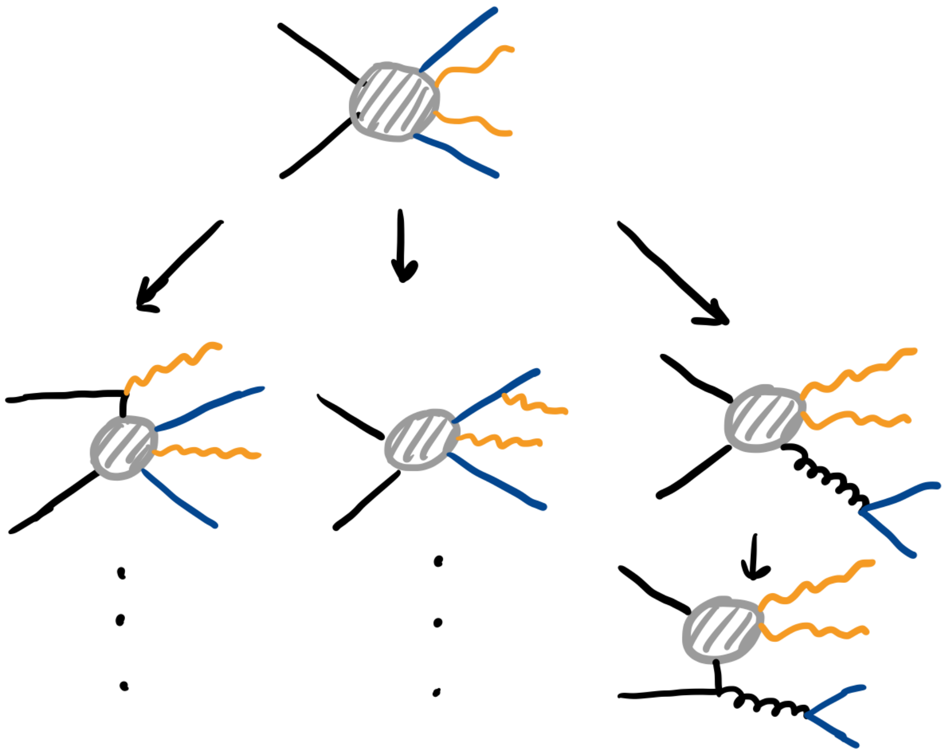
- Sherpa uses MEPS@LO and MEPS@NLO methods for different QCD accuracies

- The main idea is to cover all phase space
  - Fixed-order calculation (ME at LO, NLO…) in the **hard scale**: $p_{T,jet} > p_{T,cut}$
  - Resummation of all higher order QCD corrections (PS) in the **soft and collinear scale**: $p_{T,jet} < p_{T,cut}$ $\longrightarrow$ called **merging scale**

- PS is not only a **complement** of the ME in the phase space but also modifies the fixed-order calculation when **merging scale** < **resummation scale** $\longrightarrow$ PS starting scale
  - maintain the logarithmic accuracy in the overall calculation

Multi-jet merging in 5FS

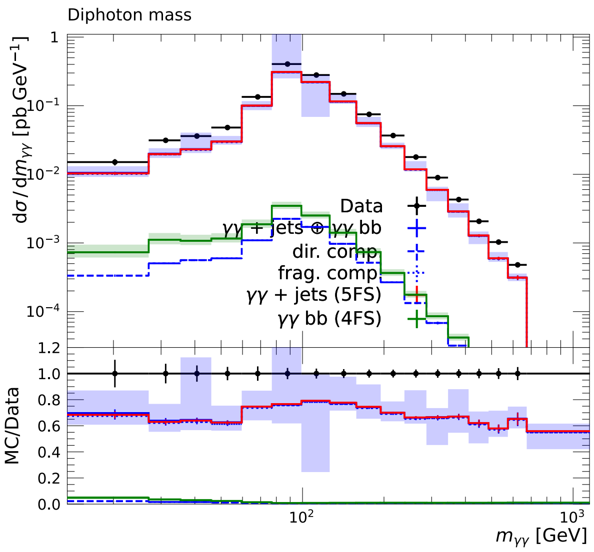
- How does resummation modify fixed-order calculation?
- **Clustering**
  - Treat the fixed-order as originated from a parton cascade
  - Find all **parton shower histories** up to $2 \to 2$ process
- α_s— **reweighting**
  - Choose proper scales for the α_s in each branching
  - $\alpha_s(\mu_R^2)^{n+k} = \alpha_s(\mu^2_{R,core-scale})^k \alpha_s(k^2_{t,1}) \ldots \alpha_s(k^2_{t,n})$
- **Sudakov reweighting**
  - Multiply by proper Sudakov factors for no-emission probability

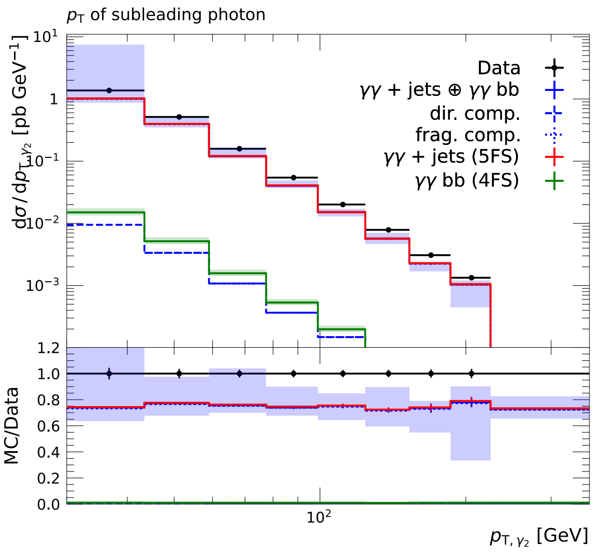


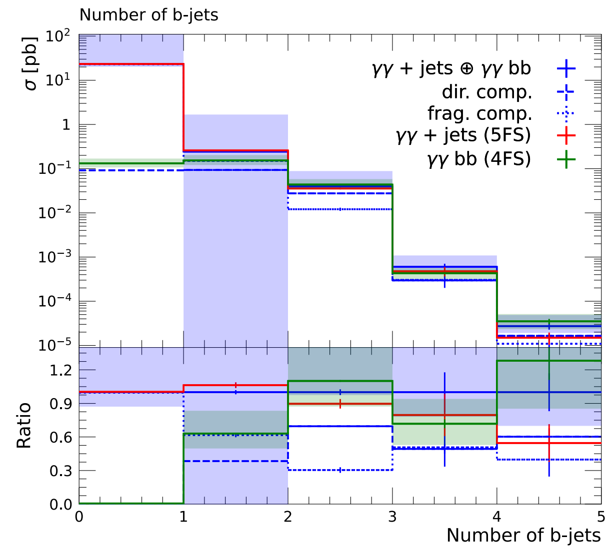
- Among all possible PS-histories, **choose probabilistically one of them** according to the associated weights
  - $w = w_{core} w_1 \ldots w_n$

Results in $N_b \geq 0$

- The fusing is consistent with the ATLAS data in shape comparison (working on ratio difference)!
- Fragmentation component is the dominant one and agrees with $\gamma\gamma + light\ jets$ (5FS)
- $\gamma\gamma + HF$ contribution is tiny.







Results in $N_b \geq 1$

- Subcomponent contributions to the fusion have mostly flat behaviour!
- When photons are soft or collimated, Sudakov suppression on the direct component is high.
- The fragmentation component becomes dominant with a larger number of light jets.