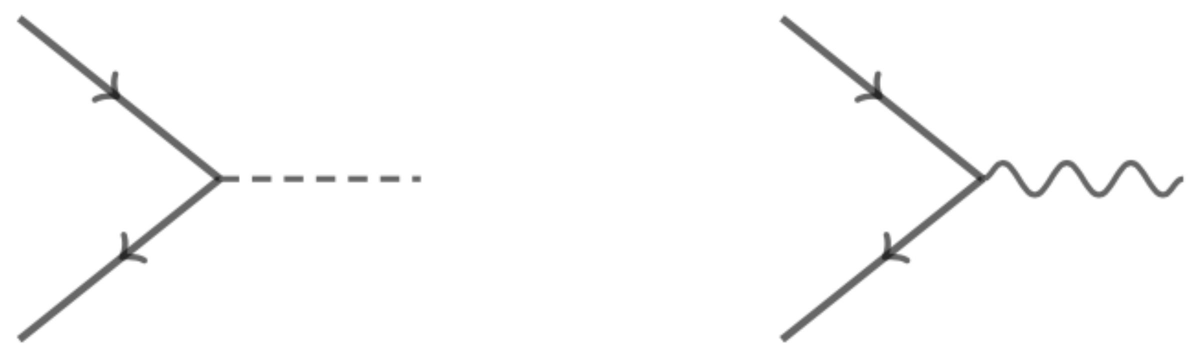
# Heavy Flavours @ the LHC

Davide Napoletano, Genova 21/11/2023

# Intro

- **Treatment of heavy flavours**
    - 4F vs 5F scheme
    - 4F with 5F scheme (FONLL)



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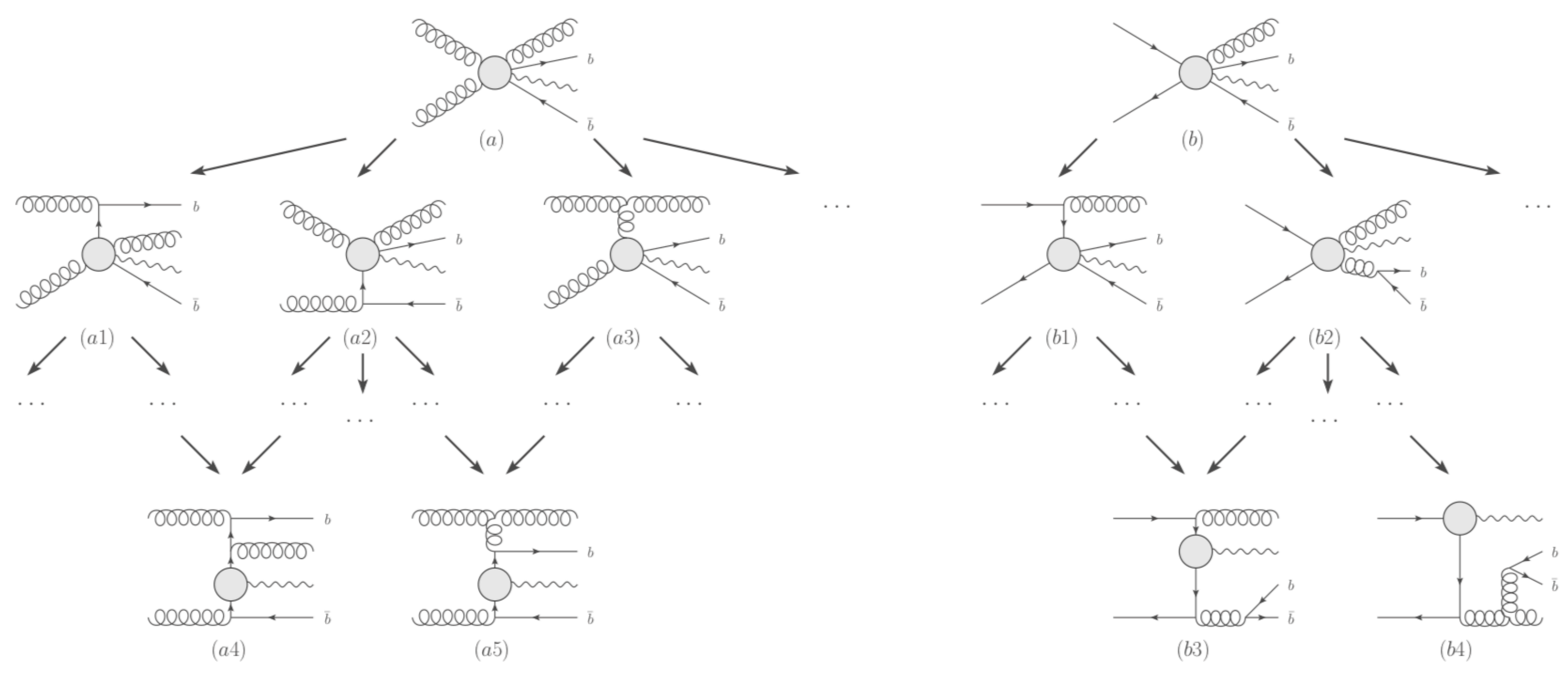
    - 4F with 5F scheme (FONLL)

- **Simulations for heavy flavours (IS)**
    - Matching á la Bagnaschi et al
    - Multijet merging for heavy flavours
    - Massive 5F scheme (FONLL)



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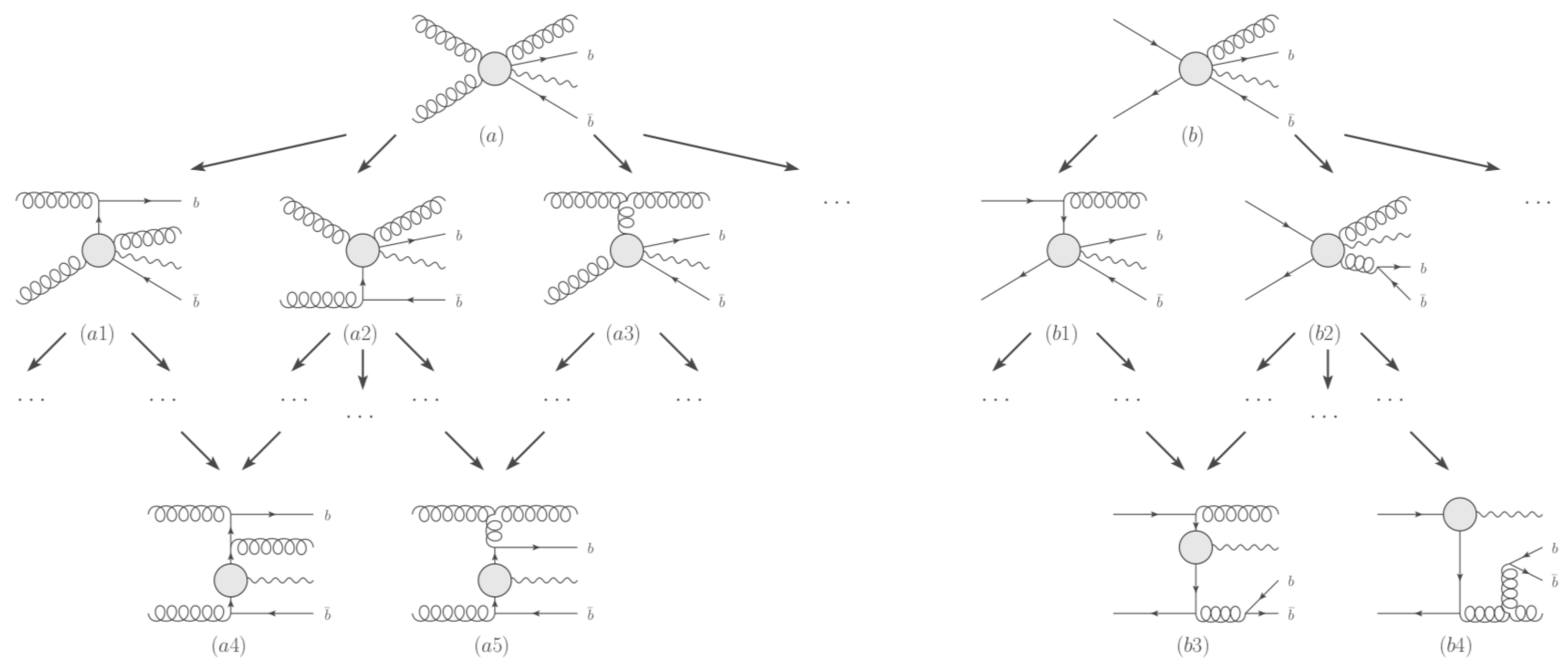
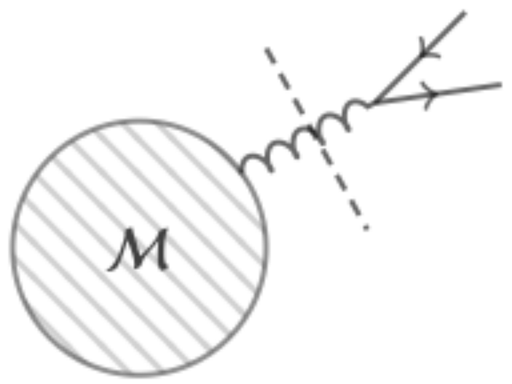
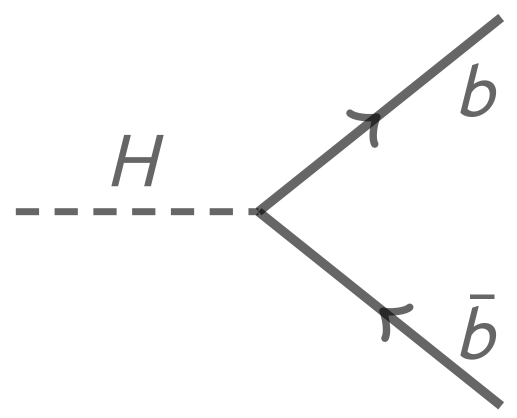


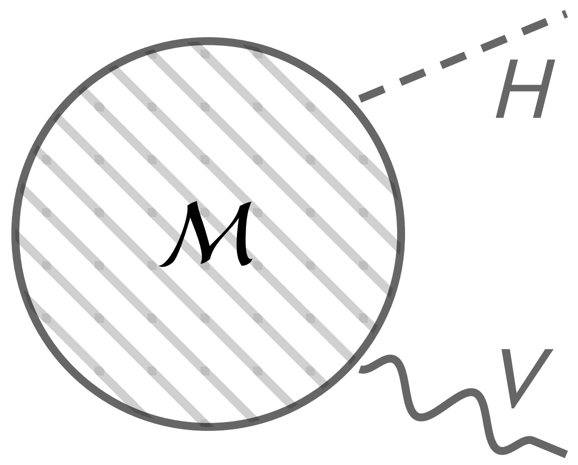
- **Simulations for heavy flavours (FS)**
  - Issues with HF in the FS
  - Parton showers for Heavy Flavours



# Treatment of Heavy Flavours

- Heavy flavour associated production quite important at colliders:

- 

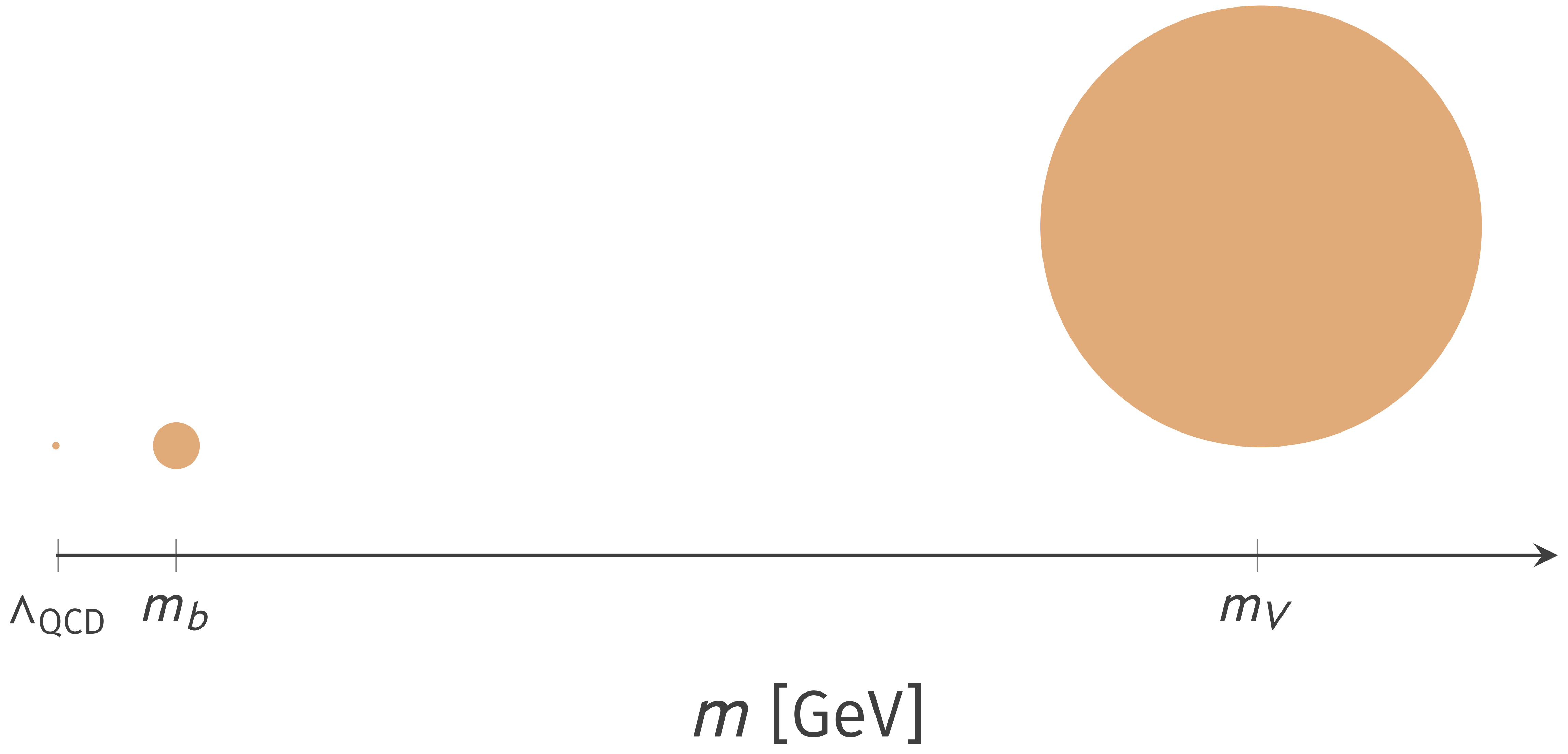
Largest BR, important for 


- Large $\tan\beta$ enhancement in many new physics model

# Treatment of Heavy Flavours

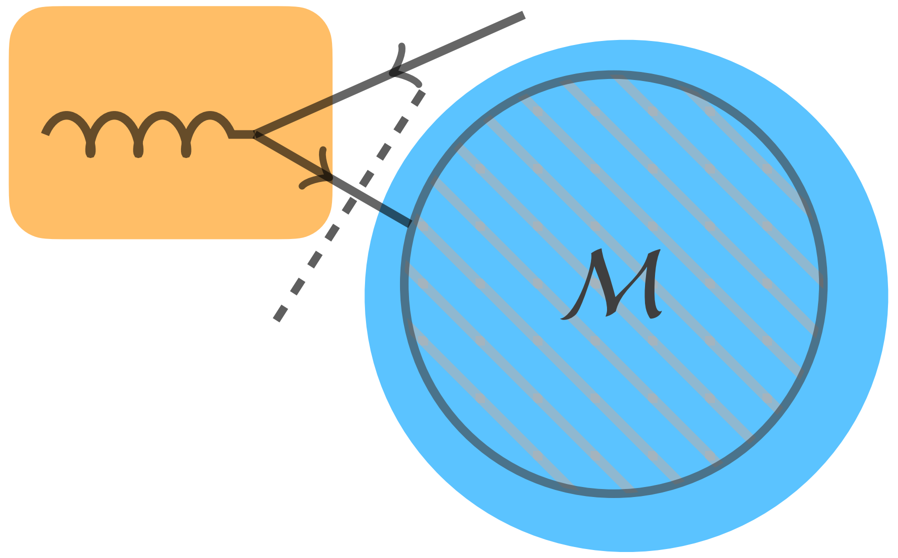
- Heavy flavour associated production quite important at colliders:

    - Theoretically, natural multi-scale problem



# 4F vs 5F scheme

- Base assumption: $b$ can only come from a $g \to b\bar{b}$ splitting




$$\sim \int^{Q^2} \mathrm{d}t \frac{\alpha_s}{2\pi\,(t-m_b^2)} |\mathcal{M}_b|^2 \otimes P_{qg}\, f_g \underset{t \gg m_b^2}{\sim} |\mathcal{M}_b|^2 \frac{\alpha_s}{2\pi} \otimes P_{qg} f_g \log \frac{Q^2}{m_b^2}$$

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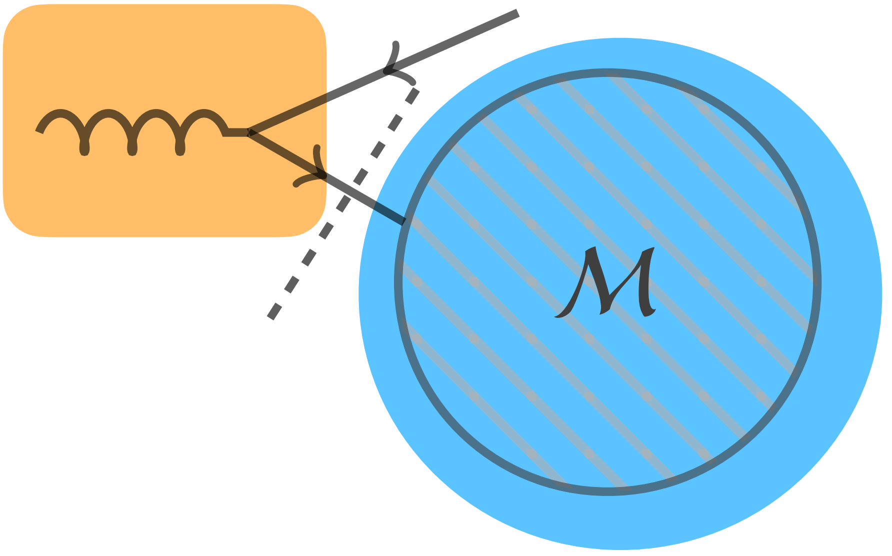

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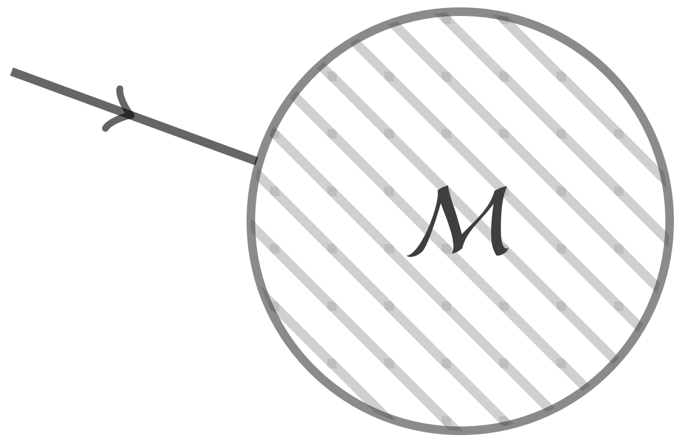
- Alternatively

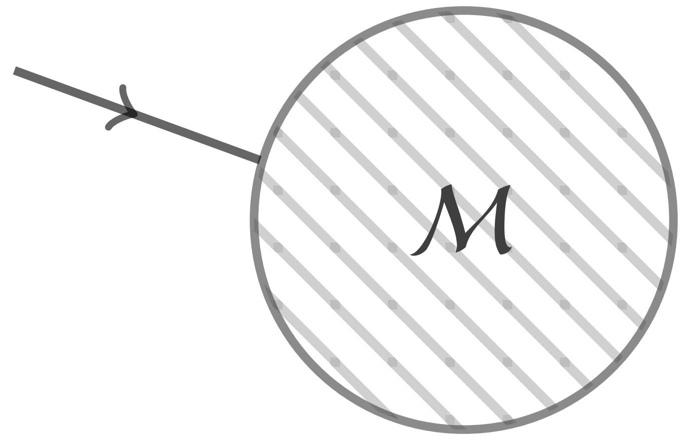
$$\tilde{f}_b(Q^2) = \frac{\alpha_s}{2\pi} \log \frac{Q^2}{m_b^2} P_{qg} \otimes f_g(Q^2)$$



$$= |\mathcal{M}_b|^2 \otimes \boxed{\tilde{f}_b(Q^2)}$$

# 4F vs 5F scheme

- We effectively defined a perturbative b-PDF

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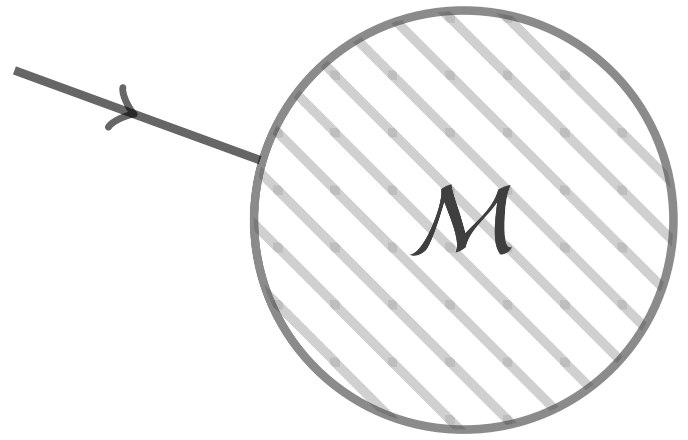



$$= |\mathcal{M}_b|^2 \otimes \tilde{f}_b(Q^2)$$

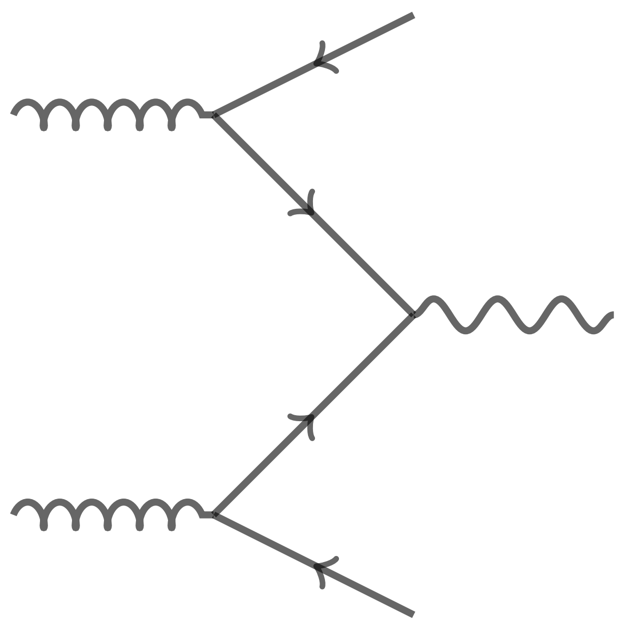
- It can be shown $\tilde{f}_b(Q^2)$ it's just the LL solution of the AP-equations:

$$\frac{\mathrm{d}}{\mathrm{d}\log Q^2} f_b(Q^2) = \frac{\alpha_s(Q^2)}{2\pi} P_{qg} \otimes f_g(Q^2)$$

- We have created the 5FS!

# 4F vs 5F (pp → V)

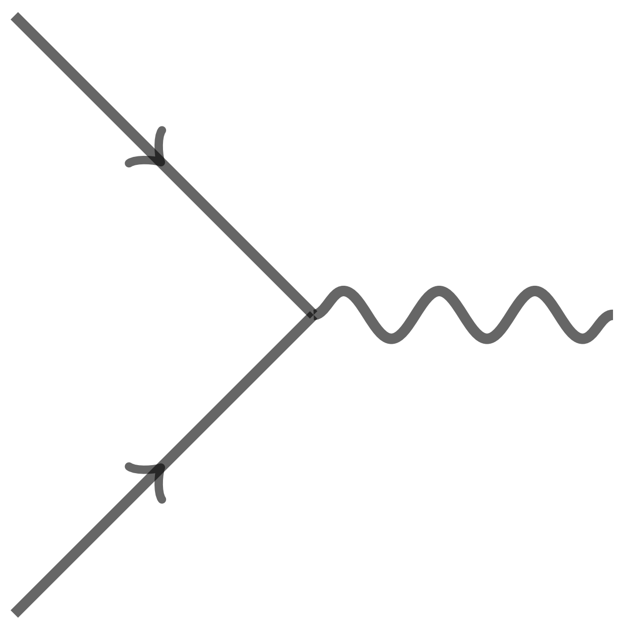
## 4FS



- Fully differential, $b$ massive
- No b-jet definition ambiguity (easy matching to showers)

- May suffer from large logs
- Not easy to extend to higher orders

## 5FS



- Need to include higher orders to be differential
- Ambiguous treatment of b-jet

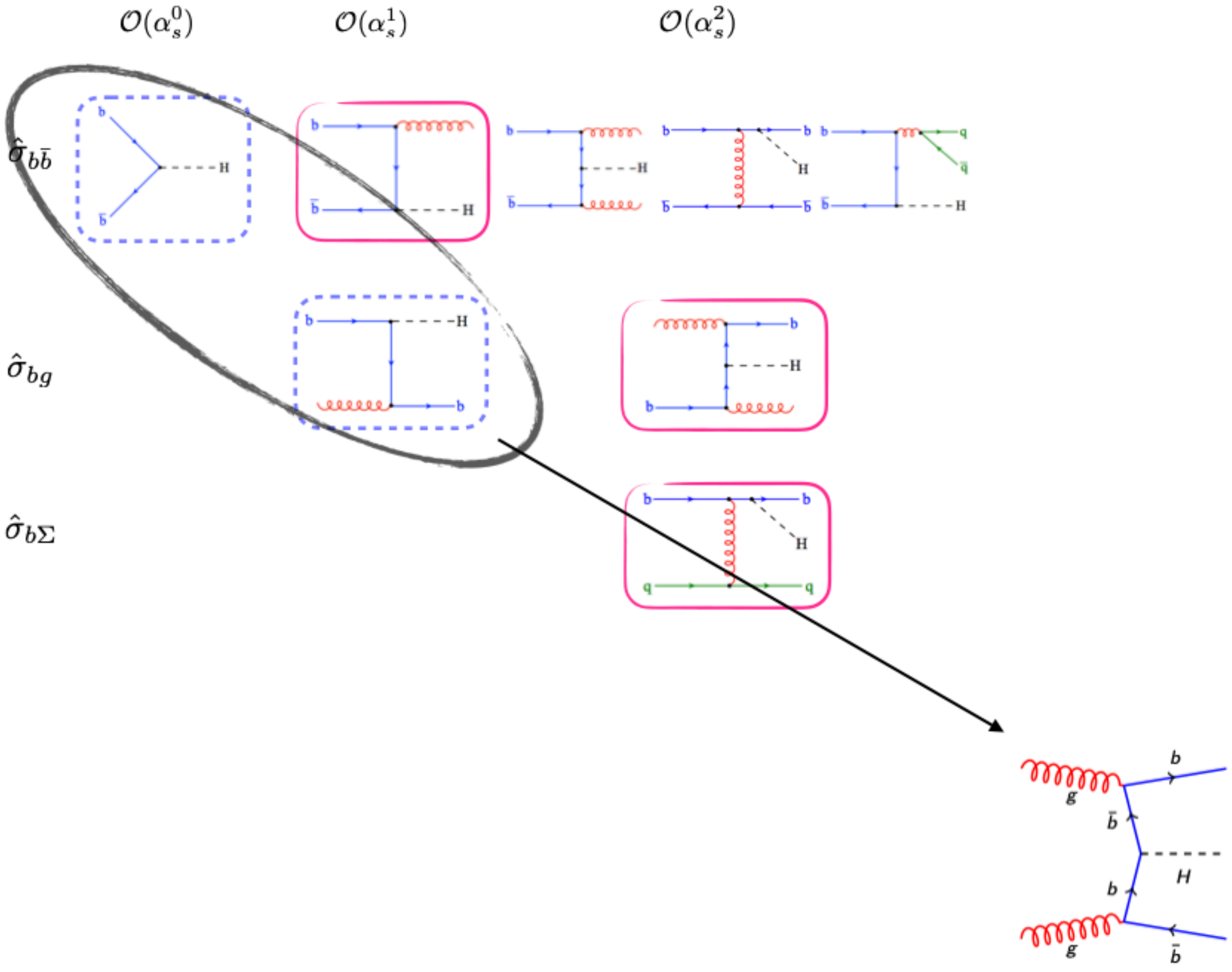
- Resummation of possibly large logs
- Higher order corrections usually come cheaper

# 4F with 5F scheme

- It’s clear that 4F and 5F scheme are different scheme for the same thing, they should also be compatible, to some extent

# 4F with 5F scheme

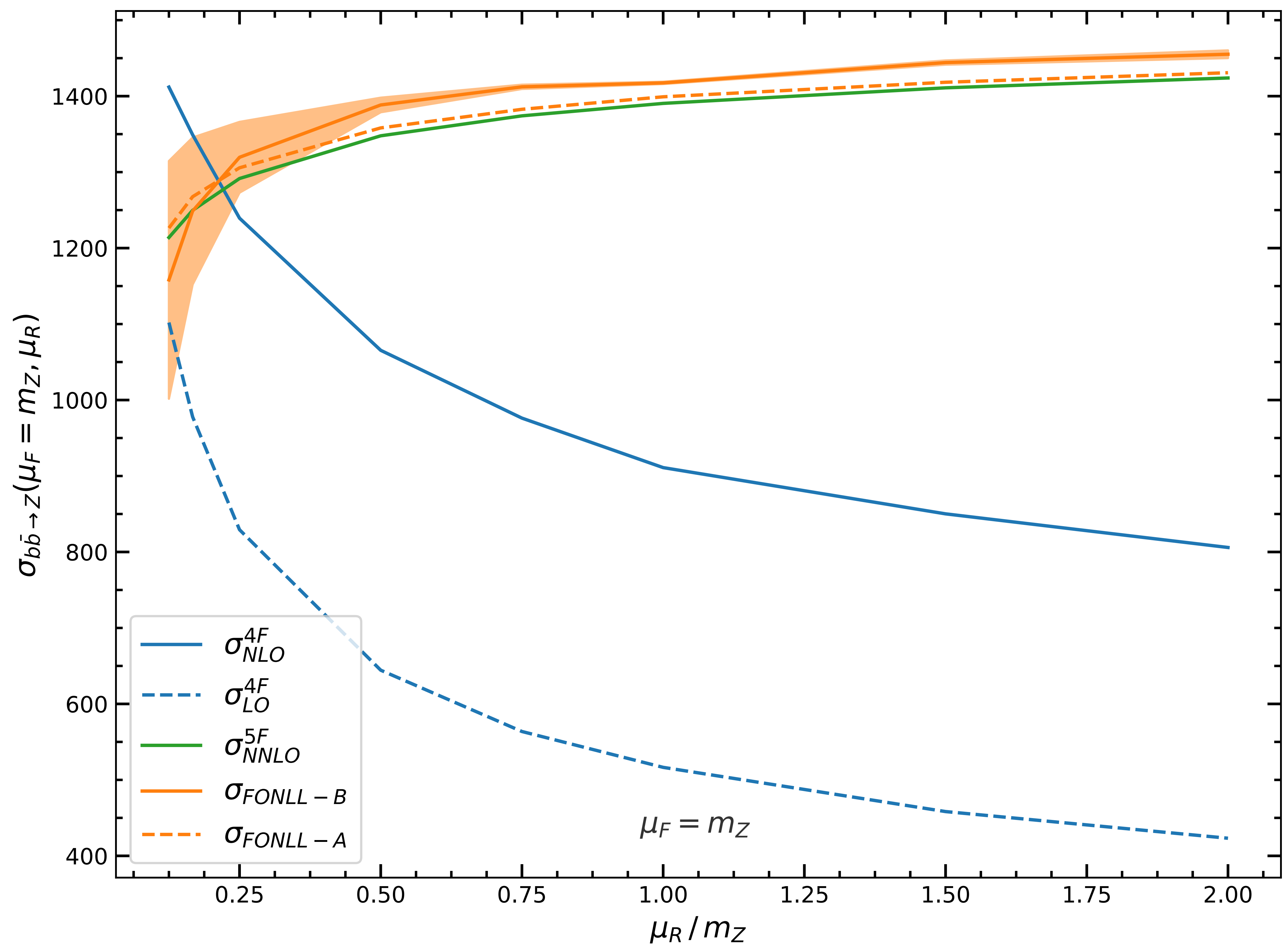
- Take as an example bbH:

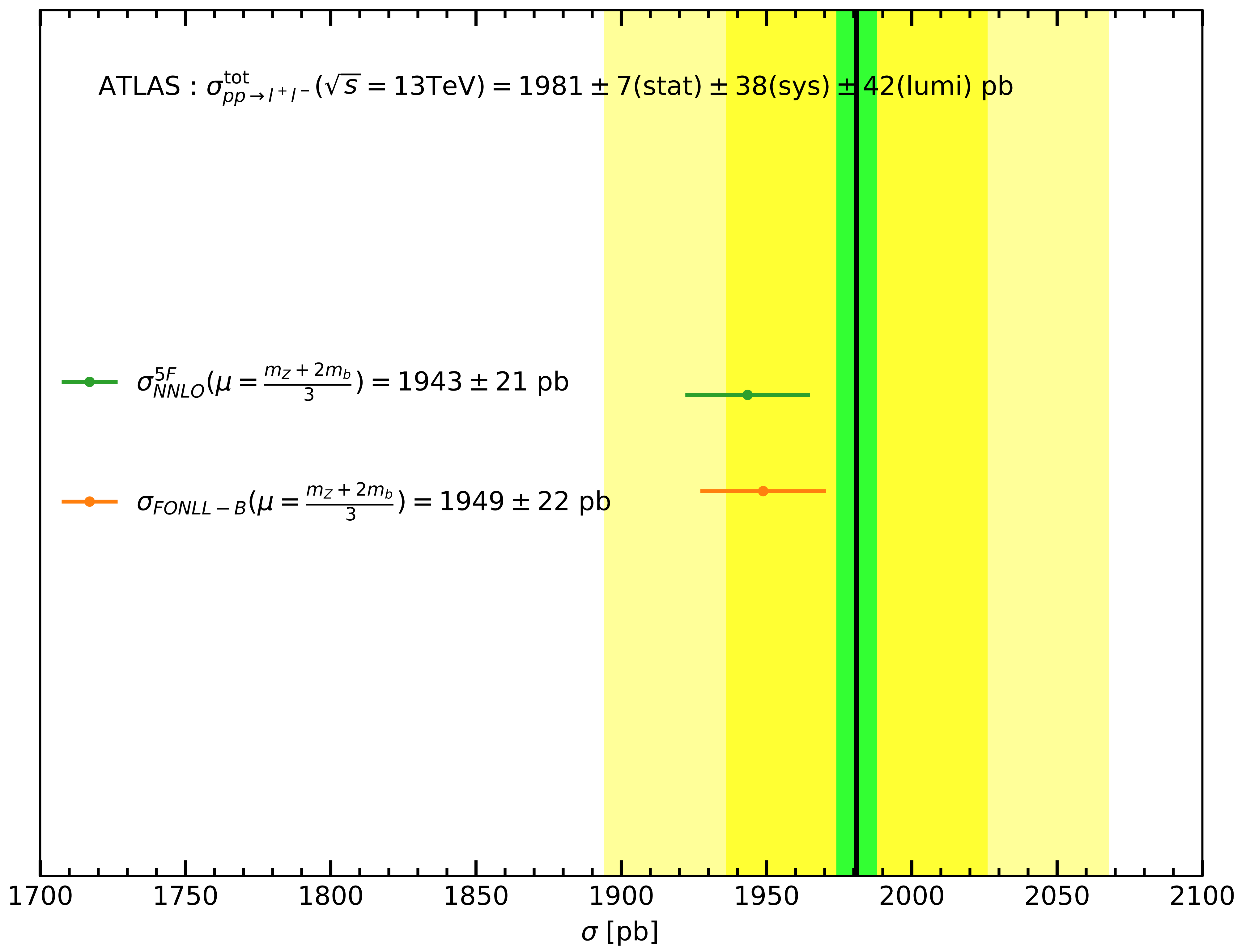


# 4F with 5F scheme

- Use this to identify double counted terms and can construct matching scheme (FONLL)

- Take for example bbZ



# Simulations for HF (IS)

- So far only for totally inclusive observables…

# Simulations for HF



- Bagnaschi et al.: Construct combination of 5 and 4FS, vetoing B-Hadrons

$$\mathrm{d}\sigma^{\text{mass}} = \mathrm{d}\sigma^{\text{5FS-Bveto}} + \mathrm{d}\sigma^{\text{4FS}}$$

# Simulations for HF

Bagnaschi et al. [JHEP 1807 (2018) 101]

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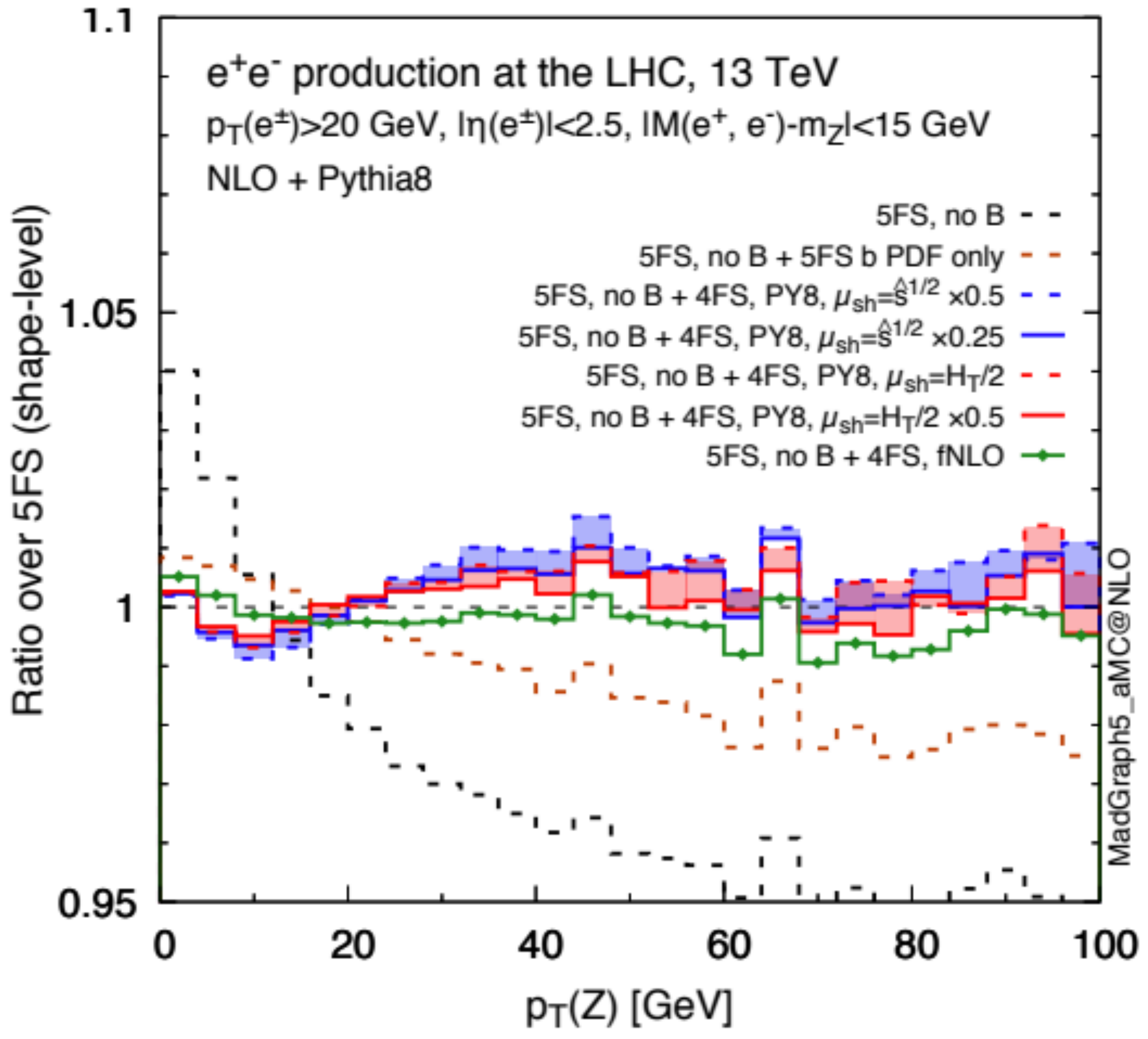
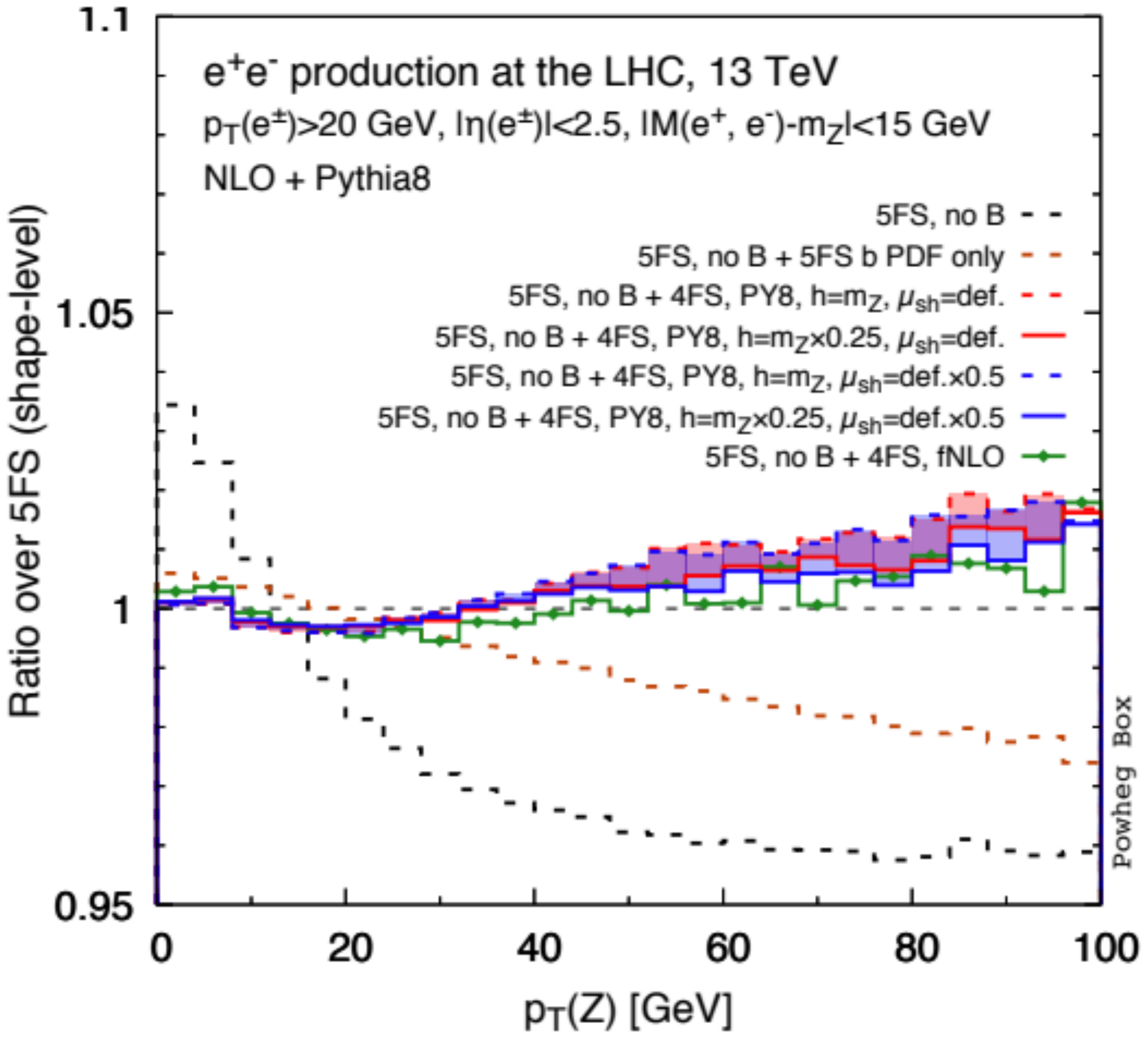
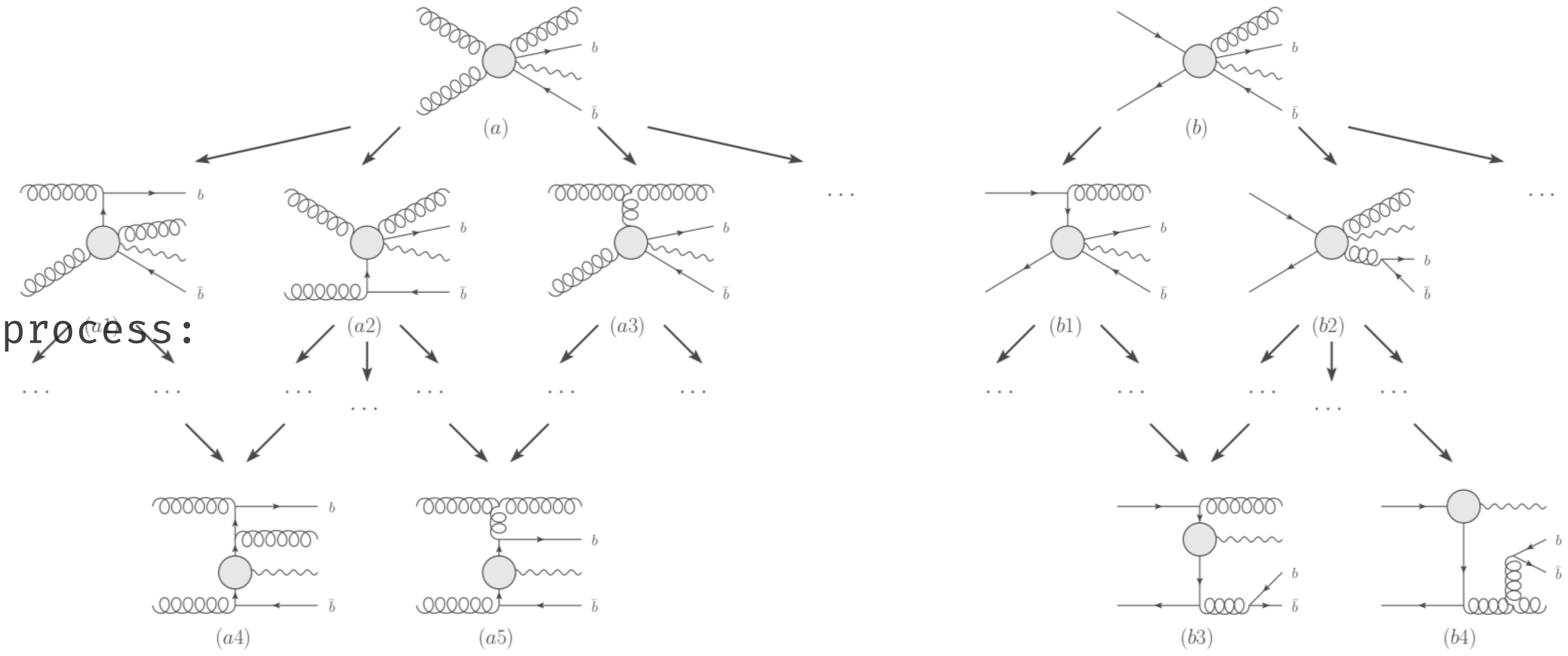


# Multi-jet-Merging

Höche, Krause, Siegert [Phys.Rev. D100 (2019) no.1, 014011]

- Generate showered events for $Z+j$




- Use clustering to determine core process:

$Z+b\bar{b}$ or $Z+j$

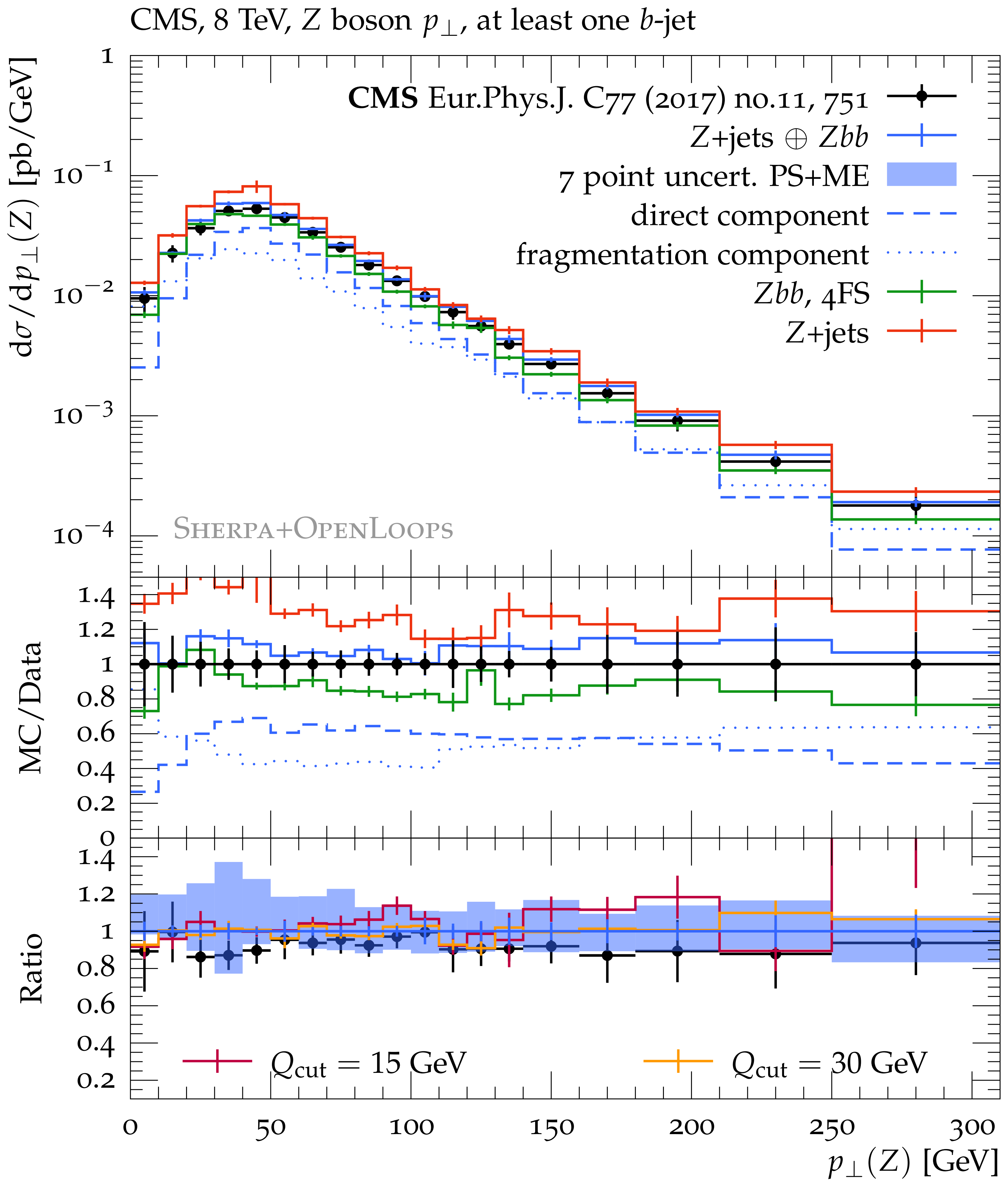
- Throw events if the first type

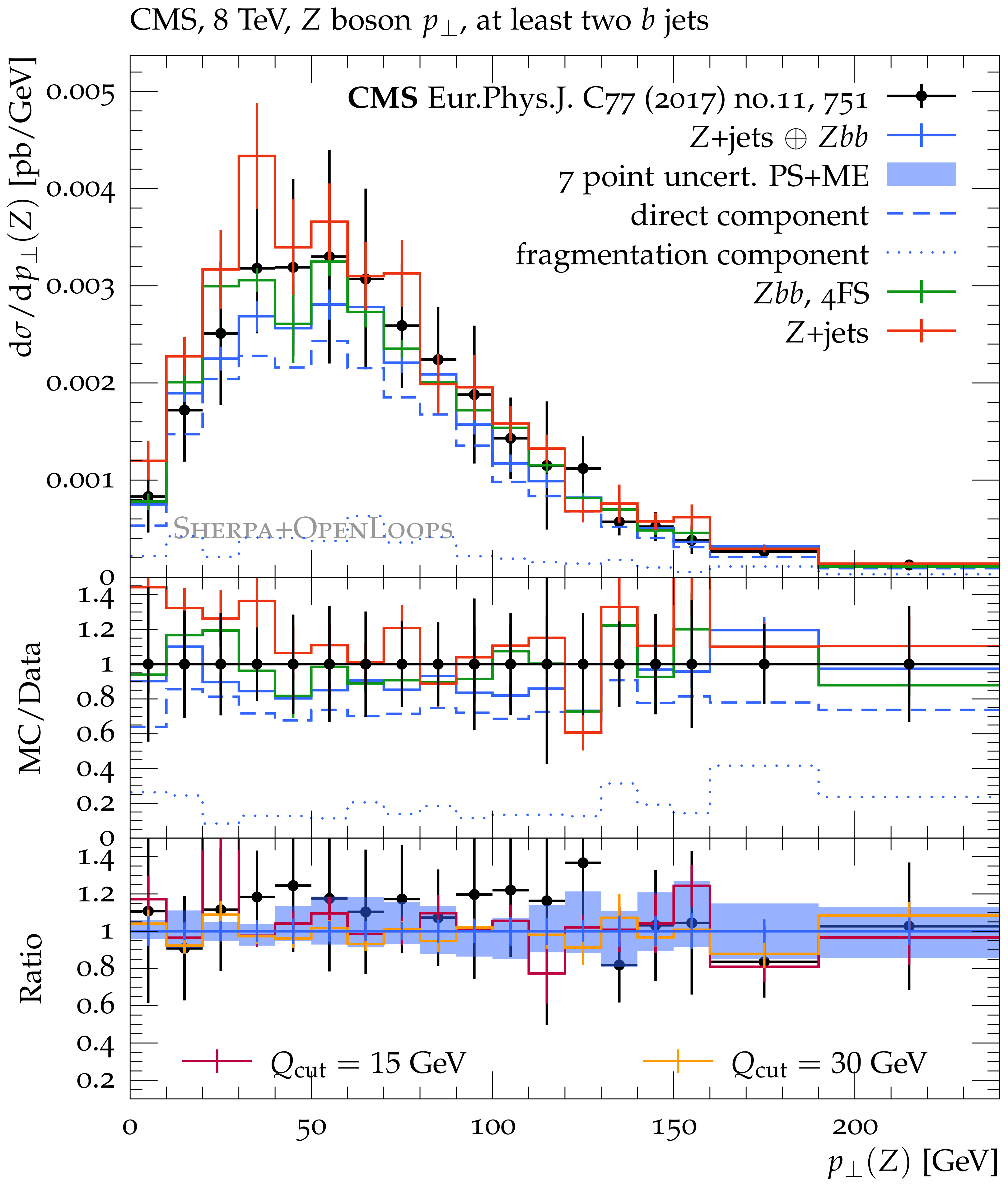
- Generate $Z+b\bar{b}$ in the 4FS

Sum the two samples with no overlap

# Multi-jet-Merging

Höche, Krause, Siegert [ArXiv:1904.09382]



# Fitting the b-PDF?

Forte, Giani, DN [Eur.Phys.J. C79 (2019) no.7, 609

- Use the FONLL matching, but drop the assumption the bs are only produced perturbatively

- the 4FS picks up b-initiated channels, and the subtraction becomes simpler:

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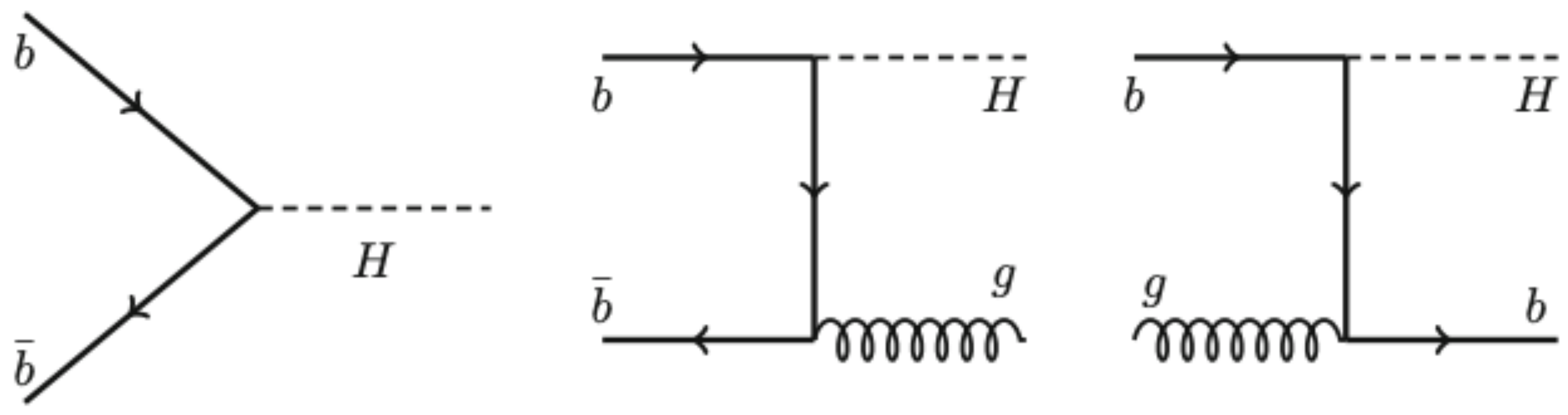


Are present both in the 4F and 5F schemes

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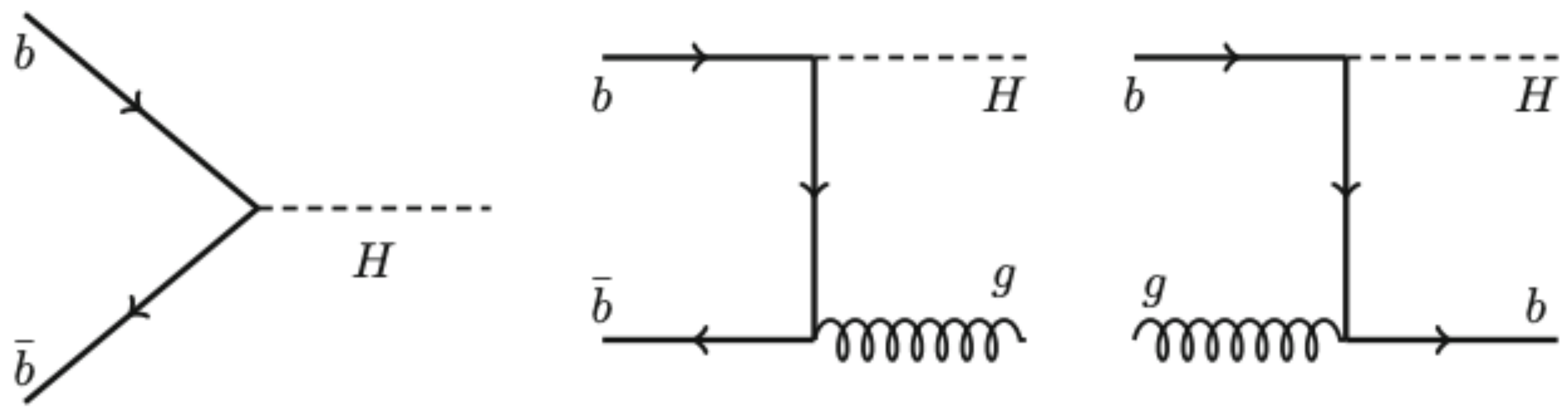


- In the 4F scheme only a static contribution

- In the 5F, Intrinsic + normal evolution with different b conditions

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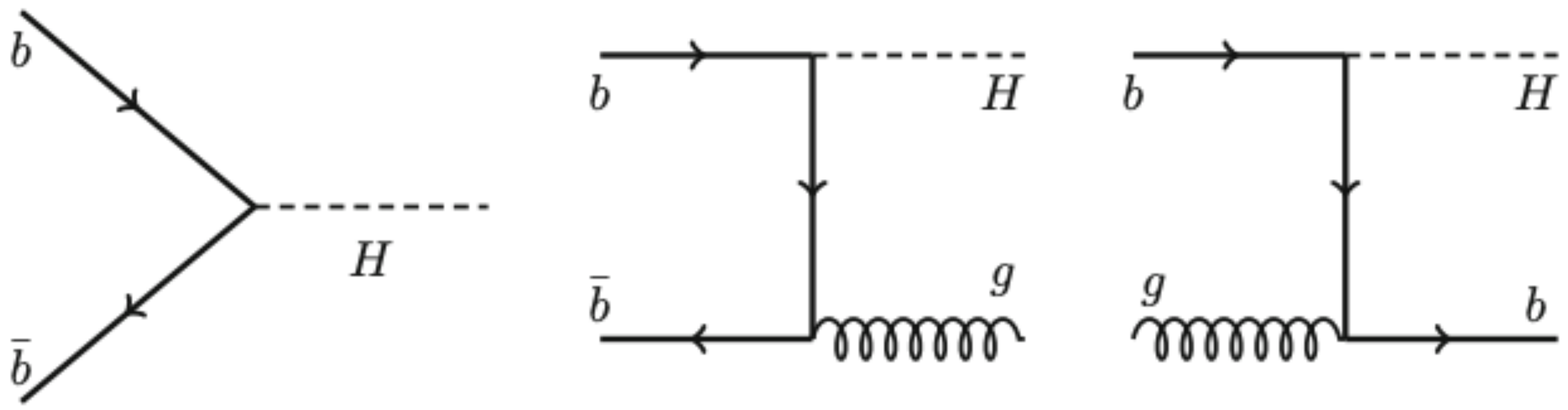
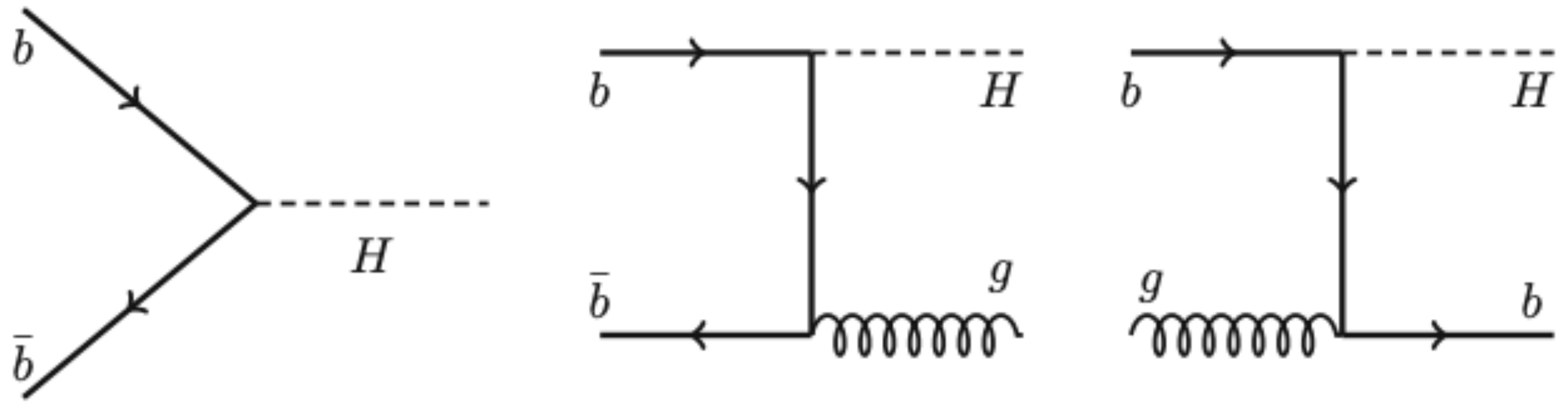
Forte, Giani, DN [Eur.Phys.J. C79 (2019) no.7, 609

The 5FS and the subtraction term cancel out, at any order!

**5FS**




**S.T.**




- $\alpha_s$ and PDFs in the 5FS with massless bs
- ME and PS also in the 5FS with massless bs

- $\alpha_s$ and PDFs in the 5FS at a given order by expanding the evolution equations
- ME and PS end up in the 5FS with massless bs after collinear renormalisation

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- Use the FONLL matching, but drop the assumption the bs are only produced perturbatively

- the 4FS picks up b-initiated channels, and the subtraction becomes simpler:

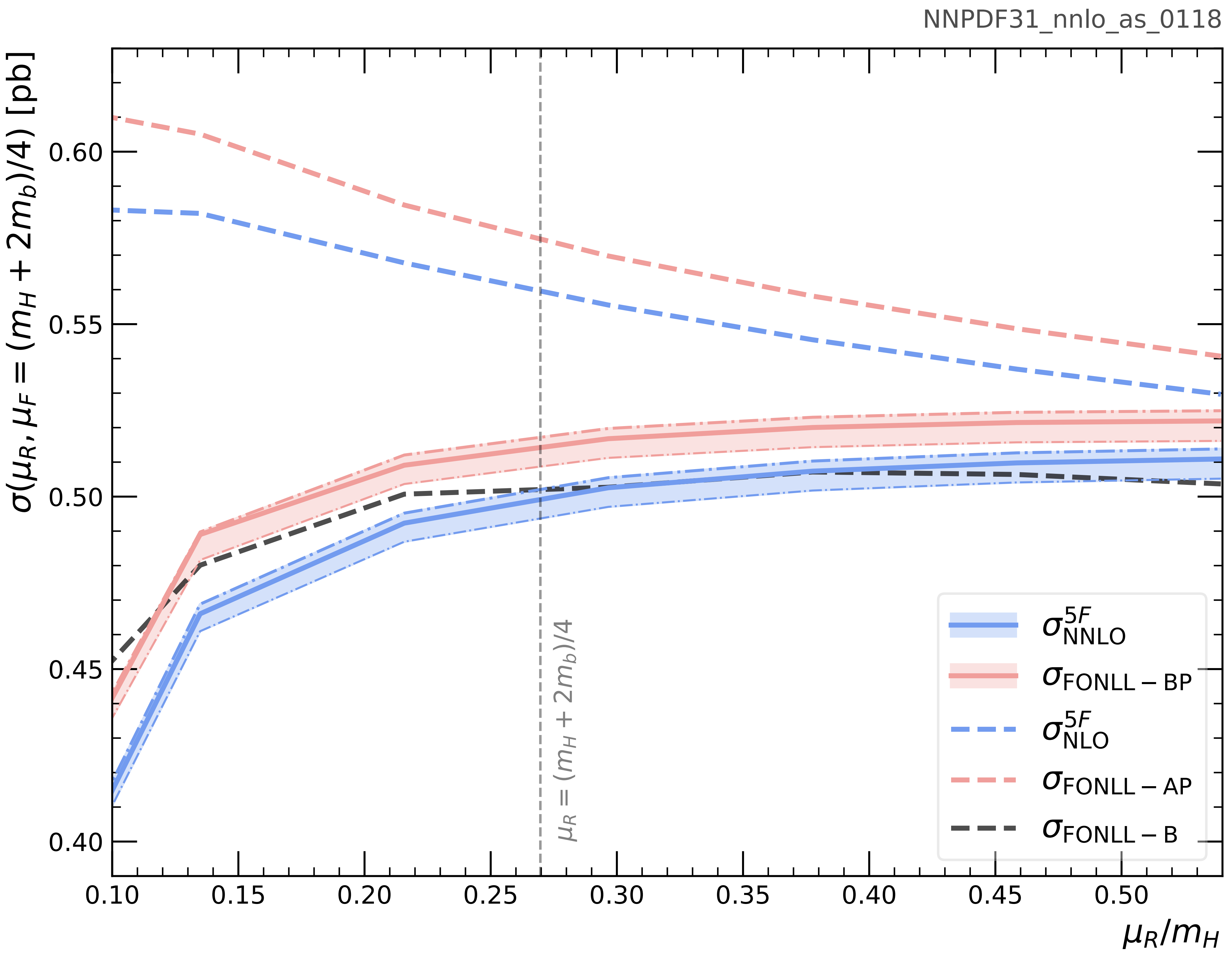
The 5FS and the subtraction term cancel out, at any order!

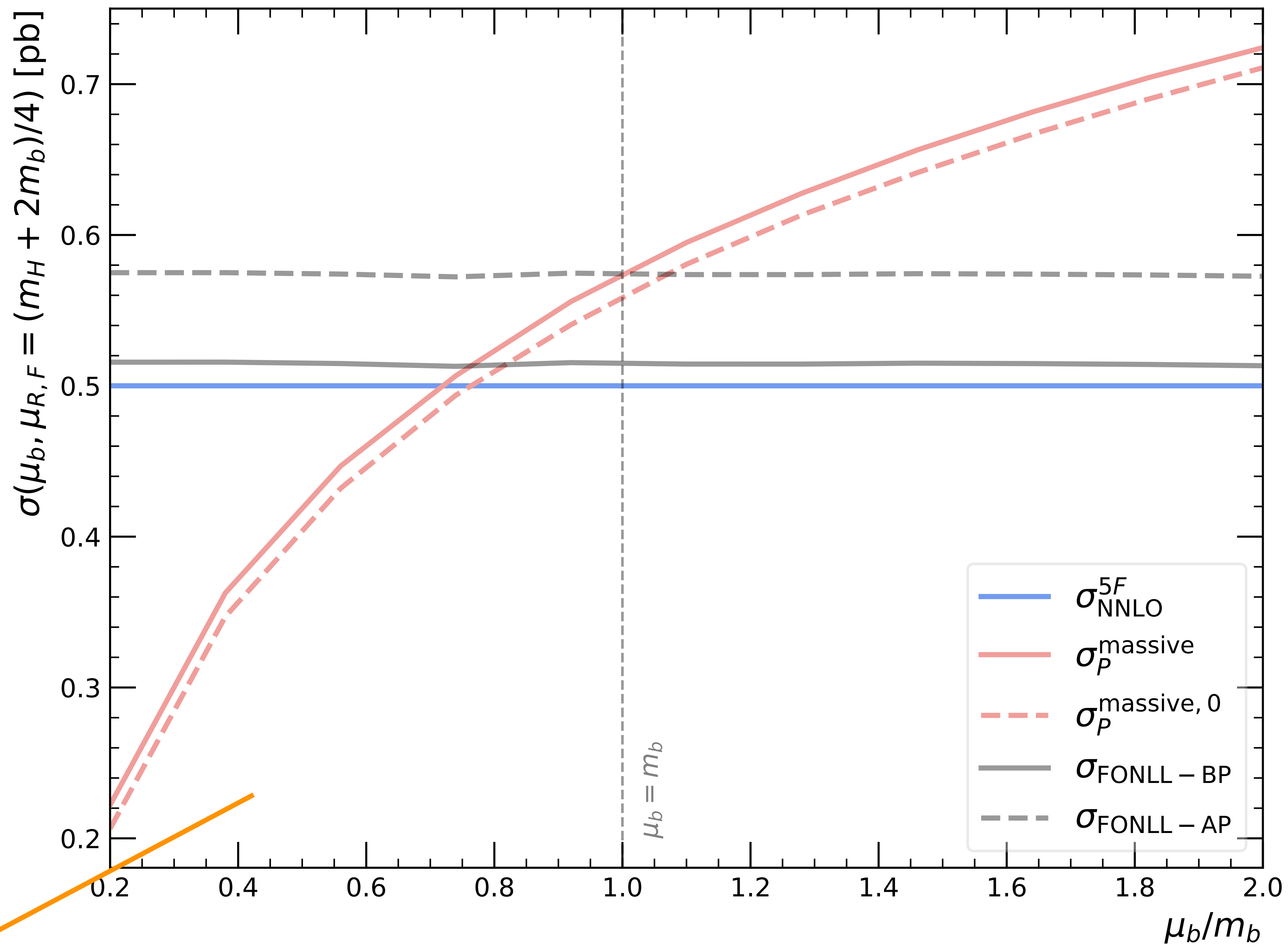
$$\sigma^{\text{FONLL-AP}} = \sum_{i,j} \sum_{l,m} \hat{\sigma}_{ij}^{\text{massive}} \left( \frac{m_h^2}{m_b^2} \right) \otimes K_{il}^{-1} \otimes f_l^{(5)} \left( Q^2 \right) K_{jm}^{-1} \otimes f_m^{(5)} \left( Q^2 \right)$$

- This is exactly the 5F Massive Scheme with standard 5FS PDFs!

Krauss, DN [Phys.Rev. D98 (2018) no.9, 096002]

# Fitting the b-PDF?

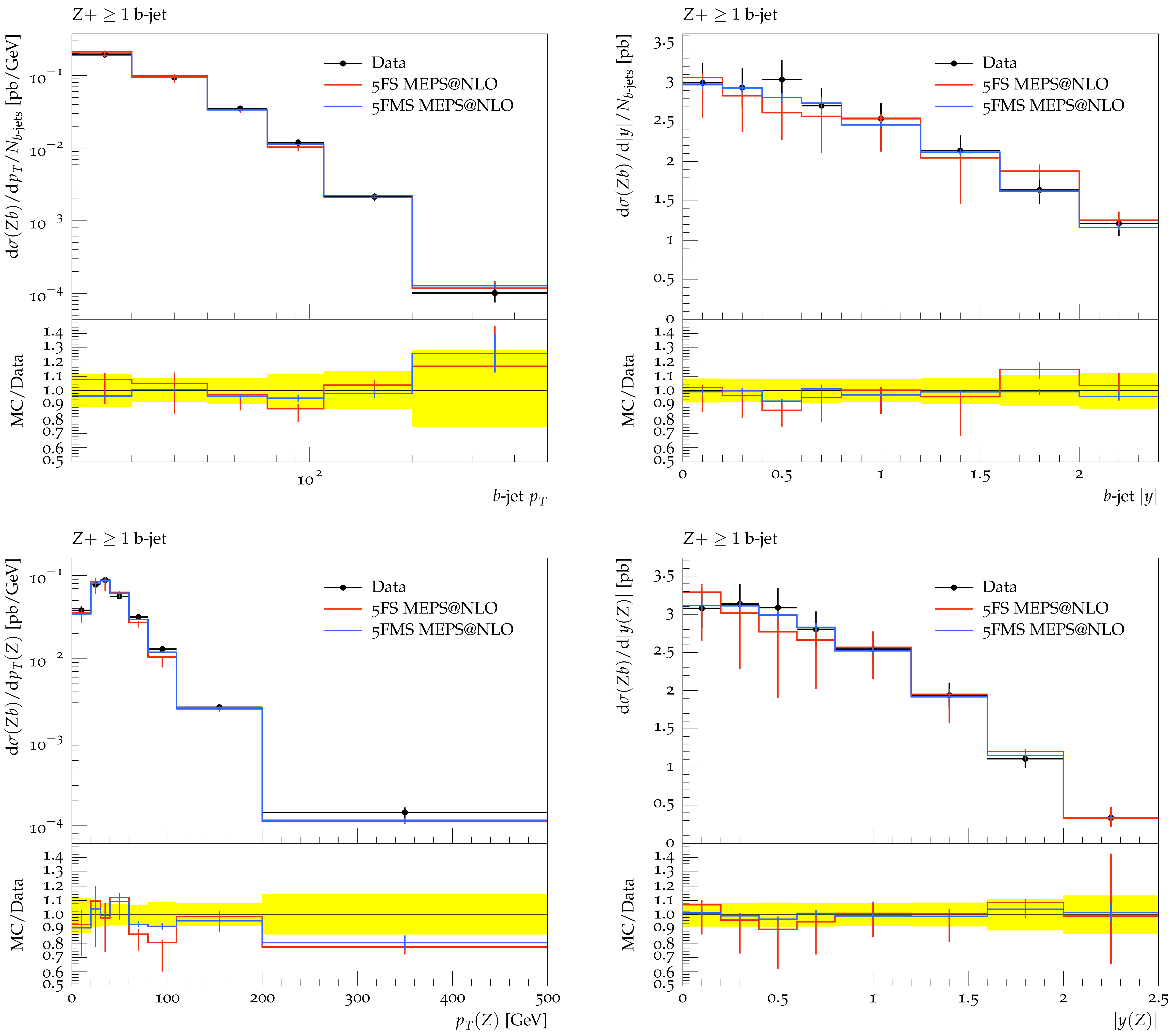



- No $\mu_b$ dependence left, after matching, as une should expect.

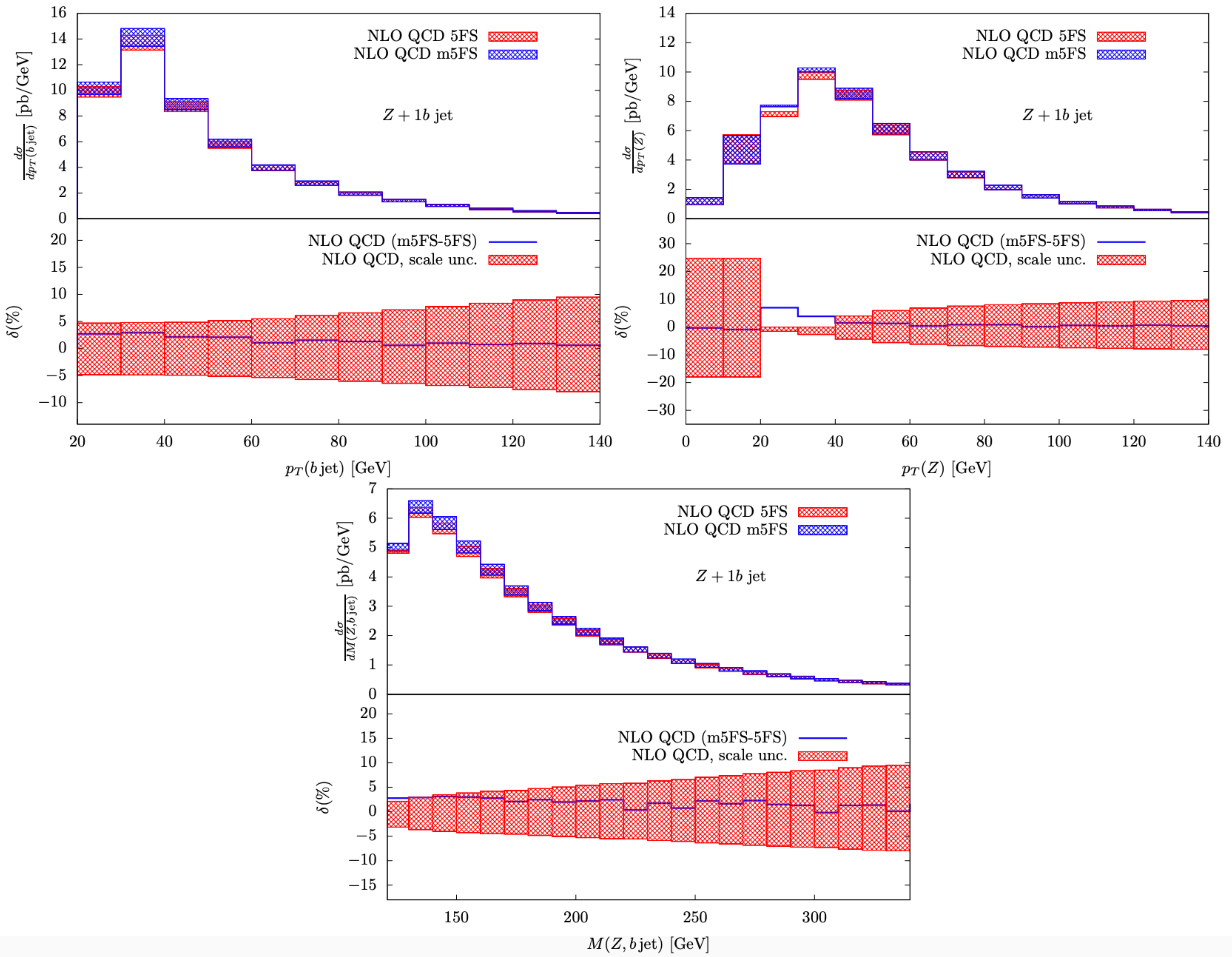
# Massive 5FS (5FMS)

Krauss, DN [Phys.Rev. D98 (2018) no.9, 096002]



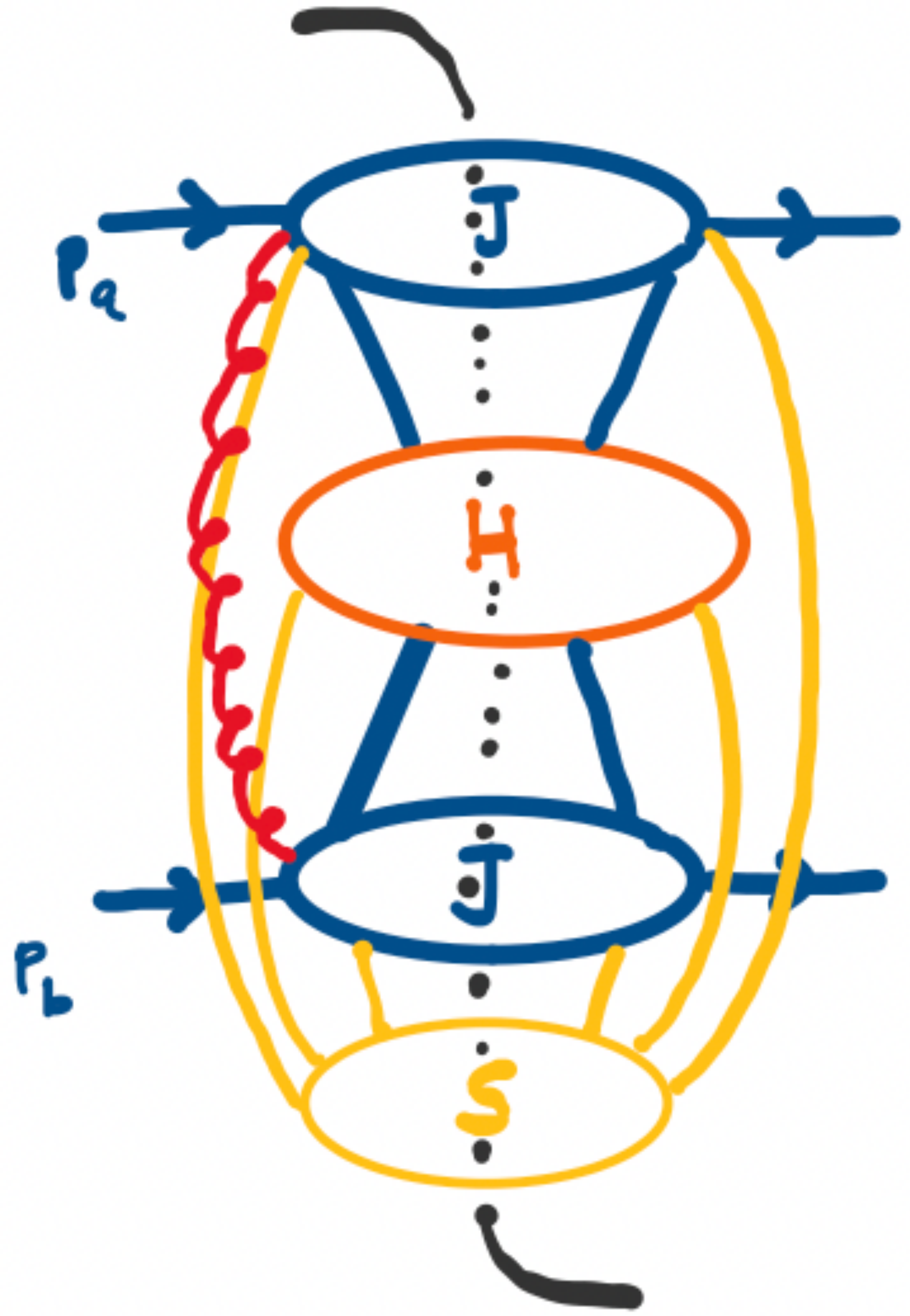
# Massive 5FS (5FMS)

*Figueroa et al. [Phys.Rev. D98 (2018) no.9, 093002]*



# Uncancelled Divergences

- Factorisation relies on

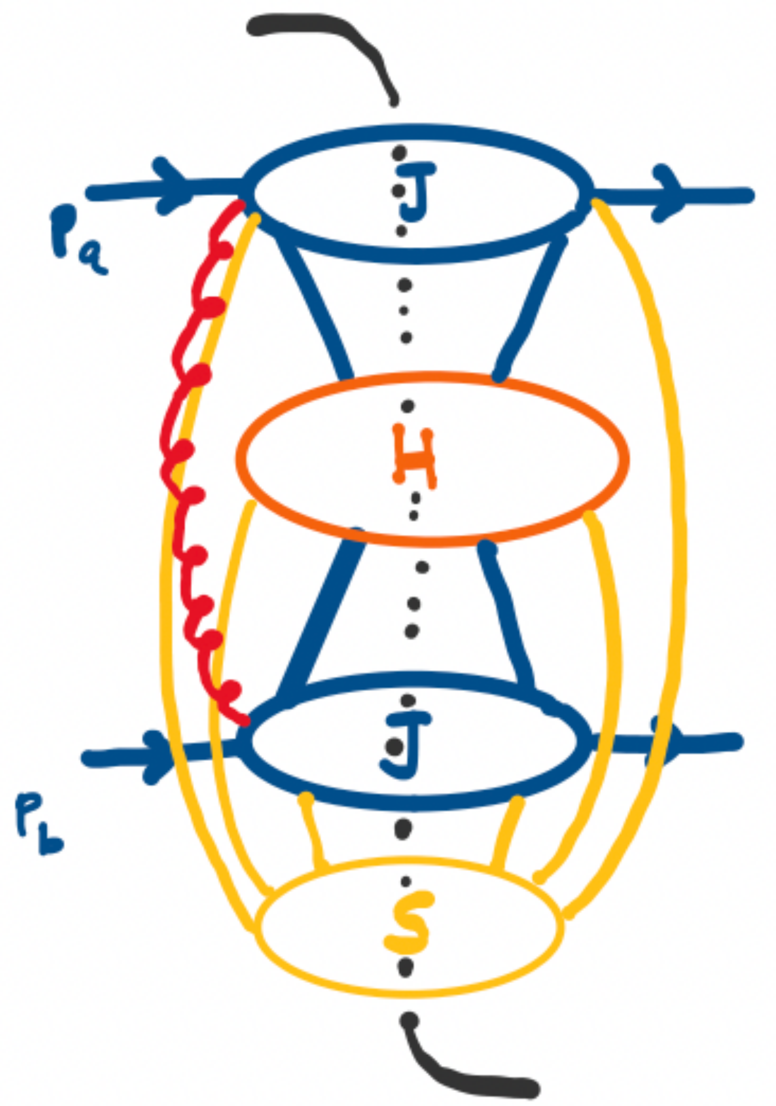



$$\Sigma^J_a + \Sigma^J_b + \Sigma^S + \Sigma^H \neq 0$$

$$\Sigma^J_a + \Sigma^J_b + \Sigma^S + \Sigma^H + \Sigma^{\#} \overset{?}{=} 0$$

# Uncancelled Divergences

- But with massive quarks, this cancellation is broken




$$\Sigma^J_a + \Sigma^J_b + \Sigma^S + \Sigma^H \neq 0$$

$$\Sigma^J_a + \Sigma^J_b + \Sigma^S + \Sigma^H + \Sigma^* \stackrel{?}{=} 0$$

$$\Delta[d\sigma_{\mathrm{RV}}^{\mathrm{div}}] = \left[\frac{\alpha_s(\mu)}{2\pi}\right]^2 \frac{2C_A C_F\,\pi^2}{\epsilon}\left[\frac{1}{2v}\ln\left(\frac{1-v}{1+v}\right)+1\right]\left(\frac{1-v}{v}\right) d\sigma_{\mathrm{LO}}.$$

# Simulations for HF (FS)

- This was mostly for IS heavy flavours… What's there in the FS?

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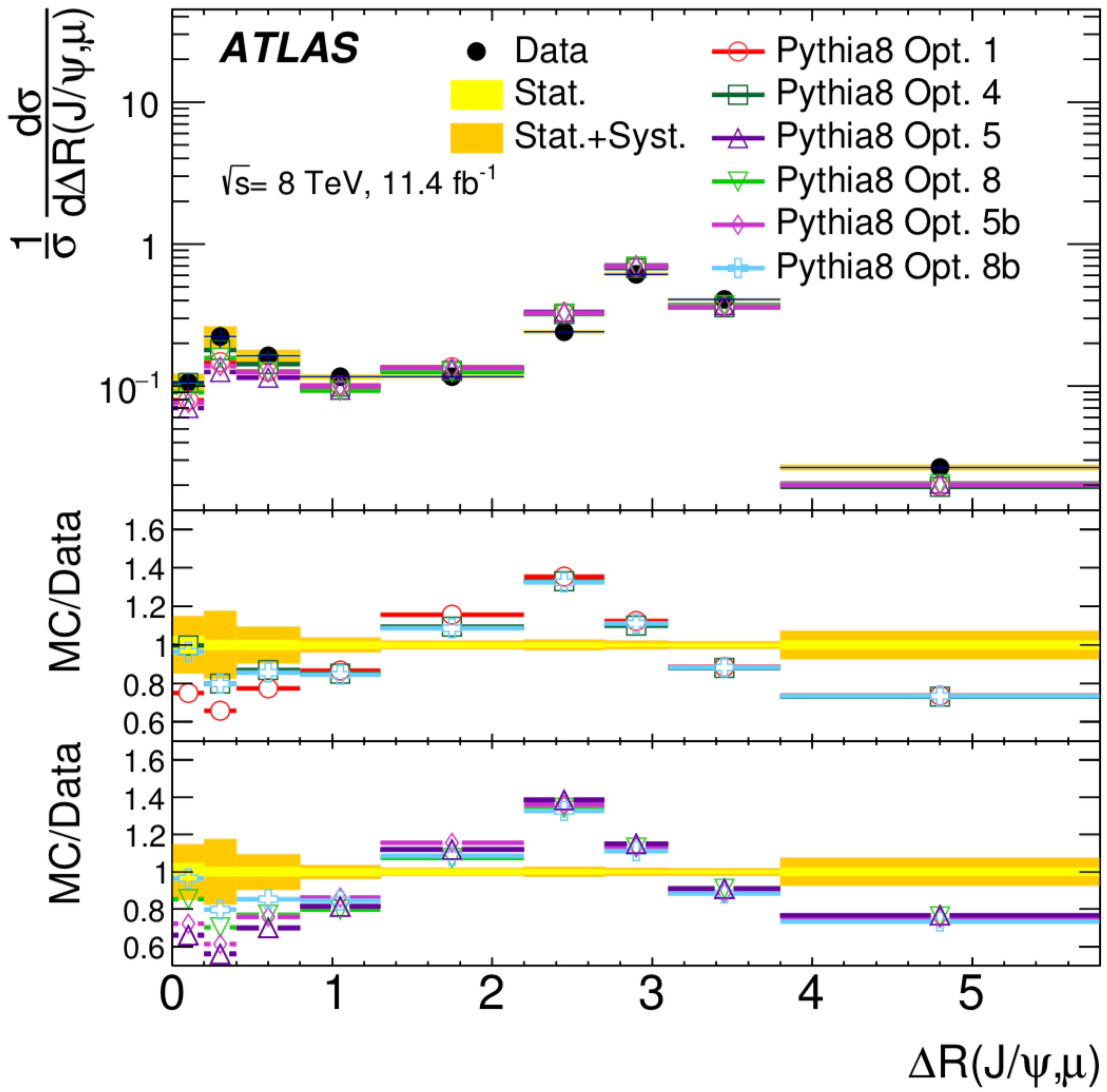
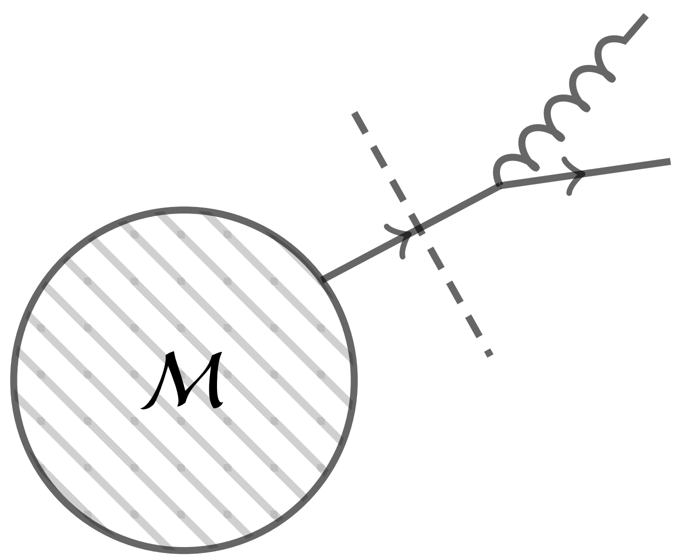


## Final state splittings (Parton Showers)

- Quarks' case well understood




$$\sim \frac{\alpha_s(k_\perp^2)}{2\pi\, k_\perp^2} |\mathcal{M}|^2 \otimes P_{qq}(x)$$

Resums all-order soft dominant terms $\left(\frac{\log^k(1-x)}{1-x}\right)_+$

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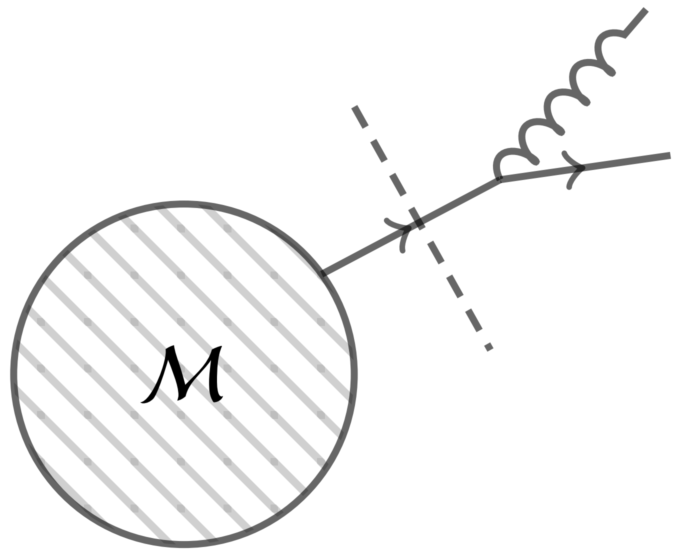
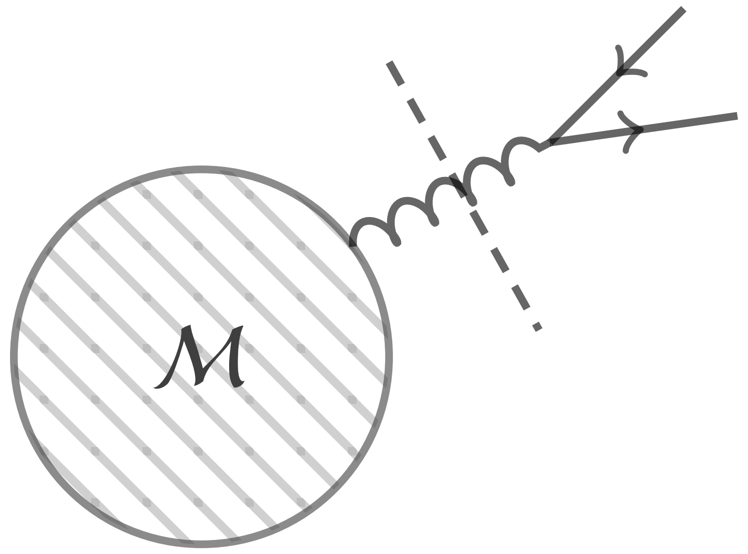



$$\sim \frac{\alpha_s(k_\perp^2)}{2\pi\, k_\perp^2}\,|\mathcal{M}|^2 \otimes P_{qq}(x)$$

Resums all-order soft dominant terms $\left(\frac{\log^k(1-x)}{1-x}\right)_+$

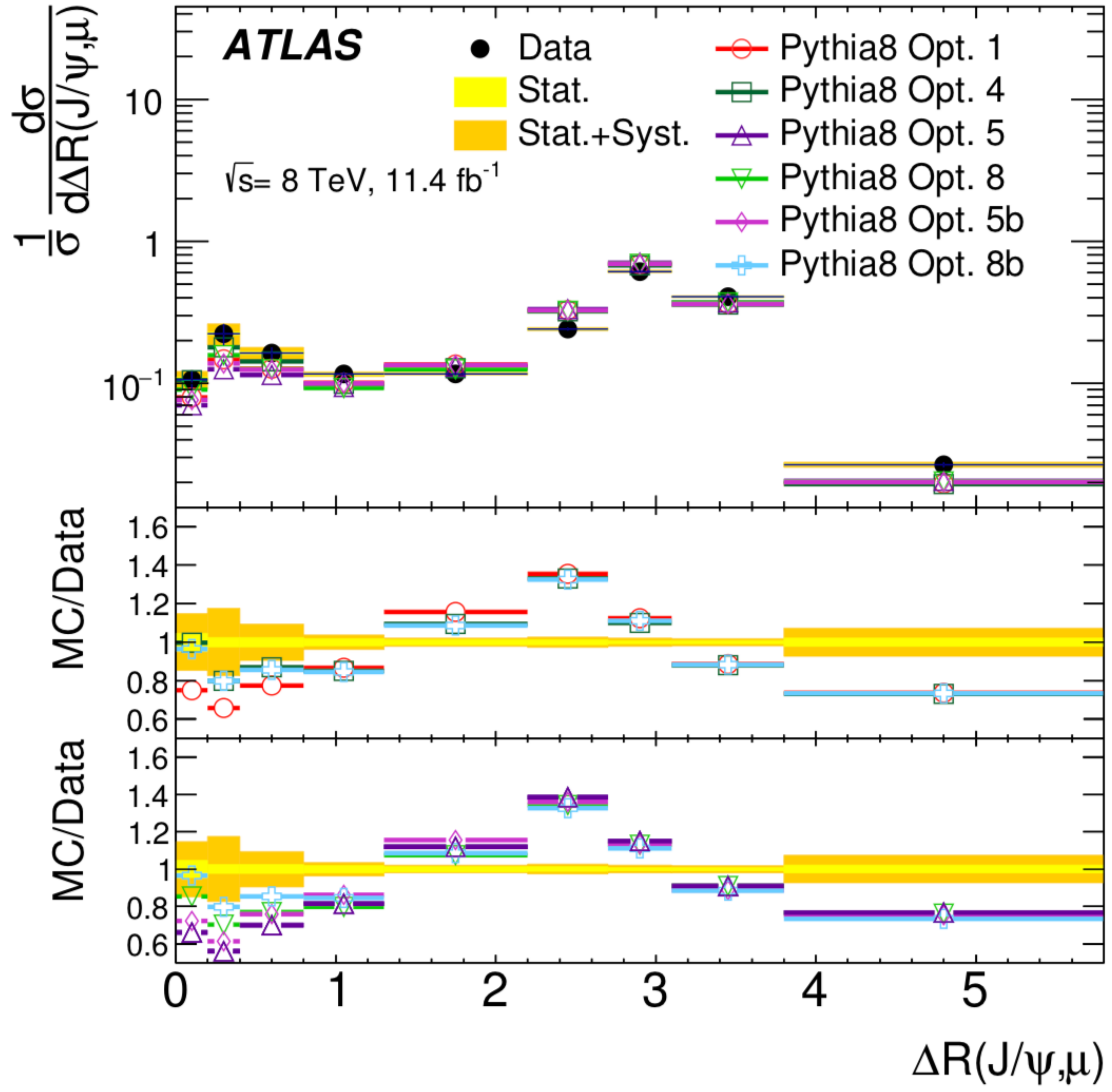
- Gluon case more delicate




$$\sim \frac{\alpha_s(?^2)}{2\pi\, k_\perp^2}\,|\mathcal{M}|^2 \otimes P_{qg}(x)$$

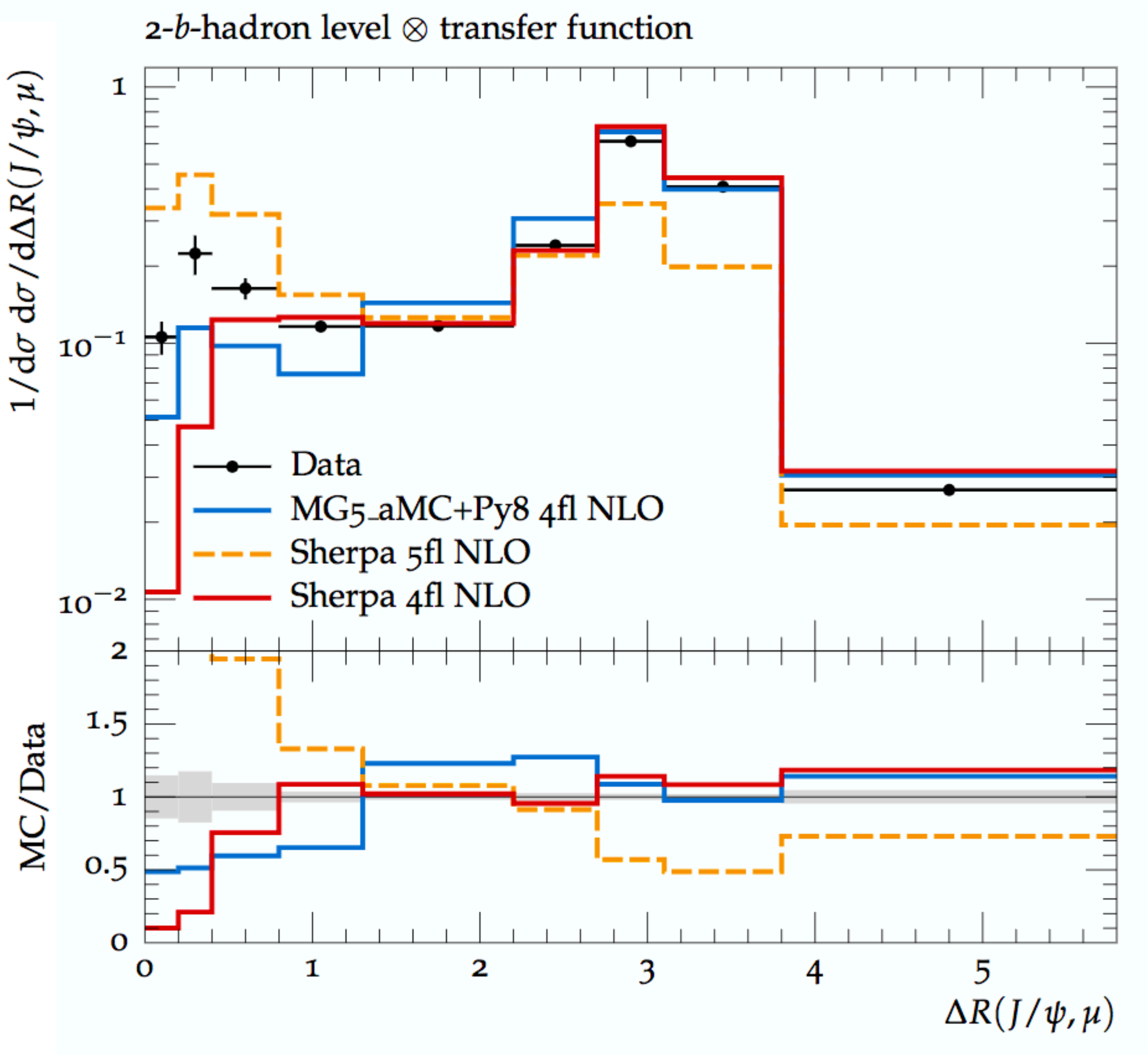
In principle no soft terms to resum…

# Simulations for HF (FS)



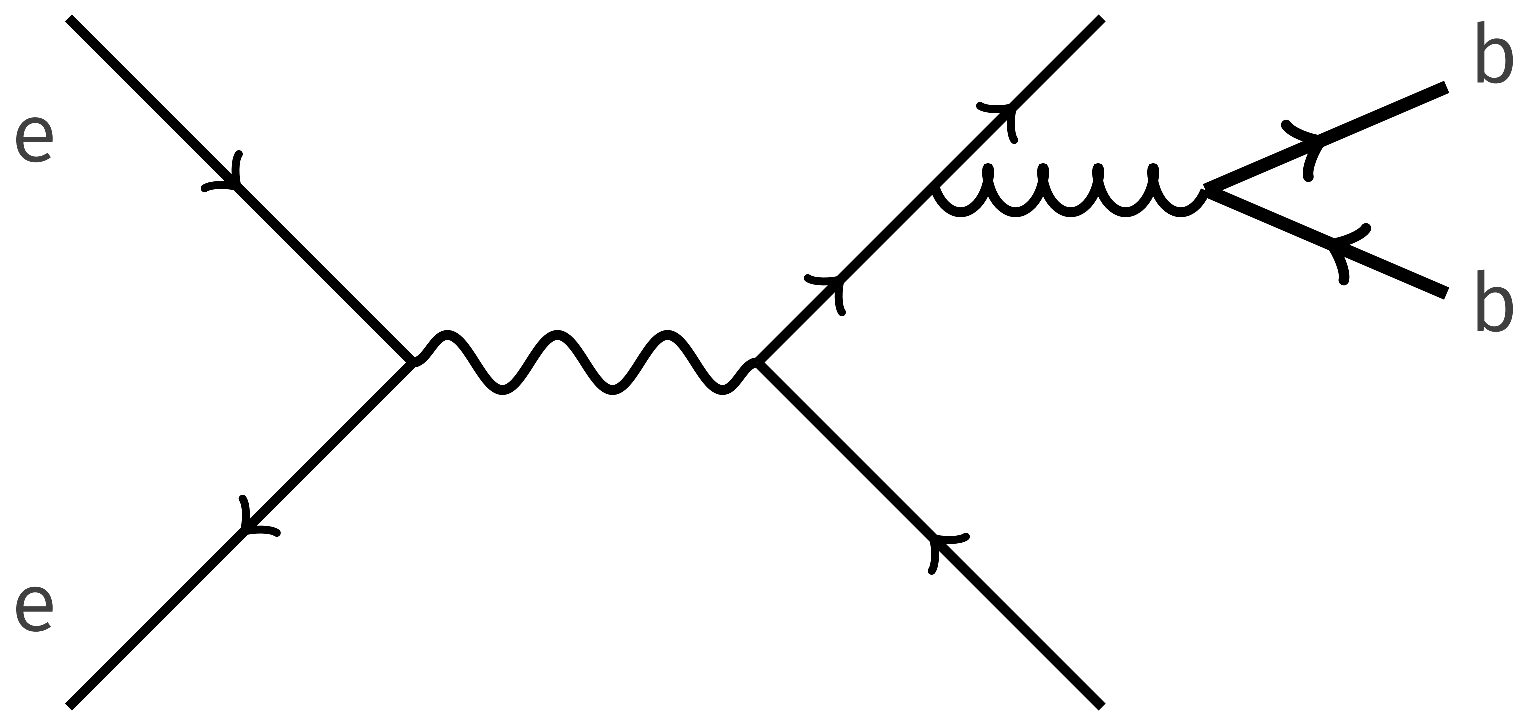

$$\frac{d\mathcal{P}}{d\log\mu^2} \propto \frac{\alpha_s(X)}{2\pi}\left[P_{qg} + A\,\frac{m^2}{Y(\mu^2)} + C\right]$$

# Simulations for HF (FS)




MCs seem to disagree on what the answer should be!

# Final state splittings



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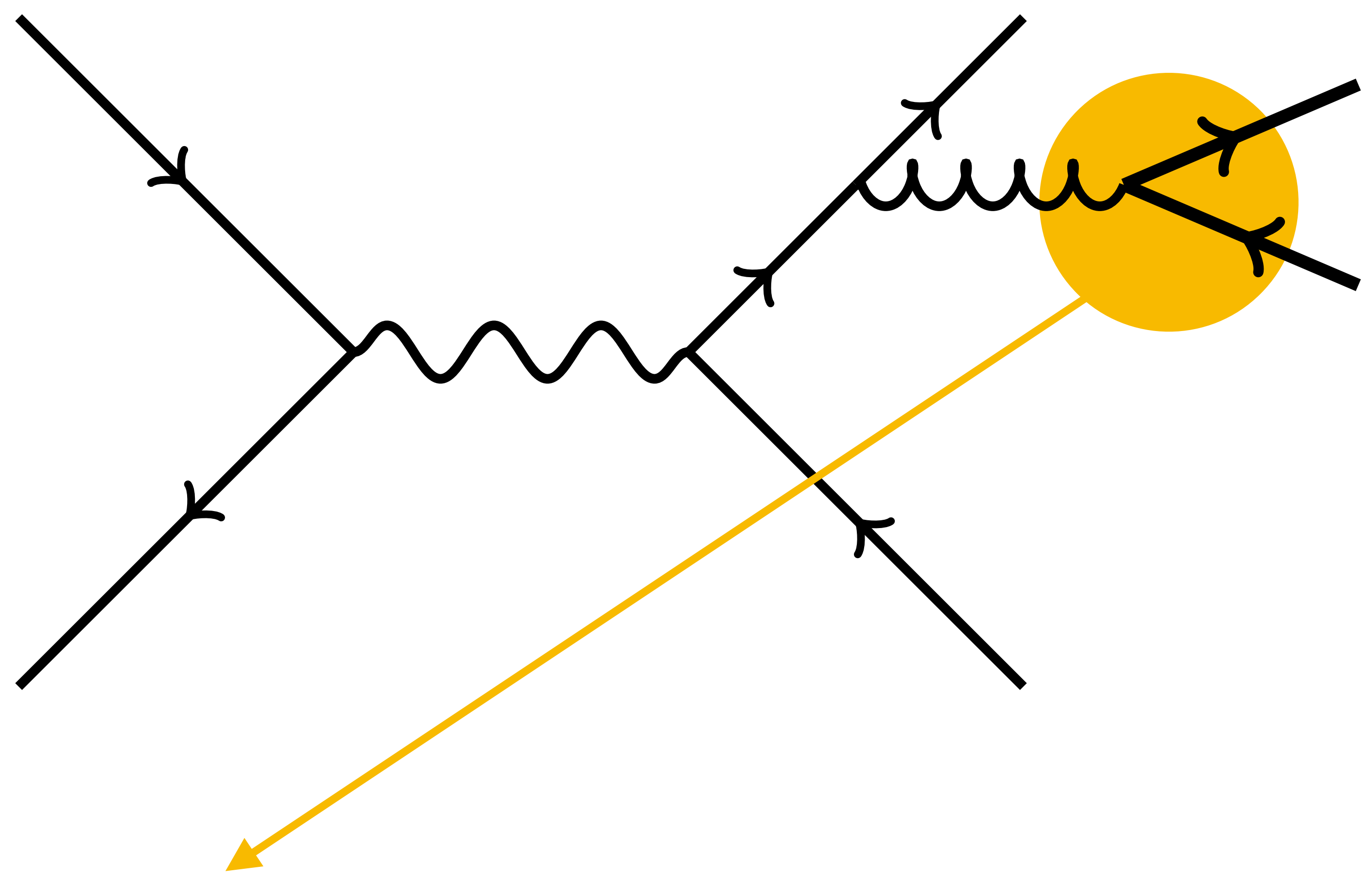
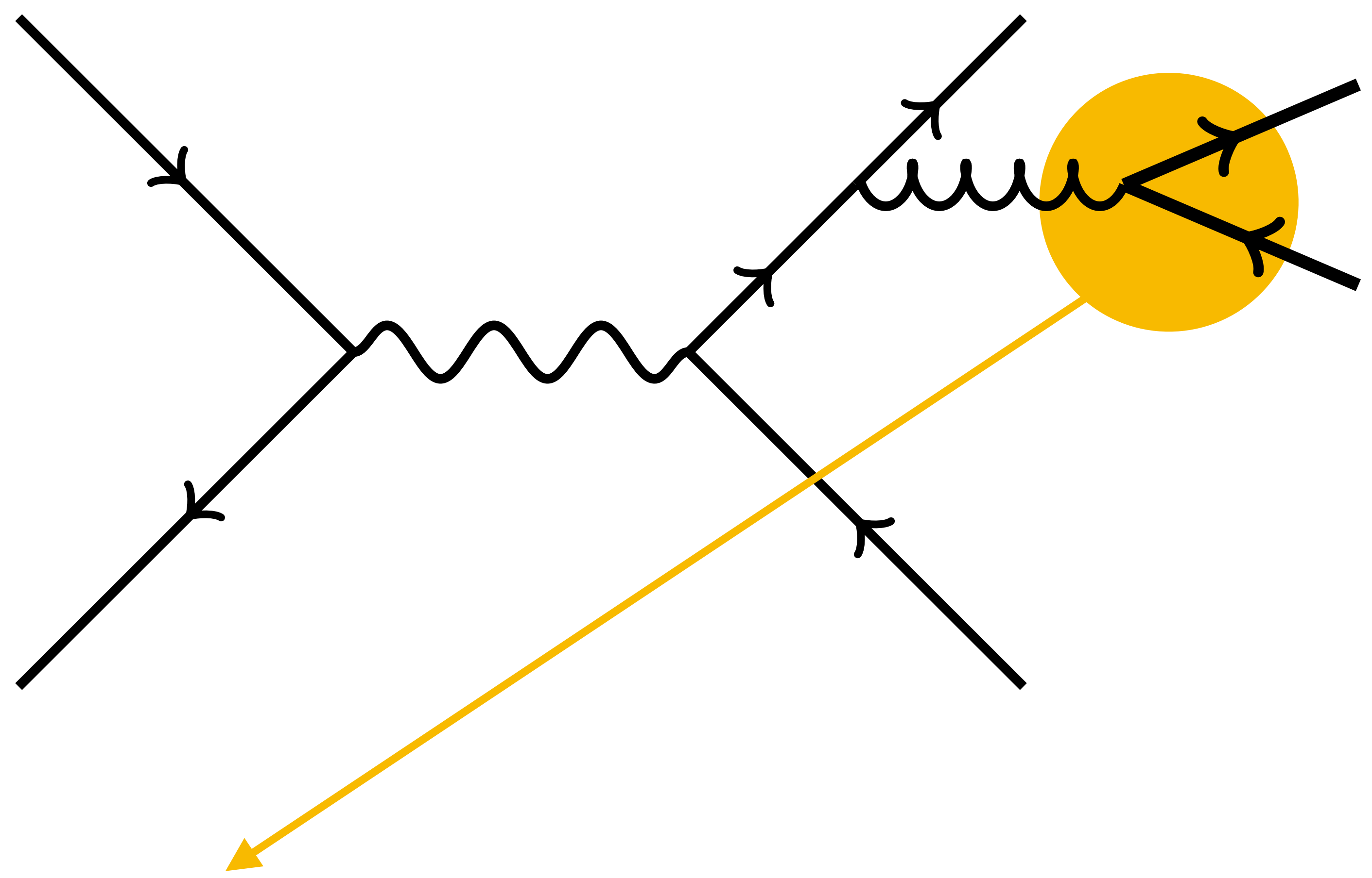


Simply count the number of b-jets

# Final state splittings

Seymour [Nucl.Phys. B436 (1995) 163-183]



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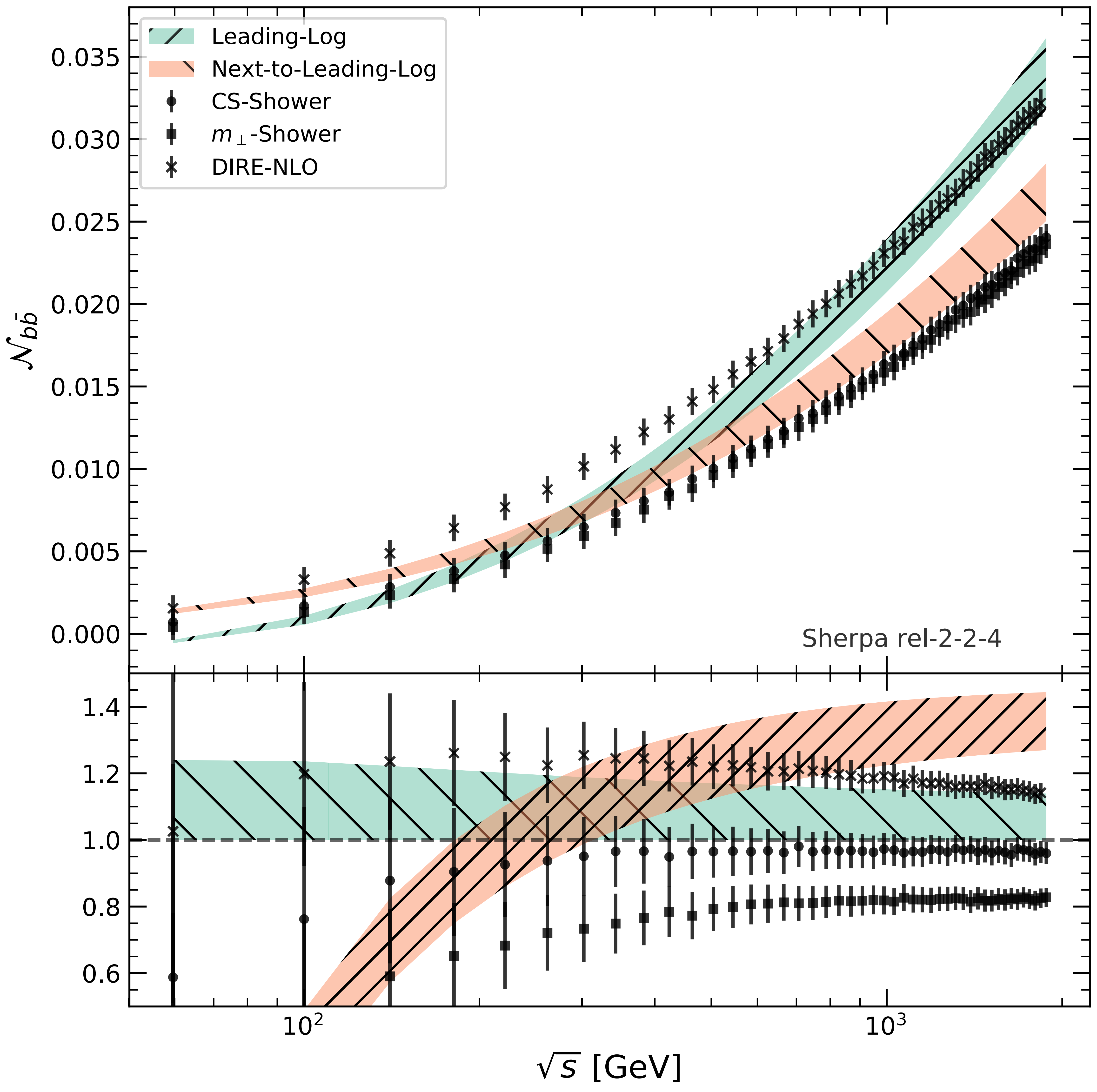

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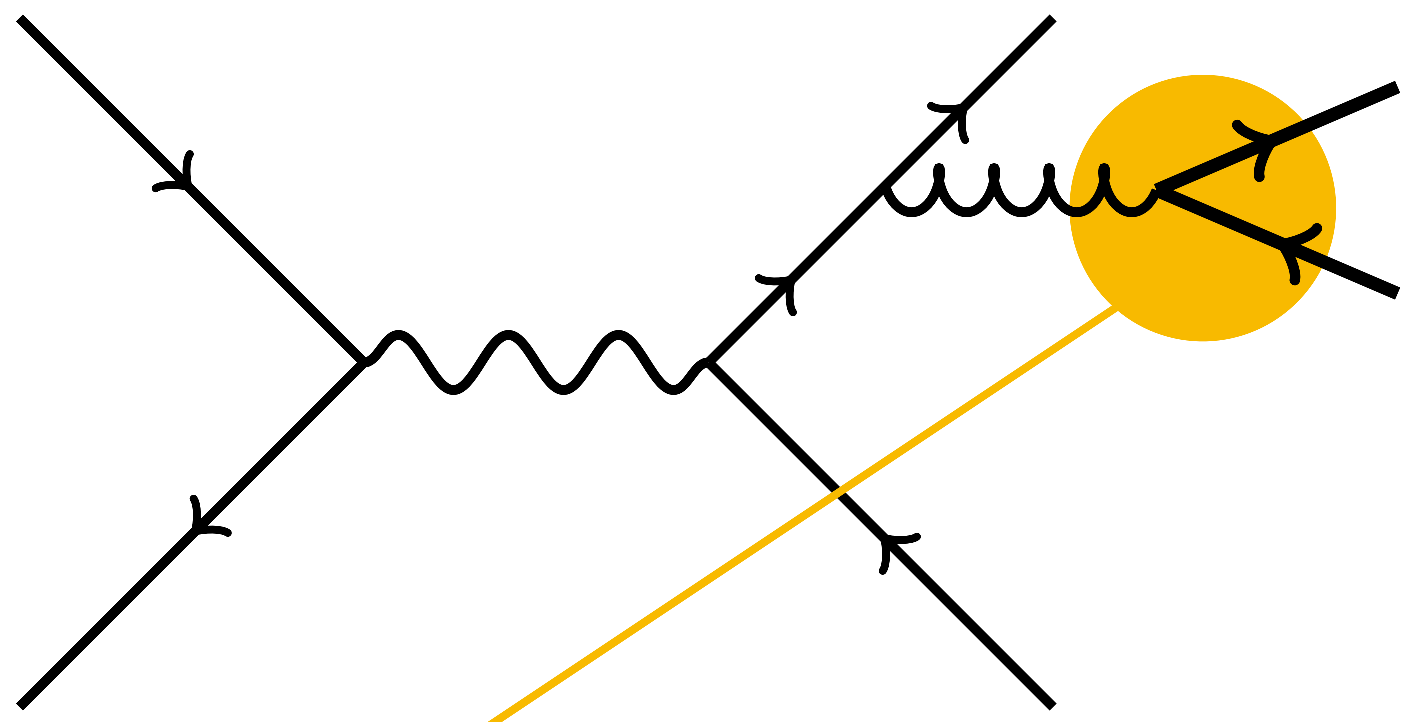

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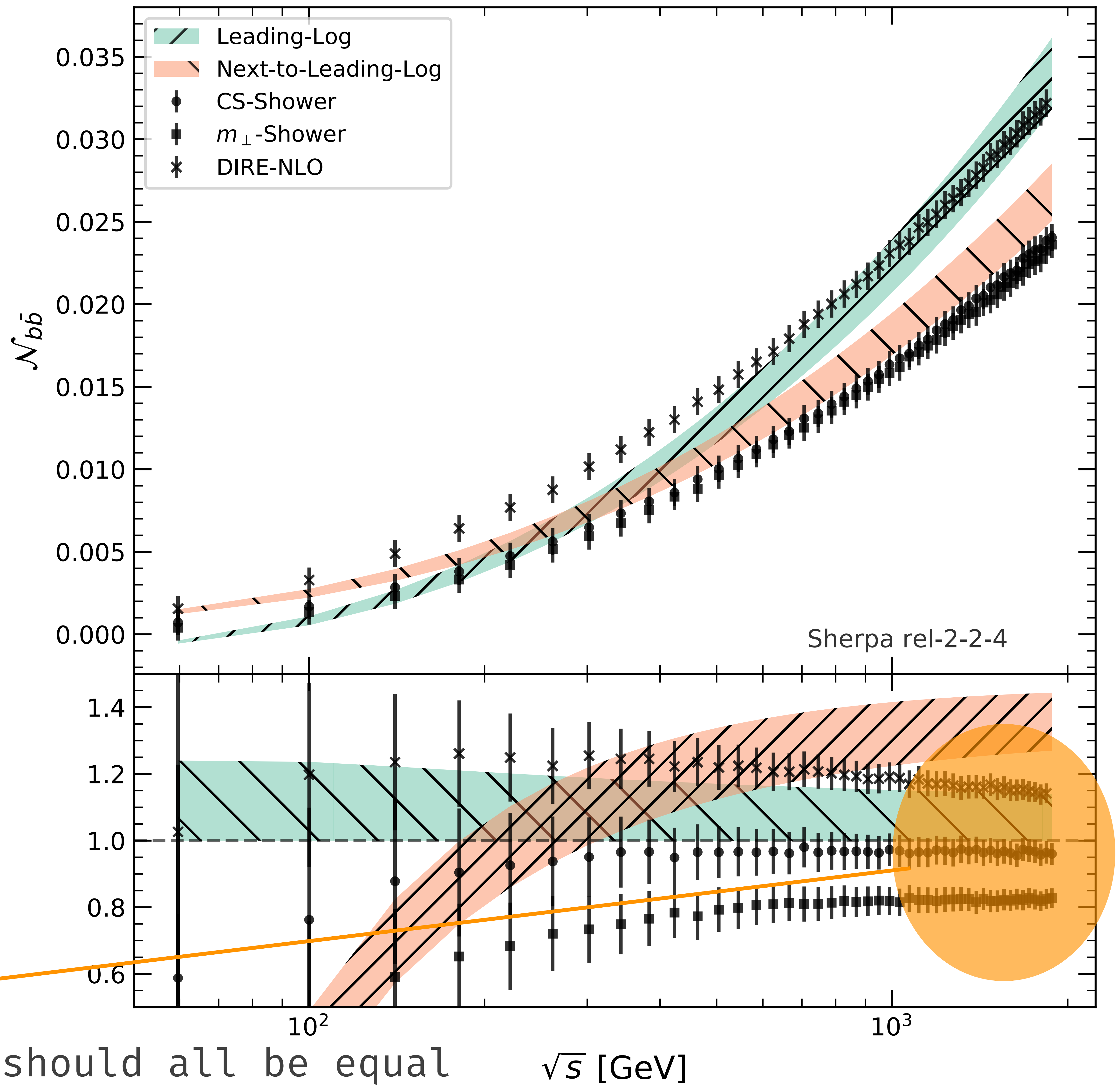
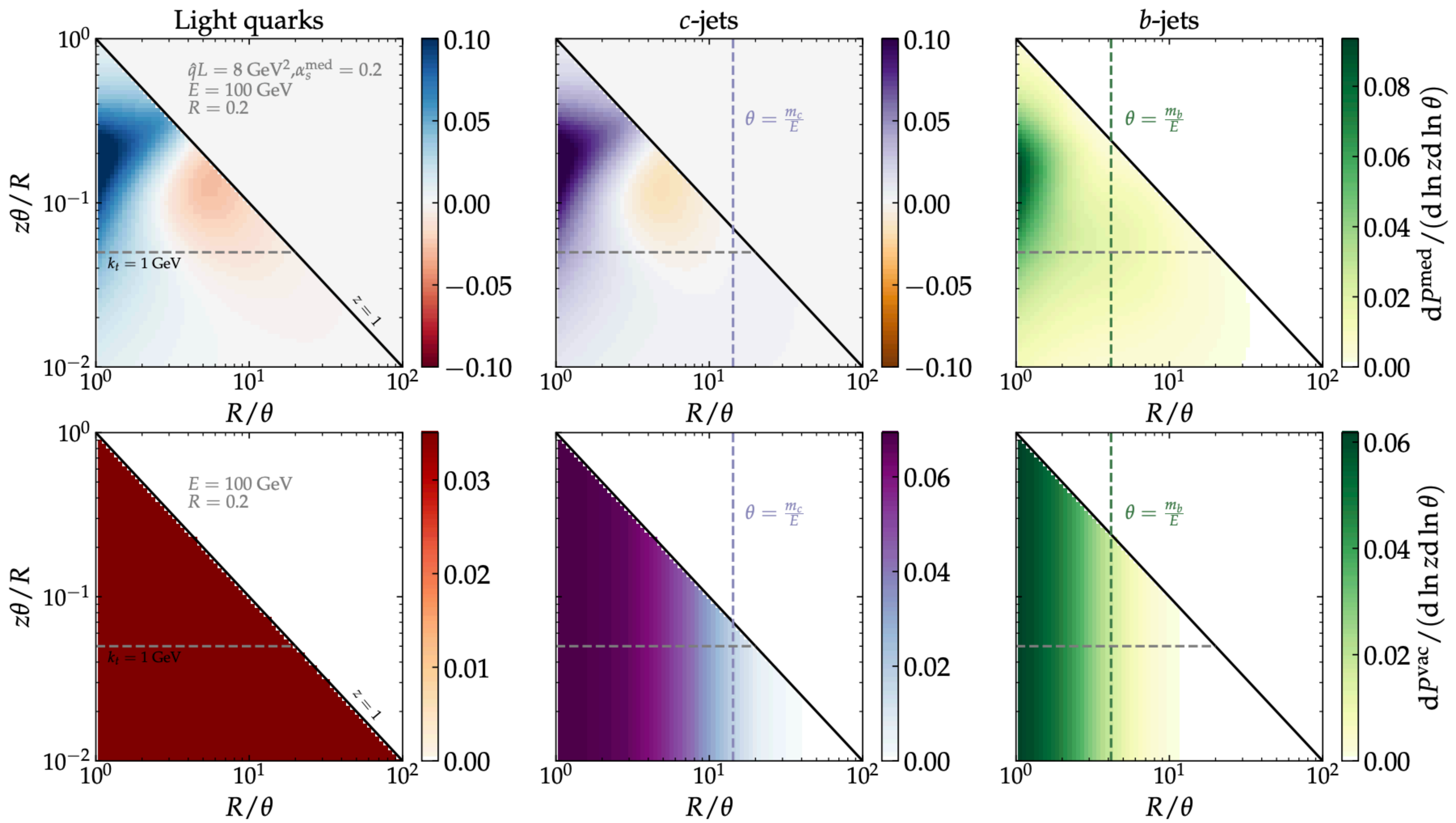



Quite large differences in a region where should all be equal
(to the LO Matrix Element!)

# Resummation for HF (Dead-cone Effect)




- **Filling of deadcone region in medium relative to vacuum**

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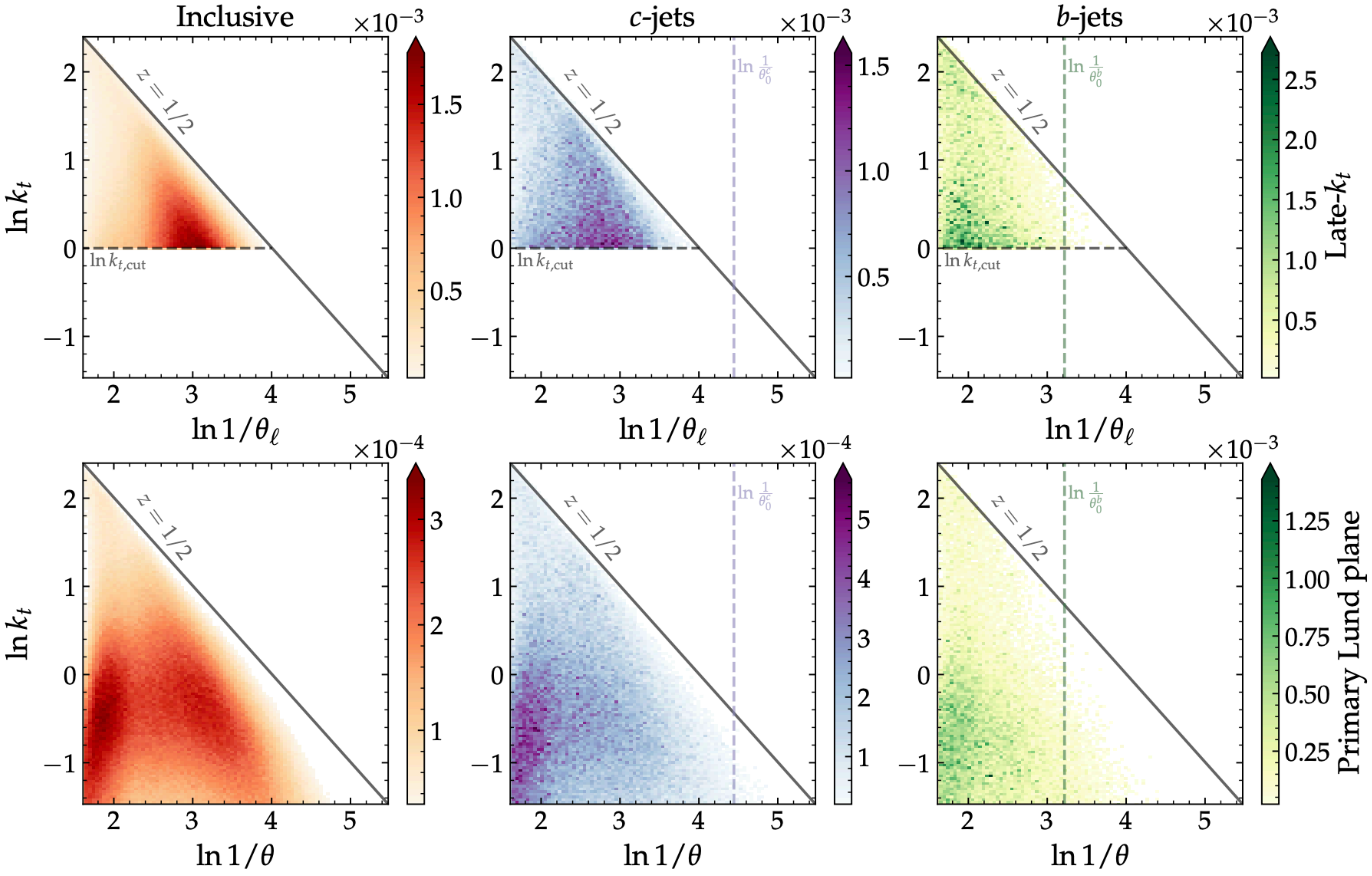
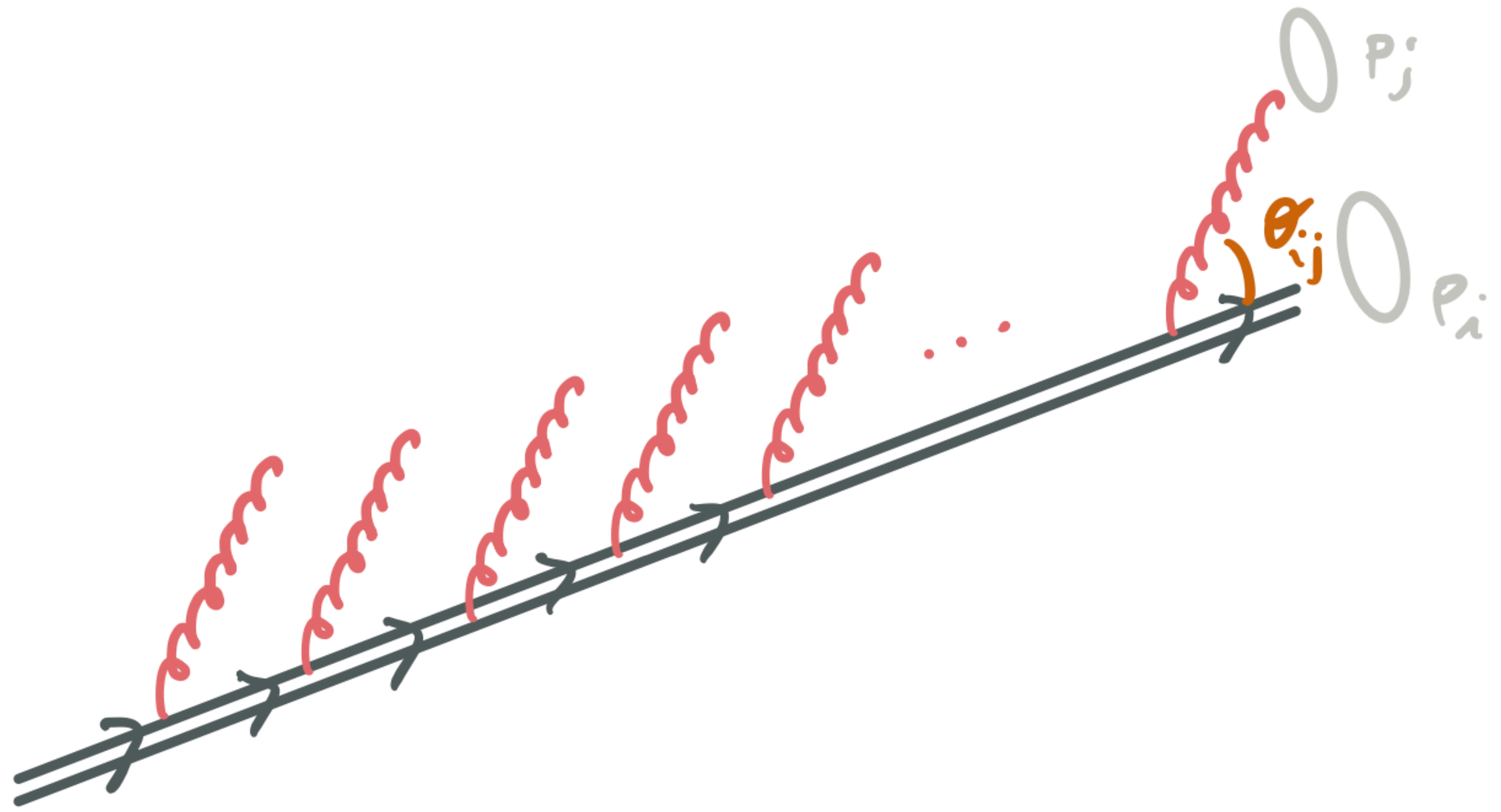



1.




2. If $k_\perp(i,j) > k_\perp^{cut}$ store $\theta_{ij} \rightarrow$ 1.

3. Find last $\theta_{ij} \mid k_\perp(i,j) > k_\perp^{cut} \Rightarrow \theta_\ell$

# Resummation for HF (Dead-cone Effect)