Herwig++ News

Keith Hamilton

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Herwig++

Bähr
Gieseke
Gigg
Grellscheid
Latunde-Dada
Plätzer
Richardson
Seymour
Tully
Webber

Main News: NLO POWHEG simulations

- A method for including NLO corrections in a parton shower simulation

  [Nason - 2004, Frixione, Nason, Oleari - 2007].

- A POWHEG code just outputs weight +1 events, according to NLO+[N]LL resummed distributions, as Les Houches event files.

- Hadronize non-radiative events and shower radiative events using any shower MC.

POWHEG

- **Hardest emission:**

  Always generated according to the NLO real ME

  [in A.O. shower ≠ 1st radiation hardest]

- **Shower independent:**

  Easy to make [we did it!]

  Easier for attempting complex NLO processes

  Insensitive to shower problems / development / fixes

  [kinematics reconstruction of HW++ has changed 3 times]

  Opens the door for the NLO community

- **Only weight +1 events:**

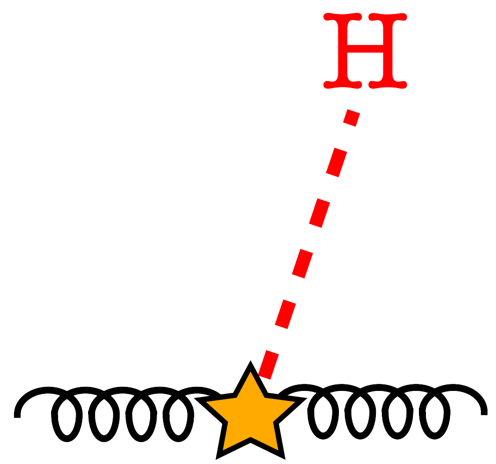
  Conventional statistical analysis

  Easier to attack complex analysis [NN's, DA's, ...]

Angular ordering

- QCD coherence can be implemented, approximately, in shower MC's by ordering emissions by their angle.

- For an A.O. shower the first emission isn't a priori the hardest:



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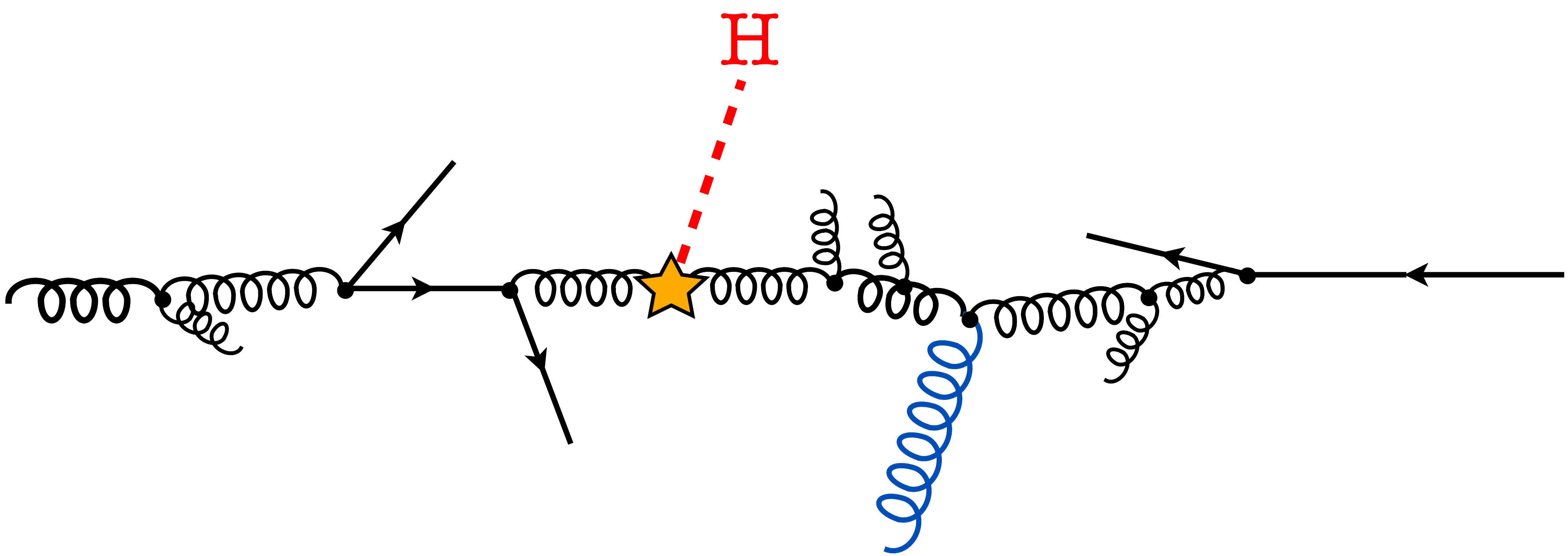
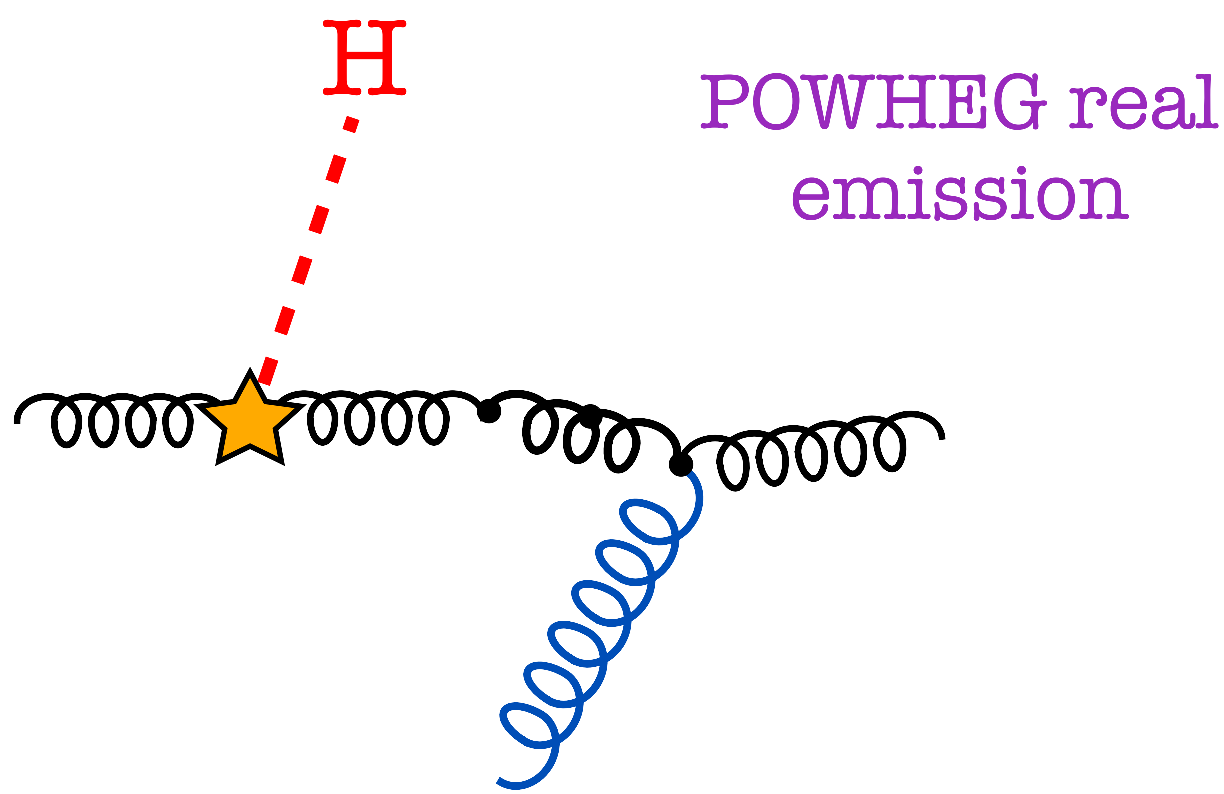


Angular ordering

- When POWHEG gives a real emission according to the NLO calculation it's supposed to be the hardest.
- So in general you just veto emissions from the shower with $p_T > p_{T,\mathrm{POWHEG}}$



[Nason 2004, Implementation KH, Richardson, Tully 2008]

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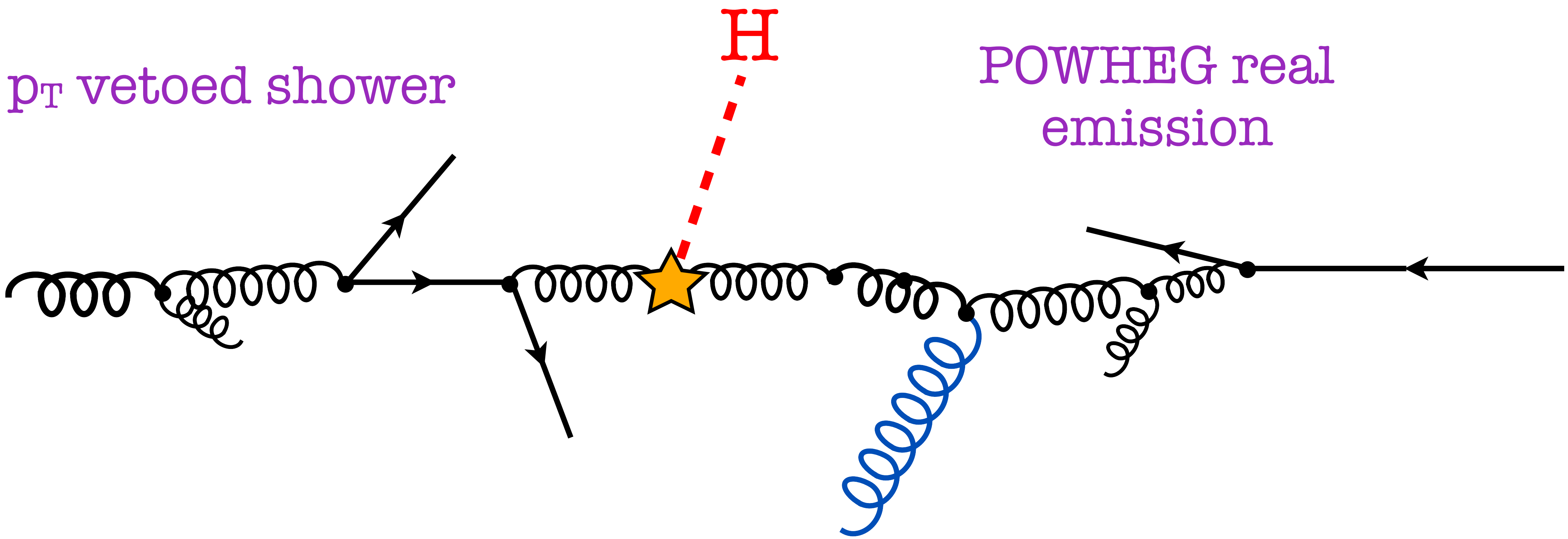

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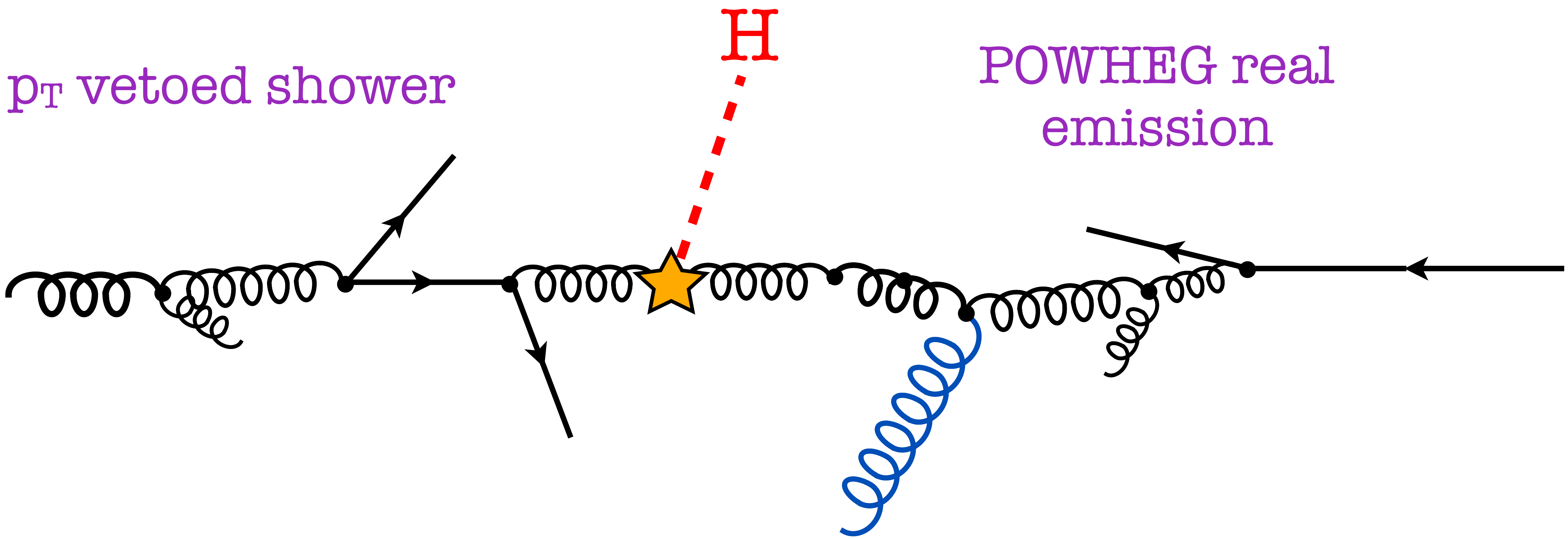

- But if the shower is A.O. then the shower should also try to include 'earlier' soft wide angle emissions

[Nason 2004, Implementation KH, Richardson, Tully 2008]

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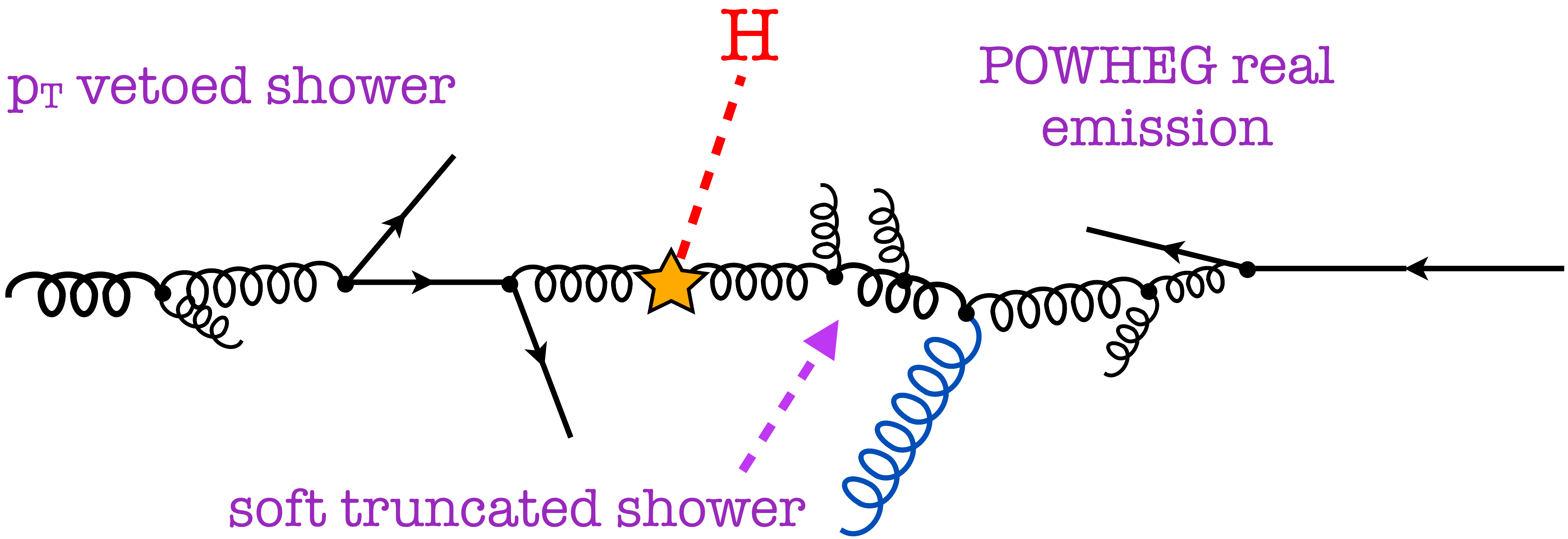

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[Nason 2004, Implementation KH, Richardson, Tully 2008]

Herwig++ in-house POWHEGs

Shipping with the current release:

- hh → γ / Z / W / H / ZH / WH [KH, Richardson, Tully]
- Spin correlations in decays [also for real emissions]
- Truncated showers

Also available in Contrib:

- POWHEG top and Higgs decays [Latunde-Dada]

Herwig++ in-house POWHEGs

Shipping in a few months:

- VBF [Under validation - D'Errico, Richardson]
- hh → WZ / ZZ / WW [Validated - KH]

Longer term:

- Enhance compatibility with POWHEG-BOX [see Re's talk]
- Colour coherent CKKW [JHEP 0911:038,2009]

Herwig++ POWHEG validation

1. MCFM:

- Total cross sections agree at O(0.1%)
- O(20) IR safe distributions checked; 'Born variables' are scrutinized and show excellent agreement.

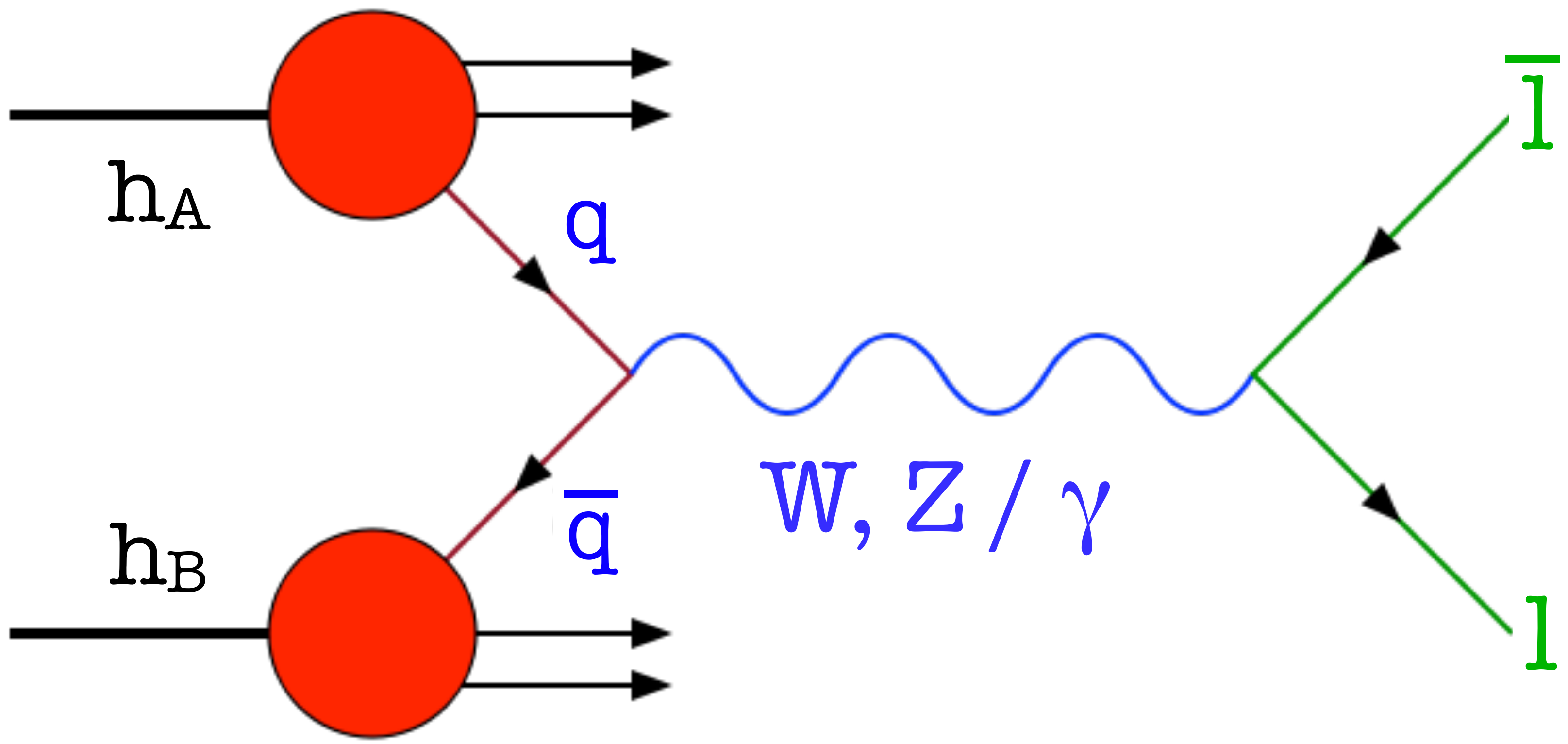
2. MC@NLO + 3. Matrix Element Corrections:

- Shift focus to resummation & radiation generation i.e. here we wanted to check the shapes ☞ normalized to 1.
- Good agreement in all 3 approaches. POWHEG & ME Corr tend to have harder spectrum [and we understand why].

4. Data:

- For e+e- and DY we compared to the data.

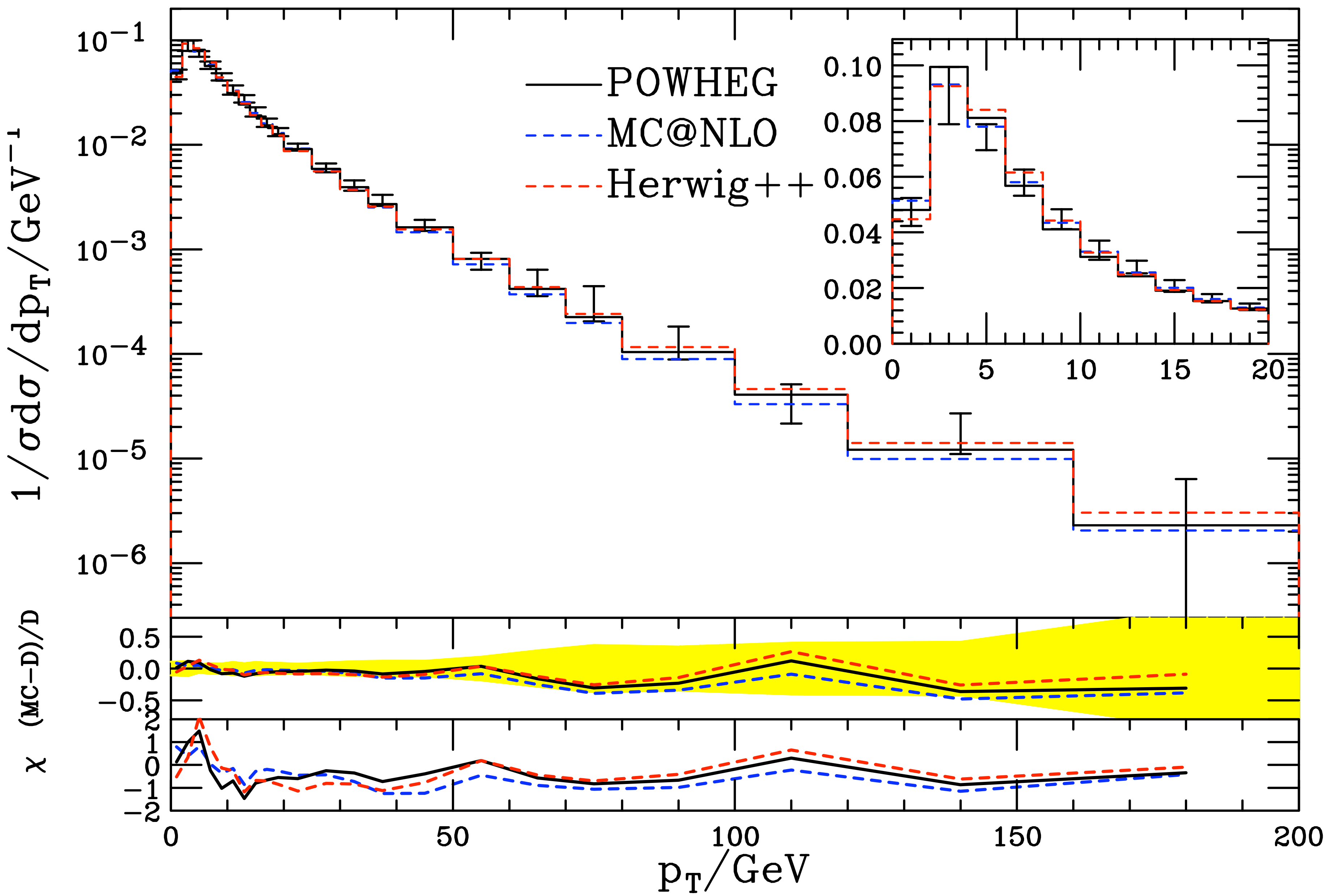
Drell-Yan vector boson production



[KH, Richardson, Tully]

Results: Drell-Yan vector boson production

W boson p_T spectrum compared to DO run I data



Solid line: NLO Herwig++ POWHEG   Blue dashes: MC@NLO
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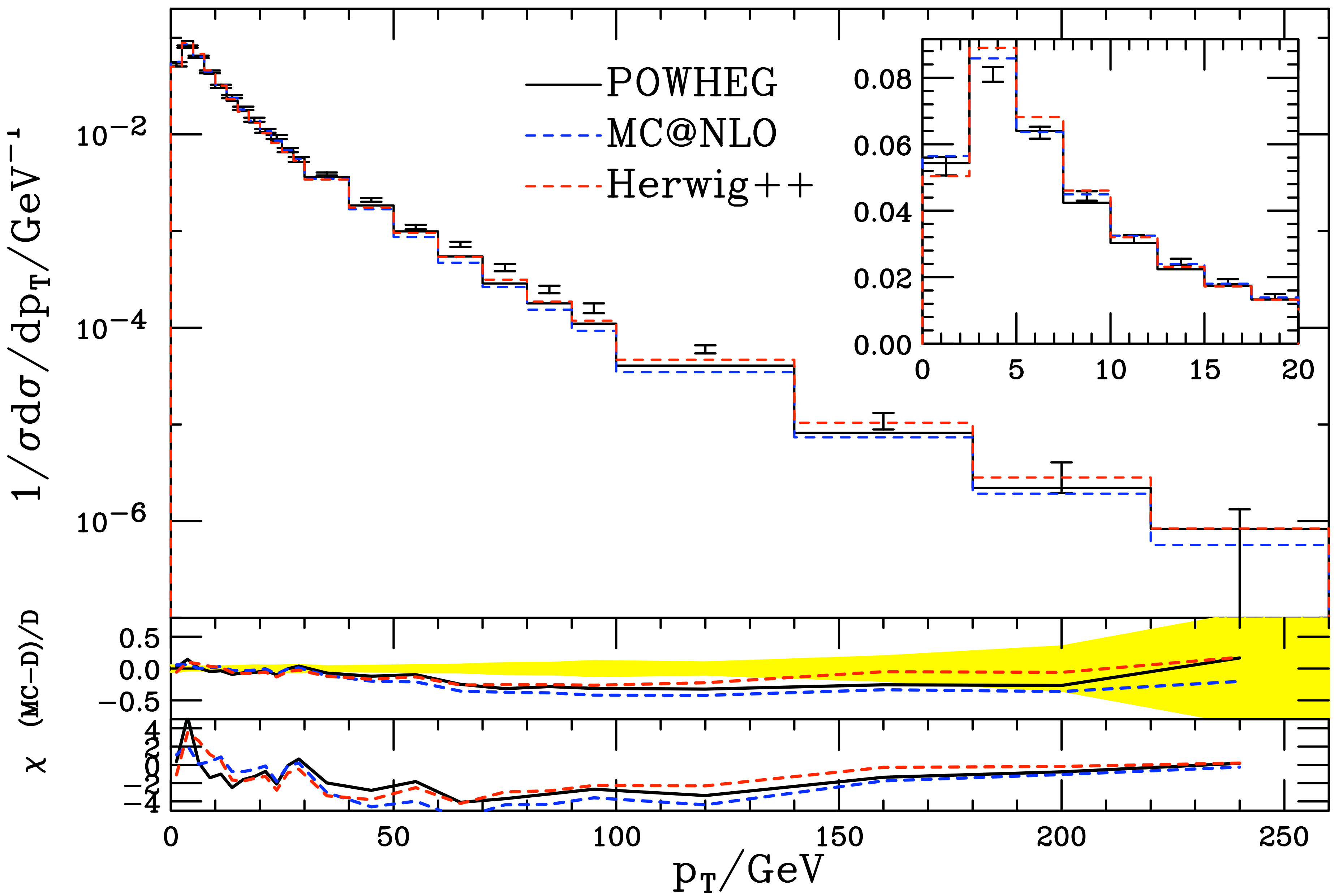
Results: Drell-Yan vector boson production

Z boson p_T spectrum compared to D0 run II data



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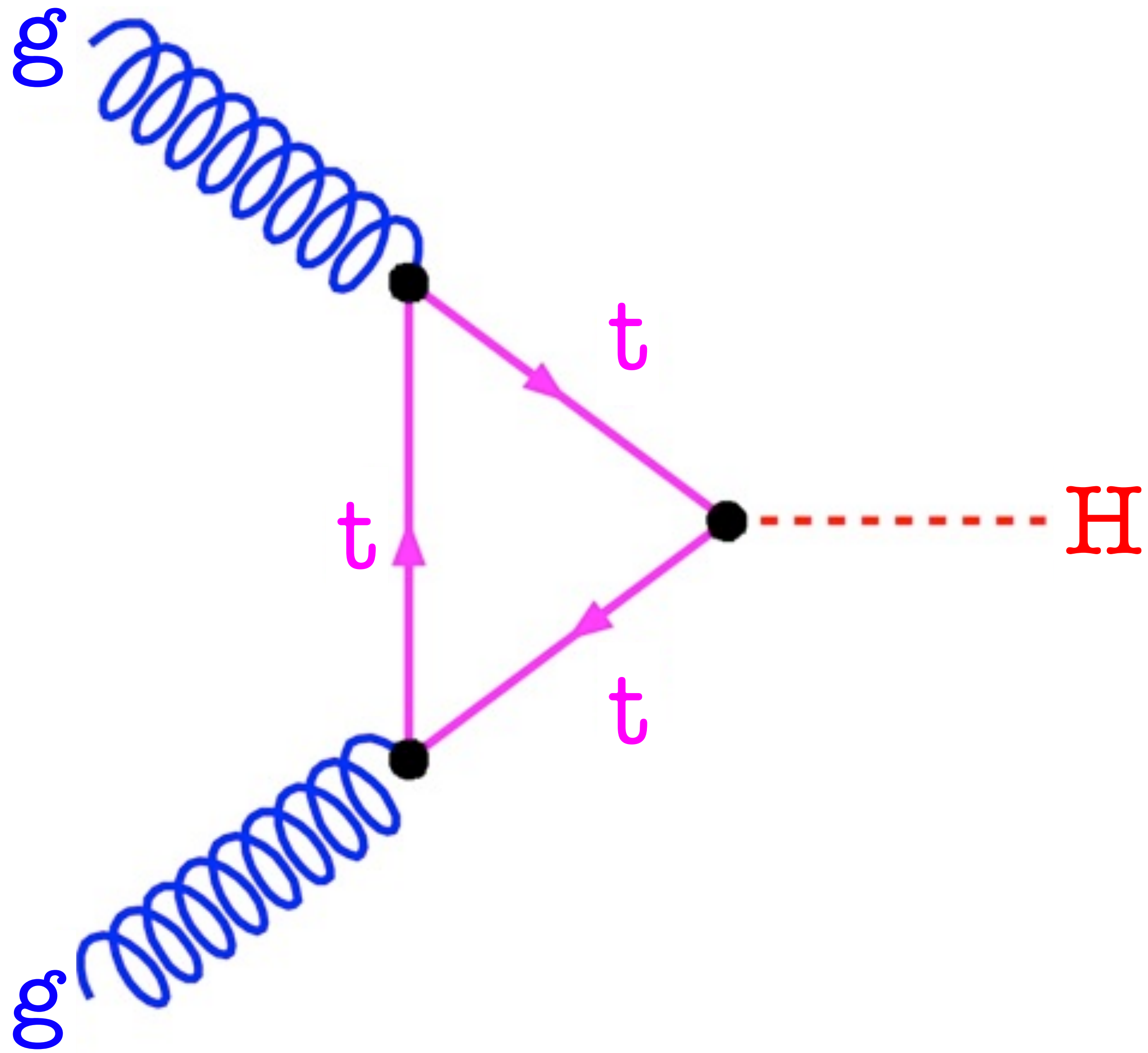
Higgs production via gluon fusion

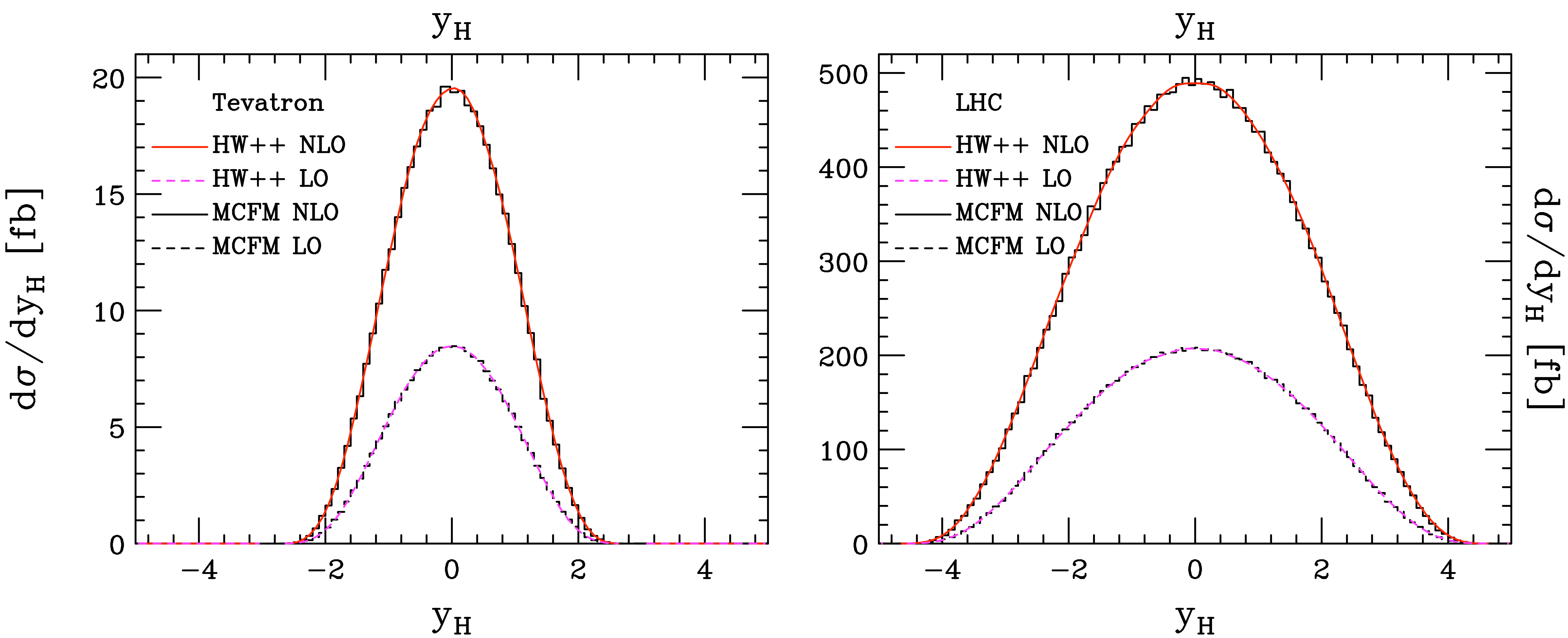


[KH, Richardson, Tully]

Results: Higgs production via gluon fusion

Higgs boson rapidities compared to fixed order NLO calculations

$gg \rightarrow H \rightarrow \tau^+\tau^-$



Red: NLO Herwig++ POWHEG
Magenta: LO Herwig++ POWHEG

Black: NLO MCFM fixed order
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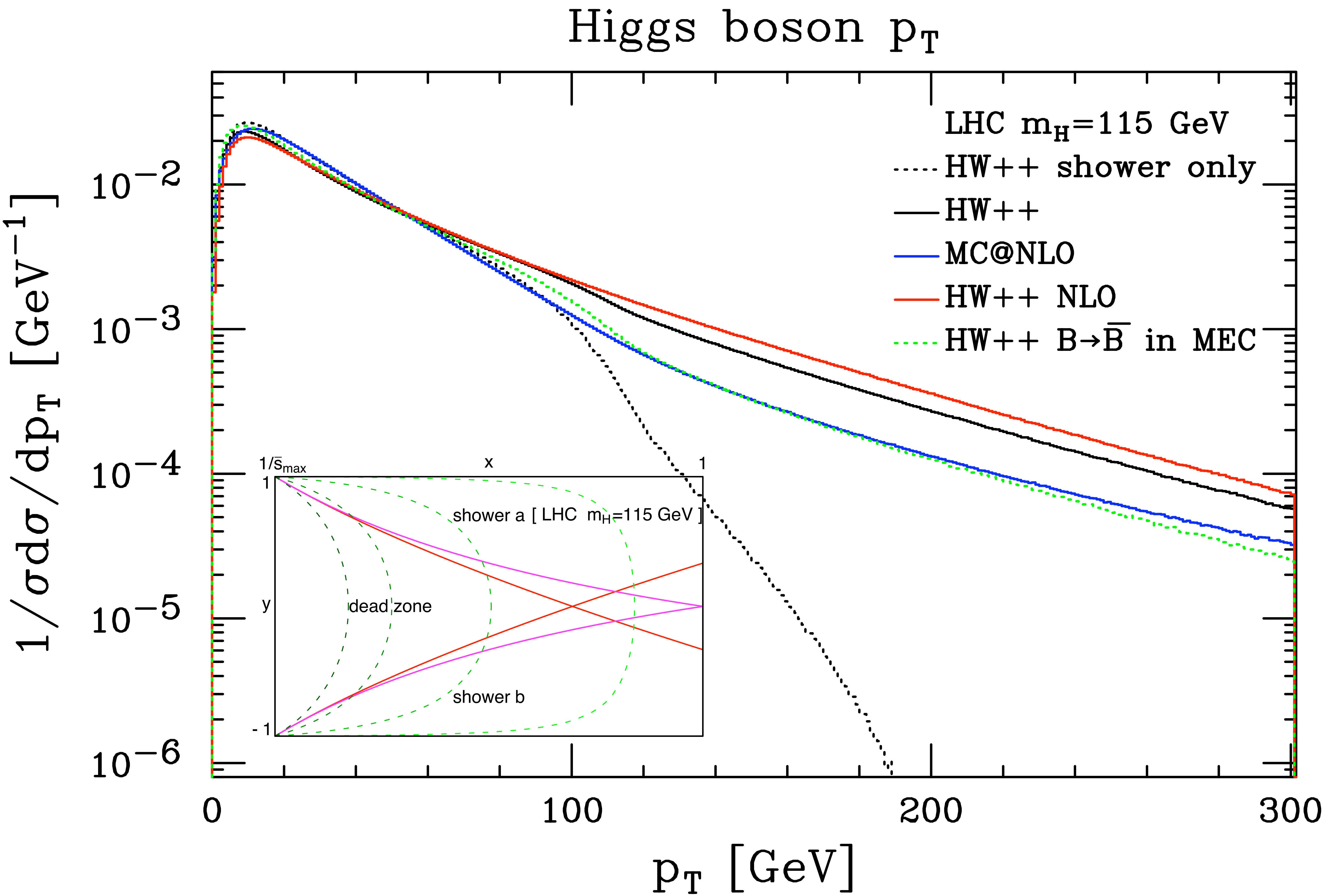
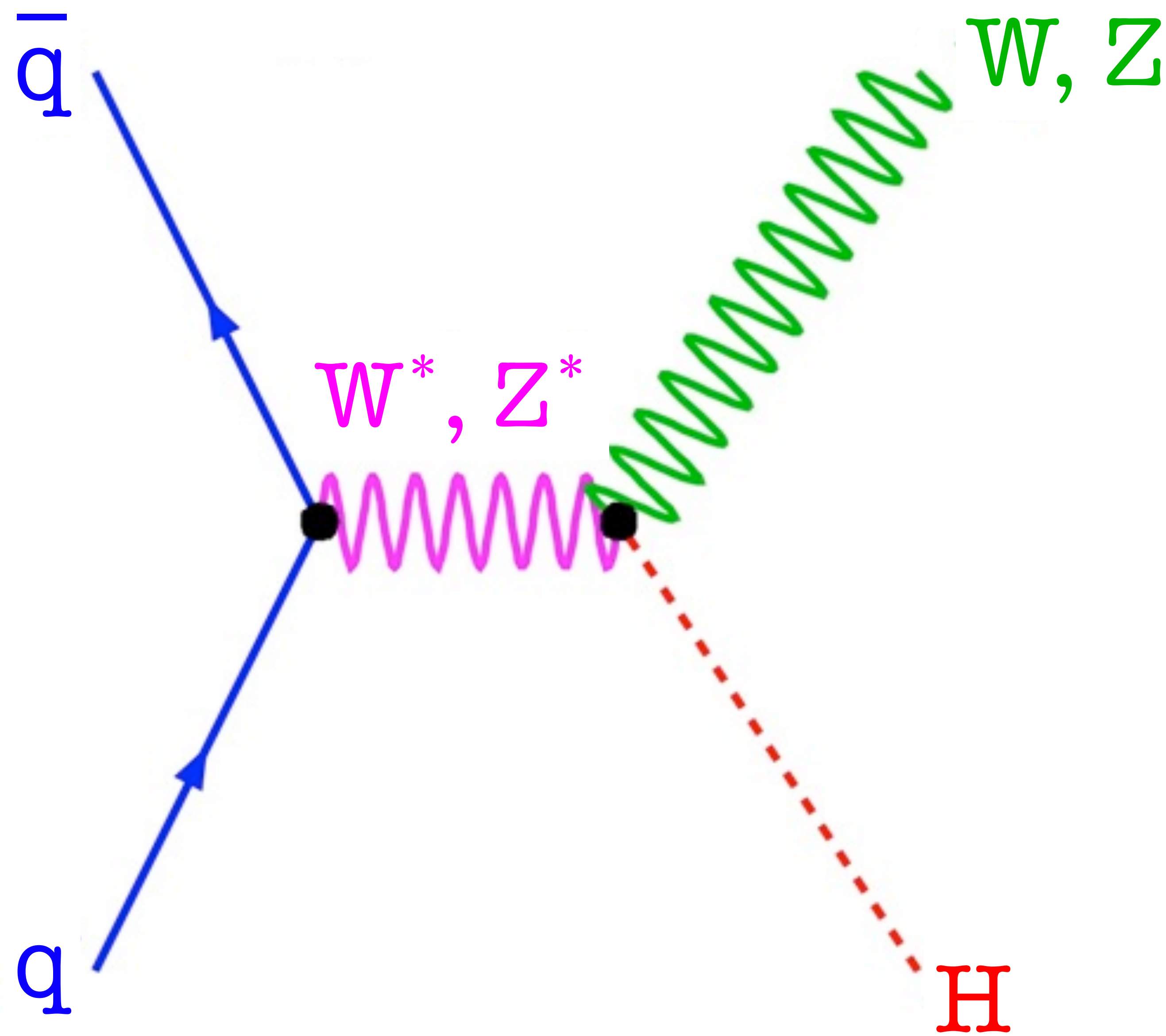
Results: Higgs production via gluon fusion



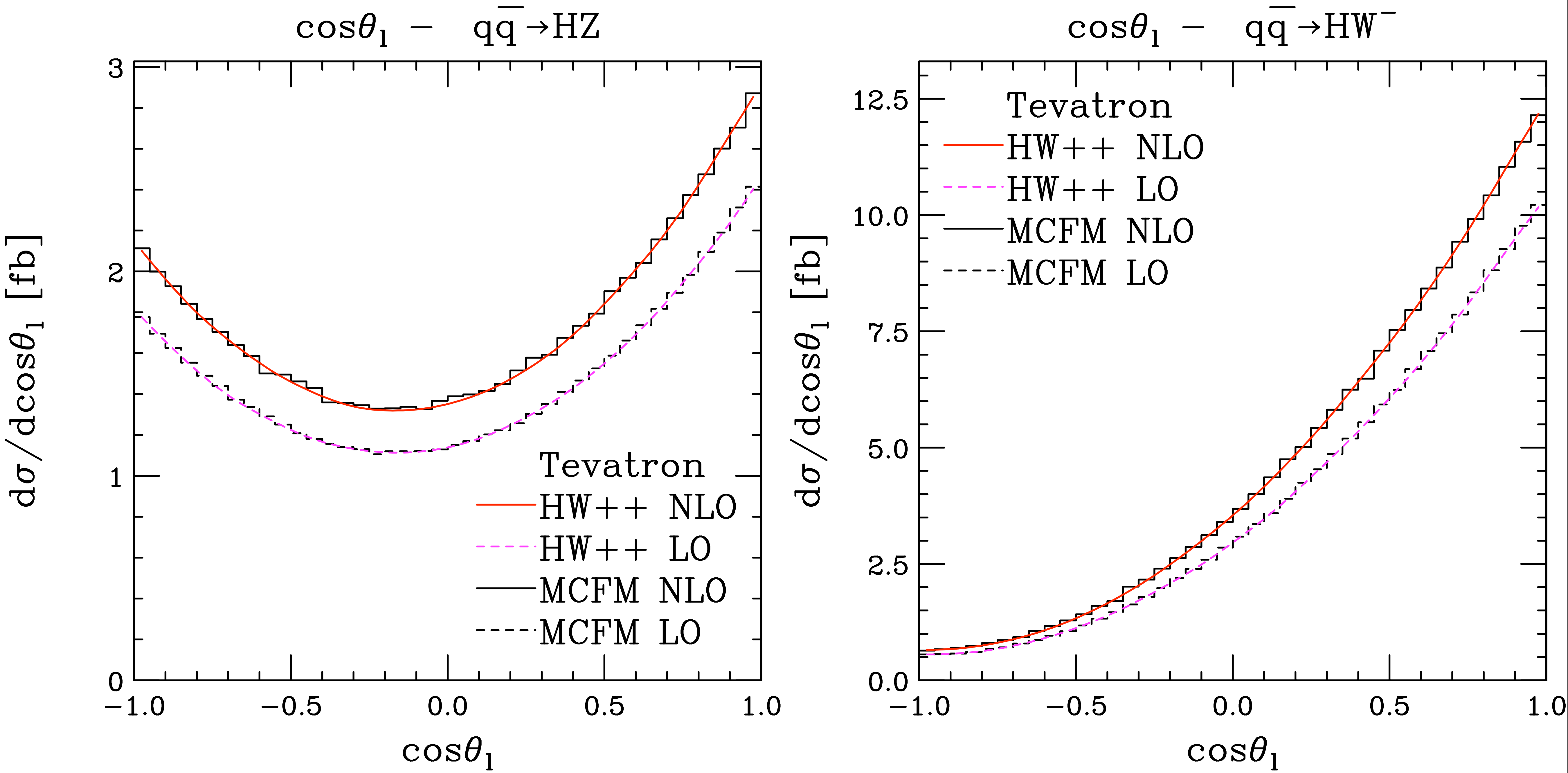
Higgs-strahlung



[KH, Richardson, Tully]

Results: Higgs-strahlung ($q\bar{q} \to HZ/W^-$)

Polar angle of electron vs fixed order NLO calculations: Tevatron



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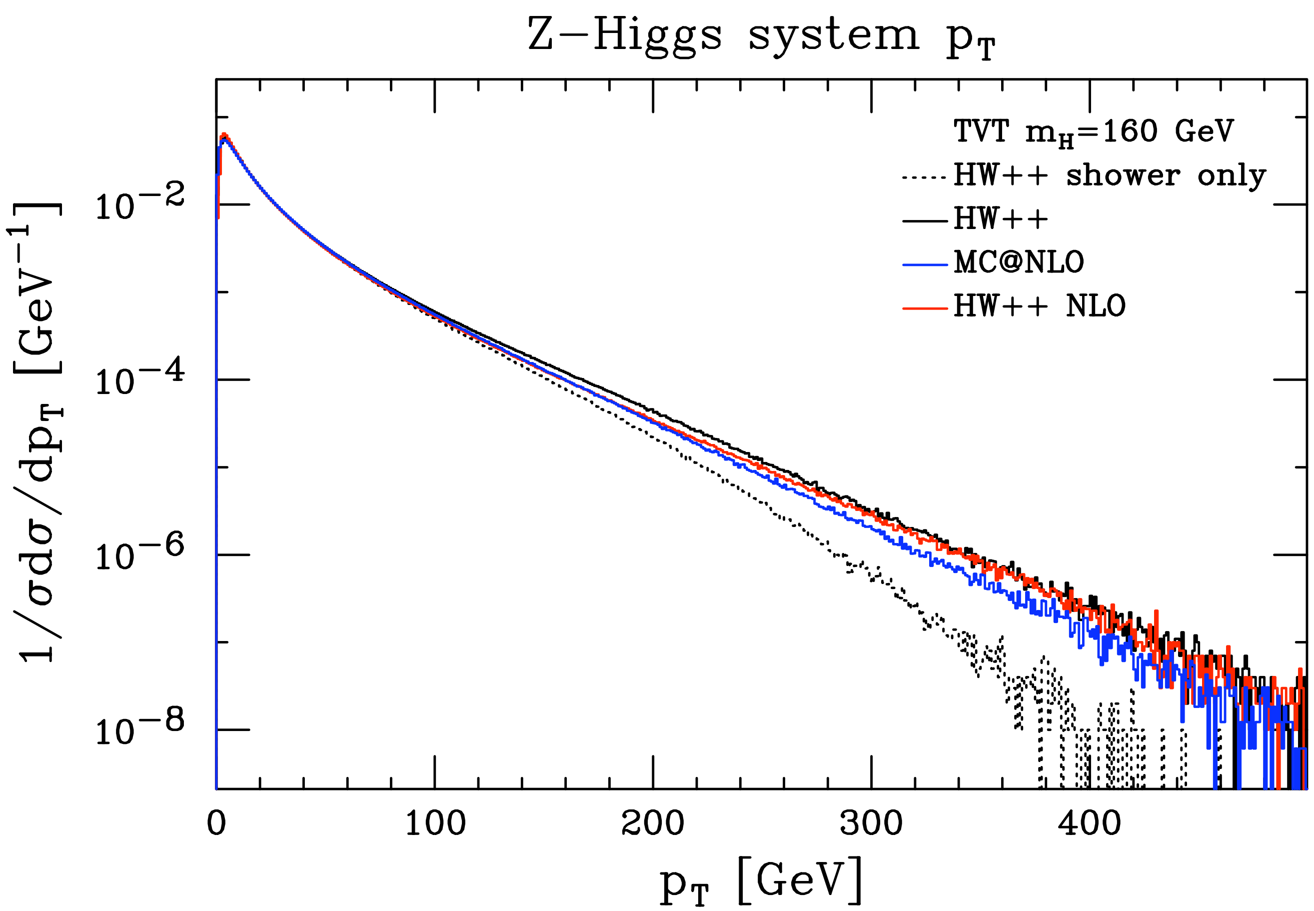
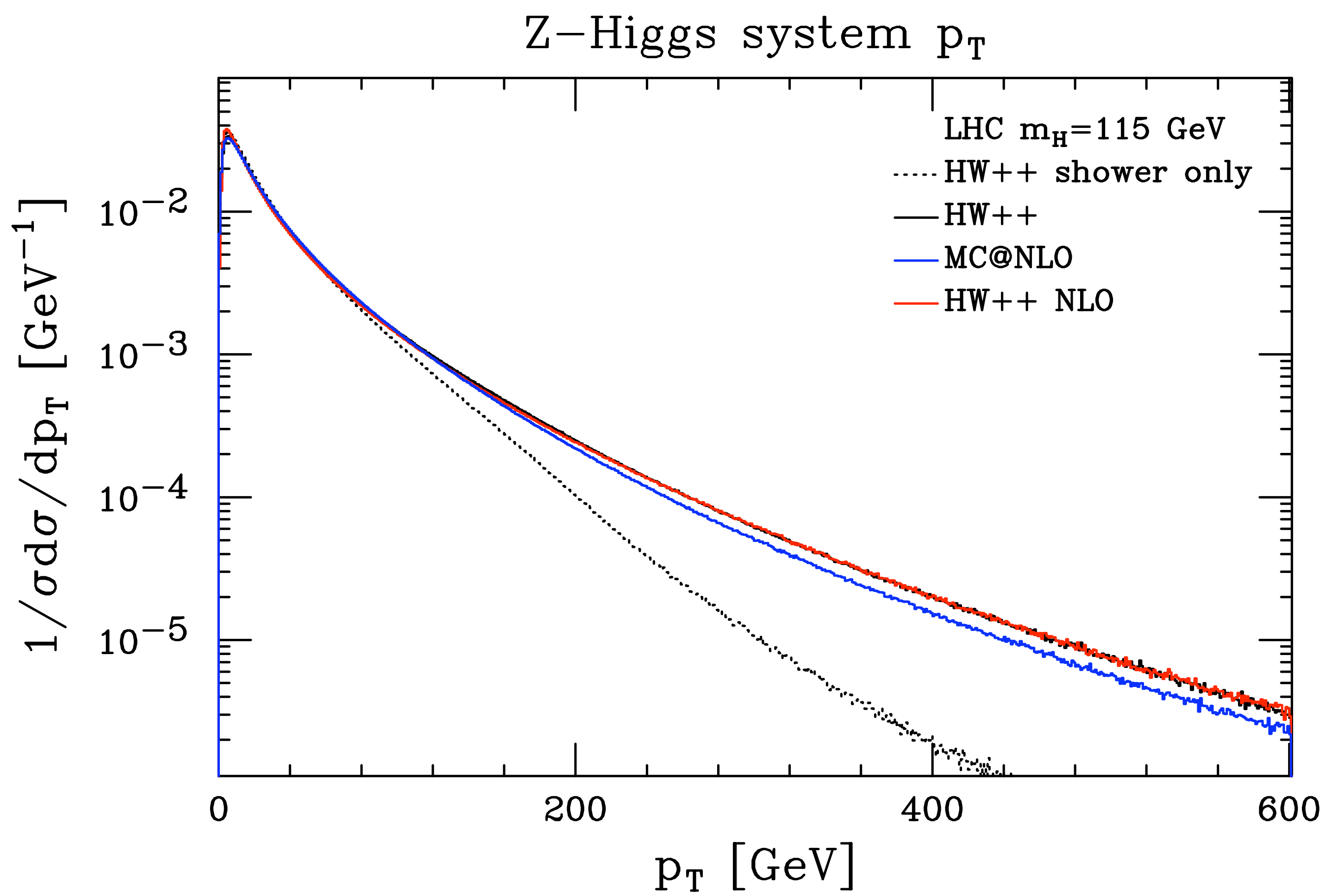
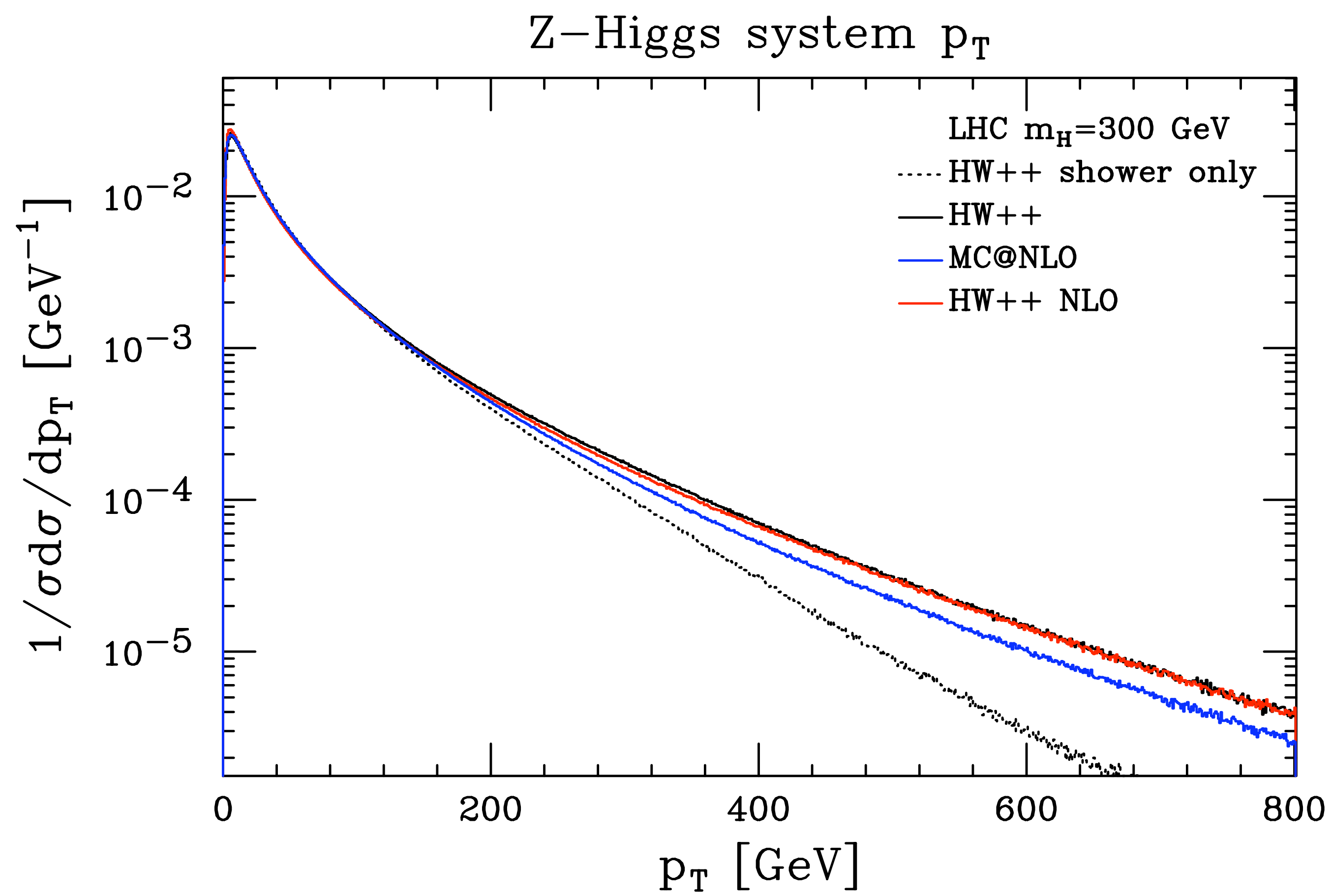
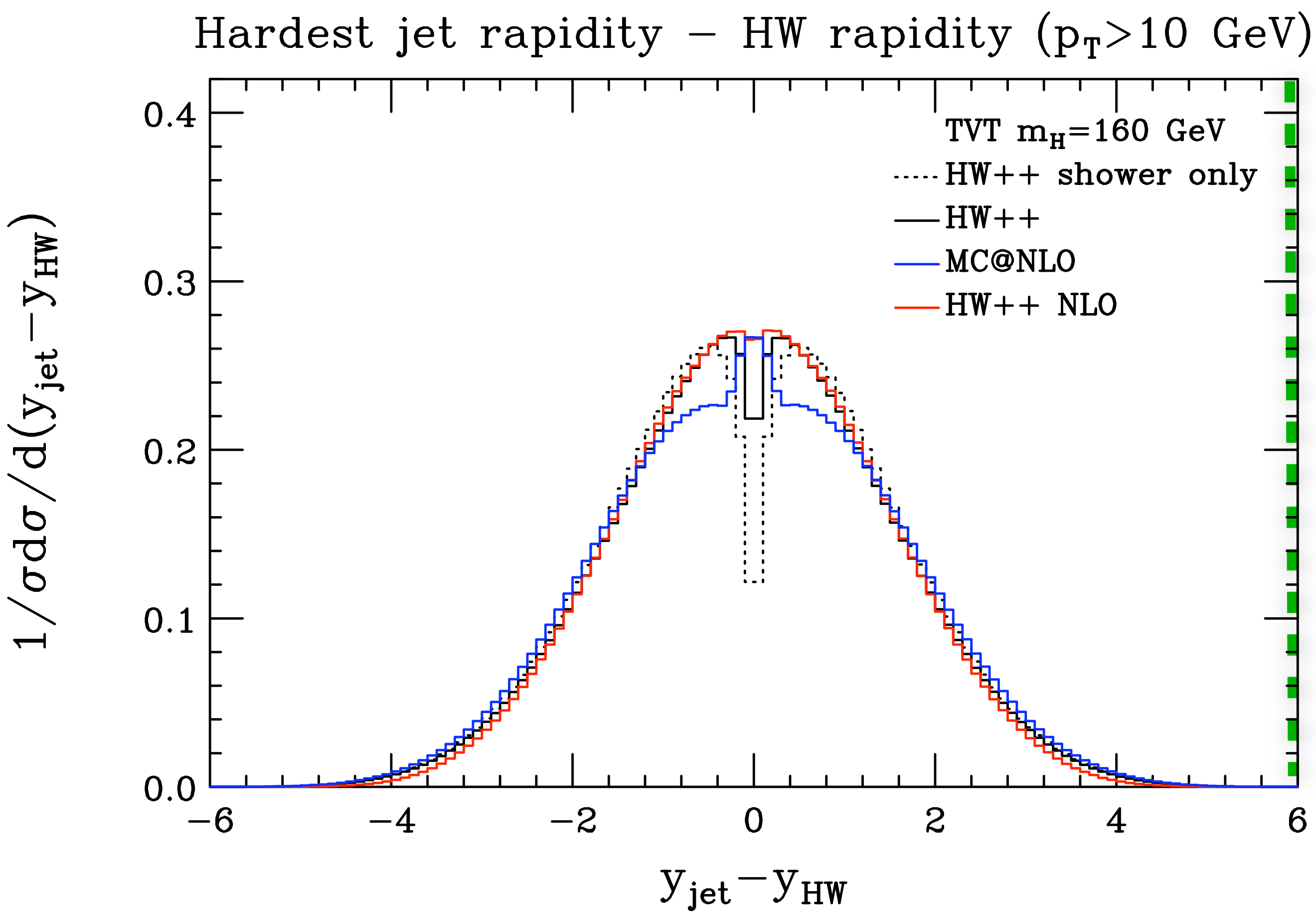
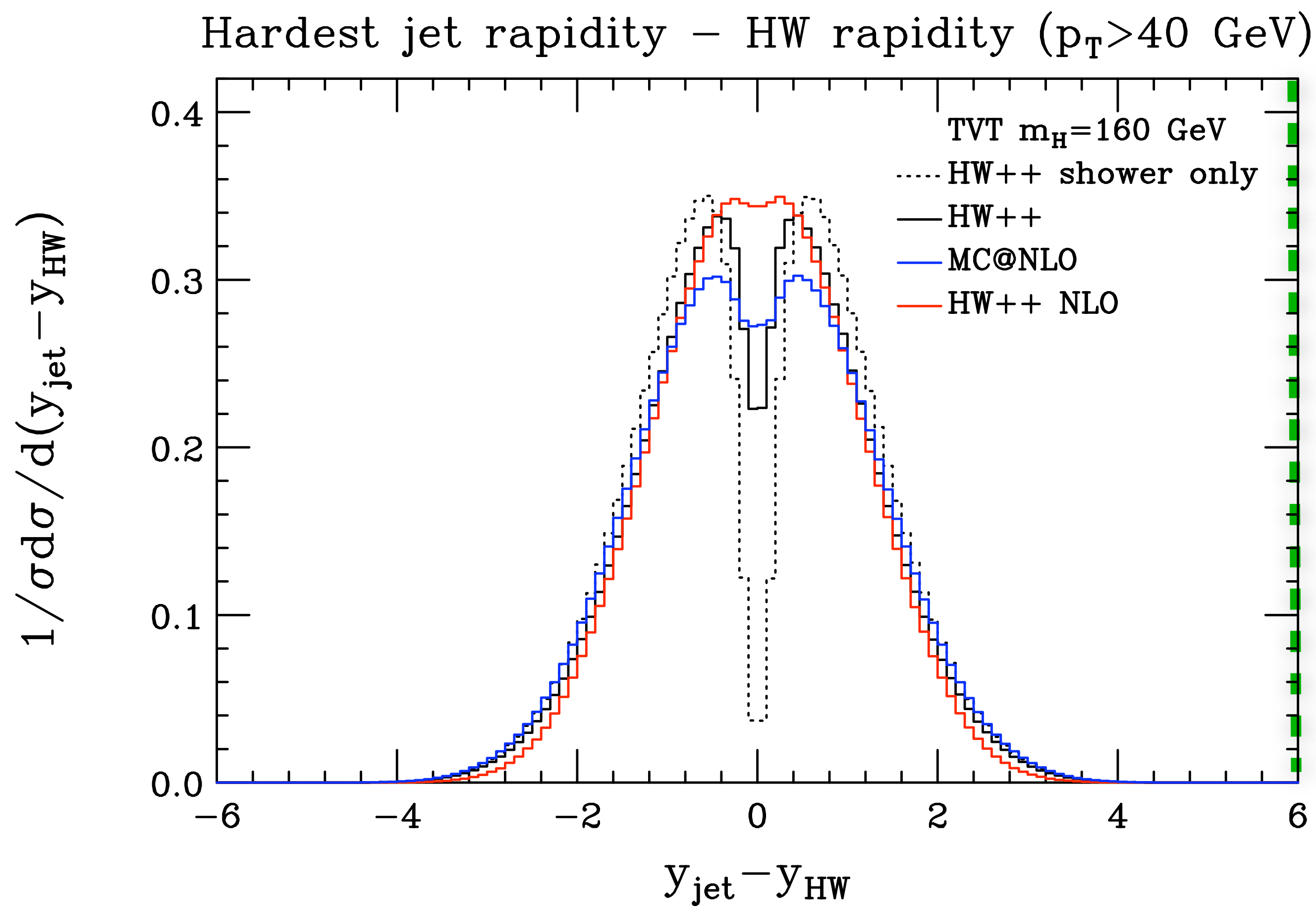


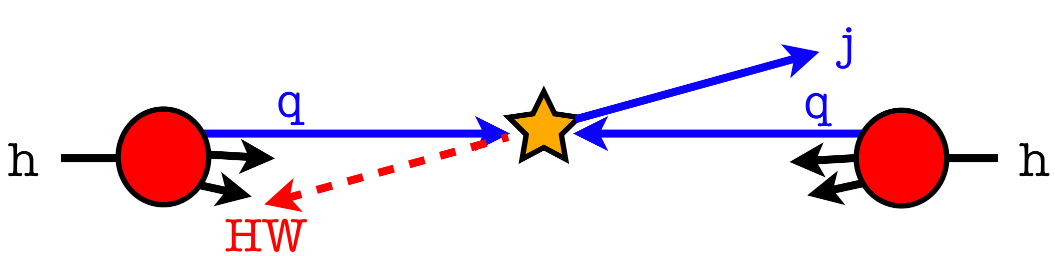


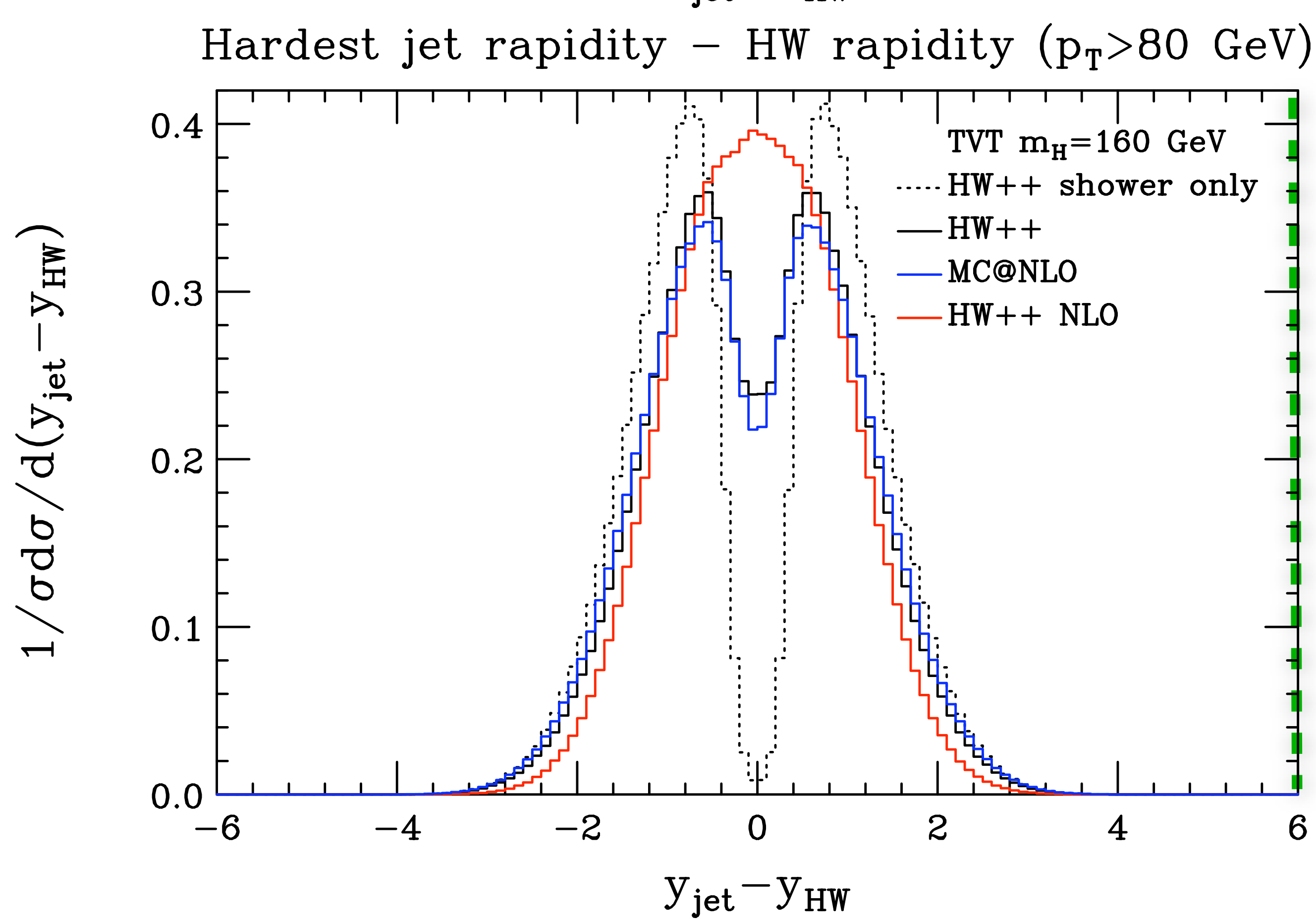


Results: Higgs-strahlung ($q\bar{q} \to HW$)









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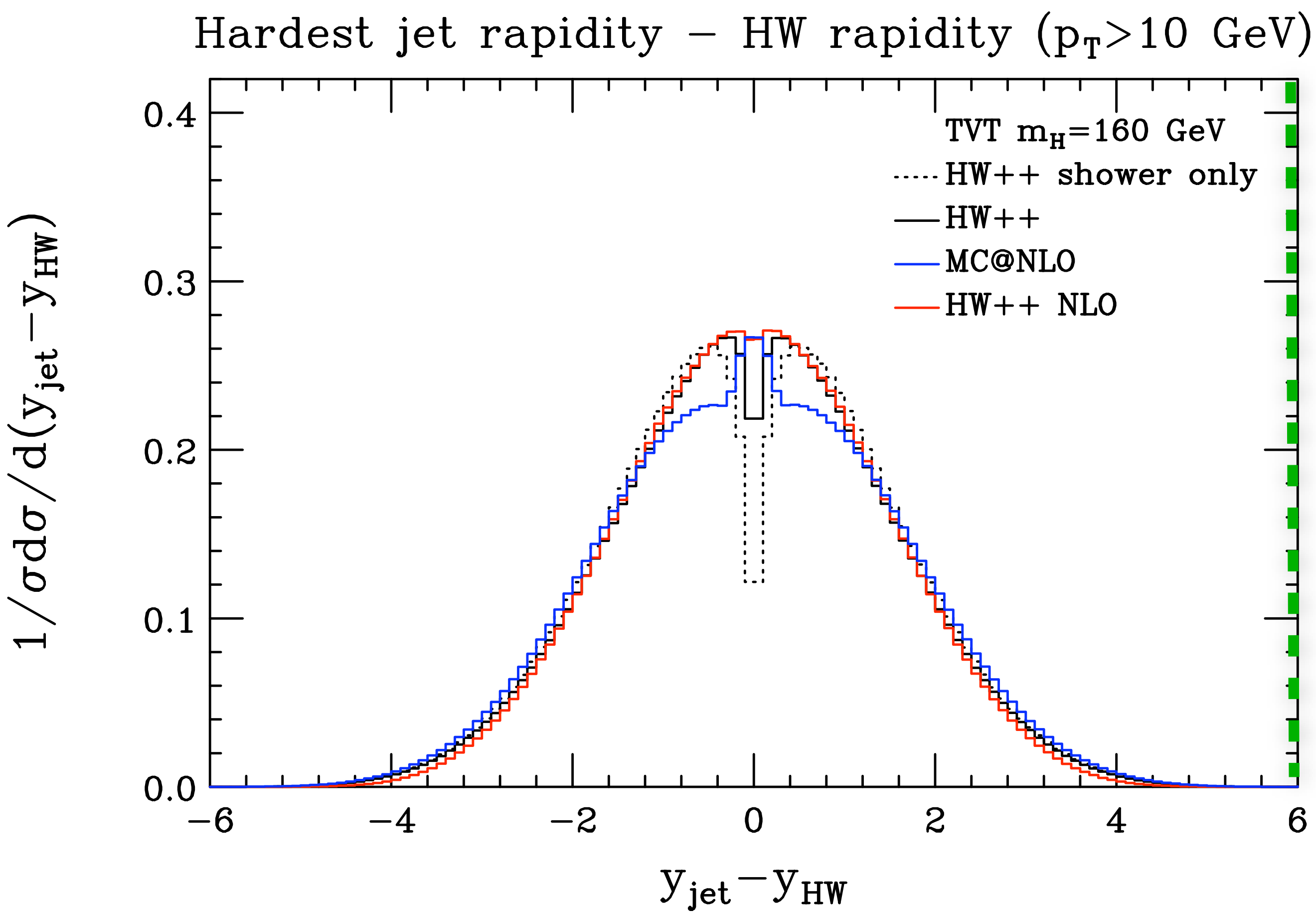
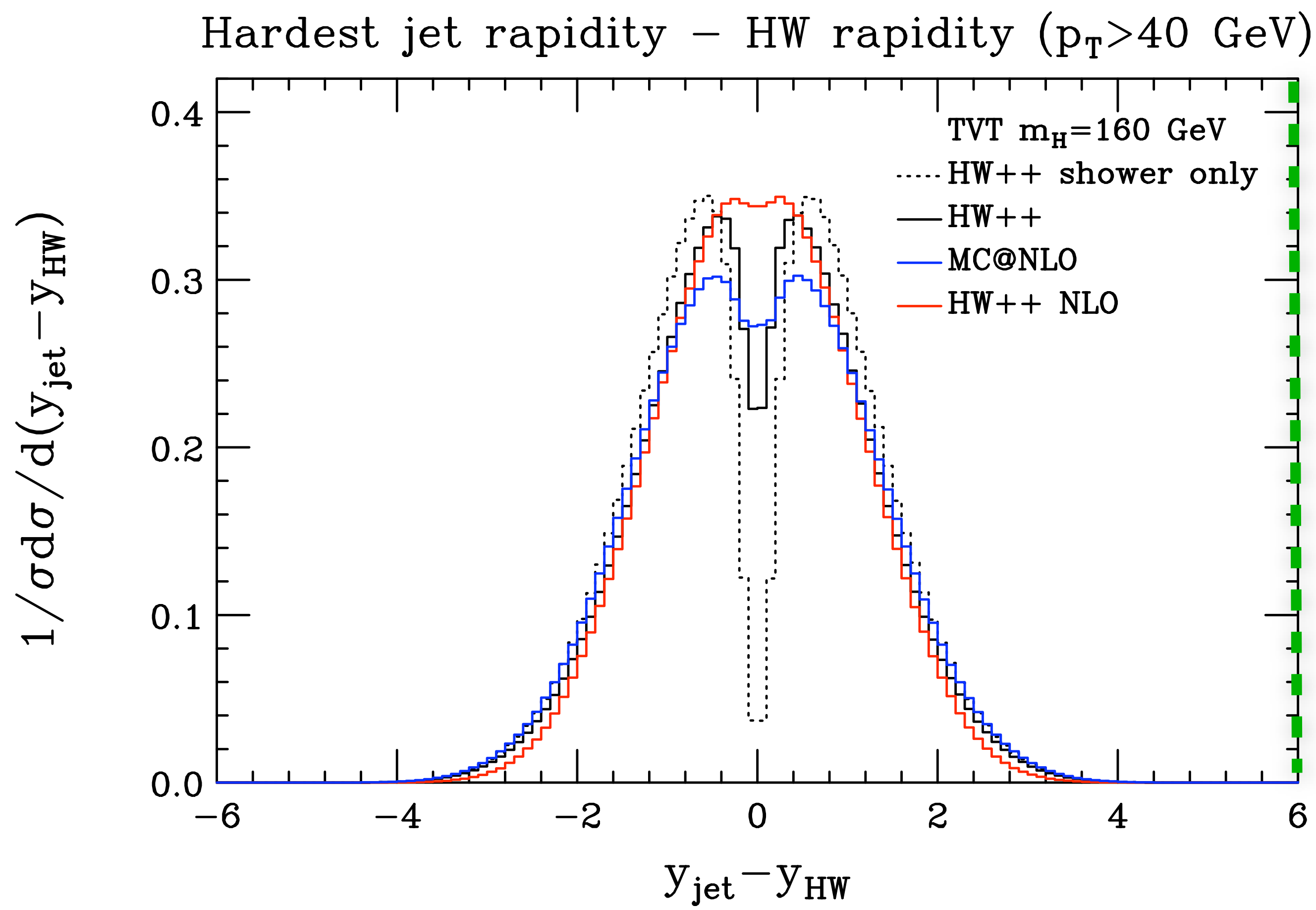
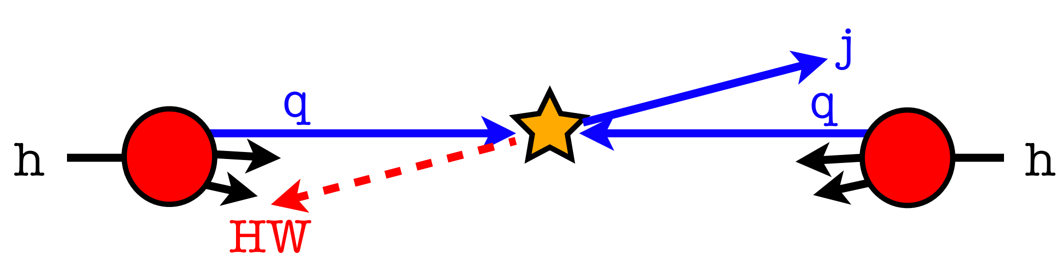
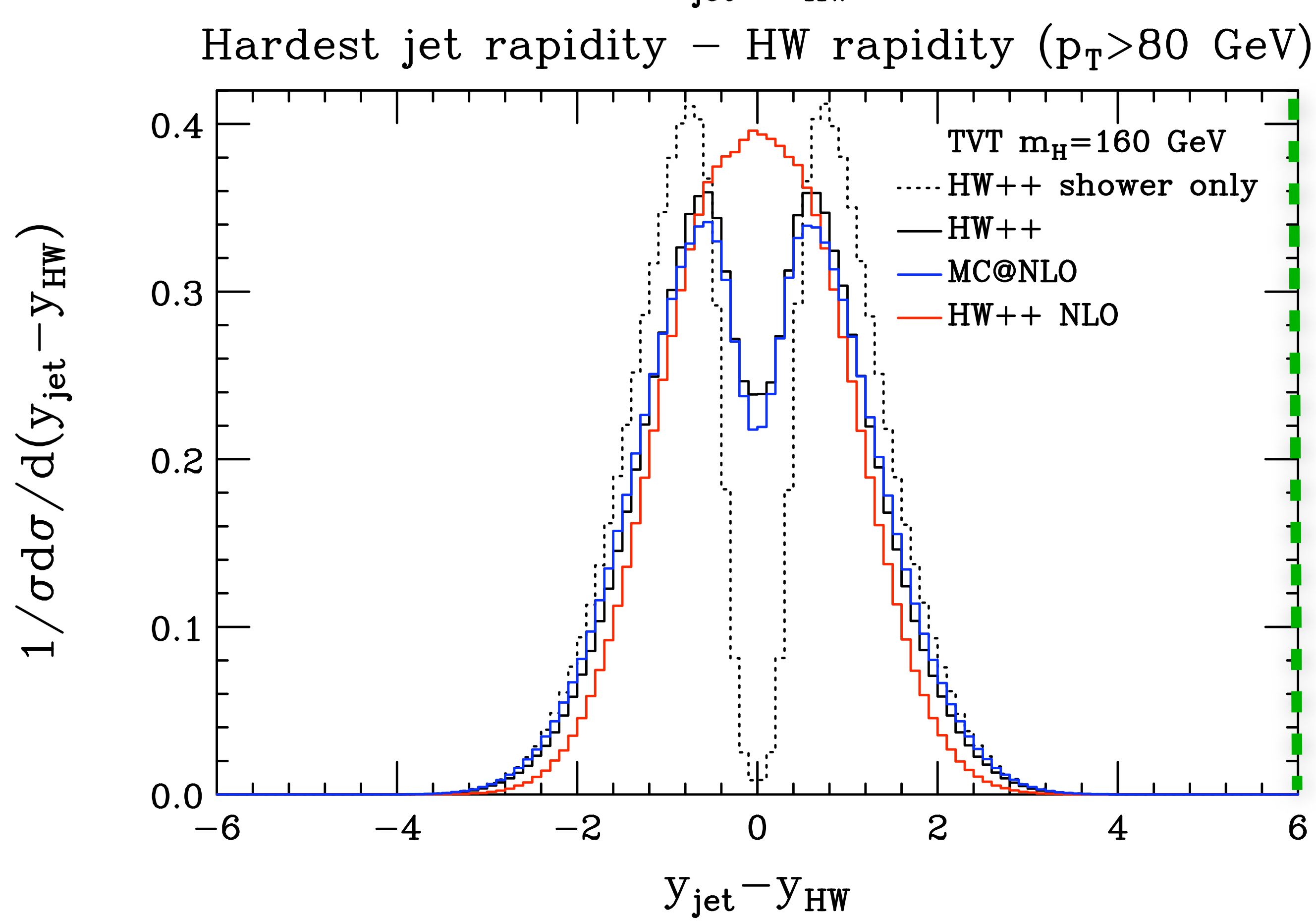
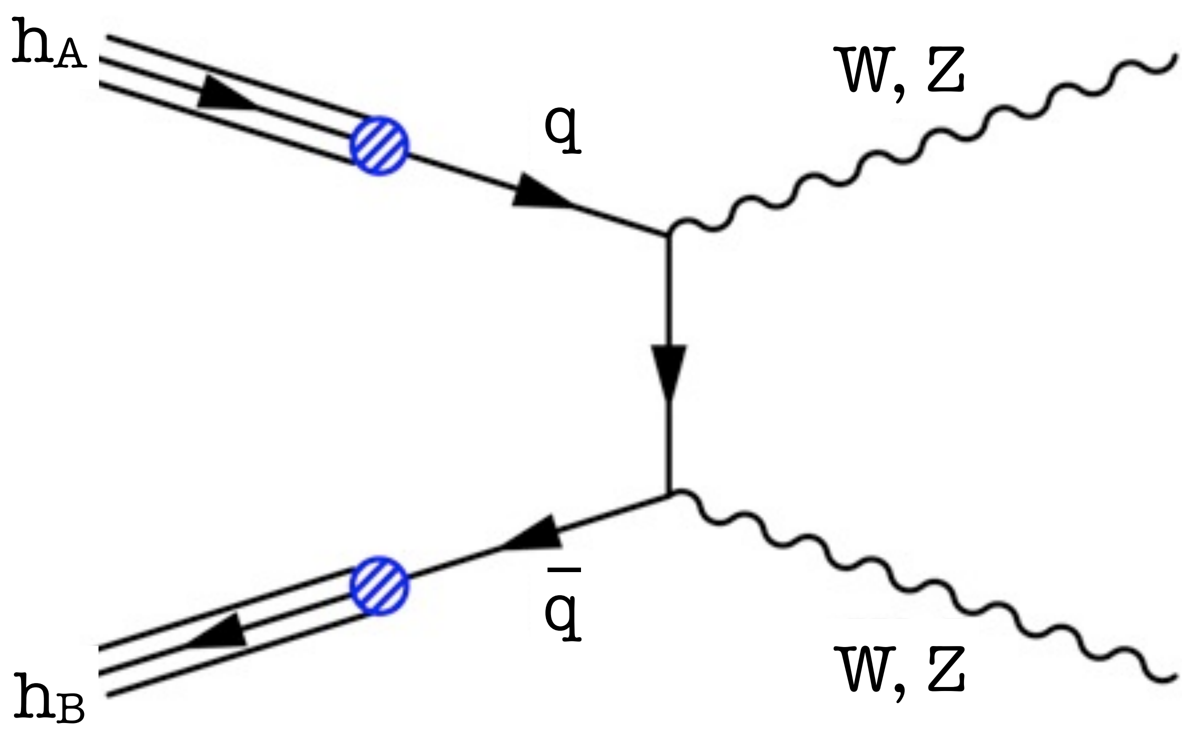


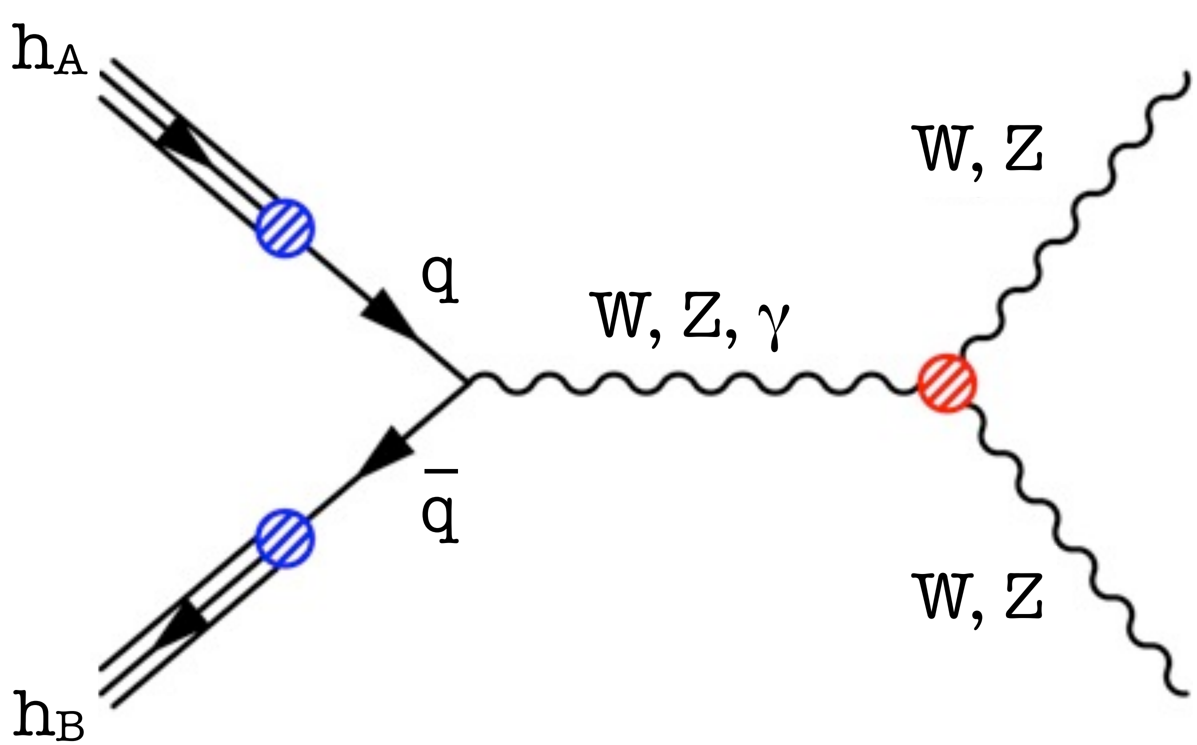






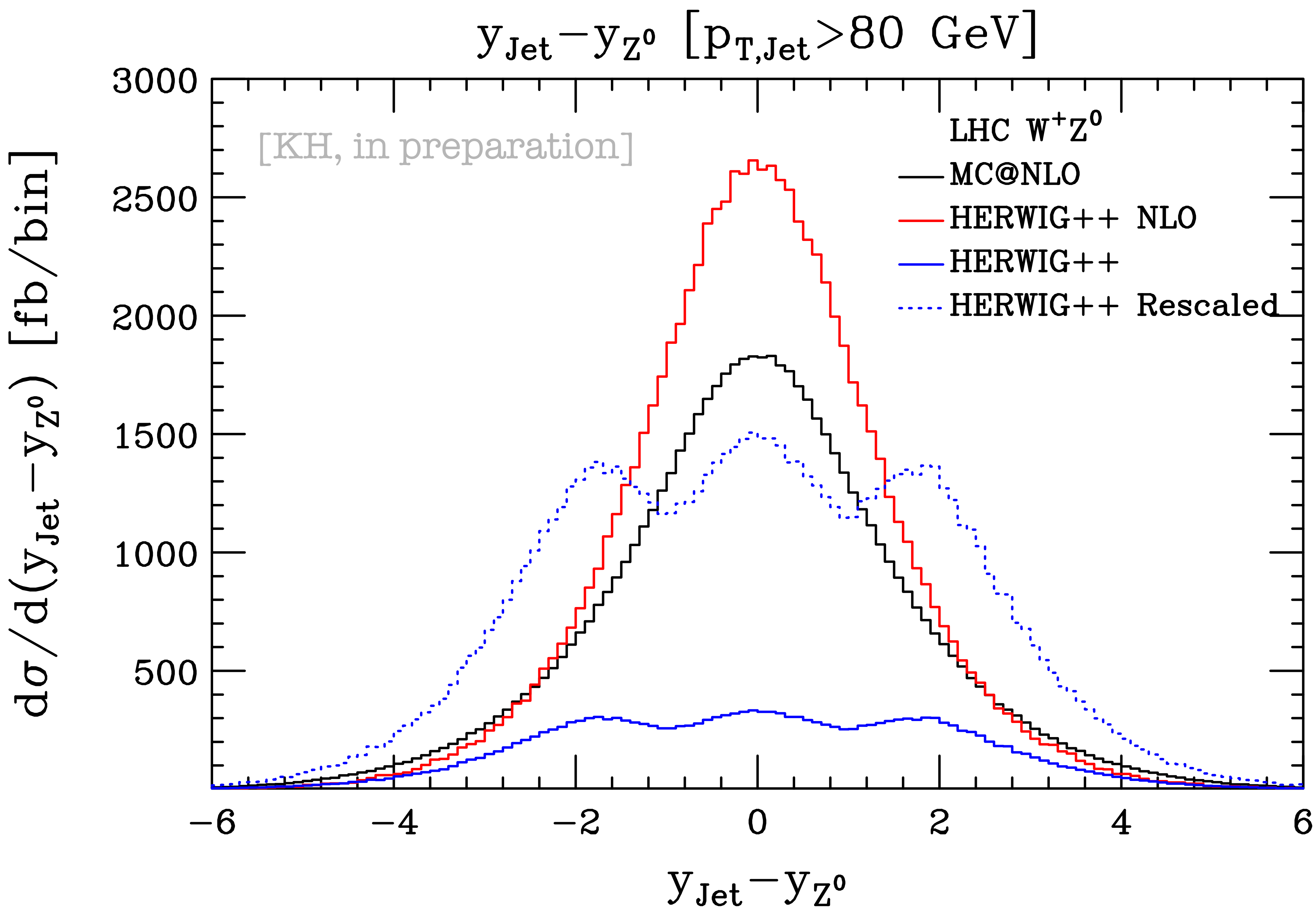
Results: Diboson production





[KH]

Results: Diboson production at LHC



- LO total inclusive cross section
- PS has half as many 80 GeV jet events [LL approx]
- Direction of hard jets not like the NLO real correction

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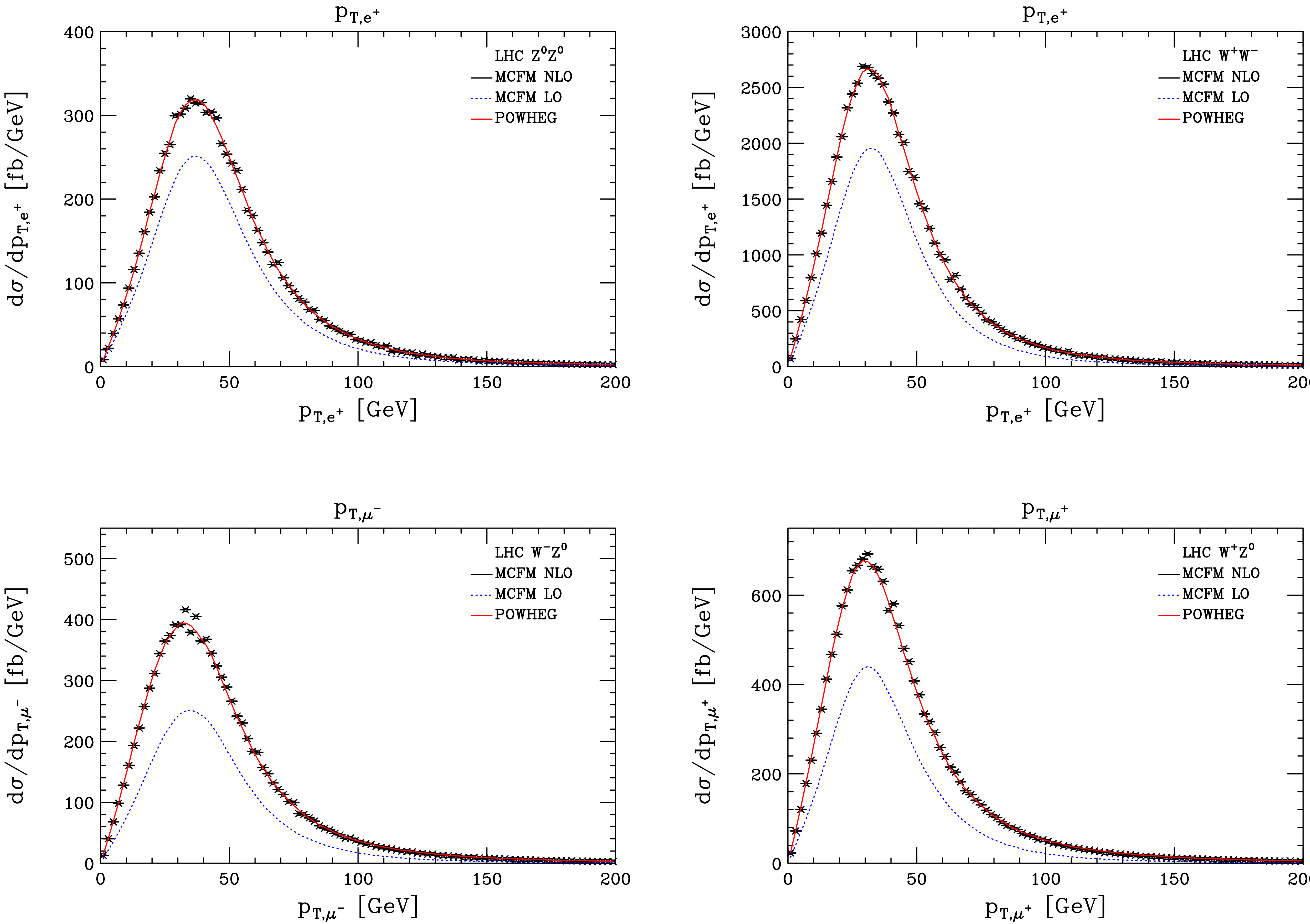

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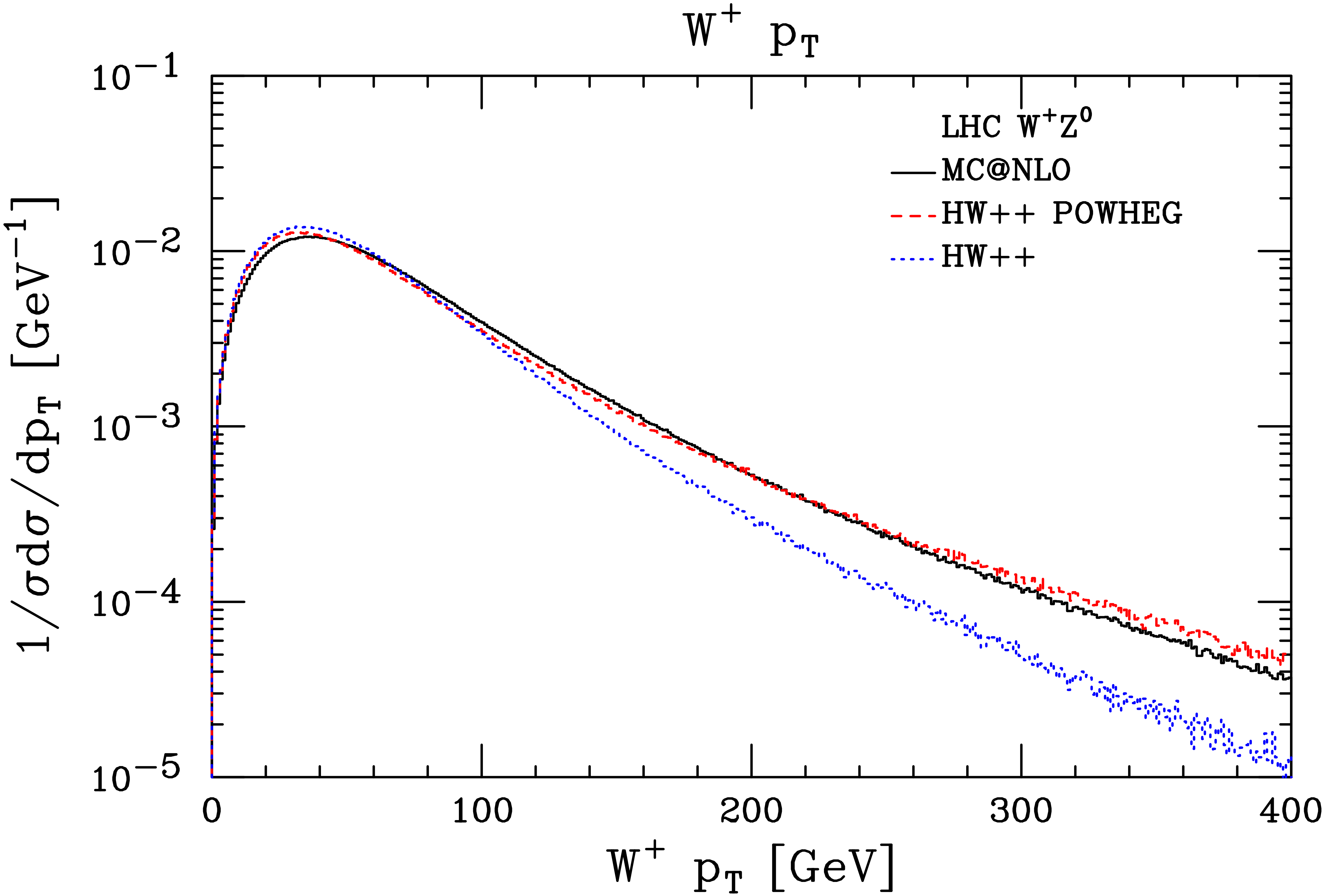
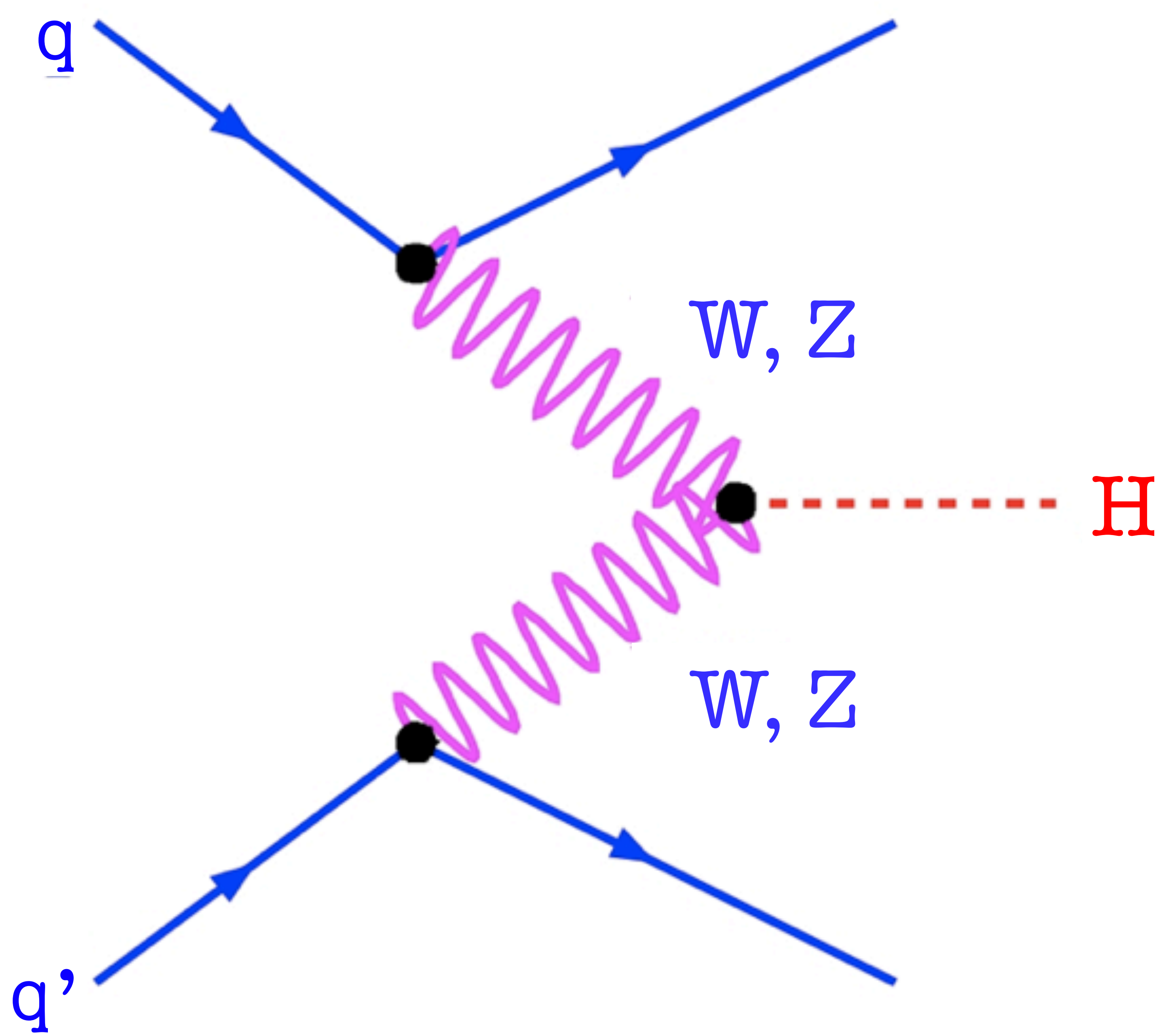


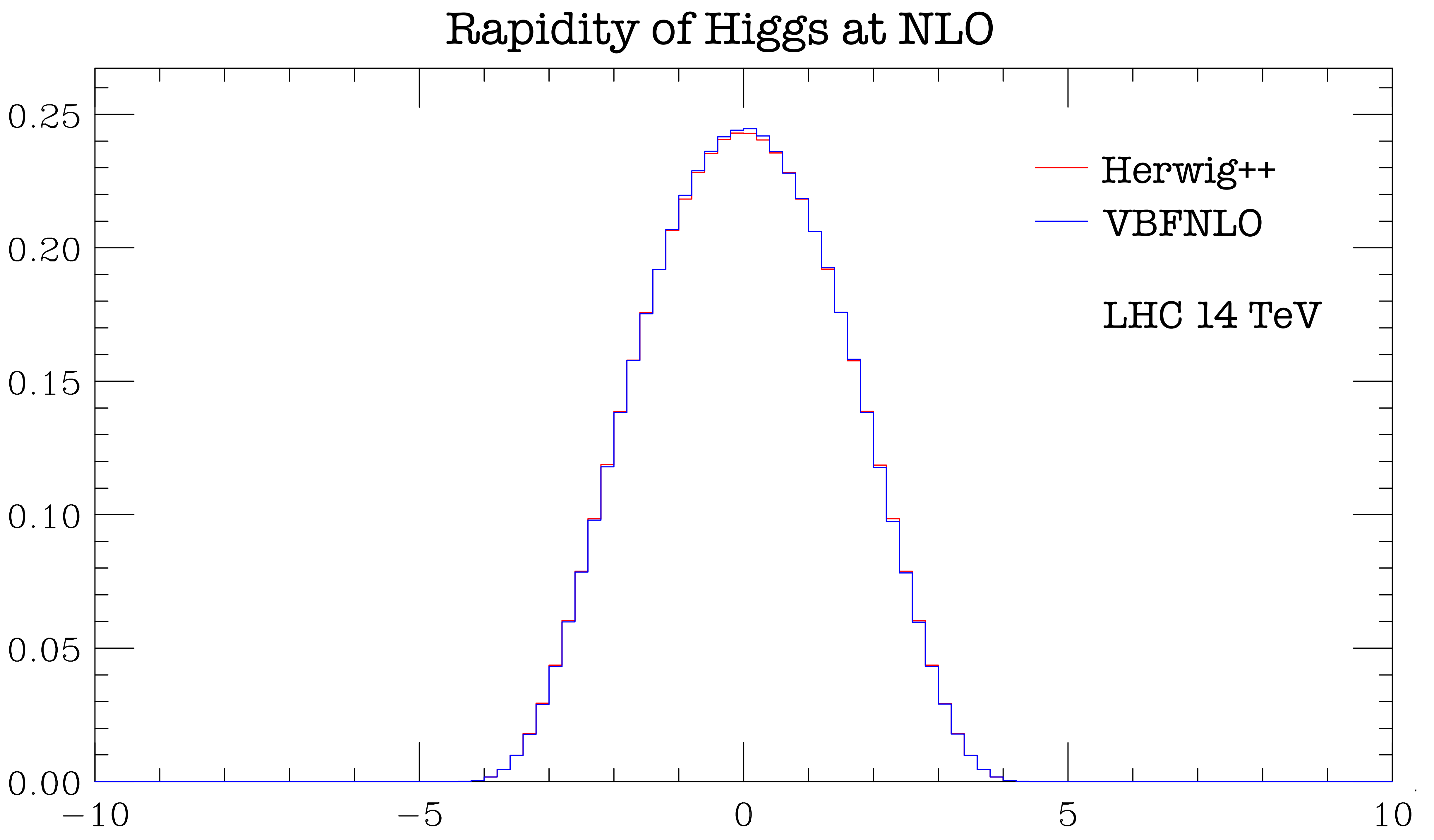
- Factor of 3 enhancement in LO distribution!
- Really "soft" W emission from hard quark qg → qZ →qWZ
- Also big enhancement due to incident gluon flux [Nason et al]

VBF



[D'Errico, Richardson]

Results: VBF



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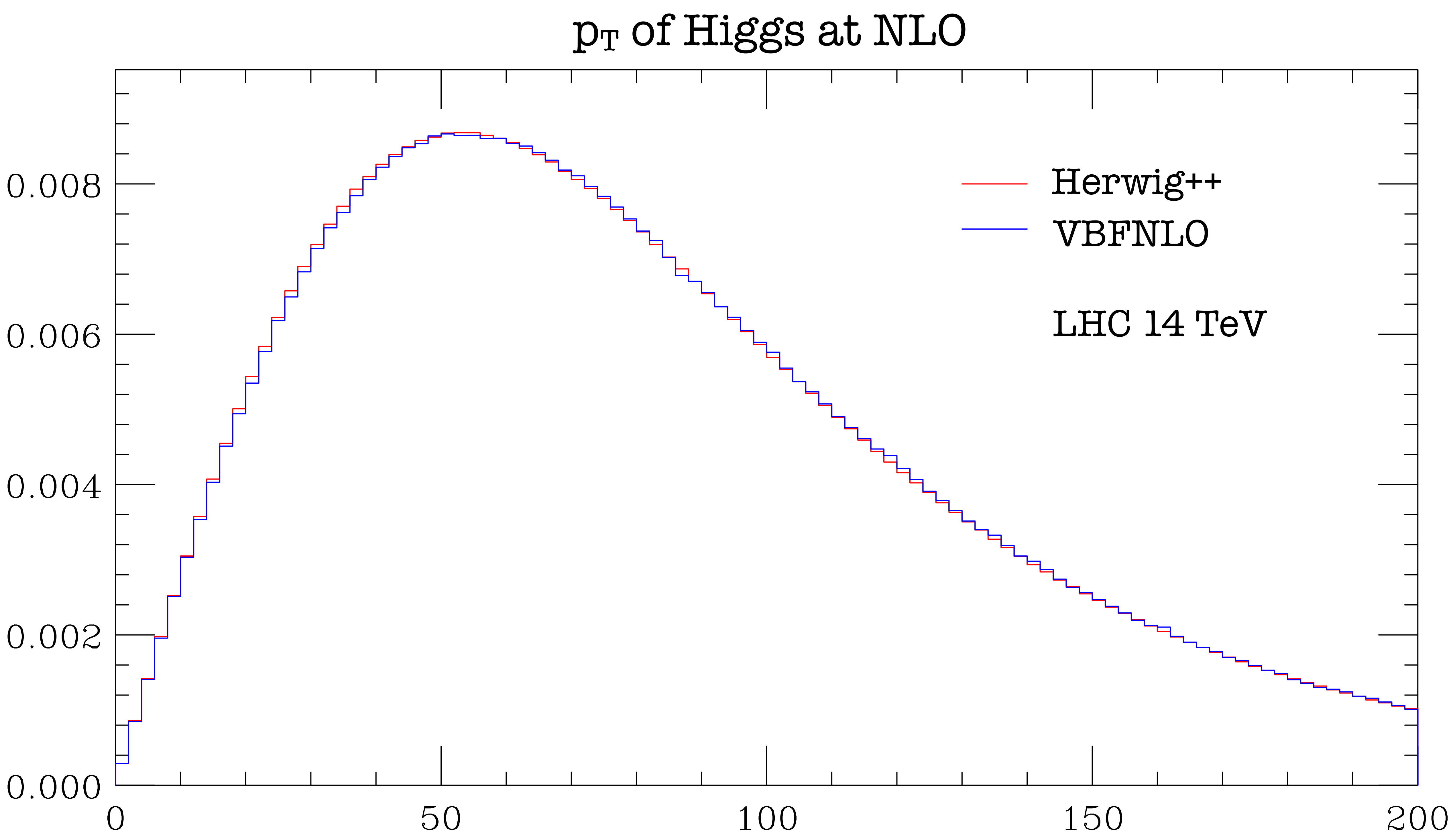


[D'Errico, Richardson]

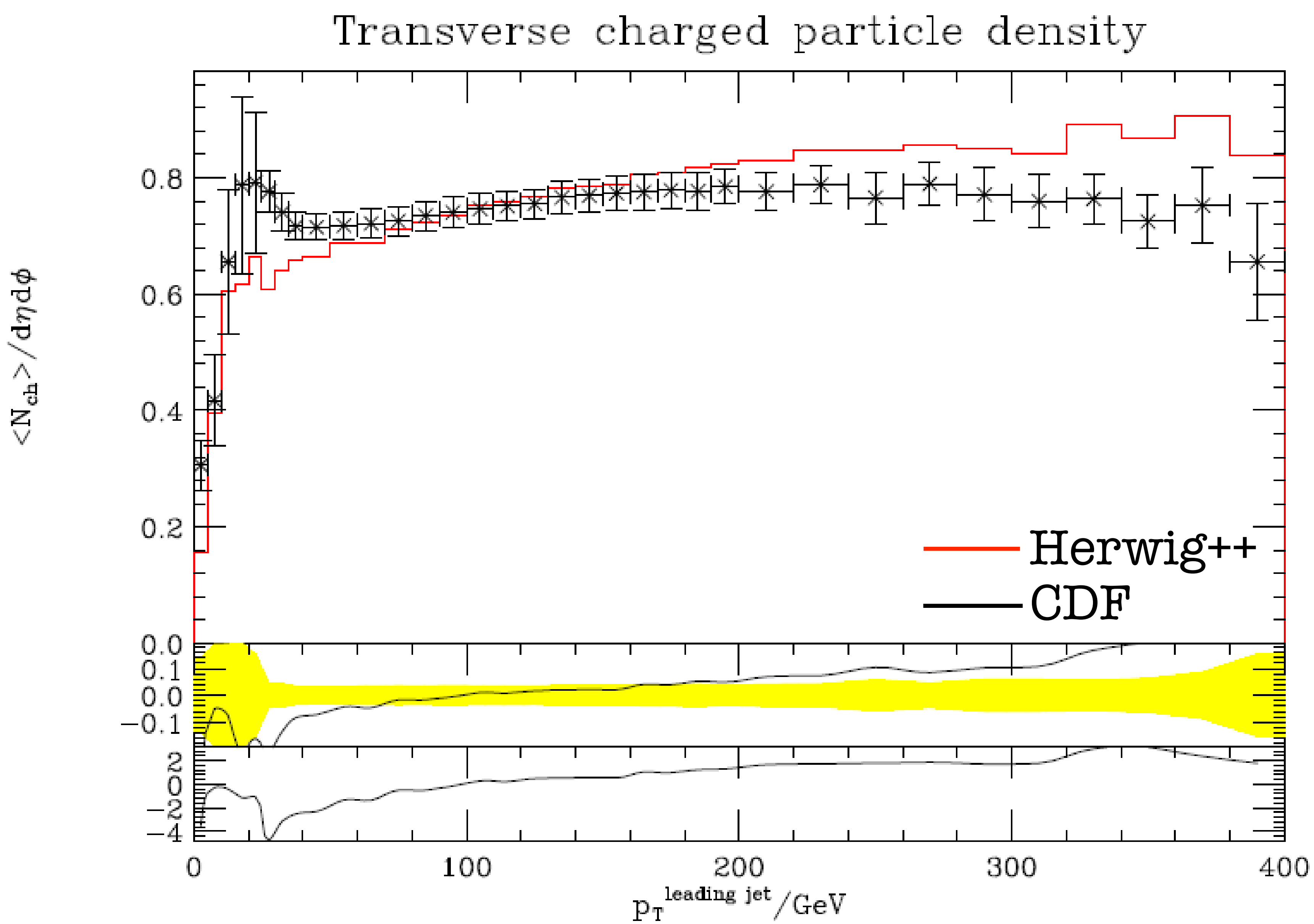
Other news

Multiple Interactions

Colour Coherent Formulation of CKKW

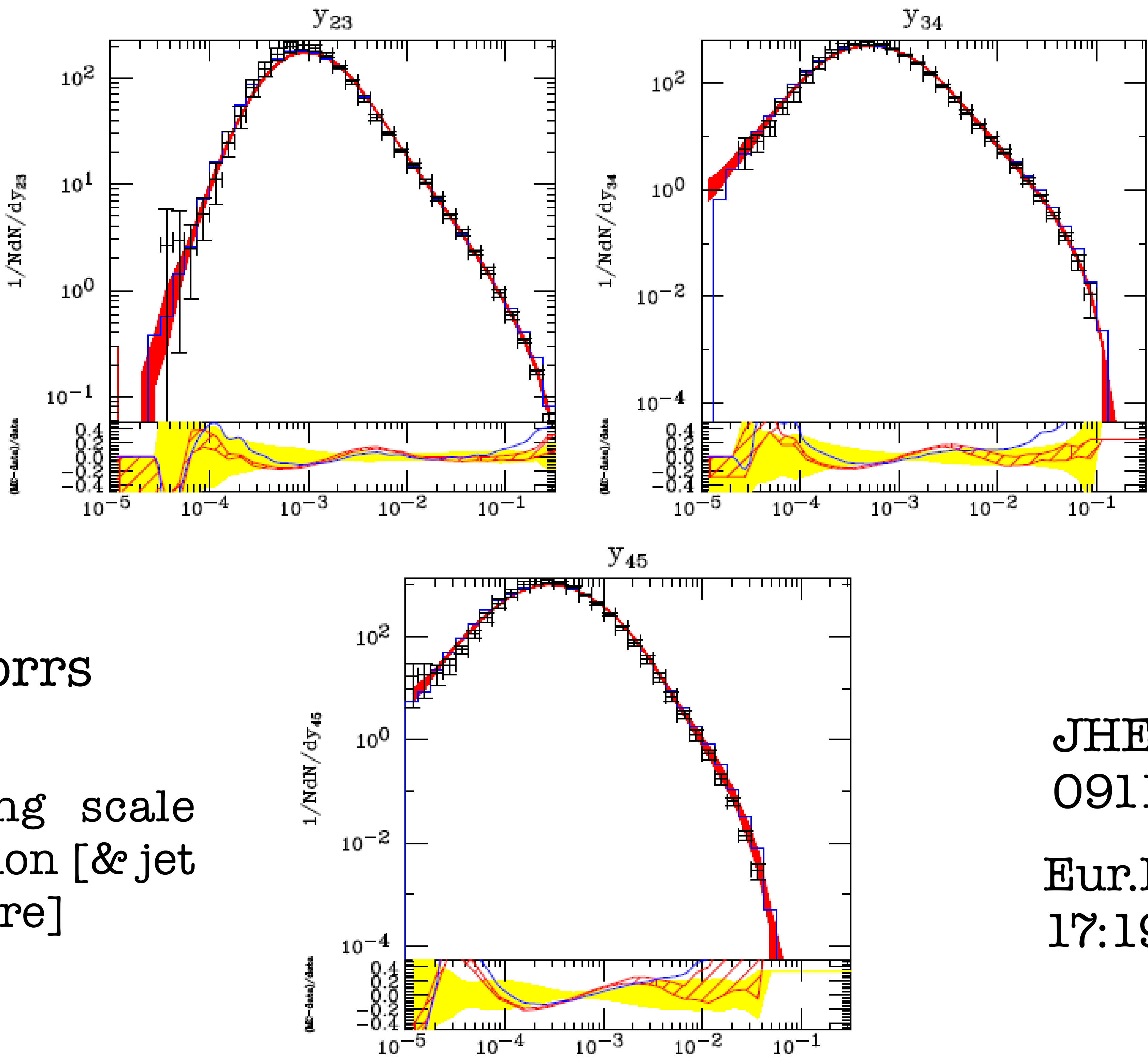
Multiple Parton Interations

- Original Herwig: UA1 model of the soft UE but option to link to JIMMY model of MPIs
- Herwig++:built in MPI model building on JIMMY technology.



[Bahr, Butterworth, Gieseke, Seymour]

Colour Coherent CKKW: LEP jet rates



ME Corrs

CKKW merging scale variation [& jet measure]

JHEP 0911:038,2009

Eur.Phys.J.C 17:19-51, 2000

[KH, Richardson, Tully]

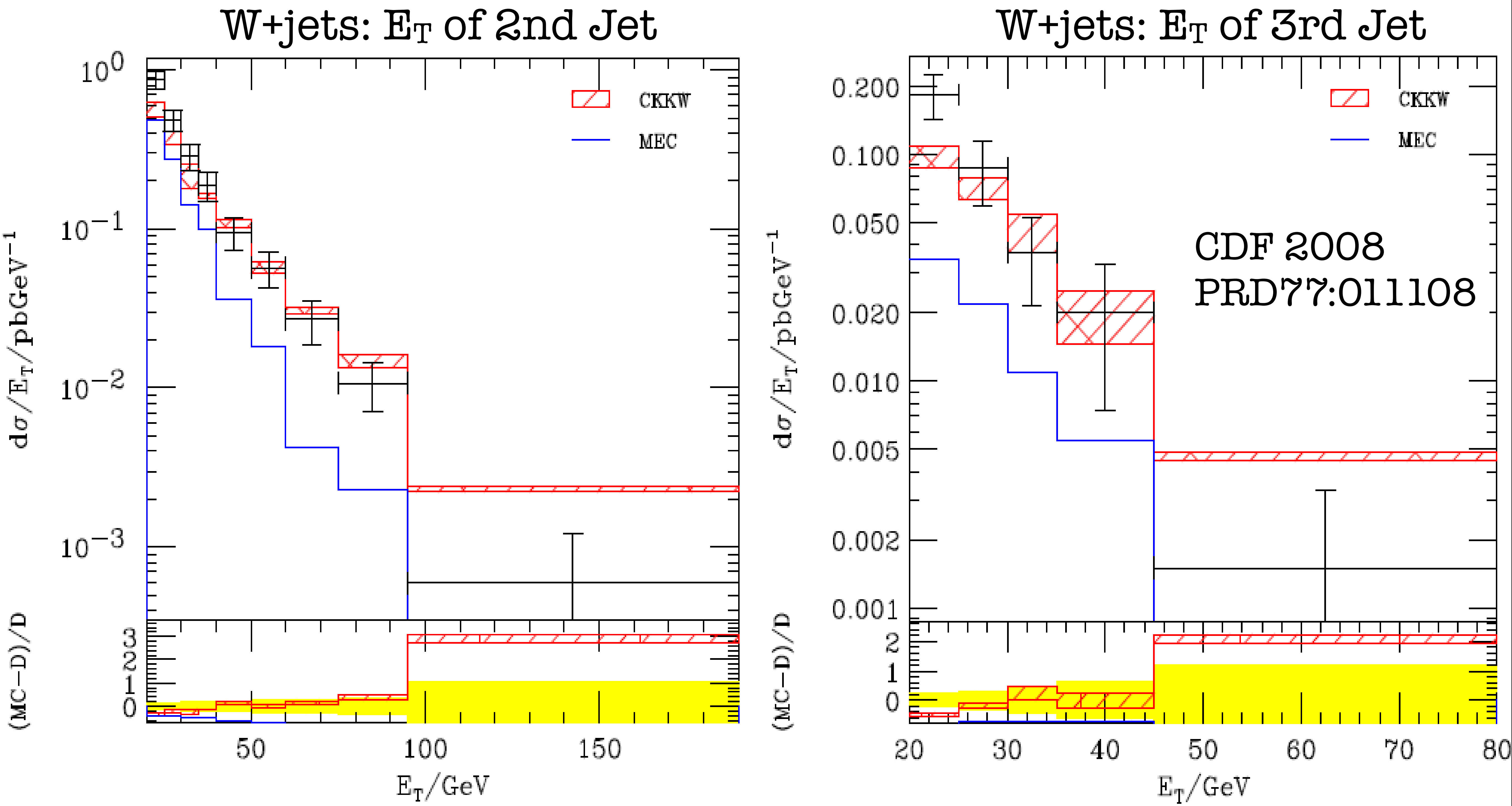
Colour Coherent CKKW: fit to LEP data

- CKKW tune at $y_{merge} = 10^{-2}$ gives much better fit to LEP data than standard tune [HW++ with ME corrections]:

Observable	Hw+ME χ^2/d.o.f	CKKW χ^2/d.o.f
Thrust	23.48	10.62
Sphericity	5.638	0.580
Oblateness	2.450	0.339
Planarity	1.249	1.211
y_{23}	2.400	0.867
y_{34}	1.887	1.026
y_{45}	4.571	2.018
$\cos\alpha_{34}$	0.569	3.301
$\cos\chi_{BZ}$	1.002	0.775
$\cos\Phi_{KSW}$	1.469	1.337
$\cos\theta_{NR}$	4.509	0.702

[KH, Richardson, Tully]

Colour Coherent CKKW: CDF jet E_T spectra



[Richardson, Tully]

Main news summary

- Herwig++ ships with the following in-house POWHEG codes:

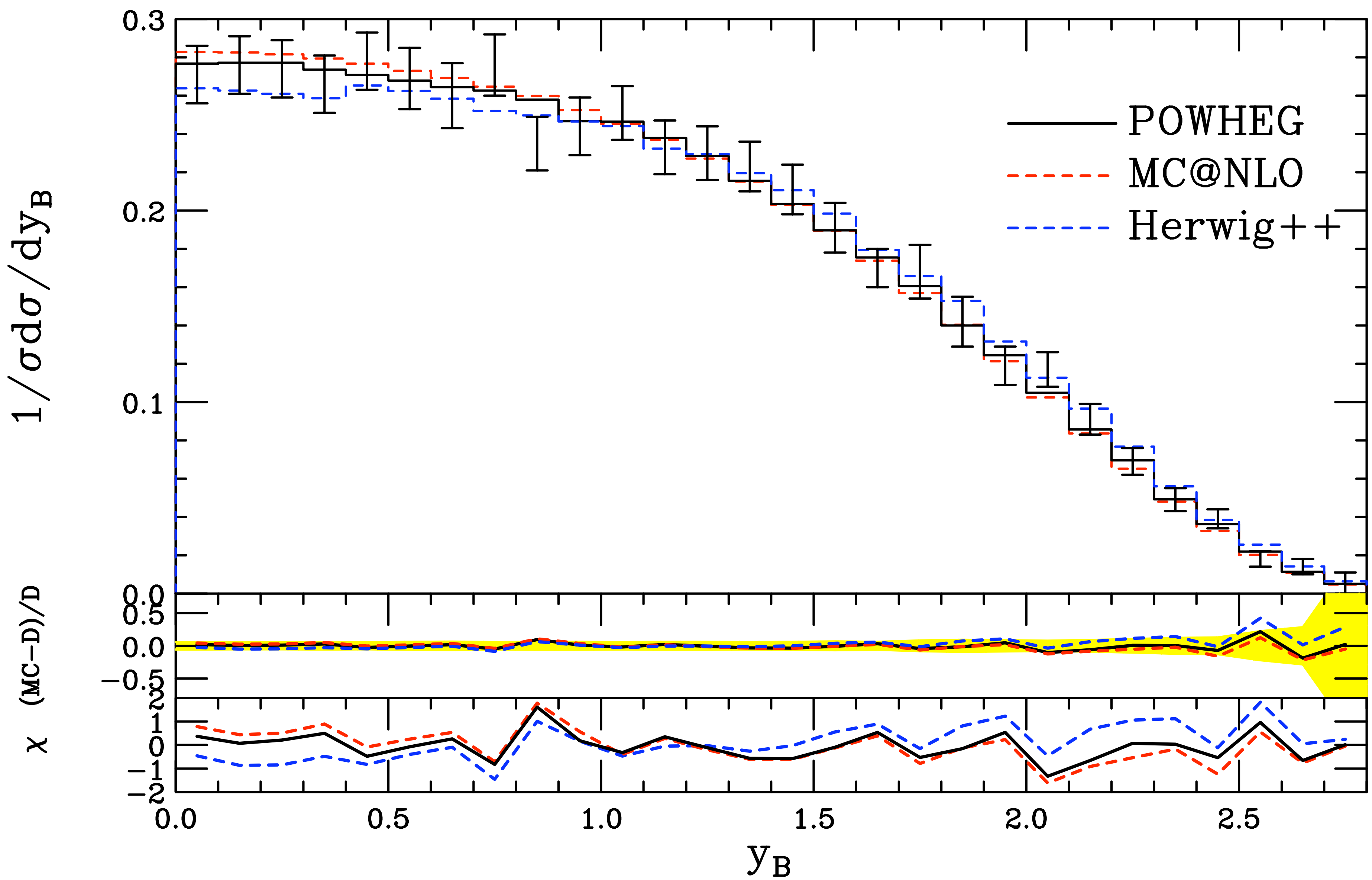
$$hh \rightarrow \gamma \,/\, Z \,/\, W \,/\, H \,/\, ZH \,/\, WH$$

- All processes underwent lengthy validations via comparison with MCFM, MC@NLO, ME Corrections and real data.
- The only sizeable discrepancies found were in p_T spectra and rapidity correlations w.r.t. MC@NLO for $gg \rightarrow H$.
- Our studies conclude that these discrepancies stem from the dependency of MC@NLO on the underlying shower MC, in particular its phase space partitioning [should not occur in MC@NLO+PYTHIA].
- VBF is being validated and WW/ZZ/WZ production is validated: HW++ will ship with these in the coming months.

Bonus material

Results: Drell-Yan vector boson production

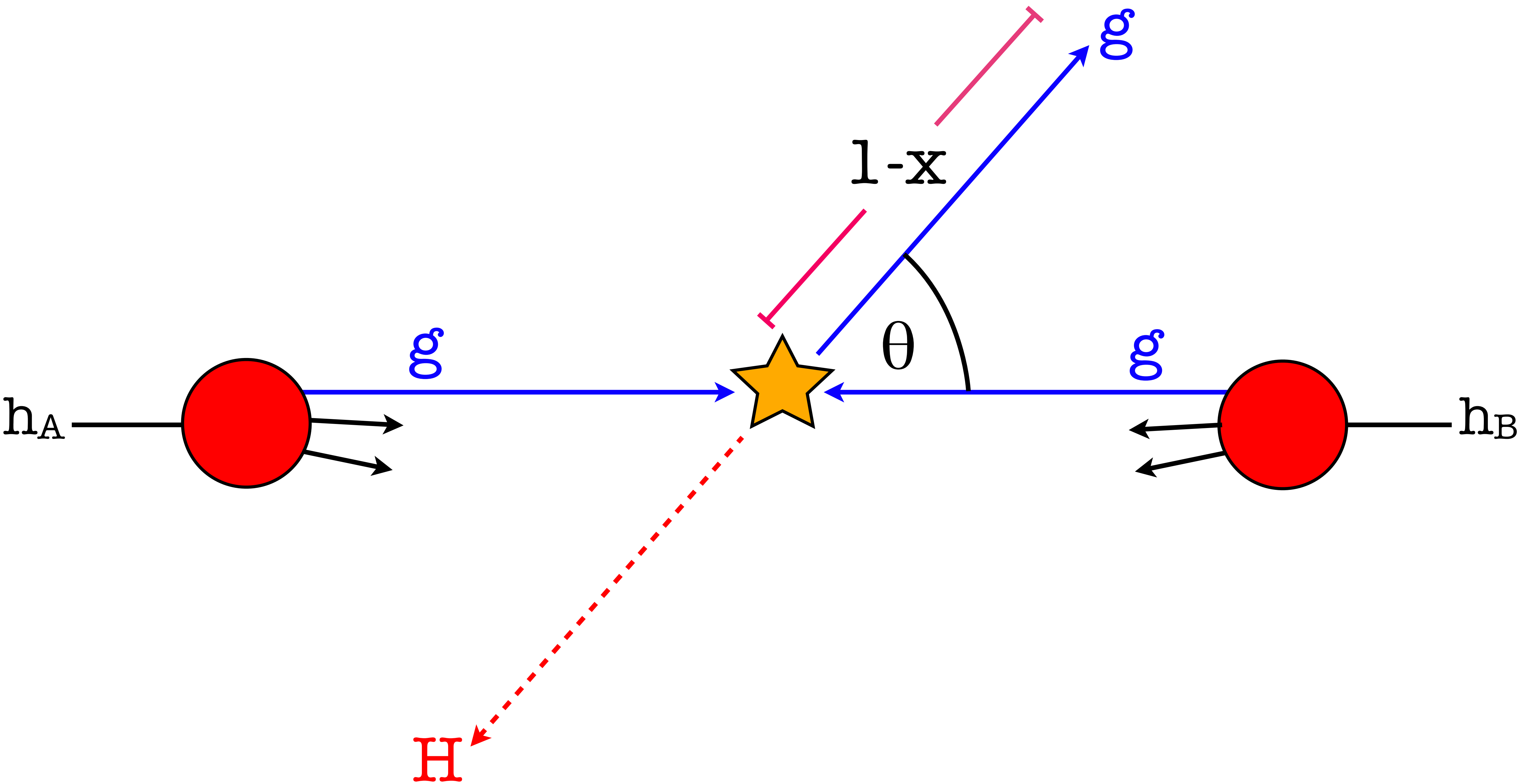
Z boson rapidity compared to D0 run II data



Solid line: NLO Herwig++ POWHEG Red dashes: MC@NLO
Blue dashes: Herwig++

Radiative phase space variables: x & y

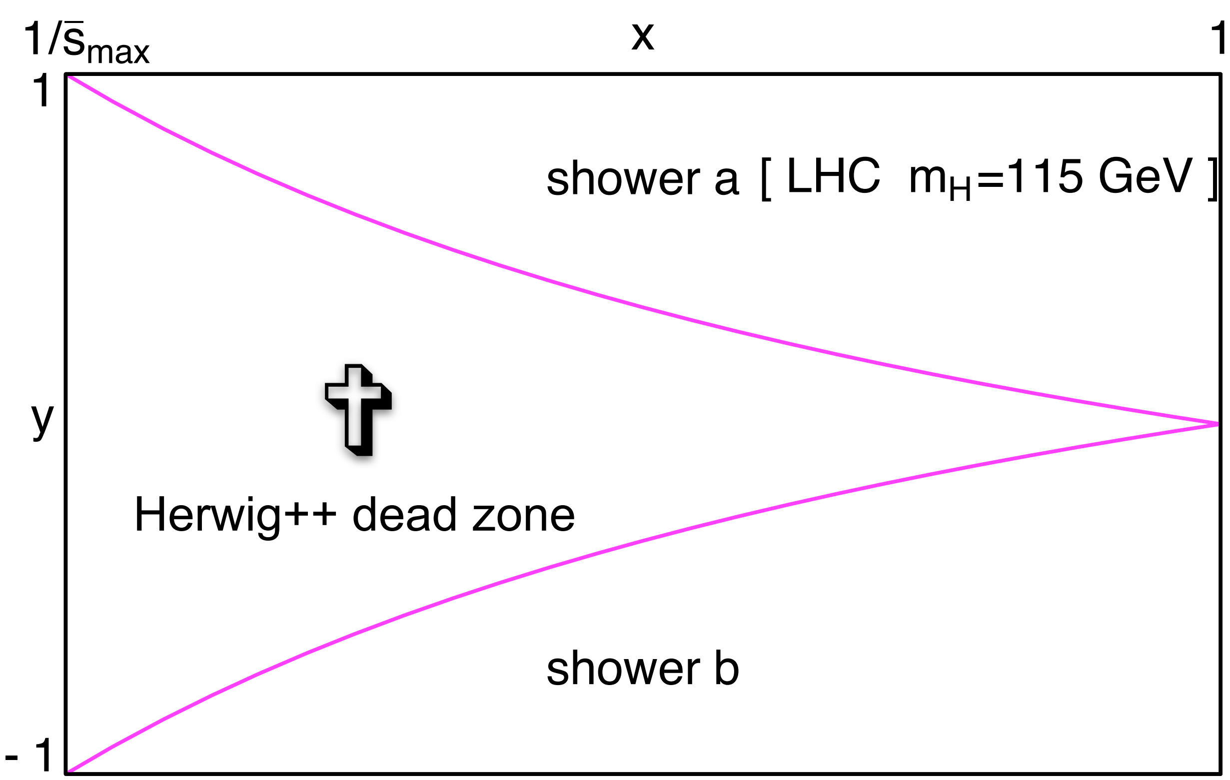
NLO real emission correction: g+g→H+g

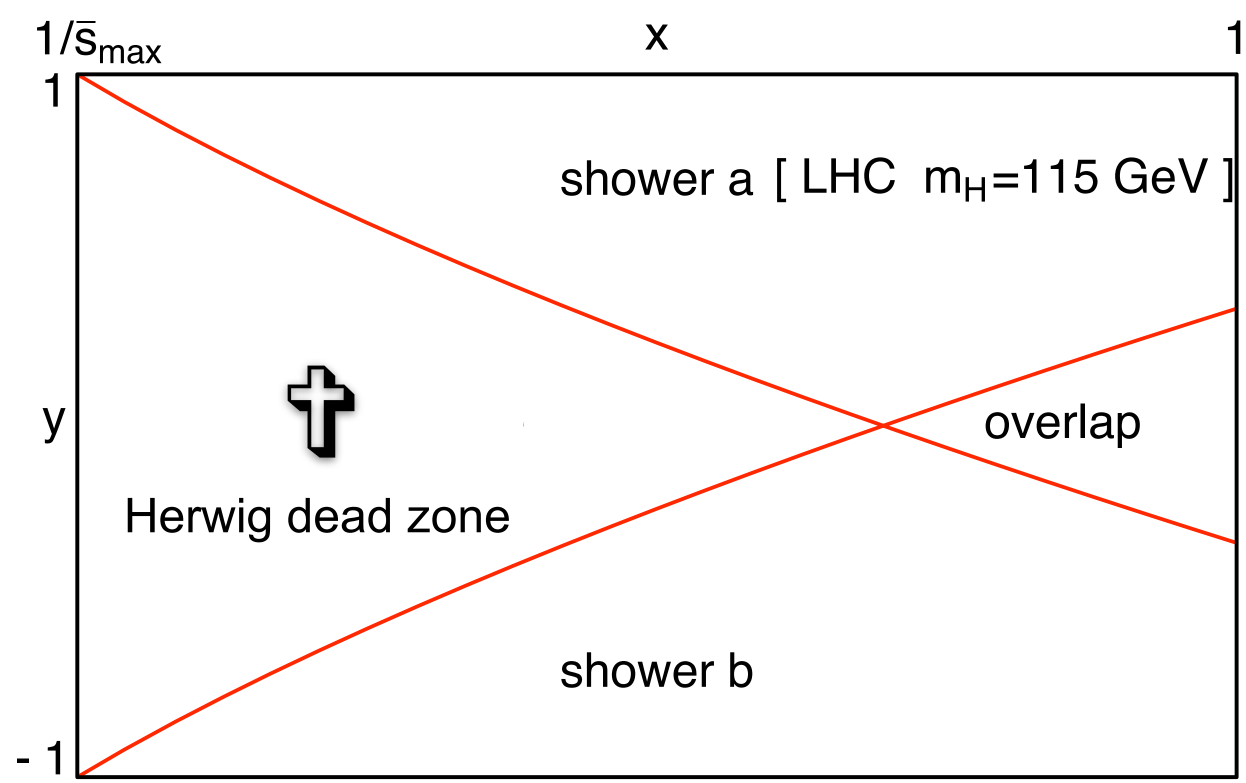


Results: Higgs production via gluon fusion

The Dead Zone

- In angular ordered parton showers like Herwig there is a region of phase space that the shower can't emit into: the dead zone.





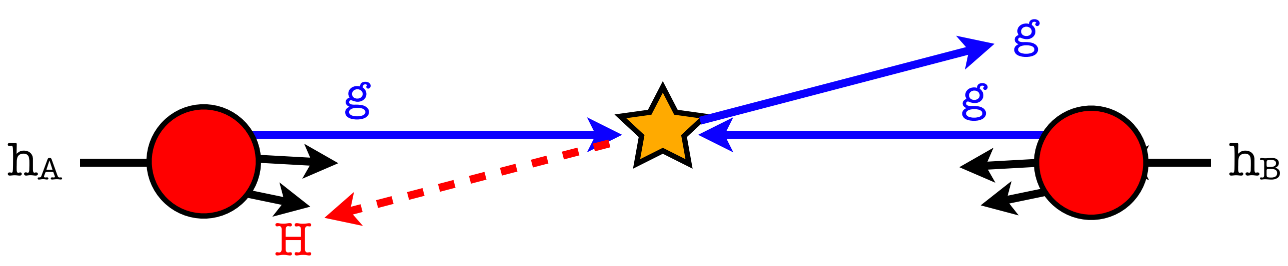
$x = 1 - E_{emitted}/E_{incoming}$

$y = \cos\theta$

- The dead zone is in the region of phase space corresponding to wide angle, high p_T emission of the first radiated parton.

Results: Higgs production via gluon fusion

Radiative Phase Space and its Dead Zone



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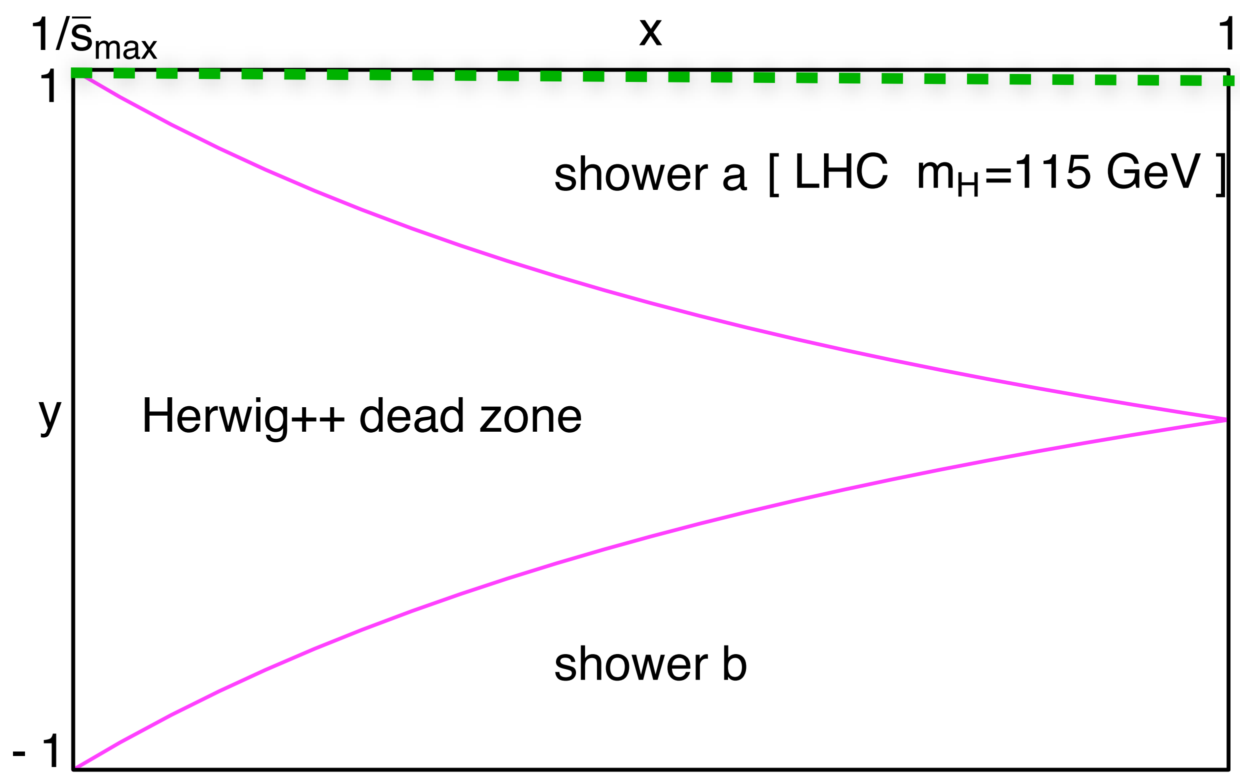

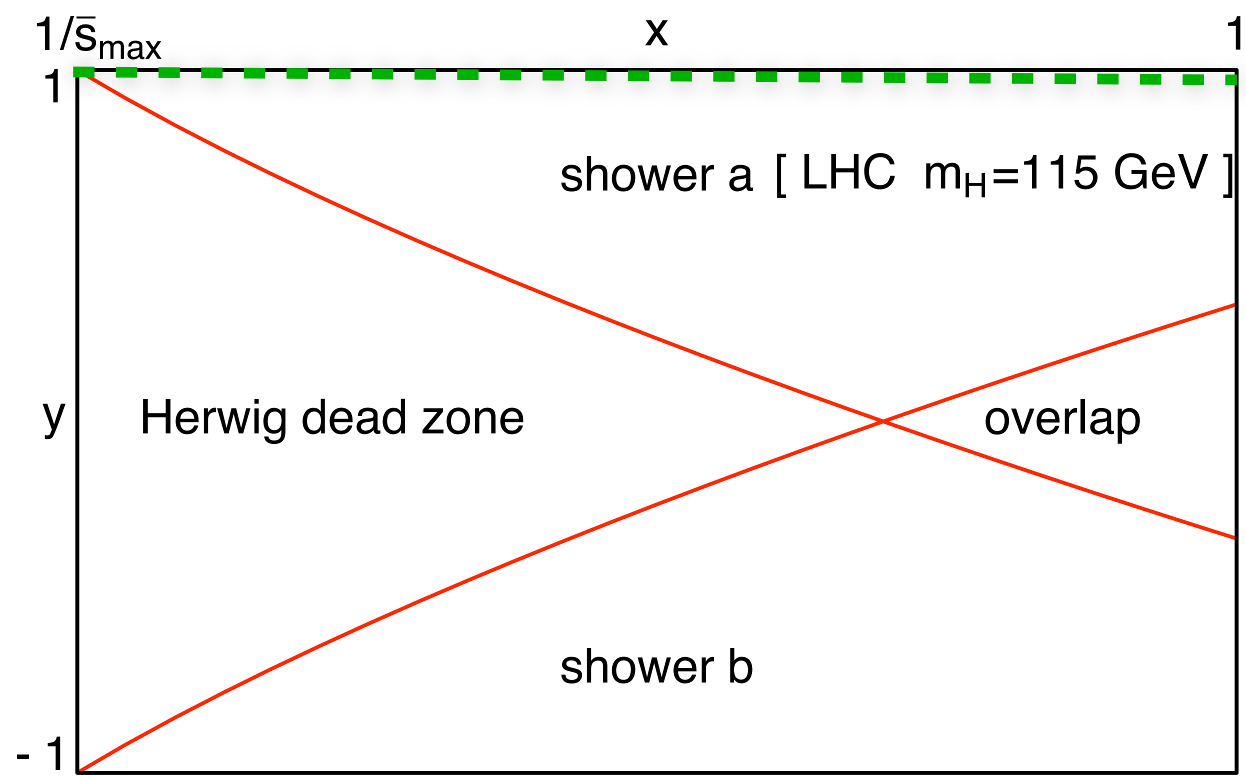

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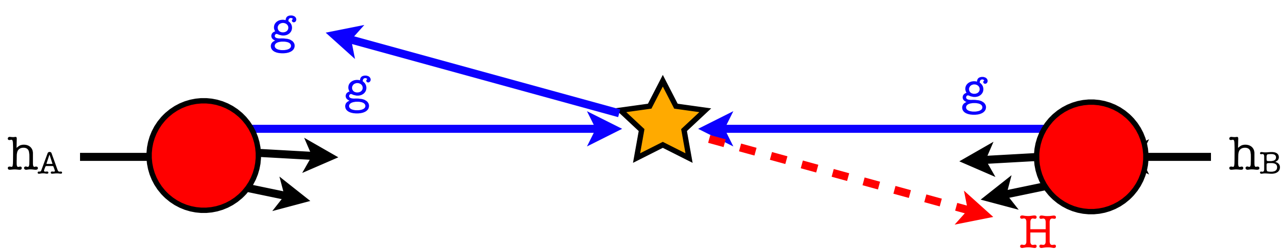

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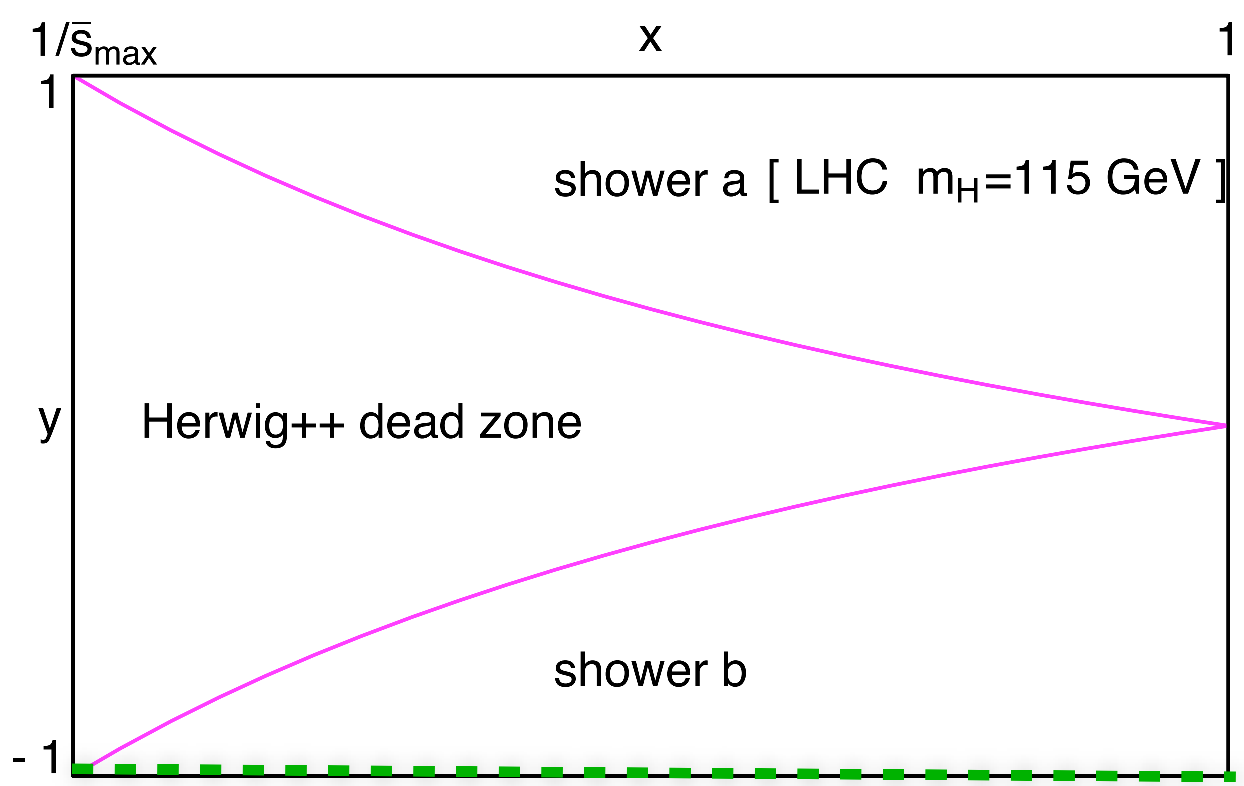

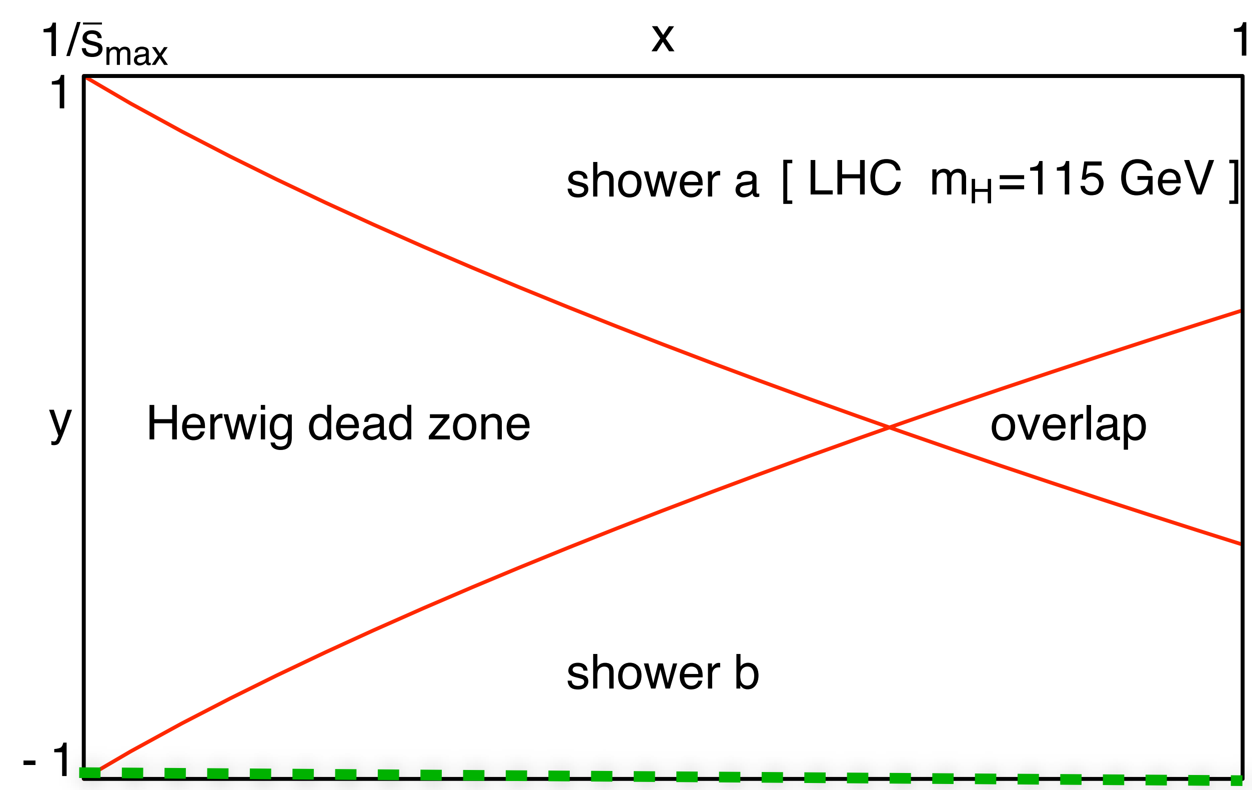

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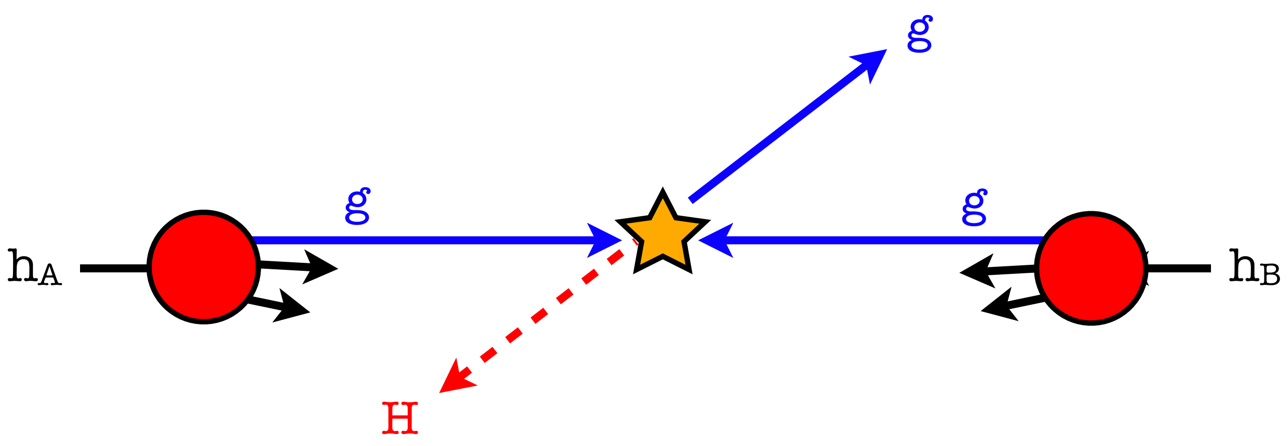

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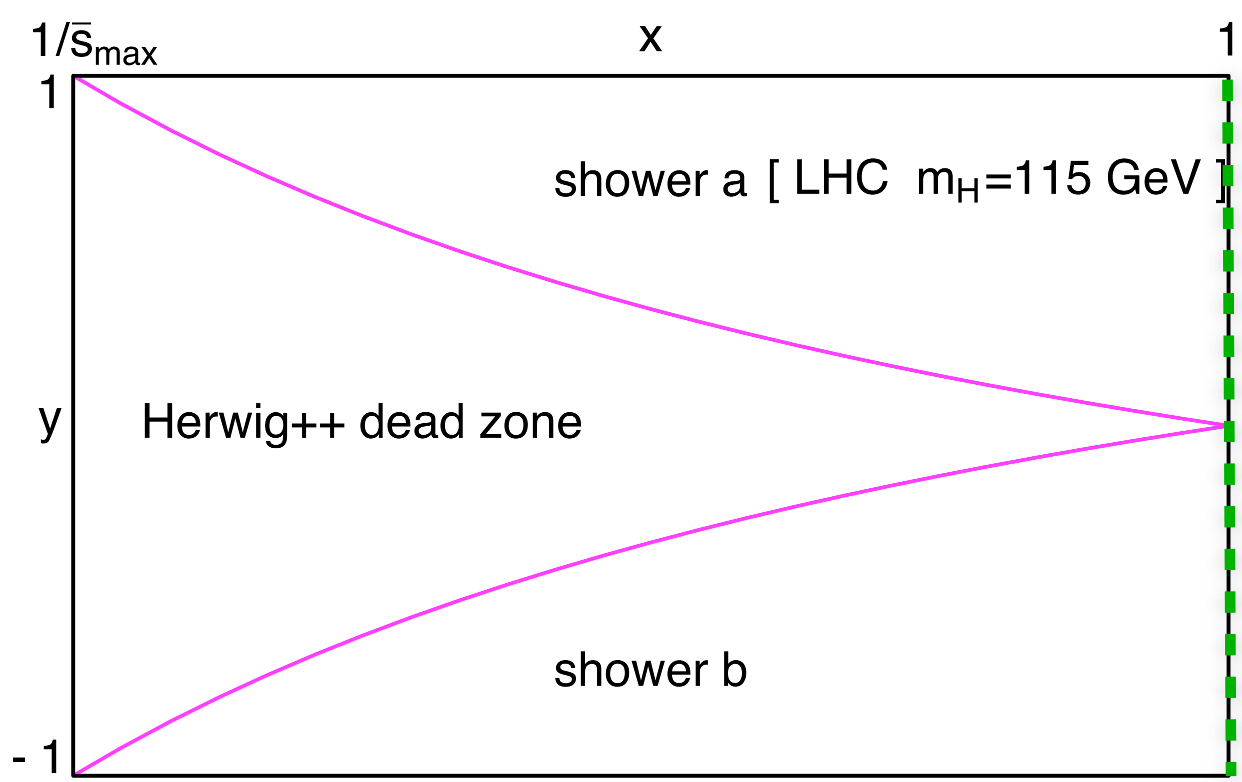

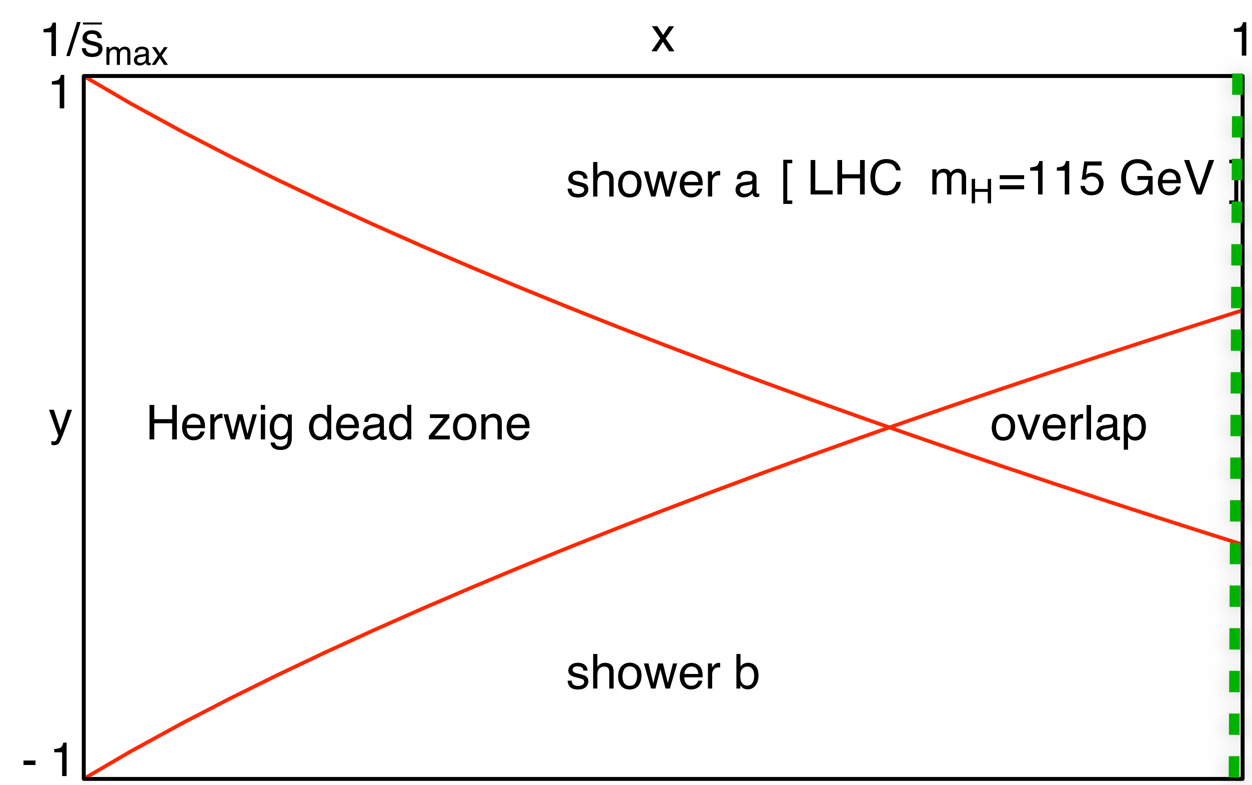

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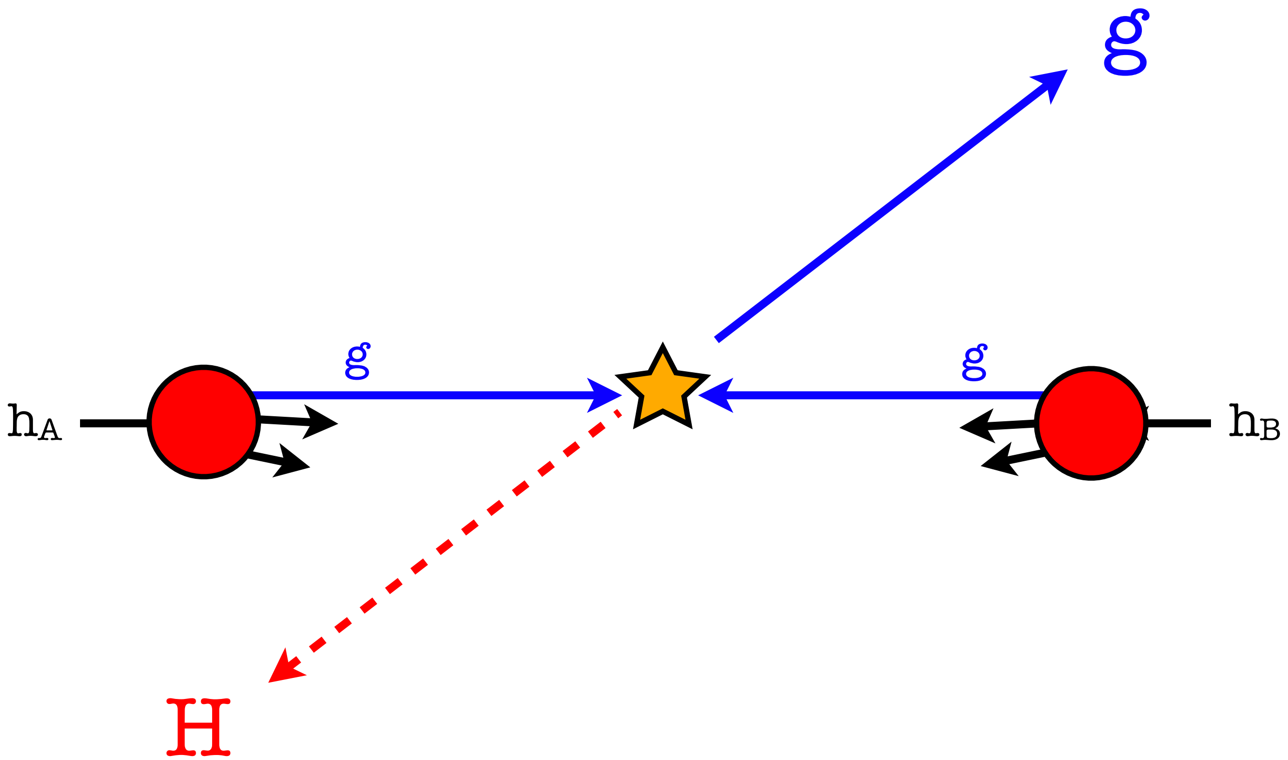

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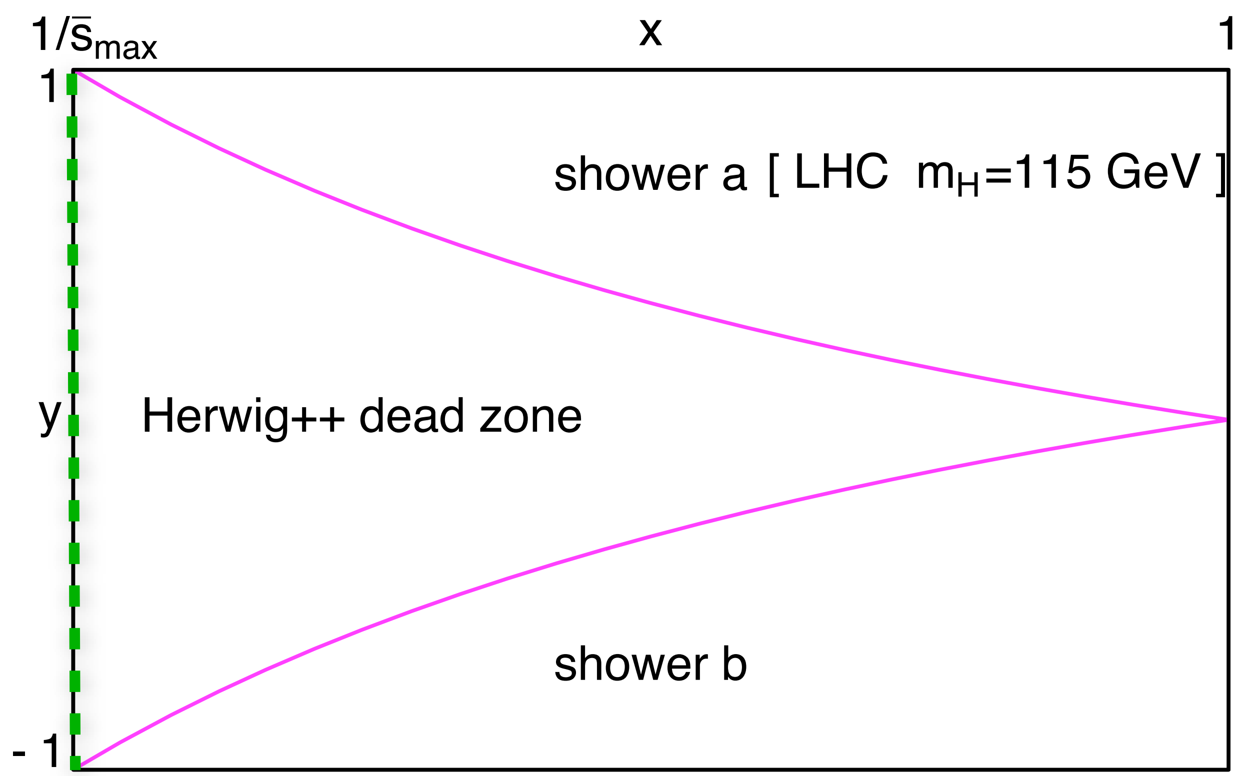
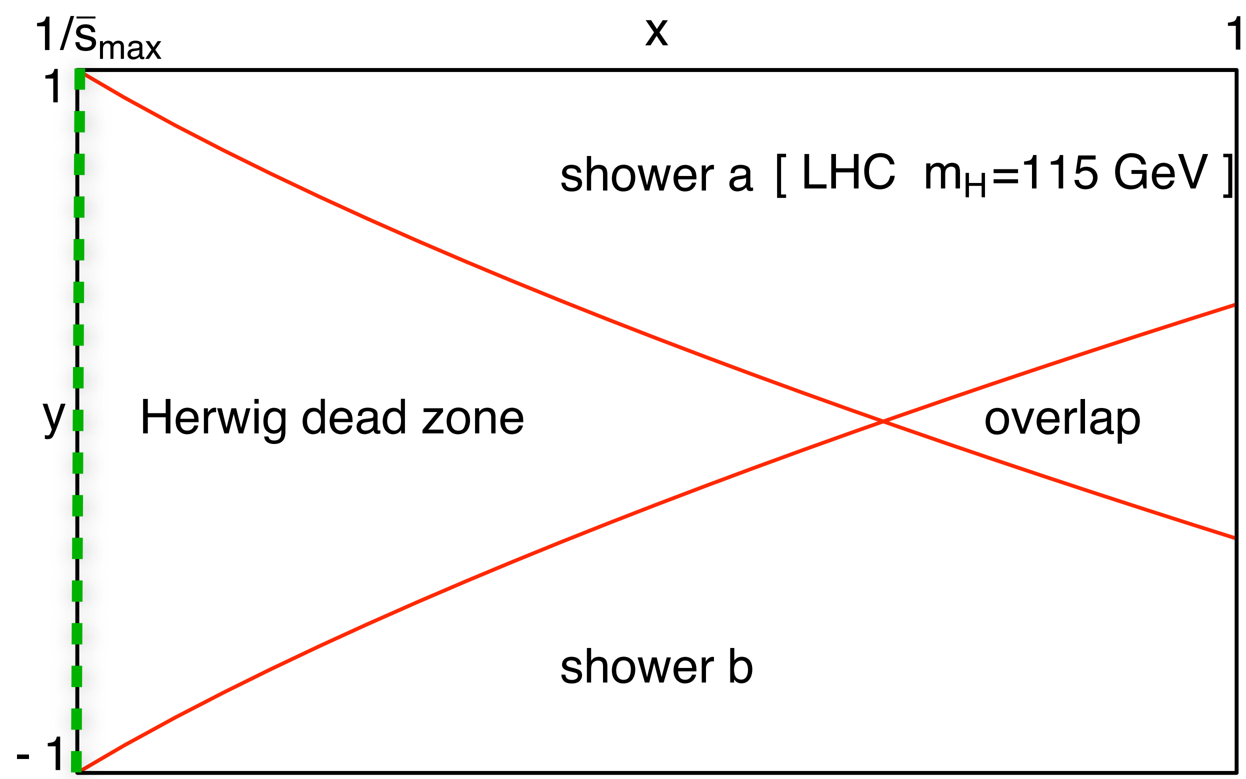




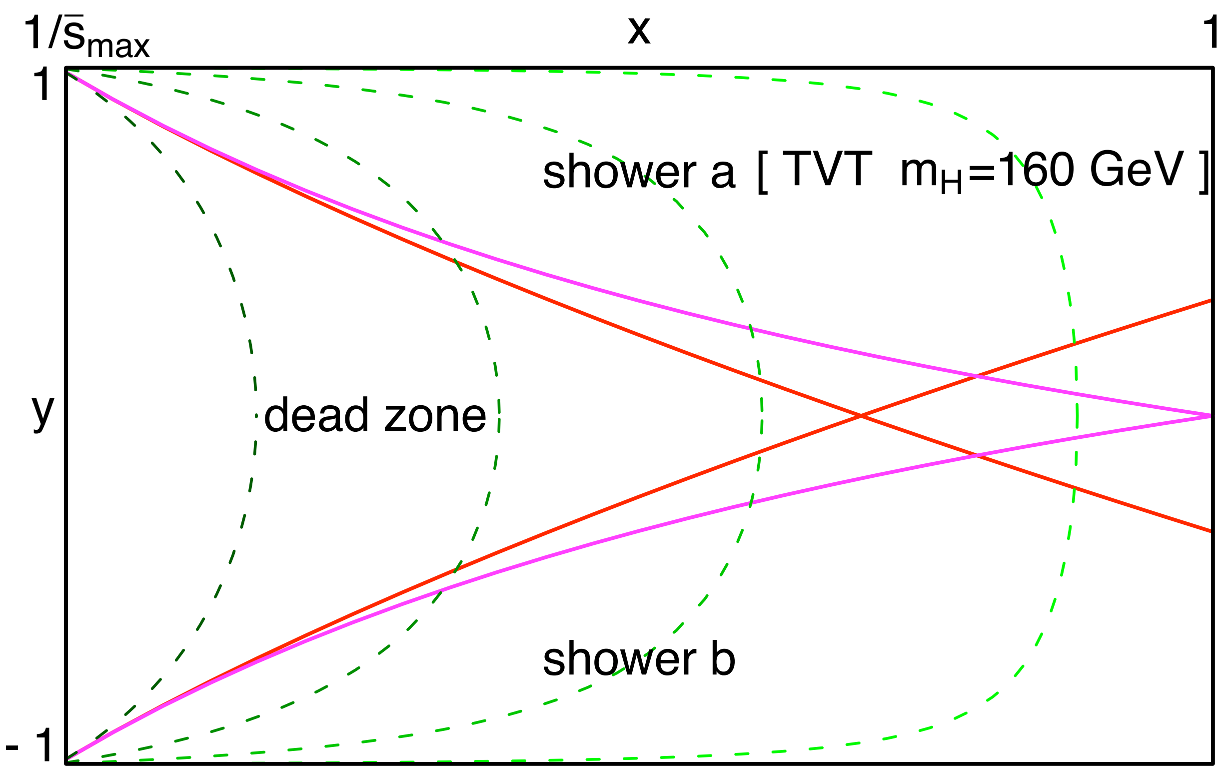
Results: Higgs production via gluon fusion

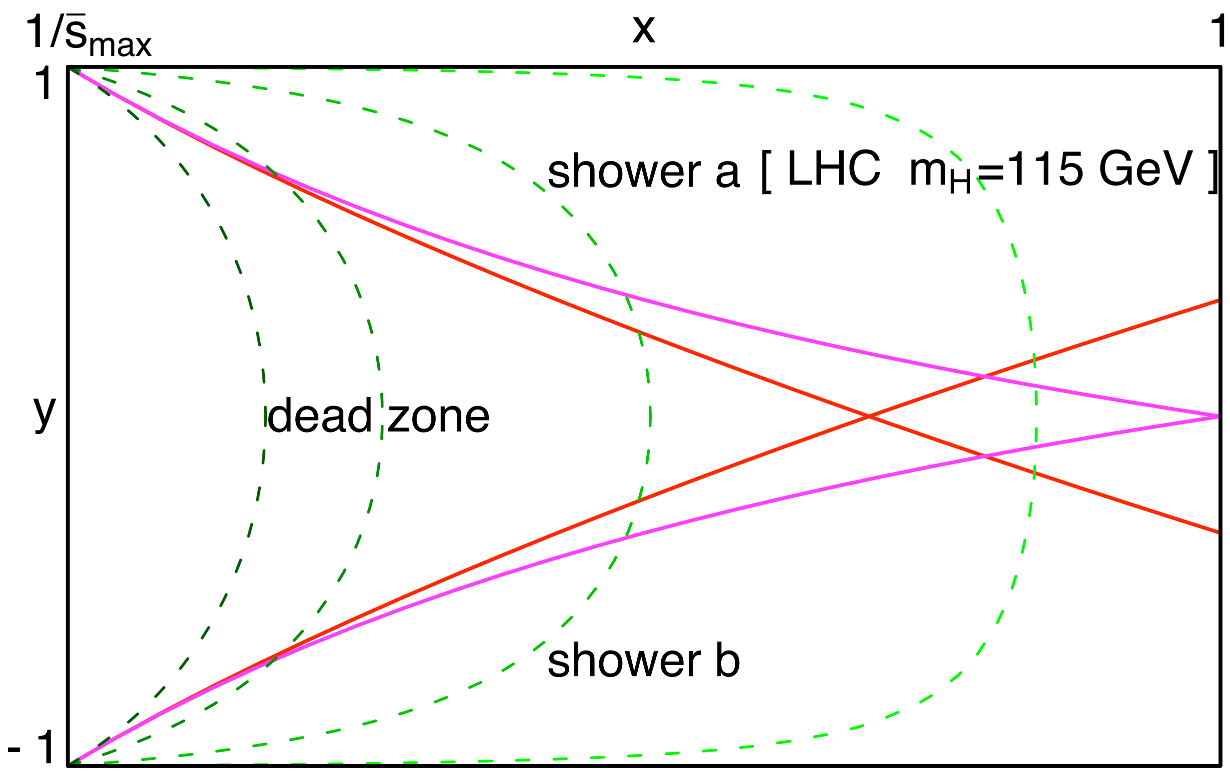
The Dead Zone

- Now we superimpose contours for

$$p_T = m_H \text{ GeV}, 80 \text{ GeV}, 40 \text{ GeV}, 10 \text{ GeV}$$

for a 160 GeV Higgs at the Tevatron and a 115 GeV Higgs at the LHC.





$x = 1 - E_{emitted}/E_{incoming}$

$y = \cos\theta$

- The dead zone is in the region of phase space corresponding to wide angle, high p_T emission of the first radiated parton.

Results: Higgs production via gluon fusion

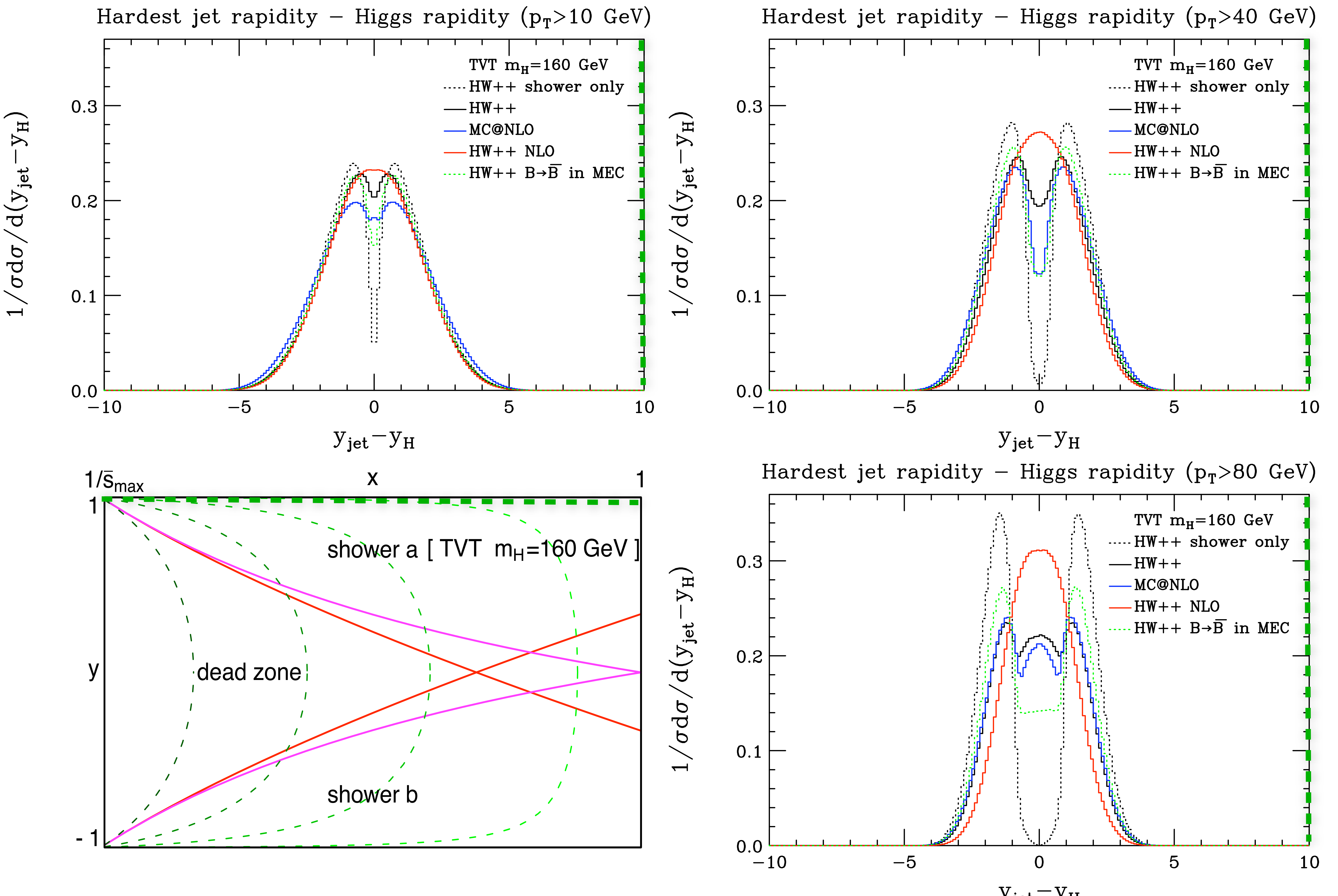
Matrix Element Corrections

- Before the days of MC@NLO and POWHEG we used Matrix Element Corrections (MECs) to fill the dead zone and correct the shower.
- With MECs you get an emission in the dead zone with probability:

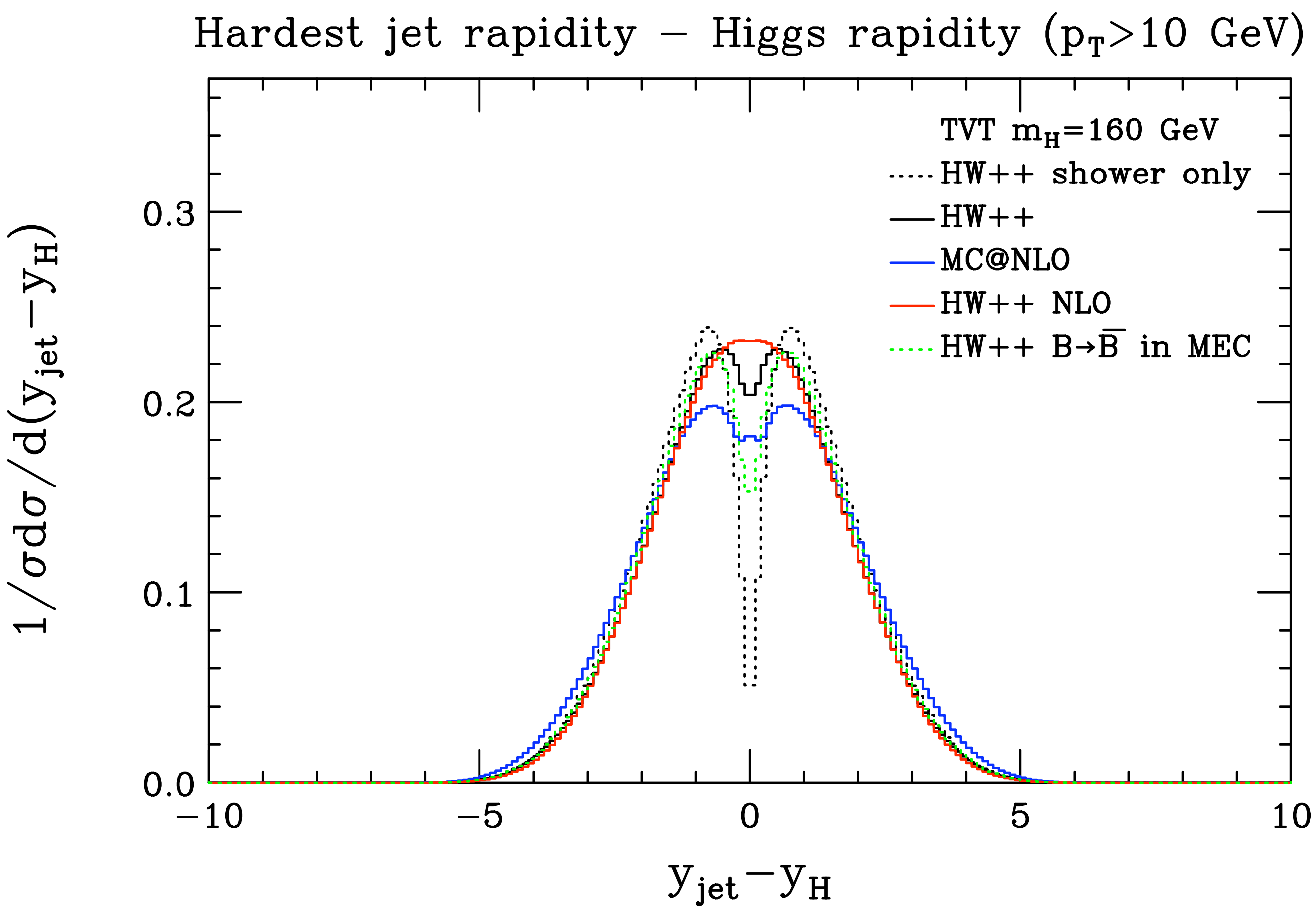
$$\mathcal{P}^{\mathrm{HW}}_{\mathrm{dead}}\left(\Phi_B\right) = \int_{\mathrm{dead}} \mathrm{d}\Phi_R \, \frac{\widehat{R}\left(\Phi_B, \Phi_R\right)}{B\left(\Phi_B\right)}$$

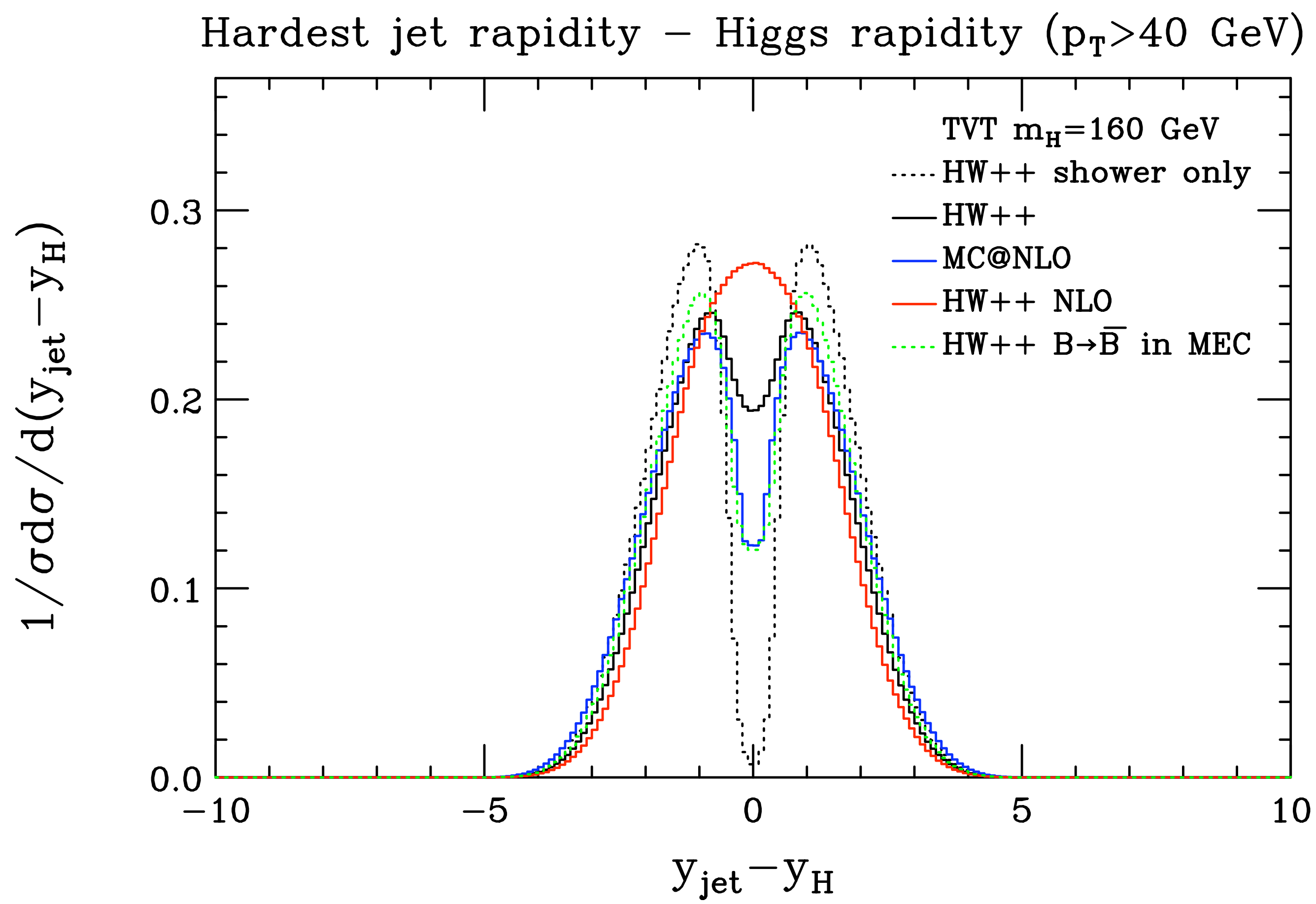
- If an emission occurs in the dead zone it's distributed according to the real emission matrix element with PDFs etc: $\widehat{R}\left(\Phi_B, \Phi_R\right)$
- All this does is correct the shape of distributions sensitive to extra emissions:
  - all normalizations and scale dependencies are as at LO
  - no virtual effects are included at all
- N.B. integrating $\mathcal{P}^{\mathrm{HW}}_{\mathrm{dead}}\left(\Phi_B\right)$ over the Born variables gives the fraction that the dead zone contributes to the NLO x-section, up to terms of order α_S^2.

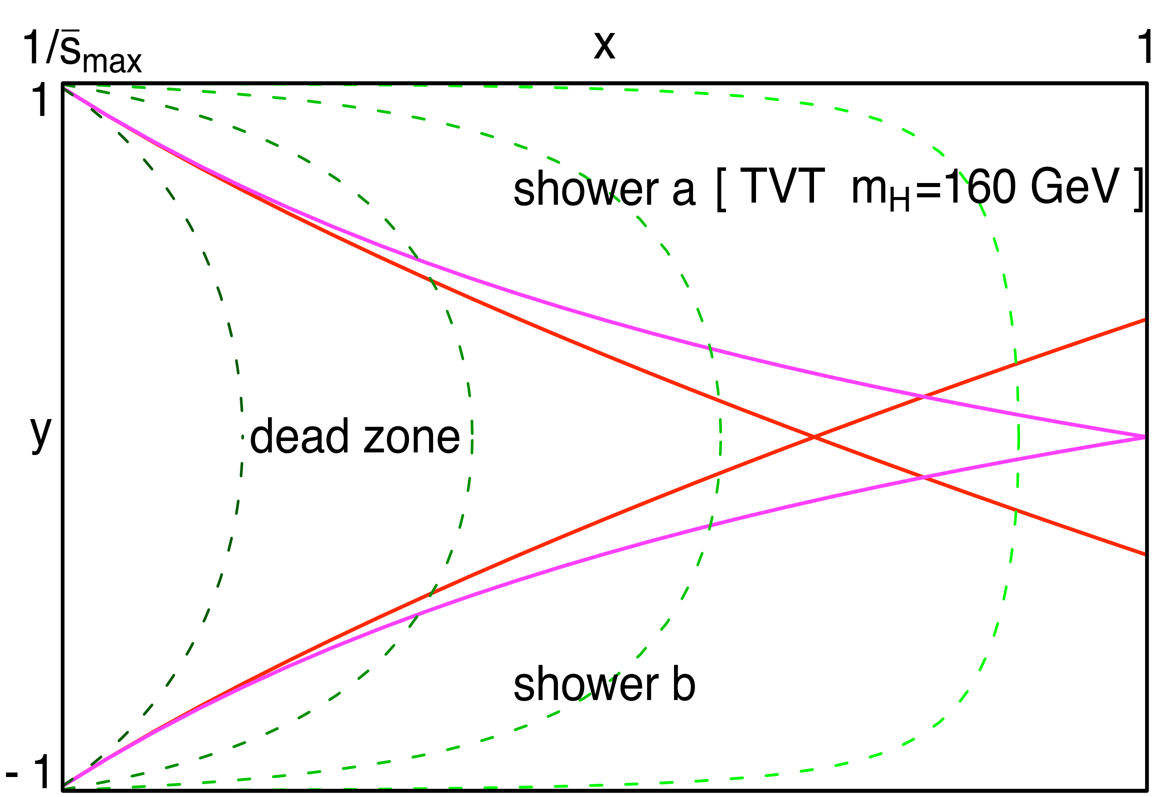
Results: Higgs production via gluon fusion

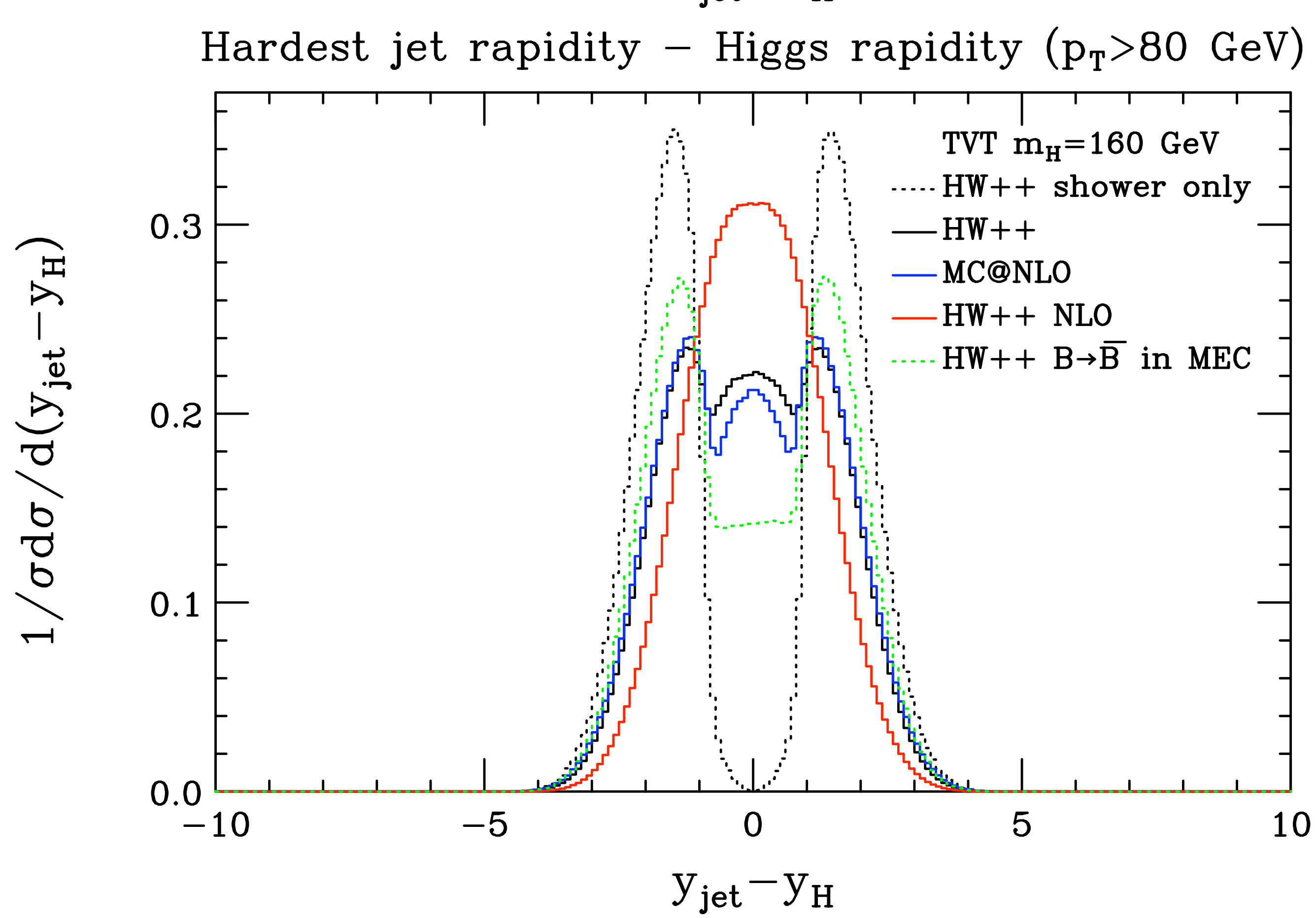


Results: Higgs production via gluon fusion

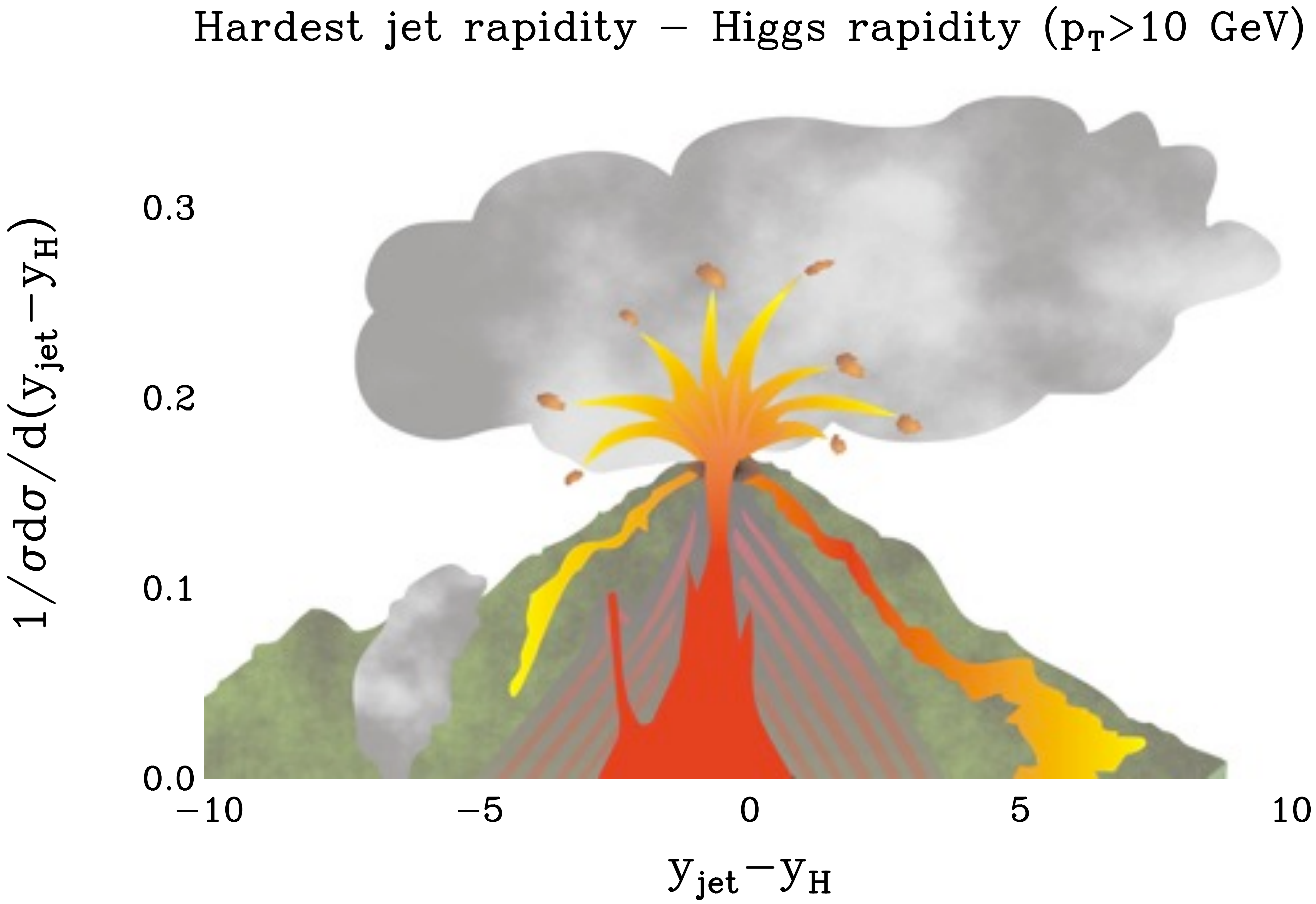


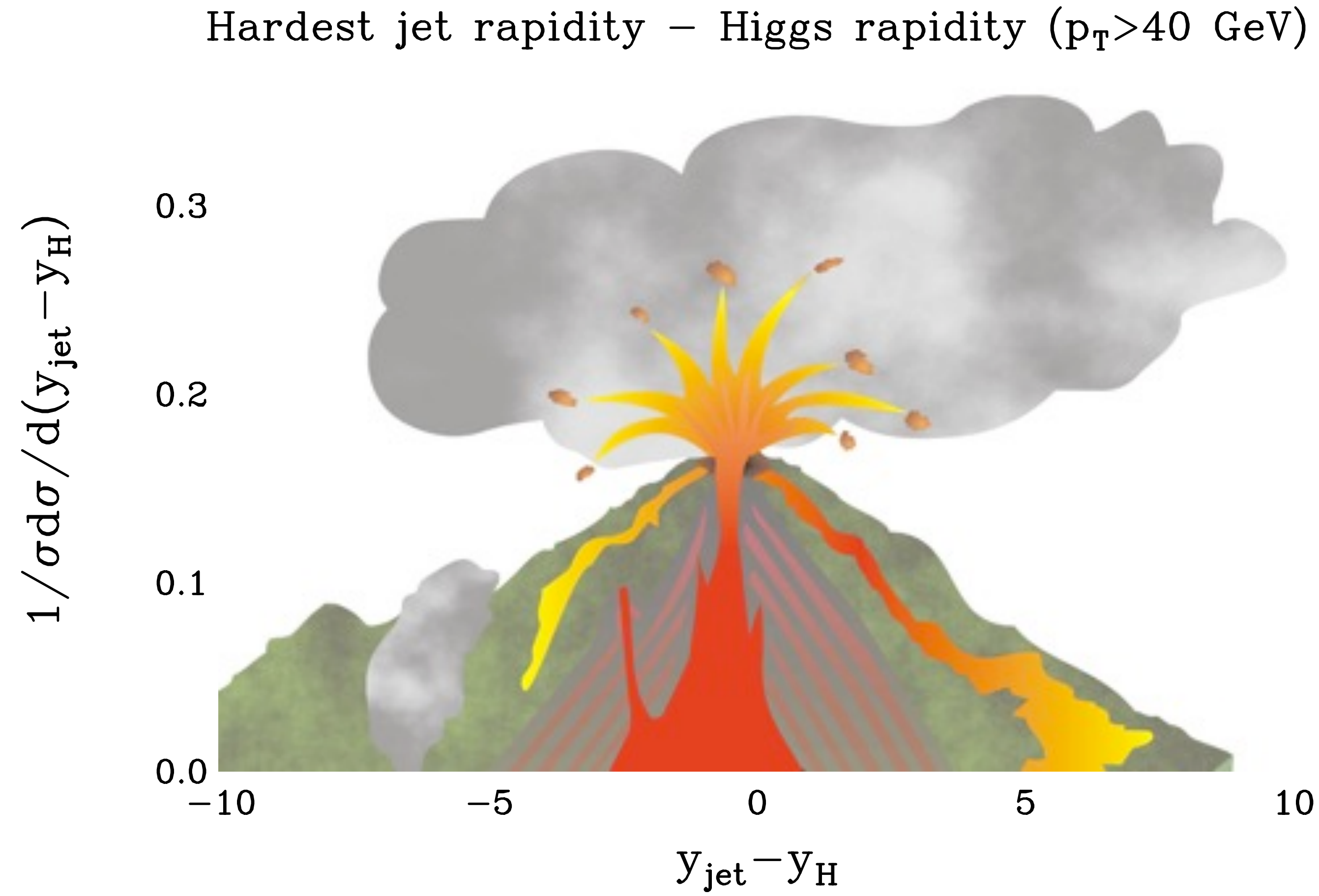


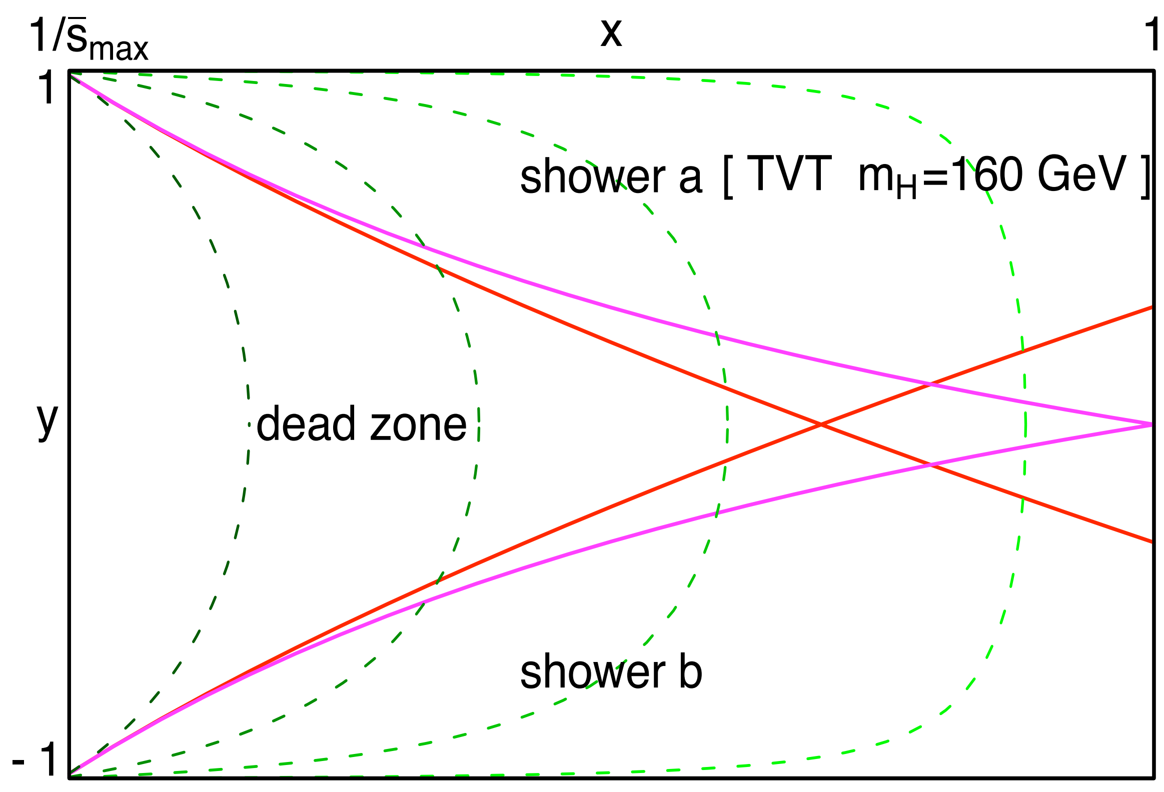


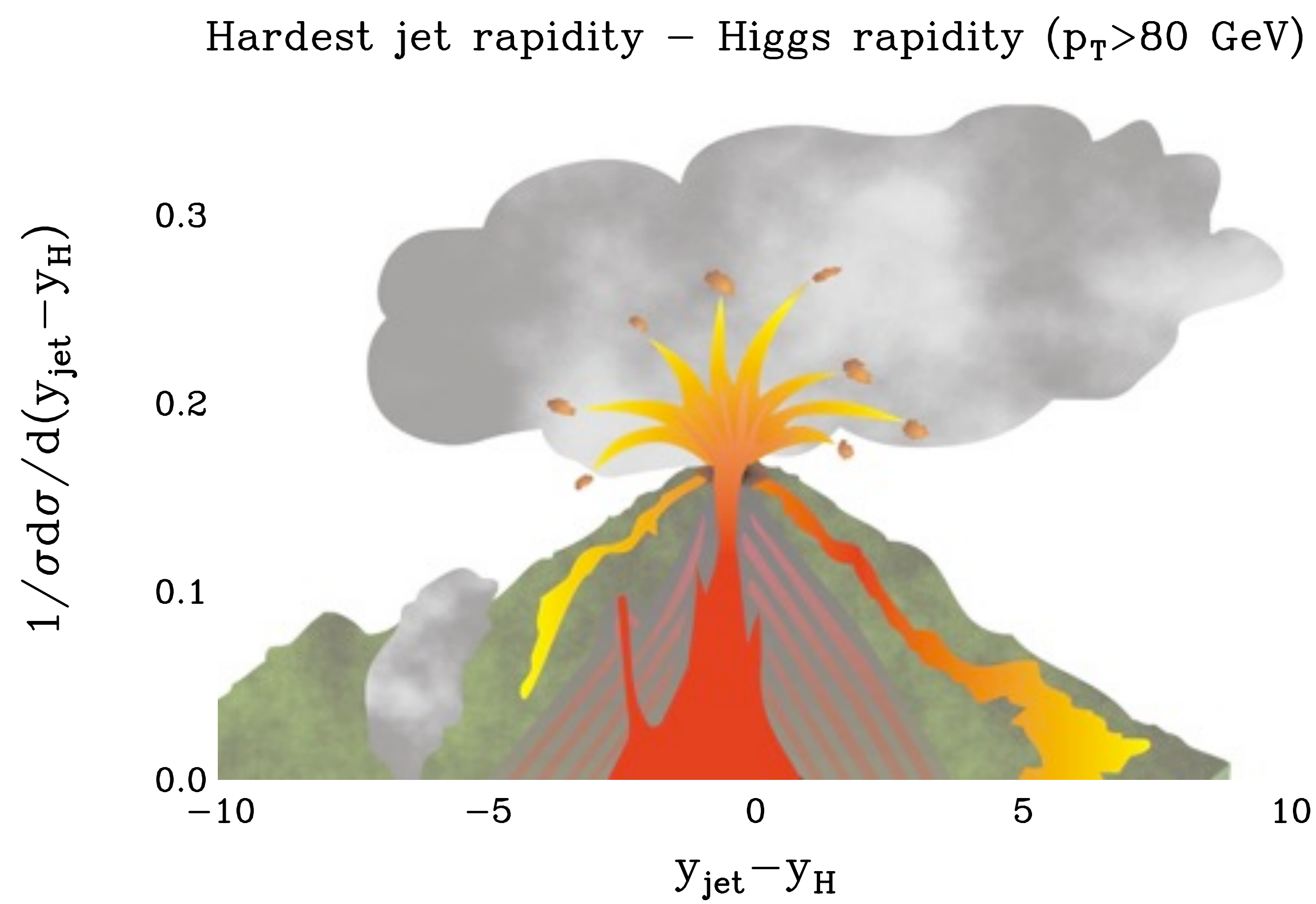


Results: Higgs production via gluon fusion









Results: Higgs production via gluon fusion

Matrix Element Corrections

- In comparing our POWHEG with MC@NLO and the MEC method for this process we also used a modified version of the MEC.
- Only the emission rate (not the shape) in the dead zone was altered:

$$\mathcal{P}_{\mathrm{dead}}^{\mathrm{HW}}\left(\Phi_B\right) \rightarrow \mathcal{P}_{\mathrm{dead}}^{\mathrm{NLO}}\left(\Phi_B\right) = \int_{\mathrm{dead}} \mathrm{d}\Phi_R \, \frac{\widehat{R}\left(\Phi_B, \Phi_R\right)}{\overline{B}\left(\Phi_B\right)}$$

- Reminder: $\overline{B}\left(\Phi_B\right)$ is the NLO differential x-sec integrated over the radiative phase space (x and y).
- Integrating $\mathcal{P}_{\mathrm{dead}}^{\mathrm{NLO}}\left(\Phi_B\right)$ over the remaining Born variables gives the fraction that the dead zone contributes to the NLO x-section exactly.
- This means it should put the same fraction of events in the dead zone as an exact NLO calculation would i.e. the same fraction as MC@NLO.

Results: a word about p_T

- The phase space maps showed that for $p_T > m_n$ all emissions are in the dead zone. So from the MEC they all occur with probability:

$$\mathcal{P}_{m_n}^{\mathrm{HW}}(\Phi_B) = \int_{m_n} \mathrm{d}\Phi_{R_1} \, \frac{\widehat{R}_1(\Phi_B, \Phi_{R_1})}{B(\Phi_B)}$$

- MC@NLO reproduces NLO results so the fraction of emissions it has with $p_T > m_n$ will be the corresponding fraction of the NLO x-sec:

$$\mathcal{P}_{m_n}^{\mathrm{NLO}}(\Phi_B) = \int_{m_n} \mathrm{d}\Phi_{R_1} \, \frac{\widehat{R}_1(\Phi_B, \Phi_{R_1})}{\overline{B}(\Phi_B)}$$

- In POWHEG, the probability that an emission occurs with $p_T > m_n$ is one minus the probability that no emission occurs with $p_T > m_n$:

$$\mathcal{P}_{m_n}^{\mathrm{PH}} = 1 - \Delta_{\hat{R}}(m_n) = \int_{m_n} \mathrm{d}\Phi_{R_1} \, \frac{\widehat{R}_1(\Phi_B, \Phi_{R_1})}{B(\Phi_B)}$$

- Hence: $\mathcal{P}_{m_n}^{\mathrm{HW}} \approx \mathcal{P}_{m_n}^{\mathrm{PH}} \approx \mathcal{K}\,\mathcal{P}_{m_n}^{\mathrm{NLO}}$

Results: a word about p_T

- What would this rate (fraction) be if we had an NNLO calculation?

$$\mathcal{P}_{m_n}^{\mathrm{NNLO}}\left(\Phi_B\right) = \int_{m_n} \mathrm{d}\Phi_{R_1} \left[\widehat{R}_1\left(\Phi_B,\Phi_{R_1}\right) + R_{1+1}\left(\Phi_B,\Phi_{R_1}\right) + \int \mathrm{d}\Phi_{R_2}\, R_2\left(\Phi_B,\Phi_{R_1},\Phi_{R_2}\right)\right]$$
$$\div\ \mathrm{d}\sigma_{\mathrm{NNLO}}\left(\Phi_B\right)$$
$$= \int_{m_n} \mathrm{d}\Phi_{R_1} \frac{\widehat{R}_1\left(\Phi_B,\Phi_{R_1}\right)}{B\left(\Phi_B\right)} \left[1 - \frac{\overline{B}\left(\Phi_B\right)}{B\left(\Phi_B\right)} + \frac{\overline{R}_1\left(\Phi_B,\Phi_{R_1}\right)}{\widehat{R}_1\left(\Phi_B,\Phi_{R_1}\right)}\right]$$

where

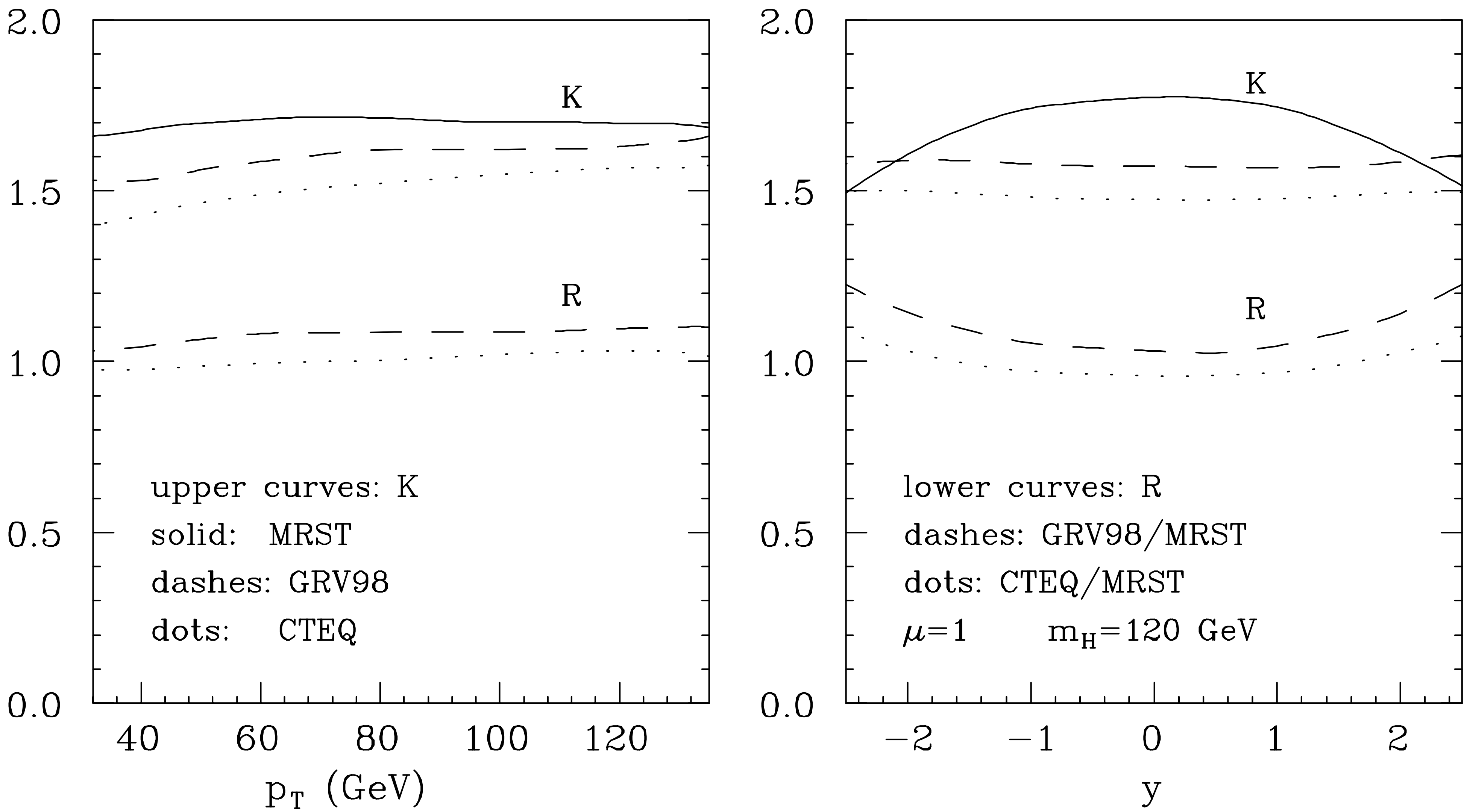
$$\overline{R}_1\left(\Phi_B,\Phi_{R_1}\right) = \widehat{R}_1\left(\Phi_B,\Phi_{R_1}\right) + R_{1+1}\left(\Phi_B,\Phi_{R_1}\right) + \int \mathrm{d}\Phi_{R_2}\, R_2\left(\Phi_B,\Phi_{R_1},\Phi_{R_2}\right)$$

- Now $\frac{\overline{B}\left(\Phi_B\right)}{B\left(\Phi_B\right)}$ and $\frac{\overline{R}_1\left(\Phi_B,\Phi_{R_1}\right)}{\widehat{R}_1\left(\Phi_B,\Phi_{R_1}\right)}$ are basically differential K-factors for e.g. in the case of gluon fusion, gg→H and gg→H+jet respectively

Results: a word about p_T

- Now it turns out that the NLO K-factors for gg→H and gg→H+jet are very similar ≈ 1.6/1.7:

Grazzini, Kunszt, De Florian PRL 82 [1999]



gg→H+jet

pp, $\sqrt{S}$ = 14 TeV

m_H = 120 GeV

- And they are fairly insensitive to the kinematics too! This is because the large contribution to the cross section are due to soft emissions and these don't alter the LO / NLO kinematics too much.

Results: a word about p_T

- So one should really expect the final two terms in the NNLO emission rate to basically cancel each other out!

$$\mathcal{P}_{m_n}^{\mathrm{NNLO}}\left(\Phi_B\right) = \int_{m_n} \mathrm{d}\Phi_{R_1} \left[\widehat{R}_1\left(\Phi_B,\Phi_{R_1}\right) + R_{1+1}\left(\Phi_B,\Phi_{R_1}\right) + \int \mathrm{d}\Phi_{R_2}\, R_2\left(\Phi_B,\Phi_{R_1},\Phi_{R_2}\right)\right]$$
$$\div\ \mathrm{d}\sigma_{\mathrm{NNLO}}\left(\Phi_B\right)$$
$$= \int_{m_n} \mathrm{d}\Phi_{R_1} \frac{\widehat{R}_1\left(\Phi_B,\Phi_{R_1}\right)}{B\left(\Phi_B\right)} \left[1 - \frac{\overline{B}\left(\Phi_B\right)}{B\left(\Phi_B\right)} + \frac{\overline{R}_1\left(\Phi_B,\Phi_{R_1}\right)}{\widehat{R}_1\left(\Phi_B,\Phi_{R_1}\right)}\right]$$

where

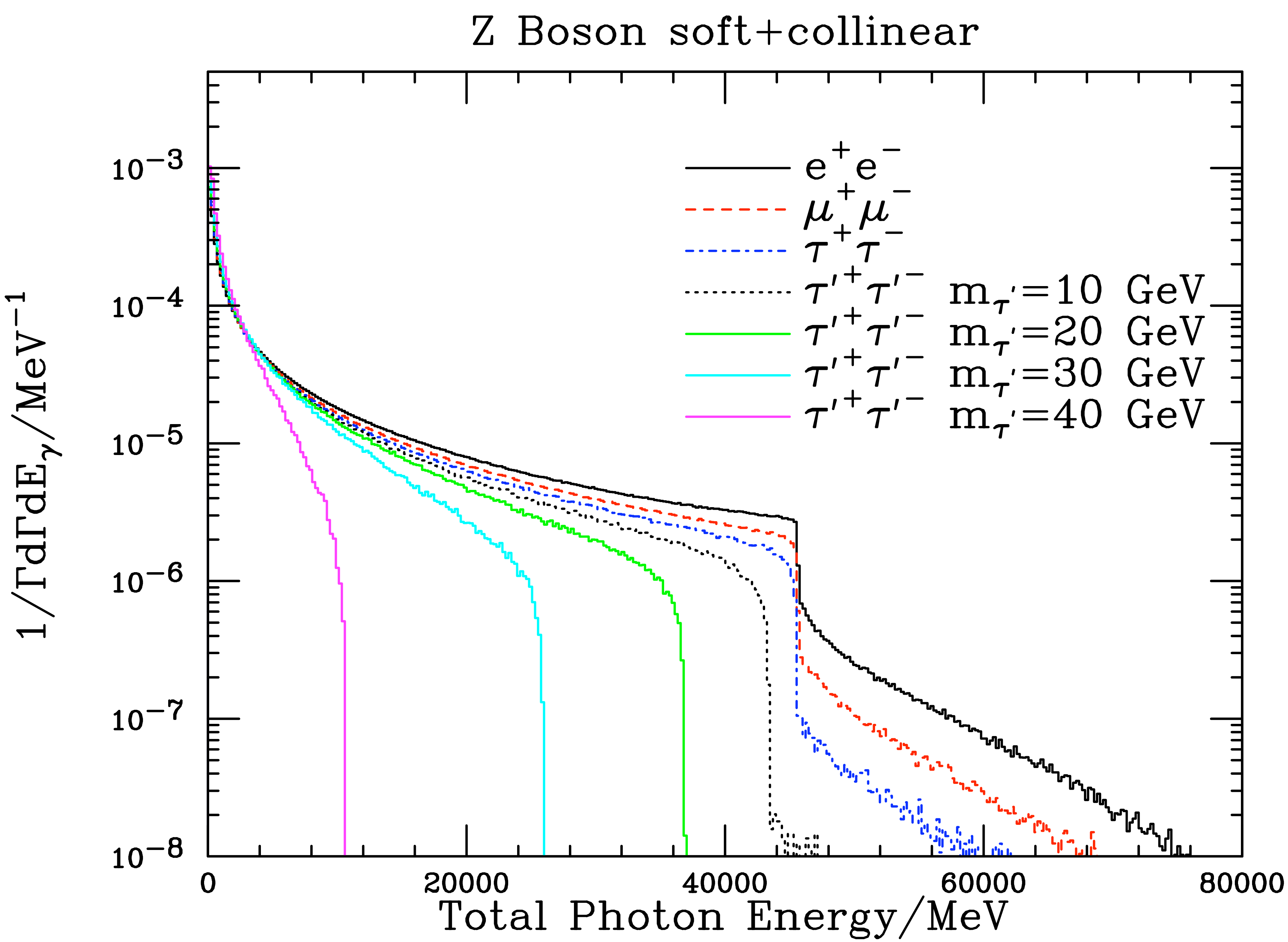
$$\overline{R}_1\left(\Phi_B,\Phi_{R_1}\right) = \widehat{R}_1\left(\Phi_B,\Phi_{R_1}\right) + R_{1+1}\left(\Phi_B,\Phi_{R_1}\right) + \int \mathrm{d}\Phi_{R_2}\, R_2\left(\Phi_B,\Phi_{R_1},\Phi_{R_2}\right)$$

- And that then makes:

$$\mathcal{P}_{m_n}^{\mathrm{NNLO}}\left(\Phi_B\right) = \int_{m_n} \mathrm{d}\Phi_{R_1} \frac{\widehat{R}_1\left(\Phi_B,\Phi_{R_1}\right)}{B\left(\Phi_B\right)}$$
$$\approx \mathcal{P}_{m_n}^{\mathrm{HW}} \approx \mathcal{P}_{m_n}^{\mathrm{PH}} \approx \mathcal{K}\,\mathcal{P}_{m_n}^{\mathrm{NLO}}$$

Results: QED radiation in the decay [Sophty]

Total photon energy radiated in Z decays



Each line corresponds to a different pair of charged leptons.
The lowest / innermost lines are for some fictional 'heavy leptons'.