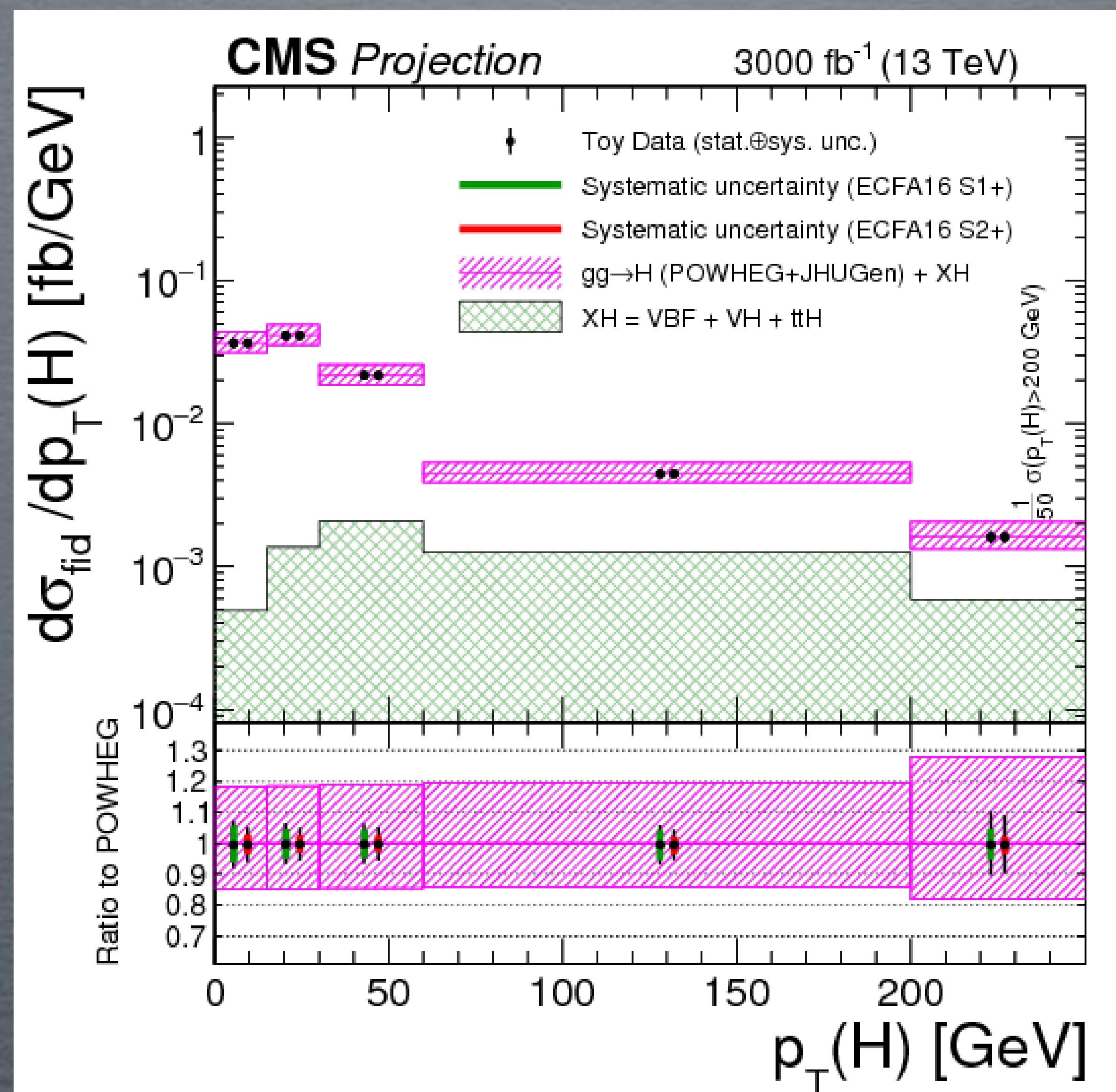
QCD for HL-LHC and beyond



Andrea Banfi

University of Sussex

HL-LHC 2018 - 3 July 2018 – IPPP Durham

Outline

Concentrate on a few case studies relevant to discovery physics

- Perturbative QCD and Higgs characterisation
- BSM effects in loops: Higgs p_T distribution
- Jet-veto effects in WW production
- Boosted object searches

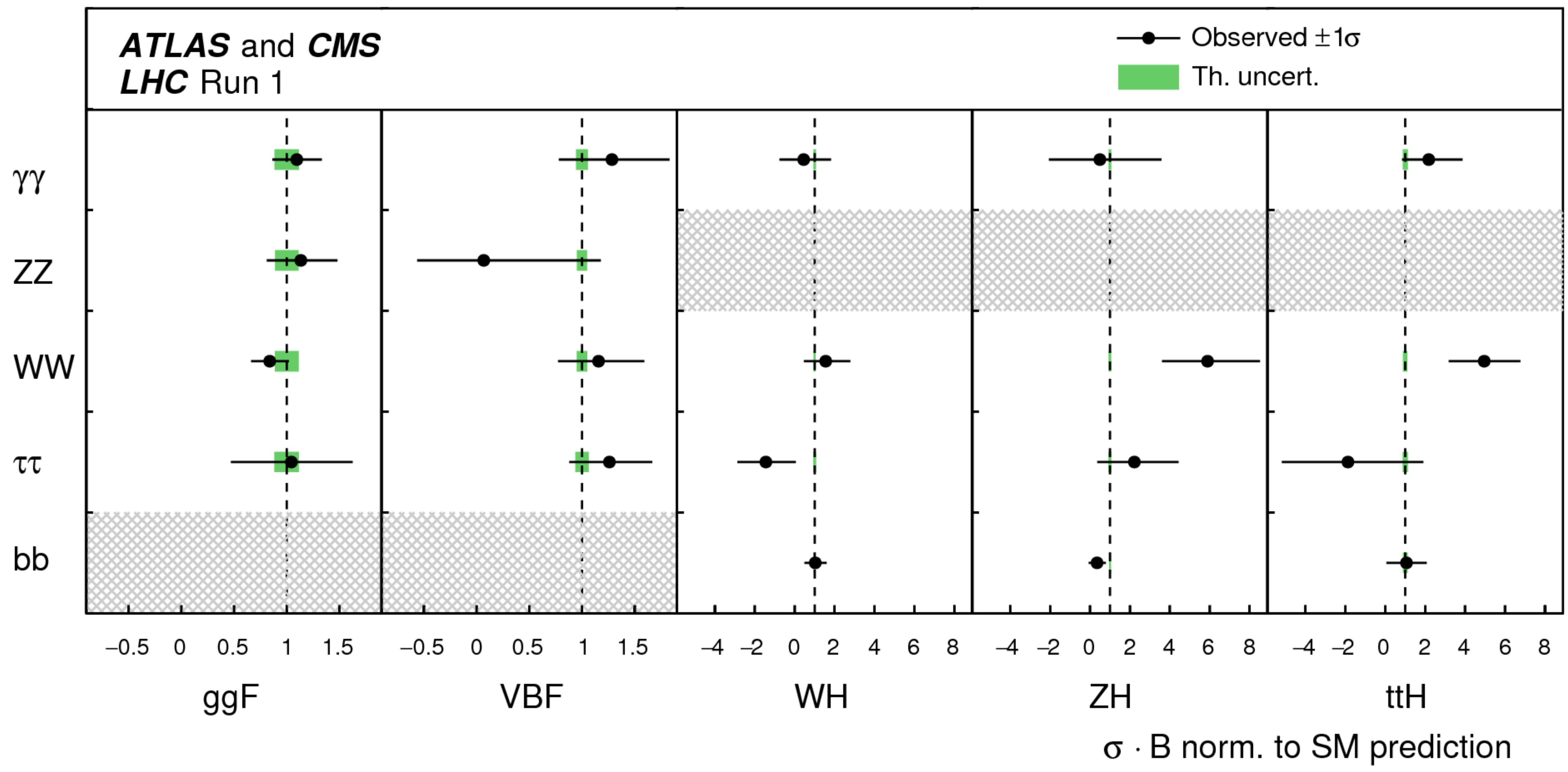
Important left-over topics, that however share similarities with the above

- Top quark production
- Double Higgs productions

Higgs characterisation at LHC

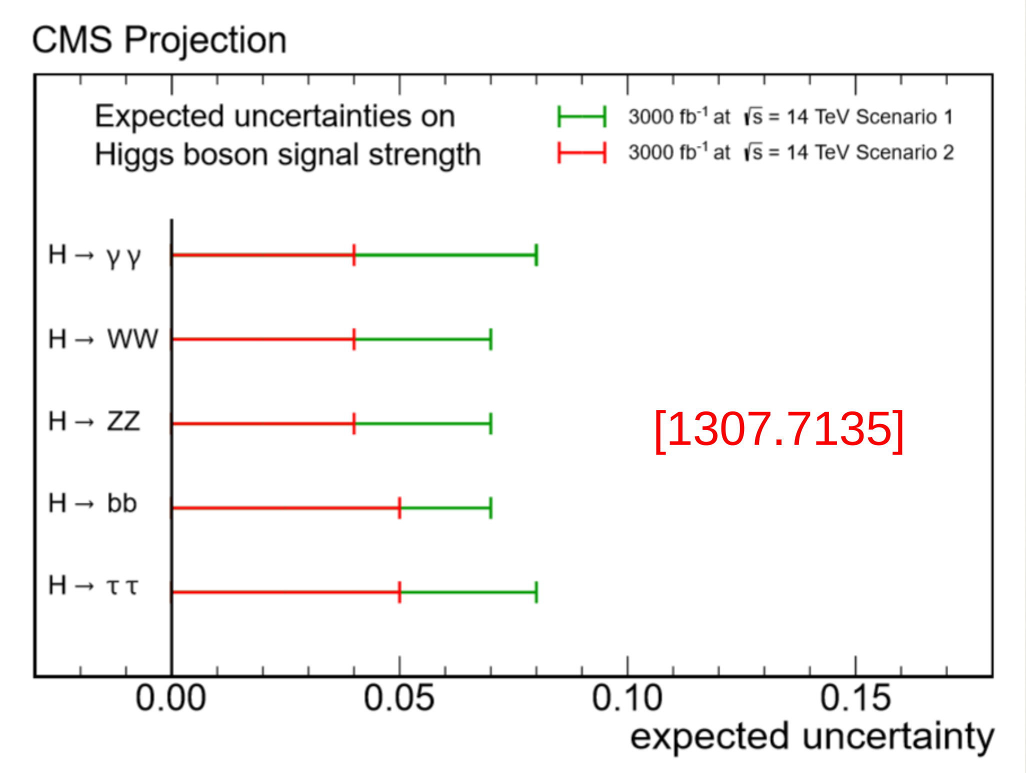
So far, current characterisations of the Higgs boson are dominated by experimental uncertainties, so theory uncertainties play a limited role

[1606.02266]



Higgs characterisation at HL-LHC

- HL-LHC gives promise to reduce experimental uncertainty to 5%
- Theory sensitivity larger for ggH and ttH
- Focus on gluon fusion, but similar remarks hold for other channels and other processes



[ATL-PHYS-PUB-2014-016]	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
κ_Z	8.1%	7.9%	7.9%	4.4%	4.0%	3.8%
κ_W	9.0%	8.7%	8.6%	5.1%	4.5%	4.2%
κ_t	22%	21%	20%	11%	8.5%	7.6%
κ_b	23%	22%	22%	12%	11%	10%
κ_τ	14%	14%	13%	9.7%	9.0%	8.8%
κ_μ	21%	21%	21%	7.5%	7.2%	7.1%
κ_g	14%	12%	11%	9.1%	6.5%	5.3%
κ_γ	9.3%	9.0%	8.9%	4.9%	4.3%	4.1%
$\kappa_{Z\gamma}$	24%	24%	24%	14%	14%	14%

Perturbative QCD

$\sim g_s$

$\mathcal{O}(\alpha_s^2)$ LO

$\sim g_s$

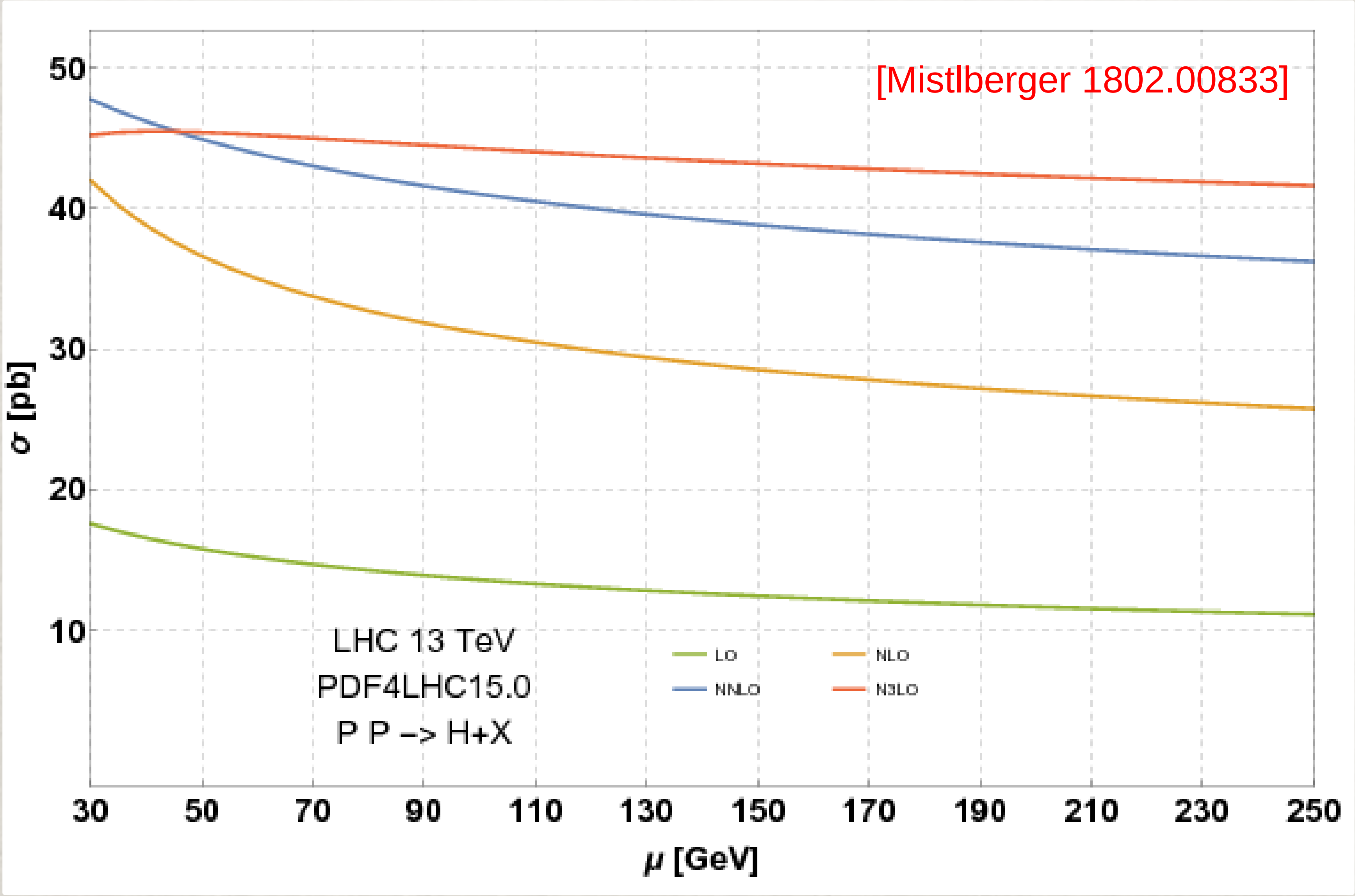
$\mathcal{O}(\alpha_s^3)$ NLO

$\mathcal{O}(\alpha_s^4)$ NNLO

Production of numerically stable results requires also clever methods to achieve cancellation of infrared singularities between real and virtual corrections

QCD is strong interactions

- Many QCD cross sections converge slowly $\Rightarrow$ need to go to high perturbative order to have theoretical control

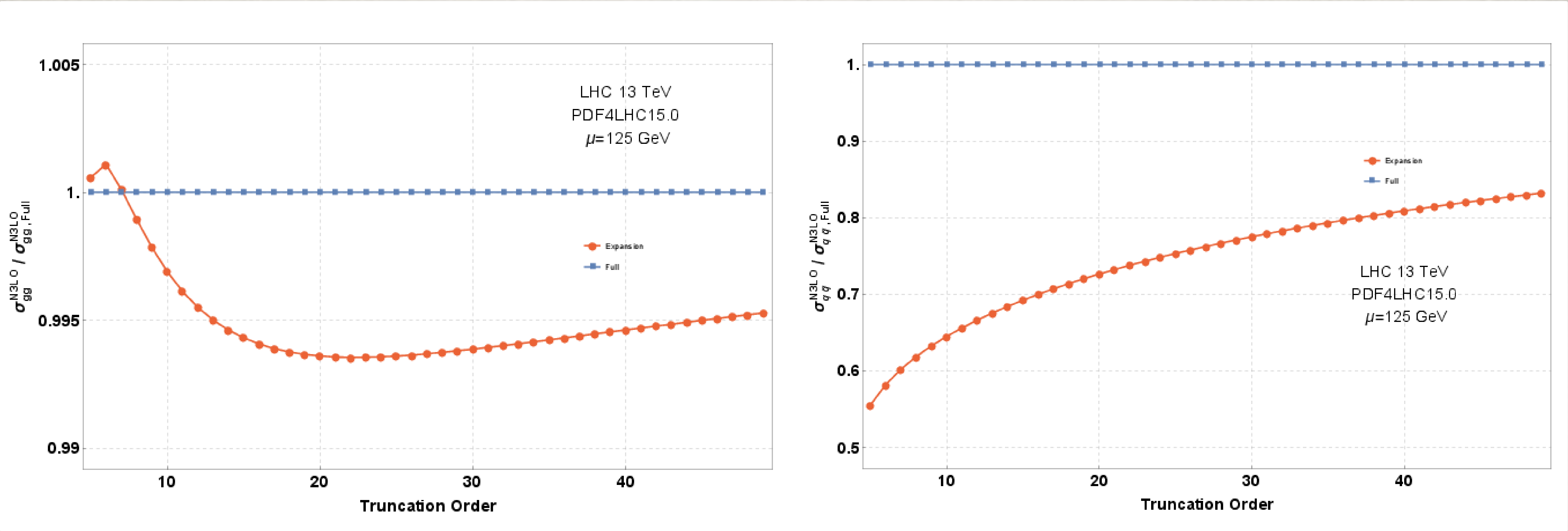


- Key to such accuracy: all loop integrals involve massless propagators

THE HIGGS TOTAL CROSS SECTION

- Exact calculation in the limit of infinite top mass (HEFT) significantly different with respect to threshold expansion in quark channels

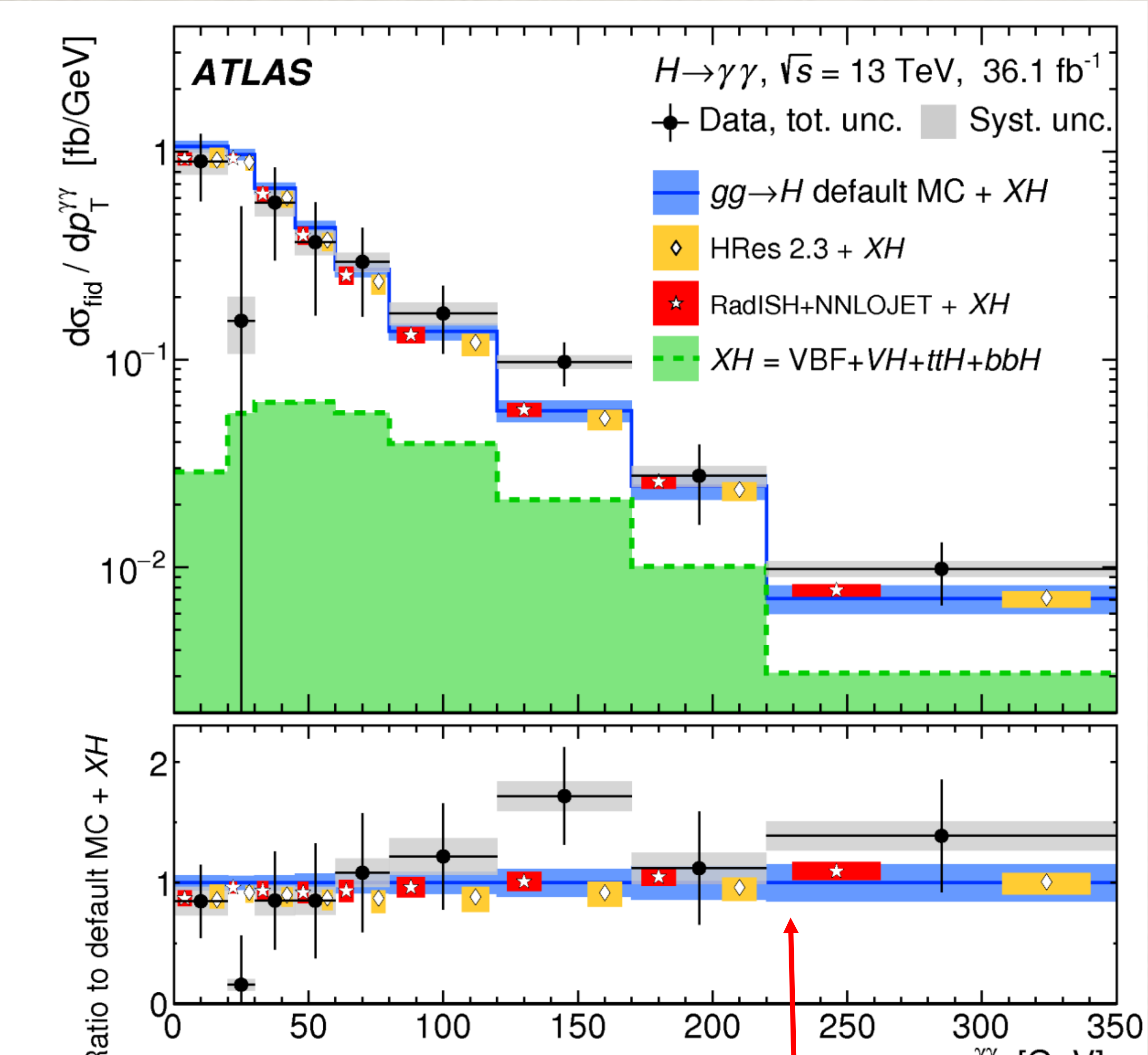
[Mistlberger 1802.00833]



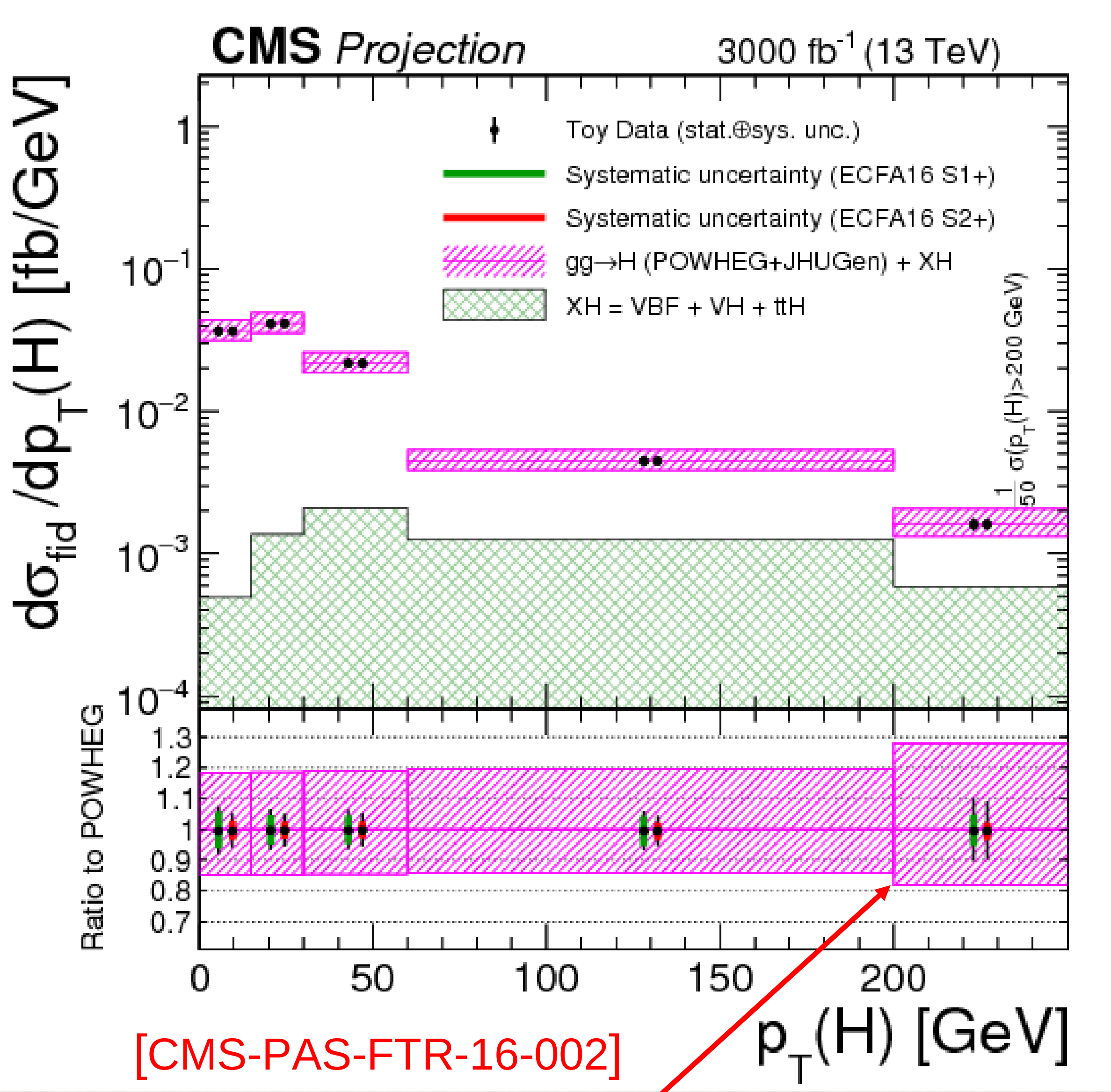
- All relevant massless integrals for 2→1 processes at N^3LO known possibility of achieving 0.1% accuracy in DY total cross section

Differential cross sections

- In differential cross section, experimental error is close to theory error
- Experimental error will shrink with higher luminosity and energy



[1802.04146]



[CMS-PAS-FTR-16-002]

high-p_T region, sensitive to new physics

Higgs p_T distribution

The Higgs p_T distribution presents various difficulties arising in many differential cross sections

- At high p_T one cannot use the HEFT limit, but needs to account for exact top-mass dependence in loops [Jones Kerner Luisoni 1802.00349]
- At small p_T we find large logarithms $\ln(m_H/p_T)$ that need to be resummed at all orders [Chen et al 1805.00736] [Bizon et al 1805.05916]
- Non-negligible shape distortions due to interference effects of amplitudes with top and bottom or charm quarks [Caola et al 1804.07632]
- New logarithms $\ln(p_T/m)$, where m is the mass of a quark running in loops, that can potentially become large both at high and at low p_T [Grazzini Sargsyan 1306.4581] [AB Monni Zanderighi 1308.4634]

Higgs at high p_T

- New physics can give an extra ggH contact interaction

$$\mathcal{L} \supset -\kappa_t \frac{m_t}{v} h\bar{t}t + \kappa_g \frac{\alpha_s}{12\pi}\frac{h}{v} G^a_{\mu\nu} G_a^{\mu\nu}$$

$$\sim (\kappa_t + \kappa_g)$$

- In many new physics models (e.g. composite Higgs) $\kappa_t + \kappa_g = 1 \Rightarrow$ no information on BSM from Higgs total cross section

Higgs at high p_T

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$$\mathcal{L} \supset -\kappa_t \frac{m_t}{v} h\bar{t}t + \kappa_g \frac{\alpha_s}{12\pi} \frac{h}{v} G^a_{\mu\nu} G^{\mu\nu}_a$$

$$\kappa_t \times \frac{4m_t^2}{p_T^2} + \kappa_g$$

- Break top loop using an extra gluon $\Rightarrow$ Higgs at high p_T

[AB Martin Sanz 1308.4771]

[Azatov Paul 1309.5273]

[Grojean Salvioni Schlaffer Weiler 1308.4771]

Higgs at high p_T

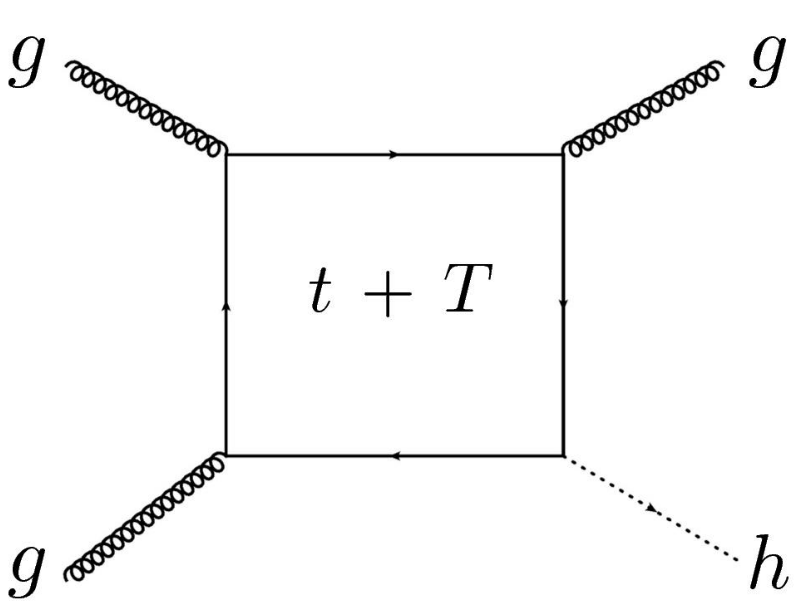
- Example: the Higgs (or jet) p_T spectrum shows significant deviations from the SM at high p_T in the presence of a top partner with $M_T \gg m_t$

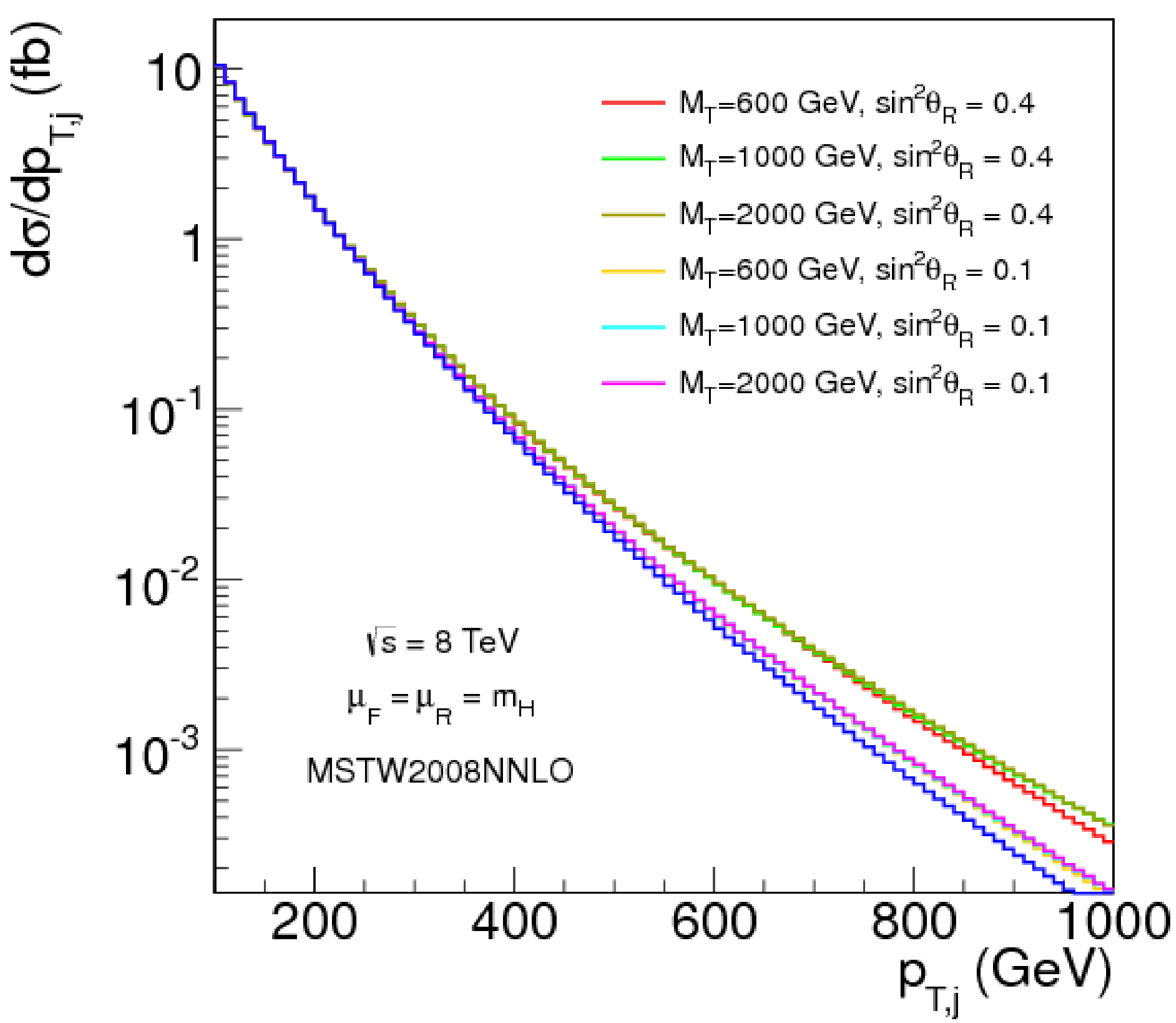
[AB Martin Sanz 1308.4771]

T-t mixing angle

$$\kappa_t = \cos^2\theta_R$$

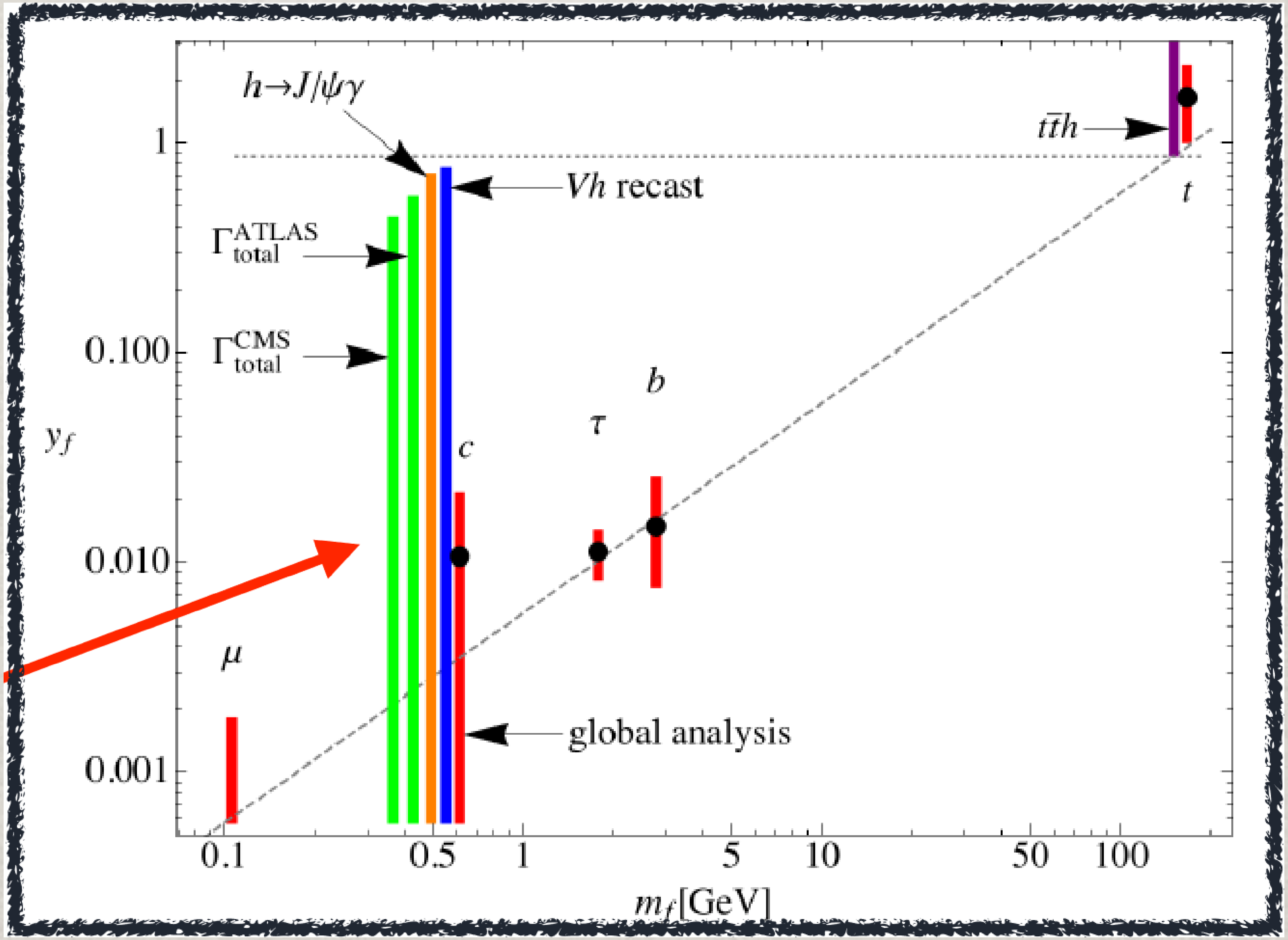
$$\kappa_g = \sin^2\theta_R$$





Charm Yukawa coupling

- Couplings to 2nd (and 1st) generation are very difficult to access

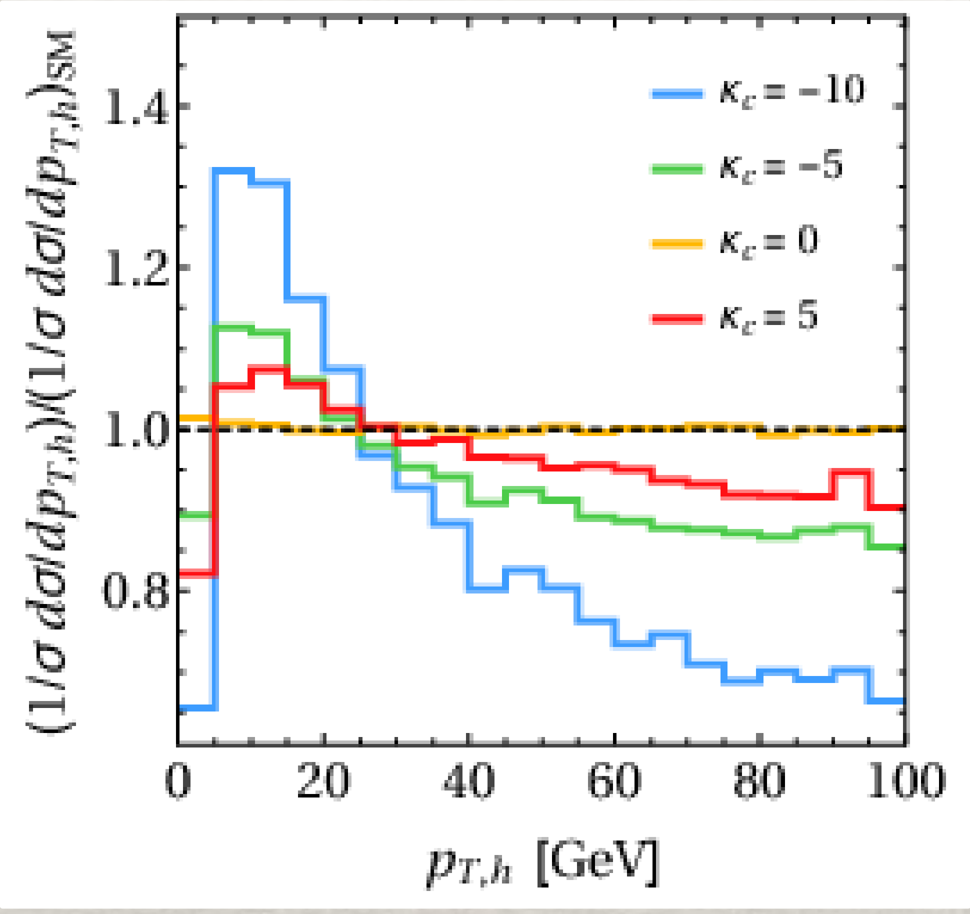


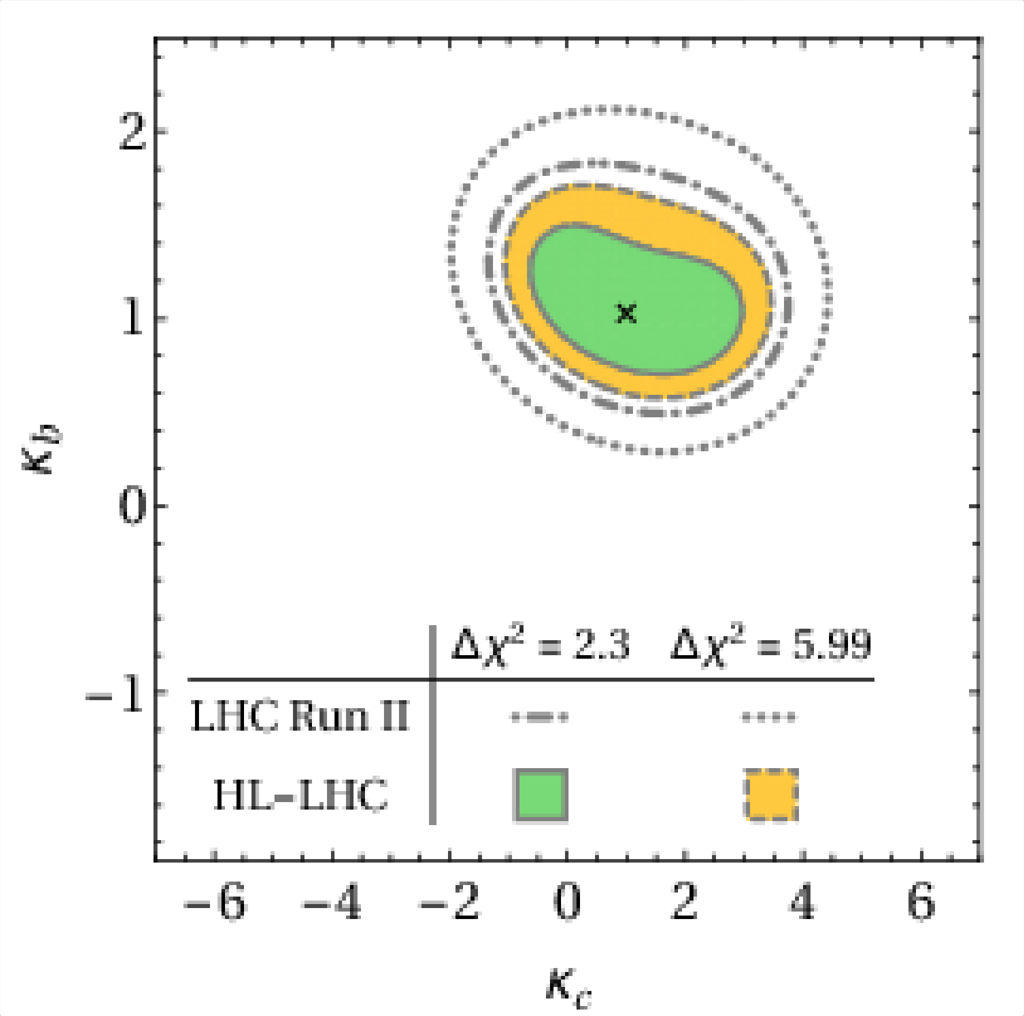
Still largely unconstrained

Charm Yukawa coupling

- Couplings to 2nd (and 1st) generation are very difficult to access
- Idea: probe these couplings through interference with top loops

[Bishara Haisch Monni Re 1606.09253]





Assumes theory uncertainty < 5%

Higgs+1jet@NLO

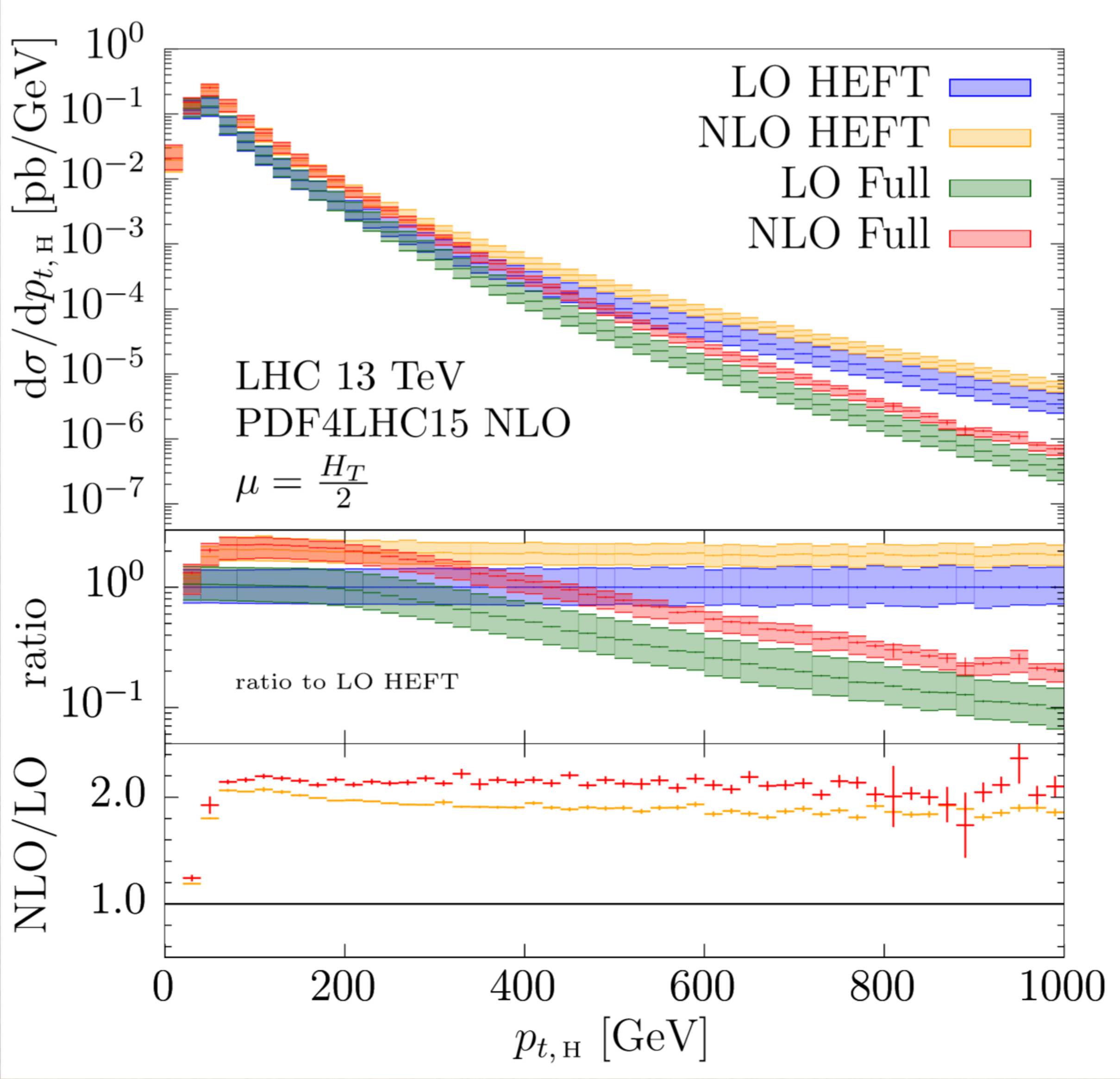
- Both BSM searches and Yukawa coupling determination require perturbative control over the Higgs p_T spectrum with full mass dependence

Higgs+1jet@NLO

- Both BSM searches and Yukawa coupling determination require perturbative control over the Higgs p_T spectrum with full mass dependence

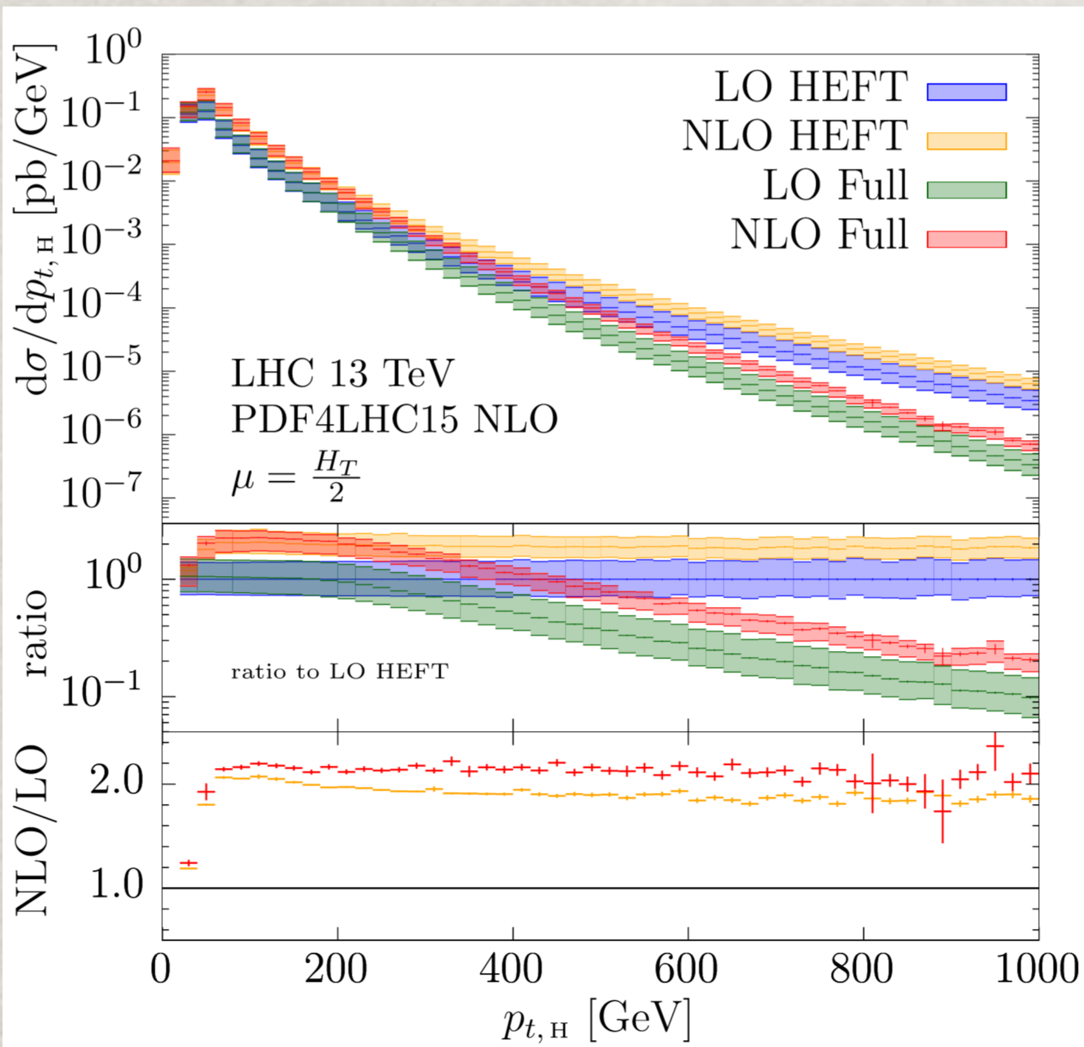
- Recent calculation of Higgs+1jet@NLO with full mass dependence from numerical evaluation of two-loop integrals with sector decomposition code SECDEC [Jones Kerner Luisoni 1802.00349]

- Numerical integration over Feynman parameters with deformation of integration contour in the presence of threshold singularities

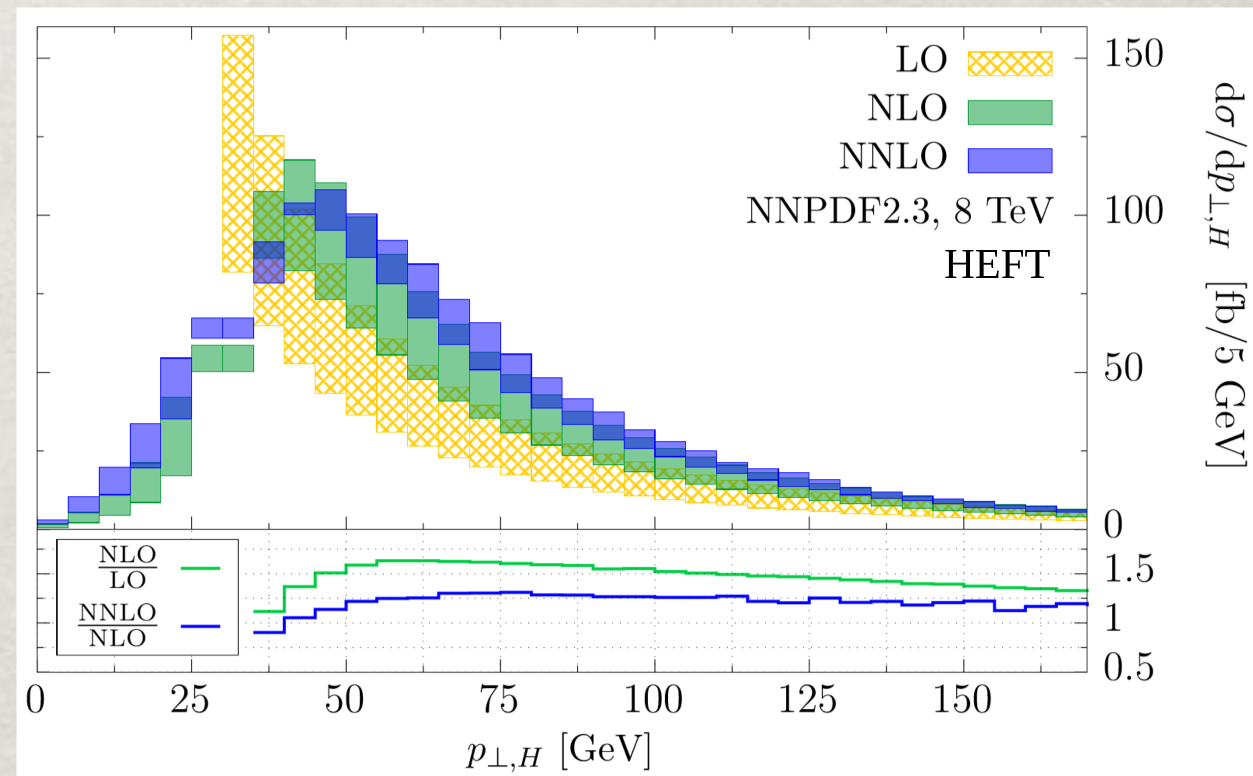


Higgs+1jet@NLO

- The K-factor for Higgs+1jet is large (about 2), of the same order as that for the Higgs total cross section ⇒ could things stabilise at NNLO?



[Jones Kerner Luisoni 1802.00349]

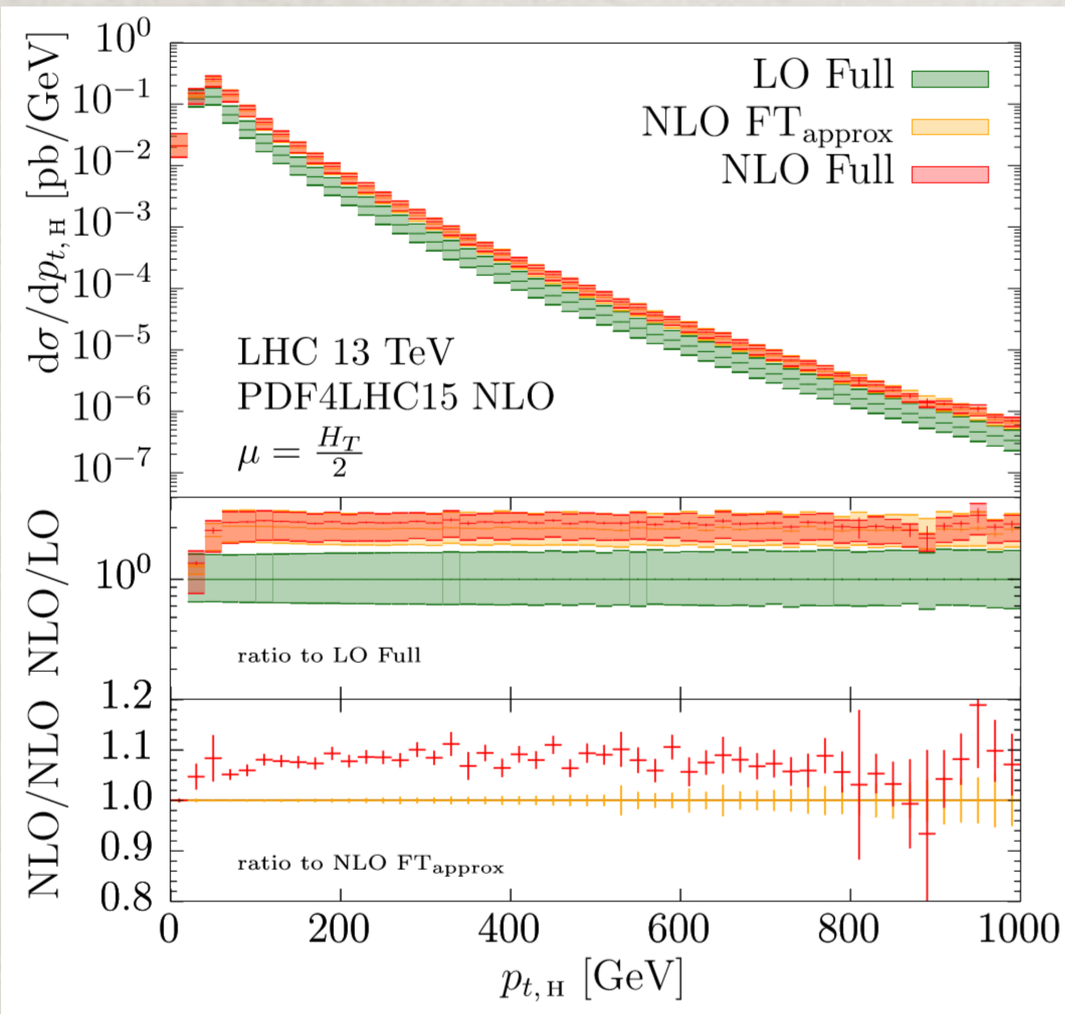


[Boughezal Caola Melnikov Petriello Schulze 1504.07922]

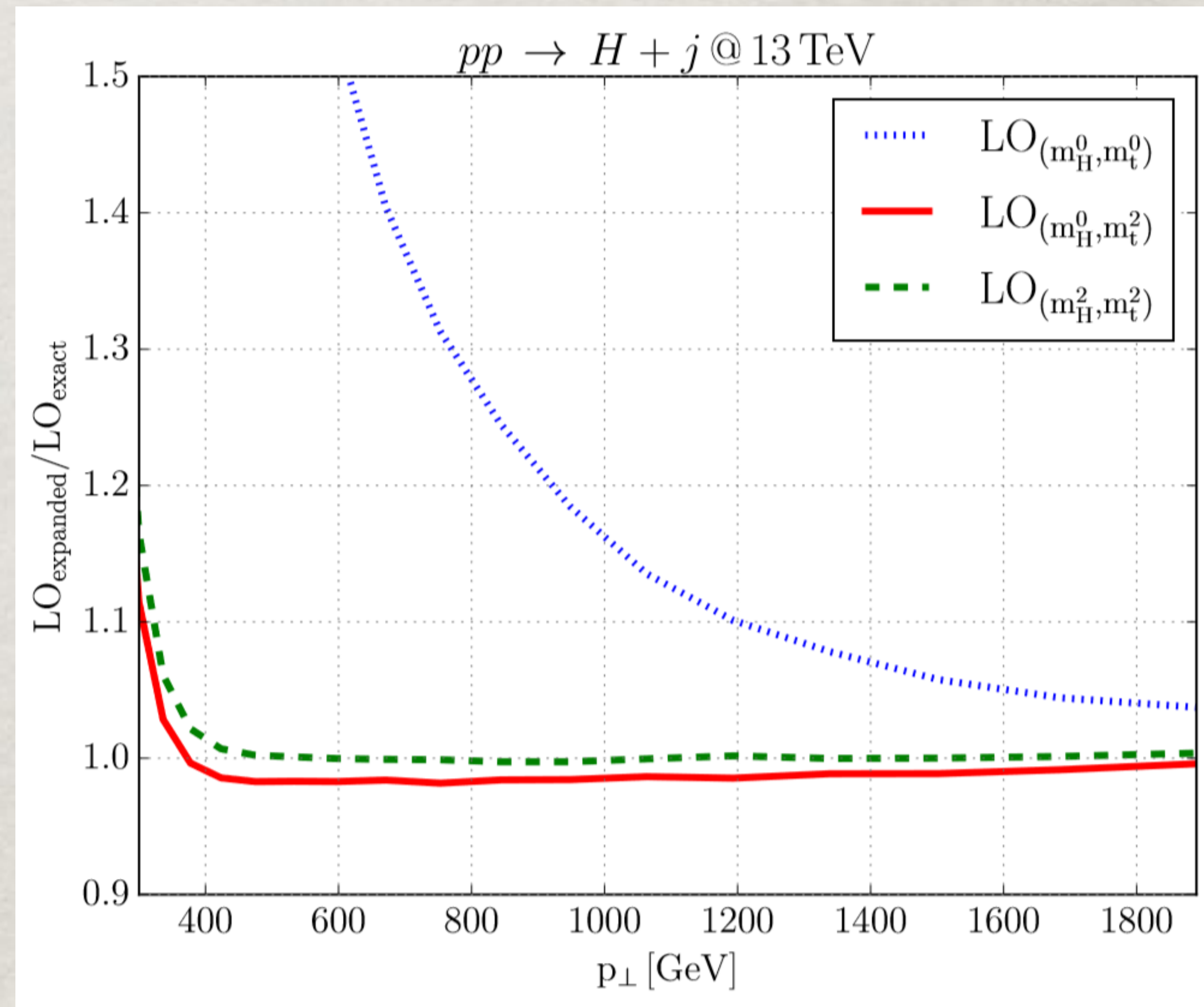
- Such large K-factors plague ggH irrespective of whether full mass dependence is kept ⇒ theoretical understanding needed here

Higgs+1jet@NLO

- Approximate methods (e.g. small mass expansion) give a comparable K-factor $\Rightarrow$ use such expansions for higher orders?



[Jones Kerner Luisoni 1802.00349]



[Lindert Kudashkin Melnikov Wever 1801.08226]

- Important contribution is logarithmically enhanced terms $\ln(p_T/m_t)$, but no clear indication that we should resum those at all orders, neither do we have a formalism to do it

Probe of BSM physics

- The simplest way to assess deviations from the SM is to consider the cross section $\sigma(p_T^{\rm cut})$ for $p_T > p_T^{\rm cut}$ and take the ratio

$$\delta(p_T^{\rm cut}) = \frac{\sigma_{\rm BSM}(p_T^{\rm cut}) - \sigma_{\rm SM}(p_T^{\rm cut})}{\sigma_{\rm SM}(p_T^{\rm cut})}$$

- In the (κ_t, κ_g) framework

$$\mathcal{L} \supset -\kappa_t \frac{m_t}{v} h\bar{t}t + \kappa_g \frac{\alpha_s}{12\pi}\frac{h}{v} G^a_{\mu\nu} G^{\mu\nu}_a$$

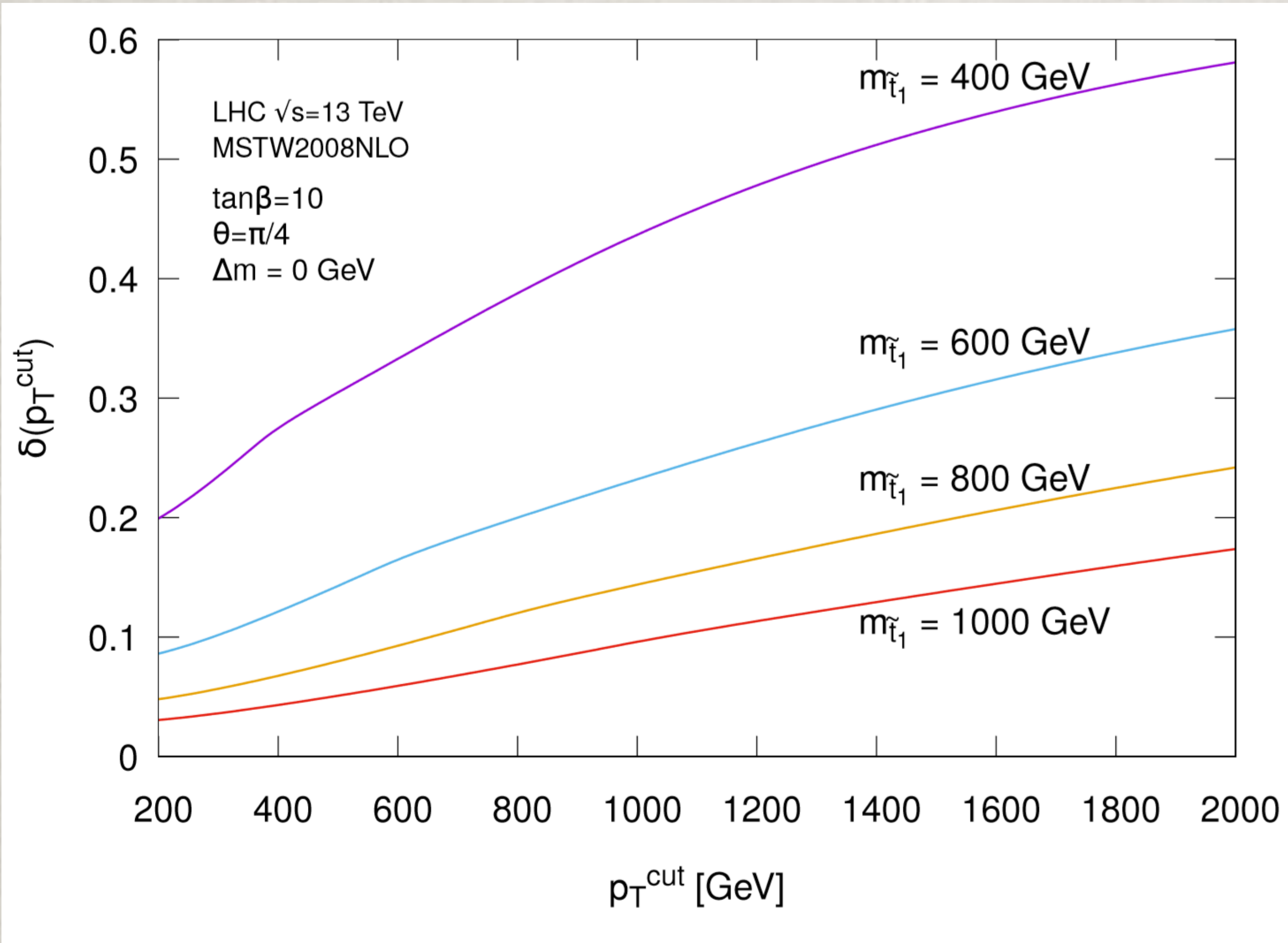
$$\delta = \frac{\kappa_g}{\kappa_t}\delta_{\rm int} + \left(\frac{\kappa_g}{\kappa_t}\right)^2 \delta_{\rm BSM}$$

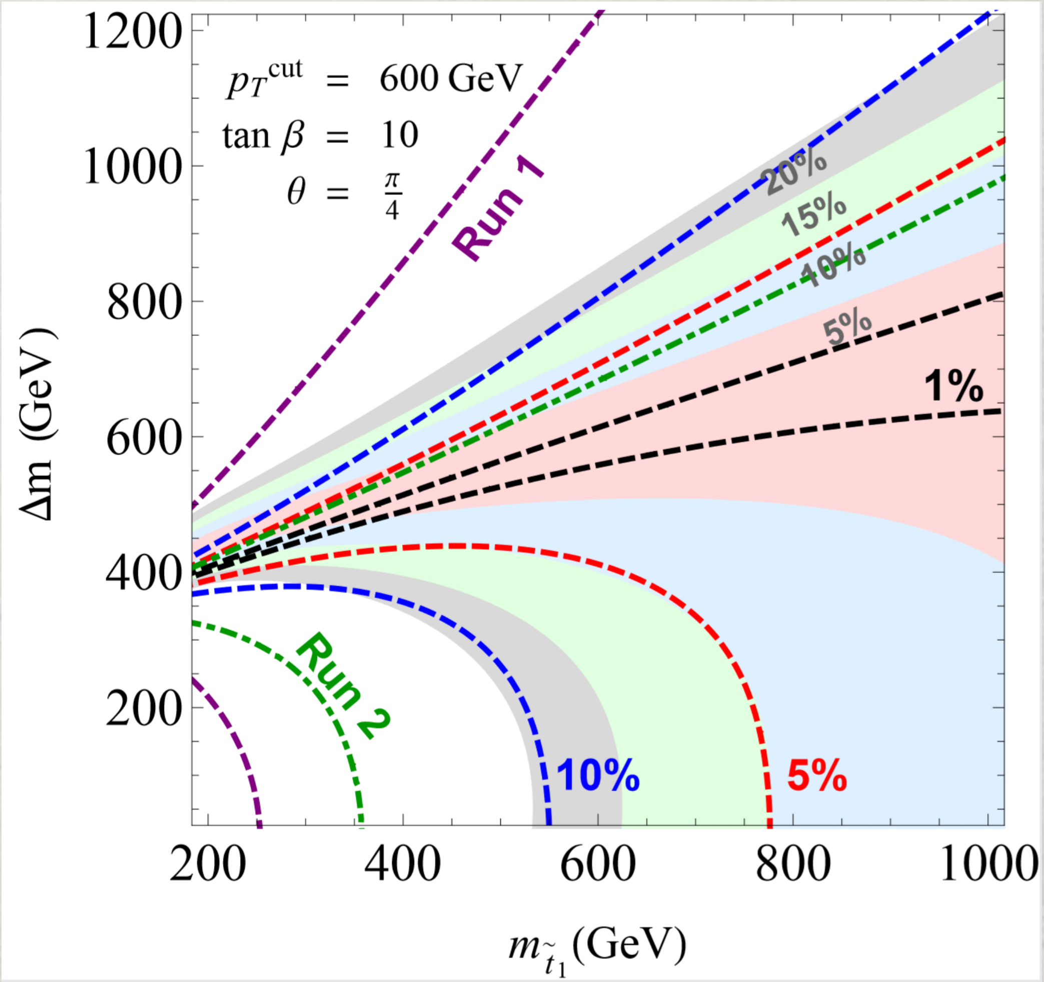
- The BSM contribution $\delta_{\rm BSM}$ is known at NLO from SM HEFT and $\delta_{\rm int}$ can be extracted from recent calculations

HIGGS AT HIGH P_T AND SUSY

- For stops in the loops, since $\kappa_t = 1$, one gains with respect to the total Higgs cross section only for p_T larger than the mass of the lighter stop

[AB Bond Martin Sanz 1806.05598]





Higgs at high p_T and SUSY

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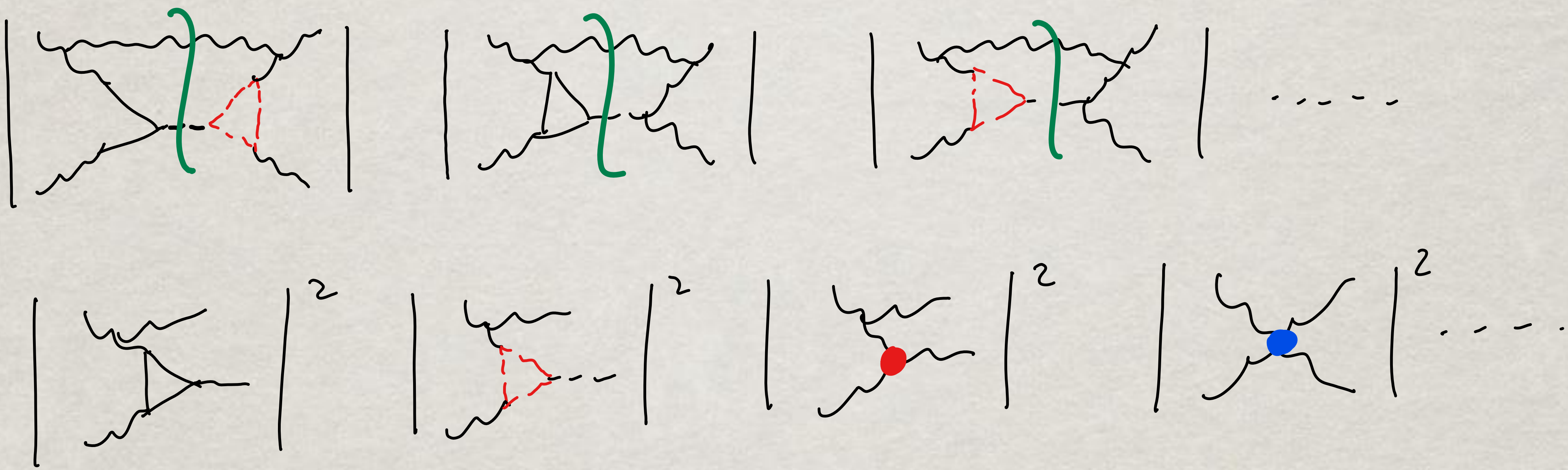
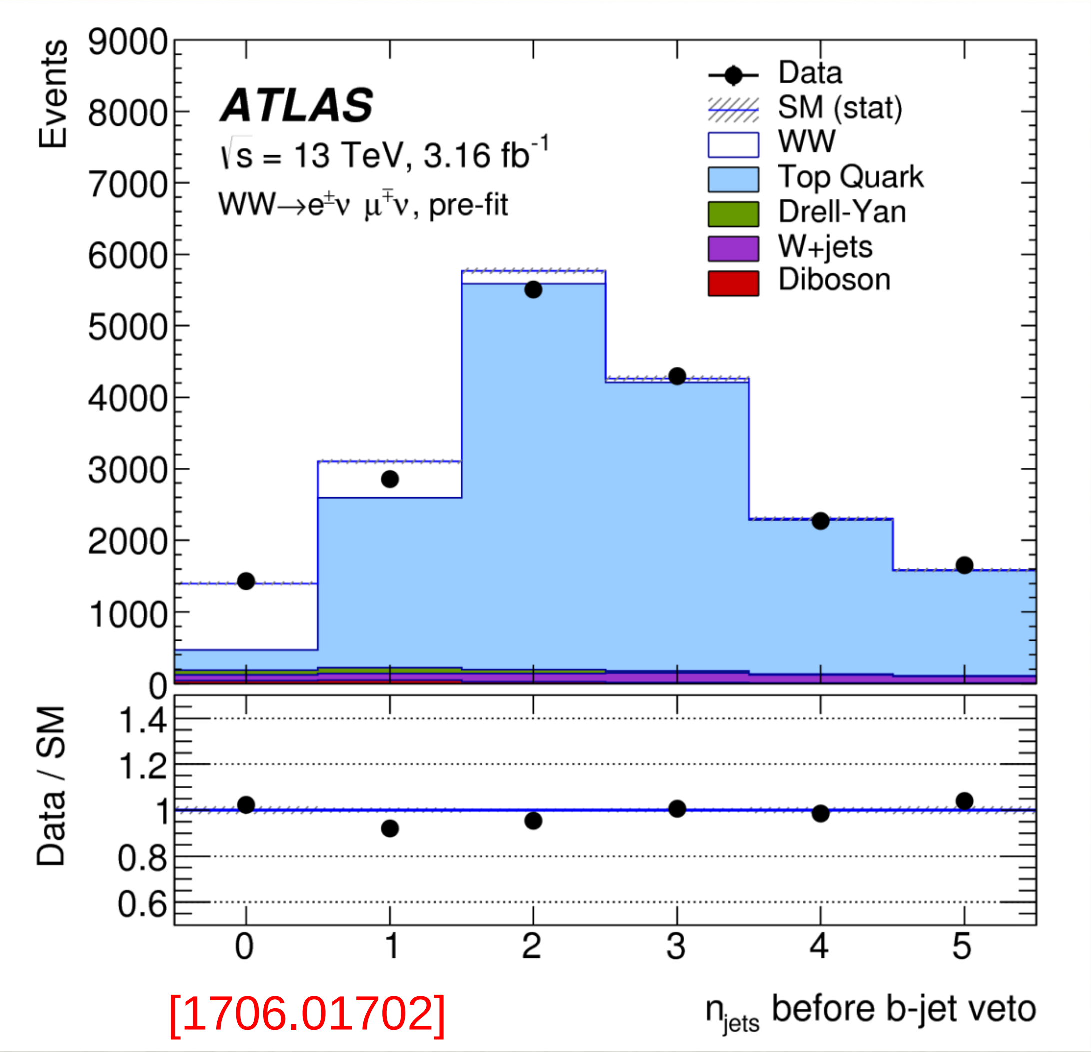


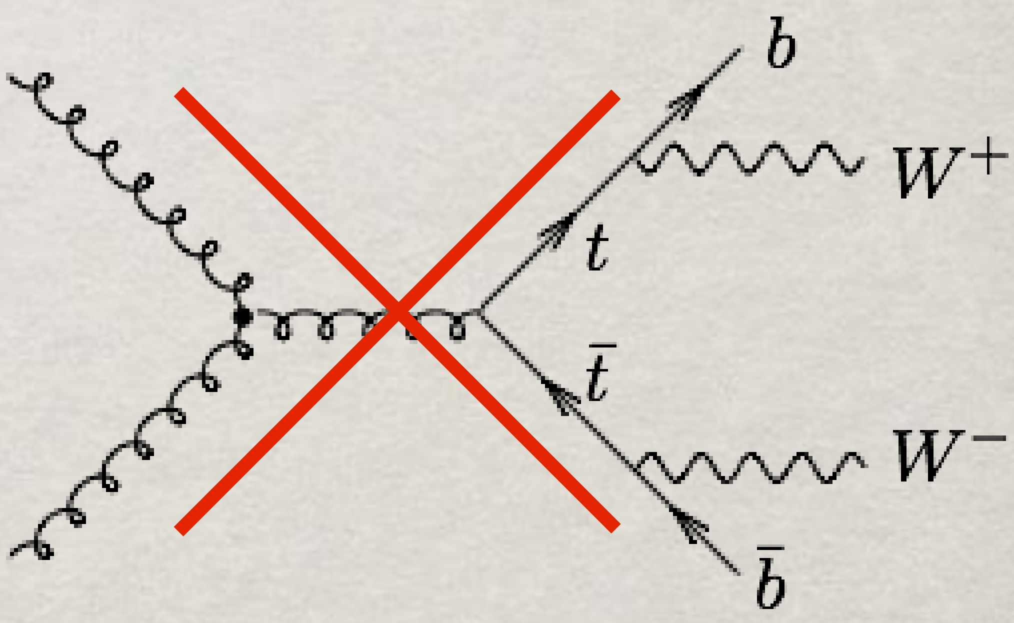
- To compute $\delta_{\rm BSM}$ and $\delta_{\rm int}$ at NLO one needs the full dependence on the lighter stop mass at two-loops $\Rightarrow$ possible with current techniques

- One expects similar K-factors as for other ggH cross sections $\Rightarrow$ LO evaluation of $\delta(p_T^{\rm cut})$ should be a good estimate $\Rightarrow$ theory uncertainties?

JET VETOES

- In WW production, one puts a jet-veto to eliminate overwhelming top-antitop background





- The main object of study is the zero-jet cross section, obtained by imposing that all jets have $p_t < p_{\mathrm{t,veto}}$

Jet-veto resummations

- The zero-jet cross section is an example of a two-scale observable, affected by logarithms $L \equiv \ln(M/p_{\mathrm{t,veto}})$ that need to be resummed at all orders

$$\sigma_{0-\mathrm{jet}} \simeq \sigma_0 \left(1 - 2C_A \frac{\alpha_s(m_H)}{\pi} \ln^2 \frac{m_H}{p_{\mathrm{t,veto}}} + \dots \right)$$

$$\downarrow$$

$$\sigma_{0-\mathrm{jet}} \sim \sigma_0 \, e^{\overbrace{Lg_1(\alpha_s L)}_{\mathrm{LL}}} \times \left(\begin{array}{ccc} 1 & + \quad \alpha_s & + \dots \\ \underbrace{G_2(\alpha_s L)}_{\mathrm{NLL}} & + \underbrace{\alpha_s G_3(\alpha_s L)}_{\mathrm{NNLL}} & + \dots \end{array} \right)$$

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JET-VETO RESUMMATIONS

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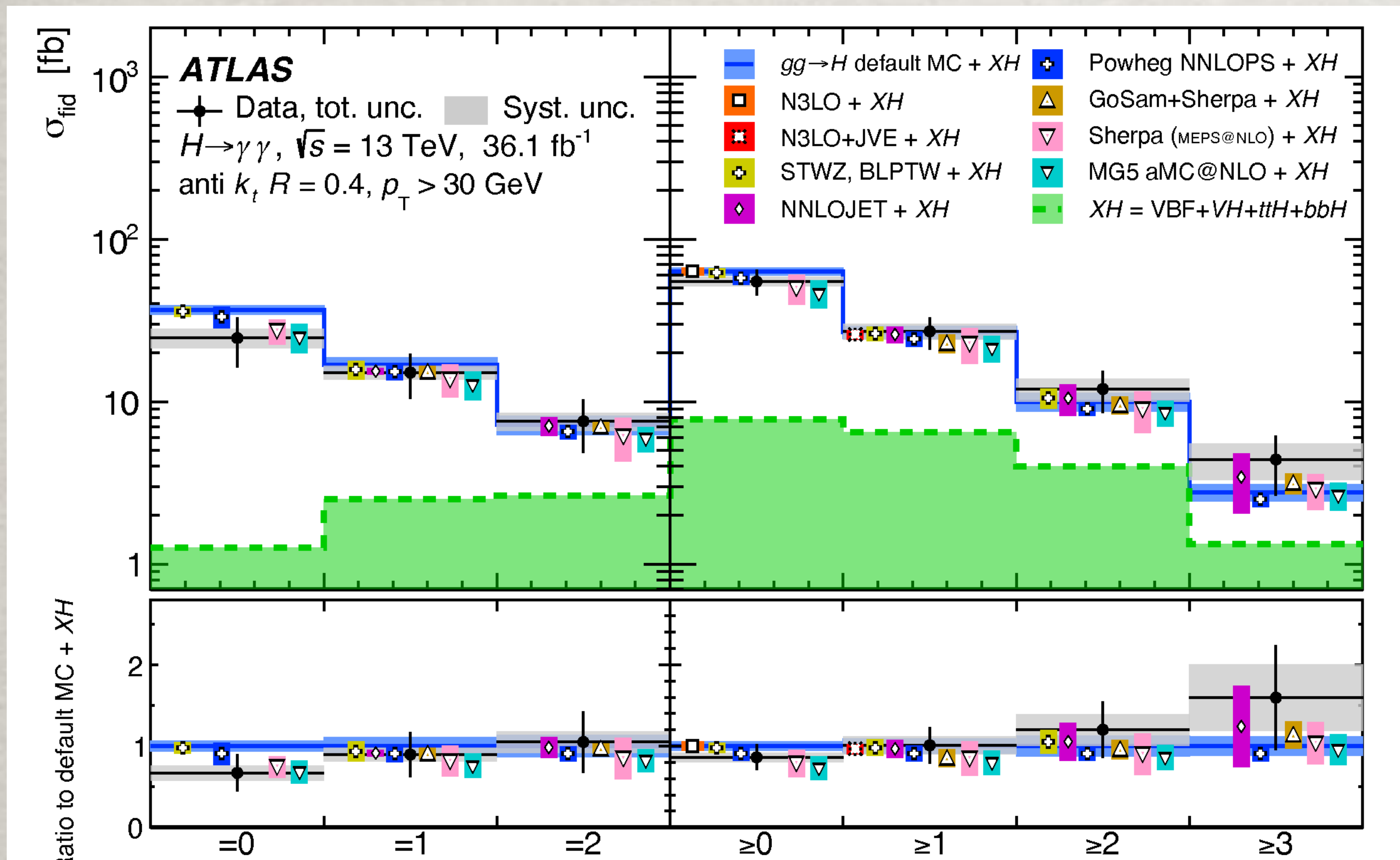
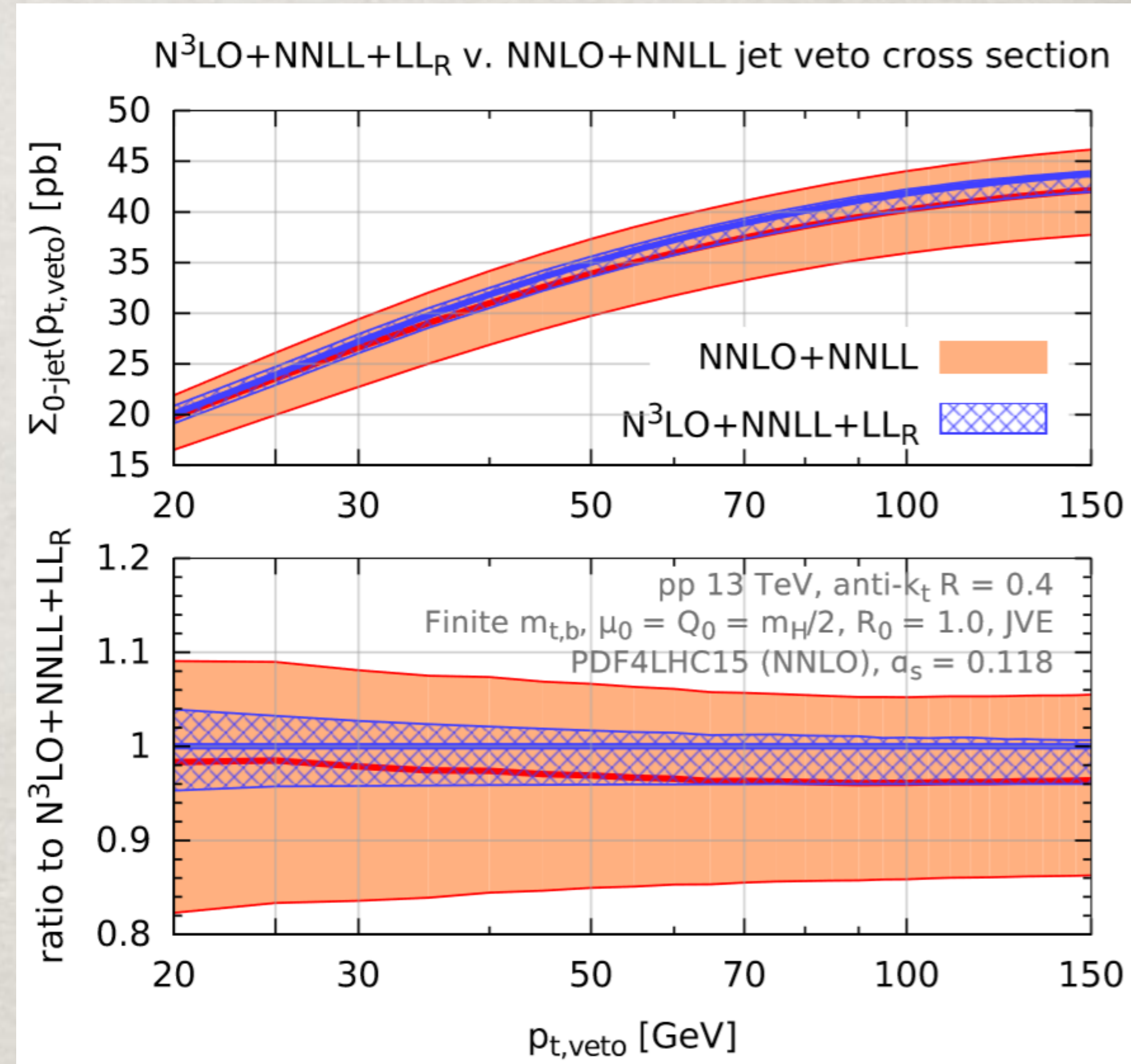
JET-VETO RESUMMATIONS

- Exclusive jet cross sections play an important role in Higgs physics, especially for H→WW



[1802.04146]



- Resummations have reached a very high accuracy (NNLL+N^{3}LO)

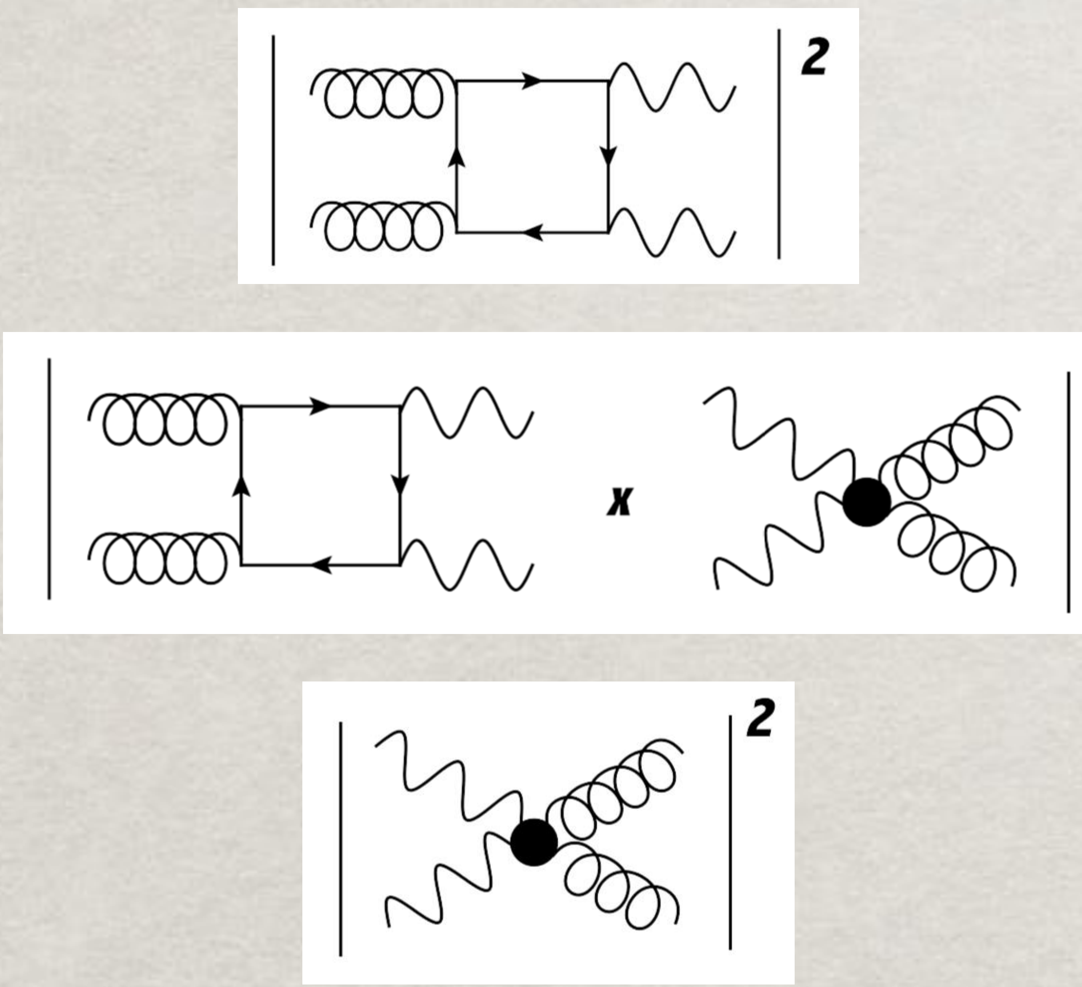
[AB Caola Dreyer Monni Salam Zanderighi Dulat 1511.02886]

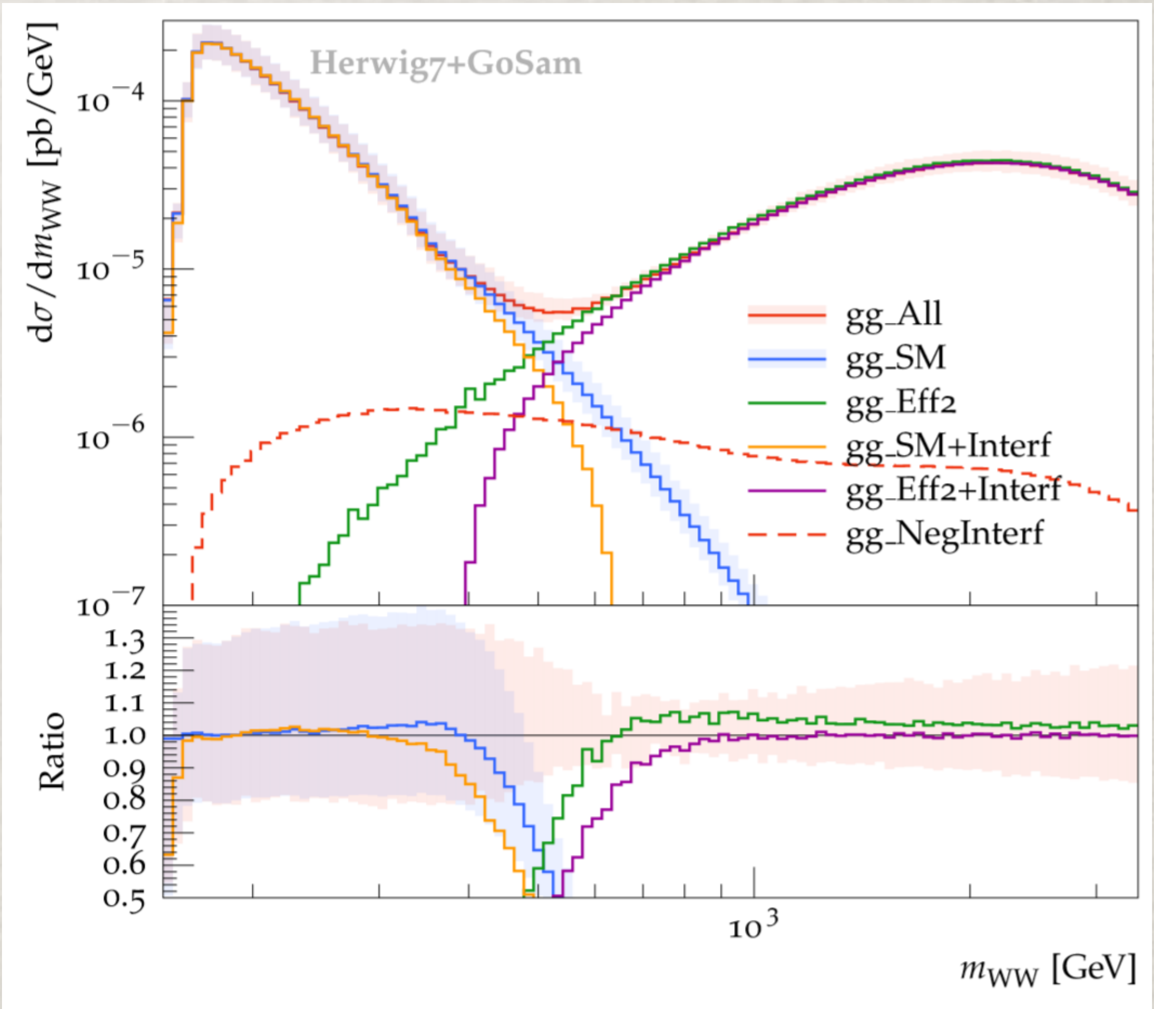
- Reduction of uncertainty due to H+1jet@NNLO ⇒ increase accuracy to N^{3}LL (conceptually feasible both in SCET and in QCD)?

WW AS BSM PROBE

- New physics (e.g. contact interactions) can modify the shape of distributions in WW production at high invariant mass ⇒ large logs $\ln(M_{WW}/p_{t,\mathrm{veto}})$ in the tails of distributions

[Bellm et al 1602.05141]



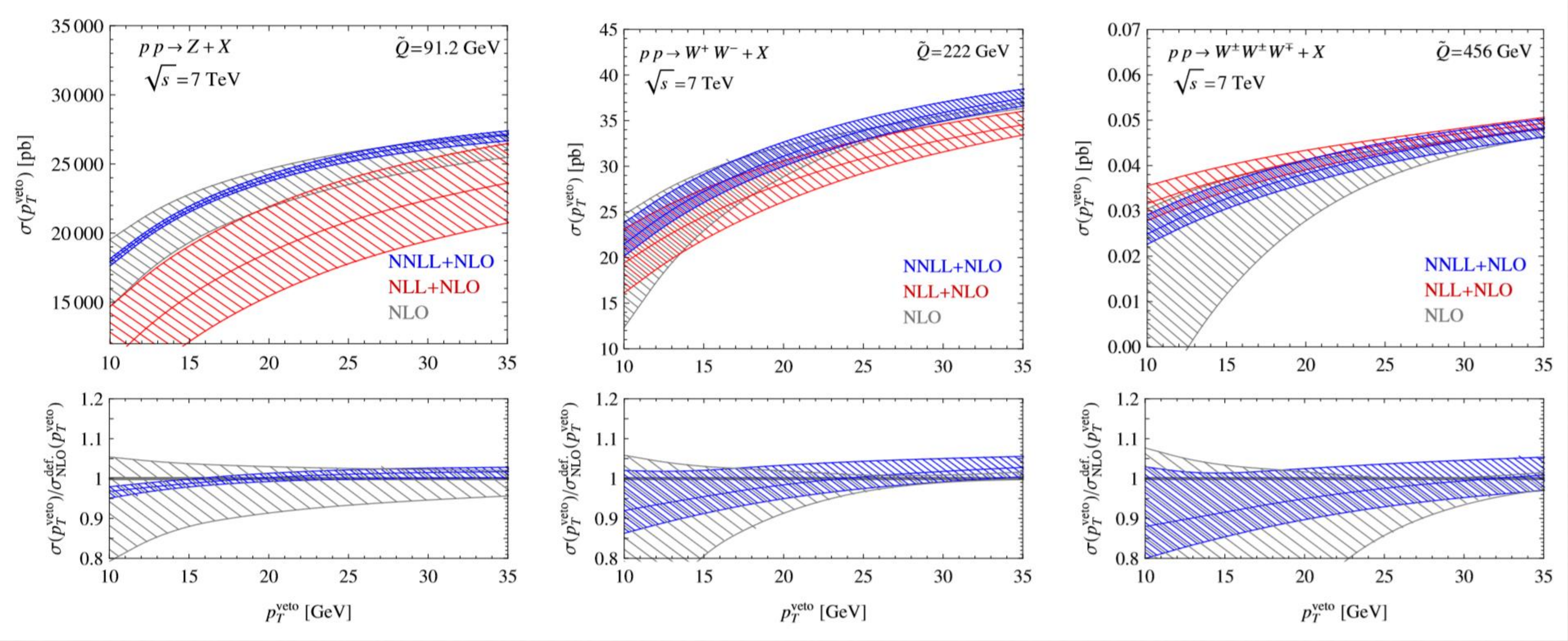


- Jet-veto resummations have to be exclusive in non-QCD particles so as to enable implementation of fiducial cuts

AUTOMATION OF RESUMMATIONS

- Automated implementation of SCET jet-veto resummation matched to NLO for colour singlets in the MADGRAPH framework available

[Becher Frederix Neubert 1412.8408]

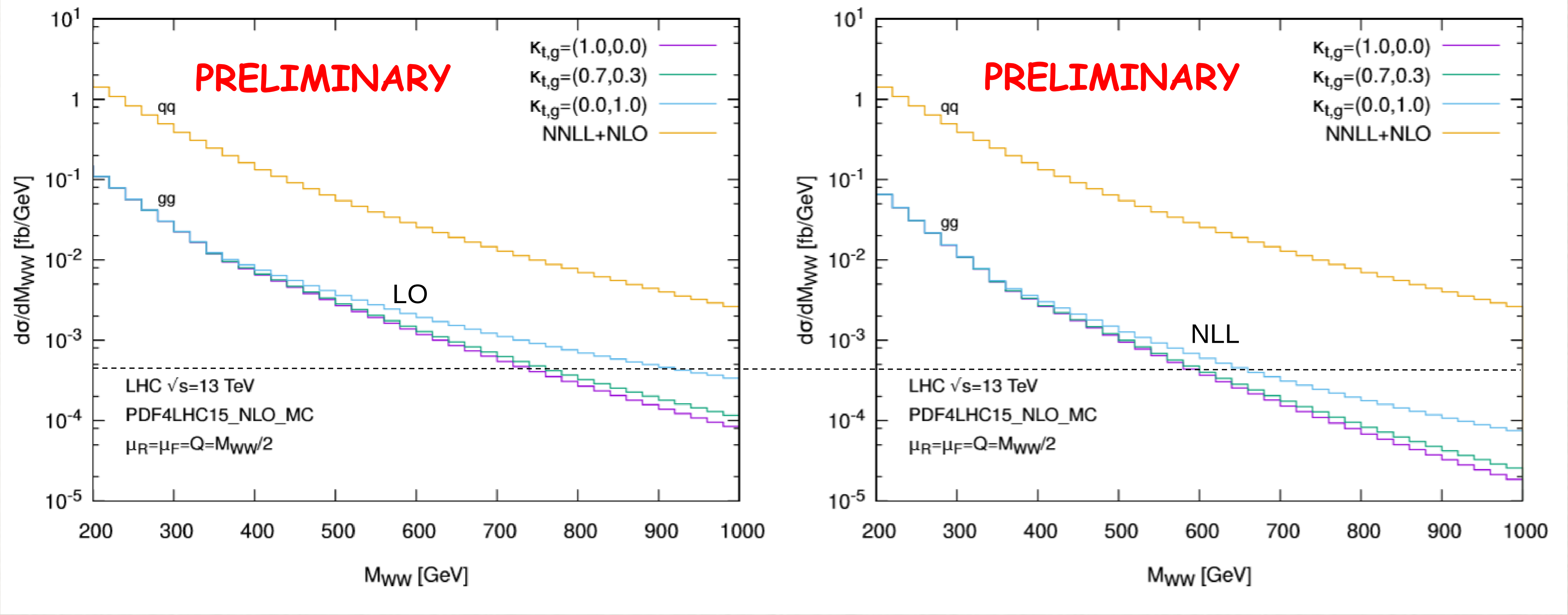


- Alternative implementation of QCD using MCFM gives separate access to interference between BSM and SM

[Arpino AB Kauer Jaeger 18xx.xxxxx]

JET VETO AND BSM SEARCHES

- Jet-veto effects play an important role in WW production at high invariant mass, especially because BSM contributions arise in gg→WW, whereas SM is mainly qq→WW [Arpino AB Kauer Jaeger 18xx.xxxxx]



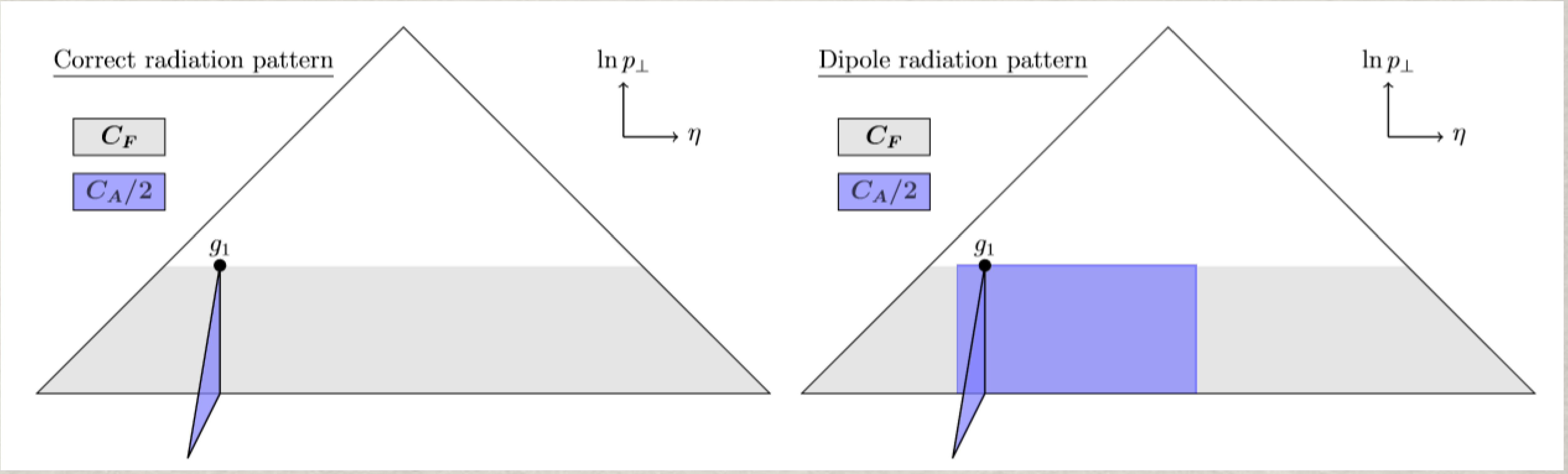
- Gluons radiate twice as much as quarks, so imposing a jet veto reduces more the signal with respect to the background
- Note: as for Higgs at high-p_T, computing NLO corrections to gg →WW requires full control over quark-mass dependence in loops

Resummations vs MC

- Can you forget about analytical resummations? In fact parton shower Monte-Carlo event generators are based the same physics
- First you need to understand the logarithmic accuracy of MC
- Recent progress in understanding the relationship between the two wrt
  - correct implementation of QCD matrix elements
  - coverage of multi-parton phase space (e.g. energy-momentum conservation)

[Hoeche Reichelt Siegert 1711.03497]

[Dasgupta Dreyer Hamilton Monni Salam 1805.09327]

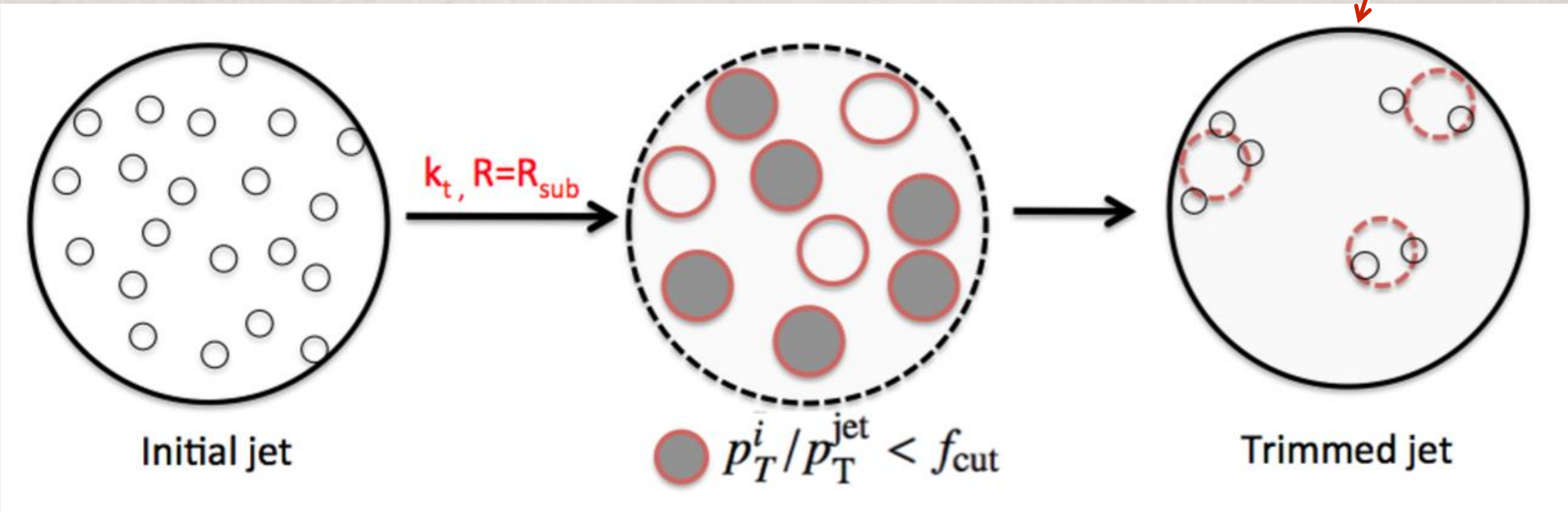


Boosted objects

- Both HL-LHC and future colliders will produce boosted heavy objects, whose decay products fall in the same jet (e.g. boosted Higgs or tops)

[Butterworth Davison Rubin Salam 0802.2470]

hadronic top candidate



- Key feature of boosted object taggers are groomers, procedures that clean jets from soft constituents irrelevant for mass reconstruction

Innovative groomer: soft drop

- Groomed jet-mass distributions cumbersome to model in QCD due to the presence of the so-called non-global logs (NGLs)
- New groomers (mMDT, soft drop) do not have any NGLs $\Rightarrow$ opens the way of solid analytical modelling of different taggers

[Dasgupta Fregoso Marzani Salam 1307.0007]

[Larkoski Marzani Soyez Thaler 1402.0007]

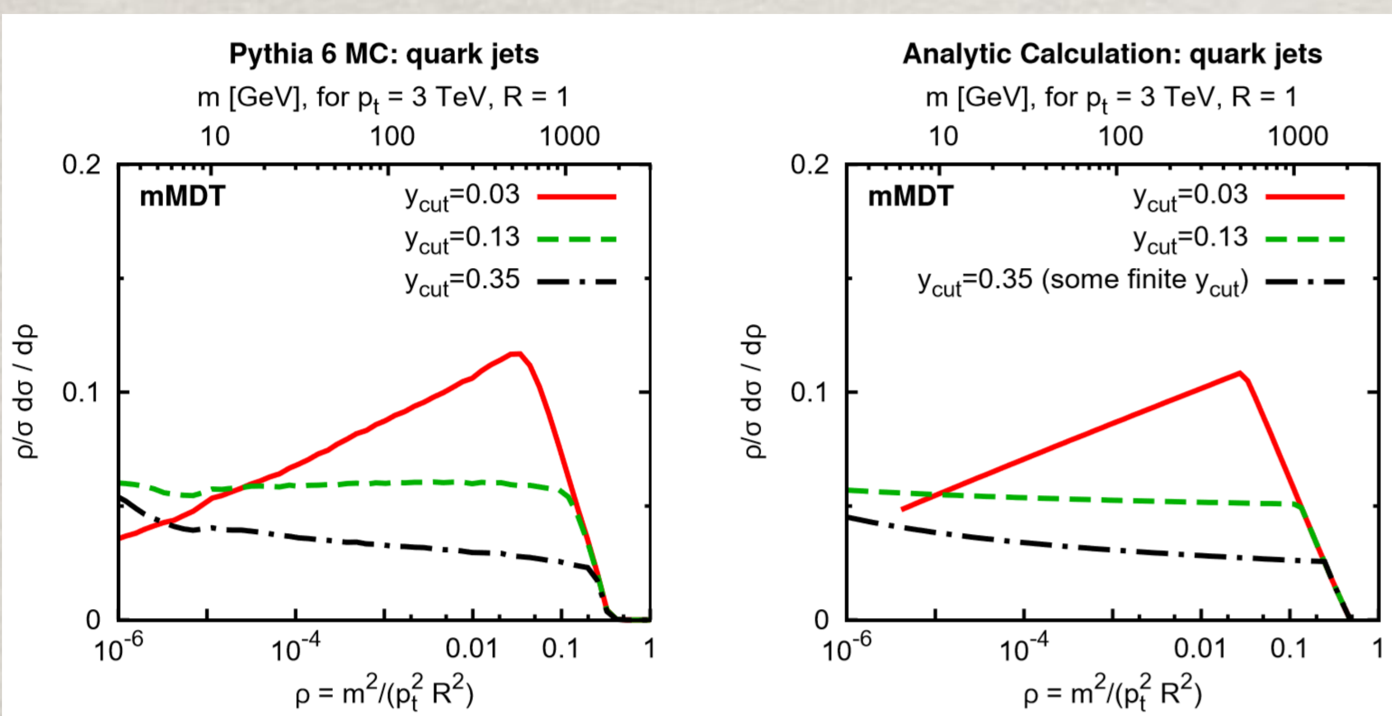
fail

pass

θ_{ij}

$$\frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}} > z_{\rm cut} \left(\frac{\theta_{ij}}{R}\right)^{\beta}$$

$\beta = 0$: mMDT



Qualitative features of jet mass distribution agrees between MC and resummations

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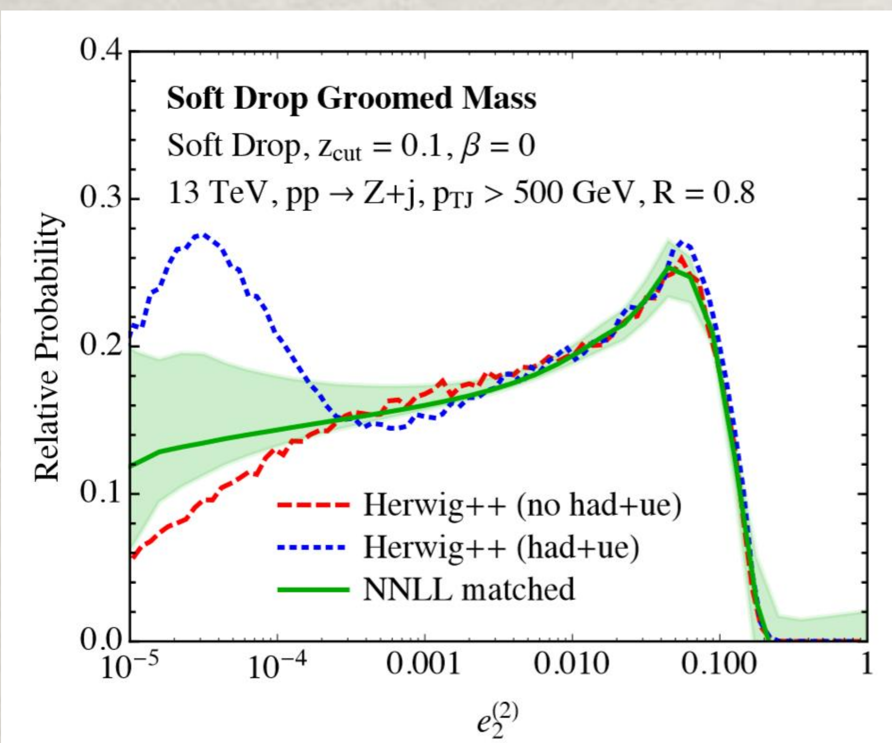
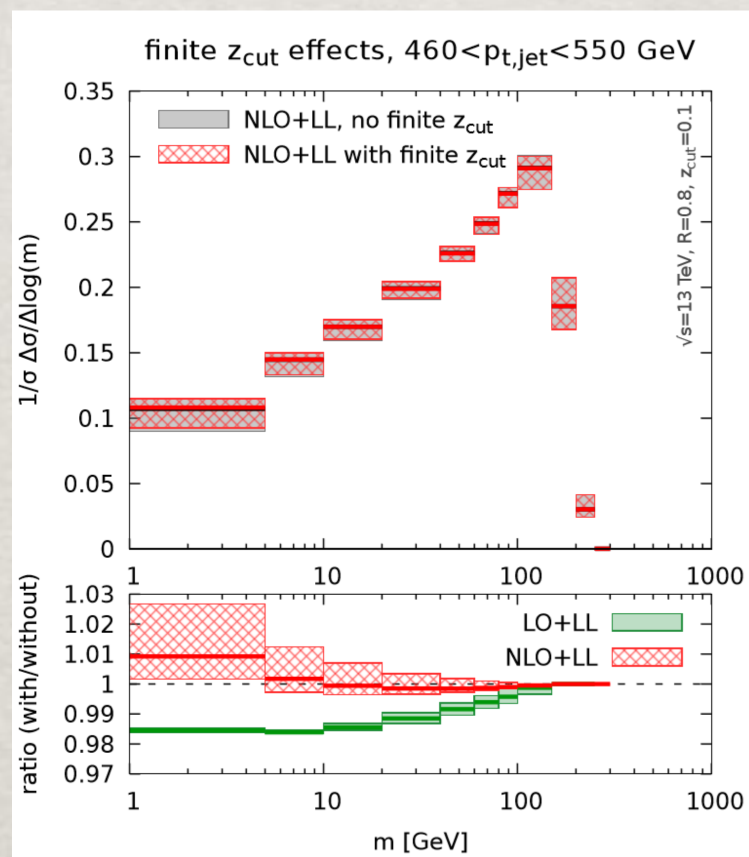
NLL resummation for $m_J^2 \ll z_{\text{cut}} p_T^2 \ll p_T^2$

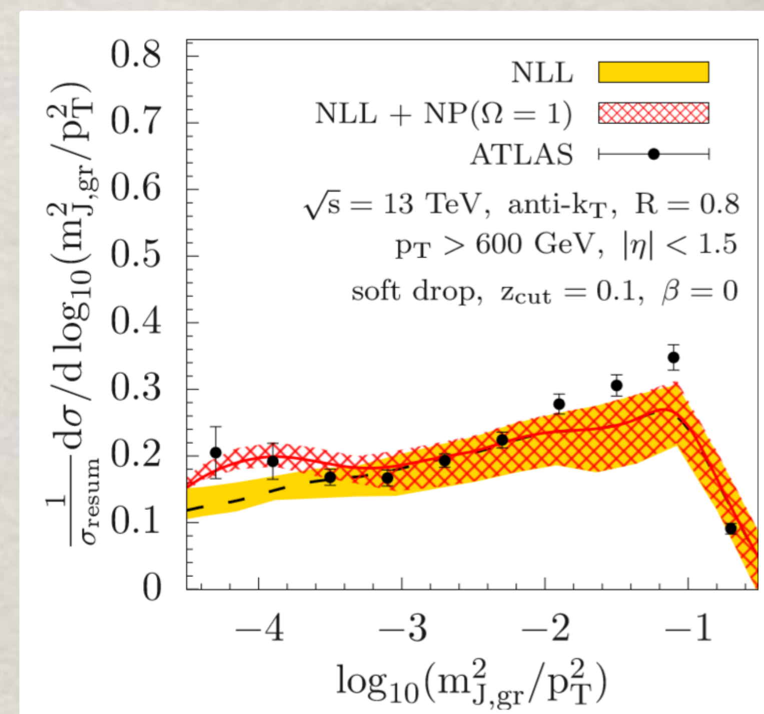


[Frye et al 1603.09338]



[Marzani et al 1704.02210]

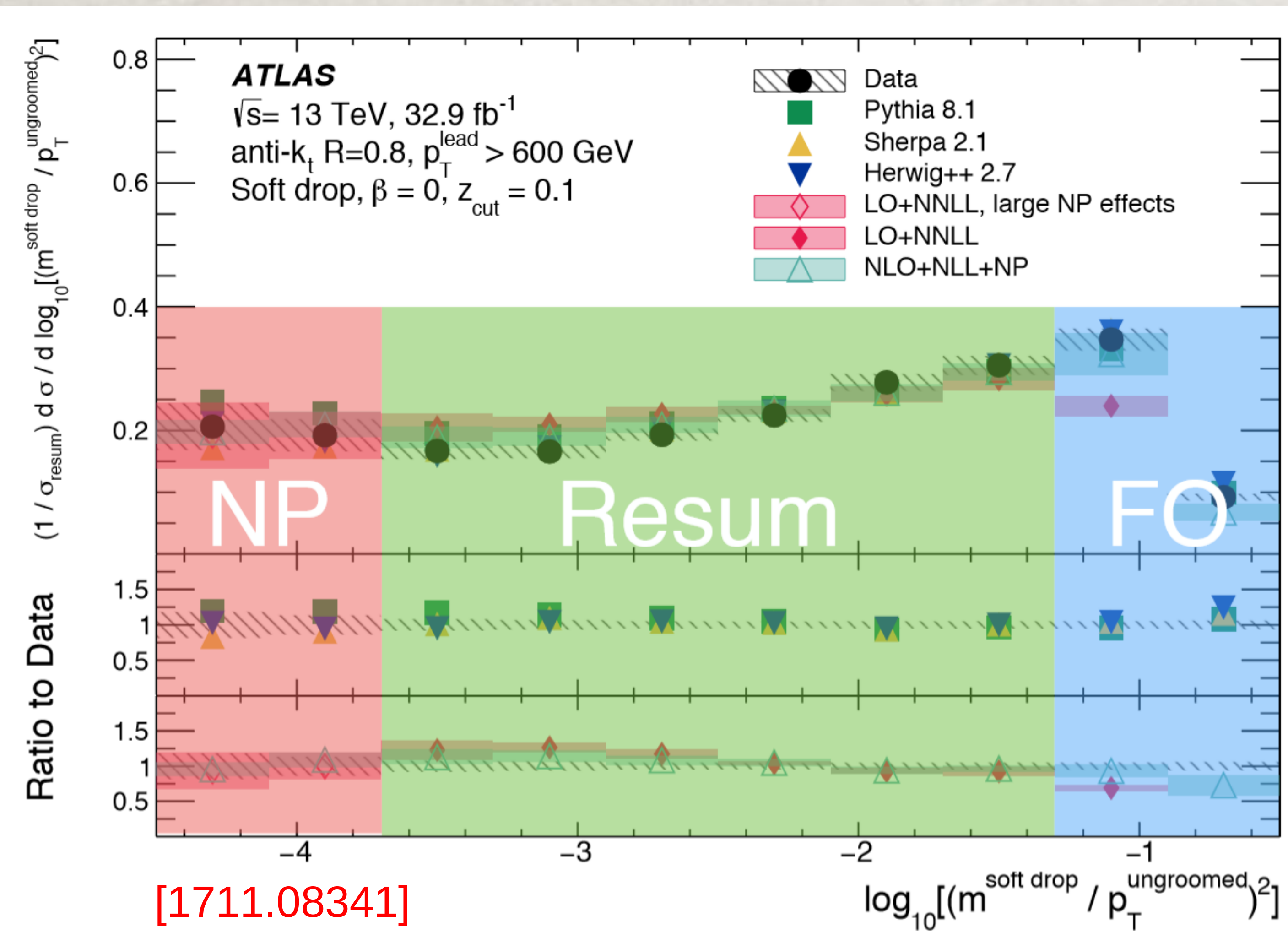
Resummation of z_{cut}

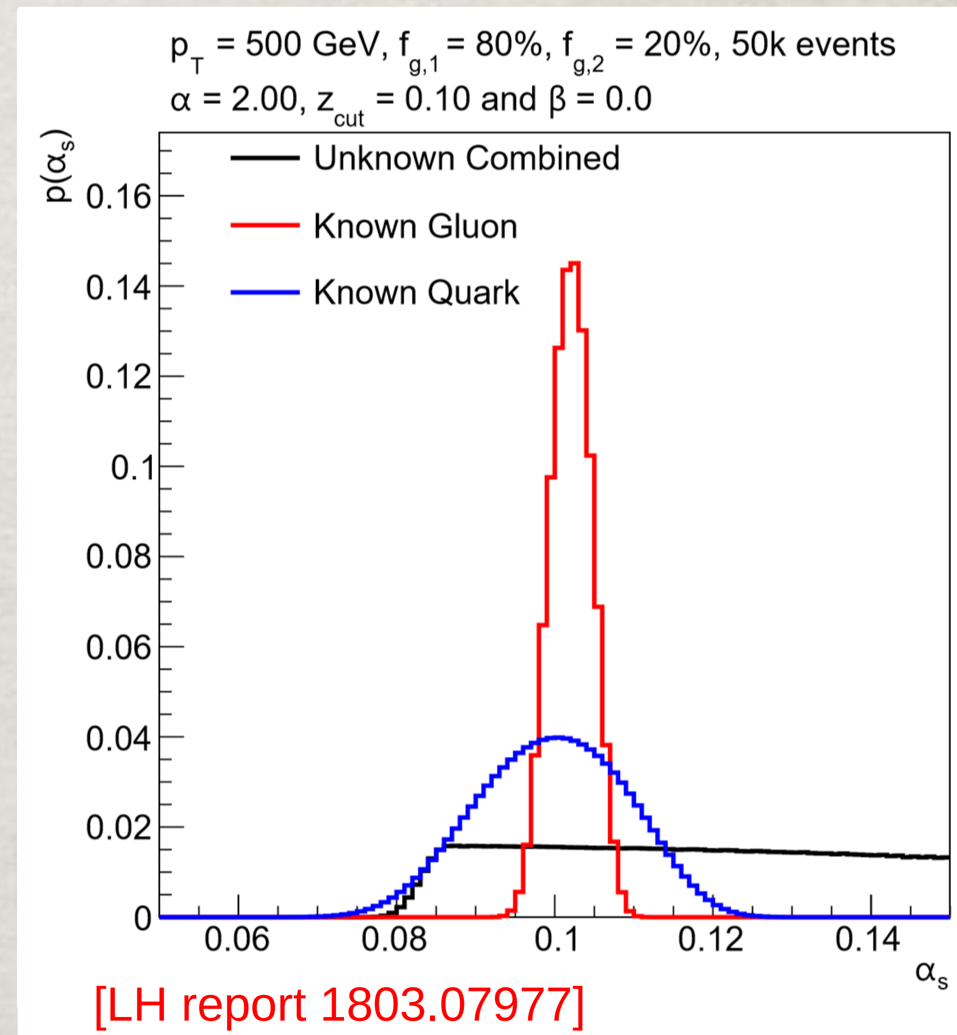


[Kang et al 1803.03645]

A NEW PRECISION ERA?

- Experimental uncertainty around 5% at the LHC $\Rightarrow$ new era of precision measurements using boosted objects





- Competitive extraction (~10%) of the strong coupling α_s at hadron colliders

Conclusions

- Total cross sections at N^3LO and many processes with massless particles in loops known at NNLO
- High-p_T Higgs sensitive to quark masses in loops $\Rightarrow$ substantial progress needed in calculation of loop integrals with different mass scales
- Jet-veto resummation can play an important role in high-mass WW $\Rightarrow$ beyond NNLL and implementation of fiducial cuts are realistic objectives
- New ideas for quantitative comparison of parton showers and resummation
- Impressive progress in analytical understanding of boosted object taggers opens the way to a new era of precision physics above EW scale

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Thank you for your attention!