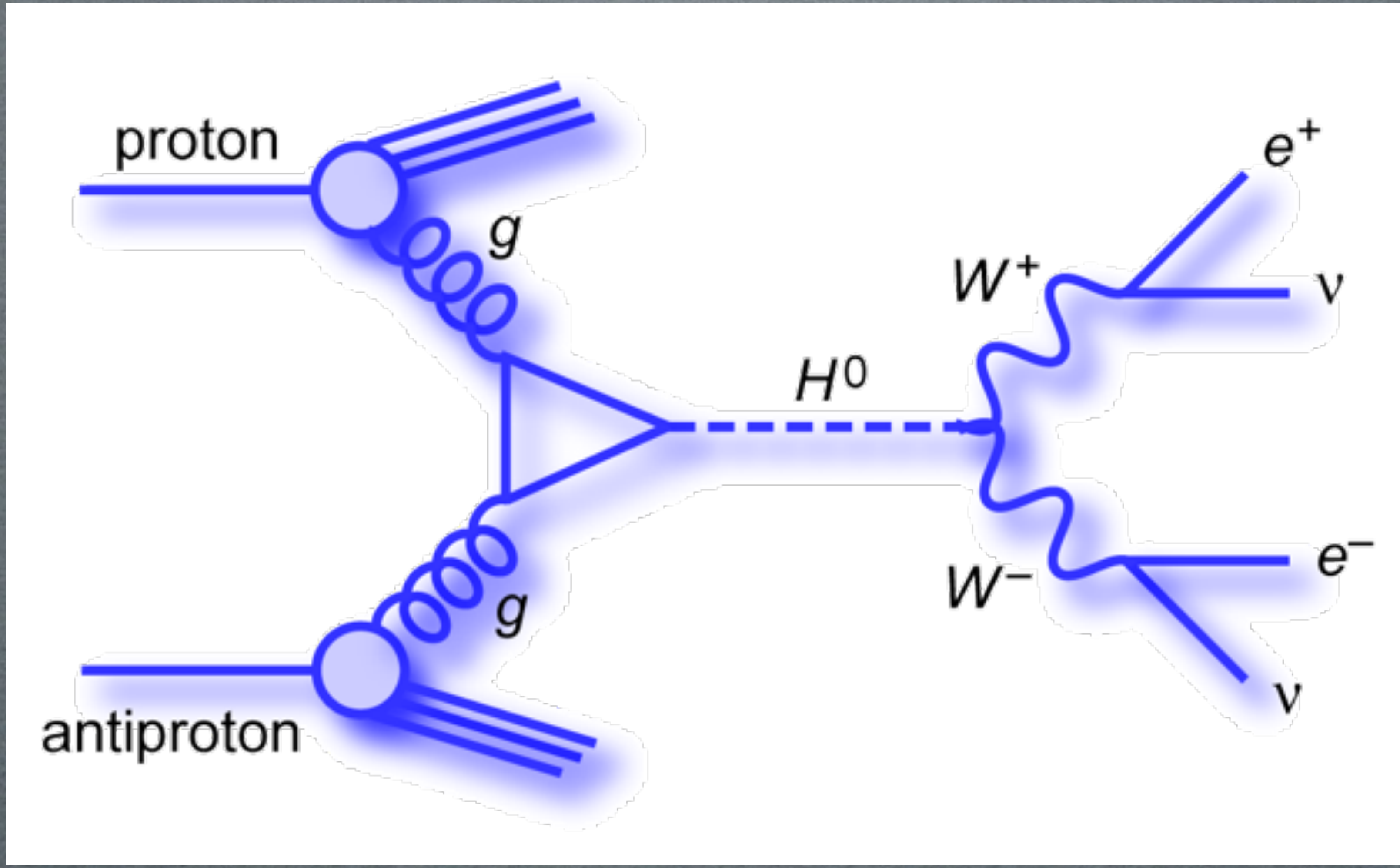
Status of Higgs and jet physics



Andrea Banfi

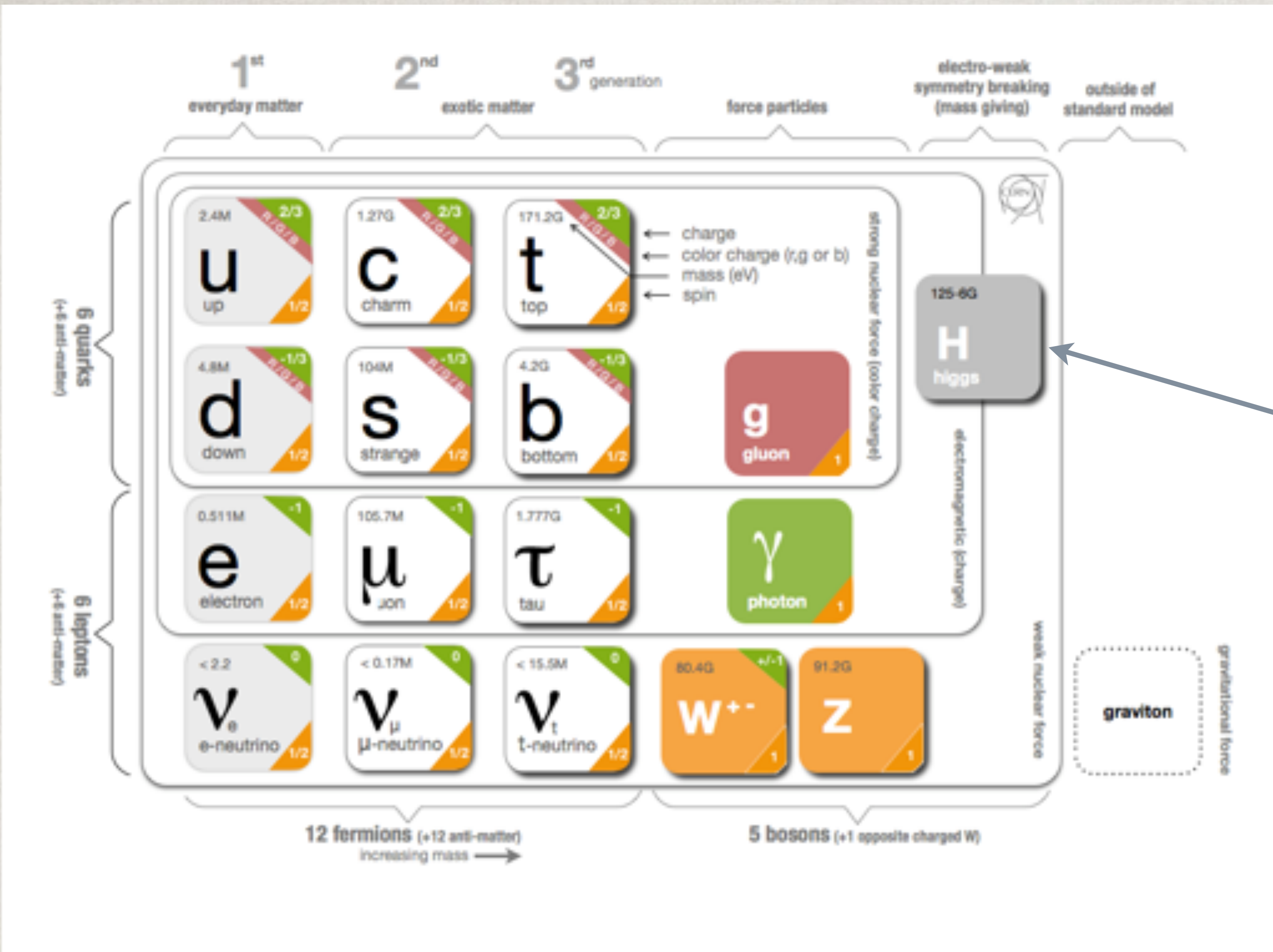
University of Sussex

Outline

- Importance of jet physics in LHC Higgs analyses
- Zero-jet cross section
  - NNLL+NNLO resummations
  - Progress in Monte Carlo event generators
- One-jet cross section
  - NLL+NLO resummations
  - Progress towards NNLO
- Two-jet cross sections
  - Discriminating between gluon-gluon and vector-boson fusion
- Further information
  - Handbook of LHC Higgs cross sections 1,2,3
    [Inclusive observables 1101.0593, Differential distributions 1201.3084, Higgs properties 1307.1347]
  - CERN workshop “Jet issues in Higgs physics"

Higgs searches at the LHC

- LHC experiments will focus on determining whether the Higgs boson found in July 2012 is truly the missing piece of the Standard Model



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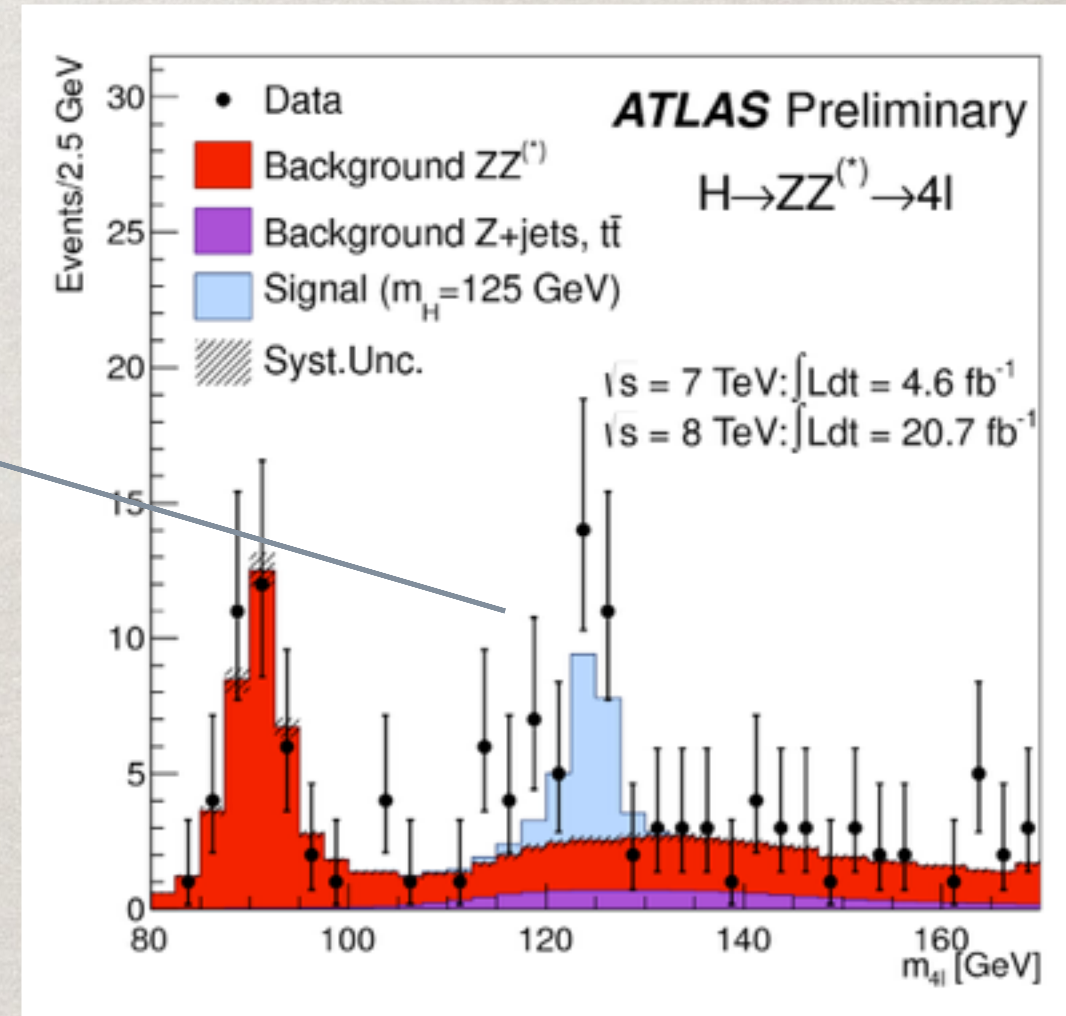
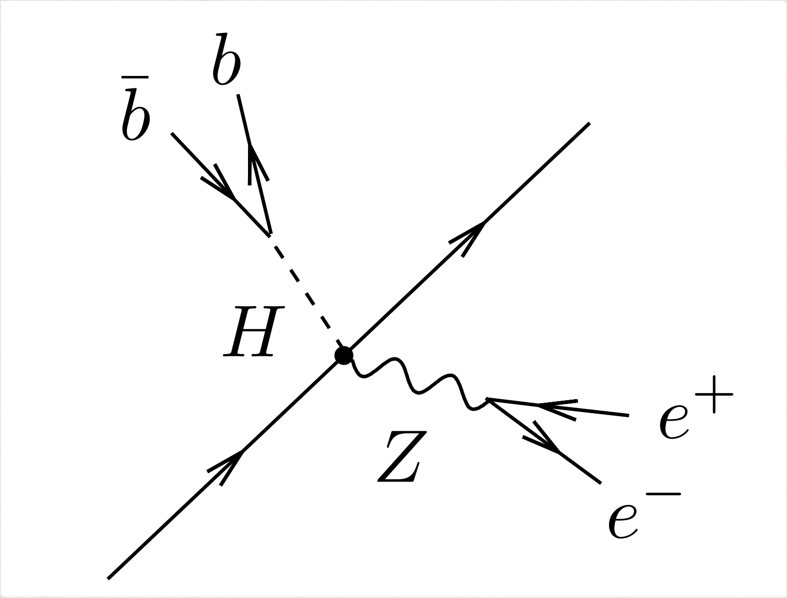
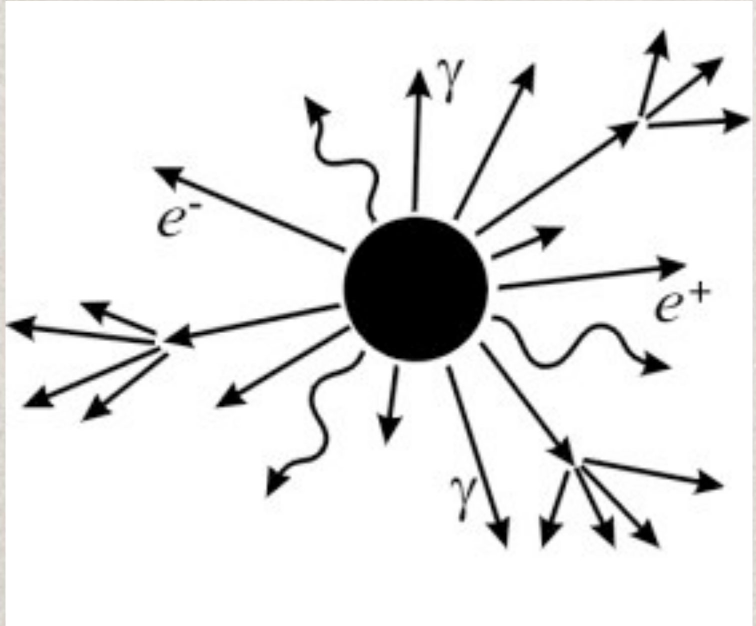


- Many analyses, both for the Higgs and for new physics searches, will involve final states containing hadronic jets

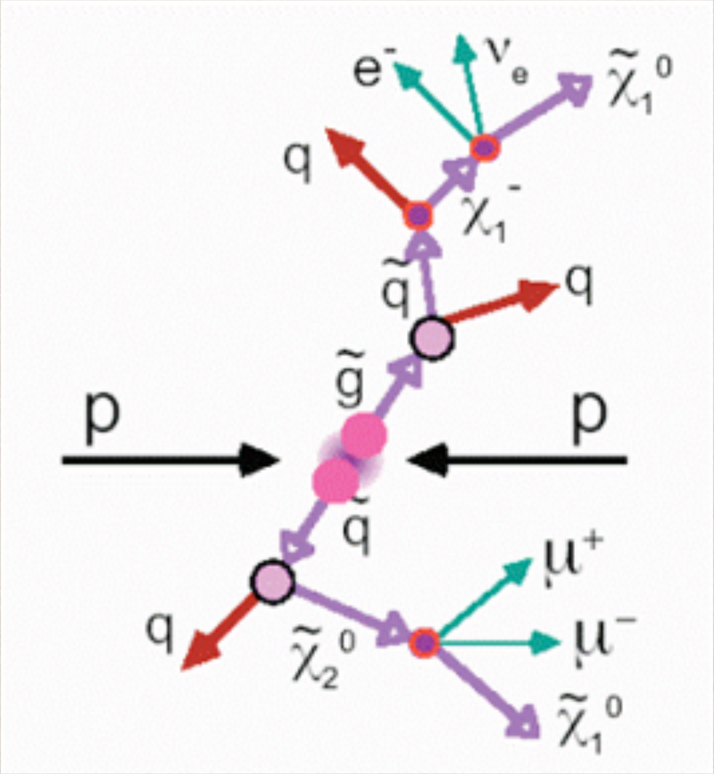
We wish to see...



Higgs boson



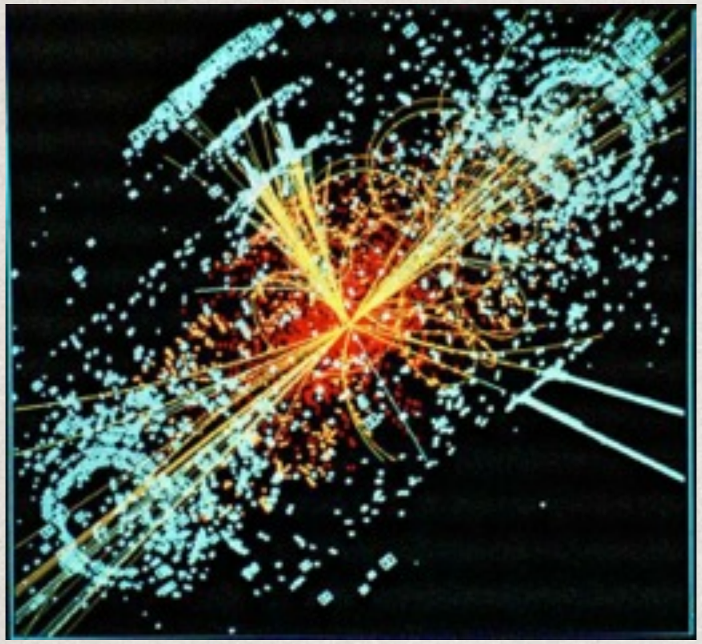
Black holes



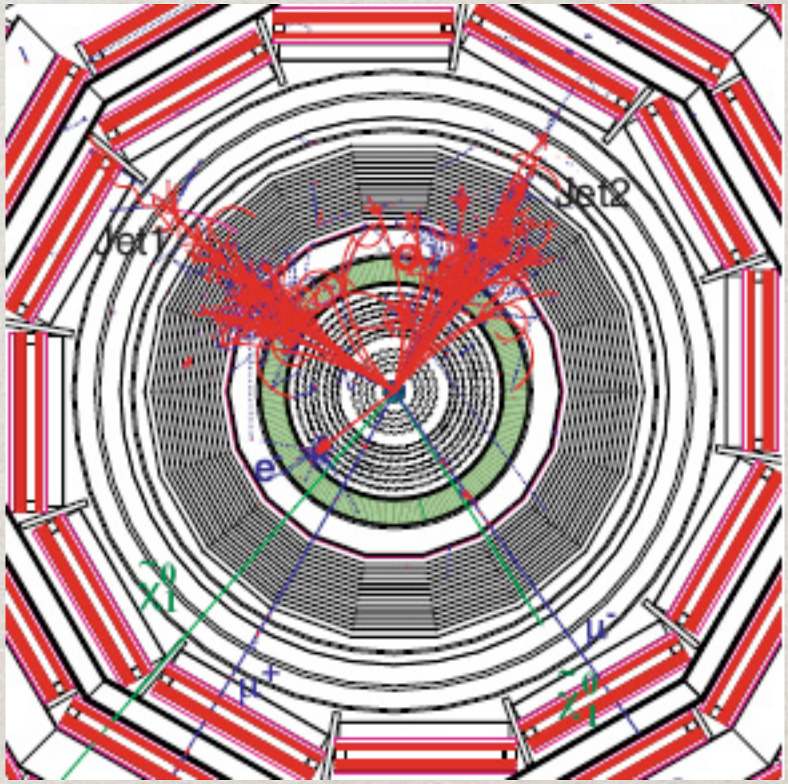
Dark matter

- At a hadron collider heavy particles are produced together with strongly interacting quarks and gluons (a.k.a. partons)

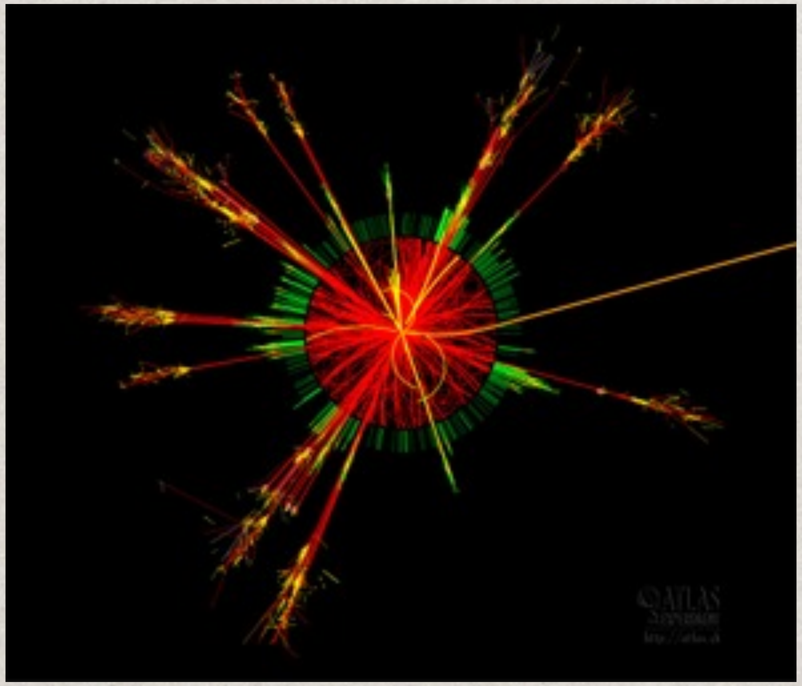
... INSTEAD WE MIGHT SEE



Higgs boson



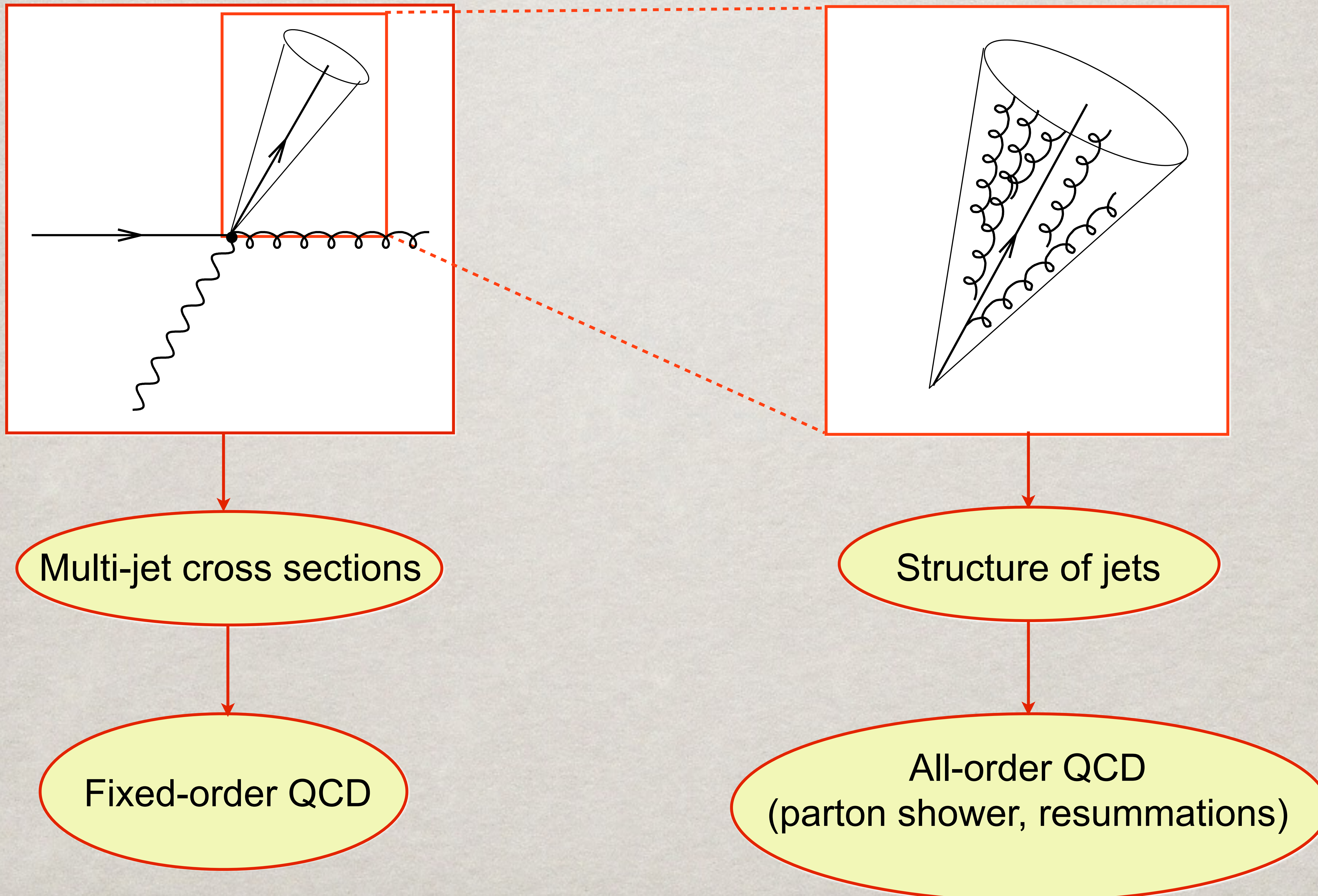
Dark matter



Black holes

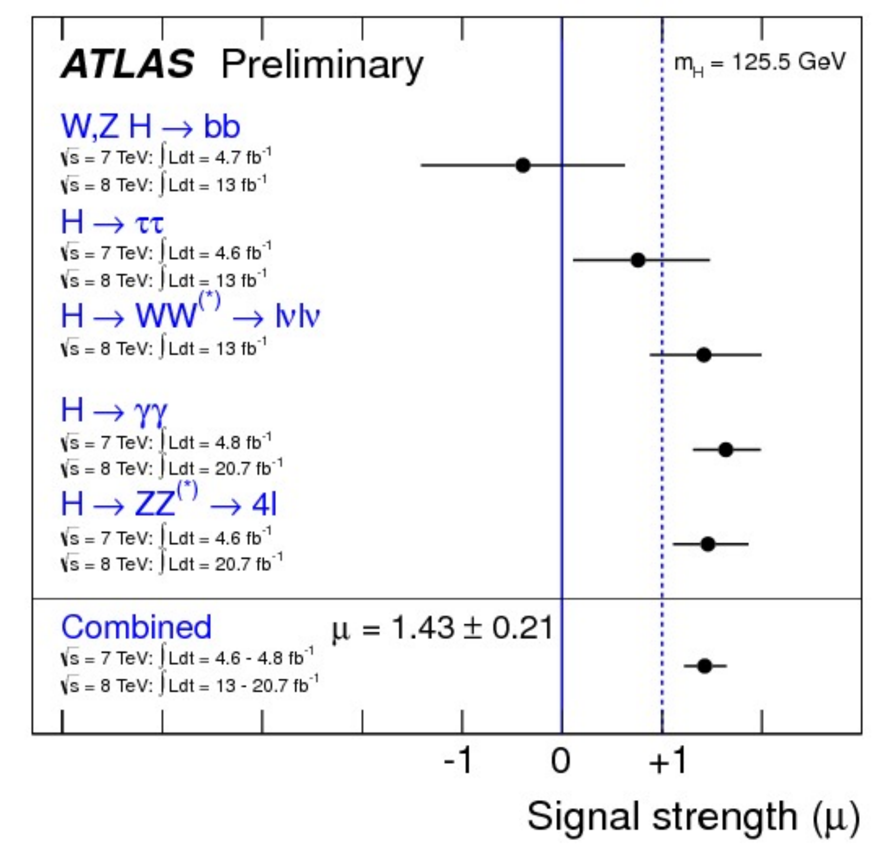
- Whatever Physics shows up at the LHC, it always involves hadronic jets, the footprints of quarks and gluons in our detectors

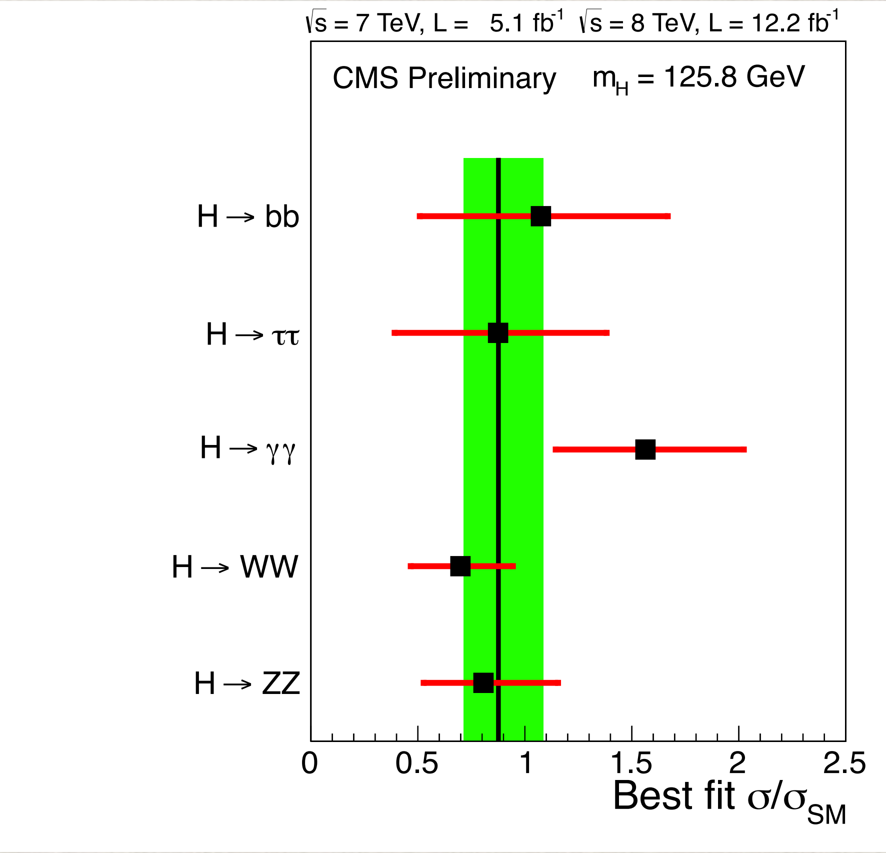
QCD as a theory of jets



Jet-veto cross sections

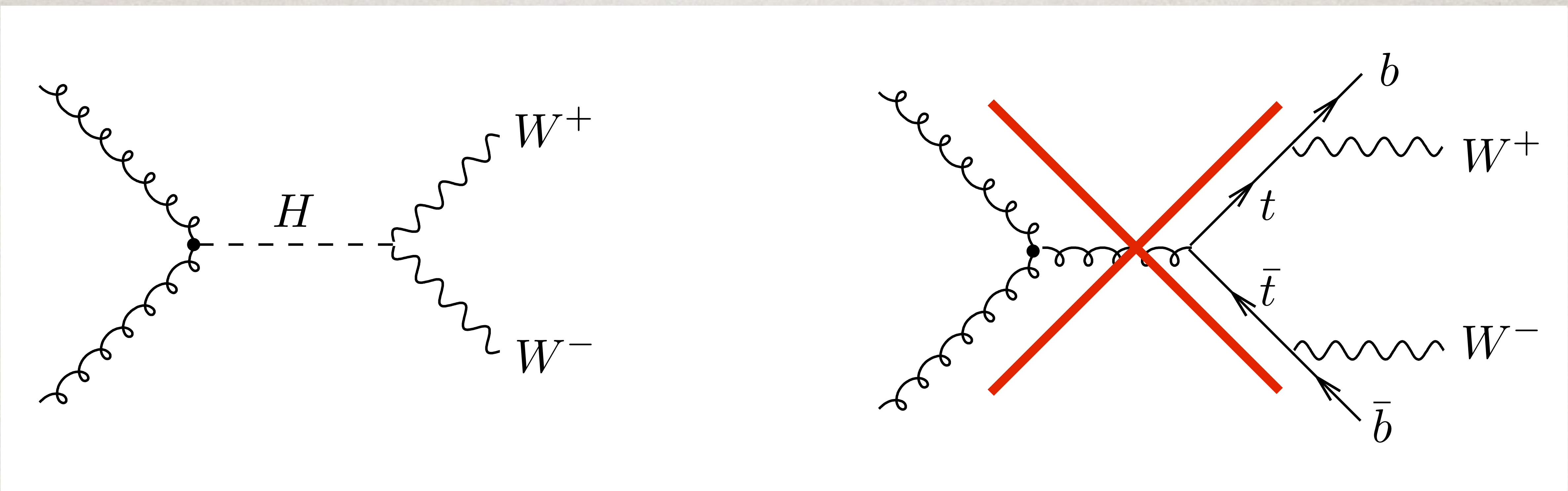
- Understanding jet-veto cross sections is crucial to establish if the recently found Higgs boson is compatible with that of the Standard Model



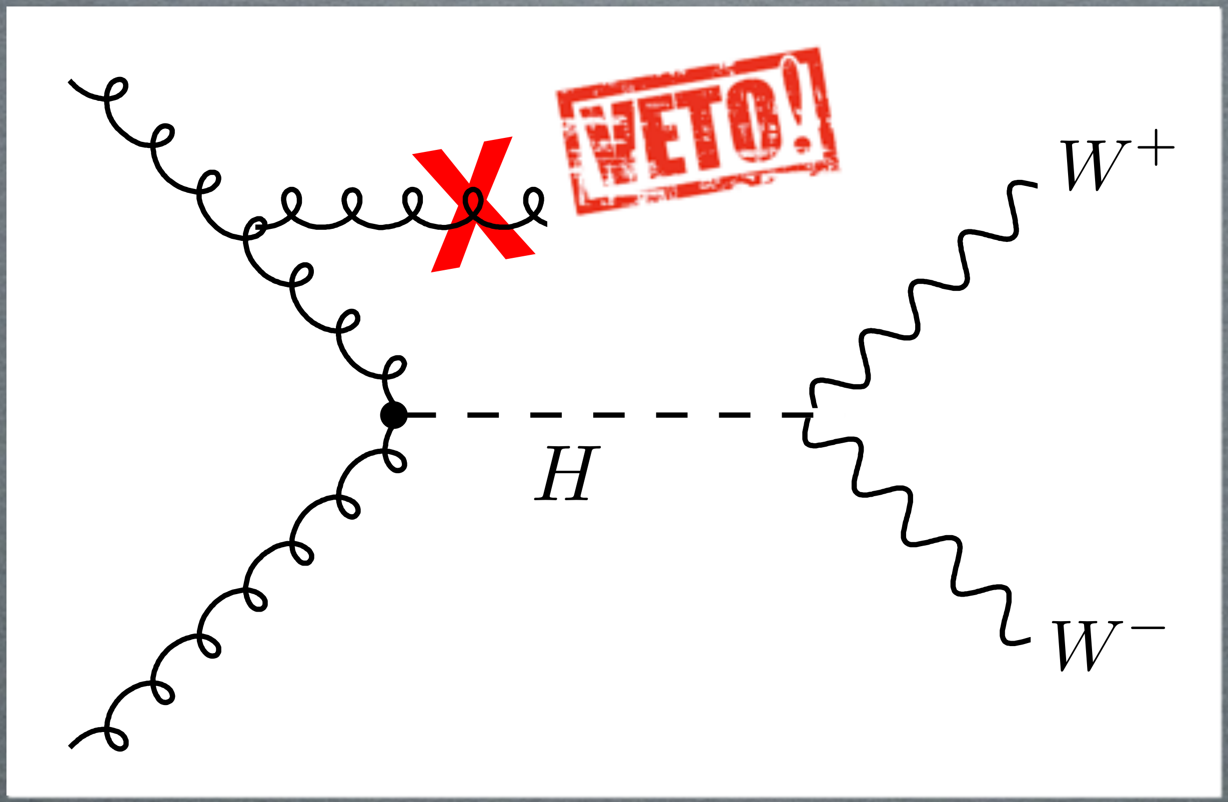


Vetoing jets: why?

- Example: Higgs decaying into WW suffers from a large background from top-antitop production



- Each top quark decays into a b-jet $\Rightarrow$ veto events with jets in the final state
- Jet-vetoes are employed in many other Higgs analyses

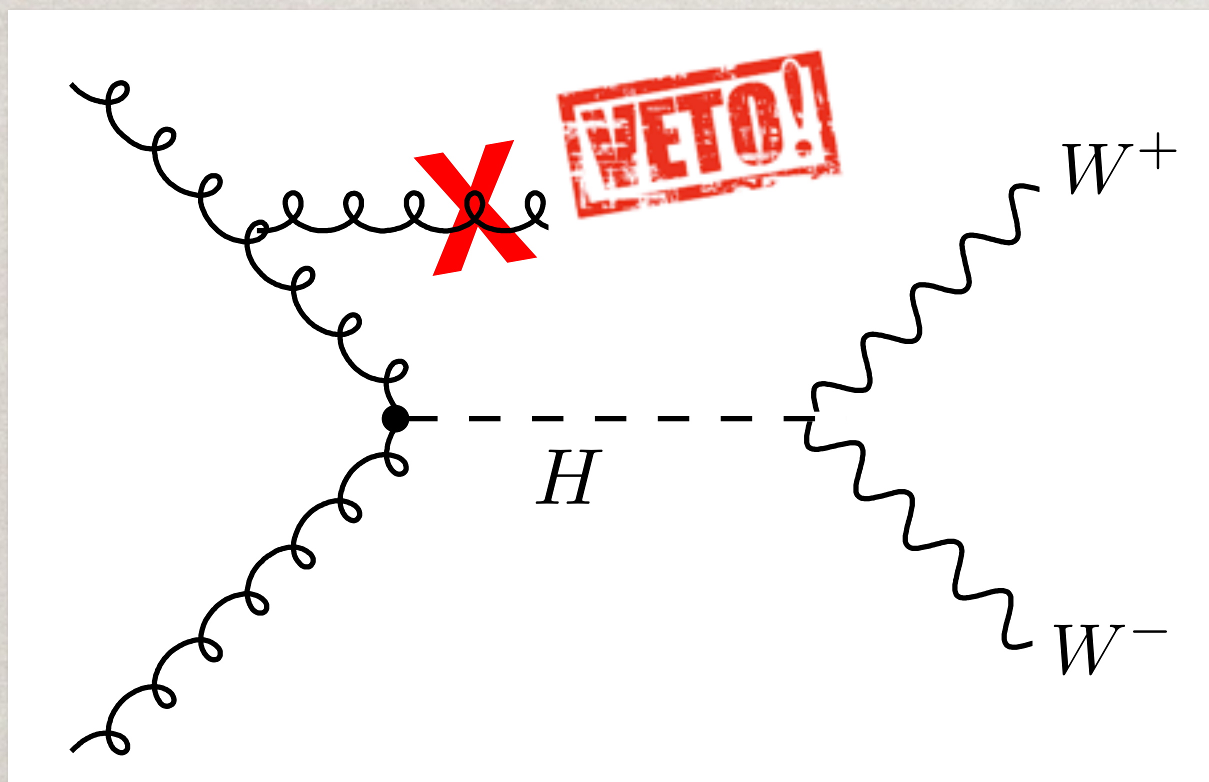


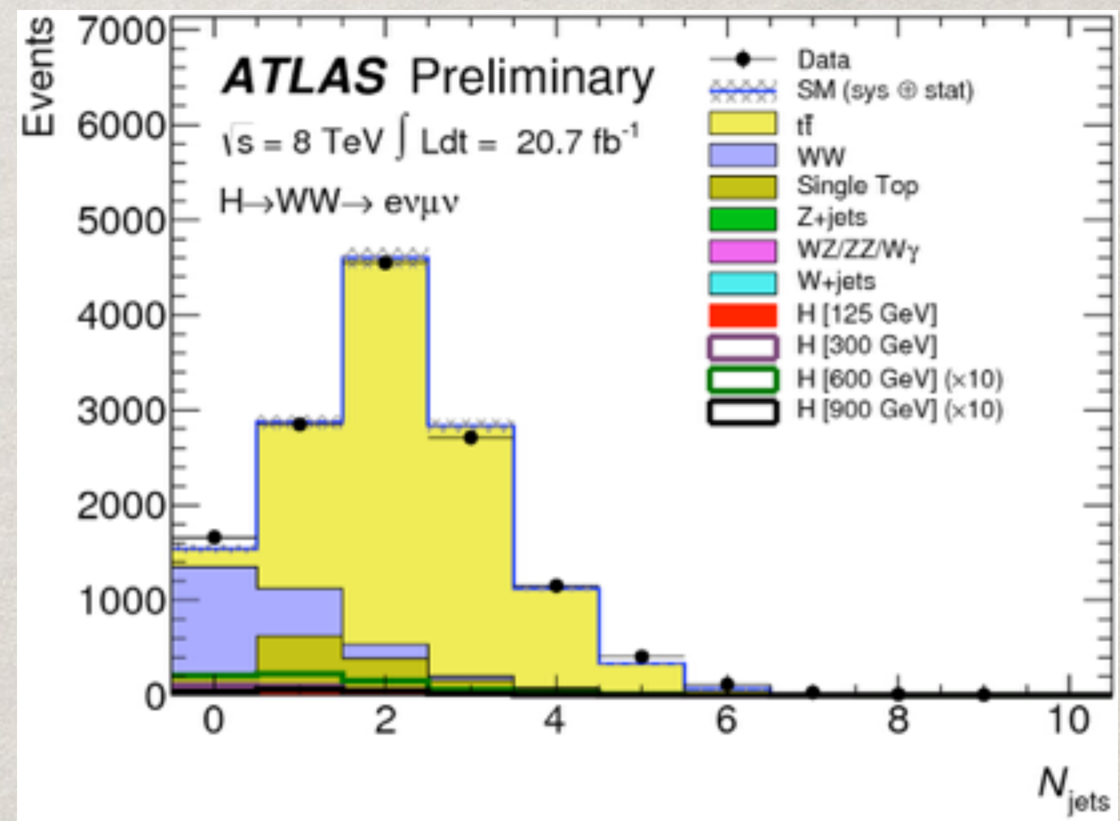
Zero-jet cross sections

Gluon fusion: Higgs to WW

- Divide events according to jet multiplicity: zero, one and two or more jets
- Zero-jet cross section ⇔ veto all jets with $p_{\mathrm{t,jet}} > p_{\mathrm{t,veto}}$

	ATLAS	CMS
0-jet selection	anti-k_T $R = 0.4$ $p_{Tj} < 25$ GeV for $\|\eta_j\| < 2.5$ $p_{Tj} < 30$ GeV for $2.5 < \|\eta_j\| < 4.5$	anti-k_T $R = 0.5$ $p_{Tj} < 30$ GeV, $\|\eta_j\| < 4.7$



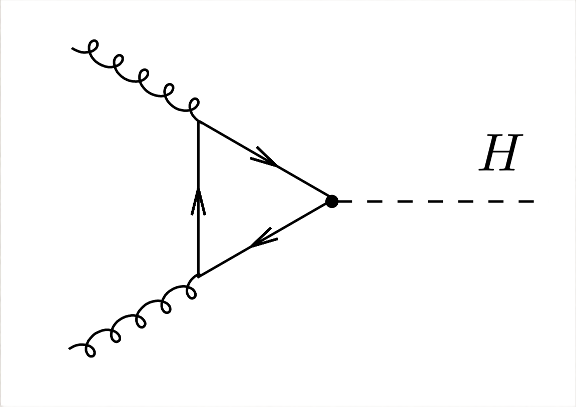


- This works well: the zero-jet cross section $\sigma_{0-\mathrm{jet}}$ is least contaminated by the huge (yellow) top-antitop background

Higgs plus zero-jets at fixed order

- The Higgs cross section in gluon fusion has been computed at very high accuracy

$$d\sigma_{\geq 0-\mathrm{jet}} \sim \alpha_s^2 \left(1 + \underbrace{\alpha_s}_{\mathrm{NLO}} + \underbrace{\alpha_s^2}_{\mathrm{NNLO}} + \ldots \right)$$



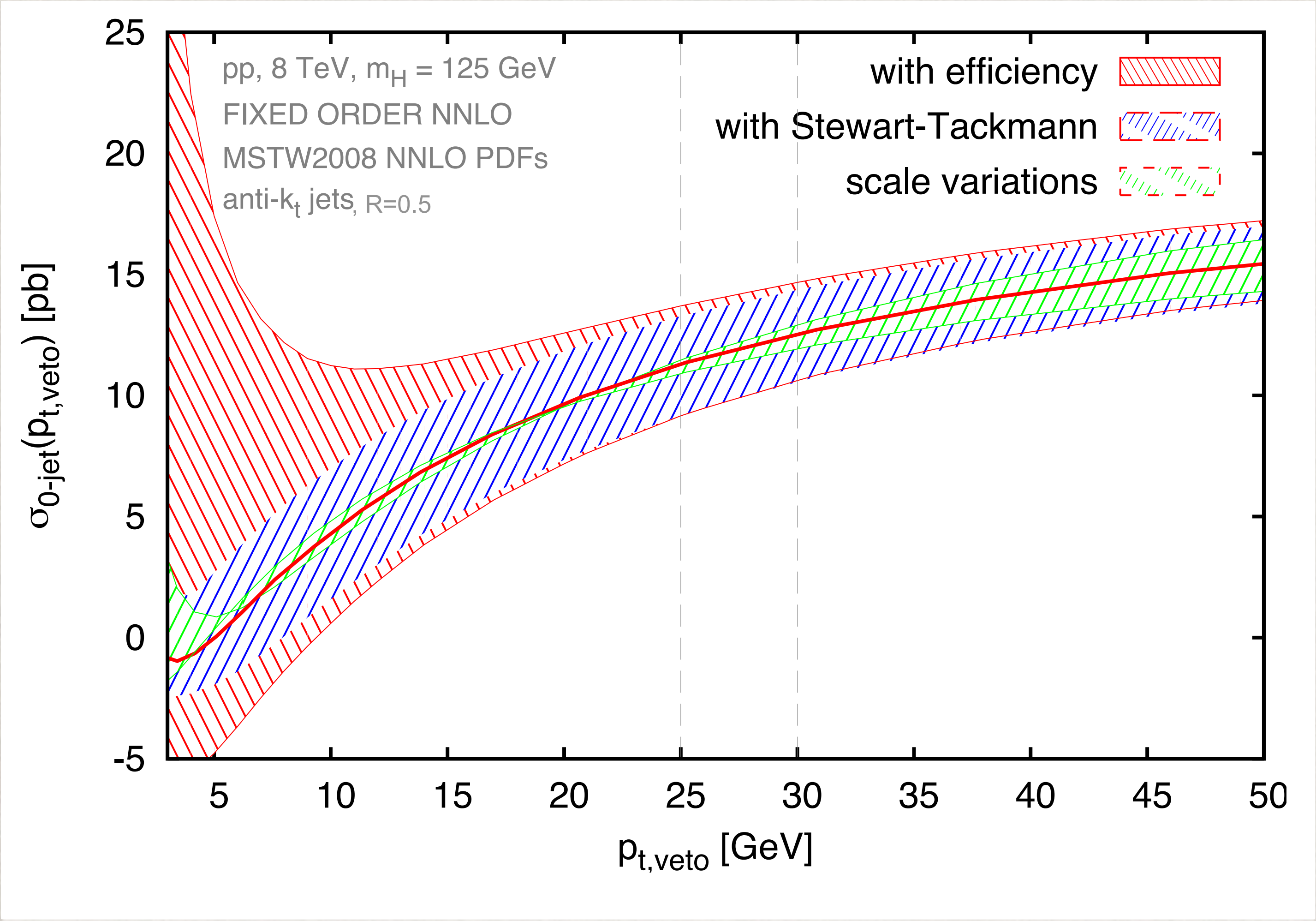
finite m_t, m_b	NLO	[Spira et al. NPB 453 (1995) 17]
large- m_t	NNLO	[Anastasiou Melnikov Petriello NPB 724 (2005) 197] [Catani Grazzini PRL 98 (2007) 222002]
large-m_W	QCD-EW	[Anastasiou Boughezal Petriello JHEP 04 (2009) 003]

- Uncertainties in the Higgs total cross section σ_{tot} are small, of order 7-8%
- These calculations are implemented in computer codes (FEHiP, HNNLO) producing exclusive events $\Rightarrow$ directly compute $\sigma_{0-\mathrm{jet}}$ at NNLO
- First steps have been made towards NNNLO

[see e.g. Anastasiou et al. 1302.4379 and 1311.1425]

Need for resummation

- At fixed-order, various ways of treating uncertainties (scale variations, Stewart-Tackmann, efficiency method) give different results



- Origin of instability: large logarithms $\ln(m_H/p_{\rm t,veto})$ at all orders in the perturbative expansion $\Rightarrow$ all order resummation needed

Zero-jet resummations

- We have performed NNLL resummation matched to NNLO, and implemented it in the code JetVHeto http://jetvheto.hepforge.org/

[AB Monni Salam Zanderighi Phys.Rev.Lett. 109 (2012) 202001]

- Our results have been independently confirmed by two different groups in the framework of Soft-Collinear Effective Theory (SCET)

[Becher Neubert JHEP 07 (2012) 108]
[Becher Neubert Rothen 1307.0025]
[Stewart Tackmann Walsh Zuberi 1307.1808]

Recent improvements:

- Ingredients beyond NNLL accuracy

[Becher Neubert Rothen 1307.0025]
[Stewart Tackmann Walsh Zuberi 1307.1808]

- Effect of top and bottom masses in loops

[AB Monni Zanderighi 1308.4634]

Zero-jet resummation summary

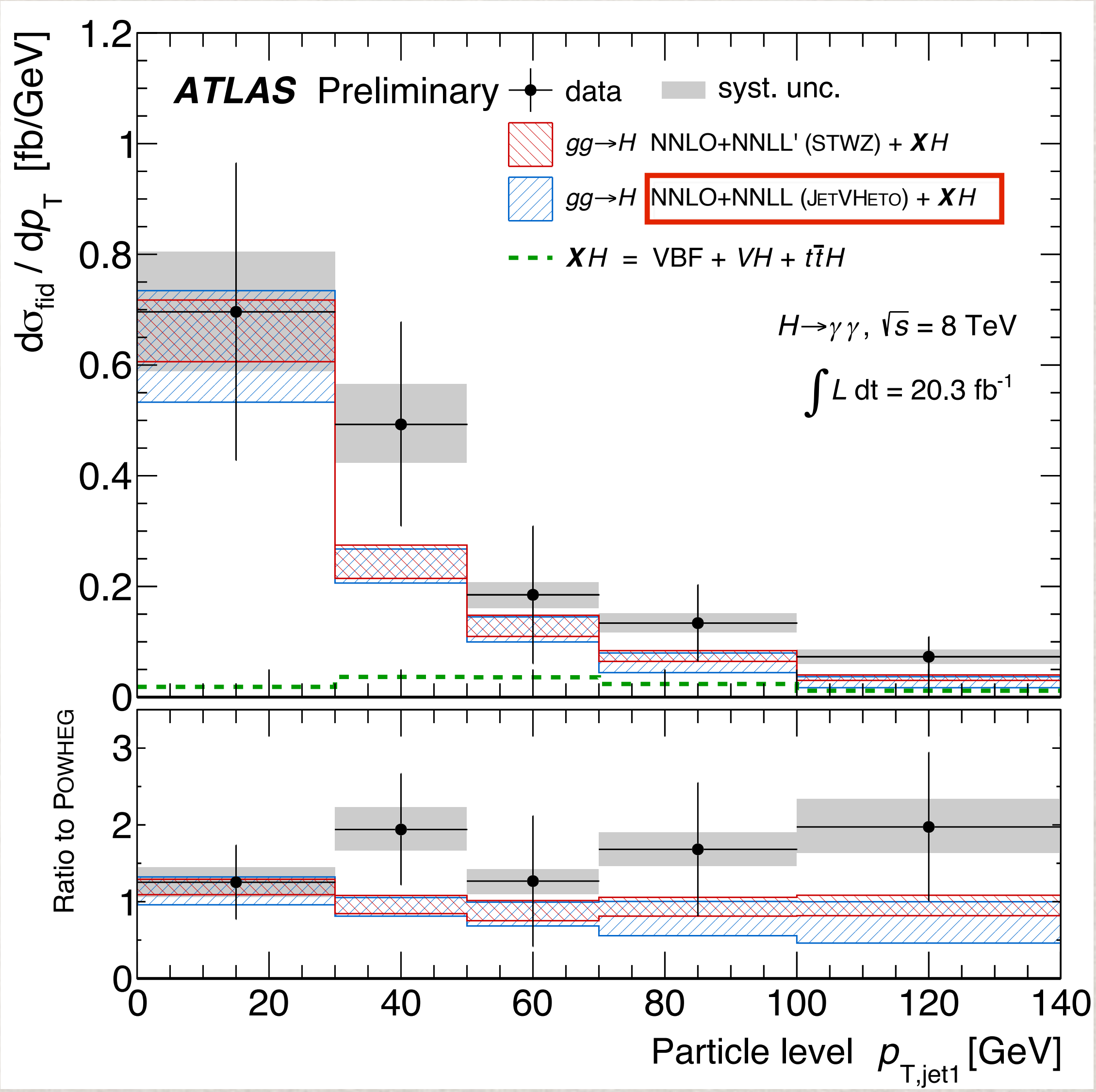
LHC $\sqrt{s} = 8\,\mathrm{TeV}$ MSTW2008NNLO

	$\sigma_{0-\mathrm{jet}}(25\,\mathrm{GeV}, R=0.4)\,[\mathrm{pb}]$	$\sigma_{0-\mathrm{jet}}(30\,\mathrm{GeV}, R=0.5)\,[\mathrm{pb}]$	
BMSZ	11.81 ± 1.51	12.86 ± 1.47	large-m_t
B'NR	$11.25^{+0.77\ (+0.65)}_{-1.25\ (-1.15)}$	n/a	large-m_t
STWZ'	$12.67 \pm 1.22_{\mathrm{pert}}(\pm 0.46_{\mathrm{clust}})$	$13.85 \pm 0.87_{\mathrm{pert}}(\pm 0.24_{\mathrm{clust}})$	large-m_t
BMZ	11.59 ± 1.72	12.64 ± 1.79	exact m_t, m_b

- All results are compatible within uncertainties
- Theoretical uncertainties are between 10% and 15%
- Inclusion of mass effects increases the uncertainty

Resummations vs data

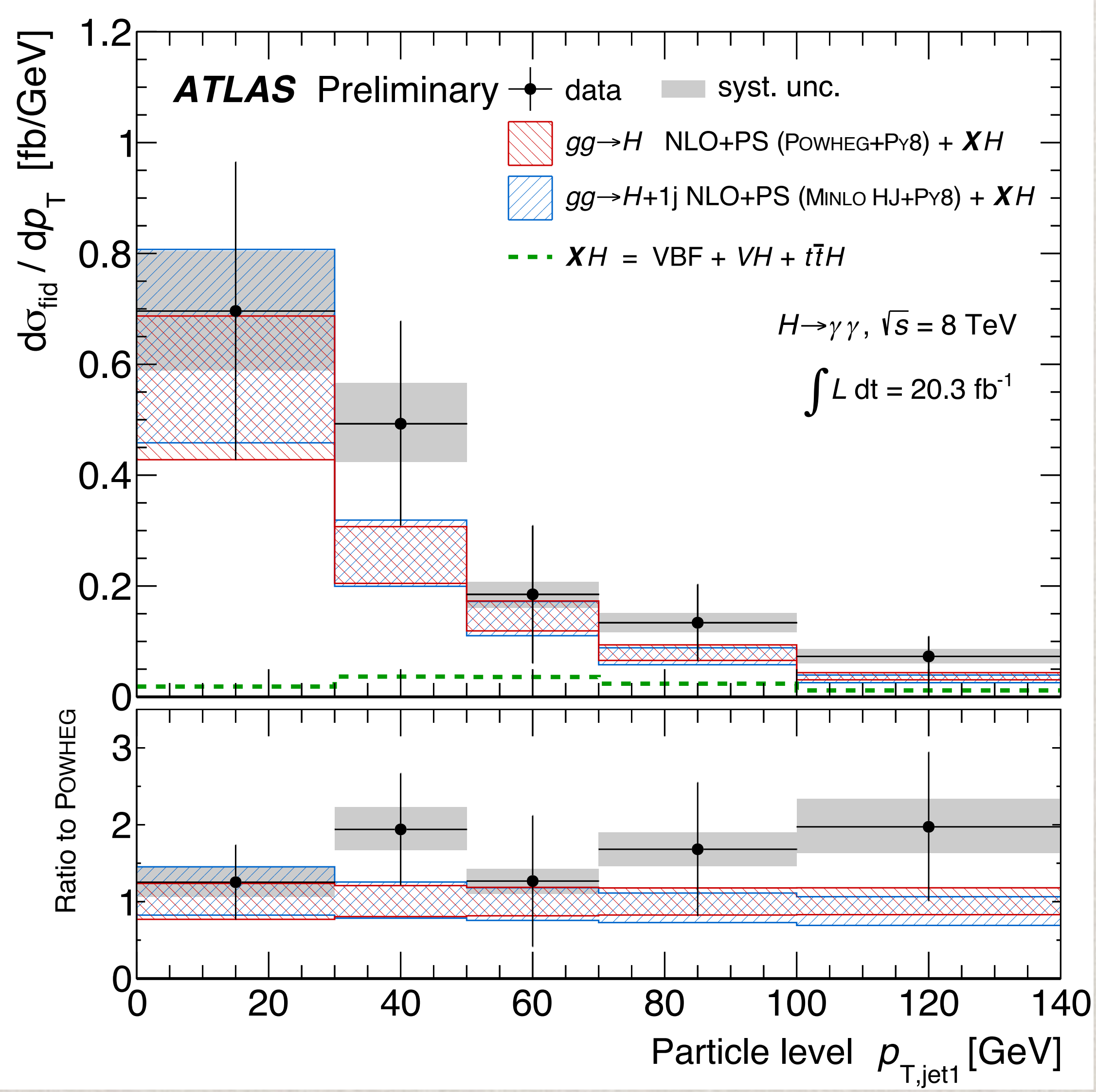
- With existing data it is already possible to have a measurement of $\sigma_{0-\mathrm{jet}}$ and perform comparison with NNLL+NNLO resummations



- Good agreement with data in the zero-jet bin p_t
- The leading-jet p_t spectrum is underestimated at high p_t

Monte Carlo vs data

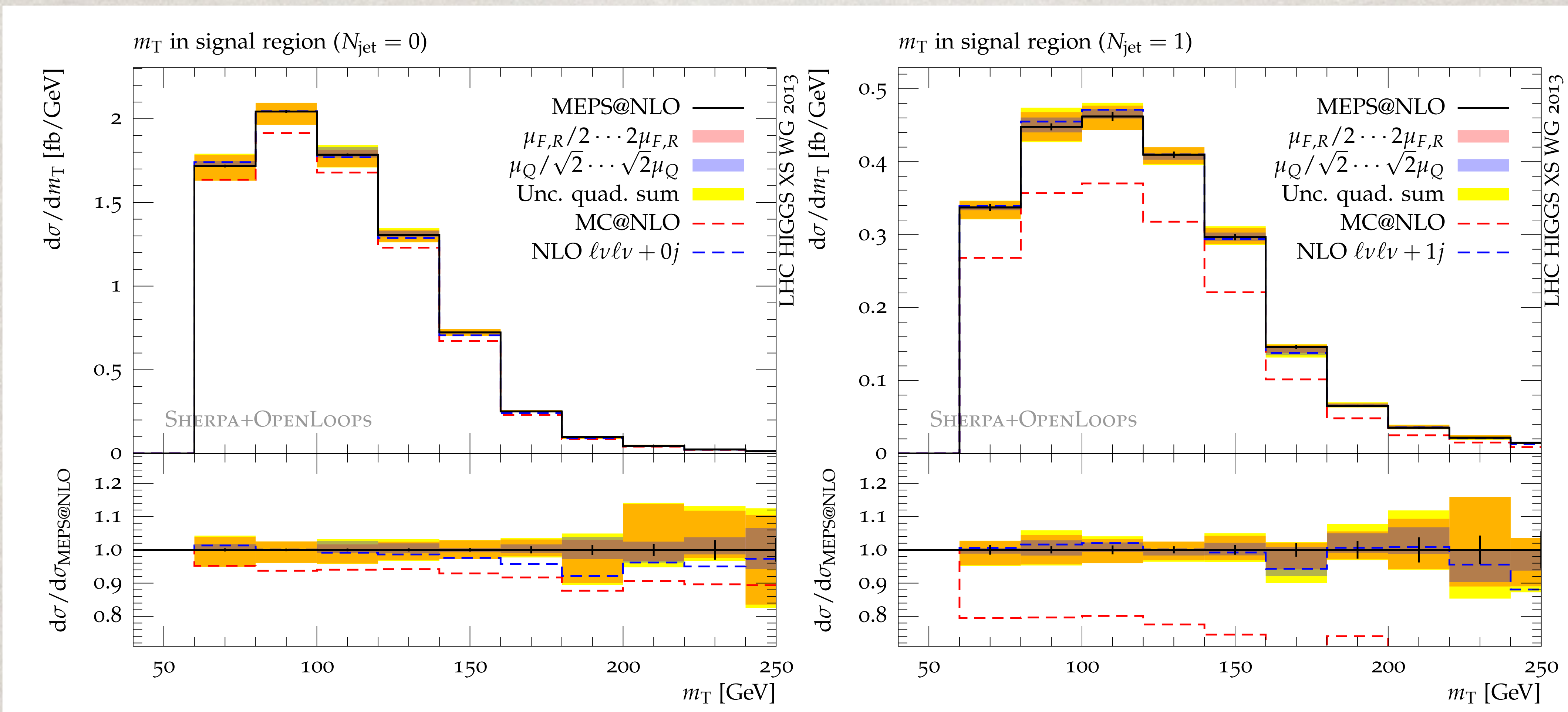
- Monte Carlo event generators simulate soft and collinear emissions at all orders (parton shower) : they are valuable alternatives for resummation



- Monte Carlo produce fully exclusive events at hadron level, ready to be interfaced with experimental detector simulations

Monte Carlo recent progress (I)

- State-of-the-art for Monte Carlo event generators is matching of parton shower with NLO calculations (POWHEG and MC@NLO)



- New methods to merge different jet multiplicities ensuring NLO accuracy for each multiplicity (MEPS@NLO, HJ-MiNLO)

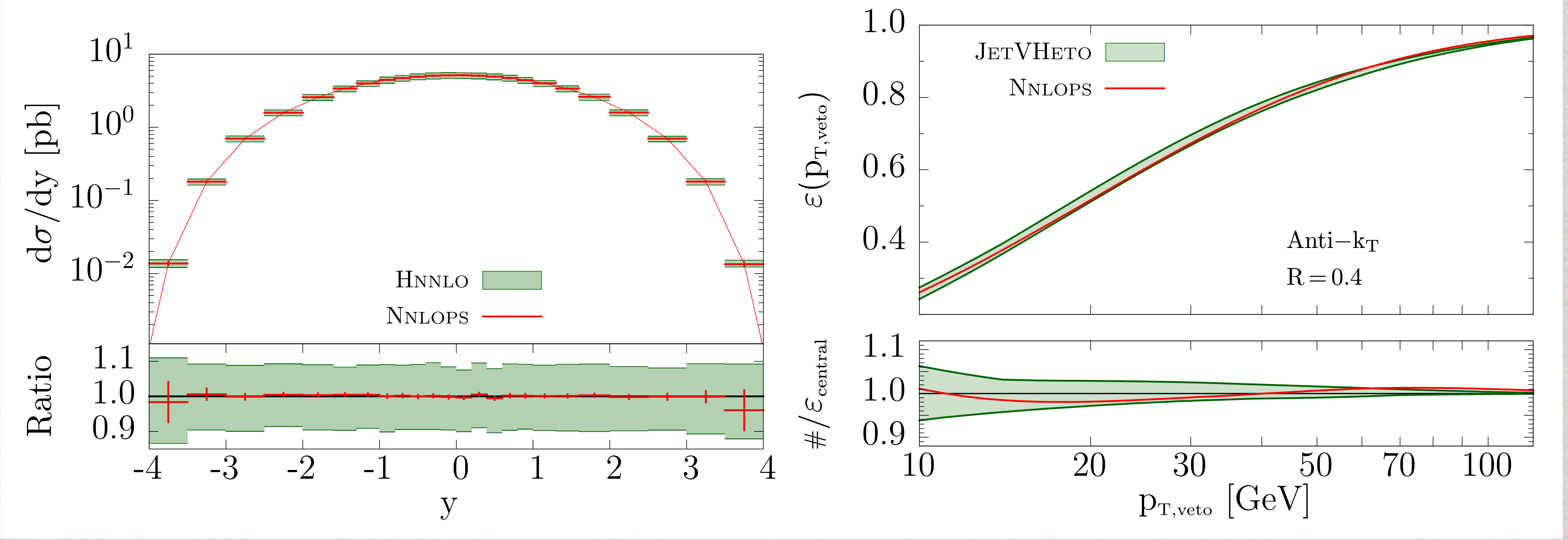
[Hoeche Krauss Schoenherr Siegert JHEP 04 (2013) 027]

[Hamilton Nason Oleari Zanderighi JHEP 08 (2013) 082]

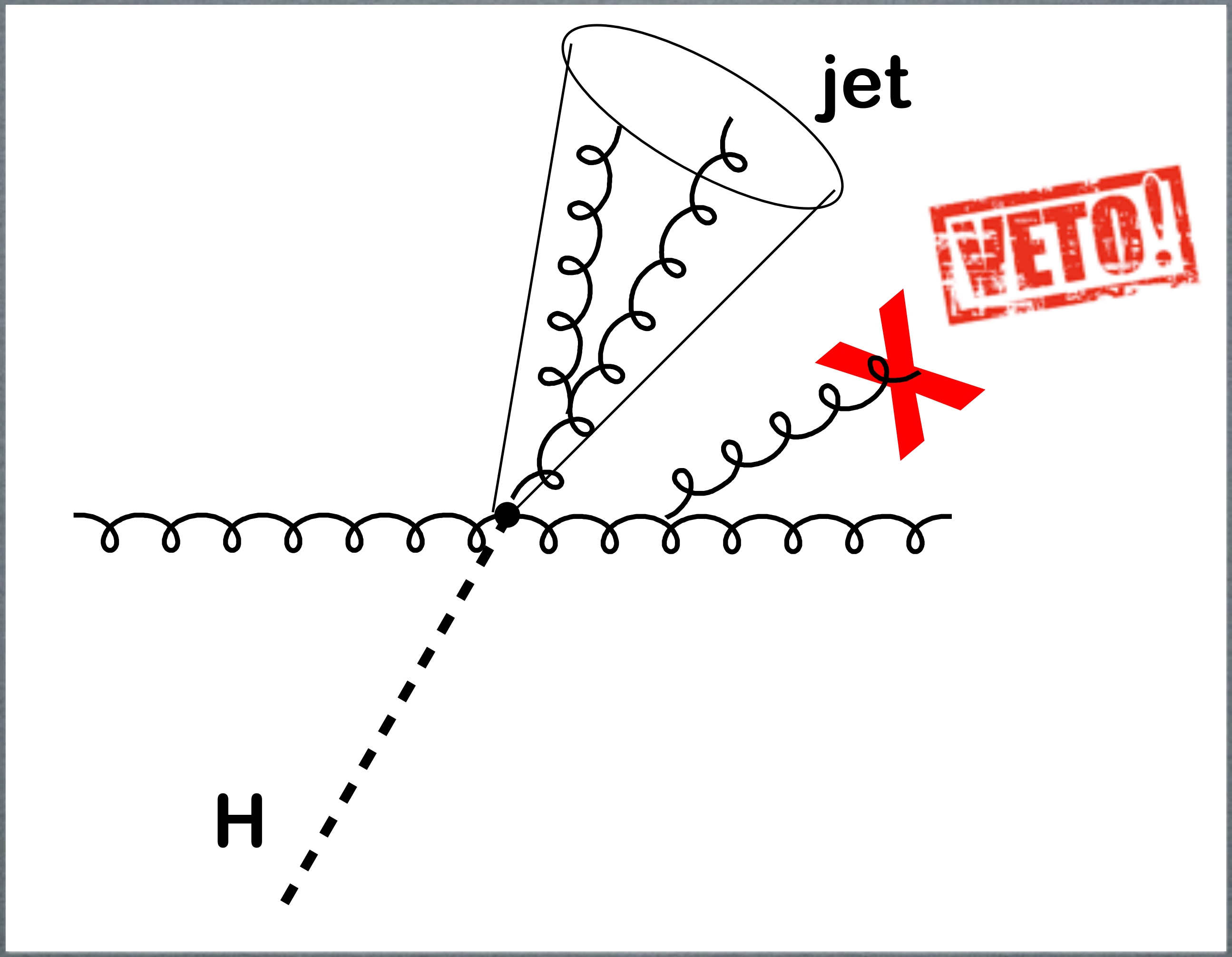
Monte Carlo recent progress (II)

- Improved HJ-MiNLO procedure gives the first parton shower that ensure NNLO accuracy for the Higgs total cross section!

[Hamilton Nason Re Zanderighi JHEP 10 (2013) 222]



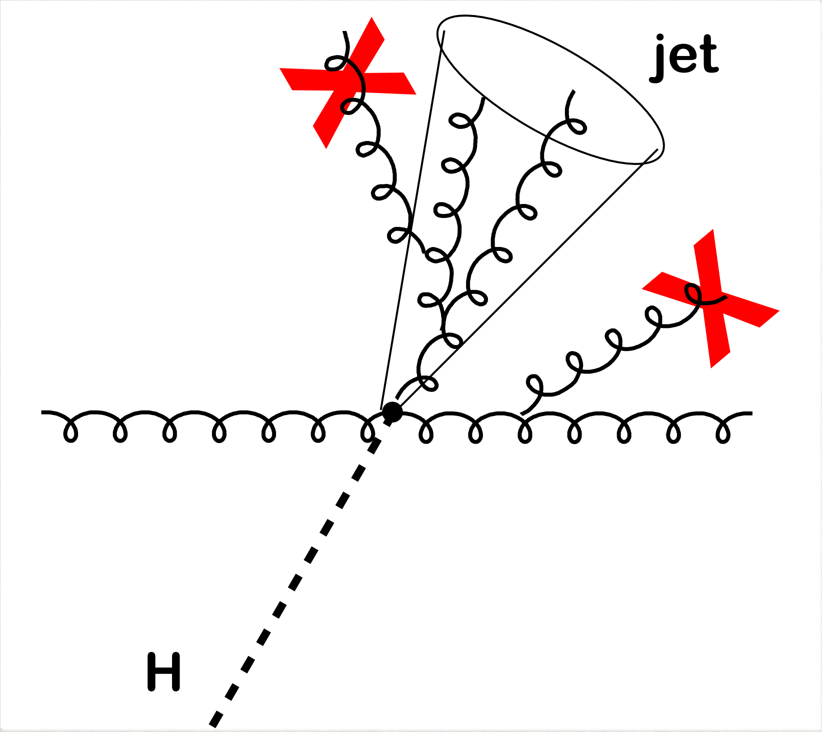
- Overall, very good agreement between Monte Carlo and analytic resummations for the zero-jet cross section

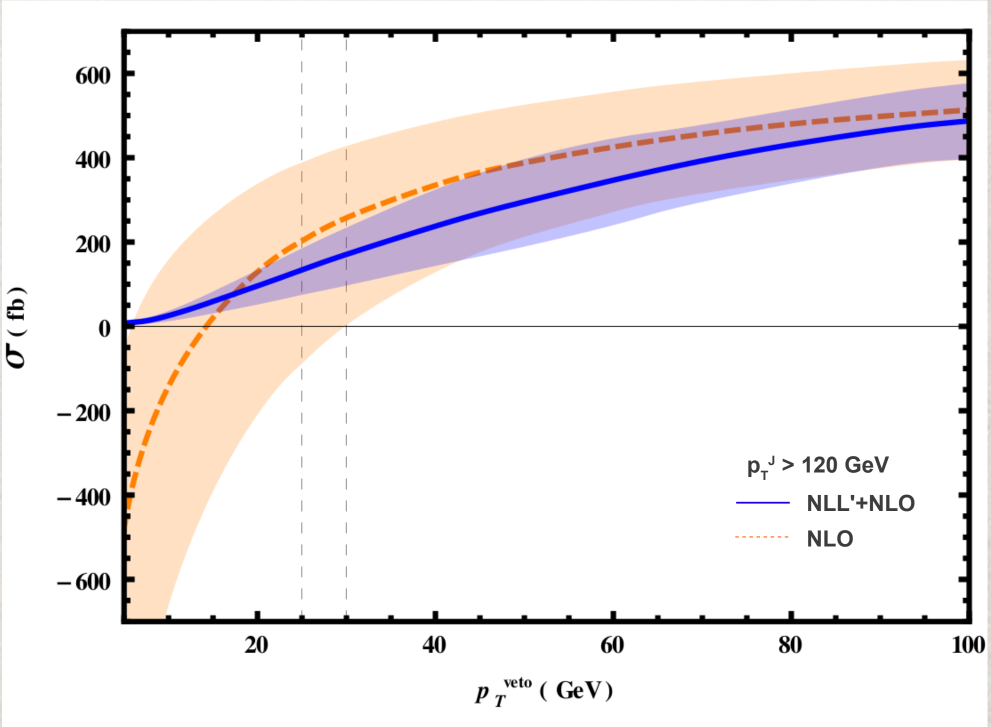


One-jet cross sections

Resummed one-jet cross section

- The region $p_{\mathrm{t,jet}} \gg p_{\mathrm{t,veto}}$ is responsible for 50% of the uncertainties of the one-jet bin $\Rightarrow$ resummation of $\ln(p_{\mathrm{t,jet}}/p_{\mathrm{t,veto}})$ needed





- Resummation performed in SCET at NLL accuracy matched to NLO

[Liu Petriello Phys.Rev. D87 (2013) 014018, Phys.Rev. D87 (2013) 094027]

- Resummation gives a reduction of theoretical uncertainties

$$\sigma^{\mathrm{NLO}}_{1-\mathrm{jet}}(25\,\mathrm{GeV}) = 5.85^{+34\%}_{-46\%} \longrightarrow \sigma^{\mathrm{NLL'+NLO}}_{1-\mathrm{jet}}(25\,\mathrm{GeV}) = 5.55^{+29\%}_{-30\%}$$

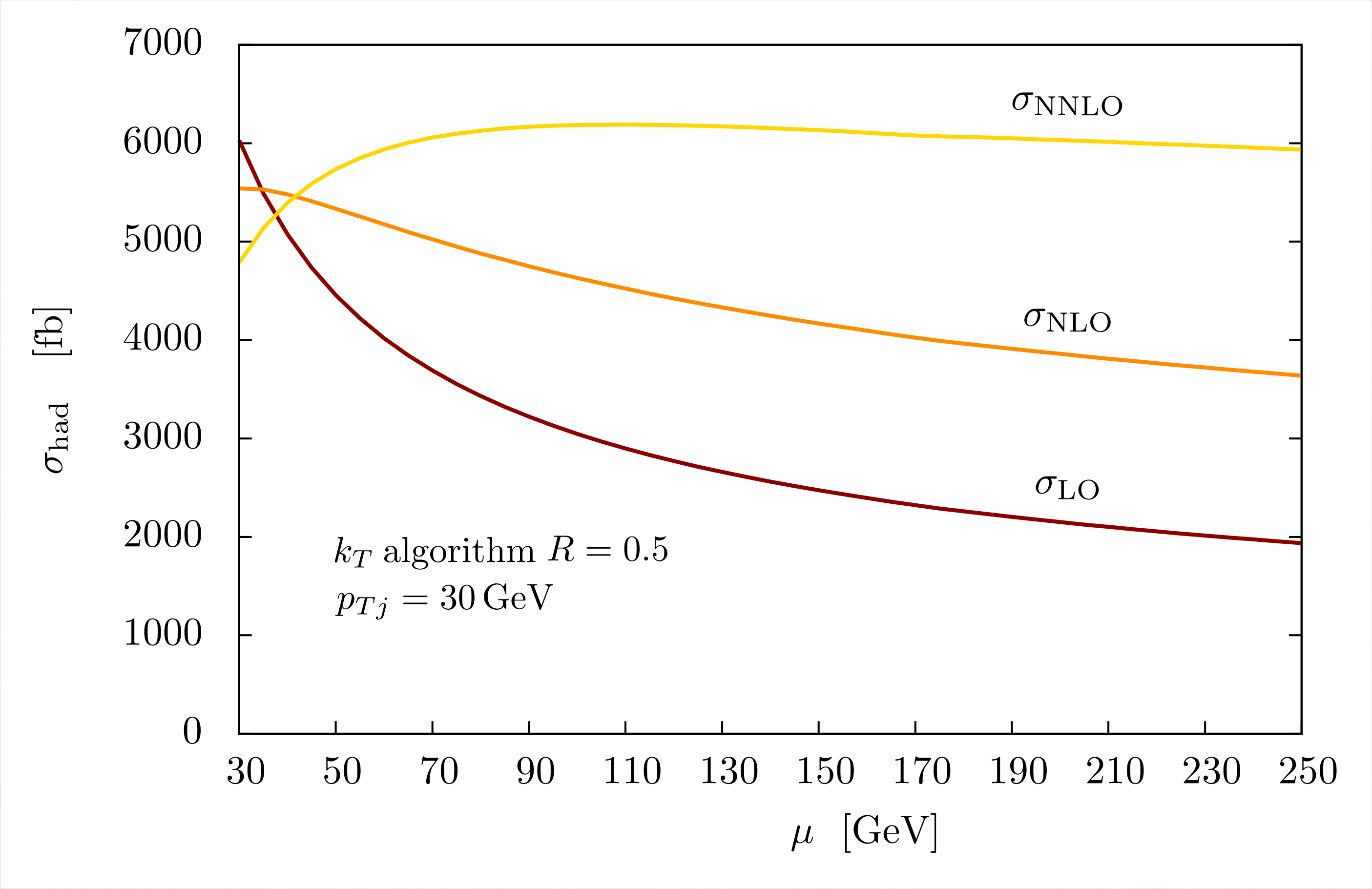
One jet at fixed order

- Origin of the large (50%) uncertainty in the one-jet bin is that $\sigma_{\geq 1-\mathrm{jet}}$ is known at NLO only (in the large-m_t limit)

One jet at fixed order

- Origin of the large (50%) uncertainty in the one-jet bin is that $\sigma_{\geq 1-\mathrm{jet}}$ is known at NLO only (in the large-m_t limit)
- Recent advances in NNLO methods made it possible to obtain $\sigma_{\geq 1-\mathrm{jet}}$ at NNLO for the gluon-gluon channel

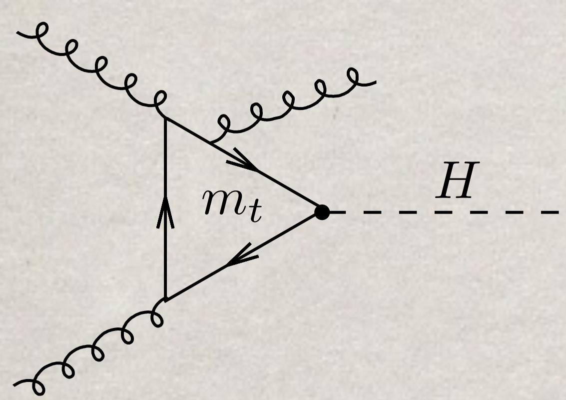
[Boughezal Caola Melnikov Petriello Schulze JHEP 06 (2013) 072]

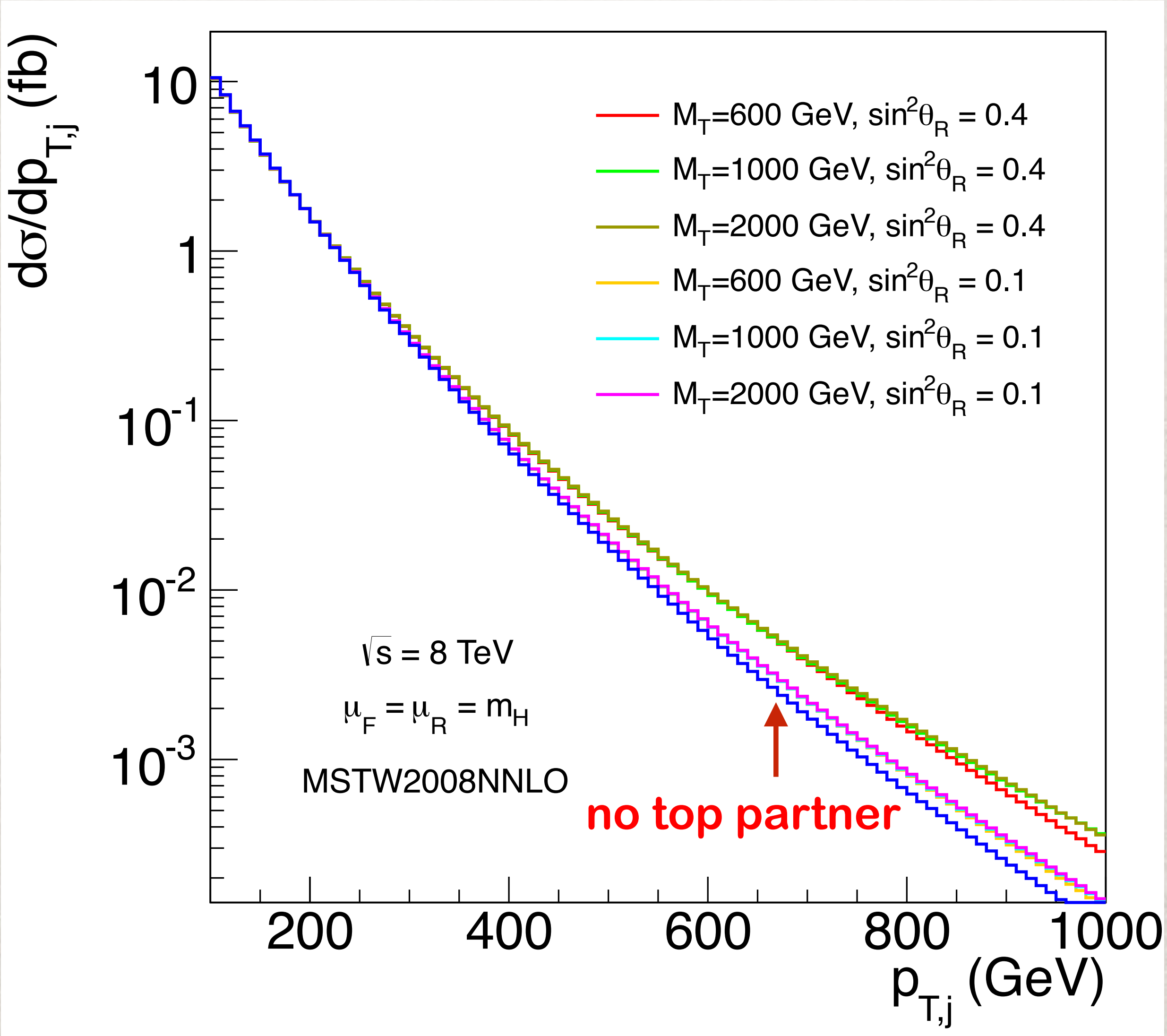


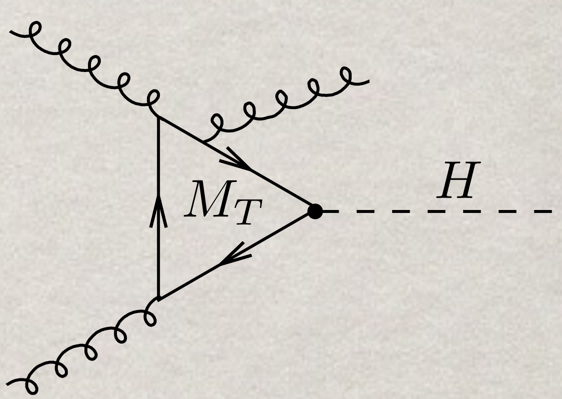
- The full NNLO should be available soon…

Finite masses at high pt

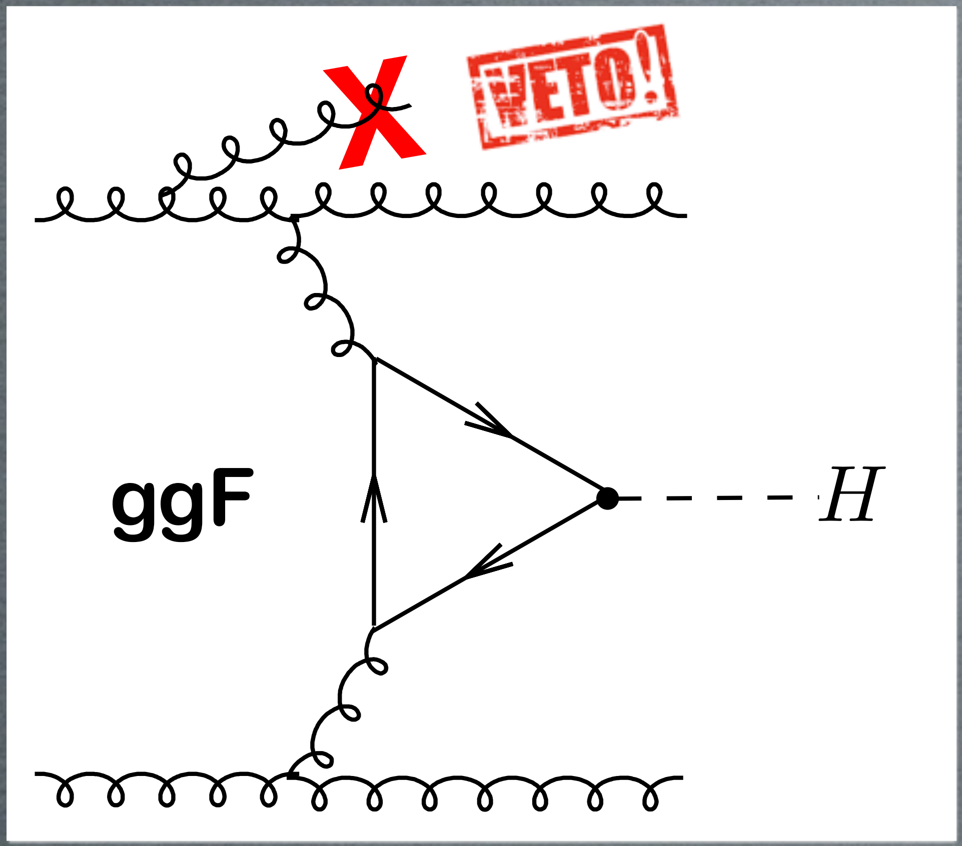
- A high-p_t gluon can resolve a loop with a top partner of mass M_T mixing with the top through an angle θ_R [AB Martin Sanz 1308.4771]

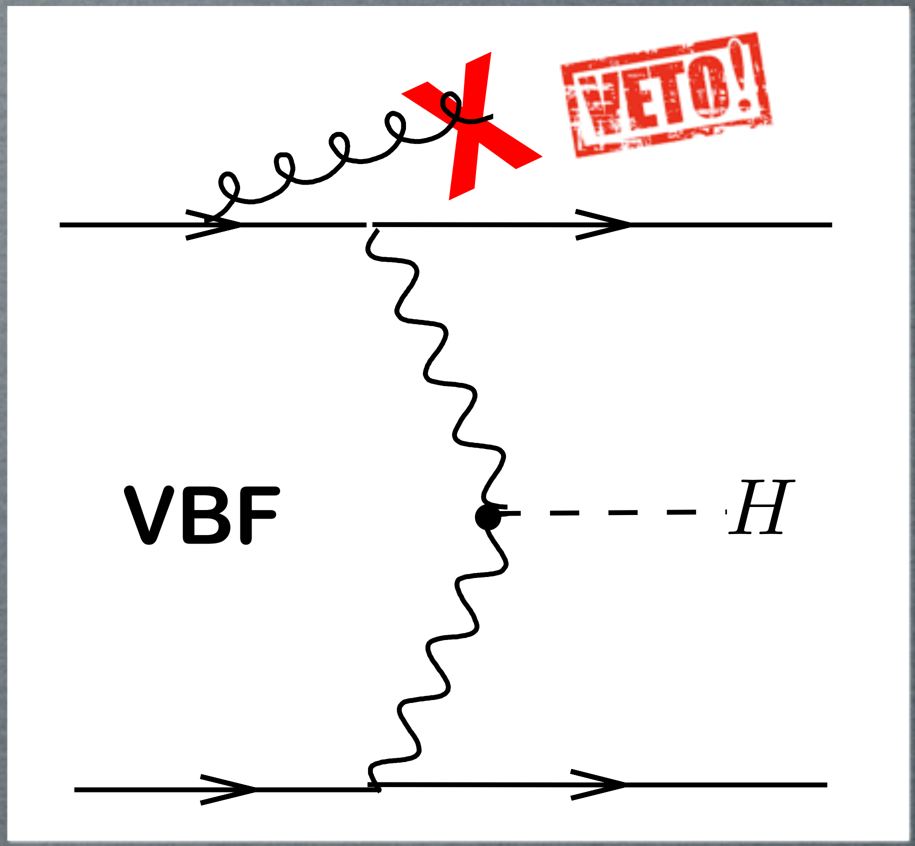






- Need perturbative control on the tail of jet-p_t distribution, where $\ln(p_{\mathrm{t,j}}/m_t)$ is large $\Rightarrow$ case for higher order corrections

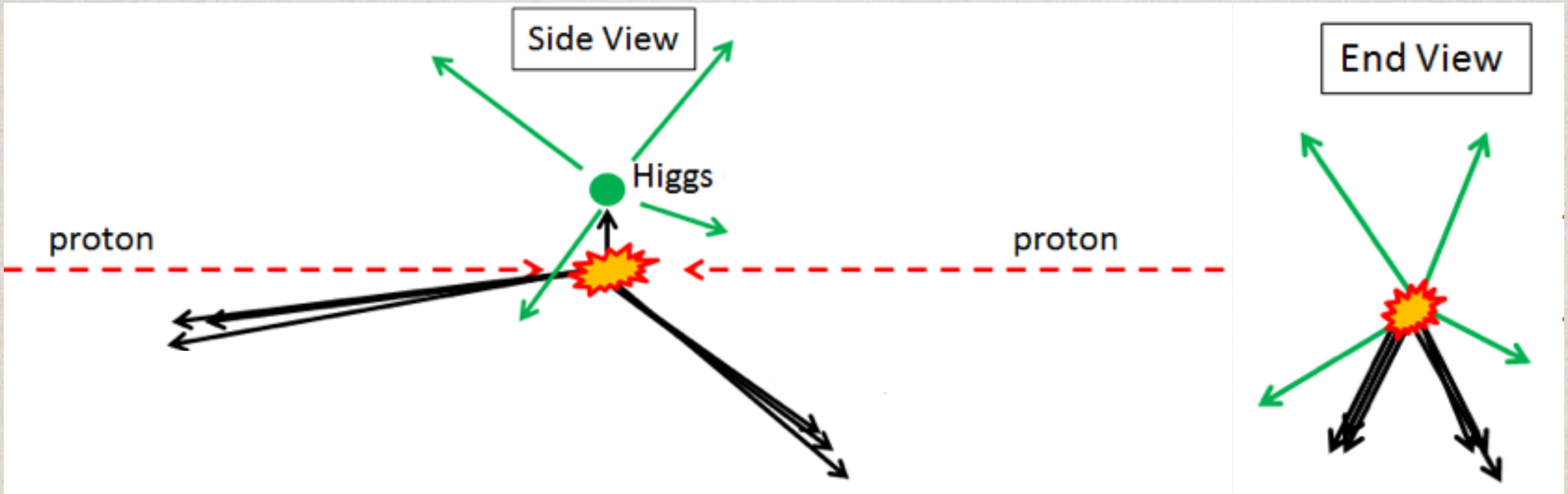




Two-jet cross sections

Two jets: VFB vs ggF

- In VBF events the Higgs tends to recoil against the two forward jets



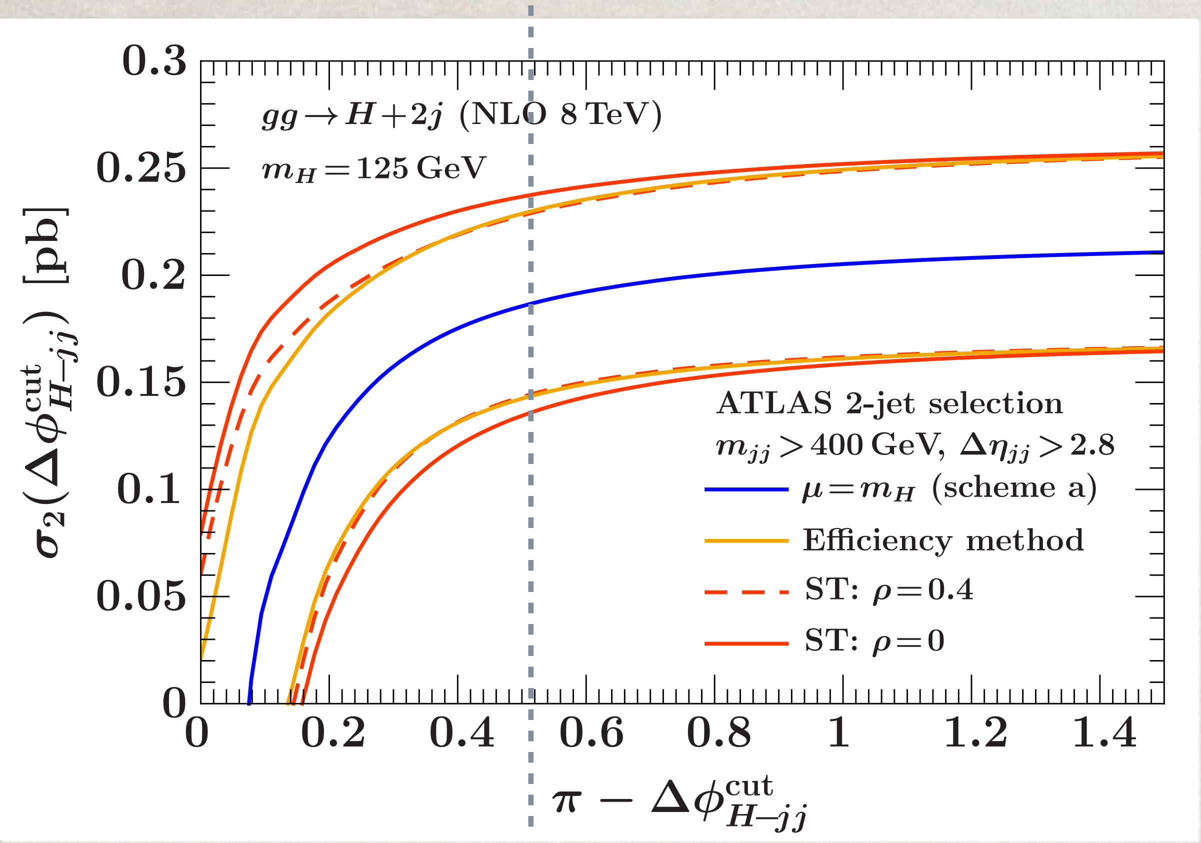
	ATLAS	CMS loose	CMS tight
2-jet selection	anti-k_T $R = 0.4$ $p_{Tj} > 25\,\text{GeV}$ for $\lvert\eta_j\rvert < 2.5$ $p_{Tj} > 30\,\text{GeV}$ for $2.5 < \lvert\eta_j\rvert < 4.5$	anti-k_T $R = 0.5$ jet 1: $p_{Tj} > 30\,\text{GeV}$, $\lvert\eta_j\rvert < 4.7$ jet 2: $p_{Tj} > 20\,\text{GeV}$, $\lvert\eta_j\rvert < 4.7$	anti-k_T $R = 0.5$ $p_{Tj} > 30\,\text{GeV}$, $\lvert\eta_j\rvert < 4.7$
$\Delta\eta_{jj} = \lvert\eta_{j1} - \eta_{j2}\rvert$	> 2.8	> 3.0	> 3.0
m_{jj}	$> 400\,\text{GeV}$	$> 250\,\text{GeV}$	$> 500\,\text{GeV}$
$\lvert\eta_H - (\eta_{j1} + \eta_{j2})/2\rvert$	-	< 2.5	< 2.5
$\Delta\phi_{H-jj}$	> 2.6	> 2.6	> 2.6

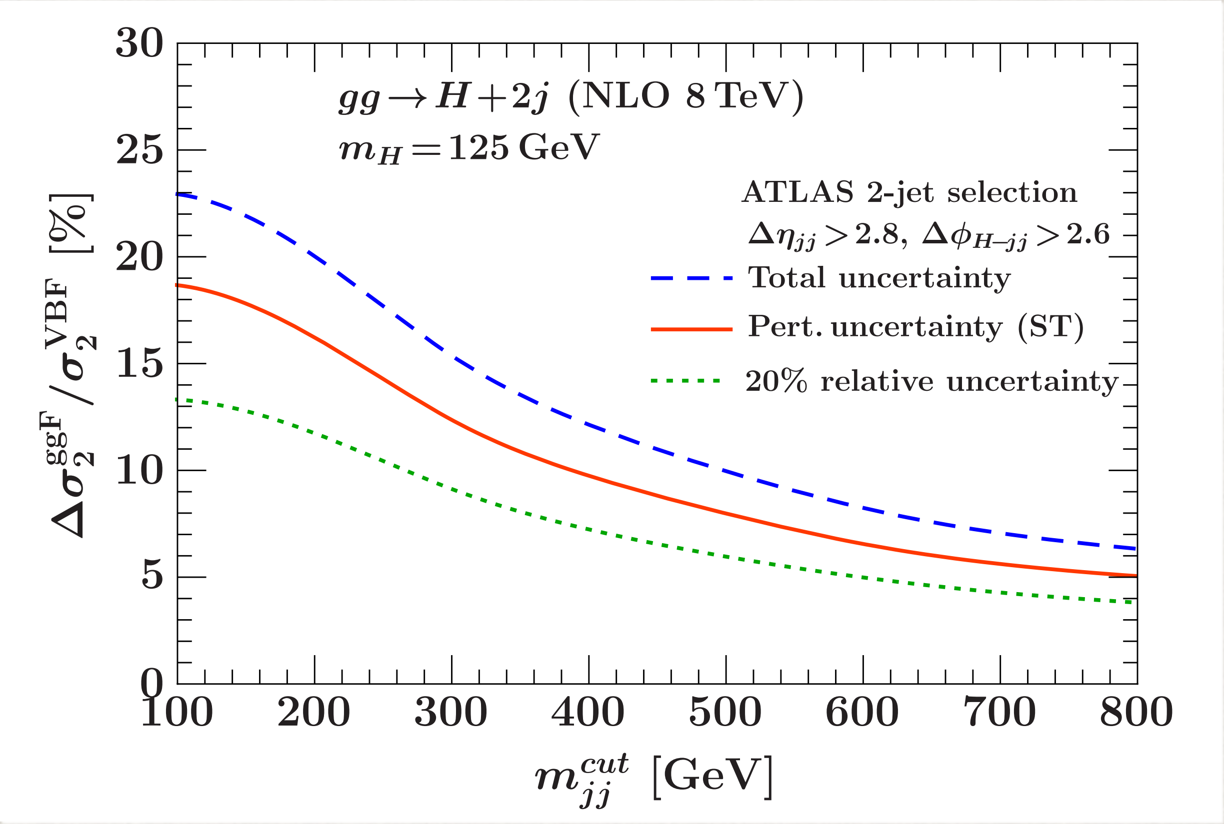
- Extra jet veto condition $\Leftrightarrow$ cut on $\Delta\phi_{H-jj}$

Two-jet uncertainties

- A cut $\Delta\phi_{H-jj} > 2.6$ is sensitive to higher order effects $\Rightarrow$ careful estimate of NLO uncertainties of gluon fusion using different methods

[Gangal Tackmann Phys.Rev. D87 (2013) 093008]

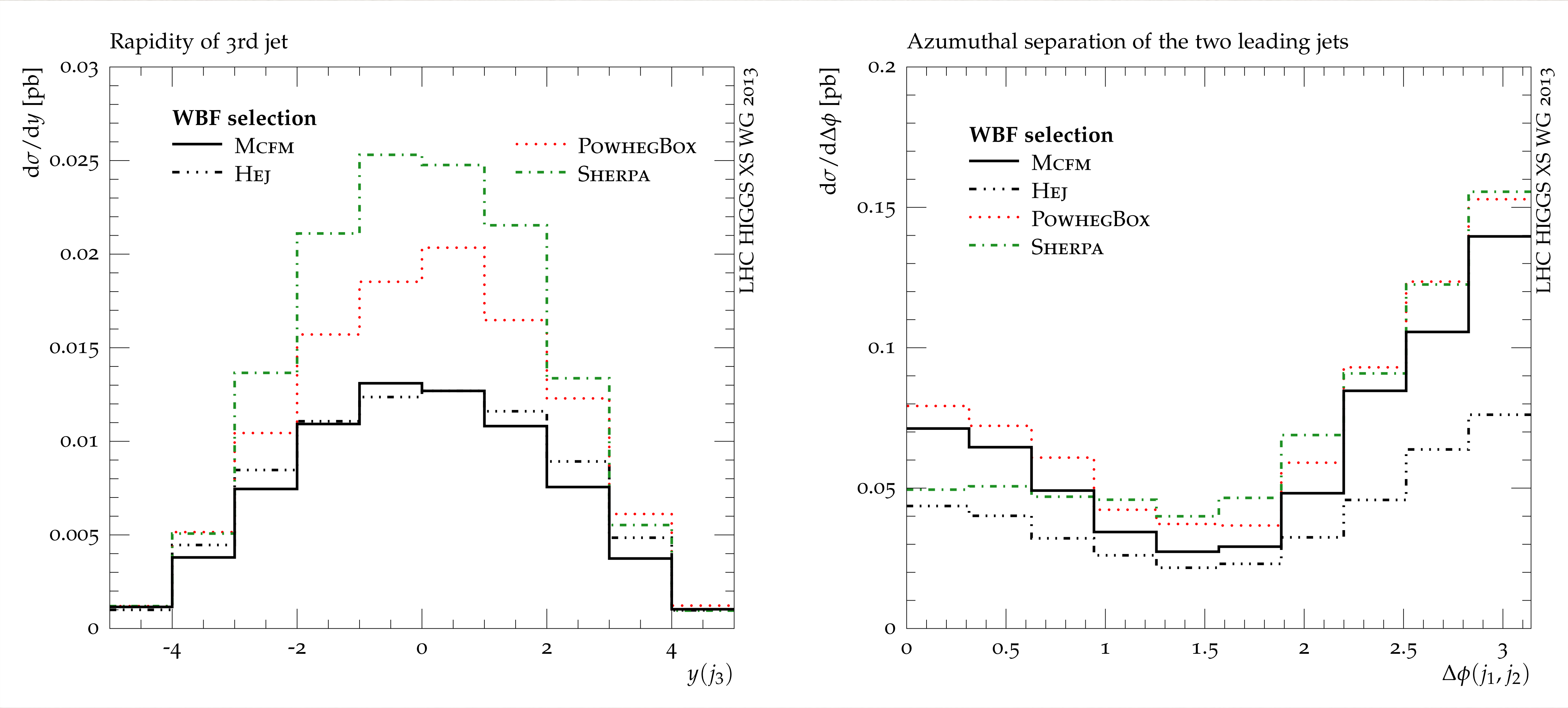




- Too extreme VBF cuts might increase the uncertainty in ggF $\Rightarrow$ check the quantity $\Delta\sigma_2^{\rm ggF}/\sigma_2^{\rm VBF}$ as a function of $m_{jj}^{\rm cut}$

VBF cuts in Monte Carlo's

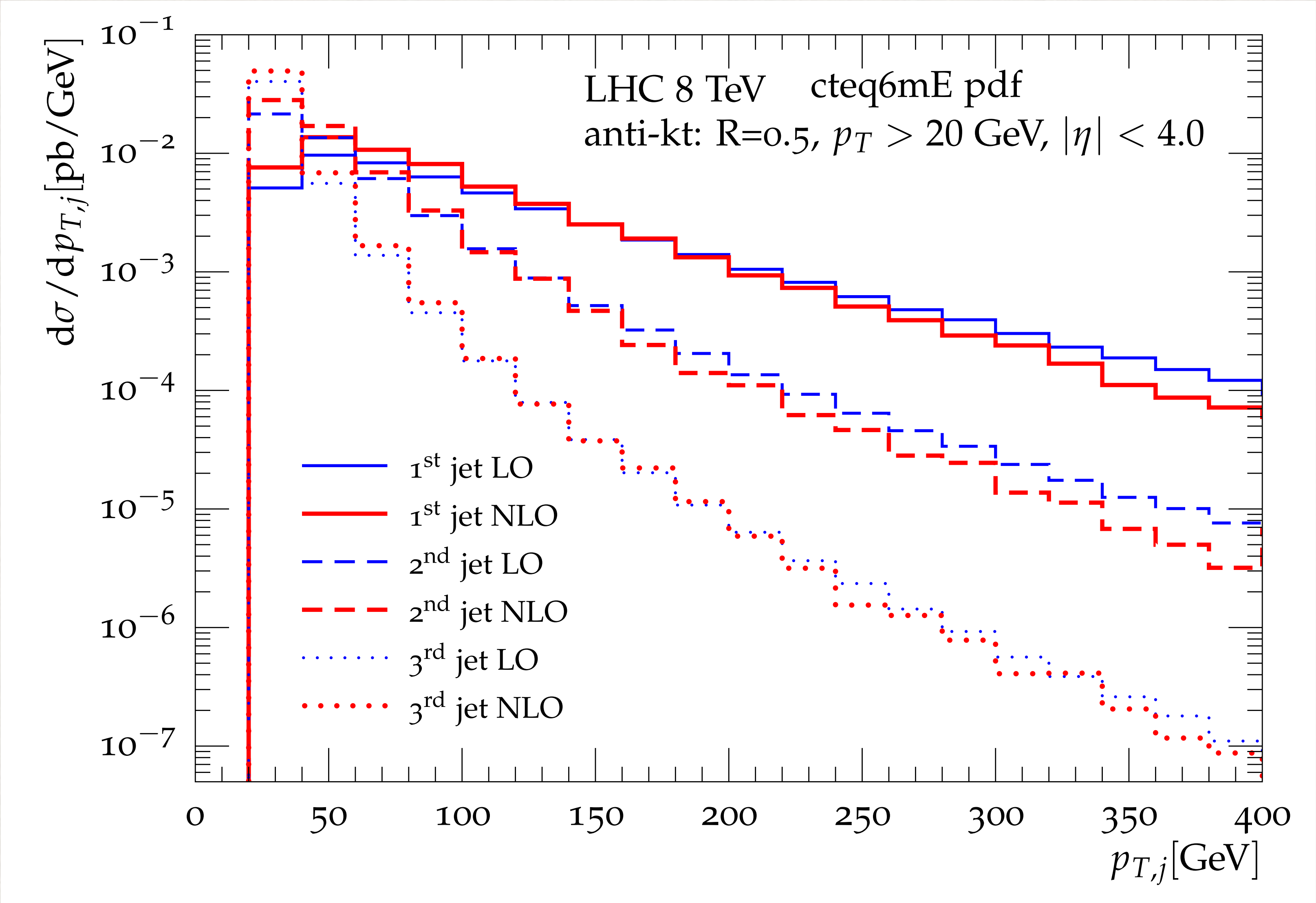
- Accurate predictions for the two-jet cross section rely on modelling of the third jet in gluon fusion



- In Monte Carlo generators the third jet is produced at LO only: discrepancies due to details of the shower and/or tree-level merging

Higgs plus three jets at NLO

- Very recently, Higgs production in gluon fusion with three additional jets has been computed at NLO with GoSam [Cullen et al. PRL 111 (2013) 131801]



- Jet-p_t distributions are stable with inclusive cuts
- Looking forward to seeing NLO distributions with extreme VBF cuts…

Conclusions

- Jets are important ingredients of many LHC Higgs analyses
- Uncertainties in exclusive jet cross sections are large ⇔ precision calculations are very important
- Study of Higgs and jets triggered many theoretical advances
  - First steps towards NNNLO Higgs production in gluon fusion
  - NNLL+NNLO resummation for zero jets, progress towards NNNLL
  - NNLOPS: first Monte Carlo generator matched to NNLO
  - Higgs plus one jet at NNLO (gg channel only)
  - Higgs plus three jets at NLO
- Comparison and validation all existing theoretical tools (fixed-order calculations, resummations, Monte Carlo generators) in progress

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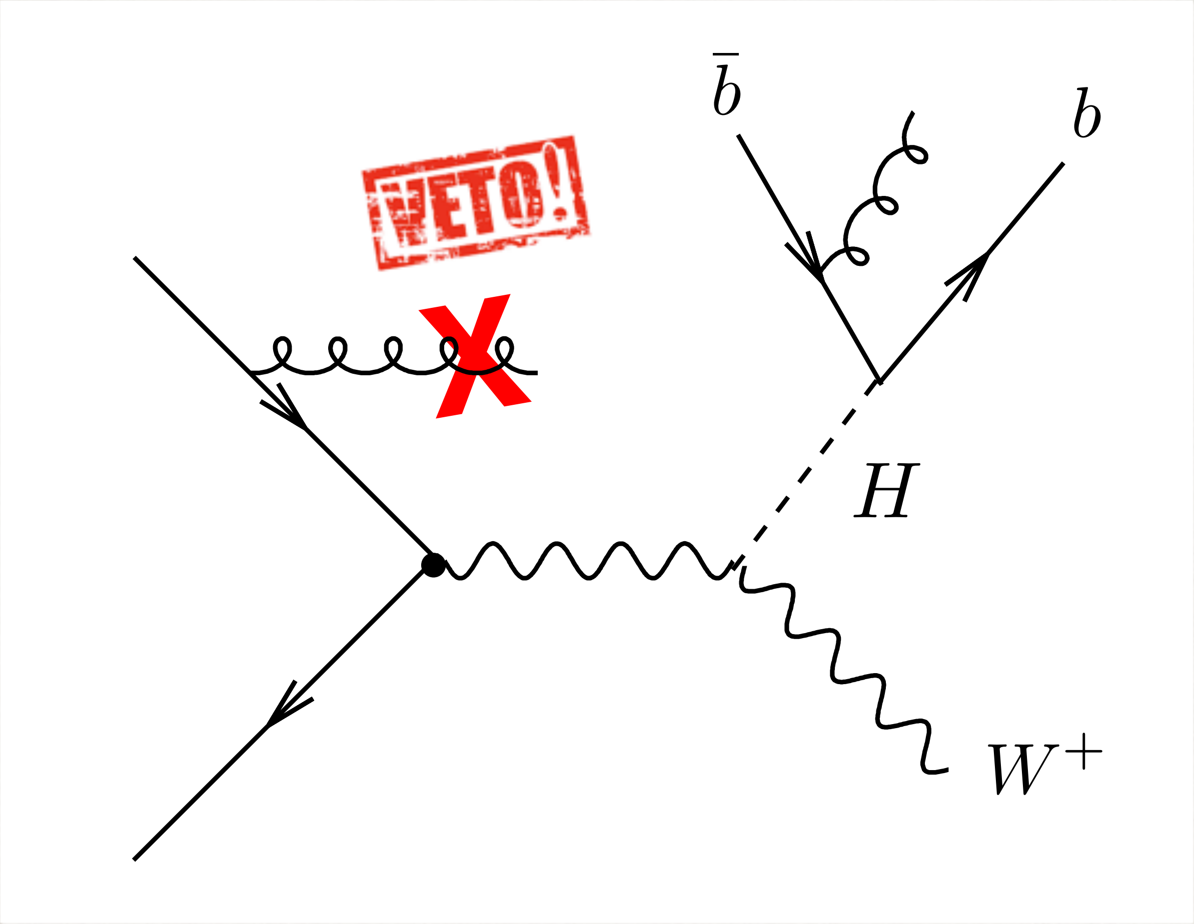
Thank you for your attention!

Extra

WH: Higgs to b-$\bar{b}$

- Tricky issue: suppress background while keeping jets from $b\bar{b}$ system



	ATLAS	CMS
b-$\bar{b}$ system	anti-k_T $R = 0.4$ $p_{Tj_1} > 45$ GeV, $p_{Tj_2} > 20$ GeV $\lvert\eta_j\rvert < 2.5$ allow extra jet with $p_{Tj} > 20$ GeV $\lvert\eta_j\rvert < 2.5$	anti-k_T $R = 0.5$ $p_{Tj_1}, p_{Tj_2} > 30$ GeV $\eta_{j_1}, \eta_{j_2} > 30$
p_{TW}	-	> 100 GeV (> 120 GeV, $\tau\nu$)
other jets	$p_{Tj} < 30$ GeV, $\lvert\eta_j\rvert > 2.5$	BDT
$\Delta\phi_{HW}$	-	BDT

- WH setup is involved and will not be considered in the rest of the talk

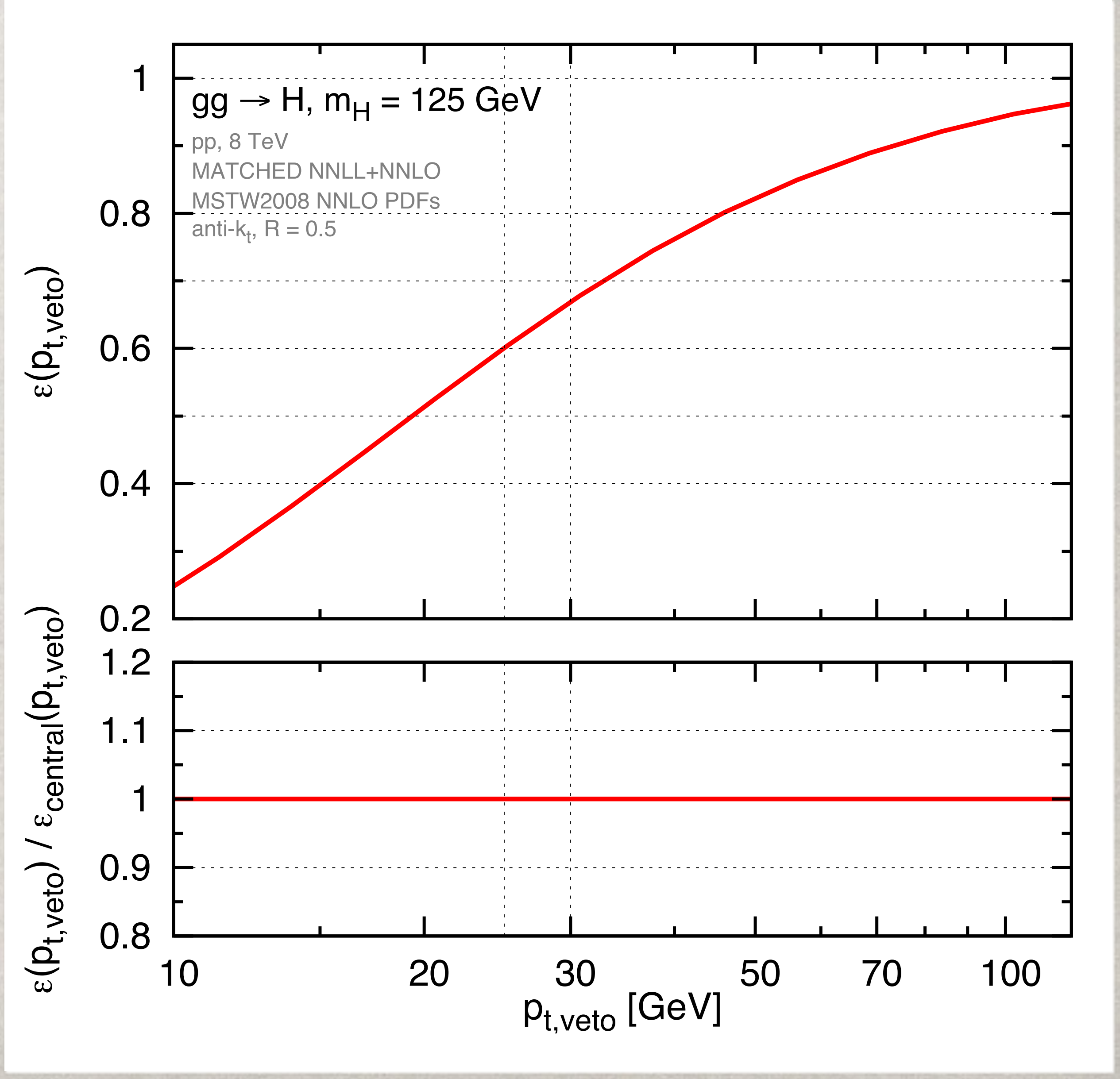
Theoretical uncertainties

- We have combined the NNLL resummation with NNLO, using three matching schemes (a), (b) and (c)

[AB Monni Salam Zanderighi '12]

- Central value: scheme (a) with $\mu_R = \mu_F = Q = m_H/2$

  Q is the resummation scale: $\ln(m_H/p_{\mathrm{t,veto}}) \to \ln(Q/p_{\mathrm{t,veto}})$



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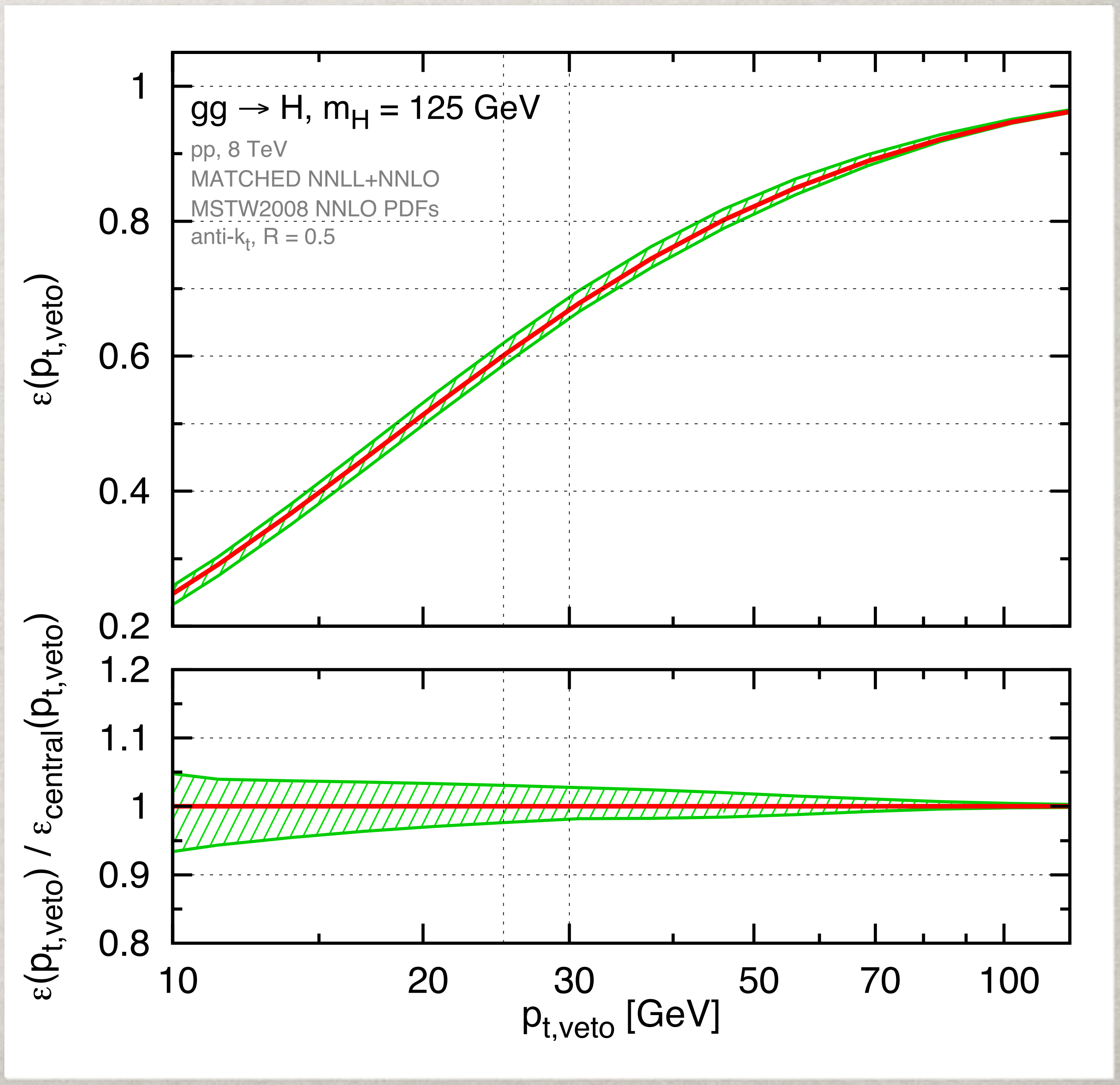
- Variation of μ_R, μ_F with $Q = m_H/2$

  $$\frac{m_H}{4} \leq \mu_R, \mu_F \leq m_H \qquad \frac{1}{2} \leq \frac{\mu_R}{\mu_F} \leq 2$$



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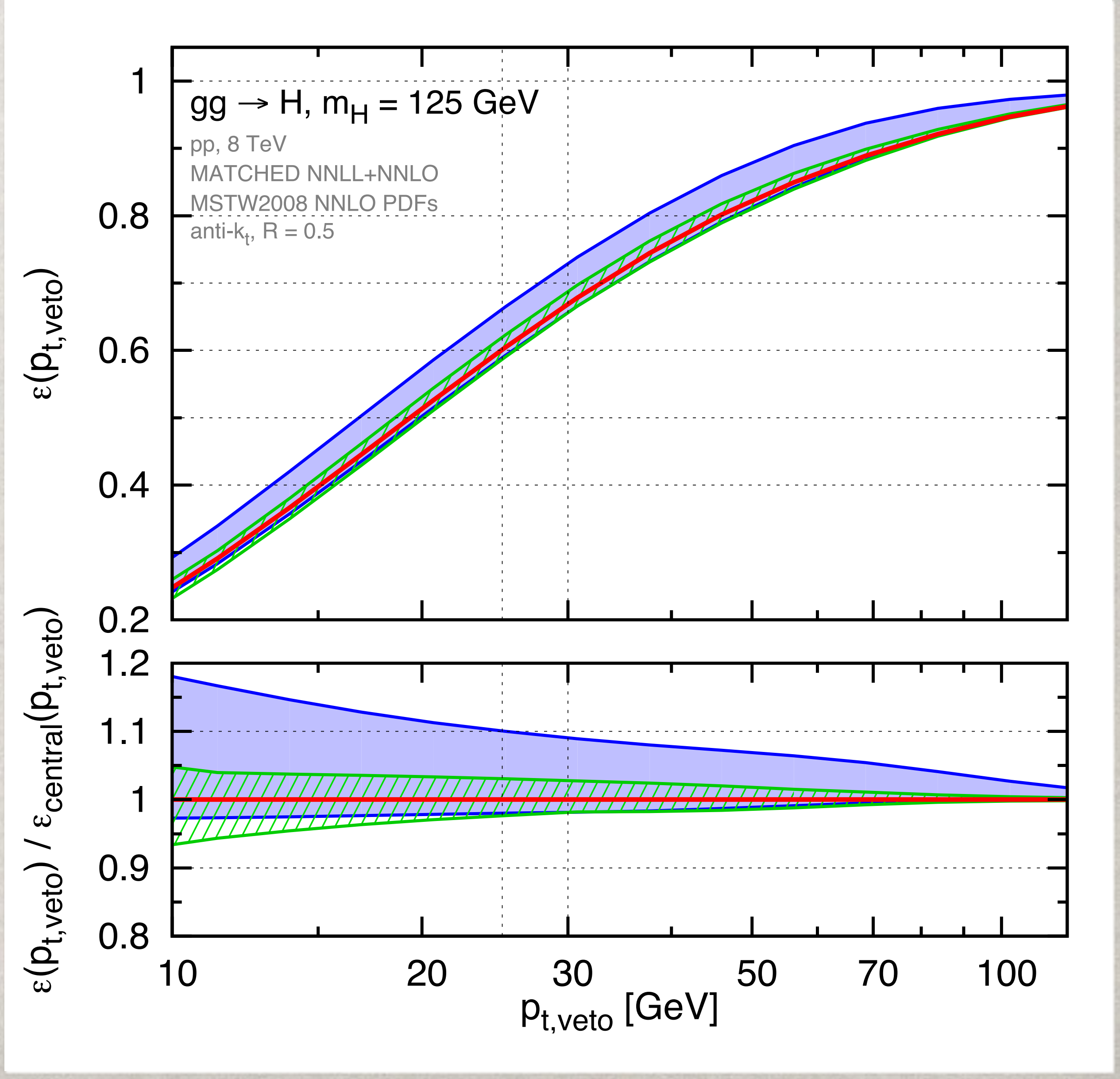
$$\frac{m_H}{4} \le \mu_R, \mu_F \le m_H \qquad \frac{1}{2} \le \frac{\mu_R}{\mu_F} \le 2$$

- Variation of Q with $\mu_R, \mu_F = m_H/2$

$$\frac{m_H}{4} \le Q \le m_H$$



Theoretical uncertainties

- We have combined the NNLL resummation with NNLO, using three matching schemes (a), (b) and (c)

[AB Monni Salam Zanderighi '12]

- Central value: scheme (a) with $\mu_R = \mu_F = Q = m_H/2$

  Q is the resummation scale: $\ln(m_H/p_{\rm t,veto}) \to \ln(Q/p_{\rm t,veto})$

- Variation of μ_R, μ_F with $Q = m_H/2$

$$\frac{m_H}{4} \leq \mu_R, \mu_F \leq m_H \qquad \frac{1}{2} \leq \frac{\mu_R}{\mu_F} \leq 2$$

- Variation of Q with $\mu_R, \mu_F = m_H/2$

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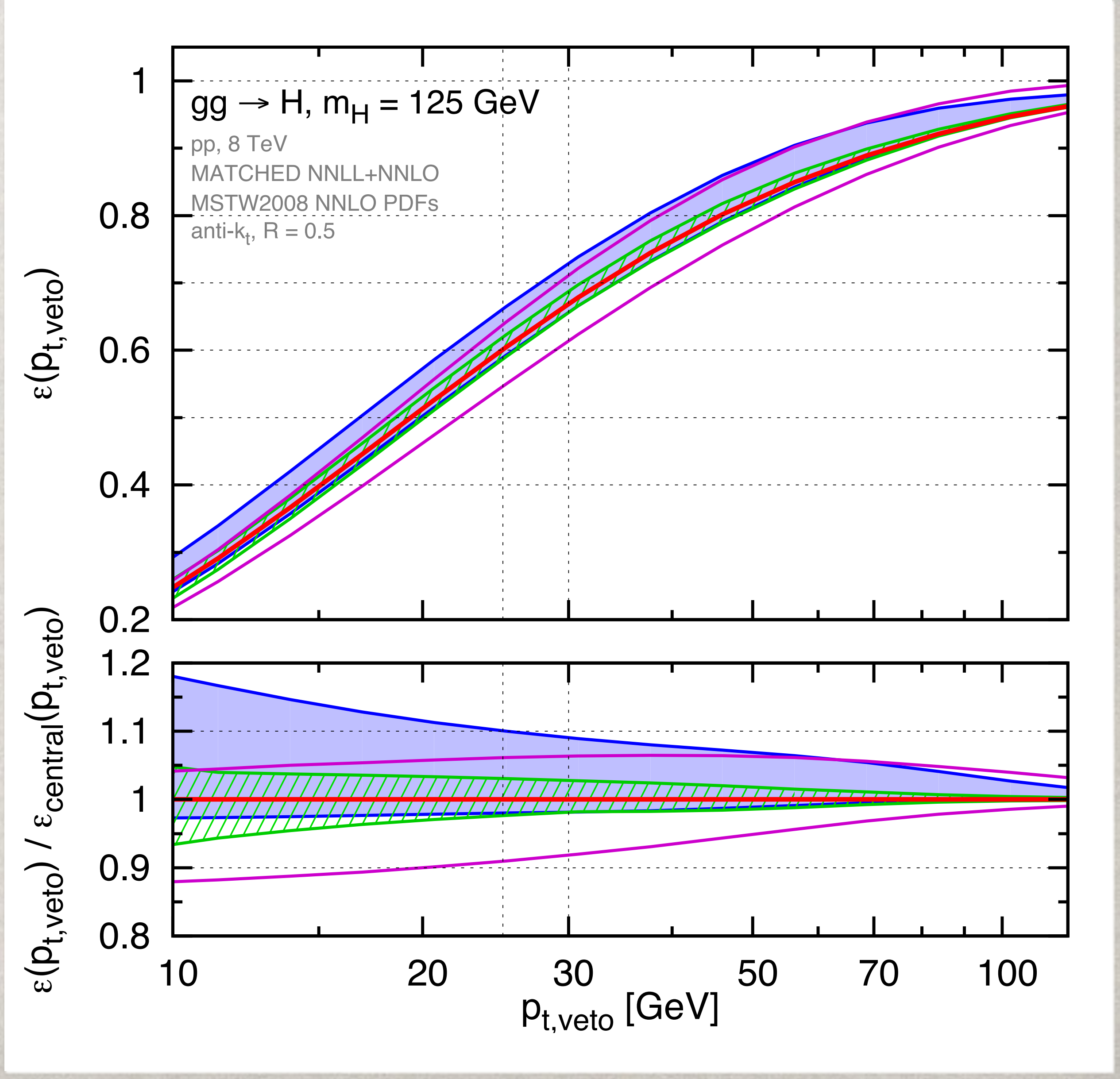
- Schemes (b) and (c) with

$$\mu_R = \mu_F = Q = m_H/2$$



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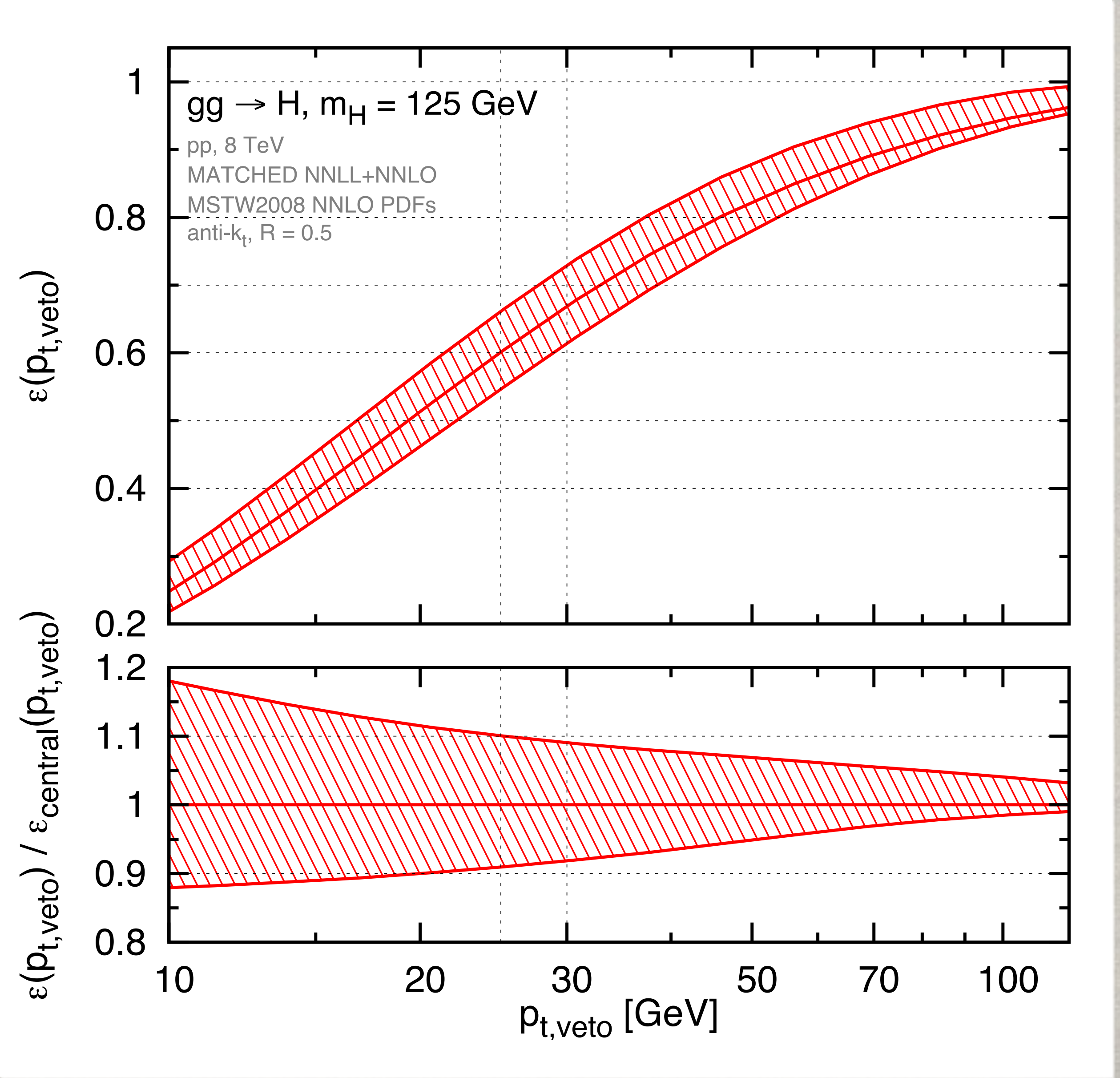
- Schemes (b) and (c) with

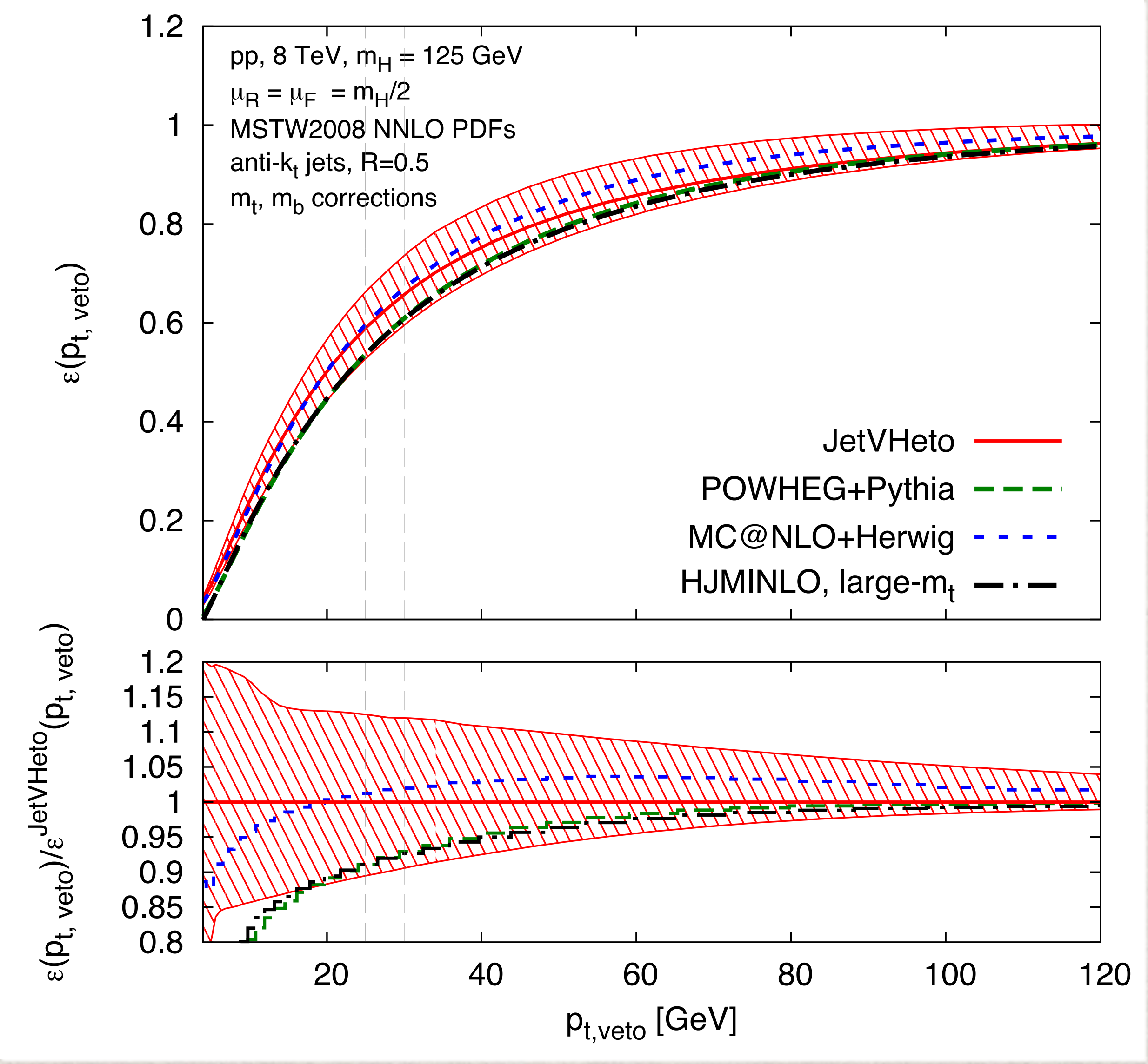
$$\mu_R = \mu_F = Q = m_H/2$$

- Total uncertainty: envelope



Comparison to Monte Carlo

- We compare the jet-veto efficiency to different Monte Carlo predictions



- All Monte Carlo results are within resummation uncertainty band
- In the region $p_{\rm t,veto} = 25 - 30\,{\rm GeV}$ NNLL+NNLO results are in better agreement with MC@NLO