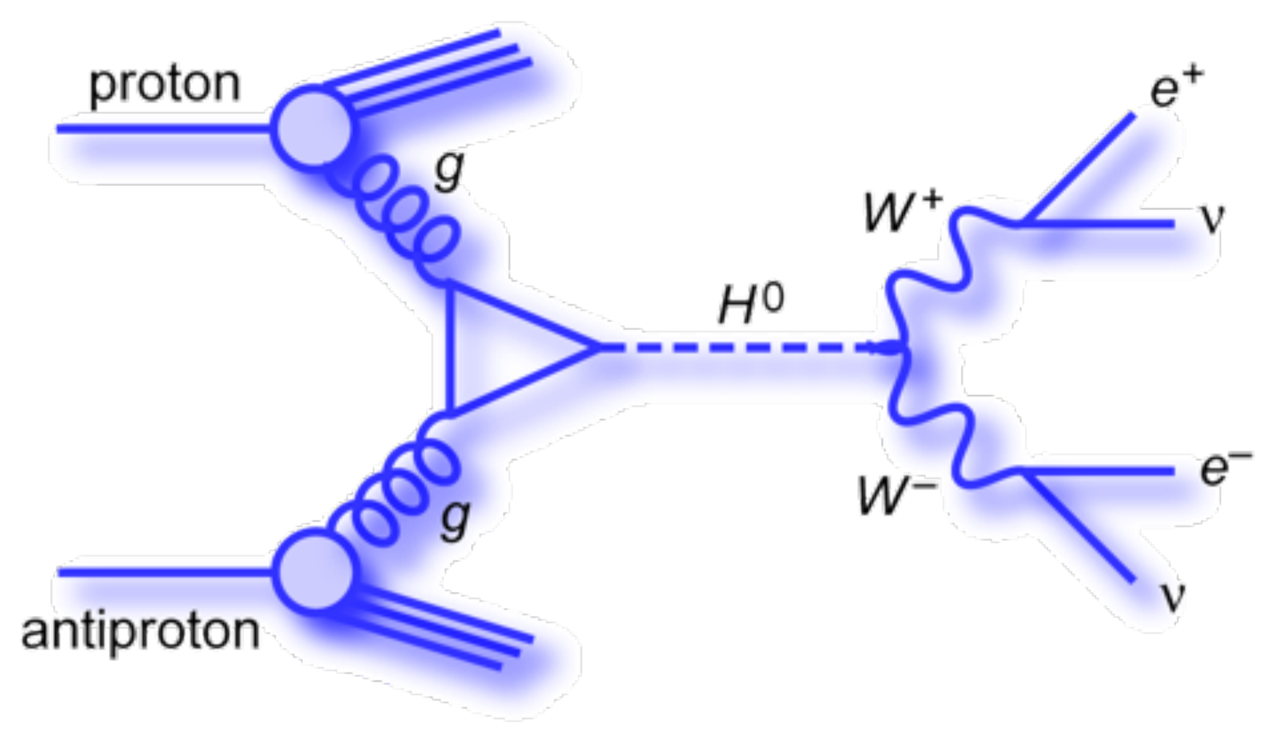
JET BINS AND JET SUBSTRUCTURE



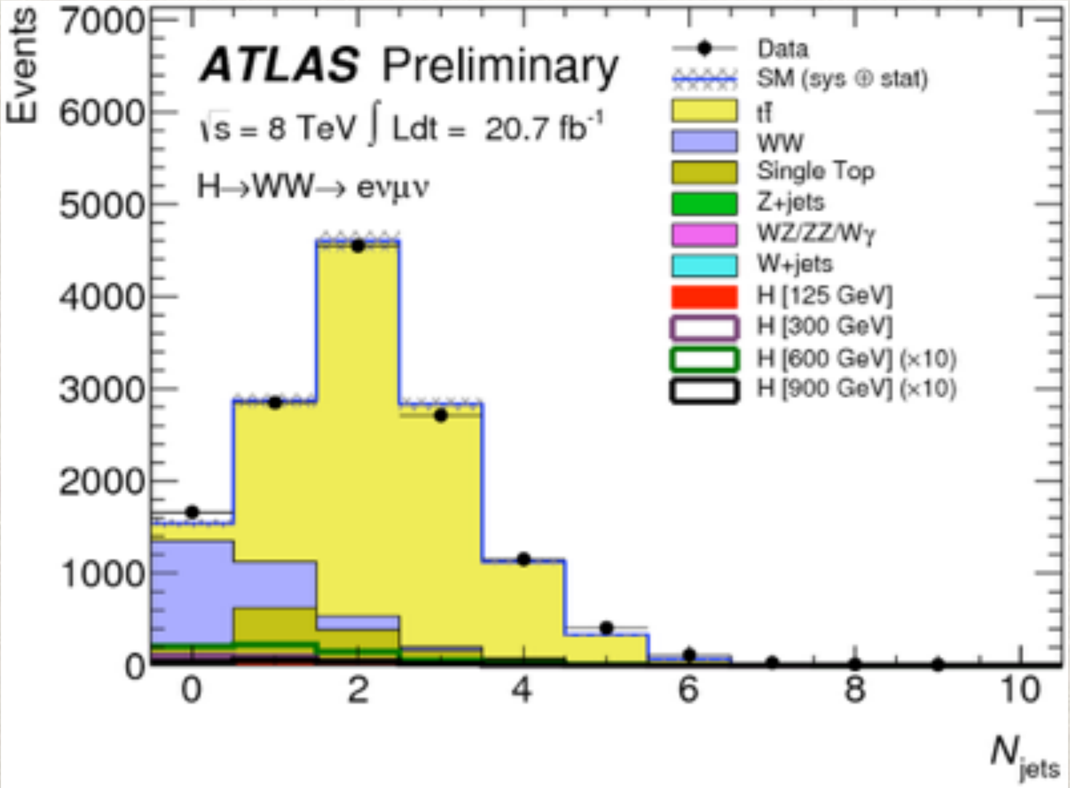
ANDREA
BANFI

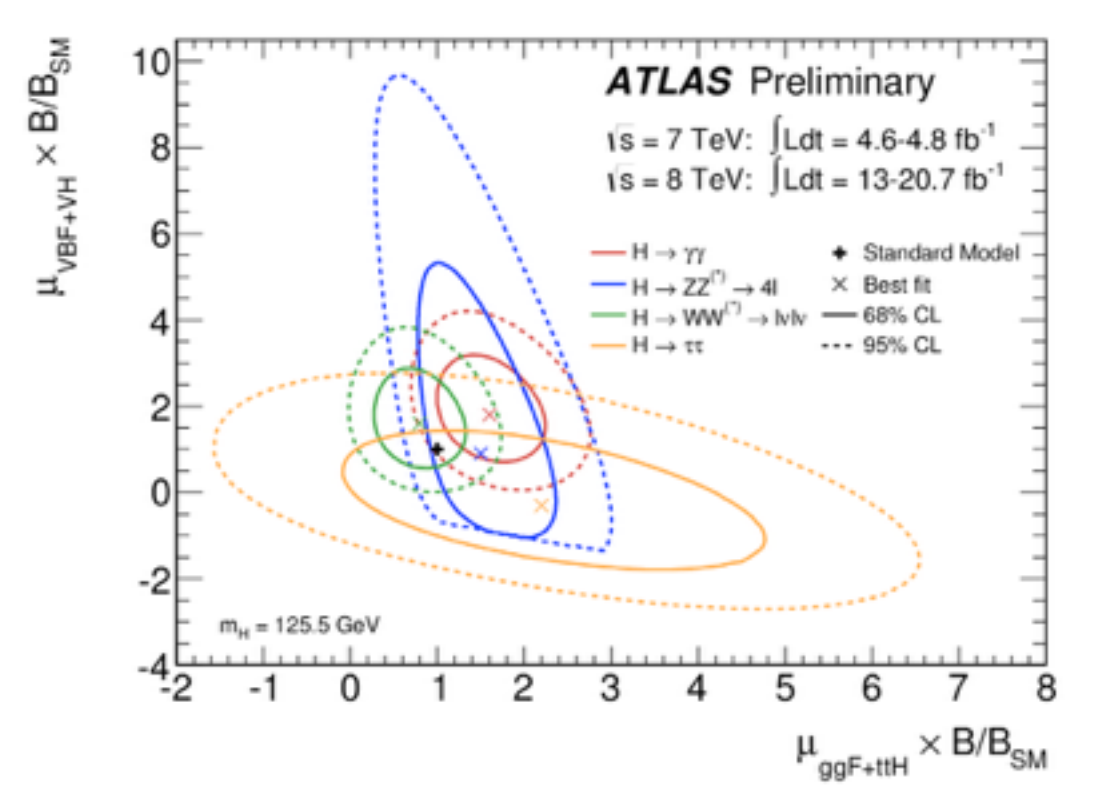
University of Sussex

HIGGS COUPLINGS 2014

JET-VETO CROSS SECTIONS: WHY?

- Experimental analyses involving the Higgs select exclusive jet samples



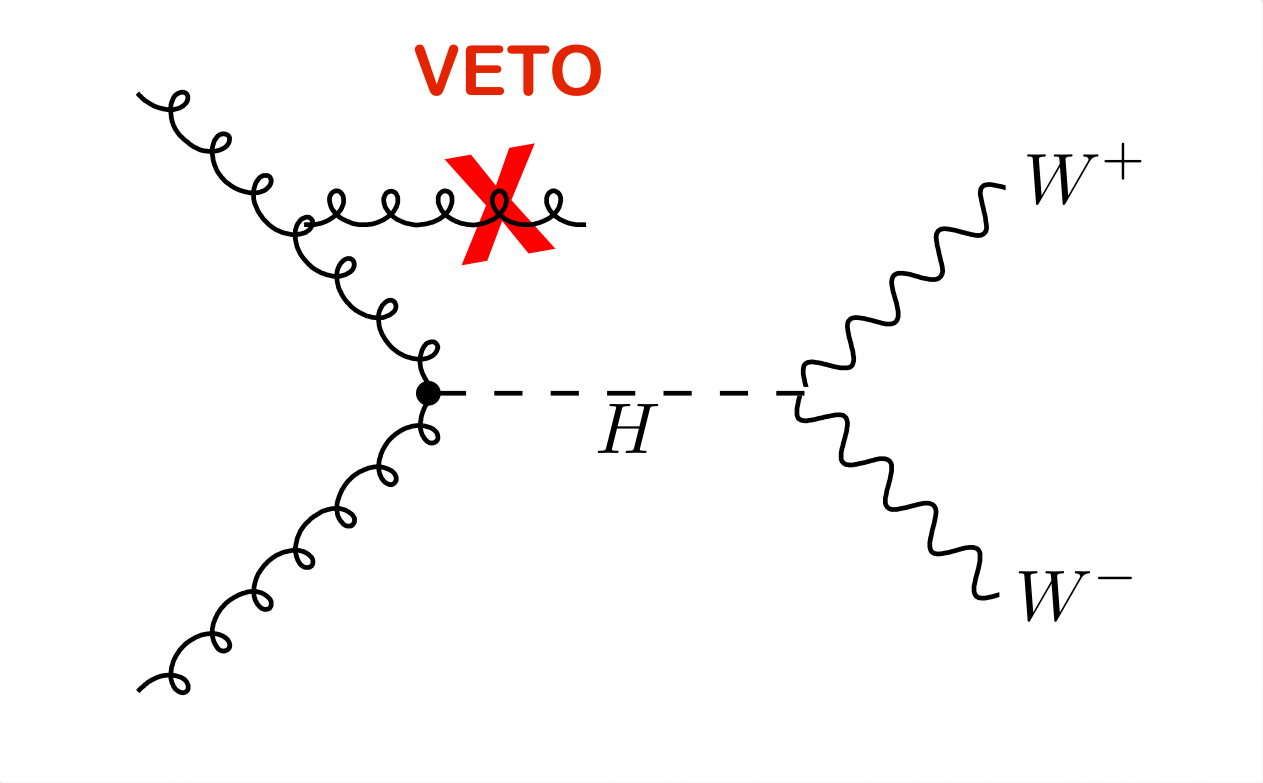


- $H \to WW$: the zero-jet bin is least contaminated by huge top-antitop background

- Two-jet exclusive samples needed to separate VFB from gluon fusion

THE ZERO-JET CROSS SECTION

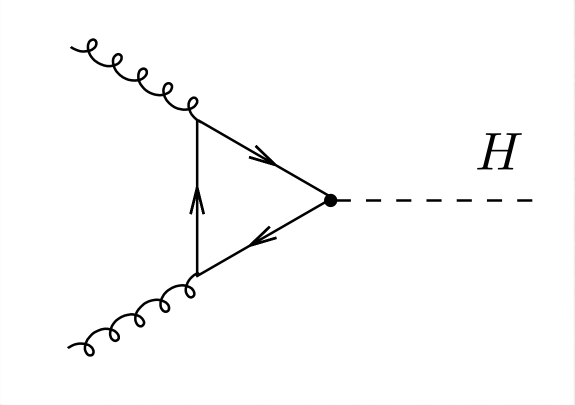
- zero-jet cross section ⇔ jet veto condition, all jets have $p_{\mathrm{t,jet}} < p_{\mathrm{t,veto}}$



HIGGS PLUS ZERO-JETS AT FIXED ORDER

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

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



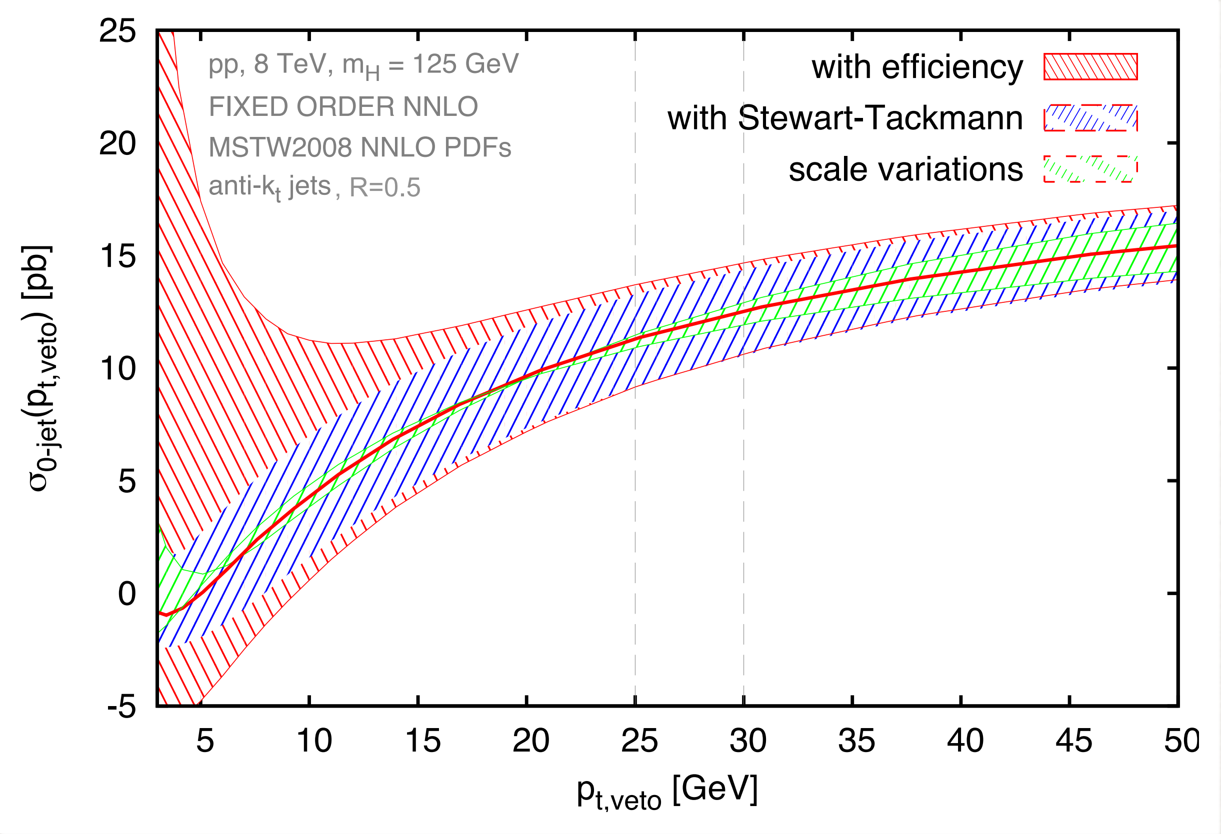
finite m_t, m_b	NLO	[Spira et al. NPB 453 (1995) 17]
large- m_t	NNLO	[Anastasiou Melnikov Petriello NPB 724 (2005) 197] [Catani Grazzini PRL 98 (2007) 222002]
large-m_W	QCD-EW	[Anastasiou Boughezal Petriello JHEP 04 (2009) 003]

- 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, 1311.1425, 1403.4616]

NEED FOR RESUMMATION

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



- Resummation of large logarithms $\ln(m_H/p_{\mathrm{t,veto}})$ needed to have stable predictions in the region considered at the LHC $p_{\mathrm{t,veto}} \simeq 25-30\,\mathrm{GeV}$

NNLL+NNLO RESUMMATIONS

- NNLL resummation matched to NNLO is implemented in the code JetVHeto
  http://jetvheto.hepforge.org/

[AB Monni Salam Zanderighi PRL 109 (2012) 202001]

- The same result has been obtained by two groups in the framework of Soft-Collinear Effective Theory (SCET)

[Becher Neubert JHEP 07 (2012) 108]
[Becher Neubert Rothen JHEP 10 (2013) 125]
[Stewart Tackmann Walsh Zuberi PRD89 (2014) 054001]

Further improvements:

- Ingredients beyond NNLL accuracy

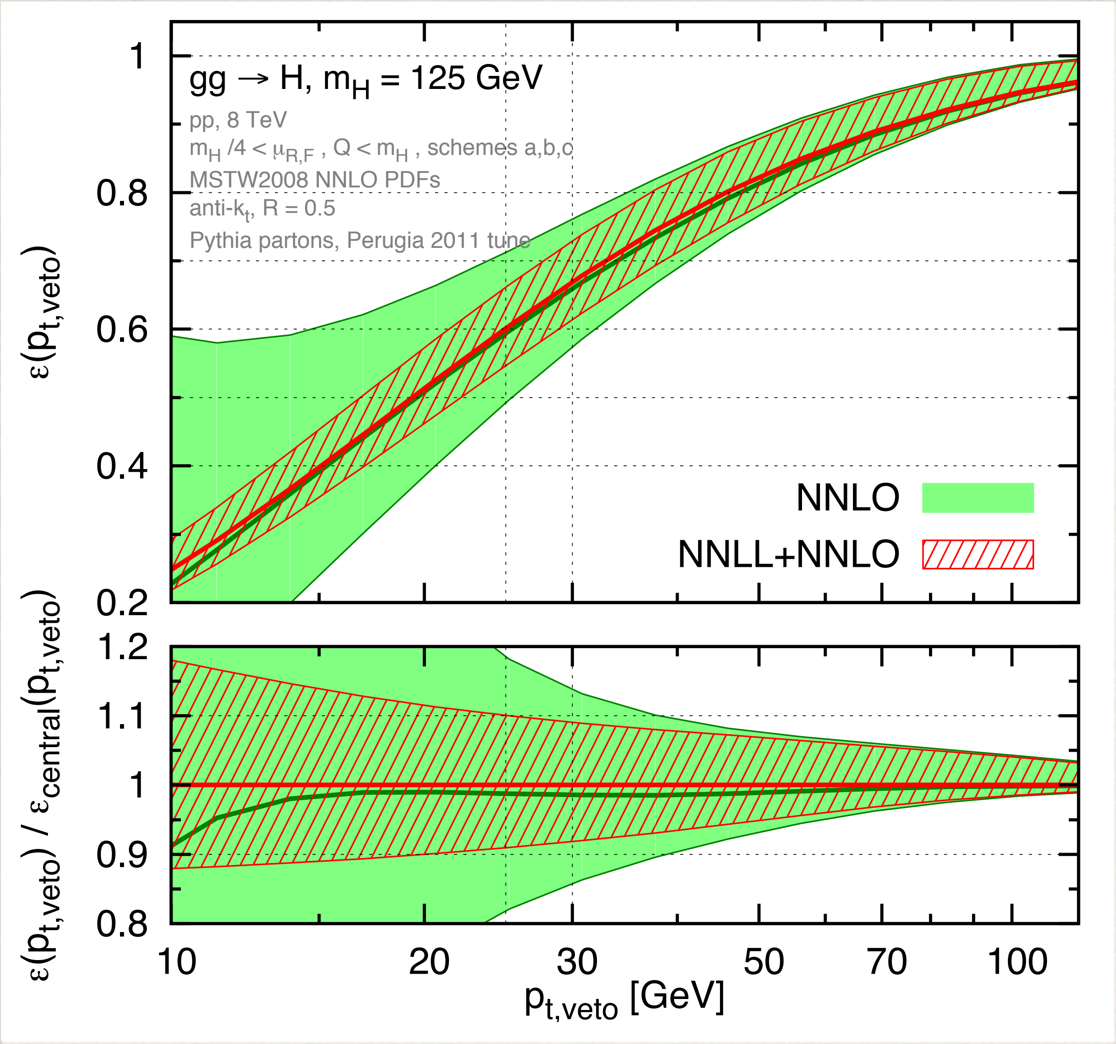
[Becher Neubert Rothen JHEP 10 (2013) 125]
[Stewart Tackmann Walsh Zuberi PRD89 (2014) 054001]

- Effect of top and bottom masses in loops

[AB Monni Zanderighi JHEP 01 (2014) 097]

PREDICTIONS FOR JET-VETO EFFICIENCY

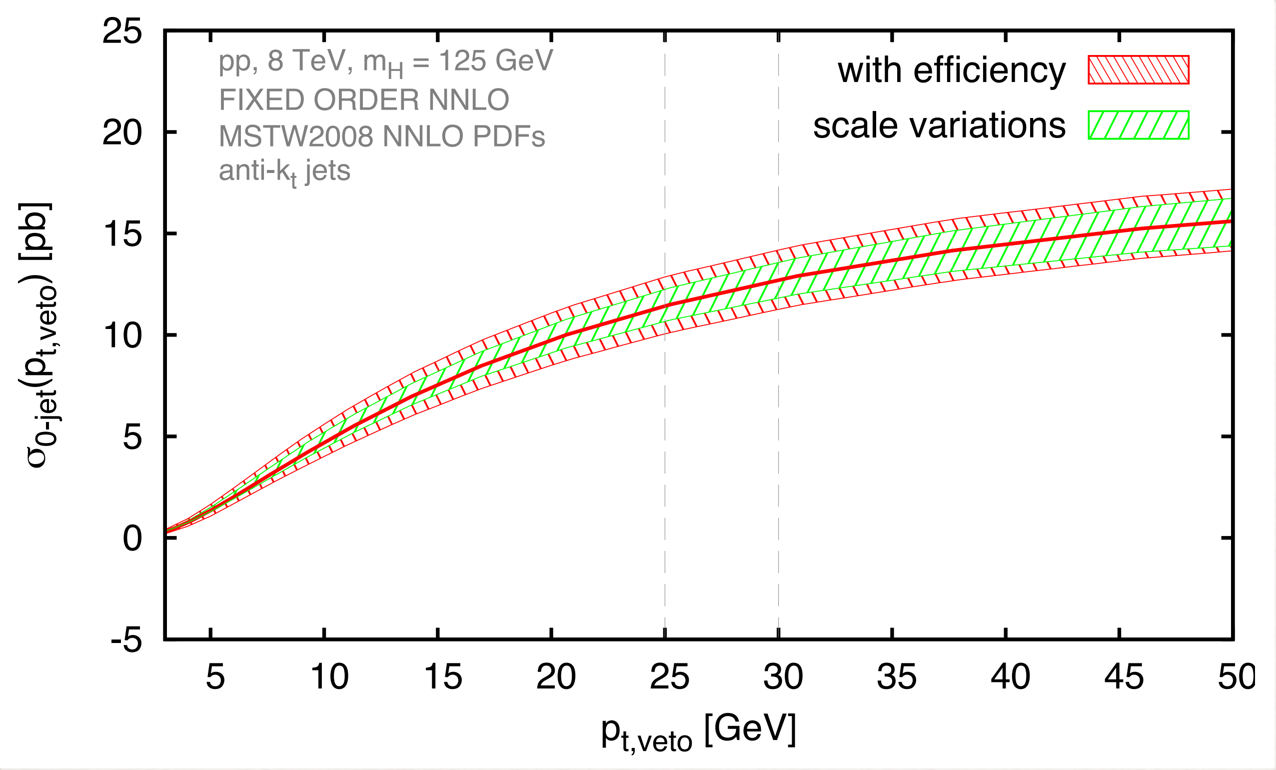
- Uncertainties of the jet-veto efficiency: independent variation of all scales by a factor two around $m_H/2$, and of schemes to match NNLL to NNLO



- Reduction of theoretical uncertainty from NNLO to NNLL+NNLO
- Uncertainty would be further reduced with a larger jet radius

UNCERTAINTIES: JVE METHOD

- Jet-veto efficiency (JVE) method for theoretical uncertainties
  - Compute the zero-jet cross section from $\sigma_{0-\mathrm{jet}} = \epsilon(p_{\mathrm{t,veto}})\,\sigma_{\mathrm{tot}}$
  - Treat uncertainties in σ_{tot} and $\epsilon(p_{\mathrm{t,veto}})$ as uncorrelated



e.g. $R = 0.4,\ p_{\mathrm{t,veto}} = 25\,\mathrm{GeV}$:

$\delta\sigma_{0-\mathrm{jet}} \sim 10\%$ [NNLL+NNLO]

$\delta\sigma_{0-\mathrm{jet}} \sim 13.8\%$ [NNLL+NNLO + JVE $\sigma_{\mathrm{tot}}^{\mathrm{NNLO}}$]

$\delta\sigma_{0-\mathrm{jet}} \sim 12.8\%$ [NNLL+NNLO + JVE $\sigma_{\mathrm{tot}}^{\mathrm{HXSWG}}$]

- Uncertainties still sizeable at NNLL+NNLO, large corrections expected from H+1jet@NNLO (gg published, full only preliminary results by BCMPS)

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

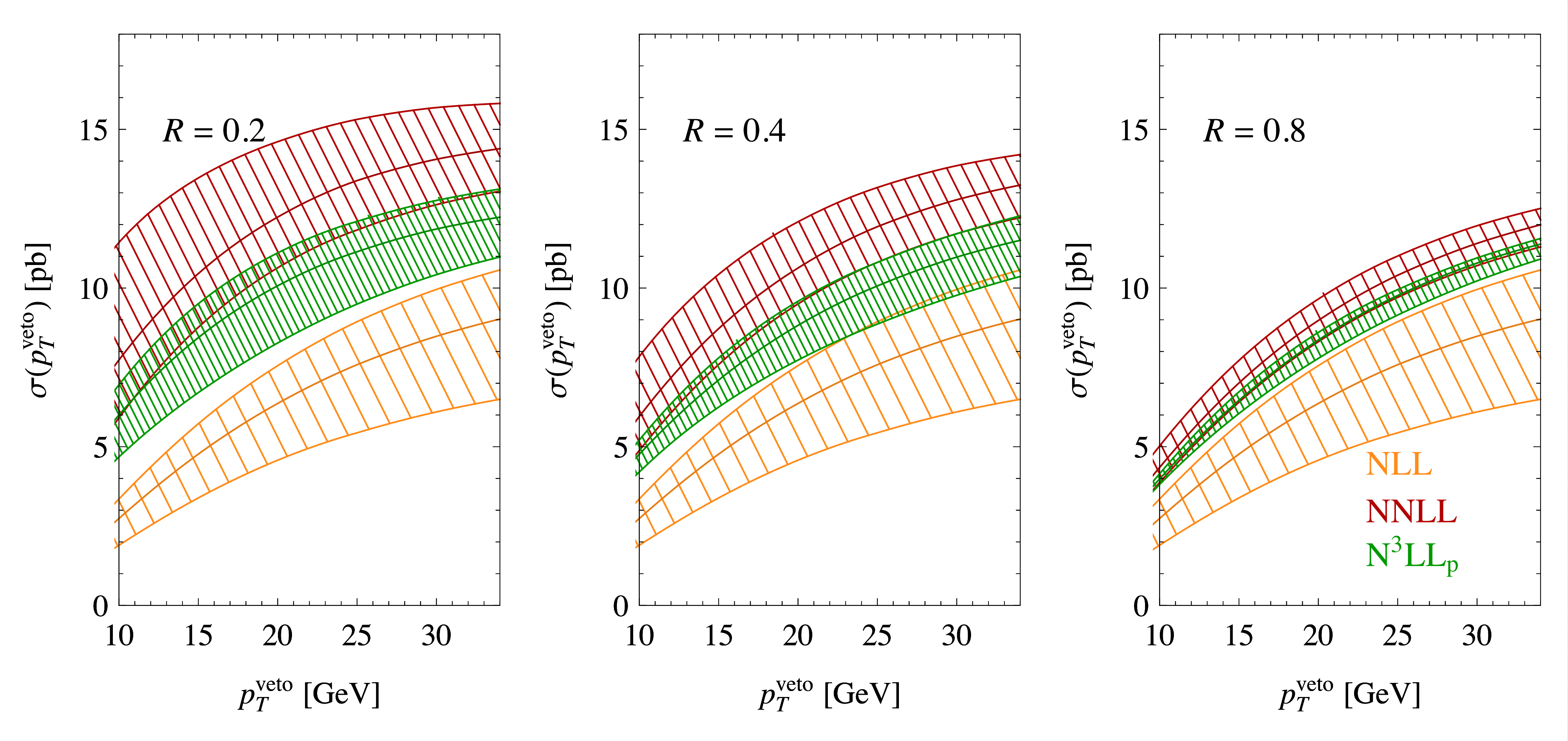
[Chen Gehrmann Glover Jaquier 1408.5325]

UNCERTAINTIES: NNNLLP PREDICTIONS

- NNNLLp predictions include terms beyond NNLL

[Becher Neubert Rothen JHEP 10 (2013) 125]

- Uncertainties in $\sigma_{0-\mathrm{jet}}$: variation of all scales by a factor of two around m_H and estimate of missing NNNLL R-dependent terms

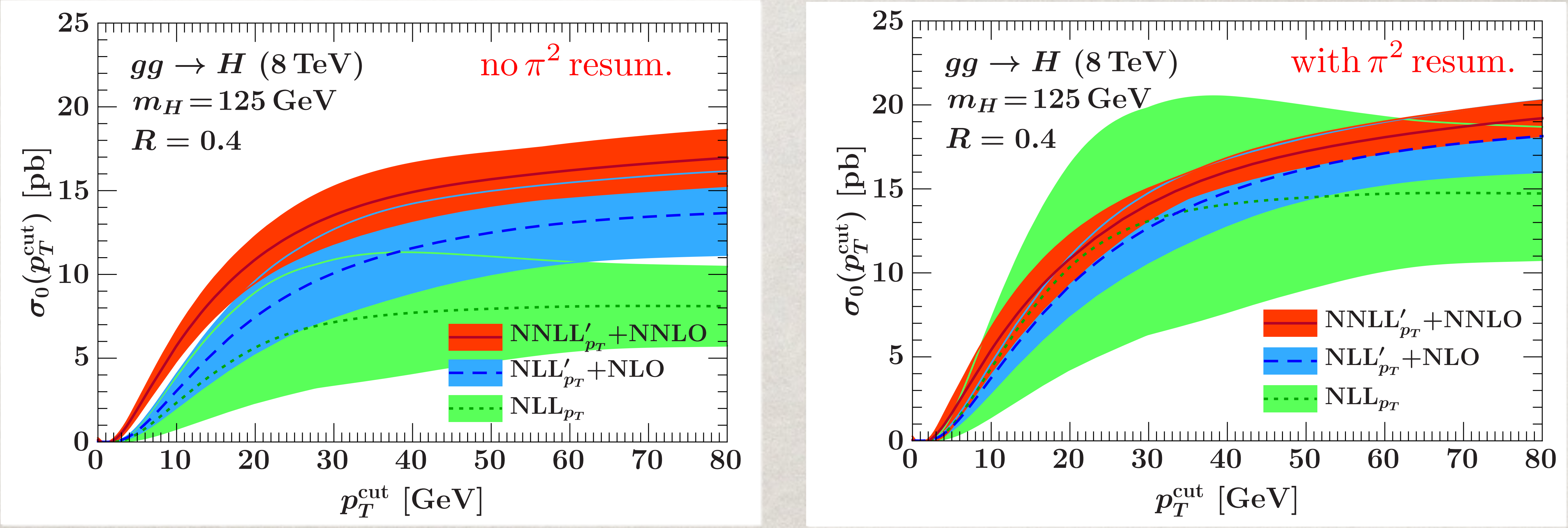


$$\text{e.g. } R = 0.4,\ p_{\mathrm{t,veto}} = 25\,\mathrm{GeV} : \delta\sigma_{0-\mathrm{jet}} \sim 9\%$$

Results include resummation of π^2 in virtual corrections: total cross section different from $\sigma_{\mathrm{tot}}^{\mathrm{HXSWG}}$

UNCERTAINTIES: NNLL'+NNLO

- Uncertainties on $\sigma_{0-\text{jet}}$ are evaluated by varying all scales around m_H with profiling functions [Stewart Tackmann Walsh Zuberi PRD89 (2014) 054001]
- Theory uncertainty reduced by performing π^2 resummation



e.g. $R = 0.4$, $p_{\text{t,veto}} = 25\,\text{GeV}$:

$$\delta\sigma_{0-\text{jet}} \sim 12.8\% \quad \overset{\pi^2\,\text{res.}}{\to} \quad \delta\sigma_{0-\text{jet}} \sim 9.6\%$$

ZERO-JET SUMMARY

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

	$\sigma_{0-\mathrm{jet}}(25\,\mathrm{GeV}, R = 0.4)$ [pb]	$\sigma_{0-\mathrm{jet}}(30\,\mathrm{GeV}, R = 0.5)$ [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

Comparing the various approaches is difficult because of different values of σ_{tot}

ACROSS JET BINS WITH JVE

- The JVE method can be generalised to arbitrary jet multiplicities

$$\sigma_{0-\mathrm{jet}} = \epsilon\,\sigma_{\mathrm{tot}} \quad \sigma_{1-\mathrm{jet}} = \epsilon_1(1-\epsilon)\sigma_{\mathrm{tot}} \quad \sigma_{\geq 2-\mathrm{jets}} = (1-\epsilon_1)(1-\epsilon)\sigma_{\mathrm{tot}}$$

- Uncertainties in the efficiency require considering different schemes to define the efficiency in terms of total cross sections

- The method does not need modification when resummed predictions become available

- The correlation matrix $\mathrm{Cov}[\sigma_{\mathrm{tot}}, \sigma_{\geq 1-\mathrm{jet}}, \sigma_{\geq 2-\mathrm{jets}}]$ can be computed by considering $\sigma_{\mathrm{tot}}, \epsilon, \epsilon_1$ as uncorrelated

[Les Houches proceedings 1405.1067]

ACROSS JET BINS WITH BLPTW

- Combination of resummed predictions and fixed-oder for different jet multiplicities [Boughezal Liu Petriello Tackmann Walsh JHEP 10 (2013) 125]

$$\sigma_{\text{tot}} = \sigma_0(p_T^{\text{cut}}) + \sigma_1(\underbrace{[p_T^{\text{cut}}, \infty]}_{\text{range of } p_{TJ}}; p_T^{\text{cut}}) + \sigma_{\geq 2}(p_T^{\text{cut}})$$

NNLL'+NNLO

[Stewart Tackmann Walsh Zuberi PRD89 (2014) 054001]

- Problem: the one-jet cross section can be resummed only for $p_{TJ} \gg p_T^{\text{cut}}$

NLL'+NLO

$$\sigma_1([p_T^{\text{cut}}, \infty]; p_T^{\text{cut}}) = \sigma_1([p_T^{\text{cut}}, p_T^{\text{off}}]; p_T^{\text{cut}}) + \sigma_1([p_T^{\text{off}}, \infty]; p_T^{\text{cut}})$$

[Liu Petriello PRD87 (2013) 014018, PRD87 (2013) 094027]

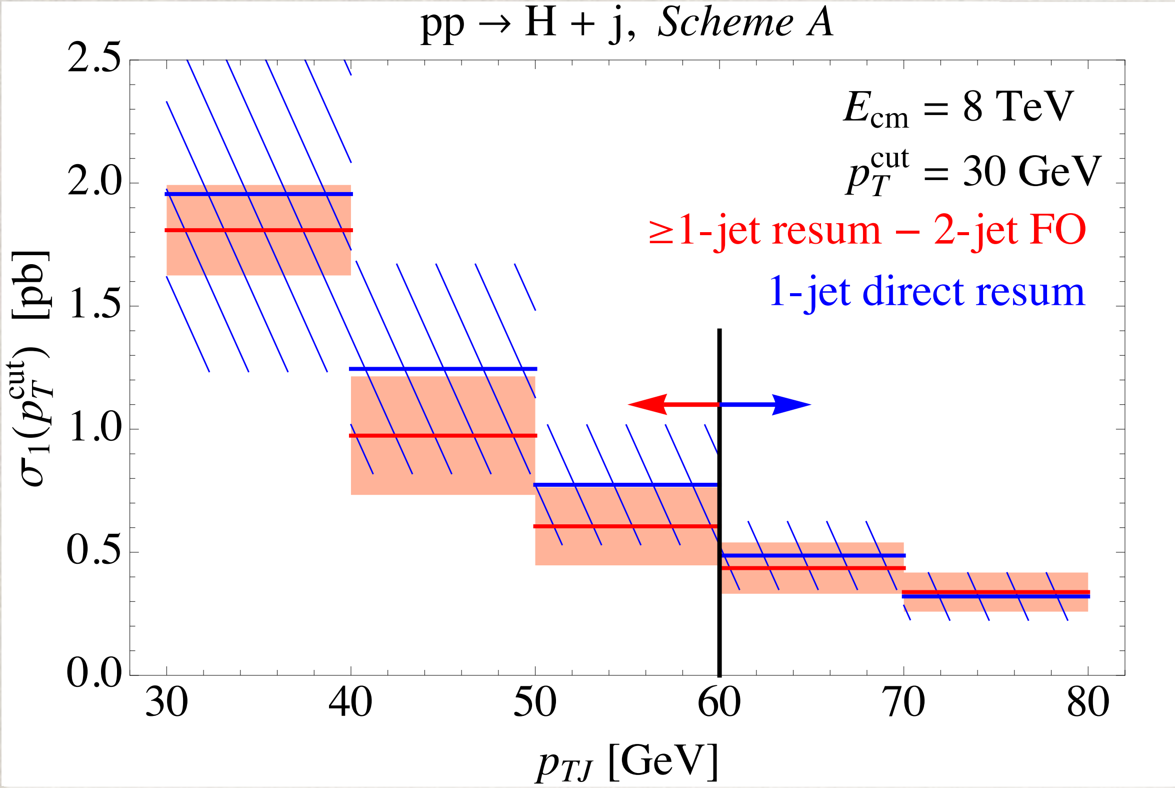
$$\sigma_1([p_T^{\text{cut}}, p_T^{\text{off}}]; p_T^{\text{cut}}) = [\sigma_0(p_T^{\text{off}}) - \sigma_0(p_T^{\text{cut}})] - [\sigma_{\geq 2}(p_T^{\text{cut}}, p_T^{\text{cut}}) - \sigma_{\geq 2}(p_T^{\text{cut}}, p_T^{\text{off}})]$$

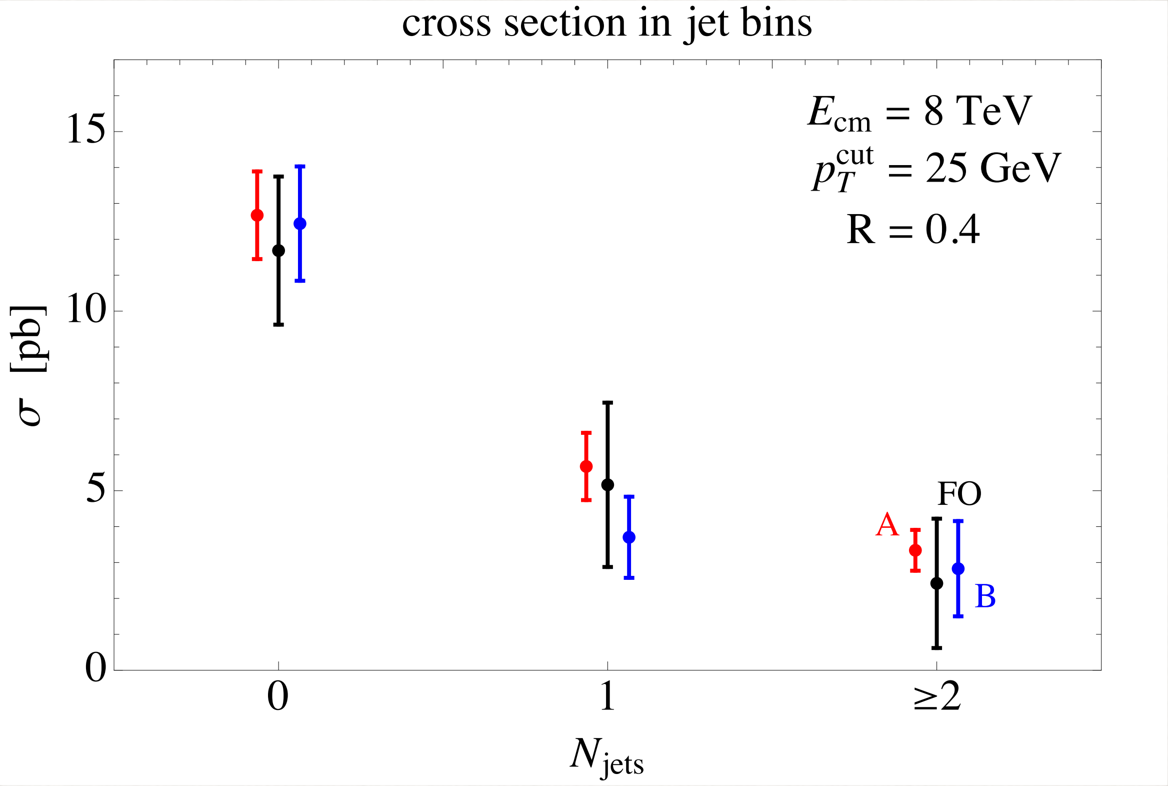
NNLL'+NNLO

NLO

H+1JET CROSS SECTION

- Considerable reduction of theoretical uncertainties with resummation





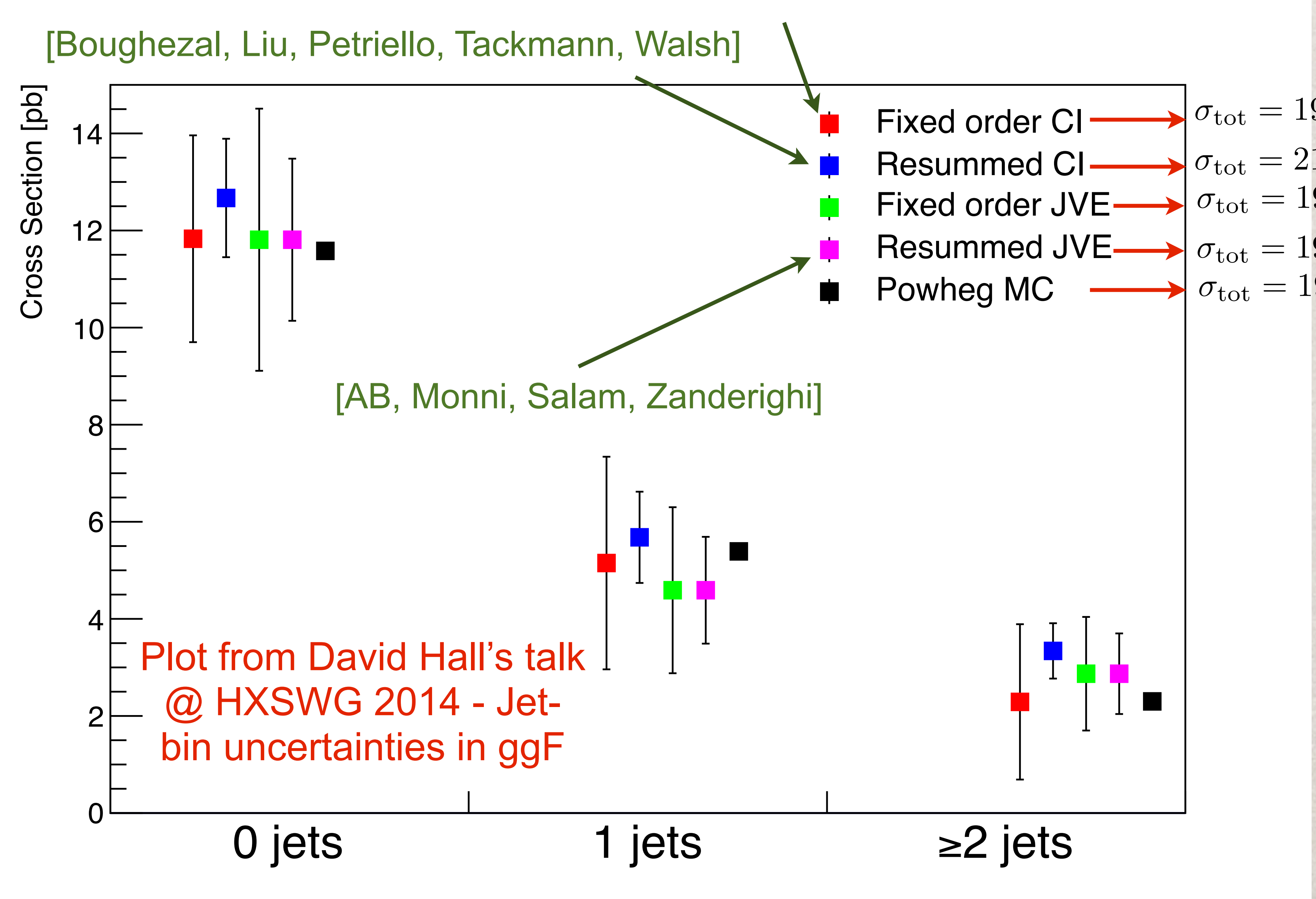
$$\text{e.g. } R = 0.4,\ p_{\rm t,veto} = 25\,\text{GeV}:\ \delta\sigma^{\rm NLO}_{1-\rm jet} \sim 40\% \to \delta\sigma^{\rm BLPTW}_{1-\rm jet} \sim 16.5\%$$

Also here the total cross section includes π^2 resummation and differs from HXSWG

UNCERTAINTIES AT THE LHC

- Comparison among different methods

$$\mathrm{anti-k_t\ \ jets,\ R = 0.4,\ p_{t,veto} = 25\ GeV}$$



[Stewart -Tackmann]

[Boughezal, Liu, Petriello, Tackmann, Walsh]

[AB, Monni, Salam, Zanderighi]

Plot from David Hall's talk @ HXSWG 2014 - Jet-bin uncertainties in ggF

Fixed order CI → $\sigma_{\rm tot} = 19.27 \pm 1.5\,{\rm pb}$ (NNLO)

Resummed CI → $\sigma_{\rm tot} = 21.69 \pm 1.49\,{\rm pb}$ $(\mathrm{NNLO} + \pi^2\,\mathrm{resummation})$

Fixed order JVE → $\sigma_{\rm tot} = 19.27 \pm 1.5\,{\rm pb}$ (NNLO)

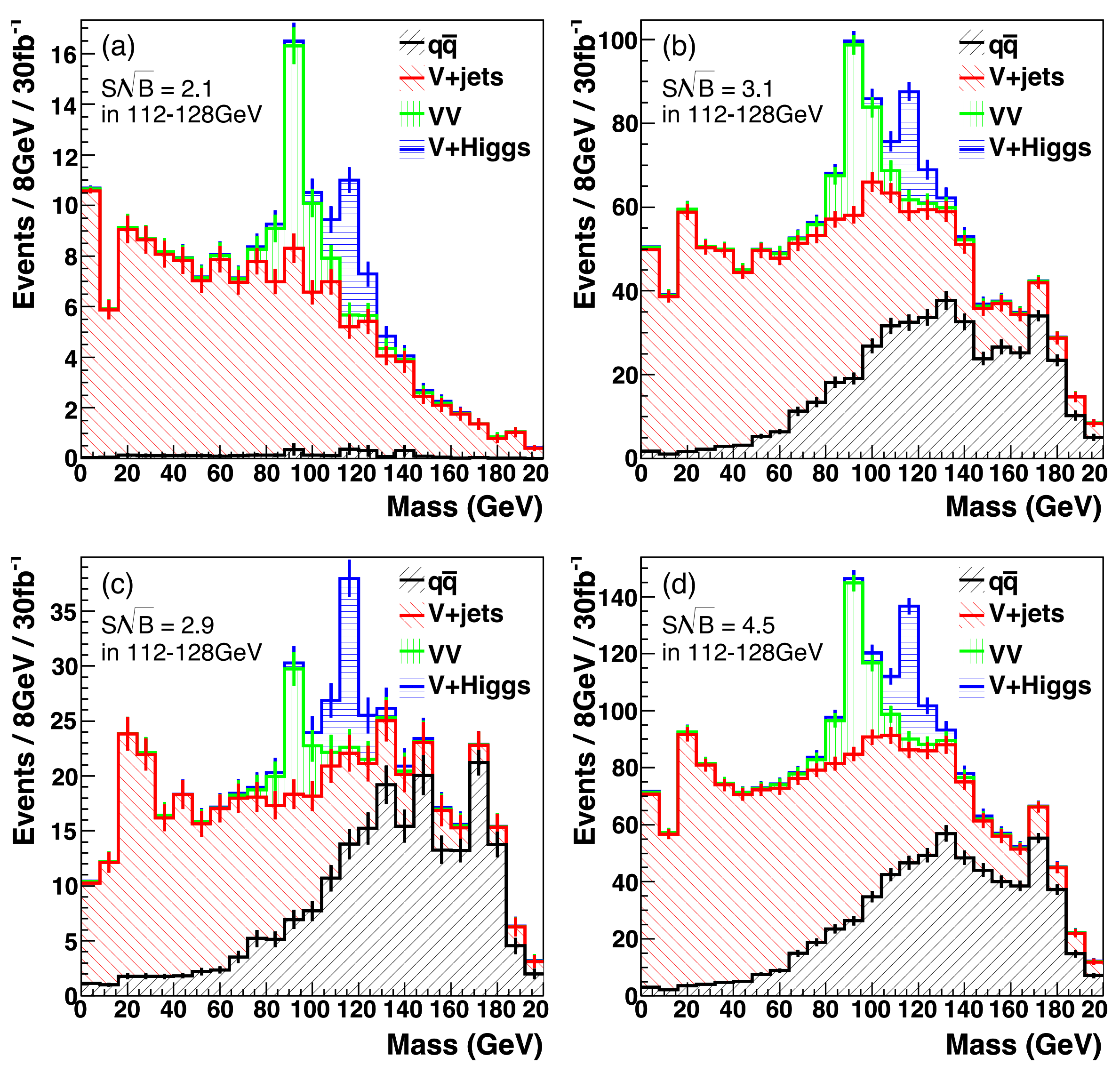
Resummed JVE → $\sigma_{\rm tot} = 19.27 \pm 1.5\,{\rm pb}$ (NNLO)

Powheg MC → $\sigma_{\rm tot} = 19.5 \pm 1.5\,{\rm pb}$ (HXSWG)

BOOSTED HIGGS SEARCHES

- It all started with the Higgs, twenty years ago

[Seymour ZPC62 (1994) 127]

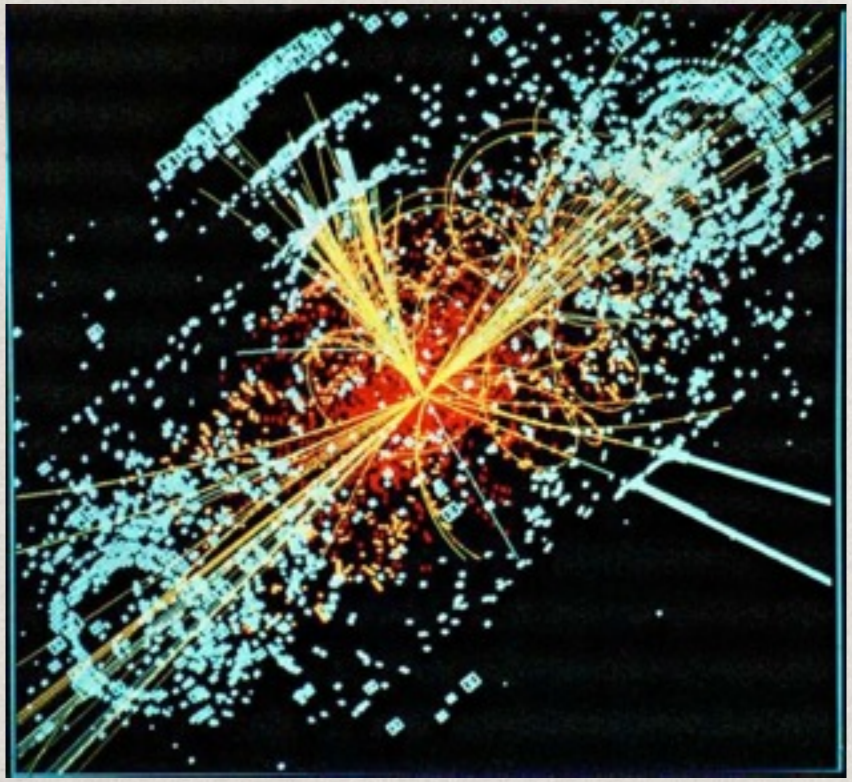


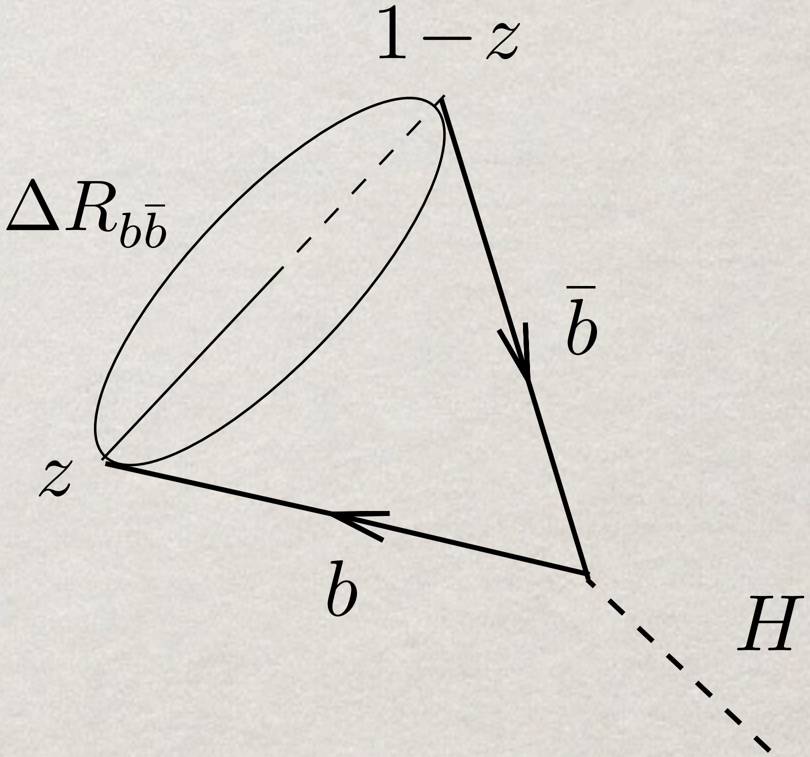
- Famous 2008 BDRS paper, showing discovery potential for a 120 GeV Higgs in VH production at LHC14

[Butterworth Davison Rubin Salam PRL 100 (2008) 242001]

BOOSTED STRATEGY

- Suppose we have a Higgs with $p_t \gg m_H$





- The angular separation between the decay products decreases with increasing transverse momentum

$$\Delta R_{b\bar{b}}^2 \simeq \frac{m_H^2}{z(1-z)p_t^2}$$

BOOSTED STRATEGY

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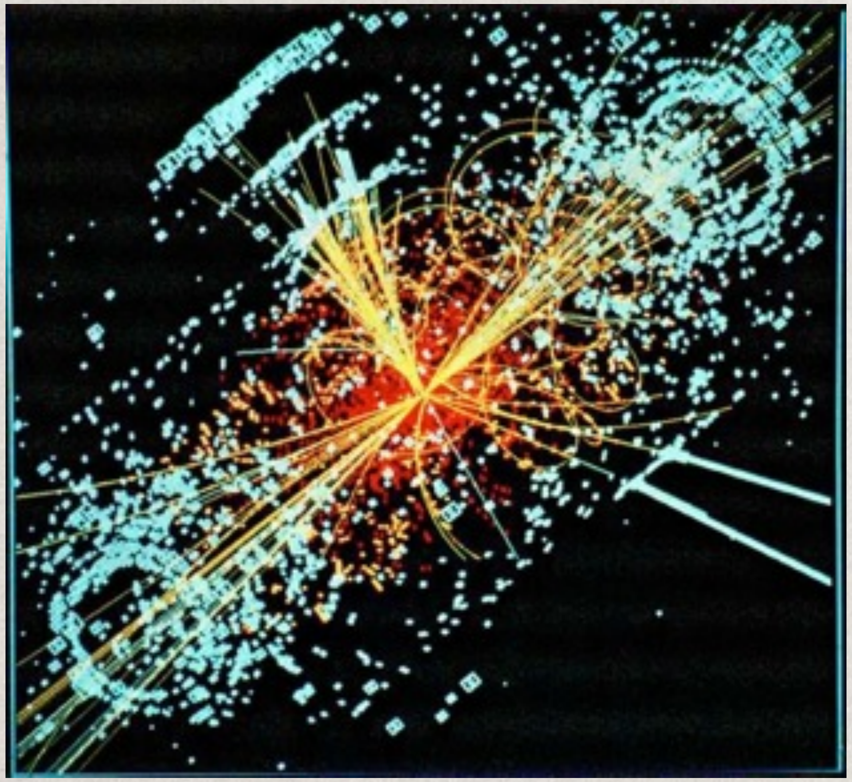
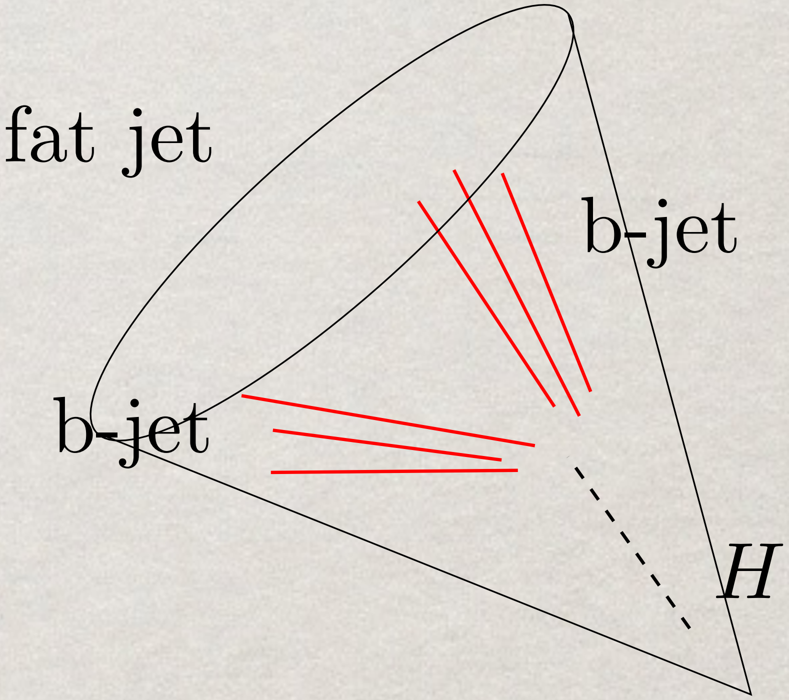




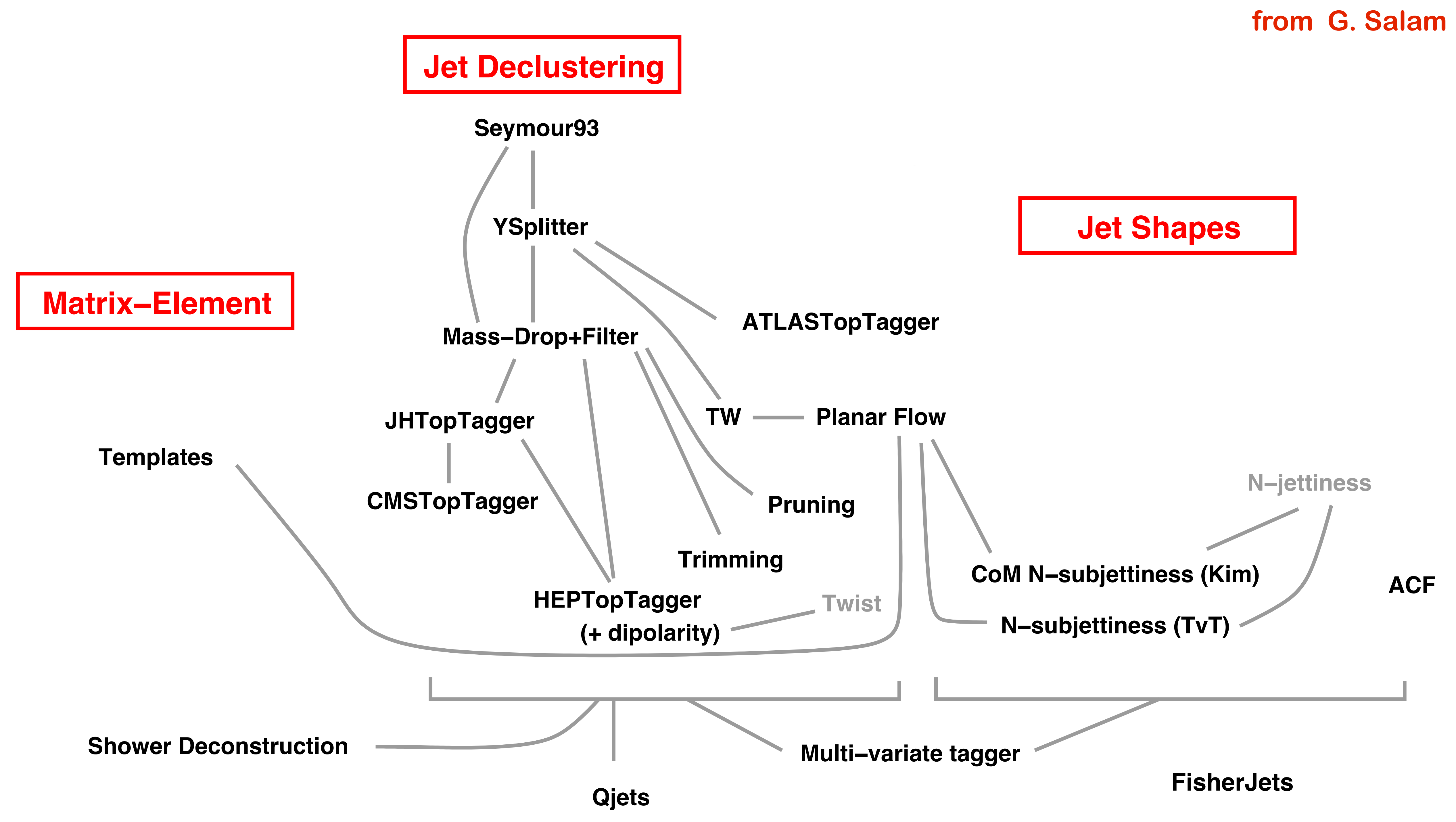
- The angular separation between the decay products decreases with increasing transverse momentum

$$\Delta R^2_{b\bar{b}} \simeq \frac{m_H^2}{z(1-z)p_t^2}$$

- Two b-jets fall into the same “fat” jet

A VARIETY OF TAGGERS

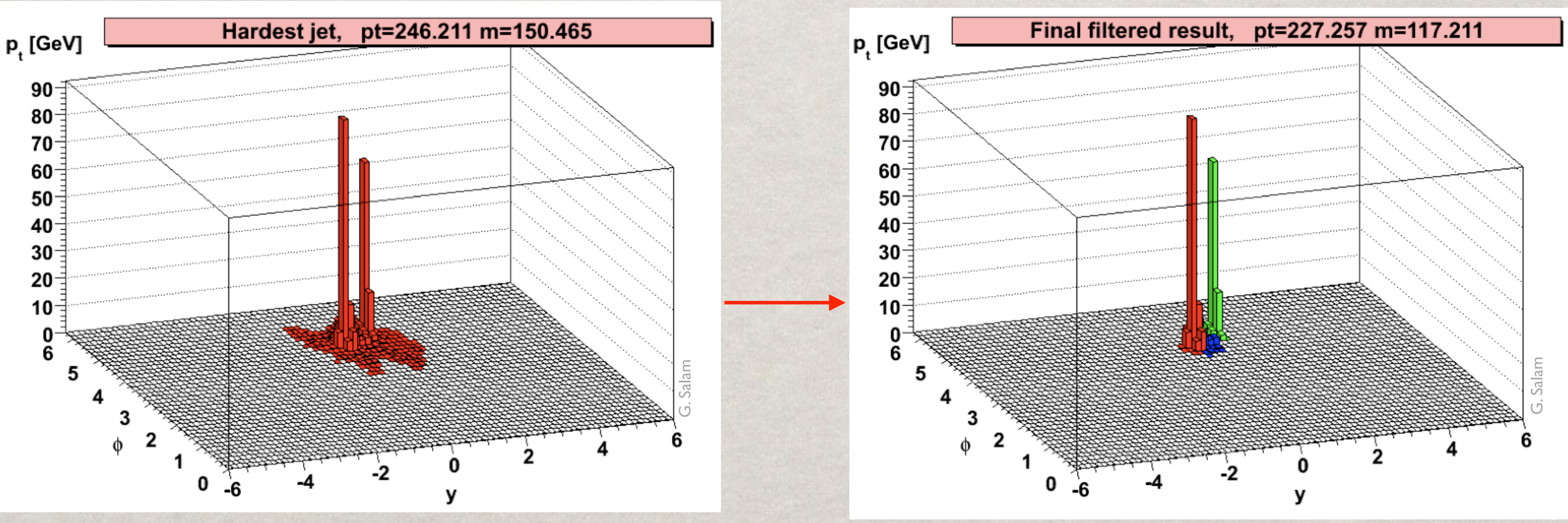
- Here are some of the tools/taggers employed to investigate jet substructure



WHAT DO THE TAGGERS DO?

A tagger for jet substructure should

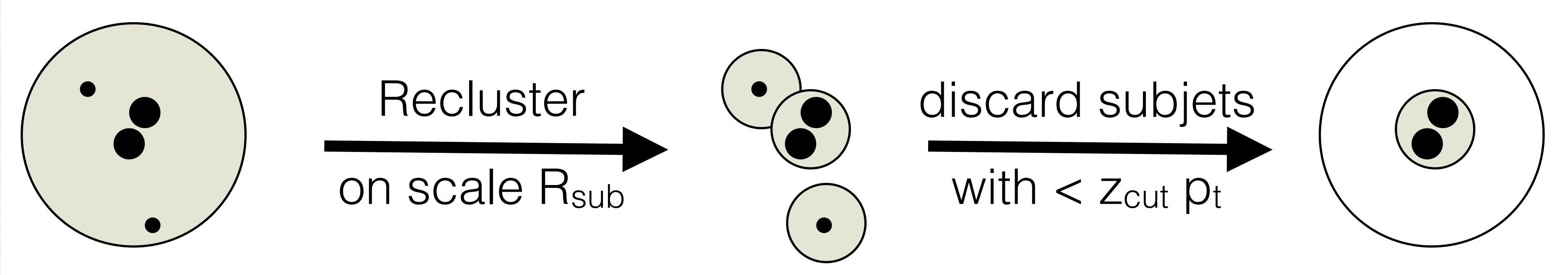
- clean the jets from soft junk
- identify the sub-jets from the decay products of a heavy particle
- discriminate between signal jets and “boring” QCD jets
- be robust again initial-state radiation and non-perturbative effects (hadronisation, underlying event)



COMPARE THREE DIFFERENT TAGGERS

- Trimming

[Krohn Thaler Wang JHEP 02 (2010) 084]



Recluster

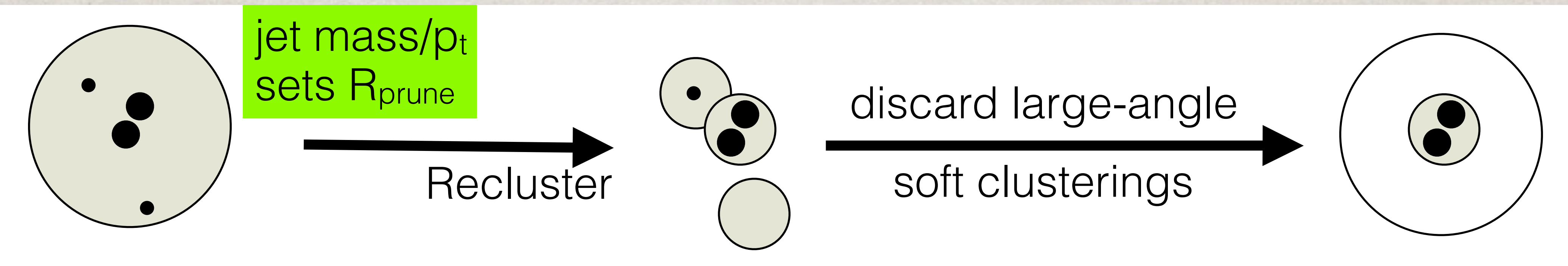
on scale R_{sub}

discard subjets

with < z_{cut} p_t

- Pruning

[Ellis Vermilion Walsh PRD80 (2009) 051501, PRD81 (2010) 094023]



jet mass/p_t sets R_{prune}

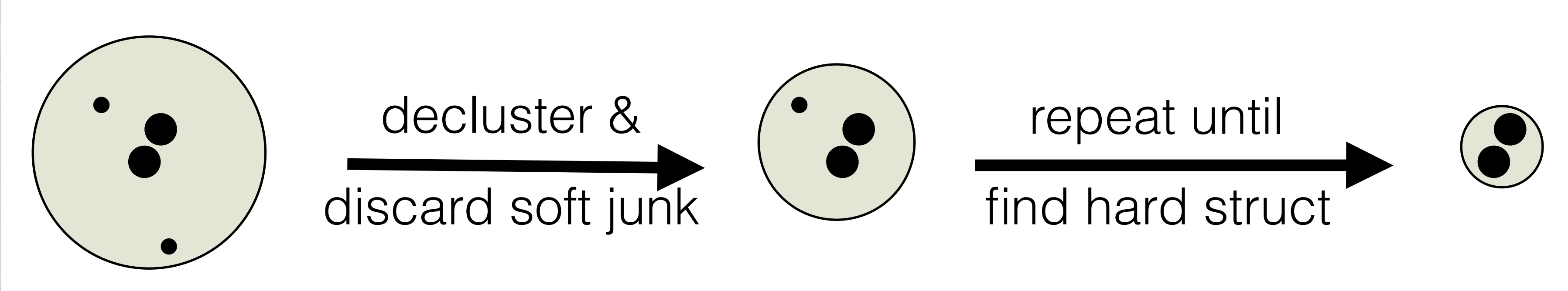
Recluster

discard large-angle

soft clusterings

- Mass-drop tagger (MDT)

[Butterworth Davison Rubin Salam PRL 100 (2008) 242001]



decluster &

discard soft junk

repeat until

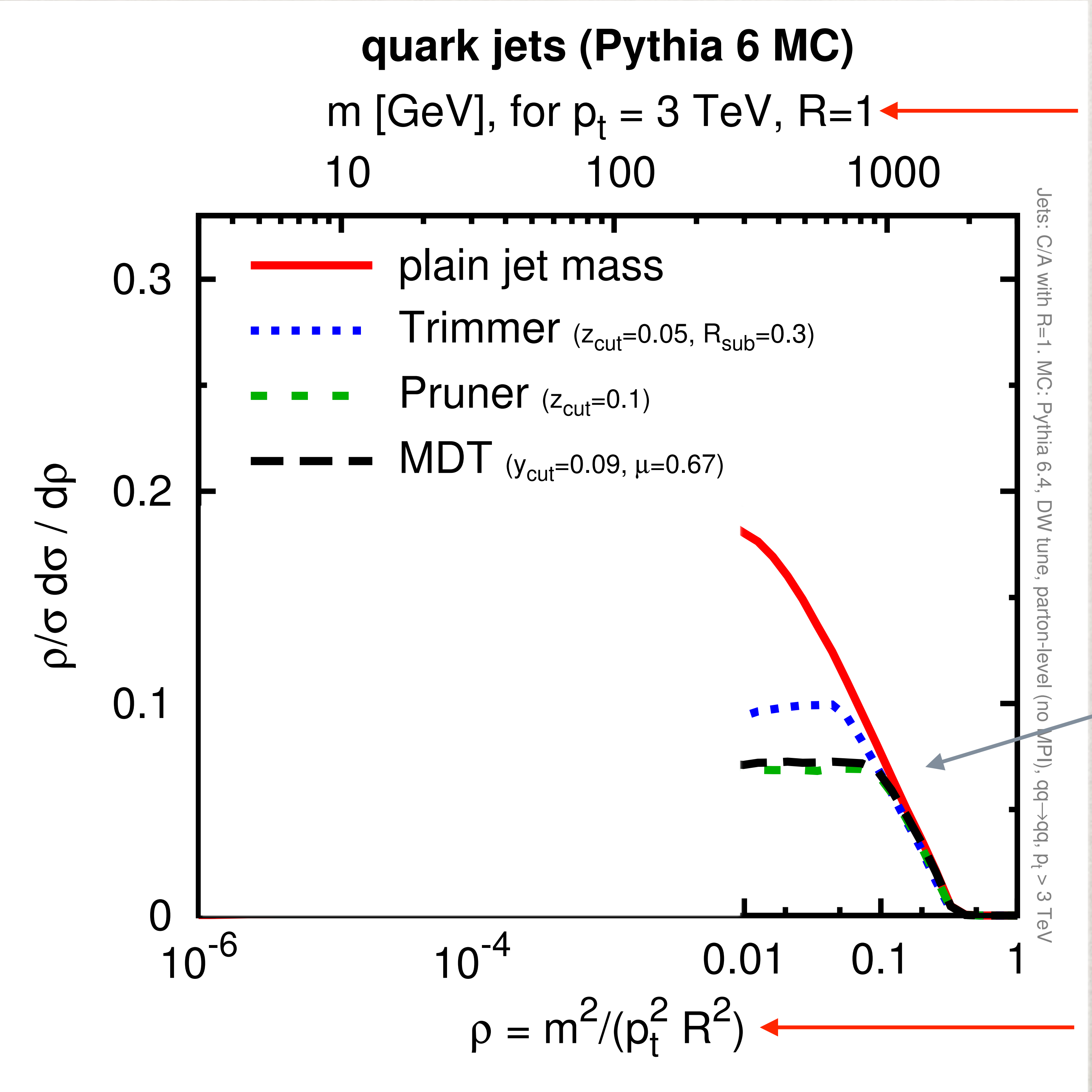
find hard struct

pictures by G. Salam

JET-MASS WITH DIFFERENT TAGGERS

- Compare the invariant mass distribution of background QCD jets

[Dasgupta Fregoso Marzani Salam JHEP 09 (2013) 029]



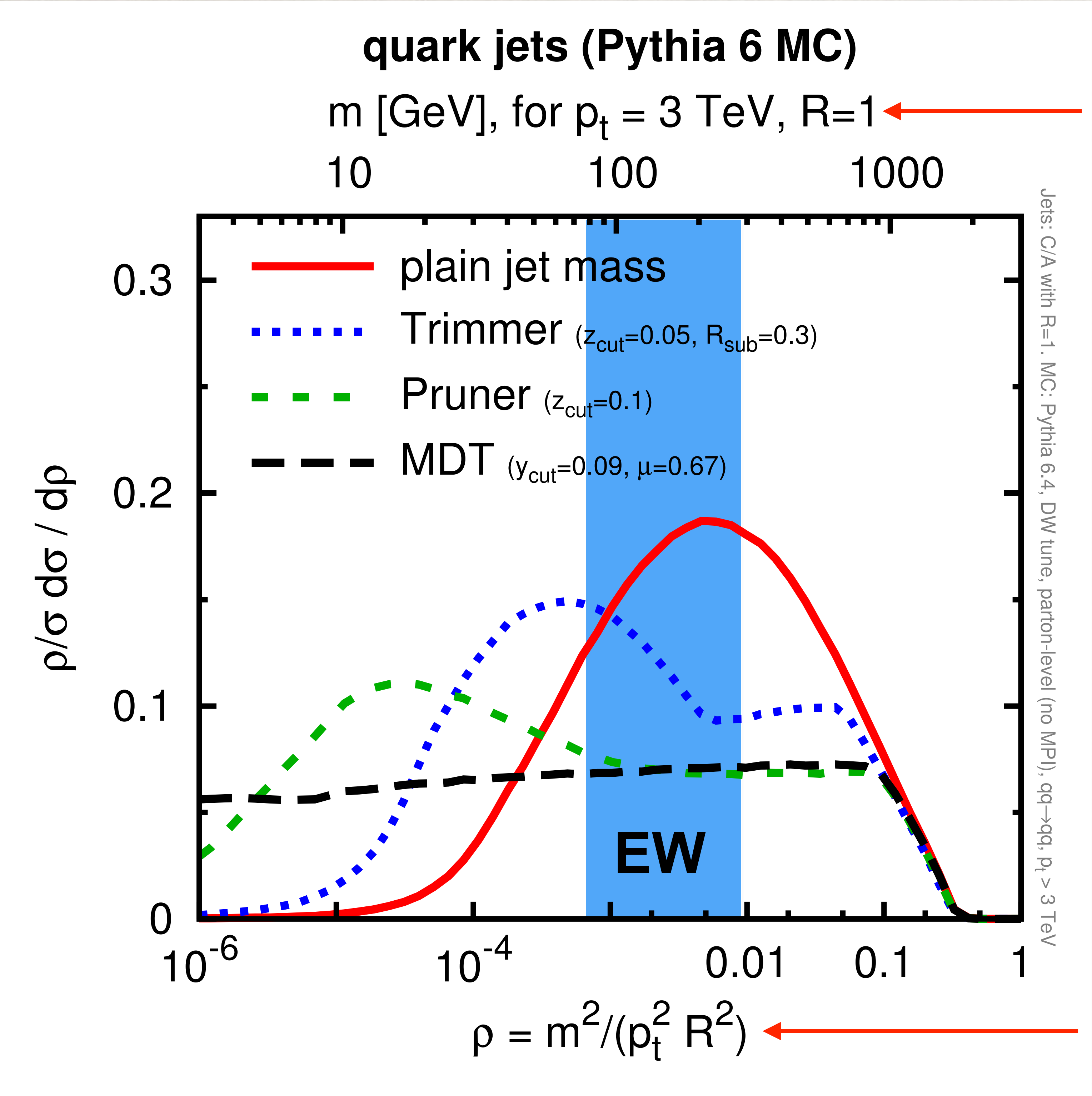
The actual jet mass

Down to masses of the order of the EW scale all taggers seem to be doing the same

Dimensionless variable for QCD studies

JET-MASS WITH DIFFERENT TAGGERS

- The performance of various jet taggers can be compared by looking at the invariant mass of background QCD jets



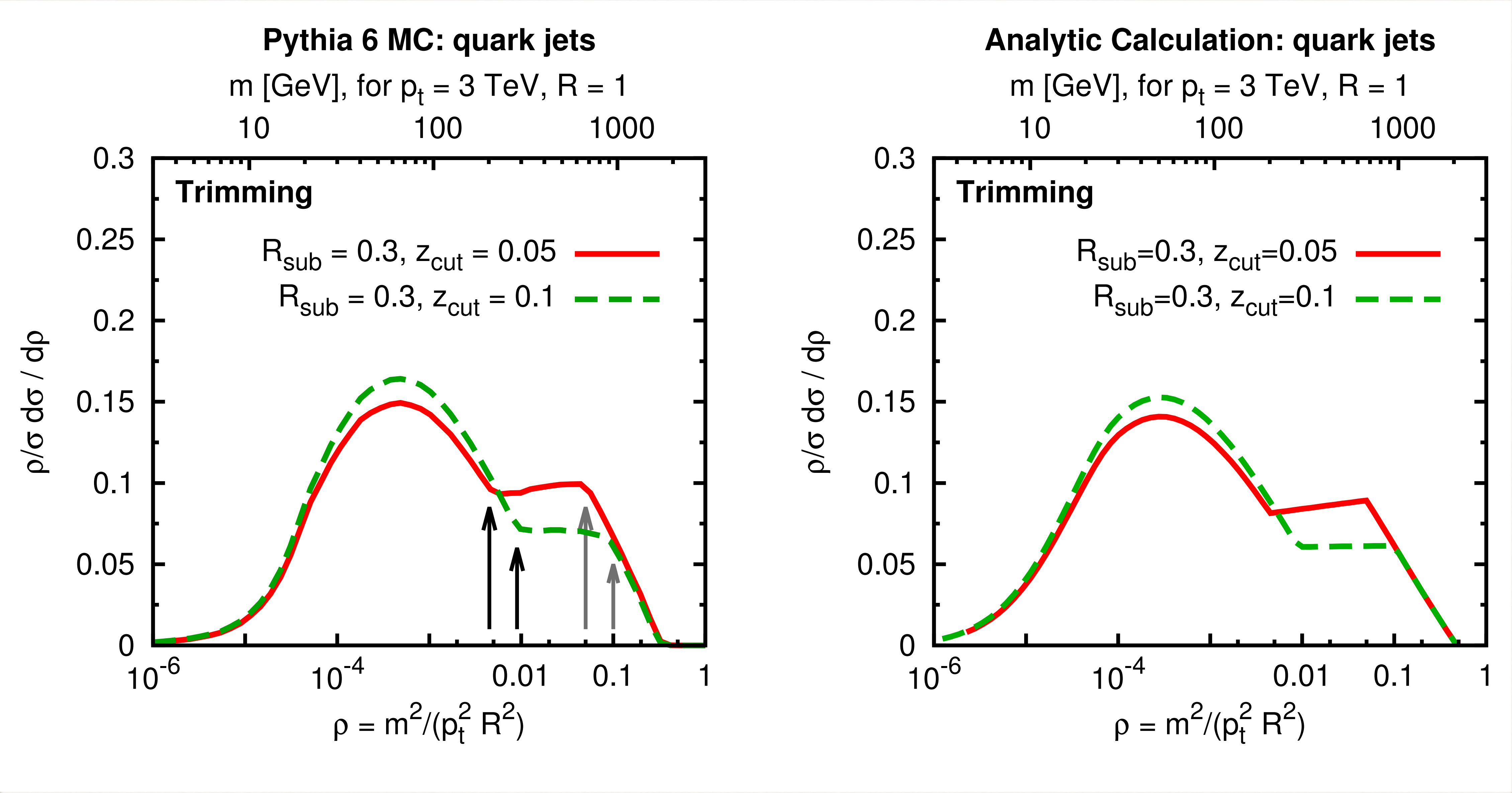
The actual jet mass

At masses of the order of the EW scale the taggers start to differ: can we understand it?

Dimensionless variable for QCD studies

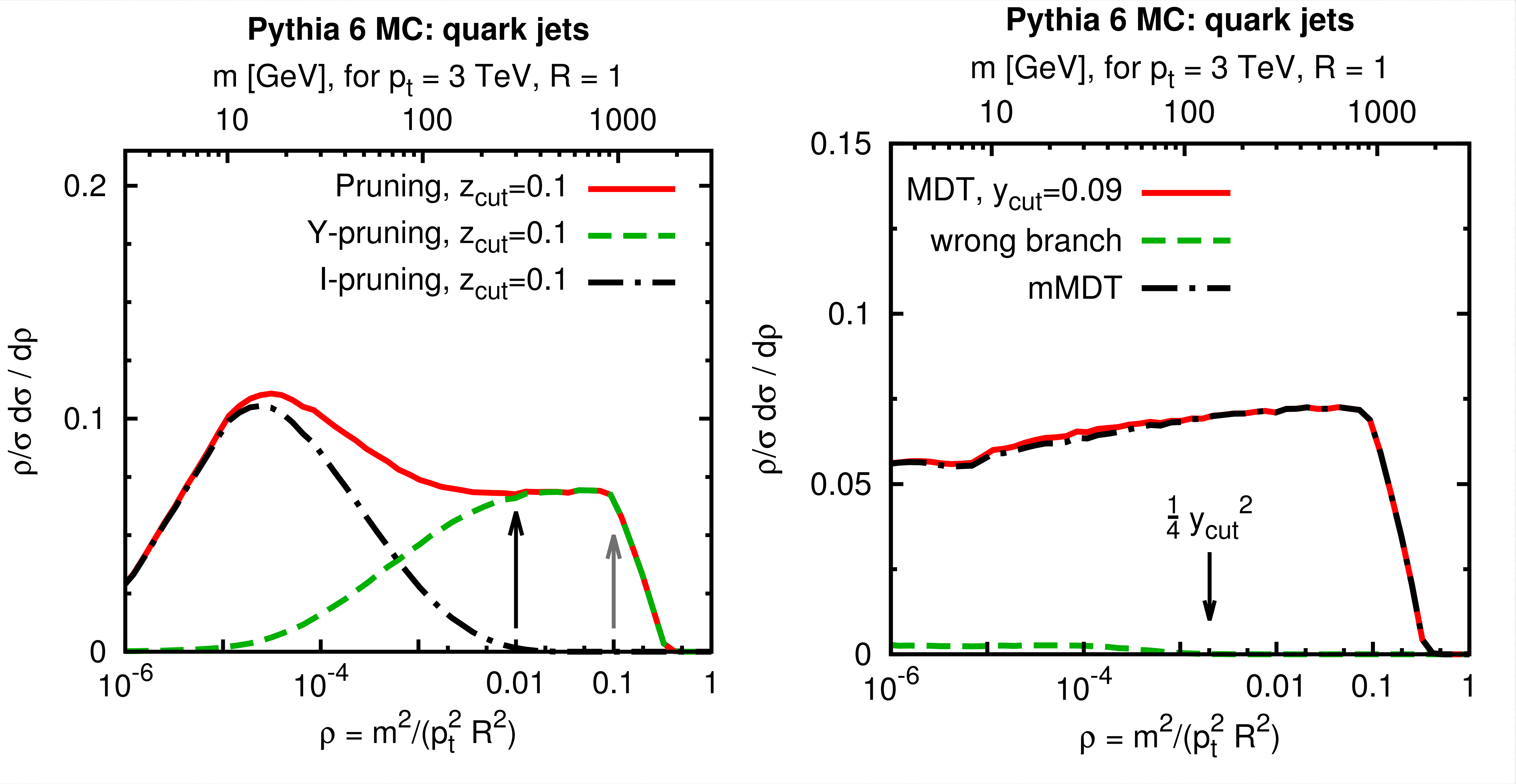
ANALYTIC STUDIES...

- The relevant features of the various taggers can be understood analytically!



...TRIGGER IMPROVEMENTS

- Y-pruning and modified MDT (mMDT) have better behaviour than the original taggers

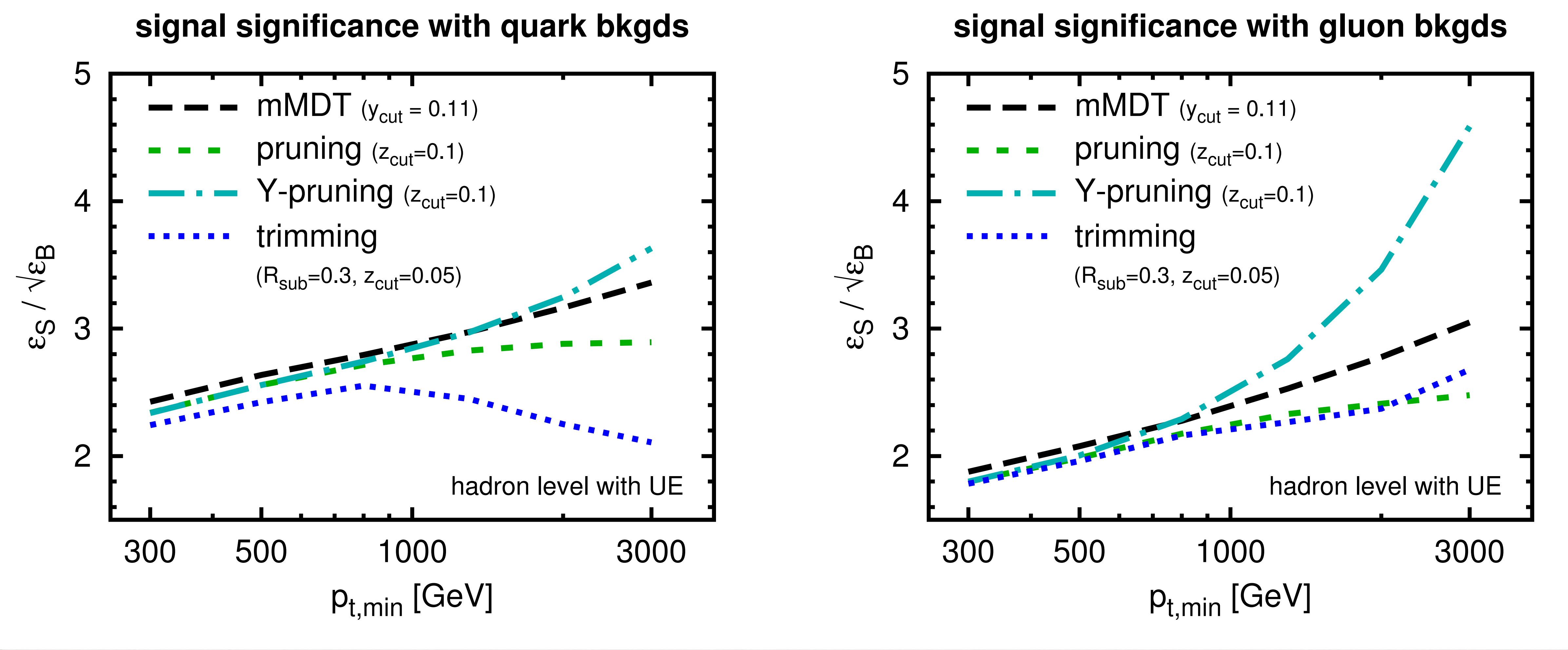


- The mMDT mass distribution is free from all soft-collinear logarithms!

PERFORMANCE OF IMPROVED TAGGERS

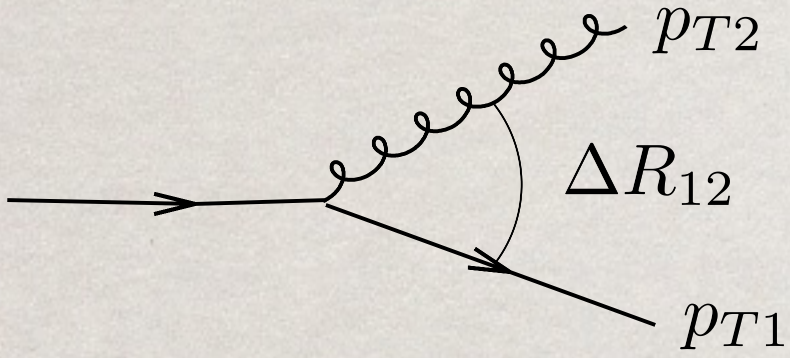
- The improved taggers perform better in discriminating signal from background

[Dasgupta Fregoso Marzani Salam JHEP 09 (2013) 029]



SOFT-DROP TAGGER

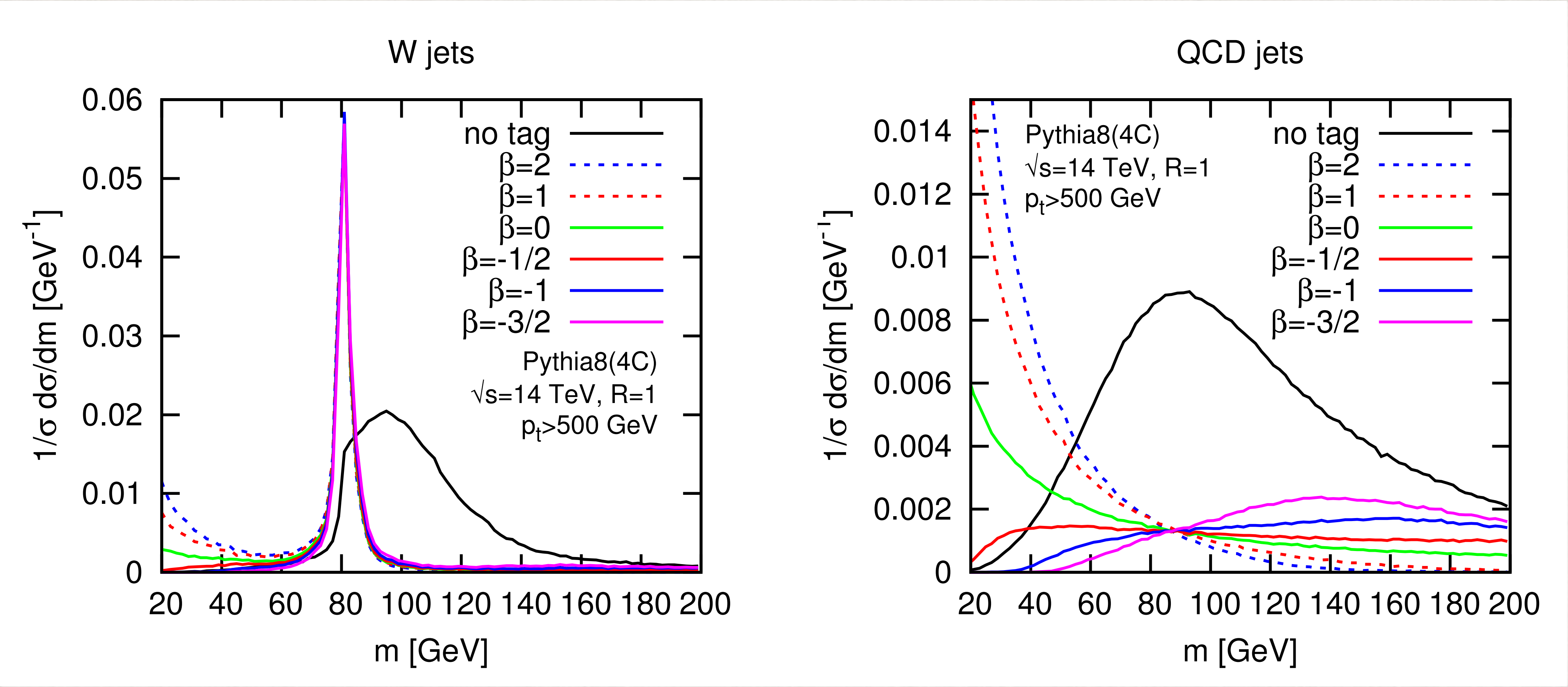
- New condition: eliminate the softer sub-jet constituent if



$$\frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} < z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

$$\beta = 0 \quad \Leftrightarrow \quad \text{mMDT}$$

[Larkosky Marzani Soyez Thaler JHEP 05 (2014) 146]



- $\beta < 0$ kills QCD jets at low invariant mass, similar to Y-pruning

HIGHLIGHTS

- Higgs cross section with zero jets
  - Three different procedures that agree at NNLL+NNLO accuracy
  - All predictions give an uncertainty of order 10-13%
  - Banfi-Monni-Zanderighi: inclusion of top and bottom mass effects gives a larger uncertainty, of order 14%
- Uncertainties across jet bins
  - JVE method can be generalised to an arbitrary jet multiplicity
  - New BLPTW method that takes advantage of resummation of the exclusive one-jet cross section
- New ideas for jet substructure studies
  - Analytical resummation methods are bringing new insight in the field and helping devise better tools/tagger
  - These ideas are being validated against experimental data (see BOOST 2014)

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Thank you for your attention!

Extra

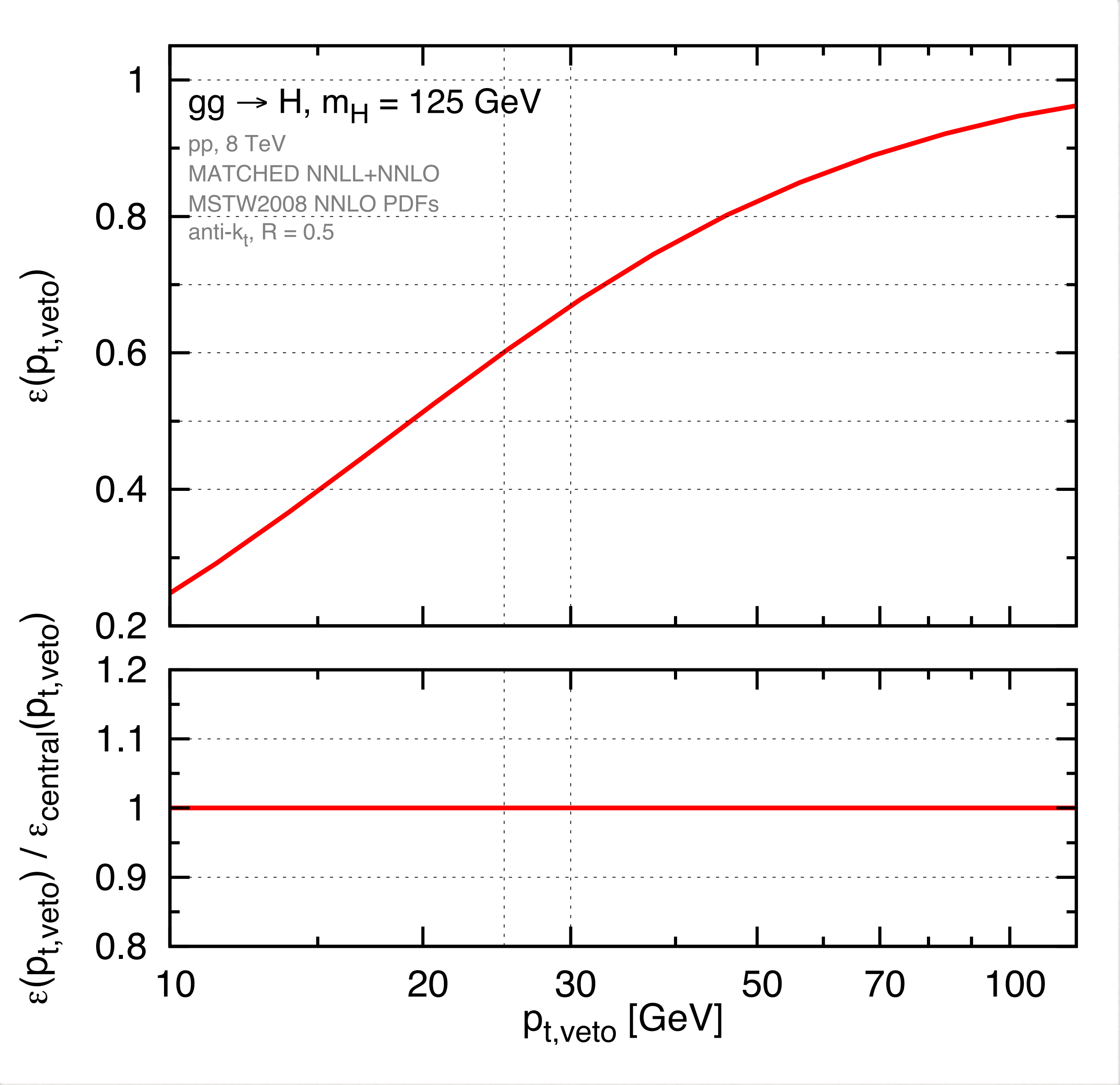
THEORETICAL UNCERTAINTIES

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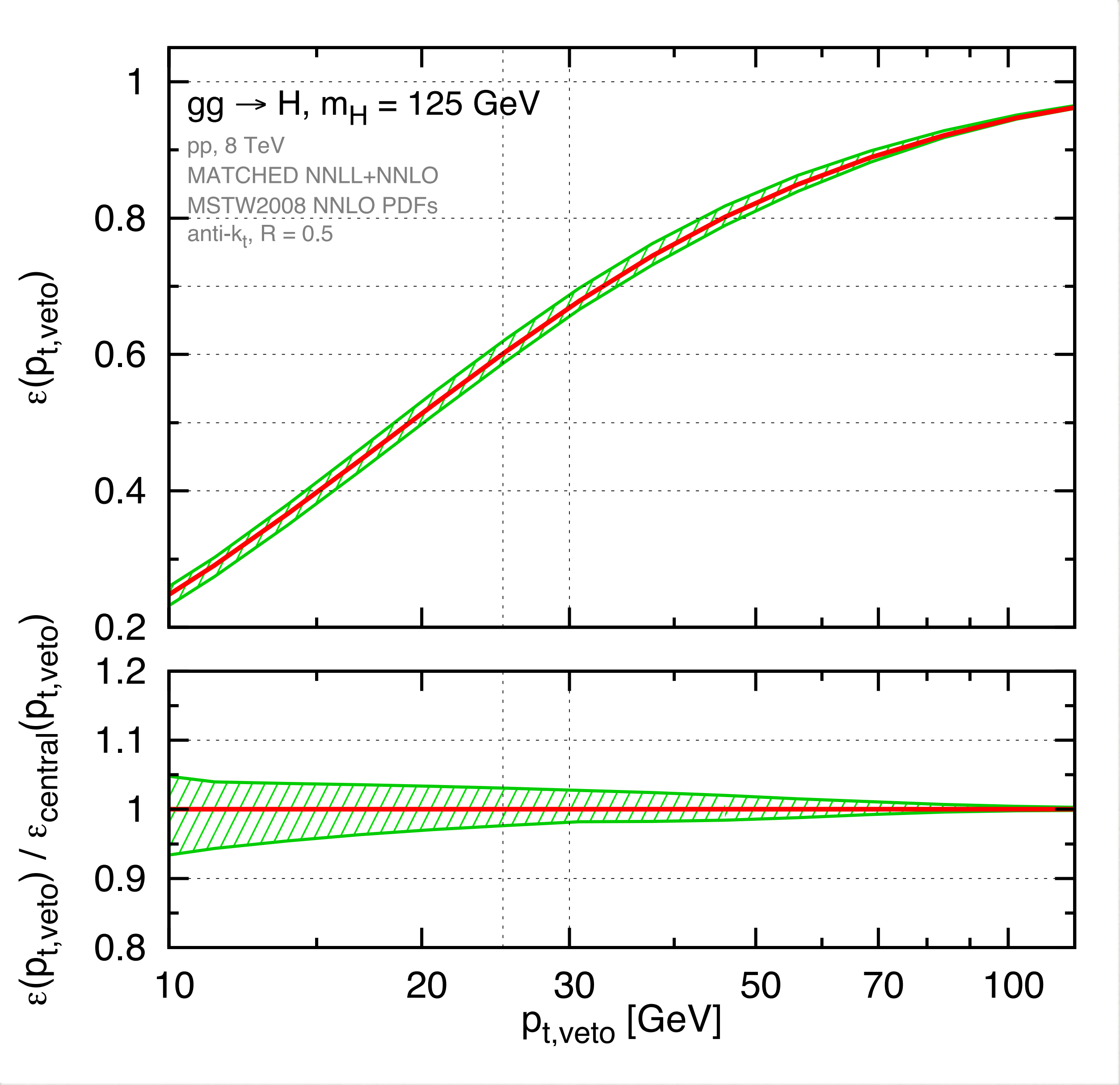
- Variation of μ_R, μ_F with $Q = m_H/2$

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



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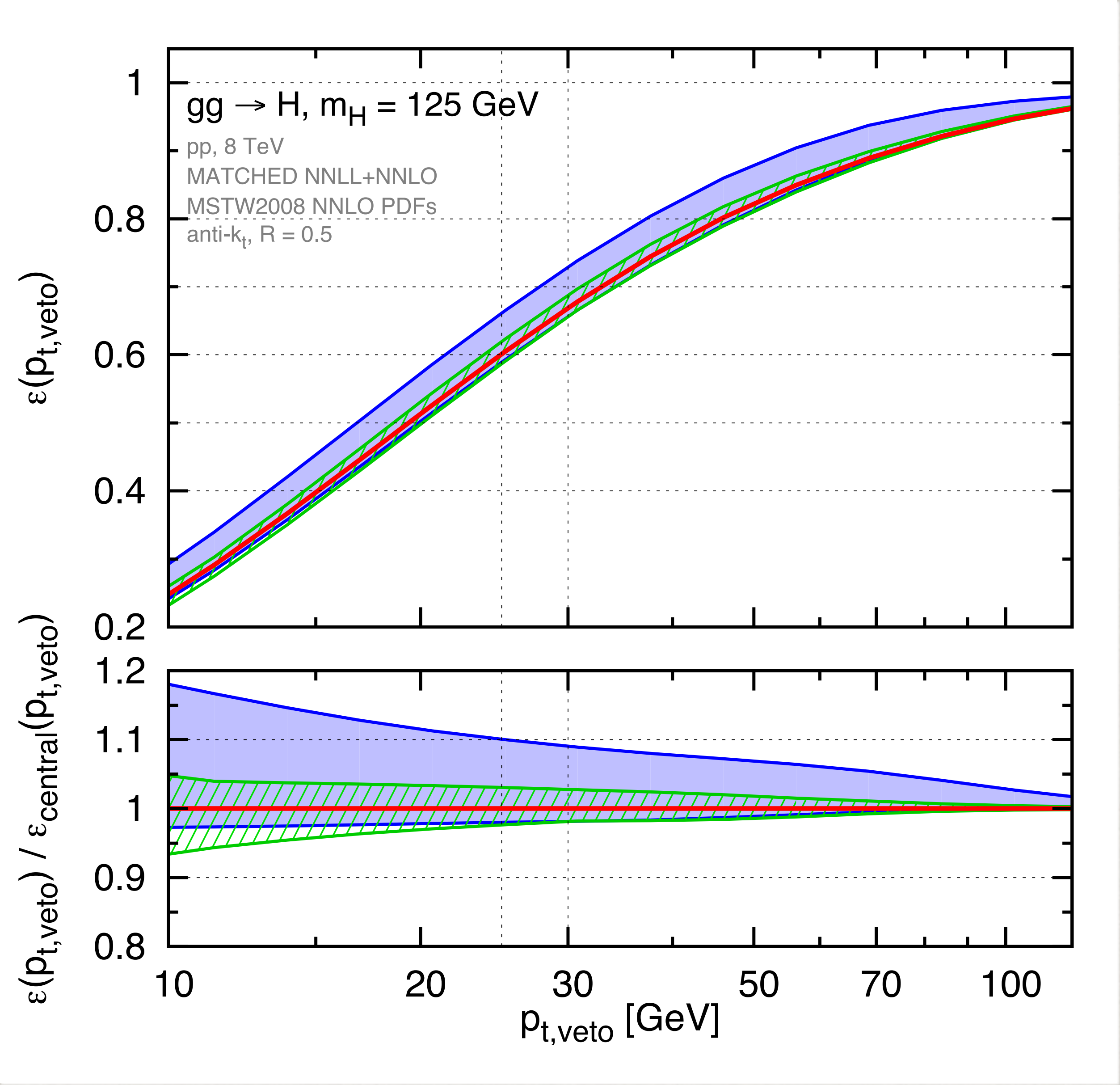
$$\frac{m_H}{4} \leq \mu_R, \mu_F \leq m_H \qquad \frac{1}{2} \leq \frac{\mu_R}{\mu_F} \leq 2$$

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

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



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

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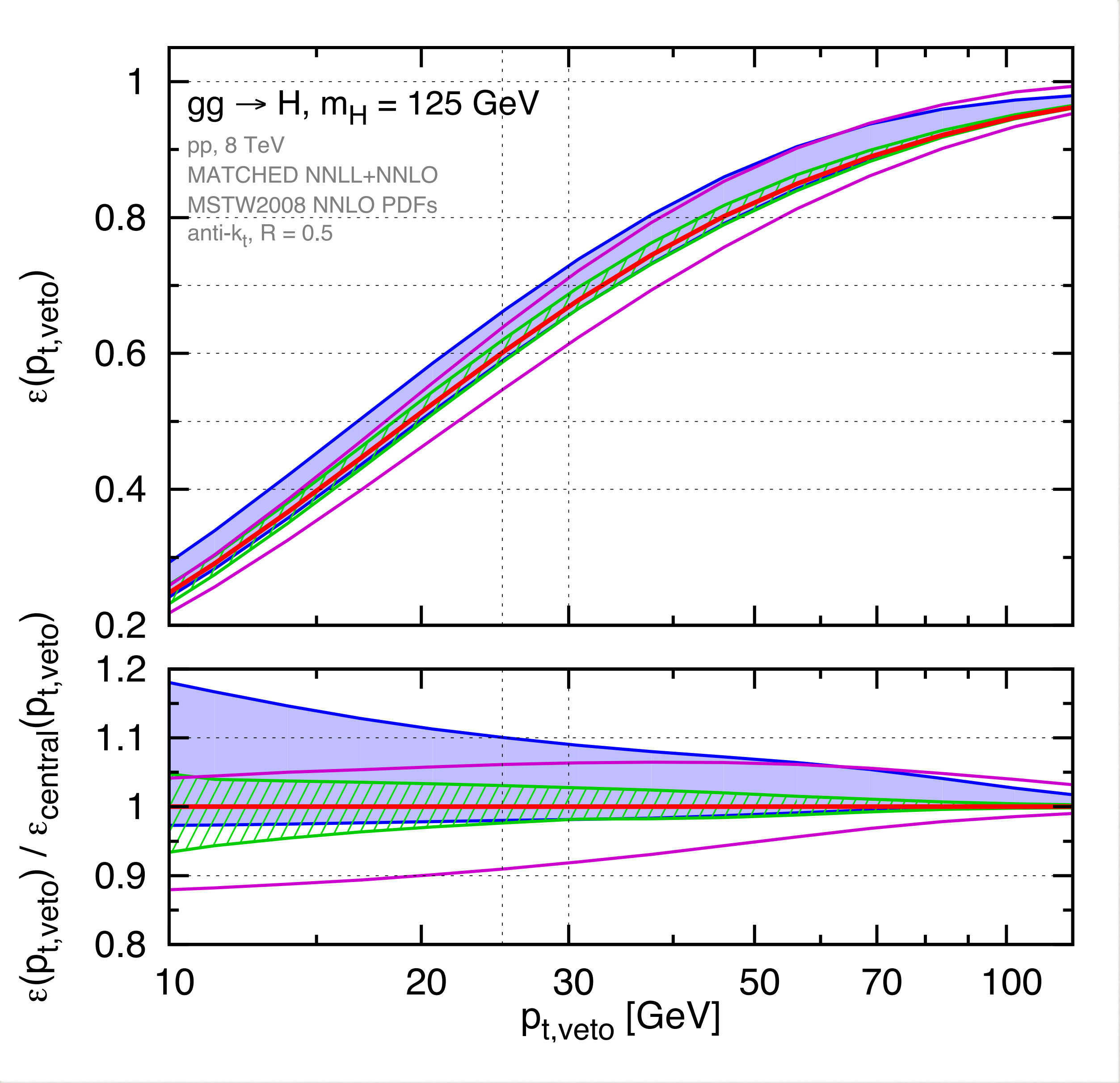

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- Total uncertainty: envelope