The Higgs Cross Section with a Jet Veto

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work with:
Frank Tackmann and Saba Zuberi - 1206.4312
Iain Stewart, Frank Tackmann, and Saba Zuberi - ongoing

The Higgs

Jet Vetoes

H + 0-jet Calculation

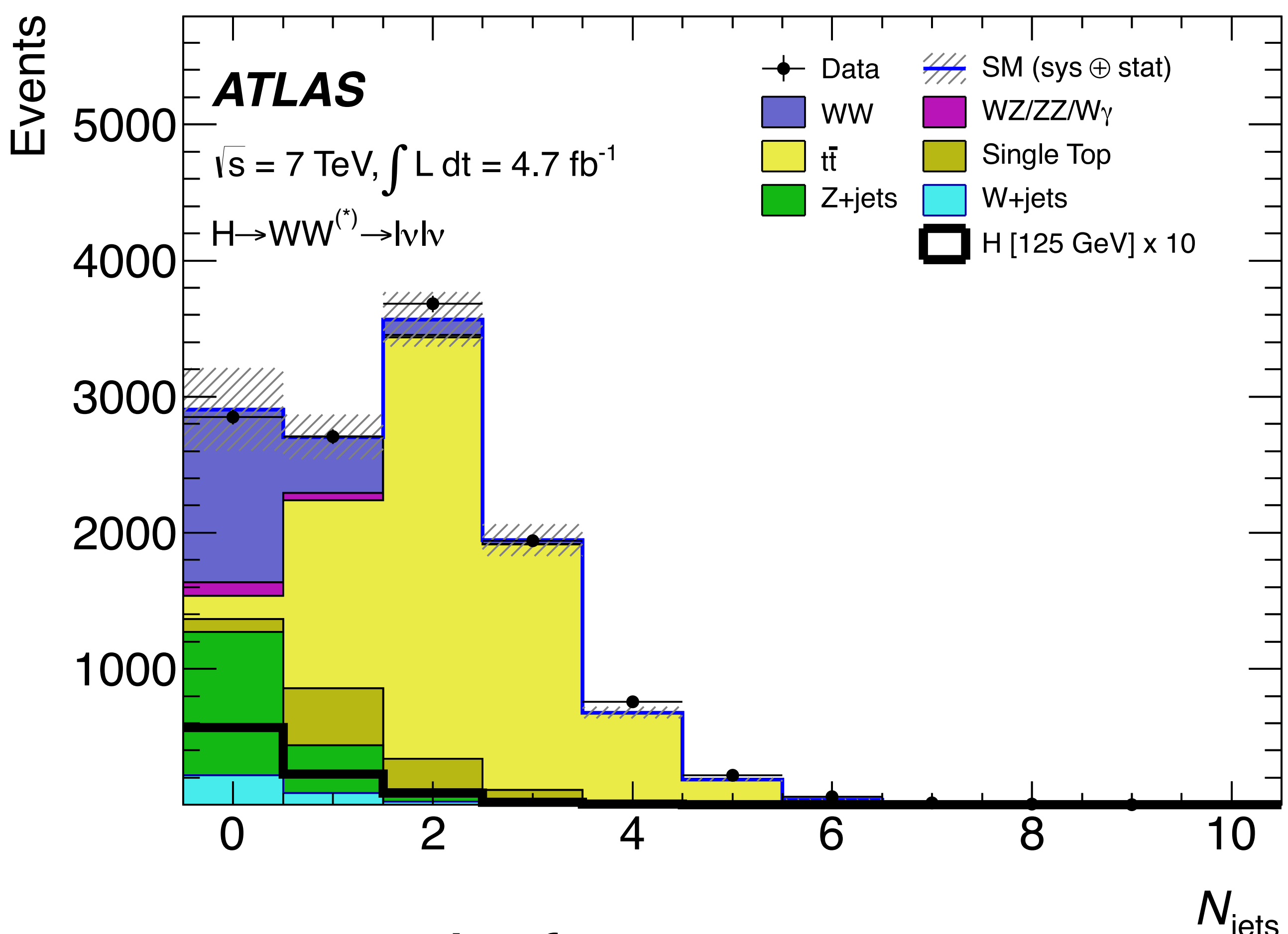
Preliminary Numerics and Uncertainties

Higgs Analysis: WW* Channel and Jet Binning

jet binning useful in separating backgrounds, maximizing sensitivity

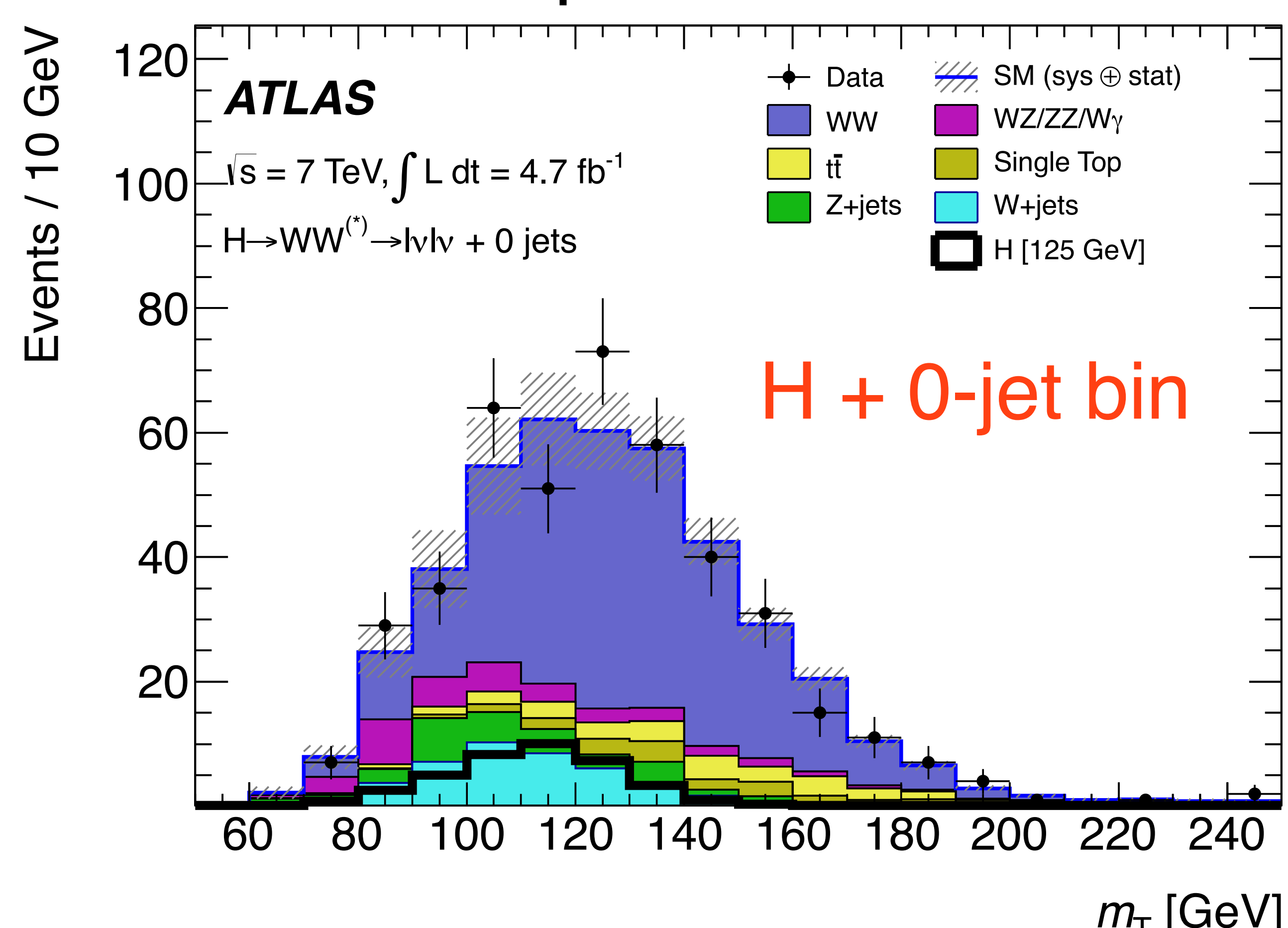
from ATLAS, 1206.0756

H→WW→2l+2ν



before cuts

No mass peak in this channel



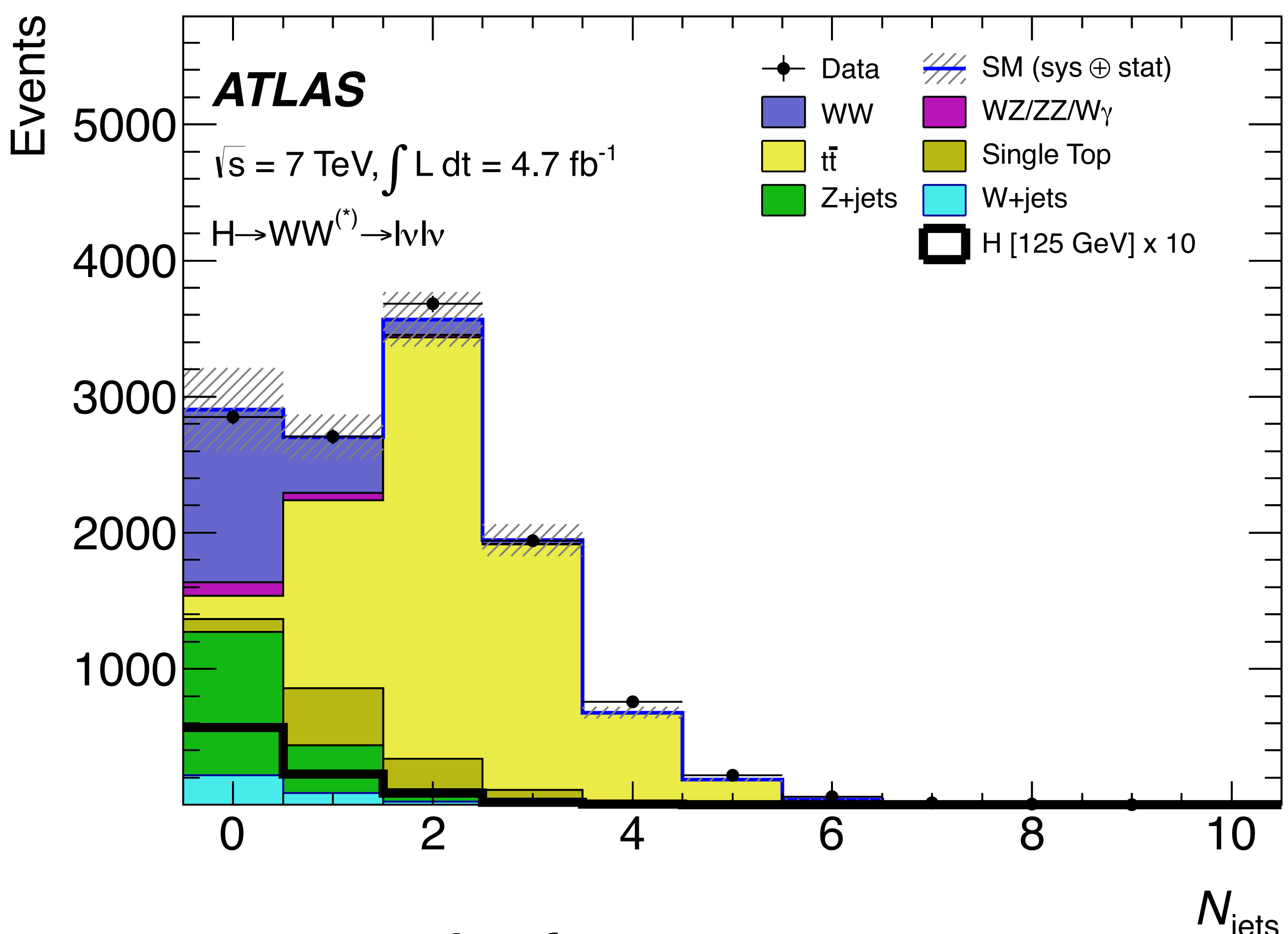
after cuts

Higgs Analysis: WW* Channel and Jet Binning

"The systematic uncertainties that have the largest impact on the sensitivity of the search are the theoretical uncertainties associated with the signal."

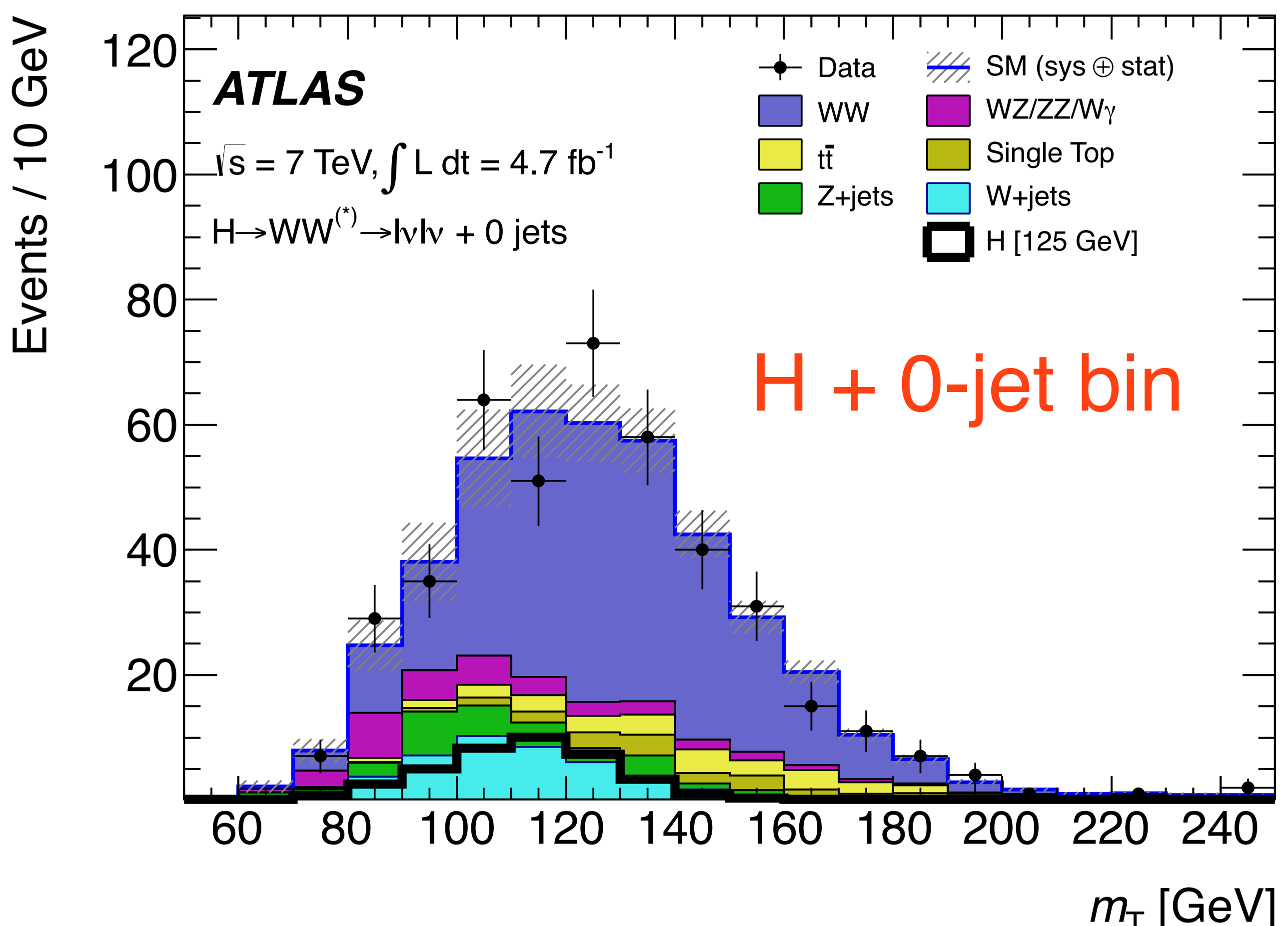
from ATLAS, 1206.0756

$H \to WW \to 2l + 2\nu$



before cuts

No mass peak in this channel



after cuts

Higgs Analysis: WW* Channel and Jet Binning

"The systematic uncertainties that have the largest impact on the sensitivity of the search are the theoretical uncertainties associated with the signal."

from ATLAS, 1206.0756

Leading systematic uncertainties

Source (0-jet)	Signal (%)	Bkg. (%)
Inclusive ggF signal ren./fact. scale	13	-
1-jet incl. ggF signal ren./fact. scale	10	-
PDF model (signal only)	8	-
QCD scale (acceptance)	4	-
Jet energy scale and resolution	4	2
W+jets fake factor	-	5
WW theoretical model	-	5
Source (1-jet)	**Signal (%)**	**Bkg. (%)**
1-jet incl. ggF signal ren./fact. scale	26	-
2-jet incl. ggF signal ren./fact. scale	15	-
Parton shower/ U.E. model (signal only)	10	-
b-tagging efficiency	-	11
PDF model (signal only)	7	-
QCD scale (acceptance)	4	2
Jet energy scale and resolution	1	3
W+jets fake factor	-	5
WW theoretical model	-	3

ATLAS-CONF-2012-158

dominant contribution:
perturbative QCD
scale uncertainties

$$\delta\sigma_{0\,\mathrm{jet}} = 16.5\%$$

$$\delta\sigma_{1\,\mathrm{jet}} = 30\%$$

The Higgs

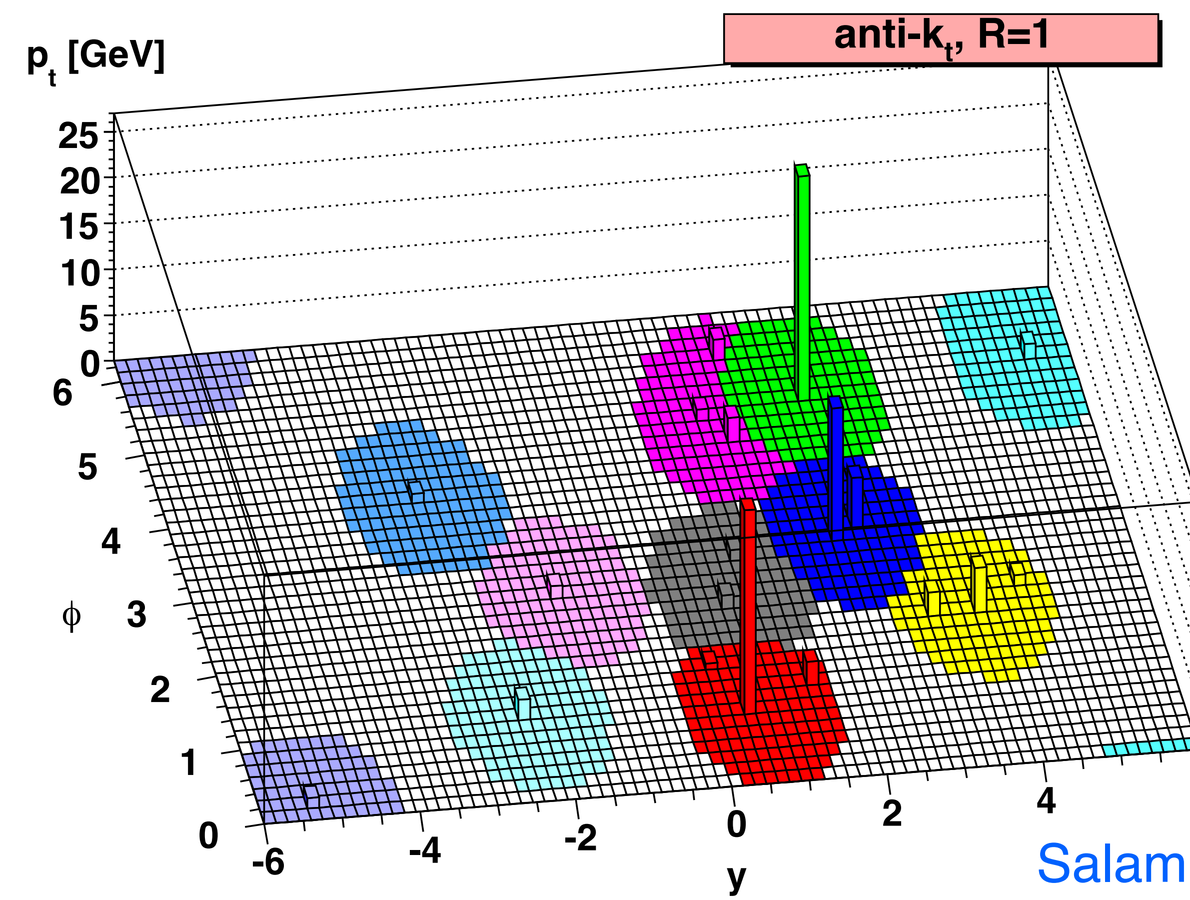
Jet Vetoes

H + 0-jet
Calculation

Preliminary
Numerics and
Uncertainties

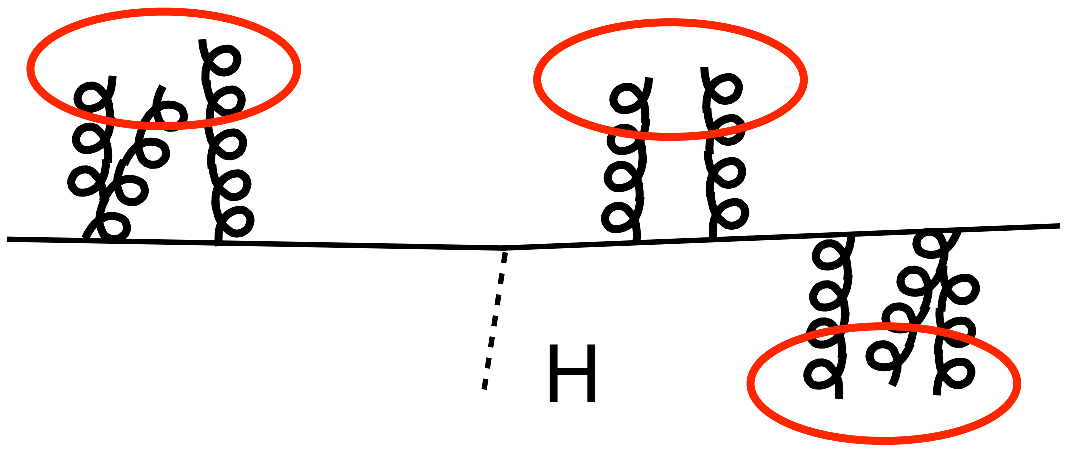
Jet Binning

- Build jets with a jet algorithm (e.g. anti-k_T)
- Experimental analysis often look at exclusive/inclusive jet bins
    - Standard veto is the jet p_T
    - e.g. 0 jets with $p_T > 25$ GeV, or at least 1 jet with $p_T > 40$ GeV
- Soft jets are poorly resolved, must be measured inclusively
- Low jet veto is useful in separating backgrounds (e.g. WW, tt~)



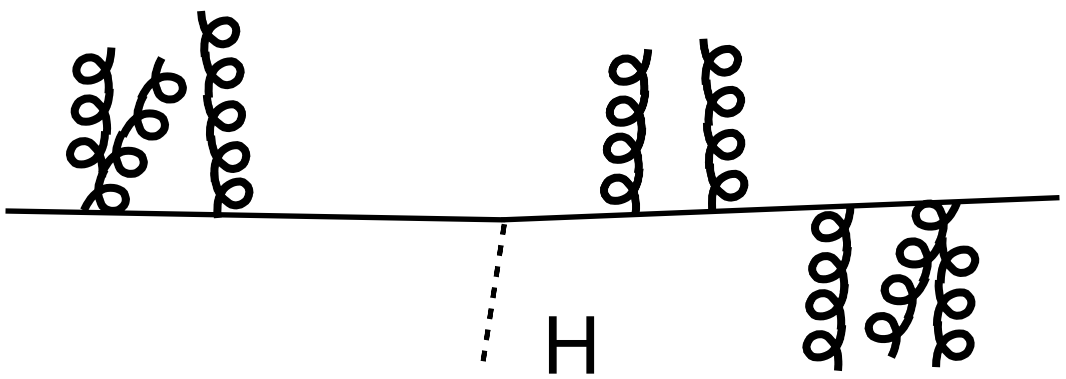
Salam 0906.1833

Approaches to Jet Vetoes



experiments veto on
the p_T of each jet

depends on
jet algorithm



the event E_T is an effective
veto against high p_T jets

doesn't

$$E_T = \sum_i p_{Ti}$$

We will bootstrap from
the *well understood* global veto (E_T)
to the *more complicated* jet veto

Types of Jet Vetoes

- Many types of vetoes to restrict jet activity have been studied, *e.g.*
  - q_T, beam thrust (*global* jet vetoes, can be calculated to high accuracy)
- Experiments often use jet p_T as a veto. Recent theory work:
  - H + 0-jets:
    - Banfi, Salam, Zanderighi (1203.5773) - NLL+NNLO
    - Becher, Neubert (1205.3806) - NNLL+NNLO (numerics being revised)
    - Banfi, Monni, Salam, Zanderighi (1206.4998) - NNLL+NNLO
    - Stewart, Tackmann, JW, Zuberi (in progress) - NNLL'+NNLO
  - H + 1-jet: Liu, Petriello (1210.1096, 1303.4405) - NLL+NLO
- High luminosity LHC will give large pileup effects, may lead to some new and creative jet vetoes (e.g. using jet substructure)

The Higgs

Jet Vetoes

H + 0-jet Calculation

Preliminary Numerics and Uncertainties

Log Structure of H + 0-jet Cross Section

Counting in the log of the cross section

LL	NLL	NLL$'$ / NNLL	NNLL$'$ / NNNLL	
$\alpha_s L^2$	$\alpha_s L$	α_s		
$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	α_s^2	
$\alpha_s^3 L^4$	$\alpha_s^3 L^3$	$\alpha_s^3 L^2$	$\alpha_s^3 L$	α_s^3

$$L = \ln \frac{p_T^{\mathrm{cut}}}{m_H}$$

Global veto log structure

Log Structure of H + 0-jet Cross Section

Counting in the log of the cross section

LL	NLL	NLL$'$ / NNLL	NNLL$'$ / NNNLL	
$\alpha_s L^2$	$\alpha_s L$	α_s		
$\alpha_s^2 L^3$	$\alpha_s^2 L^2$ $\alpha_s^2 L L_R$	$\alpha_s^2 L$ $\alpha_s^2 L, \alpha_s^2 L_R$	α_s^2	
$\alpha_s^3 L^4$	$\alpha_s^3 L^3$ $\alpha_s^3 L L_R^2$	$\alpha_s^3 L^2$ $\alpha_s^3 L L_R, \alpha_s^3 L_R^2$	$\alpha_s^3 L$ $\alpha_s^3 L, \alpha_s^3 L_R$	α_s^3

$$L = \ln \frac{p_T^{\rm cut}}{m_H}$$

$$L_R = \ln R$$

We work to NNLL'+NNLO in the veto logs

has the RGE boundary conditions for NNNLL+NNLO

Global veto log structure

Clustering corrections for the jet veto

Overview of the H + 0-jet Calculation

$$\sigma_0(p_T^{\mathrm{cut}}) = \sigma_0^{\mathrm{resum}}(p_T^{\mathrm{cut}}) + \sigma_0^{\mathrm{nons}}(p_T^{\mathrm{cut}})$$

Resum to NNLL'

New two-loop calculations,
anomalous dimensions

match to NNLO

MCFM H+jet at LO, NLO
HNNLO for the total cross section

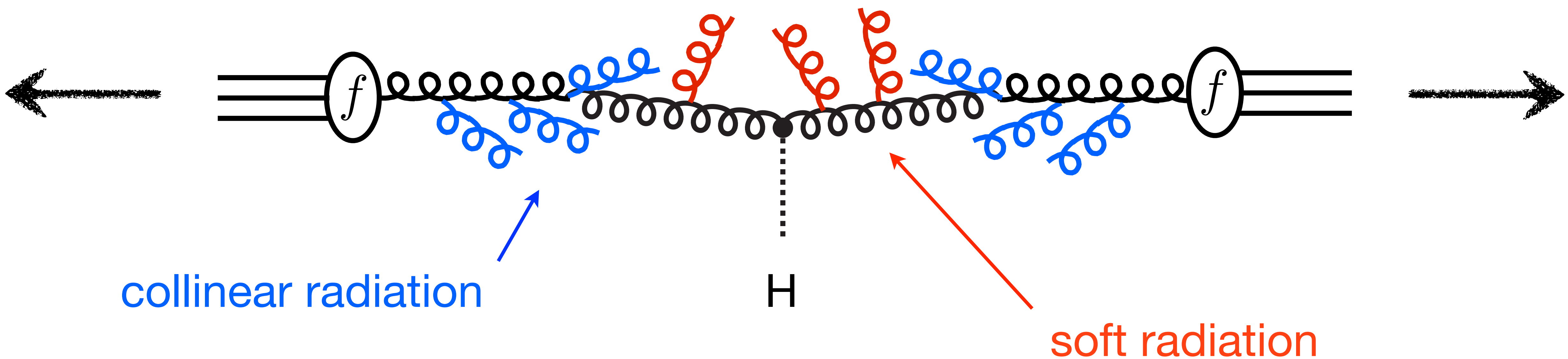
Campbell, Ellis, Williams

Catani, Grazzini

Use the global, *jet algorithm independent* E_T veto
to derive the double logarithmic resummation (+single logs)

Derive a *jet algorithm dependent* clustering correction
that affects the single log resummation

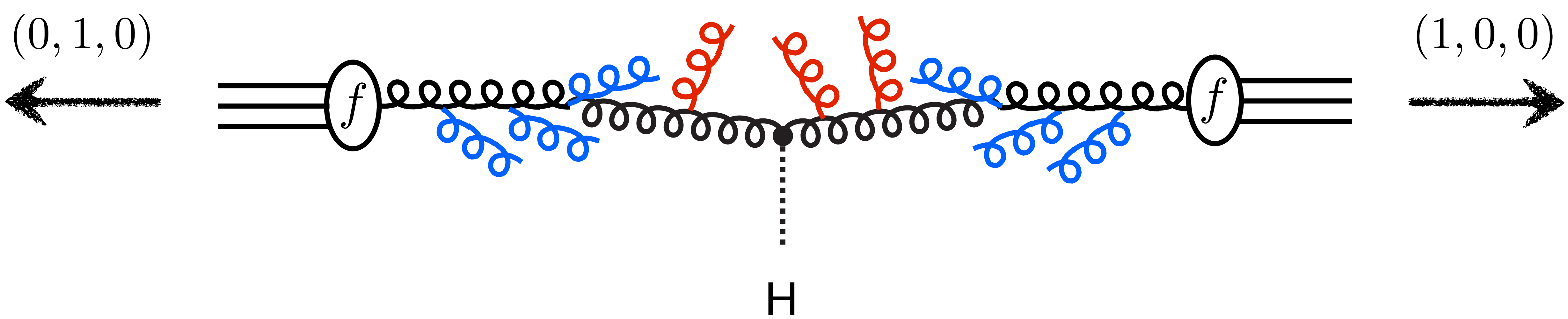
Power Counting for H + 0-jet Cross Section



soft and collinear radiation emitted with a scale $p_T \sim p_T^{\rm cut}$

for a 0-jet cross section, there are no hard jet emissions
this implies the final state can be described by SCET_{II}

Power Counting for H + 0-jet Cross Section



collinear radiation: $p_n \sim m_H(1, \lambda^2, \lambda)$ aligned with beam

anti-collinear radiation: $p_{\bar{n}} \sim m_H(\lambda^2, 1, \lambda)$ aligned with (other) beam

soft radiation: $p_s \sim m_H(\lambda, \lambda, \lambda)$ isotropic, goes anywhere

$$\lambda \sim \frac{p_T^{\mathrm{cut}}}{m_H} \ll 1$$

power counting parameter in $\mathrm{SCET_{II}}$, enforces no high-p_T jets

Rapidity Divergences and Renormalization

eikonal matrix element:

$$\int dp_T^2 \, {\color{red} dy} \, \frac{d\phi}{\pi} \frac{1}{p_T^{2+2\epsilon}} \theta(p_T < p_T^{\rm cut})$$

unregulated rapidity divergence

we use the rapidity regulator to regulate rapidity divergences and resum logs

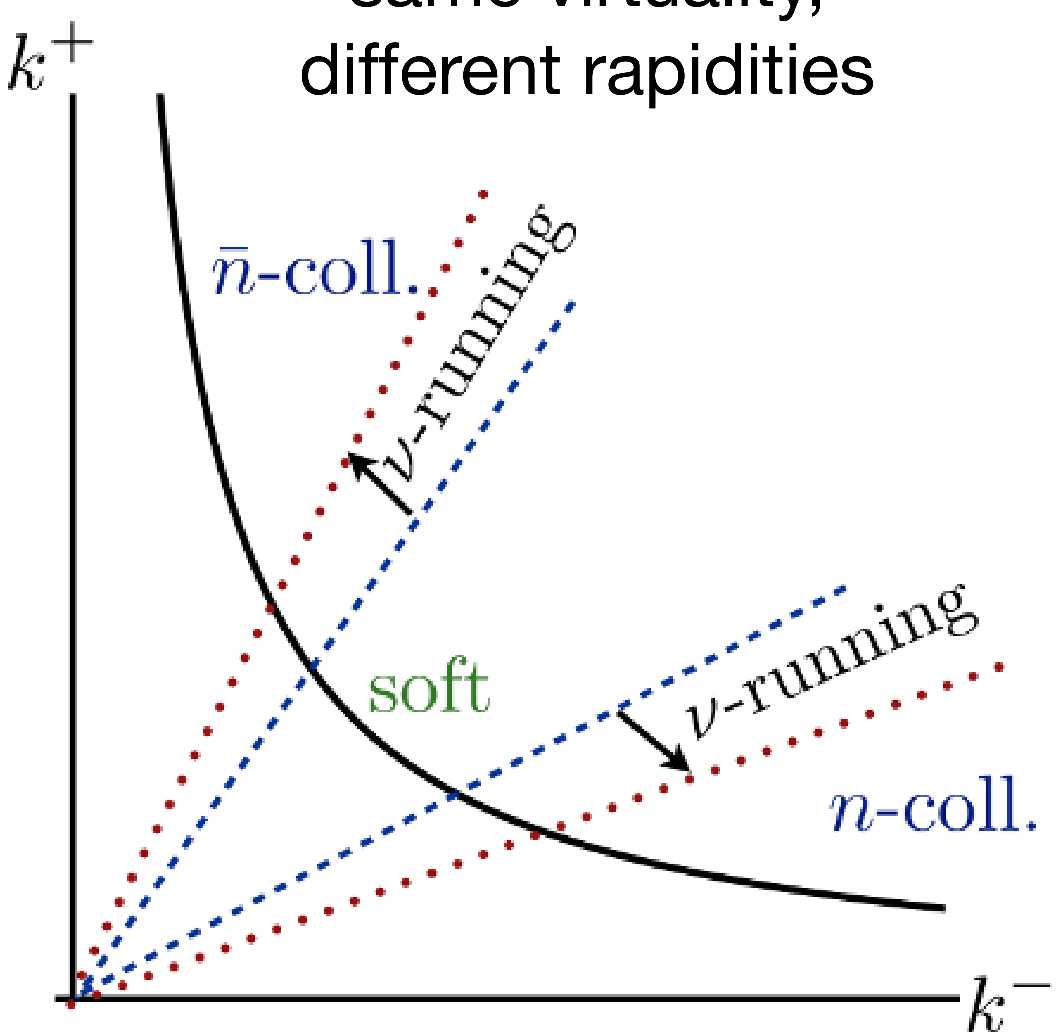
functions like dim reg:

$$\mu \longleftrightarrow \nu \,, \quad \epsilon \longleftrightarrow \eta$$

renormalization, RG evolution performed like dim reg
adds new scales to factorization theorem

SCET$_{\rm II}$ modes and running

soft/collinear modes have same virtuality, different rapidities



Chiu, Jain, Neill, Rothstein
1202.0814

Factorization Theorem for H + 0-jets in SCET

$$\sigma(p_T^{\rm cut}) = H(m_H, \mu) \int dx_a\, dx_b\, B_a(p_T^{\rm cut}, x_a, \mu, \nu) B_b(p_T^{\rm cut}, x_b, \mu, \nu) S(p_T^{\rm cut}, \mu, \nu)$$

Becher, Neubert
1205.3806

$H(\mu_H, \mu)$: hard function is universal for gg → H, known to NNLO

Harlander hep-ph/0007289 | Harlander, Ozeren 0907.2997 | Pak, Rogal, Steinhauser 0907.2998

$$B(x, p_T^{\rm cut}, \mu, \nu) = \int_0^{p_T^{\rm cut}} dE_T B_G(x, E_T, \mu, \nu) + \Delta B(x, p_T^{\rm cut}, \mu, \nu)$$

$$S(p_T^{\rm cut}, \mu, \nu) = \int_0^{p_T^{\rm cut}} dE_T S_G(E_T, \mu, \nu) + \Delta S(p_T^{\rm cut}, \mu, \nu)$$

Stewart, Tackmann, JW, Zuberi *to appear*

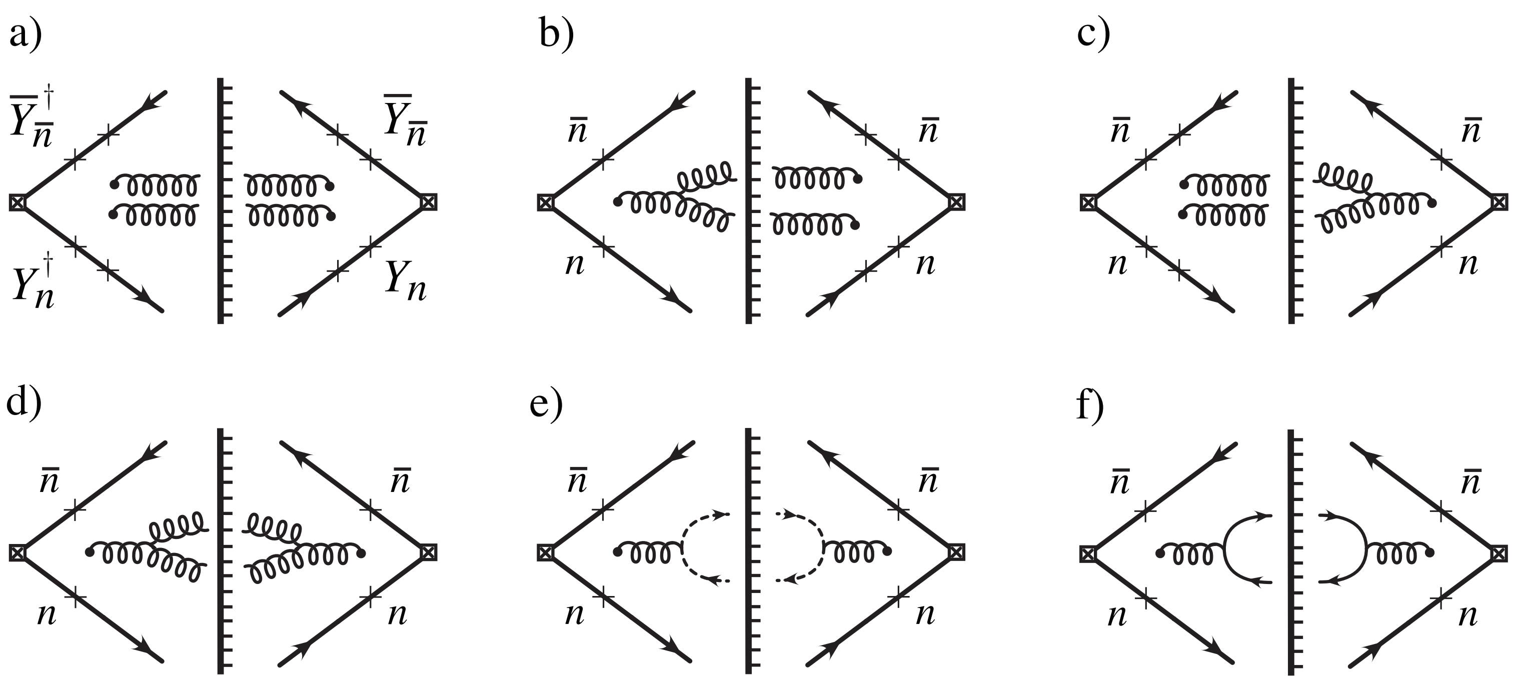
divide measurement function into global veto and clustering correction

$$\mathcal{M} = \theta(1\text{ jet})\theta(p_T < p_T^{\rm cut}) + \theta(2\text{ jets})\theta(p_{T1} < p_T^{\rm cut})\theta(p_{T2} < p_T^{\rm cut}) + \ldots$$
$$= \theta(p_T < p_T^{\rm cut}) + \theta(2\text{ jets})\left[\theta(p_{T1} < p_T^{\rm cut})\theta(p_{T2} < p_T^{\rm cut}) - \theta(p_{T1} + p_{T2} < p_T^{\rm cut})\right] + \ldots$$

Summary of Calculations

soft function: full NNLO calculation for E_T, clustering correction

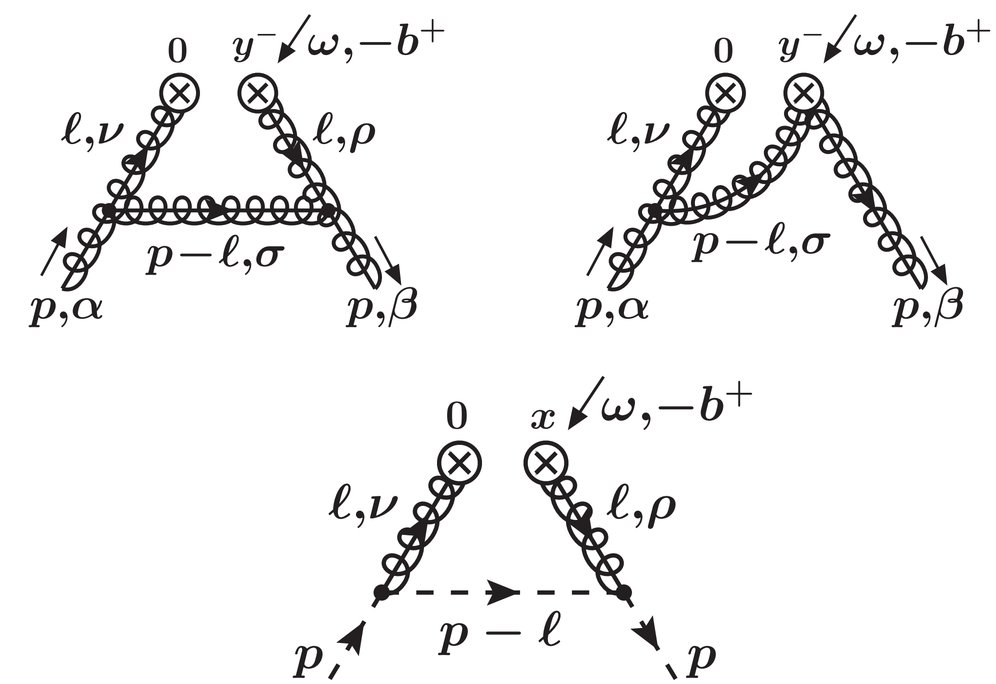
$$S(p_T^{\rm cut},\mu,\nu) = \big\langle 0 \big| Y_{\bar n}^\dagger\, Y_n\, \mathcal{M}(p_T^{\rm cut})\, Y_n^\dagger\, Y_{\bar n} \big| 0 \big\rangle$$



done as a “brute force” calculation

Certain coordinates exploit symmetries of the matrix elements, measurement function

beam function:
full NLO calculation,
dominant clustering terms at NNLO using RG invariance



remaining NNLO contributions to cross section extracted from MCFM + HNNLO

Global Veto Contribution

The global veto is interesting in its own right

Only known to NLL+NLO, we calculate to NNLL'+NNLO

$$E_T = \sum_i p_{Ti}$$

Higgs p_T is also a valid choice

renormalization scale

- hard (FO scale): $\mu_H = m_H$
- beam, soft: $\mu_B, \mu_S = p_T^{\mathrm{cut}}$

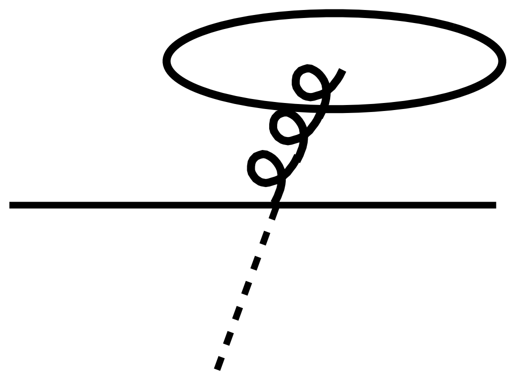
produces Sudakov double logs

rapidity scale

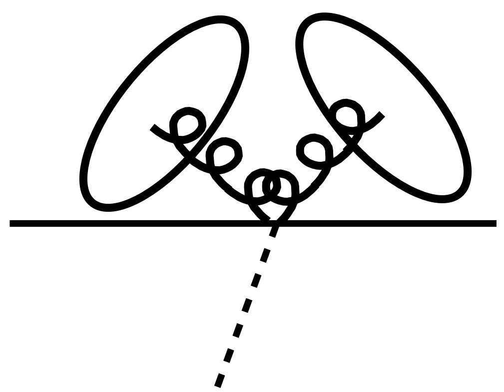
- beam: $\nu_B = m_H$
- soft: $\nu_S = p_T^{\mathrm{cut}}$

produces single logs

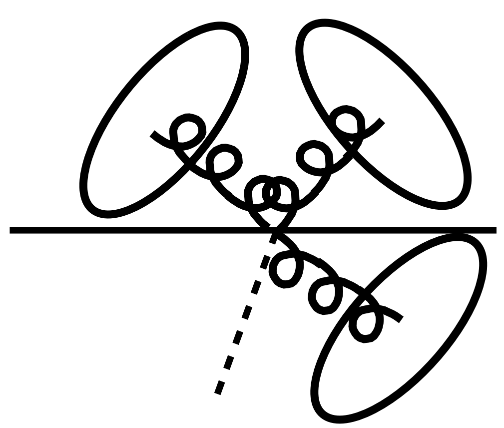
Clustering Effects (Relative to Global Veto)



NLO: only 1 parton, only 1 jet
E_T is the same as the leading jet p_T
no clustering correction



NNLO: E_T and leading jet p_T differ
when two jets in final state
lowest order clustering correction



NNNLO: jet algorithm dependent
unknown contribution

Two Clustering Effects, Two Regions of Jet Radius

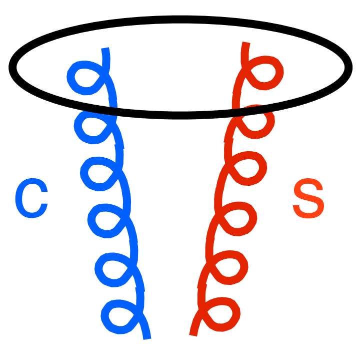
Jet algorithm effects:

$$\sigma \supset \mathcal{O}(R^n)\,,\ \mathcal{O}(\ln^n R)\ \text{terms}$$

Can induce violations to naive factorization

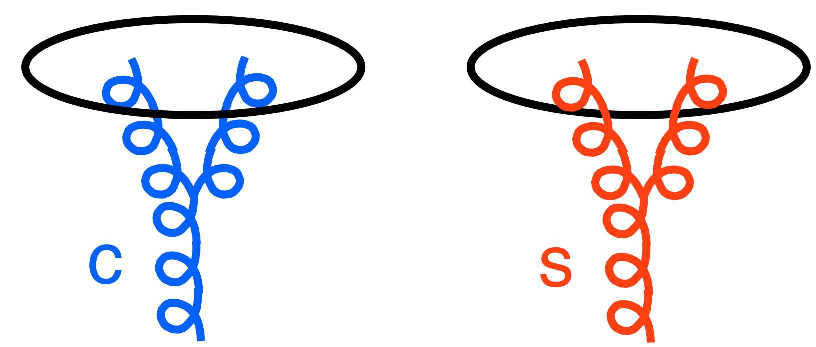
Factorization theorem valid for small jet radius

Large jet radius
R ~ 1



complicates factorization
but numerically less important

Small jet radius
R << 1



logarithms of jet radius important
but resummation is impossible

Clustering Logs

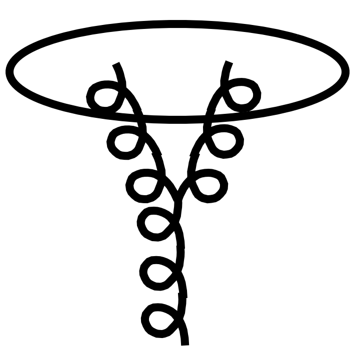
Clustering effects give rise to logs of *R*

E_T veto measurement at NNLO:

$$\mathcal{M} = \theta(p_{T1} + p_{T2} < p_T^{\rm cut})$$

correction for clustering:

$$\Delta\mathcal{M} = \theta(\Delta R > R)\Big[\theta(p_{T1} < p_T^{\rm cut})\,\theta(p_{T2} < p_T^{\rm cut}) - \theta(p_{T1} + p_{T2} < p_T^{\rm cut})\Big]$$



can write in terms of canceling IR collinear divergences

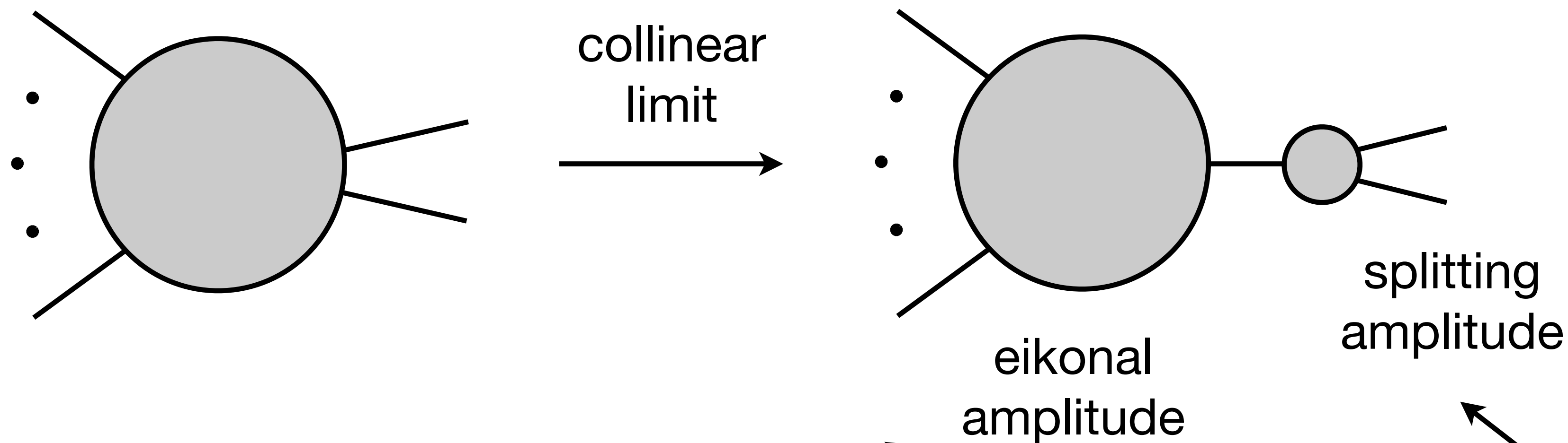
$$\mathcal{M}_{sp} : \frac{1}{\epsilon}$$

$$\Delta\mathcal{M}_{sp} : -\frac{1}{\epsilon}R^{\epsilon}$$

$\ln R$: remnant of collinear divergence sensitive to jet radius

Clustering Logs in the Soft Function

can be calculated using collinear limits of eikonal matrix elements:



$$\mathcal{A} = \mathcal{A}_{\text{eik}}\,\mathcal{A}_{\text{coll}}$$

contains an overall rapidity divergence that generates a log of the veto scale

generates the log of R when integrated against the measurement

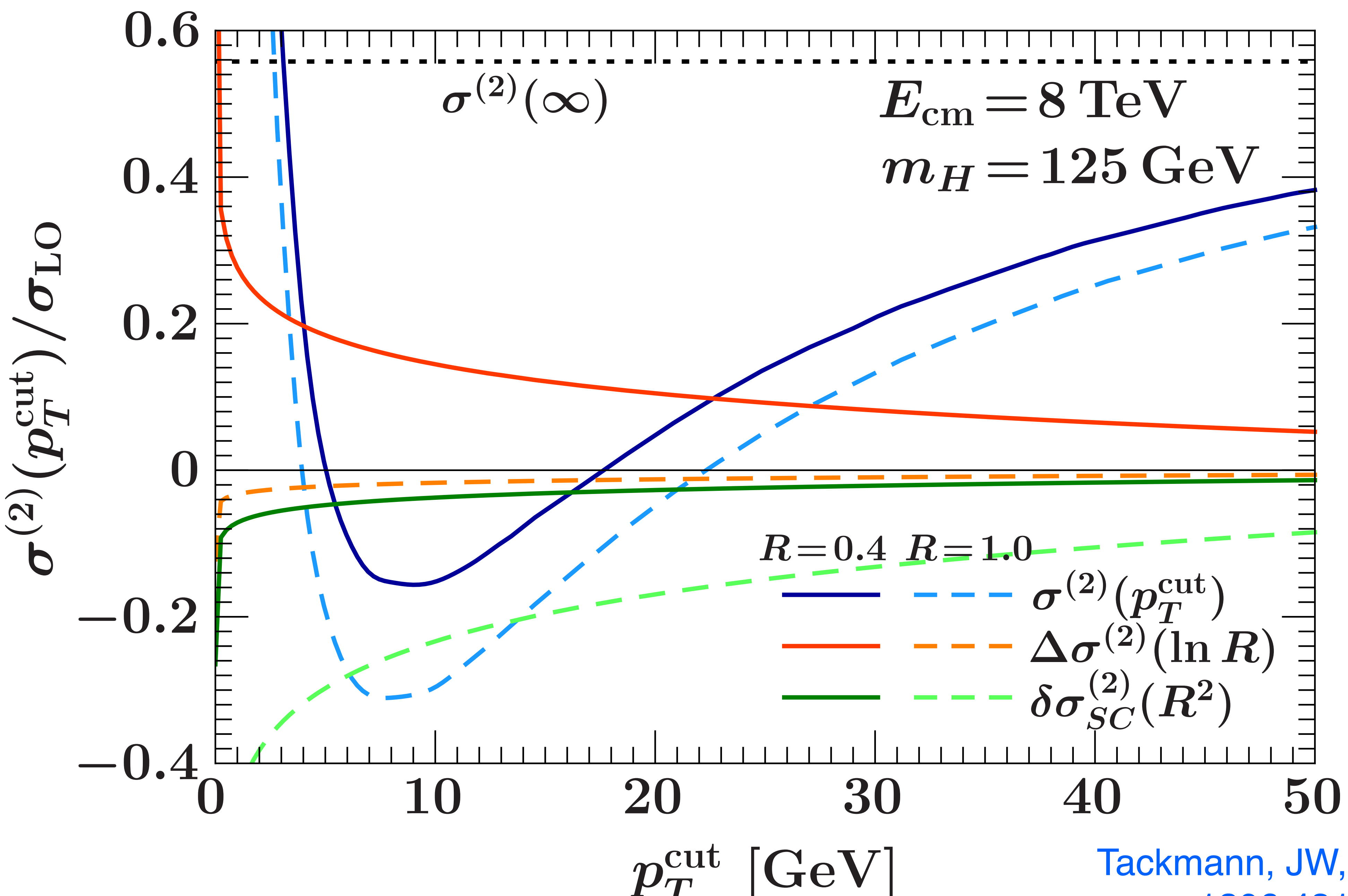
$$\Delta S^{(2)} = \left(\frac{\alpha_s C_A}{\pi}\right)^2 \ln \frac{\nu}{p_T^{\text{cut}}}\,(-4.97)\ln R$$

$$\Delta S^{(n)} = \left(\frac{\alpha_s C_A}{\pi}\right)^n \ln \frac{\nu}{p_T^{\text{cut}}}\,C_n^{(n-1)}\ln^{n-1} R$$

$$\text{NLL if } \ln R \sim \ln \frac{m_H}{p_T^{\text{cut}}}$$

resummation is unknown
impacts uncertainty estimates!

Numerical Impact of Clustering Effects



total NNLO terms

NNLO 0-jet terms

clustering logs

clustering R^n terms

R = 0.4 : solid

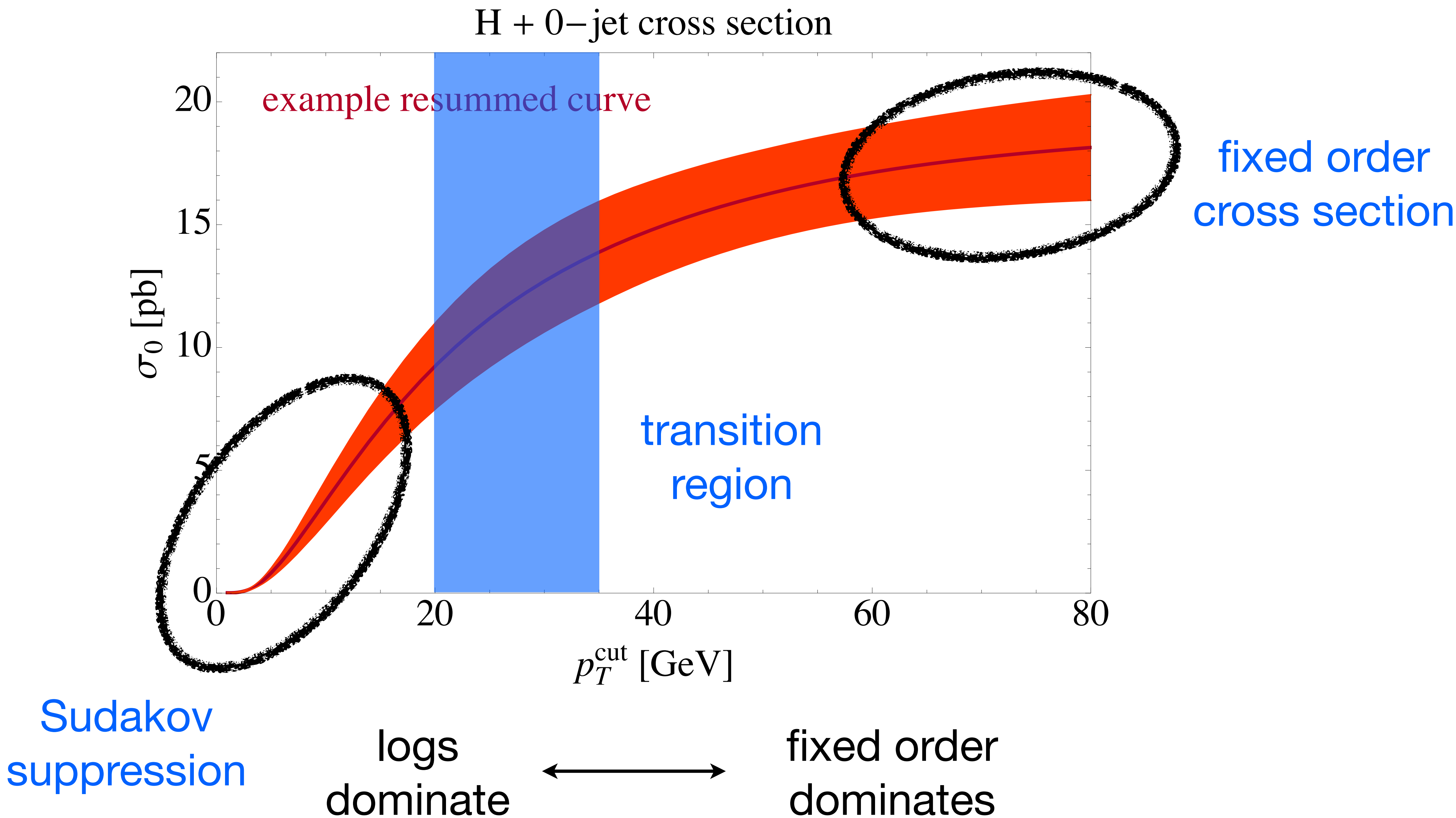
R = 1.0 : dashed

Tackmann, JW, Zuberi, 1206.4312

Summary of Resummation

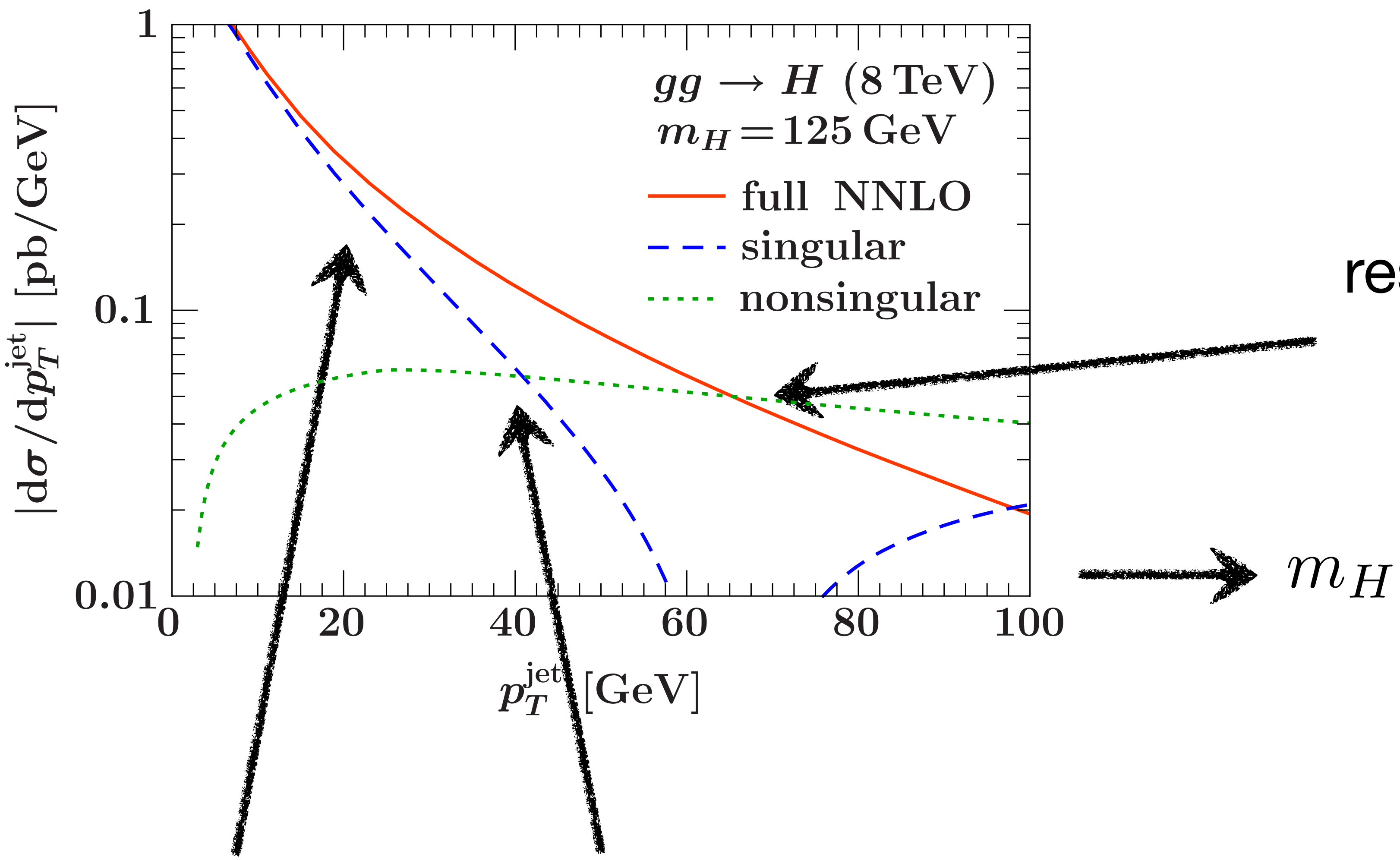
- Performed resummation to NNLL'
  - Global veto captures dominant veto logs
  - Clustering correction accounts for the jet algorithm effects, we understand the all-orders structure of these terms
  - Resummation of clustering effects unknown, potentially very important
- Only the 3-loop non-cusp (+4-loop cusp) anom. dim. unknown for NNNLL
  - Two parts: the global veto and the clustering contribution
  - Challenging to obtain, but the tools exist, and would help uncertainties
- Now let's match to NNLO and carry out numerics

Resummation vs. Fixed Order



Fixed Order Singular and Non-Singular Terms

NNLO terms (MCFM + HNNLO)



resummation should be turned off well before m_H

logs dominate

transition region

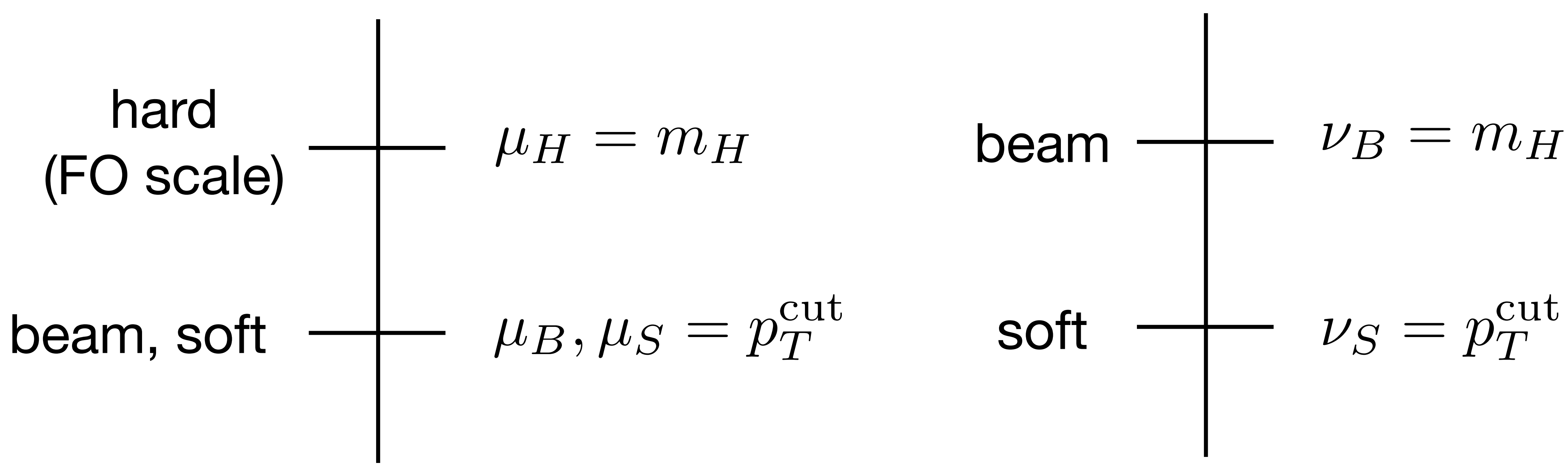
Scales and Resummation

$$\sigma(p_T^{\mathrm{cut}}) = H(m_H, \mu) \int dx_a \, dx_b \, B_a(p_T^{\mathrm{cut}}, x_a, \mu, \nu) B_b(p_T^{\mathrm{cut}}, x_b, \mu, \nu) S(p_T^{\mathrm{cut}}, \mu, \nu)$$

Natural factorization scales:

renormalization scale

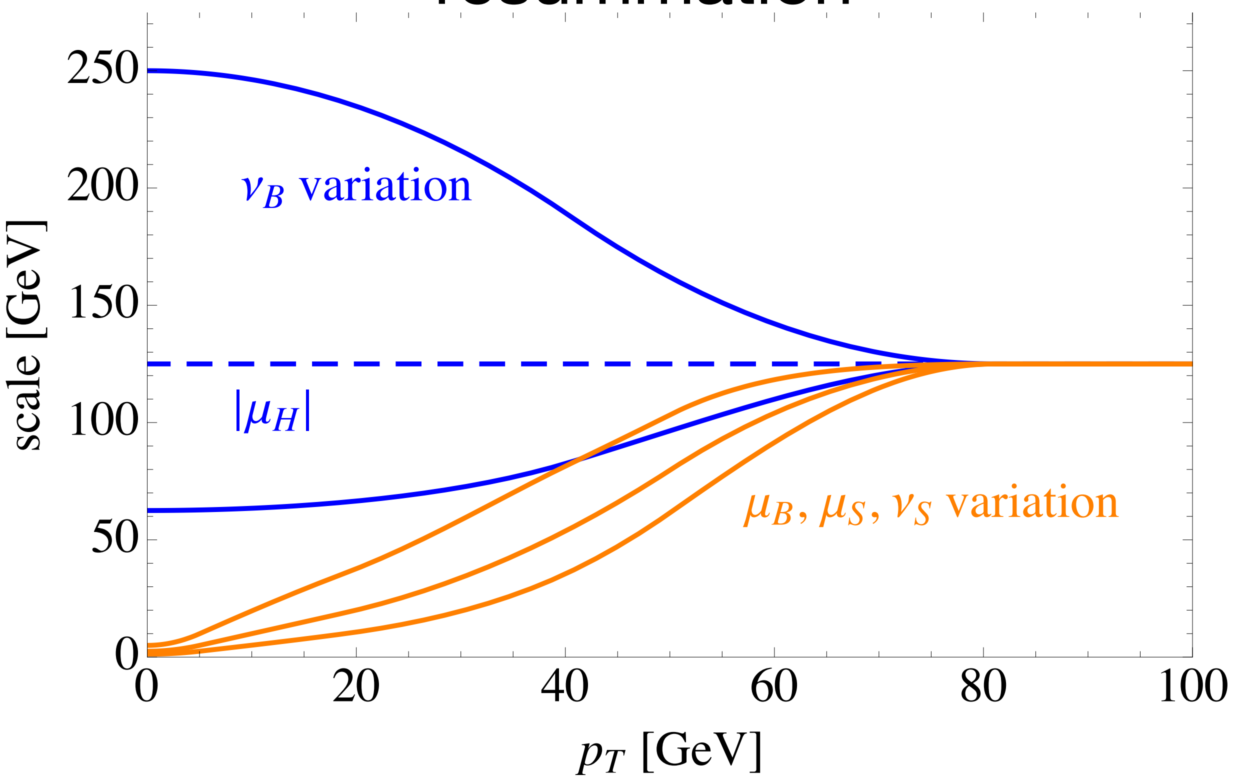
rapidity scale



Design scales that turn off the resummation
at the appropriate veto scale

Profile Scales

resummation

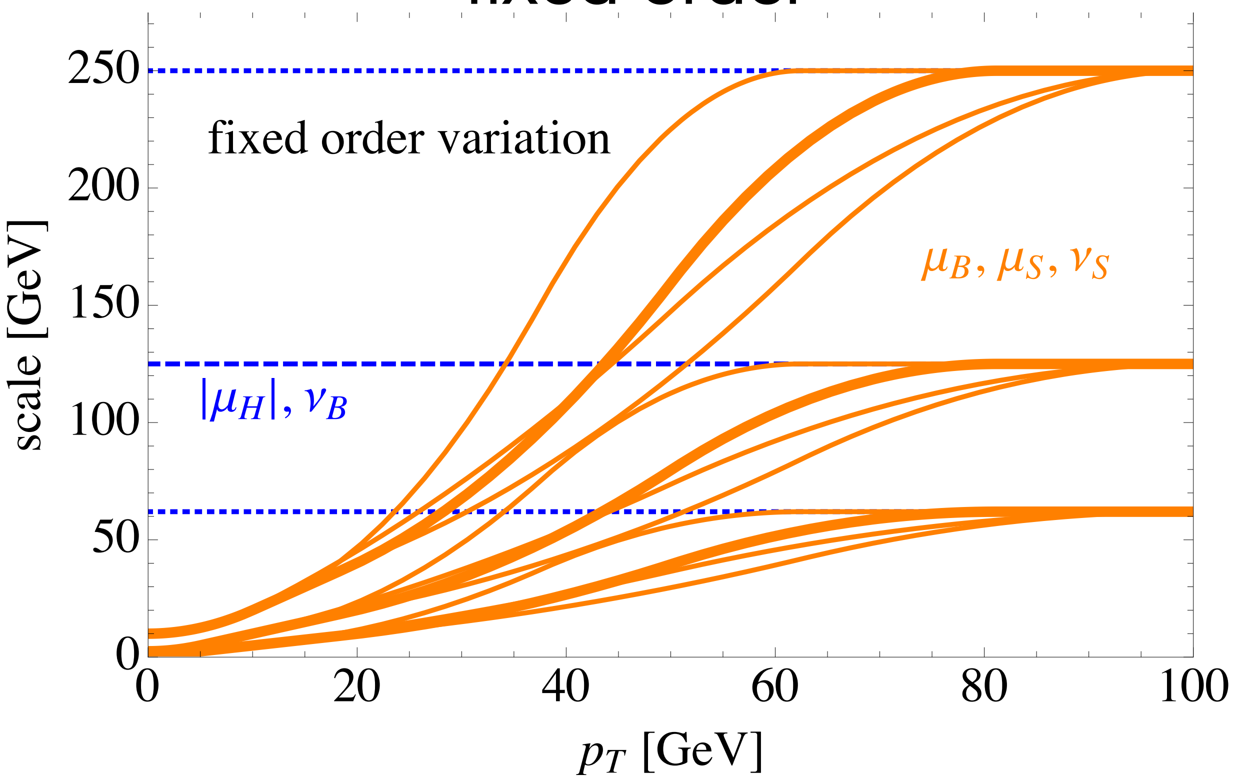


vary each beam, soft scale independently

constrain variations of scale ratios, e.g. μ_B/μ_S

26 variations

fixed order



vary all scales collectively, preserve scale ratios

also vary low profile shape
4 different shapes

11 variations

The Higgs

Jet Vetoes

H + 0-jet Calculation

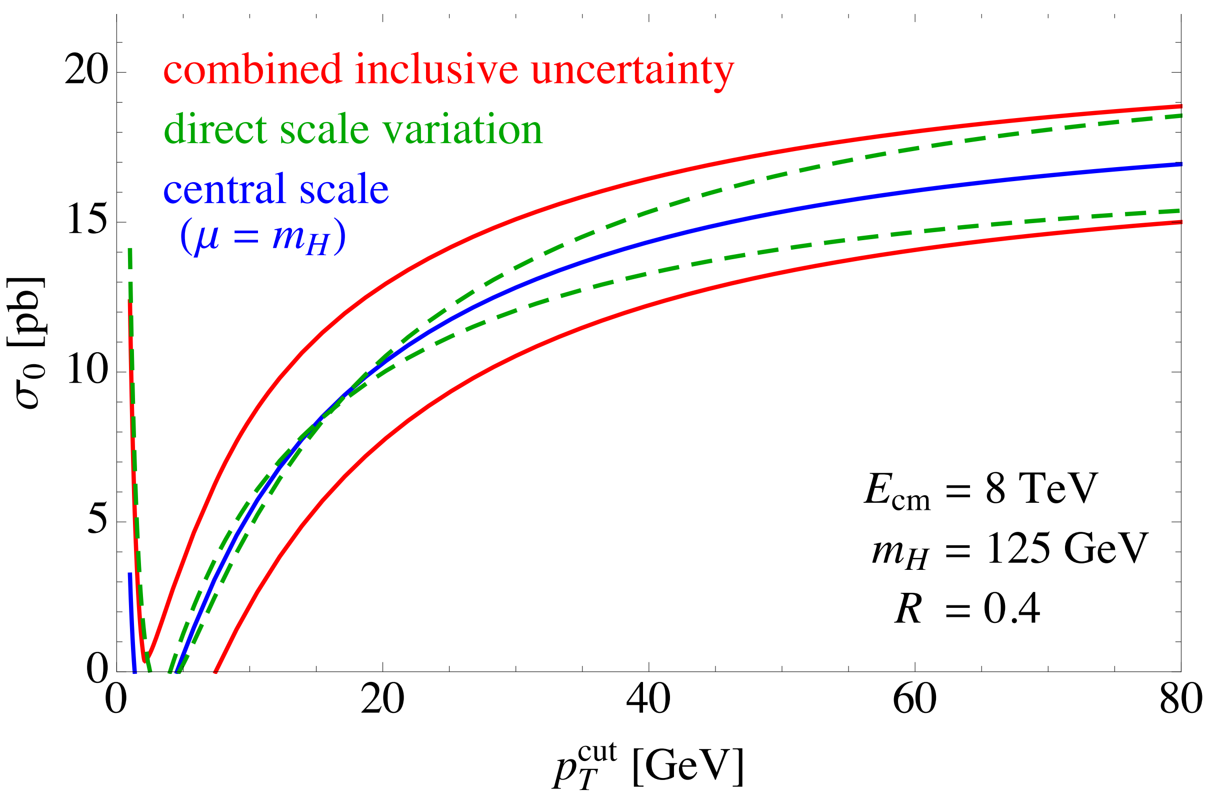
Preliminary Numerics and Uncertainties

Uncertainties: Fixed Order

Stewart, Tackmann
1107.2117

exclusive jet bins have cancellations between
large perturbative corrections and veto logs

$$C_{\rm FO}\big(\{\sigma_{\rm tot},\sigma_0,\sigma_{\geq 1}\}\big) = \begin{pmatrix} \Delta^2_{\rm tot} & \Delta^2_{\rm tot} & 0 \\ \Delta^2_{\rm tot} & \Delta^2_{\rm tot} + \Delta^2_{\geq 1} & -\Delta^2_{\geq 1} \\ 0 & -\Delta^2_{\geq 1} & \Delta^2_{\geq 1} \end{pmatrix}$$



fixed order 0-jet bin:
treat total and 1-jet inclusive uncertainties as uncorrelated

this general method currently used in many experimental analyses

Uncertainties: Resummation

With resummation, can separately estimate the fixed order and resummation uncertainties

$$C = C_{\text{resum}} + C_{\text{fixed}}\,,$$

$$C_{\text{resum}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta^2_{\text{resum}} & -\Delta^2_{\text{resum}} \\ 0 & -\Delta^2_{\text{resum}} & \Delta^2_{\text{resum}} \end{pmatrix}\,,$$

$$C_{\text{fixed}} = \begin{pmatrix} \Delta^2_{\text{tot}} & \Delta_{\text{tot}}\Delta_{H0} & \Delta_{\text{tot}}\Delta_{H\geq 1} \\ \Delta_{\text{tot}}\Delta_{H0} & \Delta^2_{H0} & \Delta_{H0}\Delta_{H\geq 1} \\ \Delta_{\text{tot}}\Delta_{H\geq 1} & \Delta_{H0}\Delta_{H\geq 1} & \Delta^2_{H\geq 1} \end{pmatrix} \quad \begin{matrix} \sigma_{\text{tot}} \\ \sigma_0 \\ \sigma_{\geq 1} \end{matrix}$$

$$\Delta_{\text{tot}} = \Delta_{H0} + \Delta_{H\geq 1}$$

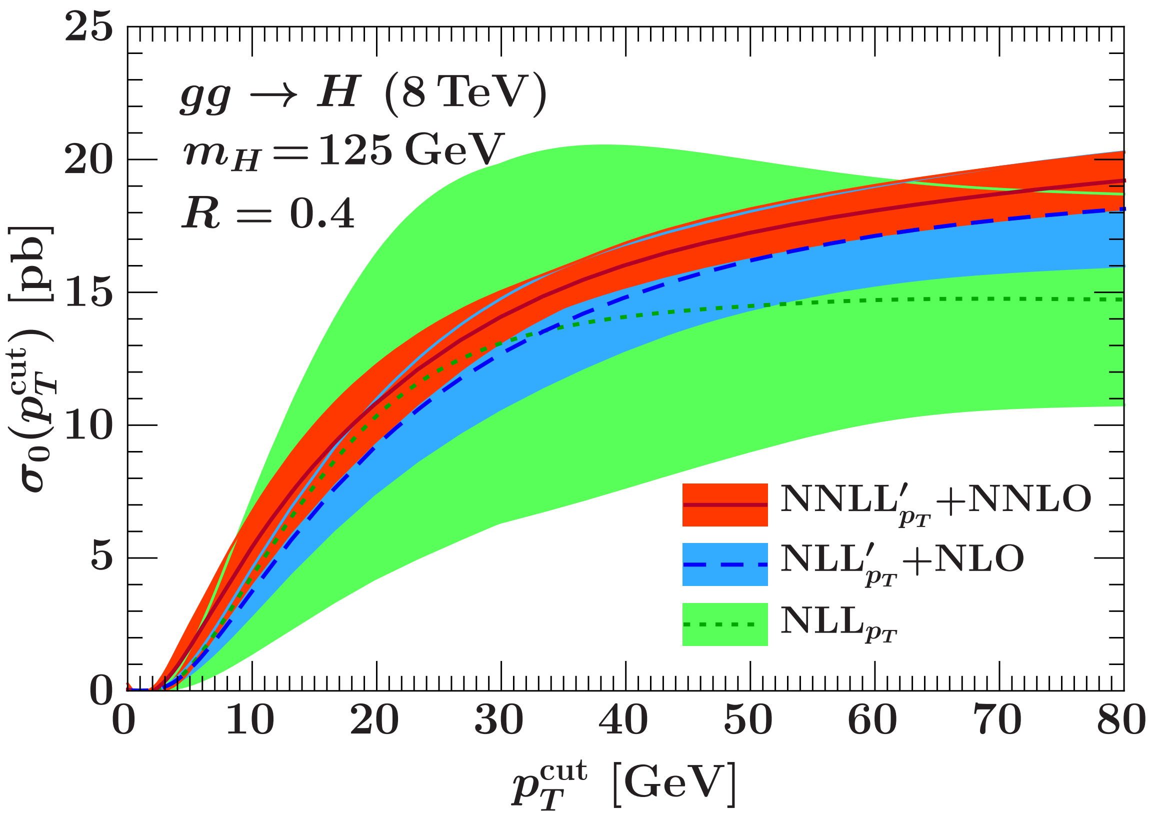
Full covariance matrix lets us determine any uncertainty and take correlations into account

H + 0-jet Cross Section

Results for E_{cm} = 8 TeV, m_H = 125 GeV, R = 0.4
Observe a modest reduction in uncertainties with larger R

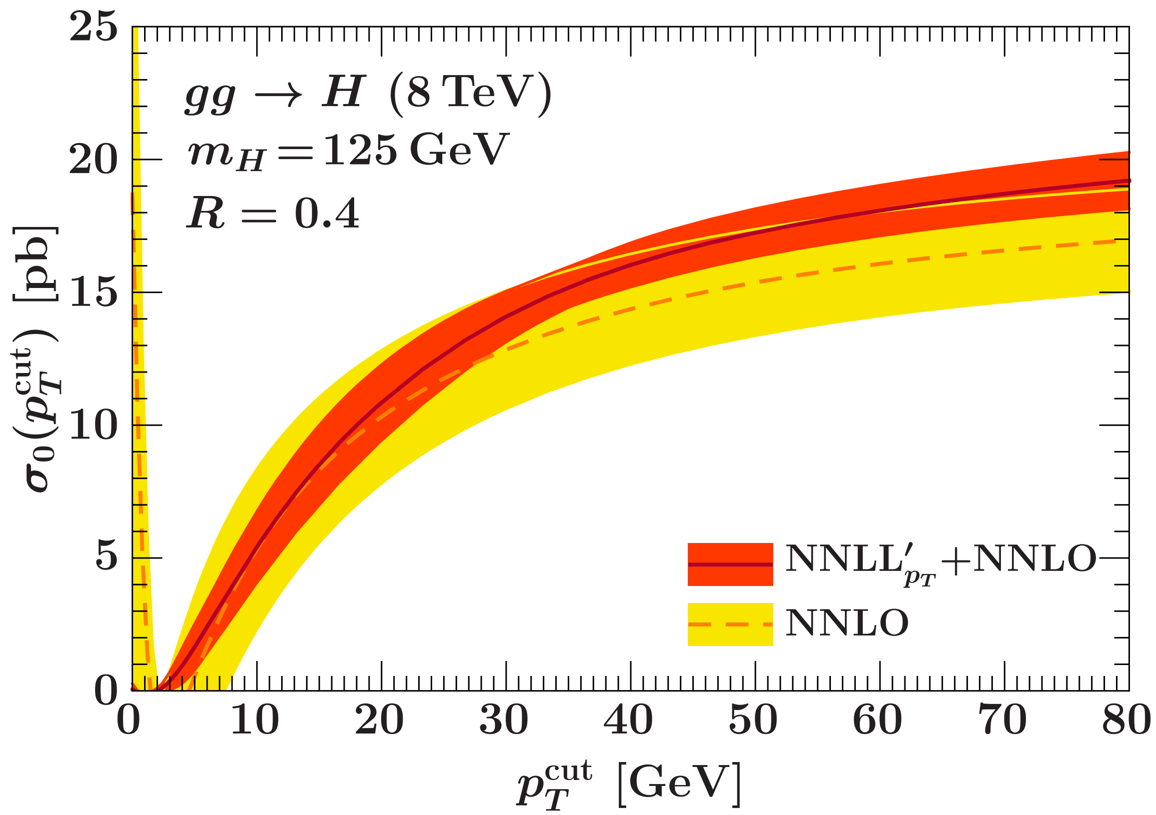
$$\Delta_0^2(p_T^{\rm cut}) = \Delta_{\rm resum}^2(p_T^{\rm cut}) + \Delta_{H0}^2(p_T^{\rm cut})$$

resummed convergence



we can estimate an additional uncertainty from higher order clustering effects

comparison to FO



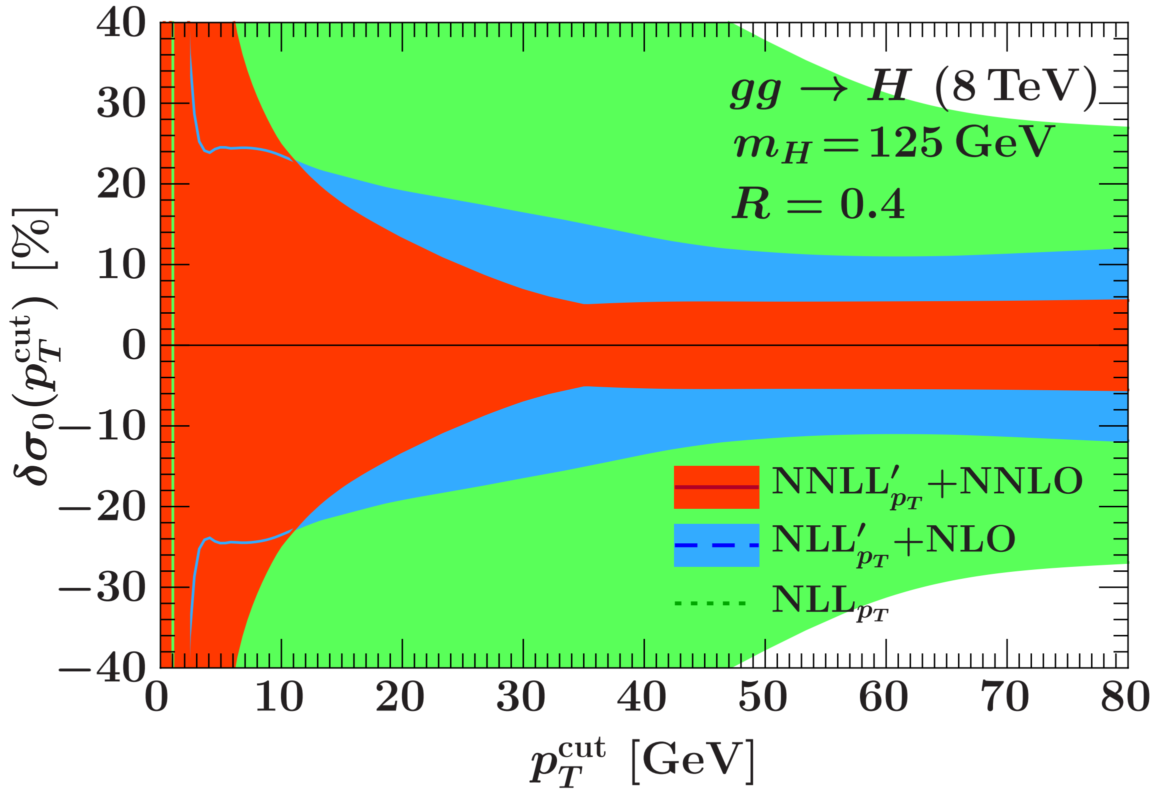
we use an imaginary hard scale ('π^2 resummation') increases σ_0 above NNLO

H + 0-jet Cross Section: Uncertainties

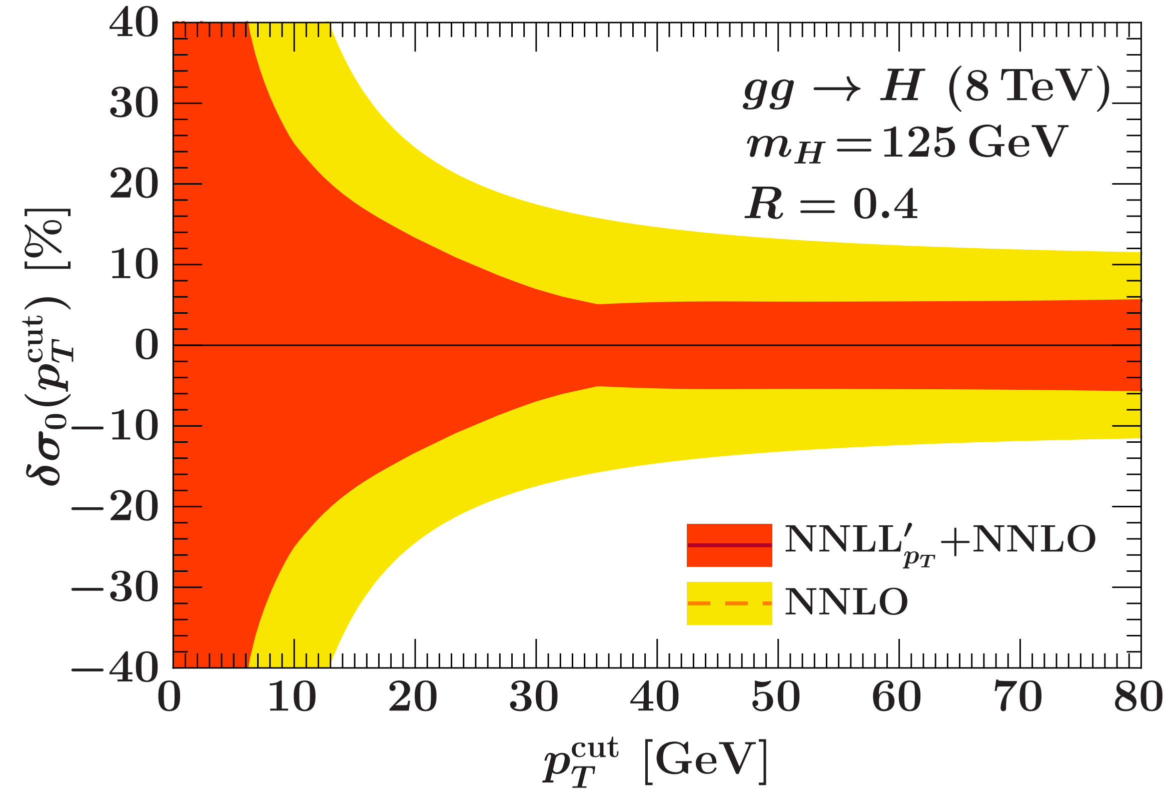
Results for E_{cm} = 8 TeV, m_H = 125 GeV, R = 0.4
Observe a modest reduction in uncertainties with larger R

$$\Delta_0^2(p_T^{\mathrm{cut}}) = \Delta_{\mathrm{resum}}^2(p_T^{\mathrm{cut}}) + \Delta_{H0}^2(p_T^{\mathrm{cut}})$$

resummed convergence



comparison to FO



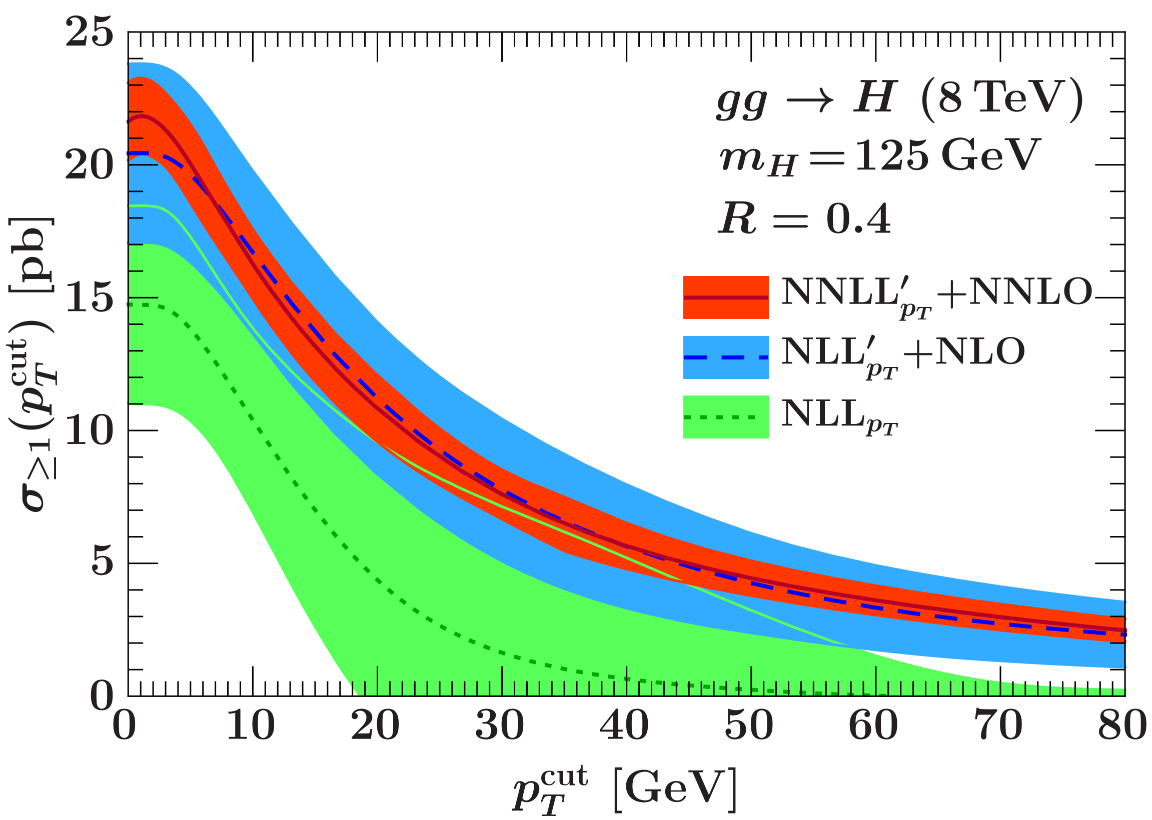
fractional uncertainty
hard work pays off!

H + 1-jet Inclusive Cross Section

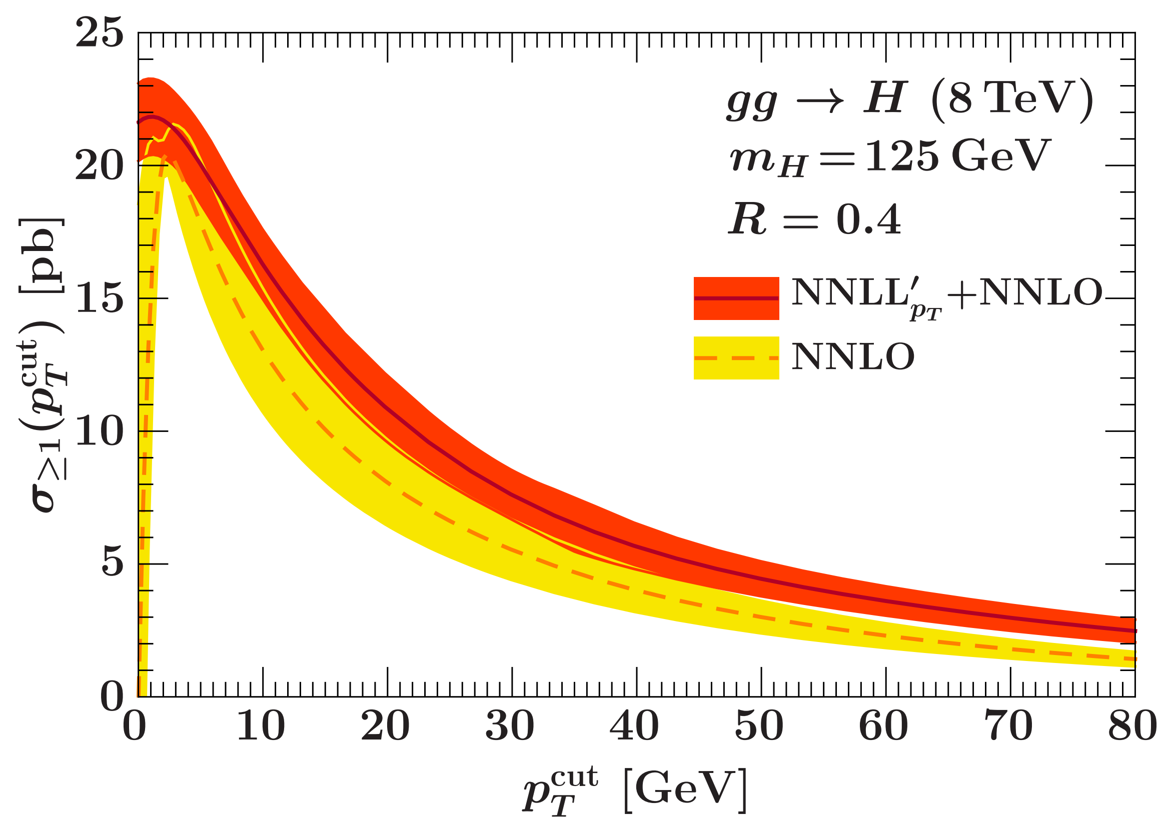
$$\sigma_{\geq 1}(p_T^{\mathrm{cut}}) = \sigma_{\mathrm{tot}}^{\mathrm{FO}} - \sigma_0(p_T^{\mathrm{cut}})$$

$$\Delta_{\geq 1}(p_T^{\mathrm{cut}}) = \Delta^2_{\mathrm{resum}}(p_T^{\mathrm{cut}}) + \Delta^2_{H\geq 1}(p_T^{\mathrm{cut}})$$

resummed convergence



comparison to FO



would be interesting to compare to H+1-jet NNLO predictions

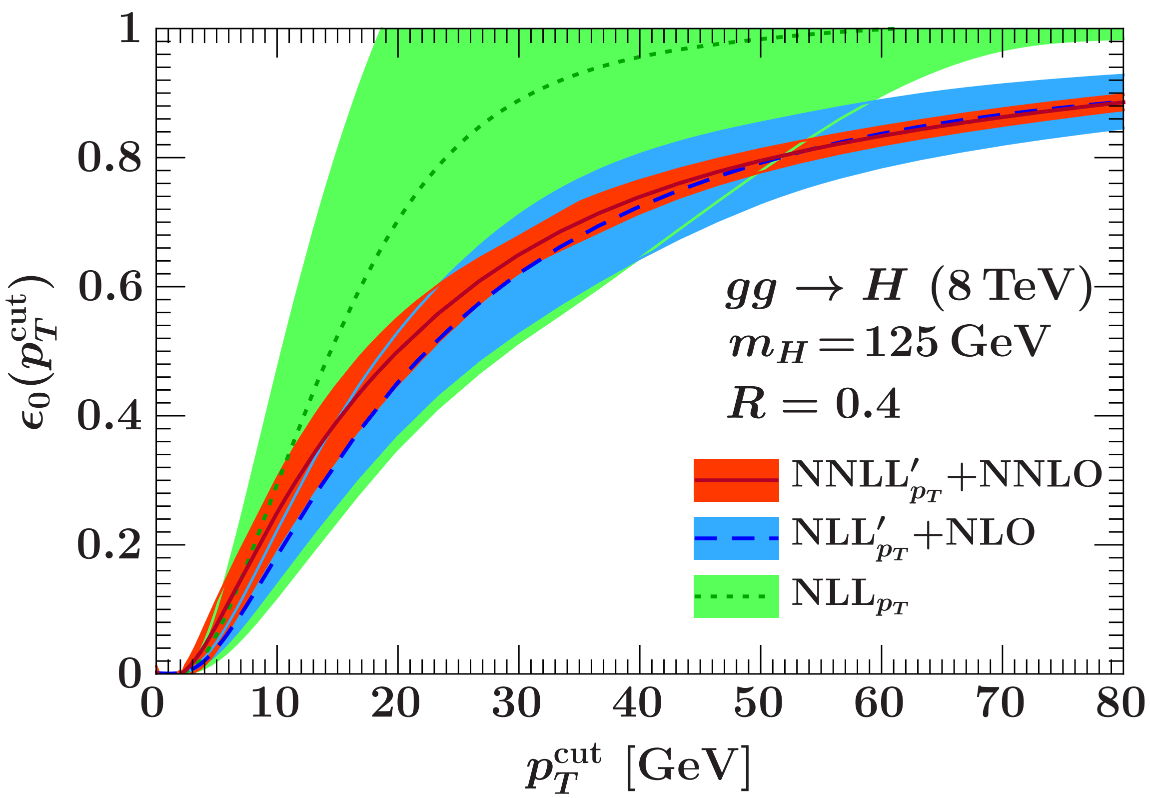
test perturbative corrections vs. logs

H + 0-jet Efficiency

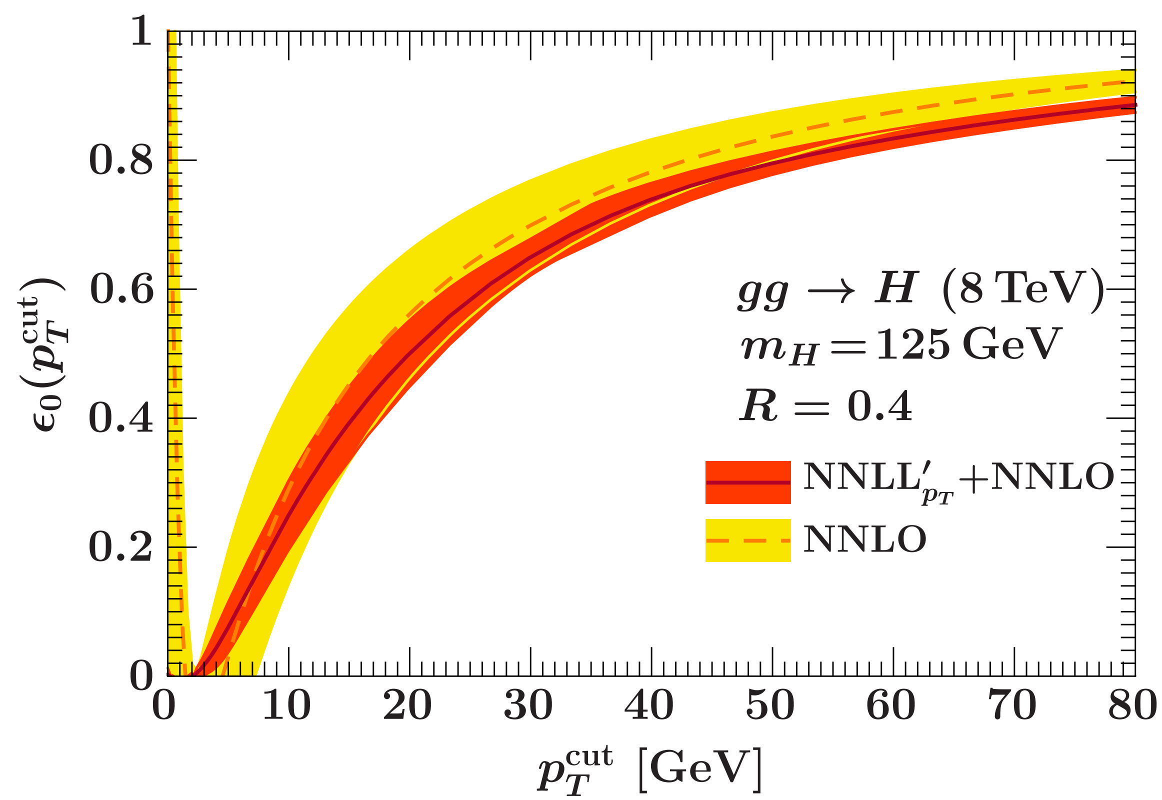
$$\epsilon_0(p_T^{\rm cut}) = \sigma_0(p_T^{\rm cut})/\sigma_{\rm tot}$$

$$\Delta_{\epsilon_0}(p_T^{\rm cut}) = \epsilon_0(p_T^{\rm cut})\left[\frac{\Delta_0^2(p_T^{\rm cut})}{\sigma_0^2(p_T^{\rm cut})} + \frac{\Delta_{\rm tot}^2}{\sigma_{\rm tot}^2} - 2\frac{\Delta_{\rm tot}\Delta_{H0}(p_T^{\rm cut})}{\sigma_{\rm tot}\sigma_0(p_T^{\rm cut})}\right]^{1/2}$$

resummed convergence



comparison to FO



correlations between fixed order scale variation in
0-jet, total cross sections reduces uncertainties

Conclusions

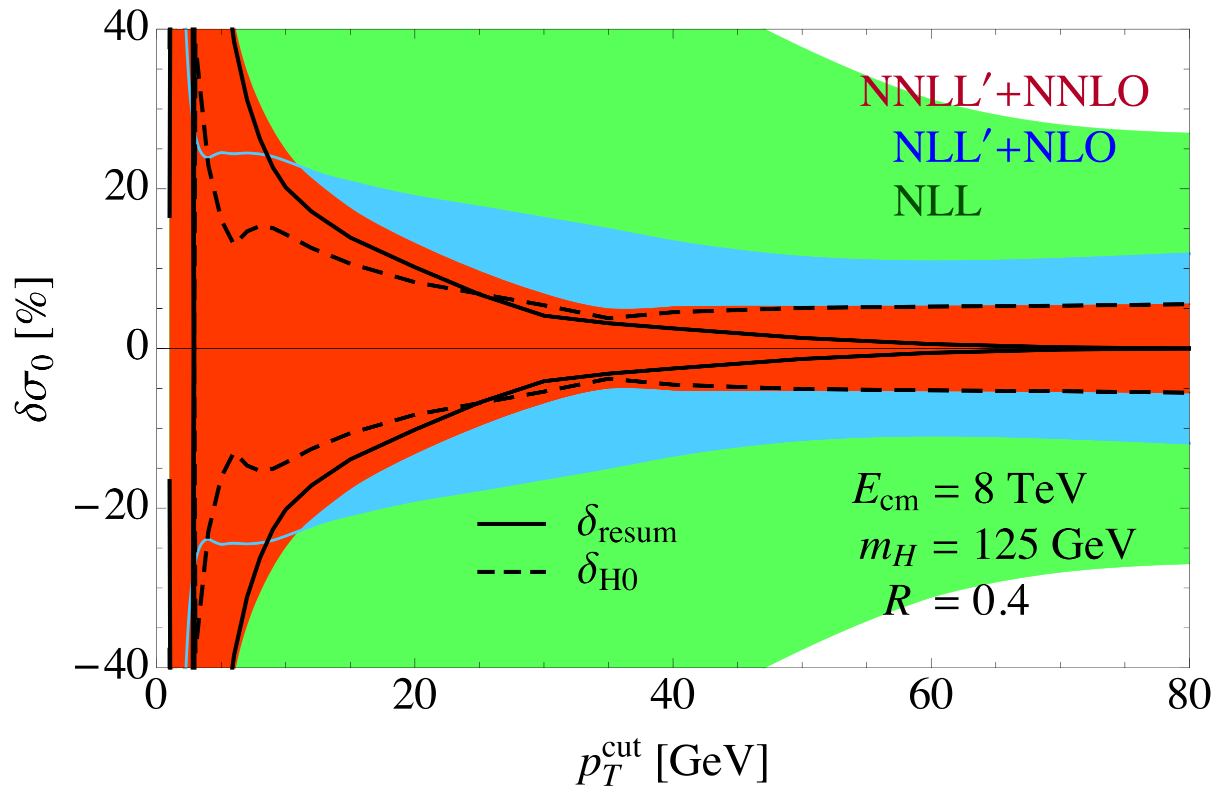
- H + 0-jet cross section is a key theoretical input to Higgs studies
  - Resummation substantially improves uncertainty
  - Comparison to Banfi, Monni, Salam, Zanderighi and Becher, Neubert, Rothen will be insightful
- Many new results
  - E_T resummation to NNLL'+NNLO (extends NLL+NLO)
  - First 2-loop calculation with rapidity (eta) regulator by Chiu *et. al.*
  - Analytic determination of dominant constant terms
  - All-orders understanding of clustering effects
- Many avenues to further improve uncertainty

Extra Slides

H + 0-jet Cross Section: Uncertainties

$$\Delta_0^2(p_T^{\mathrm{cut}}) = \Delta_{\mathrm{resum}}^2(p_T^{\mathrm{cut}}) + \Delta_{H0}^2(p_T^{\mathrm{cut}})$$

fixed order and resummation uncertainties



transition region [20,40] GeV:
both uncertainties very important!