New Developments in Perturbative QCD

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Pheno 2013
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Select New Developments in Perturbative QCD @ LHC

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Outline:

- Intro to QCD calculations at colliders

  Technology (factorization, fixed order, resummation, hadronization, ...)

- Success of QCD at the LHC

  inclusive jets, W+jets, PDFs, (Higgs...)

- Three Recent NNLO calculations
  - $pp \to 2$ jets
  - $pp \to t\bar{t}$
  - $pp \to H + 1\,\text{jet}$

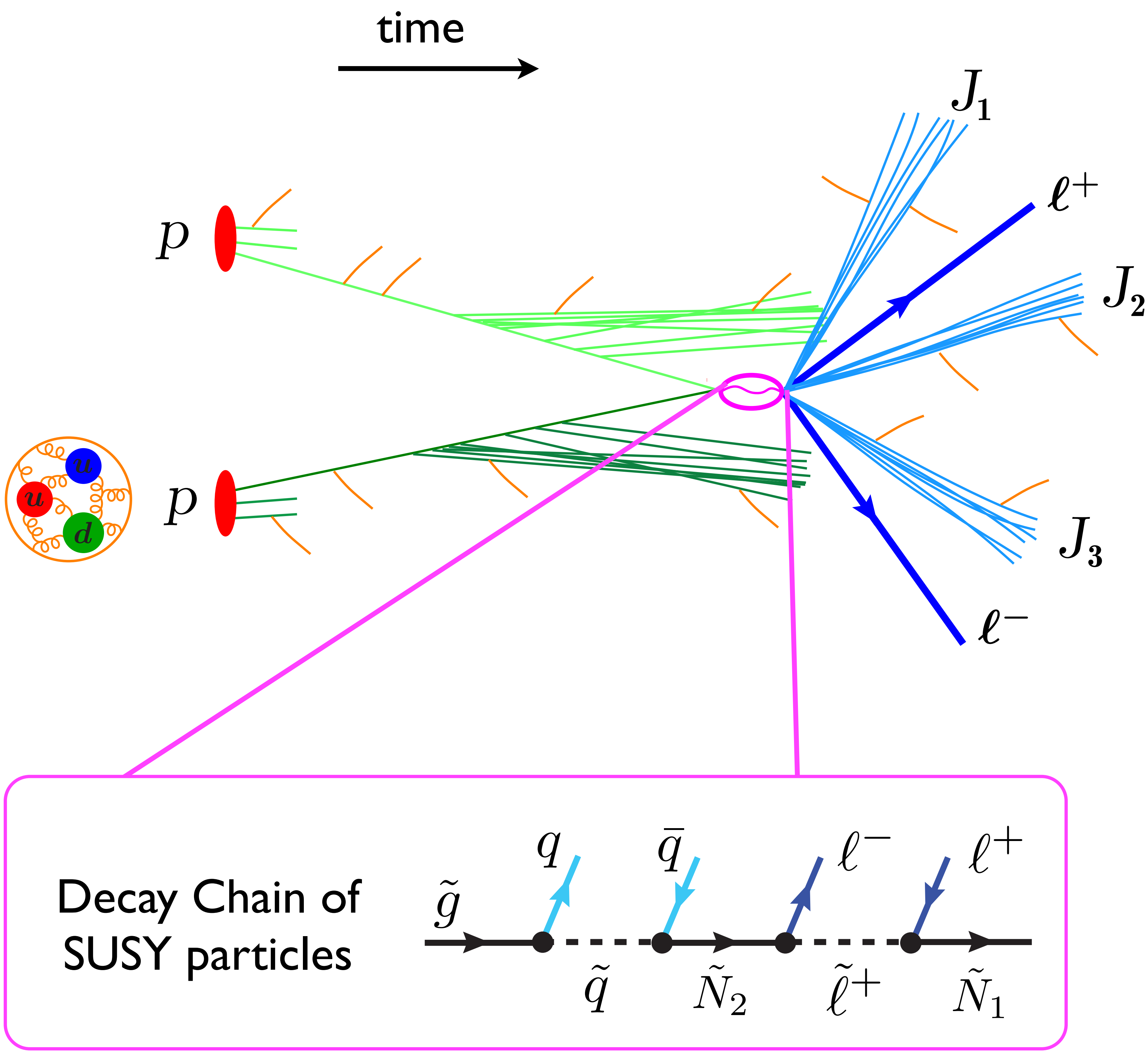
- Calculations requiring Summation of Large Logs
  - Jet Veto for Higgs
  - Jet mass spectrum

- Identifying Jets with Substructure
  - Jet charge
  - EE correlator for quark & gluon discrimination

- Summary

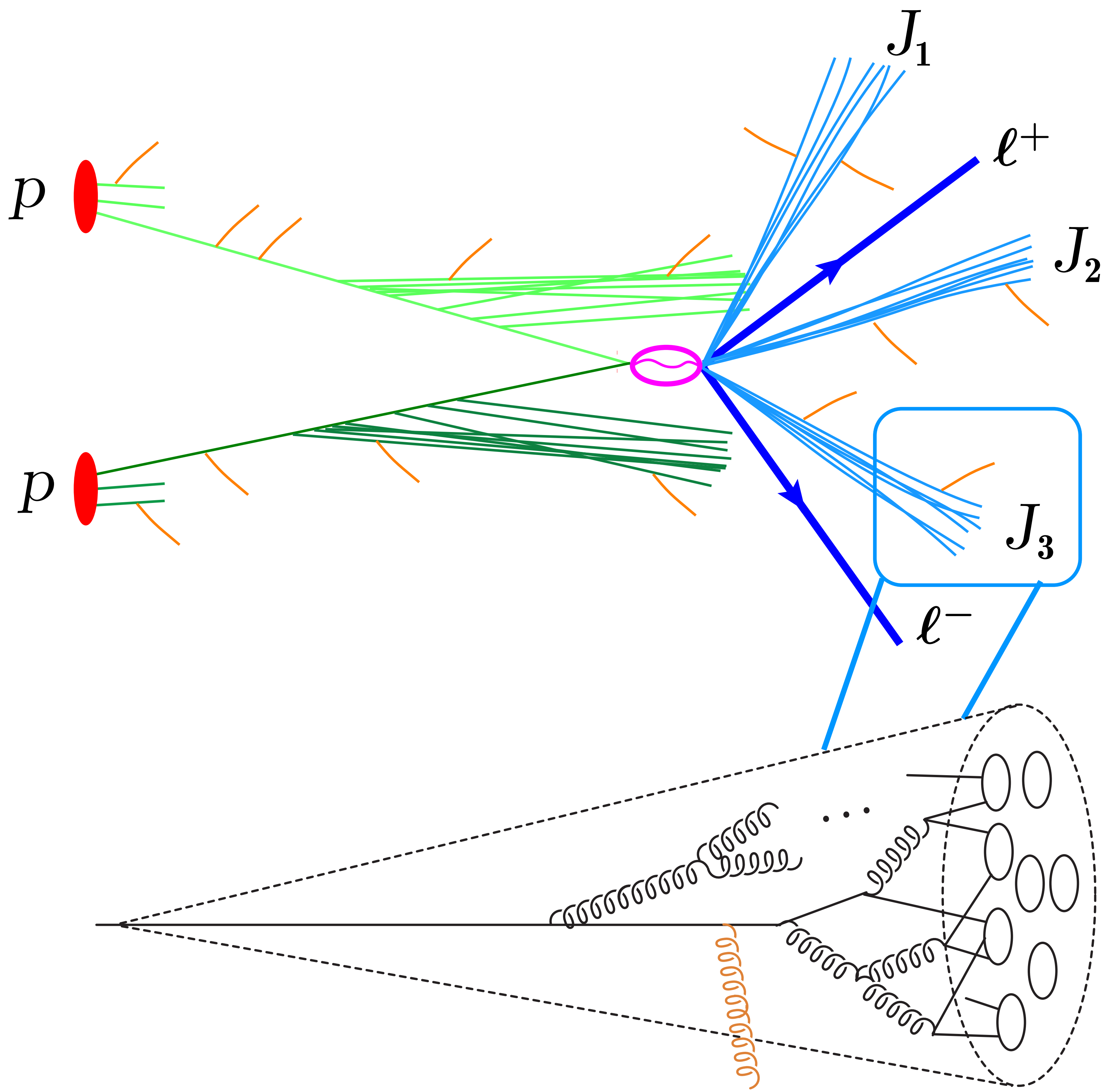
Factorization for QCD @ colliders

Events with a Hard Interaction:



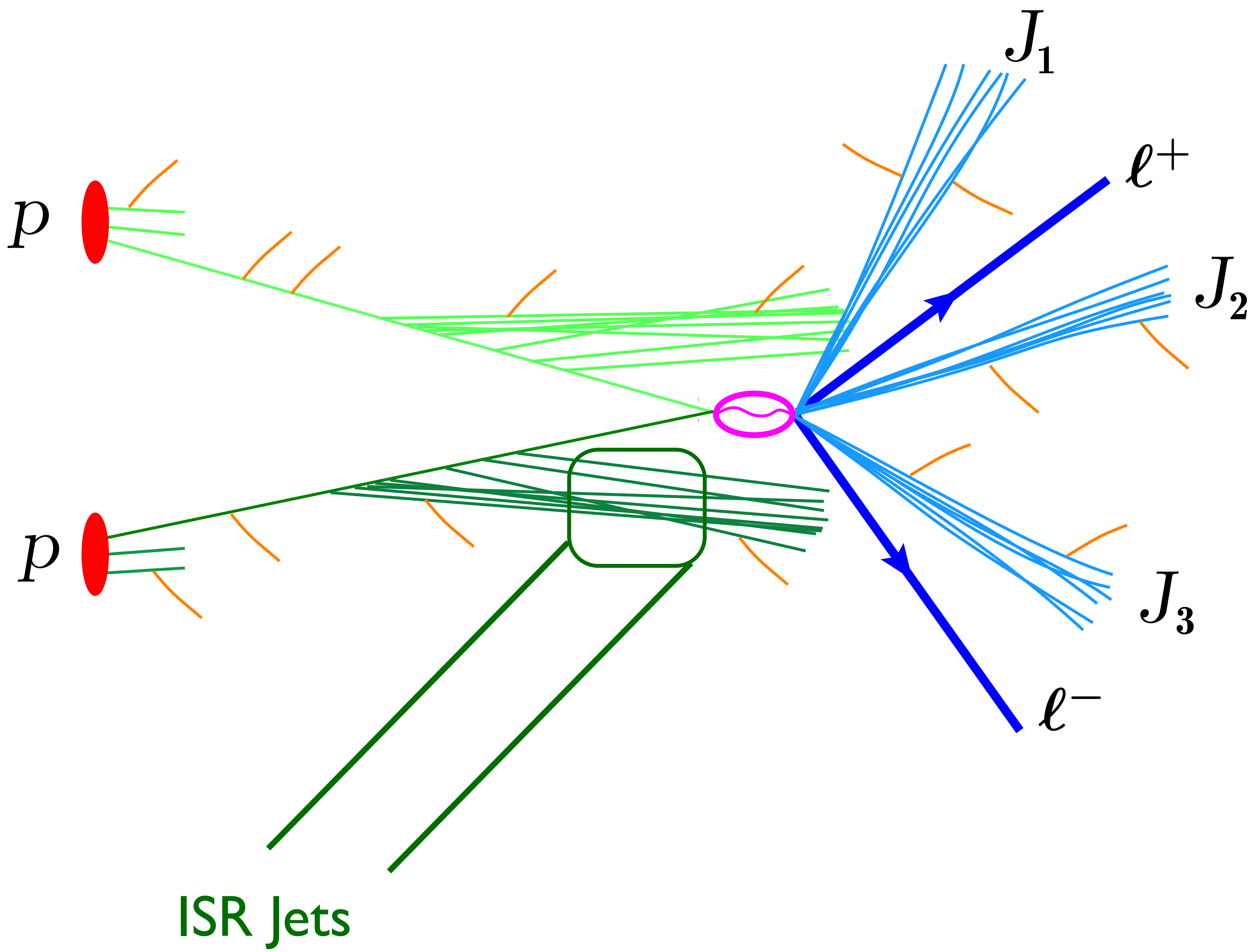
Search for New Heavy Particles at short distances

Events with a Hard Interaction:

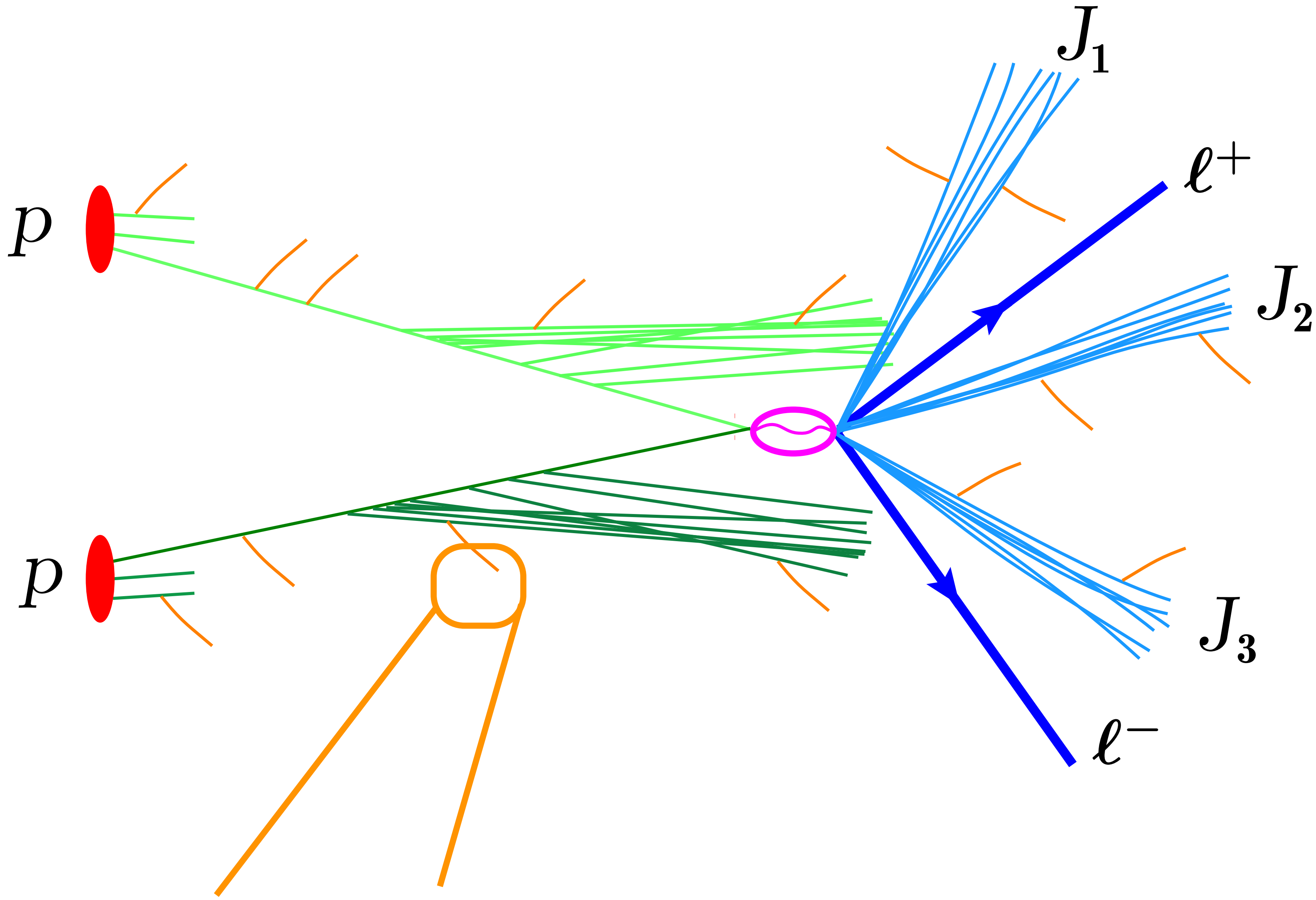


Quarks and Gluons
Form Jets

Anatomy of a High Energy Collision of Two Protons

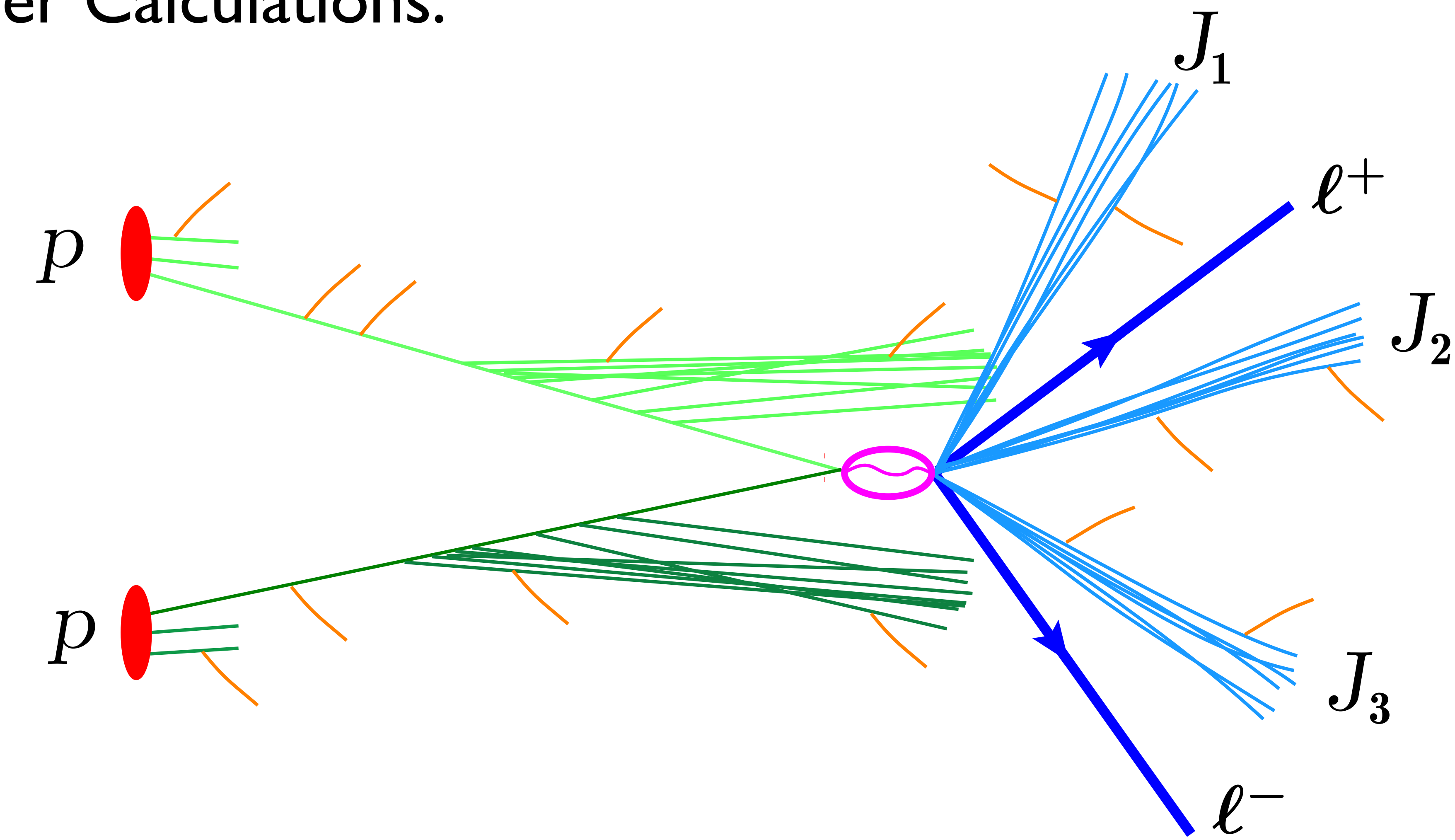


Anatomy of a High Energy Collision of Two Protons



All colored particles can also
emit lower energy
soft gluon radiation

Fixed Order Calculations:



$$d\sigma = f_a f_b \otimes \hat{\sigma} \otimes F$$

proton parton distributions

perturbative partonic cross section

hadronization model, underlying event

(includes virtual corrections, ISR, FSR, and perturbative soft radiation)

Fixed Order Calculations:

$$d\sigma = f_a f_b \otimes \hat{\sigma} \otimes F$$

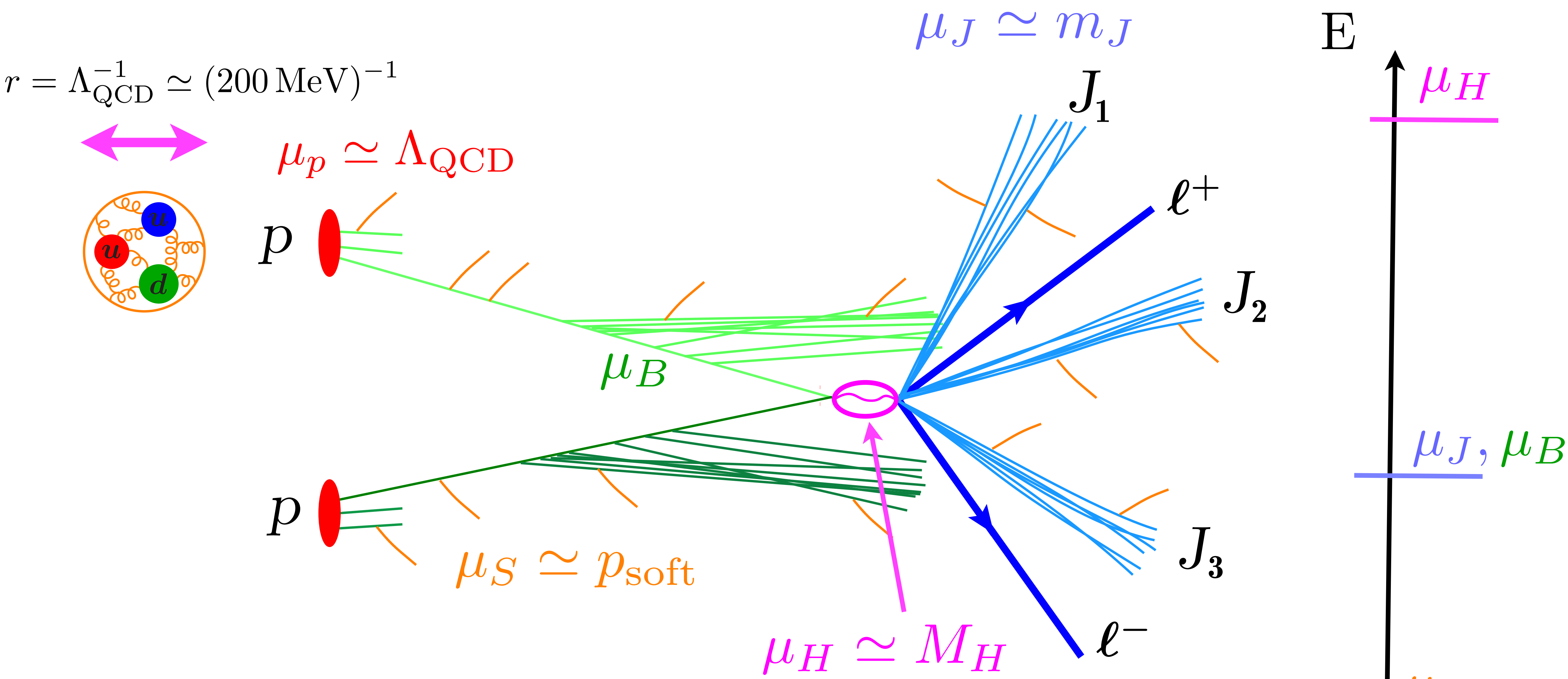
- $f_a f_b$: proton parton distributions
- $\hat{\sigma}$: perturbative partonic cross section (virtual & real radiation)
- F: hadronization model, underlying event

Schematically:

$$\hat{\sigma} = \sigma_0 \left[1 + \alpha_s + \alpha_s^2 + \ldots\right]$$

- σ_0: contains α_s^n of tree level process
- α_s: NLO
- α_s^2: NNLO, current frontier

Processes with Large Logs: hierarchy of scales



$$\alpha_s \ln^2\left(\frac{m_J}{p_T^{jet}}\right) \quad , \quad \alpha_s \ln^2\left(\frac{p_T^{veto}}{m_H}\right)$$

Processes with Large Logs:

Case I: parton shower Monte Carlo

$$d\sigma = f_a f_b \otimes \hat{\sigma}_i \otimes PS_i \otimes F$$

matrix elt. & parton shower merging

LO NLO

$$\begin{aligned}
\sigma = \sigma_0 \Big[1 \quad & + \alpha_s L^2 && + \alpha_s^2 L^4 && + \alpha_s^3 L^6 && + \ldots \quad \text{LL} \\
& + \alpha_s L && + \alpha_s^2 L^3 && + \alpha_s^3 L^5 && + \ldots \\
& + \alpha_s n_1(p_T^{\rm cut}) && + \alpha_s^2 L^2 && + \alpha_s^3 L^4 && + \ldots \\
& && + \alpha_s^2 L && + \alpha_s^3 L^3 && + \ldots \\
& && + \alpha_s^2 n_2(p_T^{\rm cut}) && + \alpha_s^3 L^2 && + \ldots \\
& && && + \alpha_s^3 L && + \ldots \\
& && && + \alpha_s^3 && + \ldots \Big]
\end{aligned}$$

eg.

$$L = \ln(p_T^{\rm cut}/m_H)$$

Parton Shower

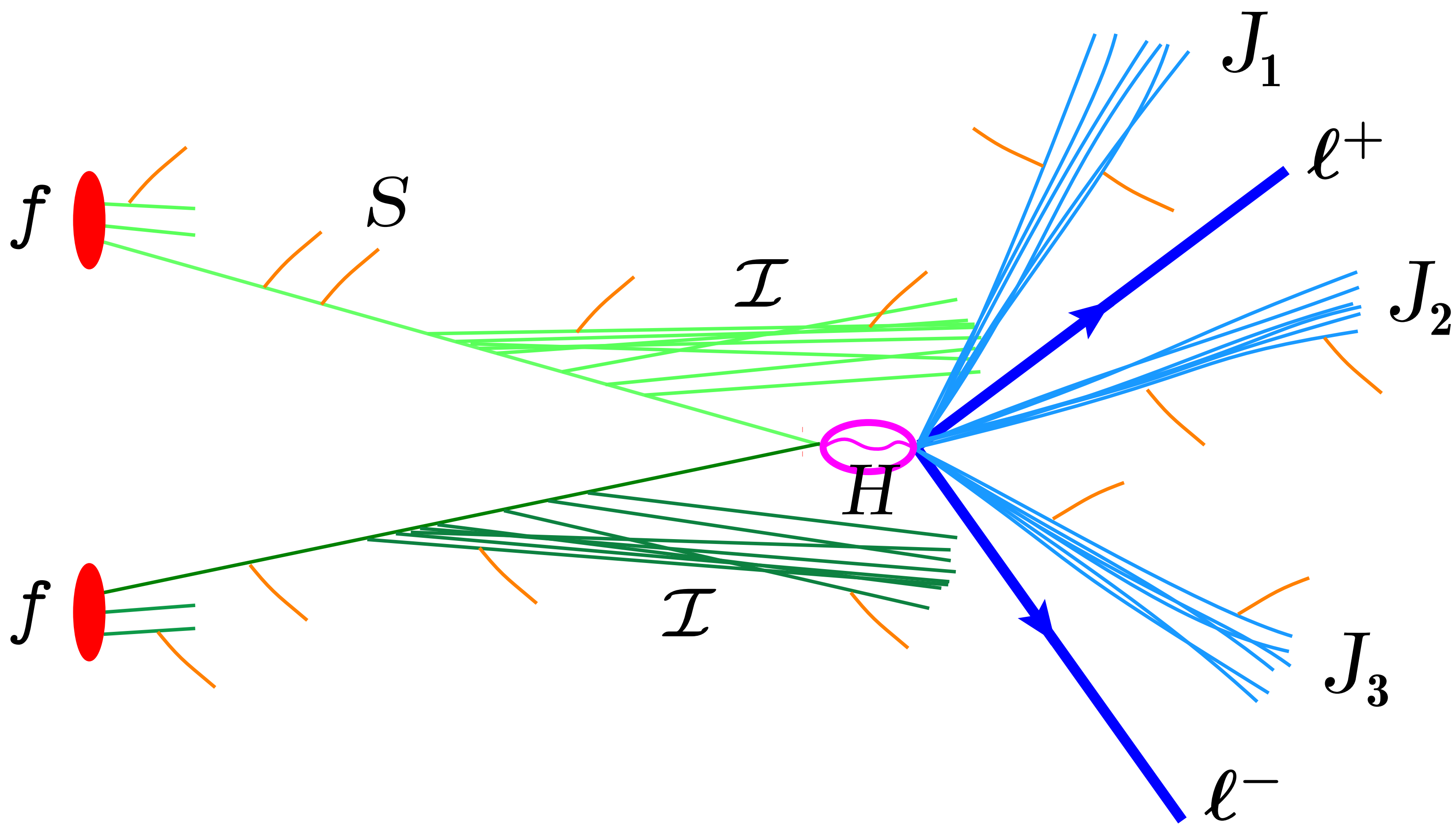
eg. Pythia is LL (+ tuning)

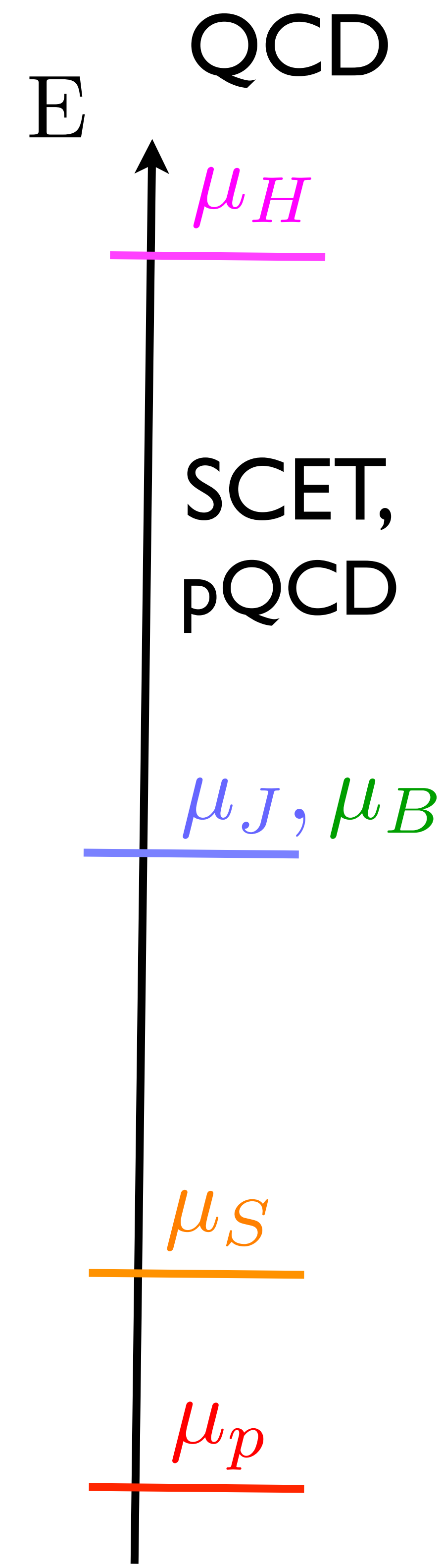
eg. MC@NLO is NLO+LL

- many processes
- full kinematics
- difficult to go to higher orders

Processes with Large Logs:

Case 2: analytic resummation





Often can exploit

Factorization formulas for individual cross sections:

$$d\sigma = f_{a,b} \otimes \mathcal{I}_{a,b} \otimes H \otimes \prod_i J_i \otimes S$$

Λ_{QCD} μ_B μ_H μ_J μ_S

Processes with Large Logs:

Case 2: analytic resummation

$$d\sigma = f_{a,b} \otimes \mathcal{I}_{a,b} \otimes H \otimes \prod_i J_i \otimes \hat{S} \otimes F$$

	LO	NLO	NNLO			
$\sigma = \sigma_0 \Big[$	1	$+ \alpha_s L^2$	$+ \alpha_s^2 L^4$	$+ \alpha_s^3 L^6$	$+ \dots$	LL
		$+ \alpha_s L$	$+ \alpha_s^2 L^3$	$+ \alpha_s^3 L^5$	$+ \dots$	NLL
		$+ \alpha_s n_1(p_T^{\rm cut})$	$+ \alpha_s^2 L^2$	$+ \alpha_s^3 L^4$	$+ \dots$	
			$+ \alpha_s^2 L$	$+ \alpha_s^3 L^3$	$+ \dots$	NNLL
			$+ \alpha_s^2 n_2(p_T^{\rm cut})$	$+ \alpha_s^3 L^2$	$+ \dots$	
				$+ \alpha_s^3 L$	$+ \dots$	
				$+ \alpha_s^3$	$+ \dots \Big]$	

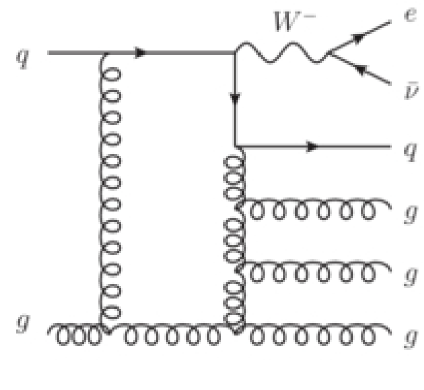
Analytic Resummation

State of the art for pp is
NNLL+NNLO
(when NNLO is available)

- can go to higher order
- analytic hadronization models
- calculations are process by process

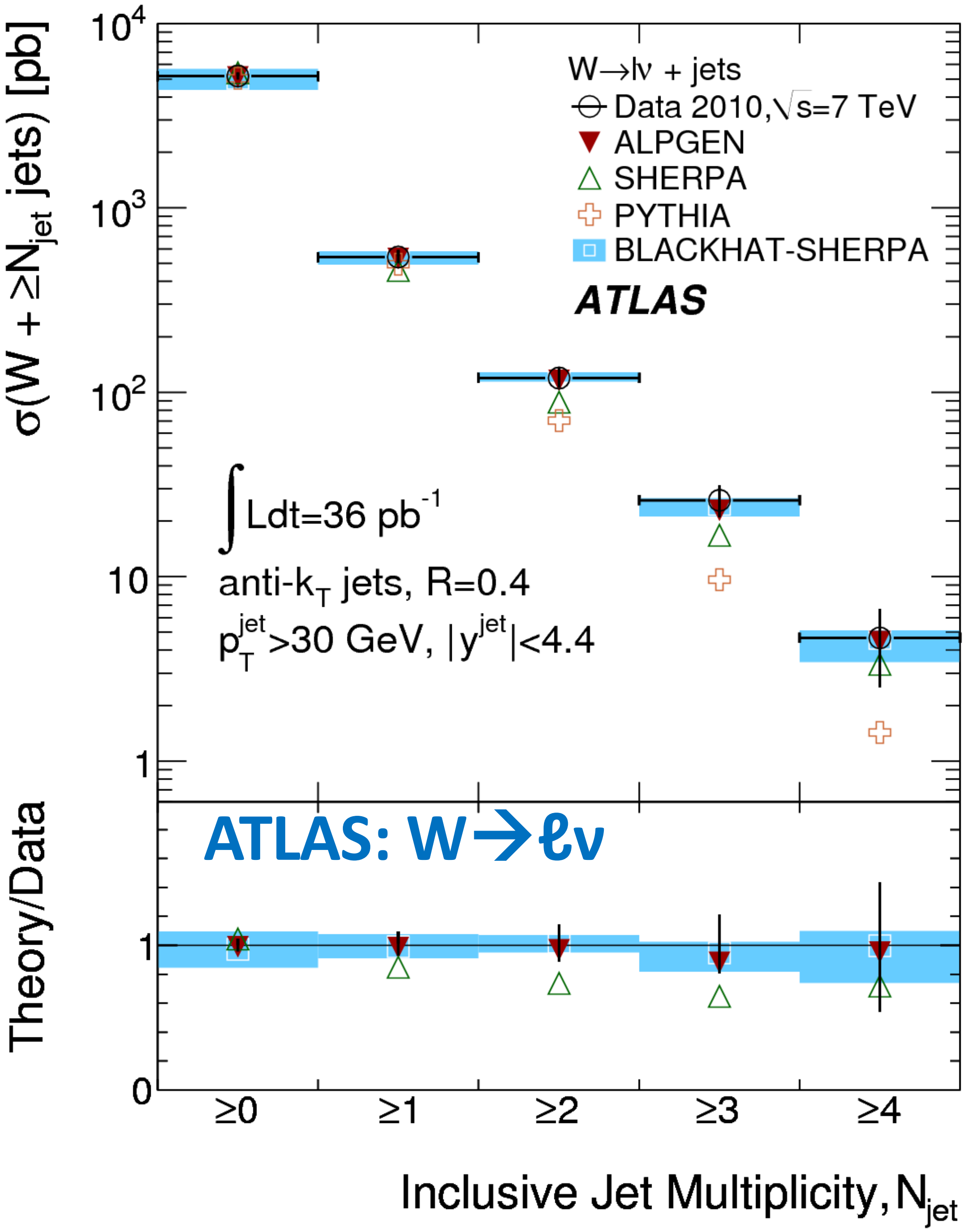
QCD @ the LHC

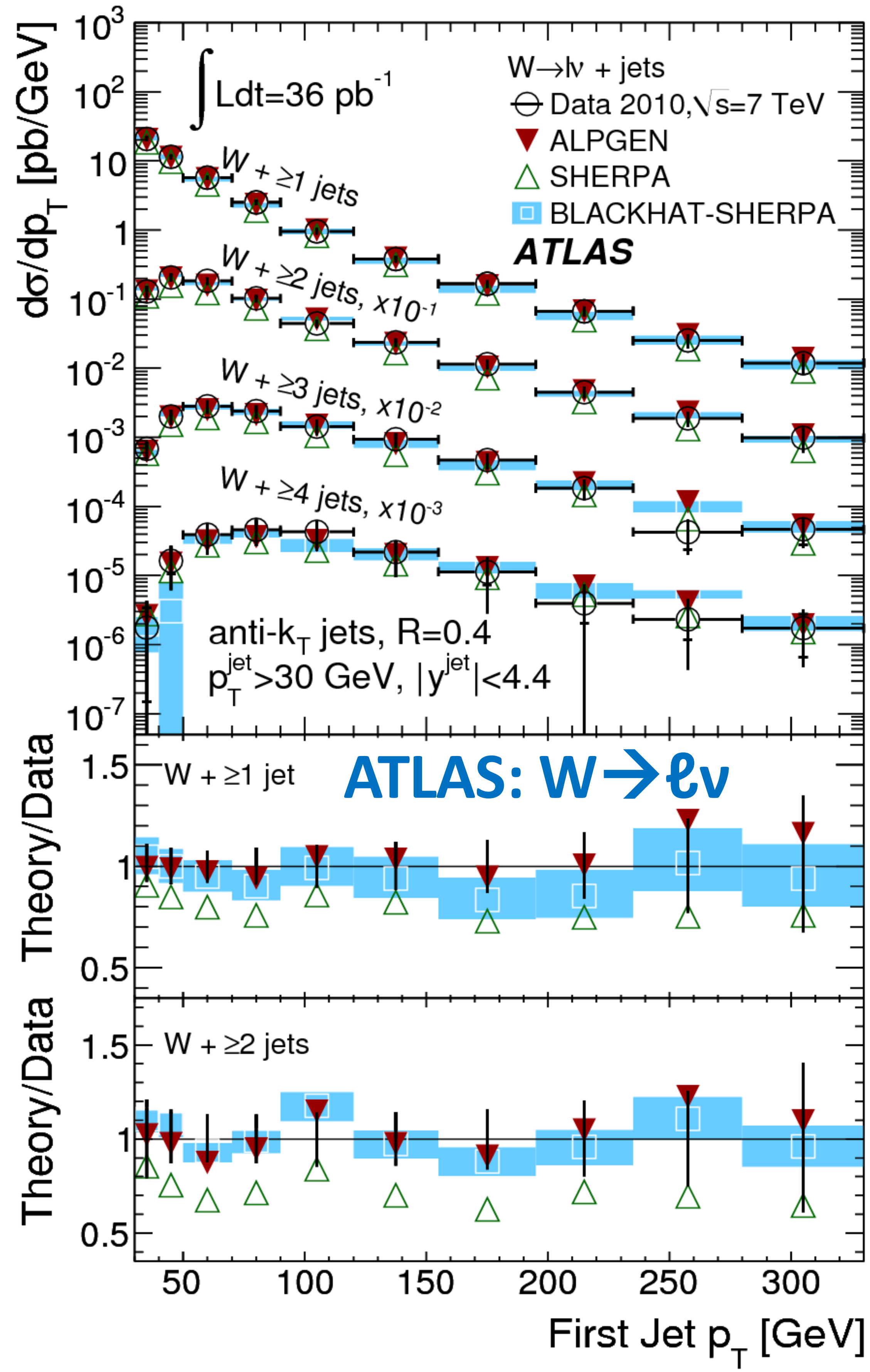
W+Jets



- important SM/BSM background

NLO: Blackhat + Sherpa

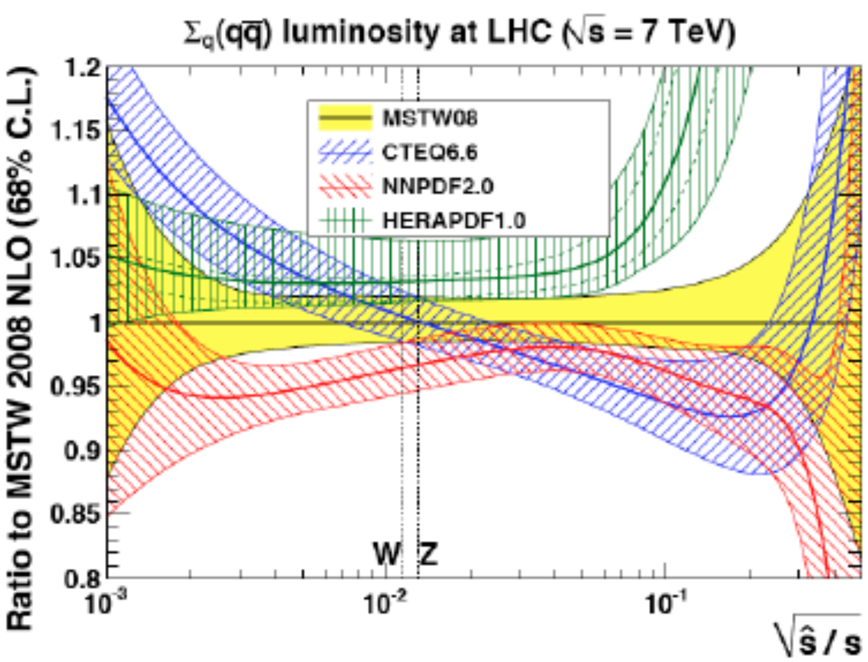


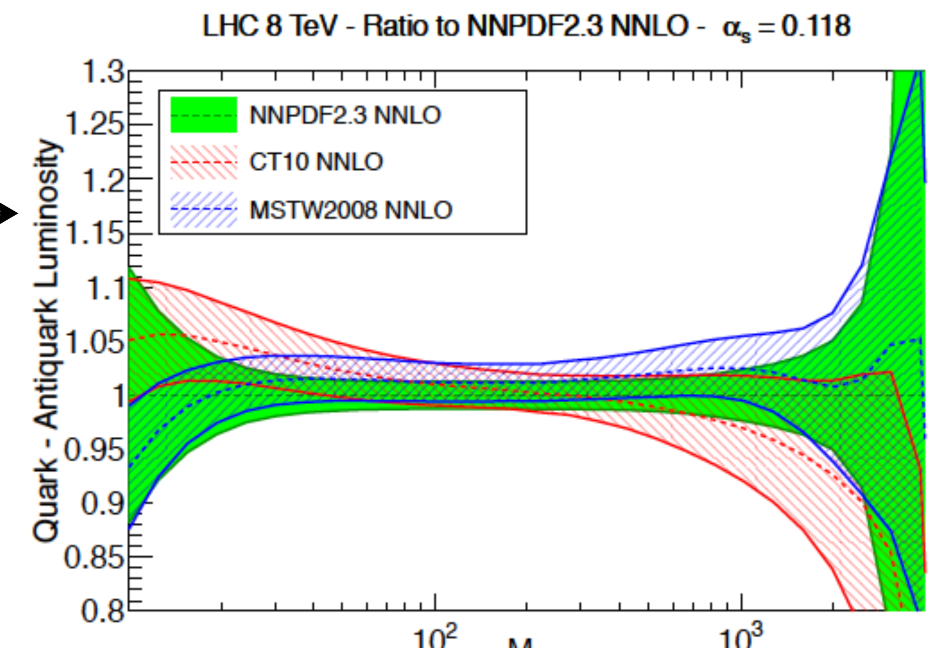


PDFs

arXiv:1211.5142

Richard D. Ball[1], Stefano Carrazza[2,3], Luigi Del Debbio[1], Stefano Forte[2,3], Jun Gao[4], Nathan Hartland[1], Joey Huston[5], Pavel Nadolsky[4], Juan Rojo[6], Daniel Stump[5], Robert S. Thorne[7], C.-P. Yuan[5]



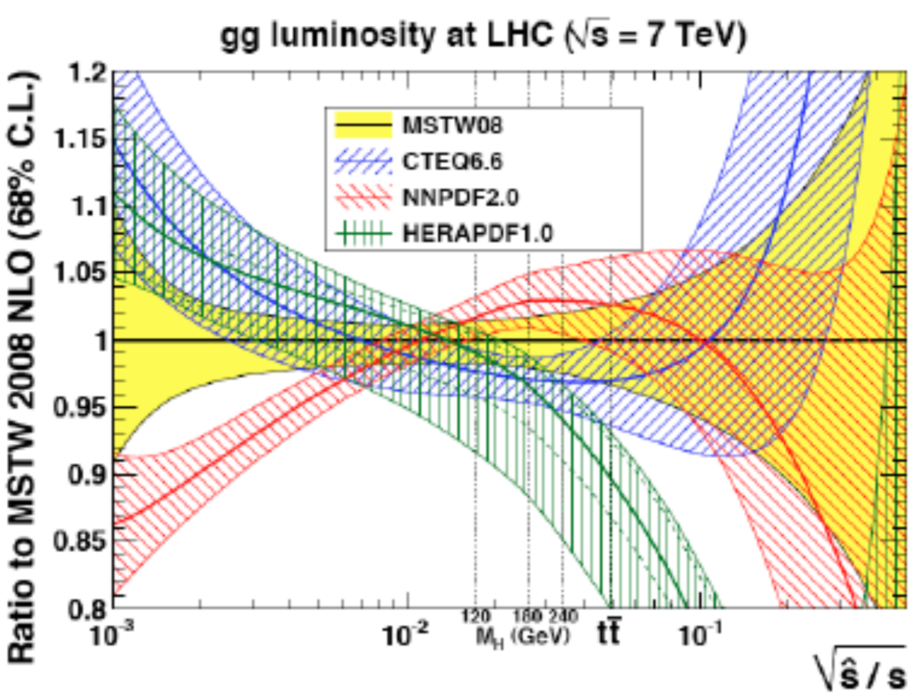


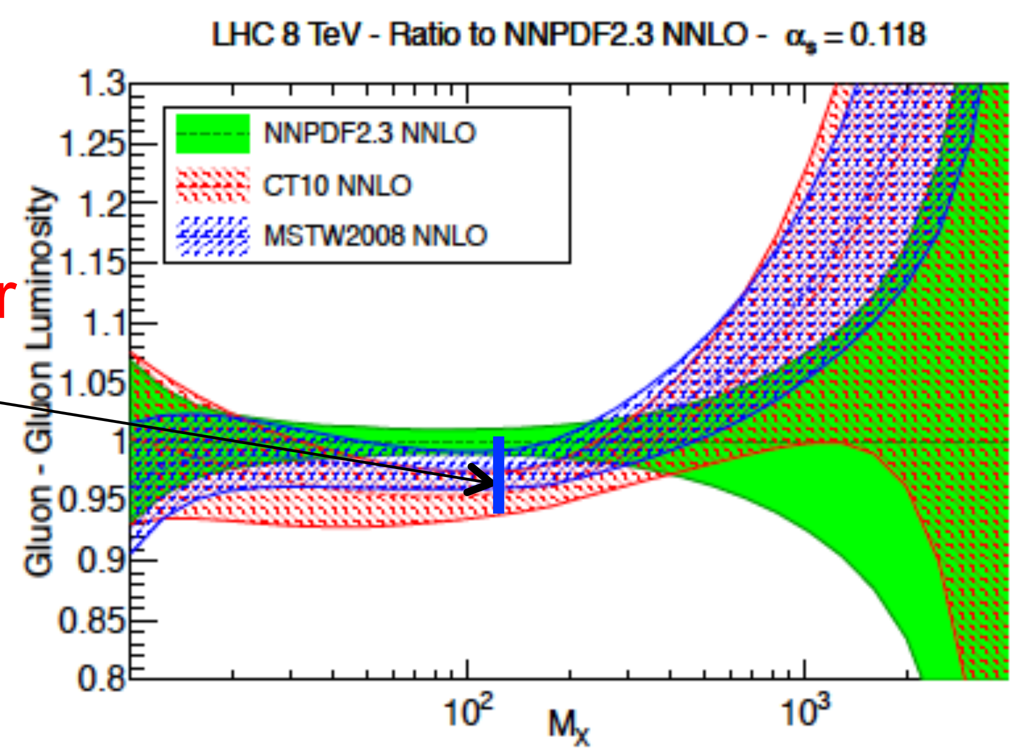
improvements from 2010 to 2012…

…and from NLO to NNLO

so Higgs PDF uncertainty under good control

α_s uncertainty still +/-0.002





$$\Phi_{ij}\left(M_X^2\right) = \frac{1}{s}\int_\tau^1 \frac{dx_1}{x_1} f_i\left(x_1, M_X^2\right) f_j\left(\tau/x_1, M_X^2\right) \qquad \tau \equiv M_X^2/s$$

from J.Huston
BNL Snowmass meeting

Inclusive Jets

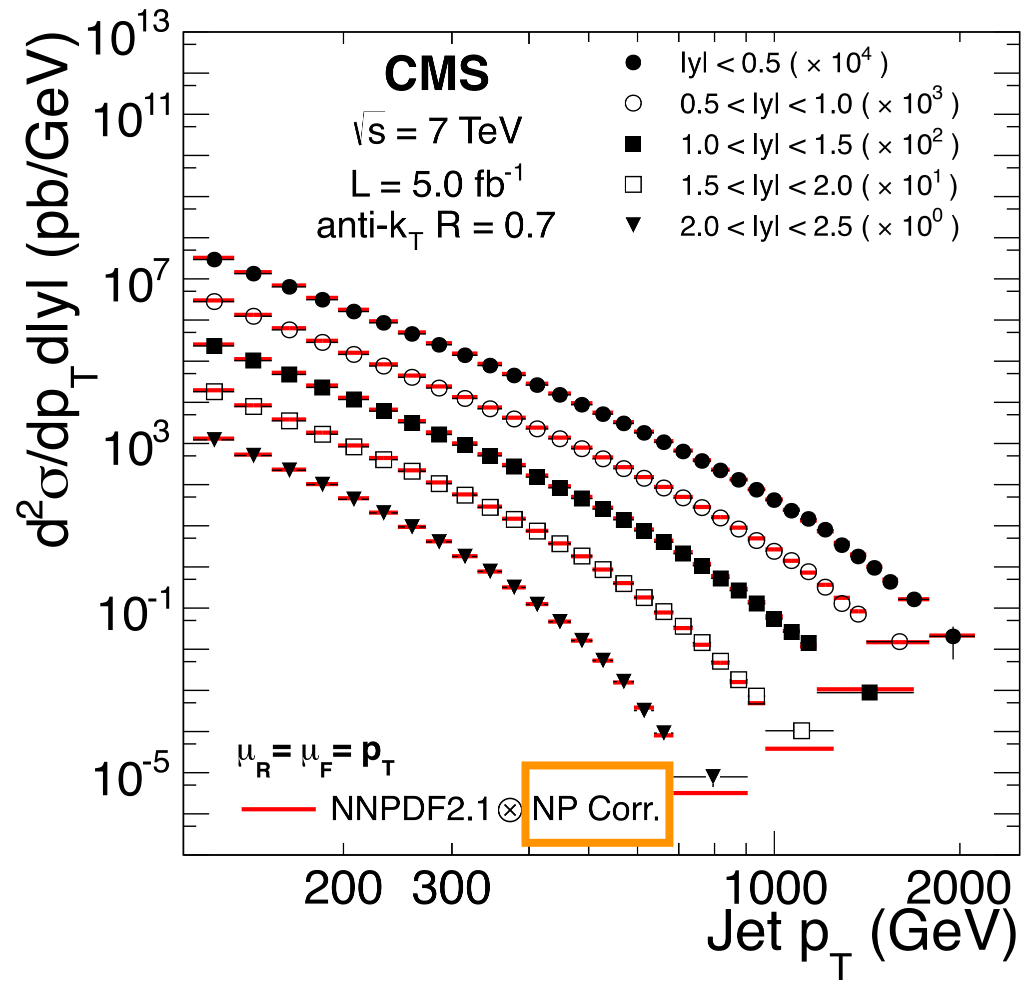
$$d\sigma = f_a f_b \otimes \hat{\sigma}_{\rm NLO} \otimes F$$

NNPDF | NLOJet++ (Z.Nagy) | Pythia/ Herwig

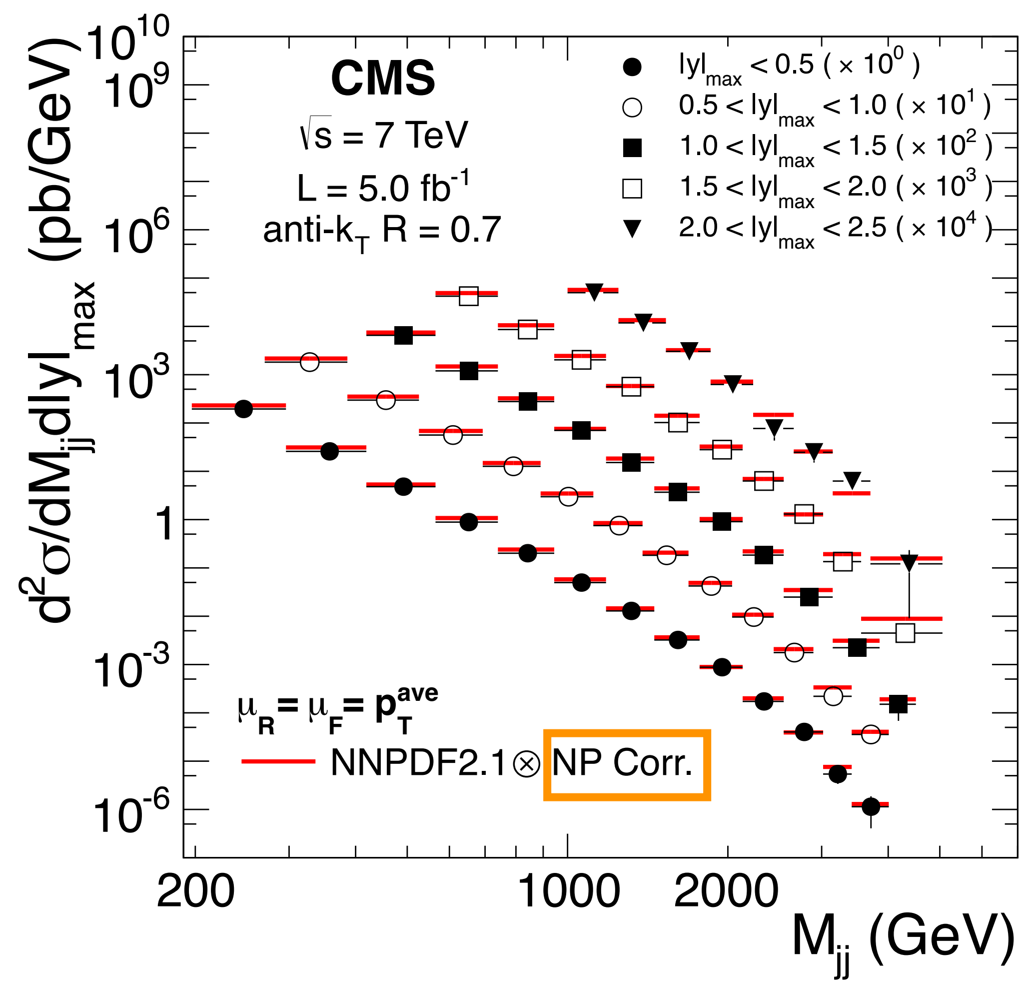
uncertainty: $\leq 30\%$ | $5\% - 10\%$, 40% (large y) | $1\% - 20\%$

agreement with QCD over many orders of magnitude up to 2 TeV

$pp \to \text{jet} + X$



$pp \to \text{dijets}$



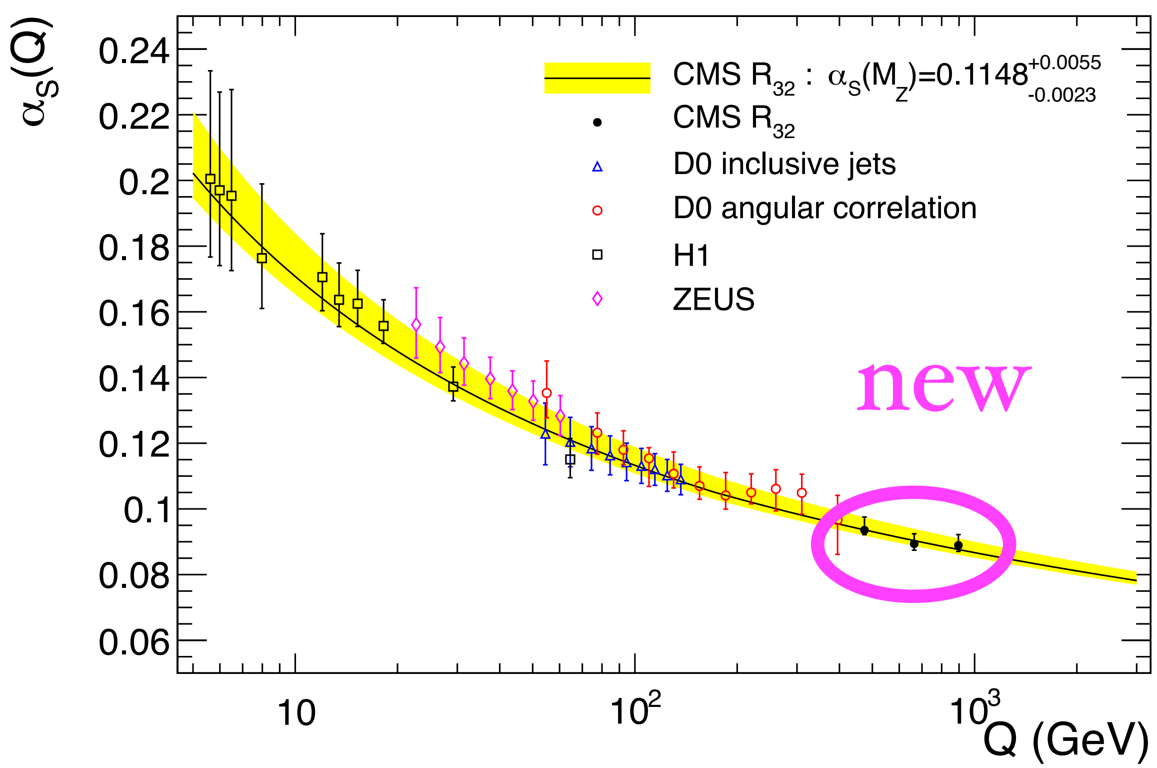
CMS, arXiv:1212.6660

What can we do with these?

measure α_s

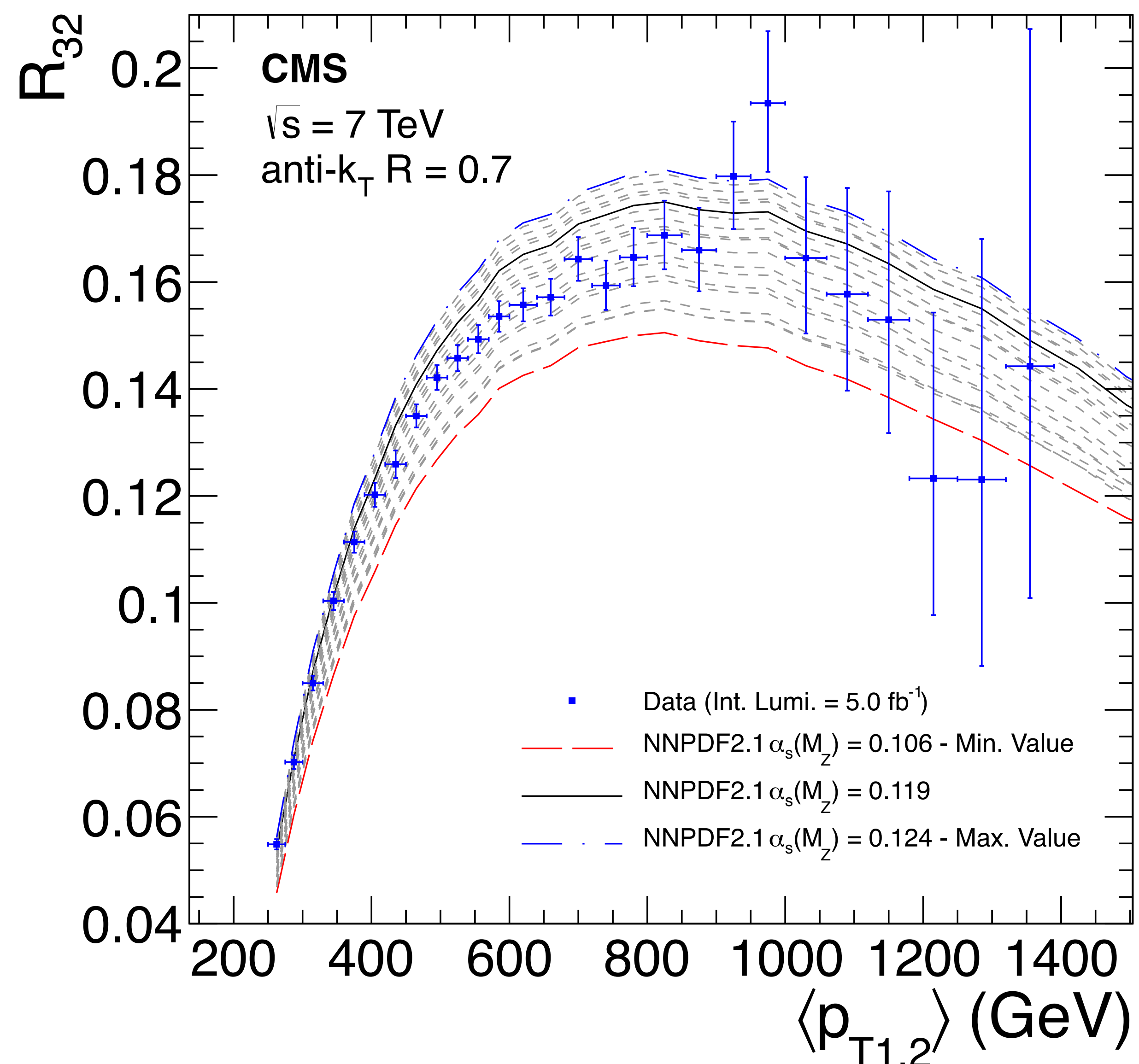
$$R_{32} = \frac{d\sigma_{\geq 3}/dp_T}{d\sigma_{\geq 2}/dp_T} \propto \alpha_s(Q)$$

less sensitive to PDFs



CMS, arXiv:1304.7498

Data sample: 2011 $\mathcal{L}_{\rm int} = 5.0\,{\rm fb}^{-1}$



NNPDF: $\alpha_S(M_Z) = 0.1148 \pm 0.0014\,(\text{exp.}) \pm 0.0018\,(\text{PDF})^{+0.0050}_{-0.0000}\,(\text{scale})$

MSTW2008: $\alpha_S(M_Z) = 0.1141 \pm 0.0022\,(\text{exp.})$

CT10: $\alpha_S(M_Z) = 0.1135 \pm 0.0019\,(\text{exp.})$

World Avg/Lattice QCD (PDG 2012):

$\alpha_S(M_Z) = 0.1184 \pm 0.0007$

important to reduce NLO uncertainty

Dijet Production at NNLO

Gehrmann-De Ridder, Gehrmann, Glover, Pires: arXiv:1301.7310

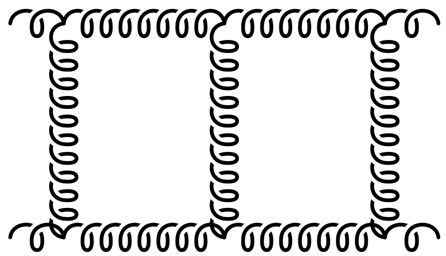
so far: $gg \to gg$, leading color

Ingredients:

Two-loop matrix elements

(C. Anastasiou, E.W.N. Glover, C. Oleari, M. Tejeida-Yeomans; Z. Bern, L. Dixon, A. De Freitas)

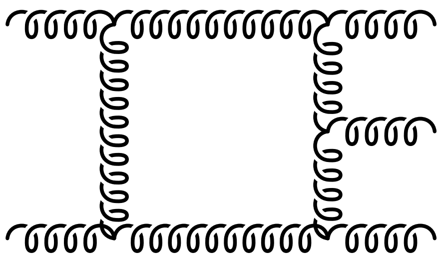
- Explicit infrared poles from loop integrals



One-loop matrix elements

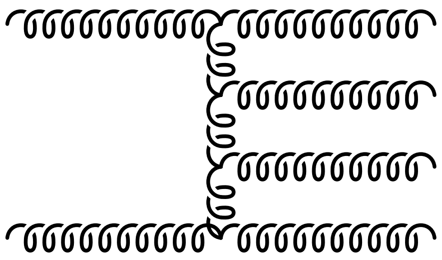
(Z. Kunszt, A. Signer, Z. Trocsanyi)

- Explicit infrared poles from loop integral
- Implicit infrared poles from real radiation



Tree-level matrix elements

- Implicit infrared poles from real radiation

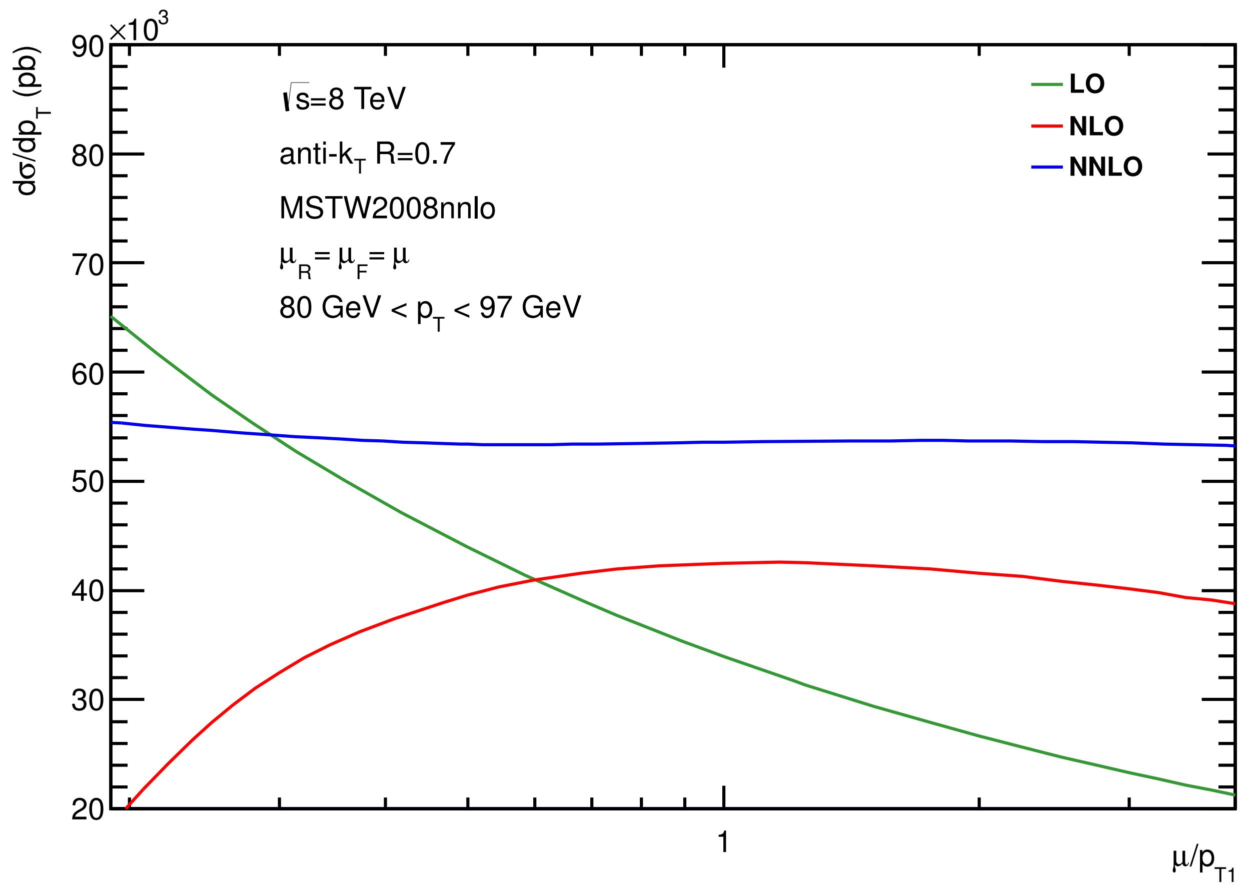


putting these together was nontrivial !

use subtractions

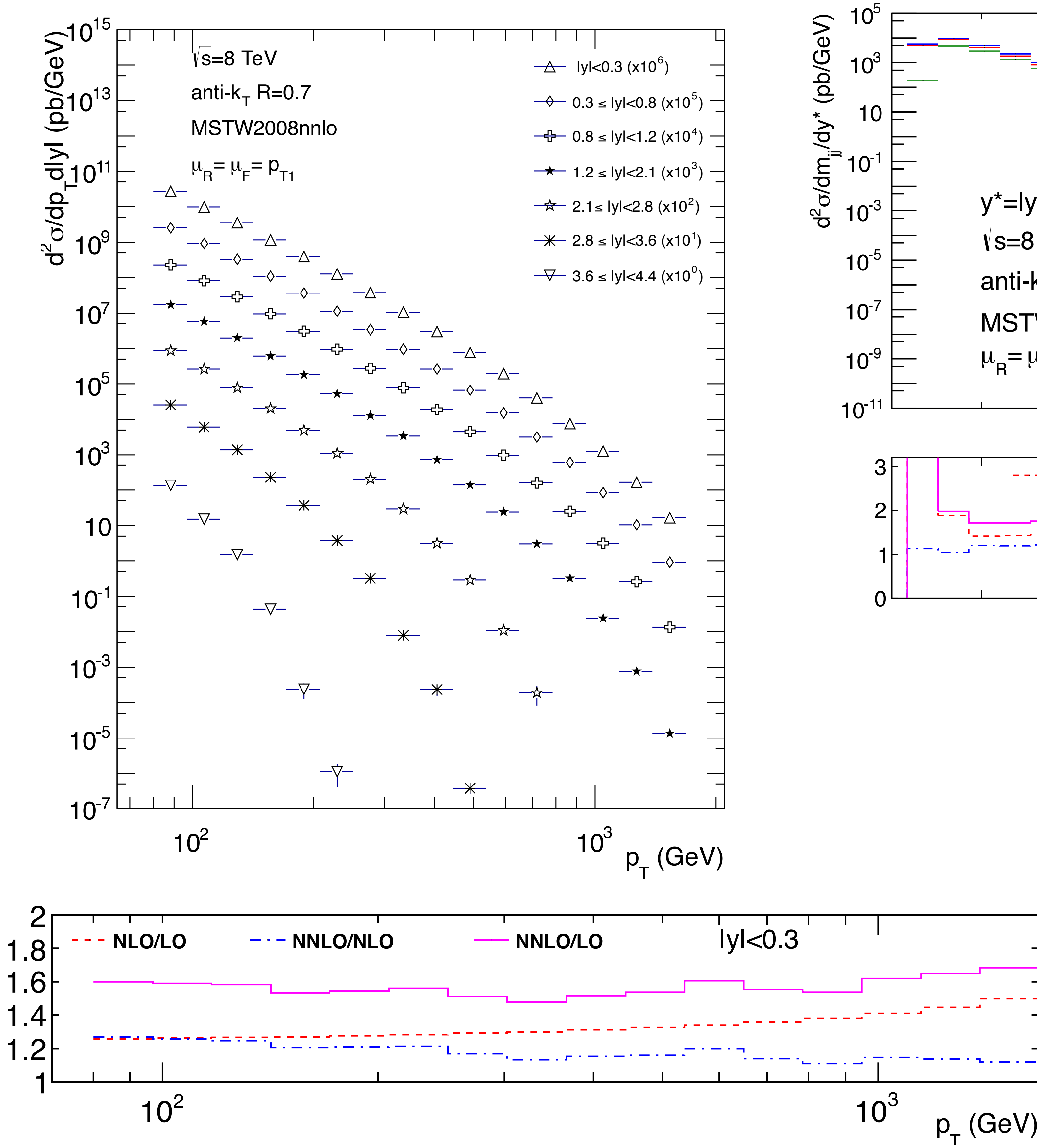
$$d\sigma_{NNLO} = \int_{d\Phi_{m+2}} \left(d\sigma^R_{NNLO} - d\sigma^S_{NNLO}\right) + \int_{d\Phi_{m+1}} \left(d\sigma^{V,1}_{NNLO} - d\sigma^{VS,1}_{NNLO}\right) + \int_{d\Phi_{m+1}} d\sigma^{MF,1}_{NNLO} + \int_{d\Phi_m} d\sigma^{V,2}_{NNLO} + \int_{d\Phi_{m+2}} d\sigma^{S}_{NNLO} + \int_{d\Phi_{m+1}} d\sigma^{VS,1}_{NNLO} + \int_{d\Phi_m} d\sigma^{MF,2}_{NNLO}$$

Inclusive jet p_T distribution: scale dependence

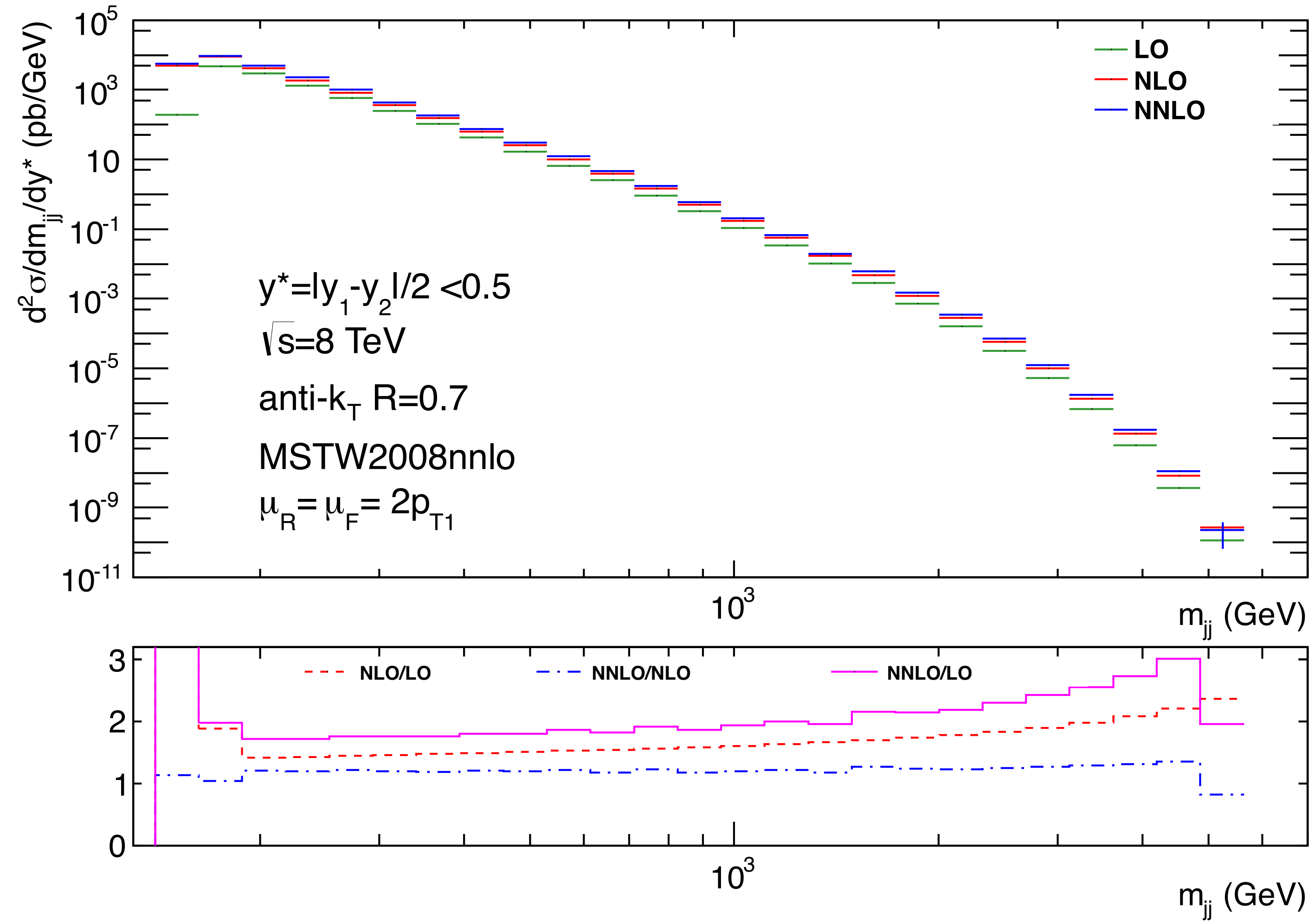


significantly improved uncertainties over NLO

$pp \to \text{jet} + X$



$pp \to \text{dijets}$



Applications:

- PDFs
- α_s

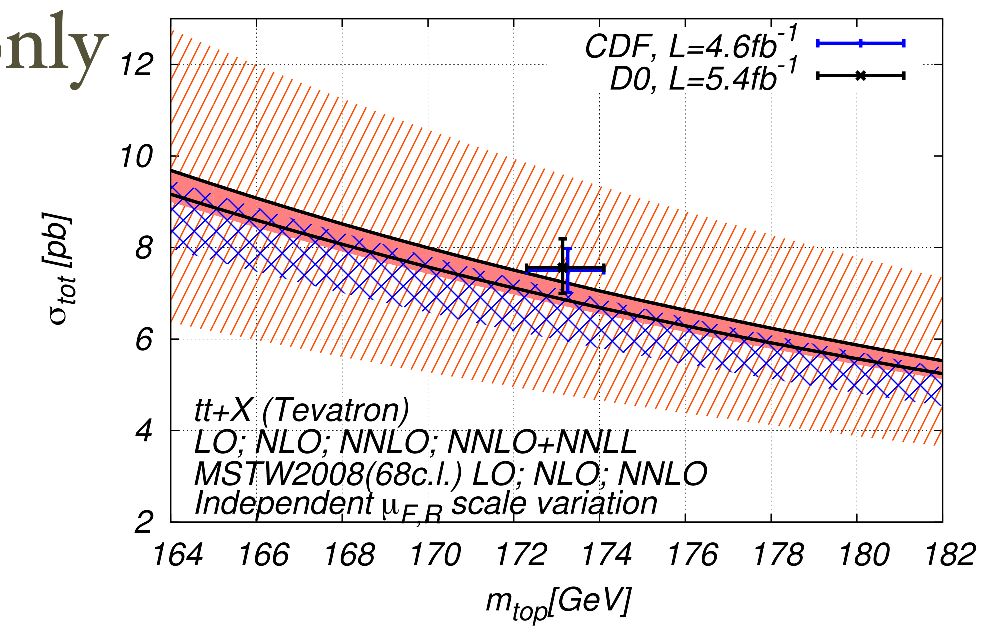
$pp \to t\bar{t}$ at NNLO

Czakon & Mitov:	arXiv:1207.0236	qq
	arXiv:1210.6832	qg
Czakon, Fiedler, Mitov:	arXiv:1303.6254	gg

complete, all channels done

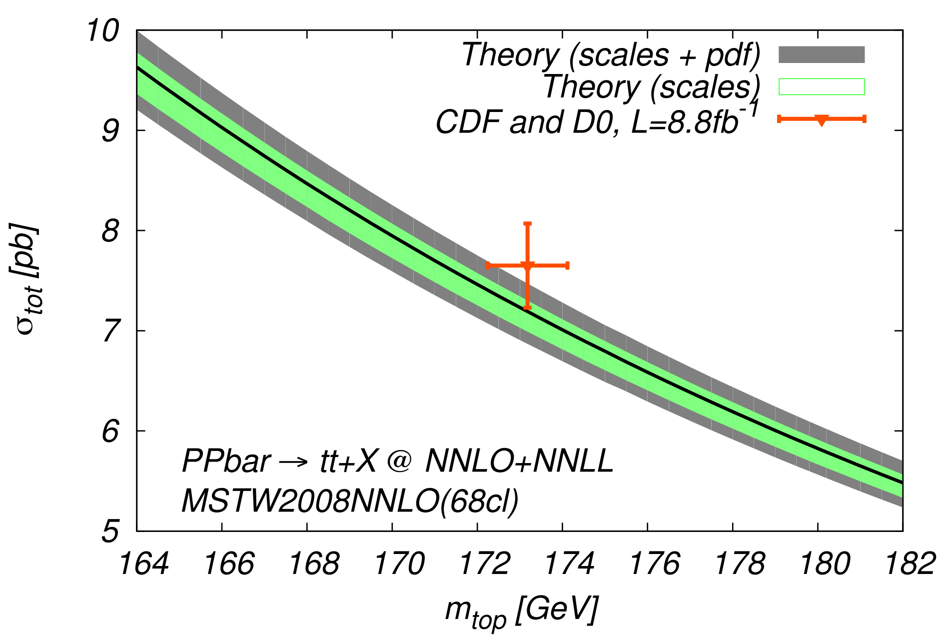
Tevatron

qq only



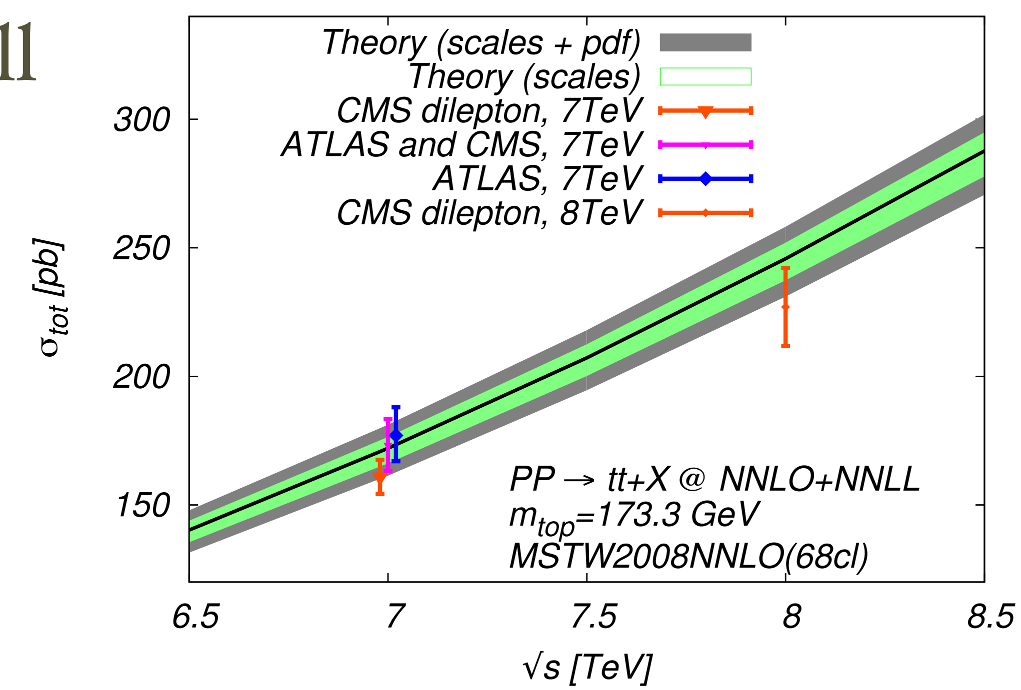
good convergence

all



LHC

all



scales ~3%

pdf ~ 2-3%

Applications:

- PDFs
- accurate top background
- constrain "stealthy stops"

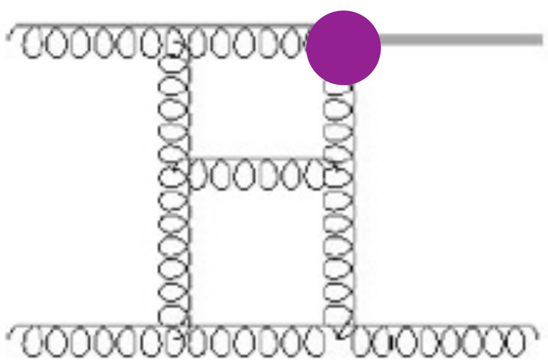
$pp \to H + 1\text{-jet}$ at NNLO

Boughezal, Caola, Melnikov, Petriello, Schulze
arXiv:1302.6216

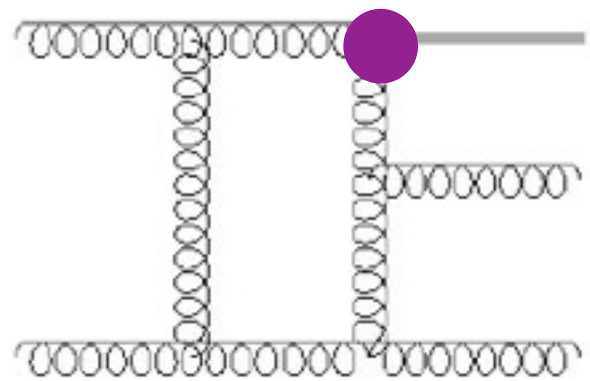
so far: $gg \to H + 1\text{-jet}$

Ingredients:

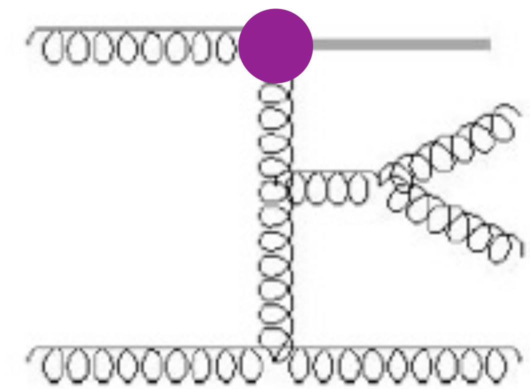
top loop $\longrightarrow$ $\mathcal{L} = -\lambda\, H\, G^{\mu\nu} G_{\mu\nu}$



Gehrmann, Jaquier, Glover, Koukoutsakis (2011)



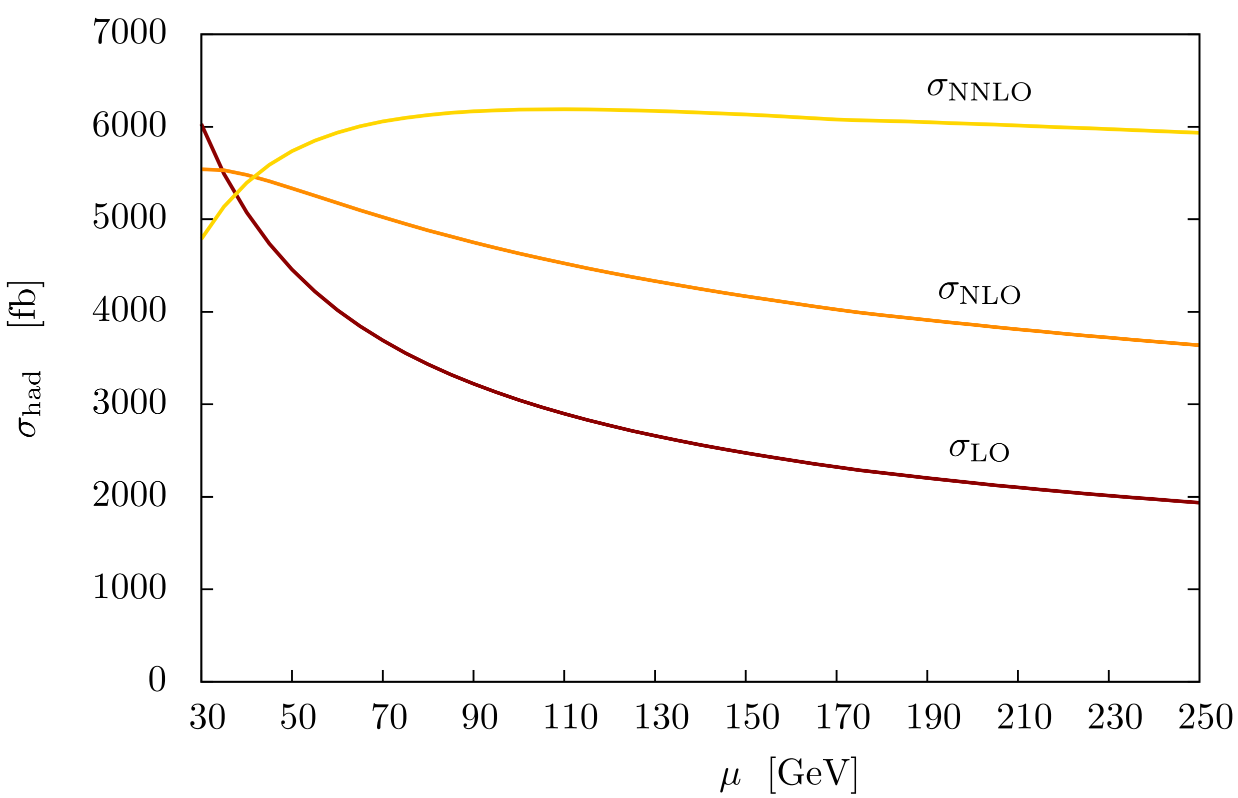
Badger, Glover, Mastrolia, Williams (2009)



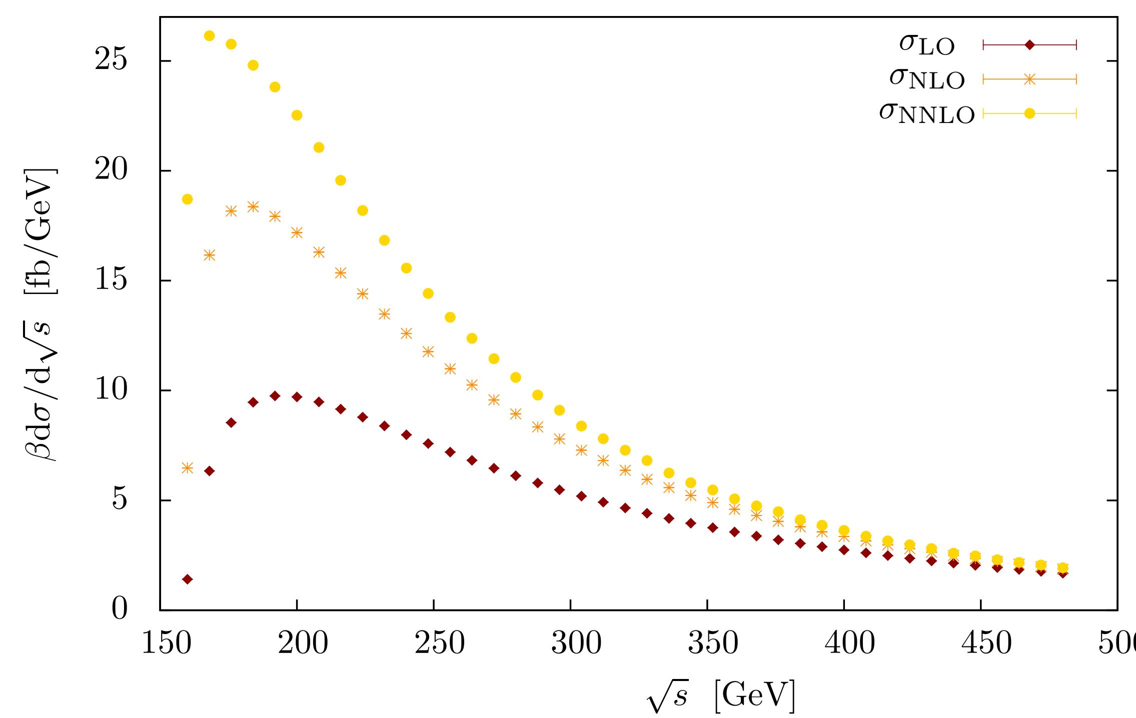
Del Duca, Frizzo, Maltoni;
Dixon, Glover, Khoze (2004)

$R = 0.5 \qquad p_T^J = 30\,\mathrm{GeV} \qquad k_T$-algorithm

scale uncertainty is significantly reduced



often a significant correction



Applications:

- Higgs coupling measurements

Jet Bins for pp

$$pp \longrightarrow H + N\text{-jets}$$

Jet Bin Motivations

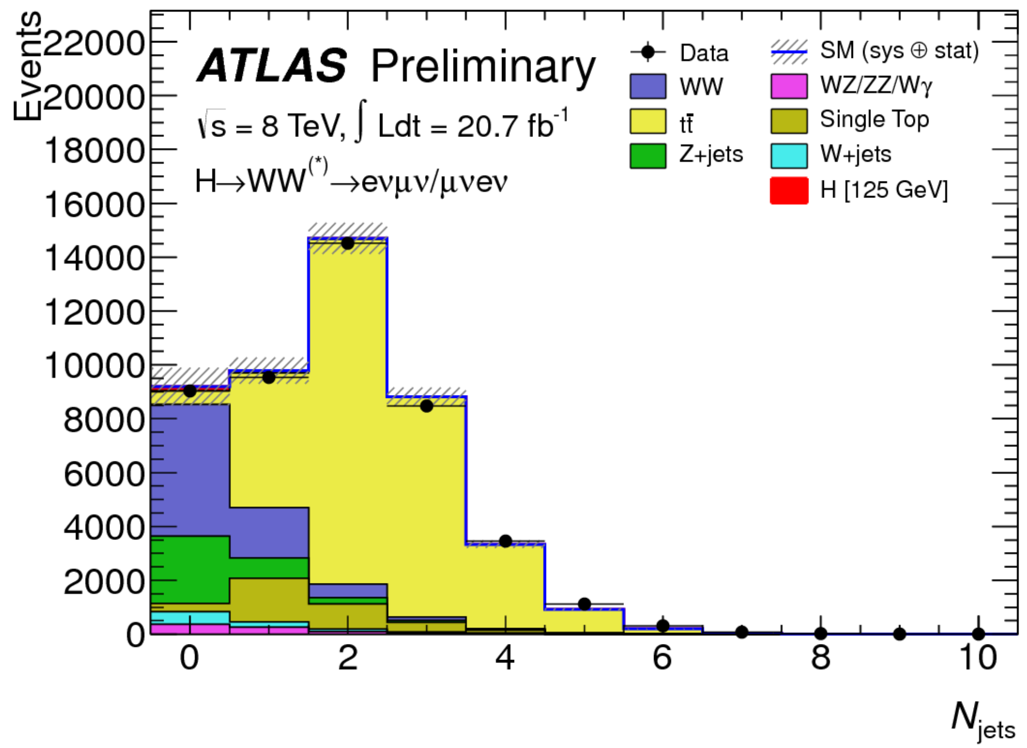
- Enhance new physics signals that like to produce jets
- Analyses where backgrounds vary with the number of jets

Use jet bins to maximize sensitivity

$$H + 0, 1, 2, \ldots \text{jets}$$

$$W/Z + \gamma + 0\text{jets}$$

eg. large top background in $H \to WW$



Jet Bins are important for coupling analyses

$H \to WW \to \ell\ell\nu\nu$
$H \to WW \to \ell\nu q'\bar{q}$

- 0–jets
- 1–jet
- 2–jets (VBF)

$H \to \tau\tau$

- 0–jets
- 1–jet
- 2–jets (VBF)

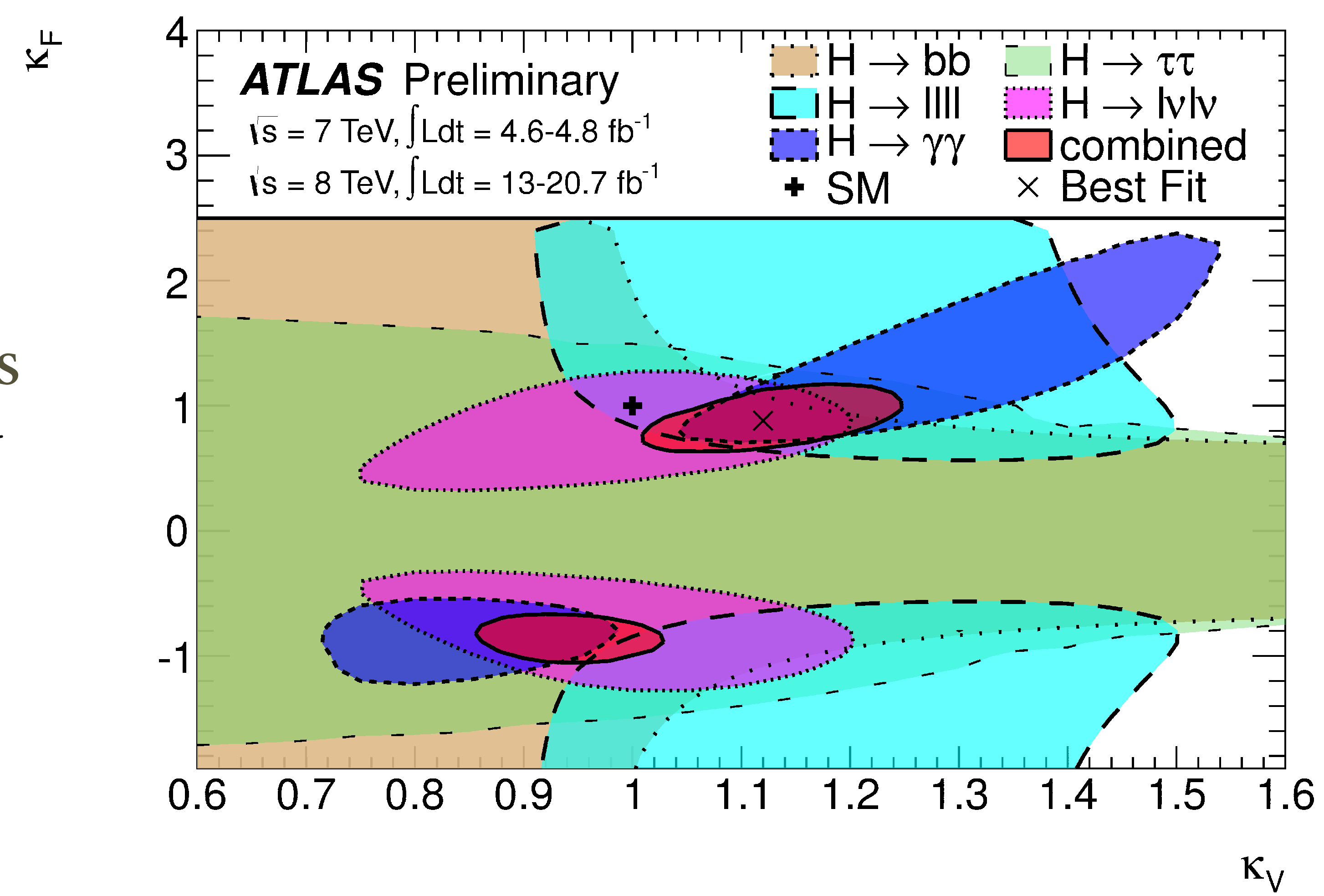
$H \to \gamma\gamma$
$H \to ZZ$

- inclusive
- 2–jets (VBF)

eg: fit for common scaling factor for vector and fermionic Higgs couplings

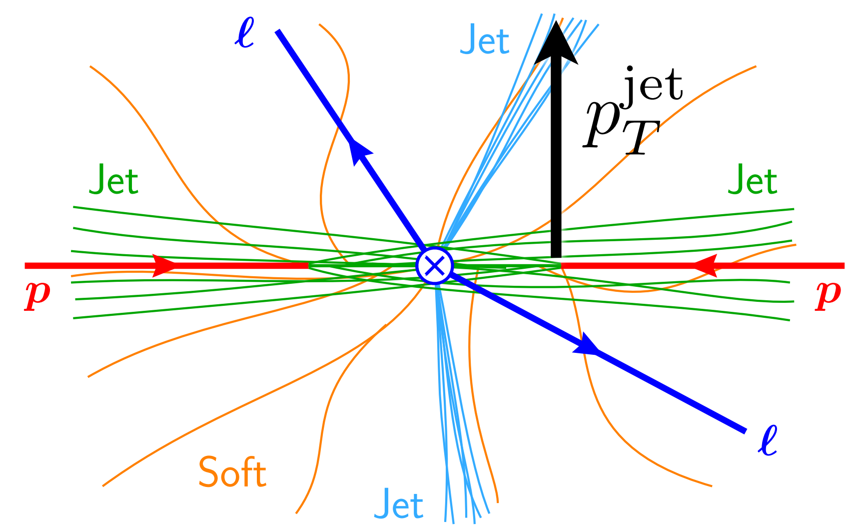
$$H \to \tau\tau, b\bar{b} \qquad H \to WW$$

involve exclusive jet bins



Jet veto gives double logs

veto > N jets $\quad p_T^{\text{jet}} \le p_T^{\text{cut}}$



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

LO NLO NNLO

$$\begin{aligned}
\sigma_{0\text{-jet}} = \sigma_{\text{LO}}\Big[1 &+ \alpha_s L^2 &&+ \alpha_s^2 L^4 &&+ \alpha_s^3 L^6 &&+ \ldots && \text{LL}\\
&+ \alpha_s L &&+ \alpha_s^2 L^3 &&+ \alpha_s^3 L^5 &&+ \ldots && \text{NLL}\\
&+ \alpha_s n_1(p_T^{\text{cut}}) &&+ \alpha_s^2 L^2 &&+ \alpha_s^3 L^4 &&+ \ldots && \text{NNLL}\\
& &&+ \alpha_s^2 L &&+ \alpha_s^3 L^3 &&+ \ldots\\
& &&+ \alpha_s^2 n_2(p_T^{\text{cut}}) &&+ \alpha_s^3 L^2 &&+ \ldots\\
& && &&+ \alpha_s^3 L &&+ \ldots\\
& && &&+ \alpha_s^3 &&+ \ldots\Big]
\end{aligned}$$

In $H \to WW$ the perturbative QCD uncertainties are the dominant systematic uncertainty

[ATLAS-CONF-2012-158]

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	-

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	-

fixed order calculations

$$\Delta^2_{\sigma_0} = \Delta^2_{\sigma_{\rm tot}} + \Delta^2_{\sigma_{\geq 1}}$$

$$\boldsymbol{\Delta\sigma_0/\sigma_0 = 17\%}$$

They can be reduced with resummation.
For 1-jet the new NNLO results are also important.

$$\sigma_0(p_T^{cut}) = \sigma_{total} - \sigma_{\geq 1}(p_T^{cut})$$
$$= \left[1 + \alpha_s + \alpha_s^2 + \cdots\right] - \left[\alpha_s(L^2 + \cdots) + \alpha_s^2(L^4 + \cdots) + \cdots\right]$$

NNLO Fixed Order:

FEHiP, HNNLO

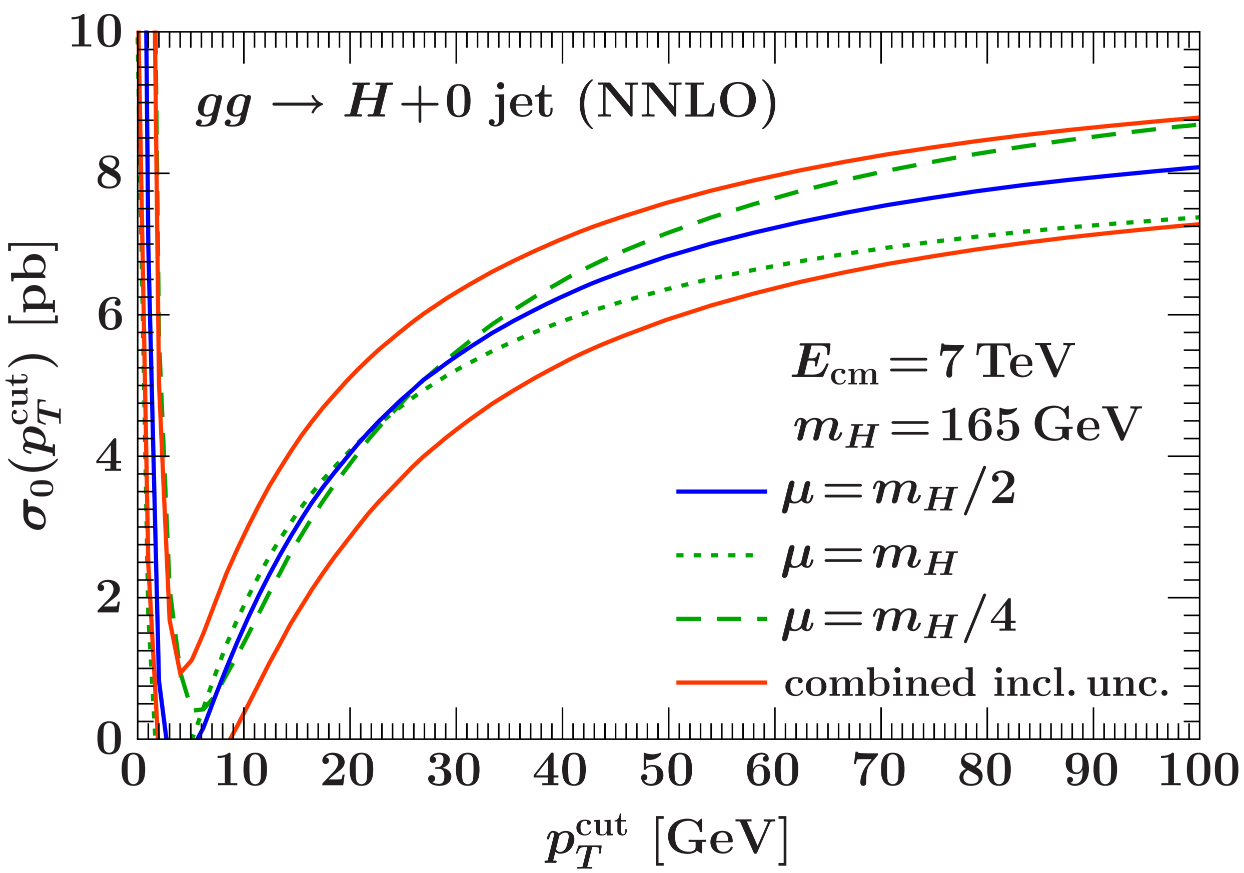
MCFM (pT spectrum)

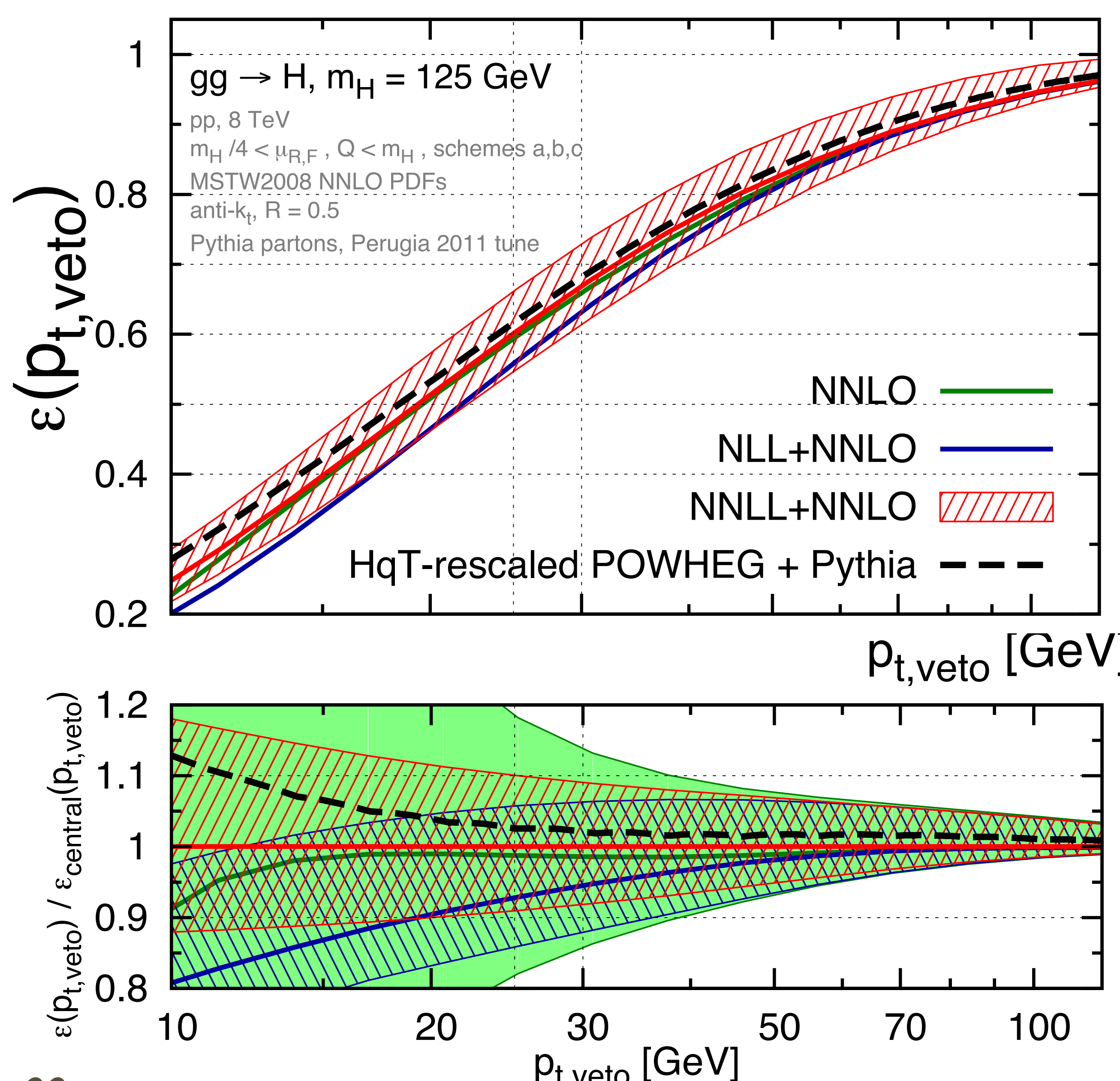
NNLL+NNLO Resummation of Veto Logs

Banfi, Monni, Salam, Zanderighi (1206.4998)

(Becher, Neubert; Tackmann, Walsh, Zuberi)

$$\varepsilon = \sigma_0/\sigma_{total}$$





NNLO uncertainty procedure:

IS, Tackmann

$$\sigma_0(p_T^{\mathrm{cut}}) = \sigma_{\mathrm{total}} - \sigma_{\geq 1}(p_T^{\mathrm{cut}})$$
$$= \left[1 + \alpha_s + \alpha_s^2 + \cdots\right] - \left[\alpha_s(L^2 + \cdots) + \alpha_s^2(L^4 + \cdots) + \cdots\right]$$

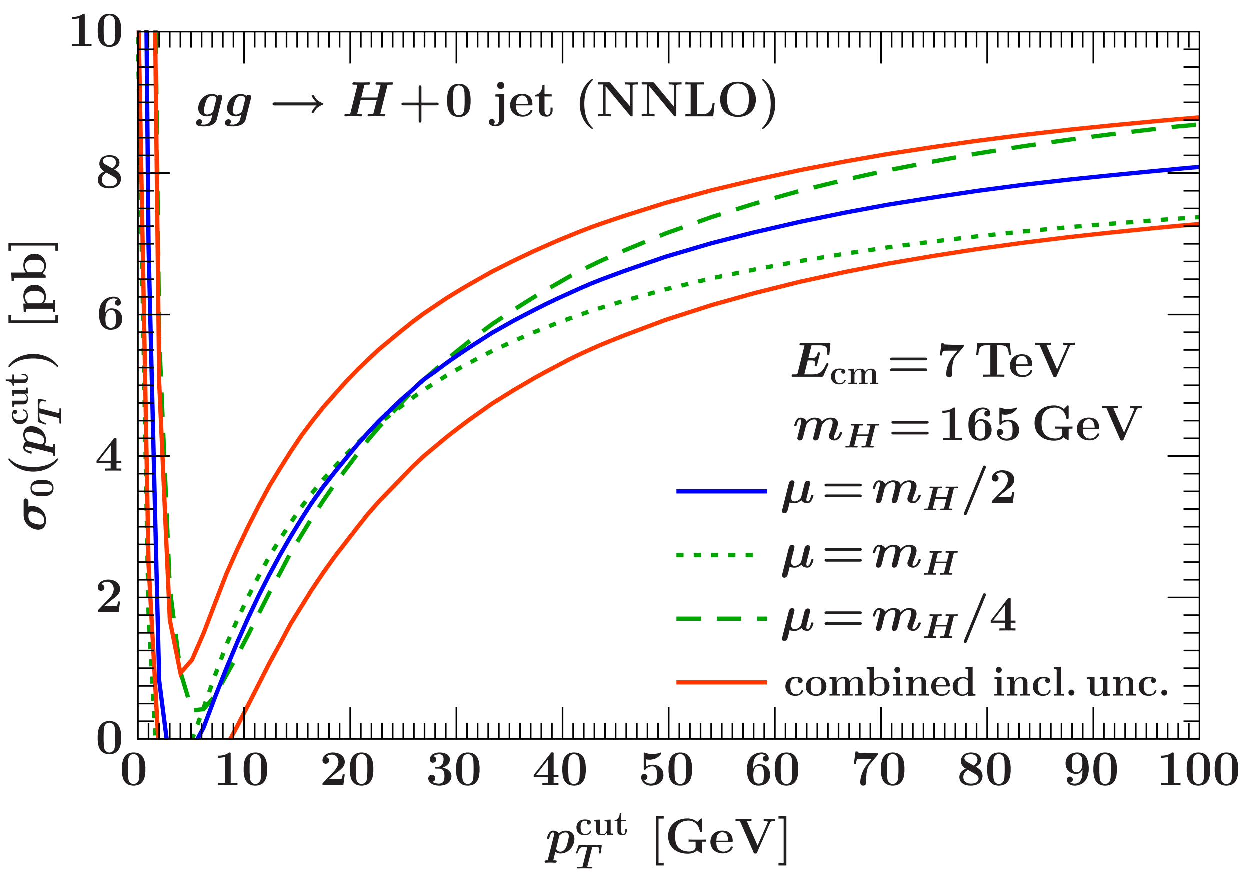
NNLO Fixed Order:

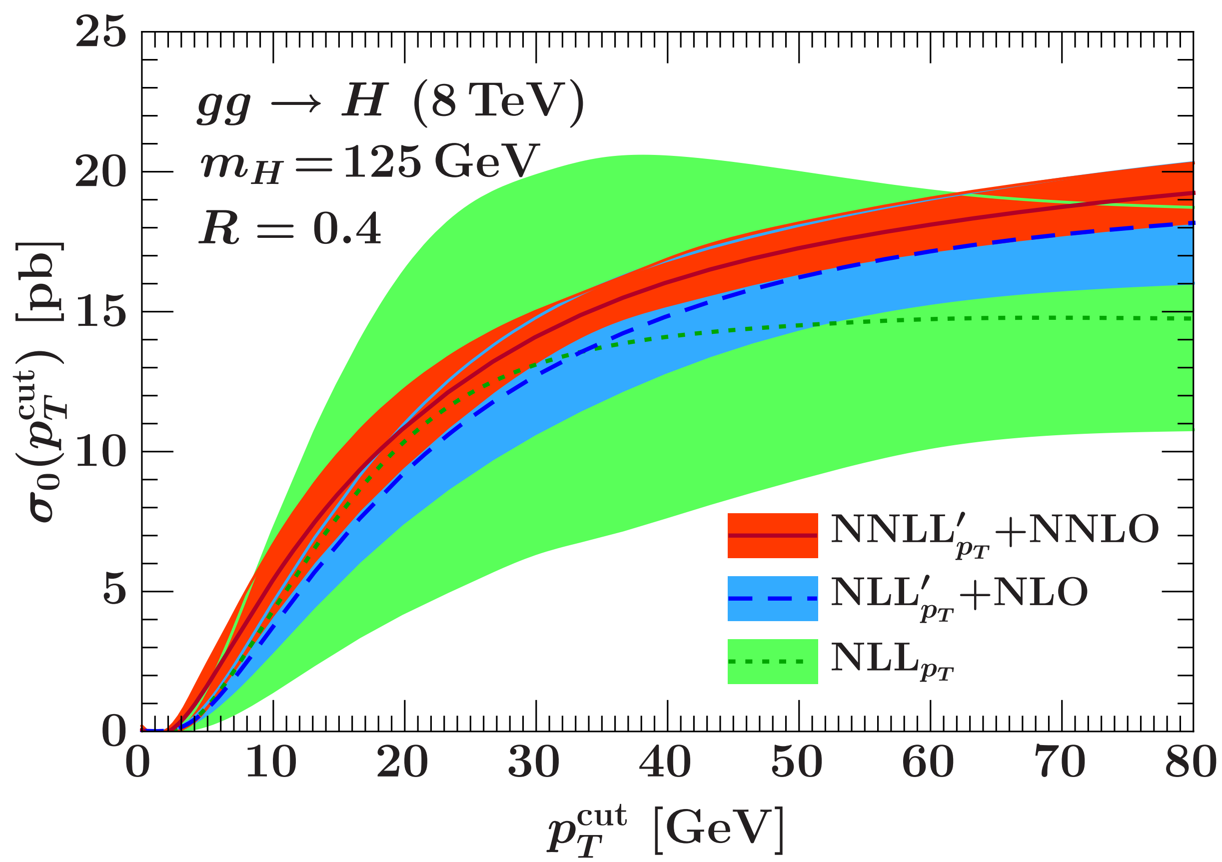
FEHiP, HNNLO

MCFM (pT spectrum)

NNLL' +NNLO Resummation of Veto Logs

IS, Tackmann, Walsh, Zuberi (in prep)





NNLO uncertainty procedure:

IS, Tackmann

Correlations in theory uncertainties

$$\sigma_0(p_T^{\rm cut}) = \sigma_{\rm total} - \sigma_{\geq 1}(p_T^{\rm cut})$$
$$= \left[1 + \alpha_s + \alpha_s^2 + \cdots\right] - \left[\alpha_s(L^2 + \cdots) + \alpha_s^2(L^4 + \cdots) + \cdots\right]$$

NNLO Fixed Order:
FEHiP, HNNLO
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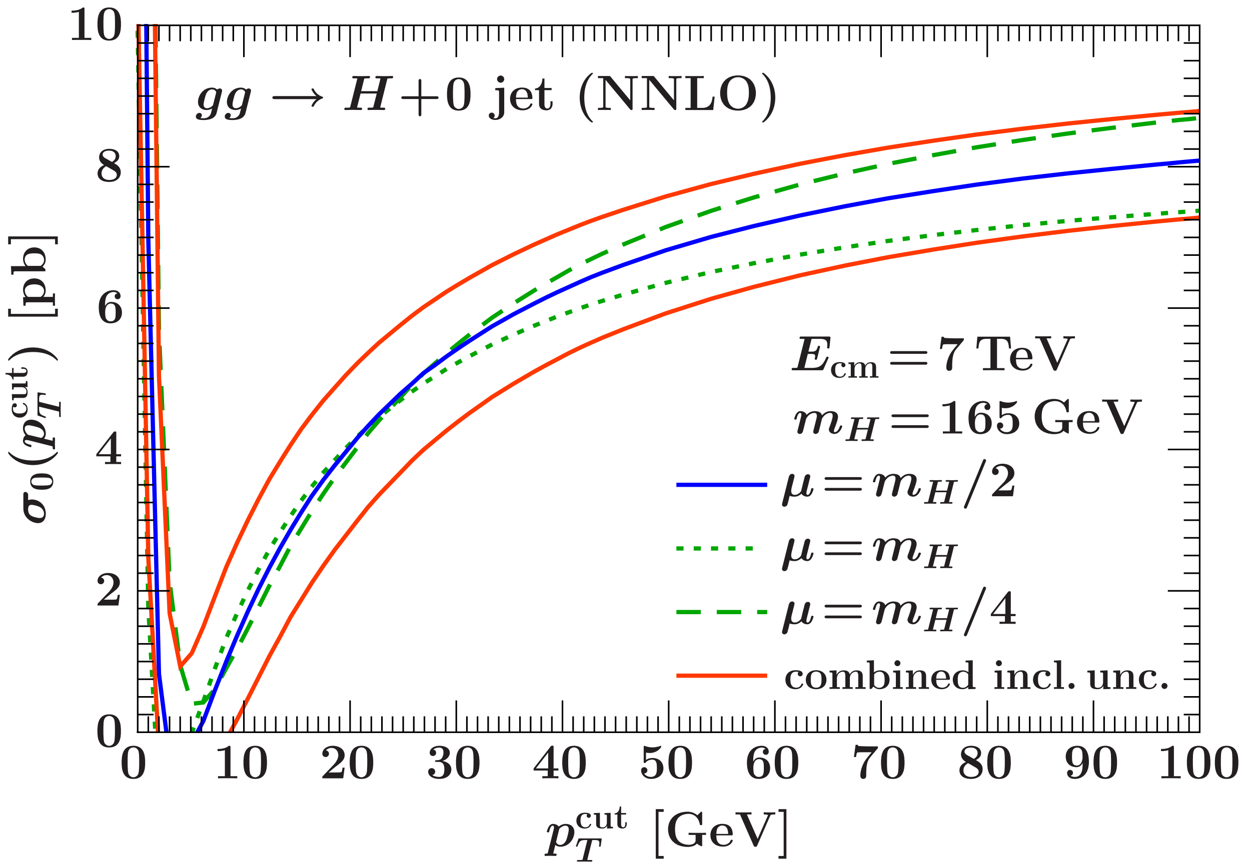
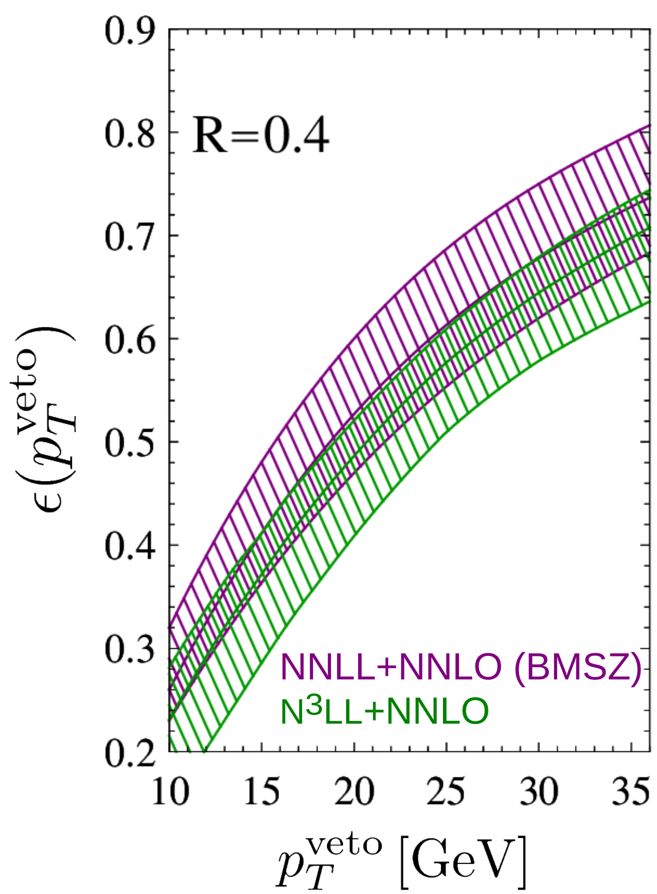


NNLL' +NNLO Resummation of Veto Logs

Becher, Neubert, Rothen (in prep)

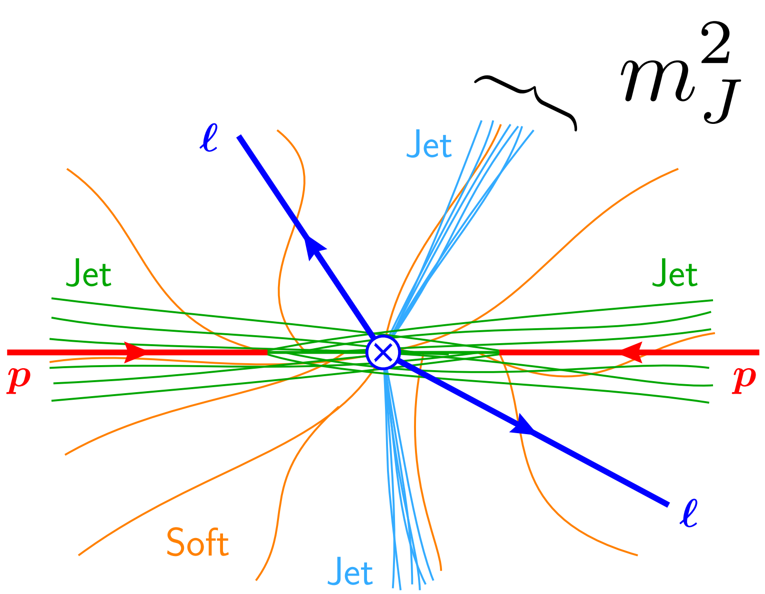


Bottom Line:

reduced uncertainty which will improve coupling measurements

Jet Mass in pp collisions

Dasgupta, Khelifa-Kerfa, Marzani, Spannowsky: arXiv:1207.1640
Chien, Kelley, Schwartz, Zhu: arXiv:1208.0010
Jouttenus, IS, Tackmann, Waalewijn: arXiv:1302.0846



Jet Mass: $m_J^2 = \Big(\sum_{i \in J} p_i^\mu \Big)^2$

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Why Compute the Jet Mass Spectrum? $d\sigma/dm_J$

- Benchmark for our ability to compute jet properties at LHC
- Test MC

Address Dependence on:

- Kinematics: $p_T^{\rm jet}\,,\ \ \eta^{\rm jet}, \ldots$
- Hard process: $pp \to 2\ \text{jets}\,,\ pp \to H + \text{jet}\,,\ pp \to Z + \text{jet}\,,\ pp \to \gamma + \text{jet}$

  - ISR - gluon vs. quark jets - color flow - incl. vs excl. jets

- Jet algorithm/grouping - anti-kT, CA, kT, N-jettiness jets, ...
- Jet size: R
- Order of the calculation: NNLL/NLL/LL (theory uncertainty)
- Non-global logs
- Underlying event
- pileup
- Hadronization
- trimming/filtering/pruning

Why Compute the Jet Mass Spectrum? $d\sigma/dm_J$

- Benchmark for our ability to compute jet-substructure at LHC
- Test MC

Address Dependence on:

✓ • Kinematics: $p_T^{\rm jet}\,,\ \eta^{\rm jet},\ldots$

✓ • Hard process: $pp\to 2\ {\rm jets}\,,\ pp\to H+{\rm jet}\,,\ pp\to Z+{\rm jet}\,,\ pp\to\gamma+{\rm jet}$

- ISR - gluon vs. quark jets - color flow - incl. vs excl. jets

$\frac{1}{2}$✓ • Jet algorithm/grouping - anti-kT, CA, kT, N-jettiness jets, ...

✓ • Jet size: R

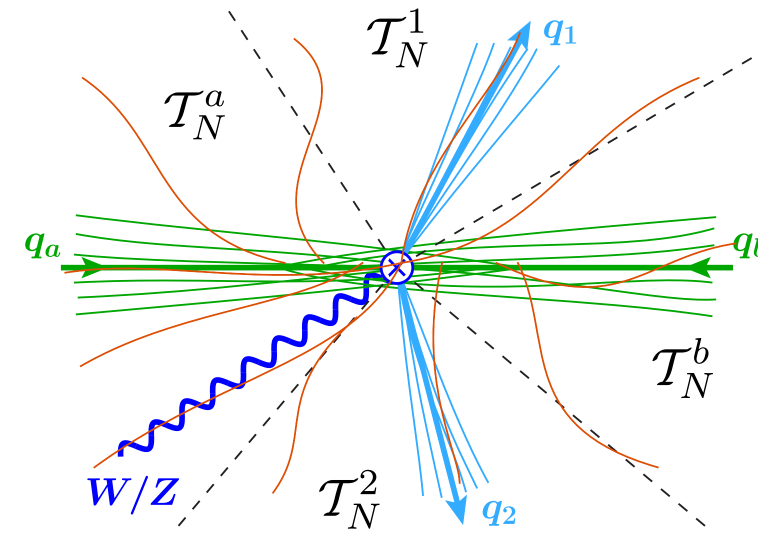
✓ • Order of the calculation: $\rm NNLL/NLL/LL$ (theory uncertainty)

✓ • Non-global logs • Underlying event • pileup

✓ • Hadronization • trimming/filtering/pruning

✓ = addressed so far

N-Jettiness Factorization Formula



$$\frac{d\sigma}{d\mathcal{T}_N^a\, d\mathcal{T}_N^b \cdots d\mathcal{T}_N^N} = \int dx_a dx_b \int d(\text{phase space})$$

$$\times \sum_\kappa \int dt_a\, B_{\kappa_a}(t_a, x_a) \int dt_b\, B_{\kappa_b}(t_b, x_b) \prod_{J=1}^{N} \int ds_J\, J_{\kappa_J}(s_J)$$

$$\times \operatorname{tr}\left[H_N^\kappa(\{q_i \cdot q_j\}, x_{a,b})\, \widehat{S}_N^\kappa\left(\mathcal{T}_N^a - \frac{t_a}{Q_a}, \mathcal{T}_N^b - \frac{t_b}{Q_b}, \mathcal{T}_N^1 - \frac{s_1}{Q_1}, \ldots, \mathcal{T}_N^N - \frac{s_N}{Q_N}, \{\hat{q}_i \cdot \hat{q}_j\}\right)\right]$$

color

jet mass

$$\hat{q}_i^\mu = \frac{q_i^\mu}{Q_i}$$

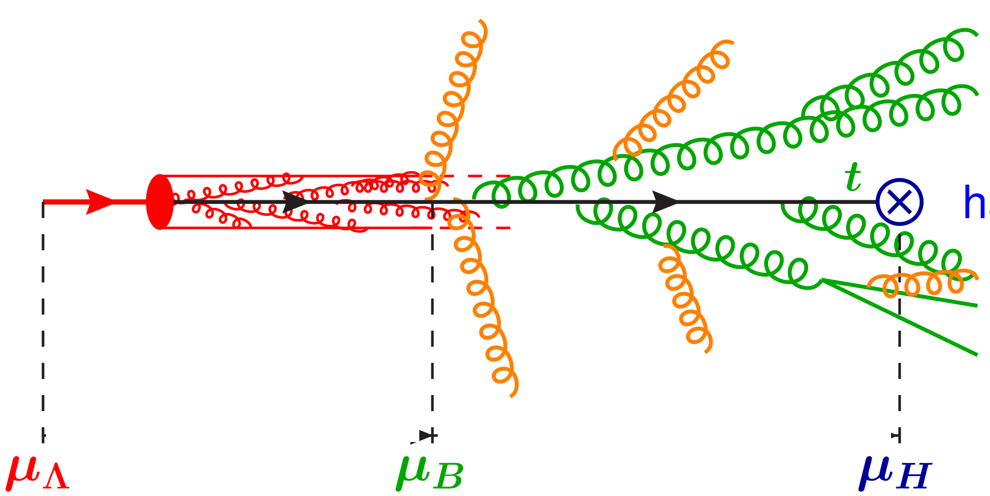
$$B_\kappa(t,x) = \sum_i \int_x^1 d\xi\, \mathcal{I}_{\kappa i}(t, x/\xi) f_i(\xi)$$

pdfs

Hard process

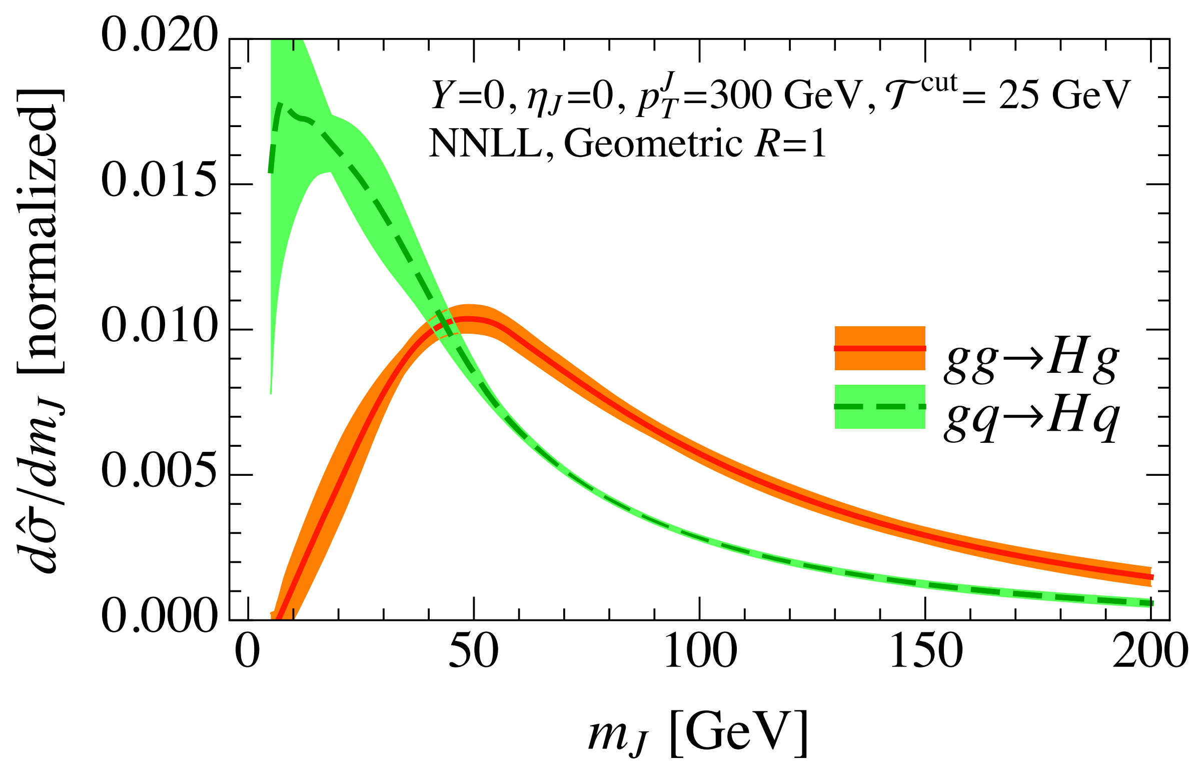
ISR

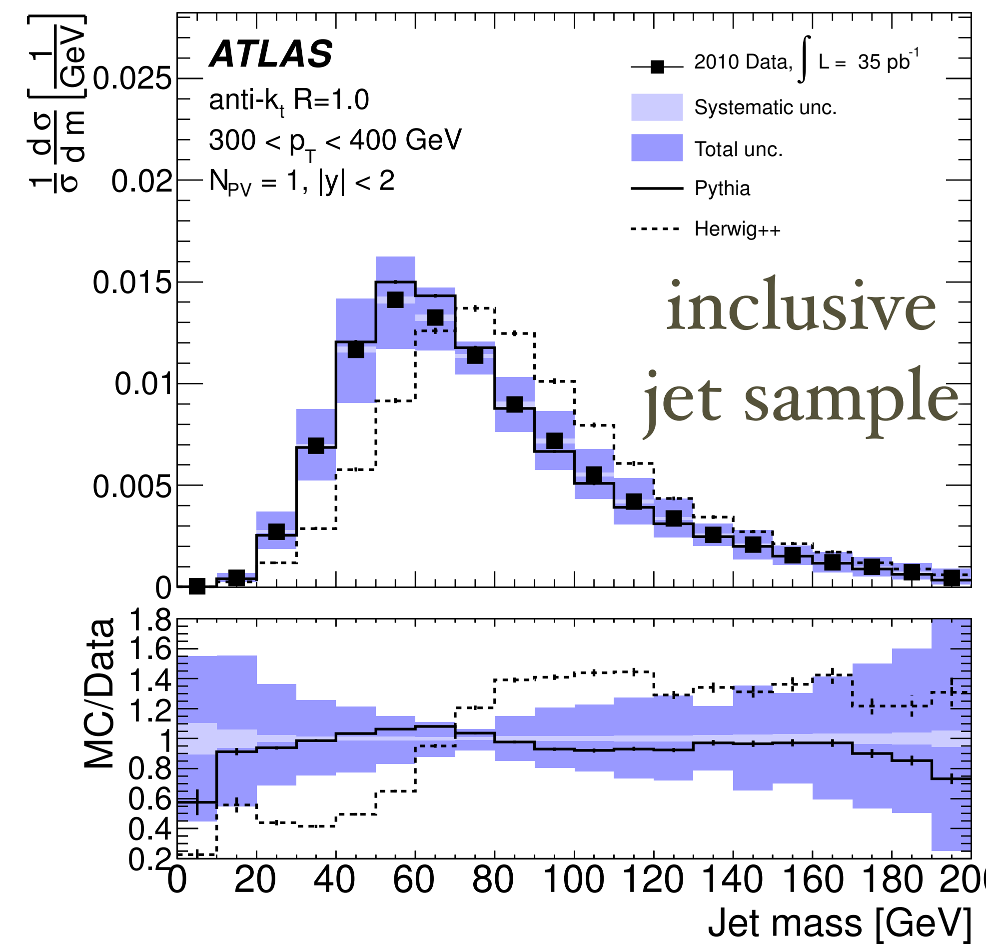
κ = gluons vs. quarks



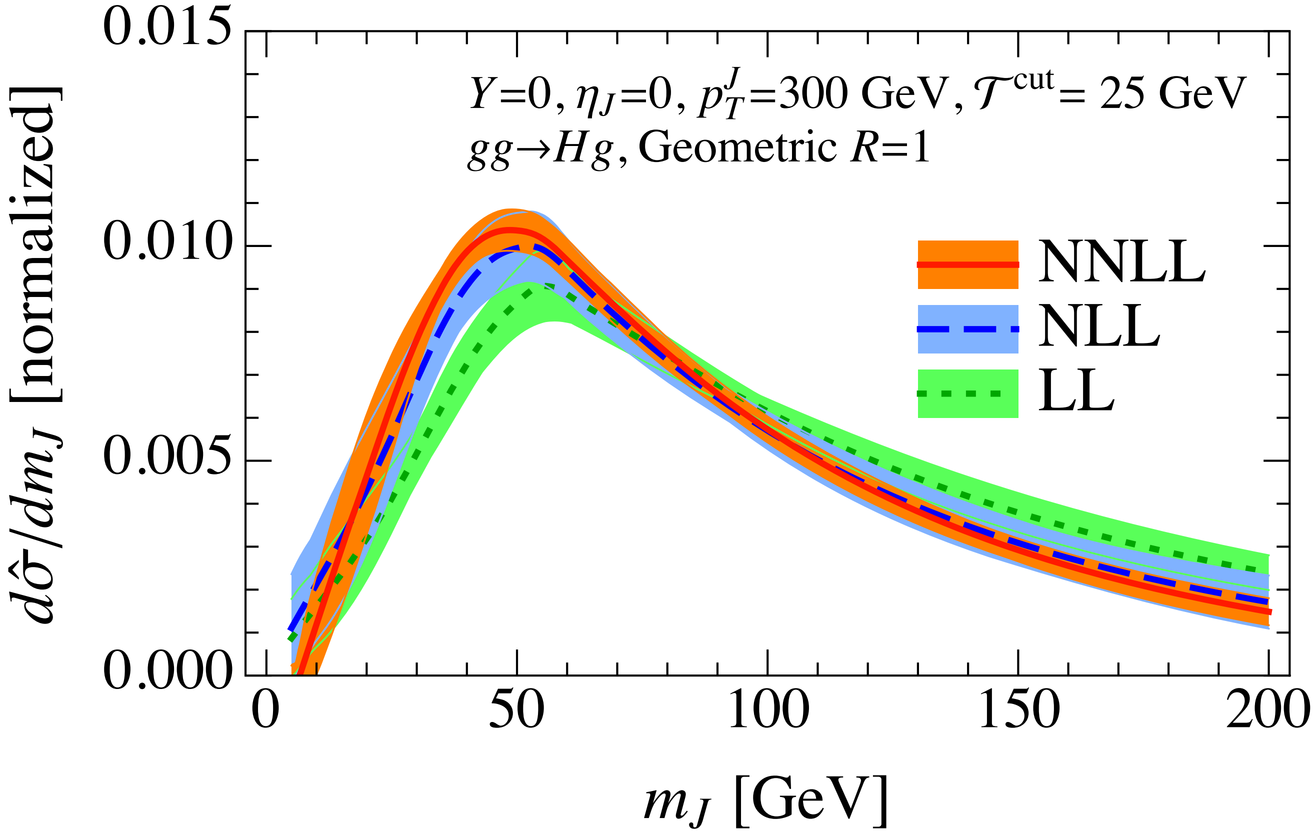
Kinematics

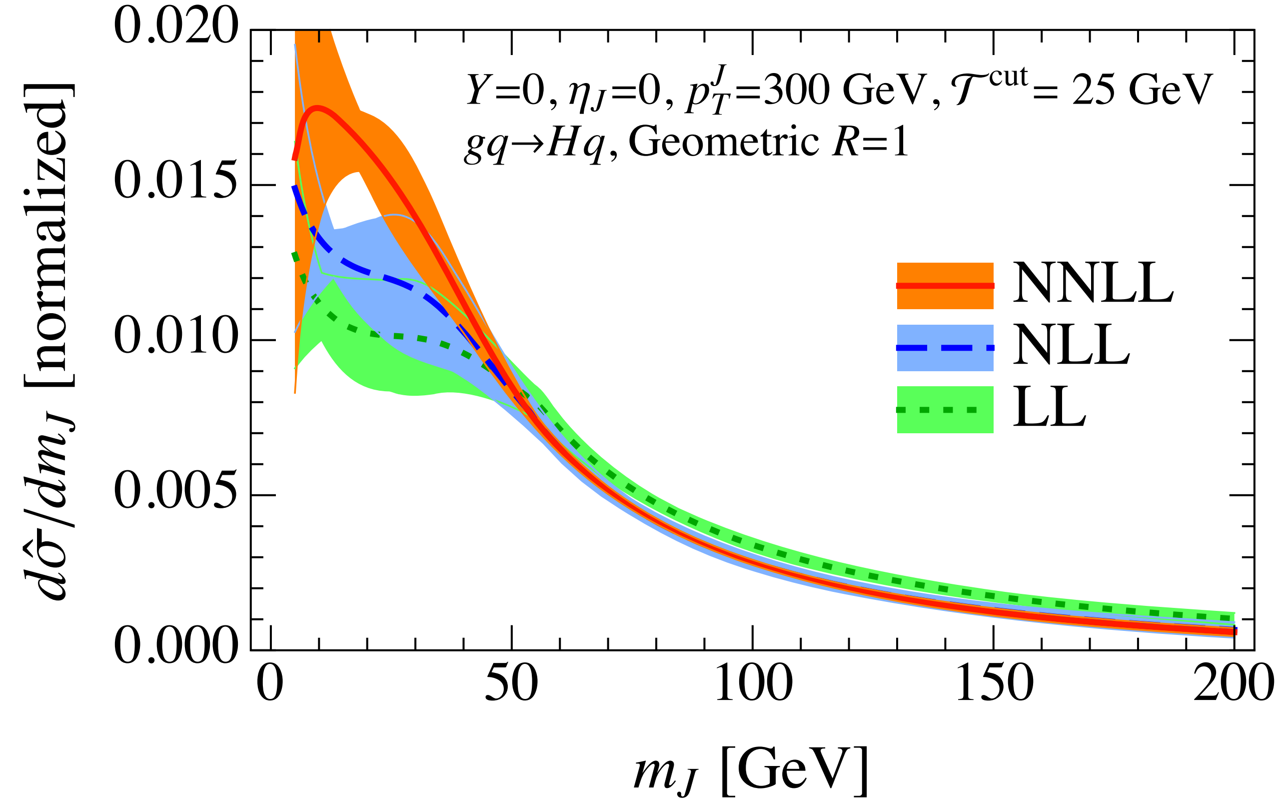
Quark and Gluon Jets (Normalized)



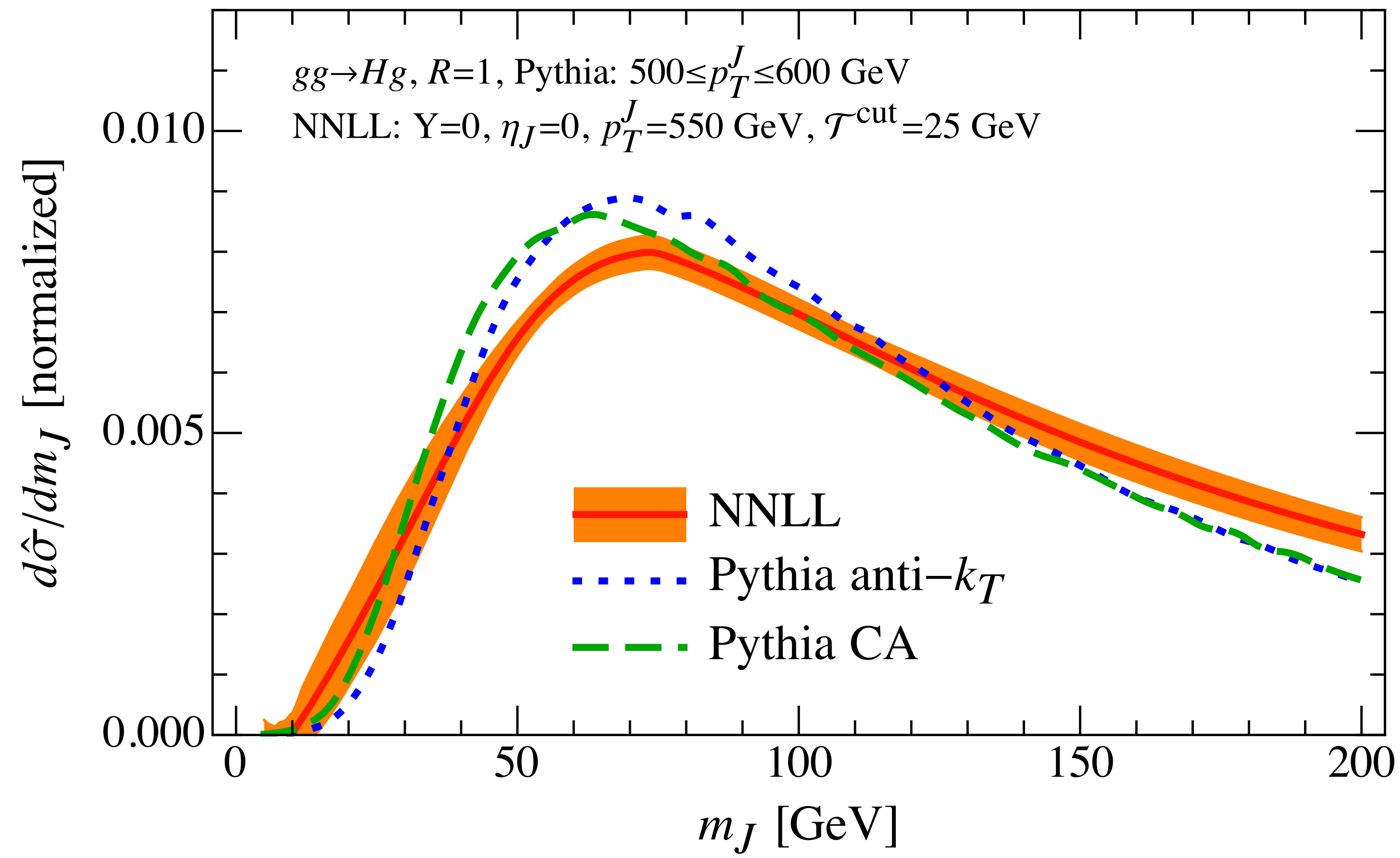


Order by Order Convergence





Preliminary Comparison to Monte Carlo (Pythia 8)

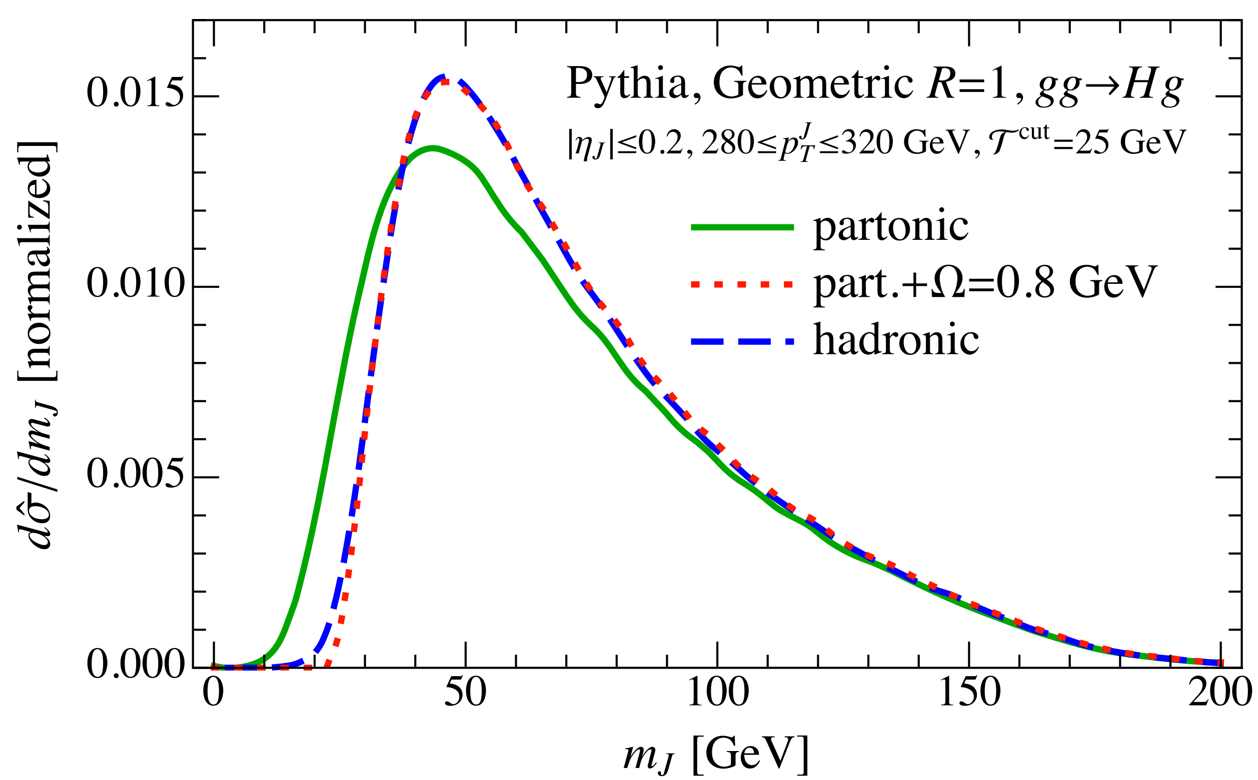


Hadronization

Pythia 8 partonic → hadronization is a simple shift

$$m_J^2 \to m_J^2 - Q_J \Omega$$

$$\Omega \sim \Lambda_{\rm QCD}$$



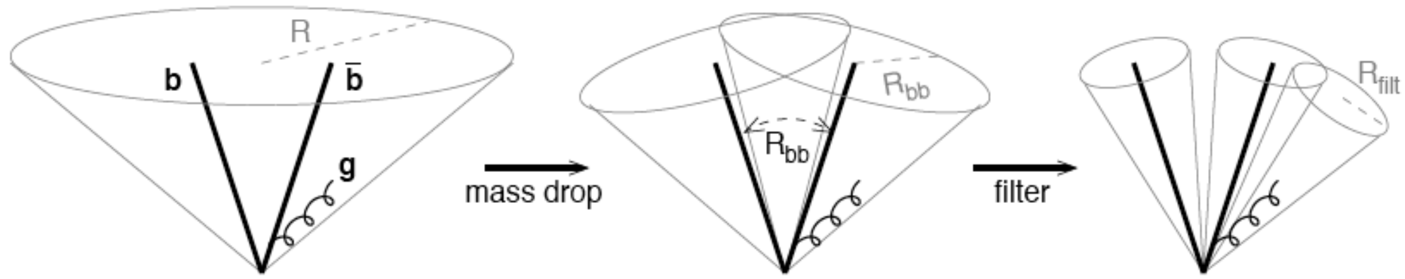
Jet Substructure

Jet Substructure

- Distinguish heavy boosted (BSM?) objects from QCD

boosted

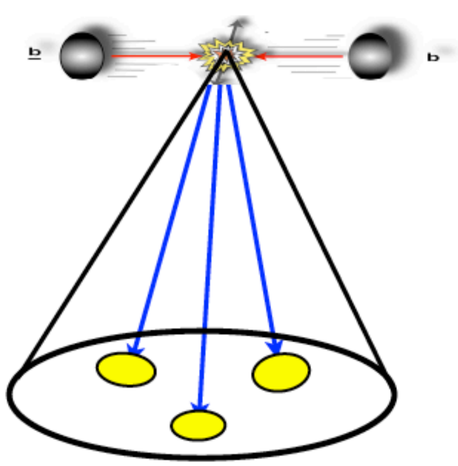
$H \to b\bar{b}$



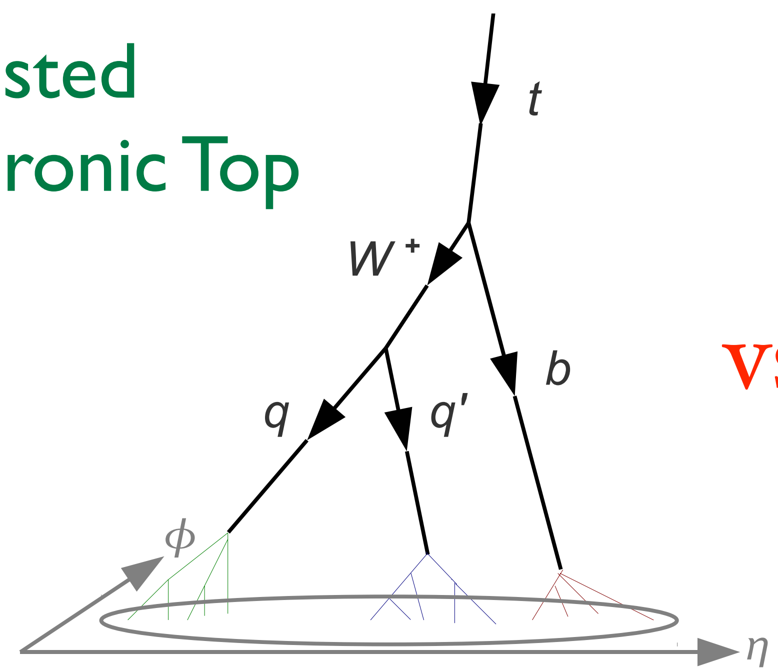
BDRS Method

[Butterworth, Davison, Rubin, Salam]

top tagging

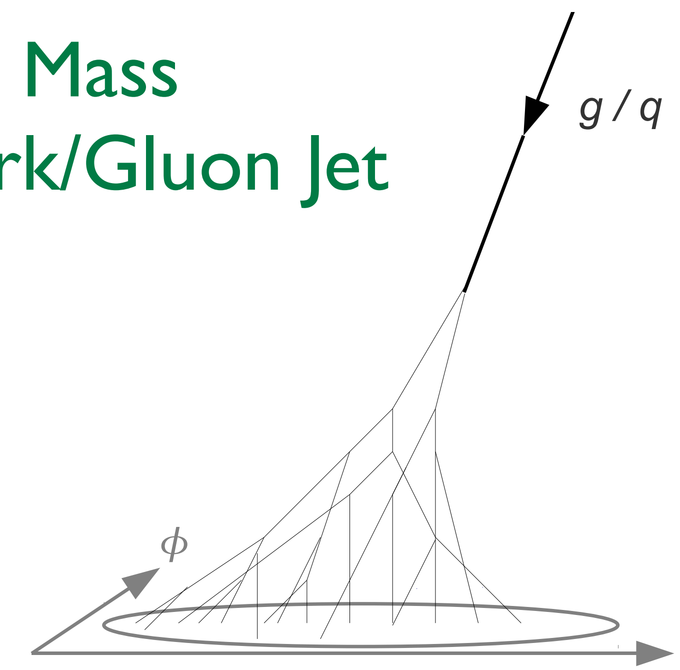


Boosted Hadronic Top



vs.

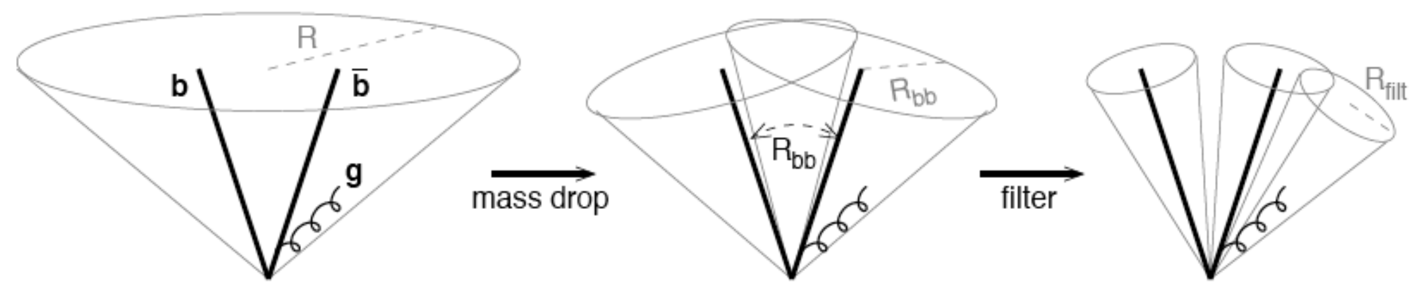
High Mass Quark/Gluon Jet



Jet Substructure

- Distinguish heavy boosted (BSM?) objects from QCD

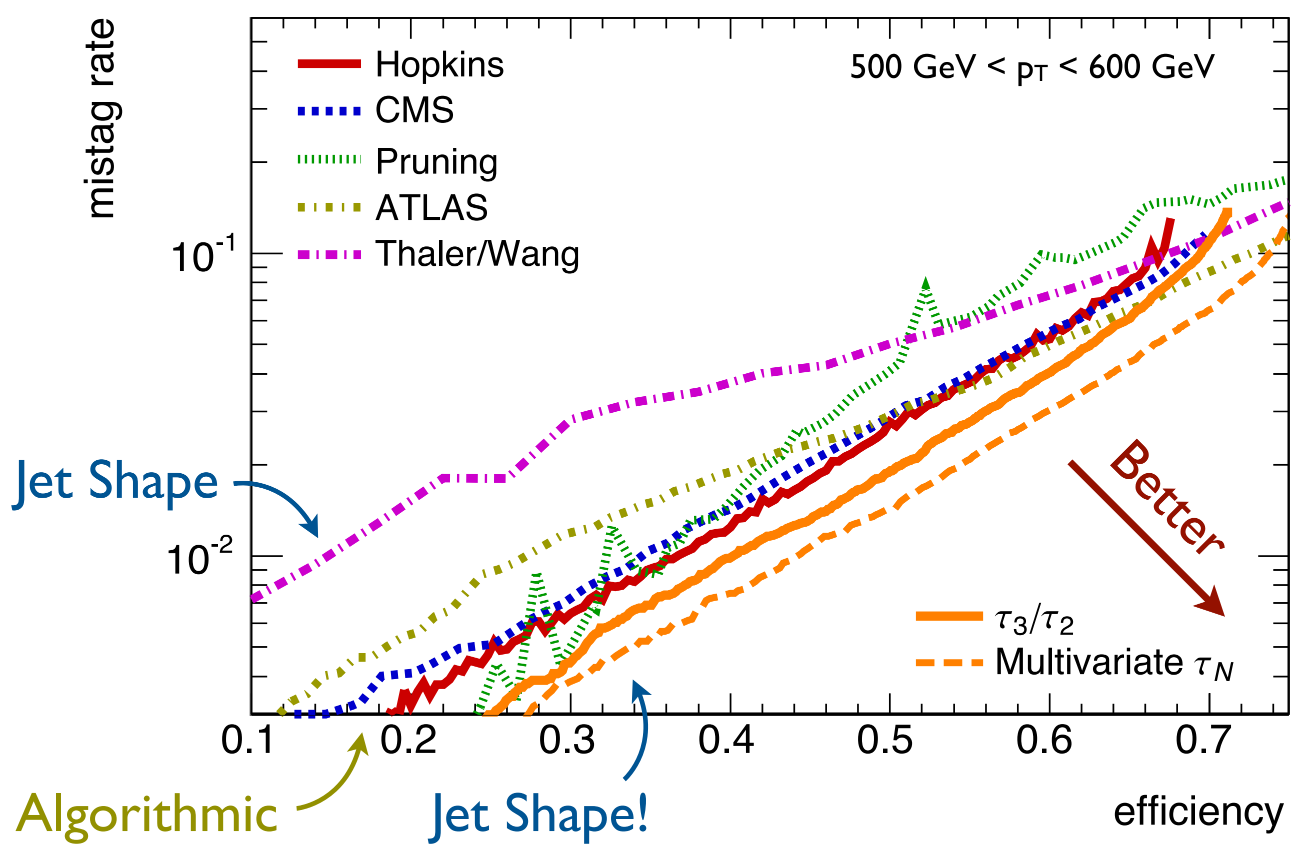
boosted
$H \rightarrow b\bar{b}$

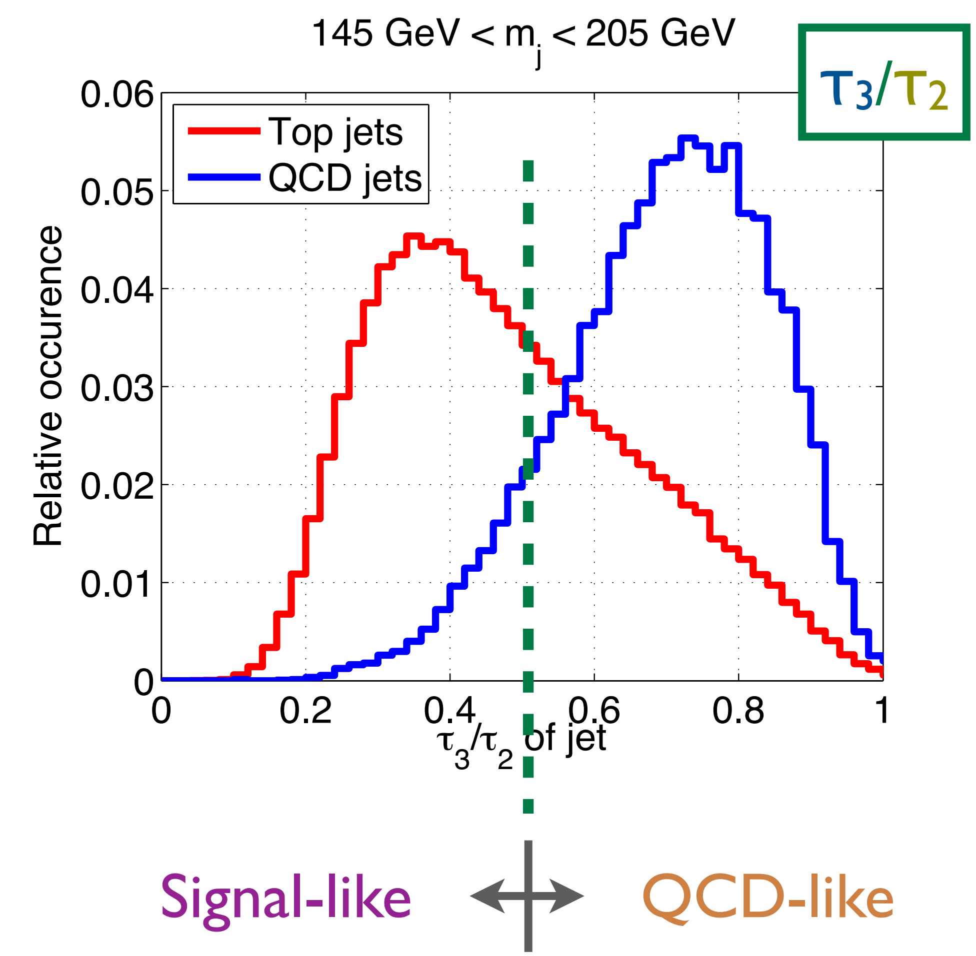


BDRS Method
[Butterworth, Davison, Rubin, Salam]

eg. top tagging with N-subjettiness

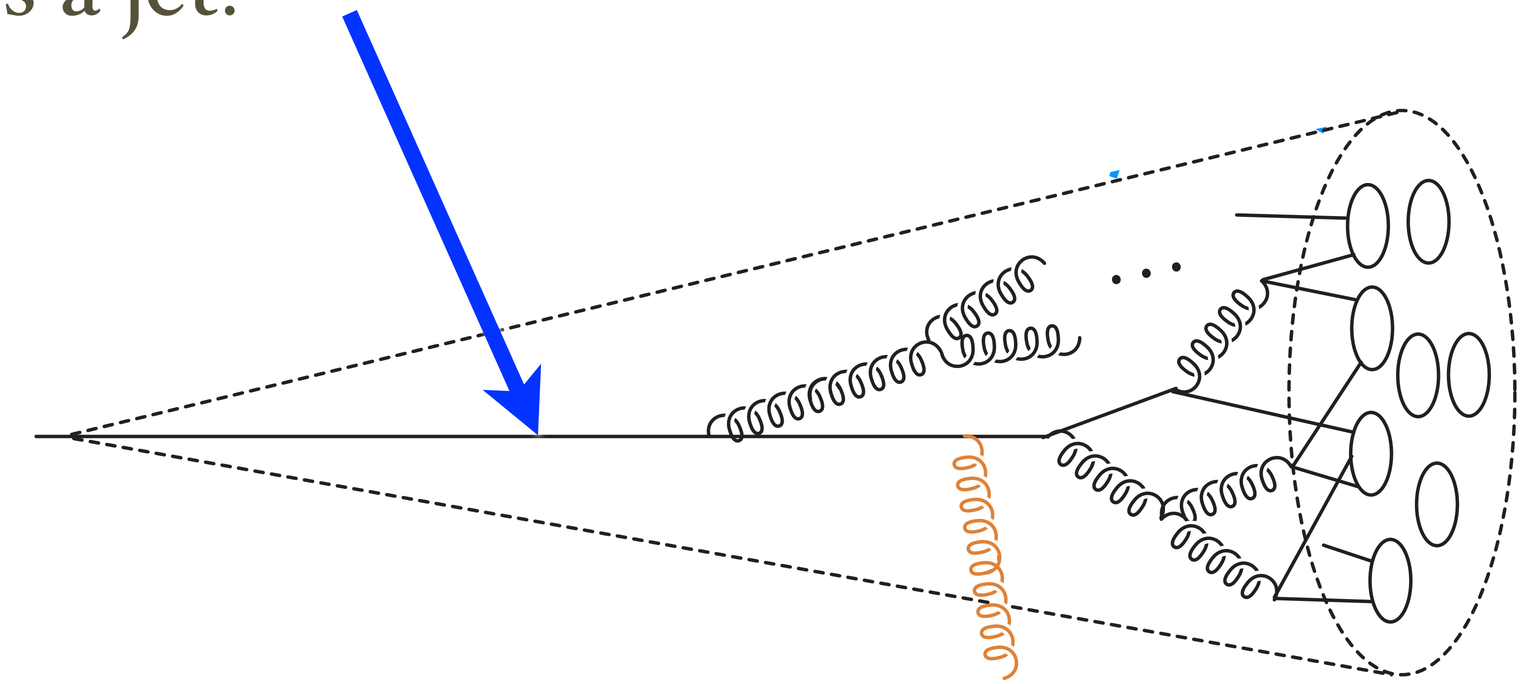
Thaler, Van Tilburg





Jet Substructure

- Measure the quantum numbers of the hard parton that produces a jet?



Quarks versus Gluons? Electric Charge?

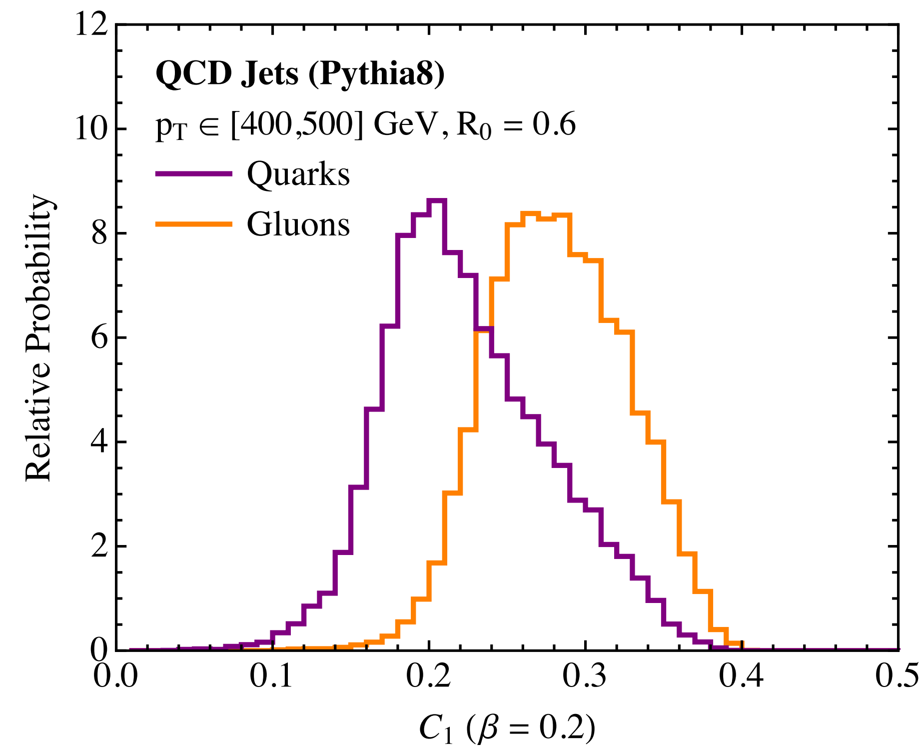
Quarks versus Gluons

Larkoski, Salam, Thaler: arXiv:1305.0007

Energy correlation function is a good variable

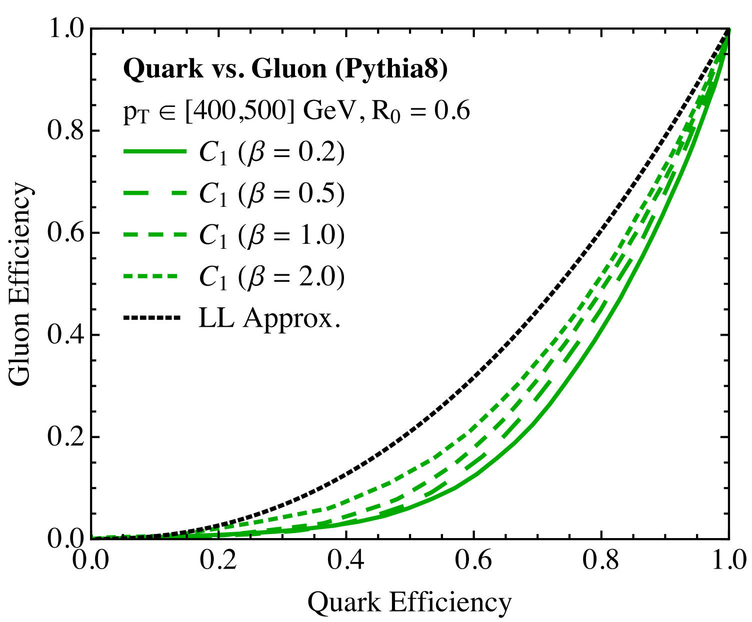
$$C_1^{(\beta)} = \frac{\sum_{i<j\in J} p_{Ti} p_{Tj} (R_{ij})^\beta}{\left(\sum_{i\in J} p_{Ti}\right)^2}$$

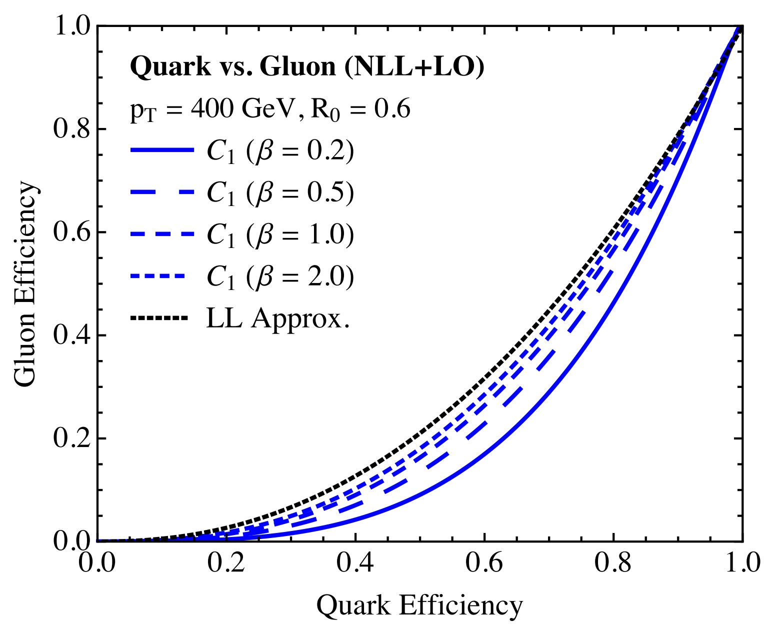
probes radiation in the jet

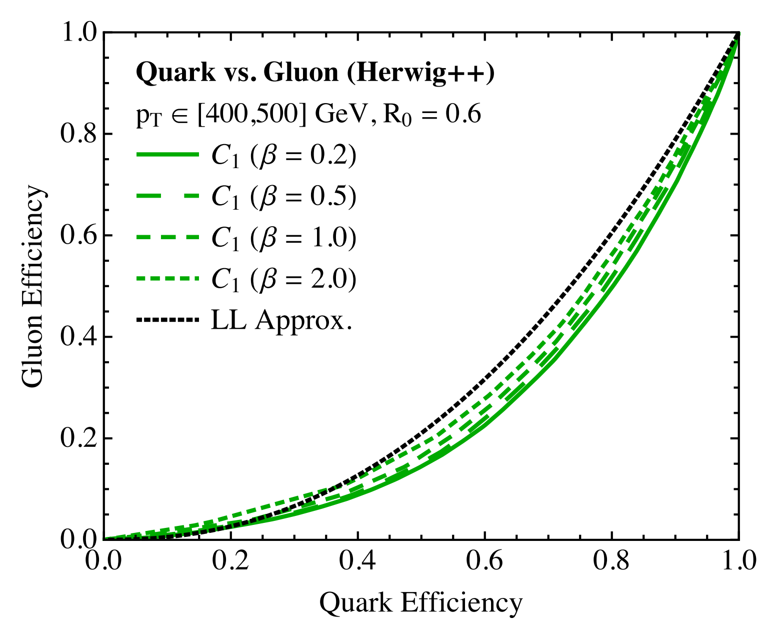


N-subjets: $C_N^{(\beta)} \equiv \frac{\mathrm{ECF}(N+1,\beta)\,\mathrm{ECF}(N-1,\beta)}{\mathrm{ECF}(N,\beta)^2}$

$$\mathrm{ECF}(3,\beta) = \sum_{i<j<k\in J} p_{Ti}\, p_{Tj}\, p_{Tk}\, (R_{ij} R_{ik} R_{jk})^\beta$$







LL: $\mathrm{disc}(x) = x^{C_A/C_F} = x^{9/4}$

$\frac{\alpha_s}{\beta}$ take $\beta > 0.2$

Jet Charge

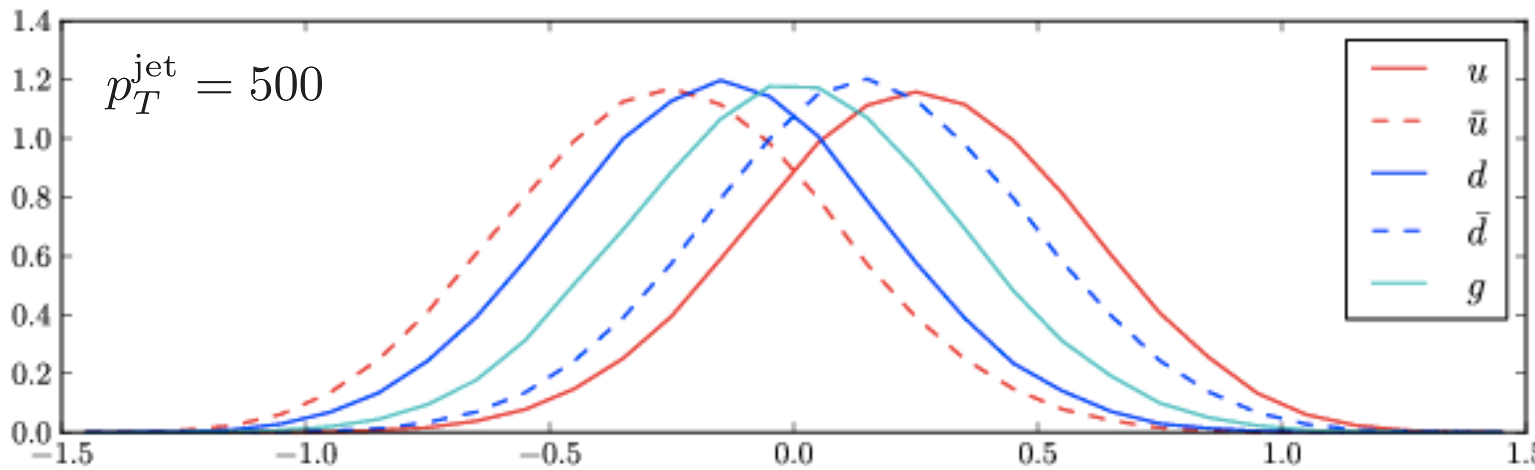
Krohn,Lin,Schwartz,Waalewijn: arXiv:1209.2421

$$\mathcal{Q}^i_\kappa = \frac{1}{(p_T^{\text{jet}})^\kappa} \sum_{j\in\text{jet}} Q_j (p_T^j)^\kappa$$

$$-\frac{2}{3}, -\frac{1}{3}, 0, \frac{1}{3}, \frac{2}{3}$$

Distinguish:
- up/down squarks
- W/Z prime
- etc.

κ=0.5



Properties of the Mean are calculable!

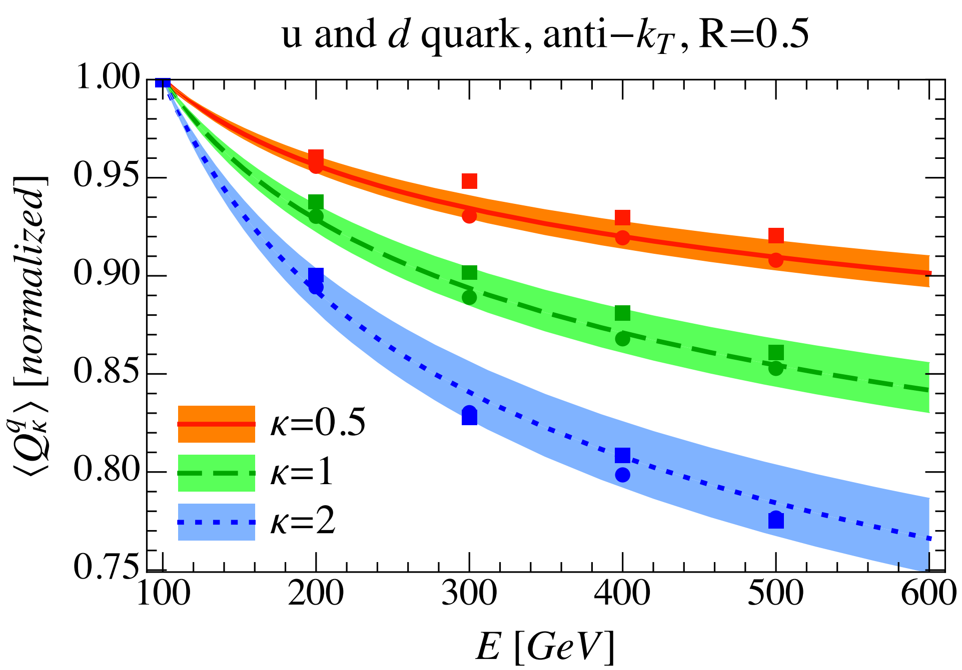
moment of frag. functions

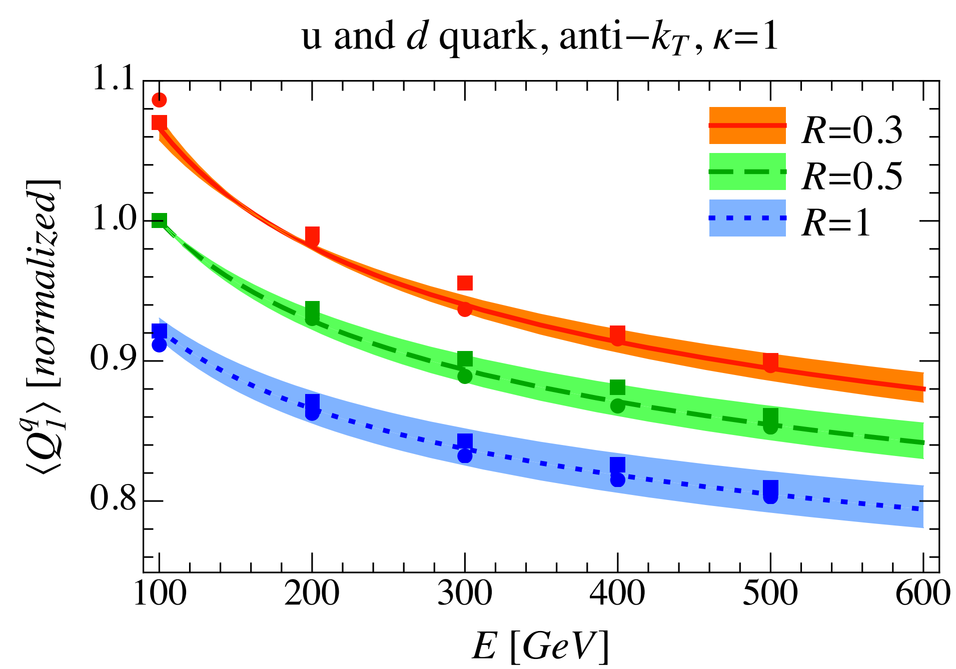
$$\langle Q^q_\kappa \rangle = \widetilde{\mathcal{J}}_{qq}(ER, \kappa, \mu = ER) \sum_h Q_h \widetilde{D}^h_q(\kappa, \mu = ER)$$

$$\tilde{D}^h_q(\kappa,\mu) = \int_0^1 dx\, x^\kappa D^h_q(x,\mu)$$

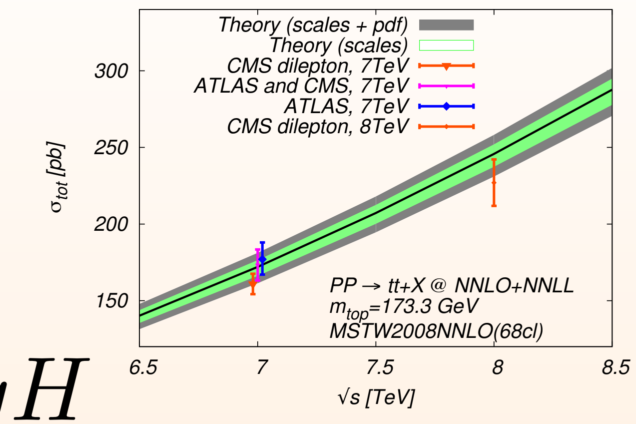
jet energy E
&
jet radius R

Pythia:
- ■ d-quarks
- ● u-quarks



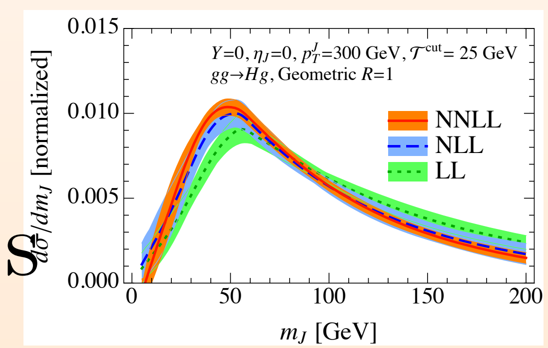


Summary



New tools for the NNLO frontier in pp

- beyond classic $pp \to H$, complete $pp \to t\bar{t}$
- pure glue for dijets and H+1-jet: $gg \to gg, gg \to gH$

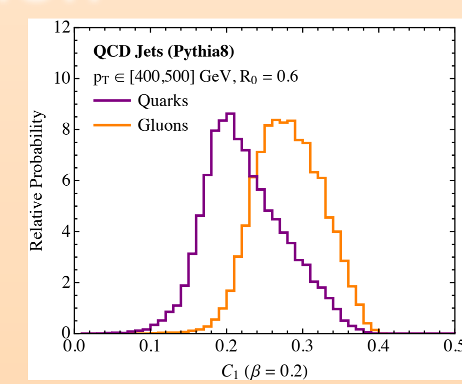


Summation of large logs for processes with 0 jets or 1 jet

- NNLL+NNLO for anti-kT jet veto in $pp \to H + 0\text{-jets}$
- (N)NLL+NLO for jet mass spectrum in $pp \to H + 1\text{-jet}$, $pp \to \text{dijets}$
  $pp \to Z+\text{ jet}$

Jet substructure: New observables with Perturbative calculations

- Quark & Gluon separation with energy correlation function



- Jet Charge with calculable dependence on the jet energy & radius

Future of pQCD at the LHC is very bright!