Unravelling Jets at Colliders

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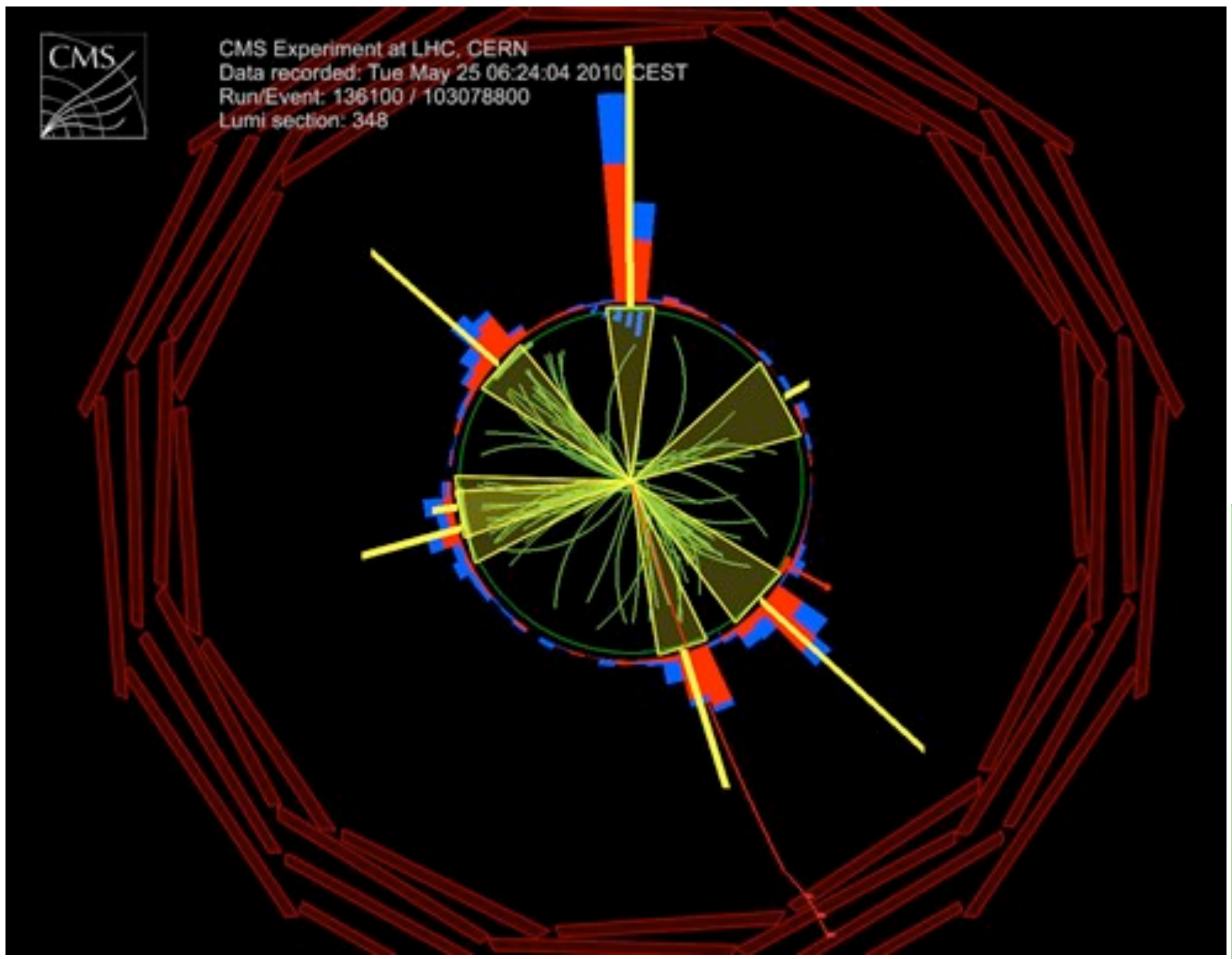
Outline

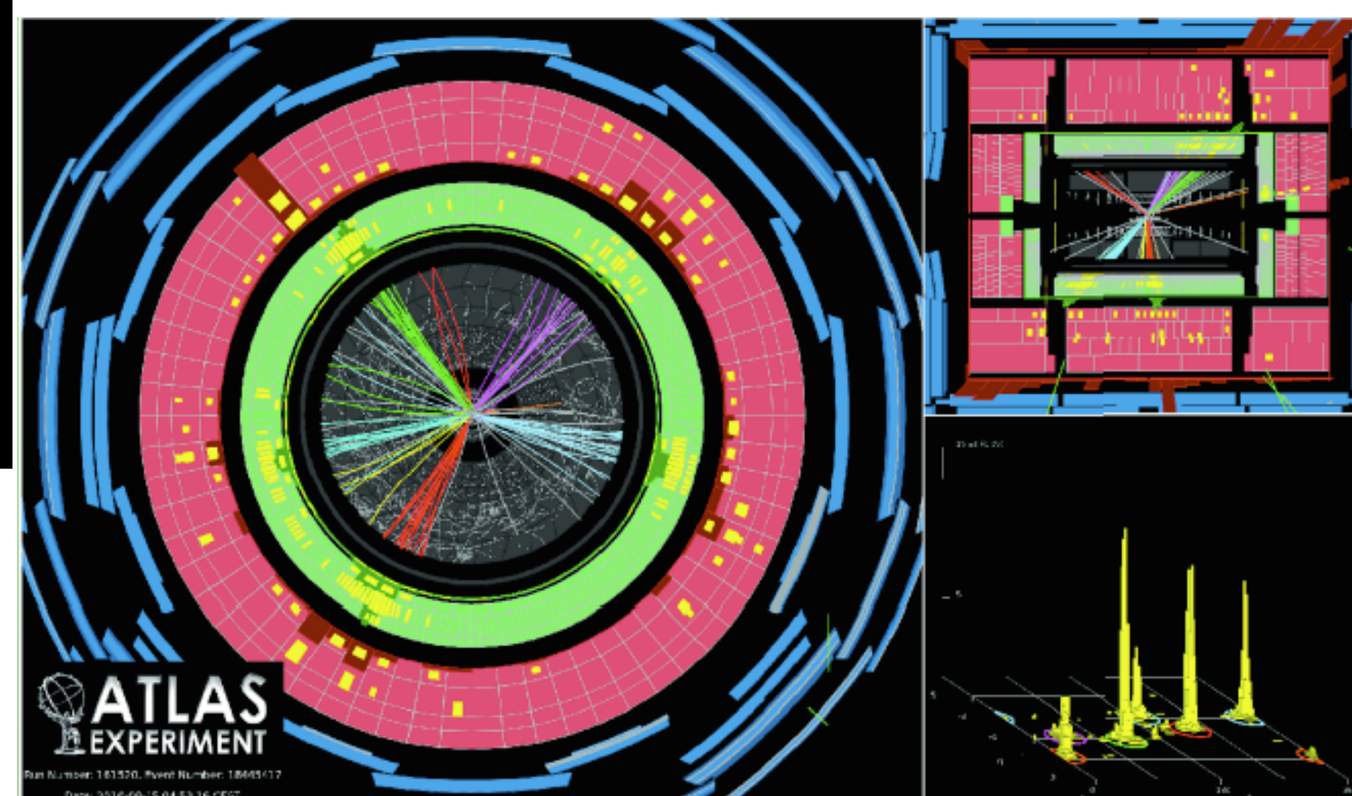
- An Event
- What's a Jet
- Jet substructure tools
- Theory tools: Analytic and Monte Carlo
- Event generation: the challenge.

Structure of an event

- **QCD at colliders: Jets!**



{triggers, tracking, calorimetry, cuts....}



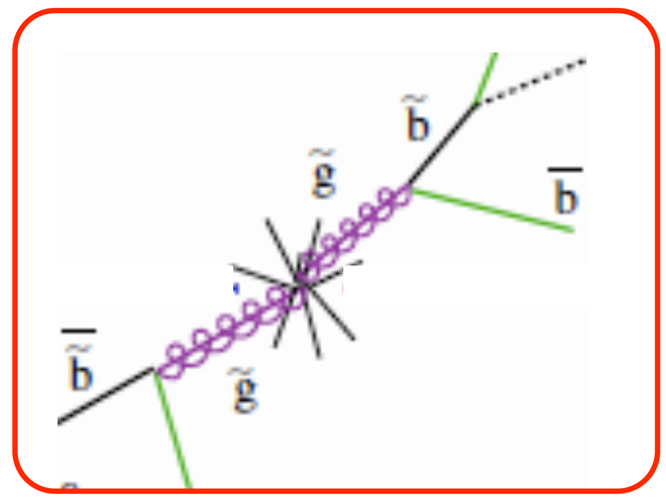
Multijet Event:
6 jets with $p_T > 60$ GeV, $|y| < 2.8$

arXiv:1107.2092,

Structure of an event: Theorist's View

$\mu_H \sim m_X$

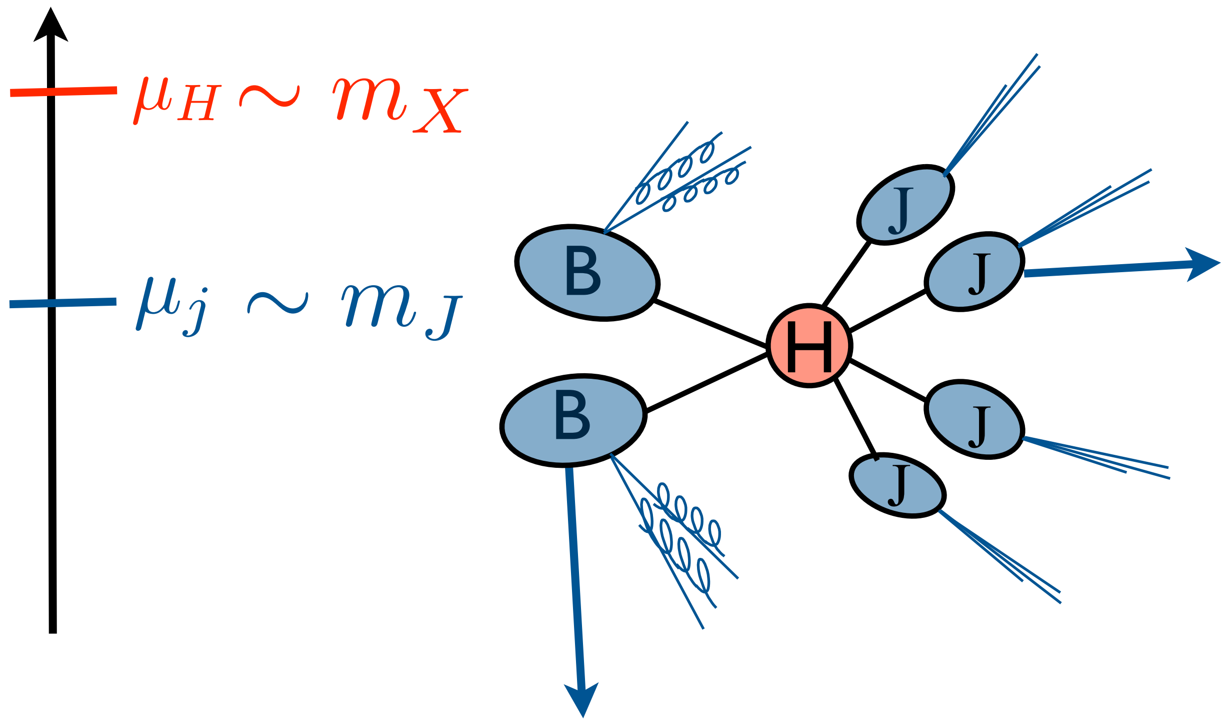
H



Perturbative Hard interaction: $\alpha_s \ll 1$
New Physics

$d\sigma =$ Hard Interaction $\otimes$

Structure of an event: Theorist's View



Final State Radiation

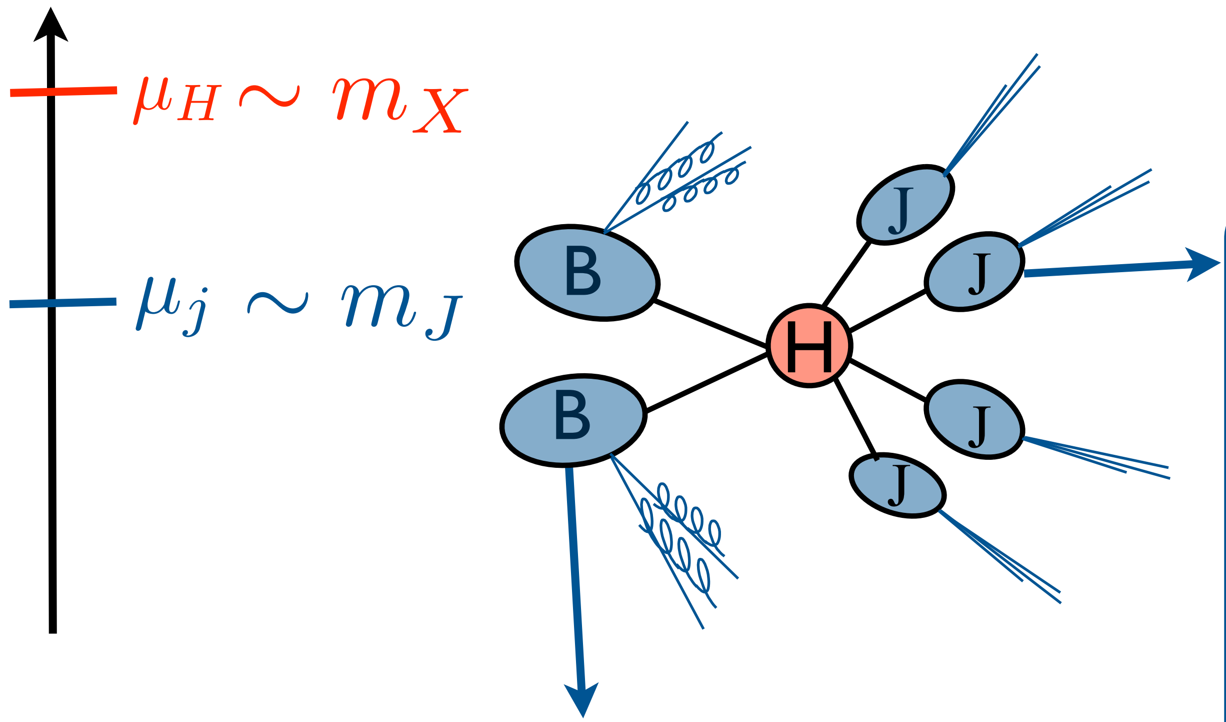
Initial State Radiation

Beam Function

(Stewart, Tackmann, Waalewijn)

$$d\sigma = \text{Hard Interaction} \otimes \text{Collinear Evolution} \otimes \text{Soft Radiation}$$

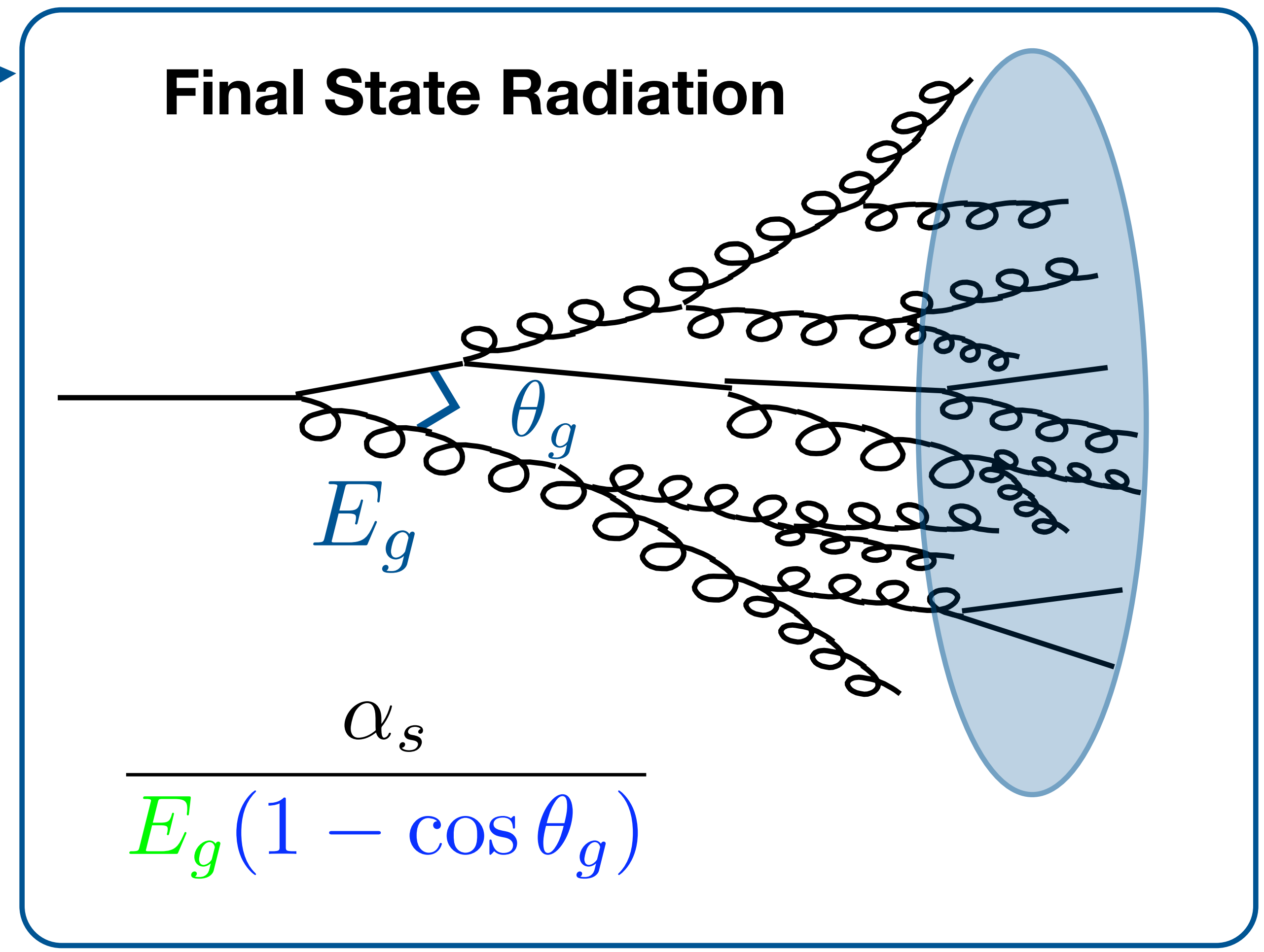
Structure of an event: Theorist's View



Initial State Radiation

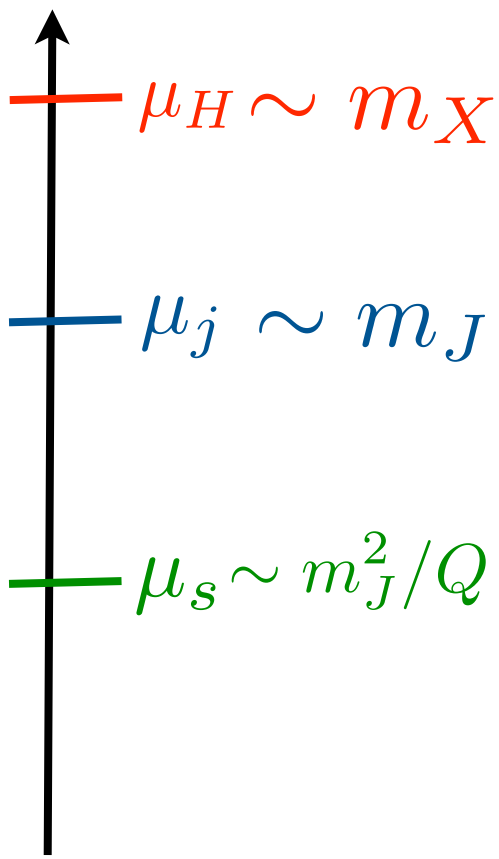
Beam Function

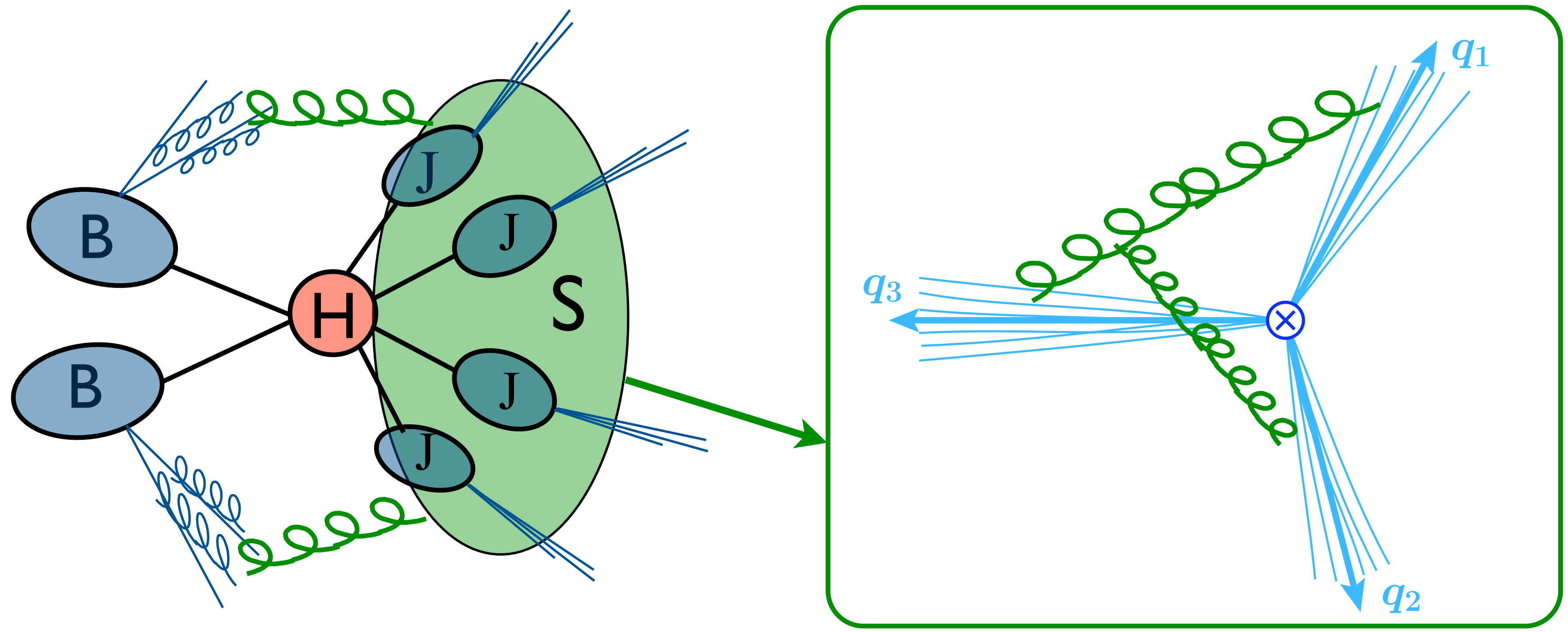
(Stewart, Tackmann, Waalewijn)



$d\sigma =$ Hard Interaction $\otimes$ Collinear Evolution $\otimes$ Soft Radiation

Structure of an event: Theorist's View

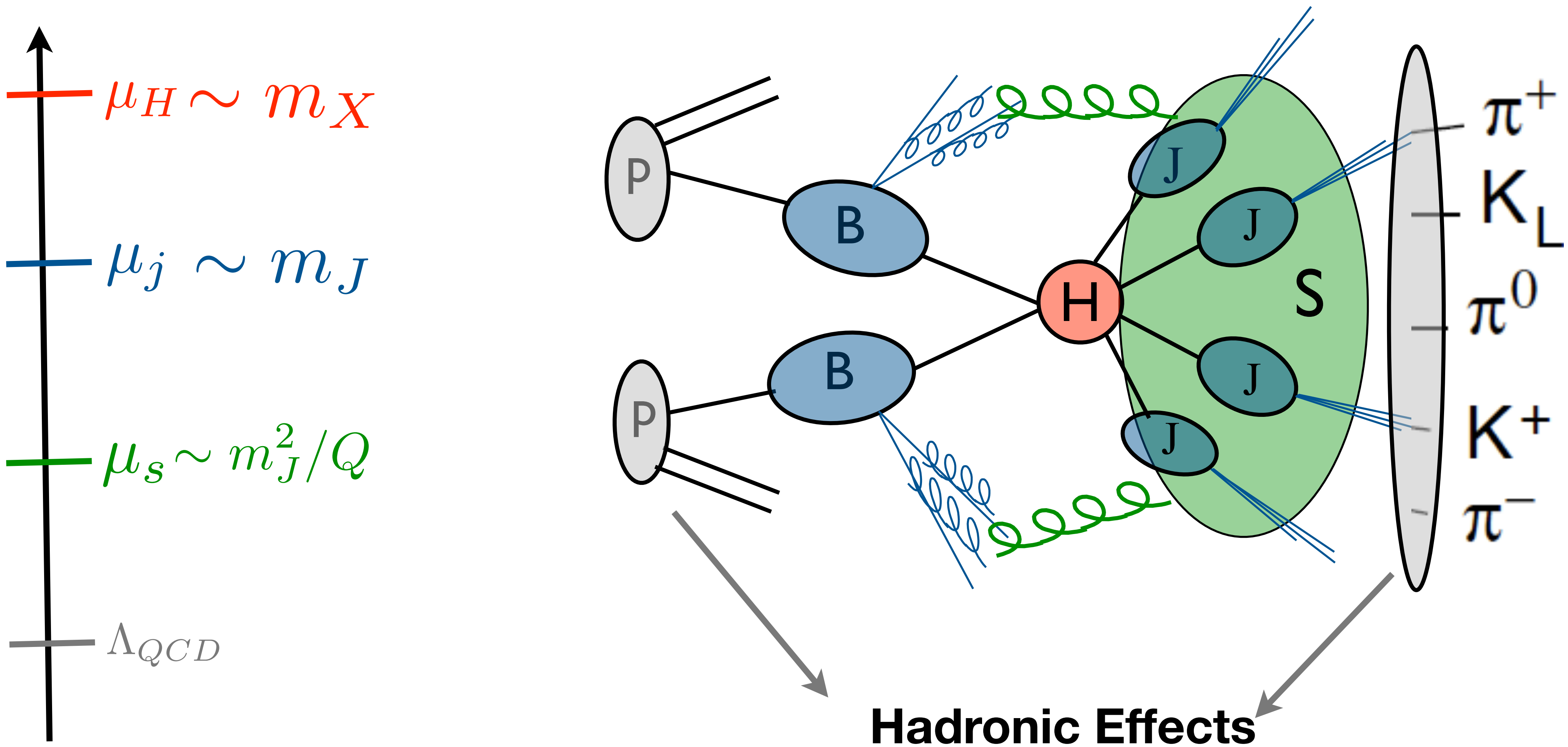




Global Soft Radiation: talks between jets

$$d\sigma = \text{Hard Interaction} \otimes \text{Collinear Evolution} \otimes \text{Soft Radiation}$$

Structure of an event: Theorist's View



$d\sigma =$ Hard Interaction $\otimes$ Collinear Evolution $\otimes$ Soft Radiation $\otimes$ PDFs Hadronization Underlying Event

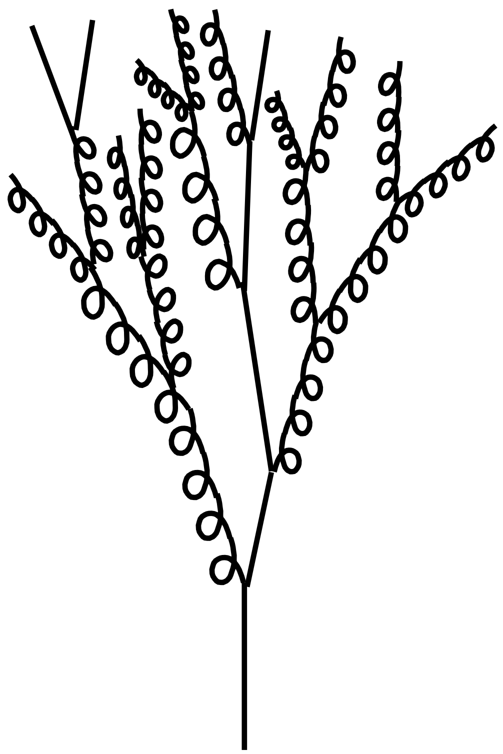
What's a Jet?

Jets: Unfolding QCD Evolution

Hadronization

QCD Evolution

Hard interaction

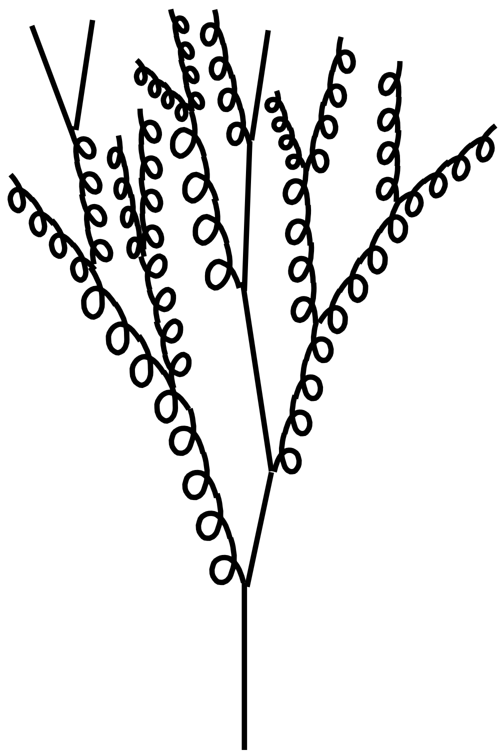


Jets: Unfolding QCD Evolution

Hadronization

QCD Evolution

Hard interaction



Hadron Momenta

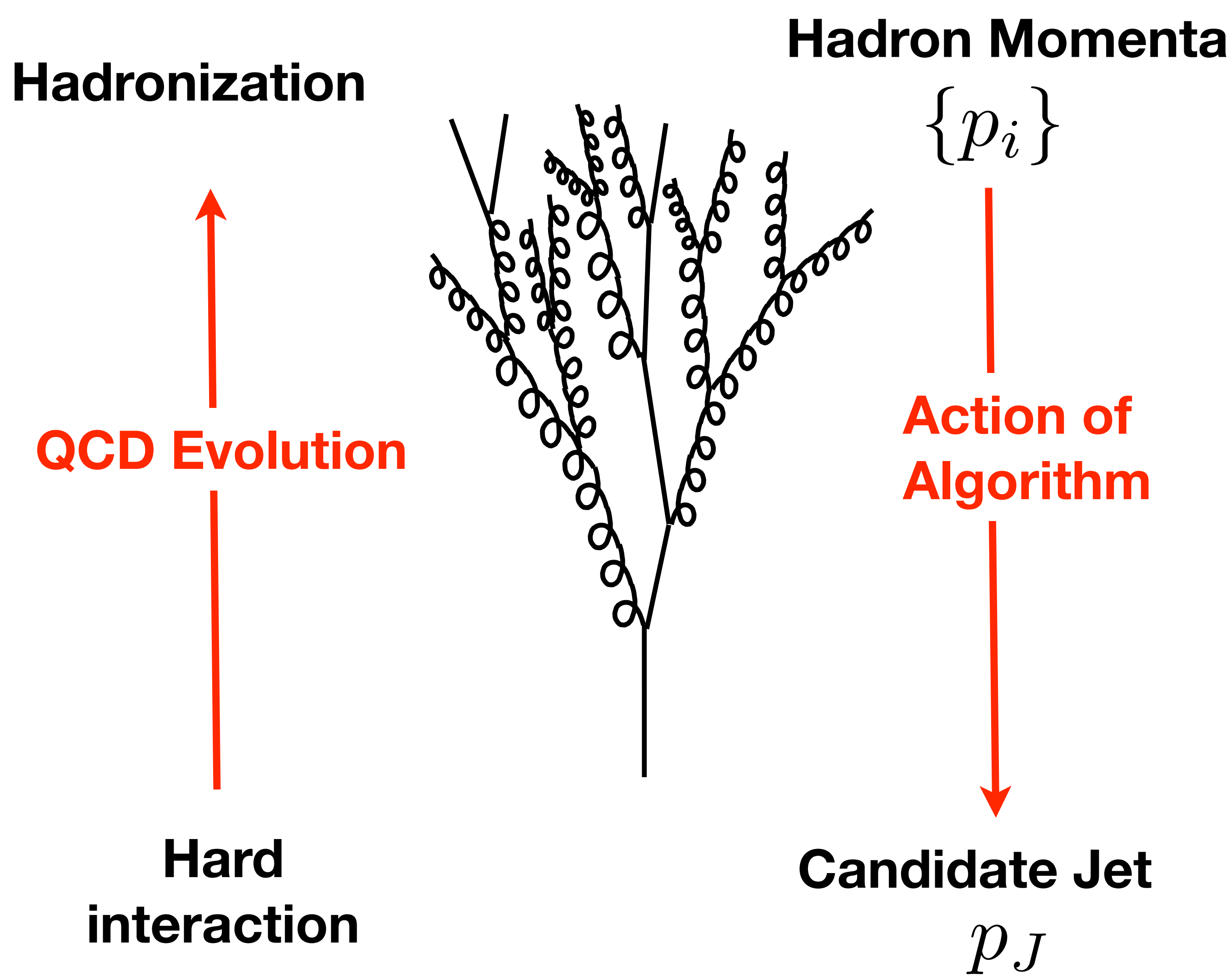
$\{p_i\}$

Action of Algorithm

Candidate Jet

p_J

Jets: Unfolding QCD Evolution



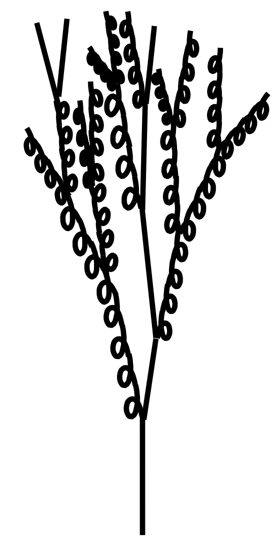
- Jet algorithms attempt to unfold QCD branchings.
- QCD effects projected onto jet over a wide range of scales
- Associate jet to single hard object
- Combine pairs with strongest divergences (soft and collinear) - most likely to belong together

$$\frac{\alpha_s}{E_g(1-\cos\theta_g)}$$

Jet Algorithms

- **Jet recombination algorithms**

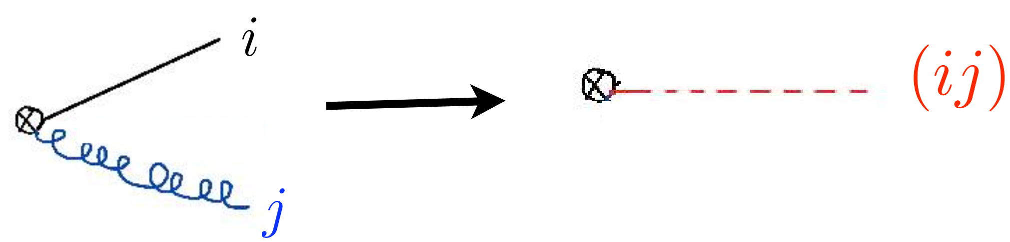
$$\rho_{ij} = \min\left(E_i^{\alpha}, E_j^{\alpha}\right)\frac{\Delta R_{ij}}{R}, \qquad \rho_i = E_i^{\alpha}$$



Algorithm start

Algorithm end

- **If** ρ_{ij} **is smallest**



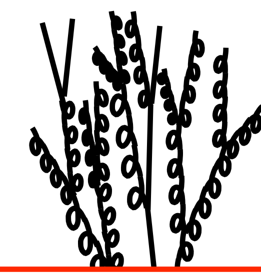
- **If** ρ_i **is smallest**, particle is promoted to candidate jet

- **Repeat** until all particles have formed candidate jets
  Apply p_T^{cut} to jets

Jet Algorithms

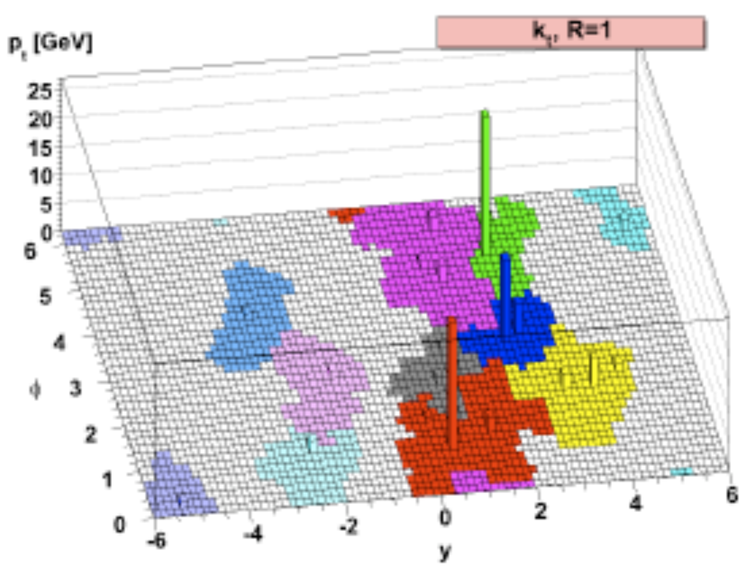
- **Jet recombination algorithms**

$$\rho_{ij} = \min\left(E_i^{\alpha}, E_j^{\alpha}\right) \frac{\Delta R_{ij}}{R}, \qquad \rho_i = E_i^{\alpha}$$

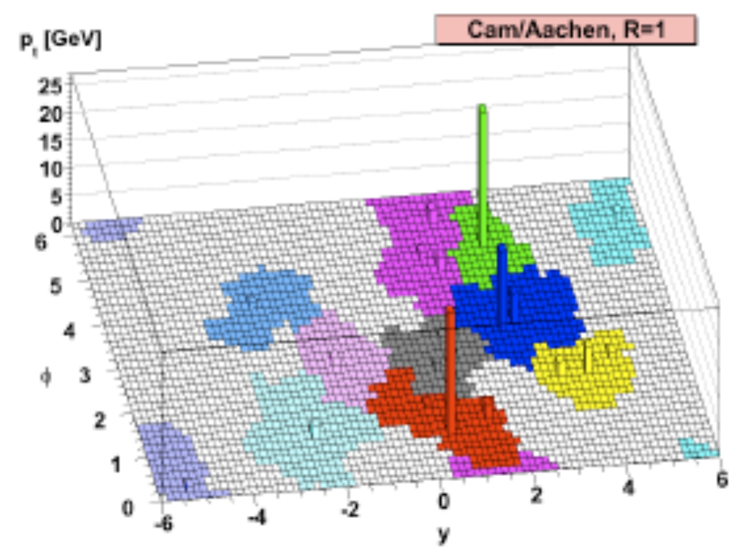


Algorithm start

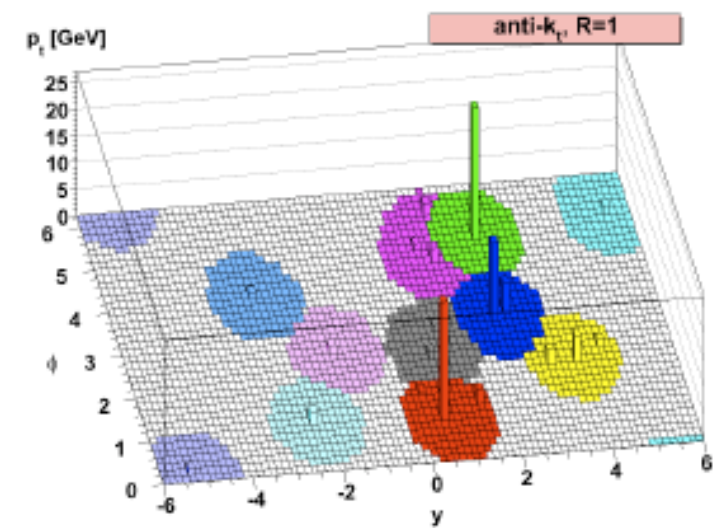
kT: $\alpha = 1$



CA : $\alpha = 0$



Anti-kT: $\alpha = -1$

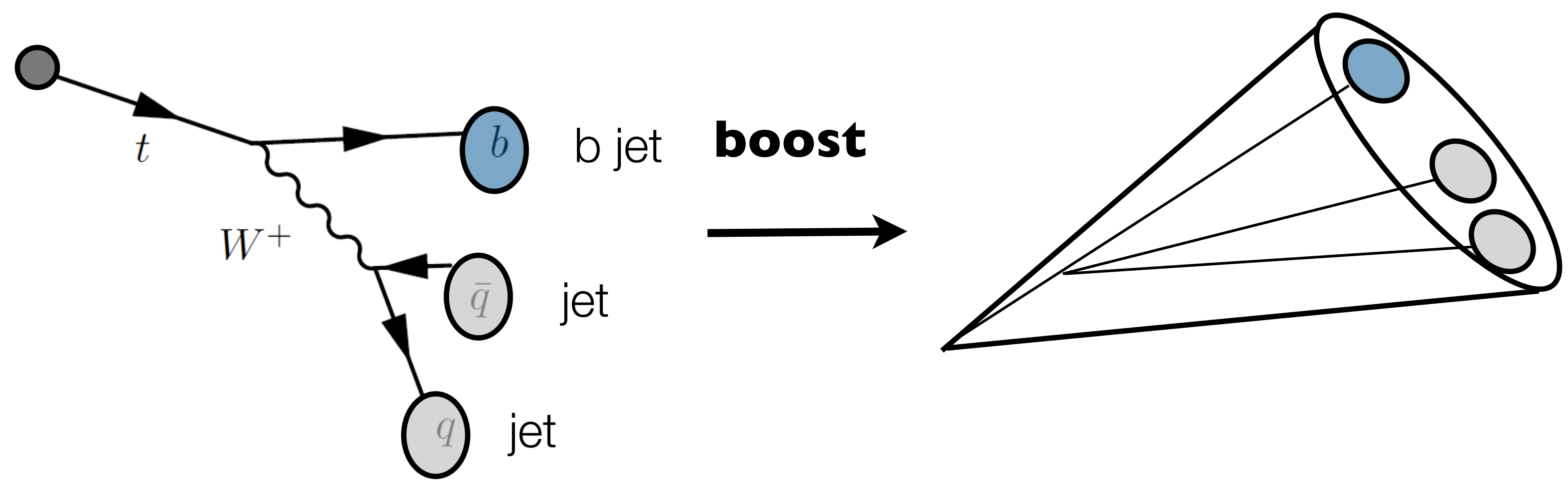


(Cacciari, Salam, Soyez ’08)

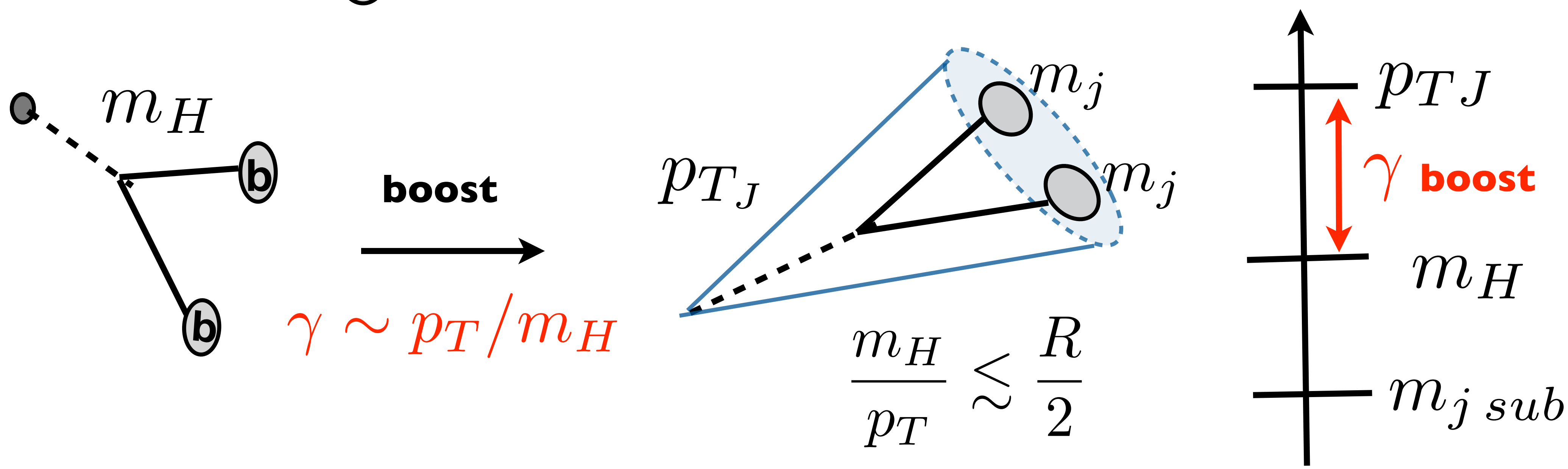
Beyond Jet to Parton Mapping

- At large p_T boosted decay products lead to fat jet

- **Top Jet**



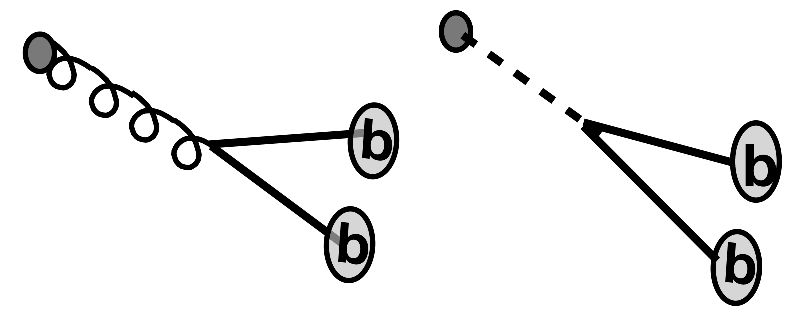
- **Higgs Jet**



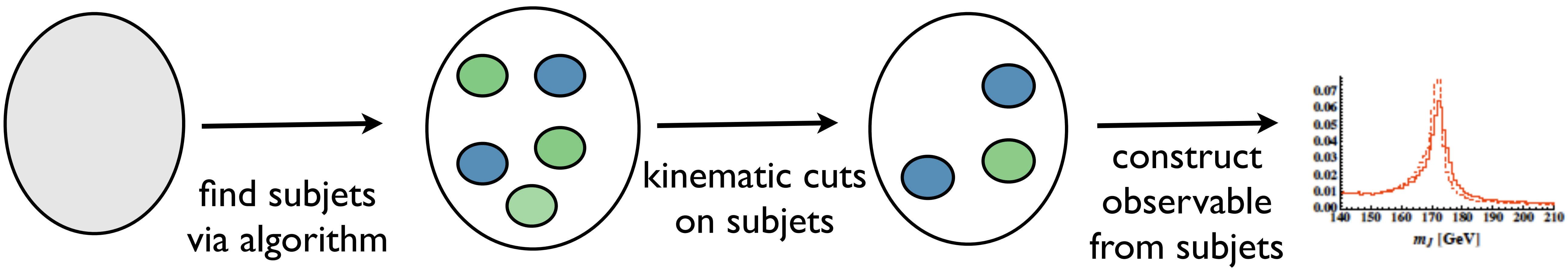
- In high p_T >> m_W regime at LHC see fat jets in many EW decays

Jet Substructure

- **Goal:** Improve discrimination between **‘QCD jets’** and **‘Higgs/top jets**



- Generic steps in jet substructure method



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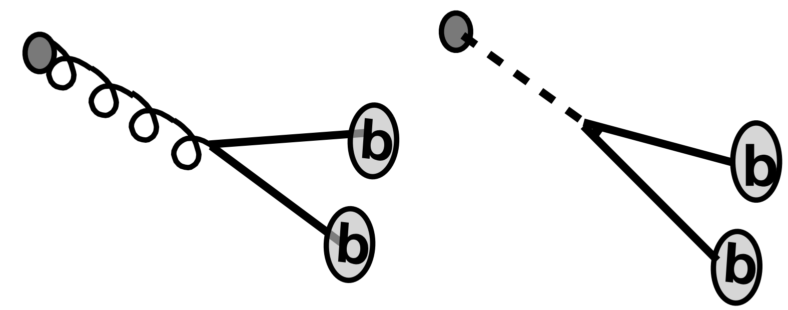

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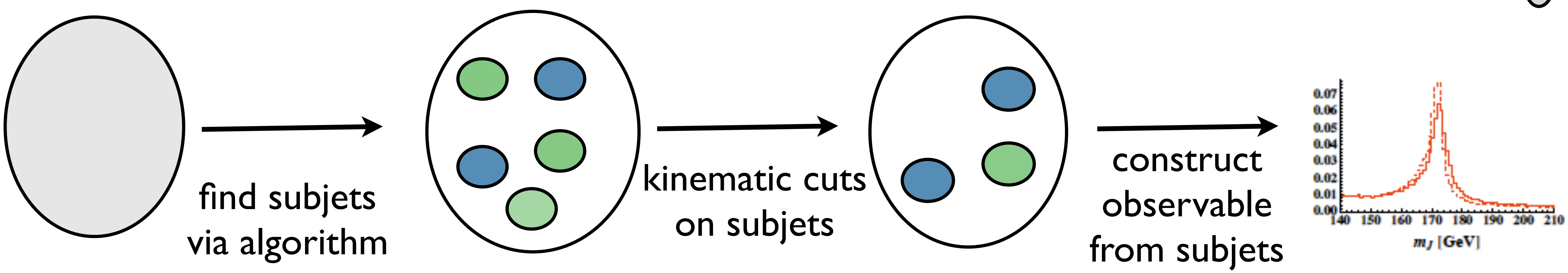
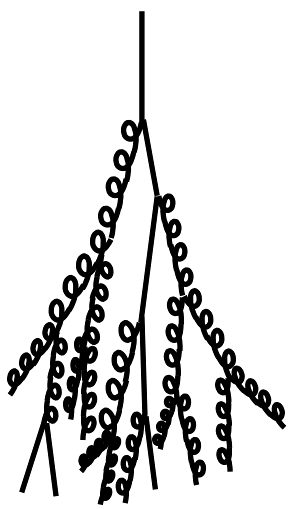


- **Approaches:**
  - Identifying subjets: use kinematics of hard splitting
  - Cuts on energy flow based on color of signal vs QCD jets
  - Grooming: remove soft contamination from UE and pile-up

Jet Substructure: Higgs

Butterworth,Davison, Rubin, Salam (2008)

- **Mass-Drop Filter**



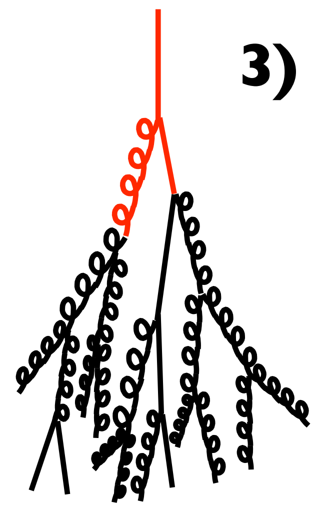
1) Decluster using CA

2) Mass Drop:

$$m_{\rm subjet} < \mu\, m_{\rm jet}$$

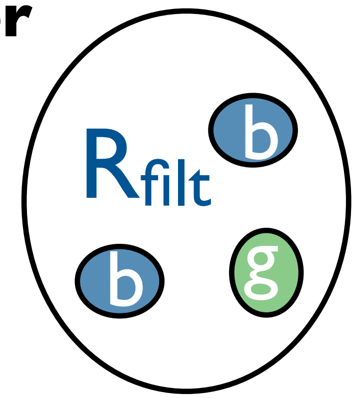
+ Cut on k_T of splitting d12

If not discard soft subjet. Repeat.



3) Grooming: Filter

Recluster
Keep 3 hardest subjets



Jet Substructure: Higgs

Butterworth,Davison, Rubin, Salam (2008)

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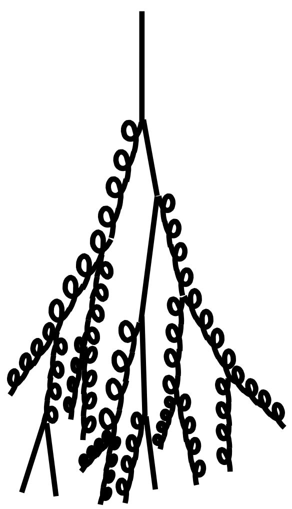

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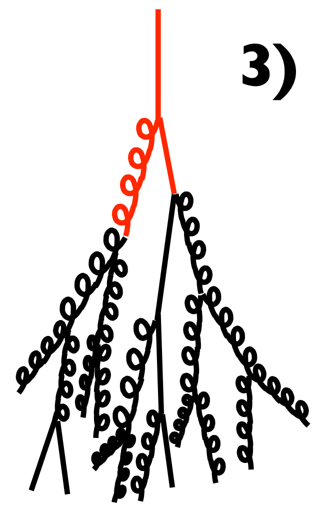

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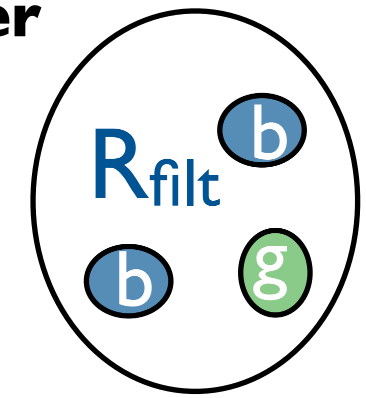

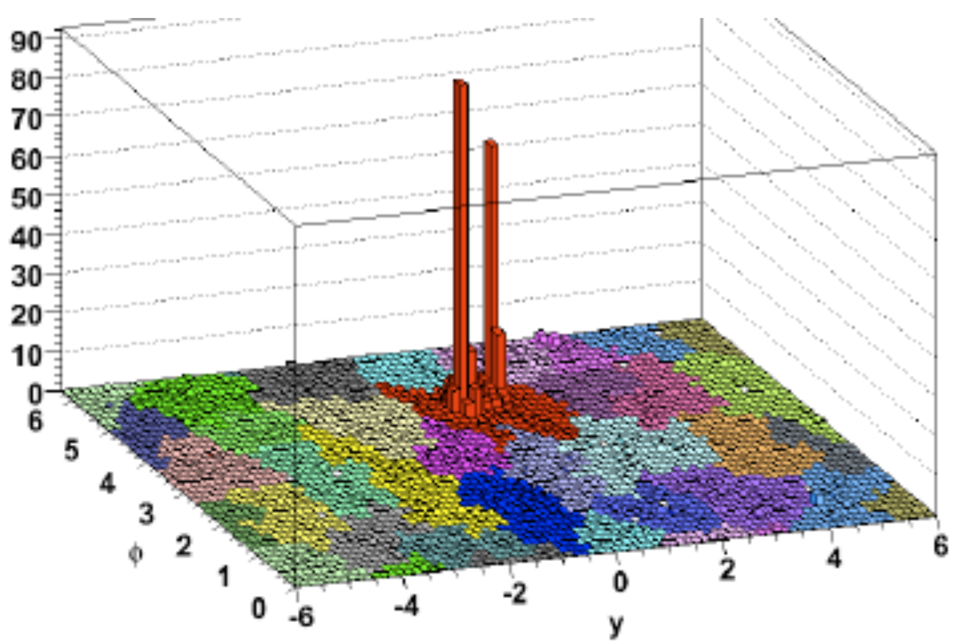

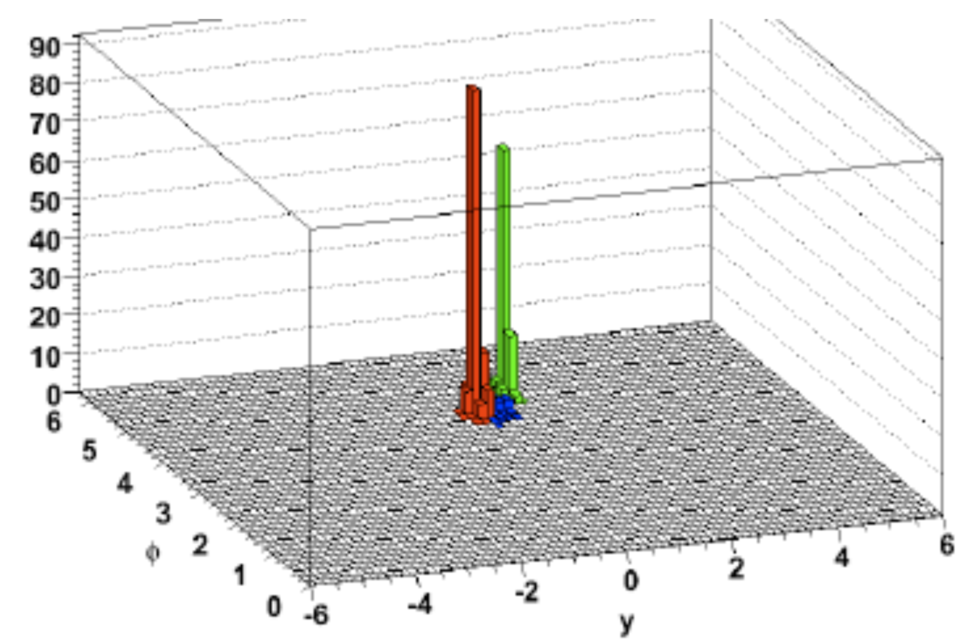

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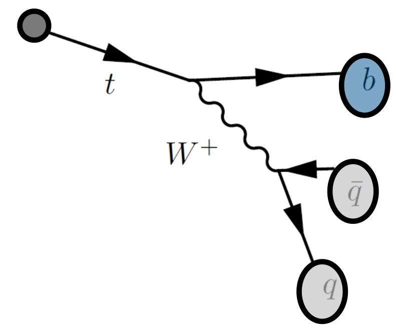
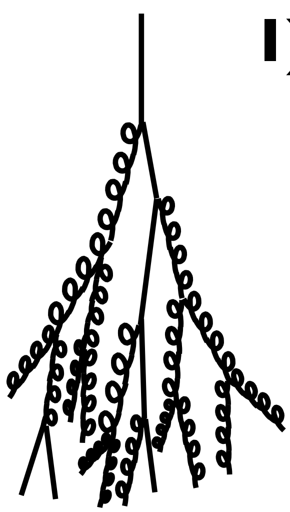
Jet Substructure: Top Tagging

- **Hopkins Top Tagger**

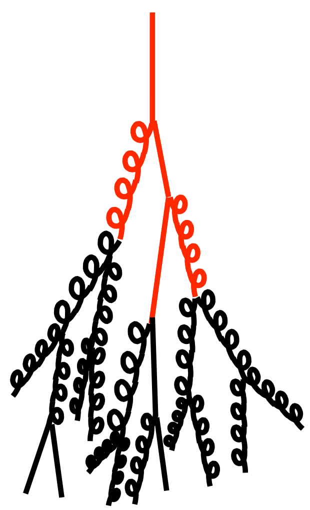


Kaplan, Rehermann, Schwartz, Tweedie (2008)



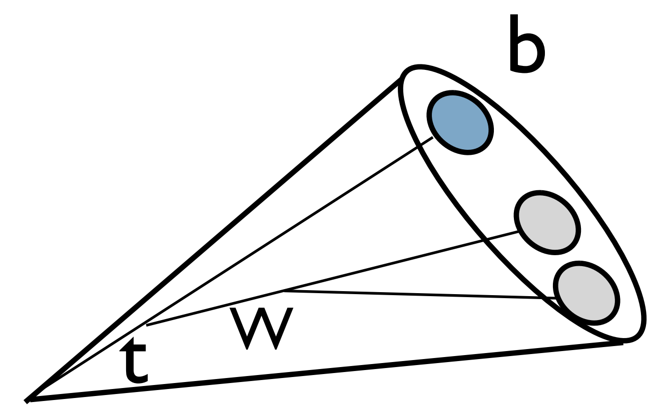
1) Decluster using CA

Discard soft branchings

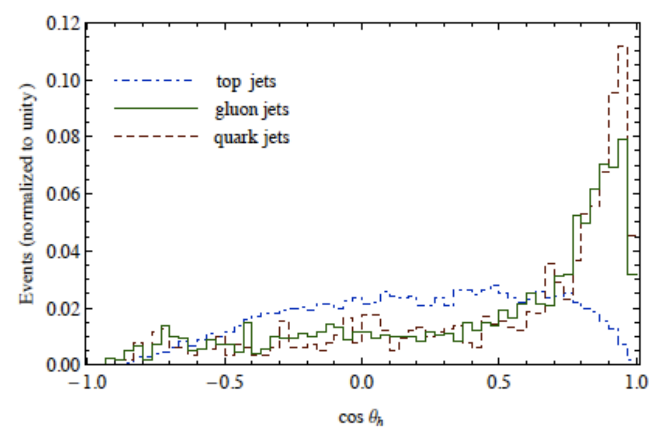


2) Kinematic Cuts

i) Whole jet near top mass
ii) Two subjets near W mass



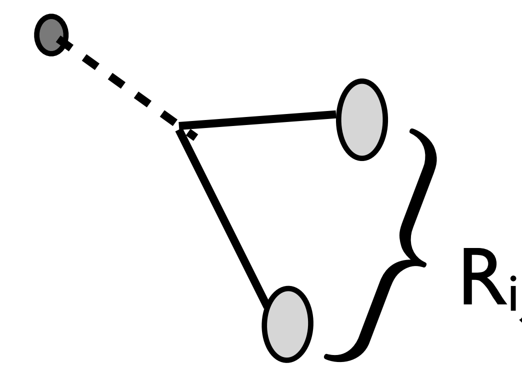
3) Remove QCD background
Cut on helicity angle of W



$$\frac{\alpha_s}{E_g(1-\cos\theta_g)}$$

Jet Grooming

- Pros: Method not tied to specific boosted heavy object
- UE lower energy, not localized.



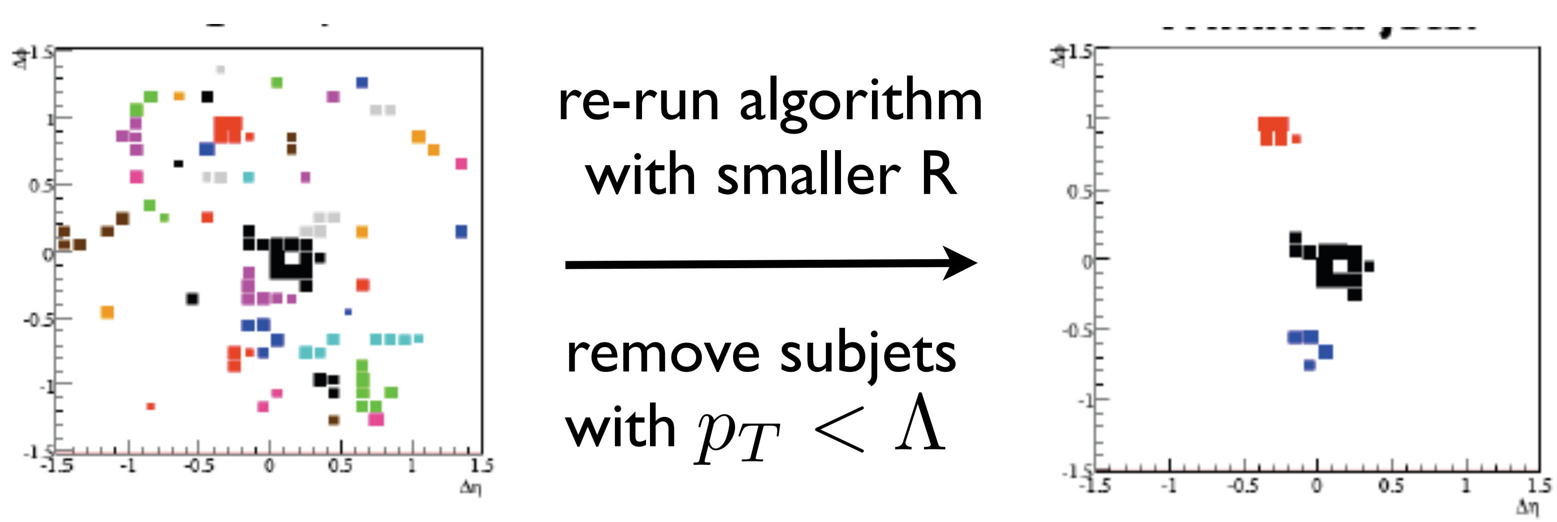
- **Pruning:** Decluster and discard softer particle if splitting is wide angled or soft

Ellis Vermillion Walsh (2008)

$$\frac{\min(p_{T_i}, p_{T_j})}{p_{T_{i+j}}} < z \quad , \quad R_{ij} > D$$

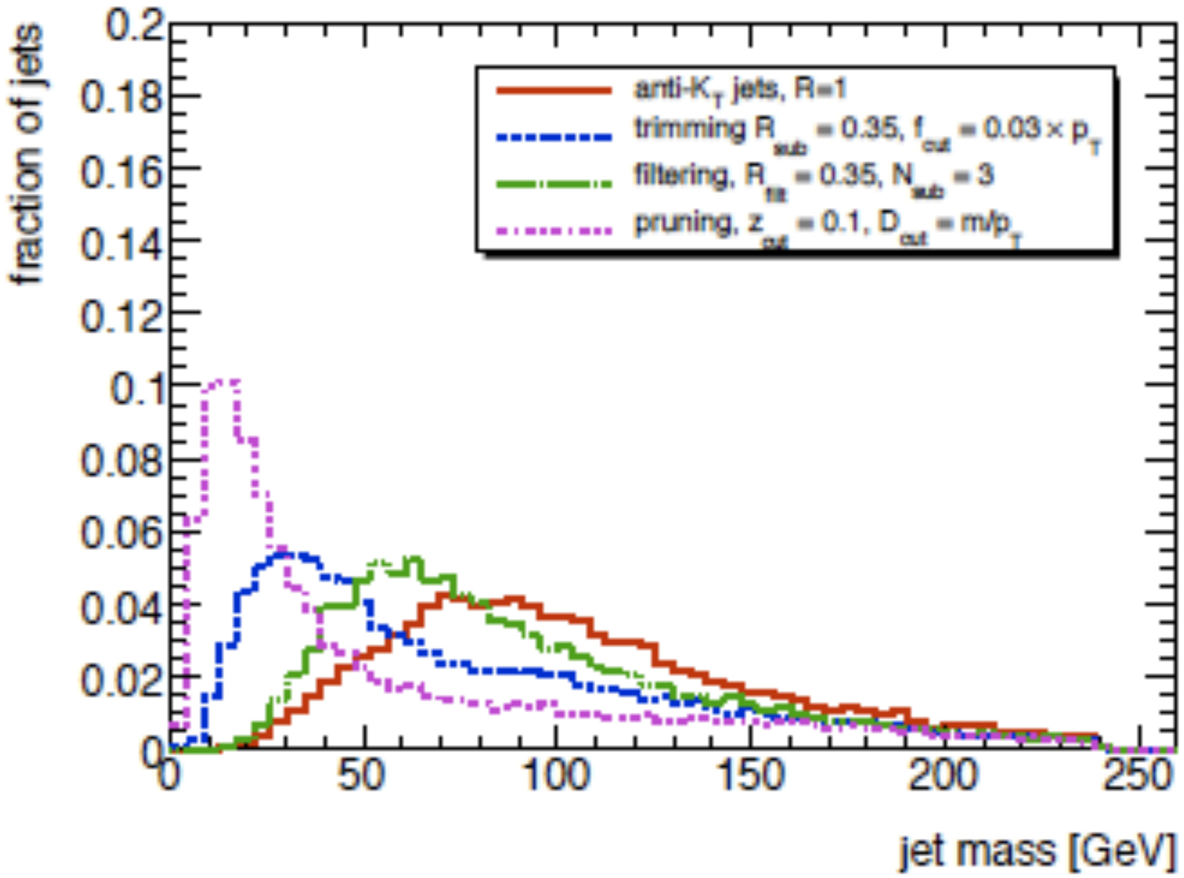
- **Trimming**

Krohn, Thaler,Wang (2009)



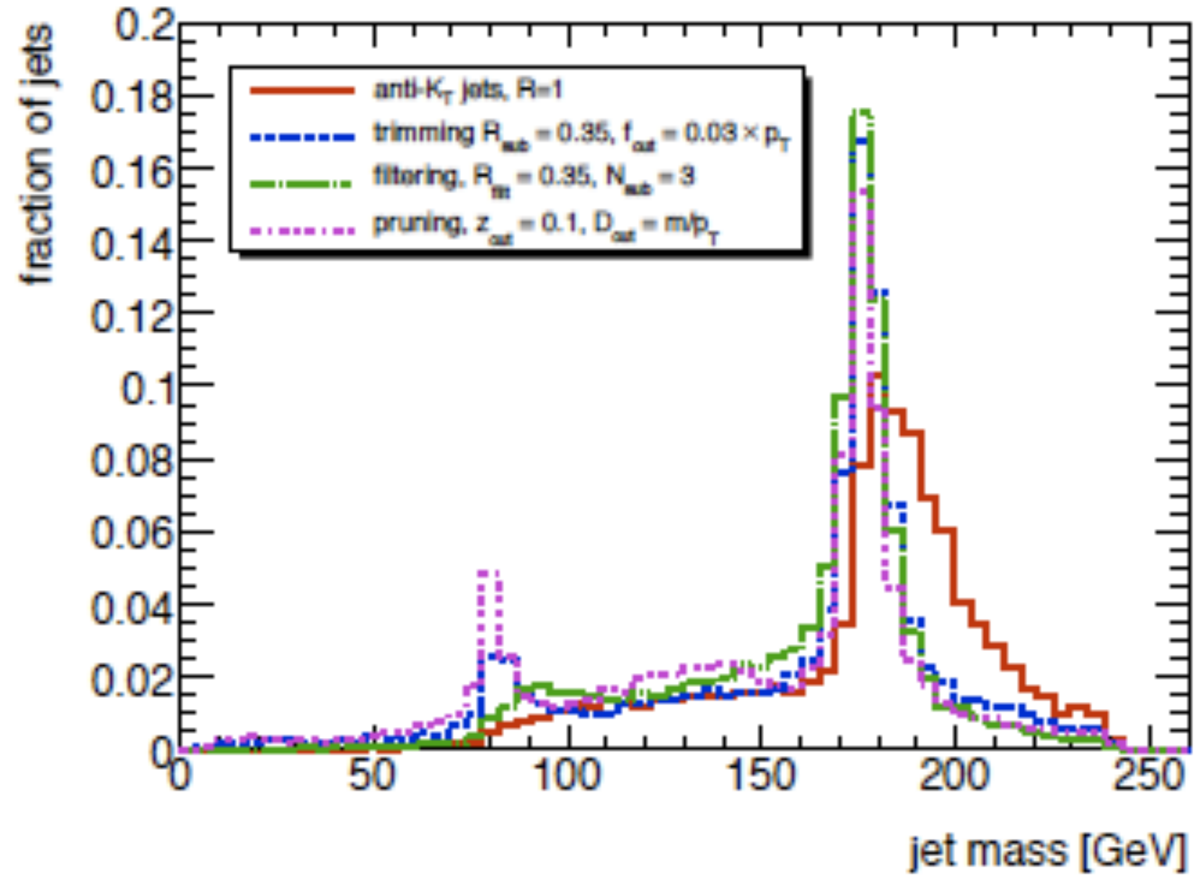
A comparison

Background



(a) dijets, 500–600 GeV

Signal

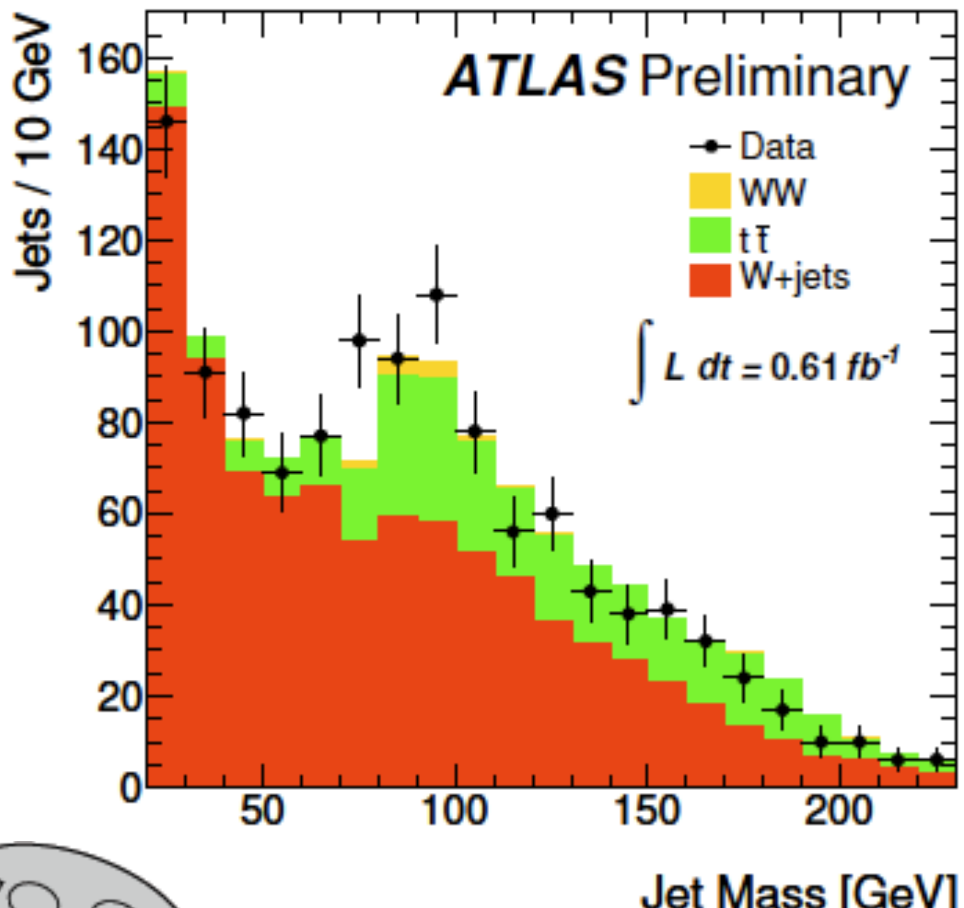


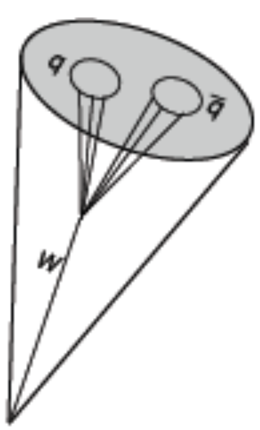
(b) $t\bar{t}$, 500–600 GeV

Boost 2010 1012.5412

Remarkable Experimental Progress

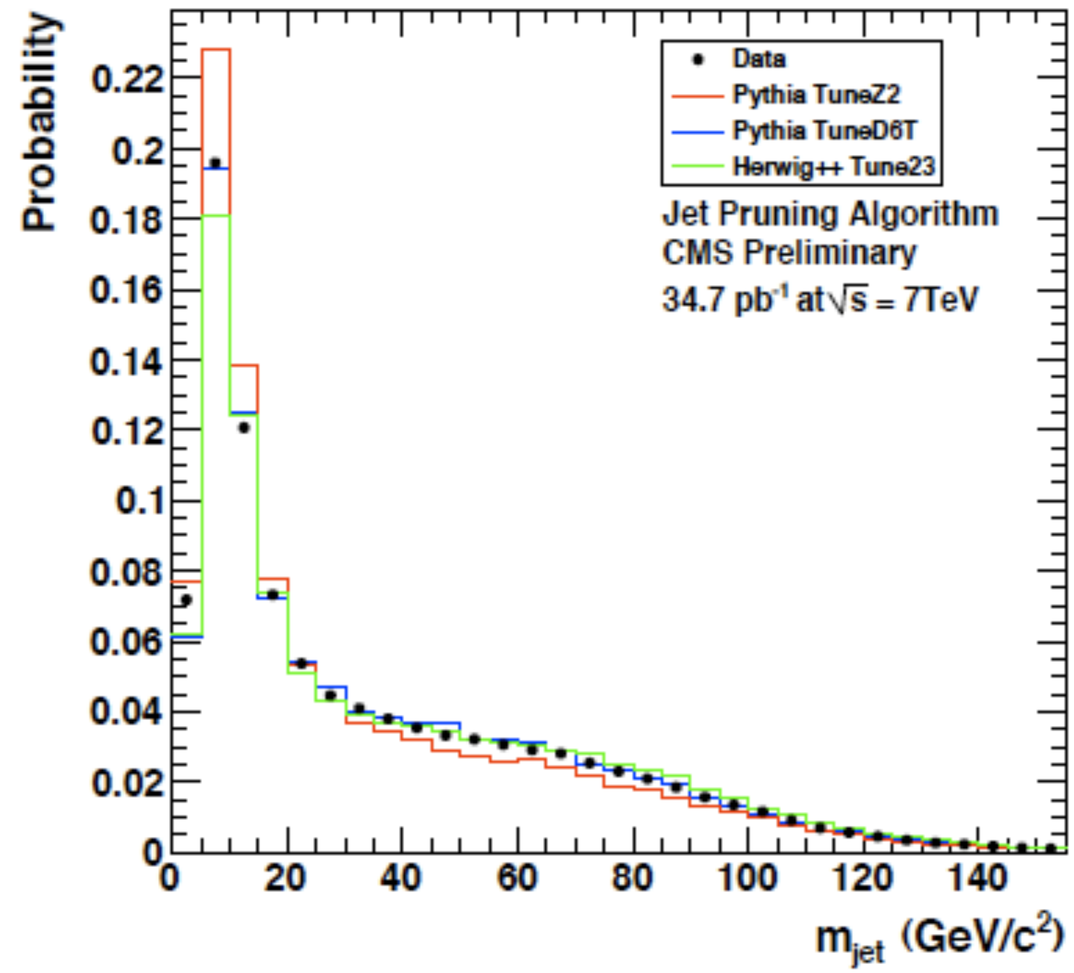
- **Mass Drop Filter**
  Events are selected to be consistent with $W \to \ell\nu + 1\mathrm{jet}$





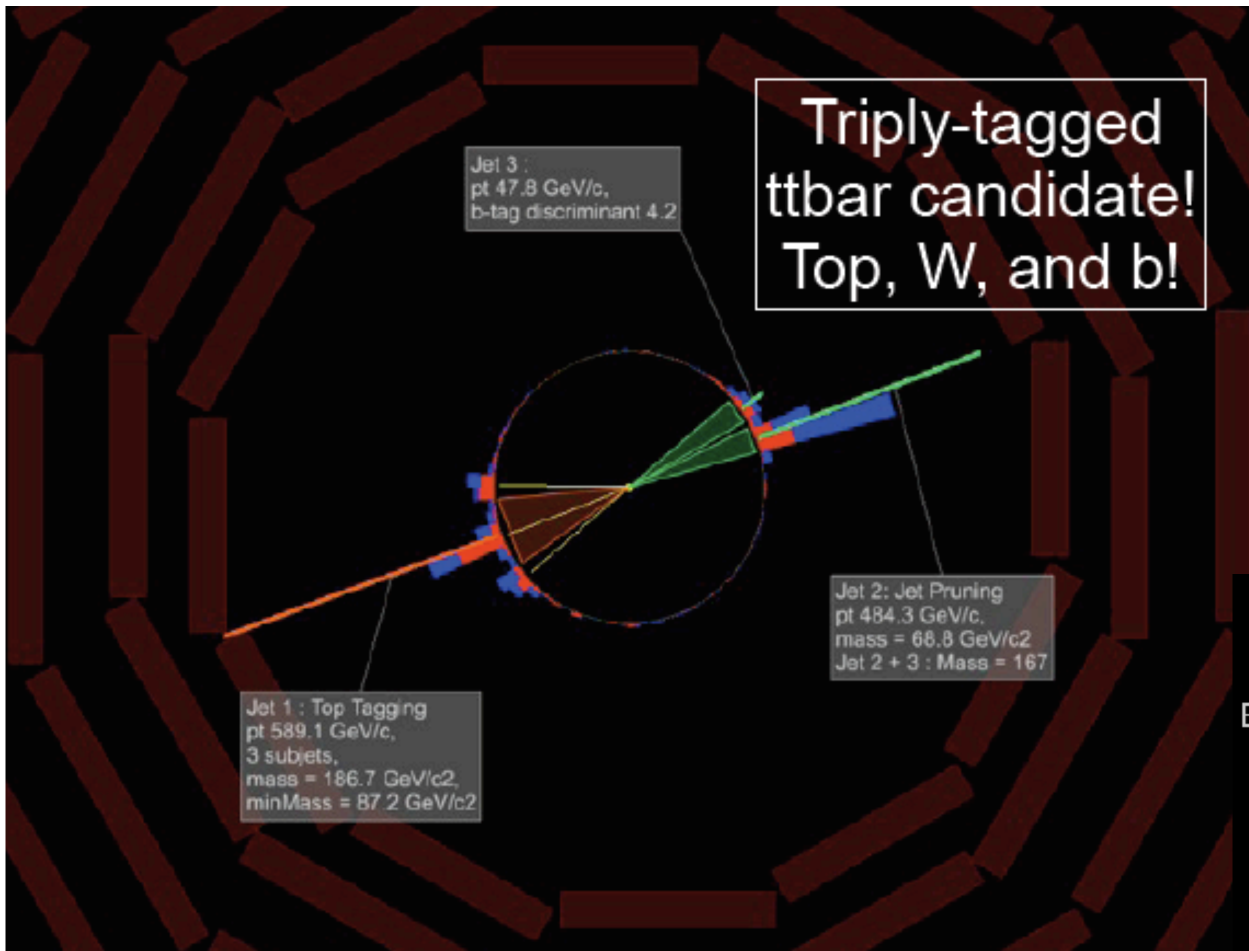
*See David Miller's talk

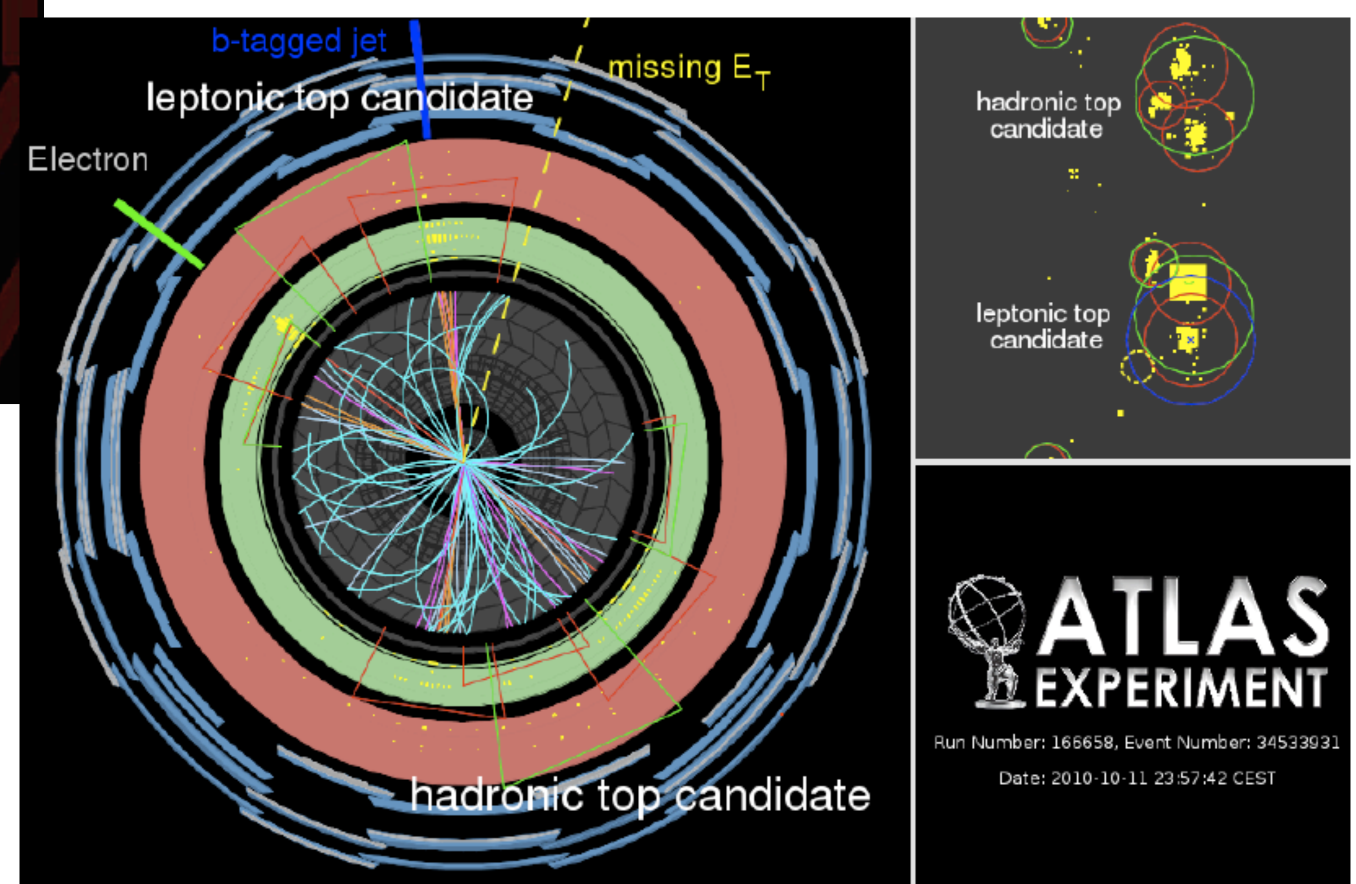
- **Pruning**
  Applied to tag W jets decaying hadronically



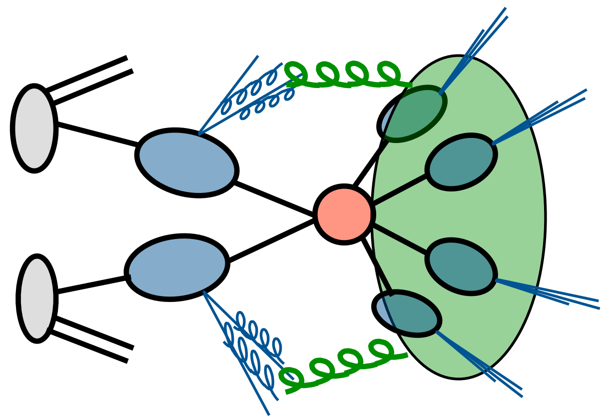
Remarkable Experimental Progress

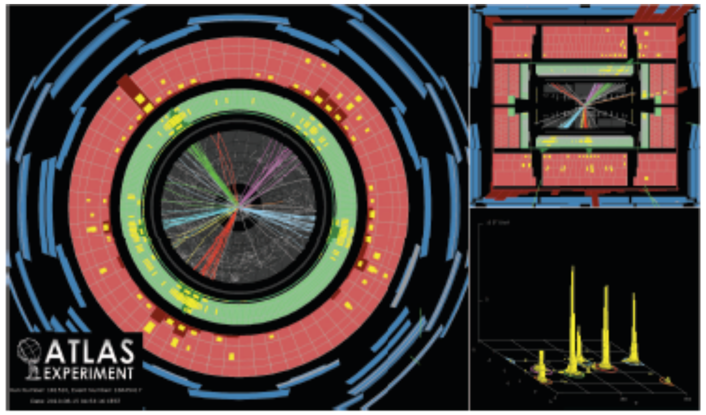
- Boosted $t\bar{t}$ event:

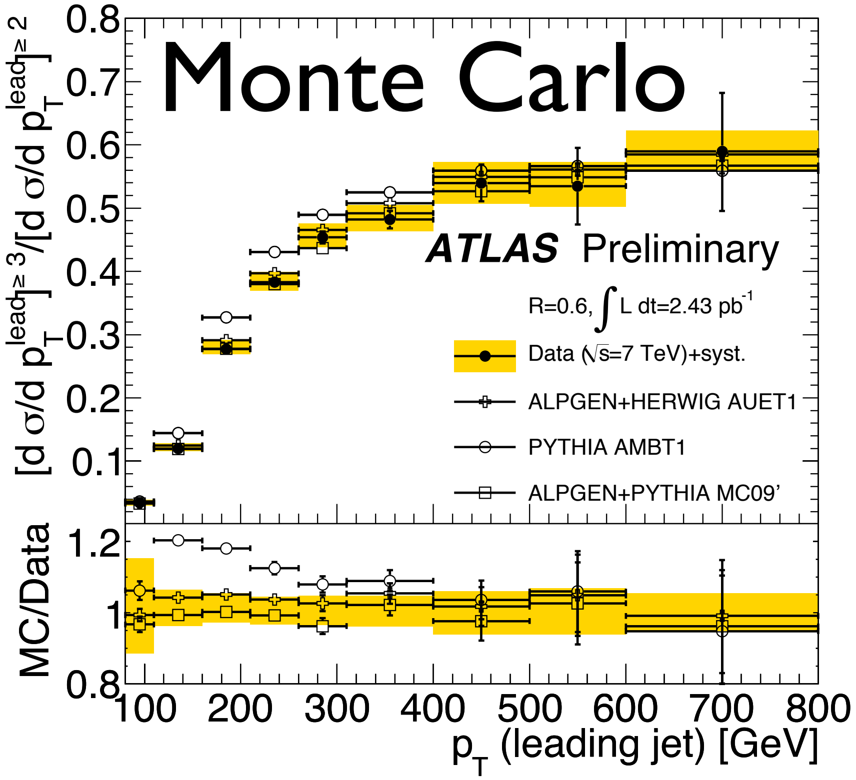


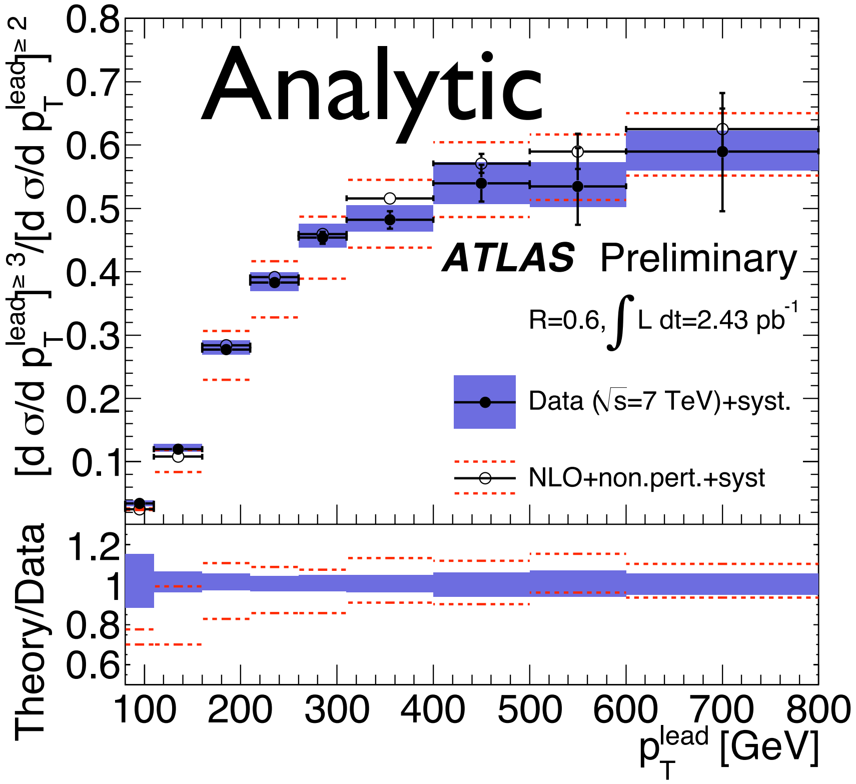


Theoretical Tools









$$d\sigma = \text{Hard Interaction} \otimes \text{Collinear Evolution} \otimes \text{Soft Radiation} \otimes \begin{array}{c}\text{PDFs}\\ \text{Hadronization}\\ \text{Underlying Event}\end{array}$$

Monte Carlo

- **Key Feature: Monte Carlos are exclusive**
  Basic role of event generator: return weight for each point in N-body phase space $\mathrm{d}\sigma/\mathrm{d}\Phi_N$
  - ➡ Can implement arbitrary experimental cuts $\{\eta_{\mathrm{cut}}, p_T^{\mathrm{cut}}, R\}$
    Major challenge for analytic calculations.
  - ➡ Leading small p_T resummation and large p_T fixed order
    Analytic calculations available to much higher precision
  - ➡ Allows one to be exclusive in jet multiplicities
    Eg. $pp \to H + 0, 1, 2\,\mathrm{jets}$ have different backgrounds and sensitivities
  - ➡ Returns hadrons not partons. Model non-perturbative physics.
    Dependence on tunes
- Analytic calculations provide a cross-check of MC eg jet substructure
- Insights in to designing/understanding jet tools

Analytic Control Over Jet Observables

- **Framework to calculate in QCD** - prove factorization, integrate hard ME and resum large logarithms
    - ➡ Soft-collinear Effective Theory (SCET)

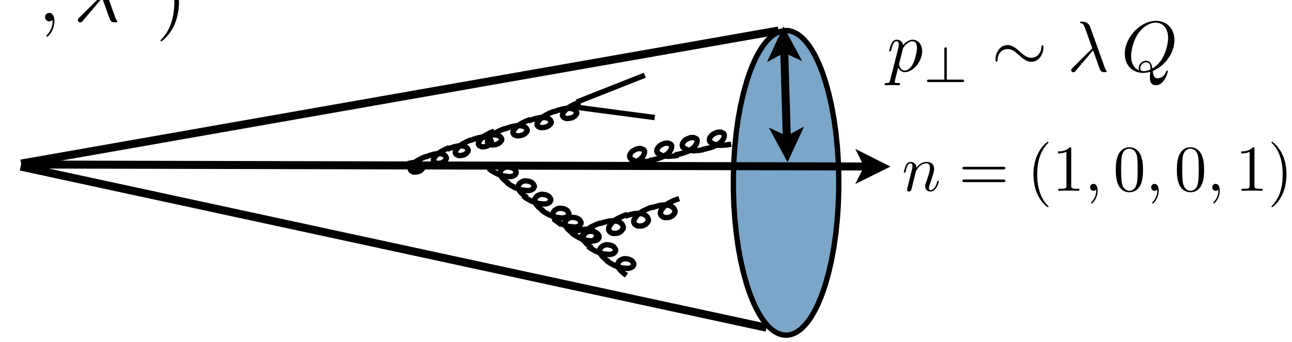
Bauer, Fleming, Luke, 2000

Bauer, Fleming, Pirjol, Stewart 2001

- Separtes key features of QCD evolution: collinear and soft with systematic power counting

$$p_c \sim Q(1, \lambda^2, \lambda) \qquad p_s \sim Q(\lambda^2, \lambda^2, \lambda^2)$$

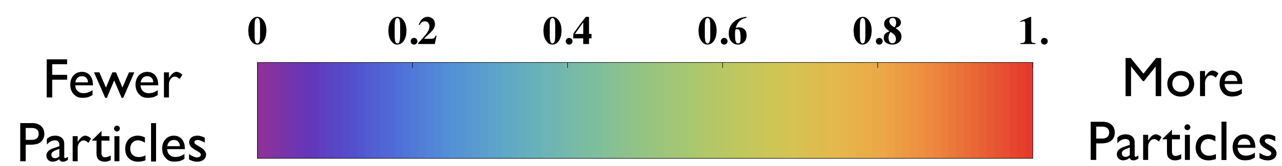
$$p = (E + p_z,\, E - p_z,\, p_\perp)$$



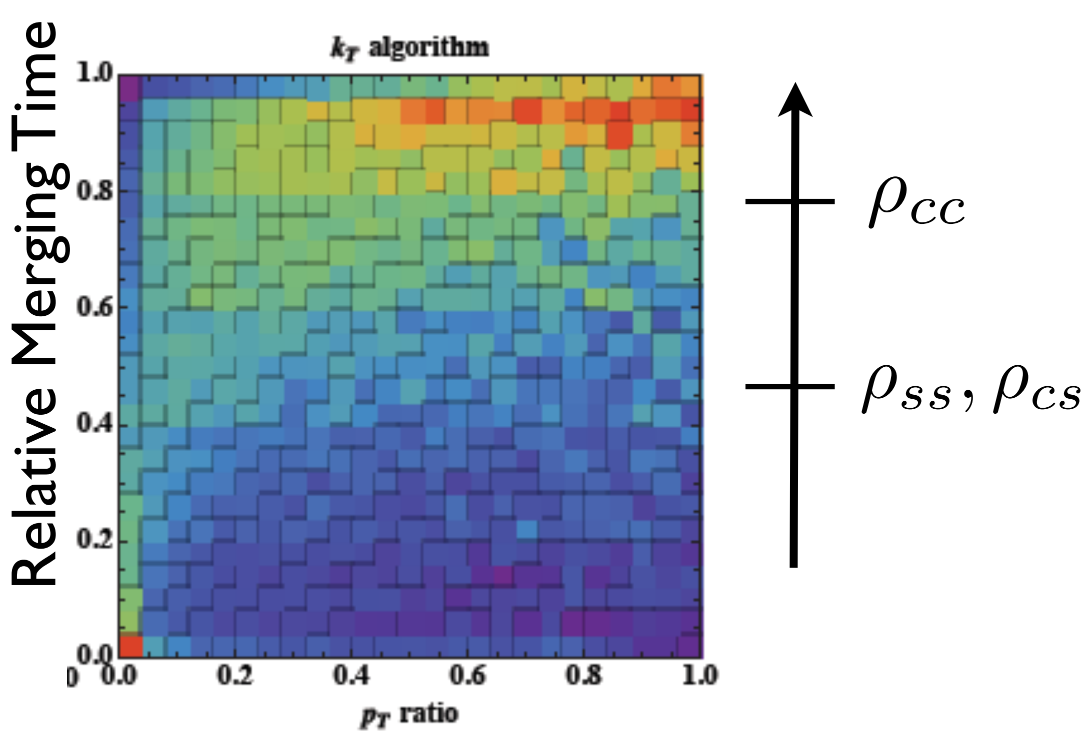
- **Many applications to jets:**
    - Jet Shapes and Jet algorithm (Ellis, Hornig, Lee, Walsh, Vermilion), pp to N-jettiness (Stewart,Tackmann,Waalewijn), H + 0 jets NNLL NNLO (Berger, Marcantonini,Stewart,Tackmann,Waalewijn), Dijet invariant mass spectra (Bauer,Tackmann, Walsh, SZ)

Understanding Jet Algorithms

- Power counting easy way to understand key features of jet structure (Walsh, SZ)
- Can use to determine test for when factorization of substructure method fails

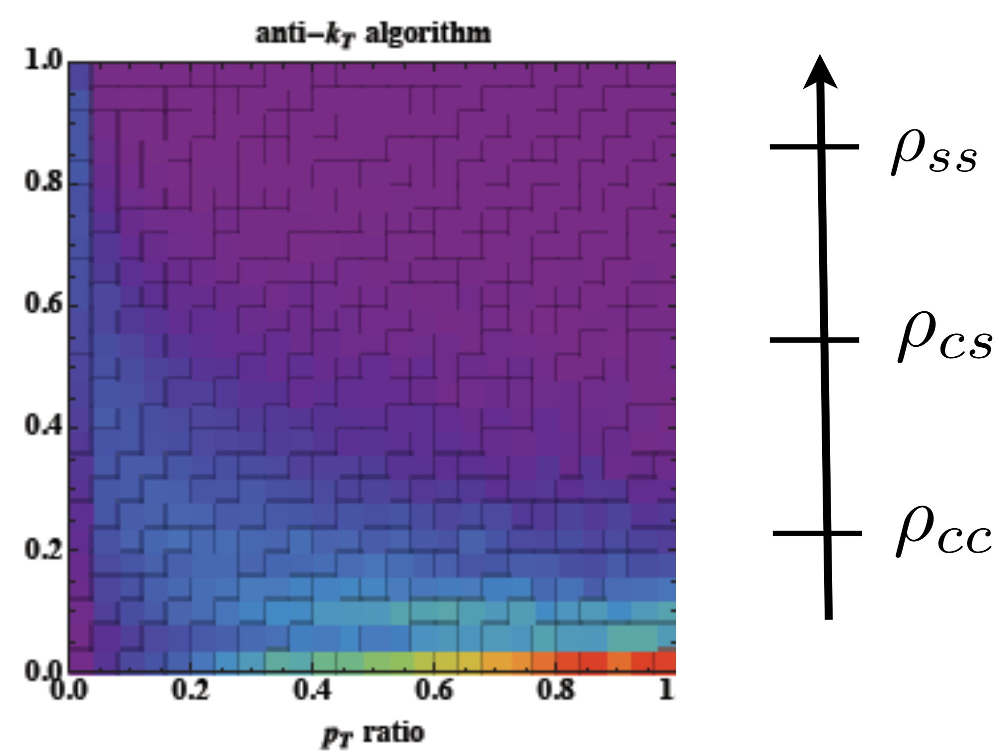


kT: $\alpha = 1$

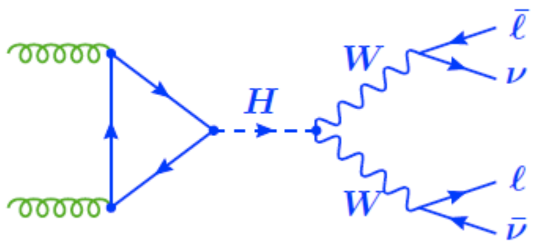


Softs combined first

Anti-kT: $\alpha = -1$

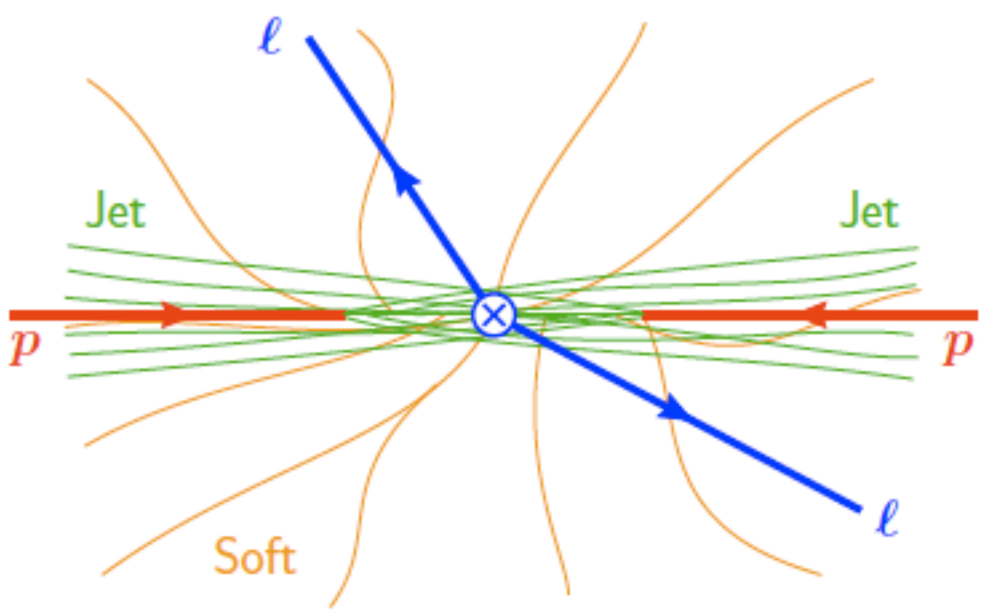


Energetic collinear particles in jet combined first

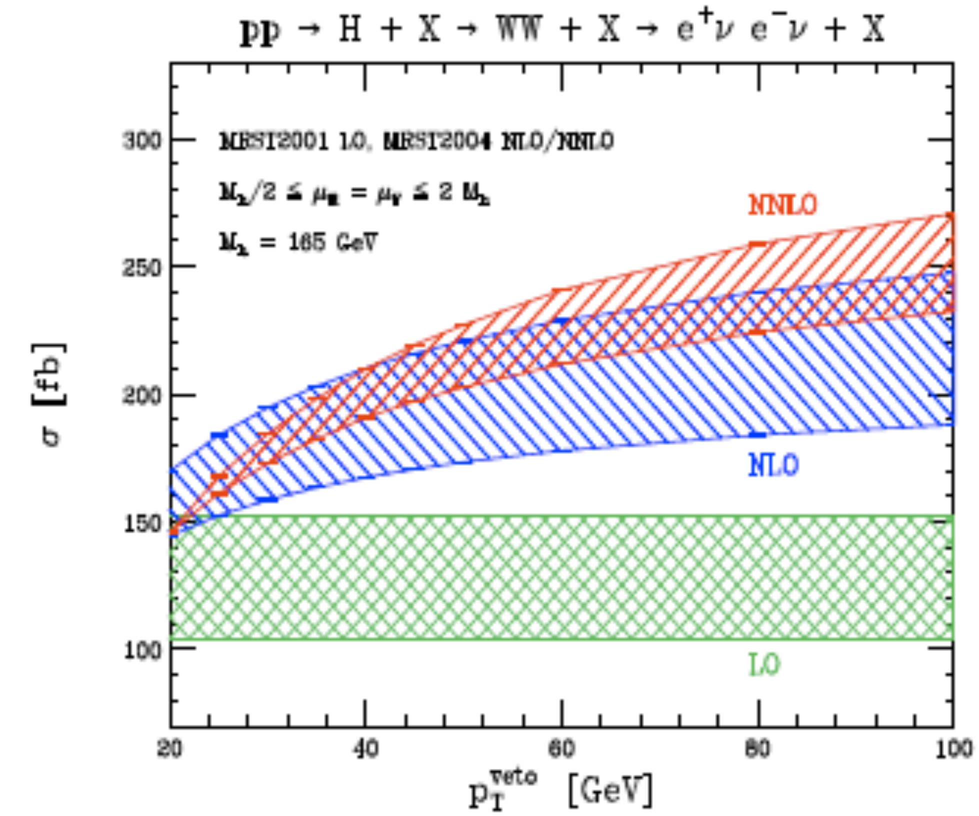


An Example: Higgs + 0 jets

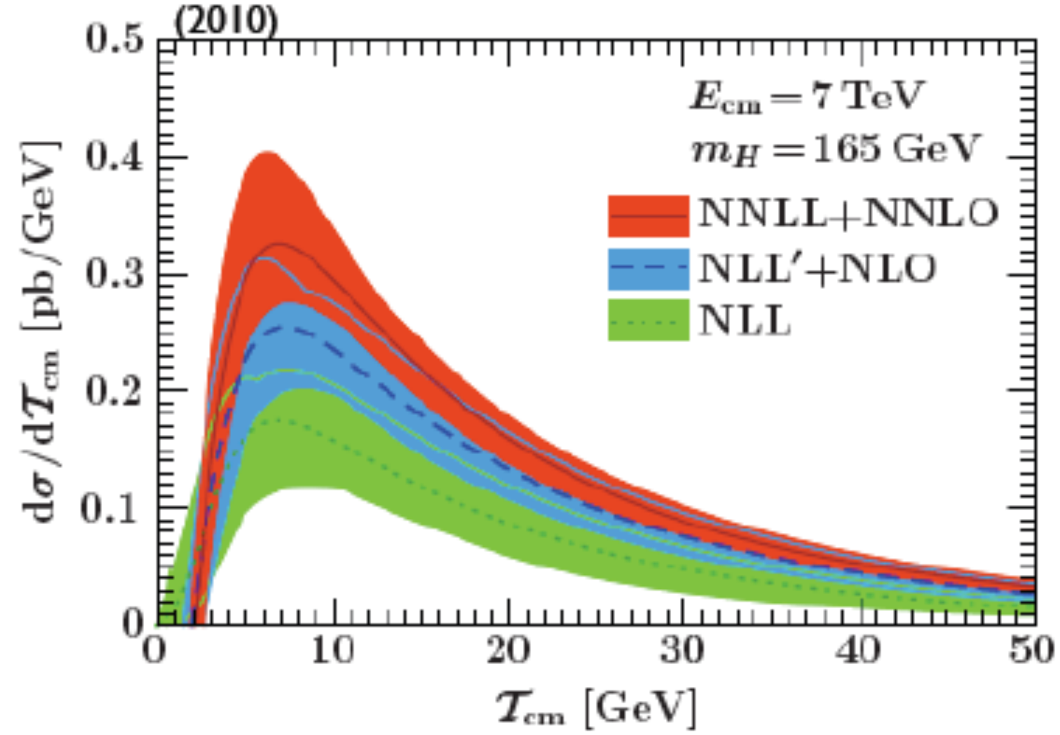
- Large fixed order corrections. Vary with p_T^{cut}
- FO α_s **expansion** describe large p_T^{cut} region
  Unreliable at small p_T^{cut}
- Need $\alpha_s \ln \dfrac{p_T^{\rm cut}}{m_H}$ resummation (parton shower)
-



Anastasiou, Dissertori, Stockli (2007)



Berger, Marcantonini, Stewart, Tackmann, Waalewijn (2010)



Perturbative Accuracy

- Perturbative structure of hard interaction $\otimes$ parton shower

$$L \sim \ln \frac{\mu_{\rm PS}}{\mu_{\rm hard}}$$

$$\begin{aligned}\sigma \quad \sim \quad & 1 \qquad LO \\ + \quad & \alpha_s L^2 + \alpha_s L + \alpha_s \qquad NLO \\ + \quad & \underbrace{\alpha_s^2 L^4}_{LL} + \underbrace{\alpha_s^2 L^3}_{NLL} + \underbrace{\alpha_s^2 L^2 + \alpha_s^2 L}_{N^2LL} + \alpha_s^2 \qquad N^2LO\end{aligned}$$

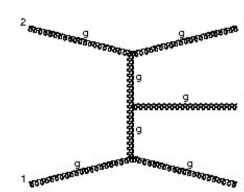
- Parton Shower has LL (partial NLL) behaviour
- MC@NLO : Parton Shower and fixed NLO
- SCET H +0 jets calculation N^2LL and N^2LO (Berger, Marcantonini,Stewart,Tackmann,Waalewijn
- In MC want to Combine Hard Matrix Element NLO with Resummation (parton shower)

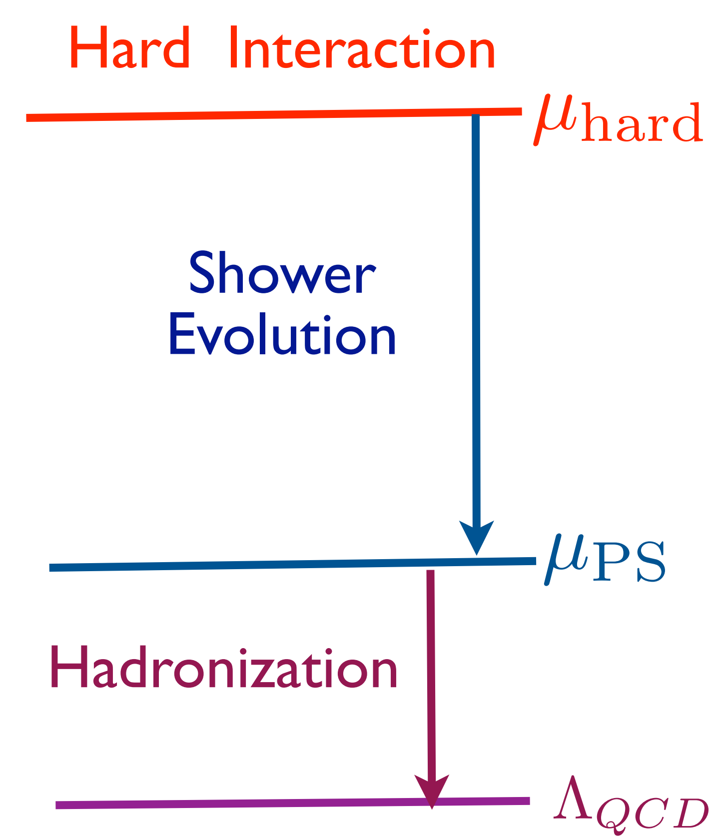
Geneva: Christian Bauer, Calvin Berggren, Nicholas Dunn, Andrew Hornig, Frank Tackmann, Jesse Thaler, Christopher Vermilion, Jonathan Walsh, SZ

Parts of the Monte Carlo

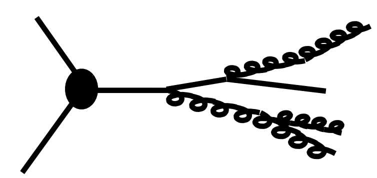
$d\sigma^{MC} =$ Hard Interaction $\otimes$ Parton Shower $\otimes$ Hadronization Underlying Event

- Hard Interaction: Fixed order partonic matrix elements. Legs + Loops.





- Parton Shower: Collinear and soft splittings. High Multiplicity final state. Logs $\alpha_s \ln^2 \frac{\mu_{PS}}{\mu_H}$.



$d\Phi_n$	$d\Phi_{n+1}$	$d\Phi_{n+2}$	$d\Phi_{n+3}$
LO Matrix Element	Parton Shower	Parton Shower	Parton Shower

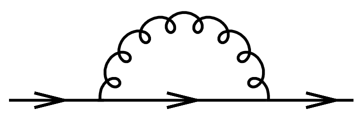
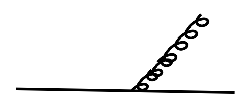
- Hadronization/ UE: Model non-perturbative physics. Partons to hadrons

Challenge : Fixed Order and Parton Shower

At LO:

$d\Phi_n$	$d\Phi_{n+1}$	$d\Phi_{n+2}$	$d\Phi_{n+3}$
LO Matrix Element	Parton Shower	Parton Shower	Parton Shower

- Beyond LO: **N-body Phase Space $\neq$ N-parton Phase Space**

IR finite NLO =  $d\Phi_n$ +  $d\Phi_{n+1}$

➡ **Make each weight well defined.**

- Both Parton Shower and NLO ME include real emission corrections
  FO: exact n+1 body, PS collinear/soft limit.

At NLO:

$d\Phi_n$	$d\Phi_{n+1}$	$d\Phi_{n+2}$	$d\Phi_{n+3}$
LO +Virtual	PS Real	Parton Shower	Parton Shower

➡ **Avoid Double Counting**

Current Approaches: Fixed Order $\otimes$ Parton Shower

*touch on just a few

- MC@NLO/ POWHEG (NLO for single jet multiplicity) $\otimes$ (LL Parton Shower)

➡ Divergences: Define Subtraction $d\Phi_n \left[V_n + \int d\Phi_{n+1|n} S \right] + d\Phi_{n+1} \left[R_{n+1} - S \right]$

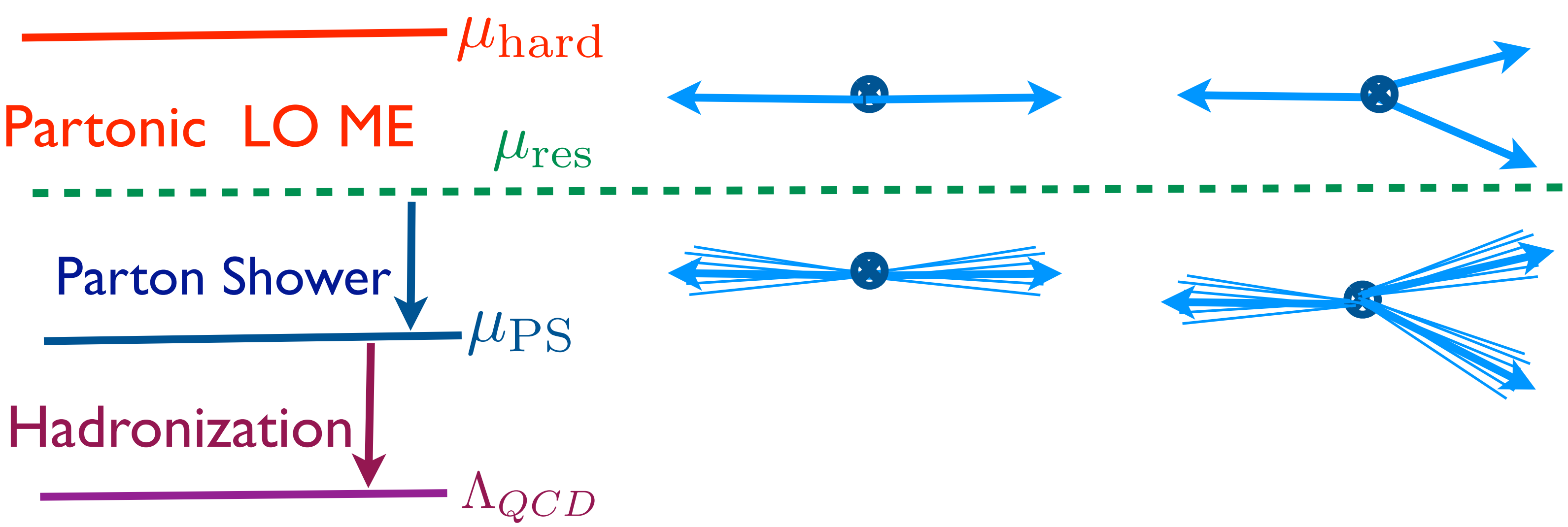
Maps N-Body Phase Space to N-Parton Phase Space

[Frixione, Webber; Nason; Frixione, Nason, Oleari]

➡ Double Counting: Modify 1st emission of parton shower. **Inclusive** jet observable at NLO

- Multi-jets at LO (LO for **all** jet multiplicities) $\otimes$ (LL Parton Shower)

[Catani, Krauss, Kuhn, Webber; Lönnblad; Mangano]



Hard matrix element combined with Sudakov to cancel $\mu_{\rm res}$ dependence.

➡ MENLOPS (NLO single jet + LO rest jet multiplicities) $\otimes$ (LL Parton Shower)

[Bauer, Tackmann, Thaler; Hamilton, Nason; Hoche, Krauss, Schonherr, Siegert]

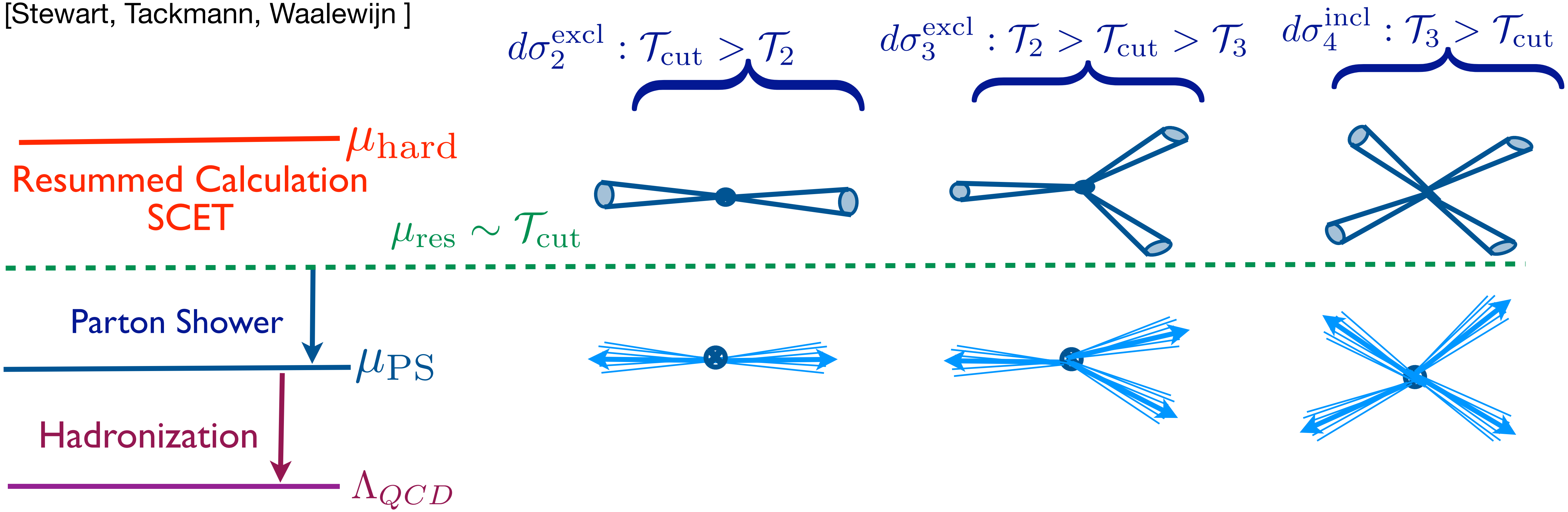
GENEVA The Geneva Approach

- **Goal:** Exclusive jet multiplicities all at NLO + resummation $pp \to H/W + 0, 1, 2\,\mathrm{jets}$
  Start with $e^+e^- \to 2, 3, 4\,\mathrm{jets}$.
  Naively 4 jets NLO would require 2 jet to N^{3}LO to be IR finite.
  Geneva: relevant pieces obtained from resummation

➡ Divergences: **Map N-jet Phase Space to N-body Phase Space**

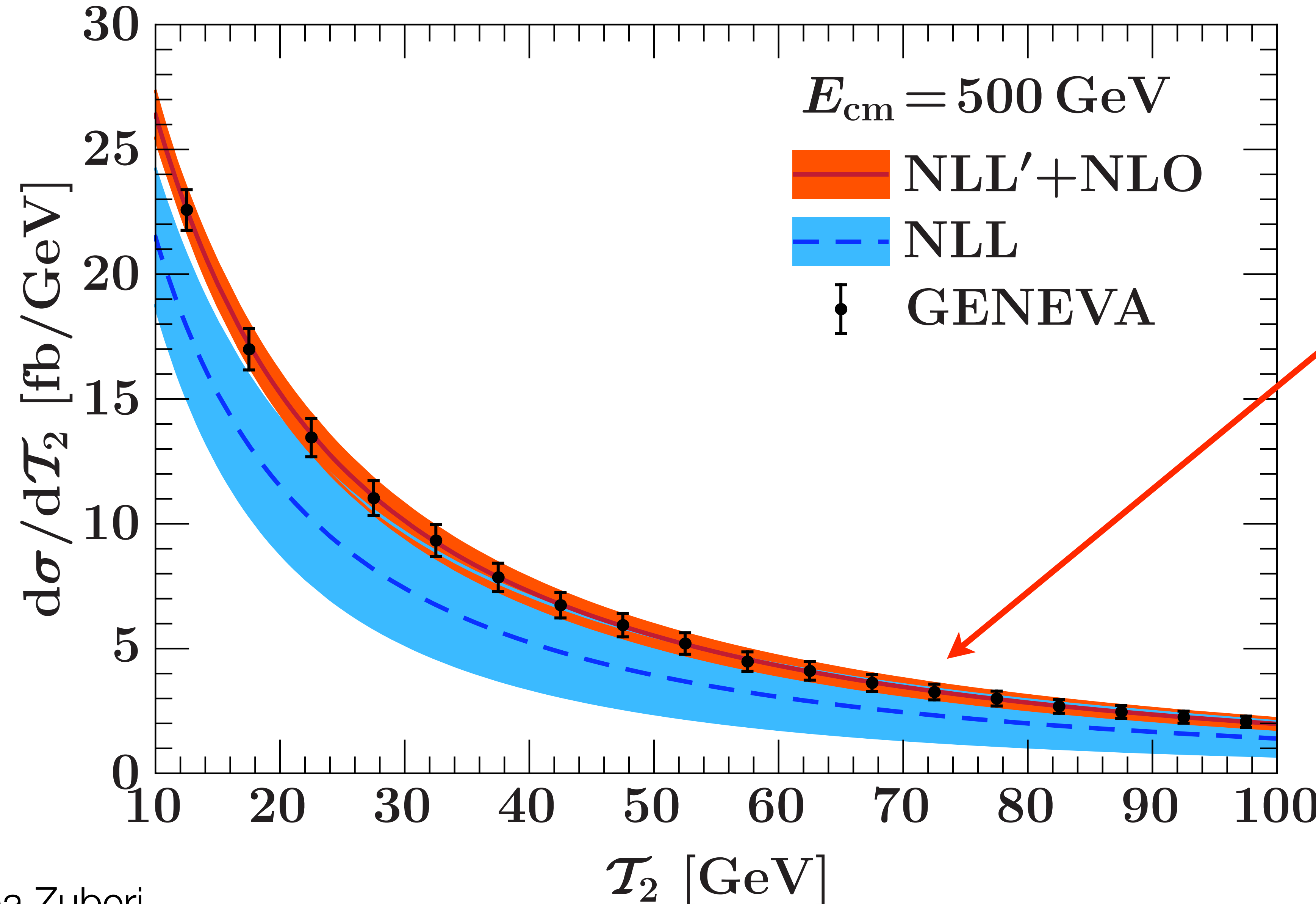
➡ **Divide Phase Space :** Resolution variable, N-jettiness $\mathcal{T}_N$. Vetos > N jets. Well defined for any number of partonic final states.

[Stewart, Tackmann, Waalewijn]

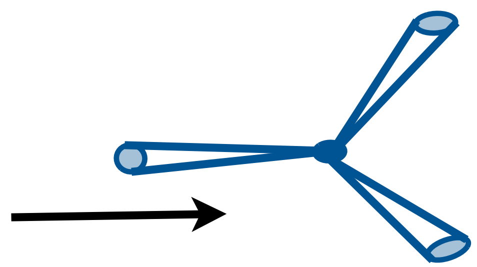


Combining Higher Jet Multiplicities

- **Previously: 2 jets at NLL+NLO and 3 jets at LO**
- **Now with Geneva have 2 jets at NLL+NLO and 3 jets at NLO**
  Systematically extendable

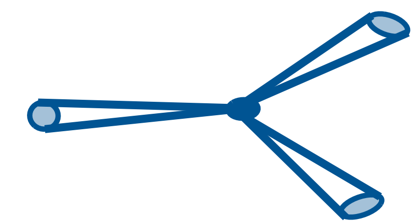


- **Monte Carlo with theory (scale) uncertainties not MC statistics!**



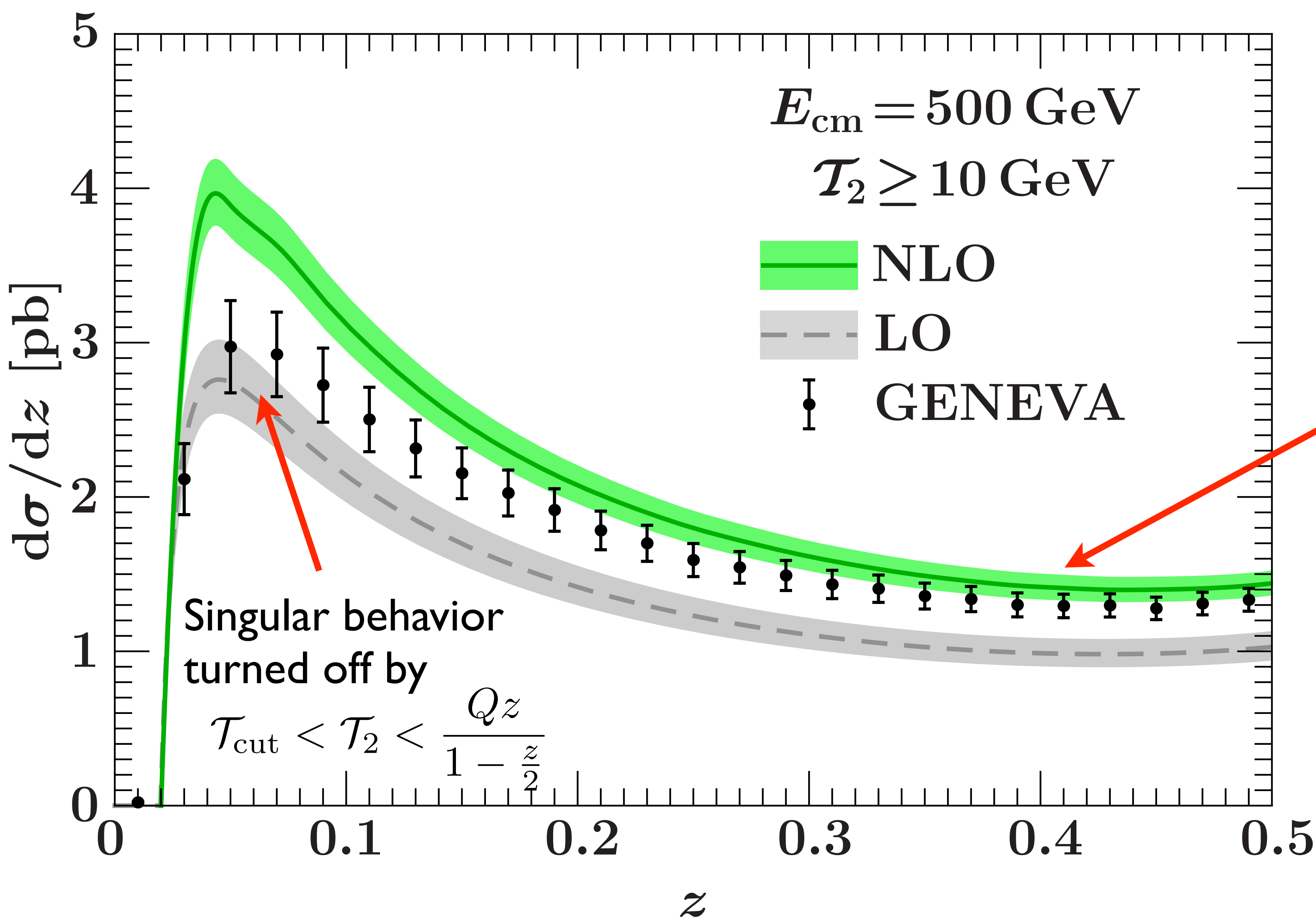
First Results: 2 and 3 jets at NLO

- Consider variable sensitive to Φ_3 angular dependence.



- Should reproduce **shape.** $\mathrm{d}\Phi_3 = \mathrm{d}\Phi_2\,\mathrm{d}z\,\mathrm{d}\mathcal{T}_2\,\mathrm{d}\phi$
  Definition of variables consistent for 3-jets (at any order).

$$z = \frac{E_1}{E_1 + E_2}$$



- **2 + 3 jets at NLO**
  3 jet NLO shift ~ α_s^2
- **Theory scale uncertainties**

Conclusions

- Remarkable experimental progress in understanding jet substructure. Increasingly sophisticated tools - promising future!

- Analytic tools play an important role in understanding algorithms, and interpreting MC

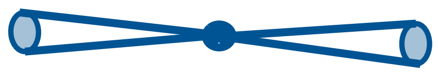
- Want event generators with best possible accuracy to connect theory and experiment

- A recent development: Can now combine several jet multiplicities at NLO with resummation/parton shower
  Expect $pp \to H + 0, 1\,\mathrm{jets}\,, \quad pp \to W + 0, 1\,\mathrm{jets}$ soon.

Thank you

Back Up Slides

Systematic Improvement of MC Using EFT

- For given N-jet 

[Bauer, Fleming, Luke, Pirjol, Stewart]

- Small $\mathcal{T}_2$: Use SCET to calculate resummed QCD distributions.

Systematically include: α_s^n matching and resum renormalization group $\alpha_s^n \ln^m(\mathcal{T}/Q)/\mathcal{T}$

$$\frac{d\sigma_2^s}{d\Omega\, d\mathcal{T}} = \frac{d\sigma_B}{d\Omega} H_2(E_{\rm cm}^2, \mu) \int ds_1 ds_2\, J_1(s_1, \mu)\, J_2(s_2, \mu)\, S_2\left(\mathcal{T} - \frac{s_1}{Q_1} - \frac{s_2}{Q_2}, \mu\right)$$

Hard Function: NLO matrix elements

Jet and Soft functions: Collinear and soft limit

- Combine with large $\mathcal{T}_2$ in 2-jet bin

$$\frac{d\sigma_2}{d\Omega\, d\mathcal{T}} = \underbrace{\frac{d\sigma_2^s}{d\Omega\, d\mathcal{T}}}_{\text{Resummed}} + \underbrace{\left[\frac{d\sigma_2^{\rm QCD}}{d\Omega\, d\mathcal{T}} - \frac{d\sigma_2^s}{d\Omega\, d\mathcal{T}}\bigg|_{\rm exp}\right]}_{\text{Non-singular NLO}}$$

NLL'= NLO FO+ $\alpha_s^n L^{2n-1}$

- Distribute events according to:

2-body events **3-body events**

$$\frac{\mathrm{d}\sigma_2}{\mathrm{d}\Phi_2}(\mathcal{T}_{\mathrm{cut}}) = \int_0^{\mathcal{T}_{\mathrm{cut}}} \mathrm{d}\mathcal{T}_2 \frac{\mathrm{d}\sigma_2}{\mathrm{d}\Omega\,\mathrm{d}\mathcal{T}_2} \quad + \quad \frac{\mathrm{d}\sigma_{\geq 3}}{\mathrm{d}\Phi_3} = \left(\frac{\mathrm{d}\sigma_2}{\mathrm{d}\Omega_2\,\mathrm{d}\mathcal{T}_2} \Big/ \frac{\mathrm{d}\sigma_2}{\mathrm{d}\Omega_2\,\mathrm{d}\,\mathcal{T}_2}\Big|_{\mathrm{exp}} \right) \frac{\mathrm{d}\sigma_{\geq 3}^{\mathrm{FO}}}{\mathrm{d}\Phi_3}\theta(\mathcal{T}_2 > \mathcal{T}_{\mathrm{cut}})$$

Constant $\mathcal{T}_2$ dependence for 2-body events

Has full Φ_3 dependence

Large $\mathcal{T}_2$: Resummation starts to turn off.
Ratio starts at $\mathcal{O}(\alpha_s^2)$

Small $\mathcal{T}_2$: Resummation important
Ratio starts at NNLL