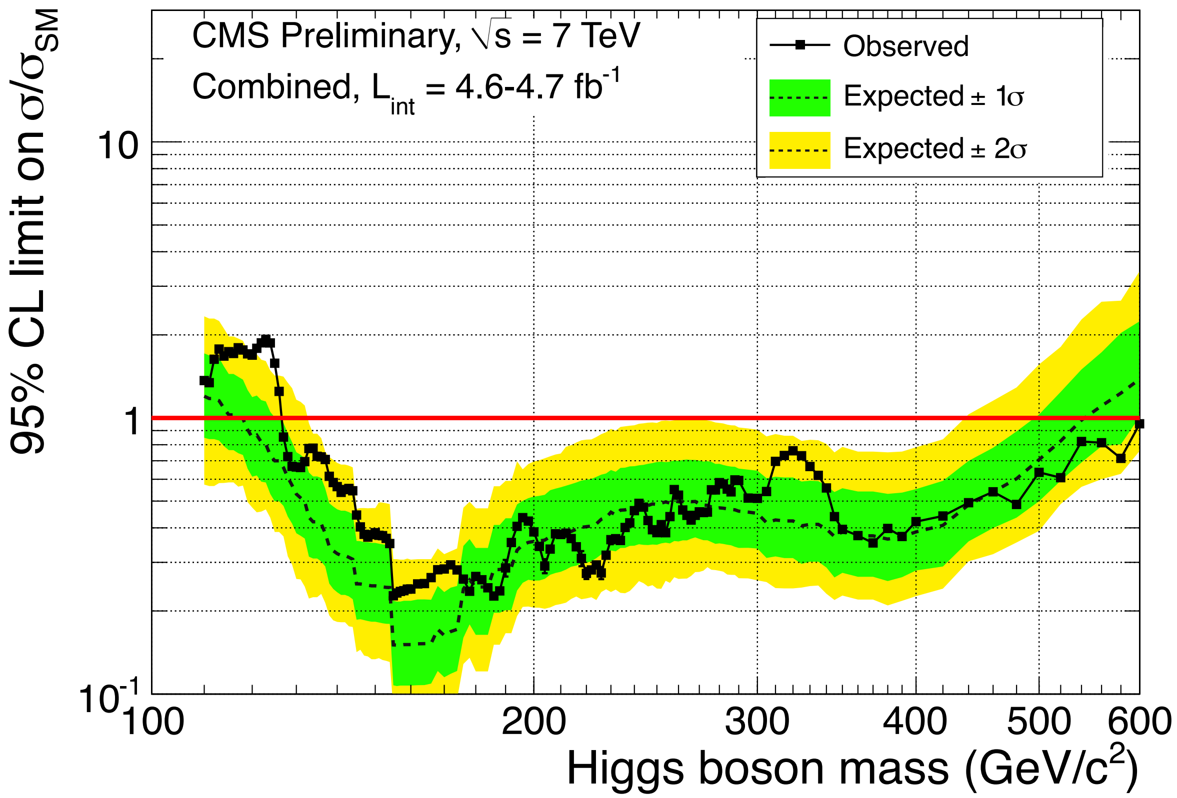
Higgs Searches in Hadronic Final States

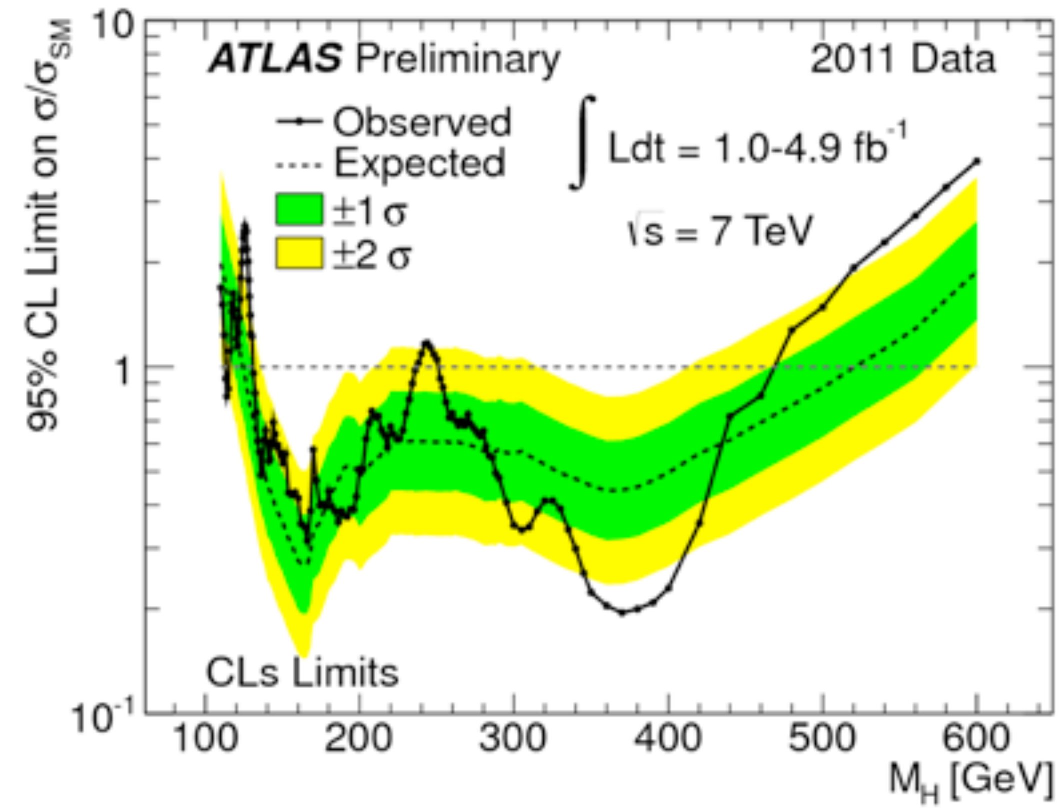
Michael Spannowsky

University of Durham

CMS combined



ATLAS combined



- Excesses around 125 GeV driven by photon and lepton final states
- 2012 Data can bring evidence for existence of 125 GeV resonance
- However, not clear if resonance is SM Higgs ...
  - ➡ Spin and CP
  - ➡ Couplings to fermions, i.e. top, bottom, taus
  - ➡ Couplings to gauge bosons
  - ➡ Higgs selfcoupling
  - ➡ Extended Higgs sector / new decay channels

Need better understanding of hadronic final states

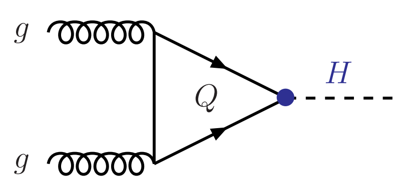
After finding a bump, we need to study its origin:

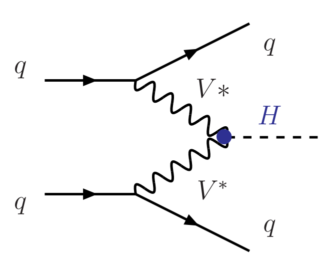
- If observed in ZZ and photons:

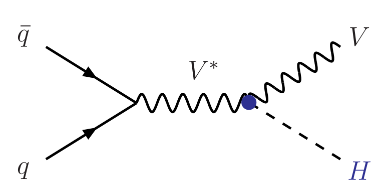
  Spin 1 ruled out by Landau-Yang theorem (photons)

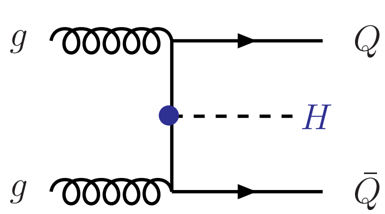
  CP-odd ruled out by Z decay (if no CP-violation in Higgs sector)

- If the Higgs is SM-like it has to show up in several channels









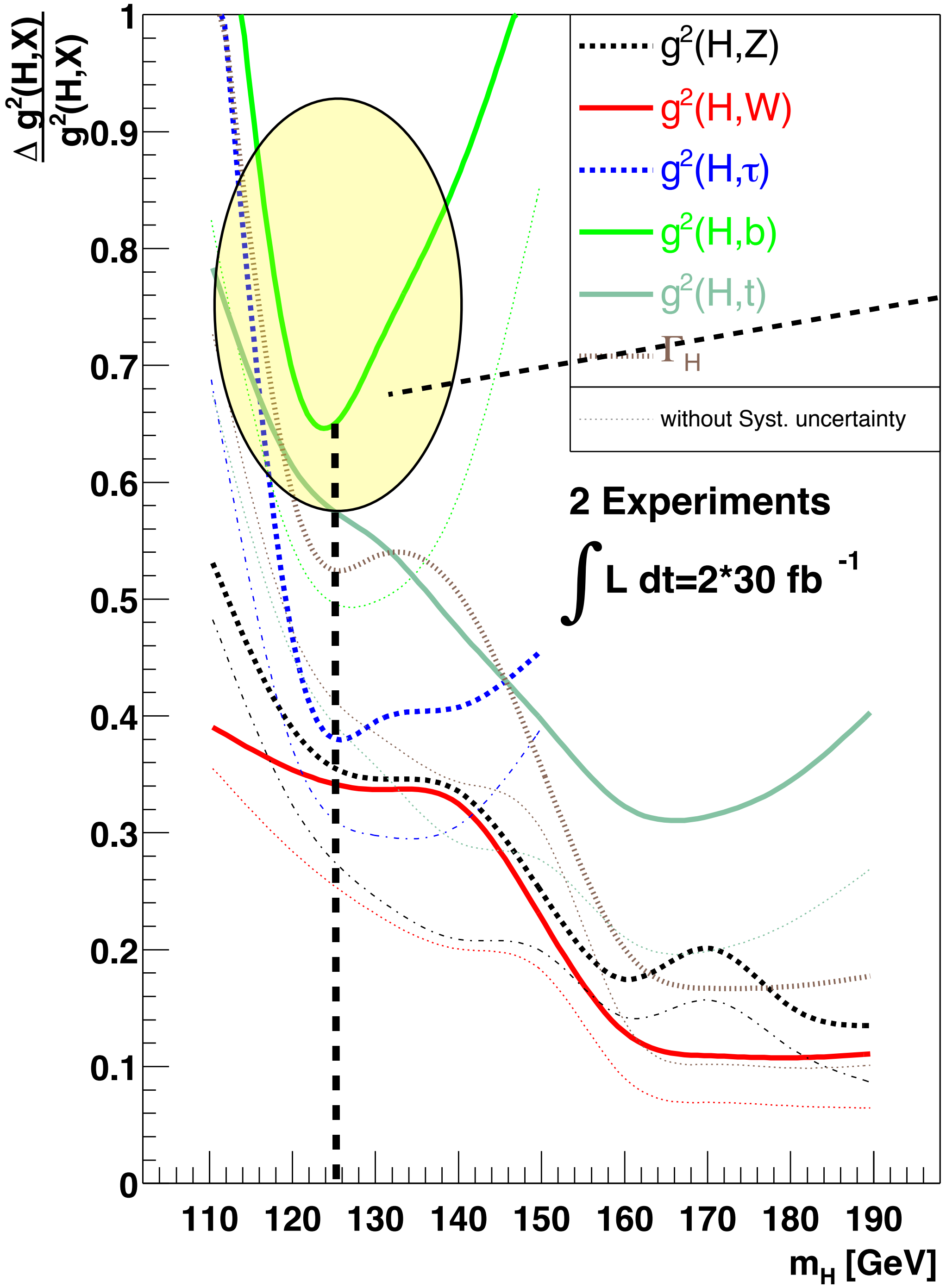
production	decay
$gg \to H$	ZZ
qqH	ZZ
$gg \to H$	WW
qqH	WW
$t\bar{t}H$	$WW(3\ell)$
$t\bar{t}H$	$WW(2\ell)$
inclusive	$\gamma\gamma$
qqH	$\gamma\gamma$
$t\bar{t}H$	$\gamma\gamma$
WH	$\gamma\gamma$
ZH	$\gamma\gamma$
qqH	$\tau\tau(2\ell)$
qqH	$\tau\tau(1\ell)$
$t\bar{t}H$	$b\bar{b}$
WH/ZH	$b\bar{b}$ (subjet)

Channels are mutually related

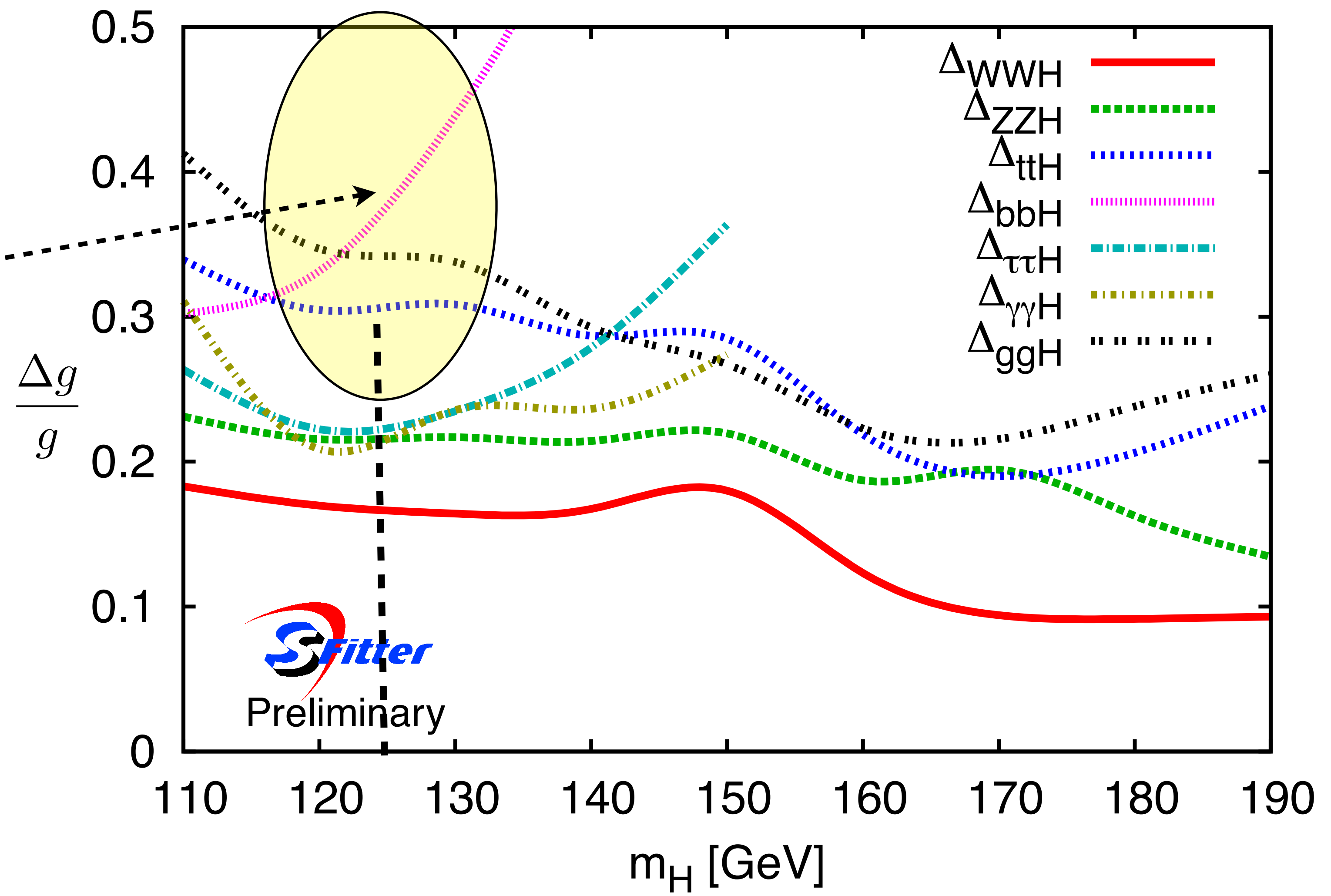
Some couplings/channels very challenging:

- Higgs decay to light fermions
- Extracting $HZ\gamma$

[Zeppenfeld, Kinnunen, Nikitenko, Richter-Was PRD 62 (2000); Duehrssen (2005)]



[Lafaye, Plehn, Rauch, Zerwas, Duehrssen (2009)]



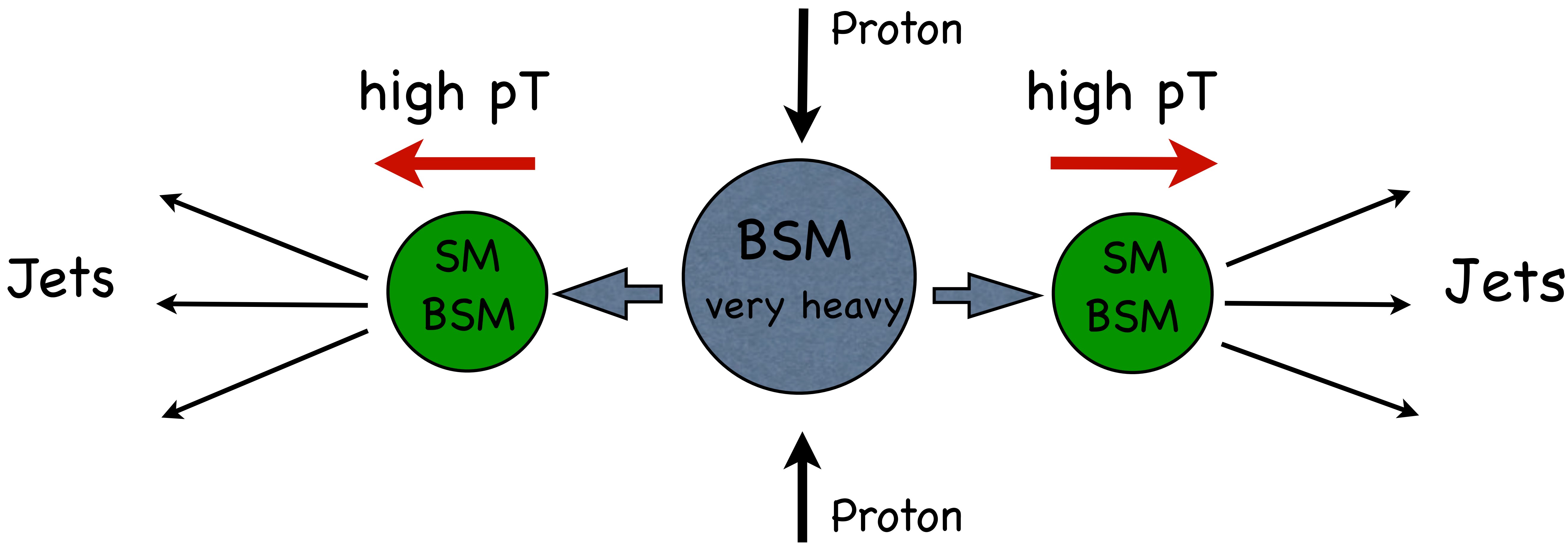
- Huge improvement from boosted Higgs analysis
- also for non-b decay modes due to better knowledge of total width

To reduce uncertainty for all coupling, need to measure b and t coupling

$$\sigma \cdot BR \propto g_p^2 \frac{g_d^2}{\Gamma_H}$$

assumed: $\Gamma_H = \Sigma_{SM} \Gamma_i \quad \Gamma_i \sim g_d^2$

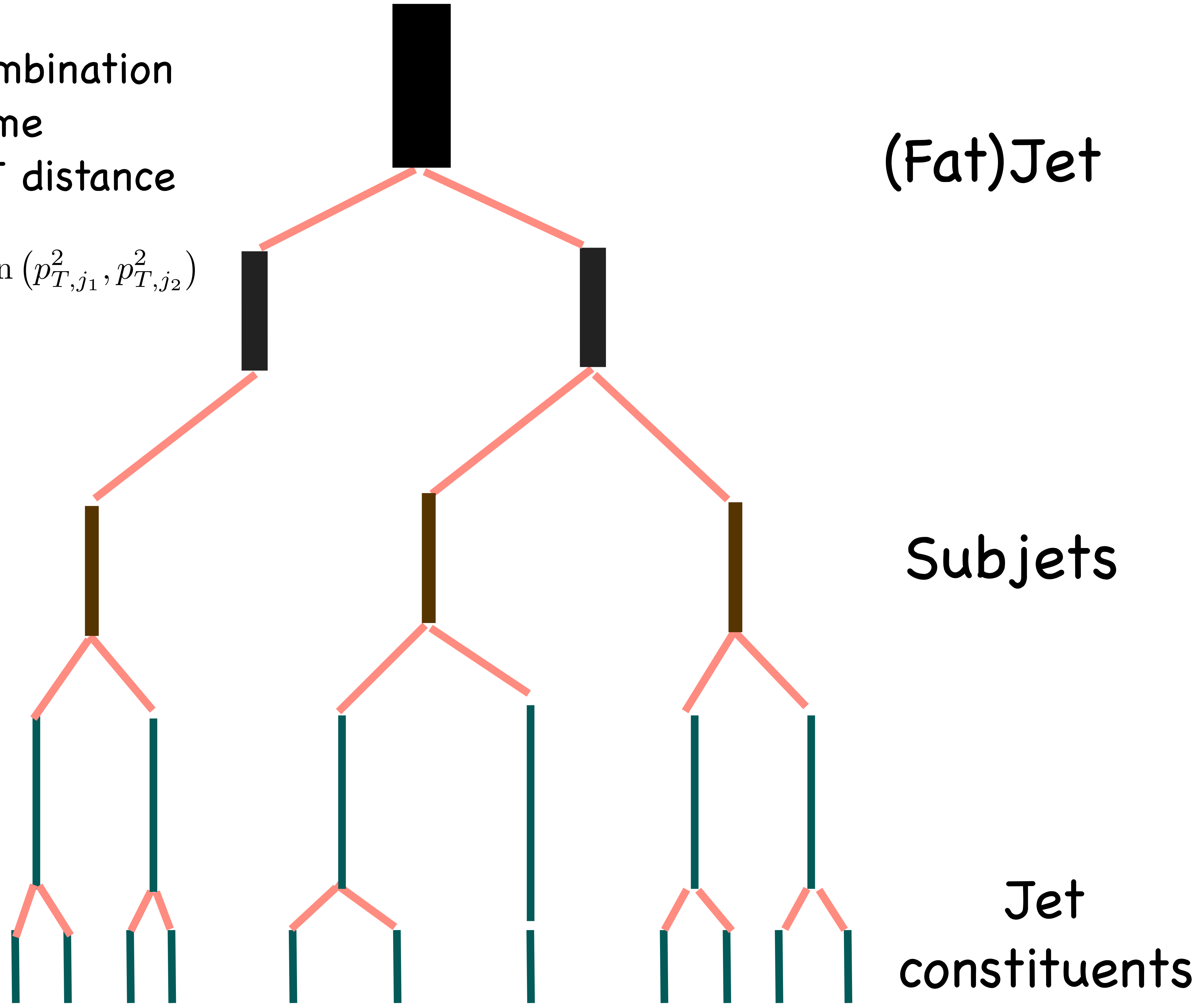
Boosted configurations help to overcome QCD backgrounds:

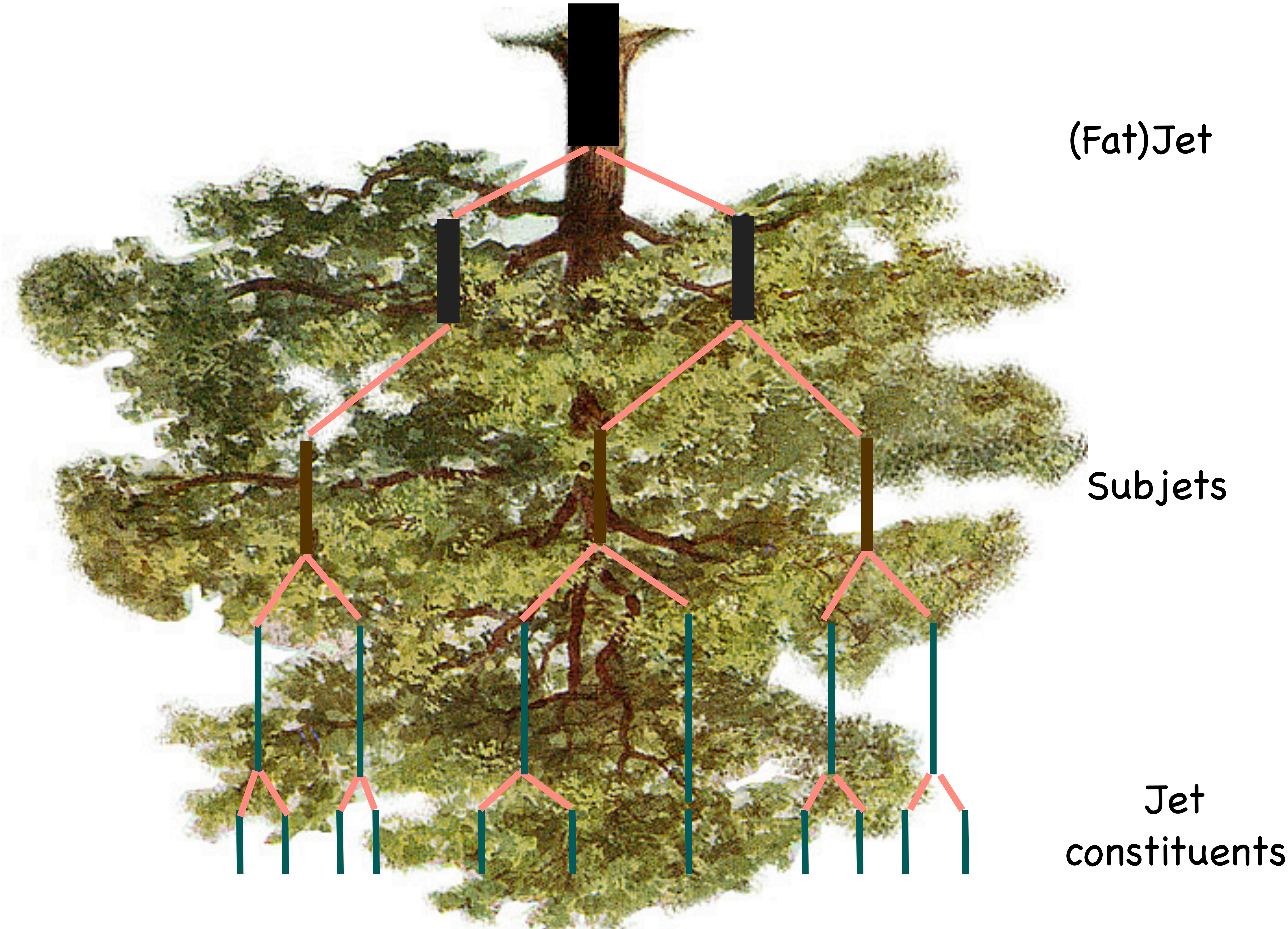


- overlapping radiation
- jet-parton matching breaks down
- need big jet cone

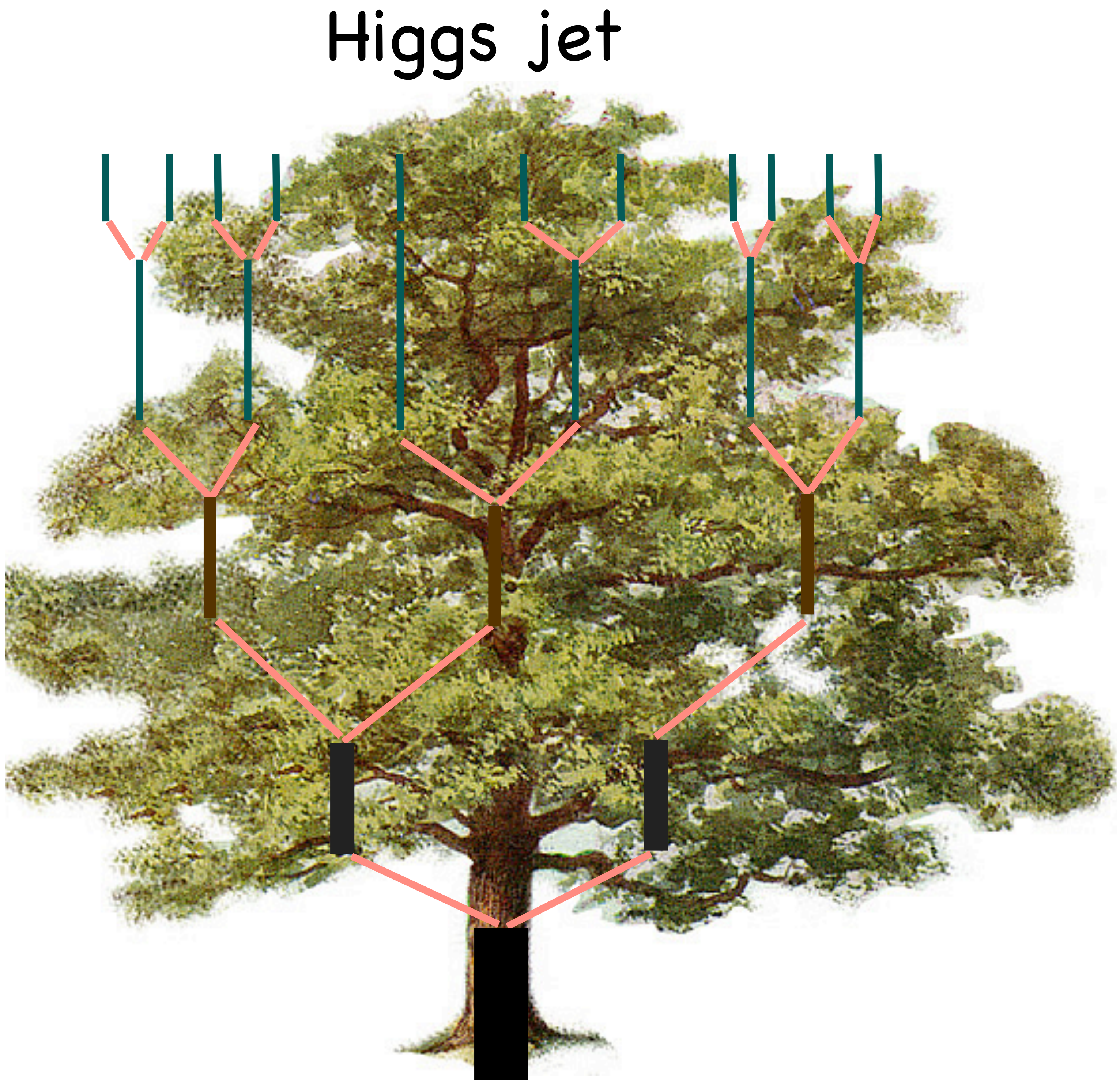
order of recombination defined by some metric, e.g. kT distance

$$d_{j_1 j_2} = \frac{\Delta R^2_{j_1 j_2}}{D^2} \; \min\left(p^2_{T,j_1}, p^2_{T,j_2}\right)$$




(Fat)Jet
Subjets
Jet
constituents

For jet substructure study reverse cluster history and analyze internal structure



Are we done?

In a perfect world (or an e+e- collider) this
would be most of the story

However, at the LHC many sources of radiation:

[Cacciari, Salam, Sapeta JHEP 1004]

- Pileup $\rightarrow$ Can add up to 100 GeV of soft radiation per unit rapidity

- Underlying Event $\rightarrow$ $\langle \delta m_j^2 \rangle \simeq \Lambda_{\mathrm{UE}}\, p_{T,j} \left(\frac{R^4}{4} + \frac{R^8}{4608} + \mathcal{O}(R^{12}) \right)$ with $\Lambda_{\mathrm{UE}} \sim \mathcal{O}(10)$ GeV

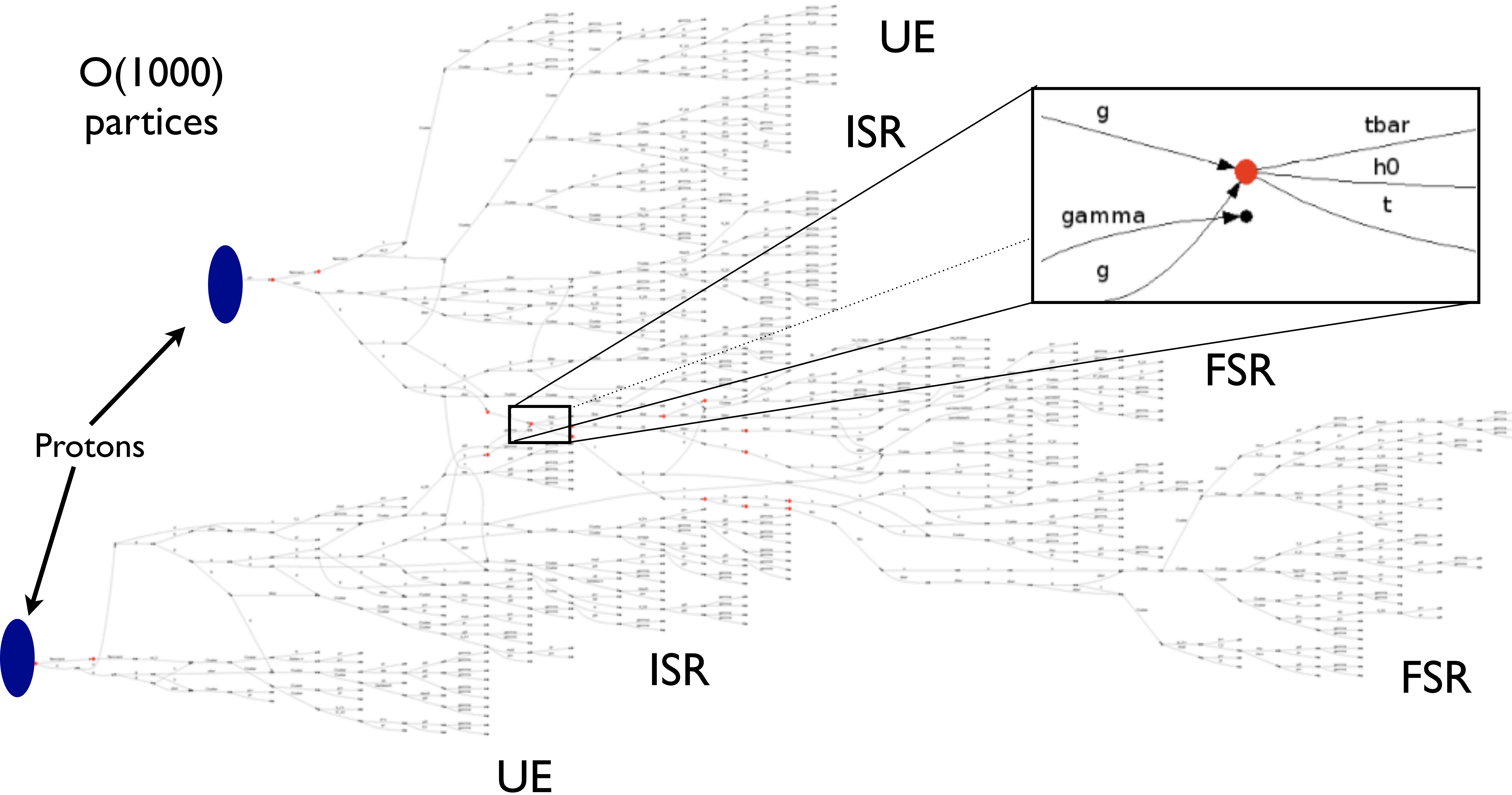
[Dasgupta, Magnea, Salam JHEP 0802]

- Initial state radiation (ISR)

- Hard radiation from many resonances in event

$\longrightarrow$ Need methods to separate final state radiation (FSR) from rest of event

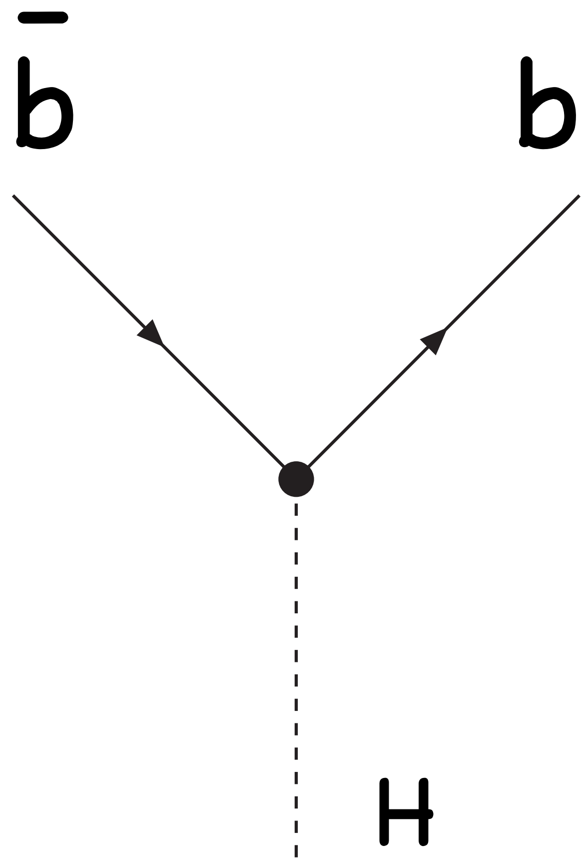
LHC hosts complex environment!



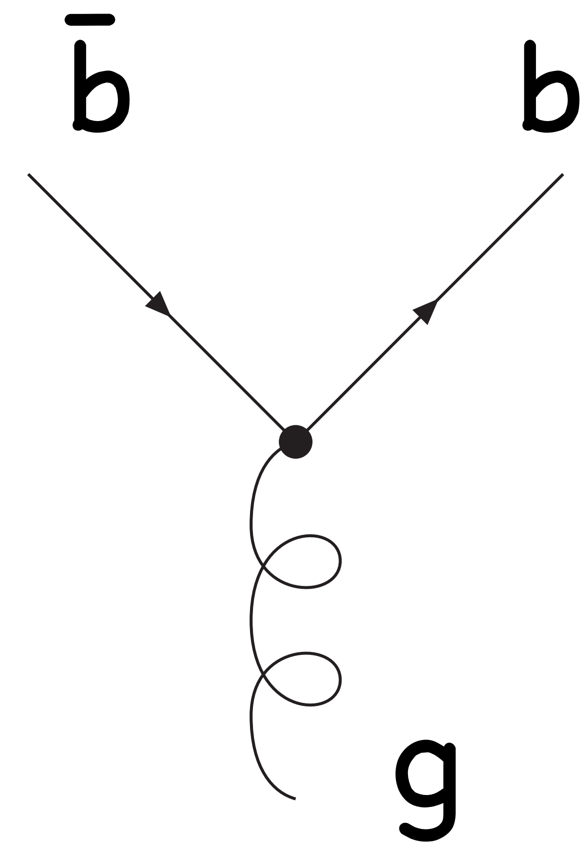
Tedious for theorists and experimentalists

I. Measuring the Higgs-bottom coupling using boosted techniques

Signal:



Background:



Novel techniques can help: "Mirror, mirror on the wall ..."

Do I look like a Higgs jet or do I look like a gluon jet?

Don't answer:

To me you just look like a fat jet

First time idea: [M. H. Seymour, Z. Phys. C 62, 127 (1994)]

Trailblazing analysis: [Butterworth, Davison, Rubin, Salam PRL 100 (2008)]
confirmed by ATLAS [ATL-PHYS-PUB-2009-088]

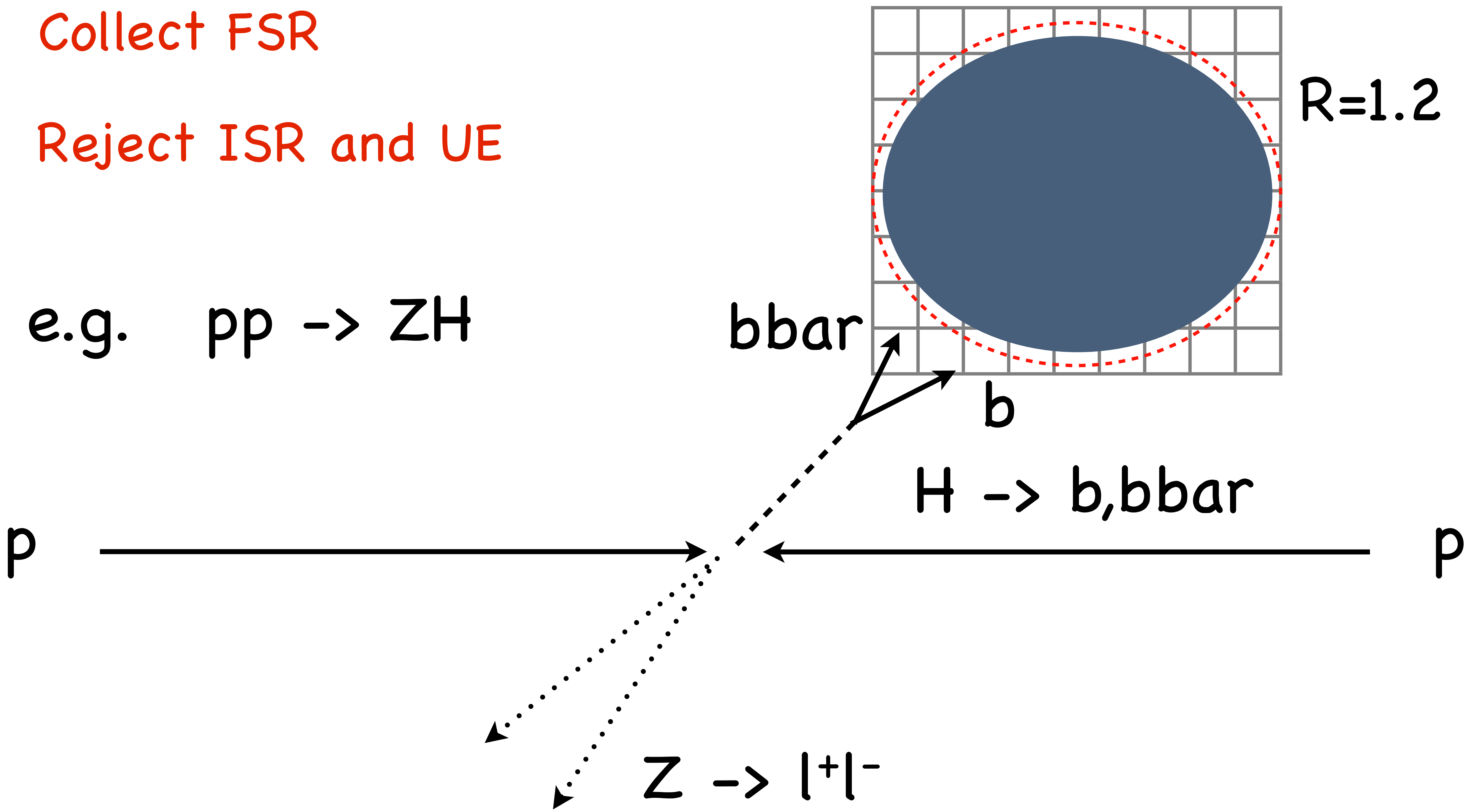
HV - Higgs discovery channel

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

Collect FSR

Reject ISR and UE

e.g. pp -> ZH



HV - Higgs discovery channel

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

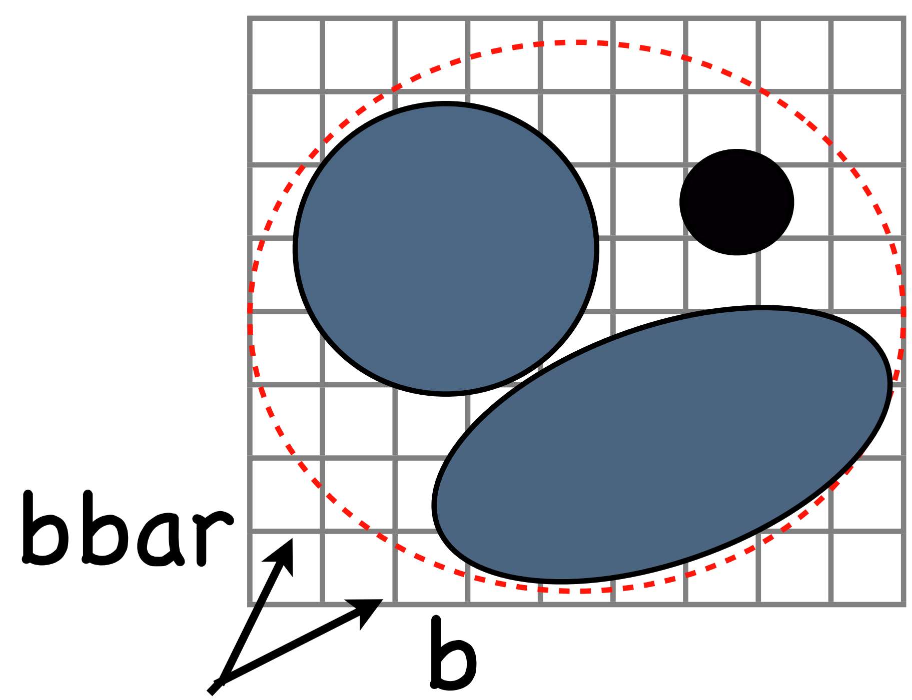
mass drop:

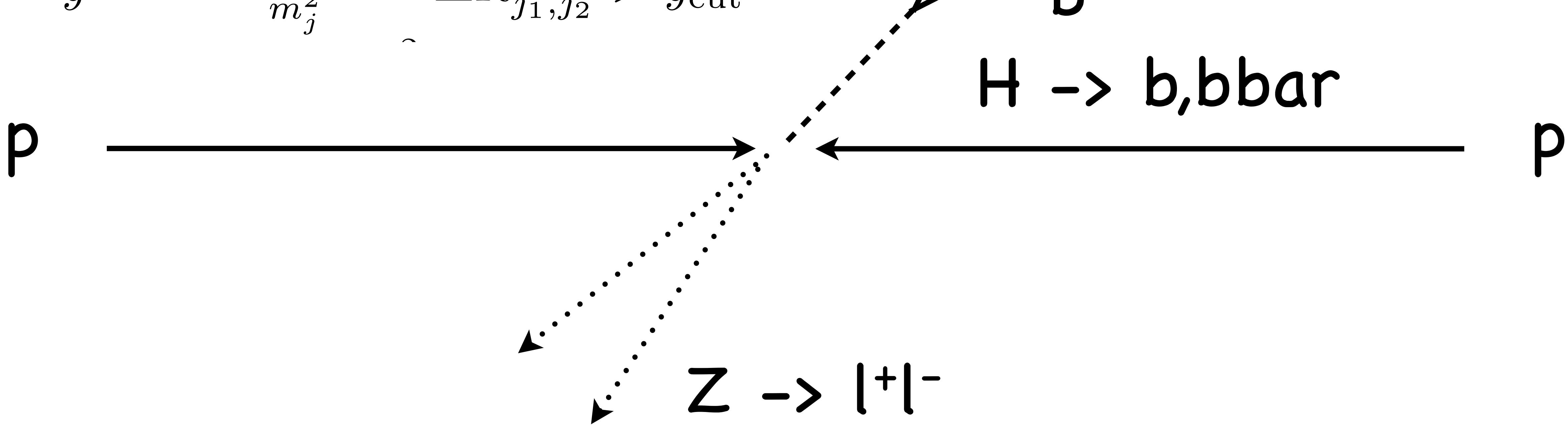
1) check for mass drop

   $m_{j1} < 0.66\ m_j$

2) check "asymmetry"

$$y = \frac{\min\left(p_{t_{j1}}^2, p_{t_{j2}}^2\right)}{m_j^2} \Delta R_{j_1,j_2}^2 > y_{\mathrm{cut}}$$



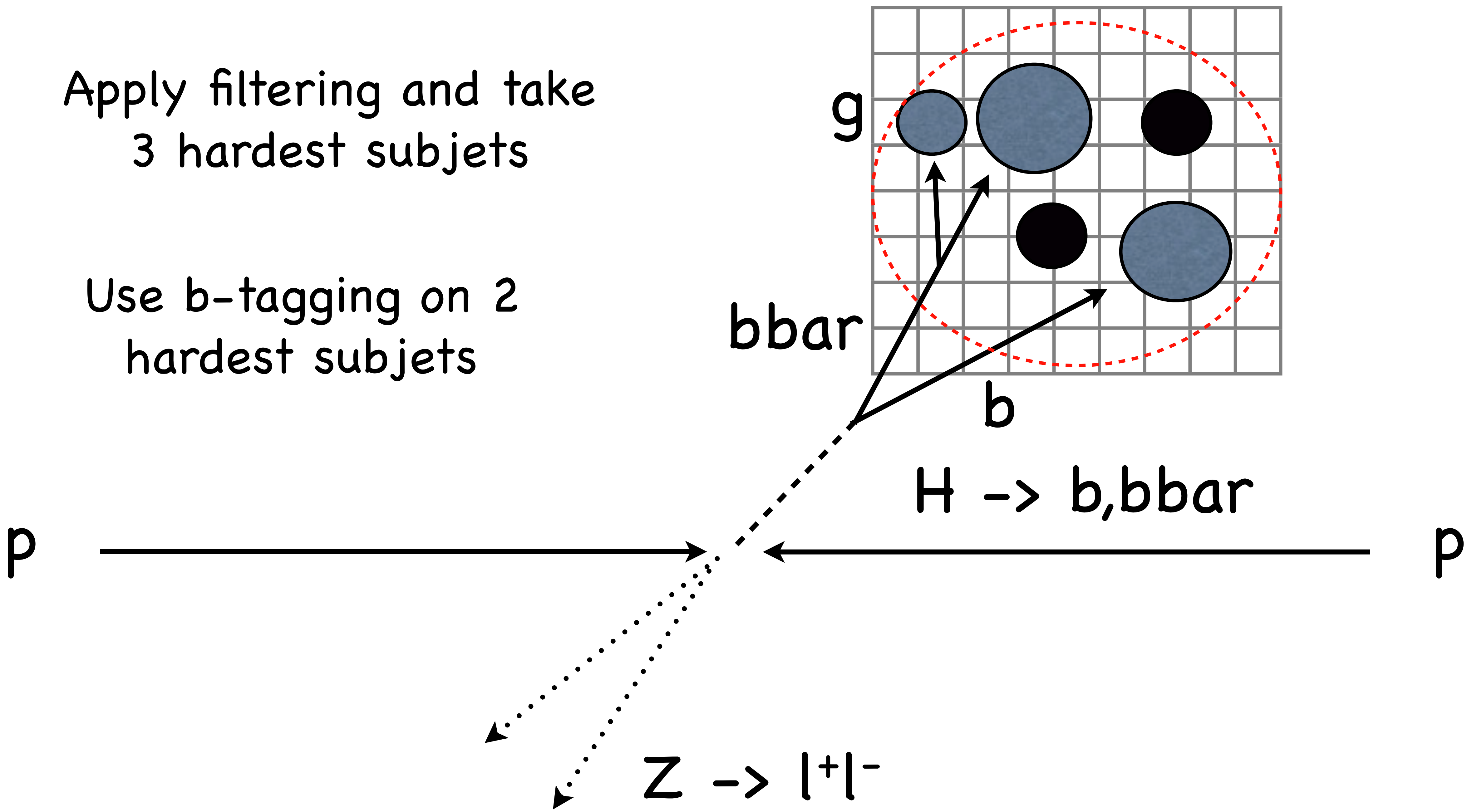


HV - Higgs discovery channel

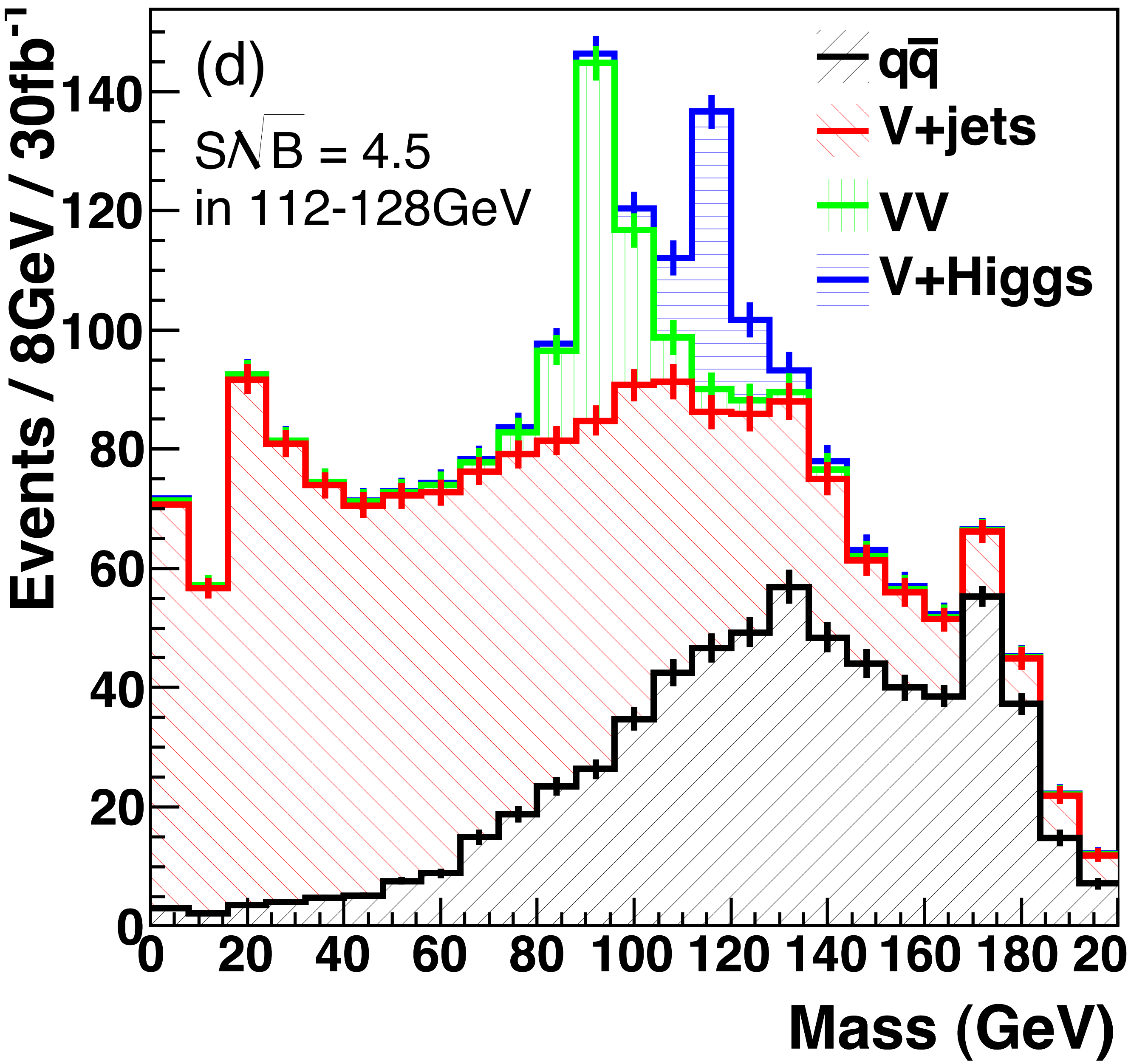
[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

Apply filtering and take 3 hardest subjets

Use b-tagging on 2 hardest subjets



BDRS Result

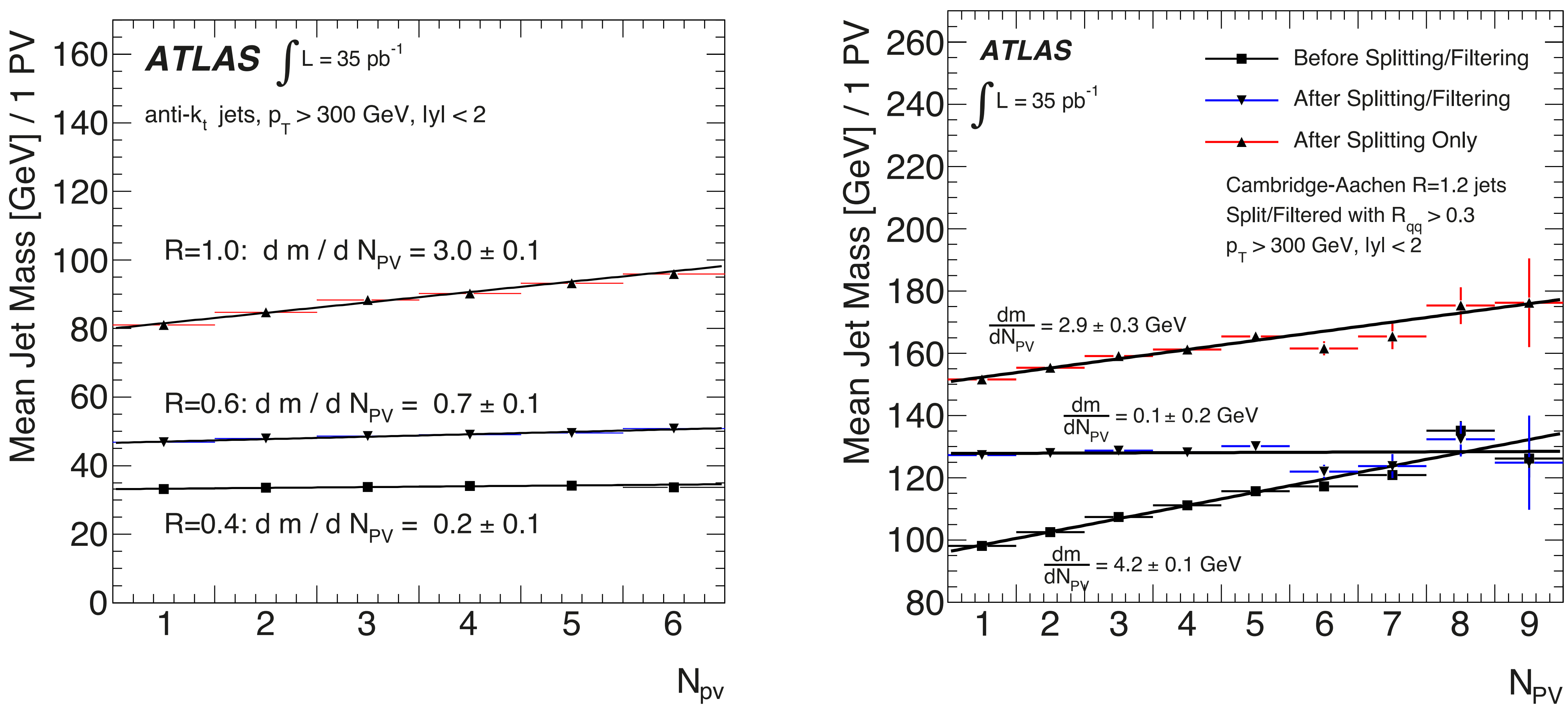


- LHC 14 TeV; 30 fb^{-1}
- HERWIG/JIMMY/Fastjet cross-checked with PYTHIA with "ATLAS tune"
- 60% b-tag; 2% mistag
- Combination of HZ and HW channels
- Further improvements are possible [Soper, MS JHEP 1008 (2010)] [Soper, MS PRD 84 (2011)]

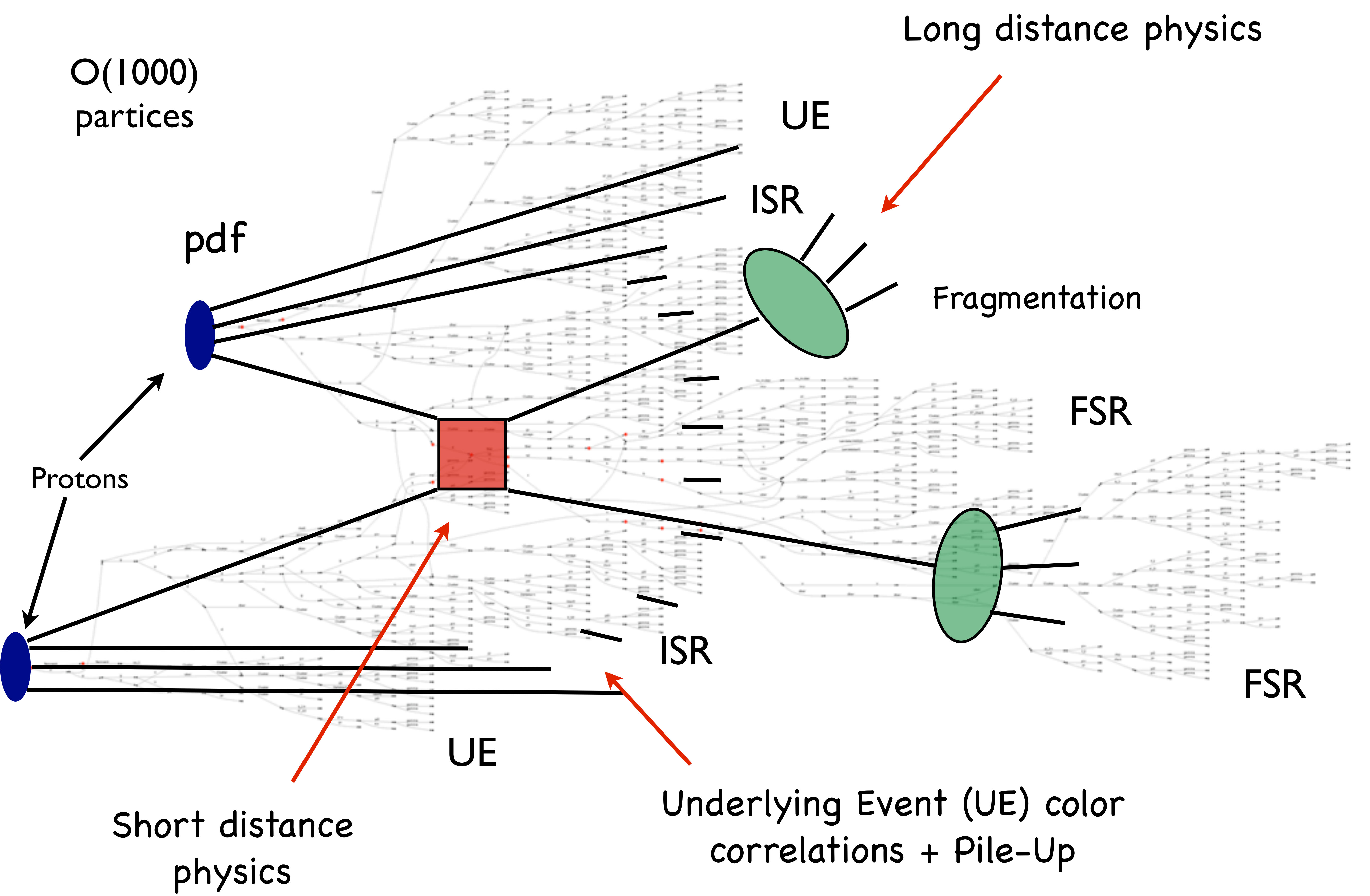
Confirmed in ATLAS full detector simulation

First studies of method using data: (see ATLAS 1203.4606)

- Jet mass in good agreement with MC
- y-splitter observable in good agreement with MC
- Massdrop + Filtering as predicted by MC
- Pileup under control so far:



All measurements indicate large potential for jet substructure techniques and good agreement with MC


Long distance physics
O(1000)
partices
UE
ISR
pdf
Fragmentation
FSR
Protons
ISR
FSR
UE
Short distance
physics
Underlying Event (UE) color
correlations + Pile-Up

More information -> better discrimination

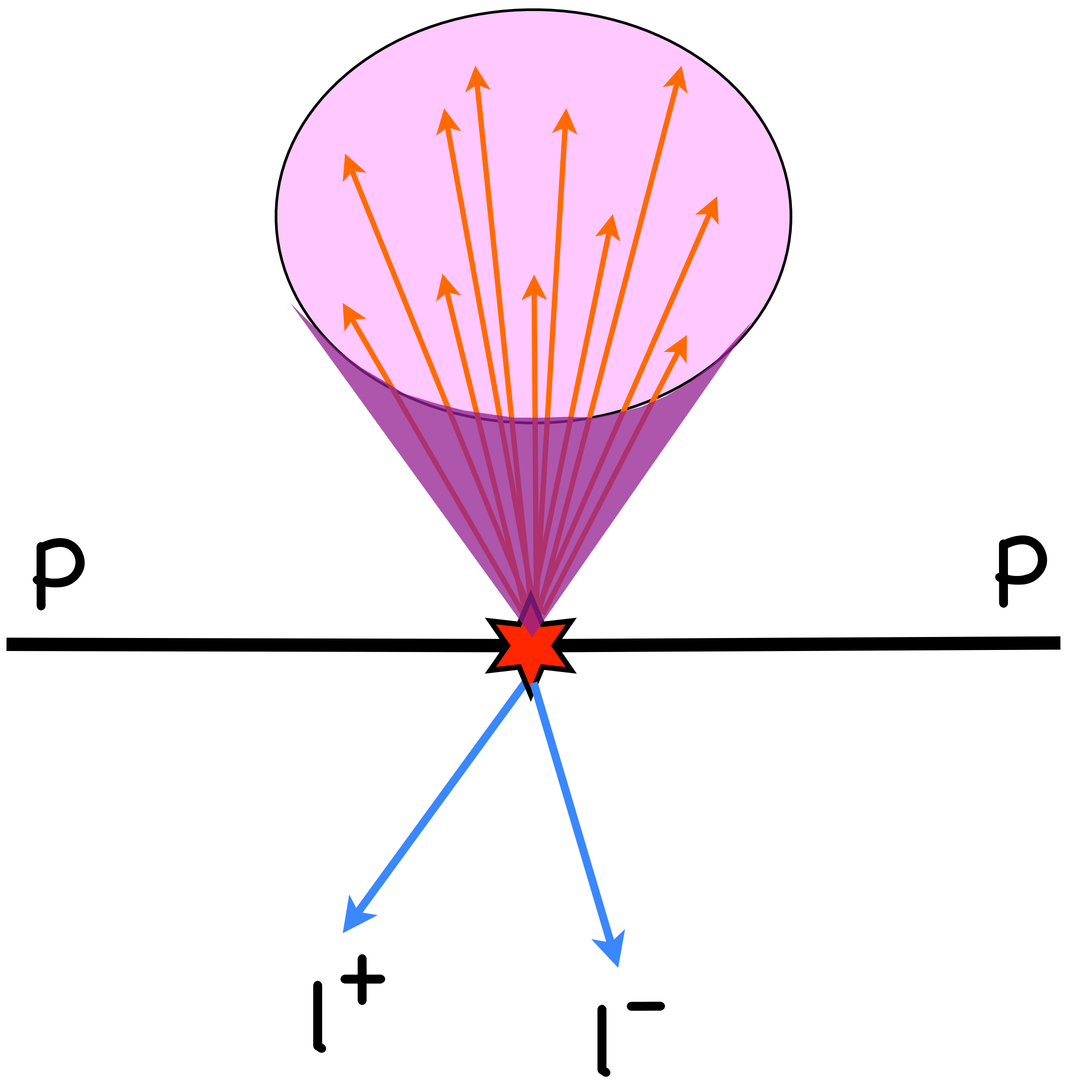
Our approach:

Shower deconstruction

- Maximal information approach to discriminate signal from backgrounds
  -> UE, ISR, FSR, hard process
- We want one discriminating analytic function
- Have to respect experimental limitations

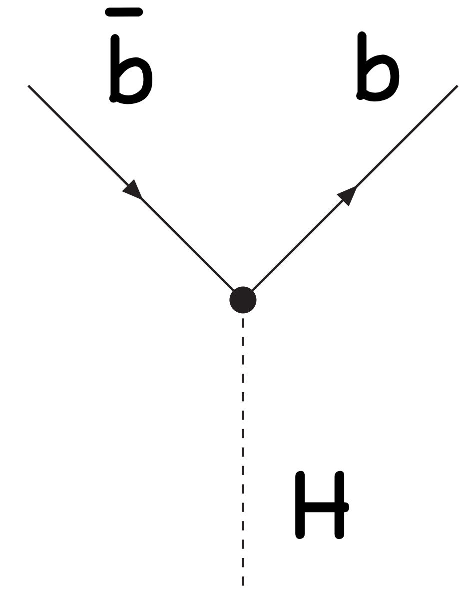
[Soper, MS PRD 84 (2011)]

Playground: Boosted HZ final state

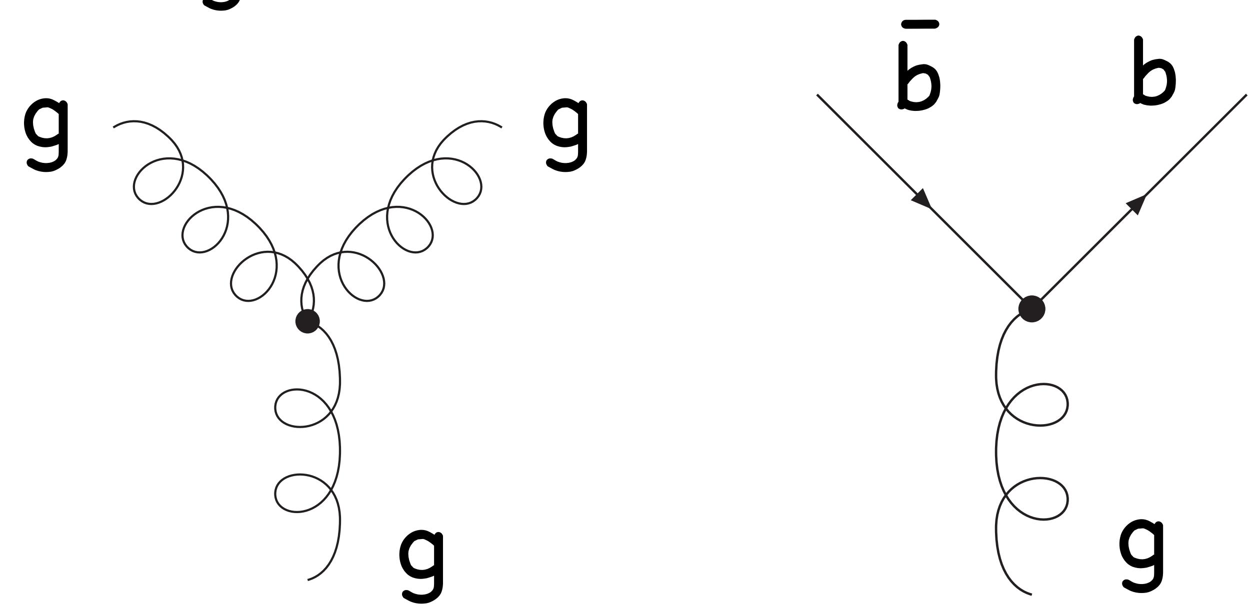


pT>200 GeV

signal



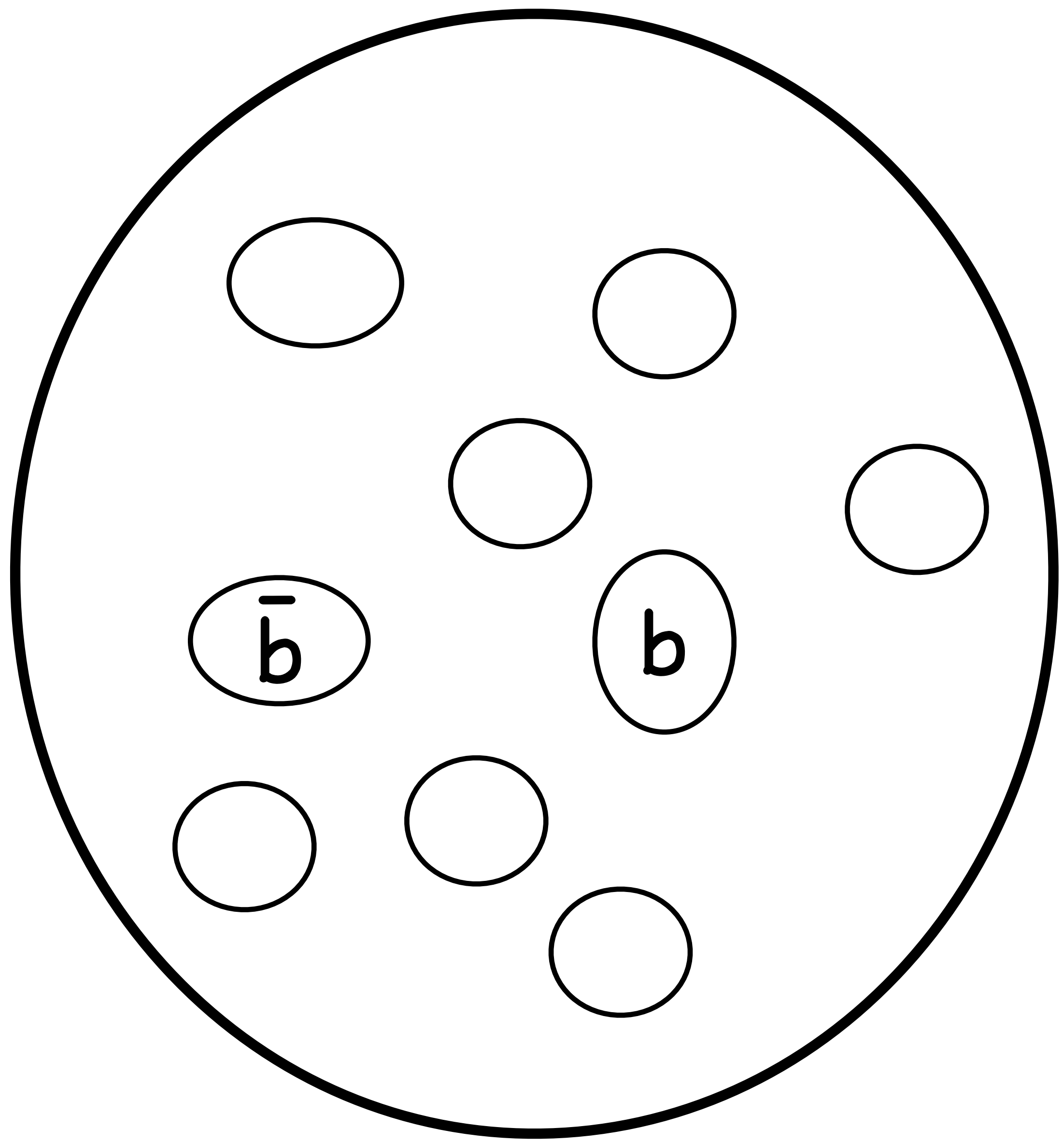
background



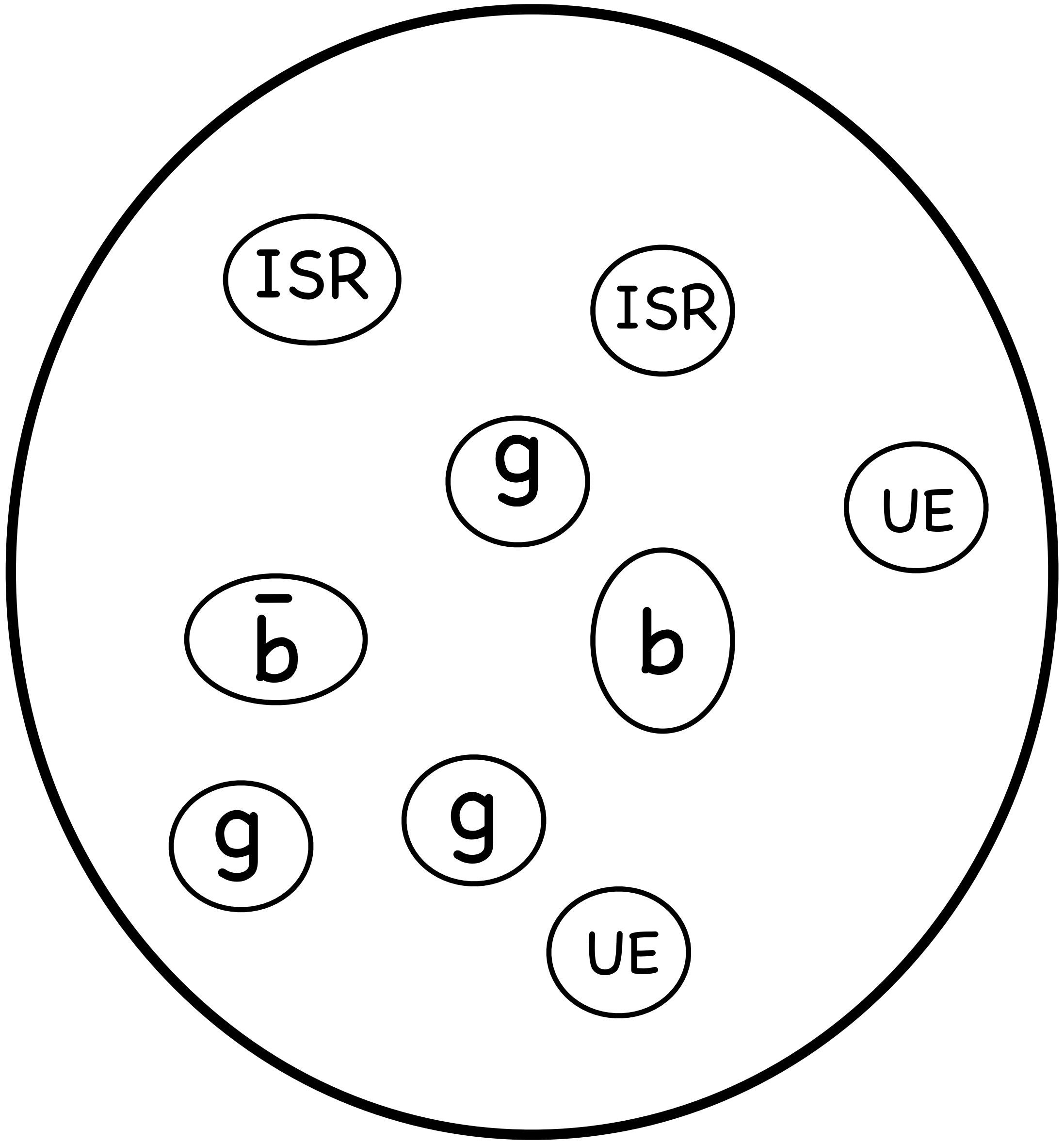
Recombine fat jet's constituents to microjets

(kT, R=0.15, pT > 2 GeV)

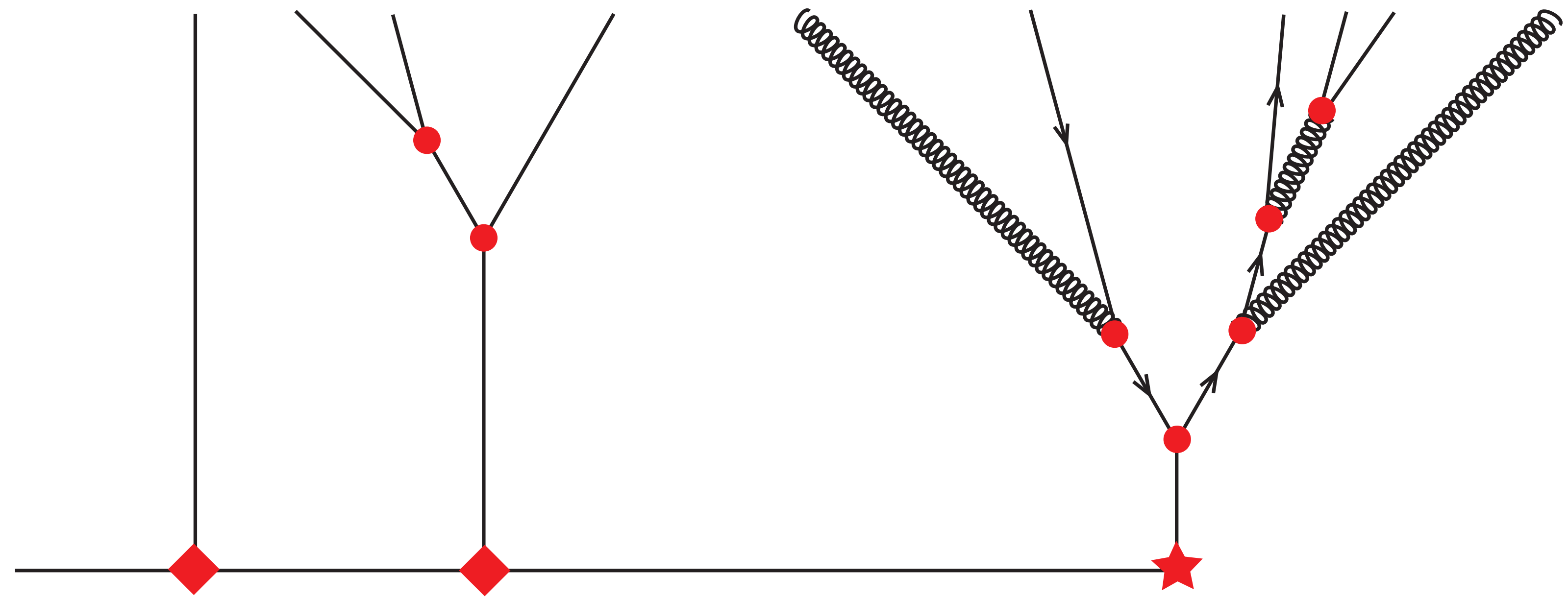
microjets are basic elements of event/fat jet



Fat jet: R=1.2, anti-kT



microjets
R=0.15, kT

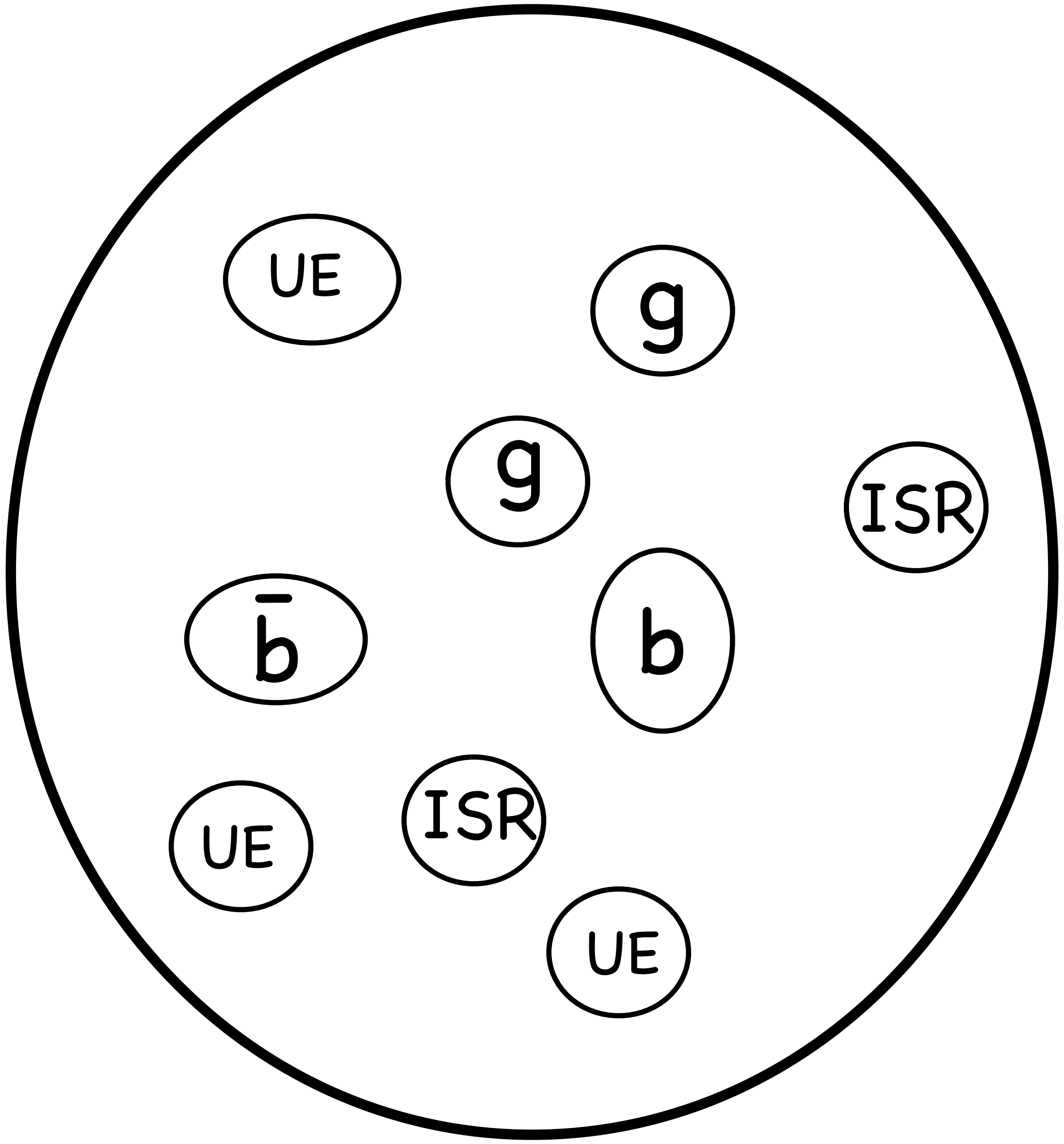


Build all possible shower histories

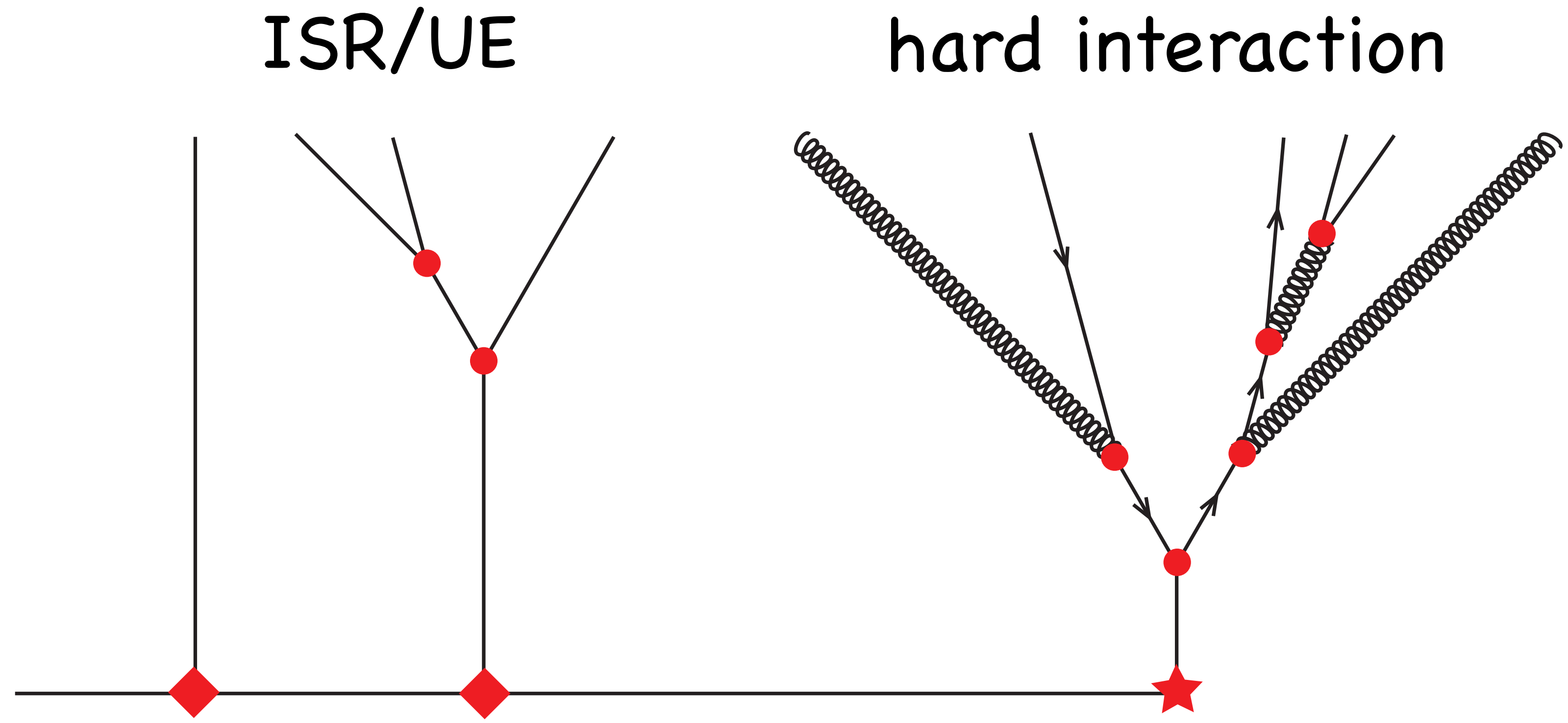
signal vs background hypothesis
based on:

- Emission probabilities
- Color connection
- Kinematic requirements
- b-tag information

Fat jet: R=1.2, anti-kT



microjets
R=0.15, kT



Build all possible shower histories

signal vs background hypothesis based on:

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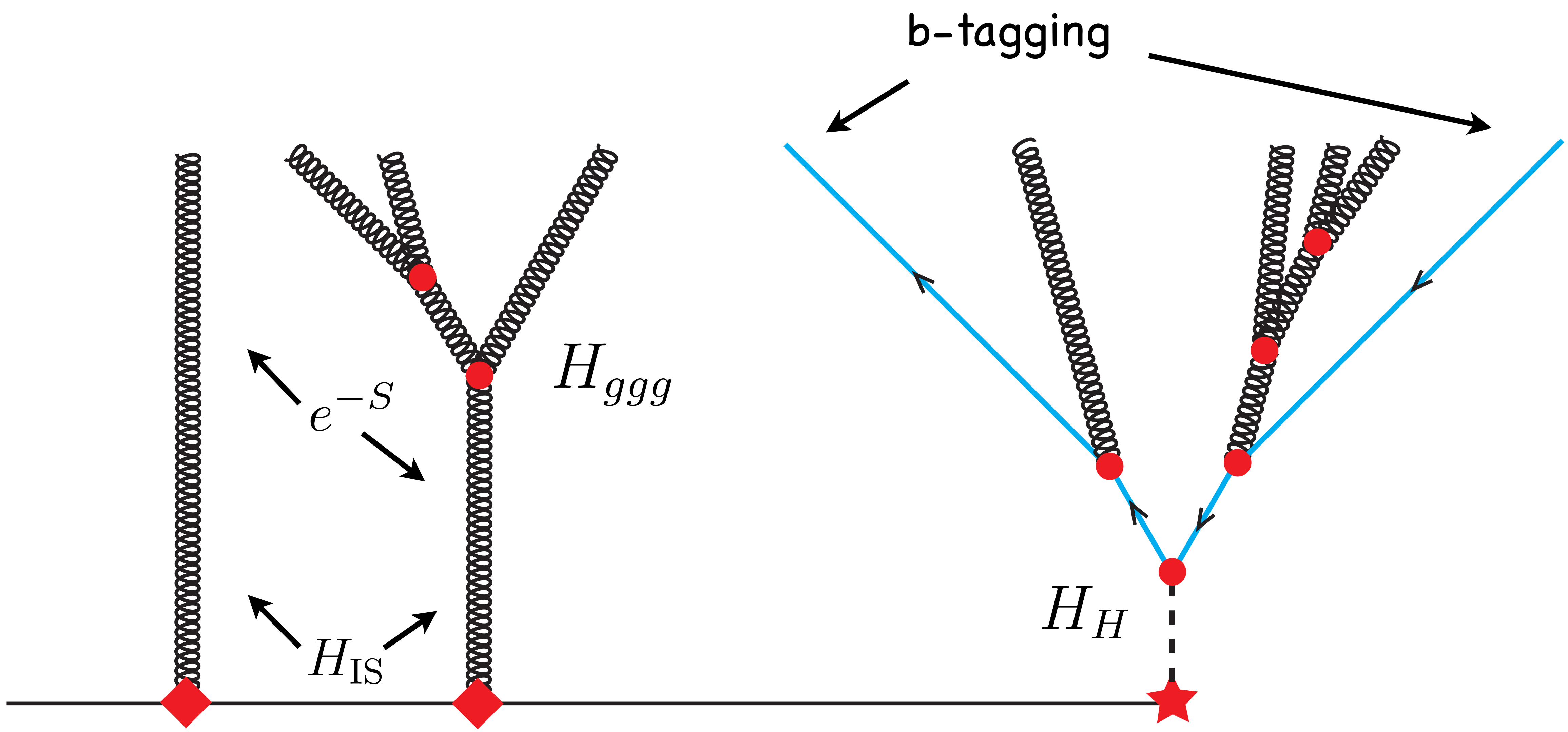


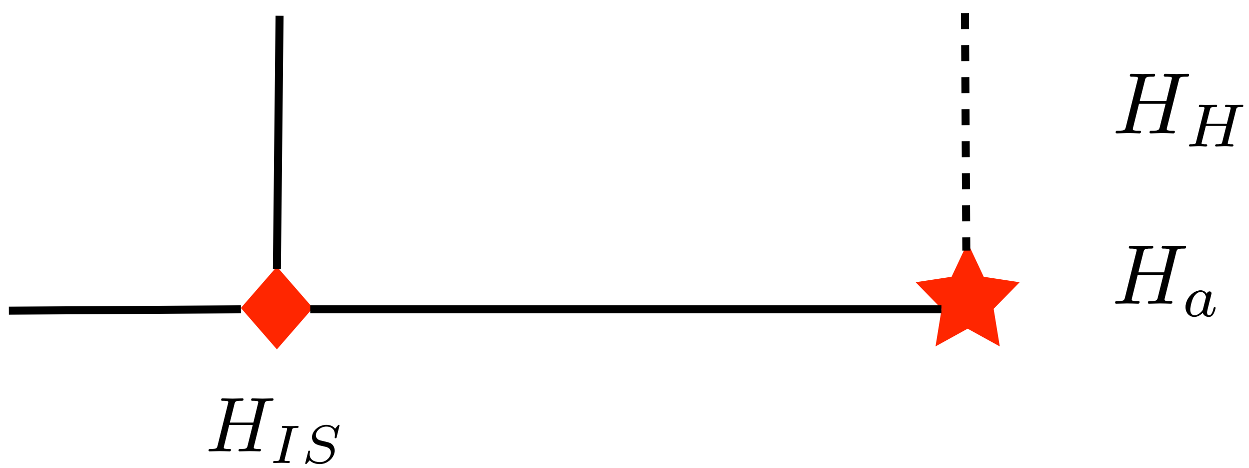
Want to convert the shower history into analytic expression

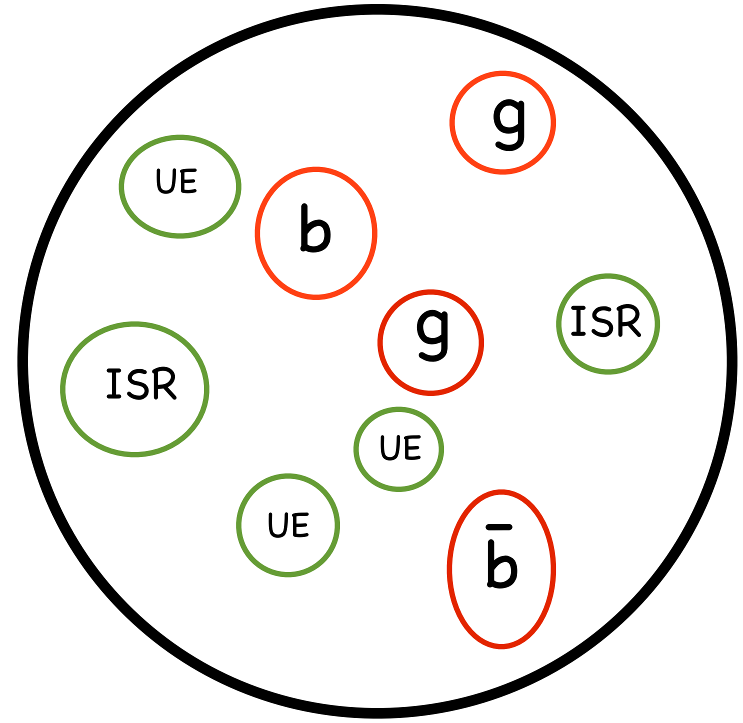
➡ Feynman Rules for Shower Deconstruction

$$\chi(\{p,t\}_N) = \frac{P(\{p,t\}_N|\mathrm{S})}{P(\{p,t\}_N|\mathrm{B})} = \frac{\sum_{\rm histories} H_{ISR} e^{-S_{I1}} \ldots \sum_{\rm histories} H_H e^{-S_{s1}} H^s_{bg} e^{-S_{s2}} \ldots}{\sum_{\rm histories} H_{ISR} e^{-S_{I1}} \ldots \sum_{\rm histories} H_{gbb} e^{-S_{b1}} H^b_{bg} e^{-S_{b2}} \ldots}$$

χ is the one analytic function to discriminate signal from background

(for more detail see [Soper, MS PRD 84 (2011)])





$$Q^2 = \left(\sum_{i \in \text{fat jet}} \vec{p}_{T,i}\right)^2 + \left(\sum_{i \in \text{fat jet}} p_i\right)^2$$

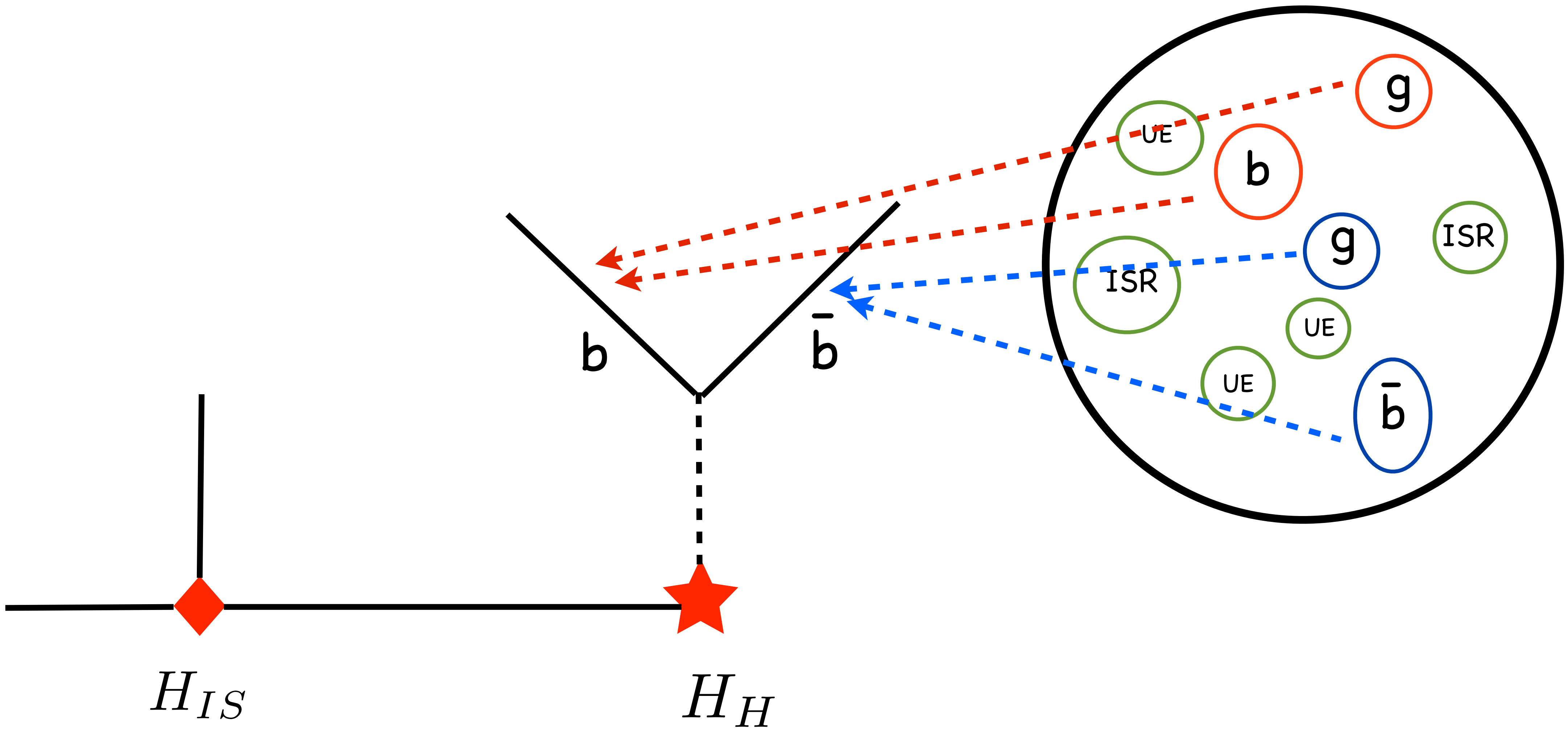
$$H_g = N_{\text{pdf}}^g \left(\frac{p_{T,\text{min}}^2}{k_0^2}\right)^{N_{\text{pdf}}^g} \frac{1}{k_0^2}\, \Theta(k_{T,\text{I}}^2 < Q^2/4)$$

ISR vs Hard scale cut

$$H_H = N_{\text{pdf}}^H \left(\frac{p_{T,\text{min}}^2 + m_H^2}{k_H^2 + m_H^2}\right)^{N_{\text{pdf}}^H} \frac{1}{k_H^2 + m_H^2}\, \Theta(k_{T,\text{I}}^2 < Q^2/4)$$

$$H_{\text{IS}} = \frac{C_{\text{A}}}{2} \frac{\alpha_{\text{s}}(k_J^2 + \kappa_{\text{p}}^2)}{k_J^2 + \kappa_{\text{p}}^2} \frac{1}{(1 + c_R\, k_J/Q)^{n_R}} + \frac{c_{\text{np}}(\kappa_{\text{np}}^2)^{n_{\text{np}}-1}}{[k_J^2 + \kappa_{\text{np}}^2]^{n_{\text{np}}}}$$

(fitted to Pythia8)



Higgs has to decay:

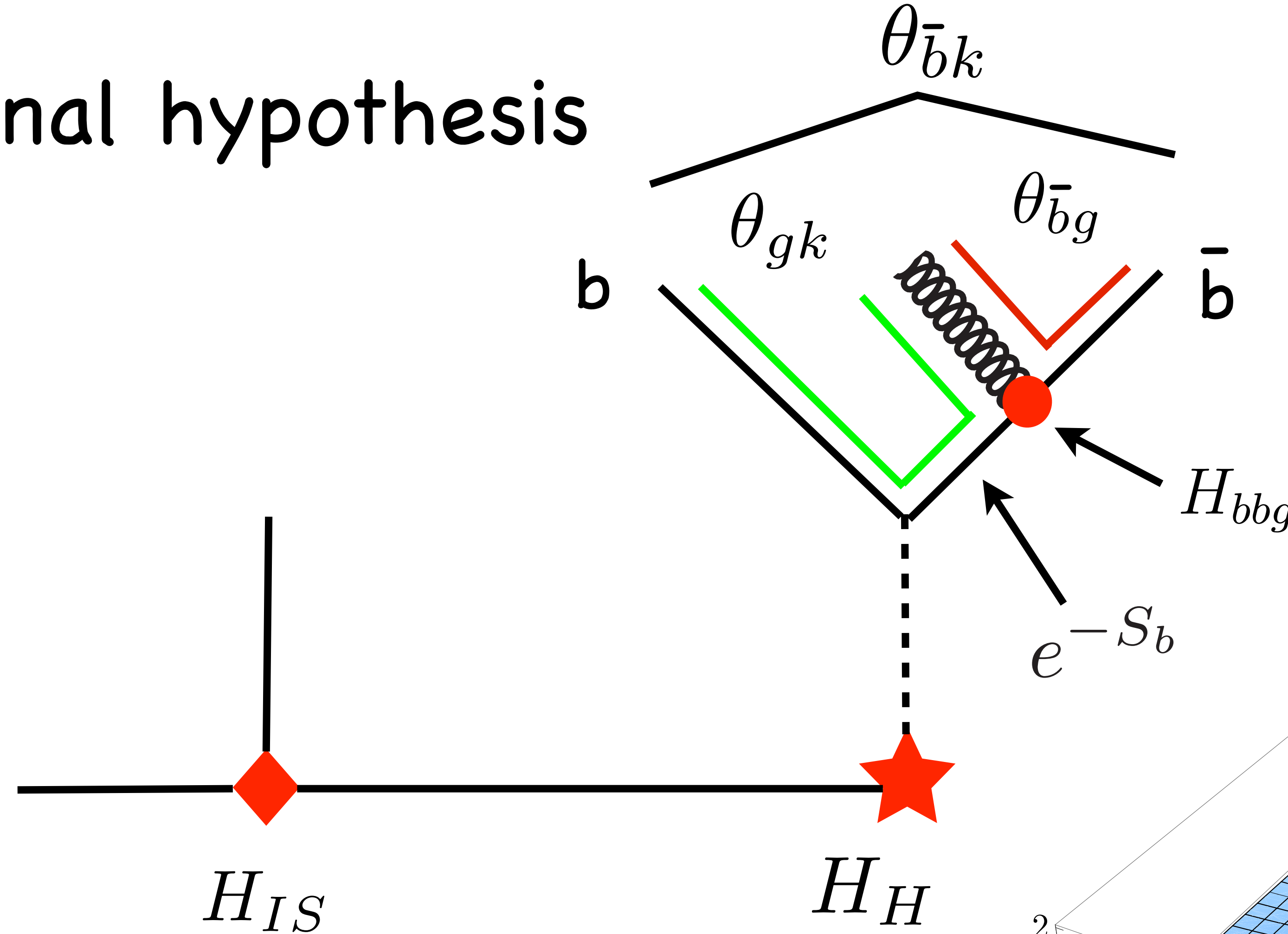
$$He^{-S} = 16\pi^2 \frac{\Theta(|m_{b\bar{b}} - m_H| < \Delta m_H)}{4 m_H \, \Delta m_H}$$

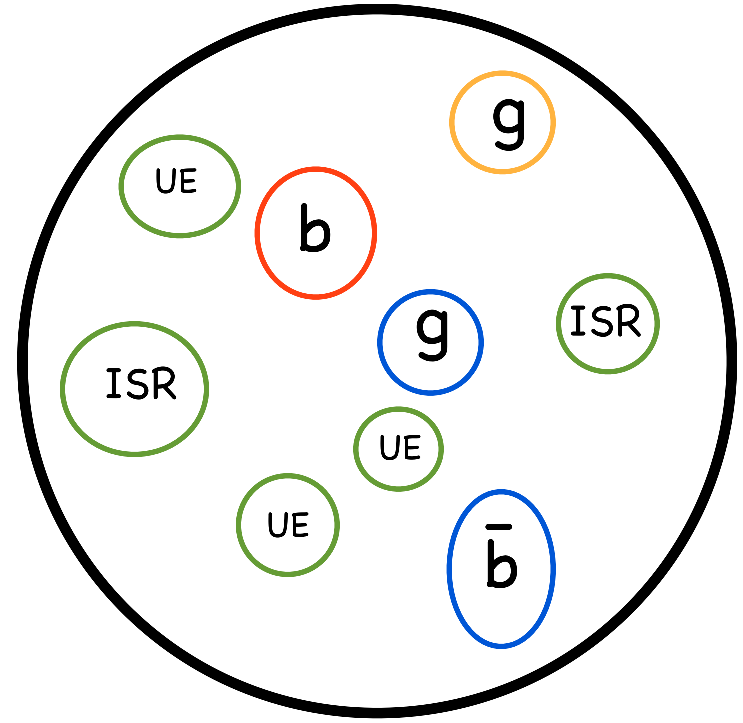
$$\frac{1}{4(2\pi)^3} \int dm^2_{b\bar{b}} \int dz \int d\varphi \; He^{-S} = 1$$

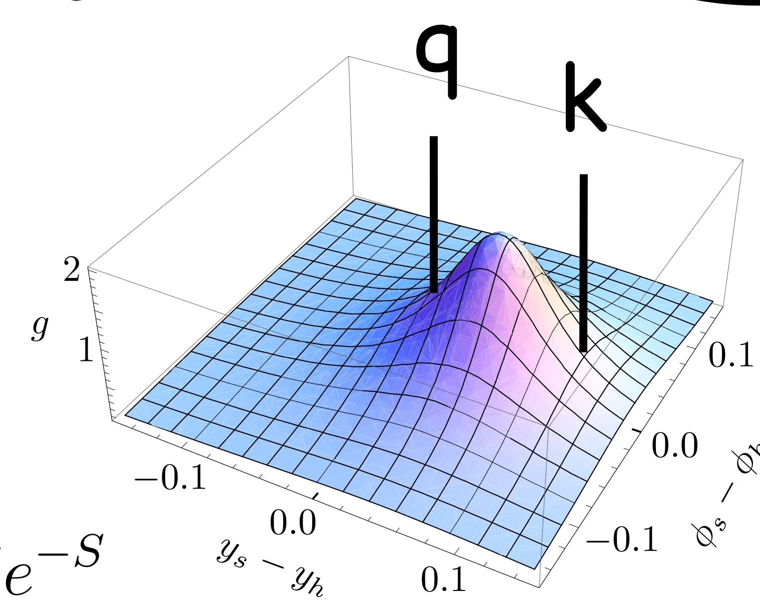
Mass window

$$\Delta m_H = 10 \text{ GeV}$$

Signal hypothesis







[Marchesini, Webber, (1984)]

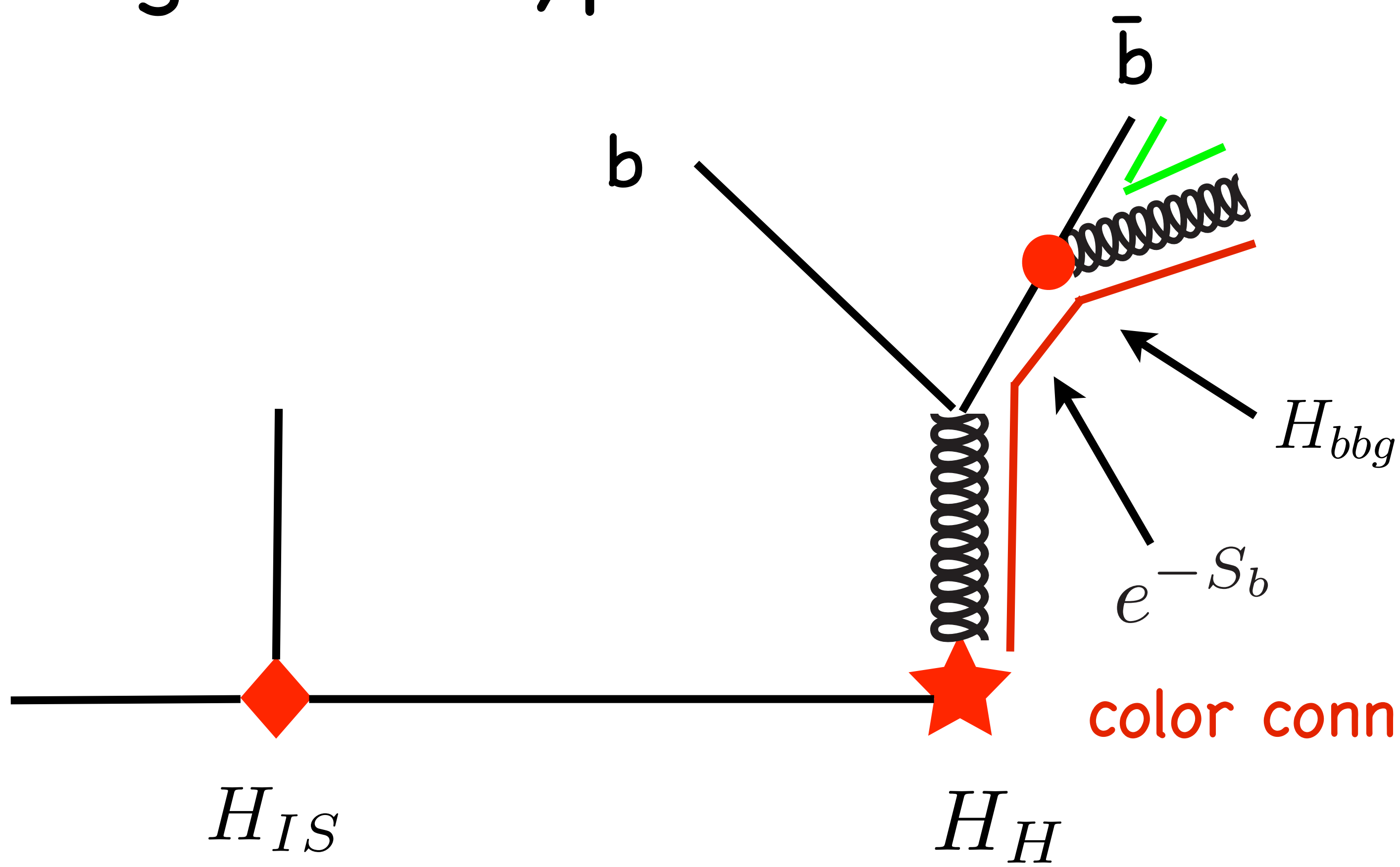
b-quarks radiate gluons

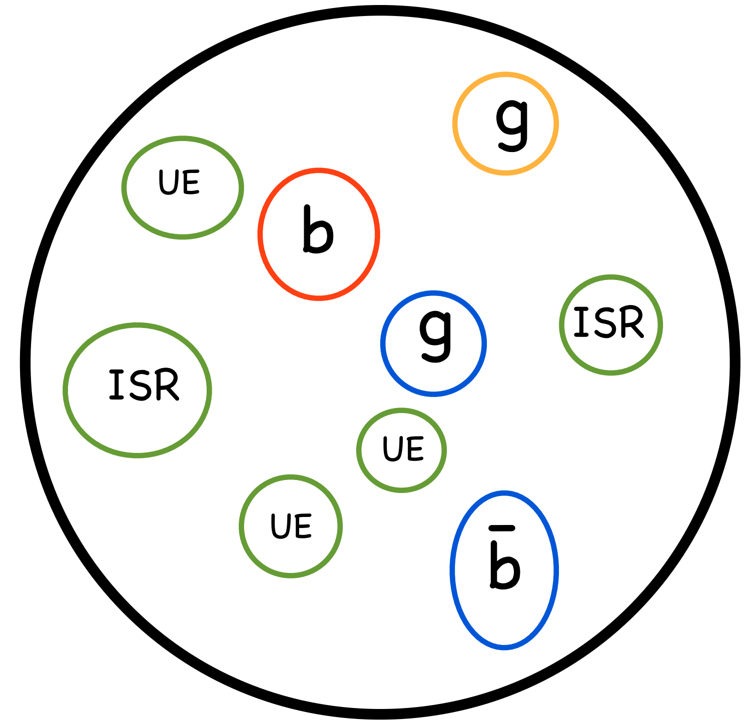
$$\int d\mathcal{P} = \int d\mu_J^2 \int d\Delta\phi \int d\Delta y \sum_s J\, H e^{-S}$$

$$S \approx \int d\bar{\mu}_J^2\, \Theta(\mu_J^2 < \bar{\mu}_J^2) \int d\Delta\bar{y} \int d\Delta\bar{\phi} \sum_{\bar{s}} \; J(\bar{p}_A, \bar{p}_B)\, H(\bar{p}_A, \bar{p}_B)\, \Theta(\{\bar{p}_A, \bar{p}_B\} \in \text{fat jet})$$

$$H_{qqg} = H_{\bar{q}g\bar{q}} = 8\pi C_{\mathrm{F}} \frac{\alpha_{\mathrm{s}}(\mu_J^2)}{\mu_J^2} \, \frac{k_J}{k_g} \left[1 + \left(\frac{k_q}{k_J}\right)^2\right] \frac{\theta_{qk}^2}{\theta_{gq}^2 + \theta_{gk}^2} \, \Theta\!\left(2\,\frac{\mu_J^2}{k_J} < \frac{\mu_K^2}{k_K}\right)$$

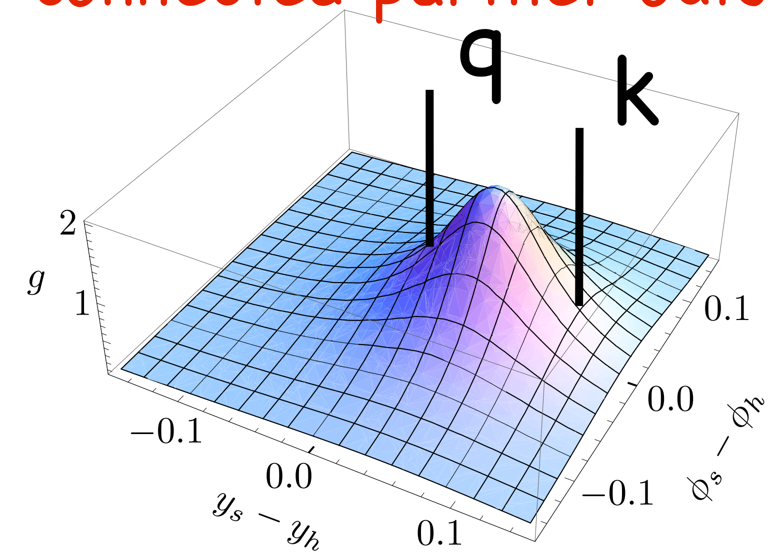
Background hypothesis





color connected partner outside fat jet

b-quarks radiate gluons



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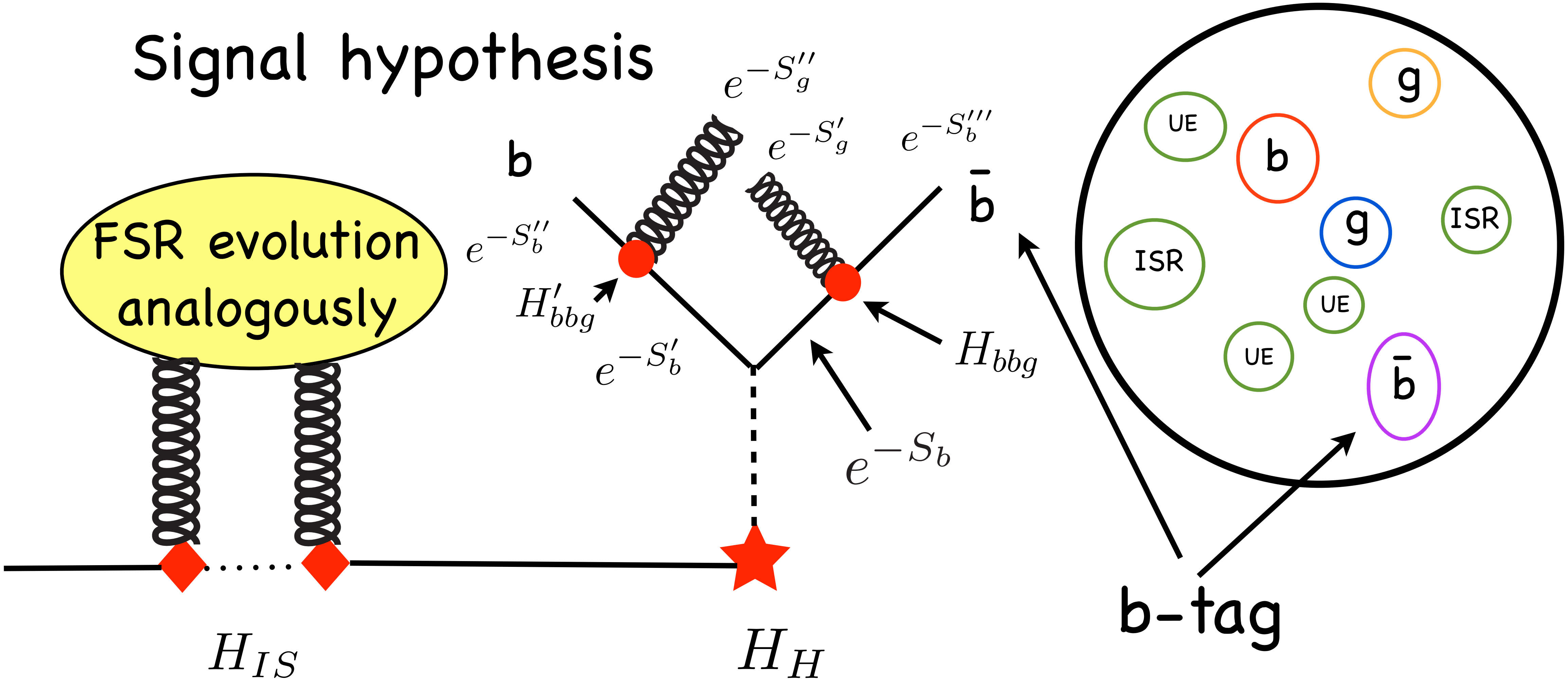
$$H_{qqg} = H_{\bar{q}g\bar{q}} = 8\pi C_{\mathrm{F}} \frac{\alpha_{\mathrm{s}}(\mu_J^2)}{\mu_J^2} \frac{k_J}{k_g} \left[1 + \left(\frac{k_q}{k_J}\right)^2\right] \frac{\theta_{qk}^2}{\theta_{gq}^2 + \theta_{gk}^2}\, \Theta\left(2\,\frac{\mu_J^2}{k_J} < \frac{\mu_K^2}{k_K}\right)$$

Signal hypothesis



Wrapping up all factors gives weight for shower history

$$\chi = \frac{\sum_{ISR/Hard}\left(\sum_i \mathrm{ISR_i} \times \sum_j \mathrm{Signal_j}\right)}{\sum_{ISR/Hard}\left(\sum_i \mathrm{ISR_i} \times \sum_j \mathrm{Backg_j}\right)}$$

Here $\mathrm{Signal_1} = \mathrm{H_H H_{split} e^{-S_{split}} H_{bbg} e^{-S_b'} e^{-S_b'''} e^{-S_g'} H'_{bbg} e^{-S_b''} e^{-S_b} e^{-S_g''}}$

Event selection cuts

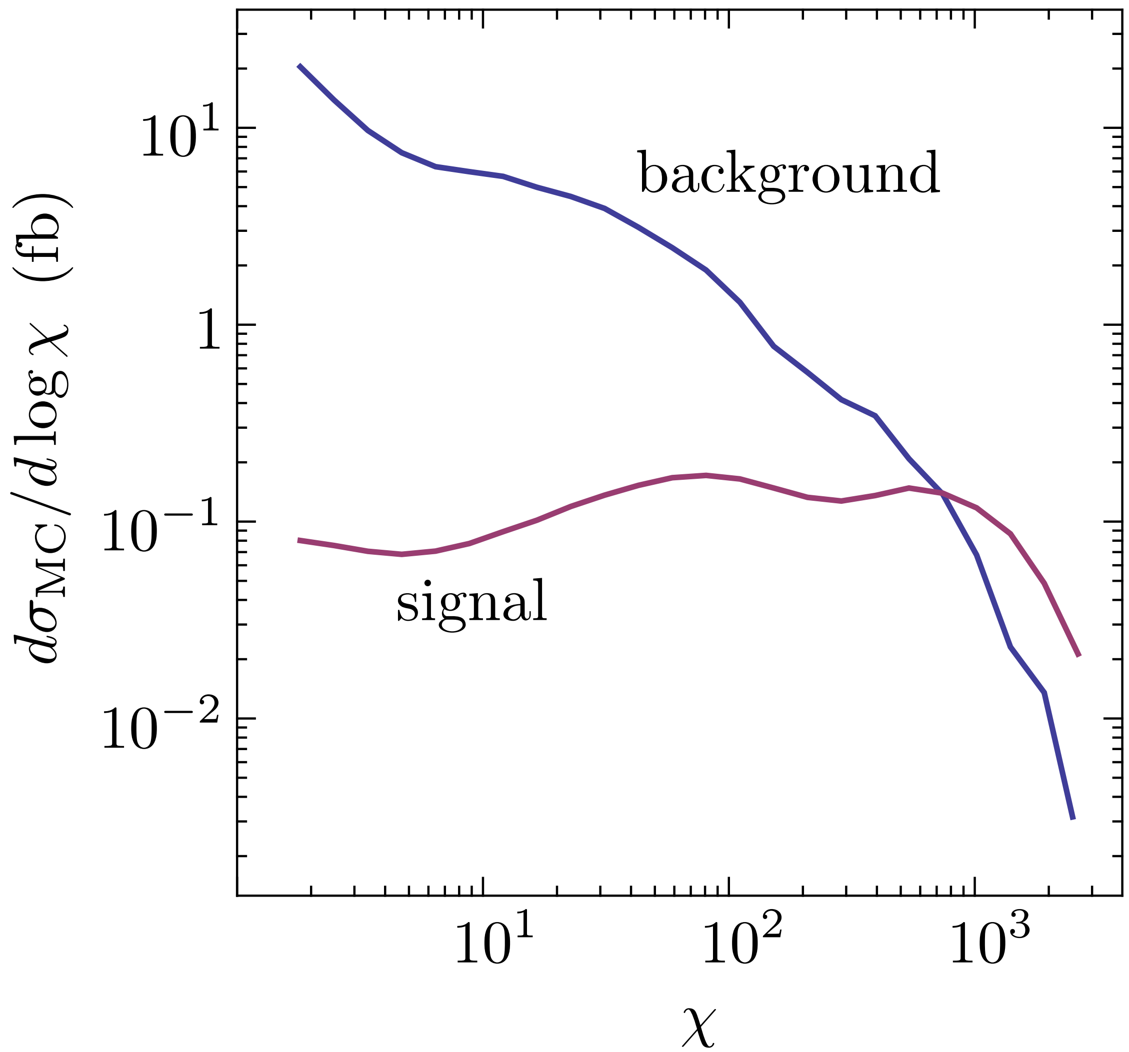
- Cluster hadrons to 'detector cells' 0.1 x 0.1, ET > 0.5 GeV
- lepton pT > 15 GeV
- two hardest leptons mZ +- 10 GeV
- at least 1 fat jet (anti-kT, R=1.2, pT>200 GeV)

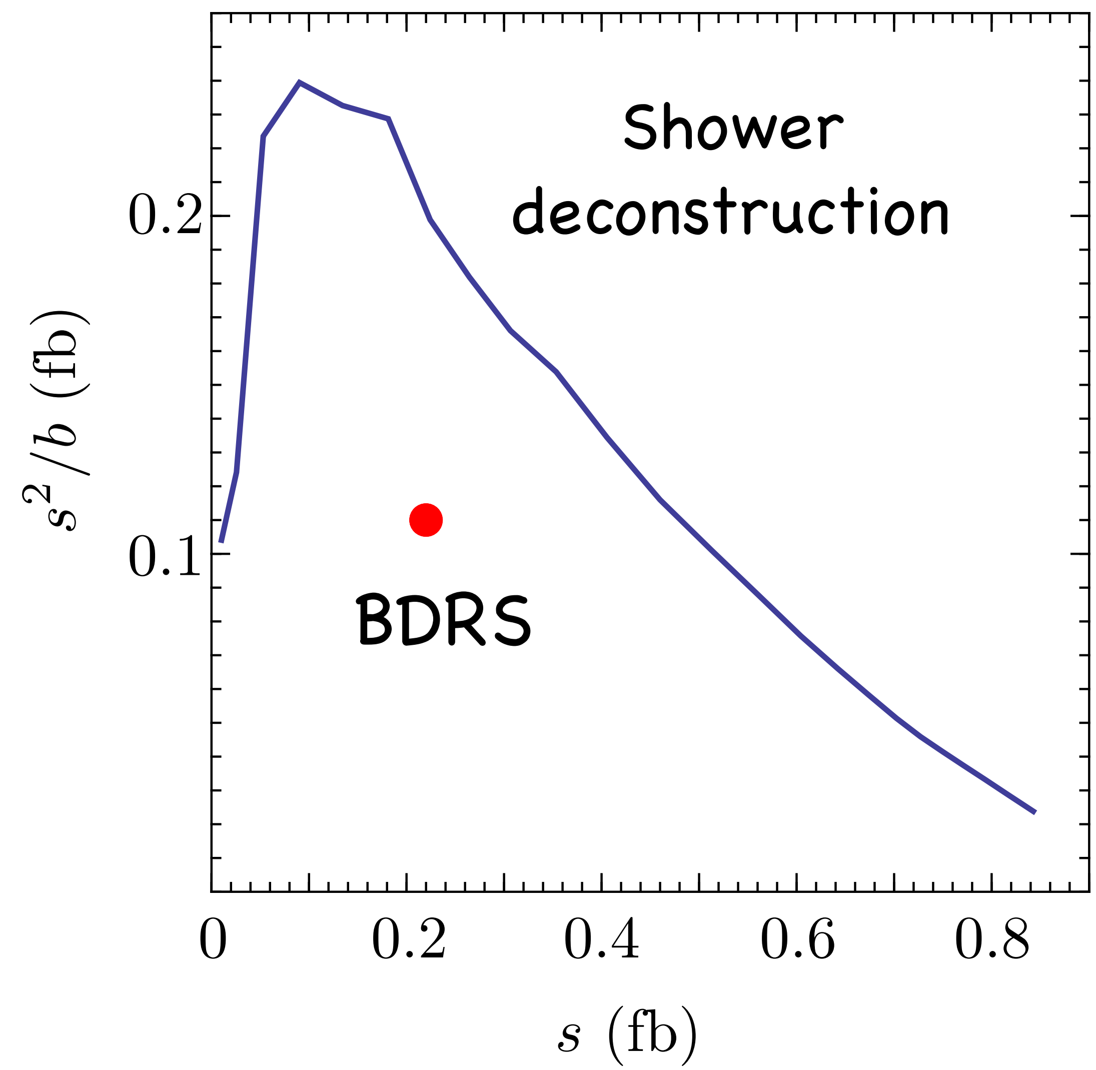
Normalize signal/background cross section
to the NLO results obtained from MCFM

$$\sigma_{\mathrm{MC}}(\mathrm{S}) = 1.48\ \mathrm{fb}$$
$$\sigma_{\mathrm{MC}}(\mathrm{B}) = 2610\ \mathrm{fb}$$
$$\frac{\sigma_{\mathrm{MC}}(\mathrm{S})}{\sigma_{\mathrm{MC}}(\mathrm{B})} = \frac{1}{1760}$$

Results of shower deconstruction (SD)

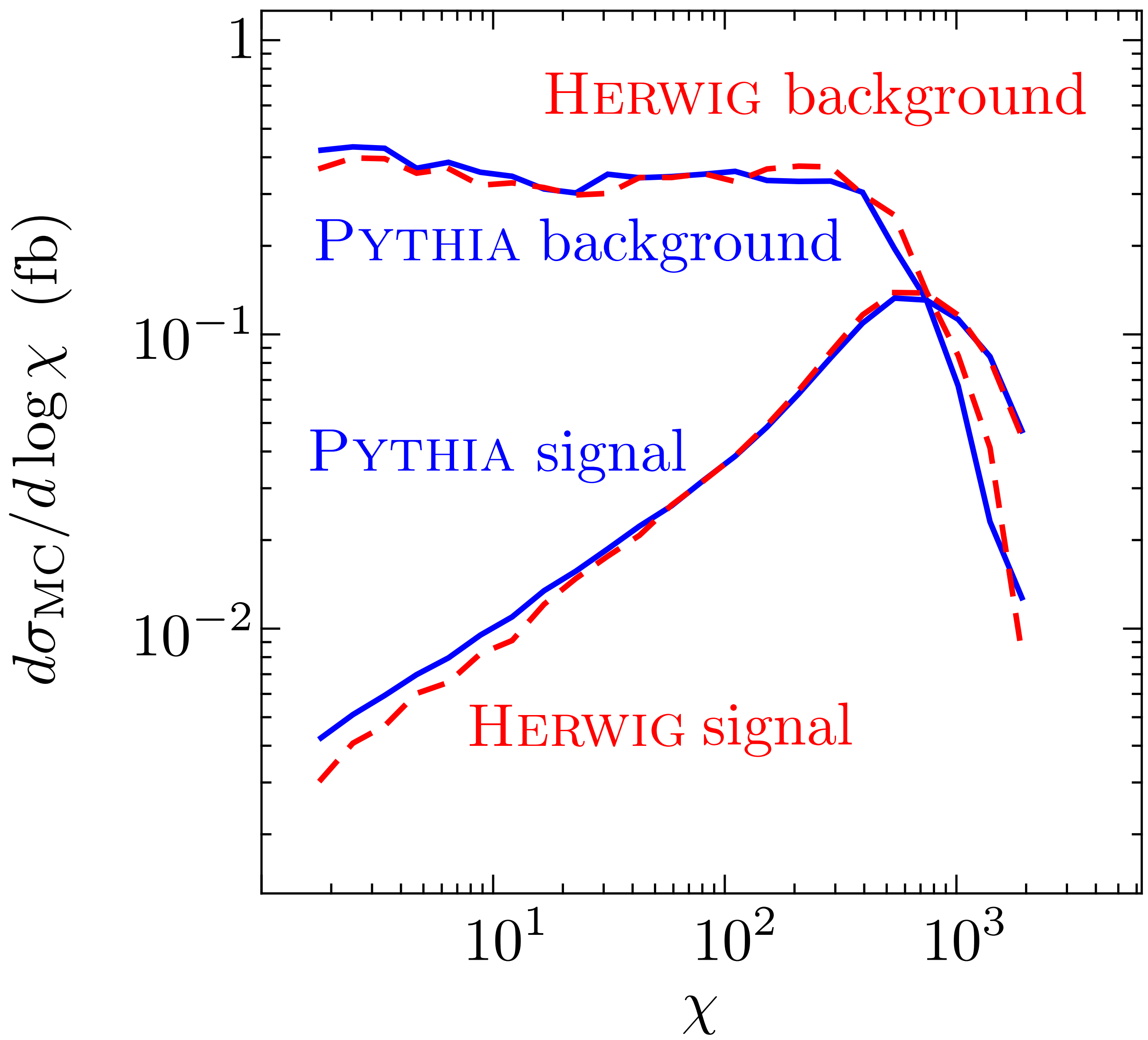
$$\chi(\{p,t\}_N) = \frac{P(\{p,t\}_N|\mathrm{S})}{P(\{p,t\}_N|\mathrm{B})}$$

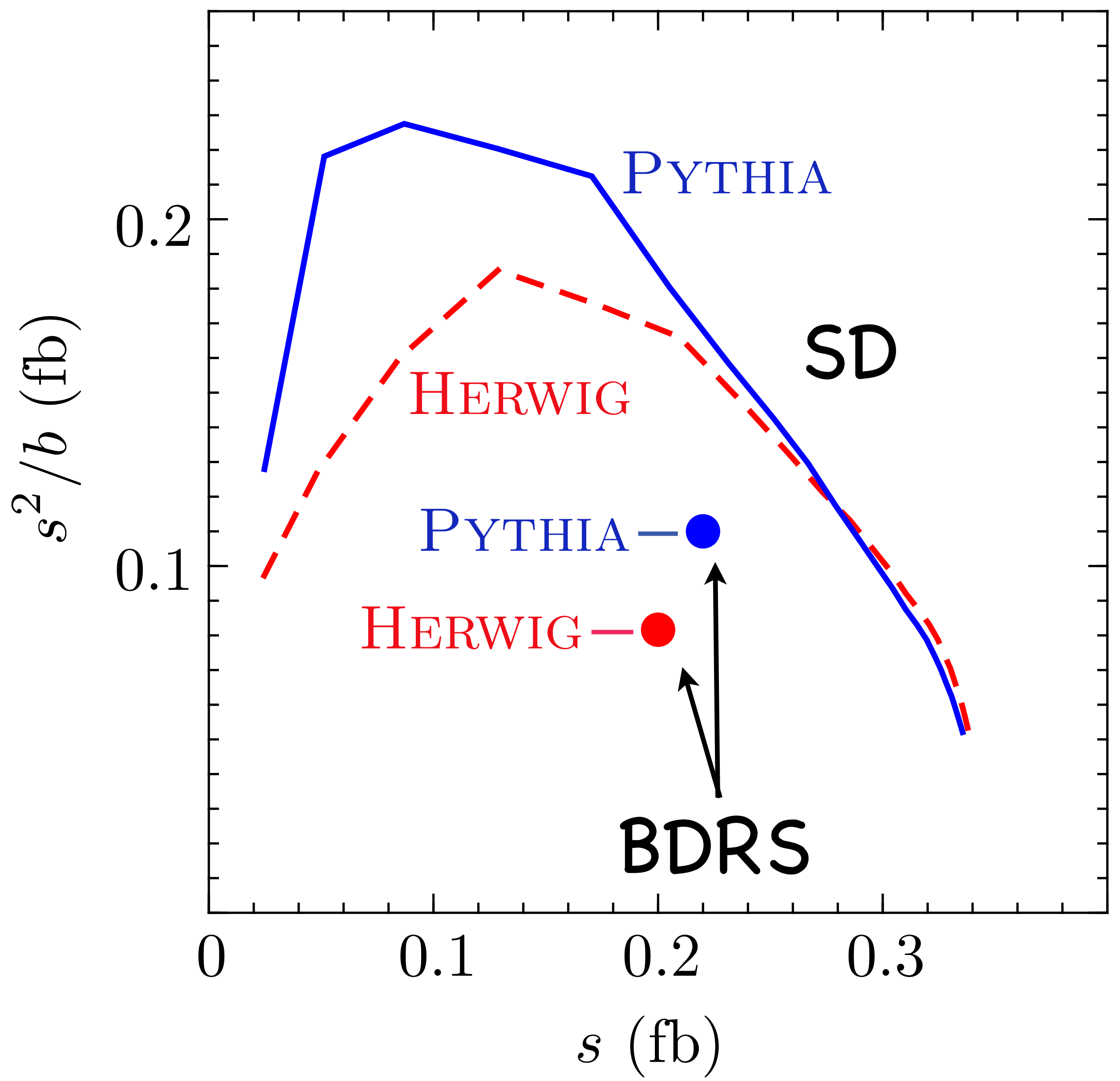




imperfect b-tagging (60%,2%) no b-tag required

Monte-Carlo uncertainties





Lots of room for improvement:

FSR simulation

ISR simulation

Matrix element

Simulation of experimental issues, e.g. b-tagging

UE simulation

Modular build -> improvements are additive

II. Measuring the Higgs-top coupling using boosted techniques

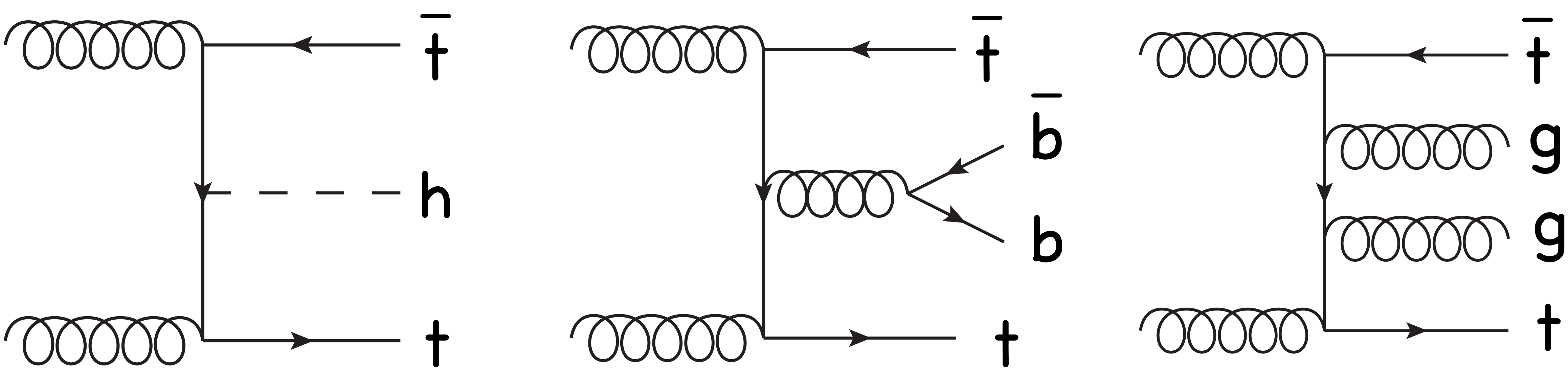
tth (Signal)
Beenakker et al., PRL 87 2001;
Reina et al., PRD 65 2002
↳ K=1.57

ttbb
Bredenstein et al., PRL 103 2009;
Belivacqua et al., JHEP 0909 2009
↳ K=2.3

tt+jets
Dittmaier et al, PRL 98 2007
Bevilacqua et al., PRL 104 2010
↳ K=1.0

ttz
Lazopoulos et al., PLB 666 2008
↳ k=1.53

w+jets
negligible after b-tags and taggers



tth

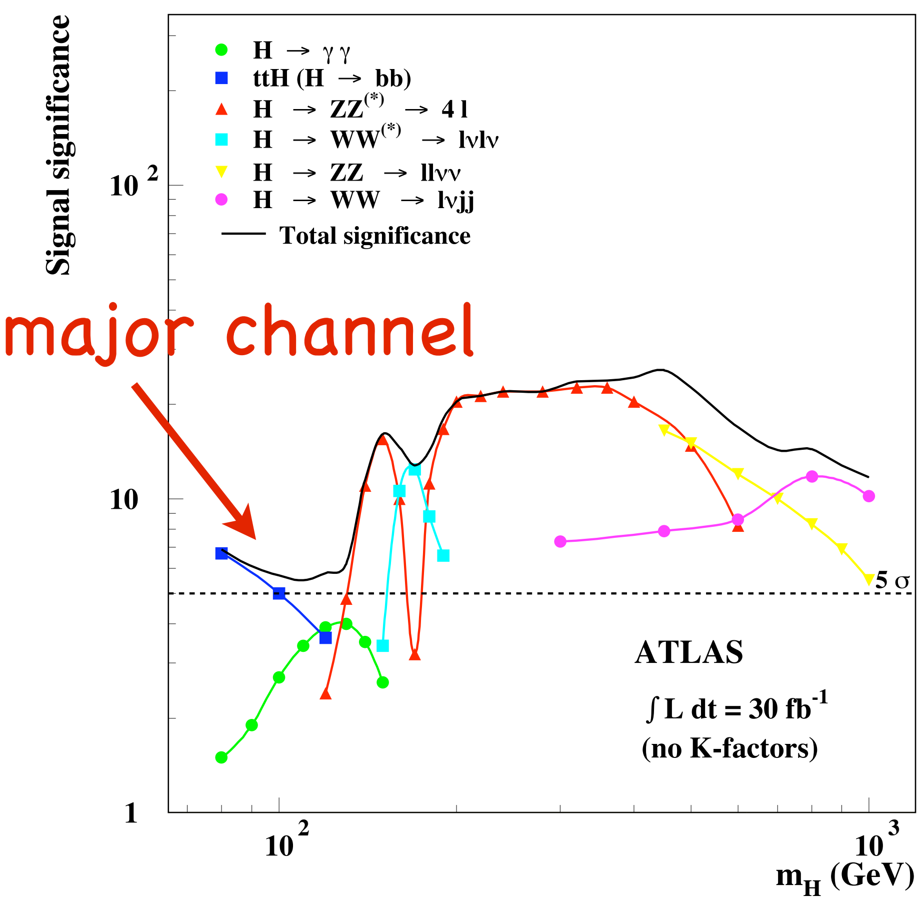
[Plehn, Salam, MS PRL 104 (2010)]

as busy as it gets in the SM

Motivation:
- sizable cross-section
- Higgs discovery contribution in low mass range
- access to t- and b-Yukawa couplings

High expectations:

tth major channel



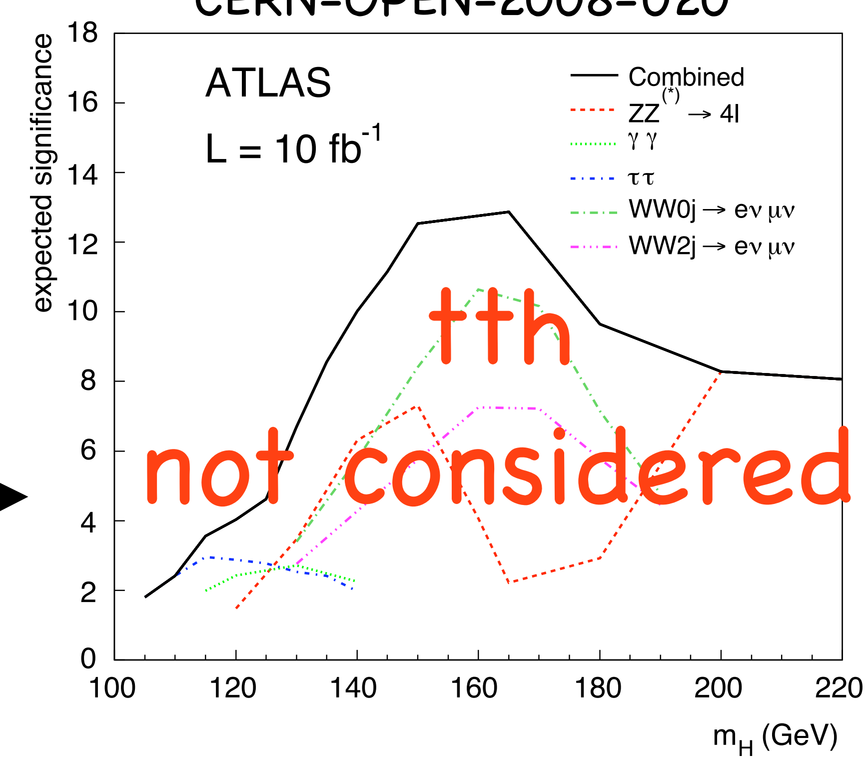
[ATLAS TDR 1999]

Cammin and Schumacher (ATLAS)

$S/B \simeq 1/9$

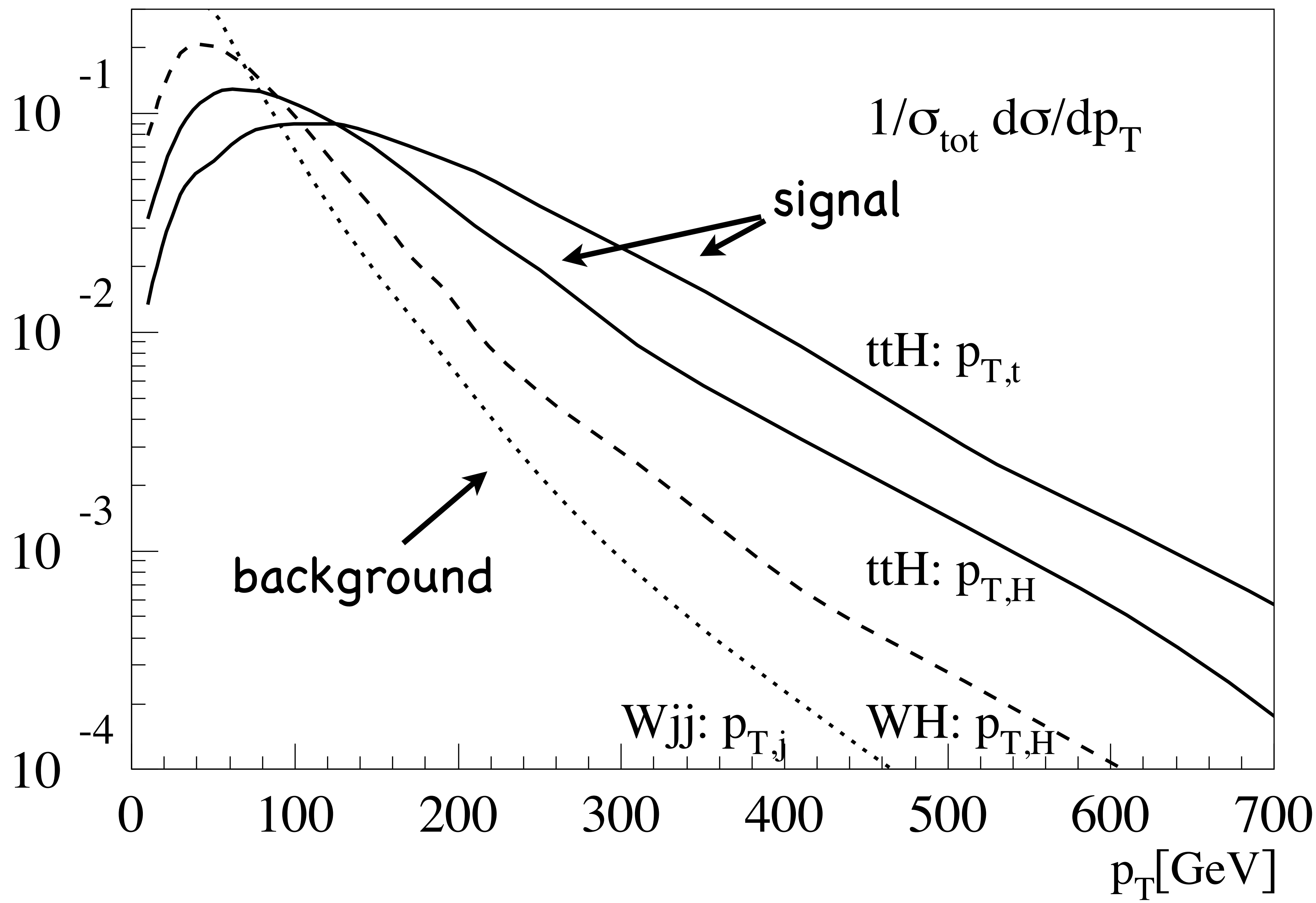
$S/\sqrt{B} \simeq 2.2$

Expected Performance of the ATLAS Experiment, CERN-OPEN-2008-020



tth
not considered

pT distributions relevant for tth



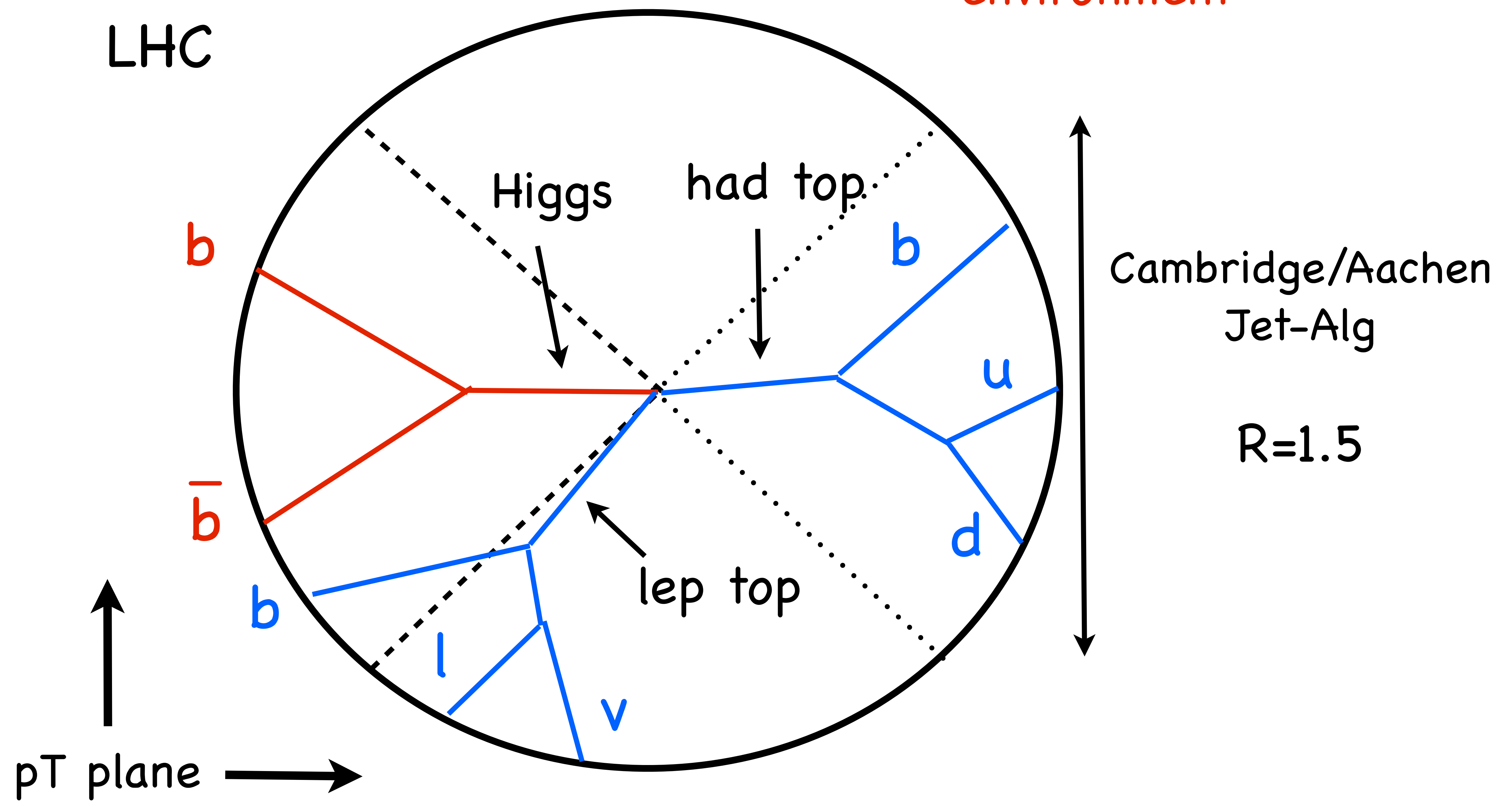
Problems in event reconstruction:

- (b-)jet multiplicity
- reconstruction efficiency

Boost should help

but

need tagger for this environment

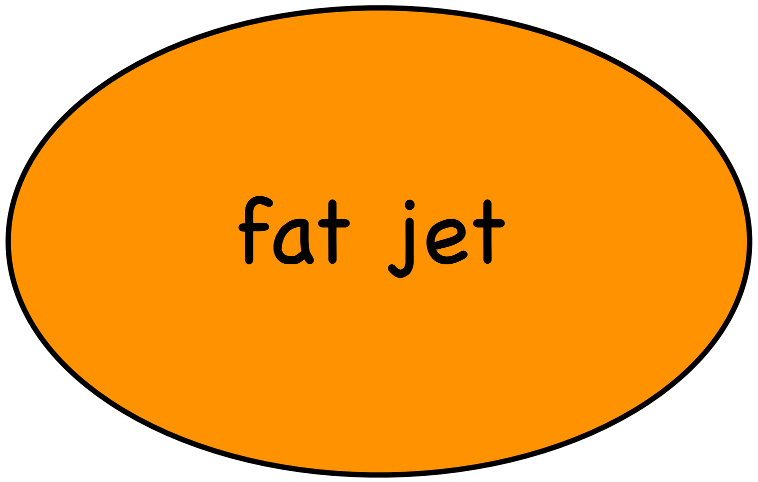


How does the HEPTopTagger work?

I. Find fat jets (C/A, R=1.5, pT>200 GeV)

II. Find hard substructure using mass drop criterion

Undo clustering, $m_{\mathrm{daughter}_1} < 0.8\, m_{\mathrm{mother}}$ to keep both daughters



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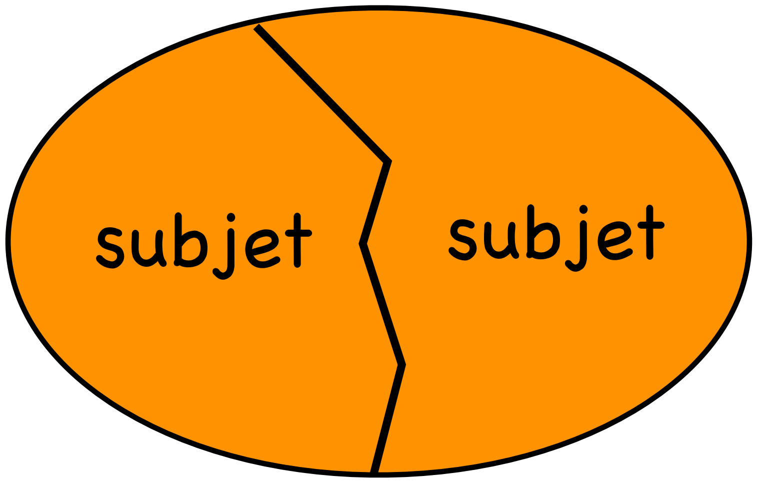

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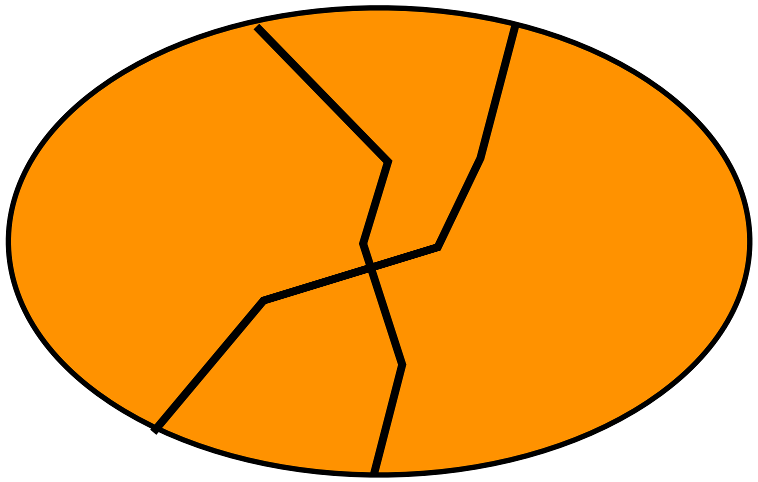

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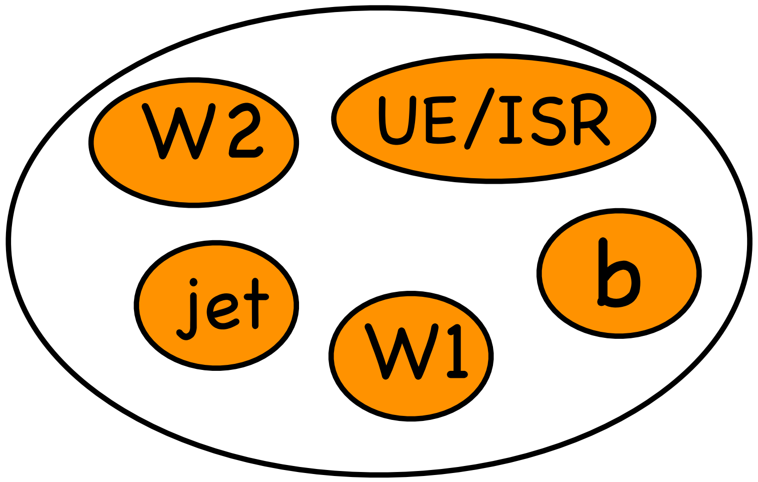
III. Apply jet grooming to get top decay candidates



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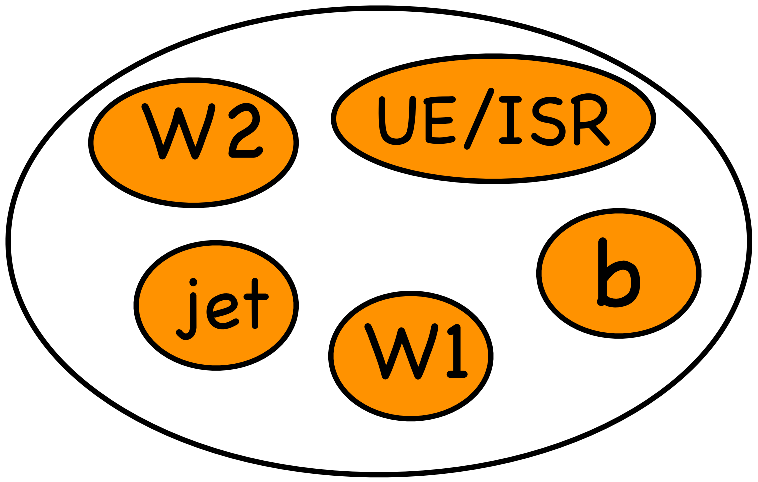
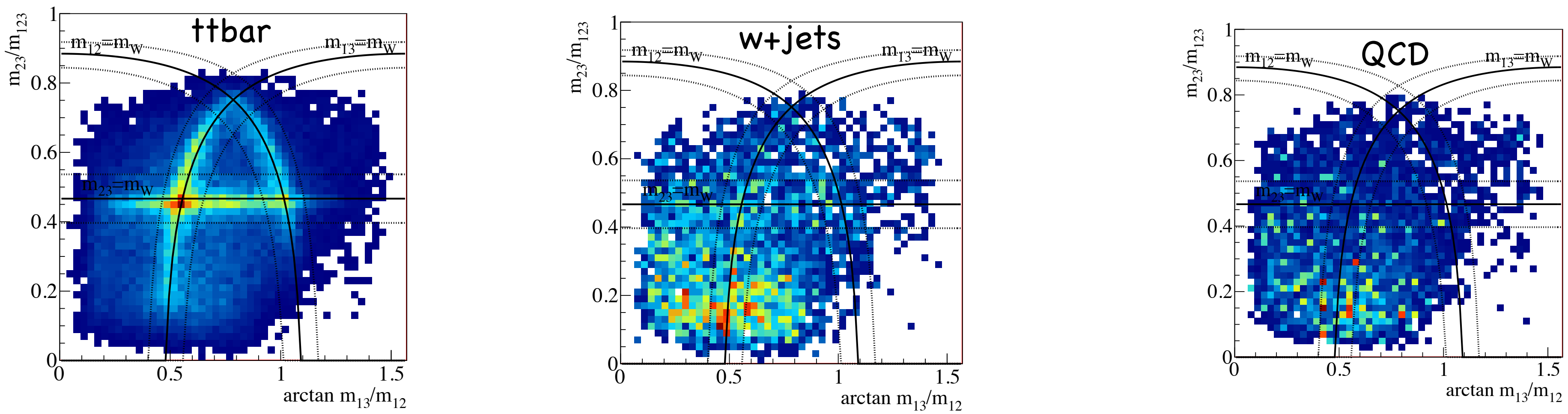
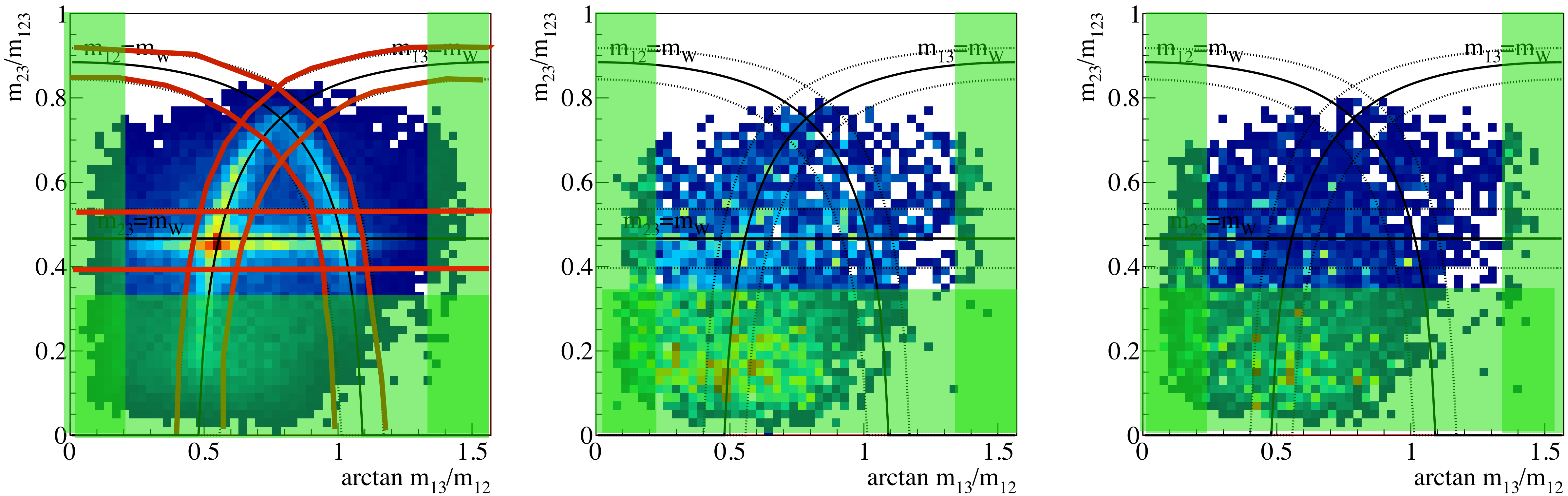


IV. Choose pairing based on kinematic correlation, e.g. top mass, W mass and invariant subjet masses



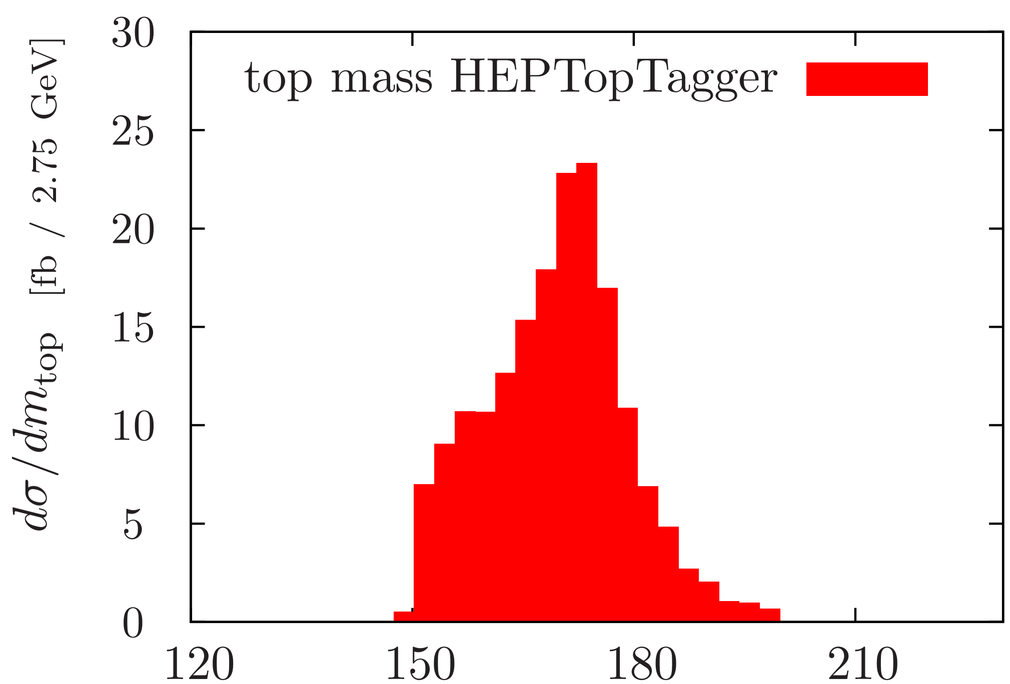
IV. check mass ratios

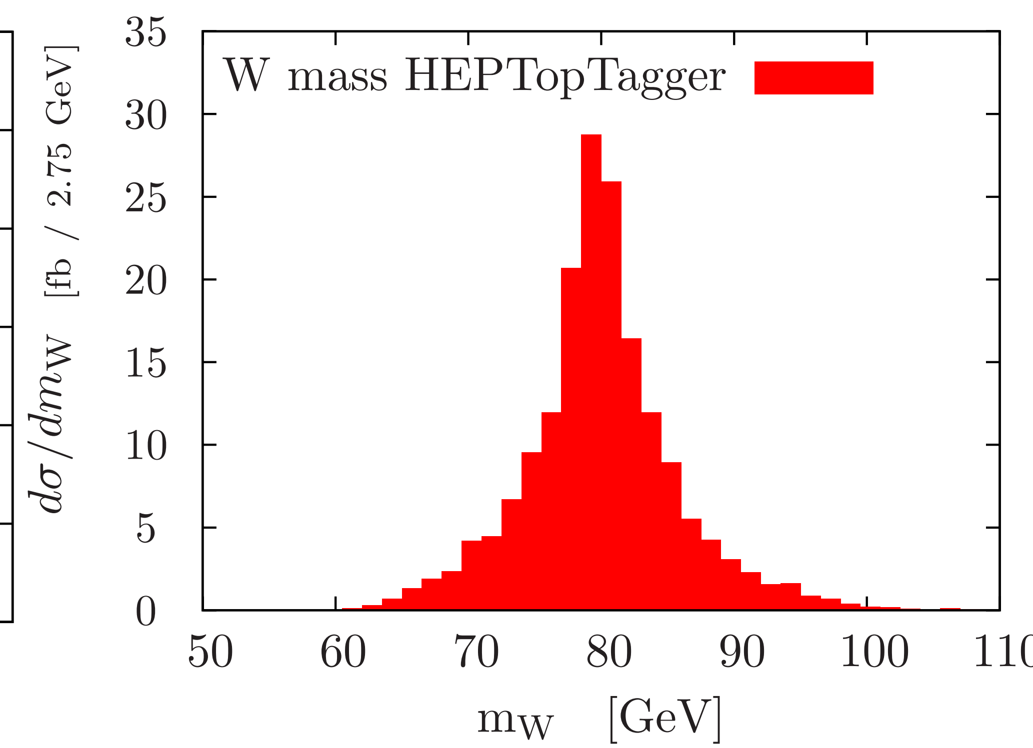
Cluster top candidate into 3 subjets j_1, j_2, j_3



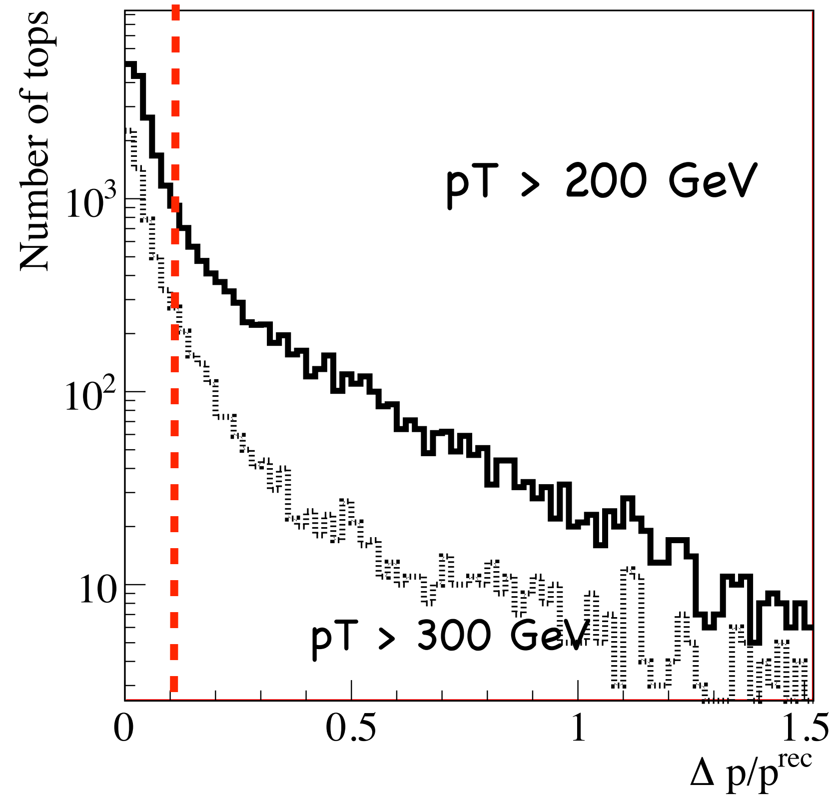
No fix pairing for W mass reconstruction

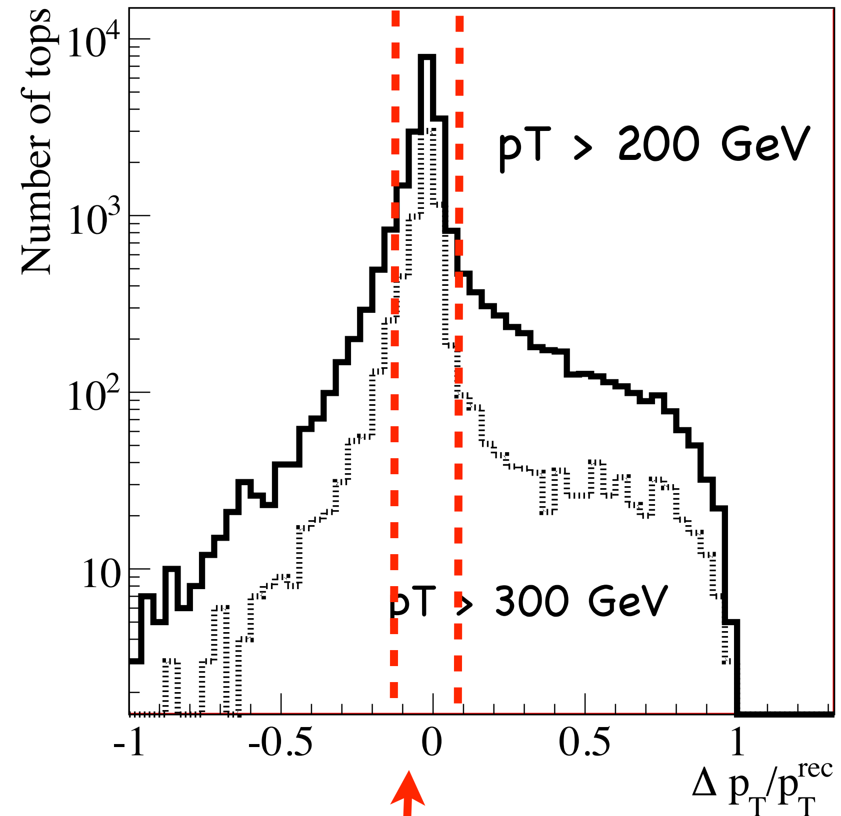
Only invariants for reconstruction

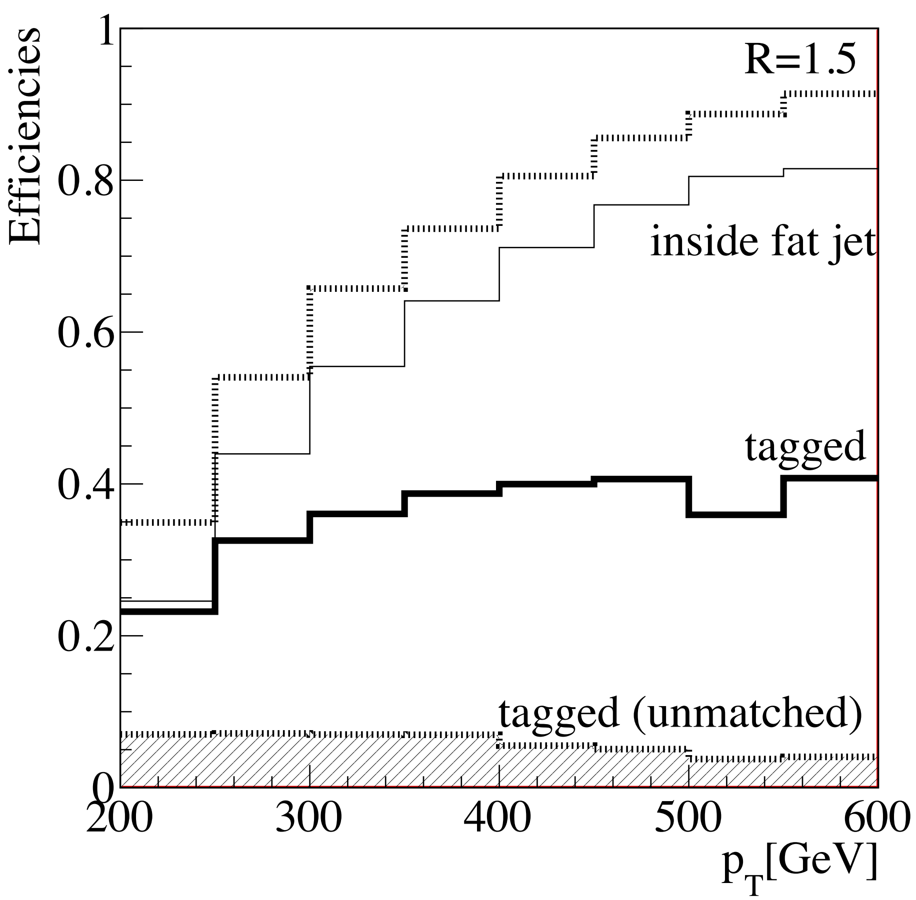




Top quark momentum reconstruction







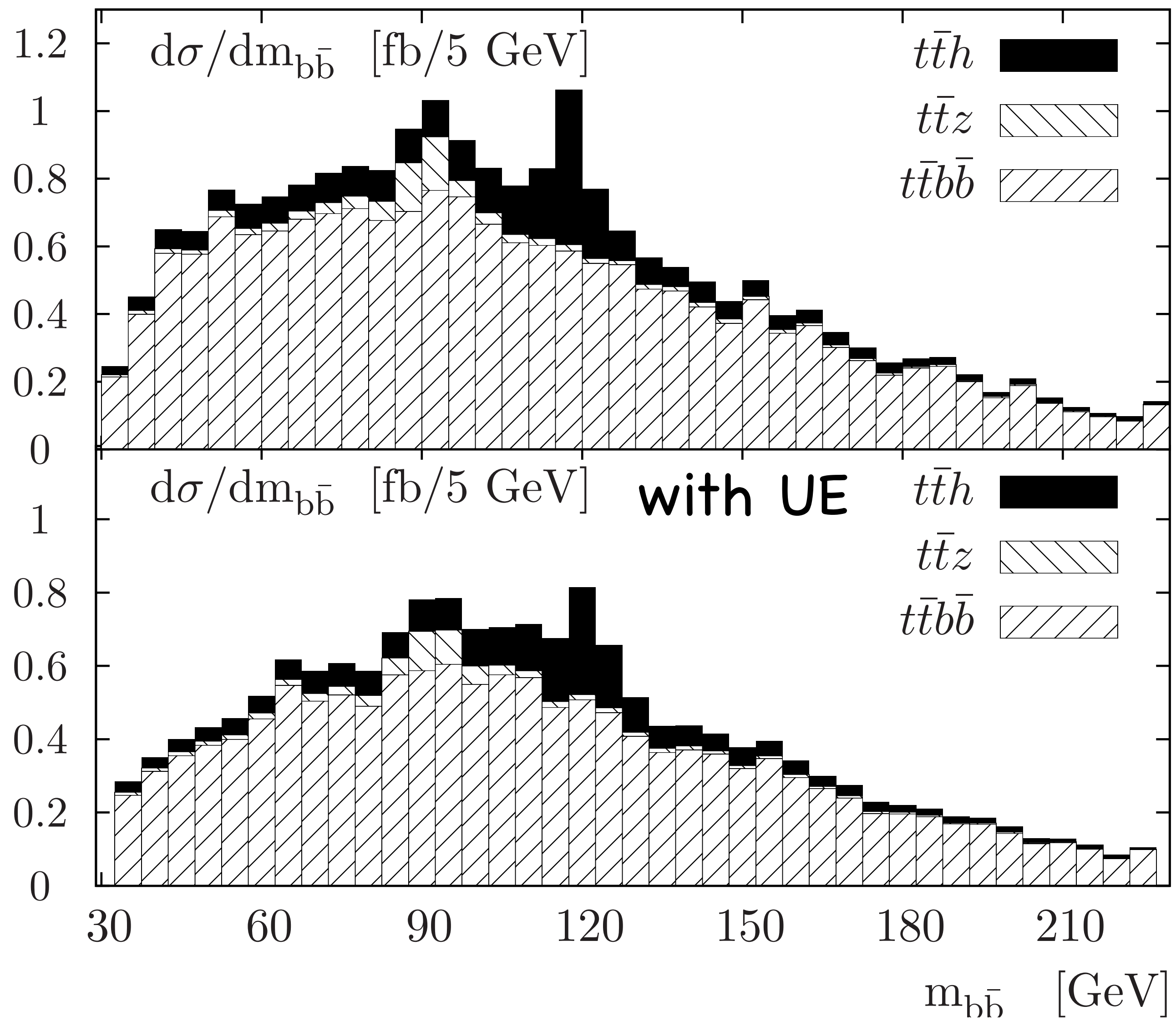
- Great reconstruction of top quark momentum

  Important for measurement of AFB [Hewett, et al. PRD 84 (2011)]

- 35% tagging efficiency

  2% W+jets fake rate

Results for tth



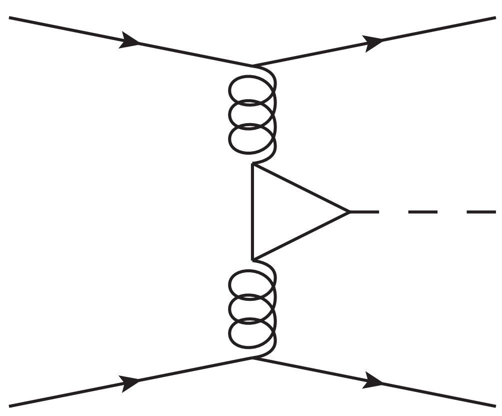
- 5 sigma sign. with 100 1/fb
- Development of Higgs and top tagger for busy final state
- Improvement of S/B from 1/9 to 1/2

⟶ tth might be a window to Higgs-top coupling

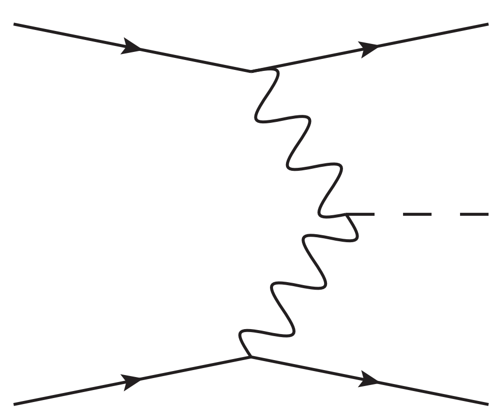
III. Measuring CP and Higgs couplings using event shapes

[Englert, MS, Takeuchi 1203.5788]

Gluon-Fusion



Weak-Boson-Fusion



- CP and Spin measurements of heavy Higgs well studied in 4 lepton or lljj modes.

  [Choi et al. PLB (2003); Buszello et al. EPJ (2004); Englert, Hackstein, MS PRD 82 (2010)]

- For light Higgs with 125 GeV CP can be measured using angular correlations of tagging jets in WBF/GF

  [Plehn, Rainwater, Zeppenfeld PRL 88 (2002)]

- Separation of WBF and GF important for coupling measurements, due to $\sigma_p \cdot \mathrm{BR}_d \sim g_p^2 \frac{g_d^2}{\Gamma_H}$ where

  $g_p \simeq g_{p,\mathrm{GF}} + g_{p,\mathrm{WBF}}$

Other ideas: jet vetos [Cox, Forshaw, Pilkington PLB 696 (2011)]

jet counting [Gerwick, Plehn, Schumann PRL 108 (2012)]

Event shapes

- Event shapes well studied experimentally and theoretically

  [Bethke, Nucl.Phys.Proc.Suppl. 121 (2003)] [Kluth. et al, EPJC 21 (2011)]

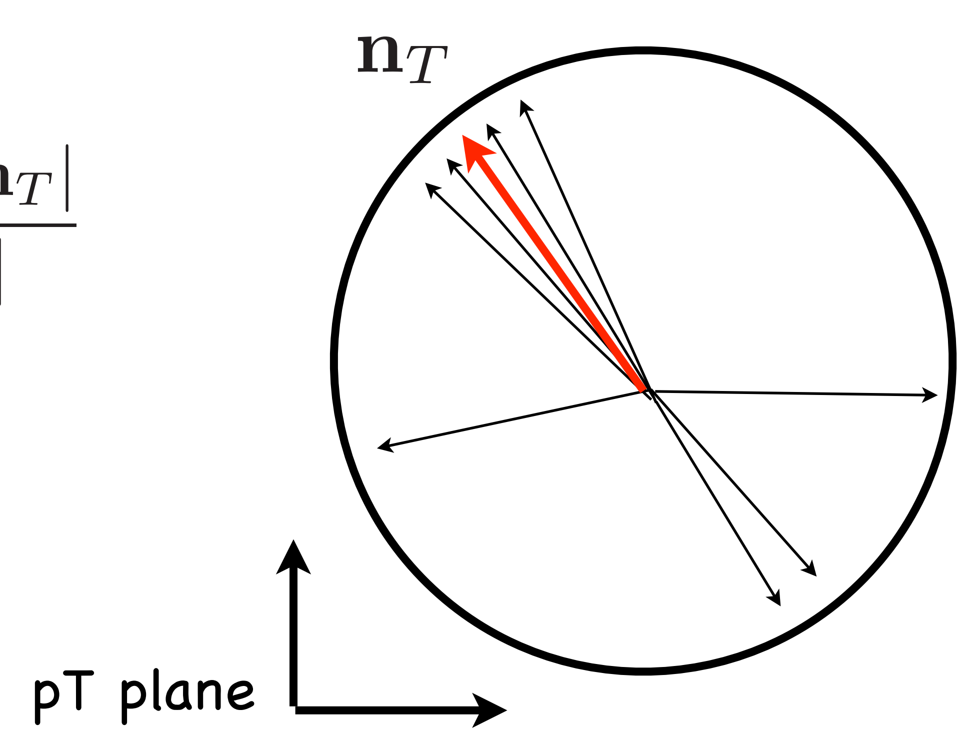
  [Banfi et al., JHEP 0408] [Gehrmann-De Ridder et al., JHEP 0712]

- Event shape measurements established in experimental collaborations already now [CMS, PLB 699 (2011)]

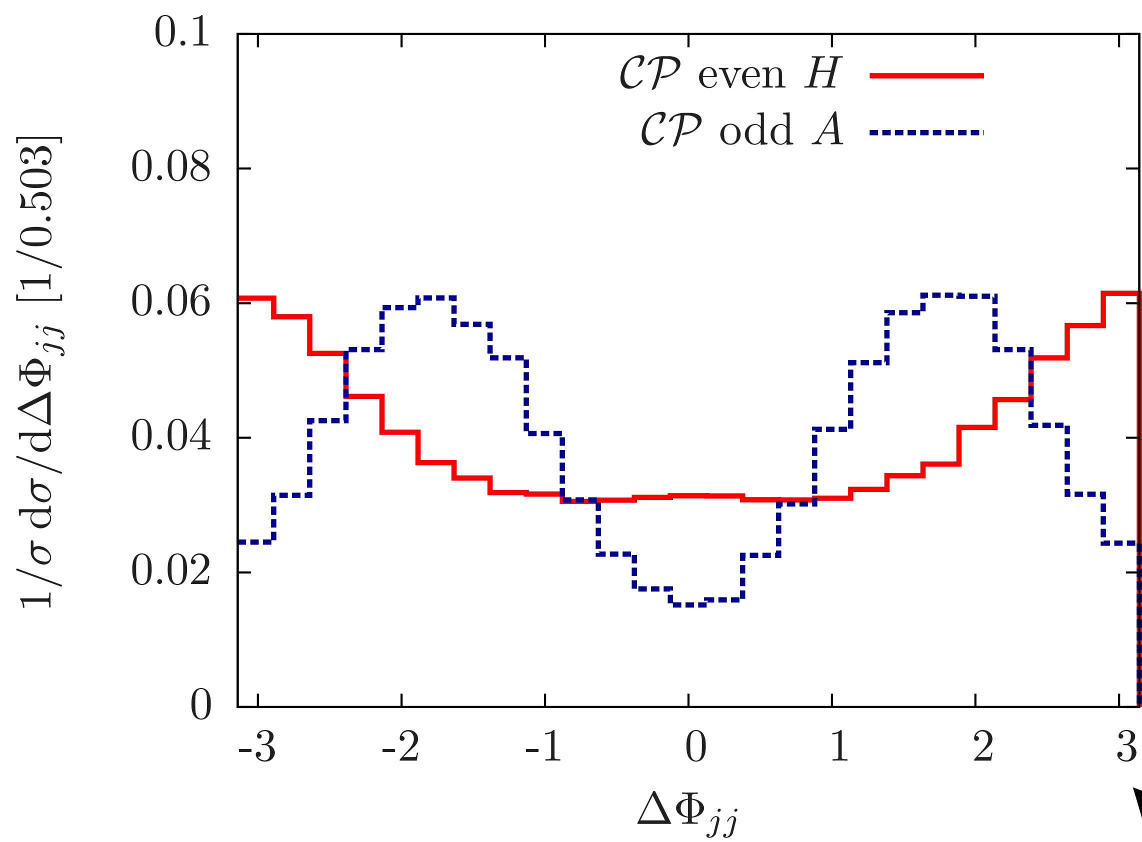
e.g.

transverse thrust $$T_{\perp,g} = \max_{\mathbf{n}_T} \frac{\sum_i |\mathbf{p}_{\perp,i} \cdot \mathbf{n}_T|}{\sum_i |\mathbf{p}_{\perp,i}|}$$

transverse thrust minor $$T_{m,g} = \frac{\sum_i |\mathbf{p}_{\perp,i} \times \mathbf{n}_T|}{\sum_i |\mathbf{p}_{\perp,i}|}$$



Standard approach:

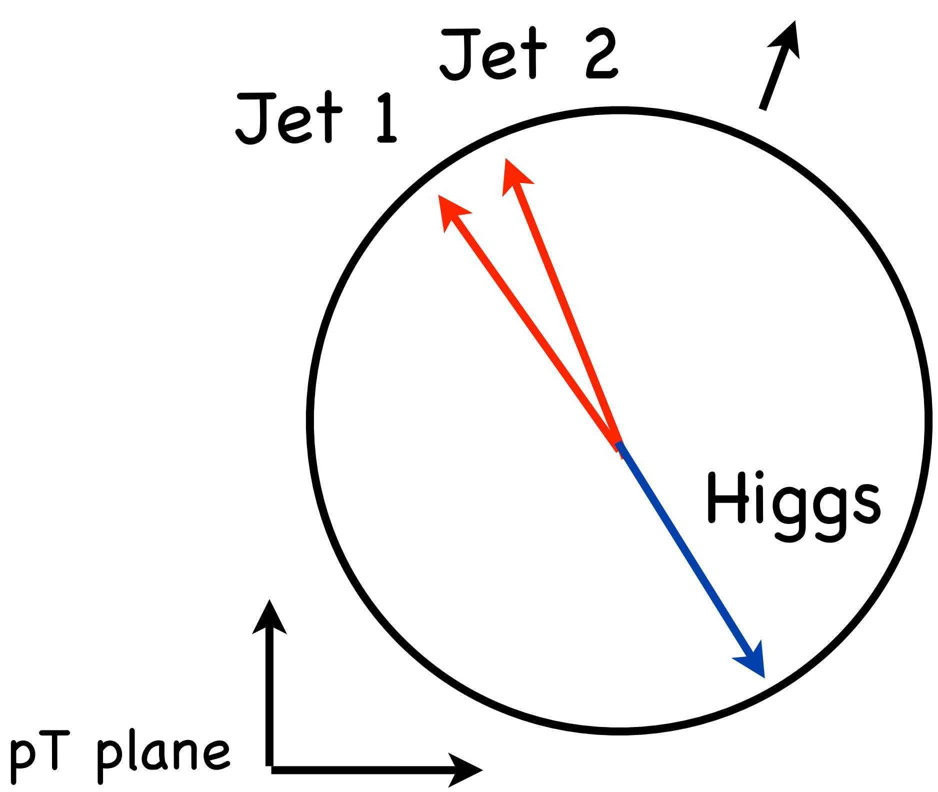


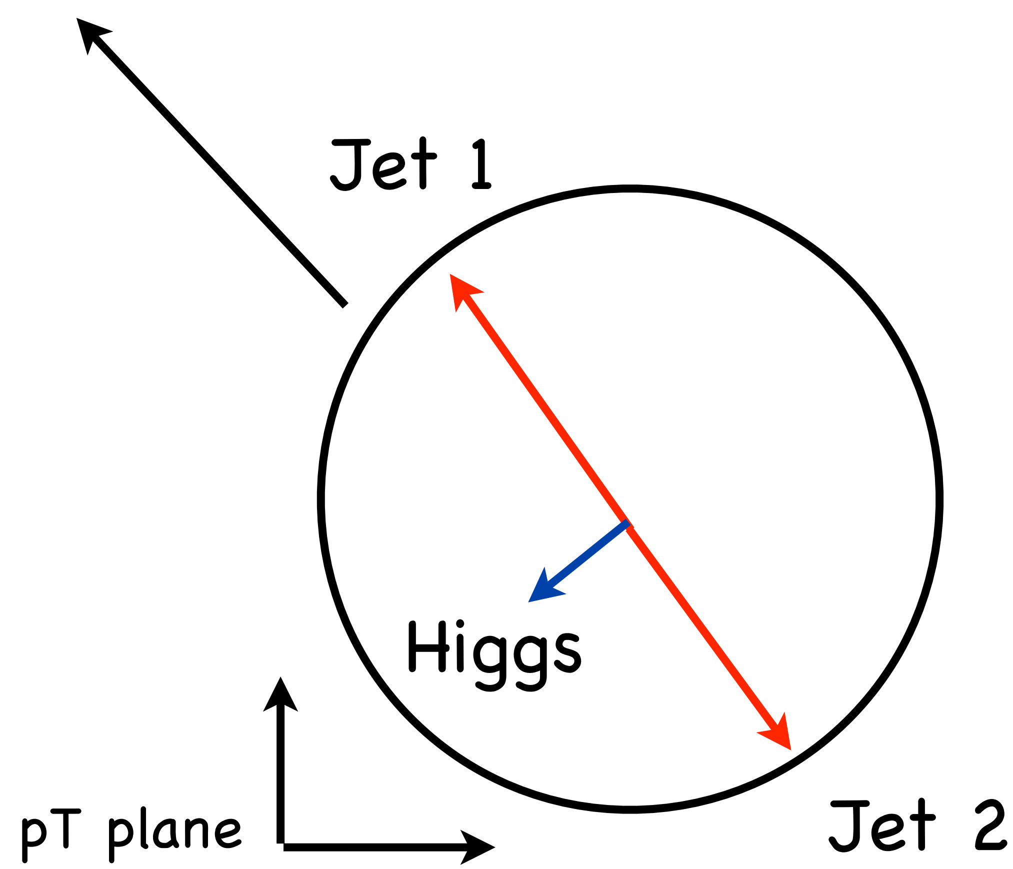
azimuthal angle between all jets with larger or smaller rapidity wrt Higgs

$$p^{\mu}_{<} = \sum_{j \in \{\text{jets: } y_j < y_h\}} p^{\mu}_{j}$$

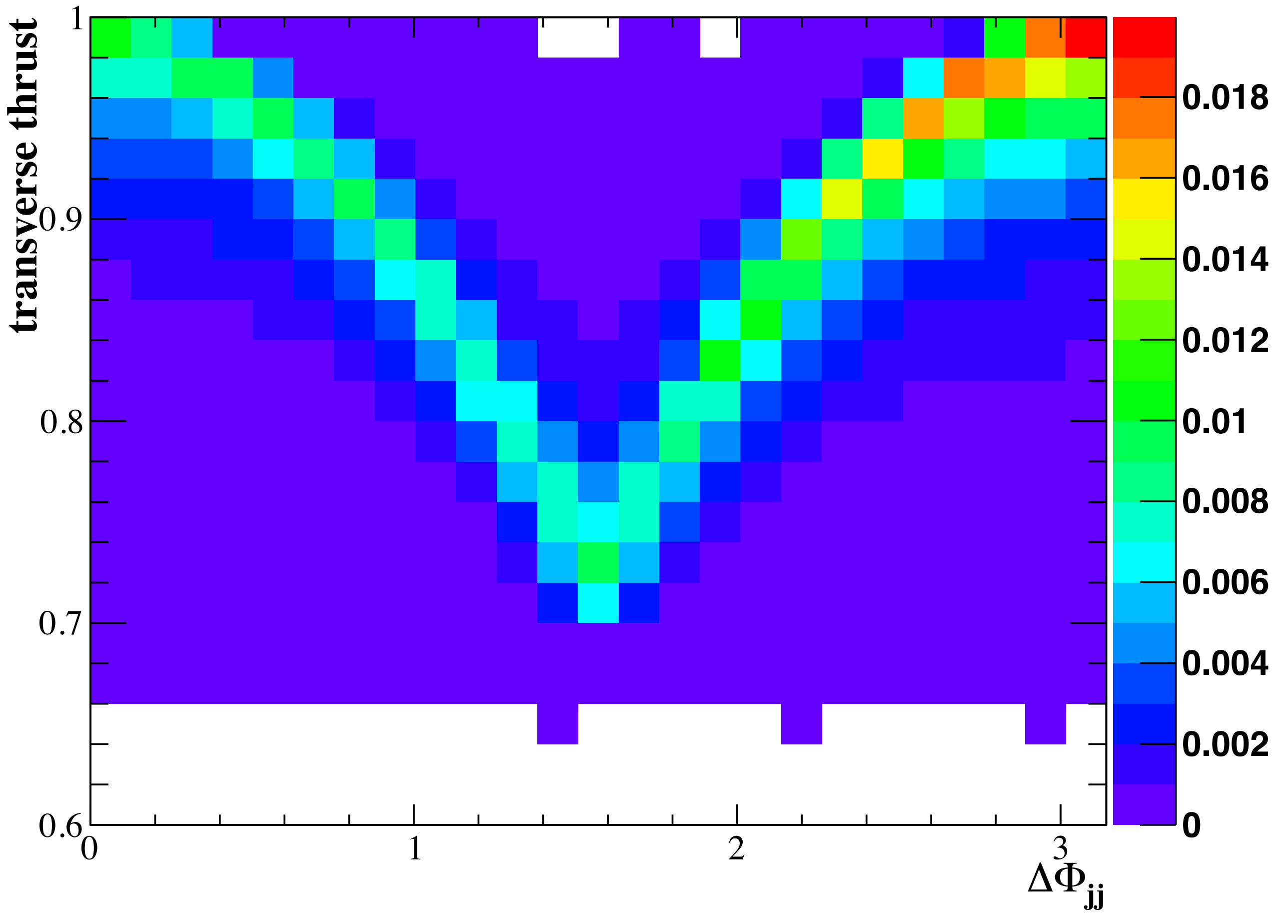
$$p^{\mu}_{>} = \sum_{j \in \{\text{jets: } y_j > y_h\}} p^{\mu}_{j}$$

$$\Delta\Phi_{jj} = \phi(p_>) - \phi(p_<)$$

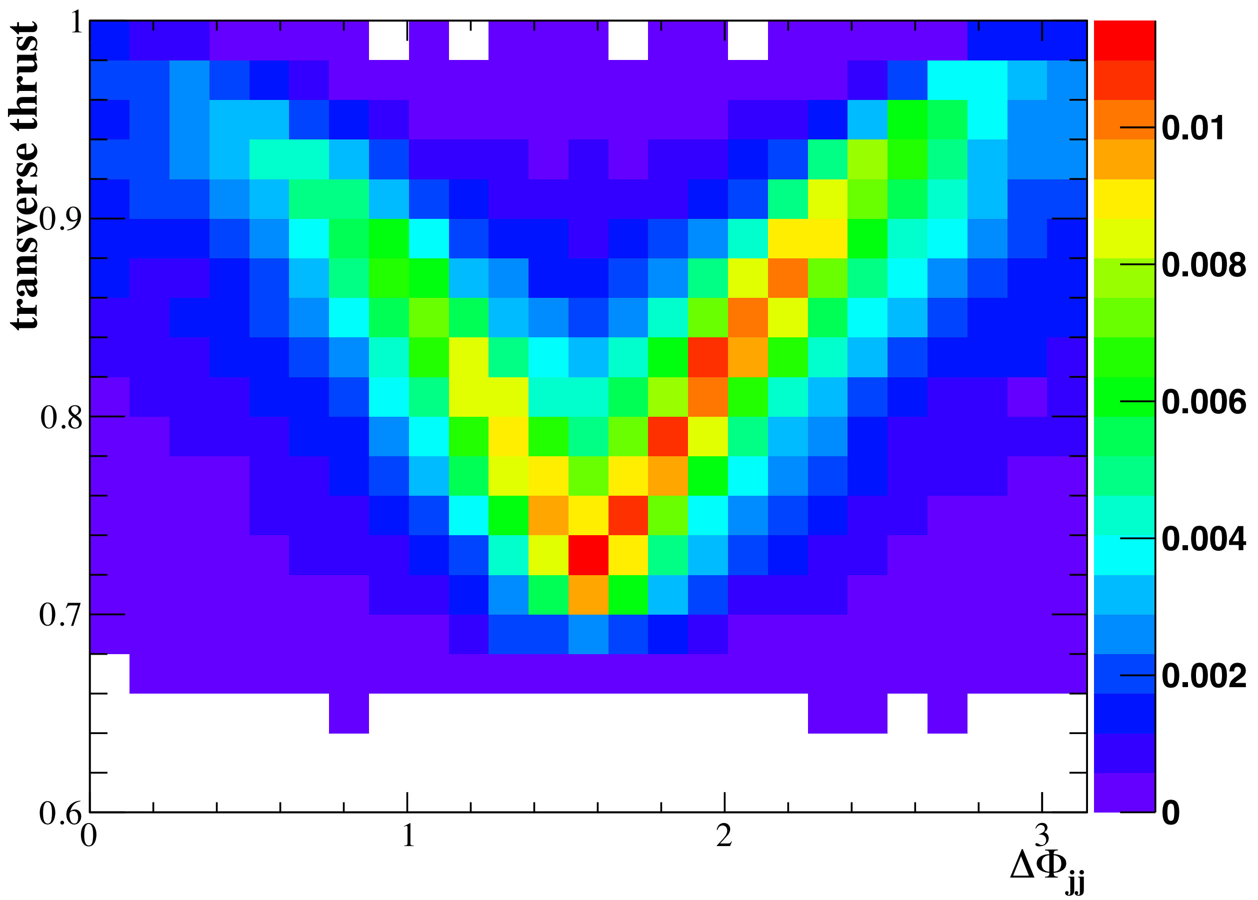




Obvious correlation between thrust and $\Delta\Phi_{jj}$



(a) $\mathcal{CP}$ even Higgs



(b) $\mathcal{CP}$ odd Higgs

Event selection cuts

two tagging jets: $p_{T,j} \geq 40\ \text{GeV},\ \text{and}\ |y_j| \leq 4.5$

$$m_{jj} = \sqrt{(p_{j,1} + p_{j,2})^2} \geq 600\ \text{GeV}$$

two taus, hard and central: $p_{T,\tau} \geq 20\ \text{GeV},\ \text{and}\ |y_\tau| \leq 2.5$

$$|m_{\tau\tau} - m_H| < 20\ \text{GeV}$$

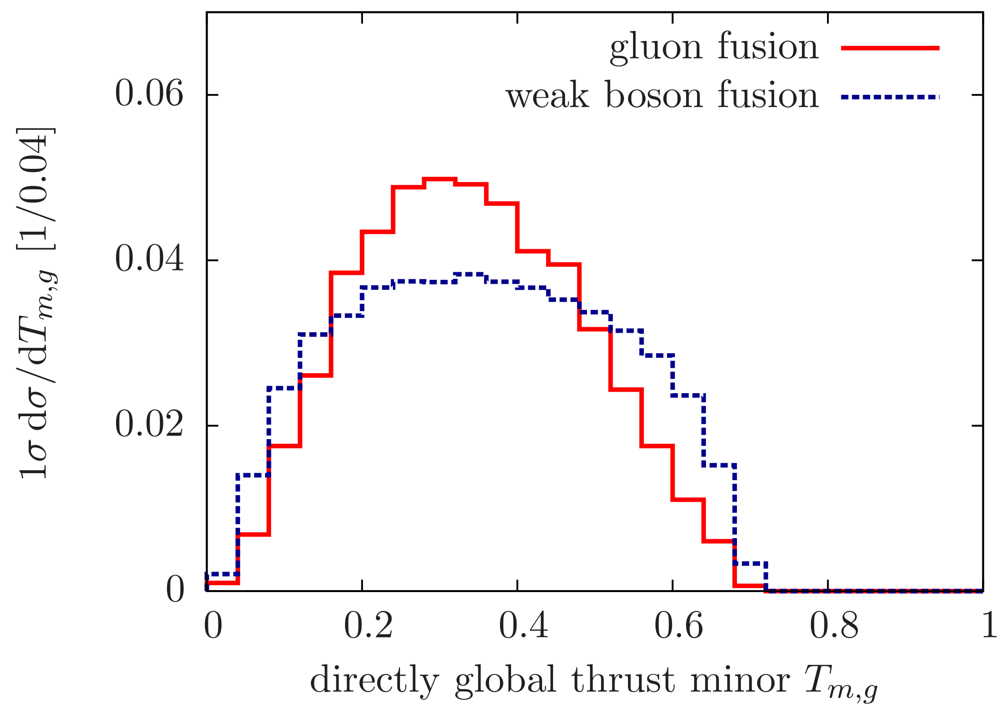
For event shapes use either constituents with

$$p_{T,i} \geq 1\ \text{GeV} \qquad |\eta_i| \ \leq \ 4.5$$

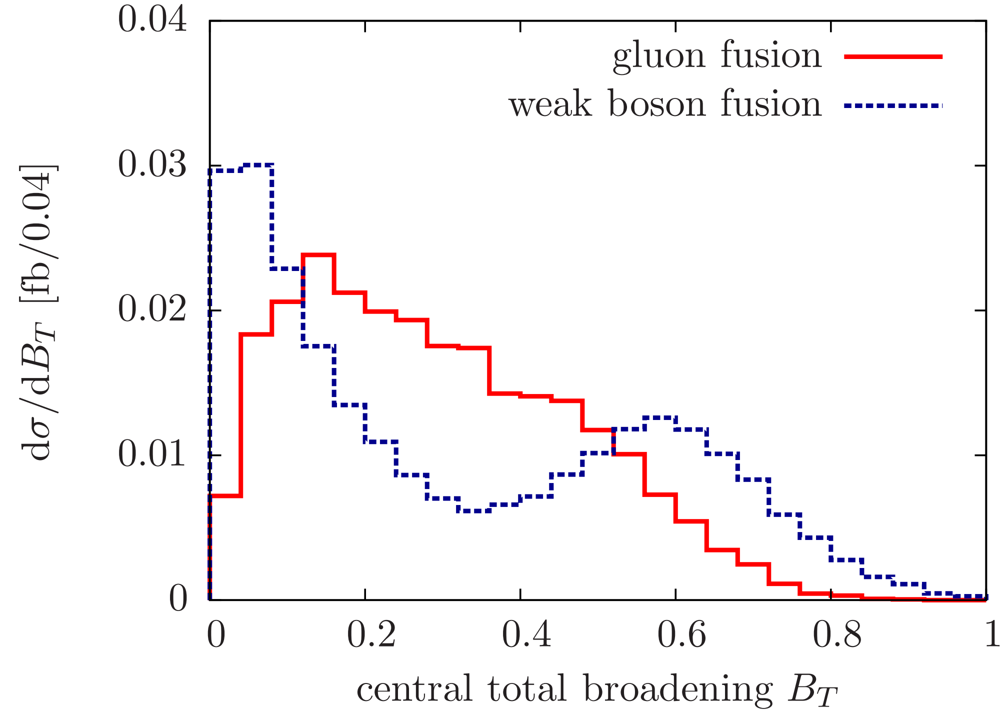
or, to reduce pileup sensitivity

$$p_{T,j} \geq 40\ \text{GeV}\,, \quad \text{if}\ 2.5 \leq |y_j| \leq 4.5\,,\ \text{and}$$
$$p_{T,j} \geq 10\ \text{GeV}\,, \quad \text{if}\ |y_j| \leq 2.5\,.$$

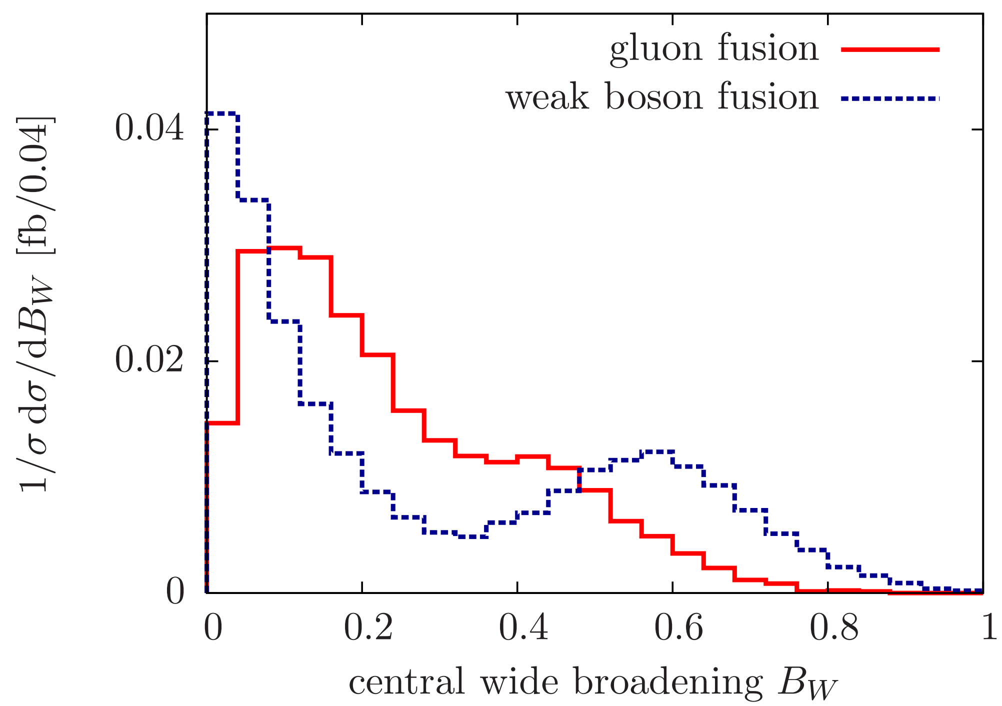
GF vs WBF



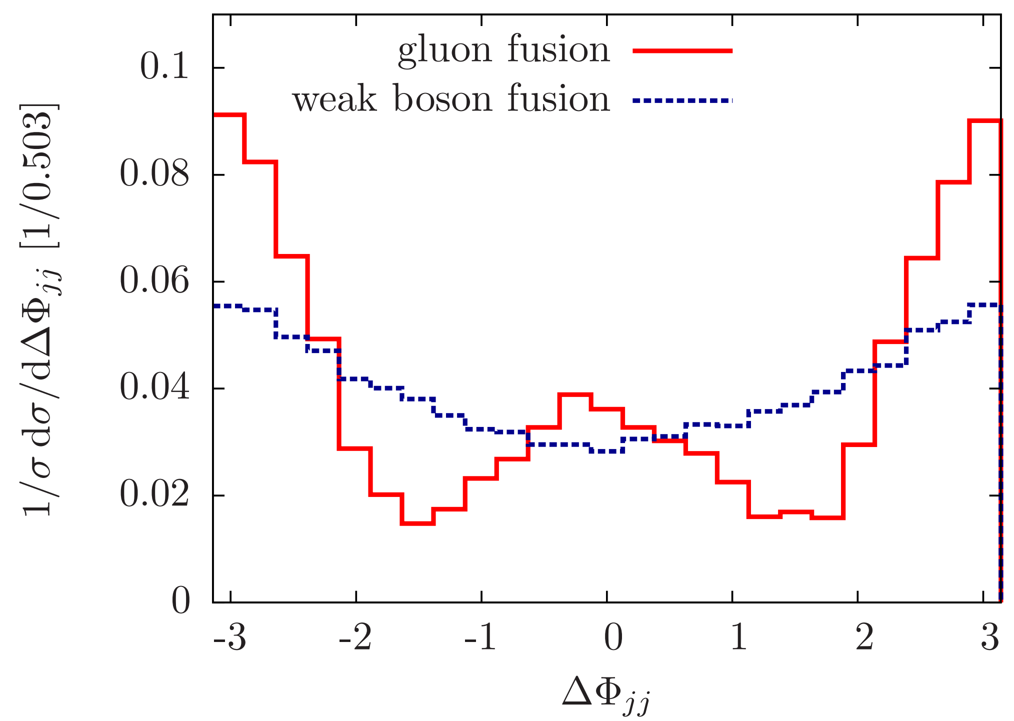
gluon fusion
weak boson fusion
$1\sigma\, d\sigma/dT_{m,g}$ [1/0.04]
0.06
0.04
0.02
0
0
0.2
0.4
0.6
0.8
1
directly global thrust minor $T_{m,g}$



gluon fusion
weak boson fusion
$d\sigma/dB_T$ [fb/0.04]
0.04
0.03
0.02
0.01
0
0
0.2
0.4
0.6
0.8
1
central total broadening B_T

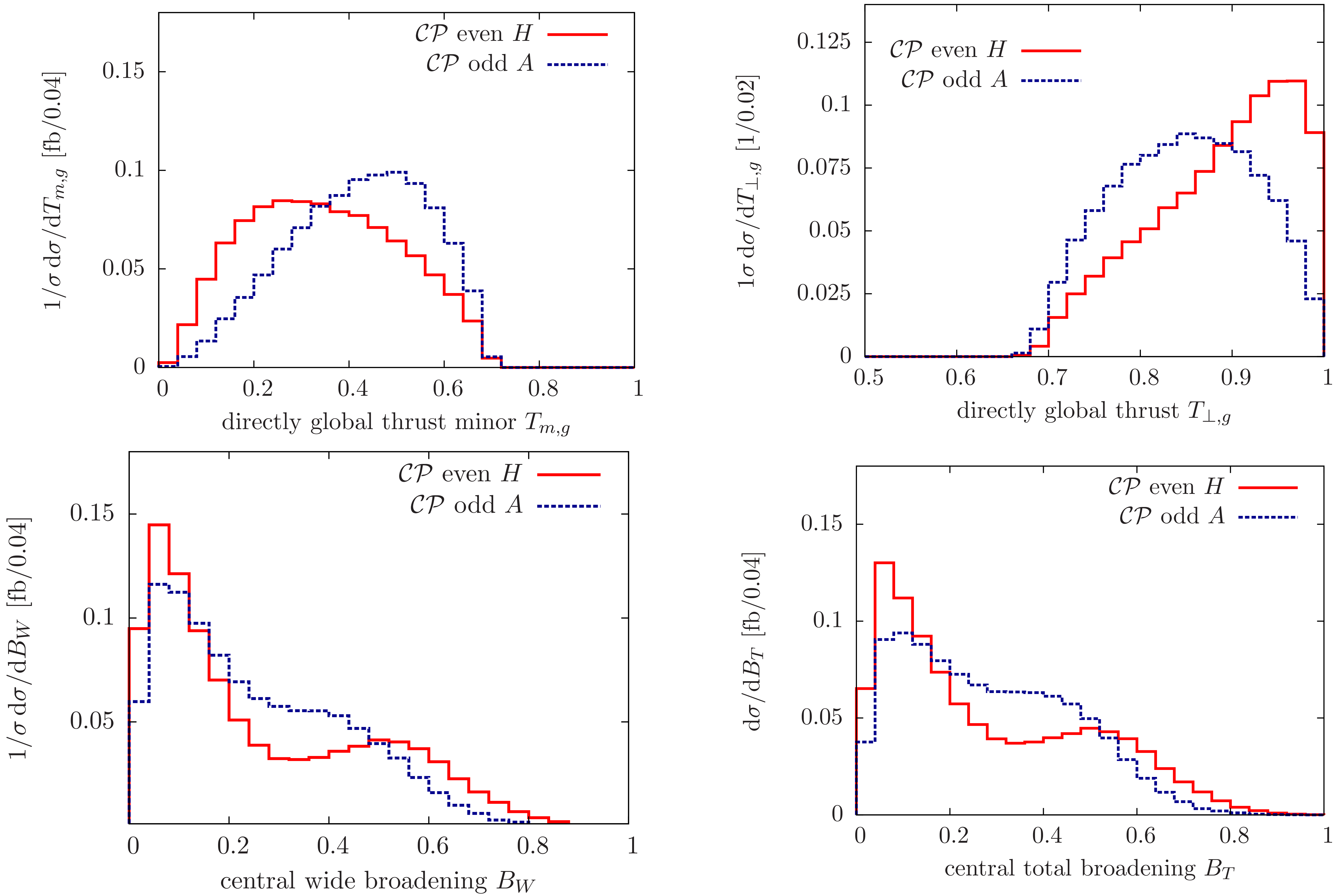


gluon fusion
weak boson fusion
$1/\sigma\, d\sigma/dB_W$ [fb/0.04]
0.04
0.02
0
0
0.2
0.4
0.6
0.8
1
central wide broadening B_W

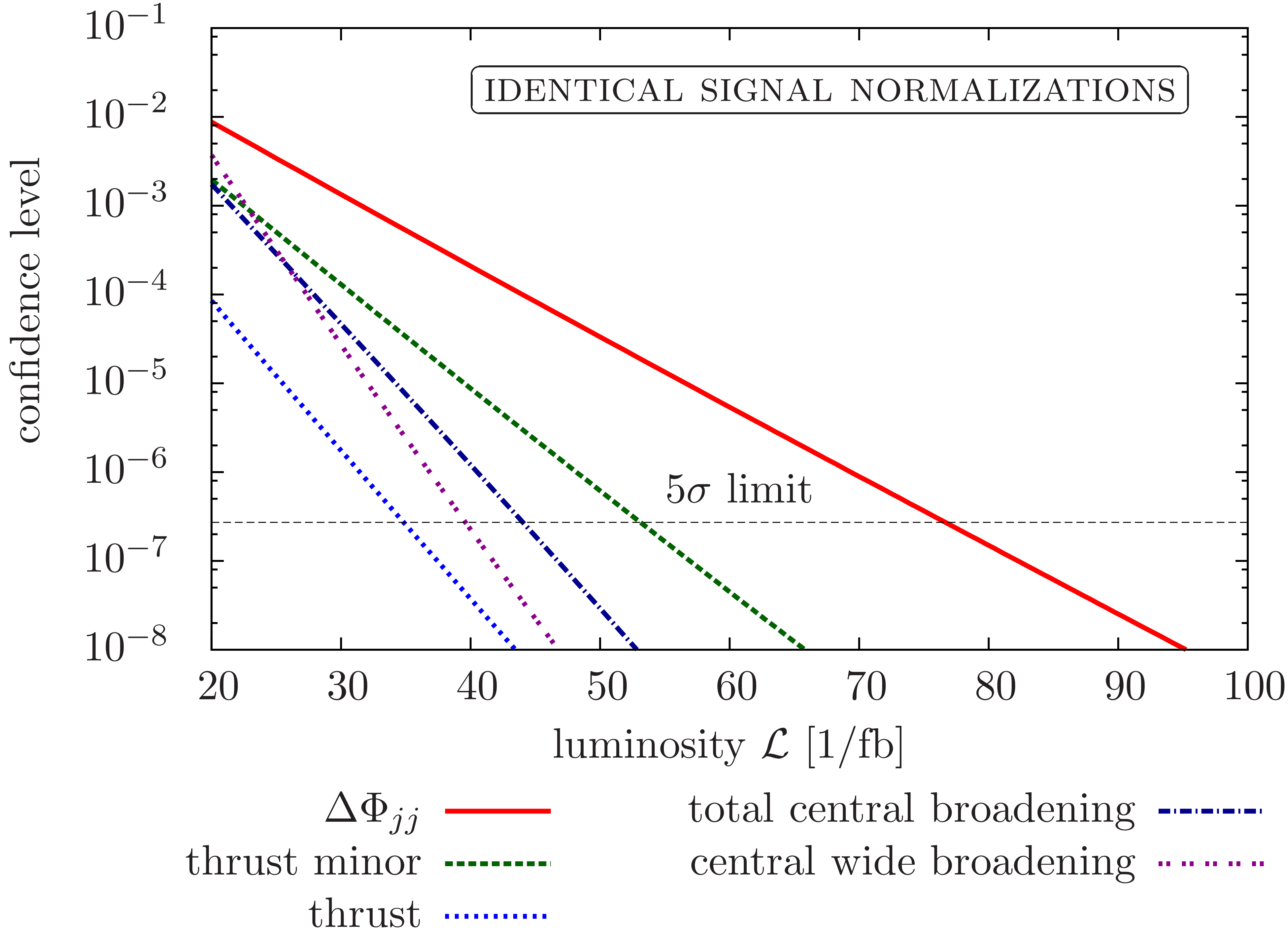


gluon fusion
weak boson fusion
$1/\sigma\, d\sigma/d\Delta\Phi_{jj}$ [1/0.503]
0.1
0.08
0.06
0.04
0.02
0
-3
-2
-1
0
1
2
3
$\Delta\Phi_{jj}$

Distributions CP-odd vs CP-even



Sensitivity for discrimination between CP and CP-odd (normalized signal rates)



Conclusions

- LHC is QCD and BSM machine -> new heavy particles? many jets!

- Great improvements in simulation of hadronic final states

  ➡ Precision (NLO, NNLO, NLL, ...), Shower, Multijet merging,...

- First jet measurements confirm theory predictions

- Boosted scenarios can be superior way to look for new physics
- Jet substructure important for Higgs measurements
- Many different substructure approaches, very active field