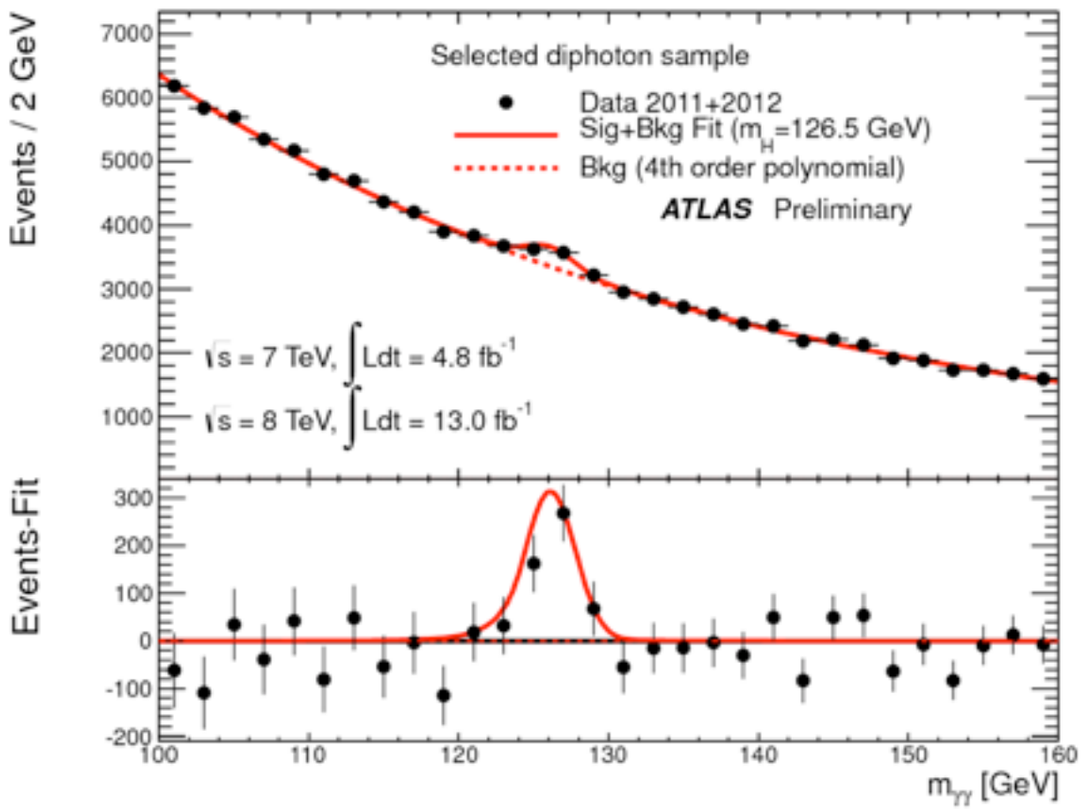
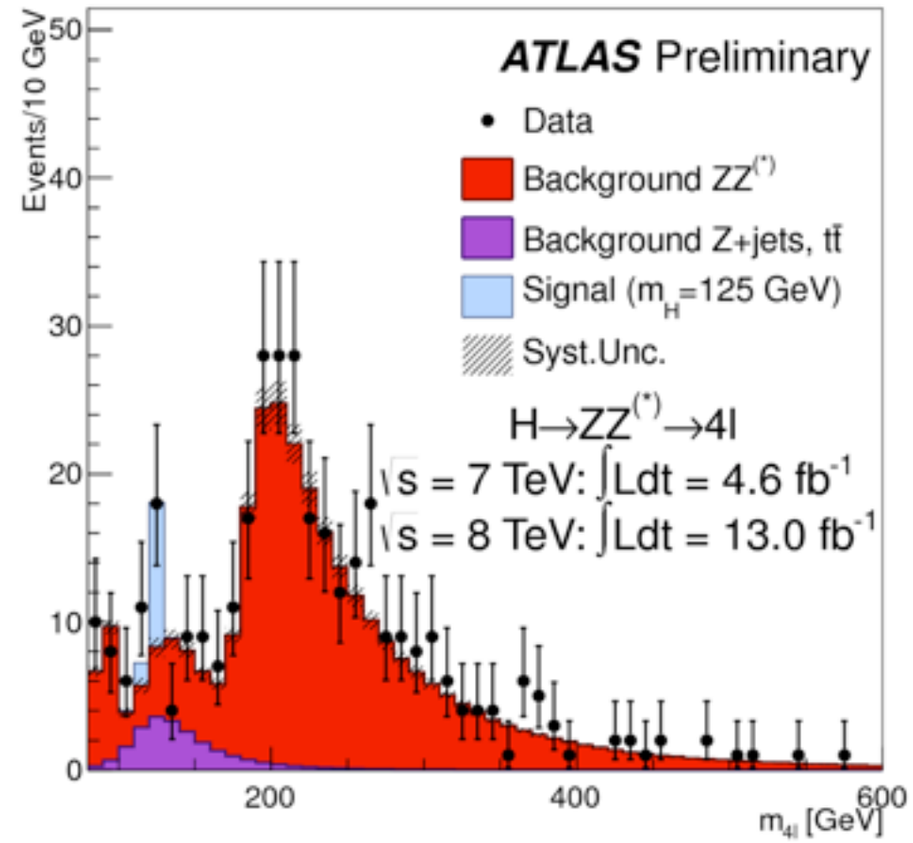
Higgs and Jets at the LHC

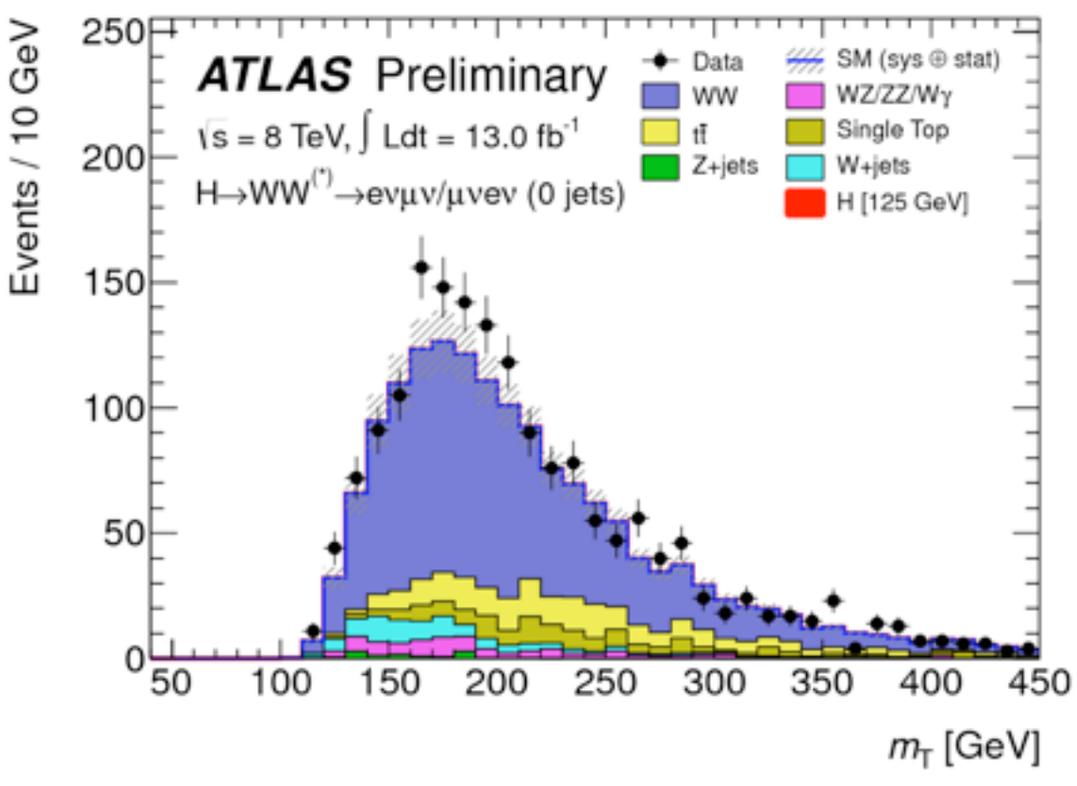
Michael Spannowsky

University of Durham

7 + 8 TeV data:



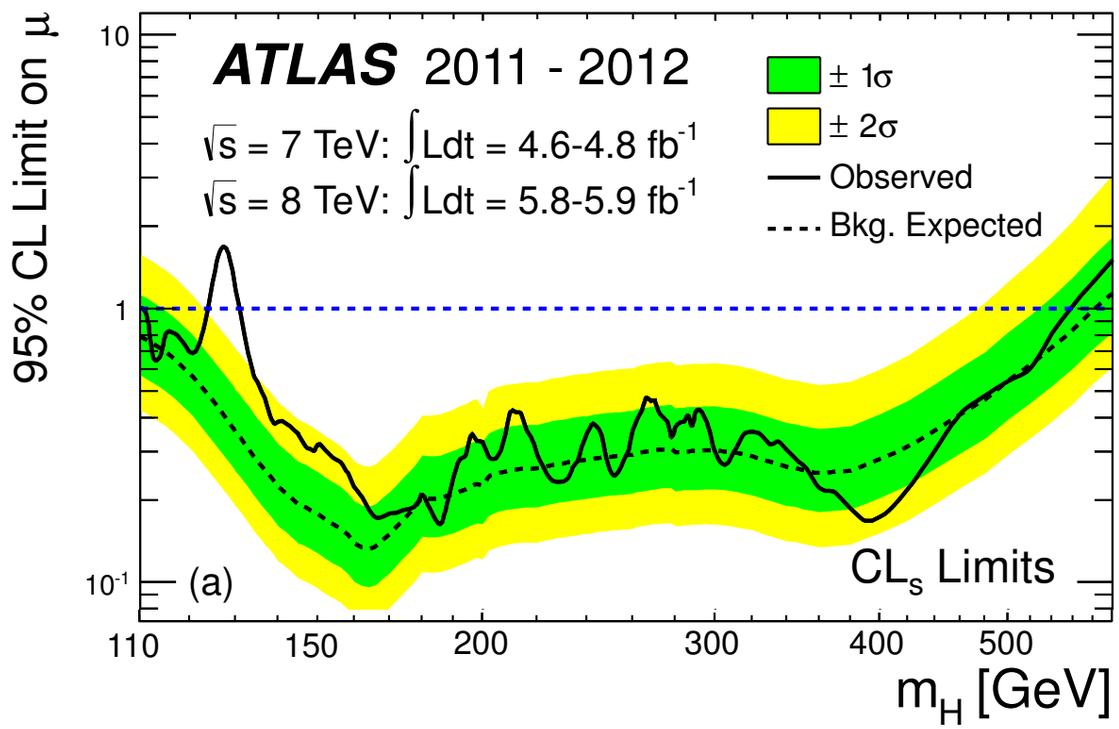


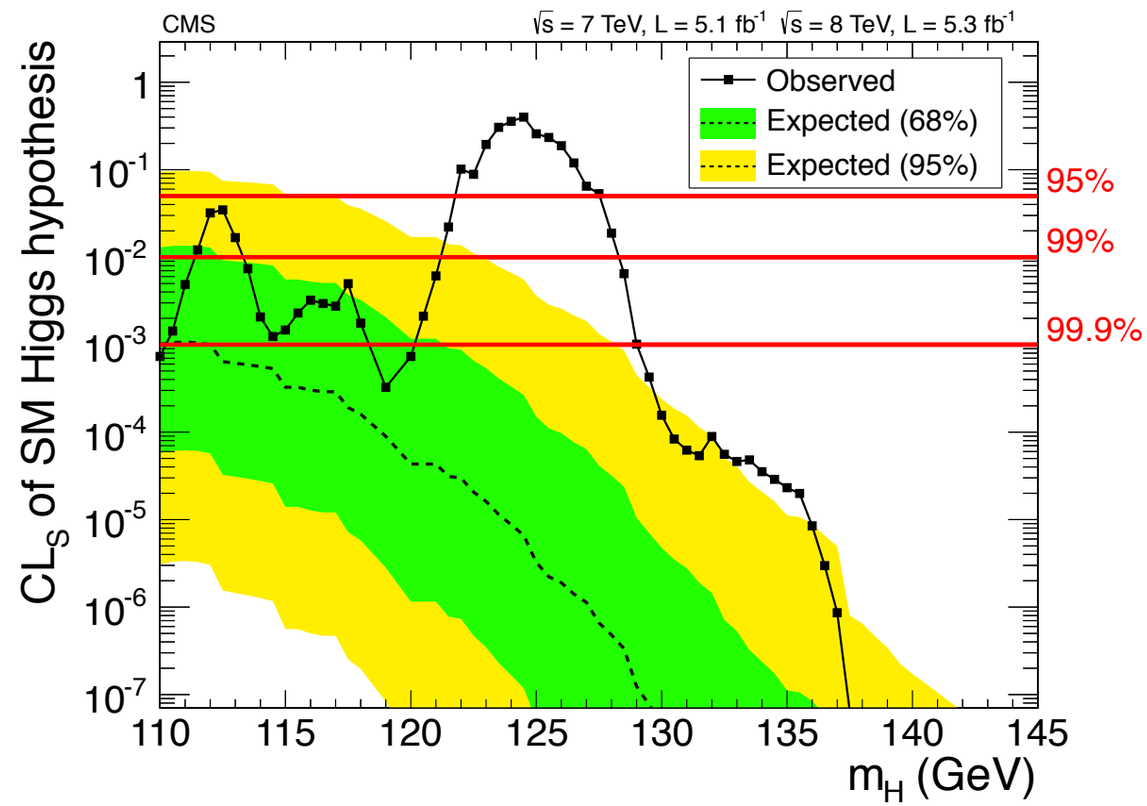


Recently observed clear excesses in 3 independent channels:

- 2 Photons
- 4 Leptons (electrons/muons)
- 2 Leptons (electrons/muons) + MET

Combined results for each experiment





Discoveries by ATLAS and CMS

- Particle consistent with Higgs boson, predicted 50 years ago
- Huge international and intergenerational success!

Whats next?

- Is what we observe "THE HIGGS BOSON"?
- Is minimal SSB mechanism realized in nature?

Only one SU(2) doublet

Couplings to Fermions

Couplings to Gauge Bosons

Higgs potential and selfcoupling

CP property of Resonance

Spin of Resonance

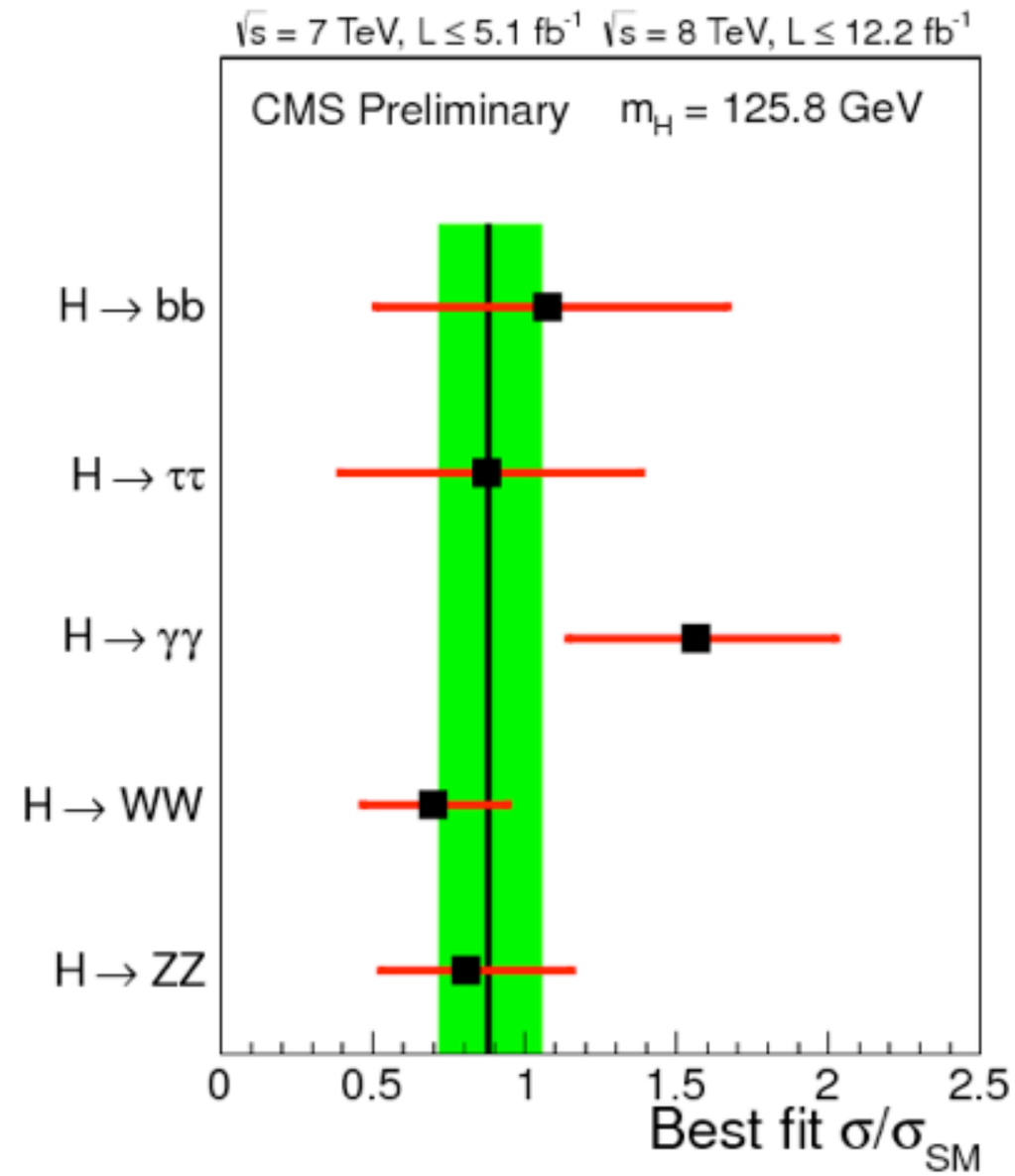
After discovery the Higgs couplings have to be measured:

Present status:

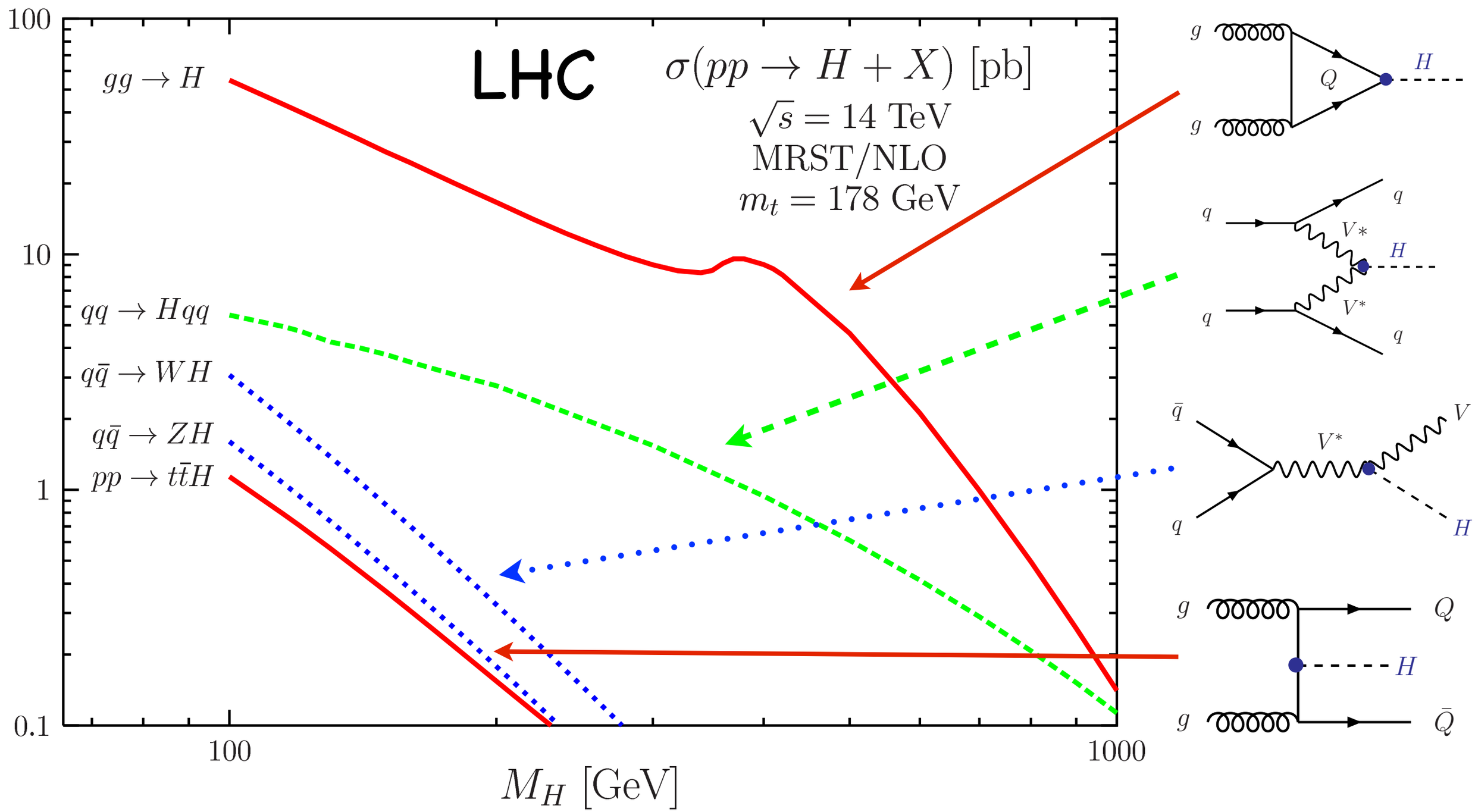
- CMS and ATLAS did fit for couplings already
- For the overall CS CMS has

$$\sigma/\sigma_{\rm SM} = 0.87 \pm 0.23$$

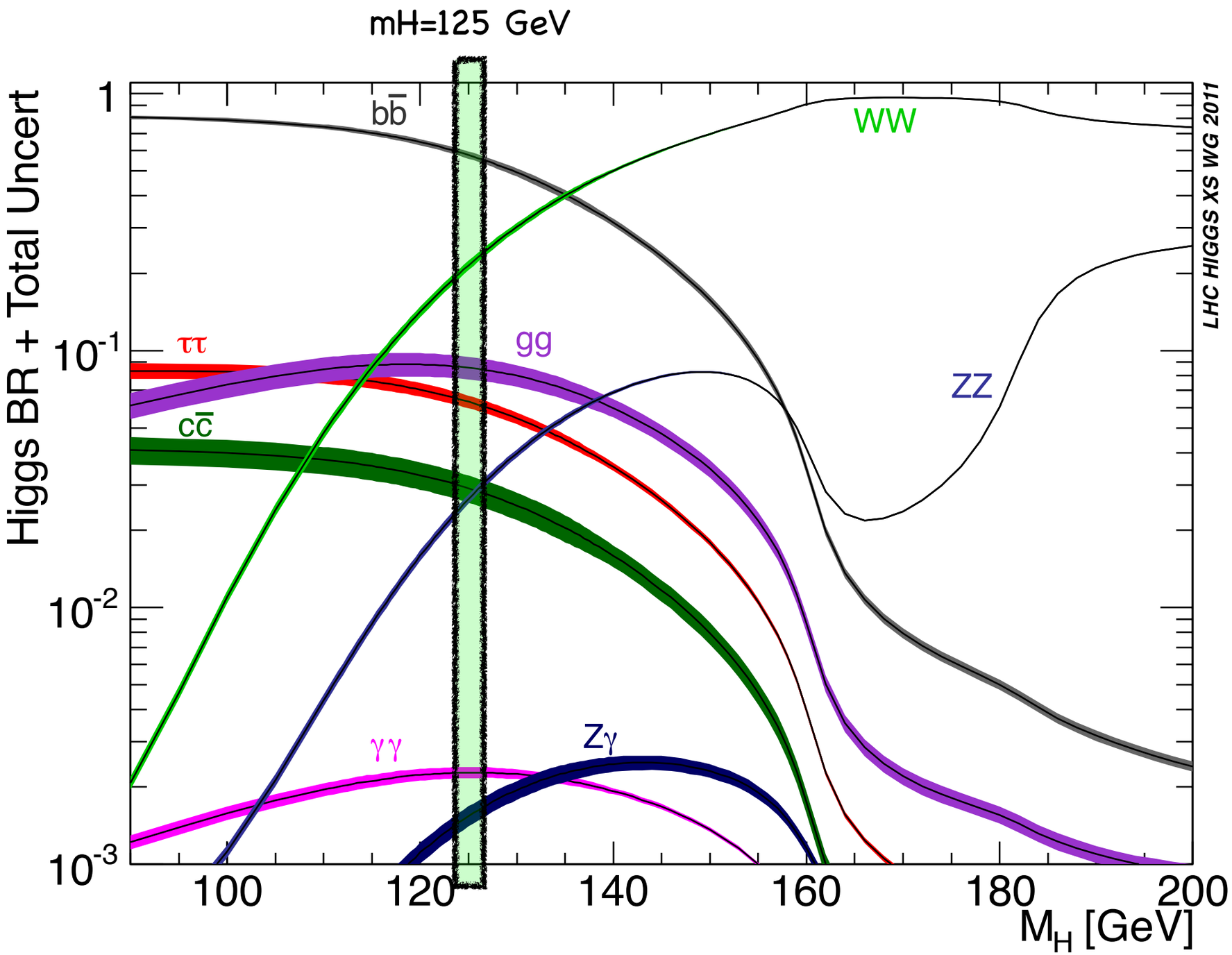
- Green band indicates $\pm 1\sigma$ uncertainty including stat. and sys. uncertainties
- Decay to photons a bit high to taus a bit low, but so far all in all good agreement with SM
- Channels are mutually related!



Production cross section at hadron colliders



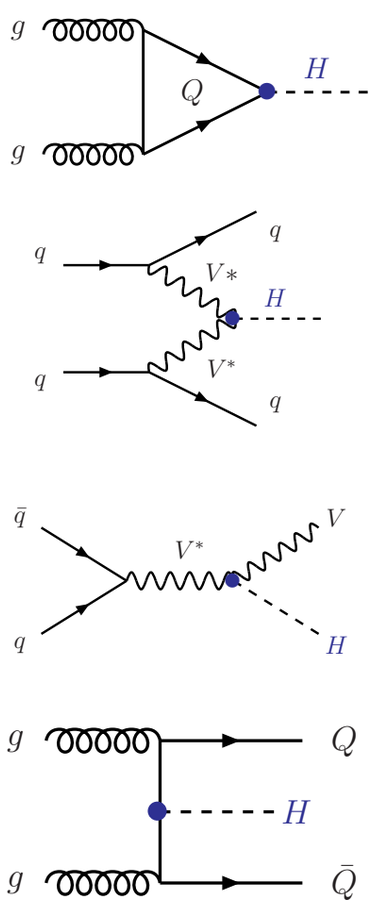
Predicted decay channels



mH = 125 GeV is smooth spot. Important couplings accessible

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

Need cross correlation between many 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)

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

Decay into spec. channel

Production

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

Sum of all possible decays

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

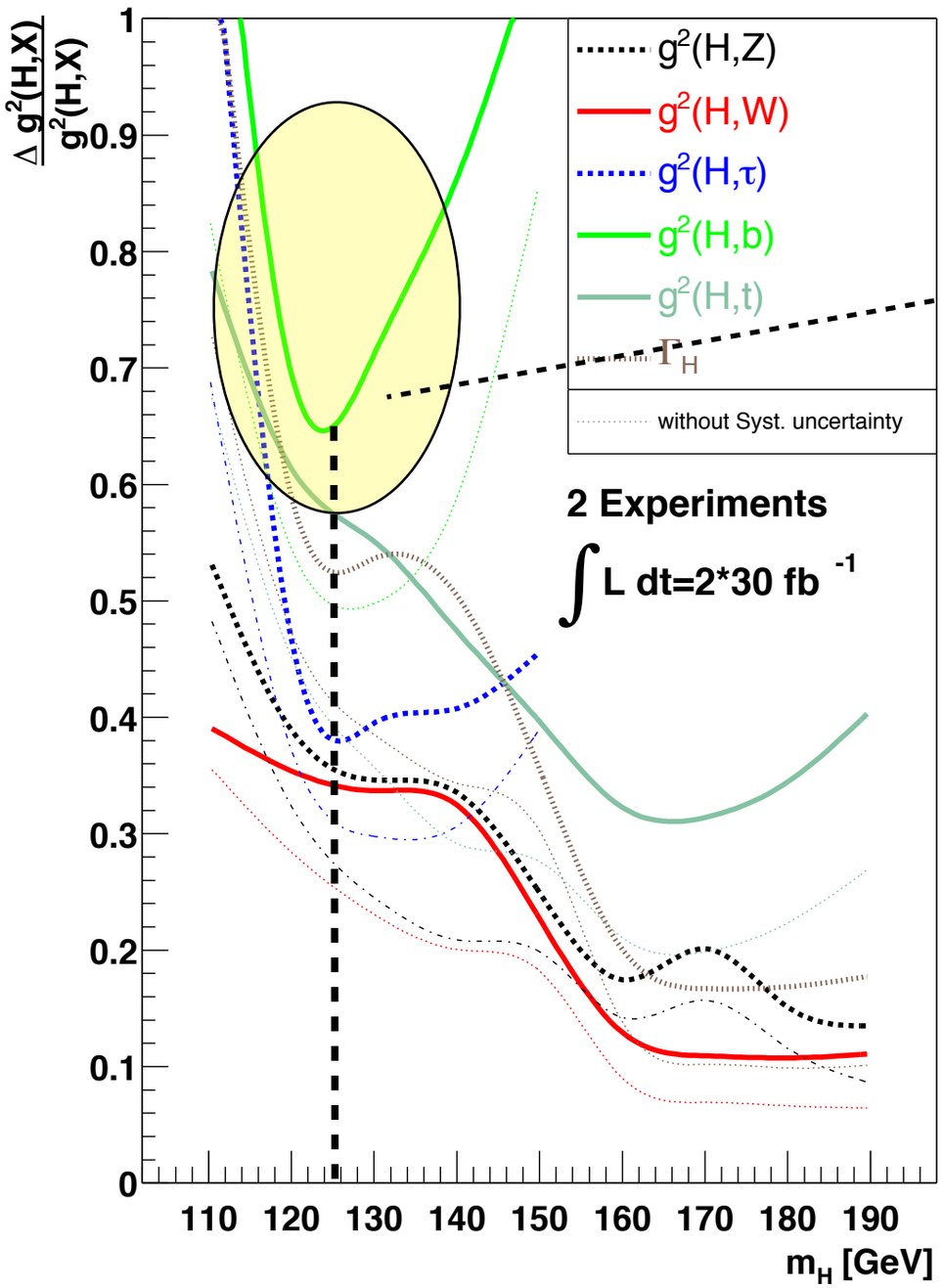
- Every measurement affected by production and decay

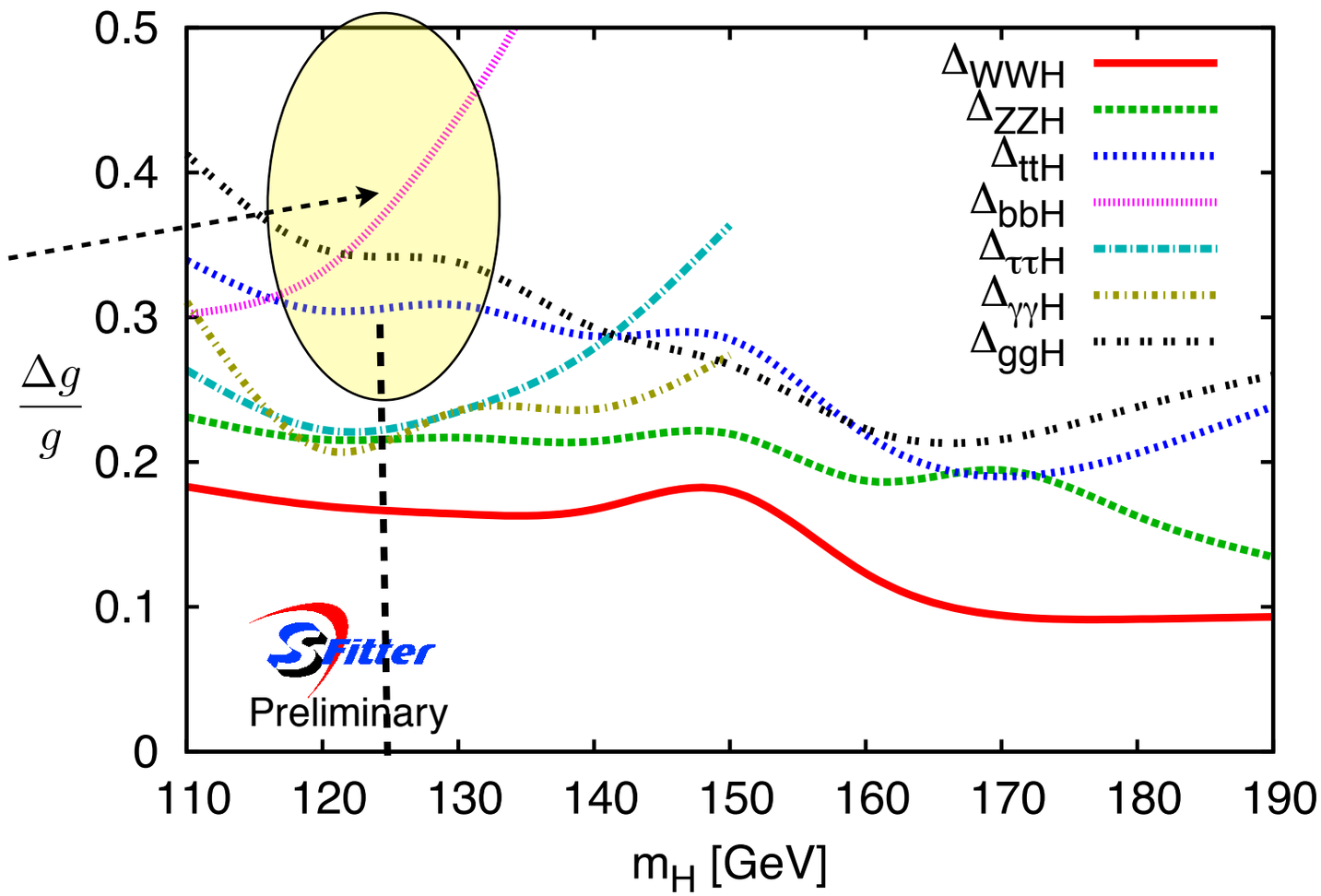
Uncertainty of all coupling measurements driven by total width, i.e. channel with largest BR: H-> bb

Hbb difficult but can use new techniques, i.e. Jet substructure!

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

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

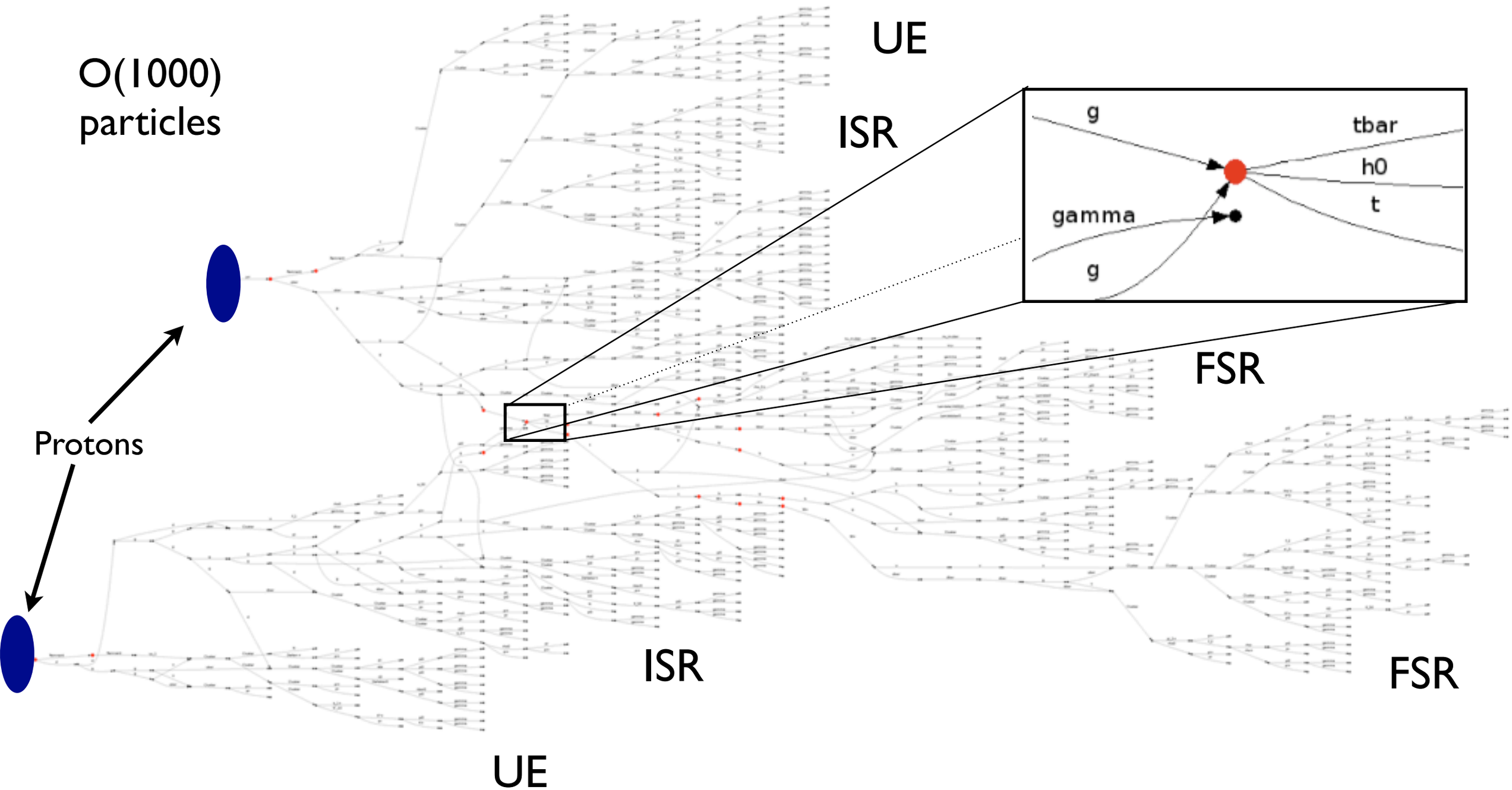




- Huge improvement from boosted Higgs analysis
- also for non-b decay modes due to better knowledge of total width

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

New techniques face difficult environment:



Tedious for theorists and experimentalists

Using jet substructure at LHC requires understanding of all radiation in event

At the LHC many sources of radiation:

- Pileup → Can add up to 100 GeV of soft radiation per unit rapidity

  [Cacciari, Salam, Sapeta JHEP 1004]

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

  [Dasgupta, Magnea, Salam JHEP 0802]

- Initial state radiation (ISR)

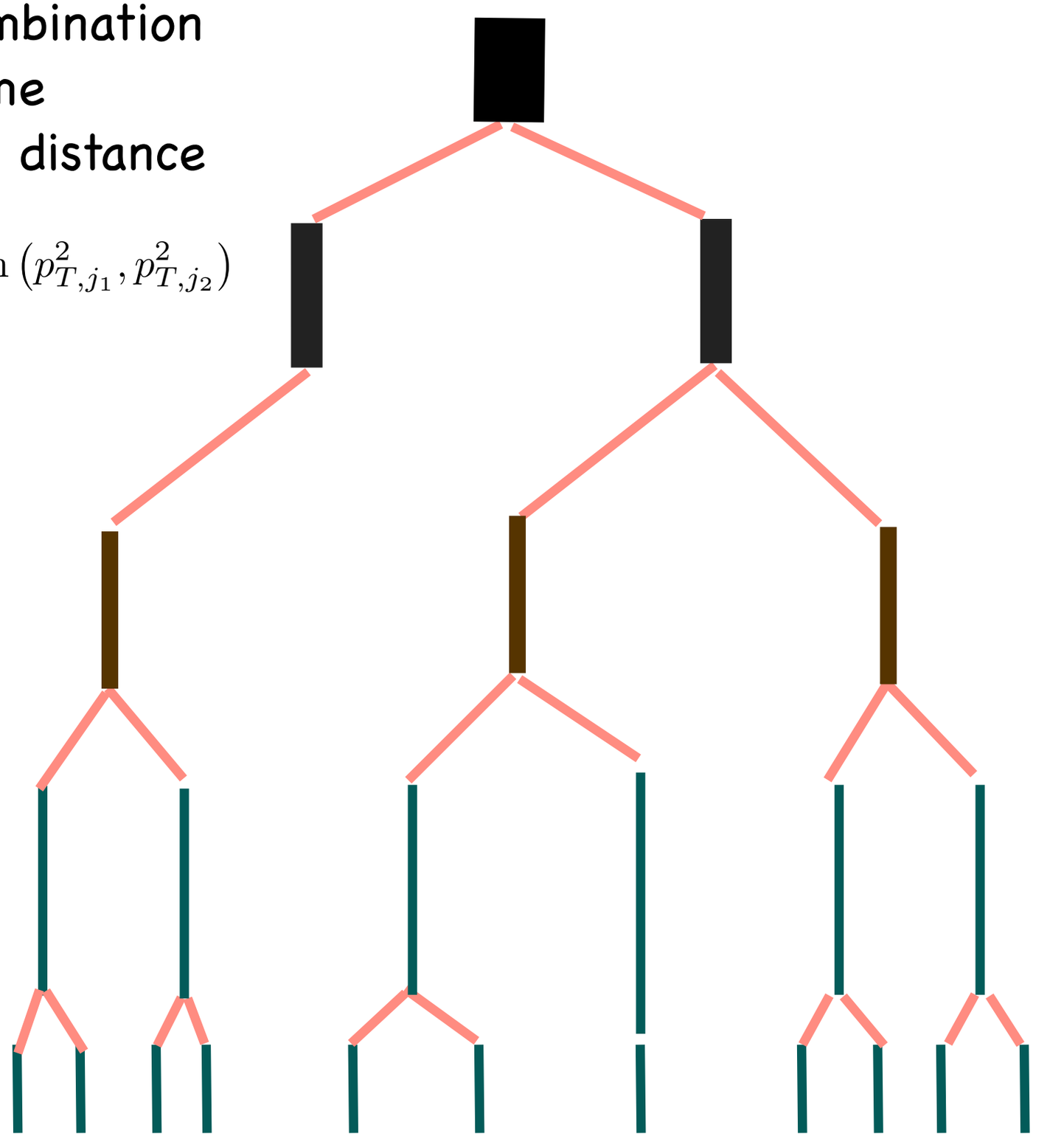
- Hard radiation from many resonances in event

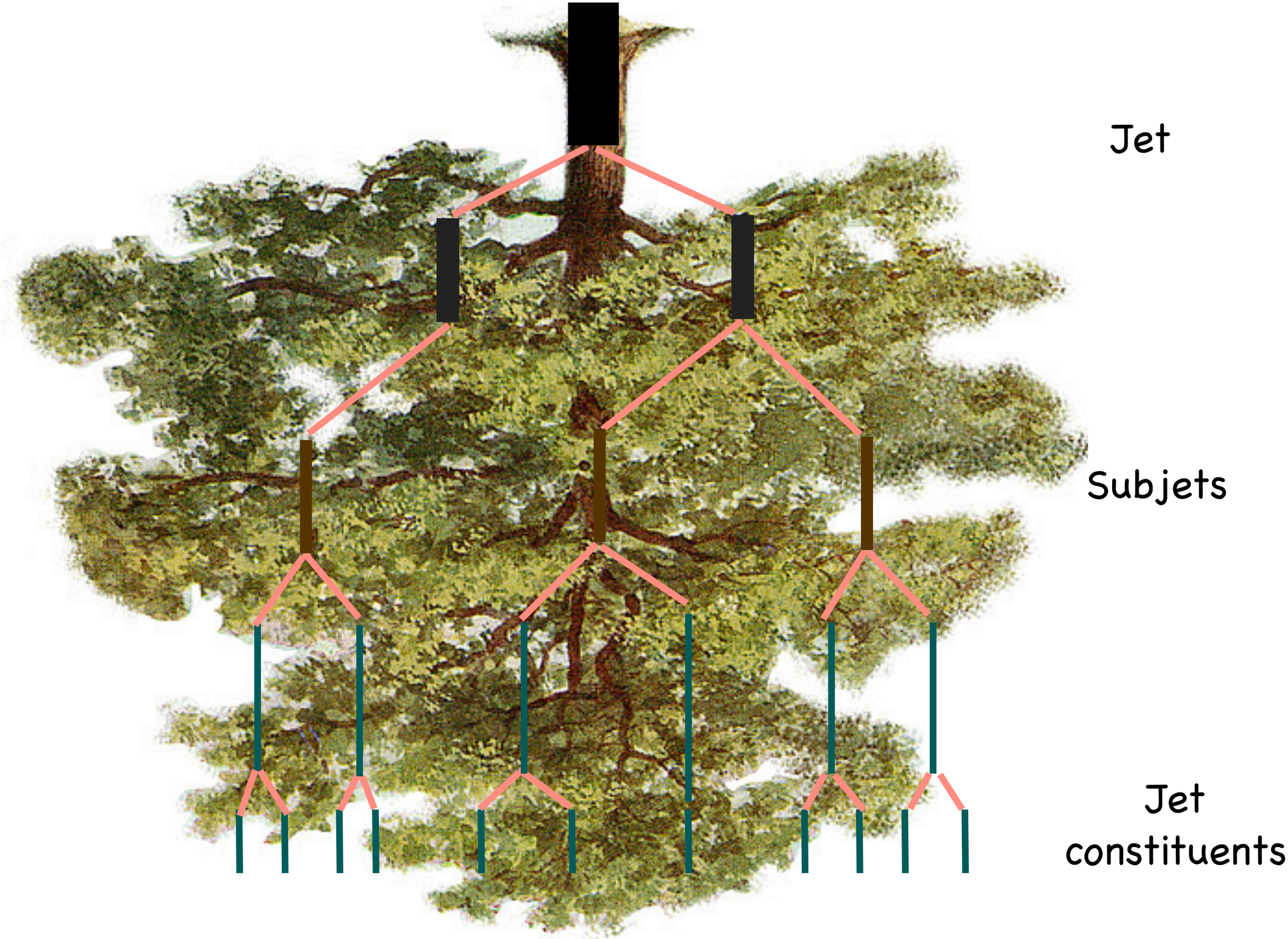
→ Need methods to separate final state radiation (FSR) from rest of event

Mass not a good discriminator -> look into jet substructure

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

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

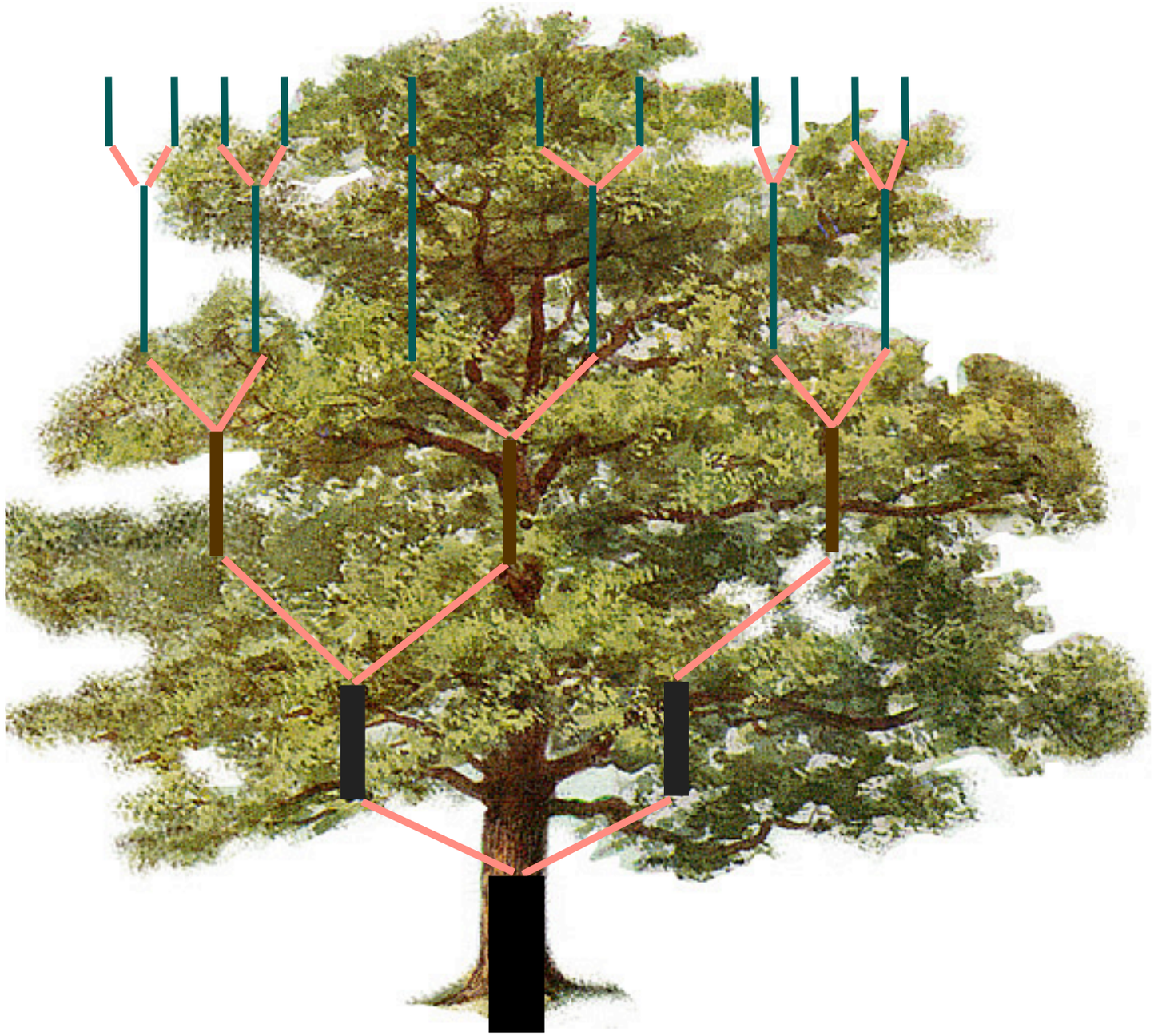



Jet
Subjets
Jet
constituents

Intrinsic scales and energy sharing of jet substructure different

→ Can be used to discriminate QCD jet from resonance jet

Higgs-boson jet



QCD jet

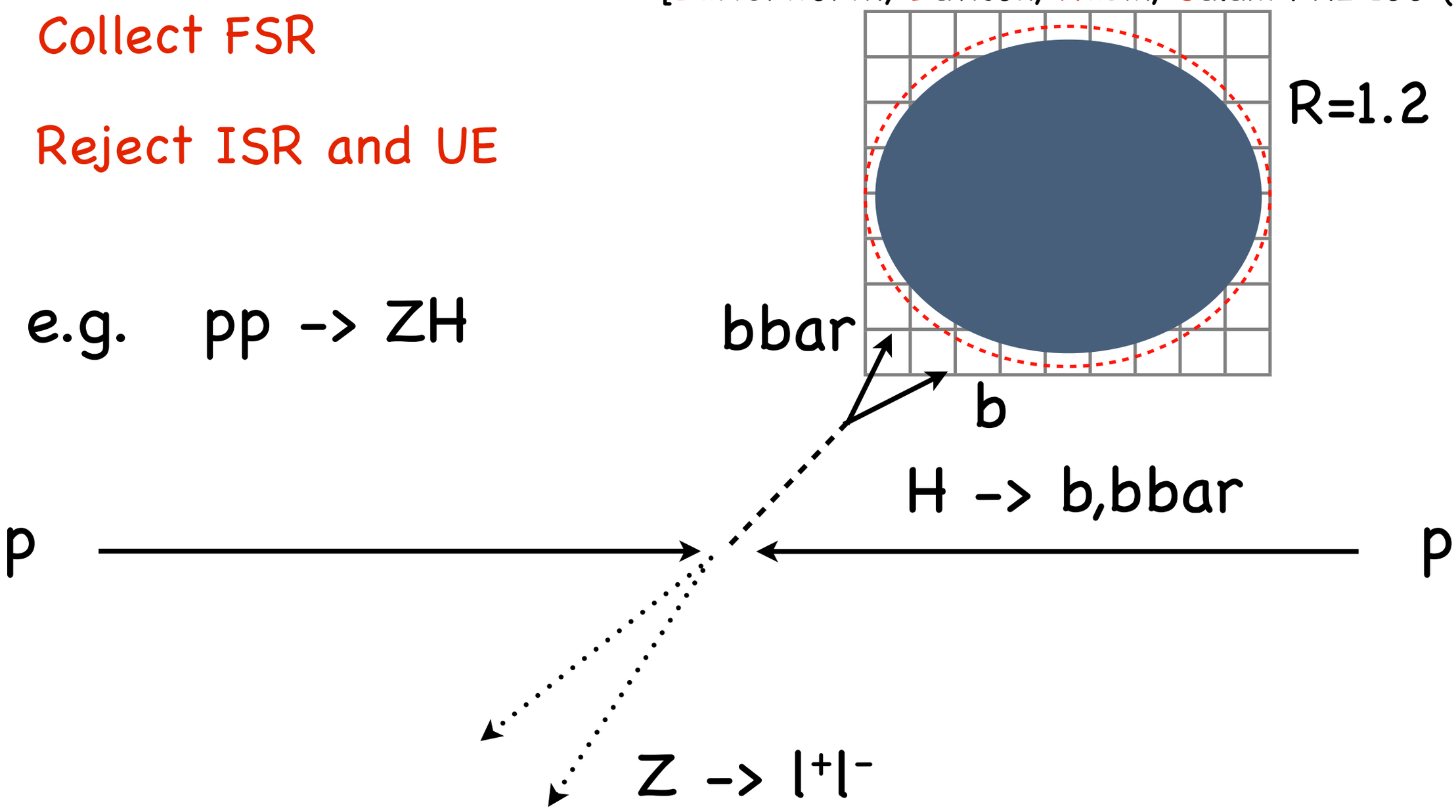
I. Measuring the Higgs-bottom coupling using jet substructure

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

Collect FSR

Reject ISR and UE

e.g. pp -> ZH



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

HV - Higgs discovery channel

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

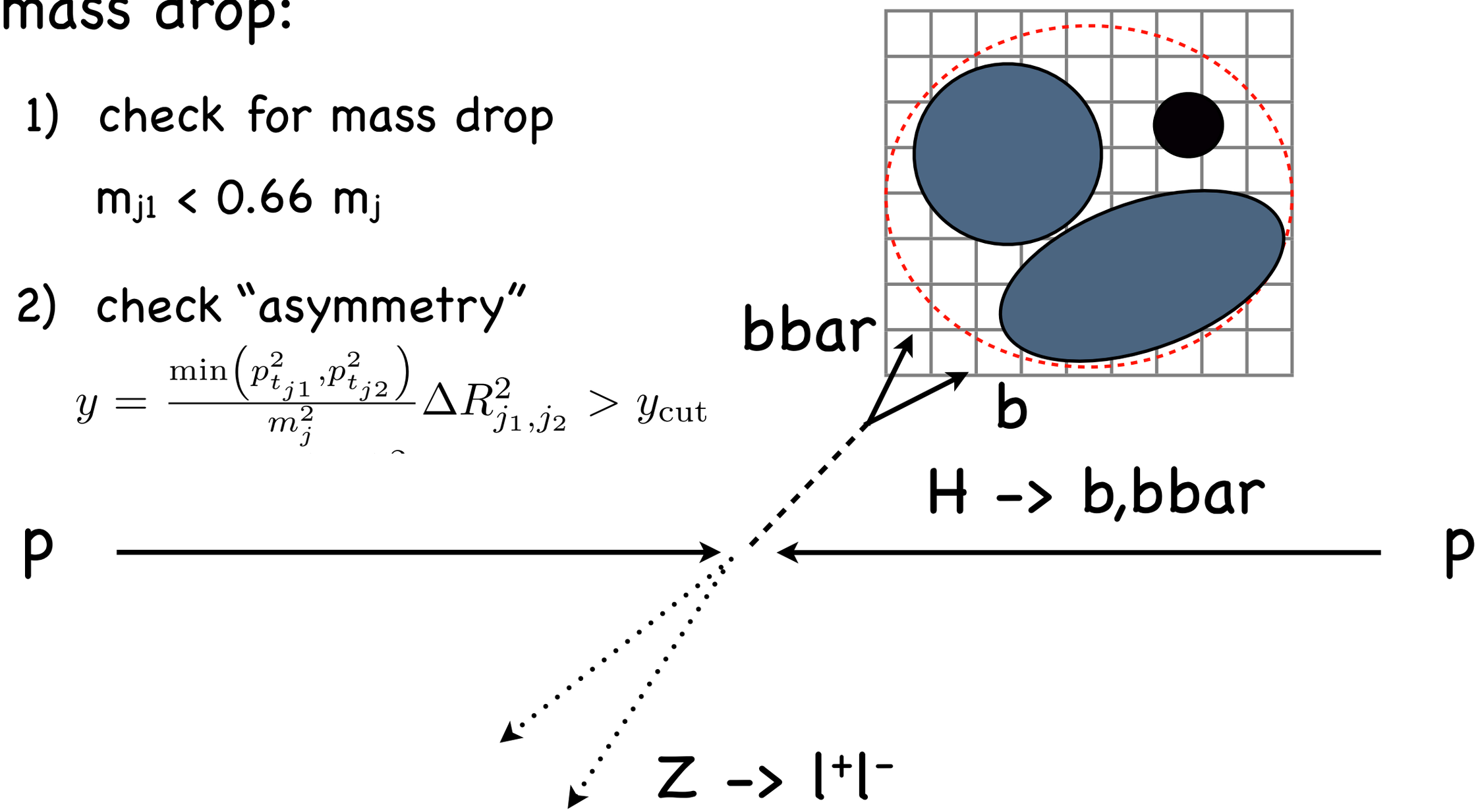
mass drop:

1) check for mass drop

$m_{j1} < 0.66\ m_j$

2) check "asymmetry"

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

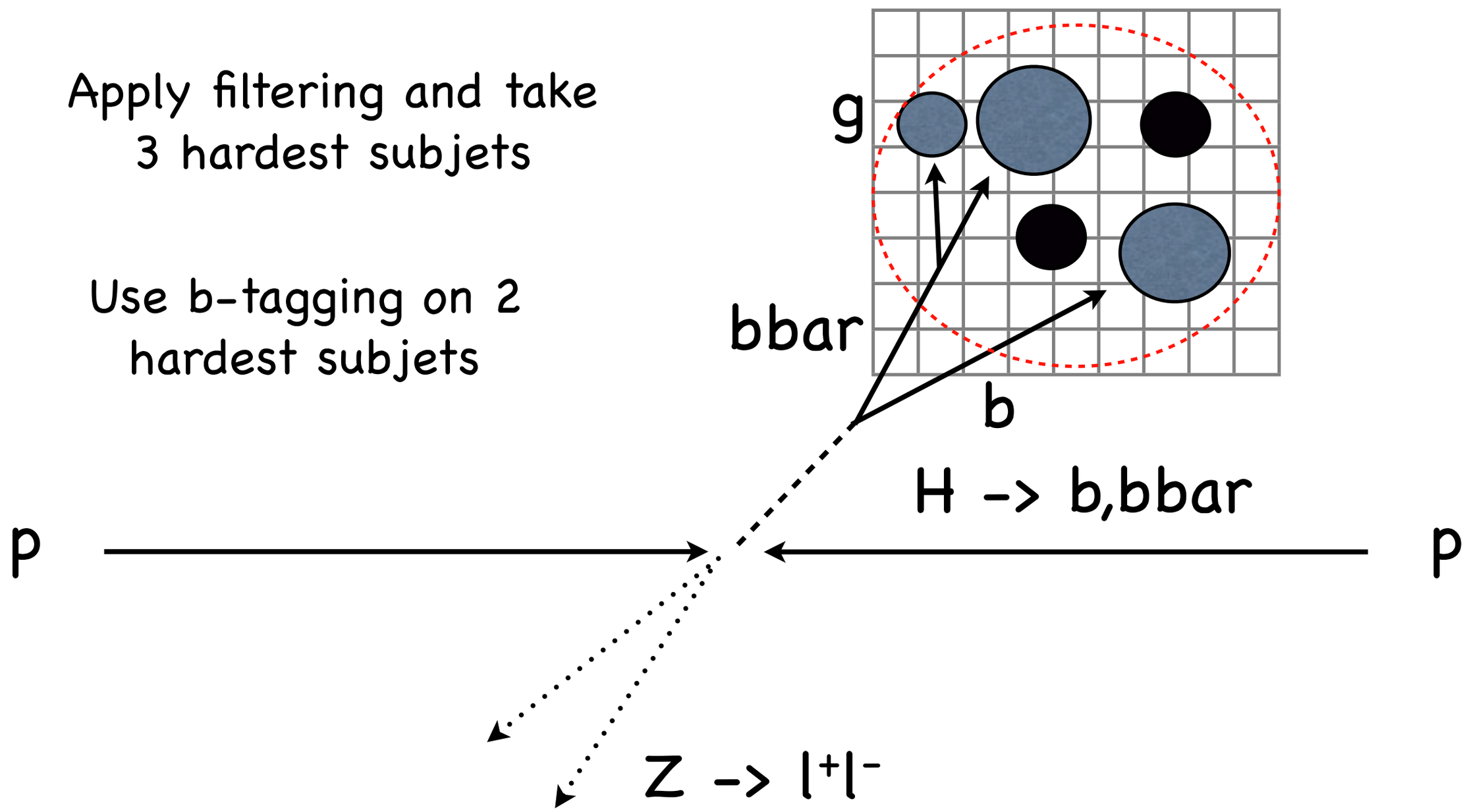


HV - Higgs discovery channel

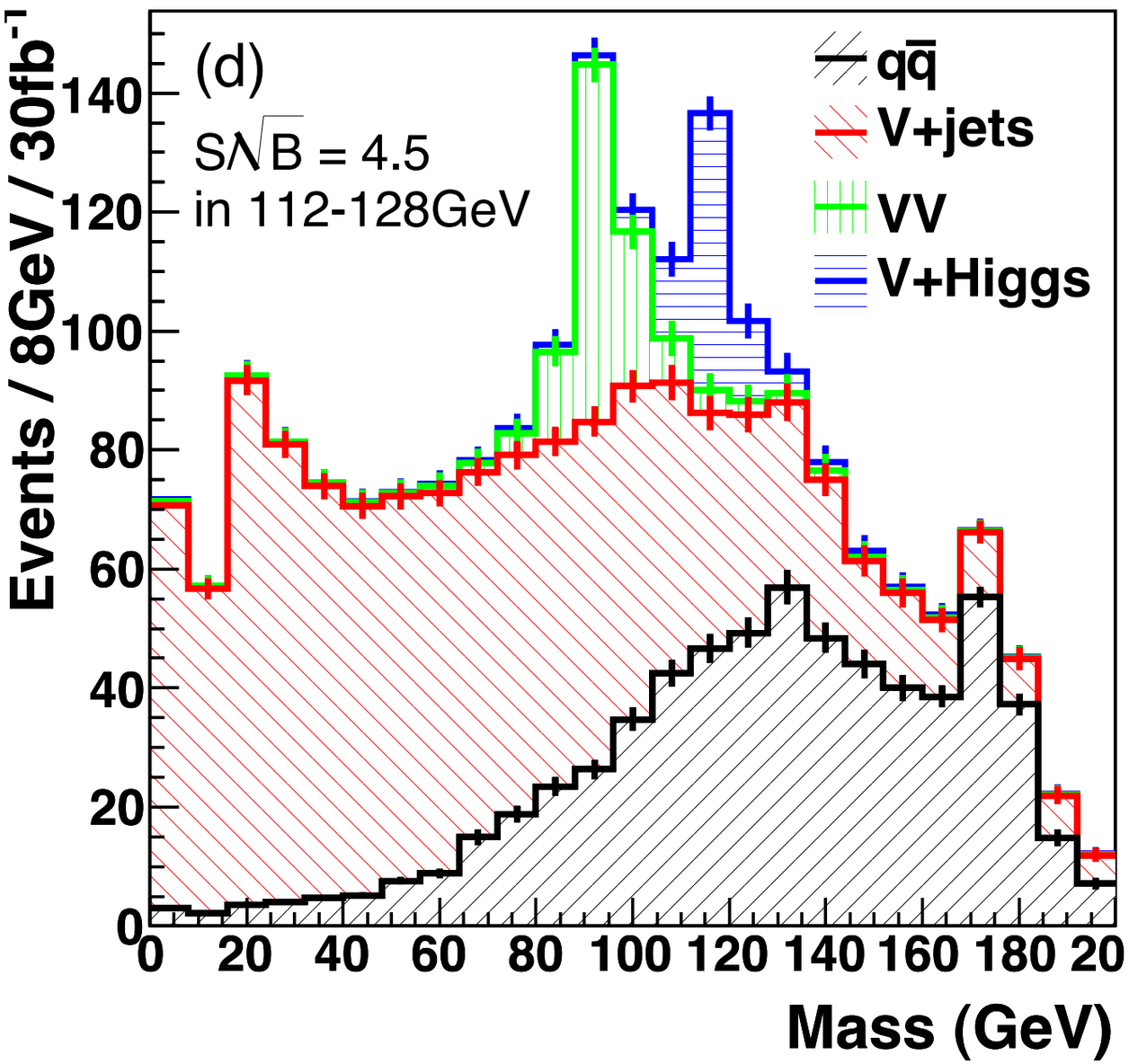
[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

Apply filtering and take 3 hardest subjets

Use b-tagging on 2 hardest subjets



BDRS Result

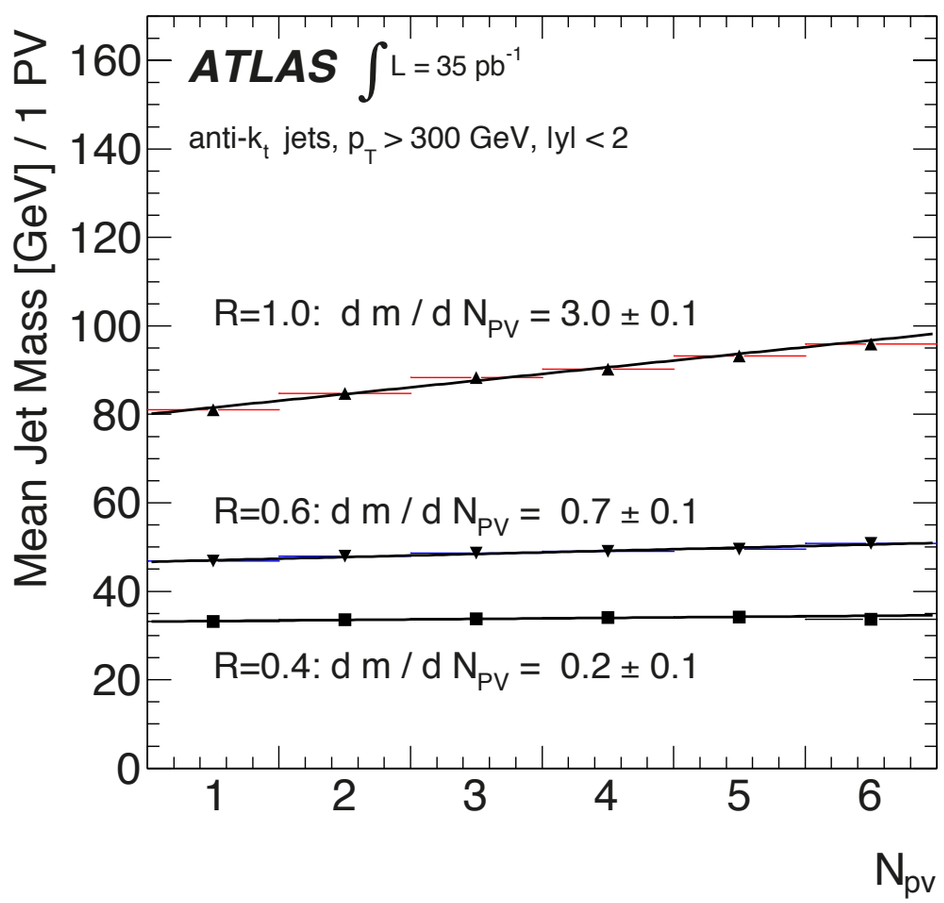


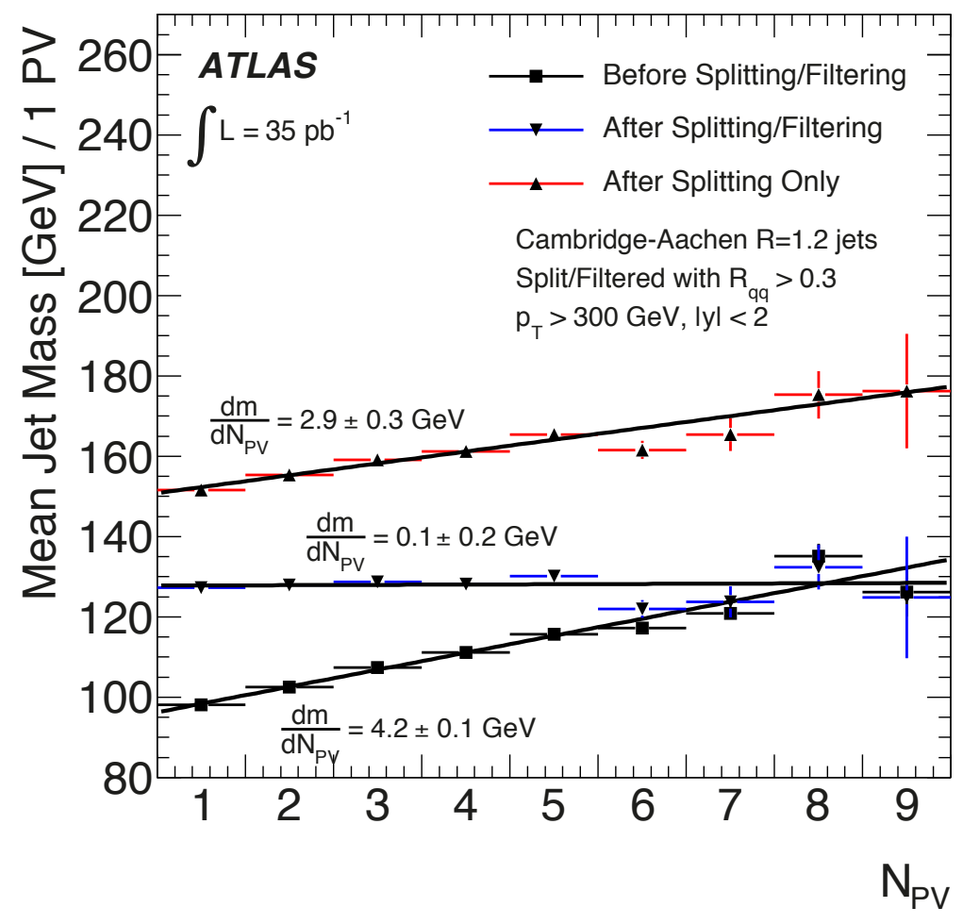
- LHC 14 TeV; 30 fb^{-1}
- HERWIG/JIMMY/Fastjet cross-checked with PYTHIA with "ATLAS tune"
- 60% b-tag; 2% mistag
- Combination of HZ and HW channels

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

Jet substructure methods can still be improved a lot!

Our approach:

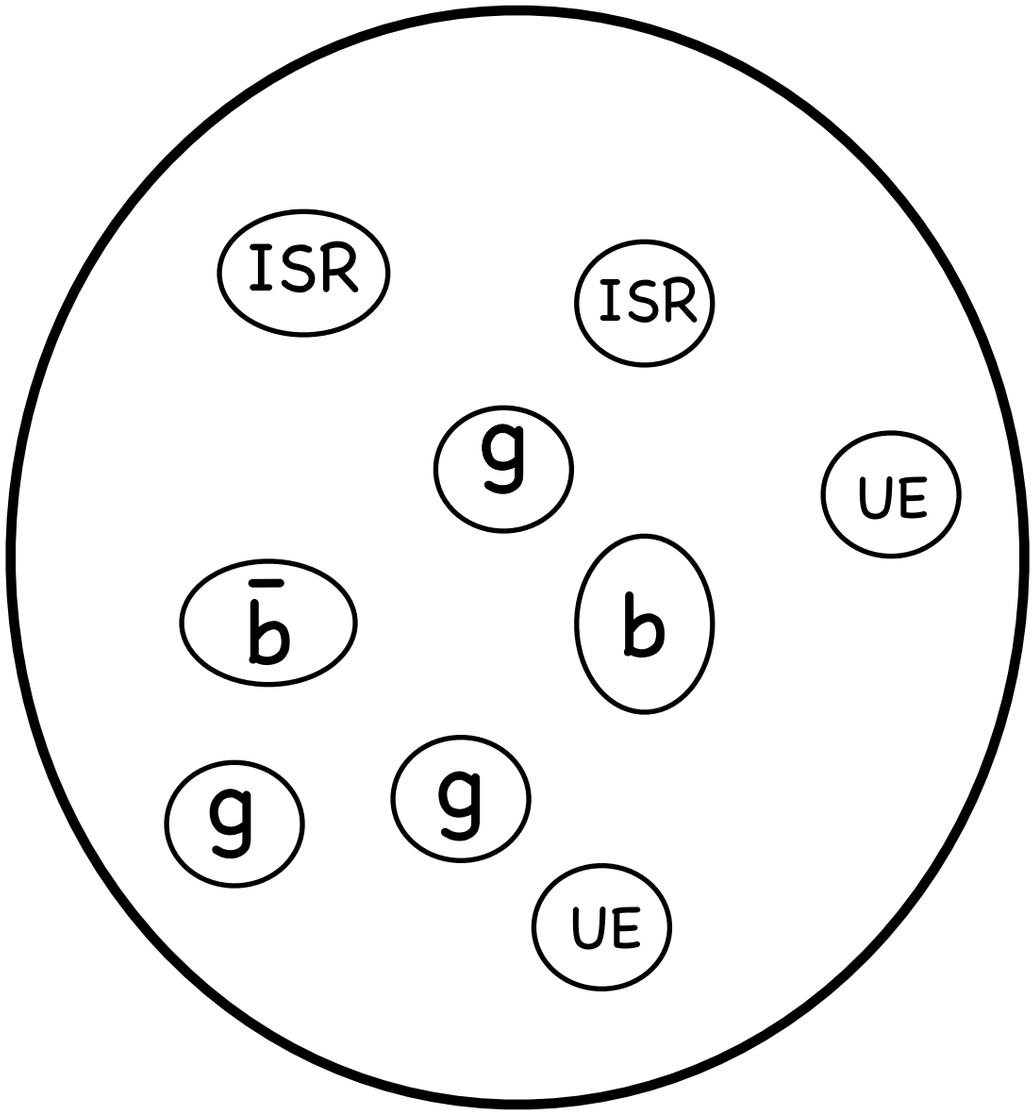
Shower deconstruction

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

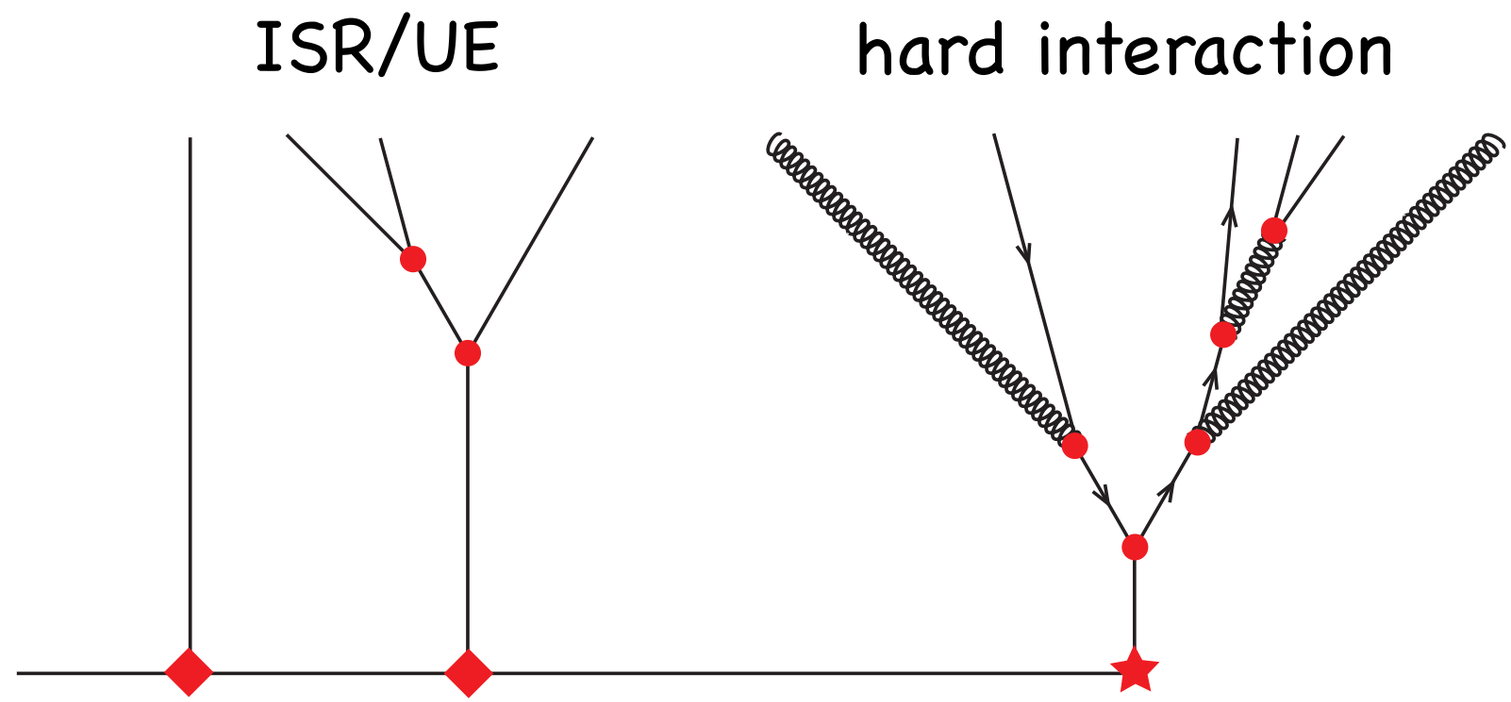
[Soper, MS PRD 84 (2011)]

Playground: Boosted HZ final state

Fat jet: R=1.2, anti-kT



microjets
R=0.15, kT

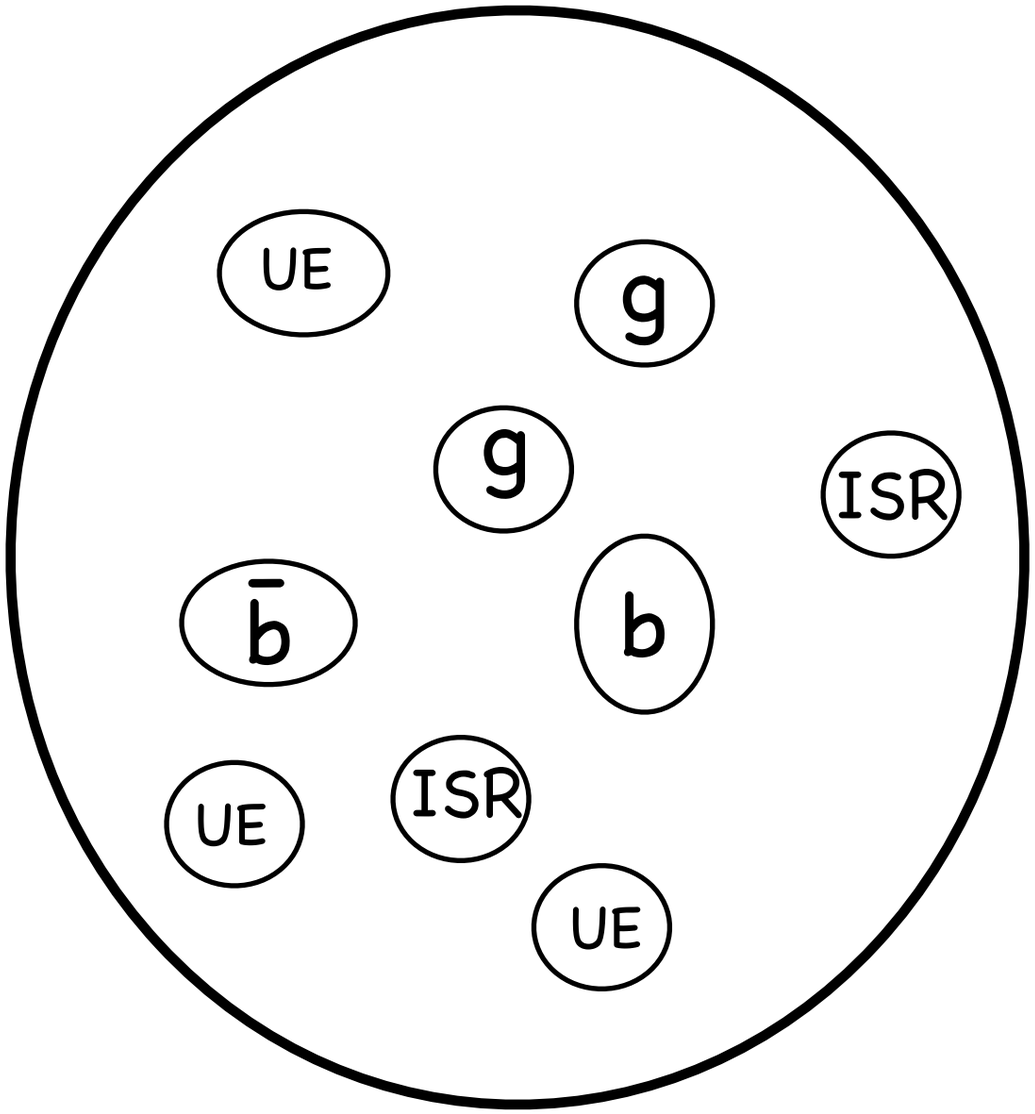


Build all possible shower histories

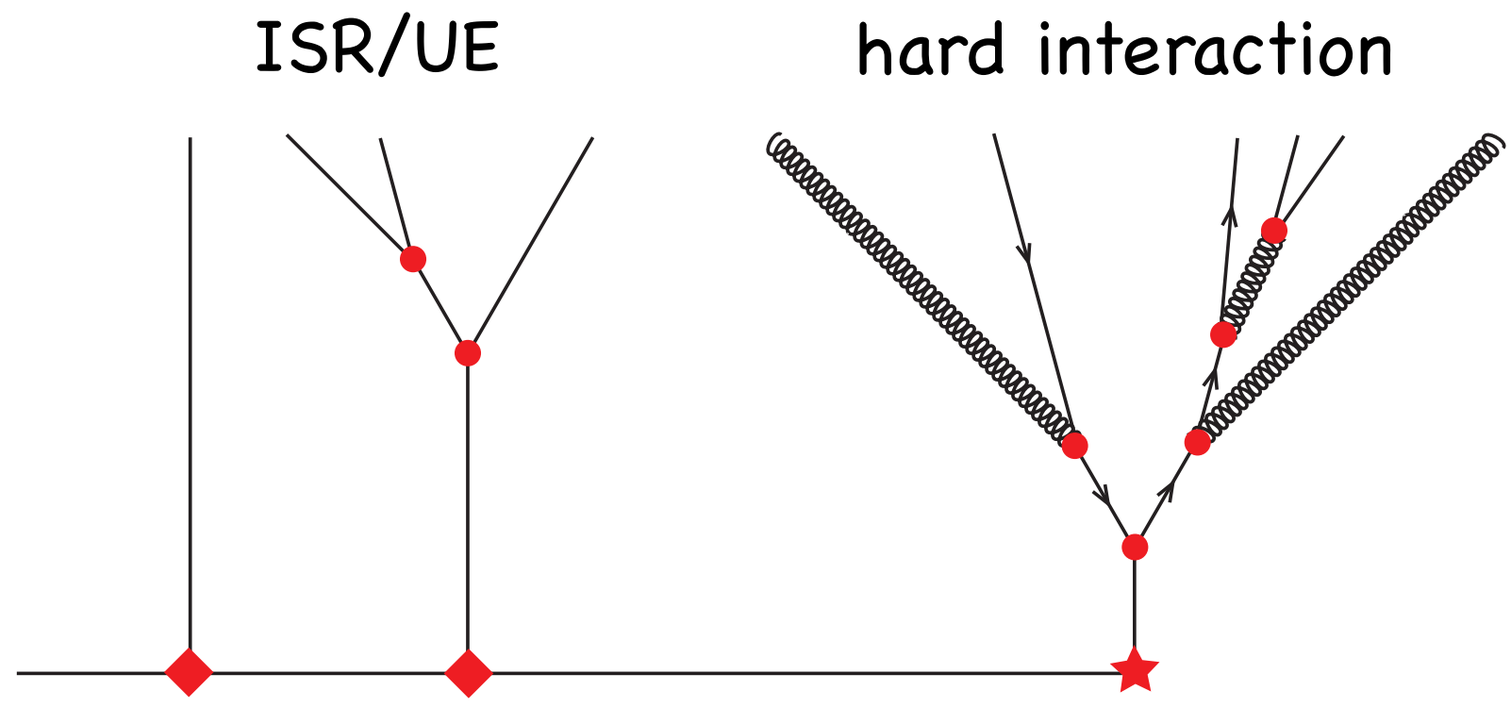
signal vs background hypothesis based on:

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

Fat jet: R=1.2, anti-kT



microjets
R=0.15, kT



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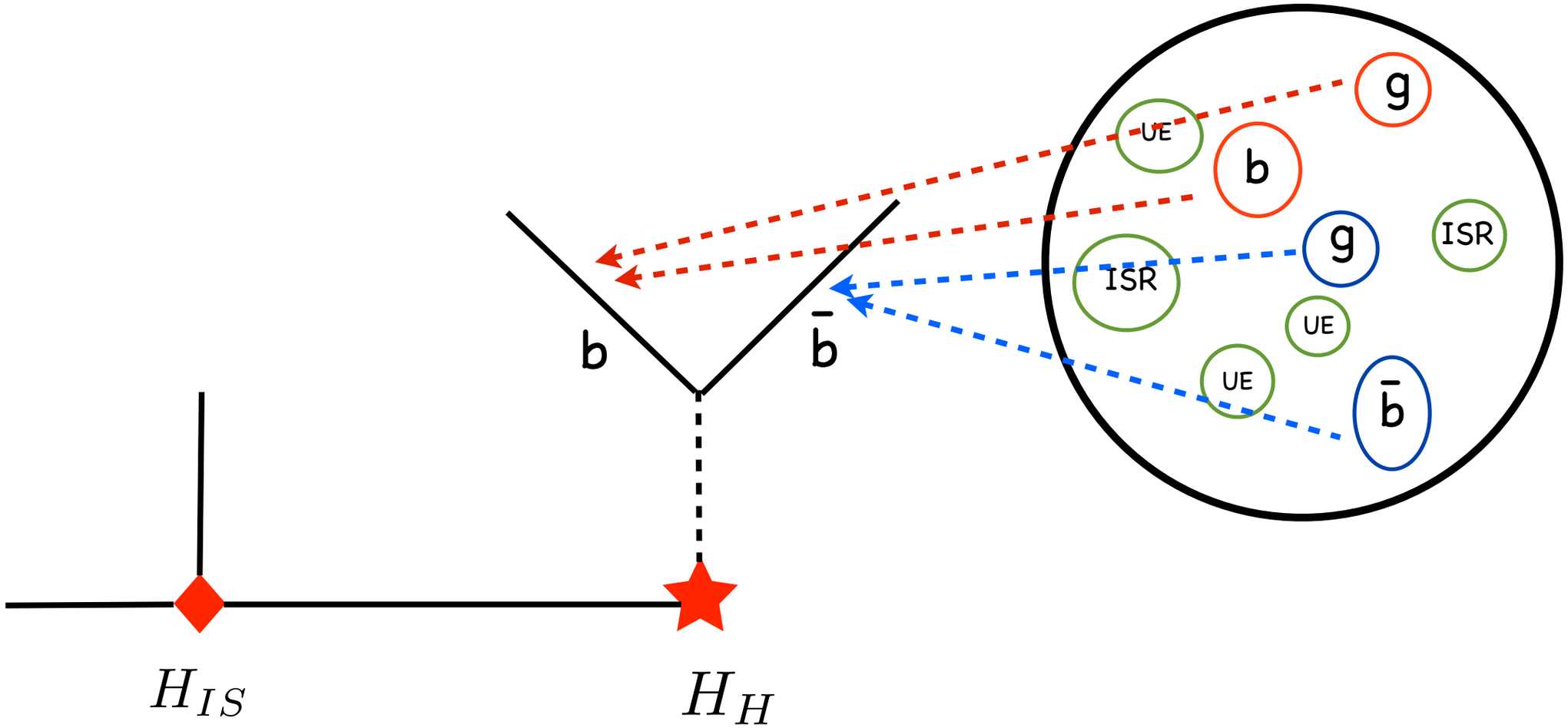


Higgs has to decay:

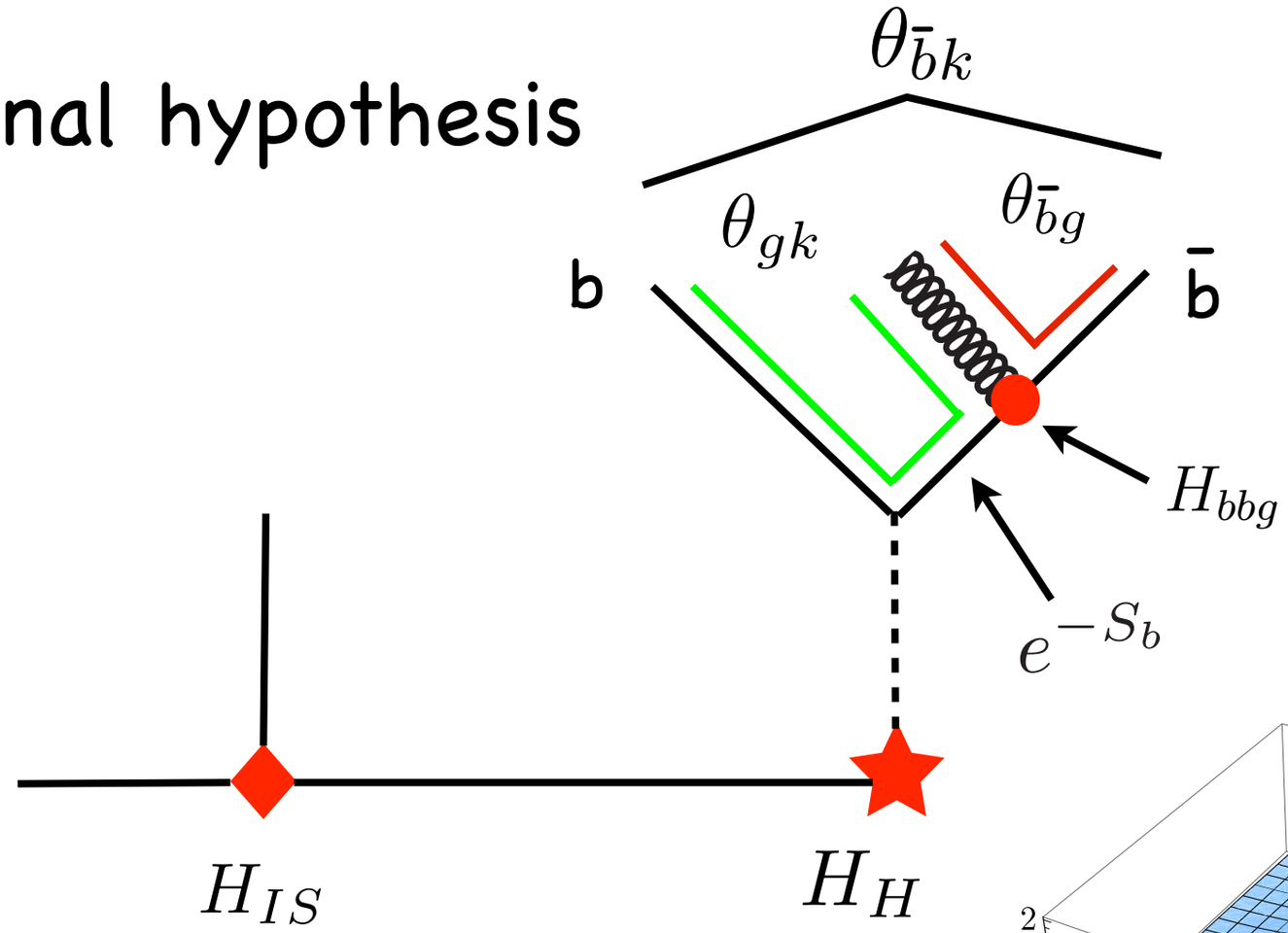
$$He^{-S} = 16\pi^2 \, \frac{\Theta(|m_{b\bar{b}} - m_H| < \Delta m_H)}{4 m_H \, \Delta m_H}$$

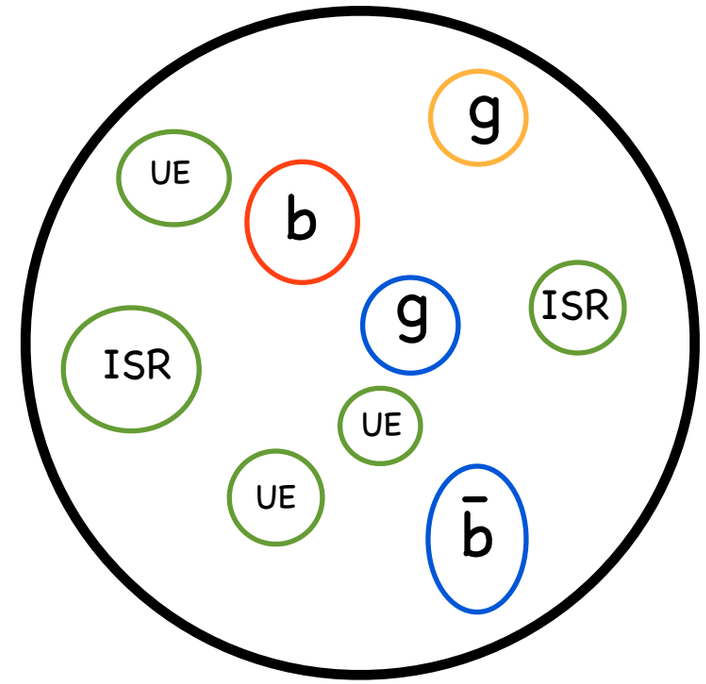
$$\frac{1}{4(2\pi)^3} \int dm_{b\bar{b}}^2 \int dz \int d\varphi \; He^{-S} = 1$$

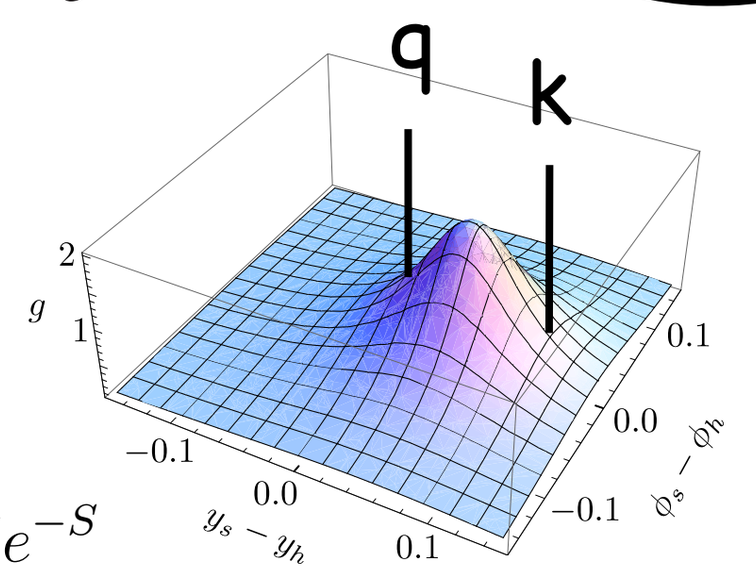
Mass window

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

Signal hypothesis







[Marchesini, Webber, (1984)]

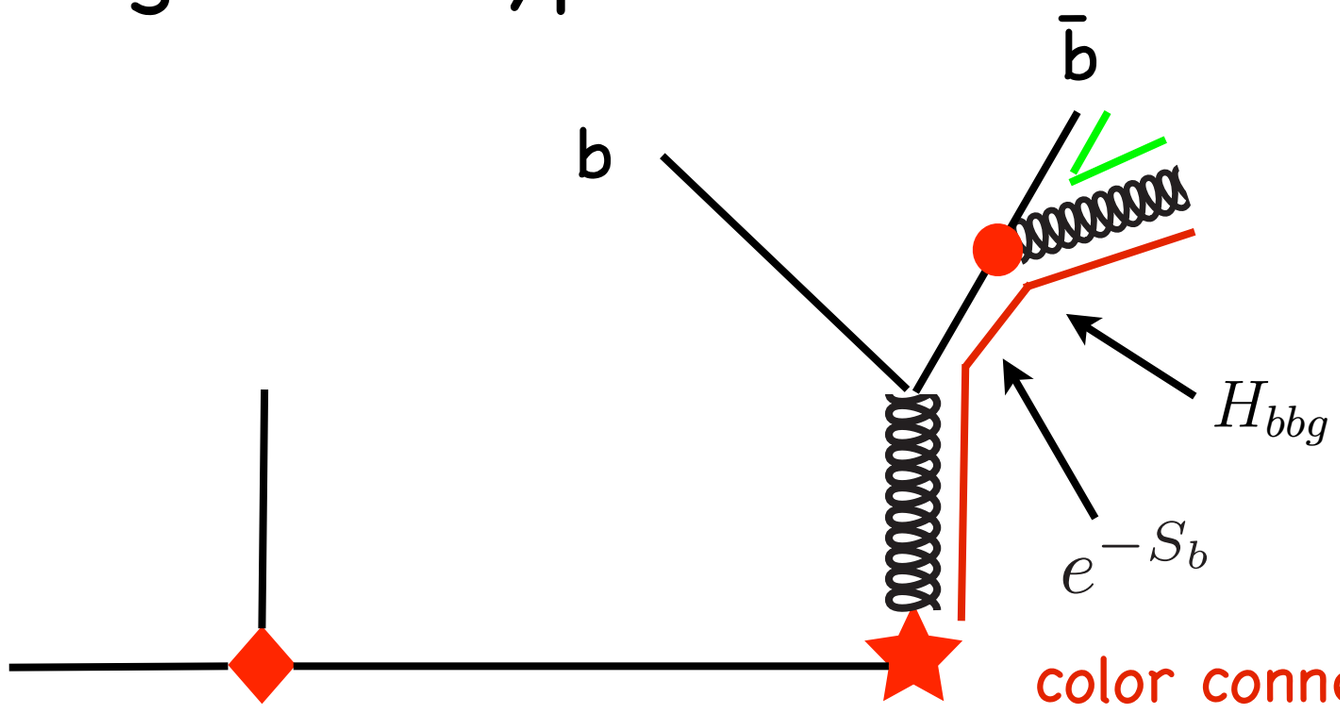
b-quarks radiate gluons

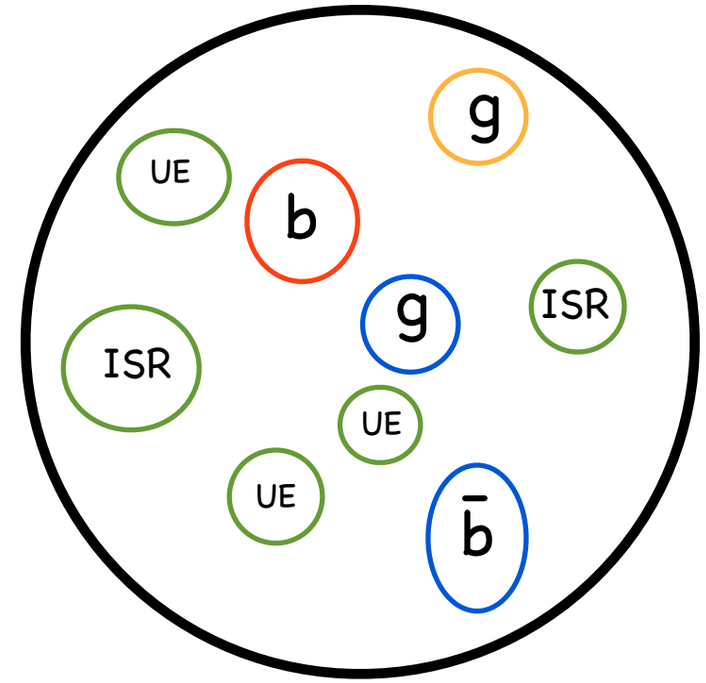
$$\int d\mathcal{P} = \int d\mu_J^2 \int d\Delta\phi \int d\Delta y \sum_s J\, H e^{-S}$$

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

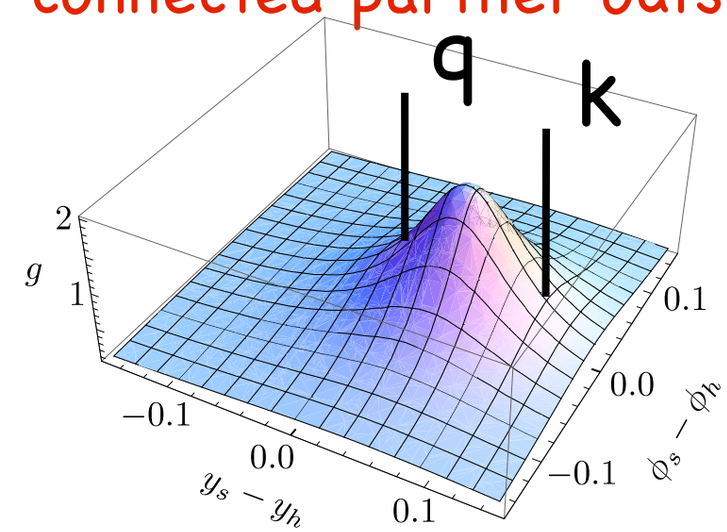
$$H_{qqg} = H_{\bar{q}g\bar{q}} = 8\pi C_{\mathrm{F}} \frac{\alpha_{\mathrm{s}}(\mu_J^2)}{\mu_J^2} \frac{k_J}{k_g} \left[1 + \left(\frac{k_q}{k_J}\right)^2\right] \frac{\theta_{qk}^2}{\theta_{gq}^2 + \theta_{gk}^2}\, \Theta\left(2\,\frac{\mu_J^2}{k_J} < \frac{\mu_K^2}{k_K}\right)$$

Background hypothesis





color connected partner outside fat jet



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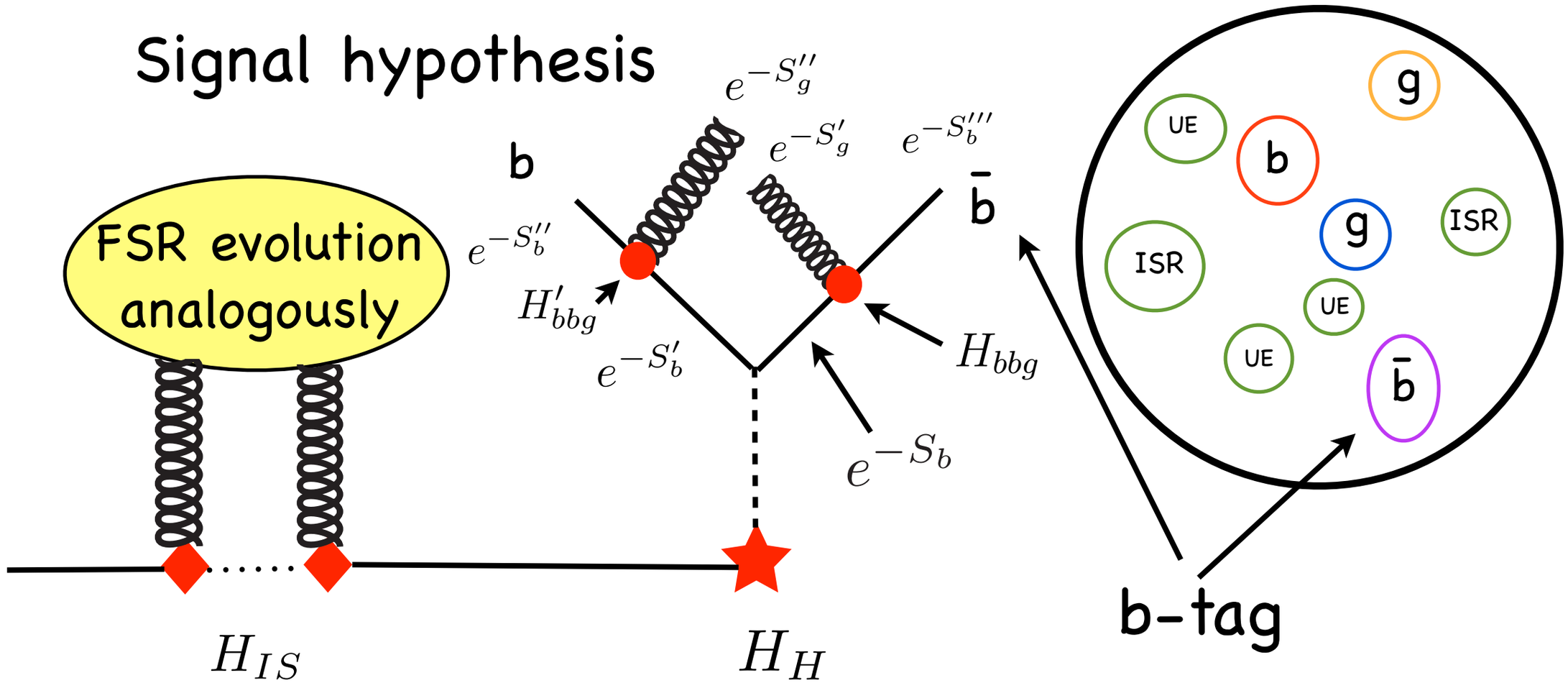
Signal hypothesis



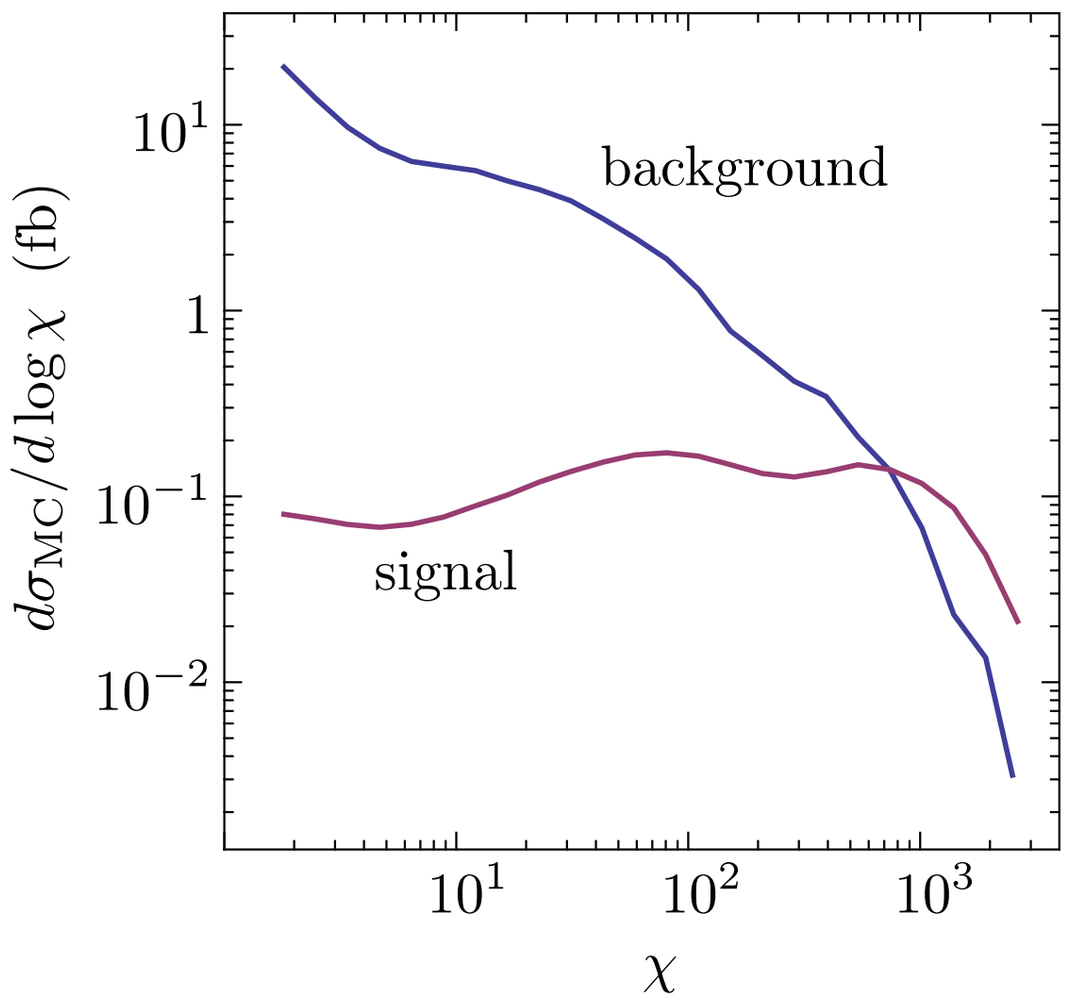
Wrapping up all factors gives weight for shower history

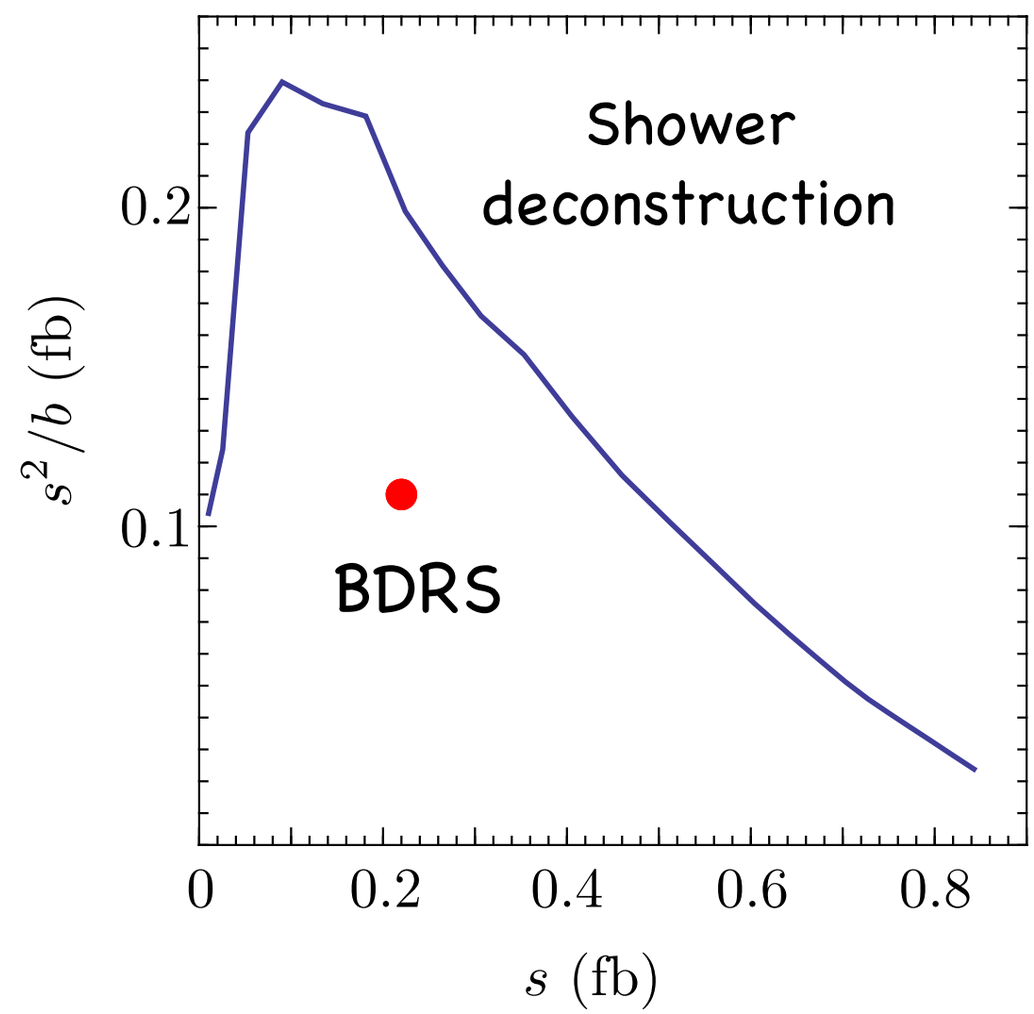
$$\chi = \frac{\sum_{ISR/Hard}\left(\sum_i \mathrm{ISR_i} \times \sum_j \mathrm{Signal_j}\right)}{\sum_{ISR/Hard}\left(\sum_i \mathrm{ISR_i} \times \sum_j \mathrm{Backg_j}\right)}$$

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

Results of shower deconstruction (SD)

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





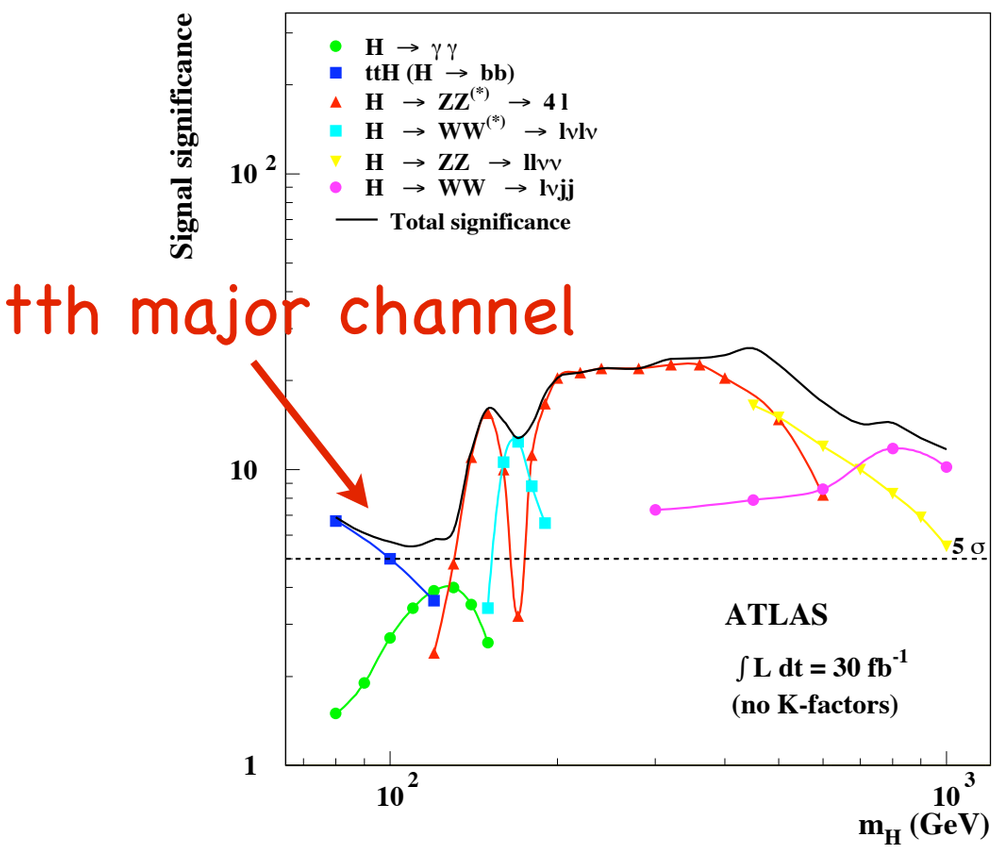
imperfect b-tagging (60%,2%) no b-tag required

II. Measuring the Higgs-top coupling using boosted techniques

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

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

High expectations:



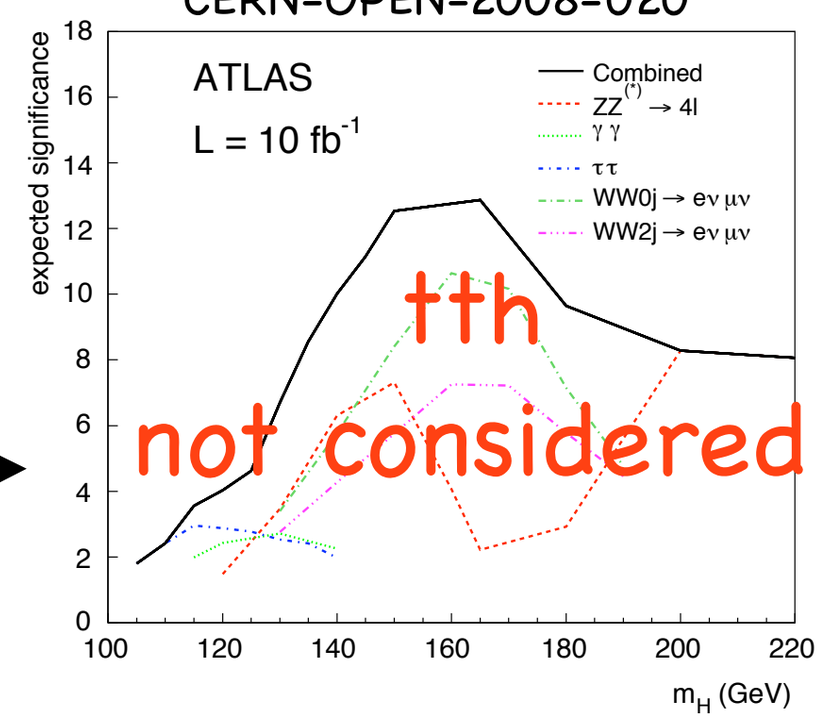
[ATLAS TDR 1999]

Cammin and Schumacher (ATLAS)

$S/B \simeq 1/9$

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

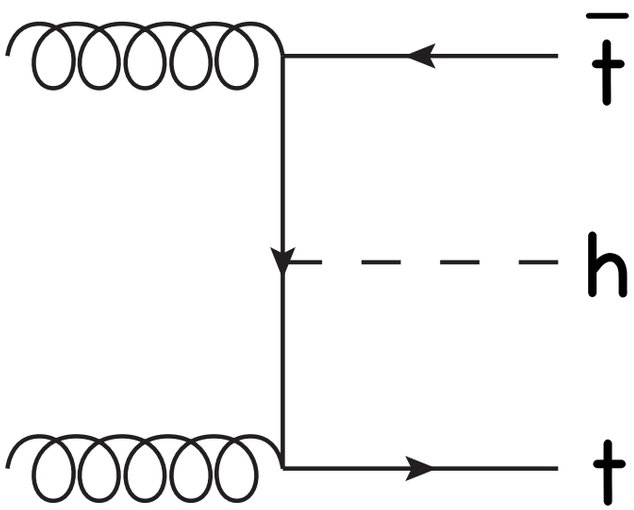
Expected Performance of the ATLAS Experiment, CERN-OPEN-2008-020



tth (Signal)

Beenakker et al.,
PRL 87 2001;
Reina et al.,
PRD 65 2002

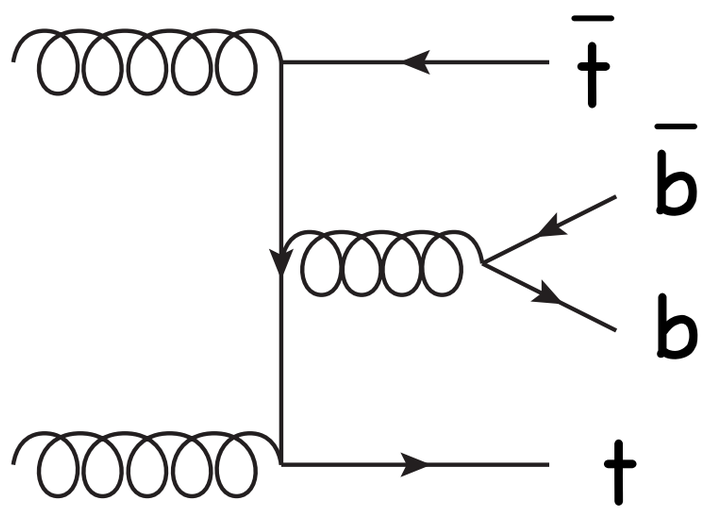
→ K=1.57



ttbb

Bredenstein et al.,
PRL 103 2009;
Belivacqua et al.,
JHEP 0909 2009

→ K=2.3



tt+jets

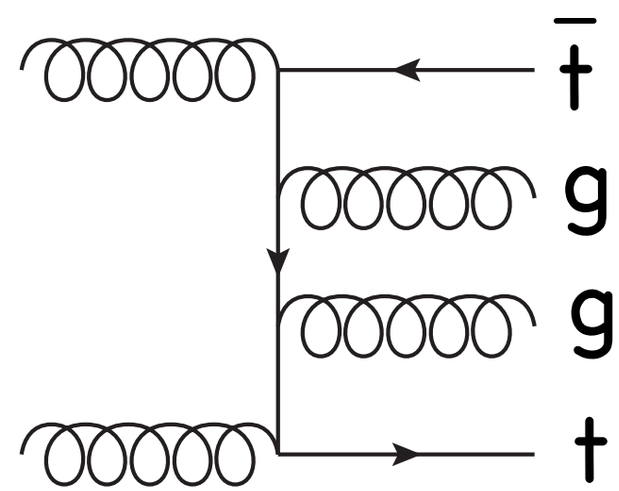
Dittmaier et al,
PRL 98 2007
Bevilacqua et al.,
PRL 104 2010

→ K=1.0

ttz

Lazopoulos et al.,
PLB 666 2008

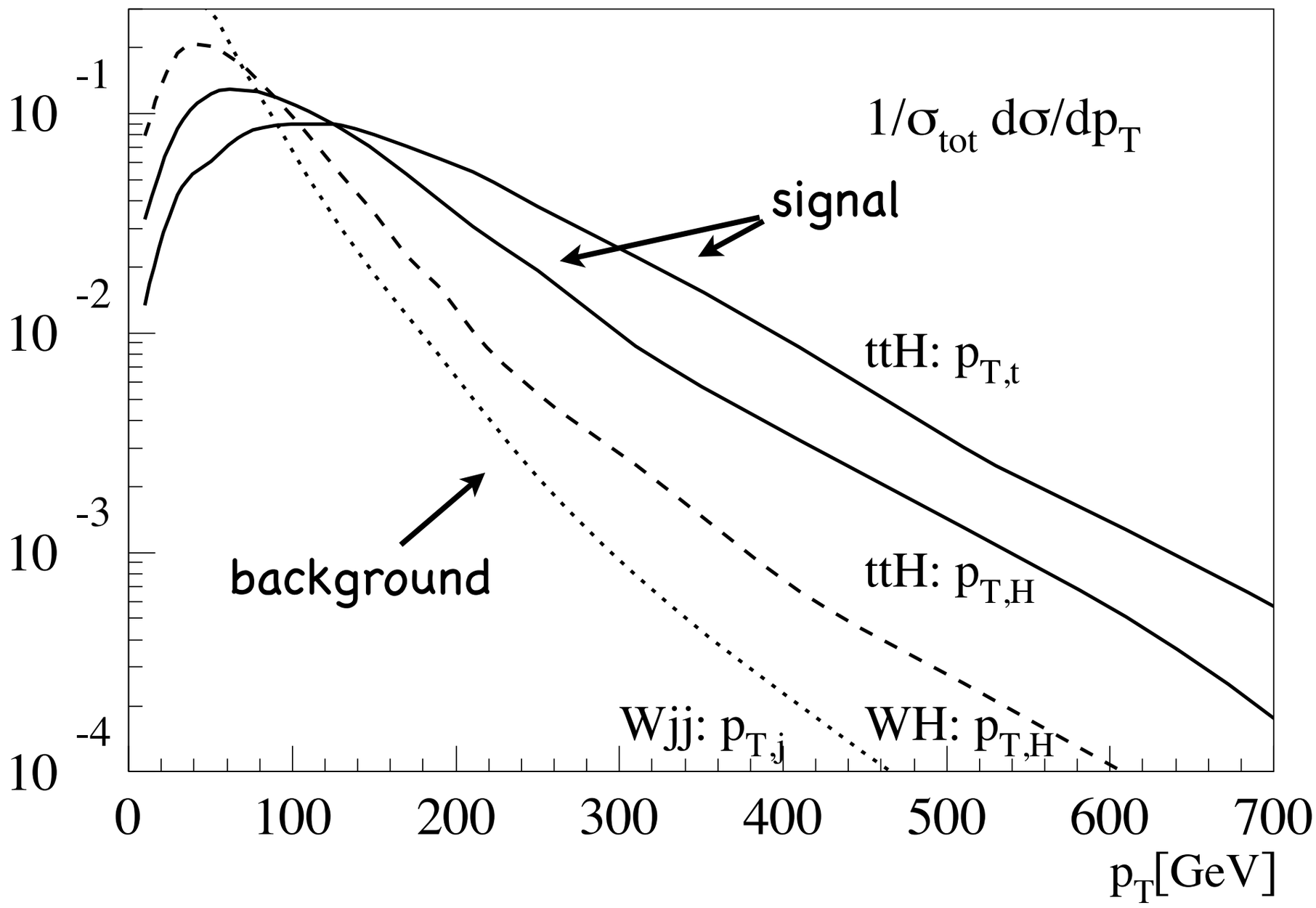
→ k=1.53



w+jets

negligible after b-tags and taggers

pT distributions relevant for tth



Problems in event reconstruction:

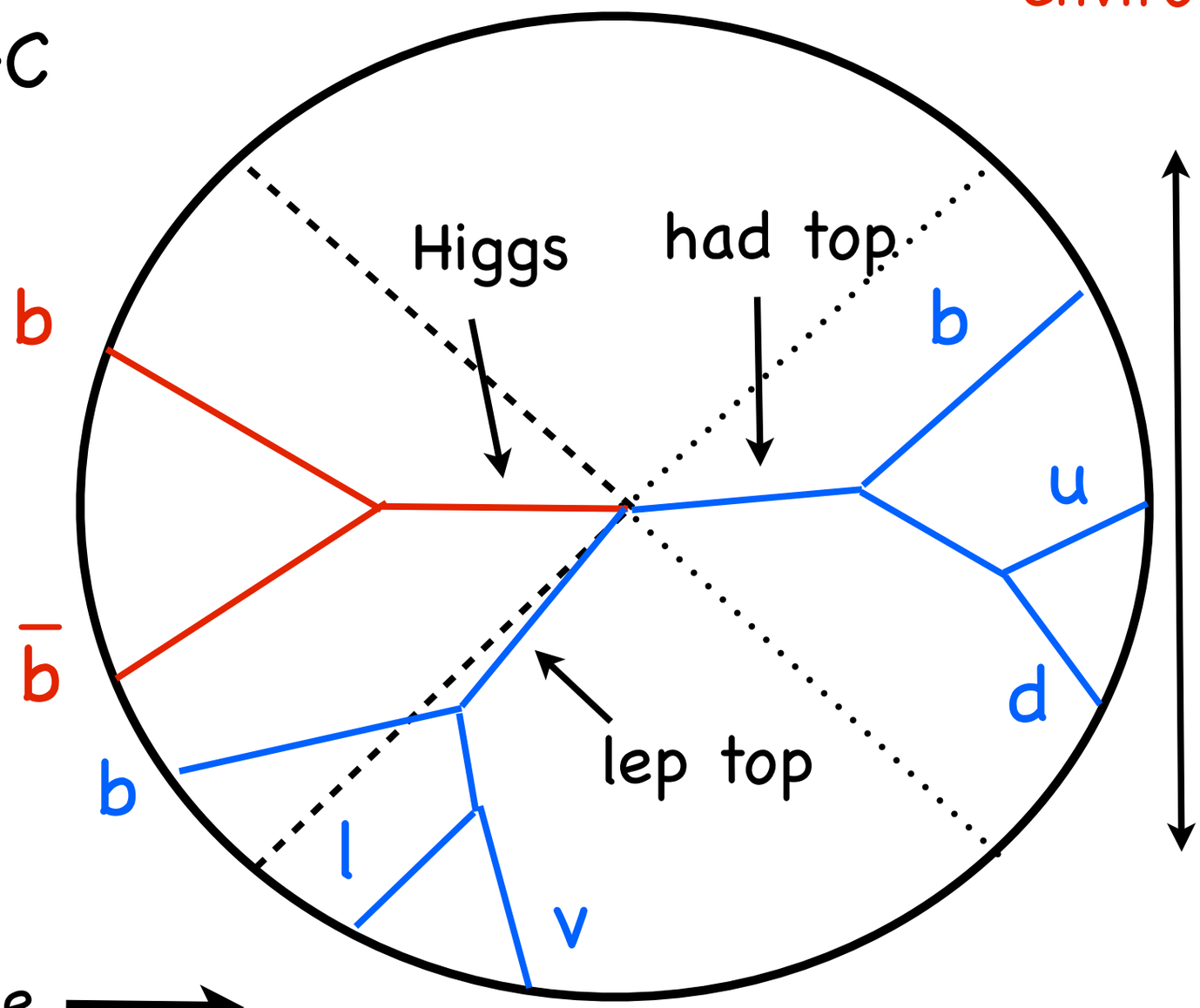
- (b-)jet multiplicity
- reconstruction efficiency

Boost should help

but

need tagger for this environment

LHC



Cambridge/Aachen Jet-Alg

R=1.5

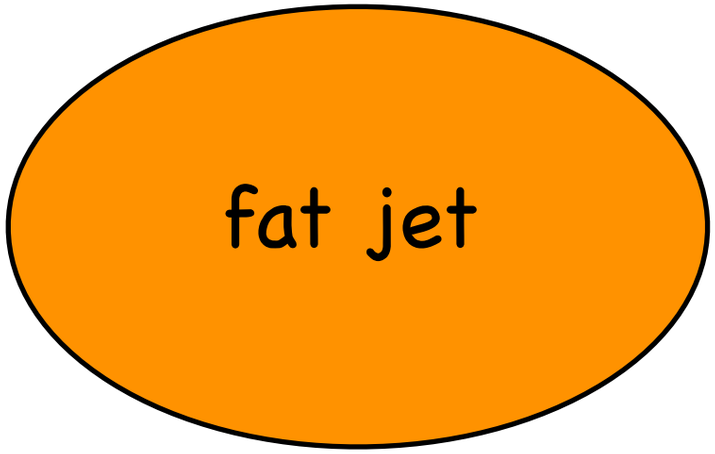
pT plane

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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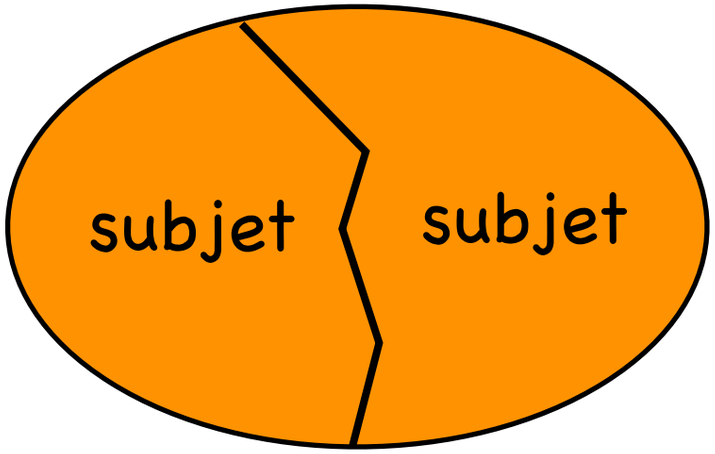

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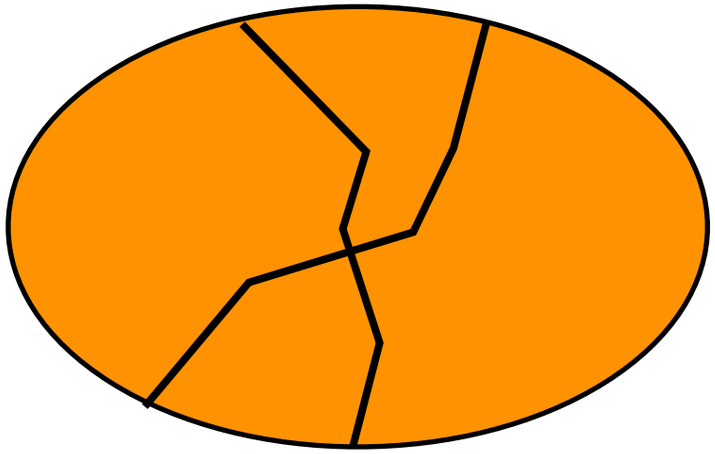

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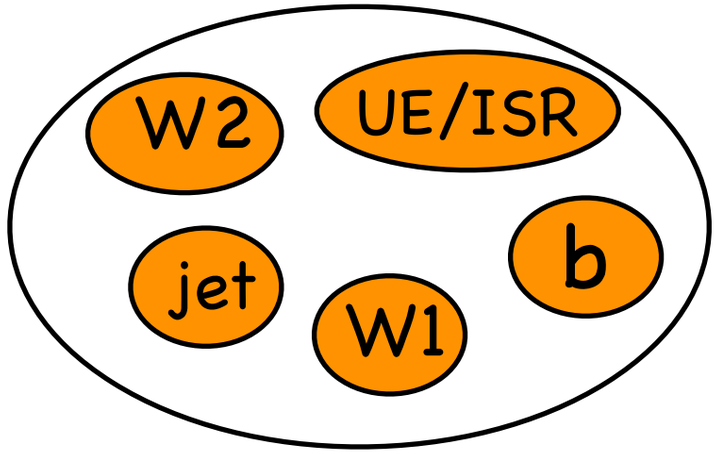
III. Apply jet grooming to get top decay candidates



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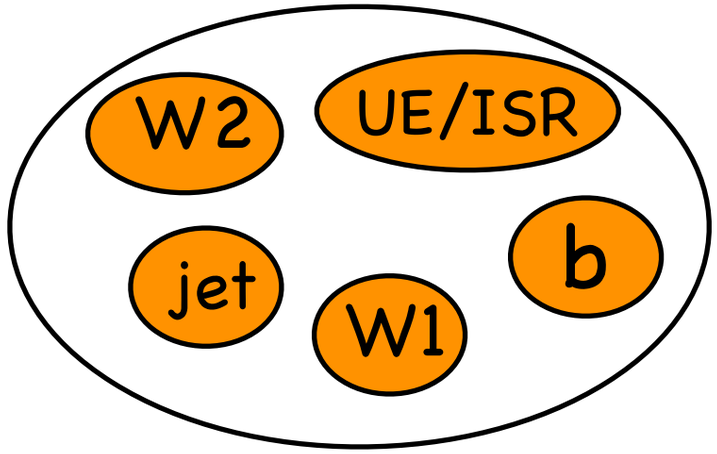
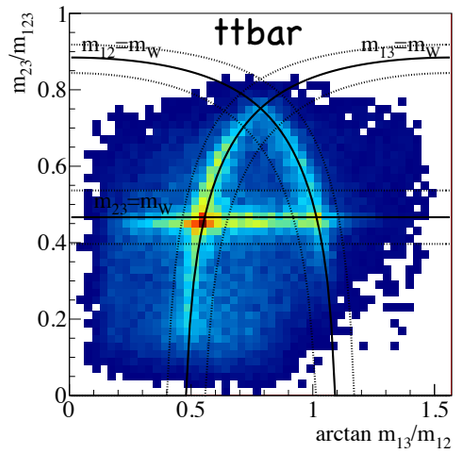
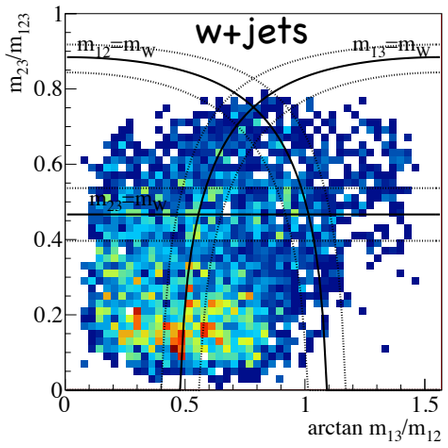
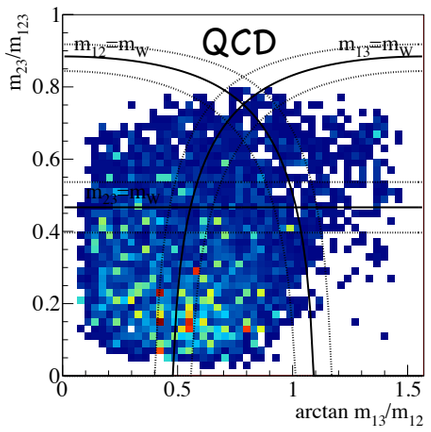
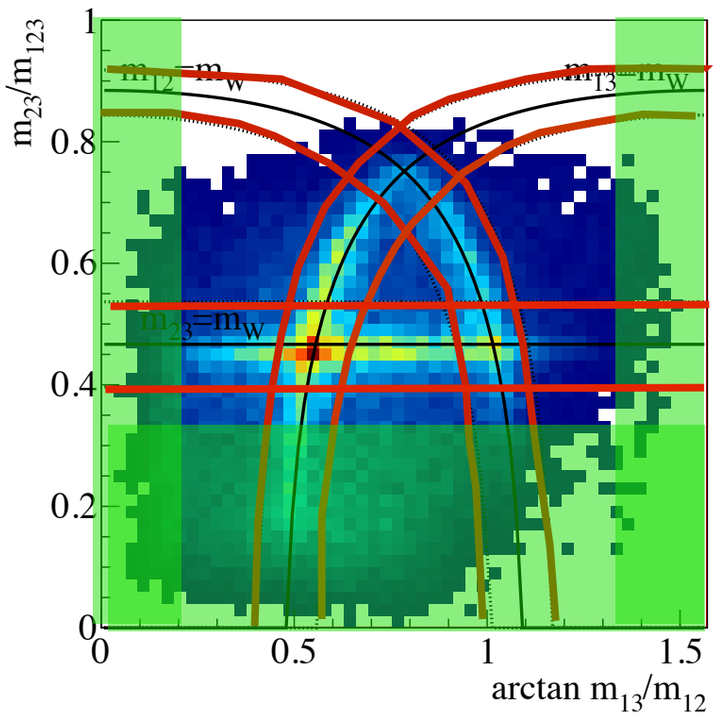


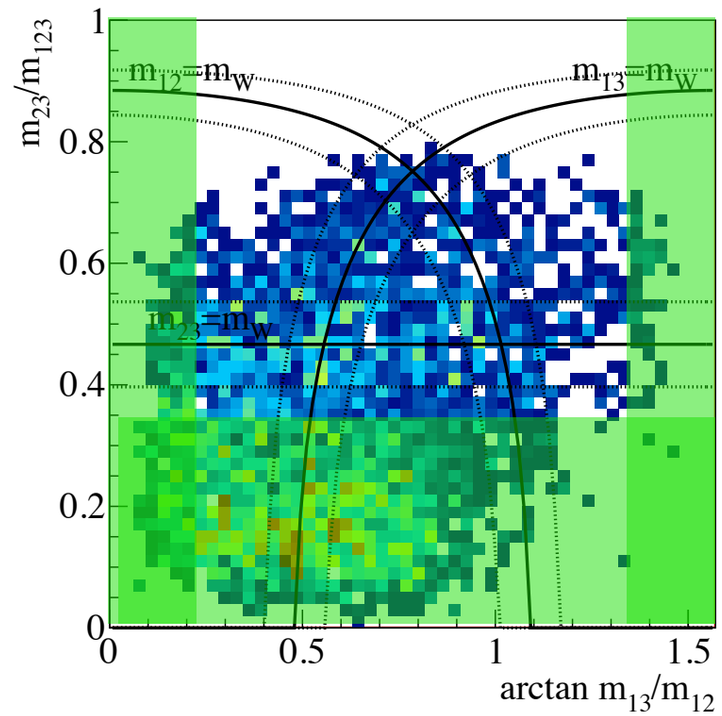
IV. Choose pairing based on kinematic correlation, e.g. top mass, W mass and invariant subjet masses

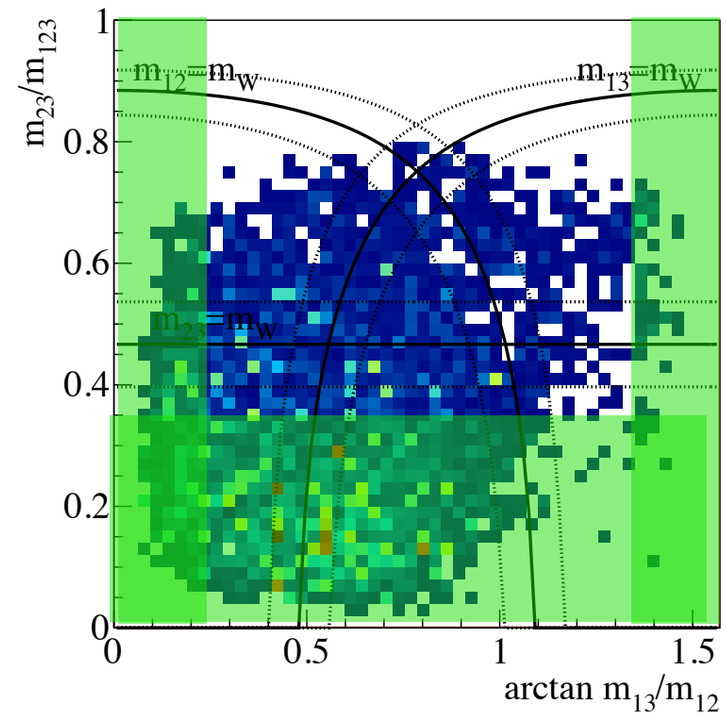


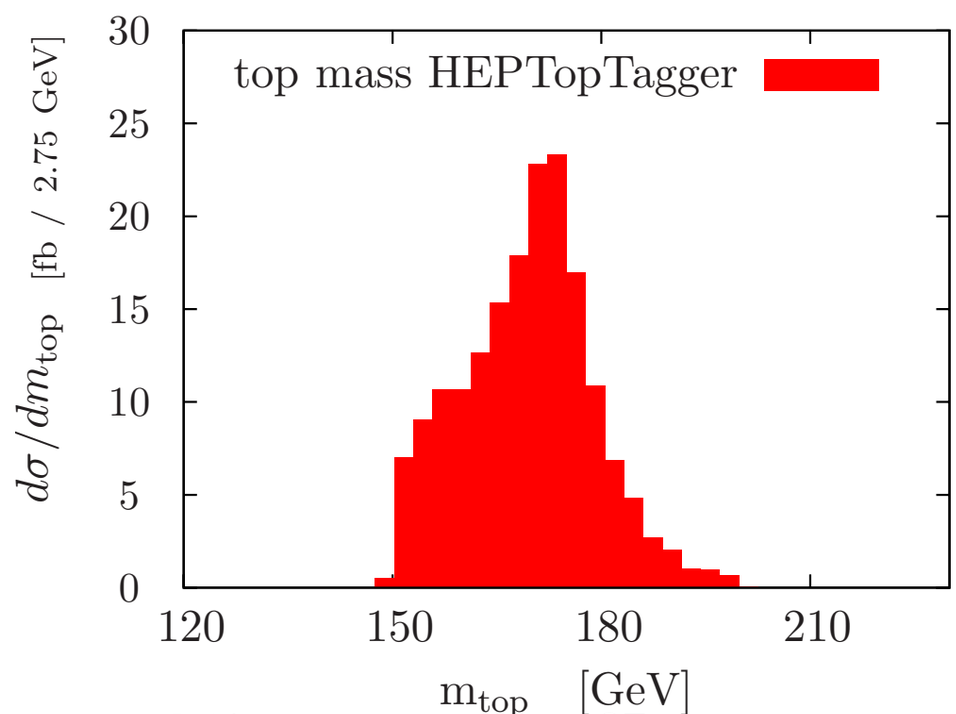


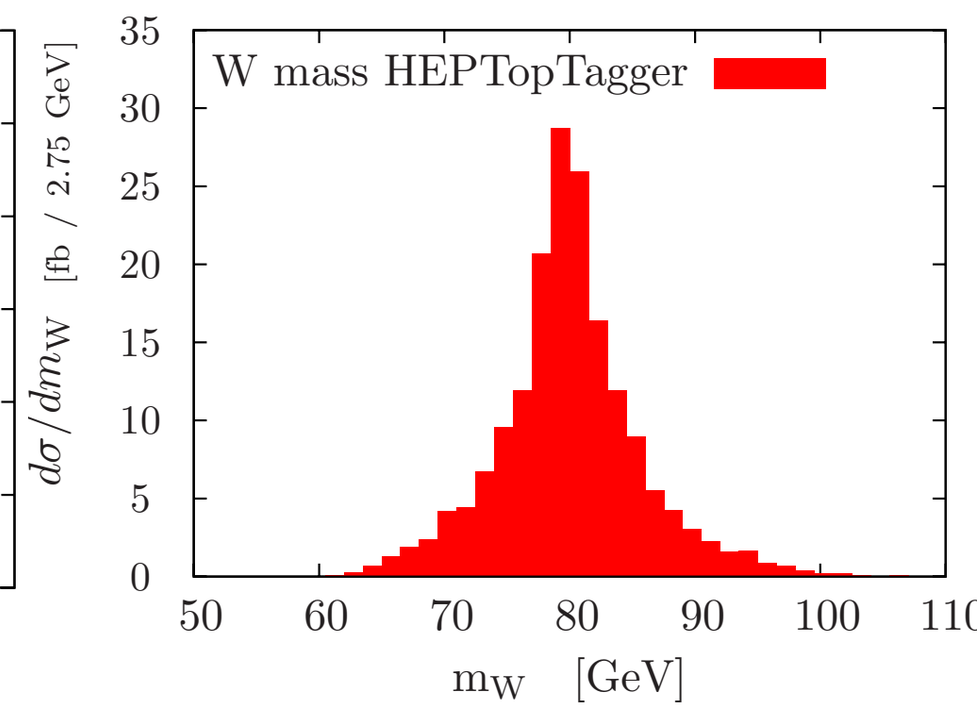












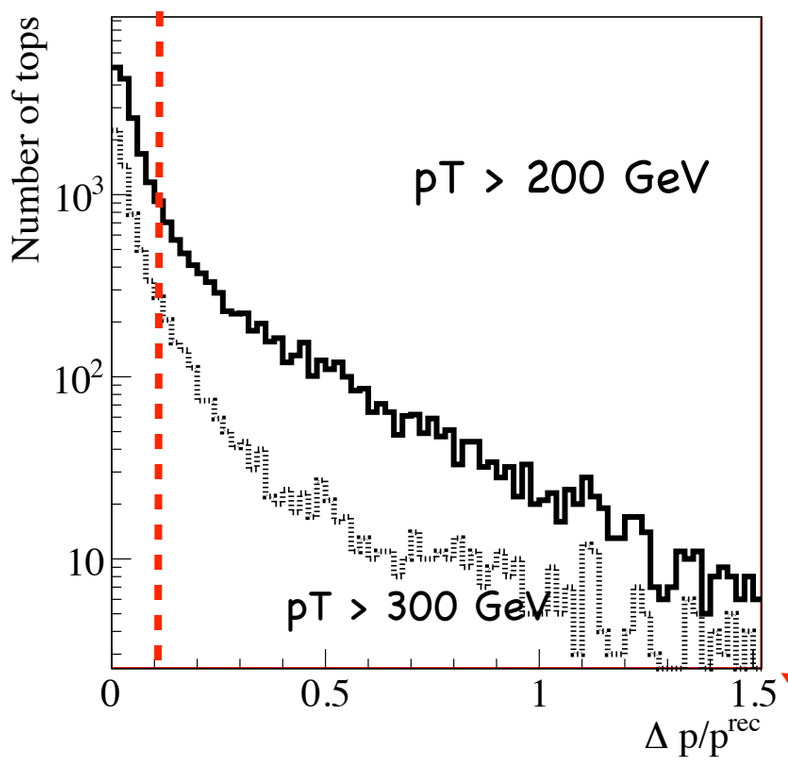
IV. check mass ratios

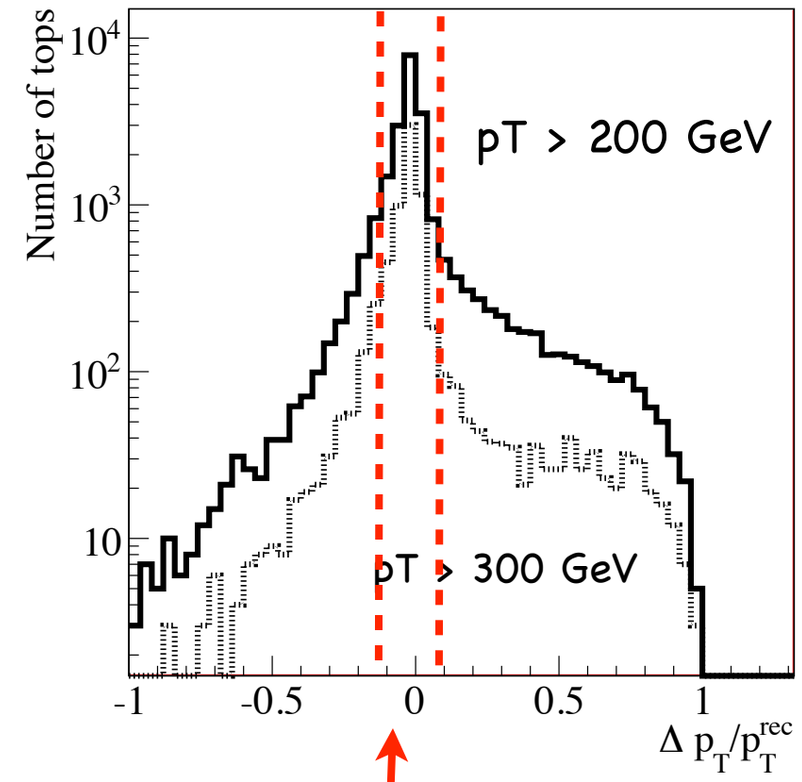
Cluster top candidate into 3 subjets j_1, j_2, j_3

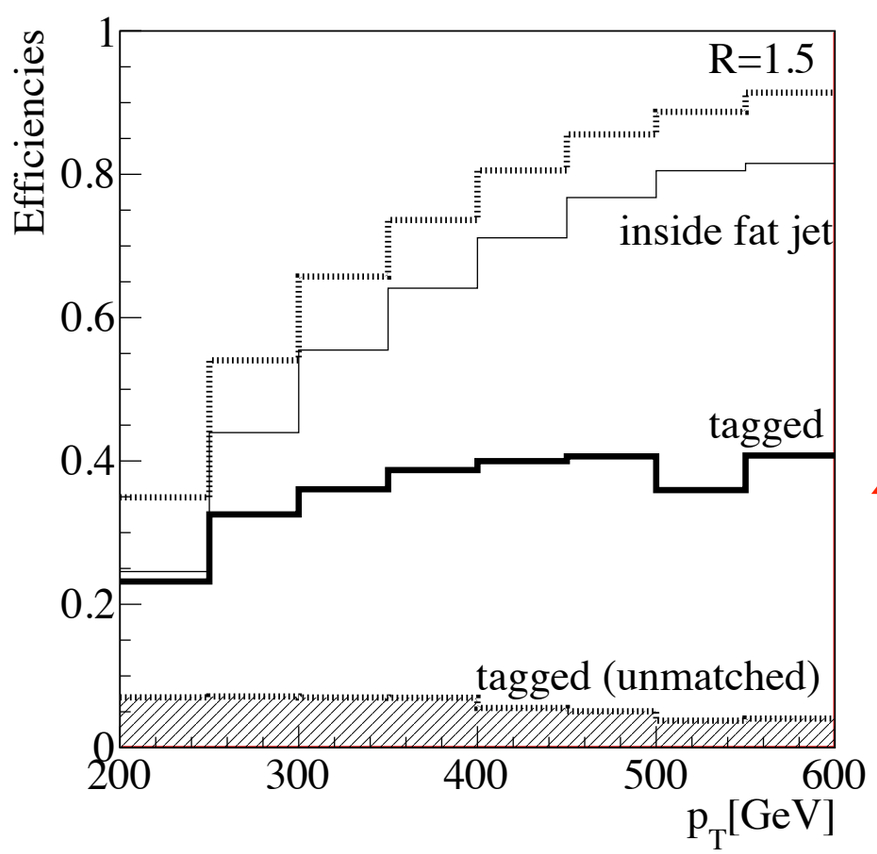
No fix pairing for W mass reconstruction

Only invariants for reconstruction

Top quark momentum reconstruction

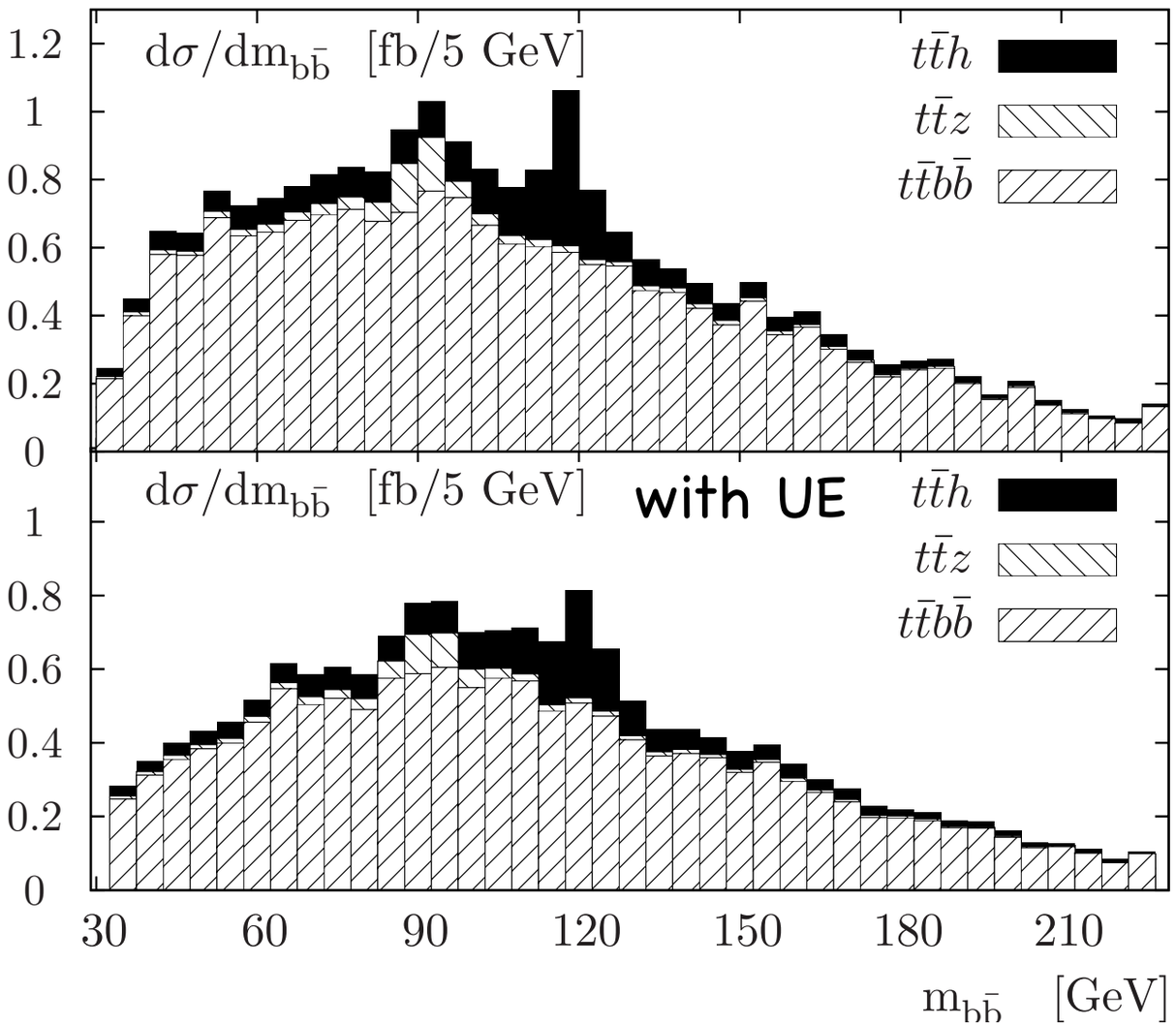






- Great reconstruction of top quark momentum
- 35% tagging efficiency
  2% W+jets fake rate
- Tagger used in resonance searches in ATLAS: 1207.2409

Results for tth



- 5 sigma sign. with 100 1/fb

- Development of Higgs and top tagger for busy final state

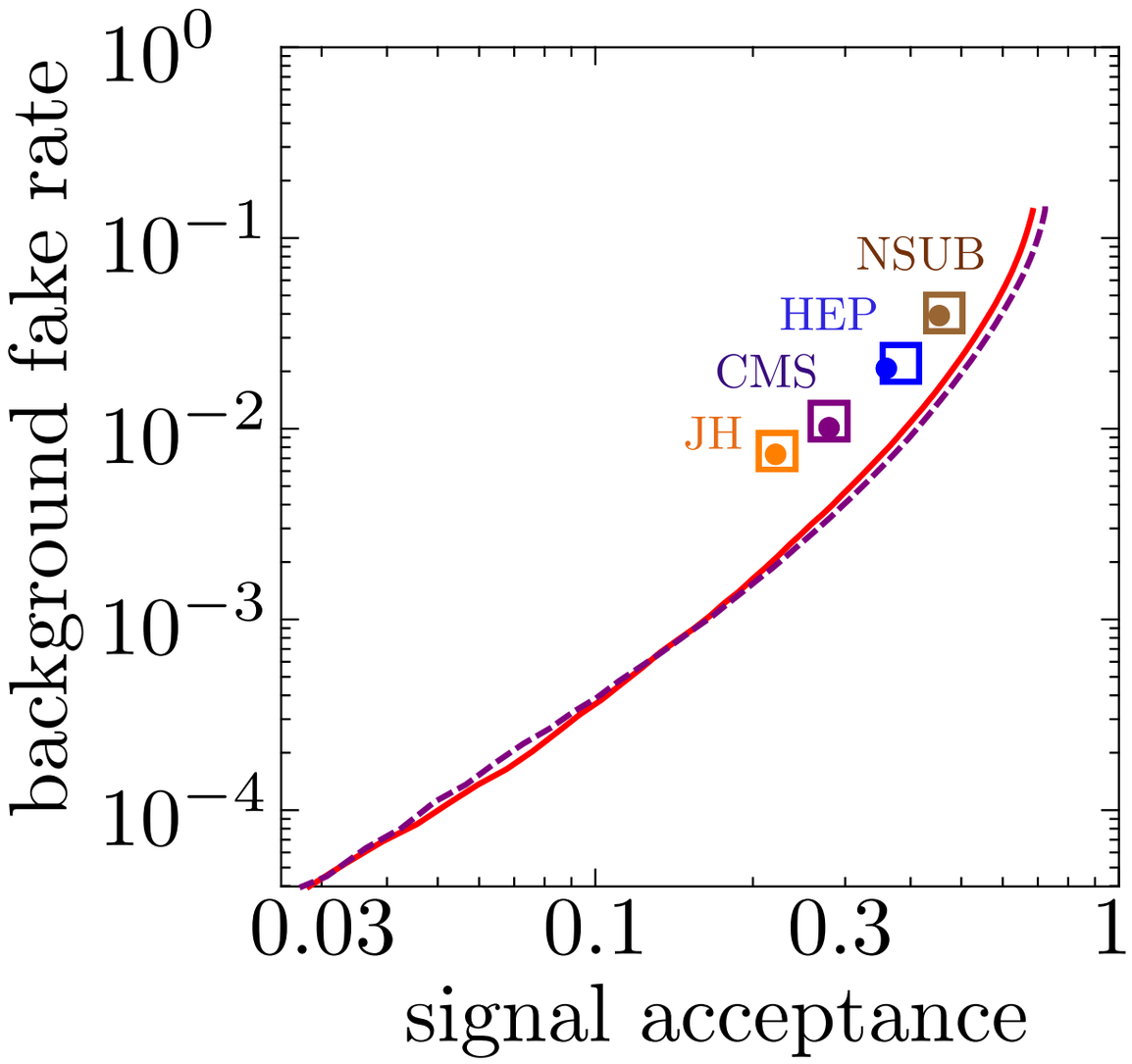
- Improvement of S/B from 1/9 to 1/2

→ tth might be a window to Higgs-top coupling

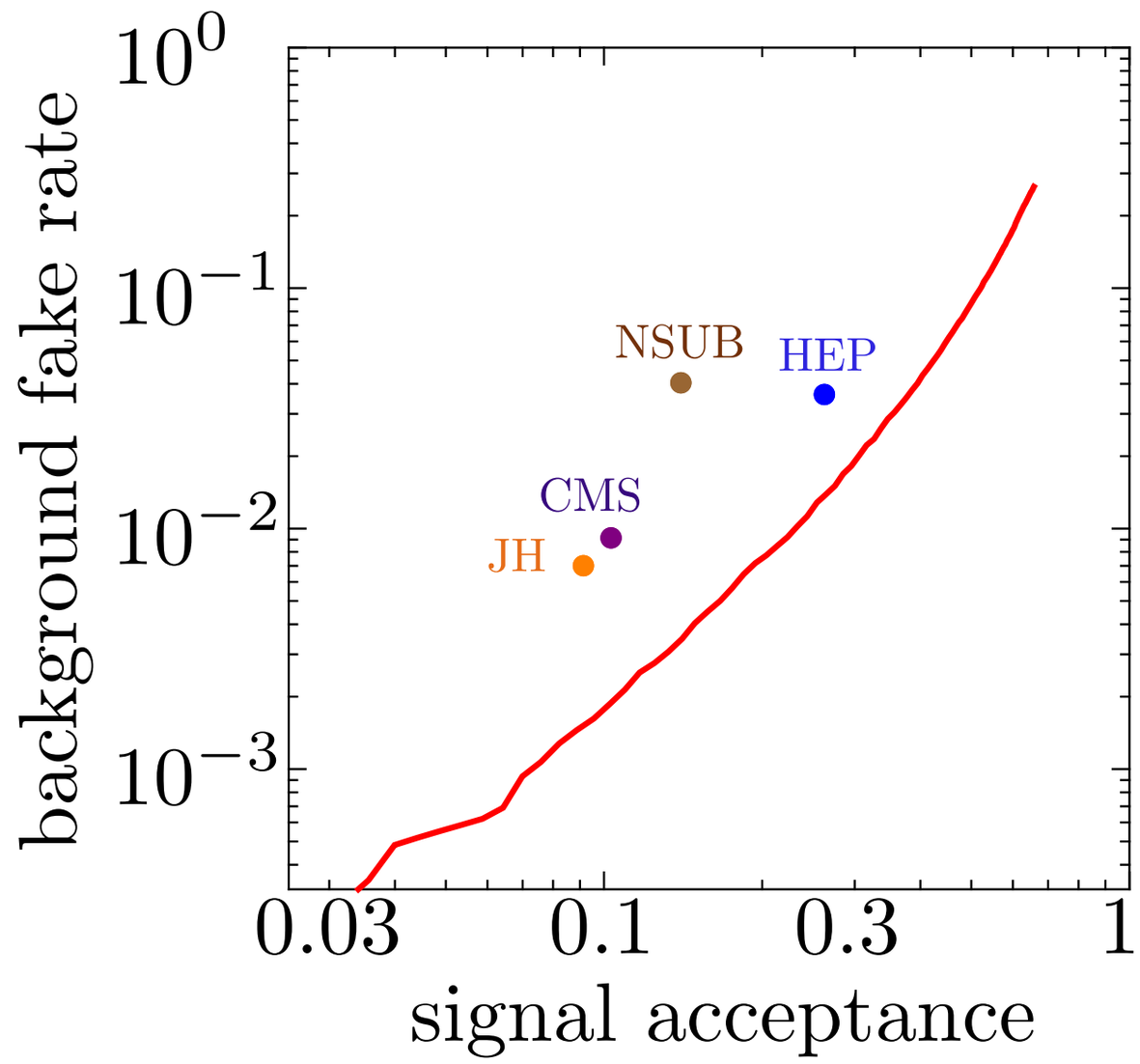
Shower deconstruction based top tagger can do even better:

Input for SD: small jets with R=0.2 and pT>5.0 GeV

fat jet pT>500 GeV and R=1.0:



fat jet pT>200 GeV and R=1.5:



III. Measuring the CP of the Higgs boson

- For light Higgs with 125 GeV CP can be measured using angular correlations of tagging jets in Gluon Fusion with 2 additional jets

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

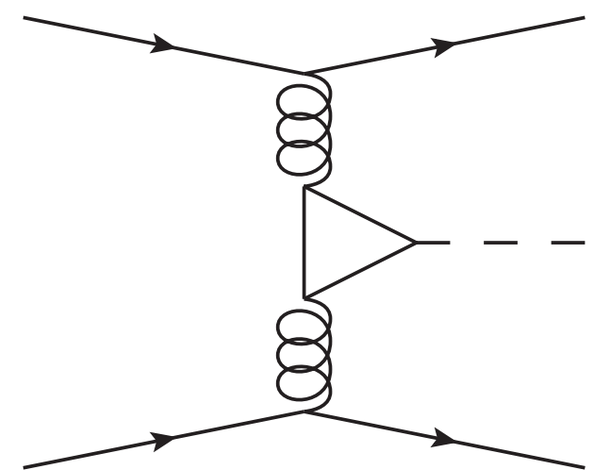
- Event shape observables can be used to measure CP of Higgs

[Englert, MS, Takeuchi 1203.5788]

Interaction:

$$\mathcal{L} = \frac{\alpha_s}{12\pi v} H G^a_{\mu\nu} G^{a\,\mu\nu} + \frac{\alpha_s}{16\pi v} A G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu}$$

Gluon-Fusion



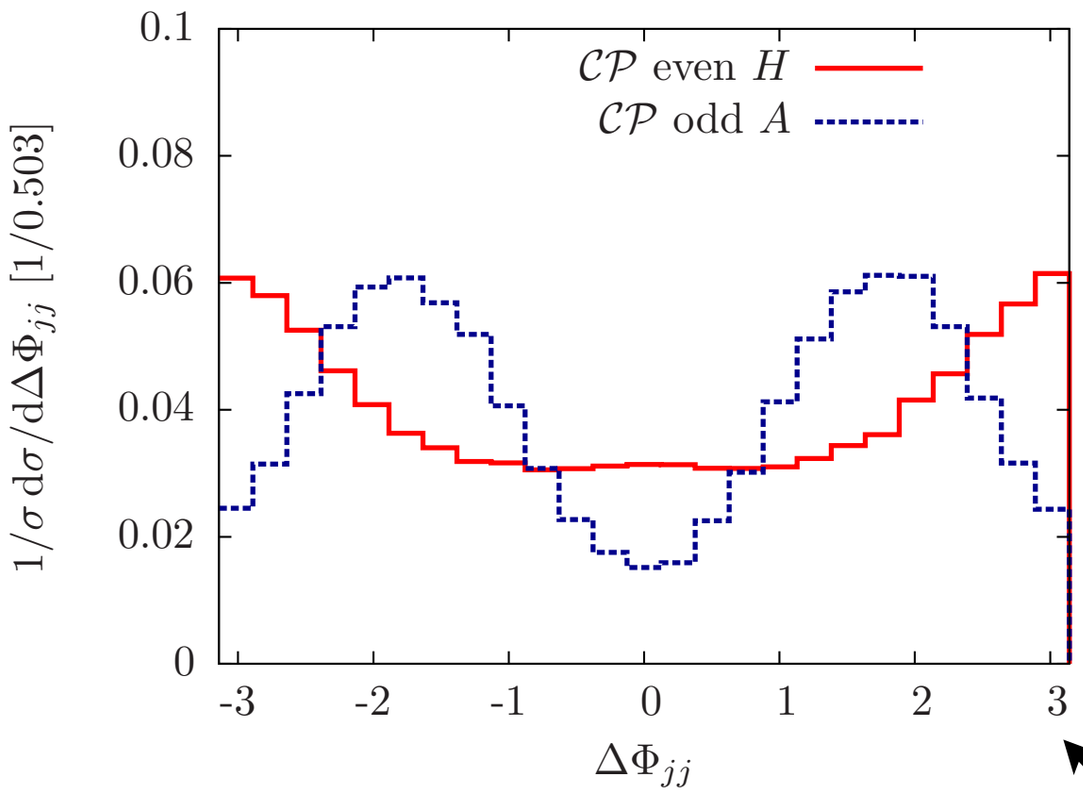
For tagging jets with $|p_z^J| \gg |p_{x,y}^J|$

$$\mathcal{M}_{\text{even}} \sim J_1^\mu J_2^\nu \left[g_{\mu\nu}(q_1 \cdot q_2) - q_{1\nu} q_{2\mu} \right]$$

$$\sim \left[J_1^0 J_2^0 - J_1^3 J_2^3 \right] \mathbf{p}_T^{J_1} \cdot \mathbf{p}_T^{J_2} \sim 0 \text{ for } \Delta\phi_{jj} = \pi/2$$

$\mathcal{M}_{\text{odd}}$ contains Levi-Civita tensor which is 0 if two of momenta linearly dependent, i.e. if $\Delta\phi_{jj} = 0$ or $\Delta\phi_{jj} = \pi$

Tagging jets approach:

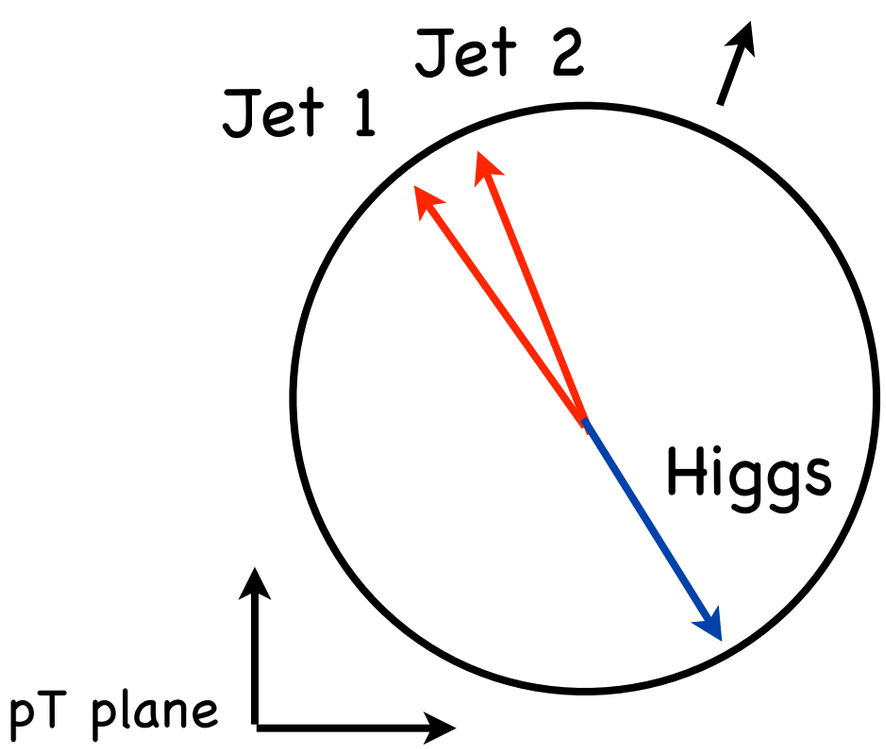


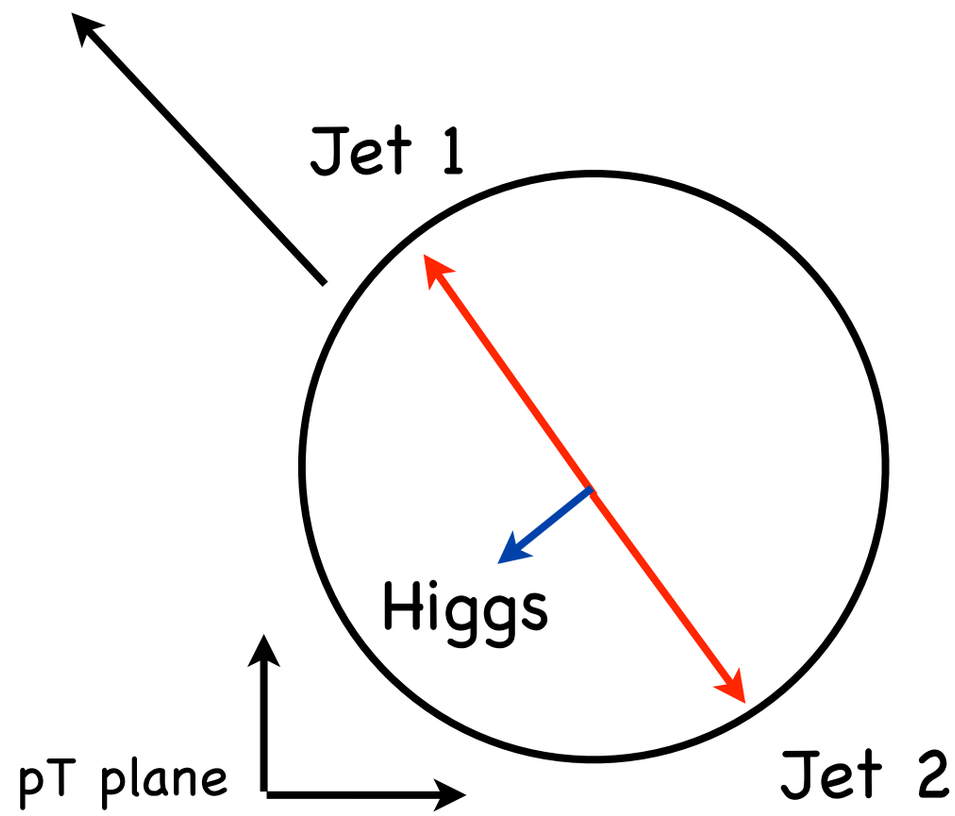
azimuthal angle between all jets with larger or smaller rapidity wrt Higgs

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

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

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





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]

- Avoids vetoing of jets which can induces large theo. uncertainties

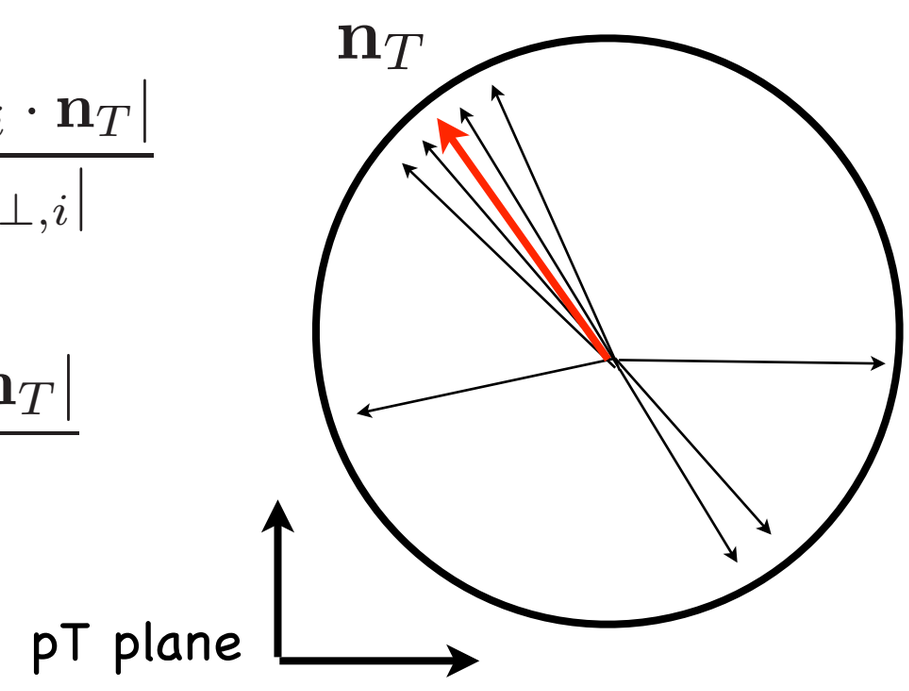
[Stewart, Tackmann PRD 85 (2012)]

- Event shape measurements established in experimental collaborations already now e.g.

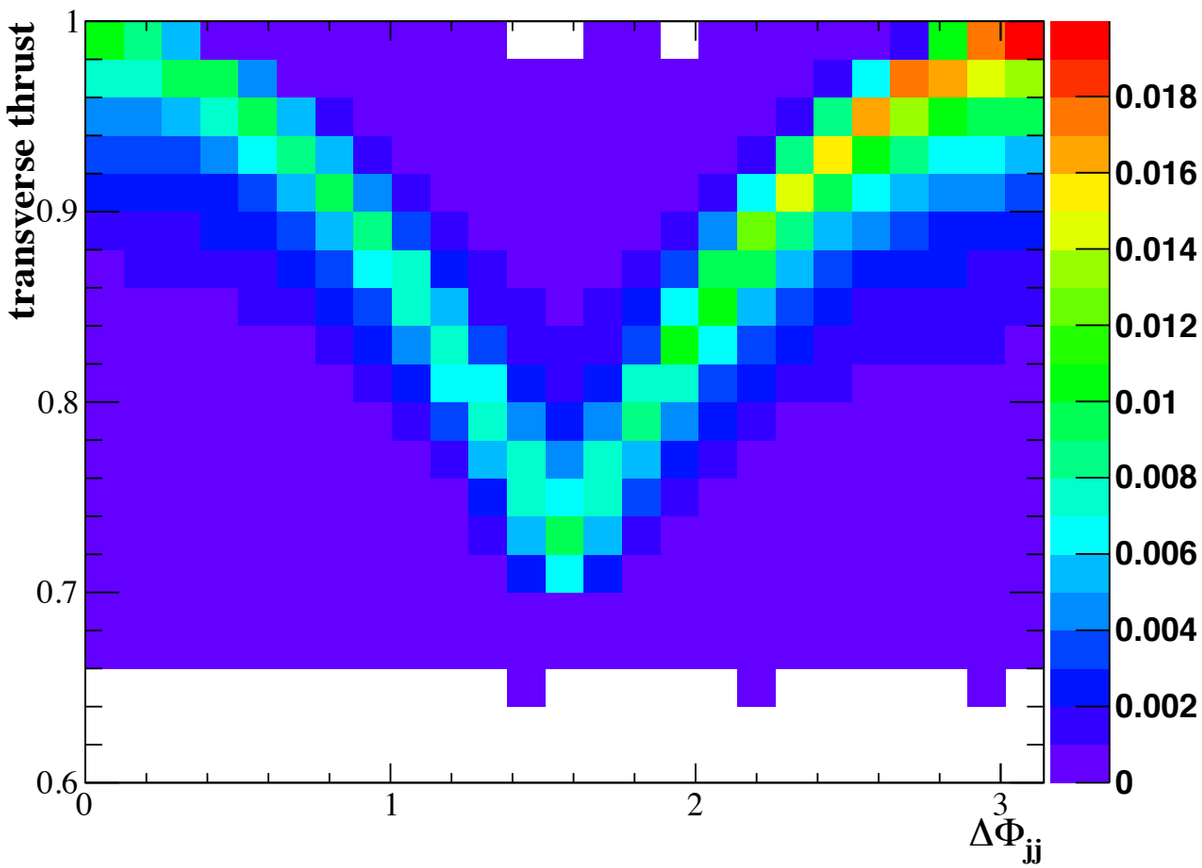
[CMS, PLB 699 (2011)]

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

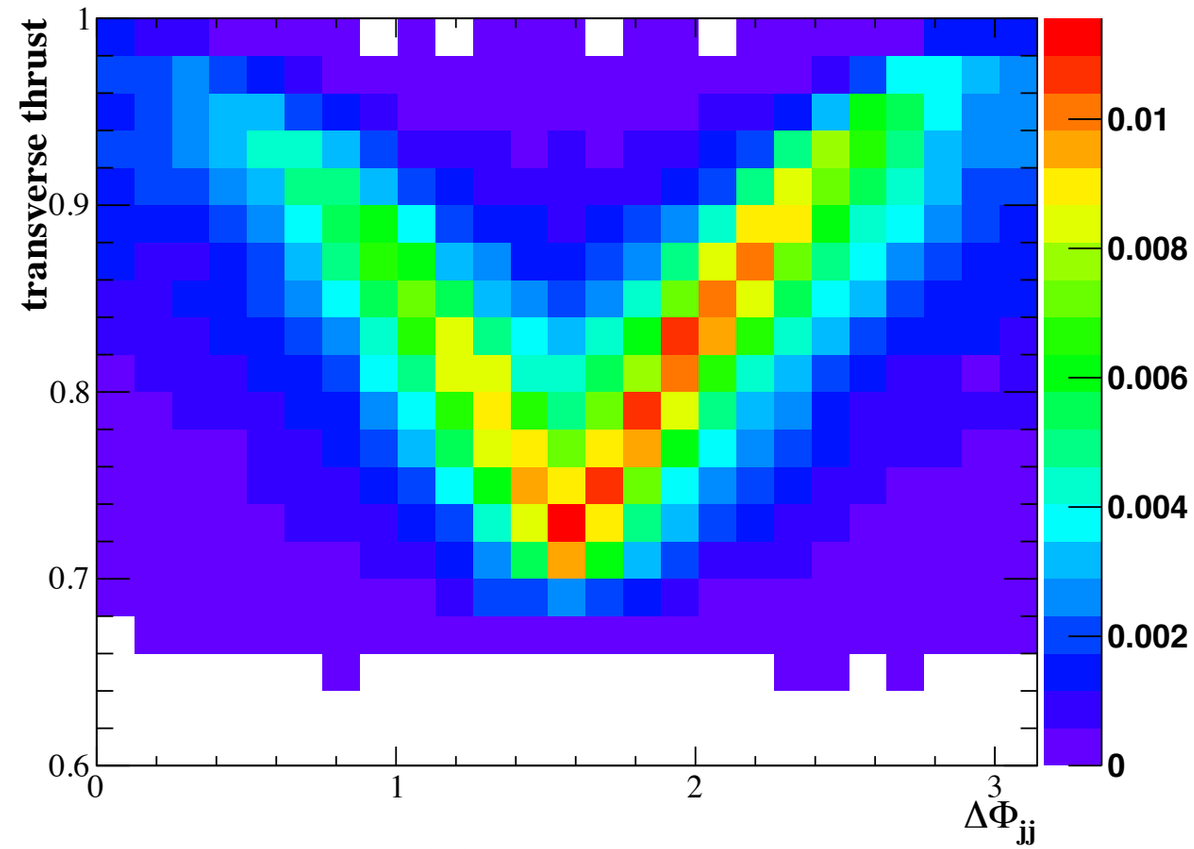
transverse thrust minor $$T_{m,g} = \frac{\sum_i |\mathbf{p}_{\perp,i} \times \mathbf{n}_T|}{\sum_i |\mathbf{p}_{\perp,i}|}$$



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

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

I. Use event shapes with constituents: (theorist's approach)

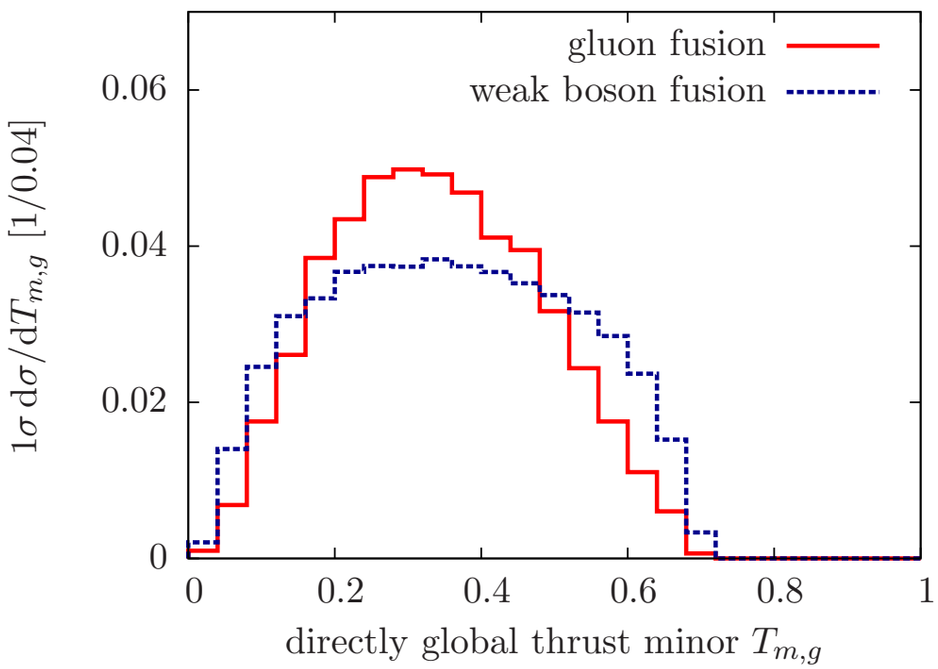
$$p_{T,i} \geq 1 \text{ GeV} \qquad |\eta_i| \leq 4.5$$

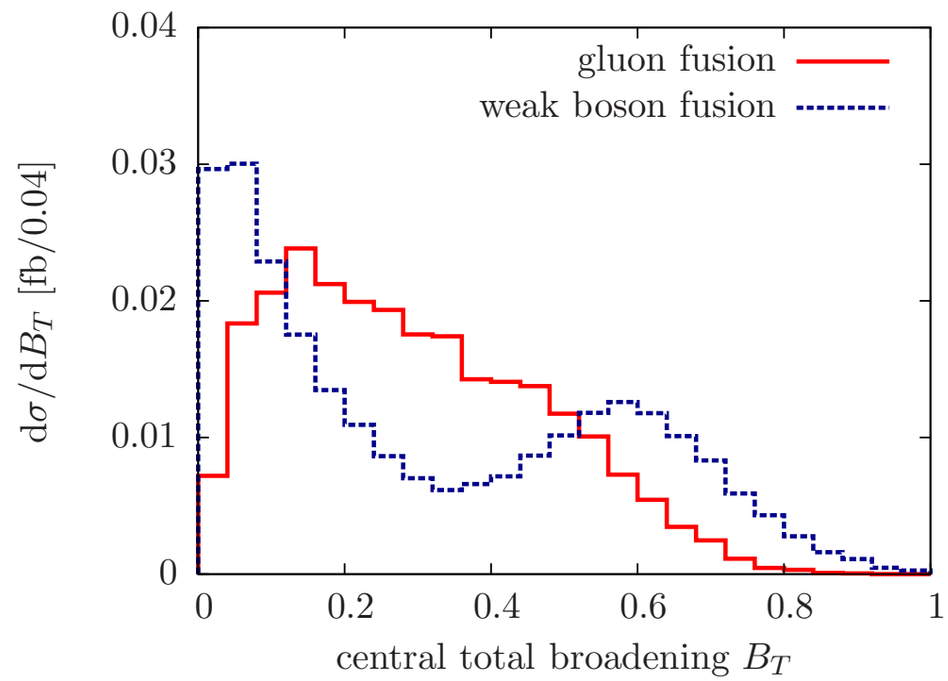
II. reduce pileup sensitivity, use

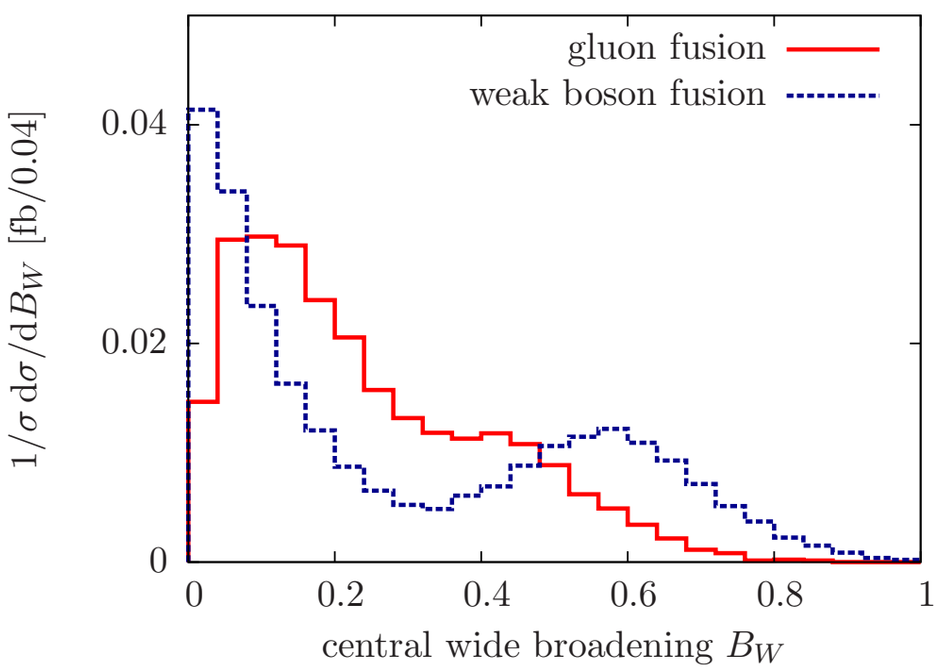
$$p_{T,j} \geq 40 \text{ GeV}, \quad \text{if } 2.5 \leq |y_j| \leq 4.5, \text{ and}$$
$$p_{T,j} \geq 10 \text{ GeV}, \quad \text{if } |y_j| \leq 2.5.$$

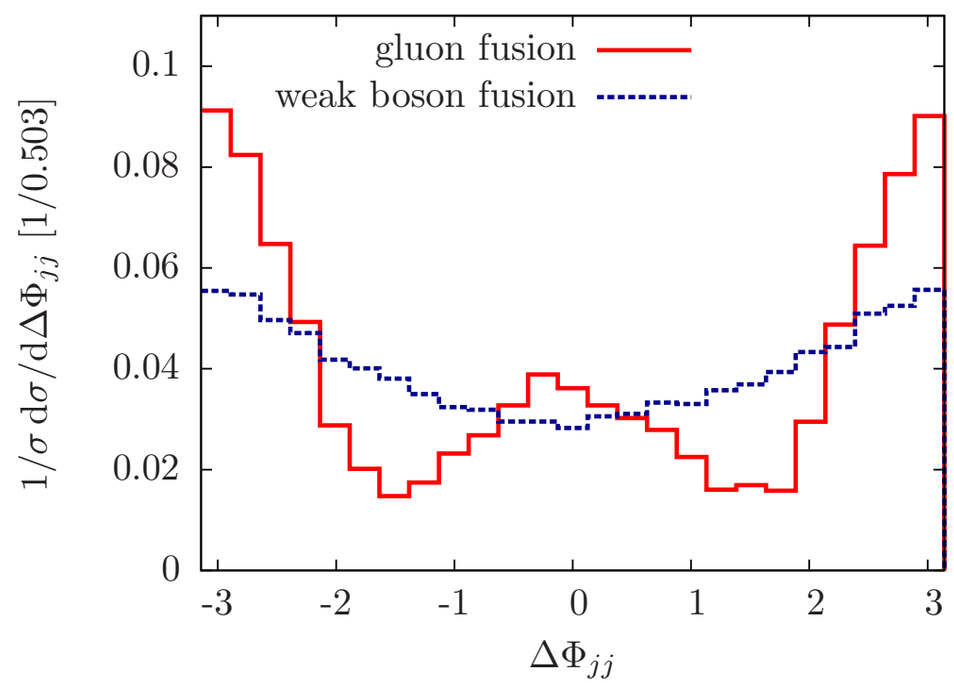
(compromise between theory and experiment)

GF vs WBF

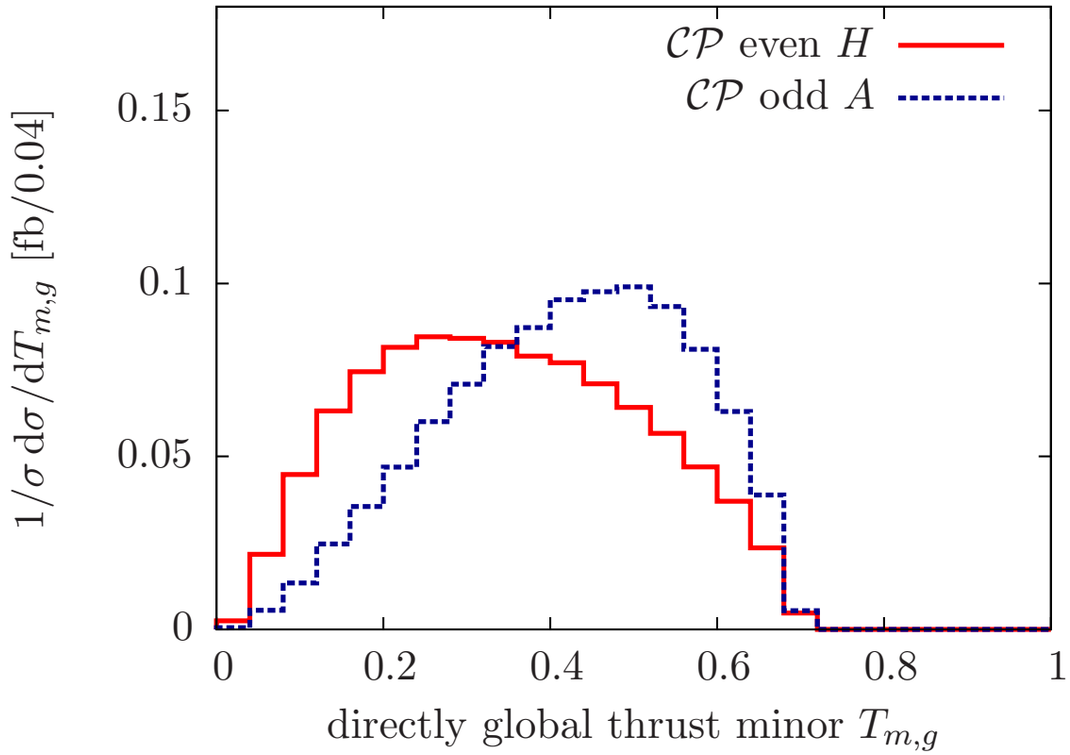

gluon fusion
weak boson fusion
$1\sigma\, d\sigma/dT_{m,g}$ [1/0.04]
directly global thrust minor $T_{m,g}$

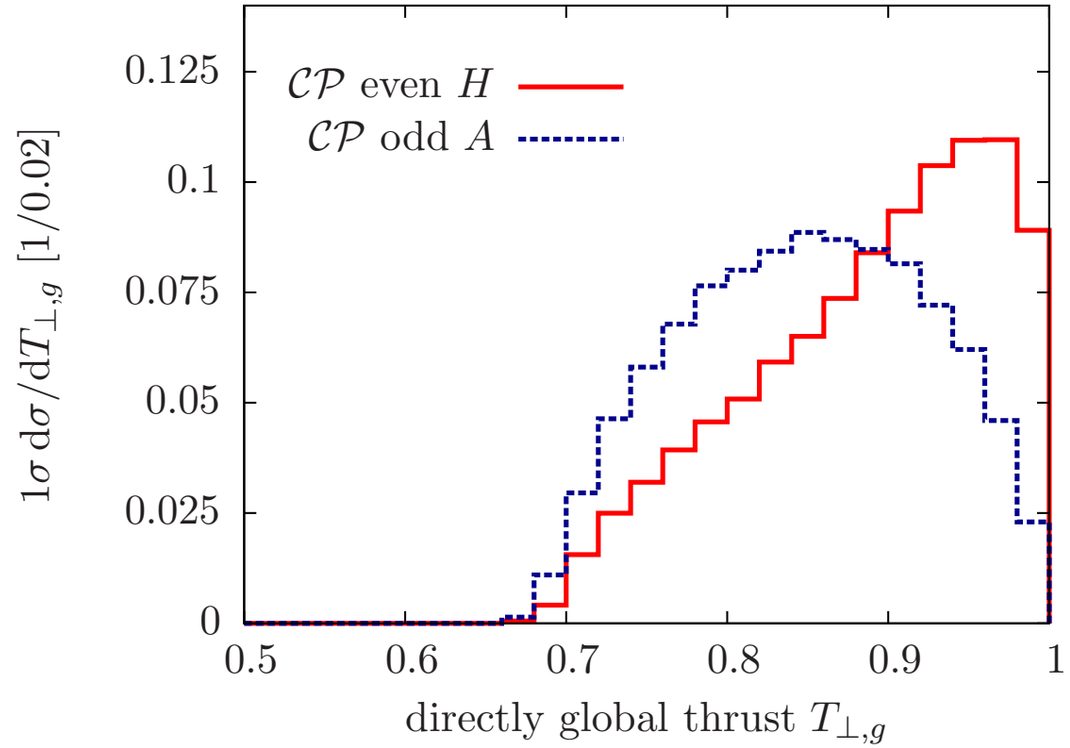

gluon fusion
weak boson fusion
$d\sigma/dB_T$ [fb/0.04]
central total broadening B_T

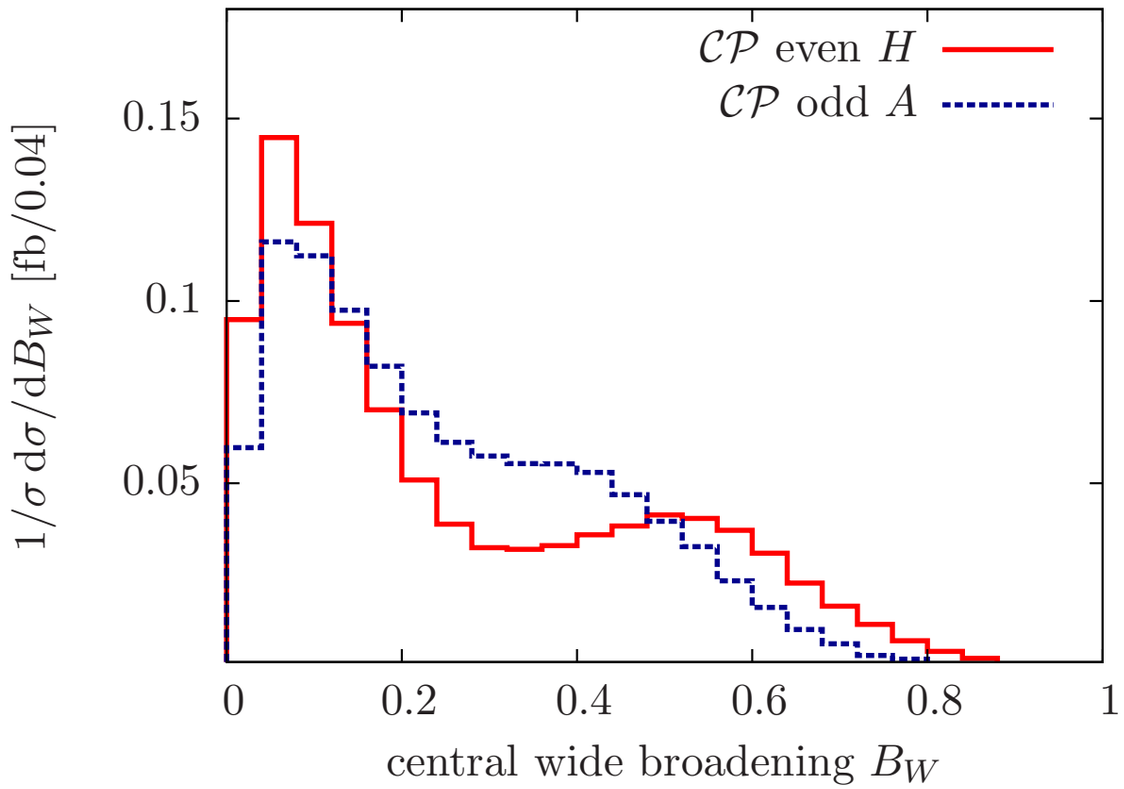

gluon fusion
weak boson fusion
$1/\sigma\, d\sigma/dB_W$ [fb/0.04]
central wide broadening B_W

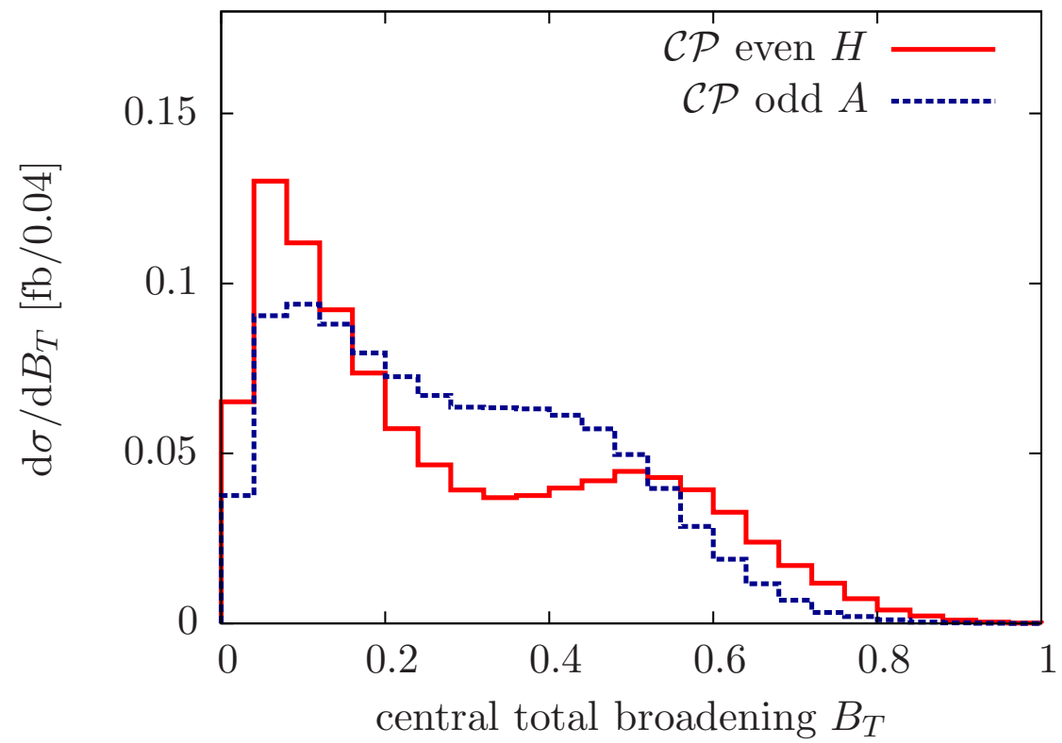

gluon fusion
weak boson fusion
$1/\sigma\, d\sigma/d\Delta\Phi_{jj}$ [1/0.503]
$\Delta\Phi_{jj}$

Distributions CP-odd vs CP-even

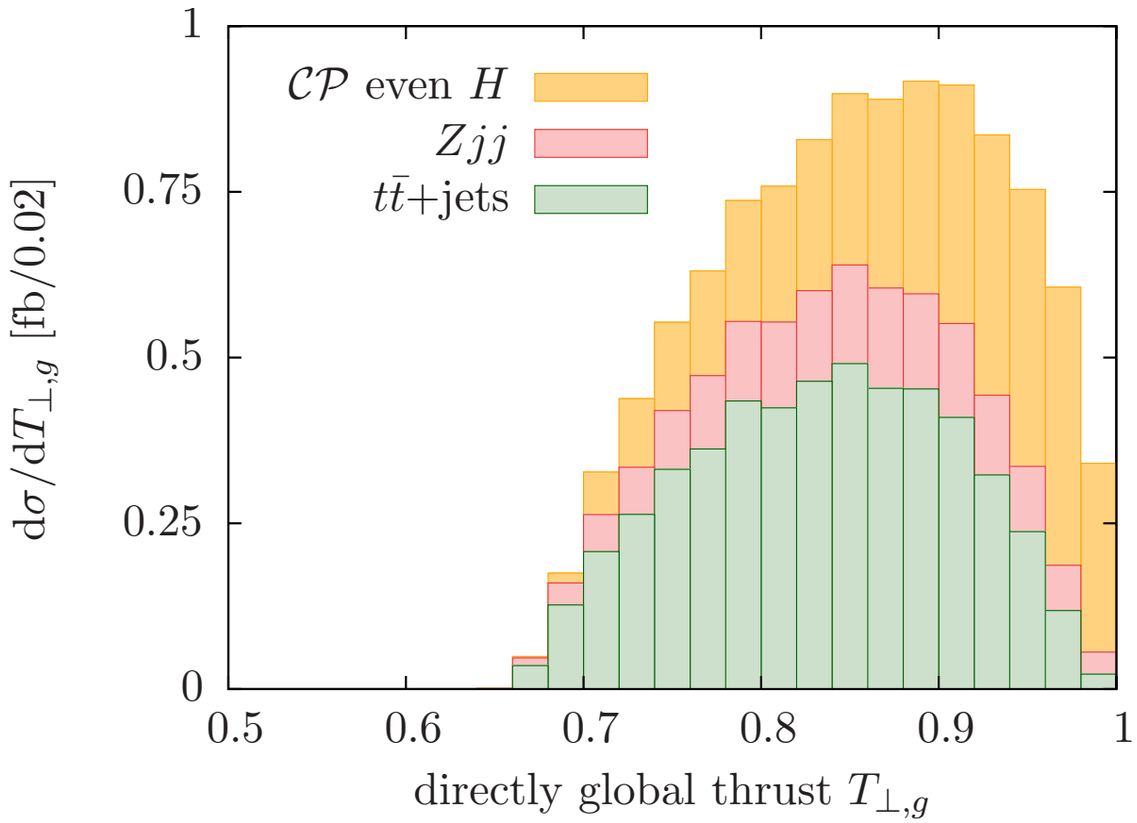


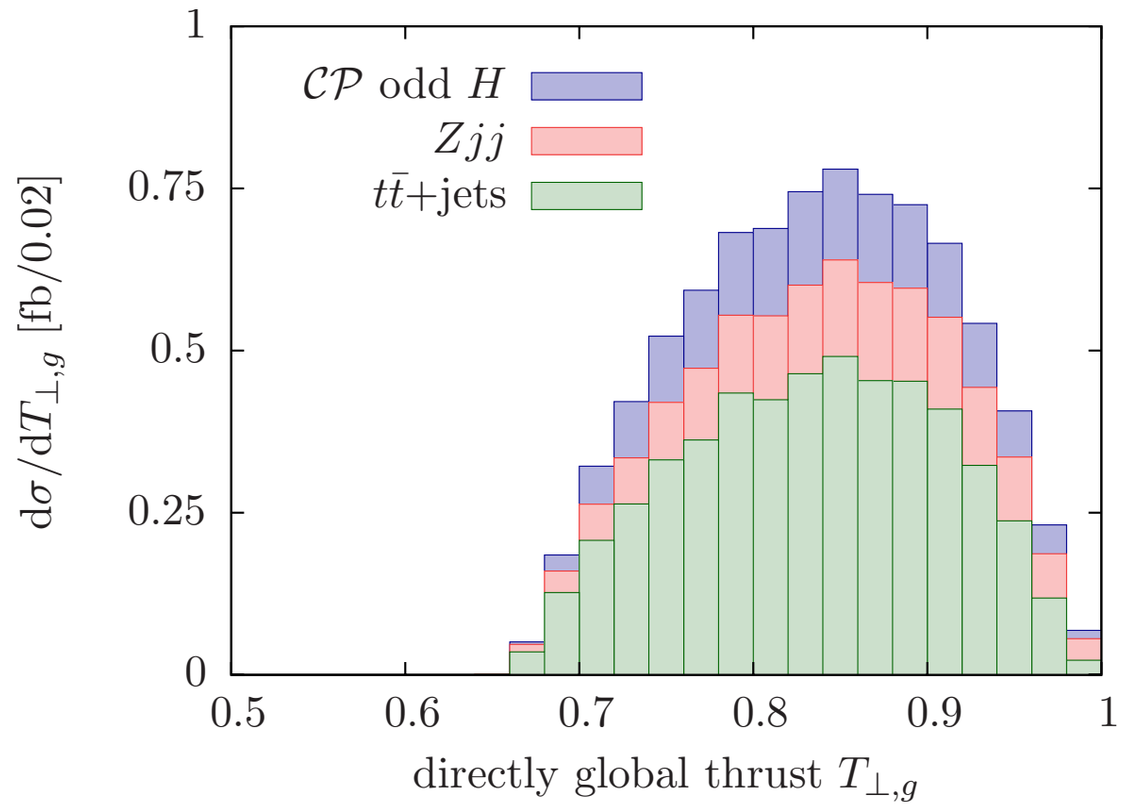


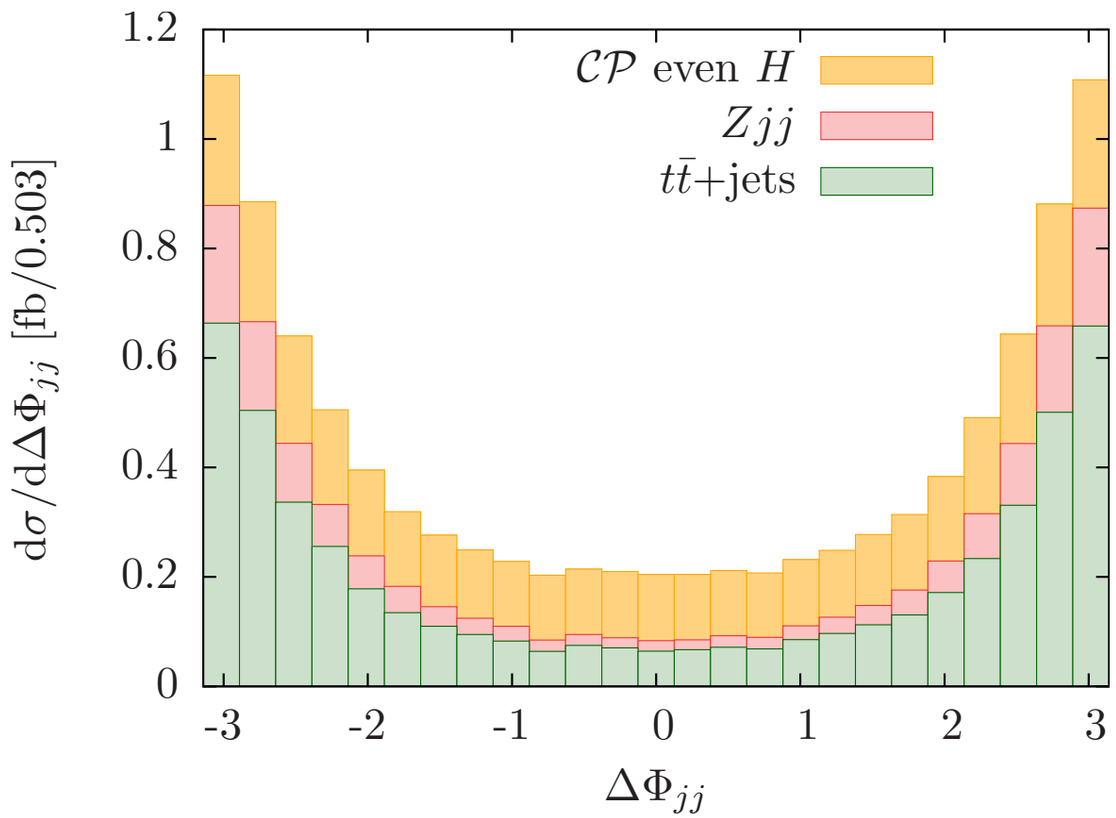


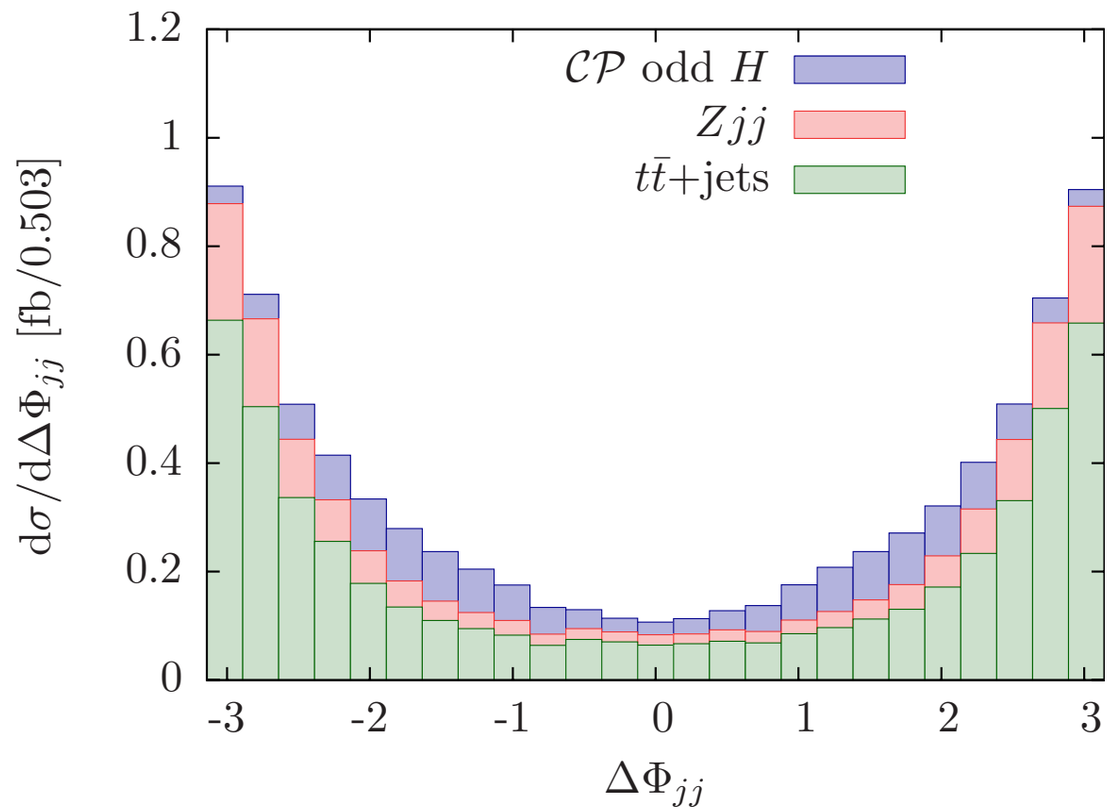


Distributions CP-odd vs CP-even

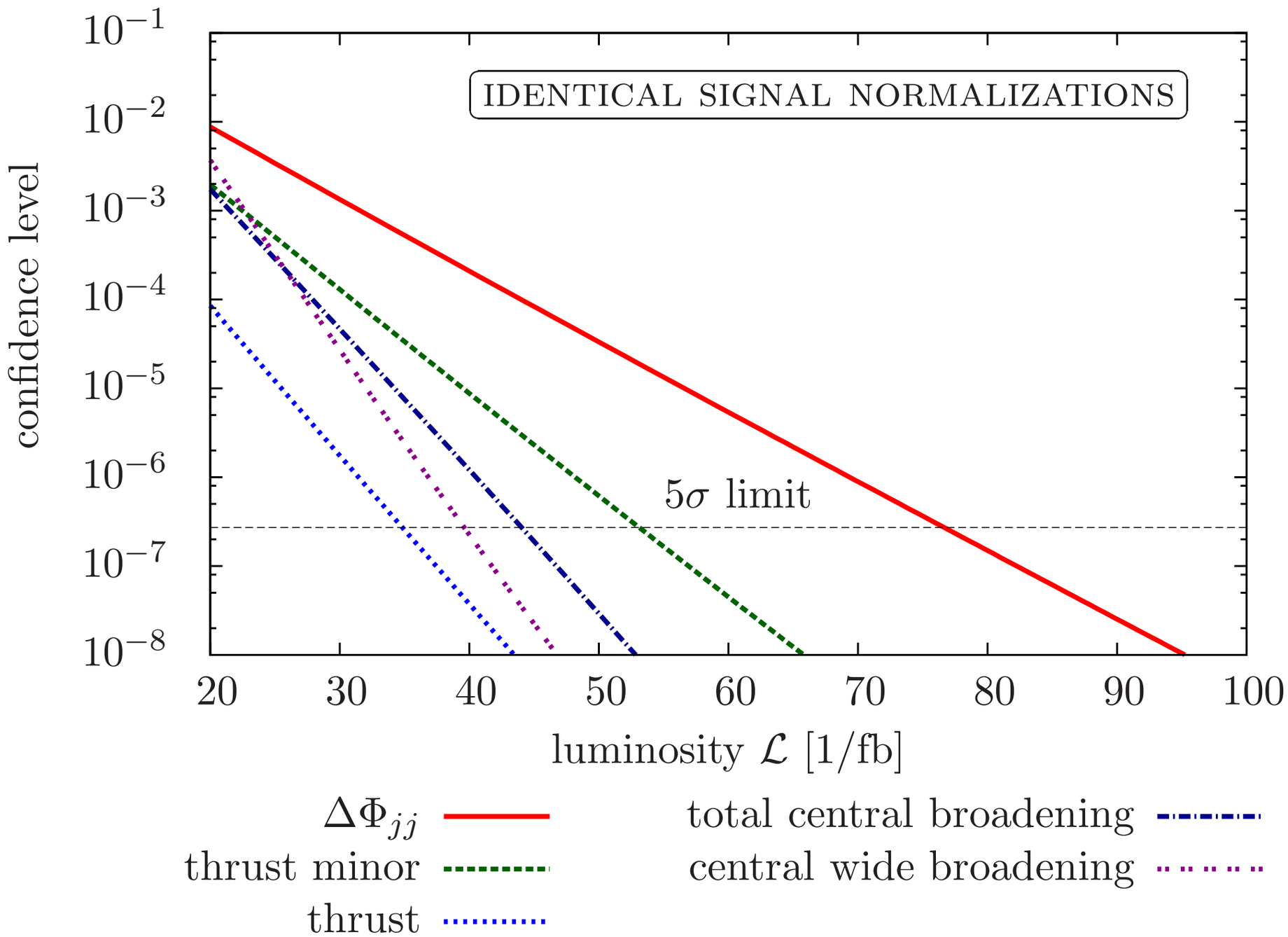








Sensitivity for discrimination between CP and CP-odd (normalized signal rates)



IV. Separation of production channels: GF vs WBF

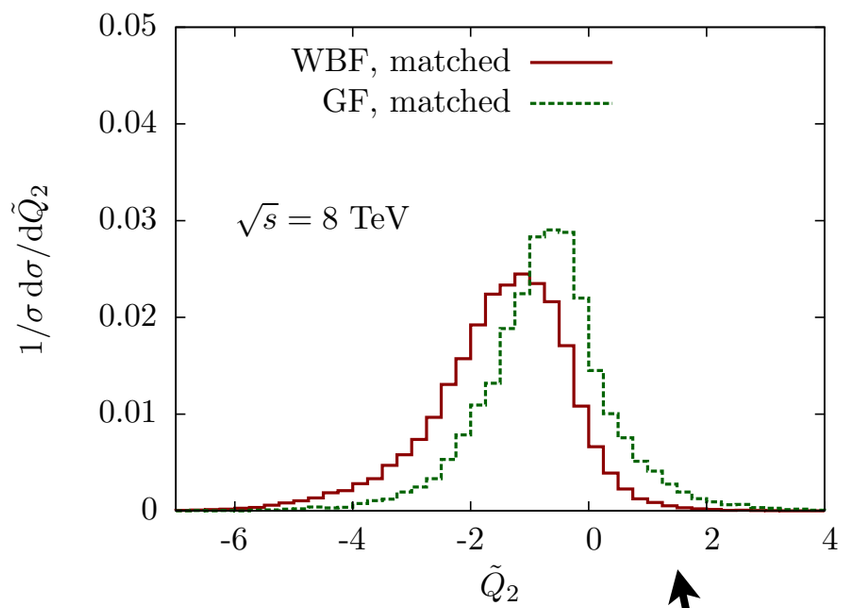
("Polishing a shiny Higgs with matrix elements")

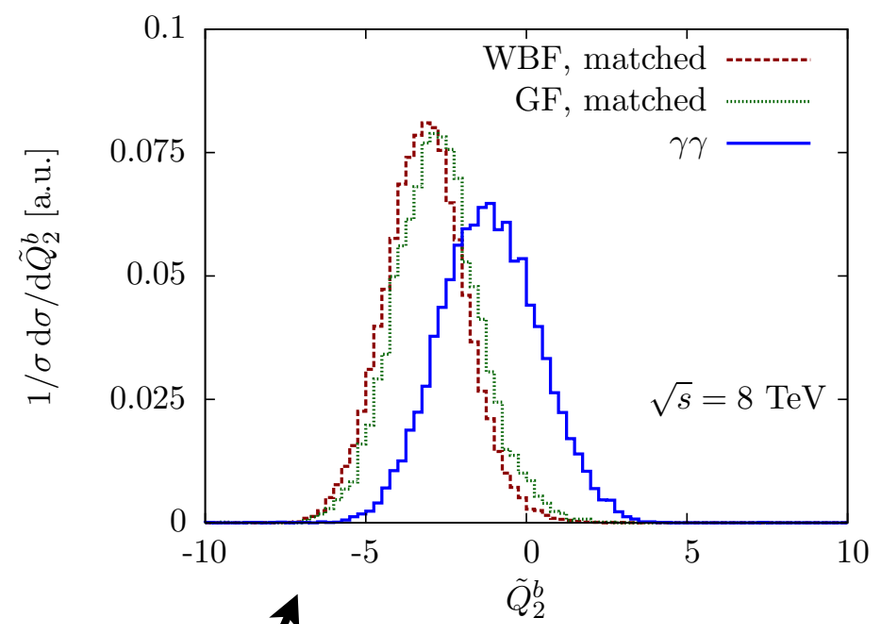
[Andersen, Englert, MS 1211.3011]

Possible to construct discriminating observable based on matrix element information:

$$\tilde{Q}_n(p_1^\gamma, p_2^\gamma, \{p_n^j\}) = -\log\left[\frac{|\mathcal{M}^{\rm WBF}(pp \to (h \to \gamma\gamma)j^n)|^2}{|\mathcal{M}^{\rm GF}(pp \to (h \to \gamma\gamma)j^n)|^2}\right]$$

$$\tilde{Q}_n^b(p_1^\gamma, p_2^\gamma, \{p_n^j\}) = -\log\left[\frac{\{|\mathcal{M}^{\rm WBF}(pp \to (h \to \gamma\gamma)j^n)|^2 + |\mathcal{M}^{\rm GF}(pp \to (h \to \gamma\gamma)j^n)|^2\}}{|\mathcal{M}^{2\gamma}(pp \to \gamma\gamma j^n)|^2}\right]$$



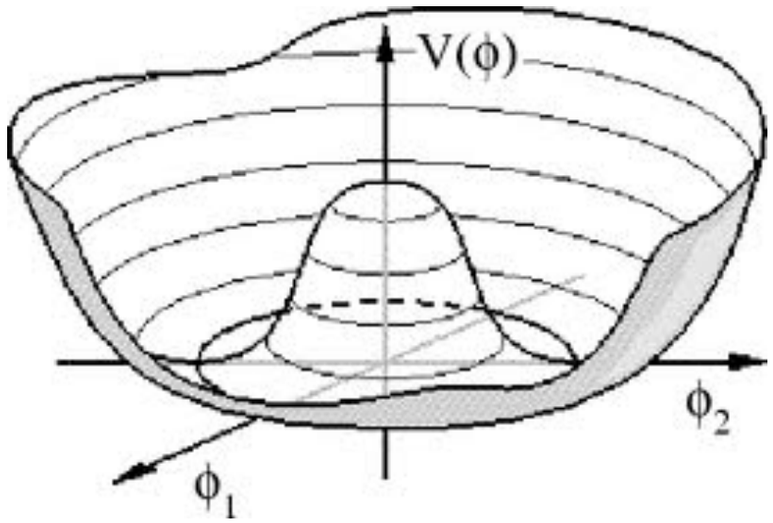


- Method separates GF vs WBF and reduces backgrounds
- Possible to loosen WBF-cuts in 8 TeV analysis to increase statistics and significance for CP measurements

V. Measuring the Higgs selfcoupling at the LHC

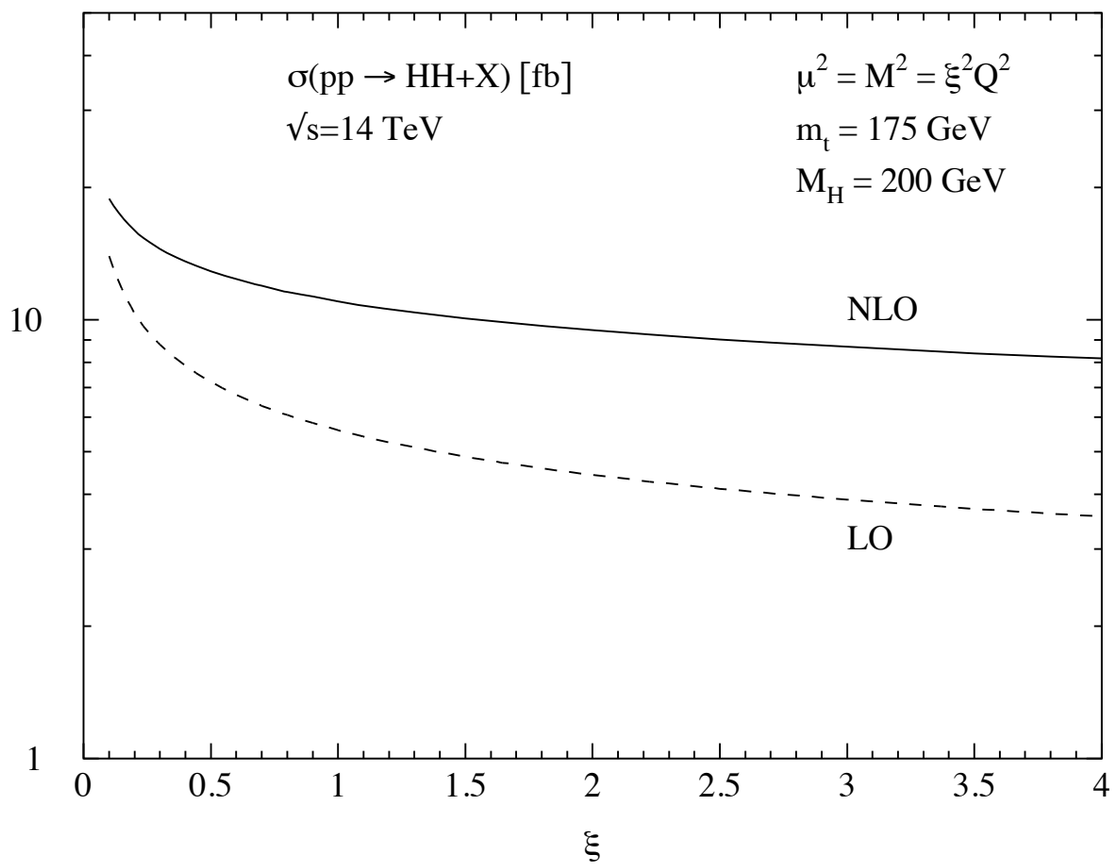
$$V(H^\dagger H) = \mu^2 H^\dagger H + \eta (H^\dagger H)^2$$
$$\supset \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\eta}{2}} m_h h^3 + \frac{\eta}{4} h^4$$

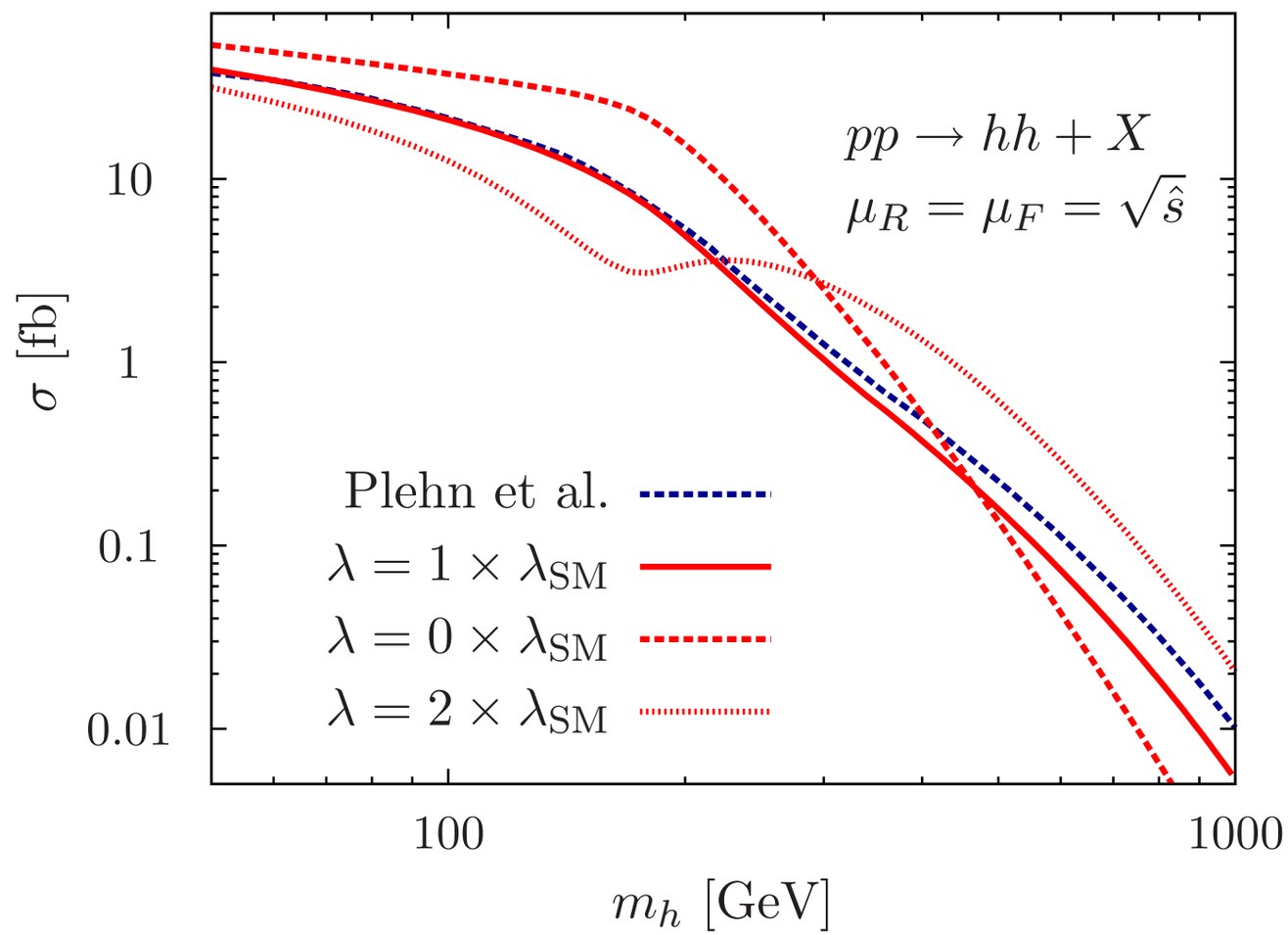
$$H = (0, v+h)^T/\sqrt{2} \qquad \lambda_{\rm SM} = \sqrt{\frac{\eta}{2}} m_h$$



- For EWSB Higgs potential needed -> measure selfcoupling
- Measuring Higgs potential 'holy grail' of Higgs physics
- λ_{HHHH} absolutely hopeless at LHC (and any of the others...)
- λ_{HHH} very difficult to measure at the LHC

Rate of di-Higgs production small!

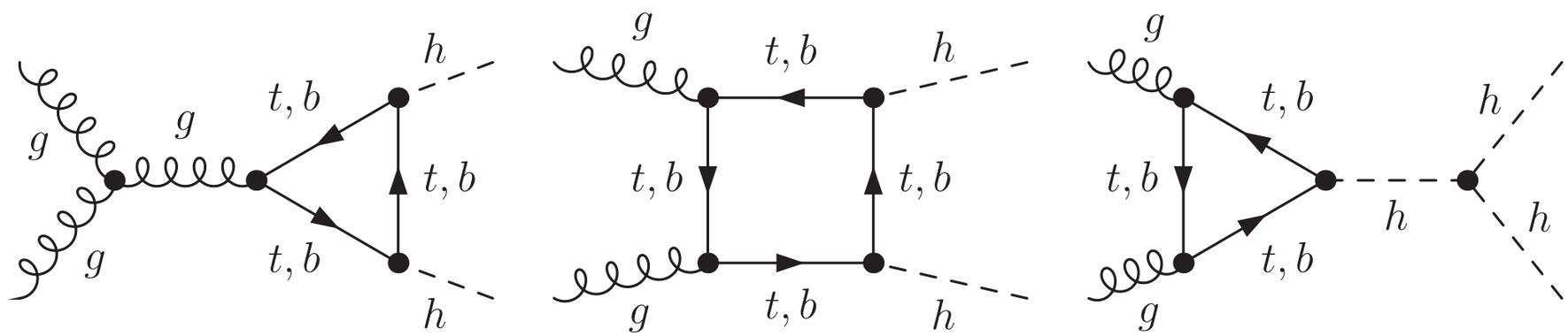




[Dawson, Dittmaier, Spira PRD 58 (1998)]

[Binoth, Karg, Kauer, Ruckl PRD 74 (2006)]

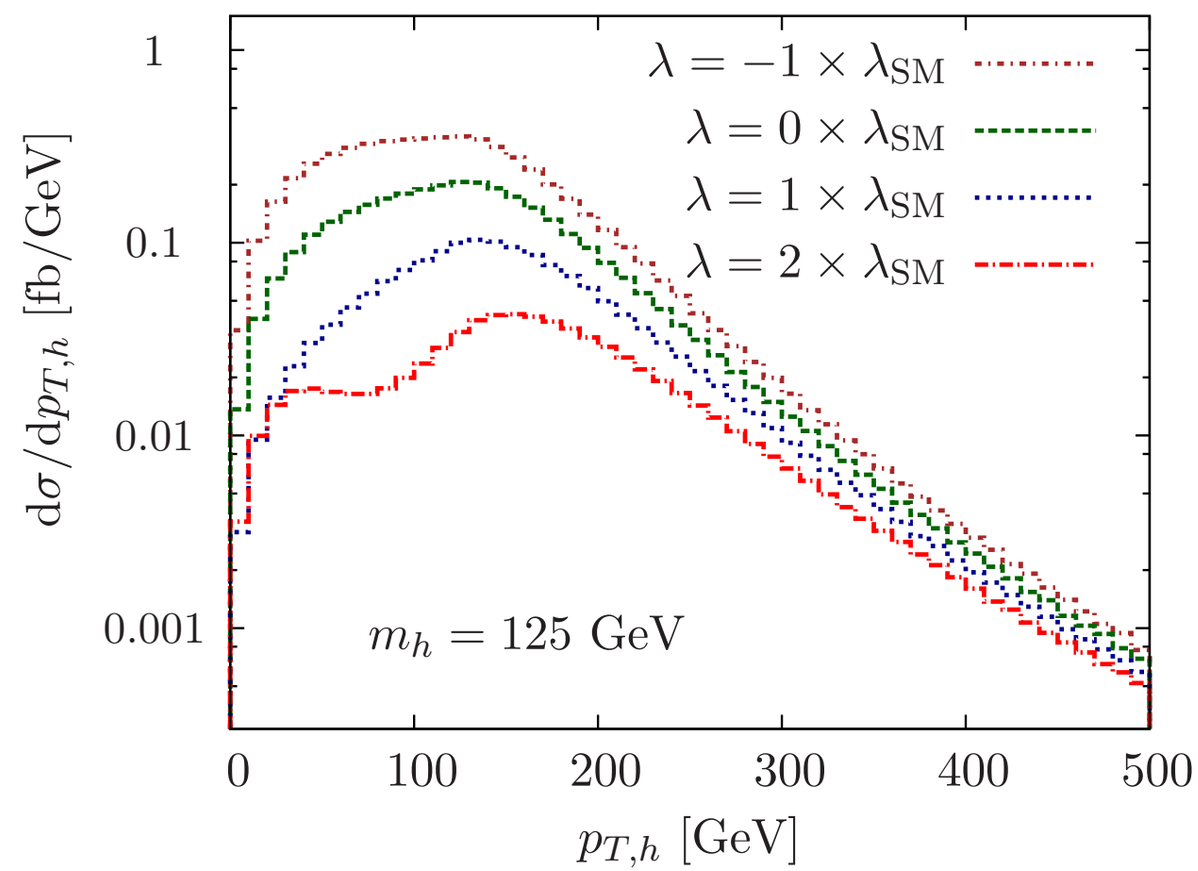
However, kinematic even more problematic



- Destructive interference in signal

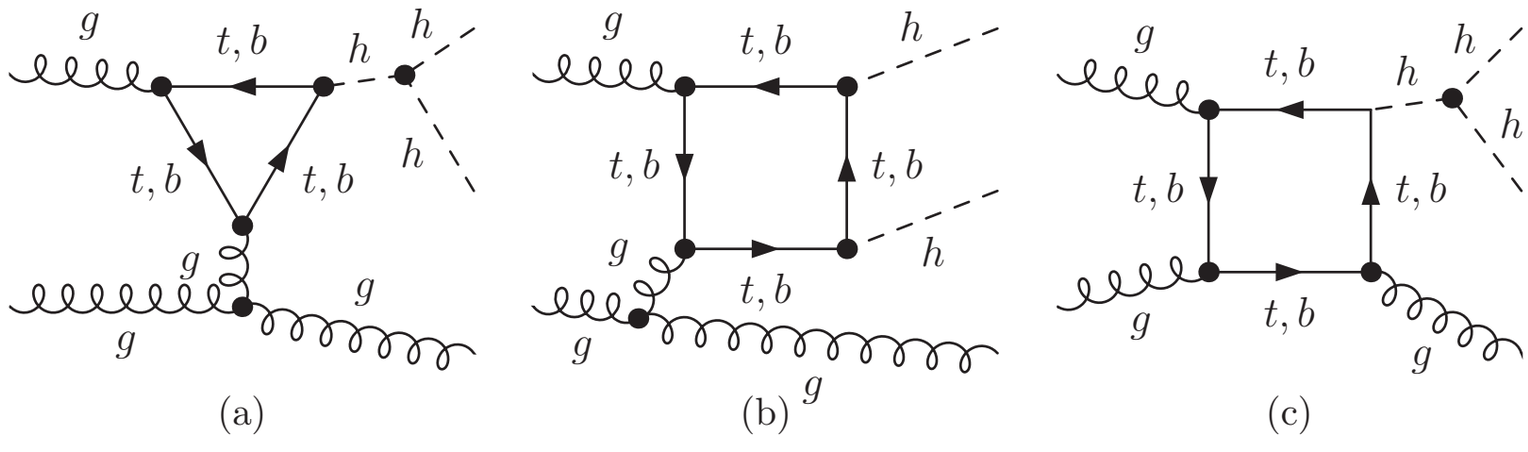
- 1/s suppression for λ_{HHH} diagram

- But signal is naturally boosted

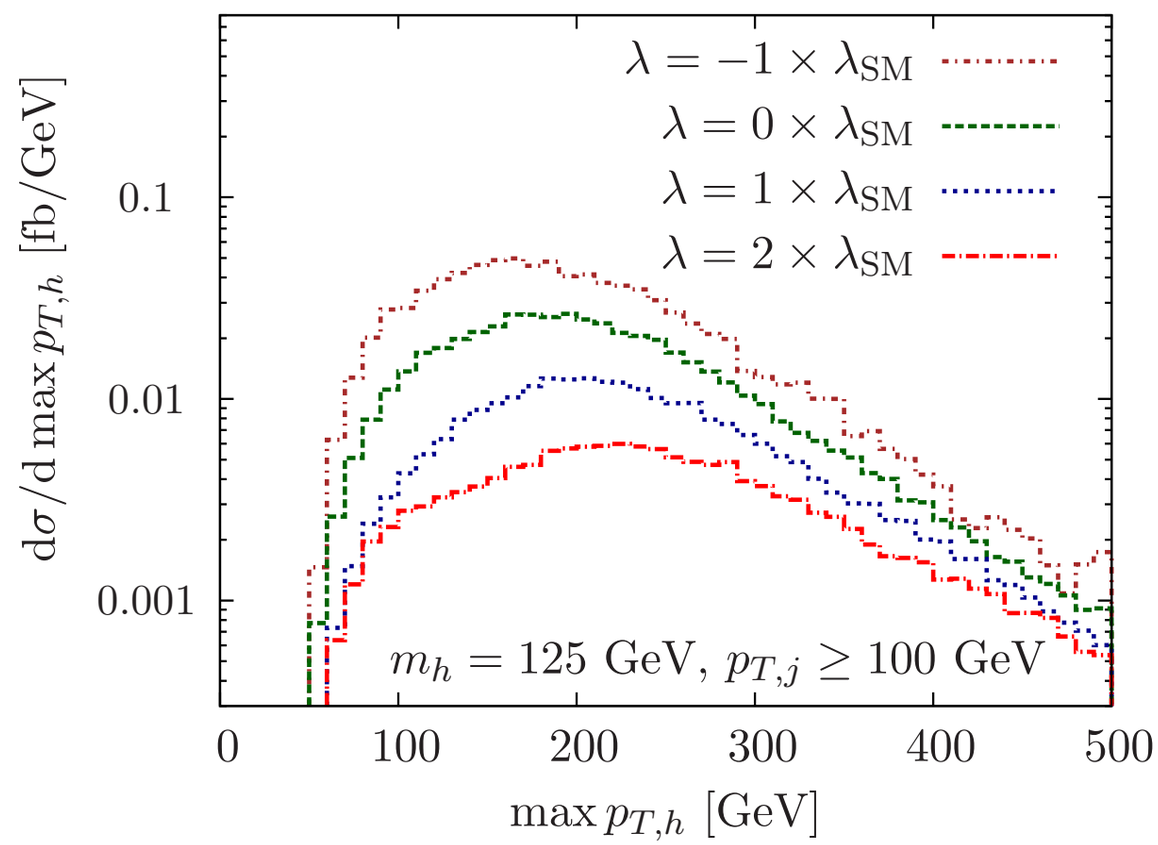


→ Need large BR due to small signal but need to discriminate from backgrounds

Novel idea: include a hard jet to make Higgs softer



- ameliorates the 1/s suppression
- rescues sensitivity on selfcoupling for boosted Higgs
- However, comes at the price of even smaller rate



Several reconstruction approaches tried in

[Baur, Plehn, Rainwater PRD 69 (2004)] [Dolan, Englert, MS JHEP 1210]

[Papaefstathiou, Yang, Zurita 1209.1489]

➡ Most promising final states probably $\bar{b}b\gamma\gamma,\ \bar{b}b\tau^+\tau^-,\ 4\tau(?)$

HH:

	$\xi=0$	$\xi=1$	$\xi=2$	$b\bar{b}\tau\tau$	$b\bar{b}\tau\tau$ [ELW]	$b\bar{b}W^+W^-$	ratio to $\xi=1$
cross section before cuts	59.48	28.34	13.36	67.48	8.73	873000	$3.2\cdot10^{-5}$
reconstructed Higgs from τs	4.05	1.94	0.91	2.51	1.10	1507.99	$1.9\cdot10^{-3}$
fatjet cuts	2.27	1.09	0.65	1.29	0.84	223.21	$4.8\cdot10^{-3}$
kinematic Higgs reconstruction ($m_{b\bar{b}}$)	0.41	0.26	0.15	0.104	0.047	9.50	$2.3\cdot10^{-2}$
Higgs with double b-tag	0.148	0.095	0.053	0.028	0.020	0.15	0.48

HHj:

	$\xi=0$	$\xi=1$	$\xi=2$	$b\bar{b}\tau^+\tau^-j$	$b\bar{b}\tau^+\tau^-j$ [ELW]	$t\bar{t}j$	ratio to $\xi=1$
cross section before cuts	6.45	3.24	1.81	66.0	1.67	106.7	$1.9\cdot10^{-2}$
2 τs	0.44	0.22	0.12	37.0	0.94	7.44	$4.8\cdot10^{-3}$
Higgs rec. from taus + fatjet cuts	0.29	0.16	0.10	2.00	0.150	0.947	$5.1\cdot10^{-2}$
kinematic Higgs rec.	0.07	0.04	0.02	0.042	0.018	0.093	0.26
$2b+hh$ invariant mass + $p_{T,j}$ cut	0.010	0.006	0.004	<0.0001	0.0022	0.0014	1.54

Channels are being studied: [ATLAS-PHYS-PUB-2012-001]

Conclusions

- A new resonance has been found at the LHC, consistent with long predicted Higgs boson
- To confirm it is Higgs boson couplings and quantum numbers have to be measured
- Measuring hadronic decays (i.e. H->bb) and Higgs production in association with Jets is paramount for this program
- Jet substructure can help to perform this task
- Jet physics will be active field for long time to come

Di-Higgs production can discriminate between different BSM scenarios

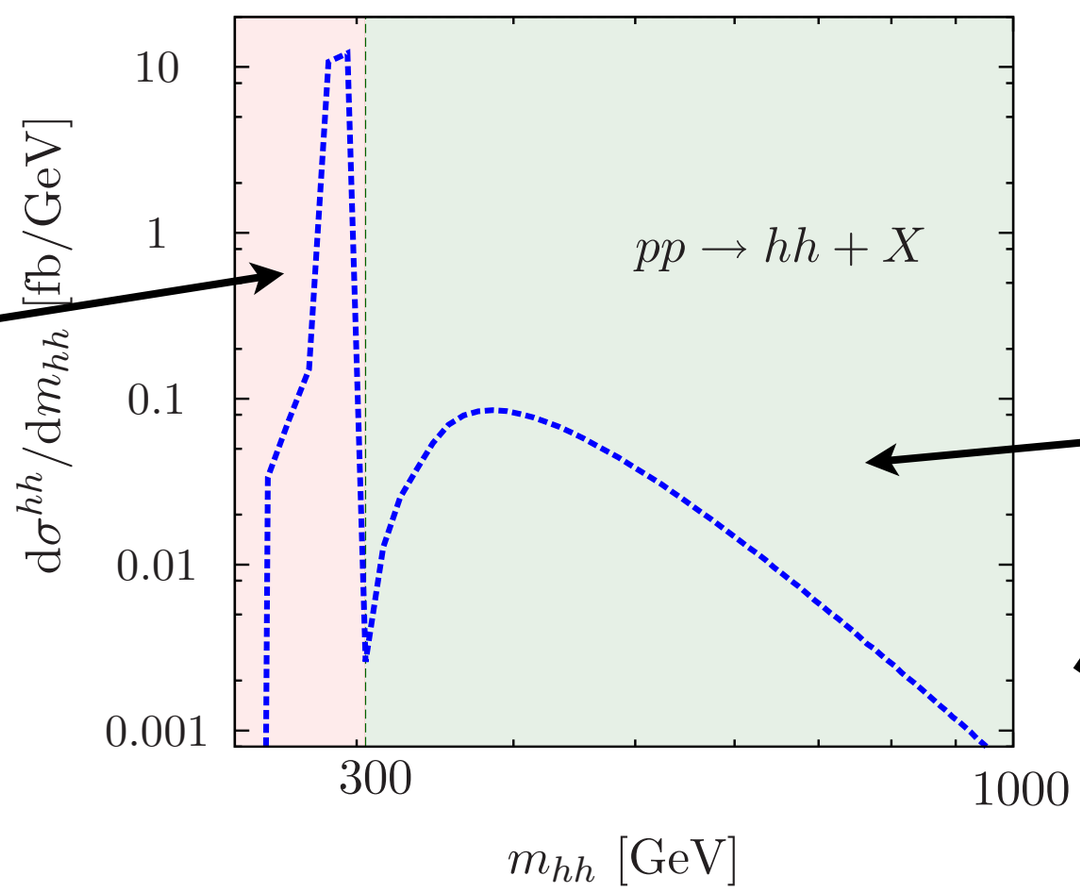
For example resonant di-Higgs production in the MSSM:

$$\begin{aligned}\lambda_{hhh} &= 3\cos 2\alpha\,\sin(\beta+\alpha)\\ \lambda_{Hhh} &= 2\sin 2\alpha\,\sin(\beta+\alpha) - \cos 2\alpha\,\cos(\beta+\alpha)\\ \lambda_{HHh} &= -2\sin 2\alpha\,\cos(\beta+\alpha) - \cos 2\alpha\,\sin(\beta+\alpha),\end{aligned}$$

Assuming decoupling limit such that MH > 2 Mh and BR(H->hh) = 45%

[Dolan, Englert, MS 1210.8166]

resonant production dominated by λ_{Hhh}



off-shell, continuums production

Allows measurement of alpha and beta angles

Higgs mechanism a brief review

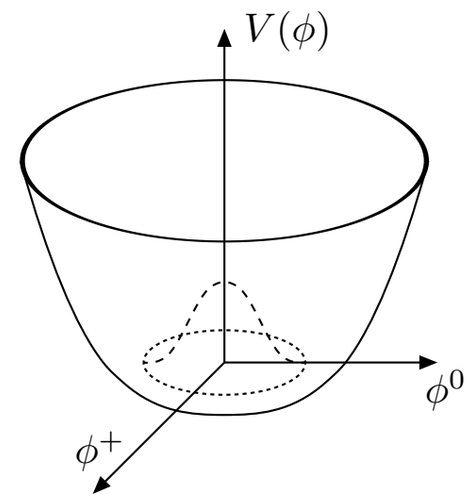
Purpose: explain existence of massive particles consistence with gauge invariance

Symmetry of the Lagrangian

$$SU(2)_L \times U(1)_Y$$

Higgs doublet

$$\Phi = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$



$$V(\Phi) = \lambda \left[\Phi^\dagger \Phi - \frac{v^2}{2} \right]^2$$

Symmetry of the vacuum

$$U(1)_{em}$$

vacuum expectation value

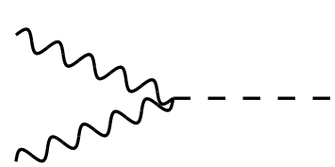
$$\langle \Phi \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

$$v = 246 \text{ GeV}$$

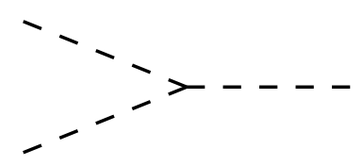
Higgs mass: $m_H = \sqrt{2\lambda} v$

couplings to

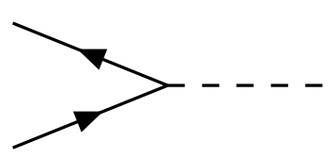
gauge bosons $\quad g_{VVH} = \frac{2m_V^2}{v}$



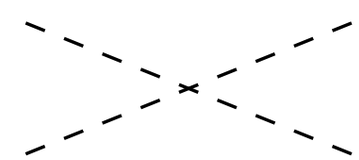
$\lambda_{HHH} = -3\frac{m_H^2}{v}$



fermions $\quad g_{f\bar{f}H} = \frac{m_f}{v}$



$\lambda_{HHHH} = -3\frac{m_H^2}{v^2}$



Higgs selfcouplings