Experimental verification of Higgs mechanism

Problem:
How to give gauge bosons mass in gauge invariant way

↓

Spontaneous symmetry breaking identified by many in early 1960

↓

Peter Higgs predicts Boson as remnant of scalar field after SSB

↓

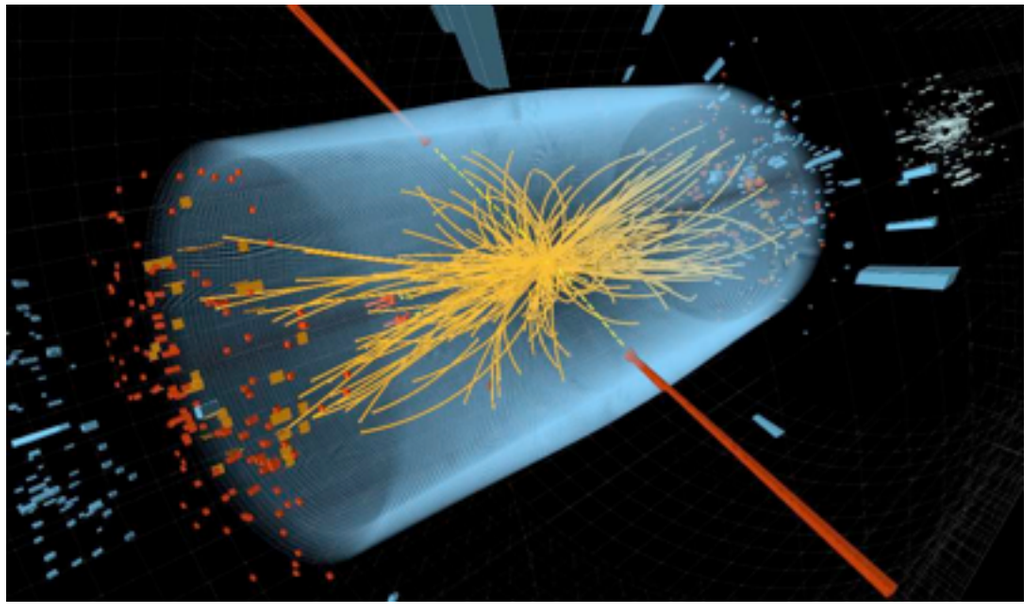
Boson likely to be discovered after 50 years!

↓

Huge international and intergenerational success!

Higgs, Brout, Englert, ... predicted in 1964

Higgs boson possibly discovered in 2012



Higgs mechanism a brief review

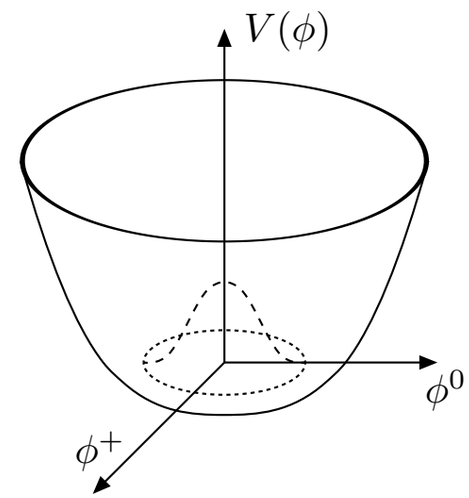
Purpose: explain existence of massive particles consistence with gauge invariance

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

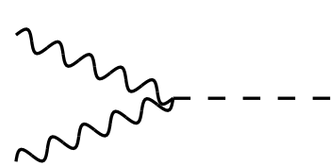
$$\langle \Phi \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

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

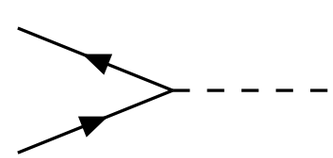
Higgs mass: $m_H = \sqrt{2\lambda} v$

couplings to

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

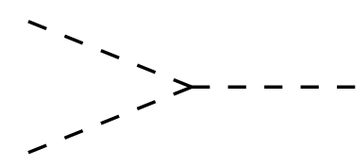


fermions $\quad g_{f\bar{f}H} = \frac{m_f}{v}$



Higgs selfcouplings

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



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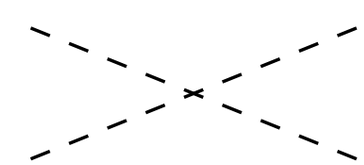


Implications of the Higgs mechanism

- massive (massless) vectors have three (two) degrees of freedom

$$k^\mu = (\sqrt{m^2+k^2}, 0, 0, k)^T$$

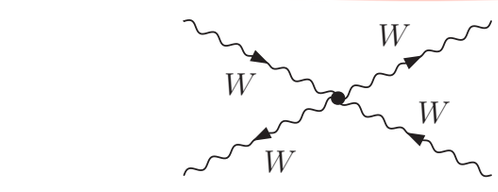
$$\epsilon_\mu k^\mu = 0, \;\; \epsilon^2 = -1$$

$$\varepsilon_\mu^{(T,1)} = (0,1,0,0)^T$$
$$\varepsilon_\mu^{(T,2)} = (0,0,1,0)^T$$
$$\varepsilon_\mu^{(L)} = (k/m, 0, 0, E/m)^T$$
$$\sim k_\mu/m \quad (|k| \gg m)$$

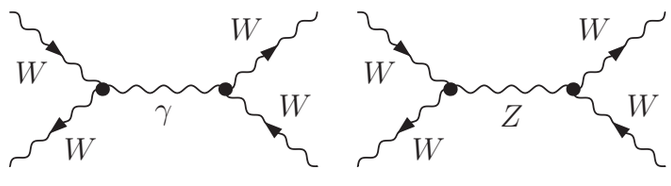
- probability conservation in scattering processes (unitarity) potentially problematic: ("cannot get out more than you put in")

$$S^\dagger S = \mathbb{1} \Longrightarrow a_\ell = \frac{1}{32\pi}\int_{-1}^{1} \mathrm{d}\cos\theta\, \mathcal{M}(\cos\theta) P_\ell(\cos\theta), \quad |a_\ell| \leq 1$$

$$\varepsilon_L^\mu = k^\mu/m_W + \mathcal{O}(m_W/E)$$



$\sim E^4$



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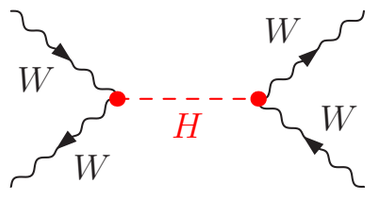

+ crossed s $\longleftrightarrow$ t

$\sim E^2$

$\sim E^0$

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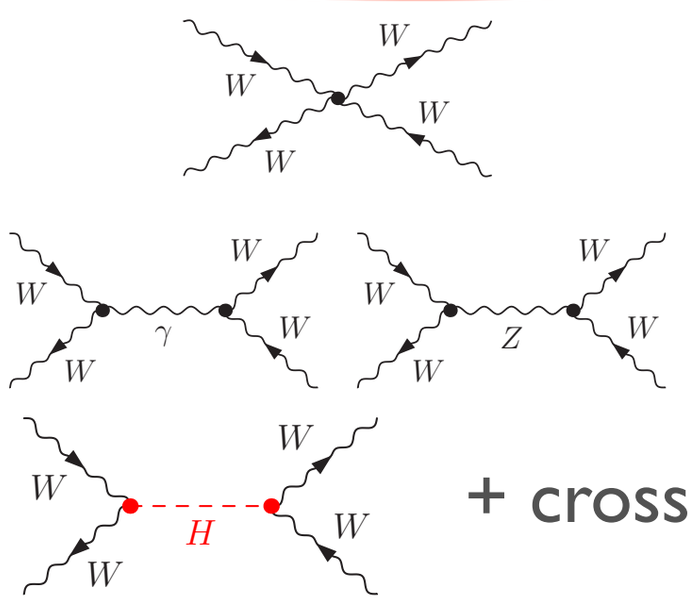


+ crossed s ⟷ t

$$a_0 \sim \frac{m_h^2}{m_W^2} \quad (....+ \text{ loops})$$

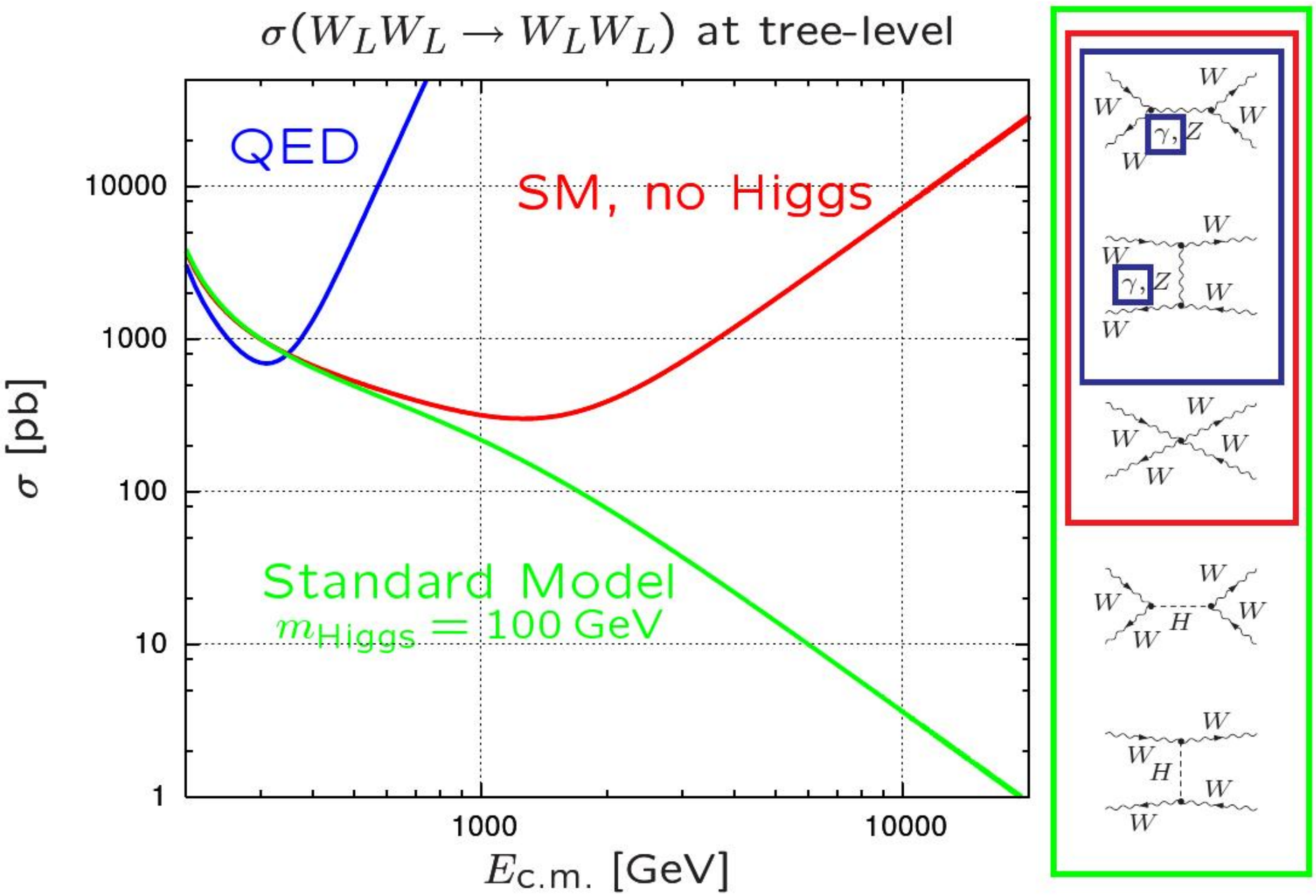
unitarity requires

$$m_h \lesssim 700 \text{ GeV}$$

in fact we need new TeV scale particles to mend unitarity violation!

⟶ beyond the SM physics

cross section $\sigma \sim \frac{|\mathcal{M}|^2}{E_{\text{c.m.}}^2}$



- two additional theoretical bounds follow from the analysis of the Higgs potential beyond leading order

$$V(\Phi^\dagger\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 \qquad m_h^2 = \frac{\lambda v^2}{2}$$

- beyond tree level all parameters become scale dependent

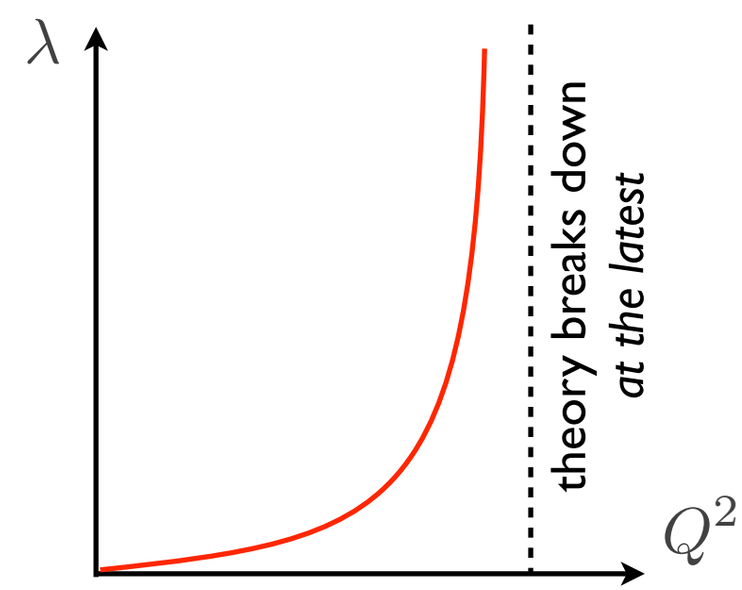
$$\frac{d\,\lambda}{d\,\log Q^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4 - \frac{3}{2}\lambda\left(3g_2^2 + g_1^2\right) + \frac{3}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

- in order to have a global minimum we need to have $\lambda > 0$ for $Q^2 < \Lambda^2$ for the SM to be well-defined at scales below the cut-off Λ

- the running of λ hits a Landau pole (coupling becomes infinite)

$$\frac{\mathrm{d}\lambda}{\mathrm{d}\log Q^2} = \frac{12\lambda^2}{16\pi^2} + \text{gauge \& fermion terms}$$

$$\longrightarrow \quad \lambda = \lambda(v^2)\left[1 - \frac{3}{4\pi^2}\lambda(v^2)\log\frac{Q^2}{v^2}\right]^{-1}$$



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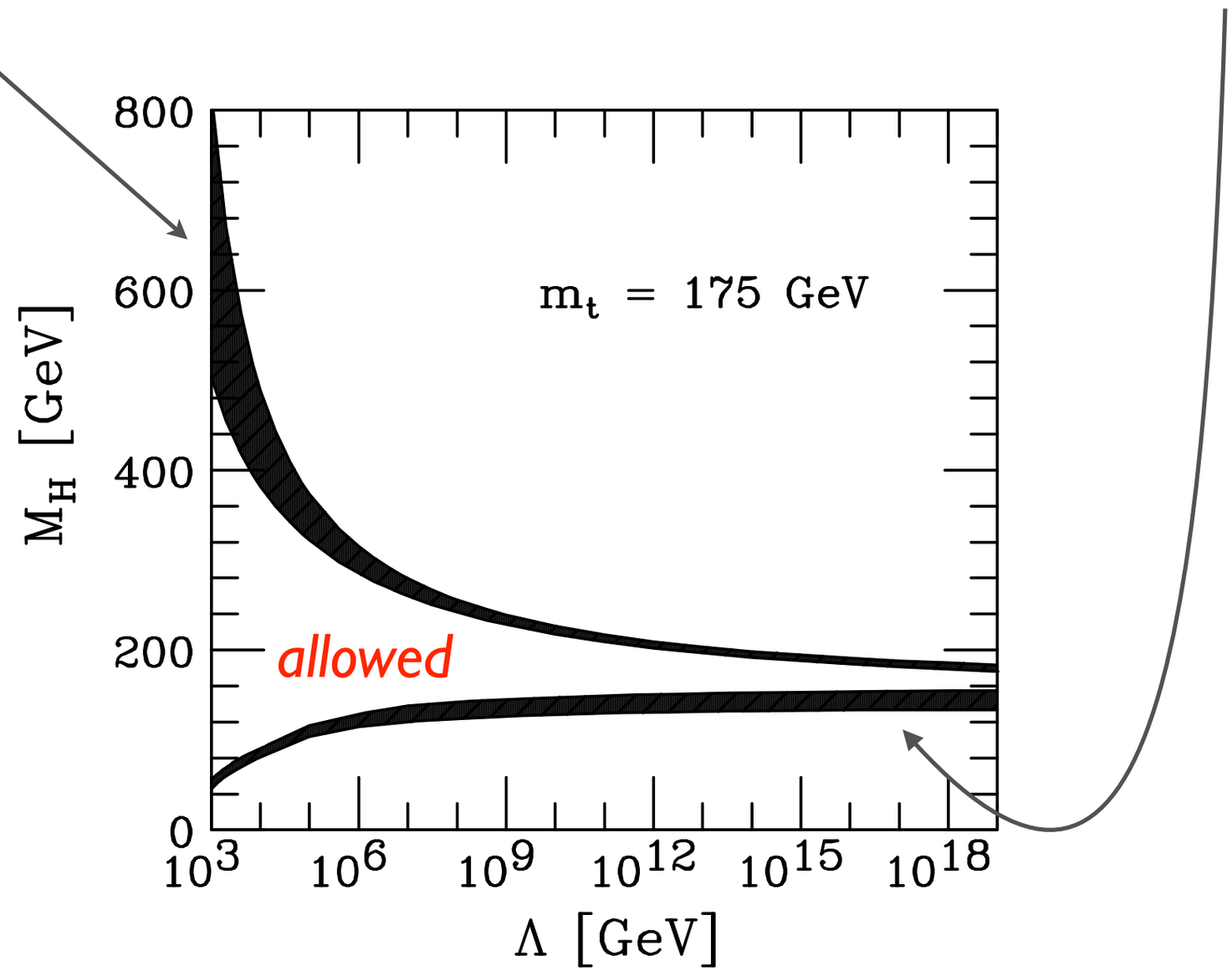
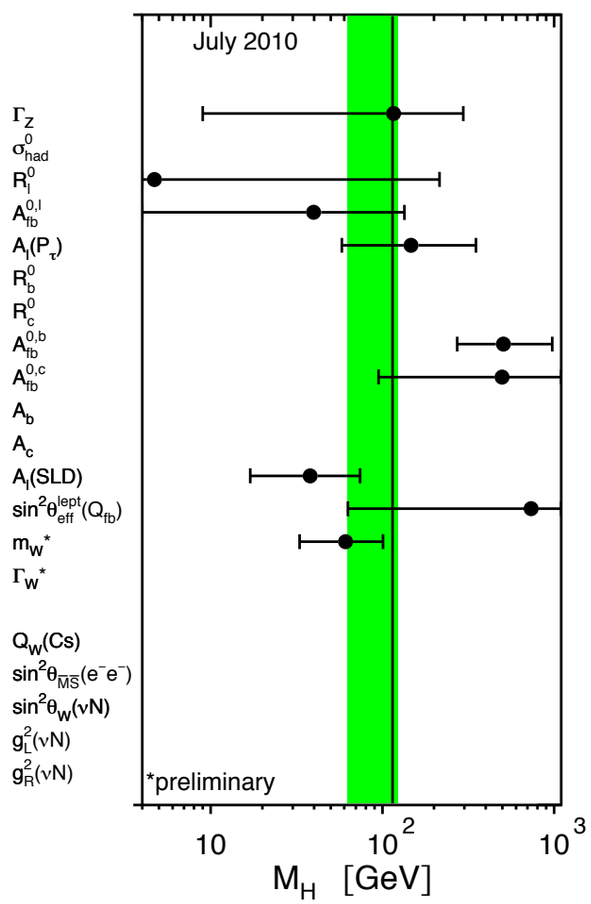
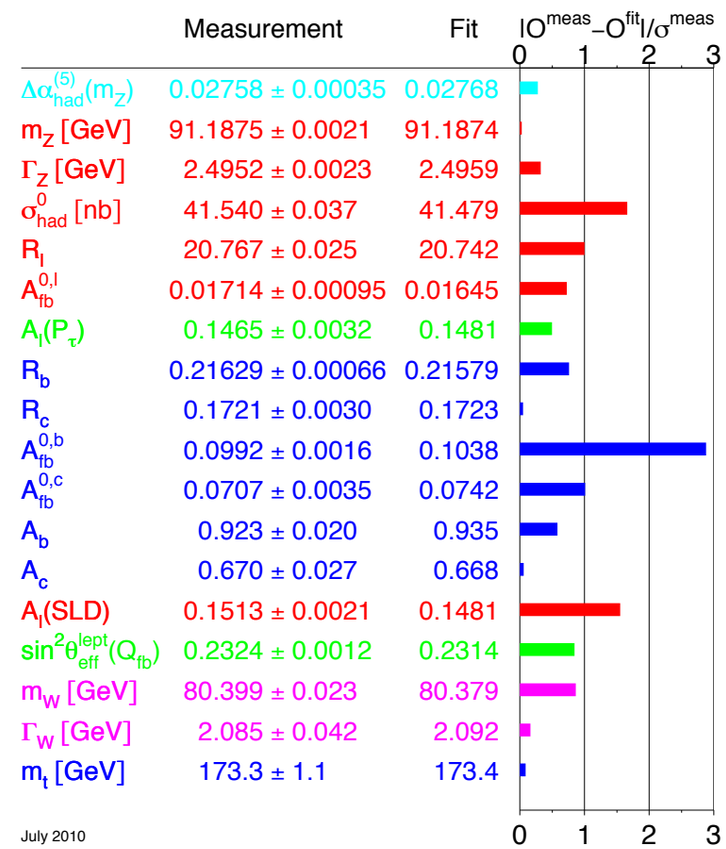
triviality bound

vacuum stability bound



- LEP2 performed precision measurements of electroweak phenomenology
- over-constrain the system of 18 free parameters by measurements and perform a global fit





→ Based on combination of many indirect measurements the Higgs boson should be very light: $70\ \mathrm{GeV} \leq m_h \leq 140\ \mathrm{GeV}$

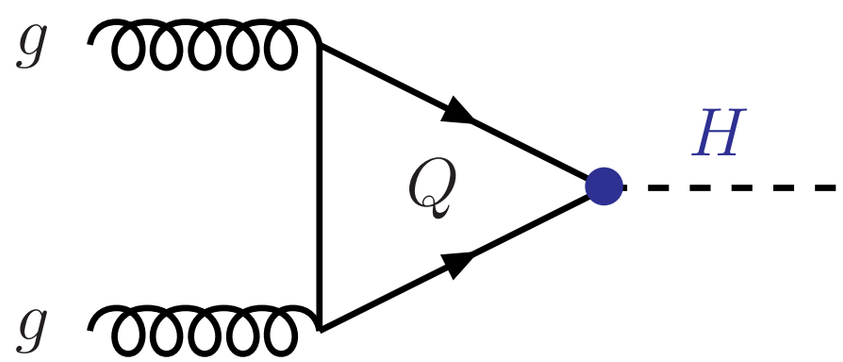
→ AND IT SEEMS TO BE!

Major production channels at hadron colliders

rule of thumb: couple the Higgs to something heavy

However, proton constituents are practically massless

gluon fusion



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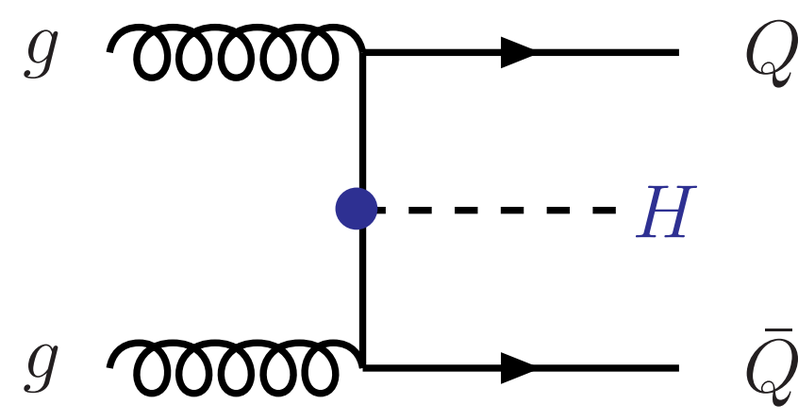
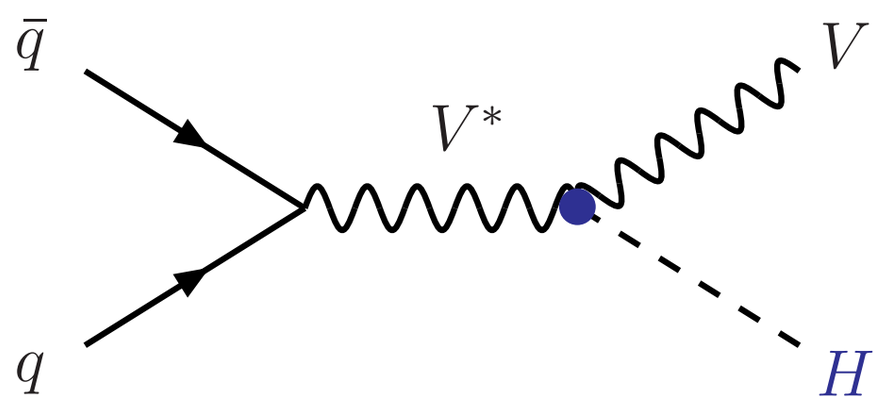
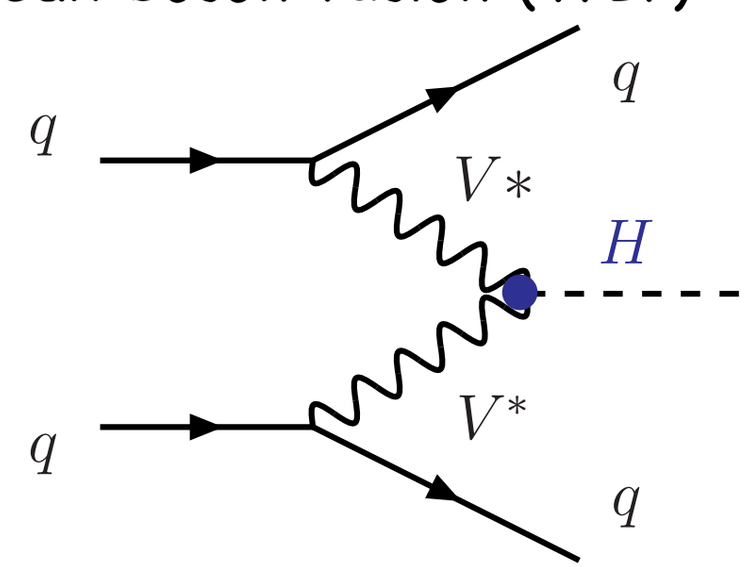


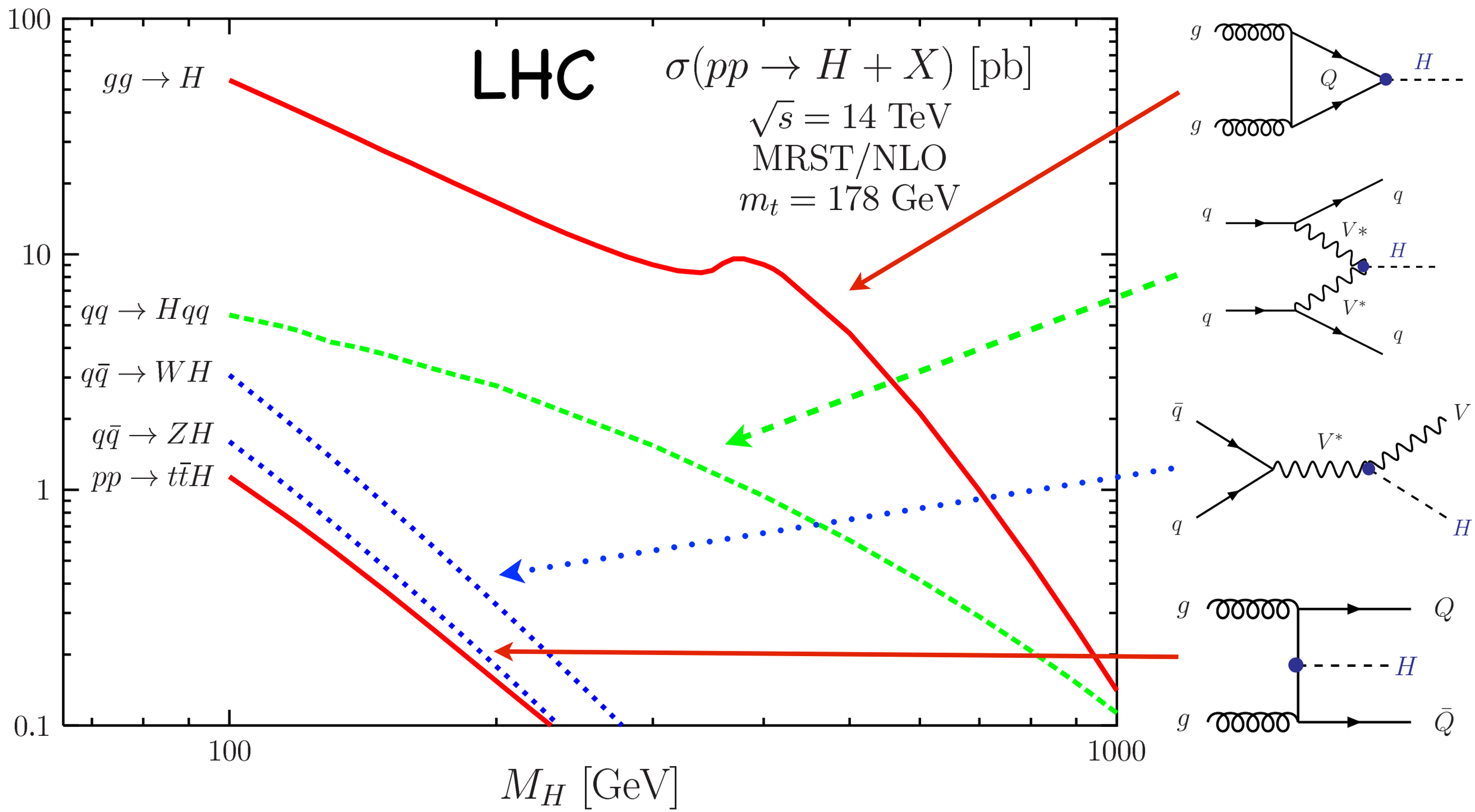
Higgs-strahlung



Weak boson fusion (WBF)



Production cross section at hadron colliders

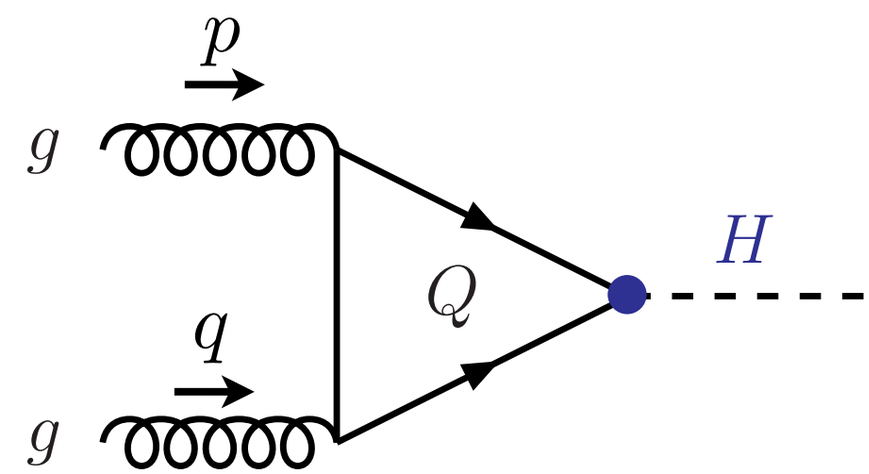


Gluon Fusion

Biggest production cross section, though:

- gluons massless
- loop suppressed
- heavy particles in loop $\longrightarrow \dfrac{\not{p} + m_f}{p^2 - m_f^2} \simeq \dfrac{1}{m_f}$

(naively for large masses)



However,

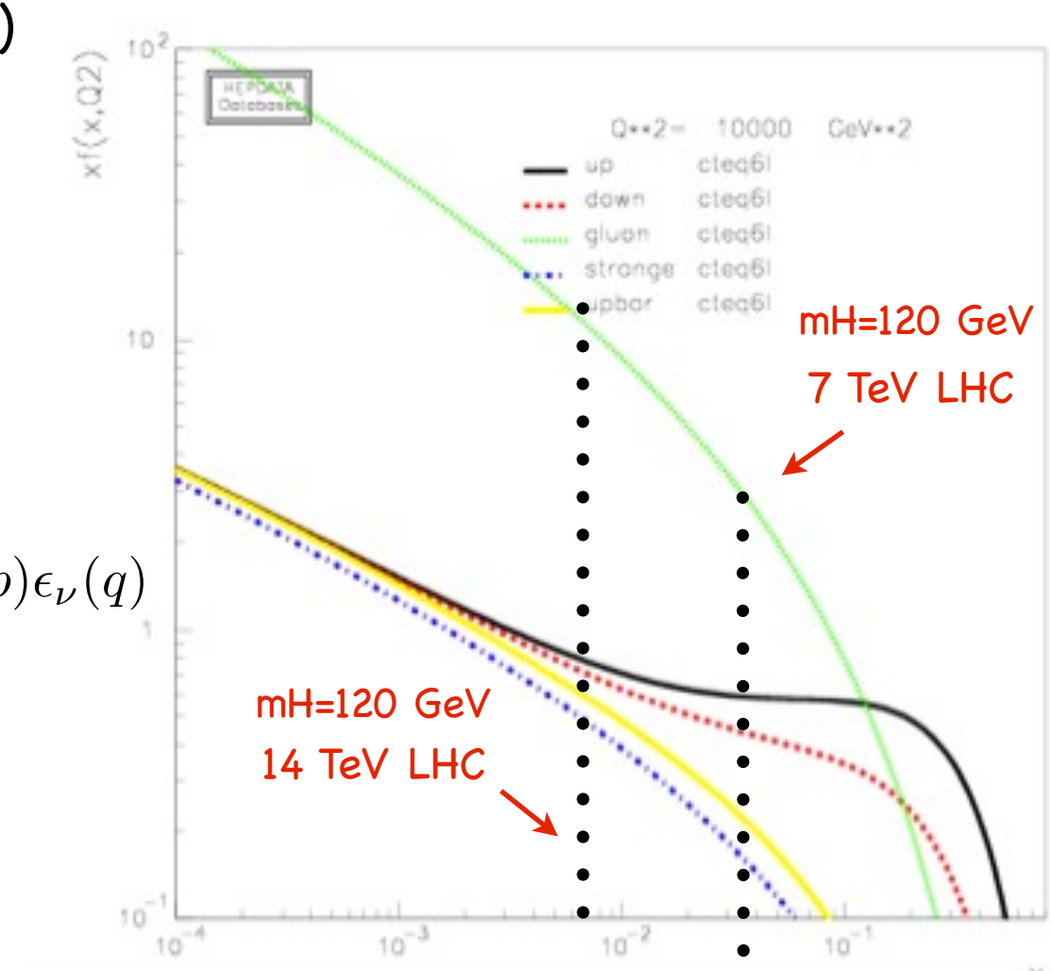
- $f\bar{f}H$ coupling proportional to m_f and loop momentum in propagator

$\longrightarrow$ non-decoupling amp. for $m_f \to \infty$

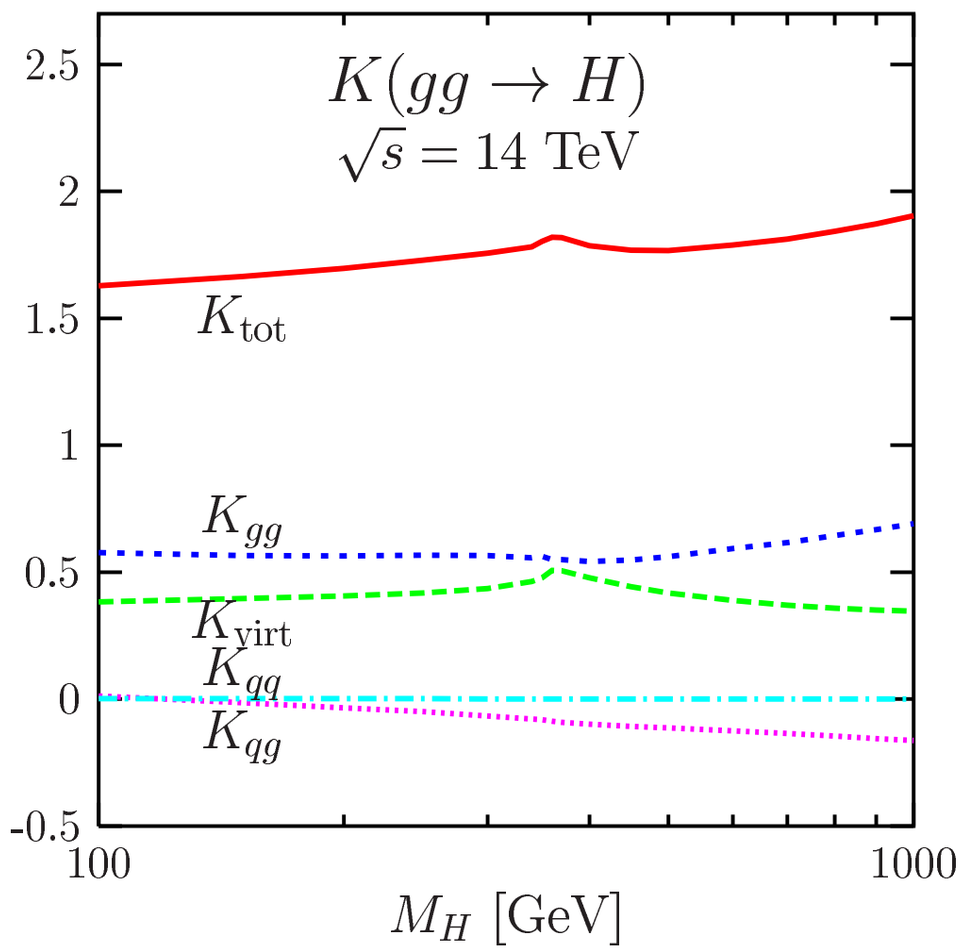
$$\mathcal{A}(gg \to H) \to_{m_f \gg m_H} -\frac{\alpha_S}{3\pi v}\delta^{ab}\left(g^{\mu\nu}\frac{m_H^2}{2} - p^\nu q^\mu\right)\epsilon_\mu(p)\epsilon_\nu(q)$$

- big gluon density at low x

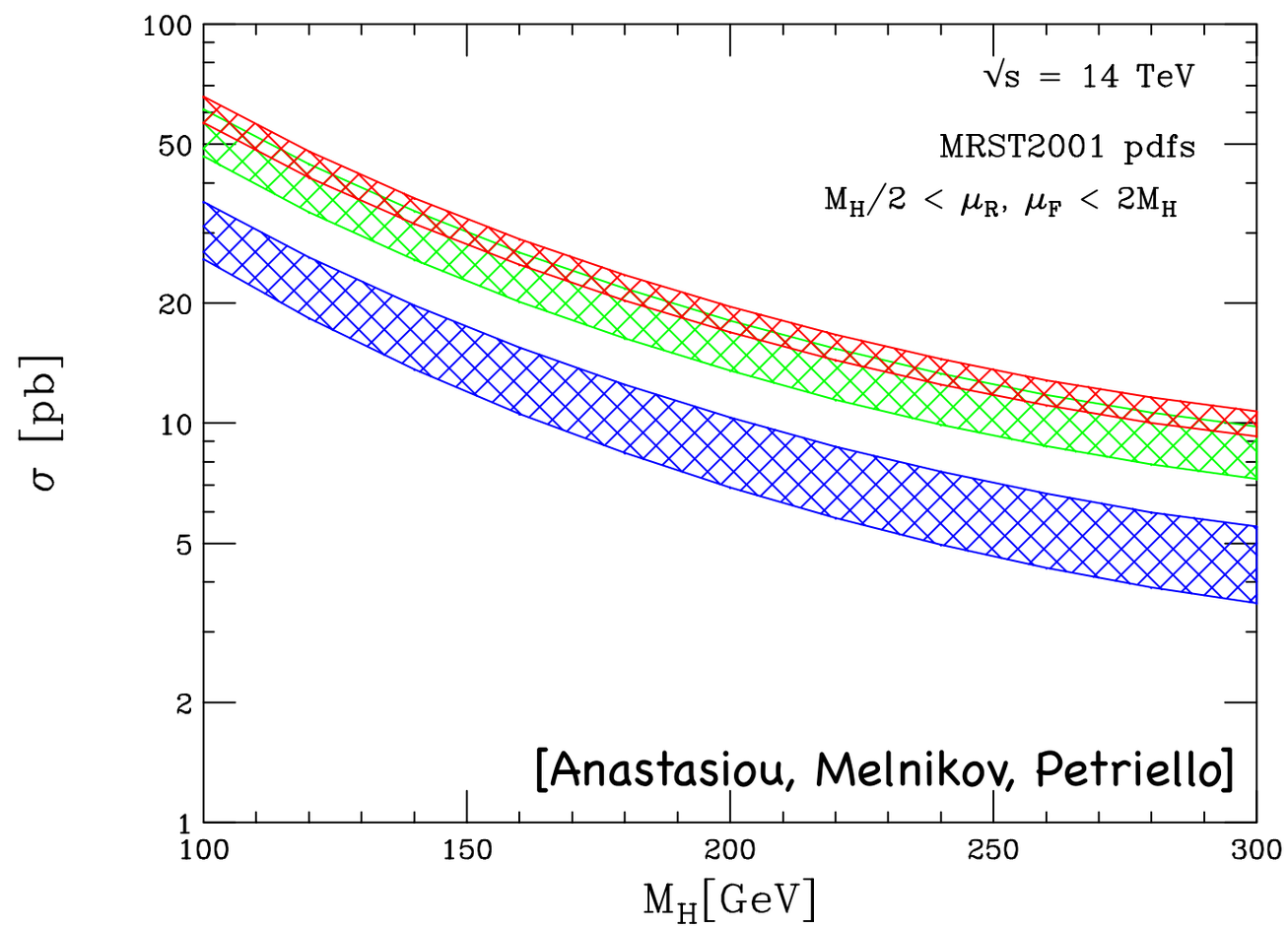
$$\hat{s} = x_1 x_2 s \longrightarrow x \simeq \sqrt{\hat{s}/s}$$



k-factor between LO and NLO



cross section for LO, NLO, NNLO

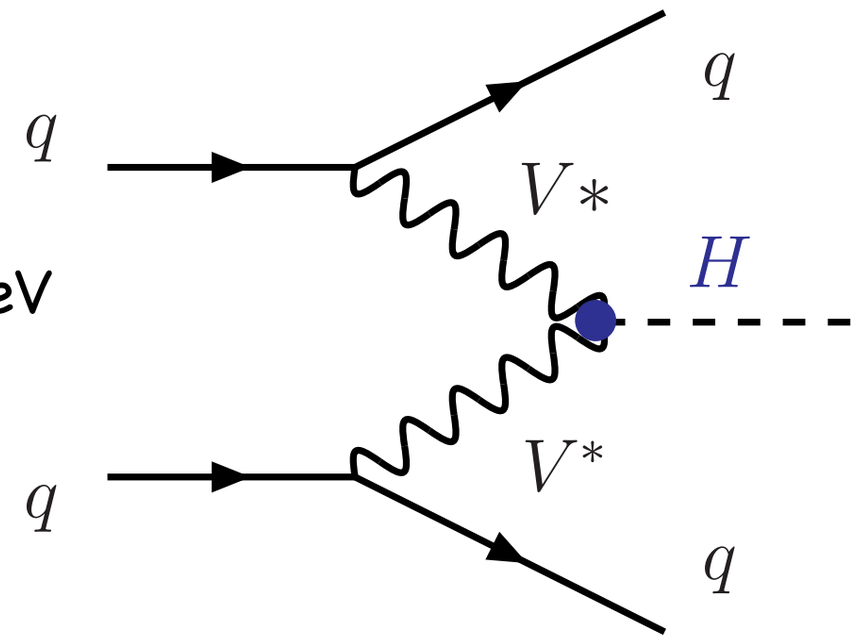


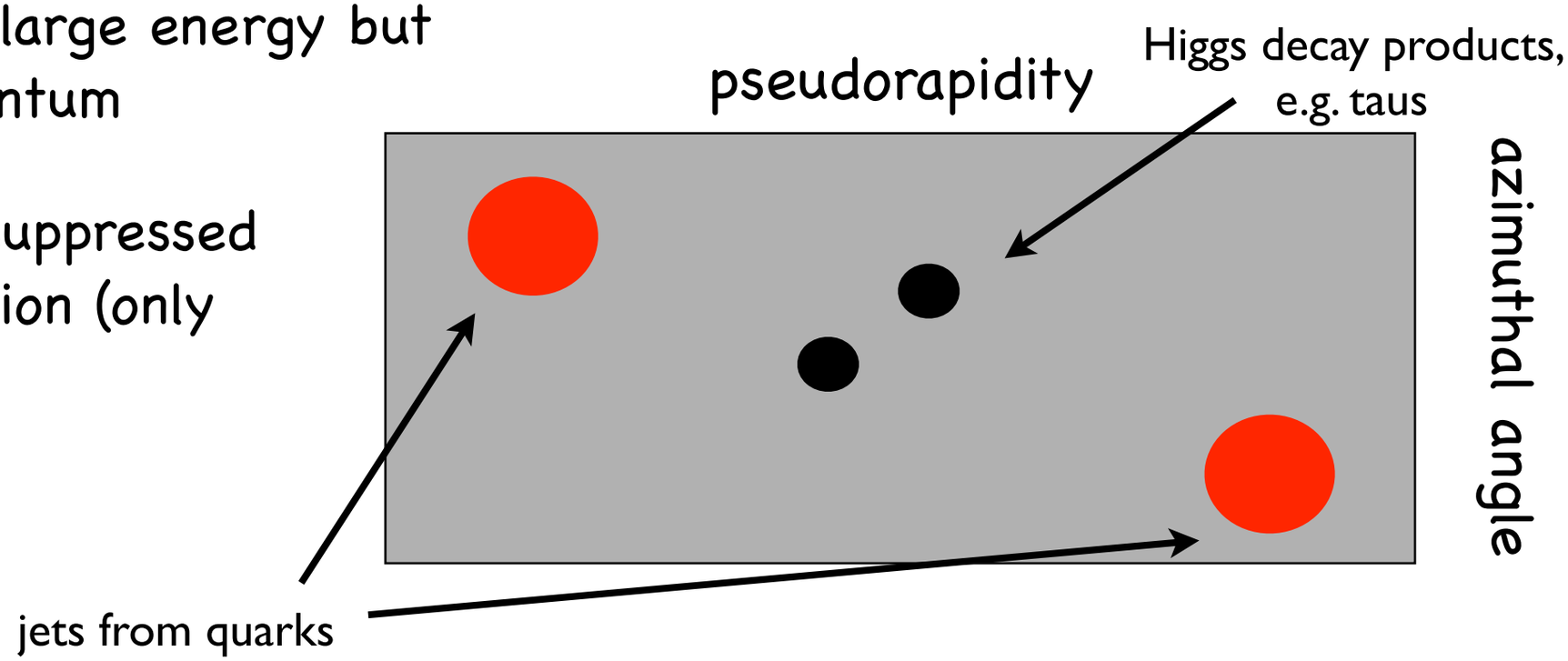
- NNLO calculation [Harlander, Kilgore (2001)]
- Large K-factor at NLO, between 1.5-2.0
- Slowly converging perturbative series
- Scale variation roughly 15% at NNLO

Weak boson fusion (WBF)

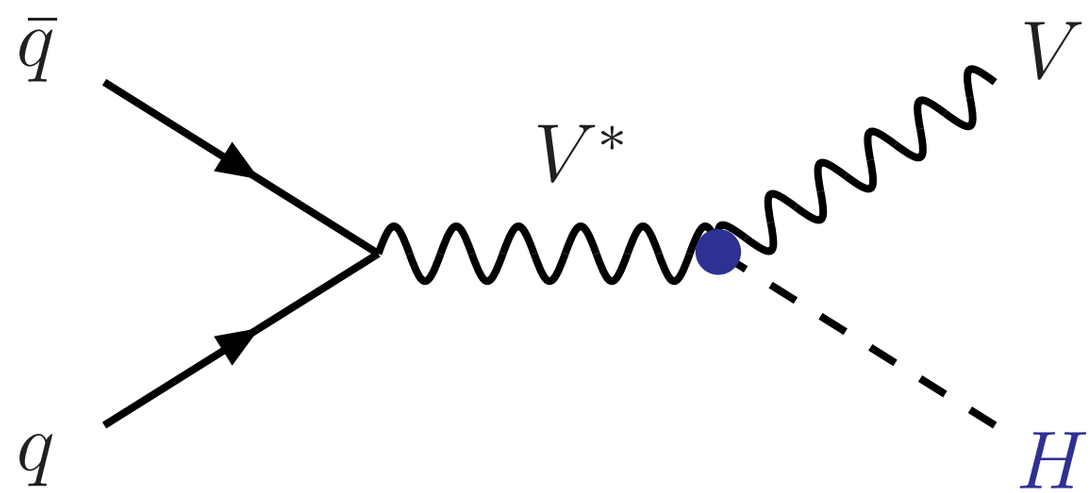
Special process:

- Most direct test of $W_L W_L \to W_L W_L$
- Because $\hat{\sigma} \sim \log \hat{s}/m_V^2$ more important at 14 TeV
- Important channel for heavy Higgs because longitudinal gauge boson component give rates $\sim m_H^3$
- scattered quarks have large energy but small transverse momentum
- forward tagging jets, suppressed radiation in central region (only QCD bremsstrahlung)
- NLO corrections small





Higgs-strahlung



- Best search channel for a light Higgs boson at Tevatron
- Due to PDFs relatively small at LHC
- However, final state gauge boson good for triggering and background suppression
- Probes Higgs coupling to gauge boson

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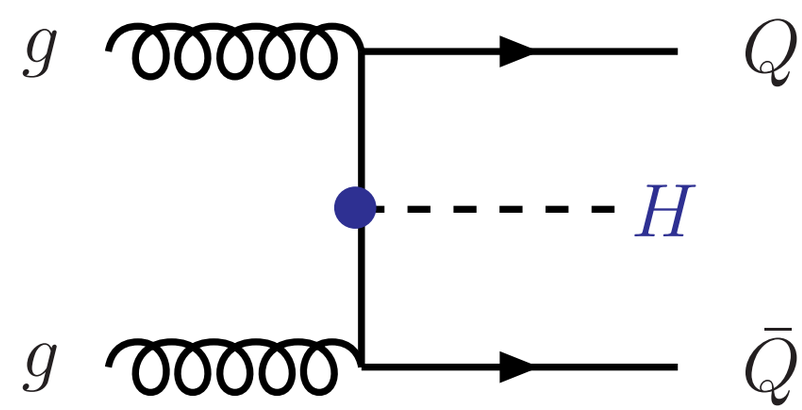
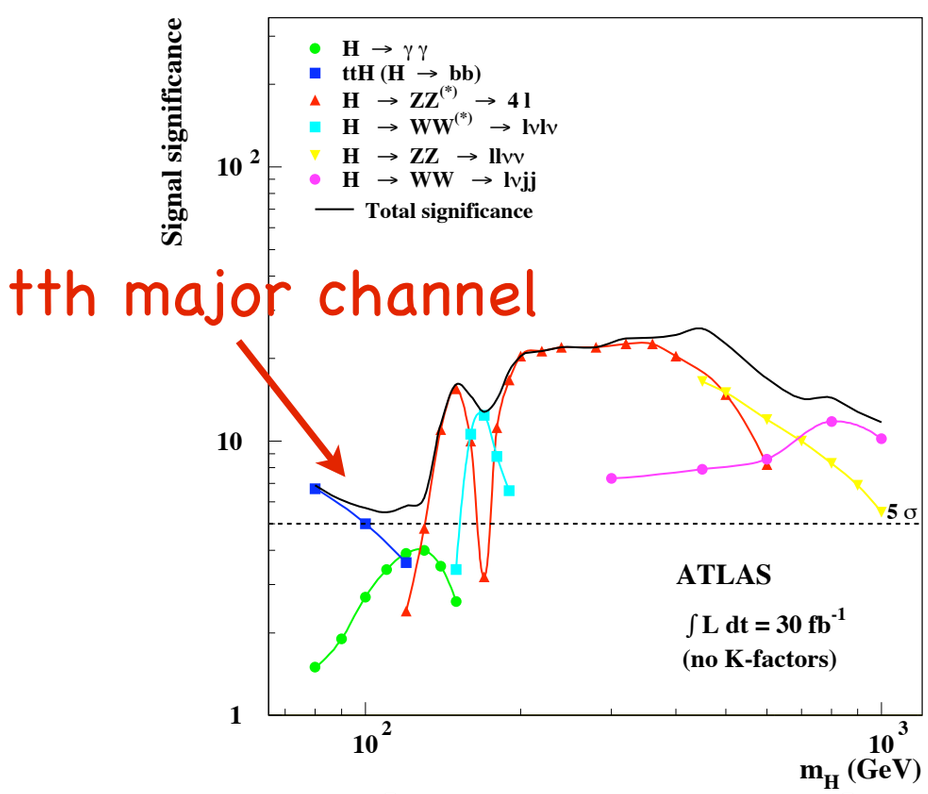
- Only sizable cross section for light Higgs (mH < 130 GeV)
- Light Higgs decays dominantly to $b\bar{b}$
- Only process to measure the Higgs-top coupling directly



High expectations:



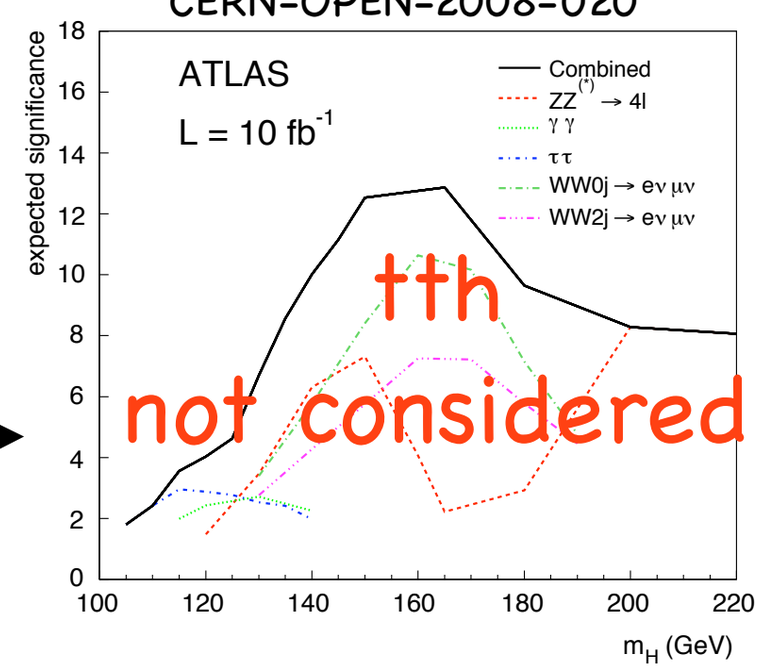
[ATLAS TDR 1999]

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



Three classes of Higgs boson decays:

1. Higgs decay into massless gauge bosons

2. Higgs decay into massive gauge bosons

3. Higgs decay into massive fermions

Partial decay width of $a \to b_1 + b_2$

$$\Gamma(a \to b_1 + b_2) = \frac{(2\pi)^4}{2m_a} \int \frac{d^3\vec{q}_1}{(2\pi)^3 2E_1} \frac{d^3\vec{q}_2}{(2\pi)^3 2E_2} \delta^4(p_a - p_1 - p_2) \overline{|\mathcal{M}|^2}$$

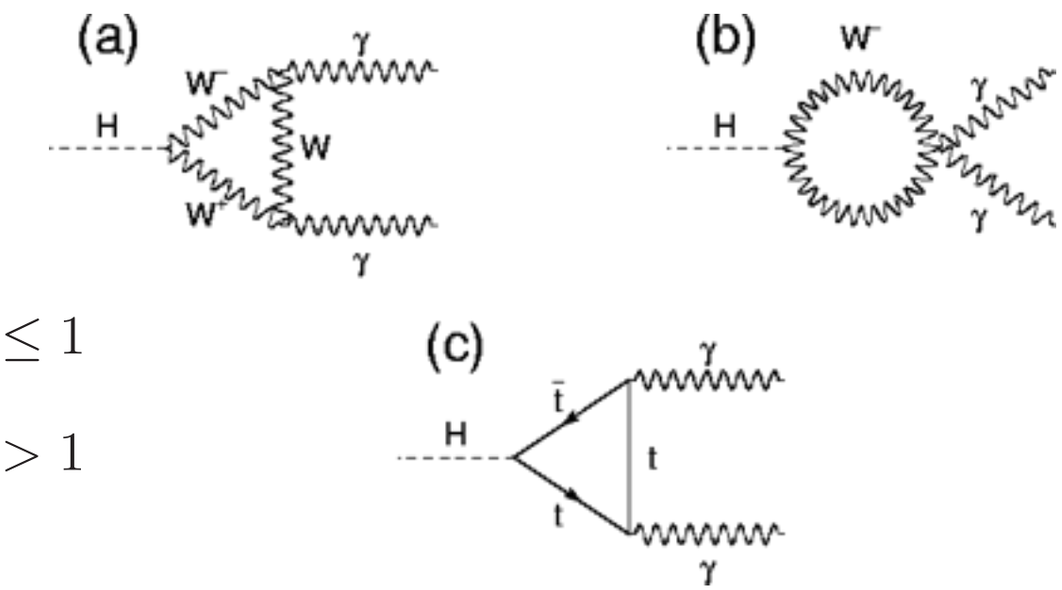
in rest frame of a can be written as $\Gamma(a \to b_1 + b_2) = \frac{|\vec{p_1}|}{8\pi m_a^2} \overline{|\mathcal{M}|^2}$

→ the width only depends on the couplings and the masses

1. Higgs decay into massless gauge bosons $H \to \gamma\gamma/Z\gamma/gg$

$$\Gamma(H \to \gamma\gamma) = \frac{G_F \alpha_W^2 m_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 A_{1/2}^H(\tau_f) + A_1^H(\tau_W) \right|^2 \qquad \tau = \frac{m_H^2}{4m_i^2}$$

top: $A_{1/2}^H(\tau) \;=\; 2[\tau + (\tau-1)f(\tau)]\,\tau^{-2}$



W: $A_1^H(\tau) \;=\; -[2\tau^2 + 3\tau + 3(2\tau-1)f(\tau)]\,\tau^{-2}$

with $f(\tau) = \begin{cases} \arcsin^2\sqrt{\tau} & \tau \le 1 \\ -\frac{1}{4}\left[\log\frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \tau > 1 \end{cases}$

- $\Gamma(H \to \gamma\gamma) \sim m_H^3$
- Effectively only top and W contribute (W dominates)
- Destructive interference between W and top
- Below WW and ff threshold W loop always dominant; falling from $A_1^H = -7$ for small τ to $A_1^H \to -2$ for large τ
- fermionic contribution grows from small τ to threshold, then falls again

2. Higgs decay into massive gauge bosons

$$\Gamma(H \to VV) = \frac{g^2 m_H^3}{128\ \pi\ m_W^2} \delta_V \sqrt{1-x}\ (1 - x + \frac{3}{4}x^2)$$

with $\quad x = \frac{4m_V^2}{m_H^2}, \quad \delta_W = 2, \quad \delta_Z = 1$

- $\Gamma(H \to VV) \sim m_H^3$ follows from the longitudinal polarized vector component, example W:

$$\overline{|\mathcal{M}|^2} = g_2^2 m_W^2 \sum_{\text{pol.}} \epsilon_\mu(p_1)\epsilon_{\nu *}(p_1)\epsilon^\mu(p_2)\epsilon^{\nu *}(p_2)$$

Higgs rest frame:

$$p_1 = \left(\sqrt{m_H^2/4 + m_W^2}, 0, 0, m_H/2\right)$$

$$p_2 = \left(\sqrt{m_H^2/4 + m_W^2}, 0, 0, -m_H/2\right)$$

$$= g_2^2 m_W^2 \left(-g_{\mu\nu} + p_{1,\mu}p_{1,\nu}/m_W^2\right)\left(-g^{\mu\nu} + p_2^\mu p_2^\nu/m_W^2\right)$$

$$= g_2^2 m_W^2 \left[2 + \left(\frac{m_H^2}{2} + m_W^2\right)^2 / m_W^4\right] \sim m_H^4$$

- Ratio between transverse and longitudinal polarization is

$$\frac{\Gamma(H \to V_T V_T)}{\Gamma(H \to V_L V_L)} = \frac{x^2/2}{(1 - x_V/2)^2} \to_{m_H \gg m_V} 0$$

$\longrightarrow$ direct test of Higgs mechanism

3. Higgs decay into massive fermions

The partial decay width is

$$\Gamma_f(H \to f\bar{f}) = \frac{G_F N_c}{4\sqrt{2}\pi} m_H m_f^2 \beta_f^3 \qquad \text{with} \qquad \beta_f = (1 - 4m_f^2/m_H^2)$$

$\longrightarrow$ strong phase space suppression at threshold $\beta_f^3 \to 0$

Total width of the Higgs boson

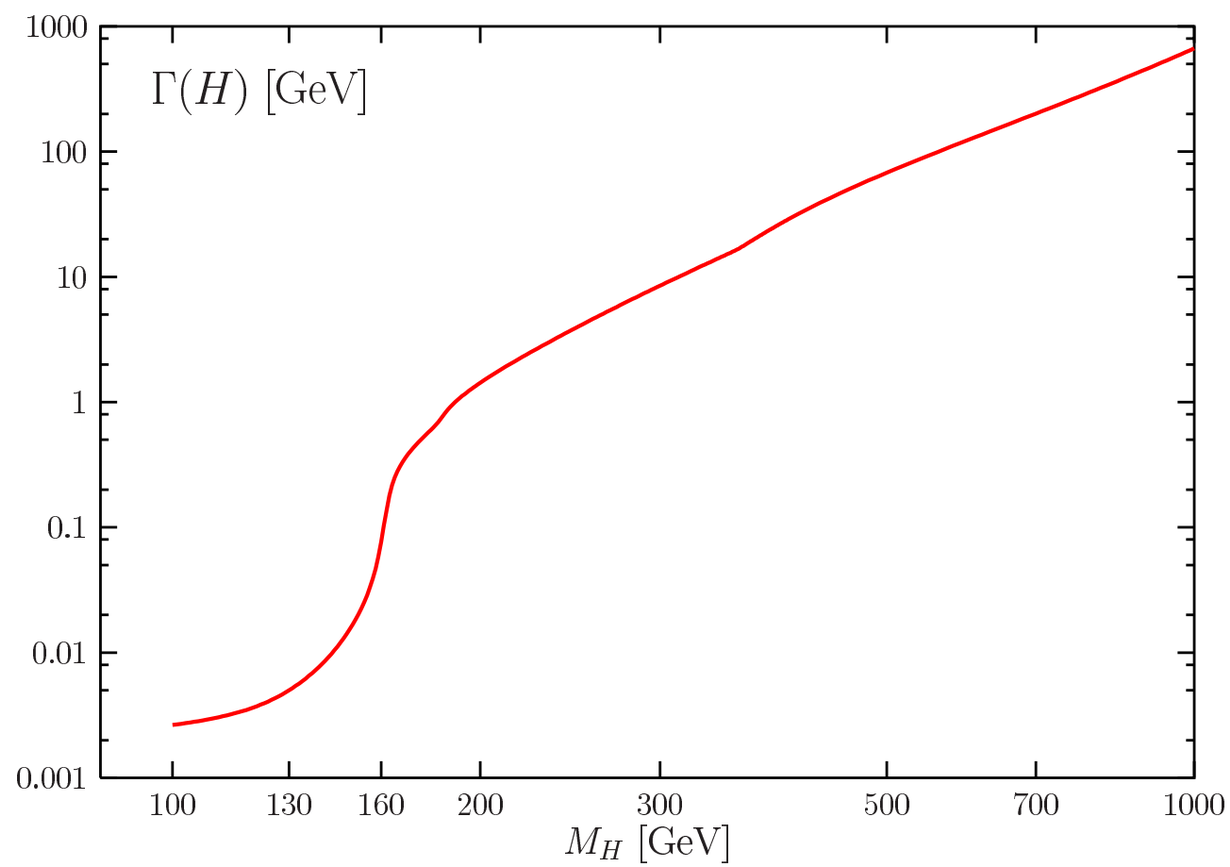
Higgs very narrow object in low mass region

Higgs obese for large mass

From $m_H \gtrsim 2m_W$

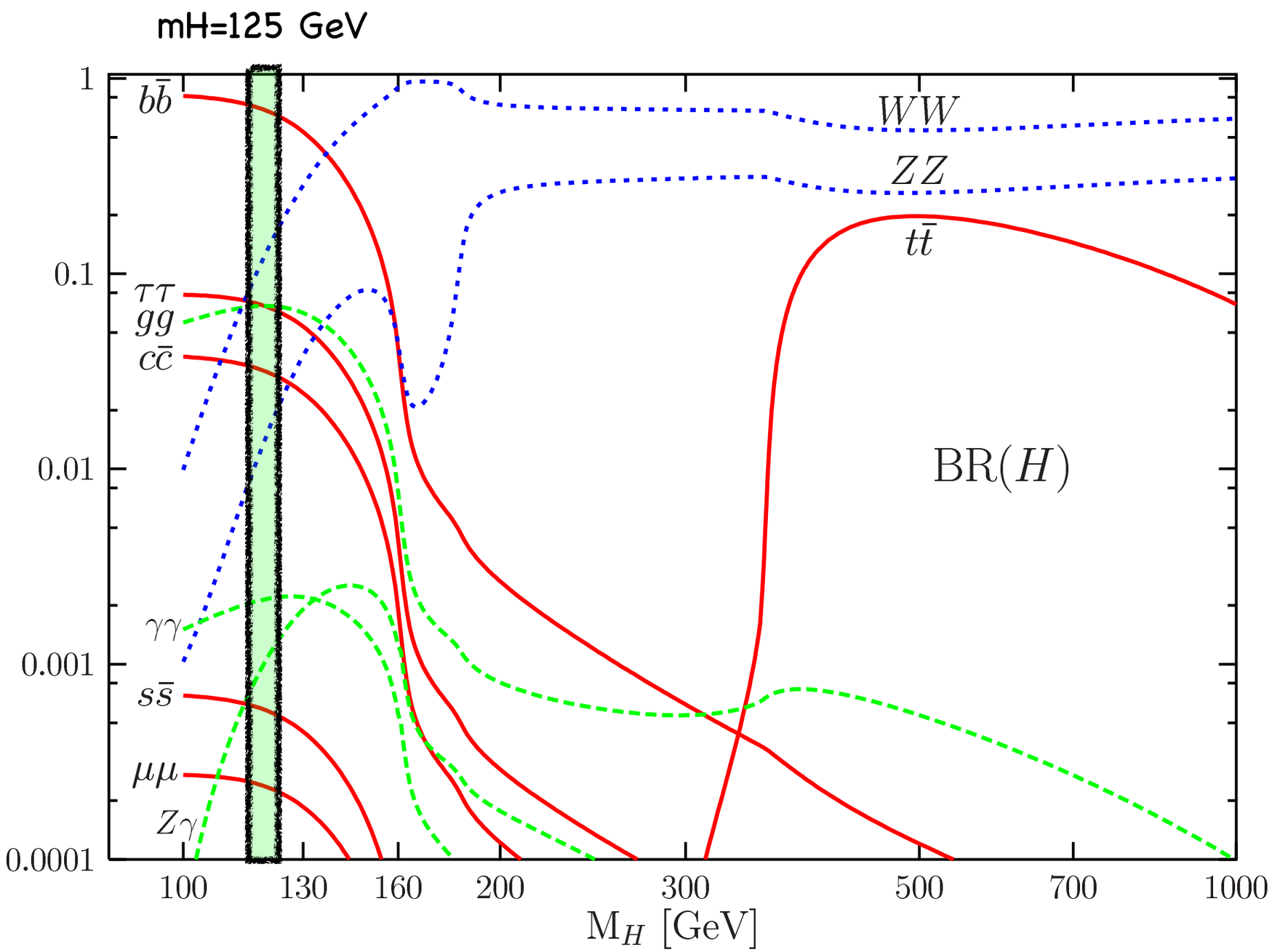
$\Gamma(H)$ grows like m_H^3

$\Gamma(m_H = 125 \text{ GeV}) = 4.07 \text{ MeV}$

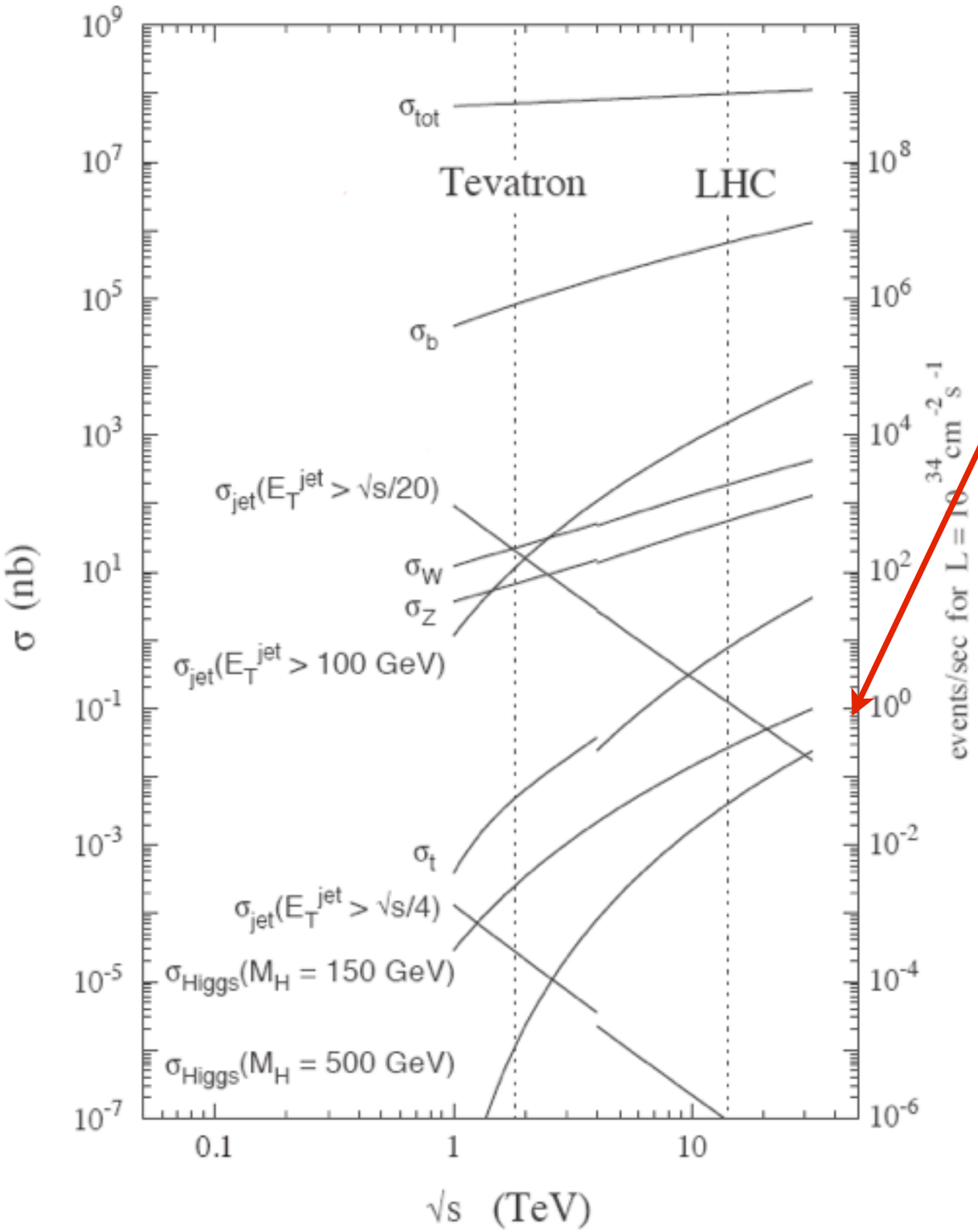


Major decay channels

rule of thumb: couple the Higgs to something heavy but lighter than mH/2



How about backgrounds?



- Higgs production comparably rare at LHC
- Need huge background noise reduction

→ stiff trigger conditions

→ focus on rare objects (leptons)

→ precise reconstruction of objects

→ smart choice of observables

Understanding of the Yellow and Green bands :

from Eilam Gross

- Upper limit on the Standard Model (SM) Higgs Boson production cross section divided by the Standard Model expectation as a function of m_{Higgs}

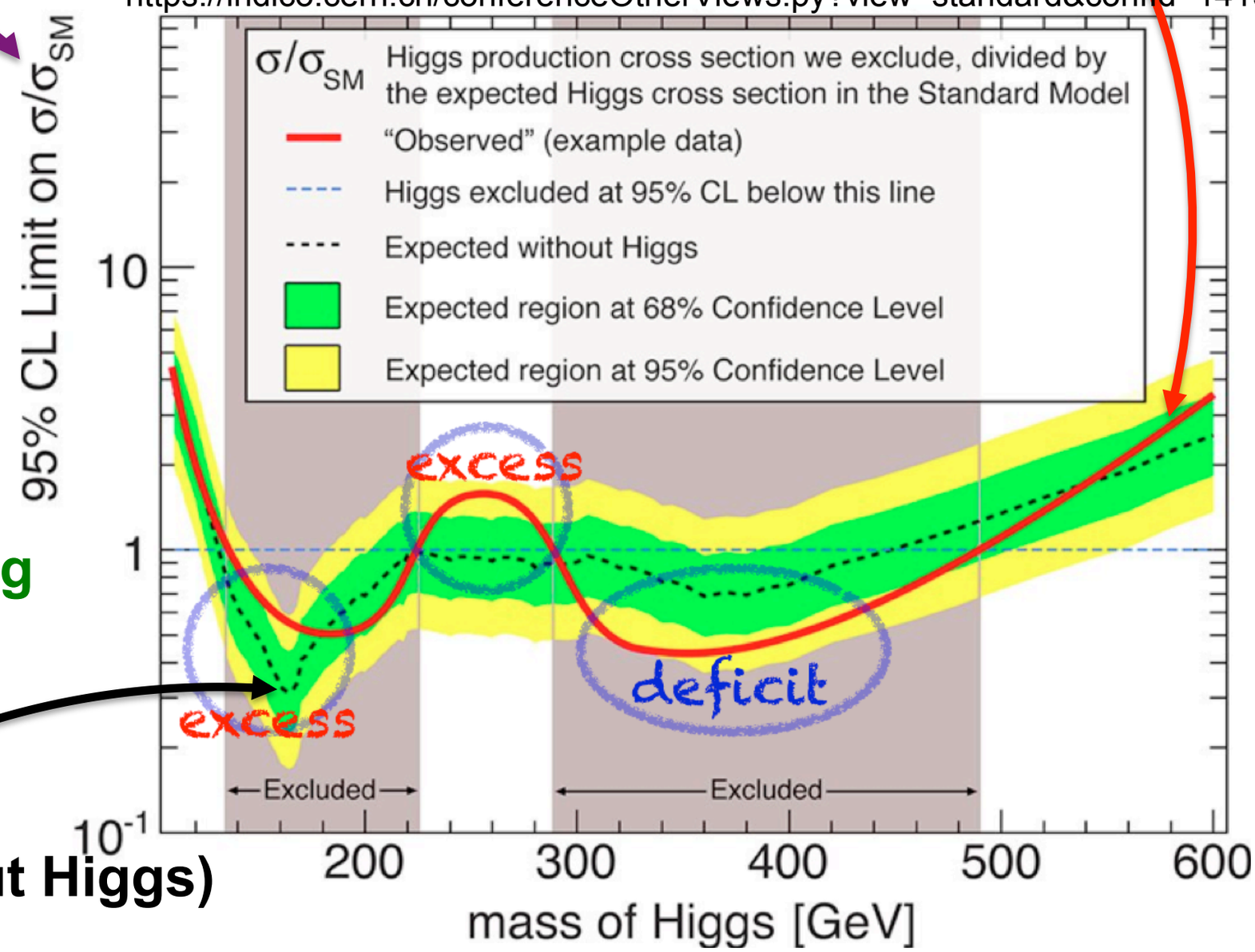
observed limit (data)

Eilam Gross
https://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=14198

$\mu=\sigma/\sigma^{SM}$

this is a 95% limit using the CLs method

expected limit (without Higgs)



I. Discovery of the Higgs(like) boson

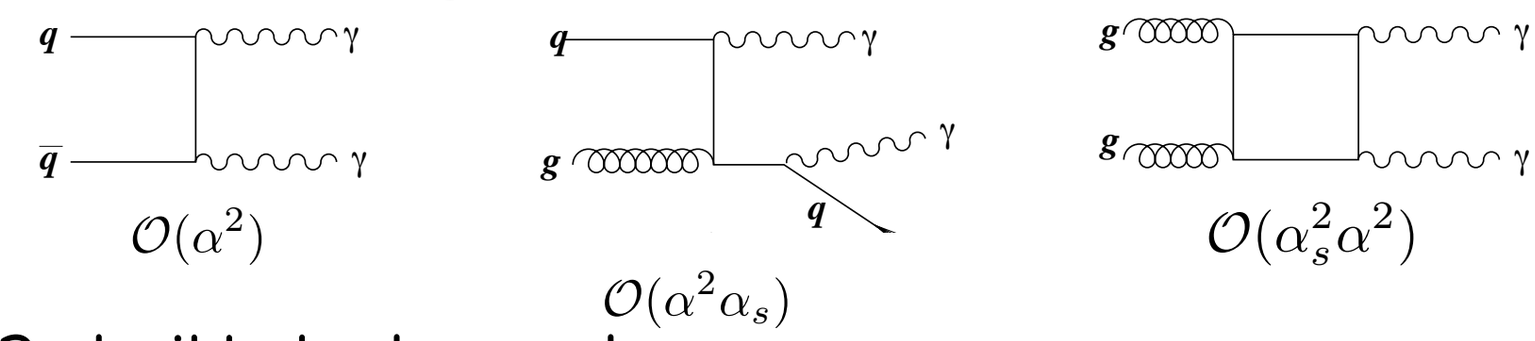
A. $pp \to H + X \to \gamma\gamma + X$

- Loop induced in production and decay
- Mainly sensitive to Htt and HWW couplings
- Excludes the resonance to be Spin-1 (Landau-Yang Theorem)

signal at 7 Tev: $\sigma \times BR(m_H = 125\ \mathrm{GeV}) \simeq 0.04\ \mathrm{pb}$

Backgrounds problematic → Channel for experimentalists (data driven techniques)

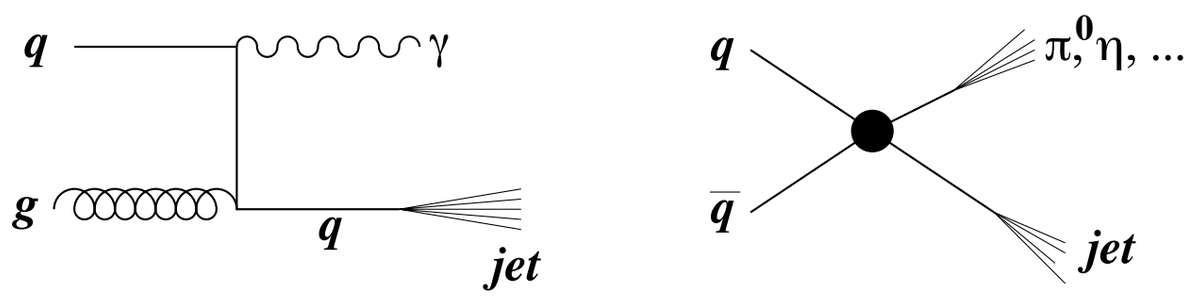
Irreducible background



qq, qg $\sigma \simeq 21\ \mathrm{pb}$

gg $\sigma \simeq 8\ \mathrm{pb}$

Reducible background



$\gamma - \mathrm{jet}$ $\sigma \simeq 1.8 \times 10^5\ \mathrm{pb}$

$\mathrm{jet} - \mathrm{jet}$ $\sigma \simeq 4.8 \times 10^8\ \mathrm{pb}$

→ Need huge rejection

Event selection cuts:

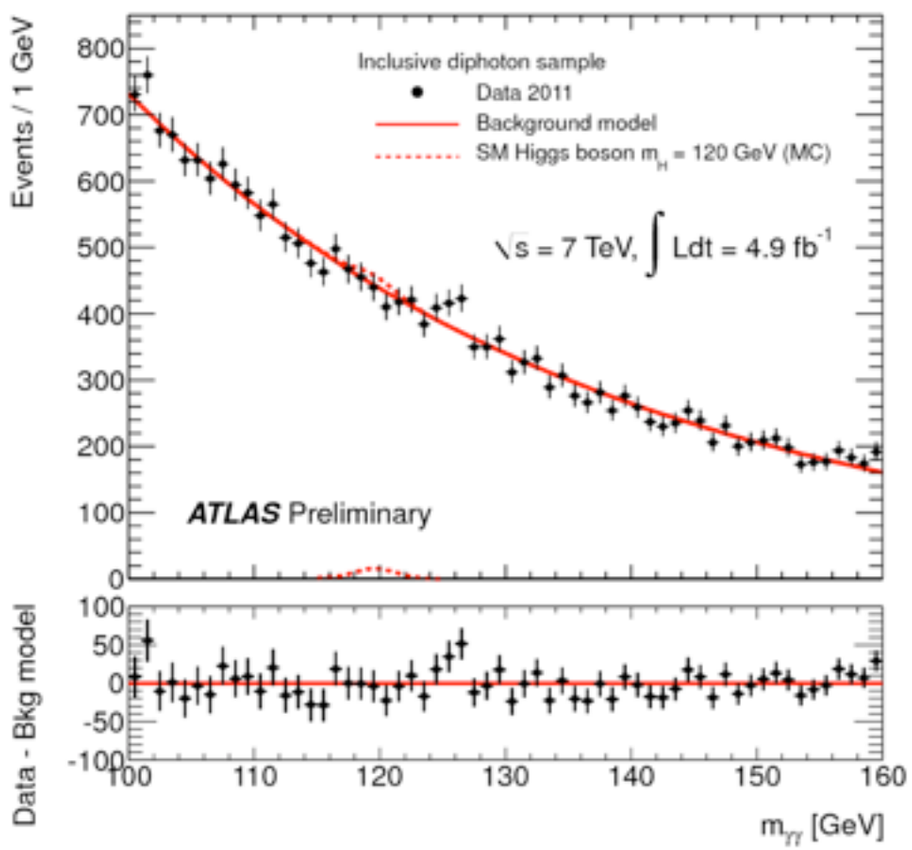
trigger level: For 7 TeV two ECAL cluster with $E_T > 20$ GeV

For 8 TeV two ECAL cluster with $E_{T,1} > 35$ GeV and $E_{T,2} > 25$ GeV

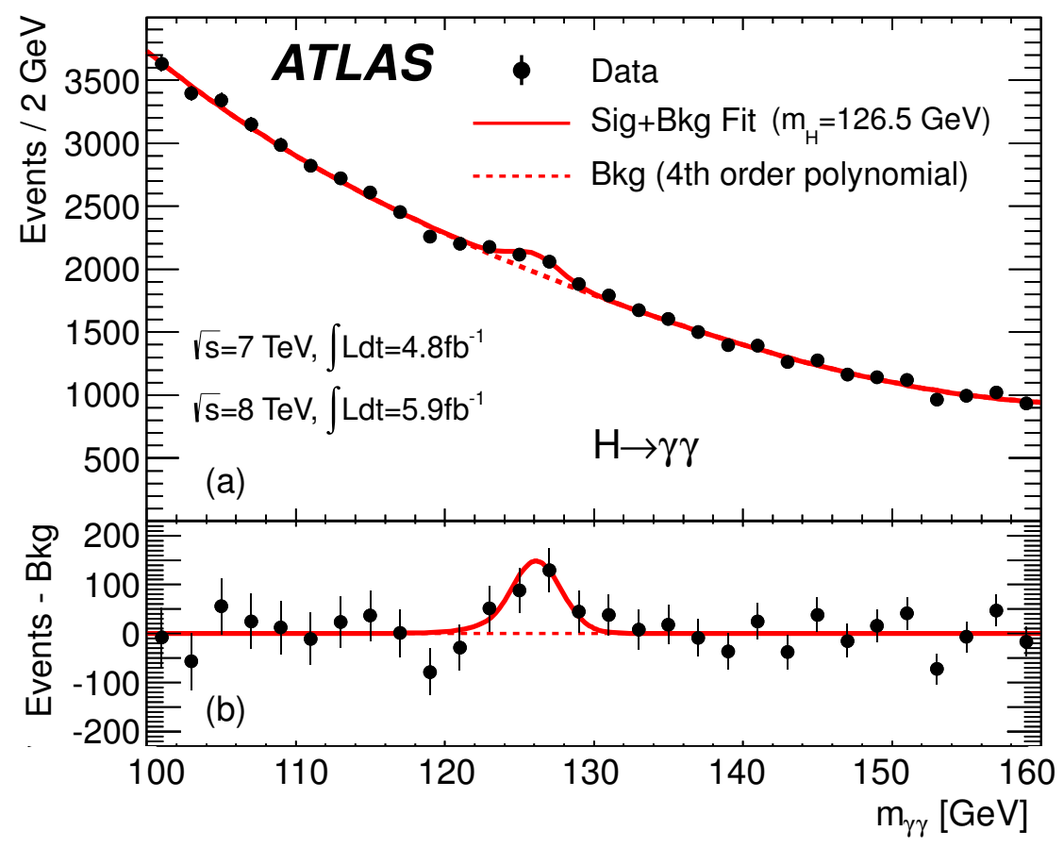
Reconstructed photon candidates have to be isolated in a cone $\Delta R < 0.4$

Reconstructed isolated photons are required to have $p_{T,1} > 40$ GeV and $p_{T,2} > 30$ GeV

7 TeV data:



7 + 8 TeV data:



⟶ 4.5 standard deviations at 126.5 GeV

B. $pp \to H + X \to ZZ^* + X \to l^+l^-l'^+l'^- + X$

- Probes HZZ coupling in decay. Direct test of EWSB.
- Very clean channel
- Allows precise reconstruction of resonance's mass

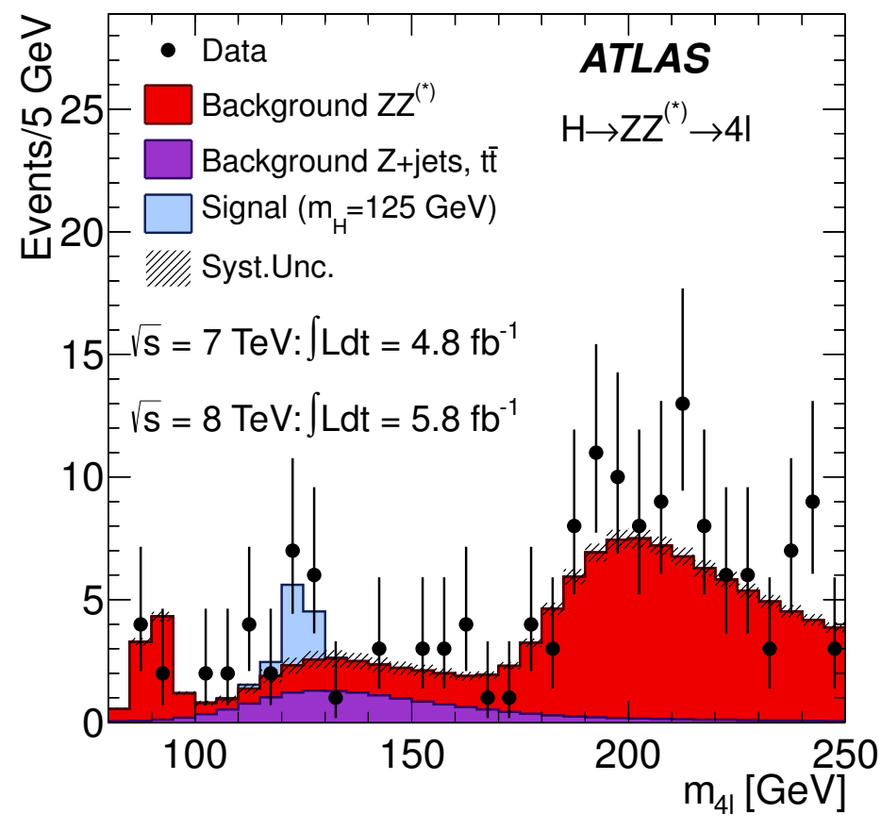
Event selection:

- Single- or dilepton trigger
- All possible combinations with same-flavor opposite-charge lepton paris are formed
- Staggered cuts:

$$p_{T,e\ (\mu)} > 7\ (6)\ \text{GeV} \qquad p_{T,l_1} > 20\ \text{GeV}$$
$$p_{T,l_2} > 15\ \text{GeV} \qquad p_{T,l_3} > 10\ \text{GeV}$$

- Leptons have to be separated, isolated and pairwise in broad mass windows

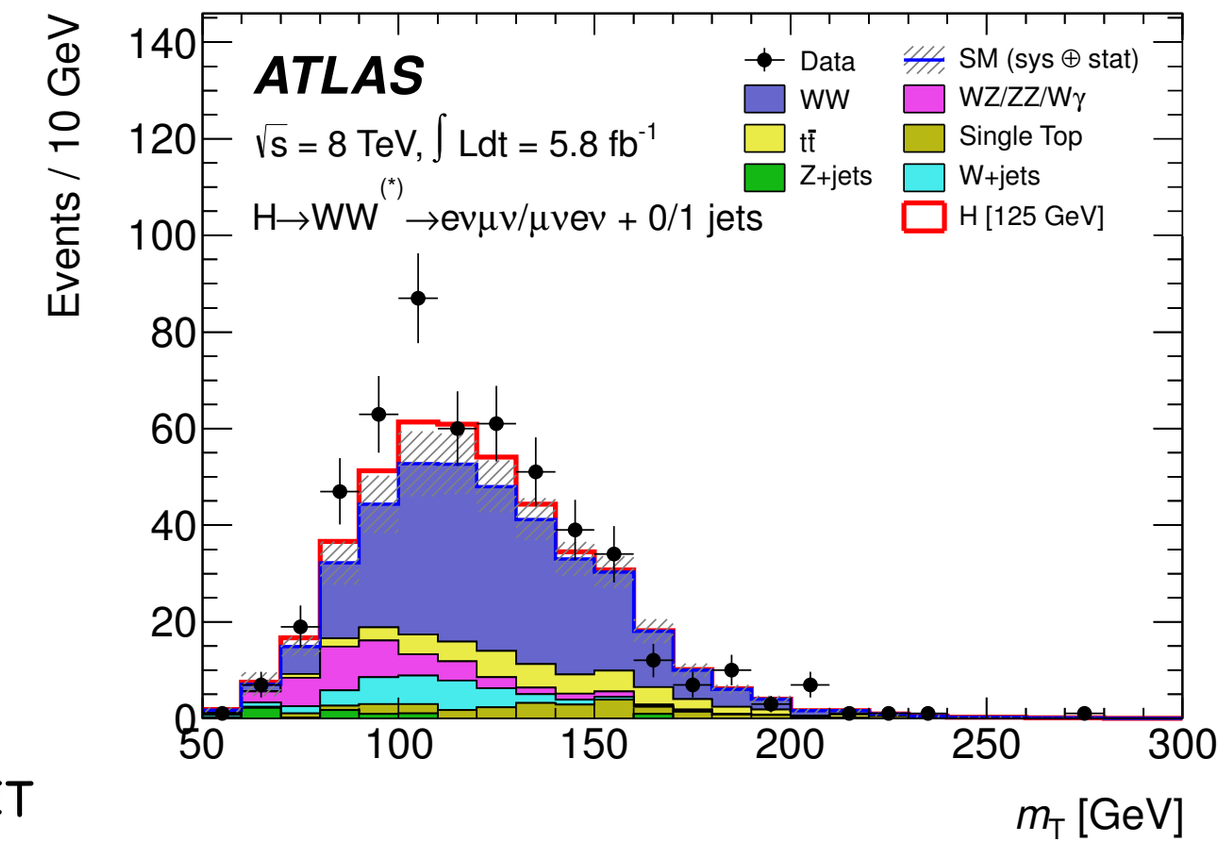
$\longrightarrow$ 3.4 standard deviations at 125 GeV



	Signal	$ZZ^{(*)}$	Z + jets, $t\bar{t}$	Observed
4μ	2.09±0.30	1.12±0.05	0.13±0.04	6
$2e2\mu/2\mu2e$	2.29± 0.33	0.80±0.05	1.27±0.19	5
$4e$	0.90±0.14	0.44±0.04	1.09±0.20	2

C. $pp \to H + X \to WW^* + X \to l^+ \bar{\nu} l'^- \nu' + X$

- Probes HWW coupling in decay
- Direct test of EWSB, particularly in combination with HZZ
- Backgrounds difficult to simulate (MC input very important)



Event selection

- Exactly two oppositely charged leptons with different flavor and

  $p_{T,l_1} > 25$ GeV $\quad p_{T,l_2} > 15$ GeV

- $E_{T,rel}^{\rm miss} = E_T^{\rm miss} \sin \Delta\phi_{\rm miss} > 25$ GeV

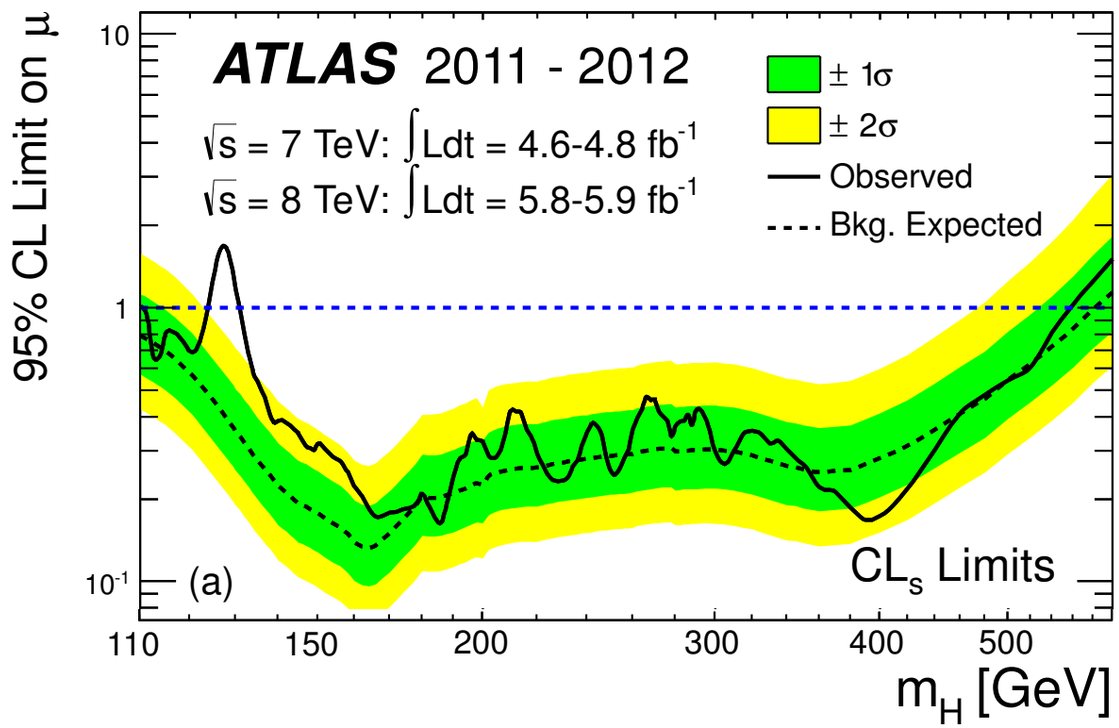
  with $\Delta\phi_{\rm min} = \min(\Delta\phi, \pi/2)$

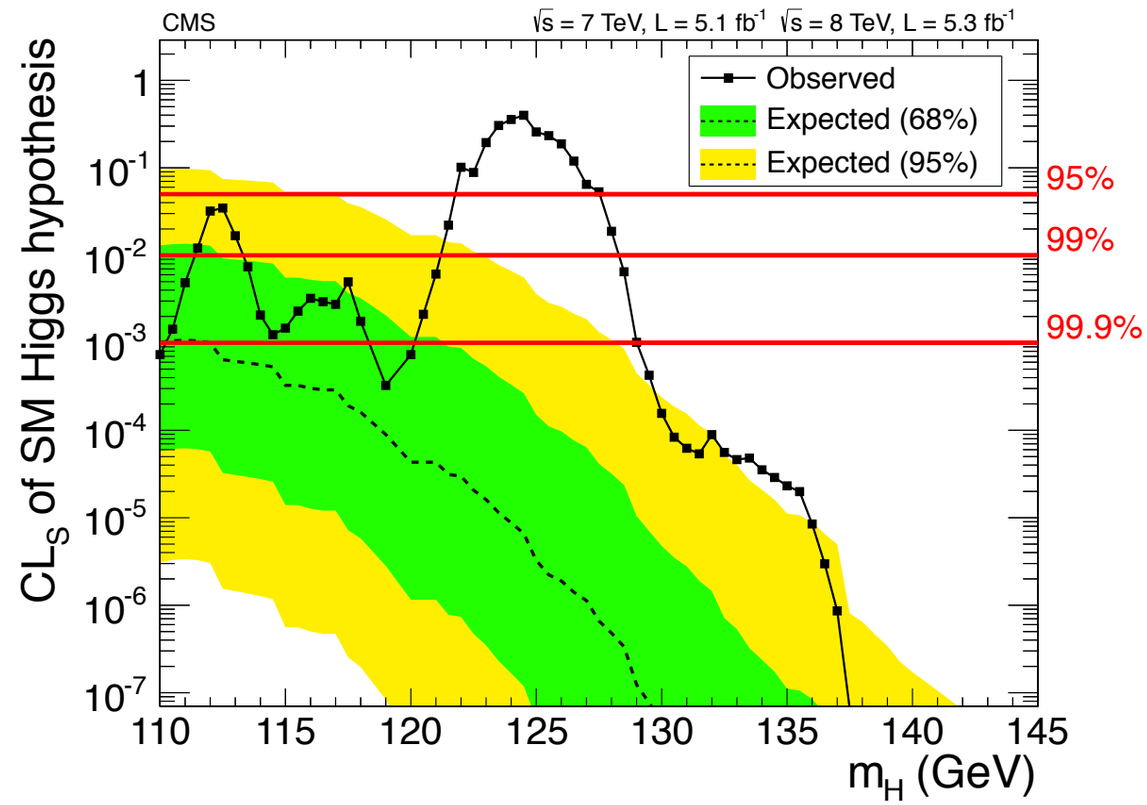
min azimuthal between jet or leptons and MET

- Require $|\Delta\phi_{\ell\ell}| < 1.8$ and $m_{ll} < 50$ GeV
- Construct transverse mass $m_{\rm T} = \sqrt{(E_{\rm T}^{\ell\ell} + E_{\rm T}^{\rm miss})^2 - |\mathbf{p}_{\rm T}^{\ell\ell} + \mathbf{E}_{\rm T}^{\rm miss}|^2}$, $E_{\rm T}^{\ell\ell} = \sqrt{|\mathbf{p}_{\rm T}^{\ell\ell}|^2 + m_{\ell\ell}^2}$.

$\longrightarrow$ 2.8 standard deviations at 125 GeV

Combined results





- ATLAS has a local significance of 5.9 sigma and a global significance in 110-600 GeV of 5.3 sigma

  → Discovery

- CMS has local significance of 5.8 sigma and a global significance of 4.6 sigma

  → Discovery

II. Higgs couplings measurements

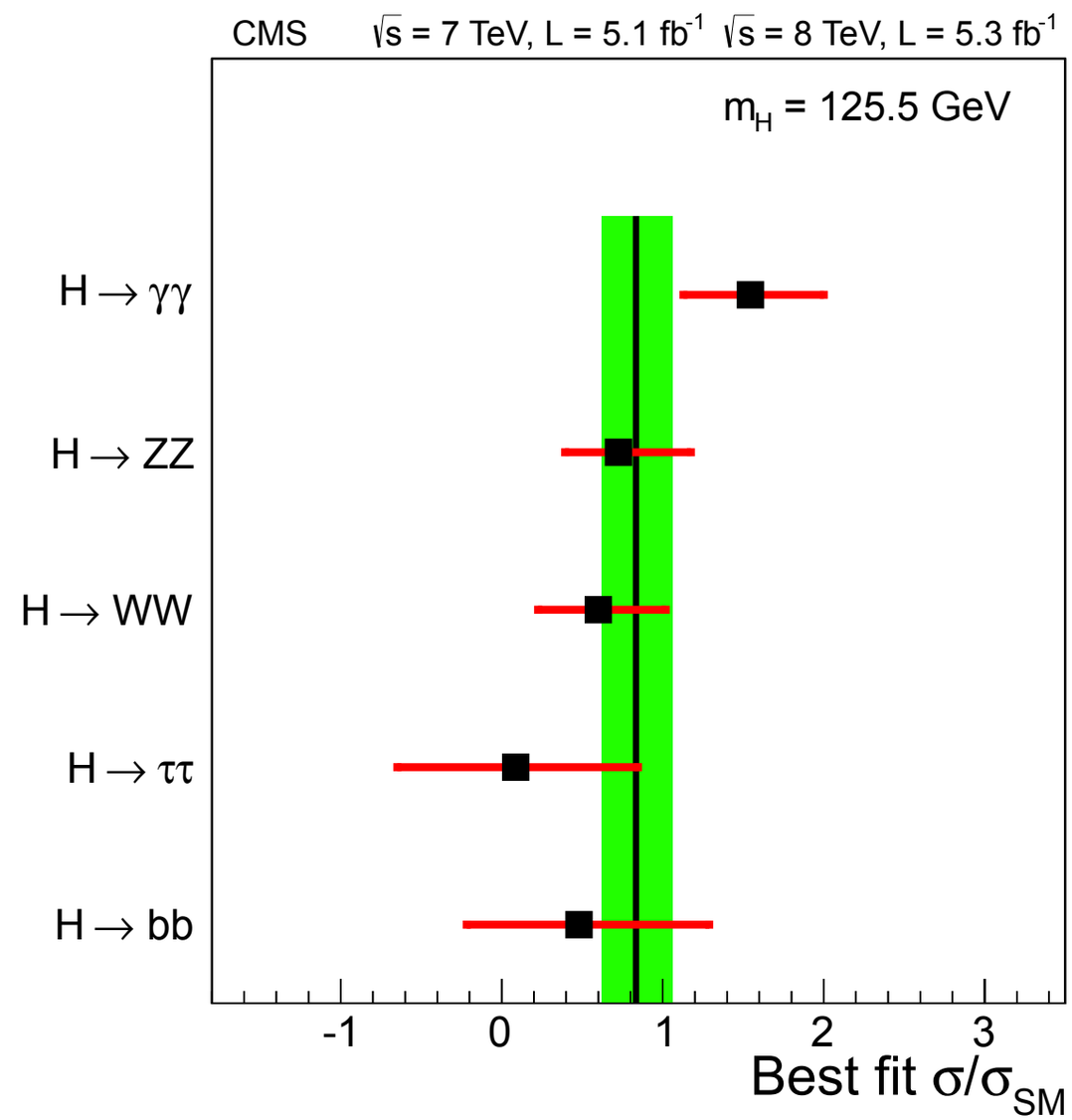
After discovery the Higgs couplings have to be measured:

Present status:

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

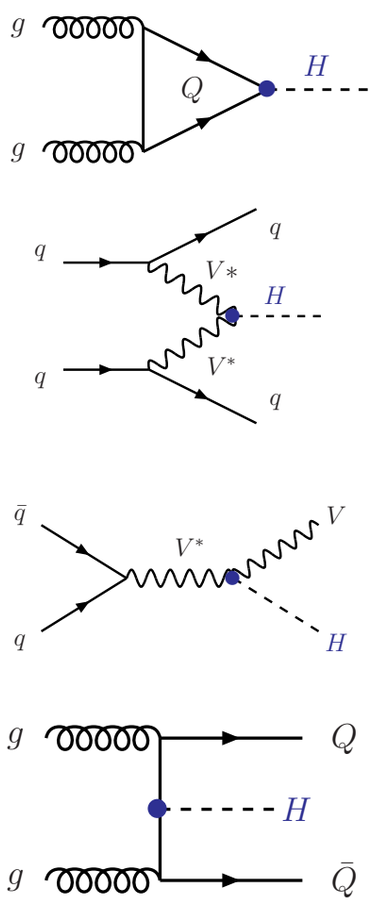
$$\sigma/\sigma_{\rm SM} = 0.87 \pm 0.23$$

- 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



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

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



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 $HZ\gamma$

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

- Every measurement affected by production and decay
- Need cross correlation between many channels!

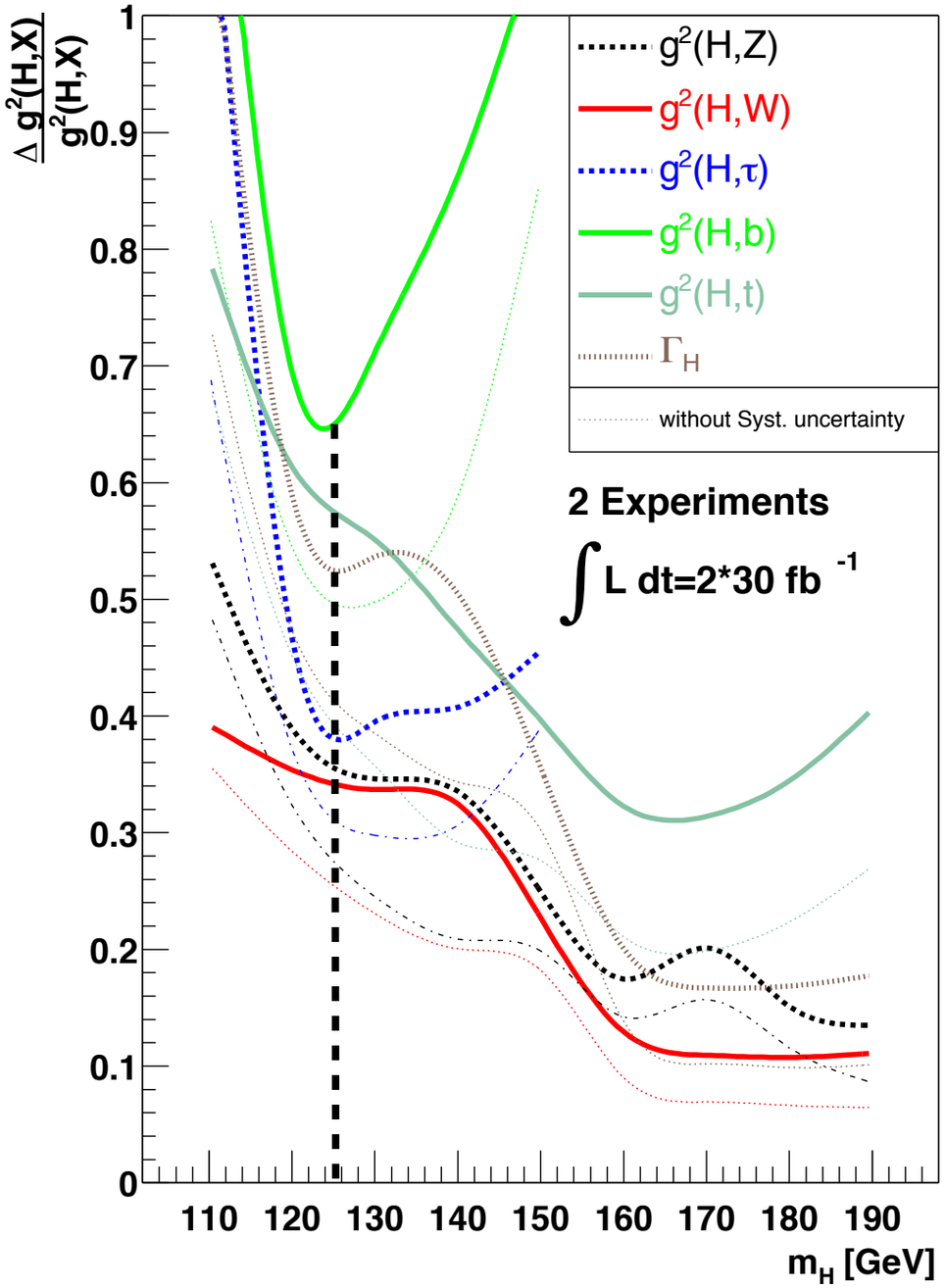
Decay into spec. channel

Production

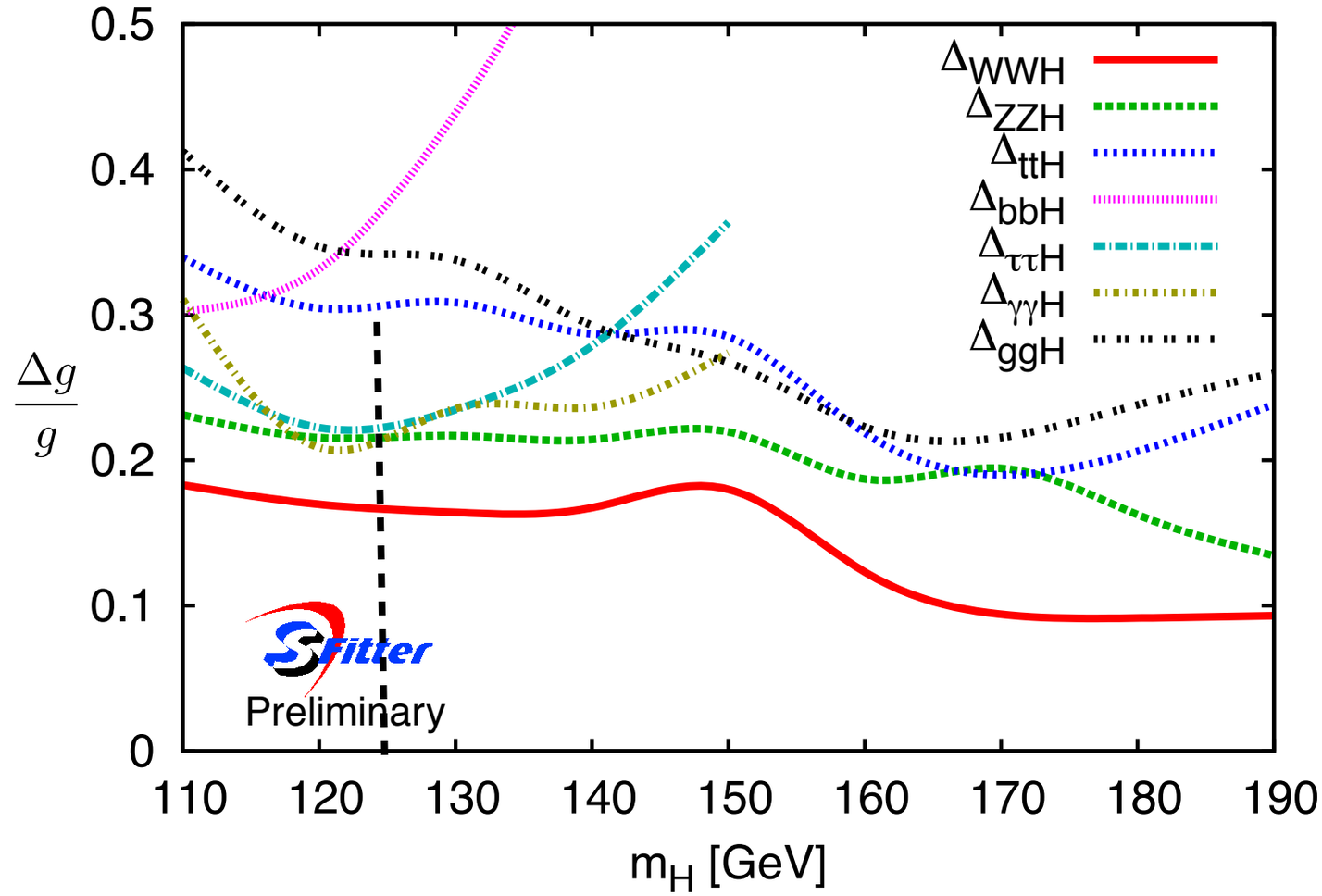
$$\sigma \cdot BR \propto g_p^2 \frac{g_d^2}{\Gamma_H}$$

Sum of all possible decays

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



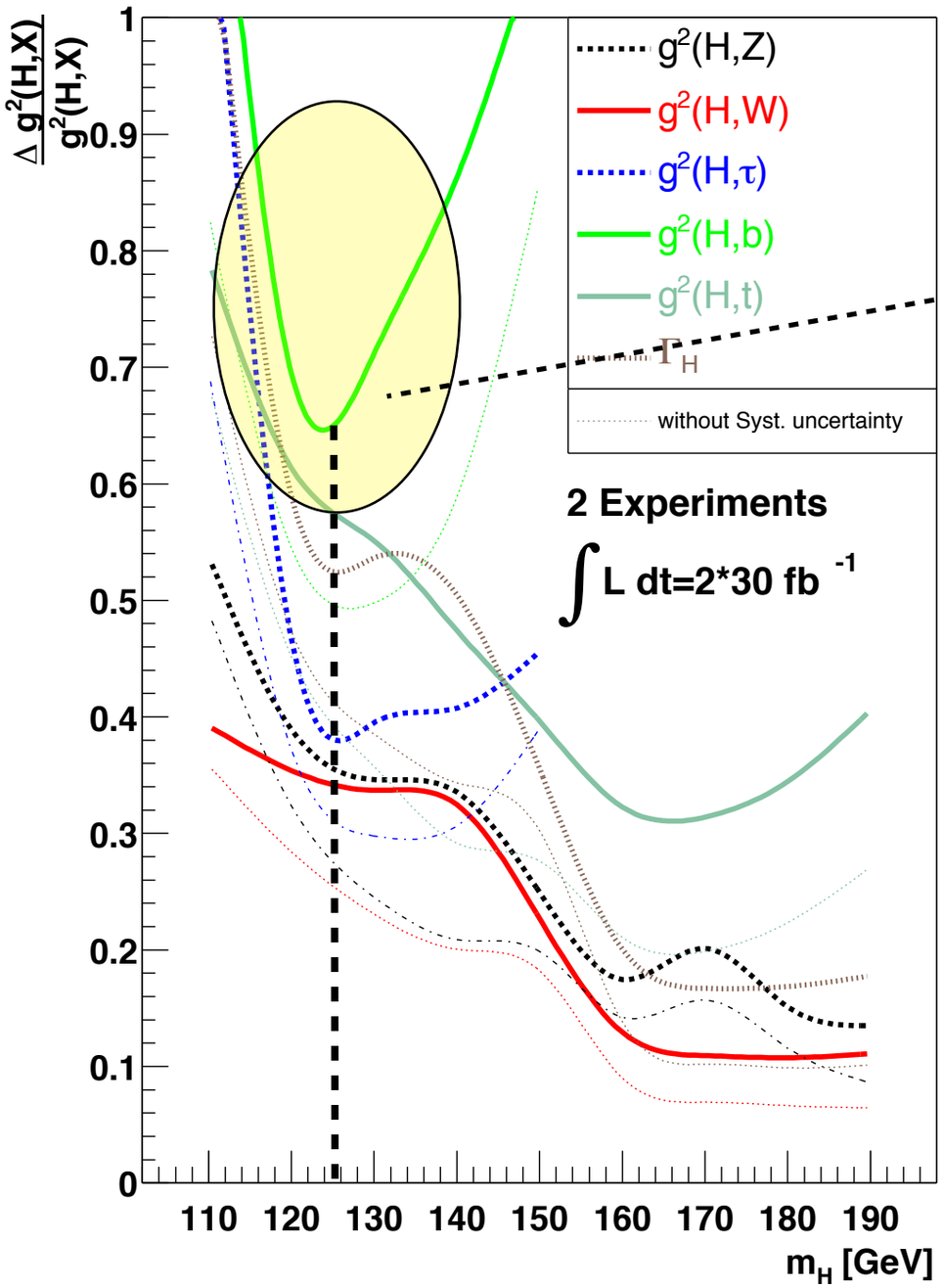
[Lafaye, Plehn, Rauch, Zerwas, Duehrssen (2009)]



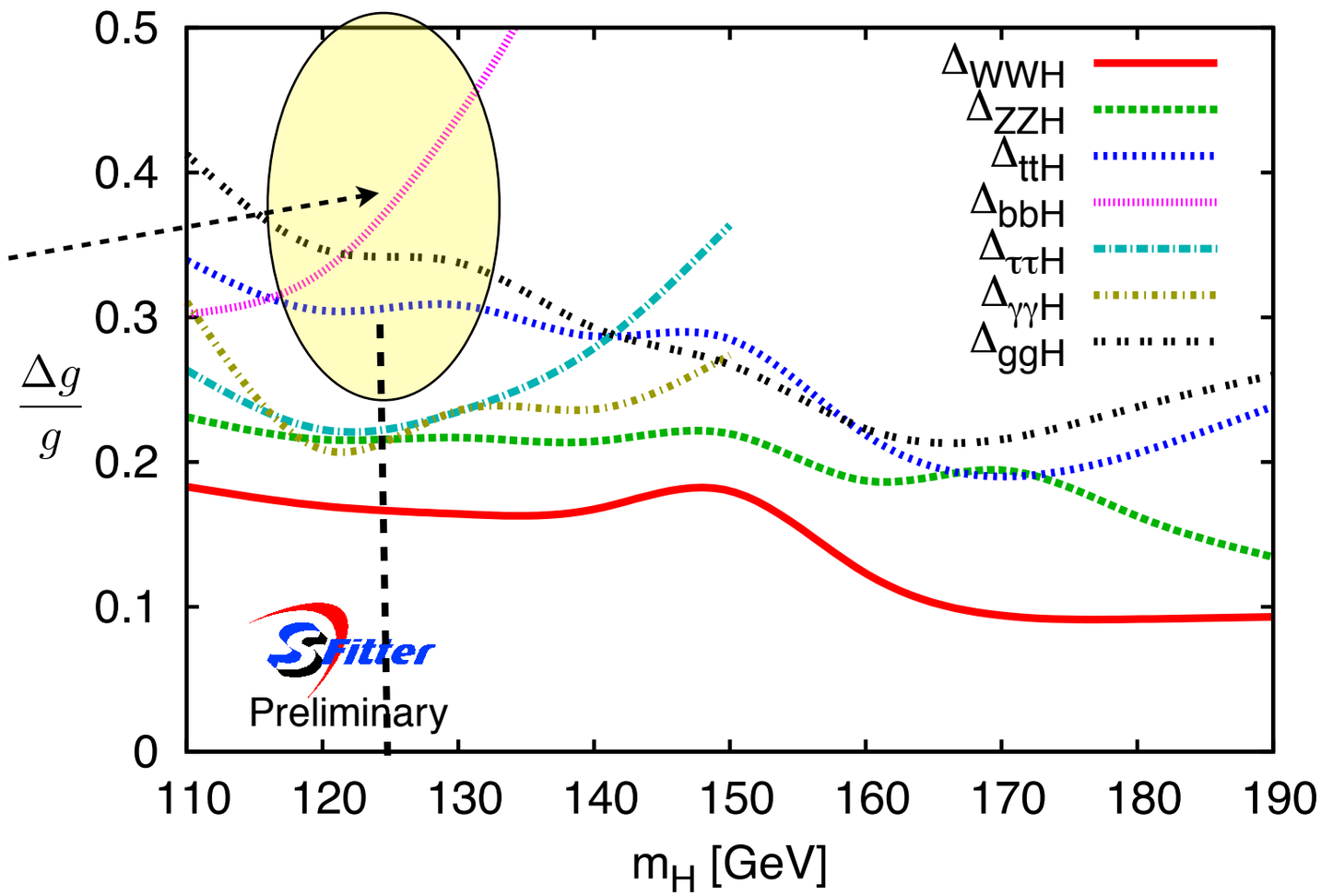
- Huge improvement from boosted Higgs analysis
- also for non-b decay modes due to better knowledge of total width

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

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



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



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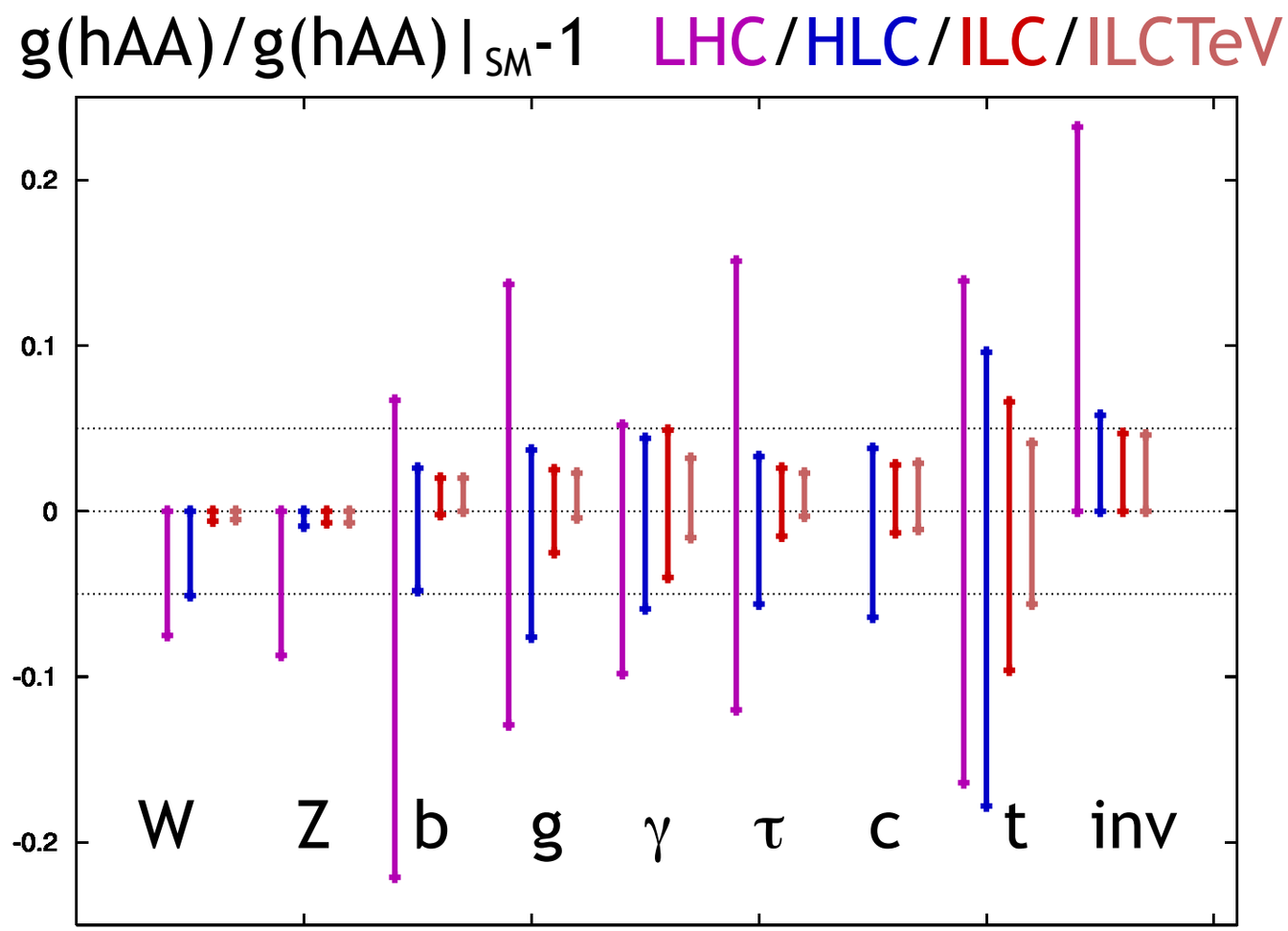
coupling comparison LCs vs LHC



[Peskin, 1207.2516]

- ILCs better suited to measure Higgs couplings
- However, for uncertainty estimate new techniques (jet substructure) not taken into account

→ Techniques might be useful to improve on hbb and htt couplings

"Mirror, mirror on the wall ..."

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

"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

"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

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]

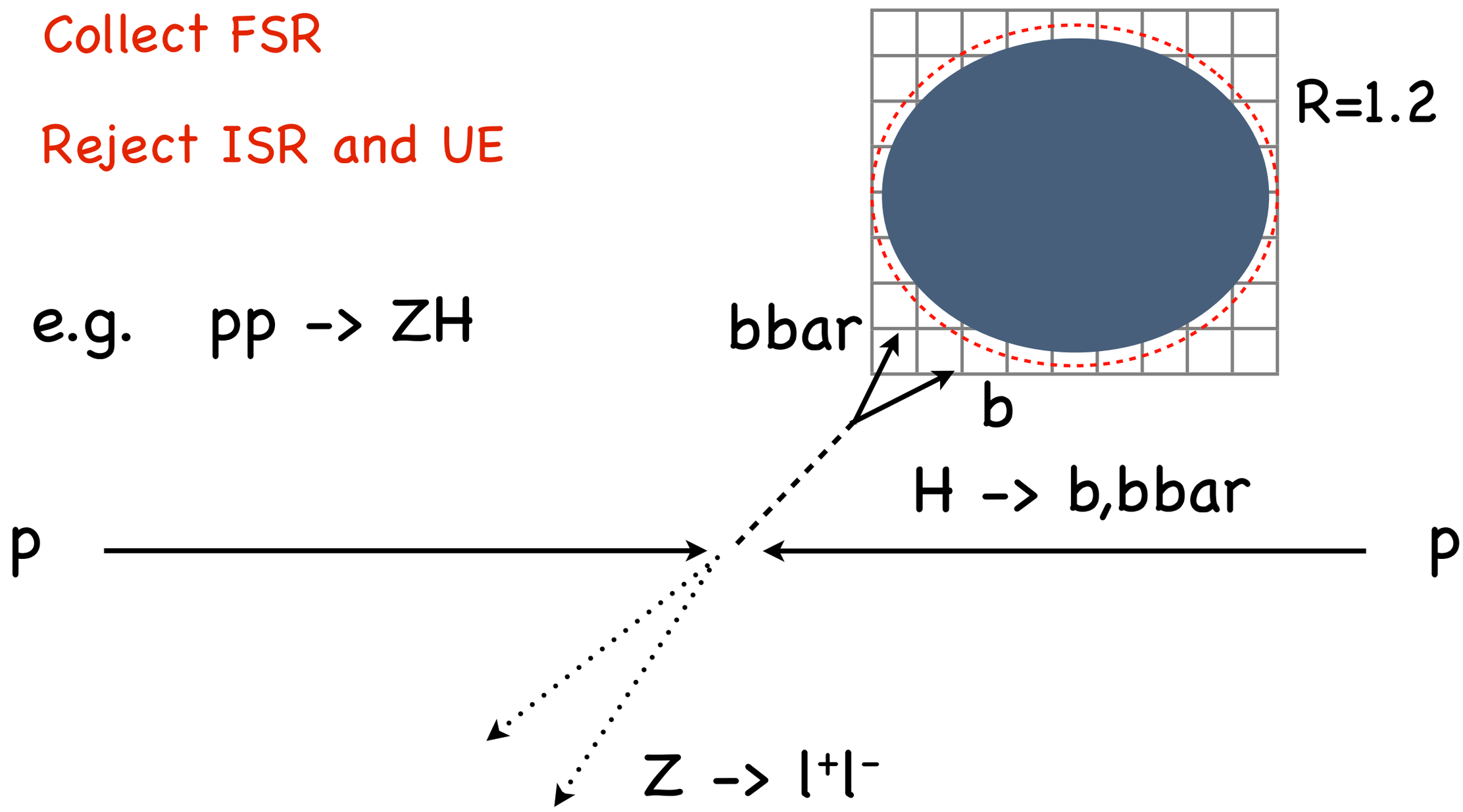
HV - Higgs discovery channel

[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)]

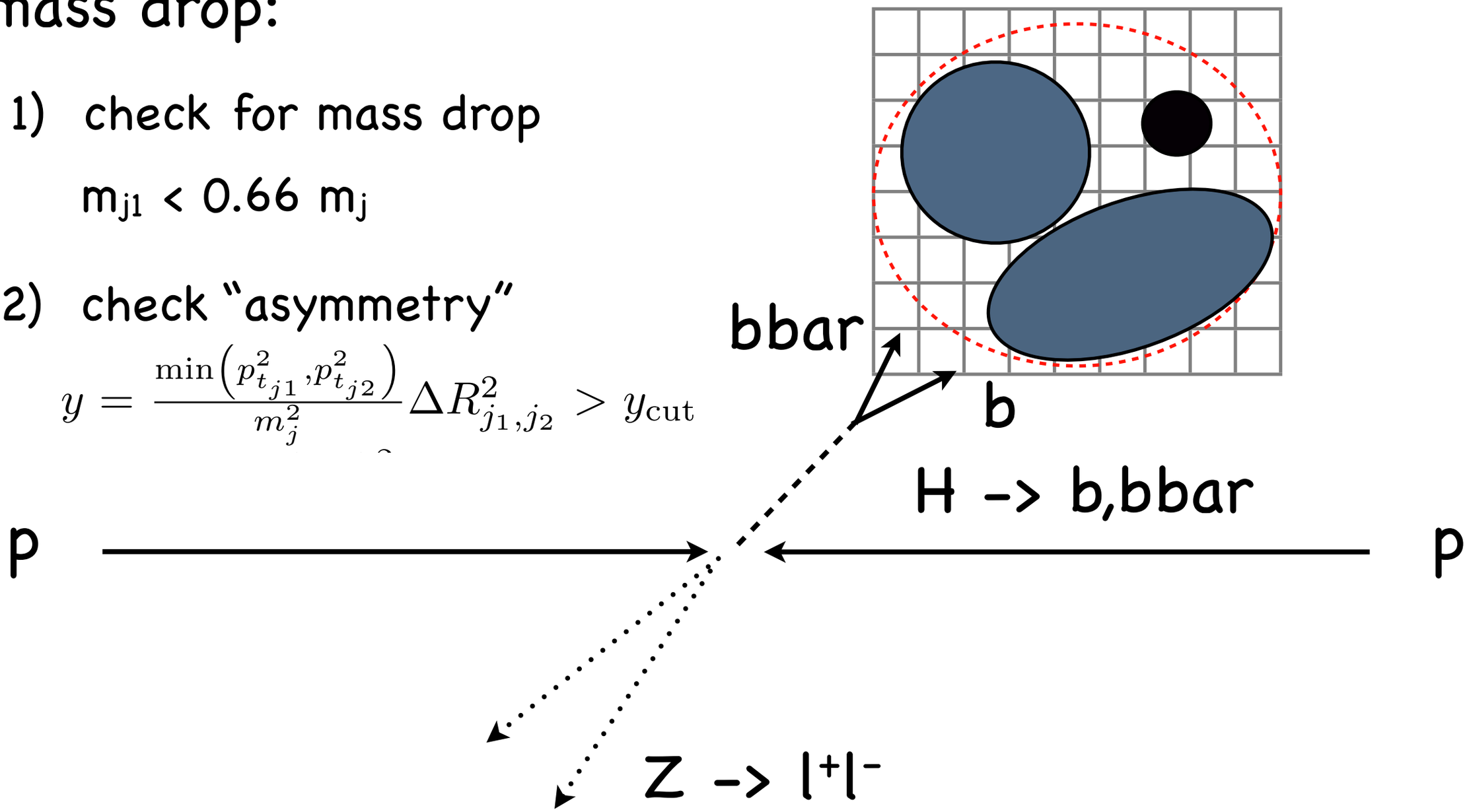
mass drop:

1) check for mass drop

$m_{j1} < 0.66\ m_j$

2) check "asymmetry"

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

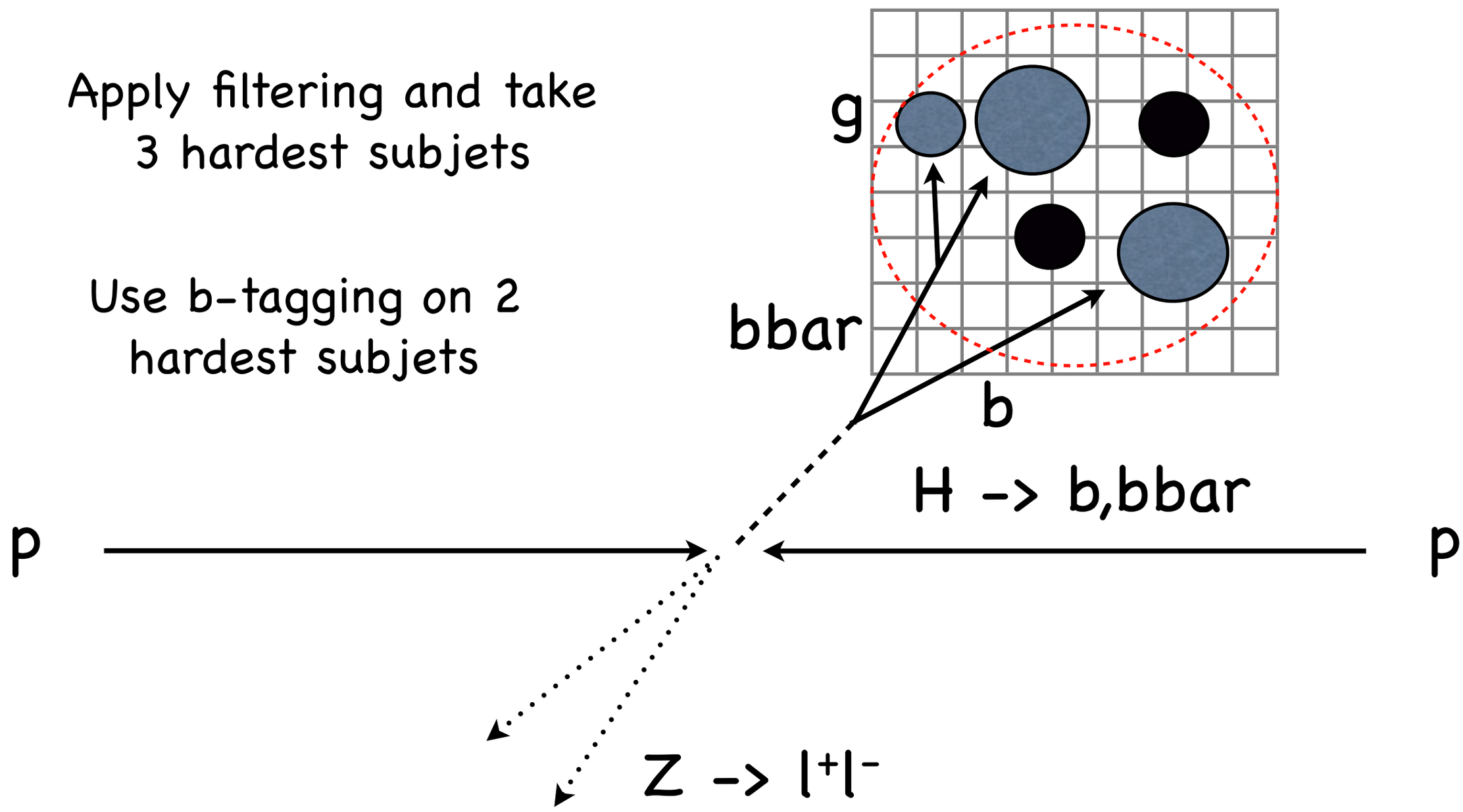


HV - Higgs discovery channel

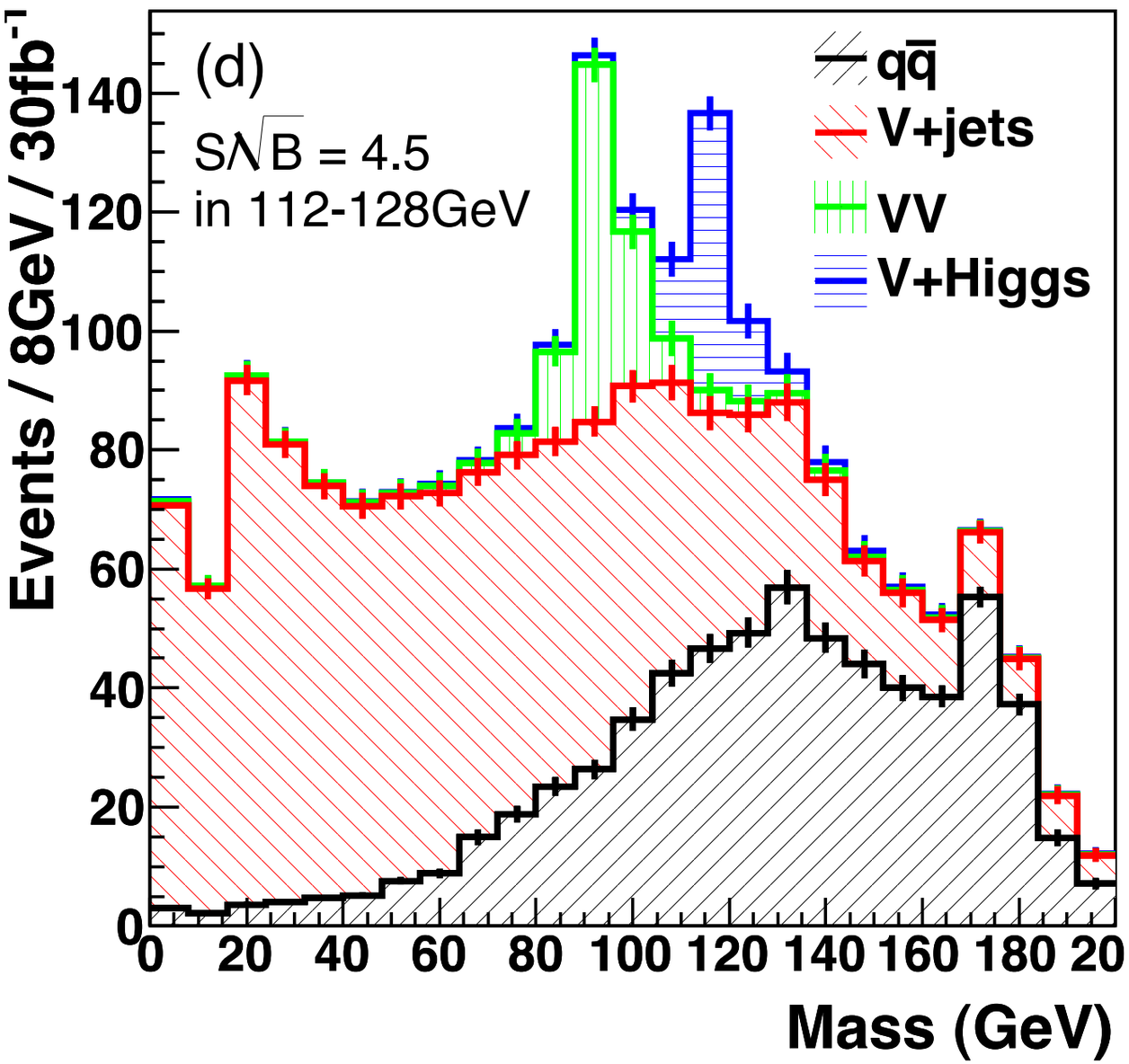
[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

Apply filtering and take 3 hardest subjets

Use b-tagging on 2 hardest subjets



BDRS Result

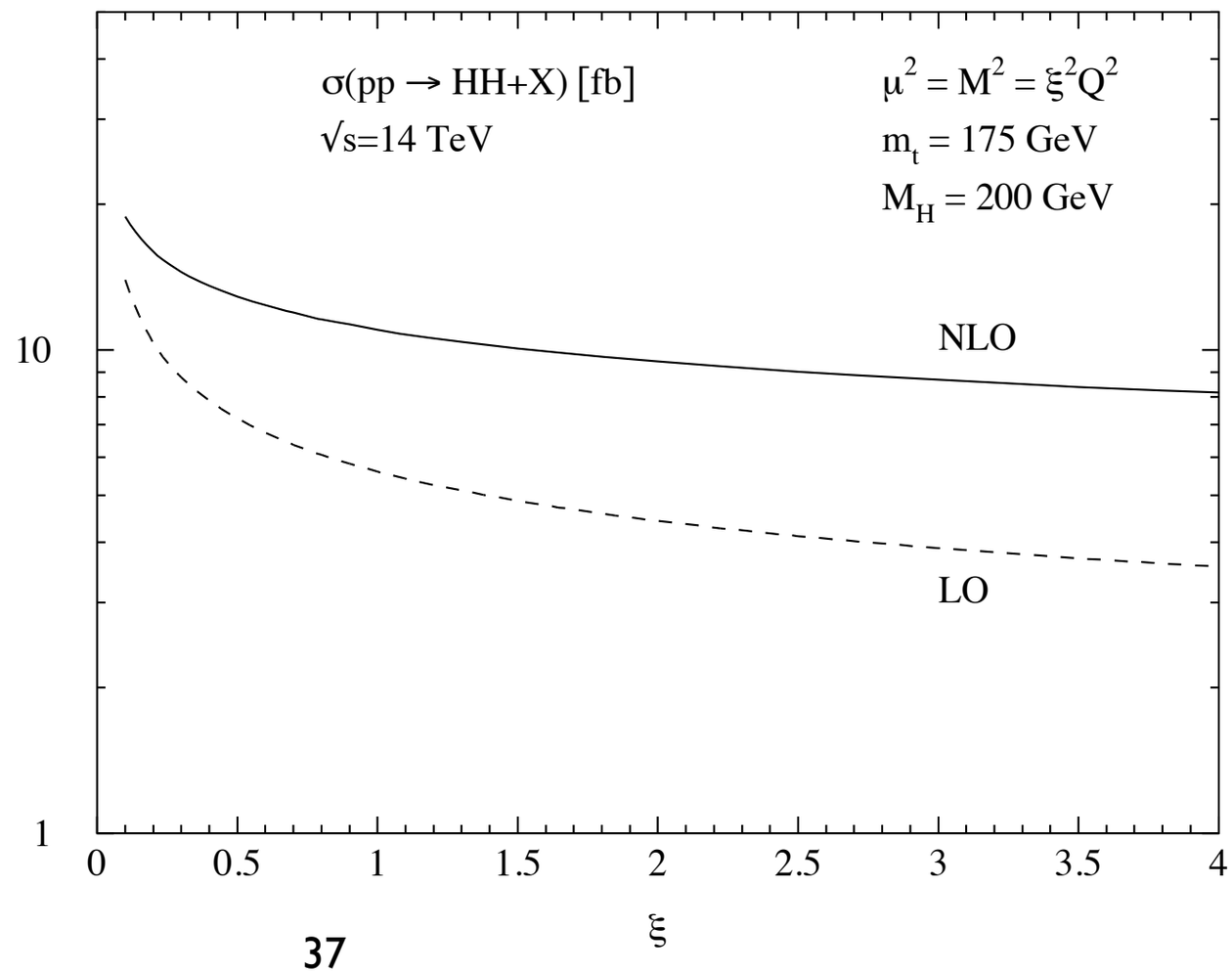


- LHC 14 TeV; 30 fb^{-1}
- HERWIG/JIMMY/Fastjet cross-checked with PYTHIA with "ATLAS tune"
- 60% b-tag; 2% mistag
- Combination of HZ and HW channels

Confirmed in ATLAS full detector simulation

Higgs Selfcoupling

- For EWSB Higgs potential needed -> measure selfcoupling
- λ_{HHHH} absolutely hopeless at LHC (and any of the others...)
- λ_{HHH} very difficult to measure at the LHC
  - small rate:

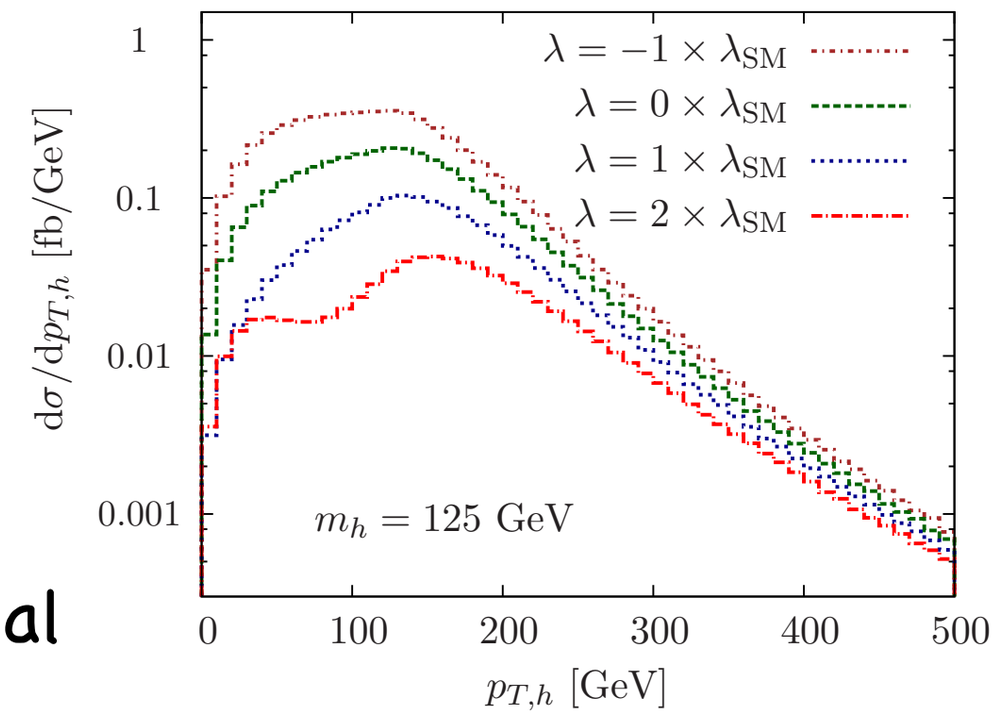


- potentially large backgrounds

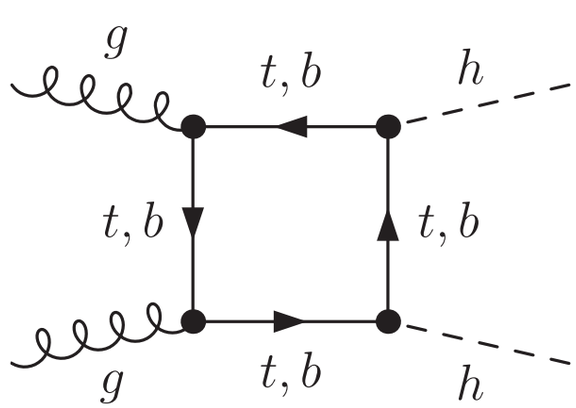
For Higgs with 125 GeV decay to bottoms dominating.

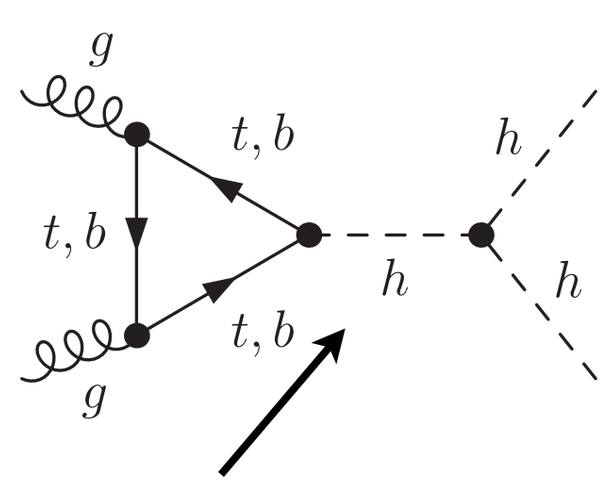
Thus, QCD induced g -> bb splitting gives large backgrounds.

+ But naturally boosted, can jet substructure help?



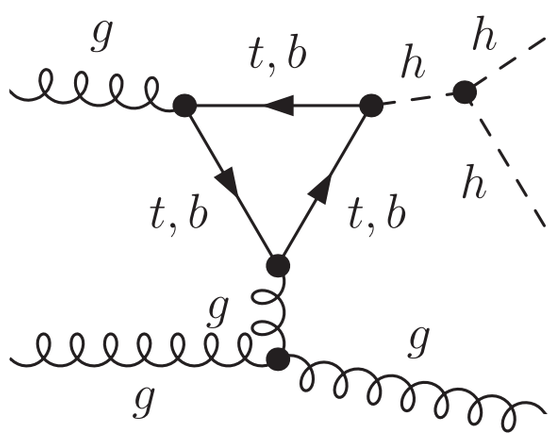
- Destructive interference in signal

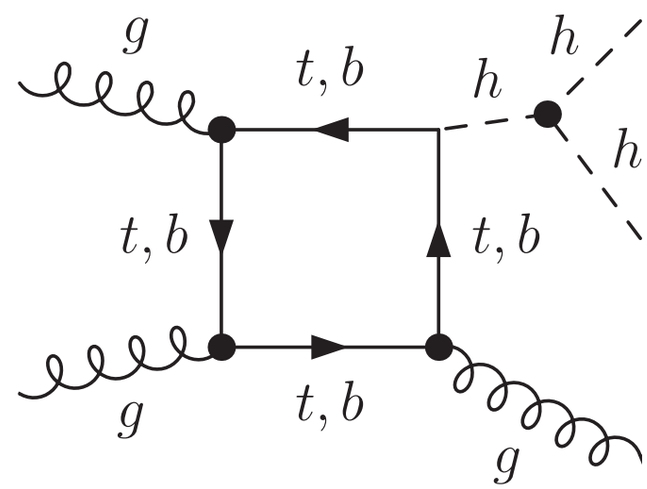




- 1/s suppression for λ_{HHH} diagram

+− Additional hard jet can ameliorate 1/s suppression but is expensive





➡ Many - and just a few +

➡ Several reconstruction approaches tried in

[Baur, Plehn, Rainwater PRD 69 (2004)] [Dolan, Englert, MS 1206.5001]

[Papaefstathiou, Yang, Zurita 1209.1489]

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

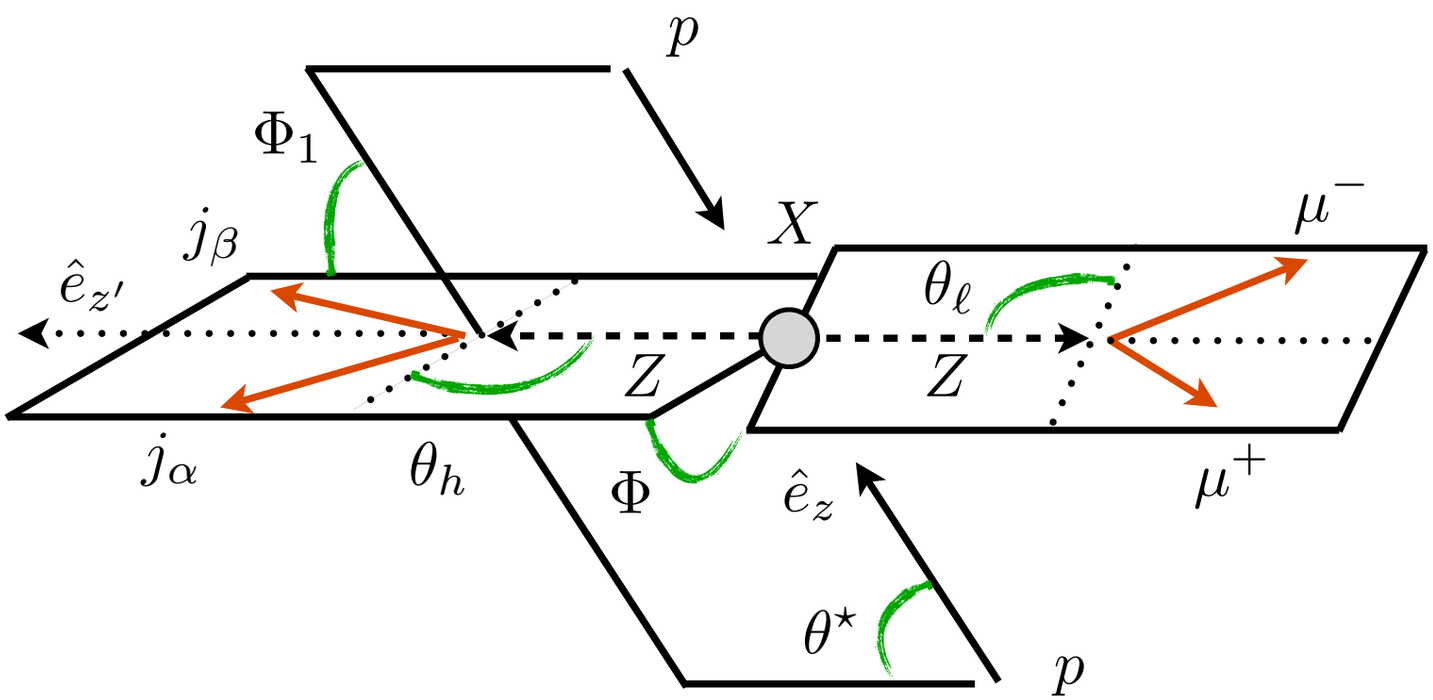
$\bar{b}bW^+W^-$

But all tough!

III. Higgs spin and CP

Although Landau-Yang theorem rules out spin-1 particles it will be necessary to measure spin of Higgs.

5 angles determine the kinematics of the process



$$\cos\tilde{\Phi} = \frac{(\hat{e}_z \times \hat{e}_{z'}) \cdot (\mathbf{p}_- \times \mathbf{p}_+)}{\sqrt{(\mathbf{p}_- \times \mathbf{p}_+)^2}}\Bigg|_X$$

$$\cos\Phi = \frac{(\mathbf{p}_\alpha \times \mathbf{p}_\beta) \cdot (\mathbf{p}_- \times \mathbf{p}_+)}{\sqrt{(\mathbf{p}_\alpha \times \mathbf{p}_\beta)^2\,(\mathbf{p}_- \times \mathbf{p}_+)^2}}\Bigg|_X$$

$$\cos\theta_h = \frac{\mathbf{p}_\alpha \cdot \mathbf{p}_X}{\sqrt{\mathbf{p}_\alpha^2\,\mathbf{p}_X^2}}\Bigg|_{Z_h} \qquad \cos\theta_\ell = \frac{\mathbf{p}_- \cdot \mathbf{p}_X}{\sqrt{\mathbf{p}_-^2\,\mathbf{p}_X^2}}\Bigg|_{Z_\ell} \qquad \cos\theta^\star = \frac{\mathbf{p}_{Z_\ell} \cdot \hat{e}_{z'}}{\sqrt{\mathbf{p}_{Z_\ell}^2}}\Bigg|_X$$

III. Higgs spin and CP

$\cos\theta^*$ Φ_1 $\cos\theta_1$ or $\cos\theta_2$ Φ

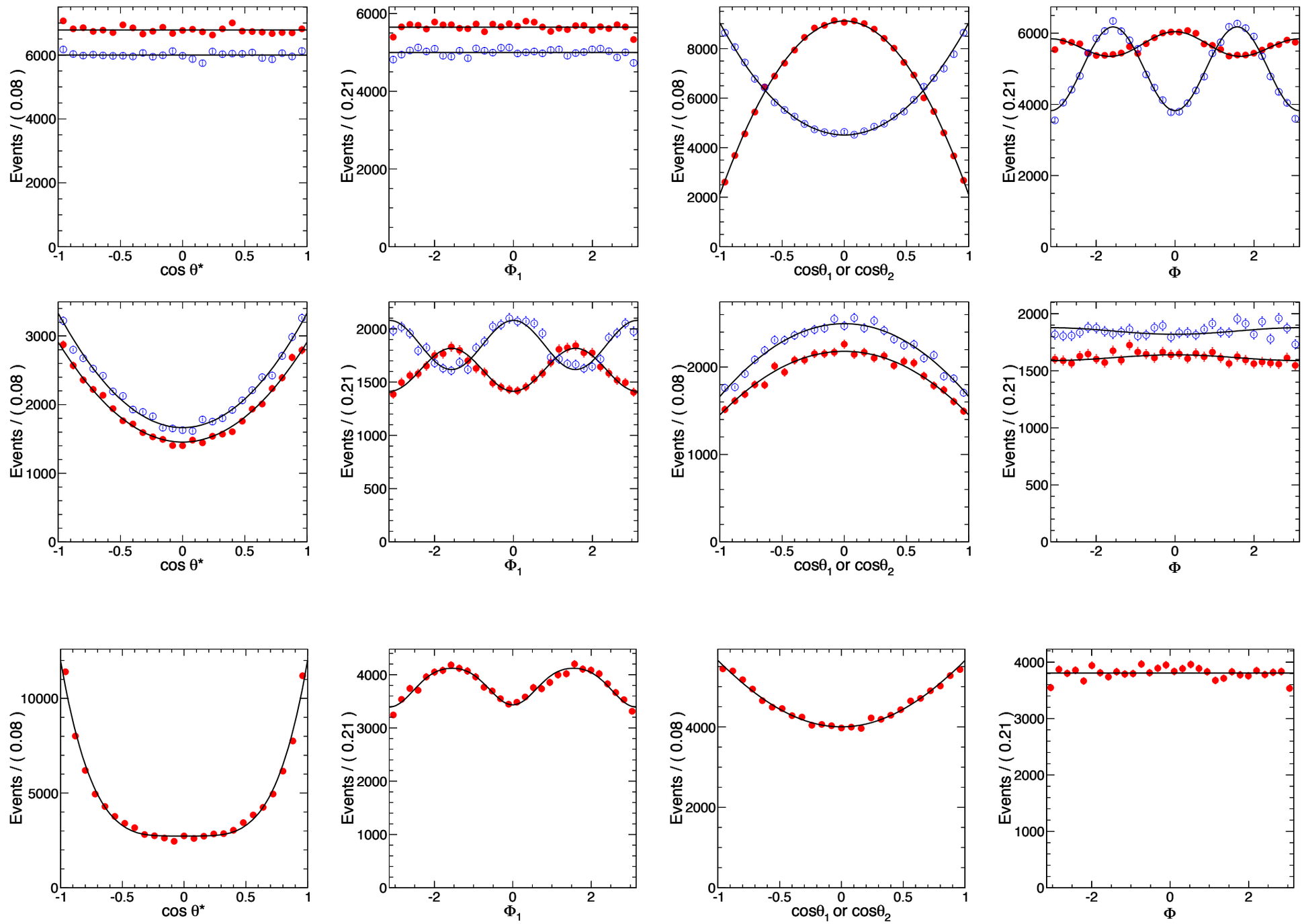
scalar (red)

pseudo-scalar (blue)

axial-vector (red)

vector (blue)

background

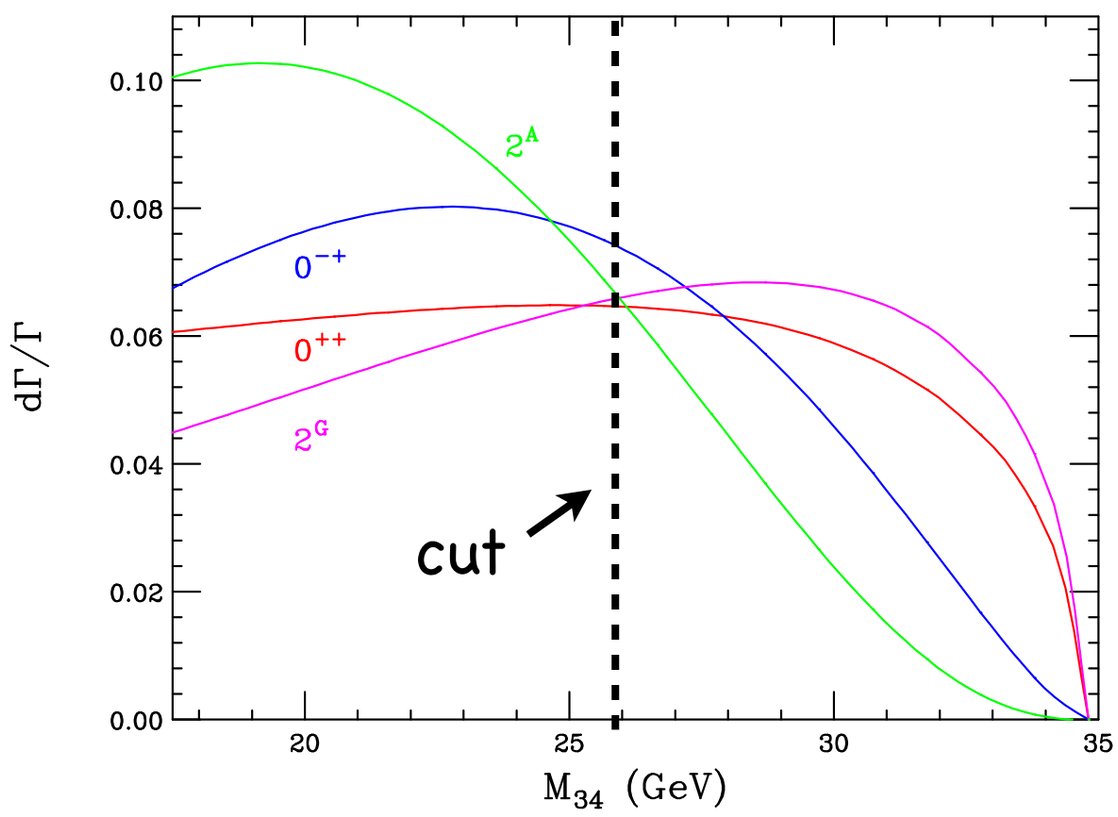


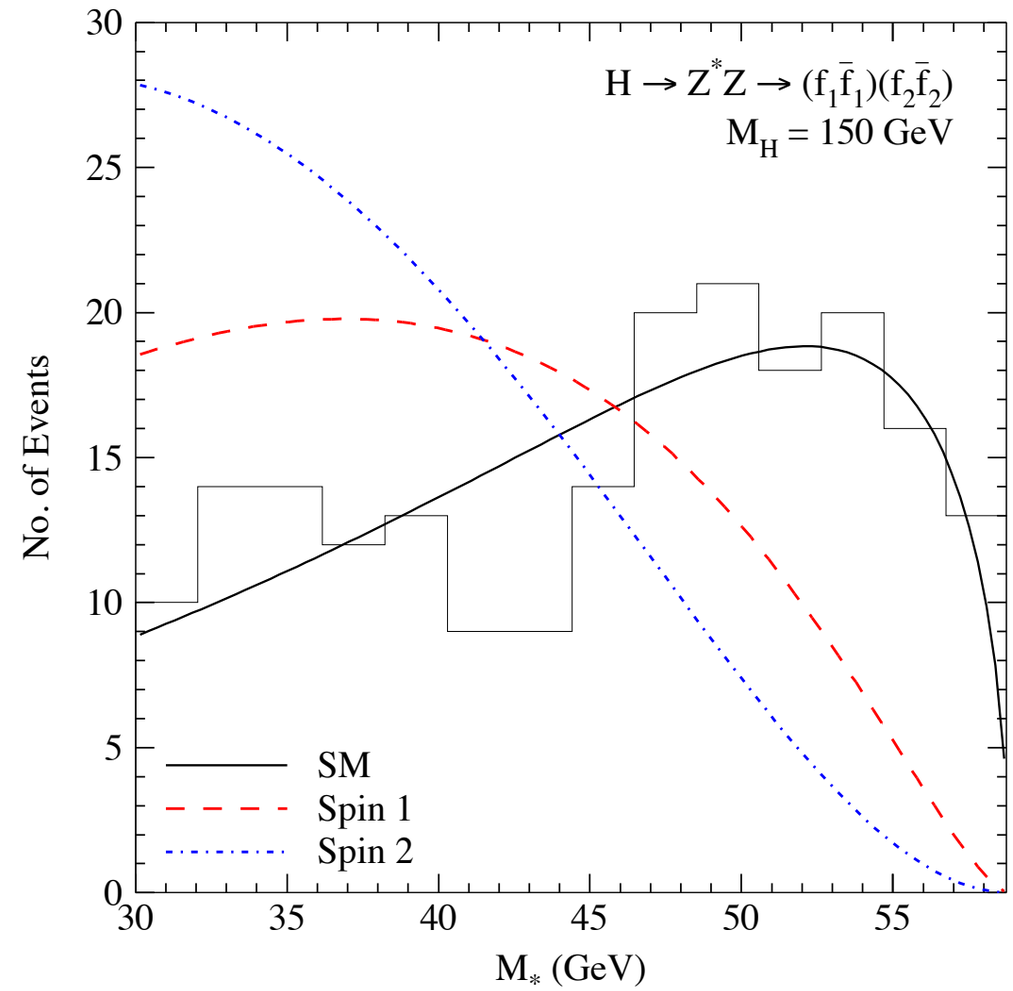
[Gao, Gritsan, Guo, Melnikov, Schulze, Tran]

III. Higgs spin and CP

For the Higgs with $m_H \gtrsim 170\ \mathrm{GeV}$ the invariant mass of the reconstructed off-shell Z can be studied to measure the spin of the Higgs:

[Choi, Miller, Muehlleitner, Zerwas PLB 553 (2003)]





[Boughezal, LeCompte, Petriello 1208.4311]

$$\mathcal{A}_{M_{cut}} = \frac{N(M_{34} > M_{cut}) - N(M_{34} < M_{cut})}{N(M_{34} > M_{cut}) + N(M_{34} < M_{cut})}$$

CP of Higgs: 2 options for light Higgs

- 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)]

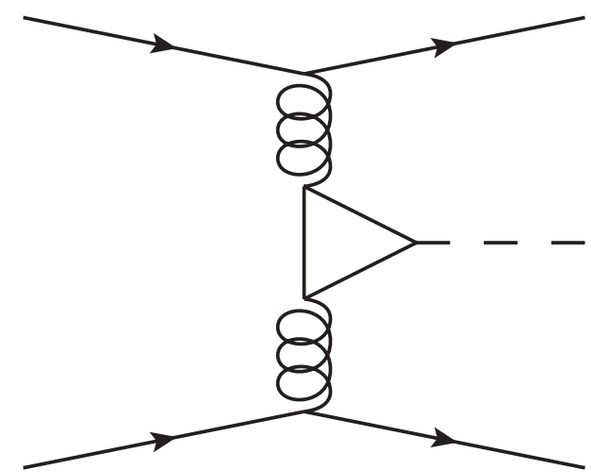
- Event shape observables can be used to measure CP of Higgs

[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 $\Delta\phi_{jj} = \pi$

Event shapes

- Event shapes well studied experimentally and theoretically

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

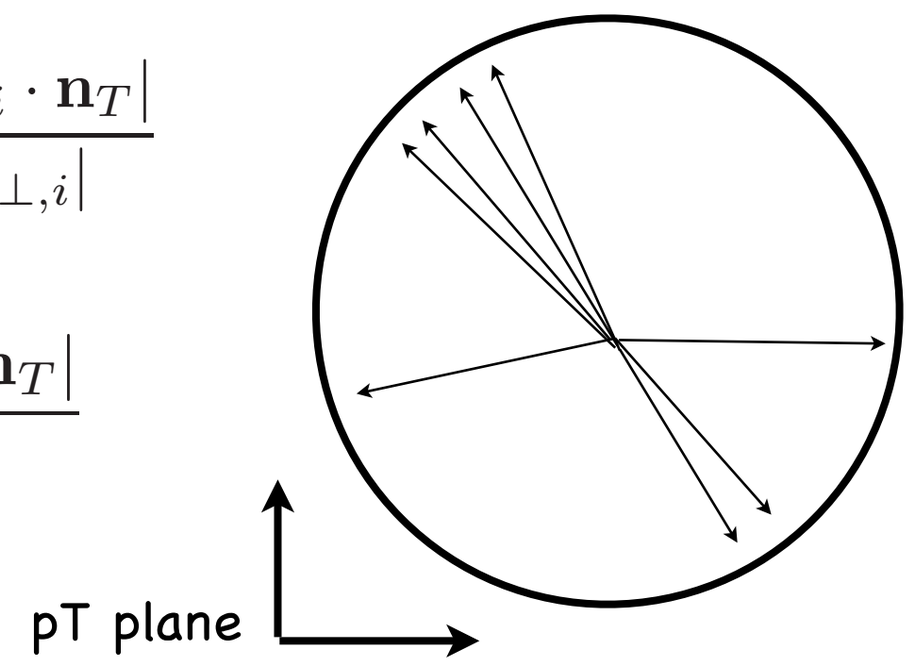
  [Banfi et al., JHEP 0408] [Gehrmann-De Ridder et al., JHEP 0712]

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



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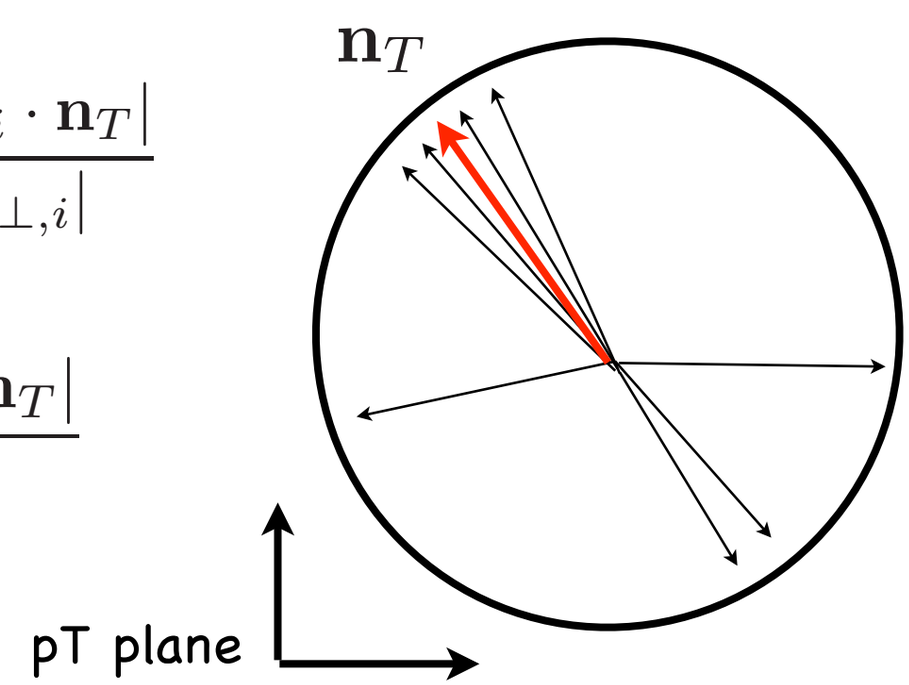
- Event shape measurements established in experimental collaborations already now [CMS, PLB 699 (2011)]

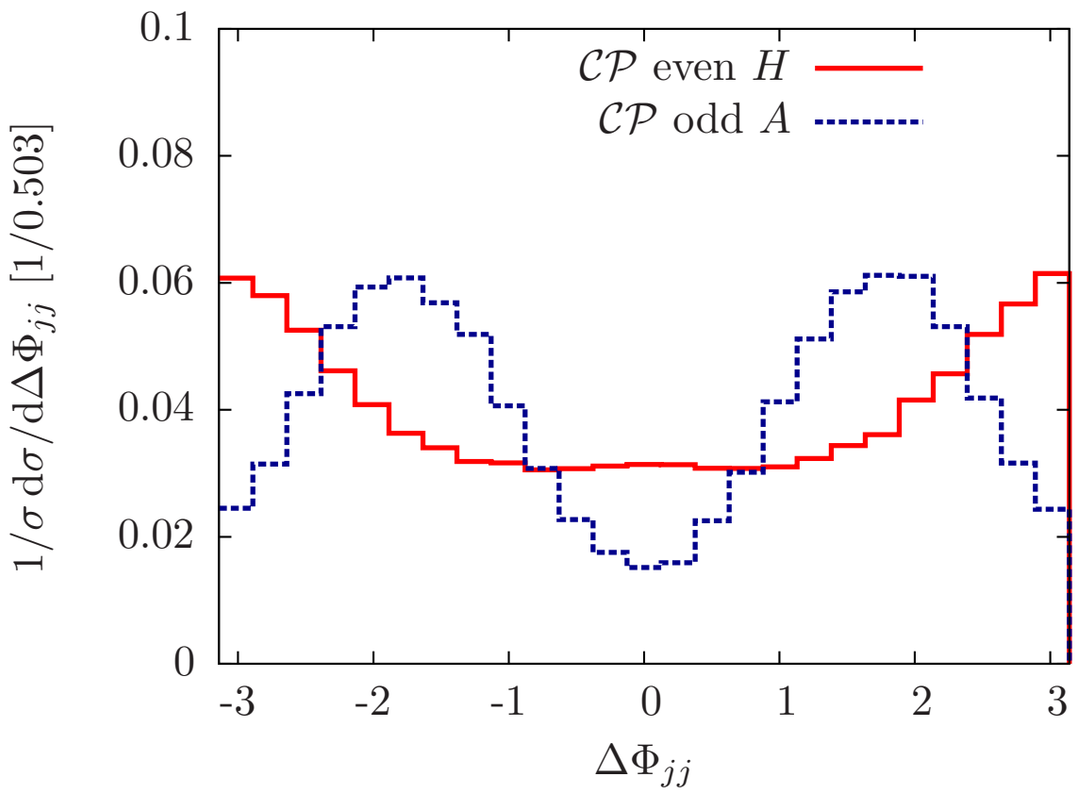
e.g.

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



Tagging jets approach:



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

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

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

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

Tagging jets approach:

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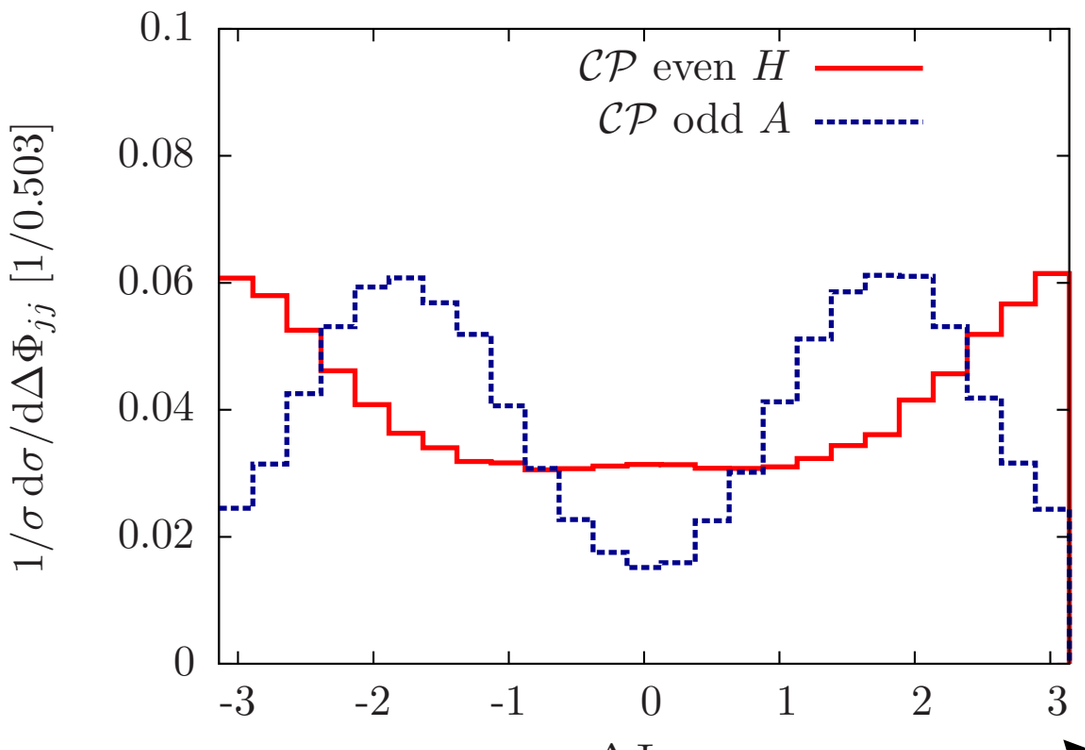
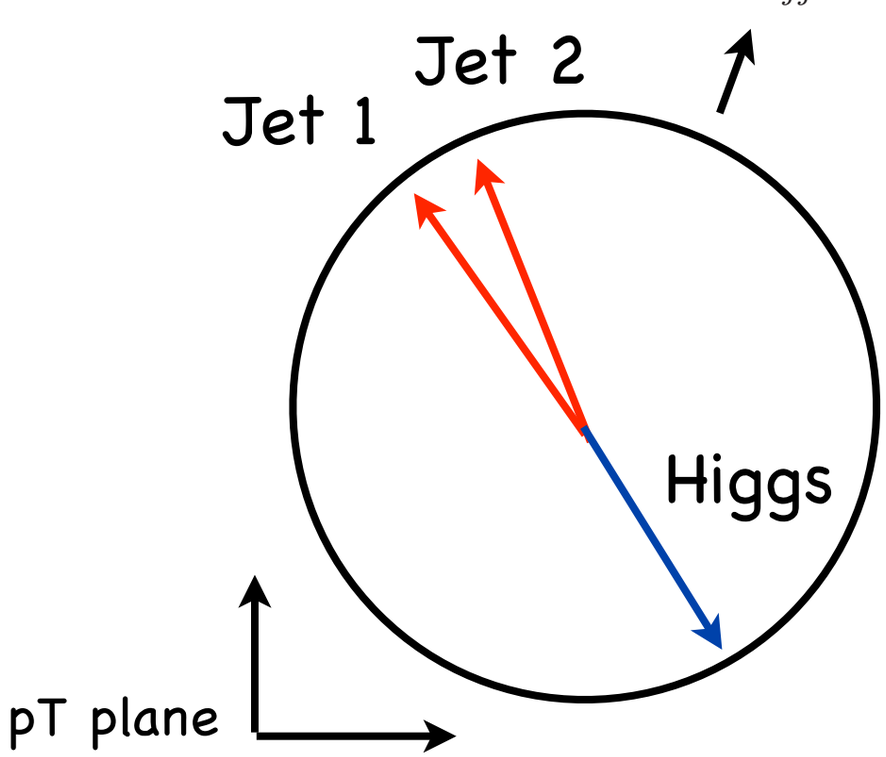
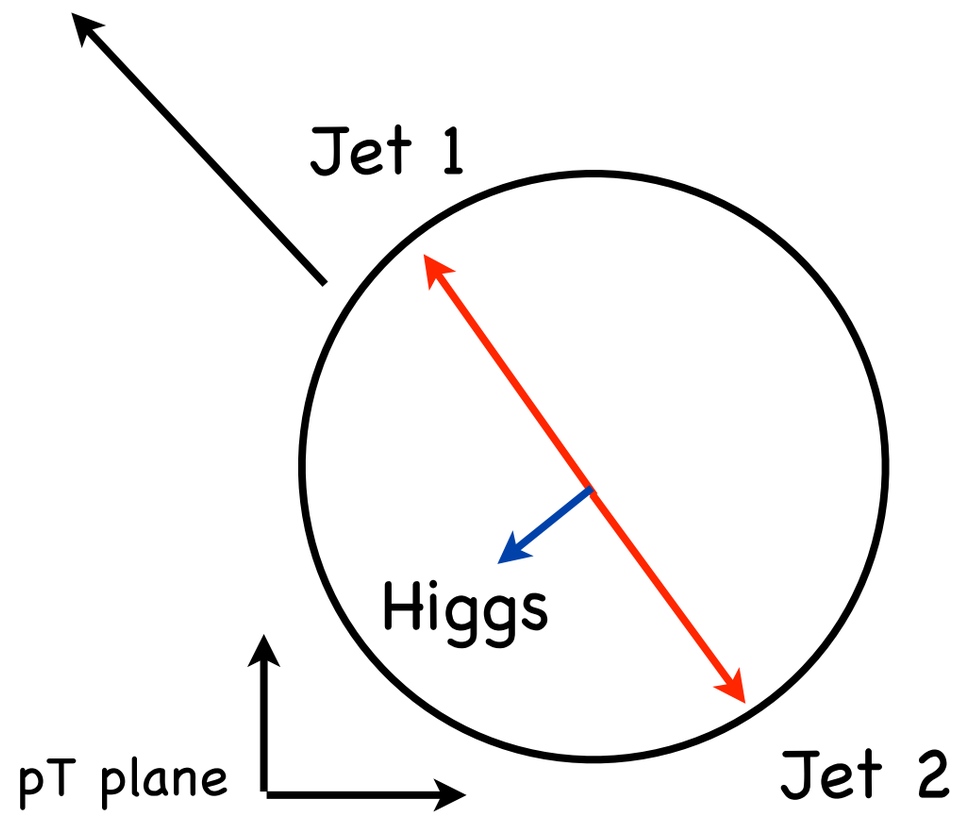


$$p^{\mu}_{<} = \sum_{j\in\{\text{jets: } y_j < y_h\}} p^{\mu}_j$$

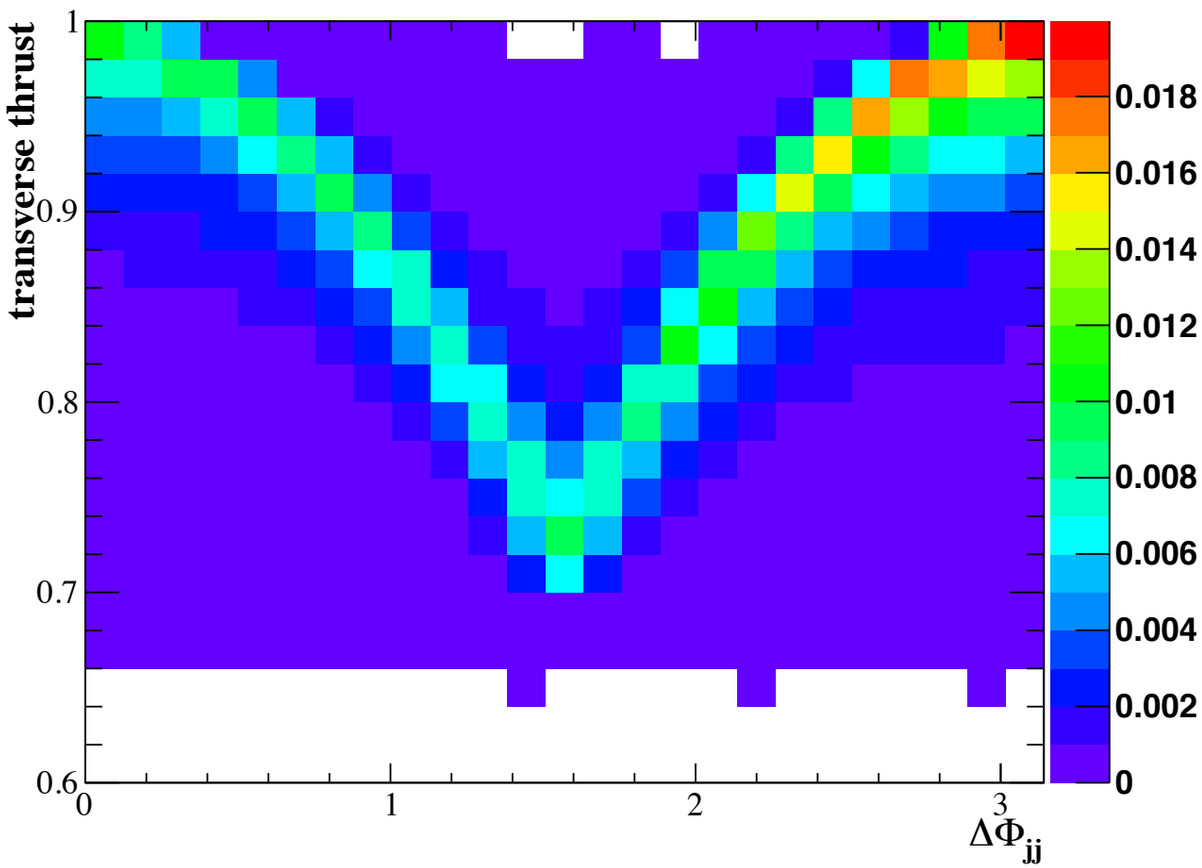
$$p^{\mu}_{>} = \sum_{j\in\{\text{jets: } y_j > y_h\}} p^{\mu}_j$$

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

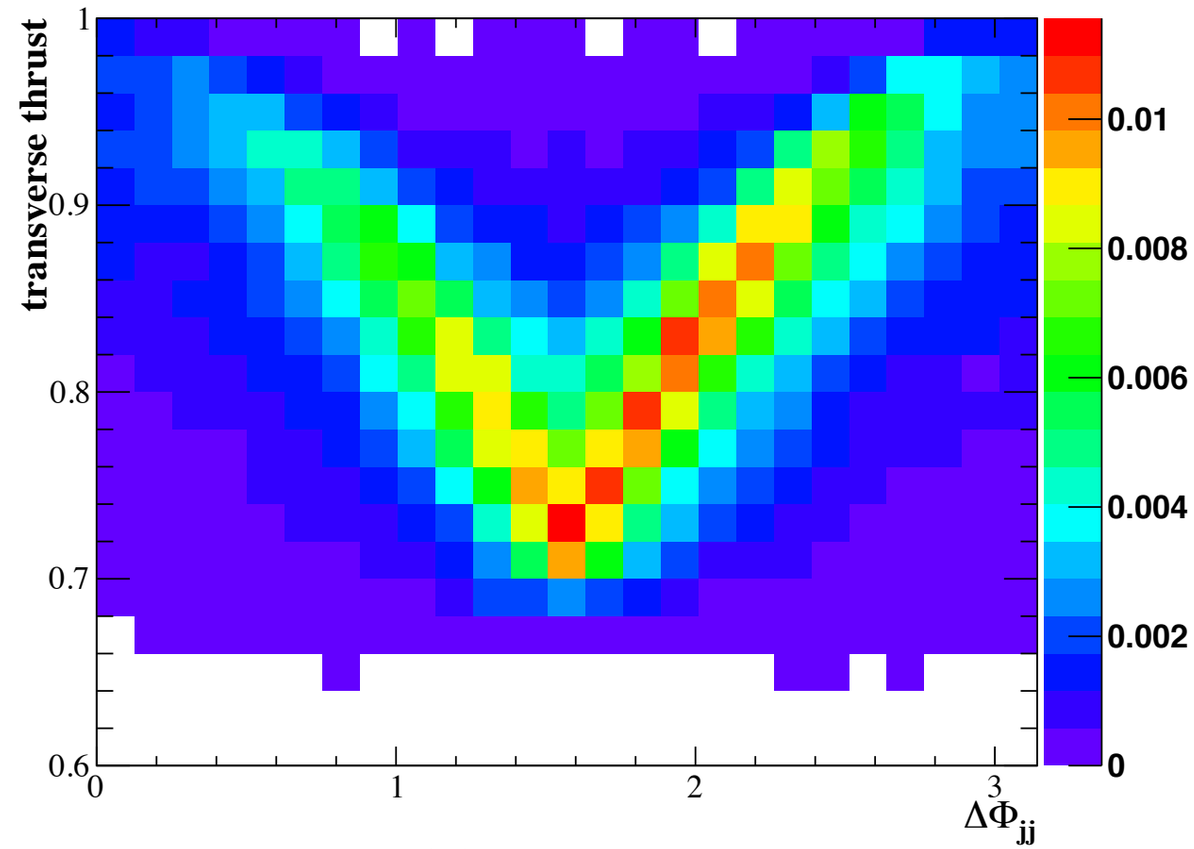




Obvious correlation between thrust and $\Delta\Phi_{jj}$



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

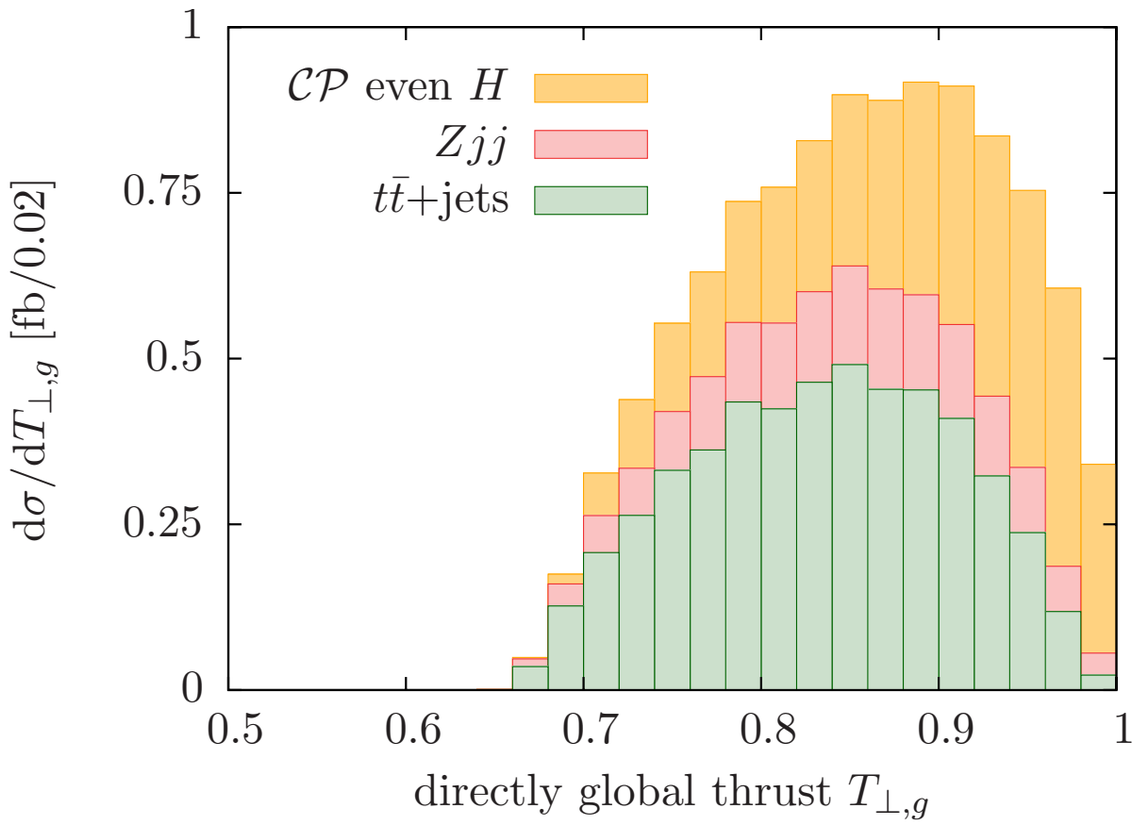
$$|m_{\tau\tau} - m_H| < 20 \text{ GeV}$$

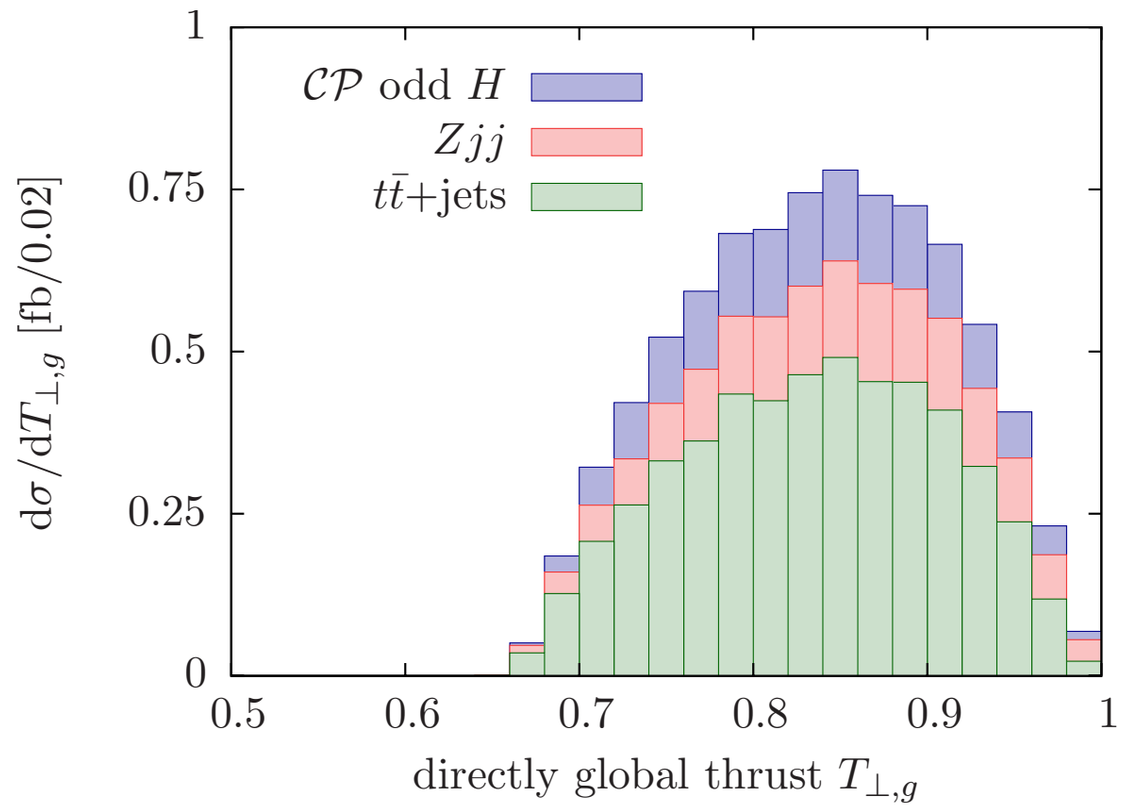
For event shapes use either constituents with

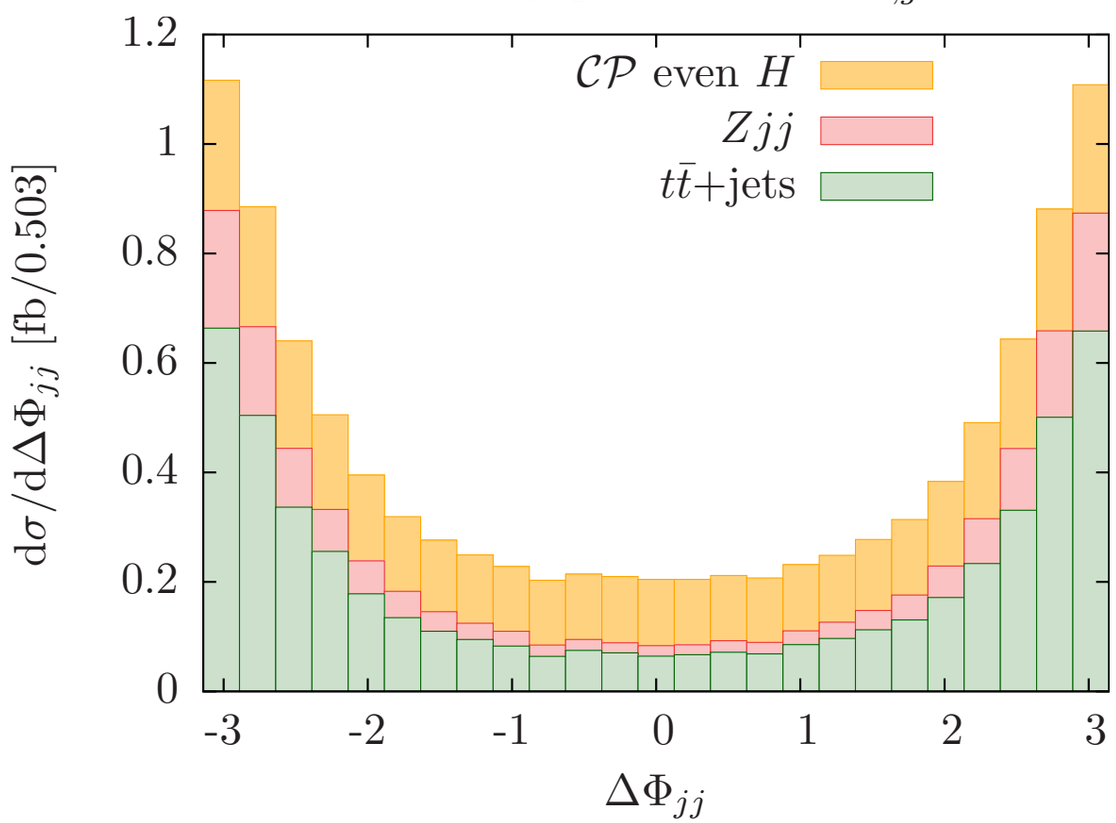
$$p_{T,i} \geq 1 \text{ GeV} \qquad |\eta_i| \leq 4.5$$

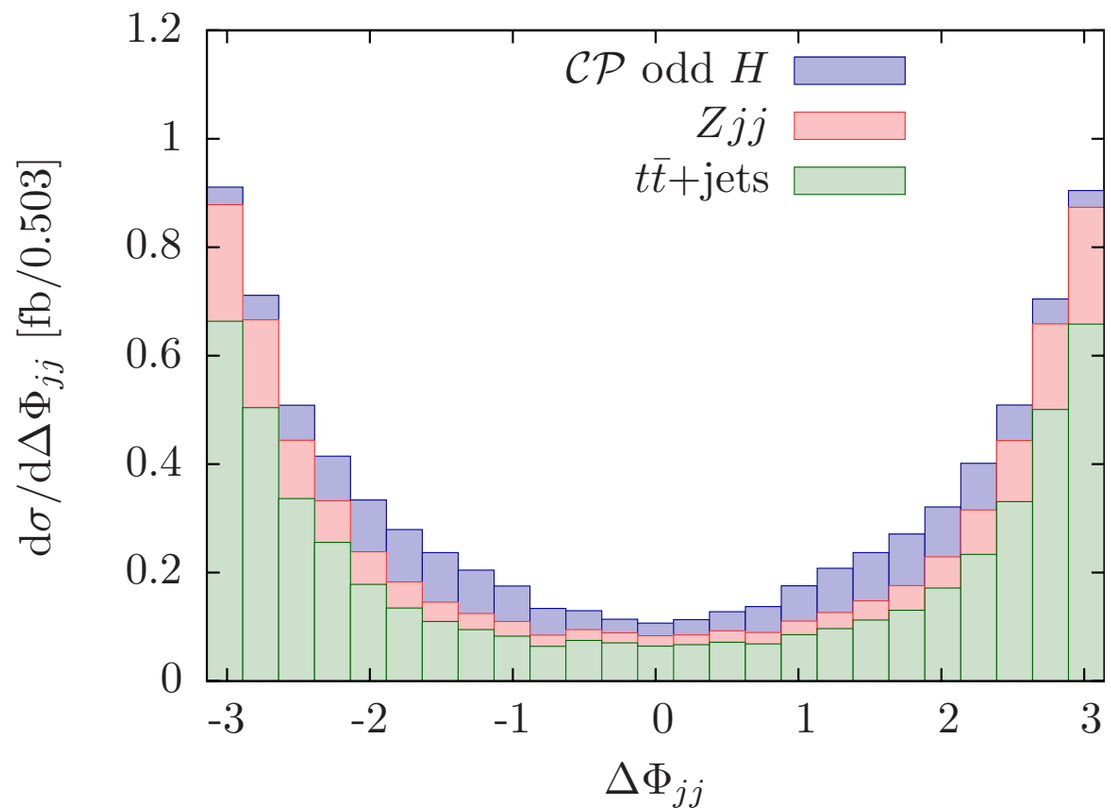
or, to reduce pileup sensitivity $p_{T,j} \geq 40 \text{ GeV}, \quad \text{if } 2.5 \leq |y_j| \leq 4.5, \text{ and}$
$p_{T,j} \geq 10 \text{ GeV}, \quad \text{if } |y_j| \leq 2.5.$

Distributions CP-odd vs CP-even









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