

# Higgs Search at the ~~LHC~~ ATLAS

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# Motivation

# Lagrangian in the Standard Model

$$\begin{aligned}
 \mathcal{L} = & \bar{\nu}(i \not{\partial} - m_\nu)\nu + \bar{l}(i \not{\partial} - m_l)l + \frac{1}{2}(\partial_\mu\chi\partial^\mu\chi - \mu^2\chi^2) \\
 & - \frac{1}{4}F_{\mu\nu}^i F^{i\mu\nu} + m_W^2 W_{+\mu}^* W_+^\mu - \frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \frac{m_Z^2}{2}Z_\mu Z^\mu \\
 & + eA_\mu(\bar{l}\gamma^\mu l) - \frac{g}{\sqrt{2}}[W_+^\mu(\bar{\nu}\gamma^\mu P_L l) + c.c.] \\
 & - \bar{g}Z_\mu[\bar{\nu}\gamma^\mu(s_{\nu L}P_L + s_{\nu R}P_R)\nu + \bar{l}\gamma^\mu(s_{l L}P_L + s_{l R}P_R)l] \\
 & + \frac{2v\chi + \chi^2}{4}(g^2 W_{+\mu}^* W_+^\mu + \frac{\bar{g}^2}{2}Z_\mu Z^\mu) \\
 & - \frac{m_l}{v}\chi(\bar{l}l) - \frac{m_\nu}{v}\chi(\bar{\nu}\nu) \\
 & + \dots
 \end{aligned}$$

# Gauge invariance vs mass term

## ❖ Gauge boson mass term

$$m^2 A^\mu A_\mu \rightarrow m^2 (A^\mu + \partial^\mu \Lambda)(A_\mu + \partial_\mu \Lambda) \neq m^2 A^\mu A_\mu$$

⇒ need to be massless

## ❖ Fermion mass term

▶ Not necessarily massless

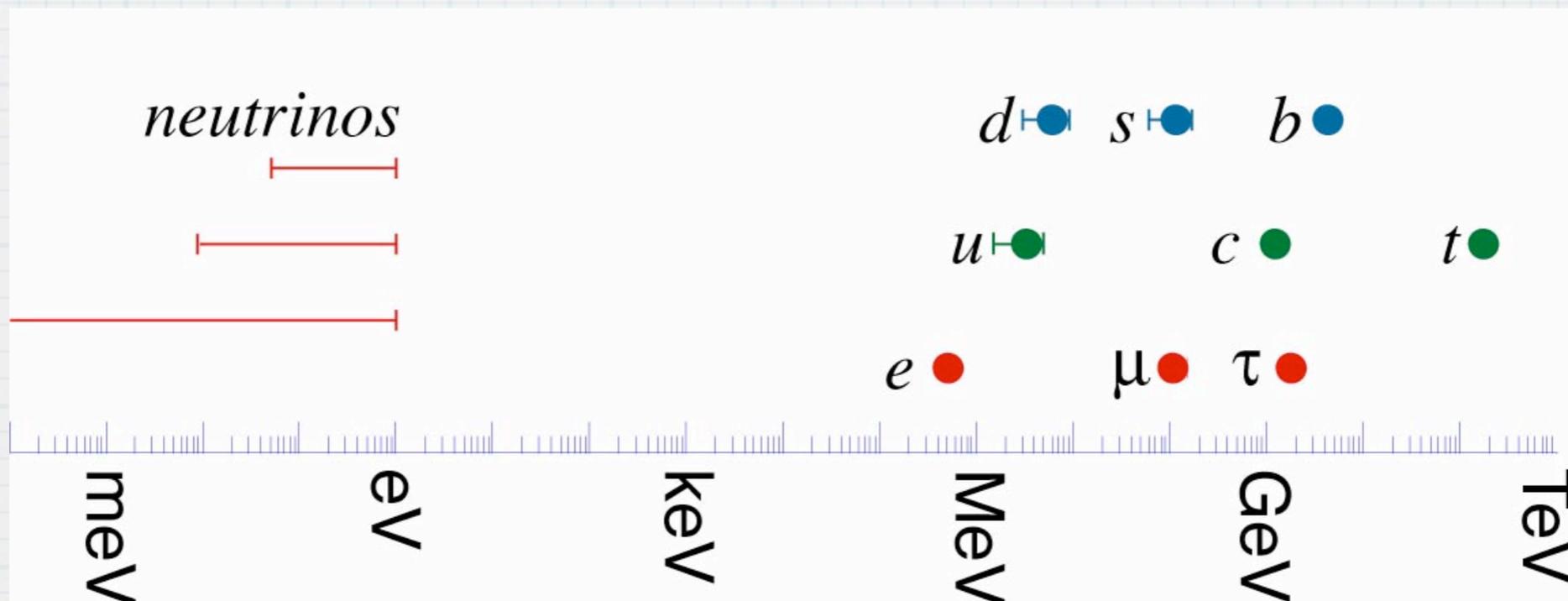
# Economical solution

- ❖ One Higgs doublet gives mass to both gauge boson and fermion?
- ❖ Introduction of Yukawa coupling

# Mass Difference

❖ Insect 0.7g vs man 70kg vs elephant 7t  
= 1 : 100,000 : 10,000,000

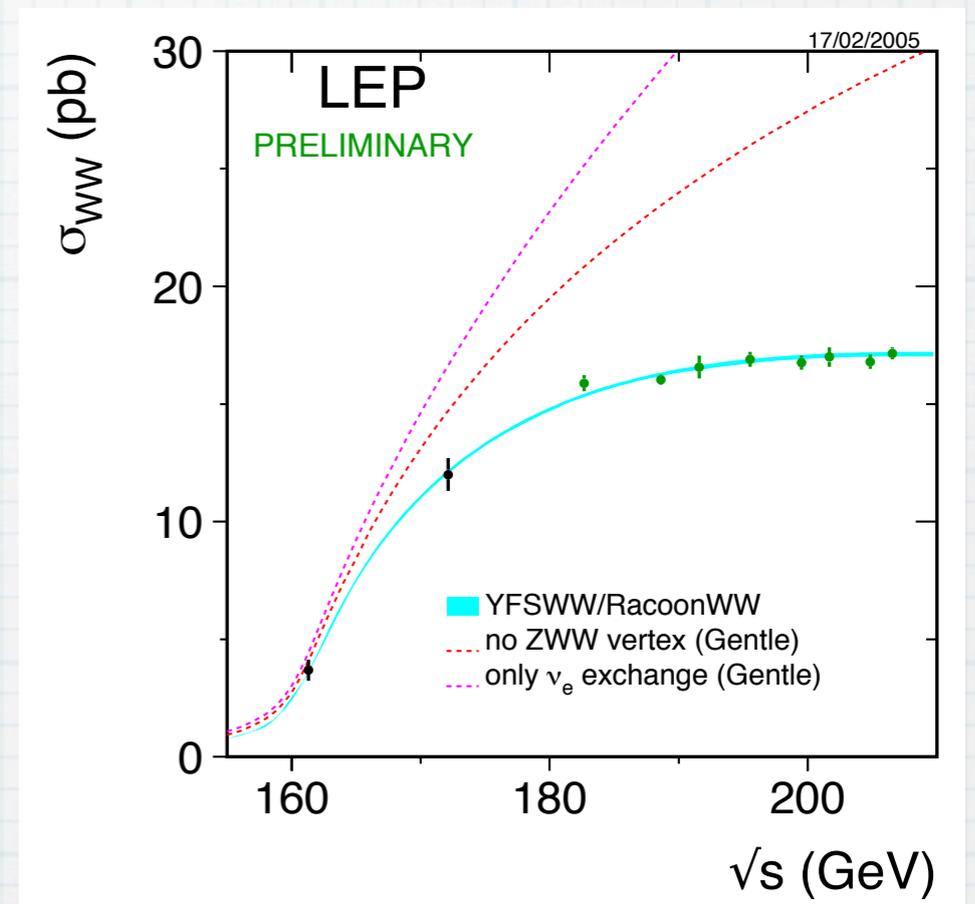
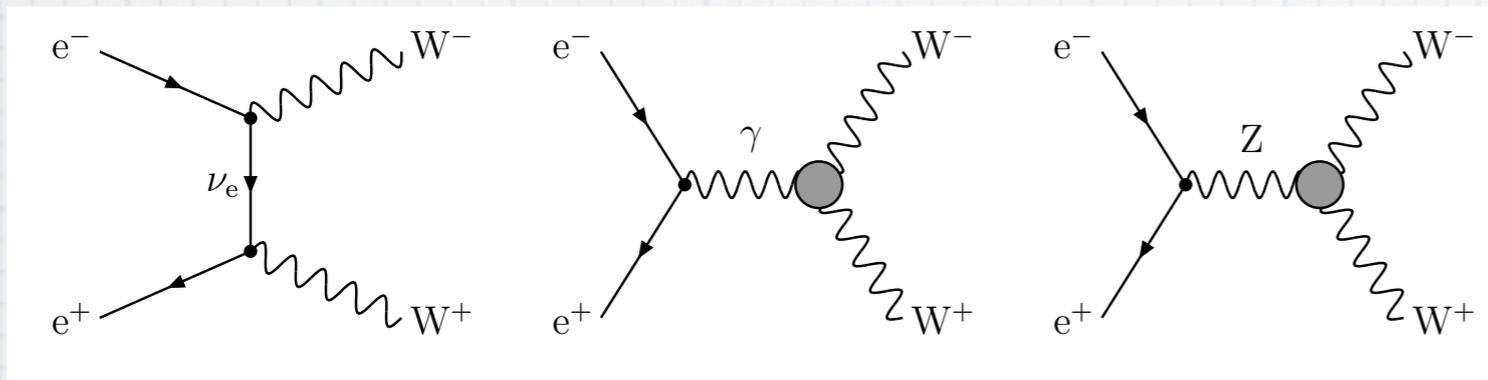
❖ Point-like (?) particle



GWS model

Very unnatural,  
however...

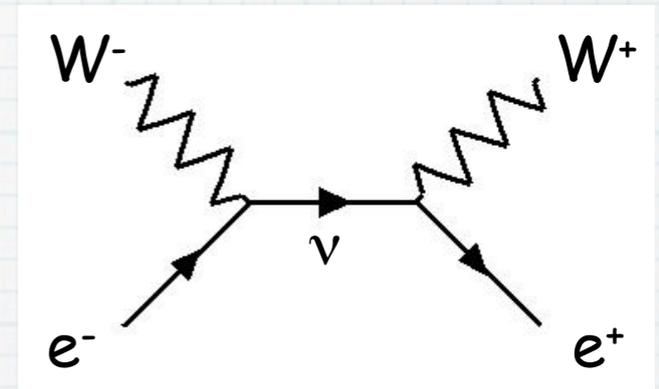
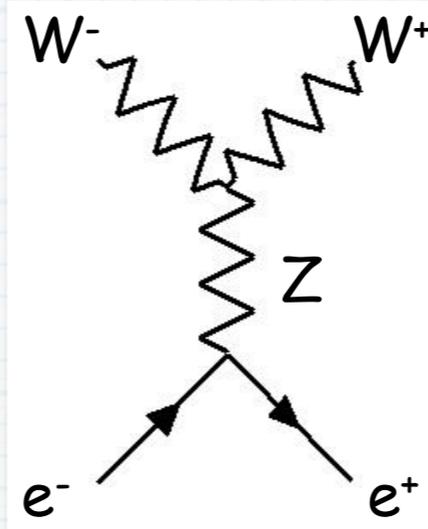
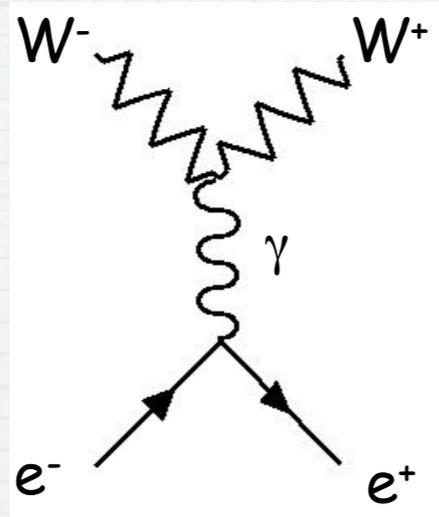
# Gauge Cancellation



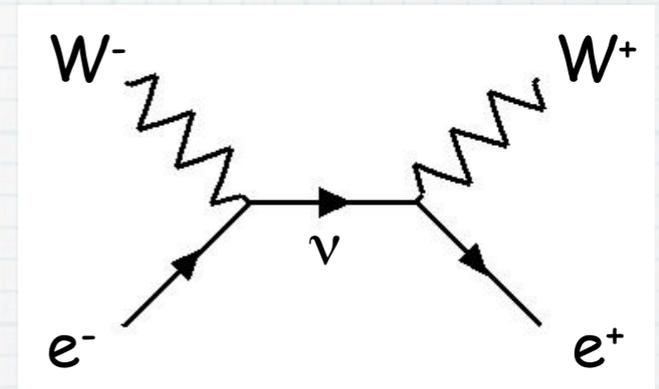
❖ Strong evidence of correctness of gauge theory

# Another Gauge Cancellation

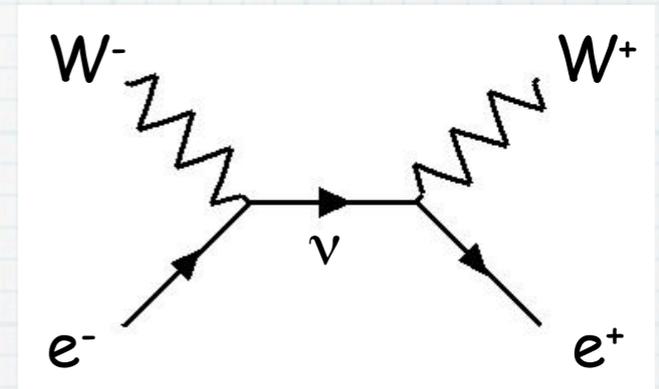
Spin 1



# Another Gauge Cancellation

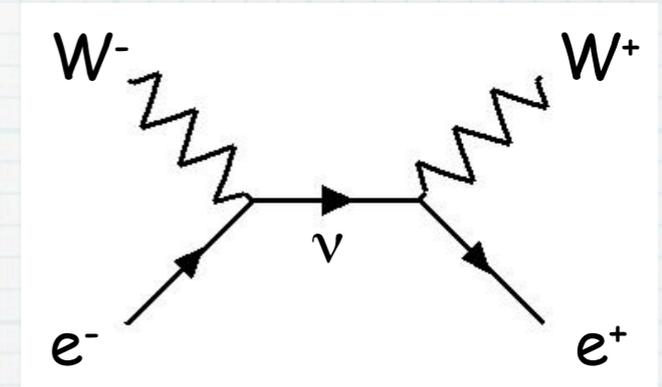
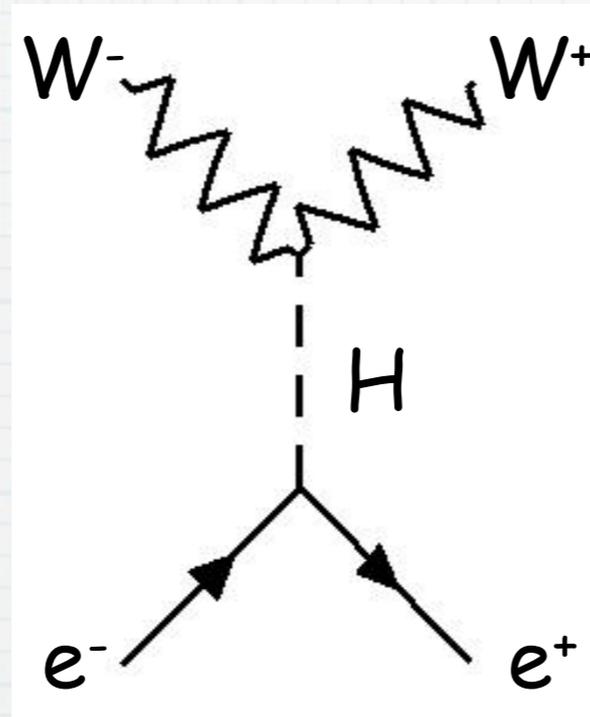


# Another Gauge Cancellation



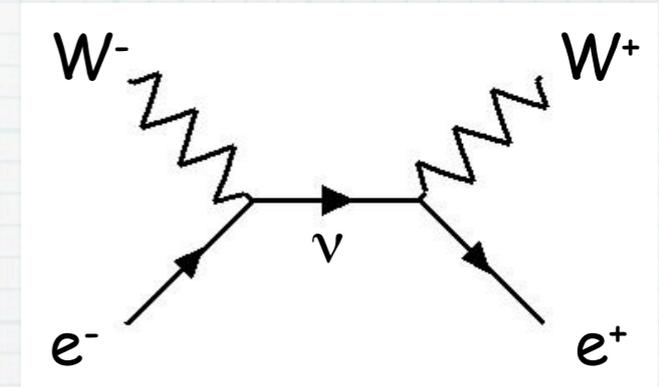
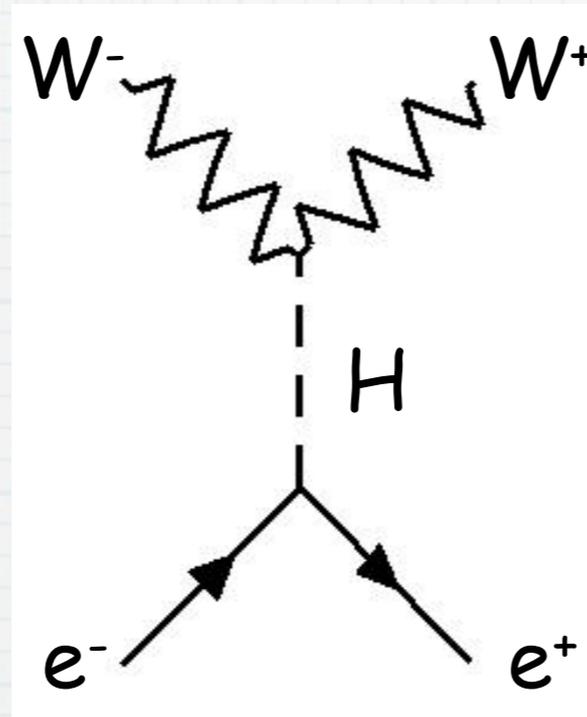
Spin 0  
from wrong  
helicity state

# Another Gauge Cancellation



Spin 0  
from wrong  
helicity state

# Another Gauge Cancellation



Spin 0  
from wrong  
helicity state

- ❖ Wrong helicity state  $\propto m_e$
- ❖  $eeH$  coupling  $\propto m_e$   
 $\Leftarrow$  very well modeled?

$$\begin{aligned}
\mathcal{L} = & \bar{\nu}(i \not{\partial} - m_\nu)\nu + \bar{l}(i \not{\partial} - m_l)l + \frac{1}{2}(\partial_\mu \chi \partial^\mu \chi - \mu^2 \chi^2) \\
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& - \bar{g} Z_\mu [\bar{\nu} \gamma^\mu (s_{\nu L} P_L + s_{\nu R} P_R)\nu + \bar{l} \gamma^\mu (s_{l L} P_L + s_{l R} P_R)l] \\
& + \frac{2v\chi + \chi^2}{4} (g^2 W_{+\mu}^* W_+^\mu + \frac{\bar{g}^2}{2} Z_\mu Z^\mu) \\
& - \frac{m_l}{v} \chi (\bar{l} l) - \frac{m_\nu}{v} \chi (\bar{\nu} \nu) \\
& + \dots
\end{aligned}$$

Find Higgs and measure its property

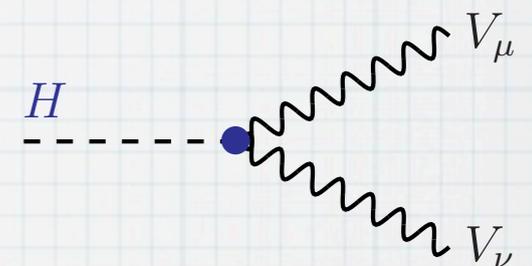
# Considerations in Experiment

# Coupling to Higgs

## ❖ HWW

### ▶ Coupling

$$\frac{g^2}{2}v = gm_W = \frac{e}{\sin \theta_W} m_W$$



## ❖ HZZ

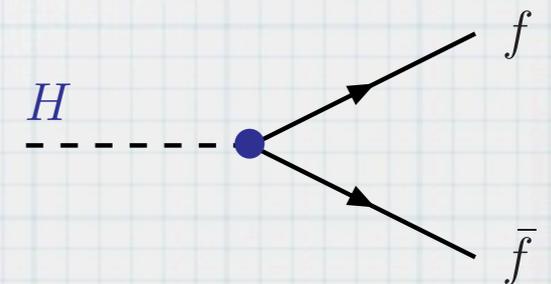
### ▶ Coupling

$$\frac{\bar{g}^2}{4}v = \frac{gm_Z}{\cos \theta_W} = \frac{2e}{\sin(2\theta_W)} m_Z$$

## ❖ Hff

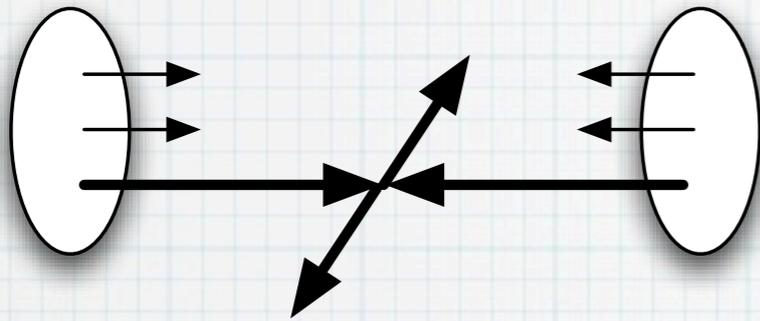
### ▶ Coupling = Yukawa (by definition)

$$Y_f \equiv \frac{\sqrt{2}}{v} m_f$$



In any case, coupling proportional to mass

# What really collides

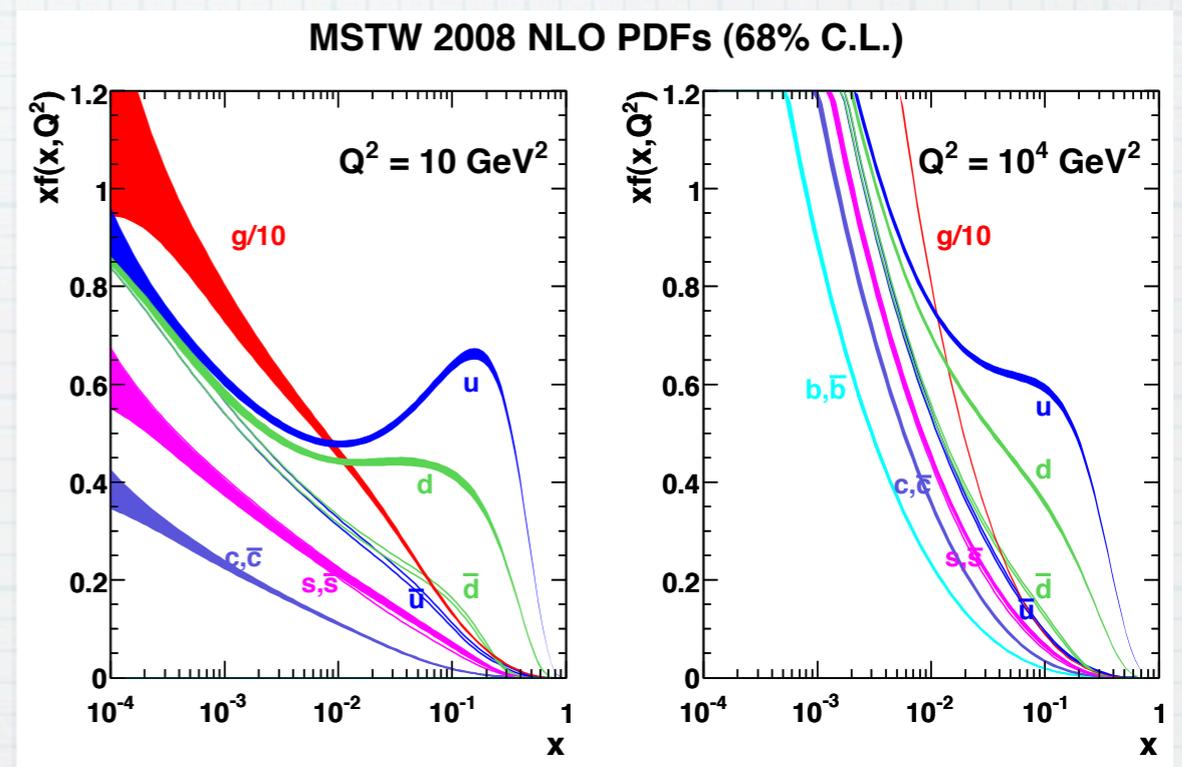


$$\hat{p}_1 = (x_1 E; 0, 0, x_1 E), \quad \hat{p}_2 = (x_2 E; 0, 0, -x_2 E),$$

$$\hat{s}^2 = (x_1 + x_2)^2 E^2 - (x_1 - x_2)^2 E^2 = 4x_1 x_2 E^2$$

$$\therefore \sqrt{\hat{s}} = \sqrt{x_1 x_2} \sqrt{s} \quad (\sqrt{s} = 2E)$$

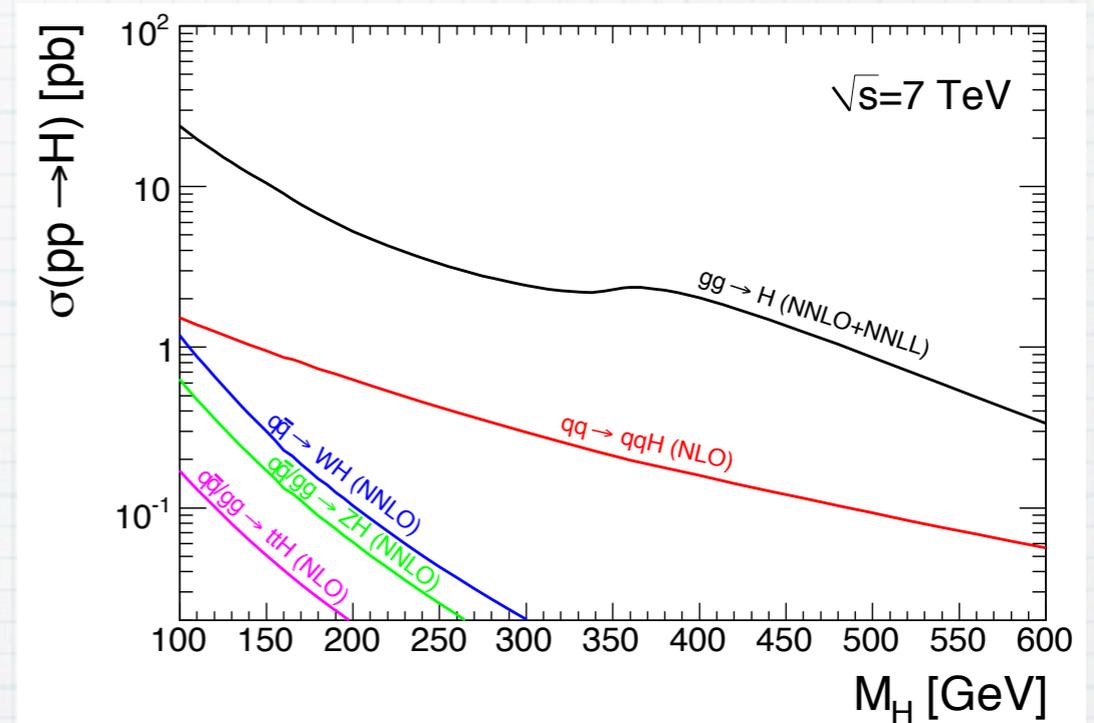
$$\sqrt{\hat{s}} \sim 100 \text{ GeV} \Rightarrow \sqrt{x_1 x_2} \sim 10^{-2}$$



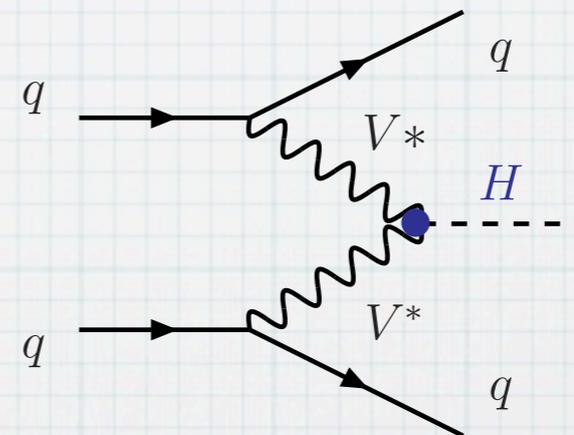
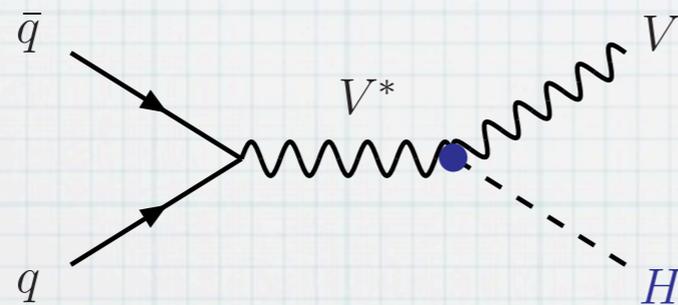
- ❖ gluon collider for light objects
- ❖ quark collider for heavy objects

# Higgs Production at LHC

- ❖ Coupling  $\propto$  mass
  - ▶ top the largest among fermions
- ❖ Gauge boson relatively larger

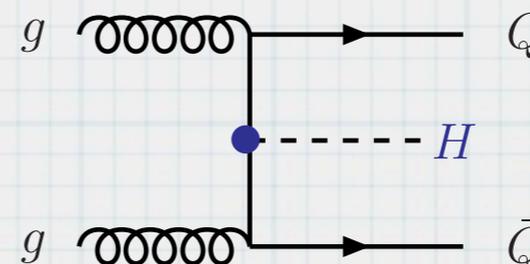
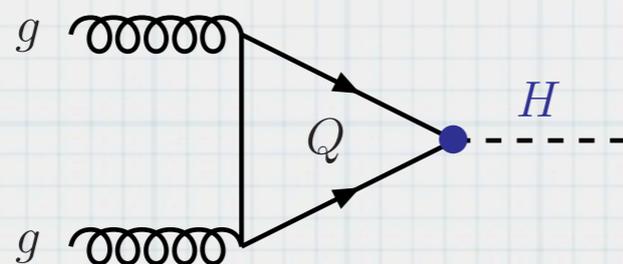


associated production of vector boson



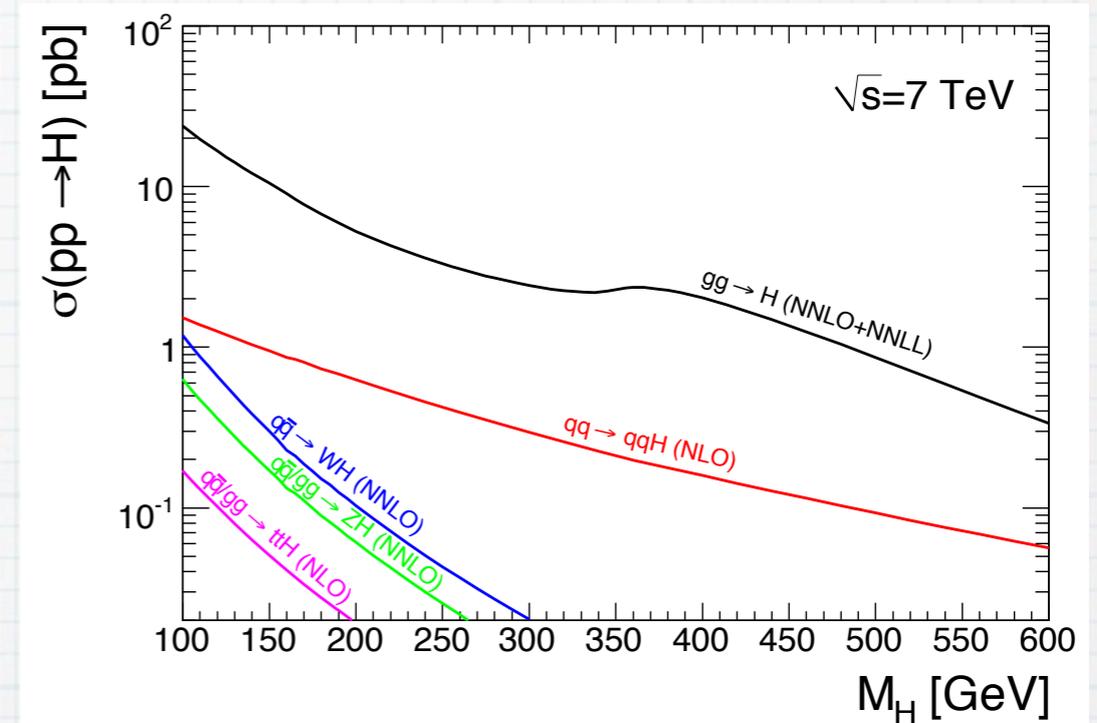
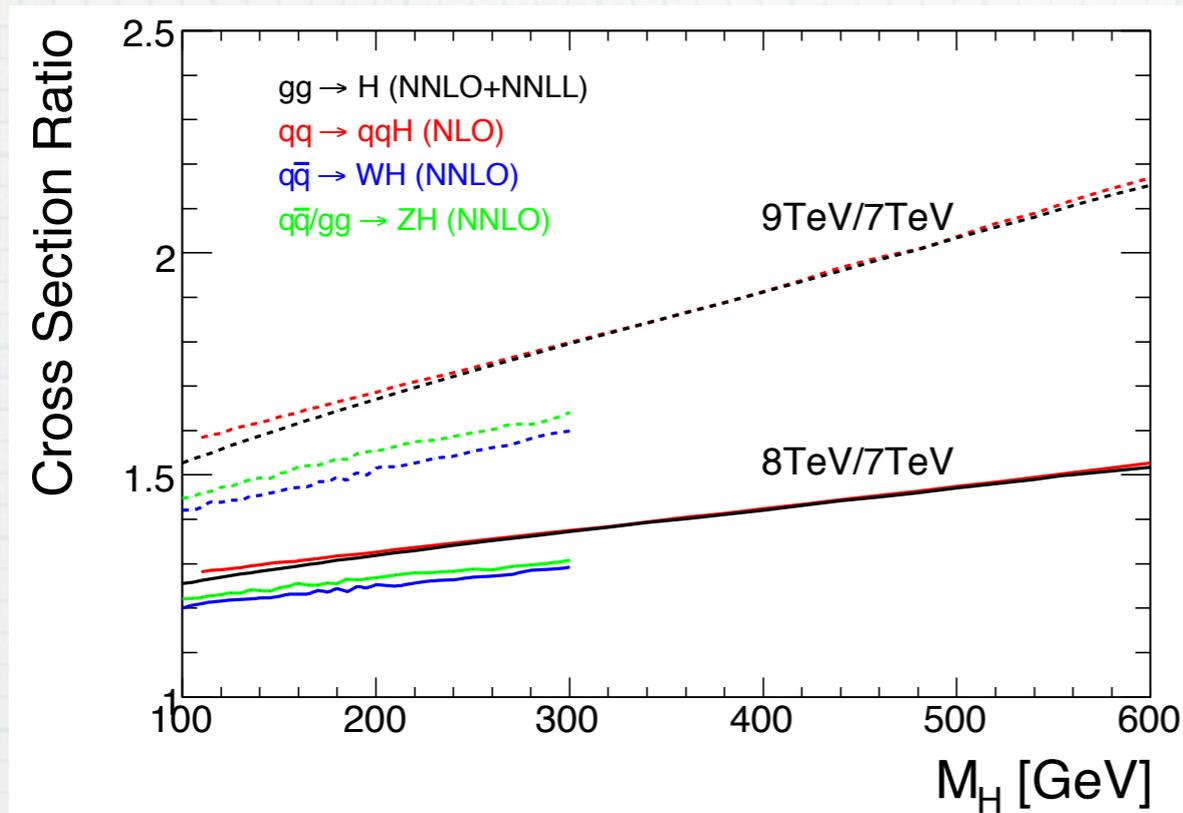
vector boson fusion (VBF)

gluon fusion (GF)

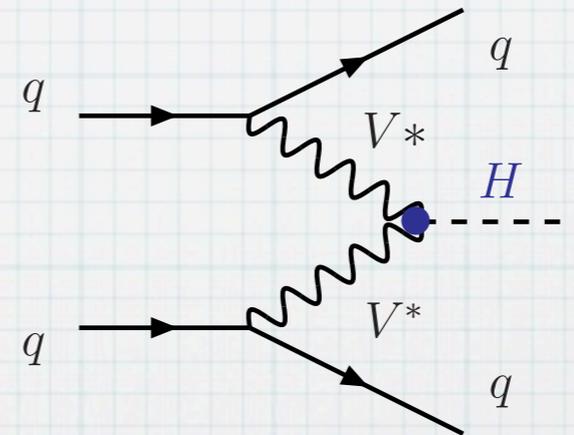
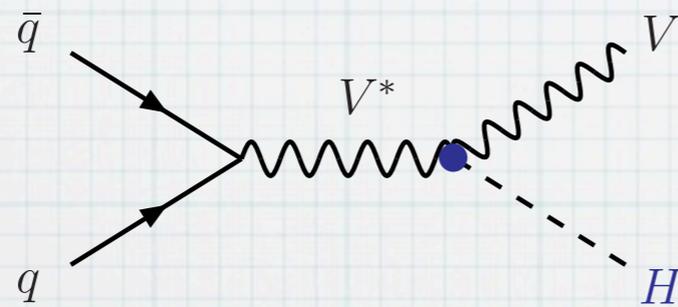


associated production of heavy quark (t, b)

# Higgs Production at LHC

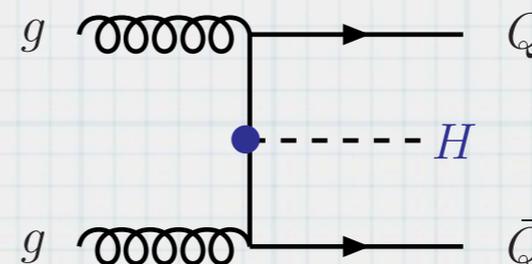
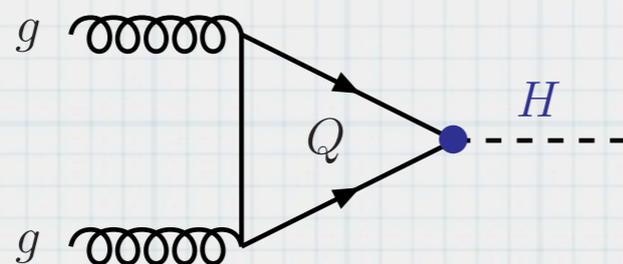


associated production of vector boson



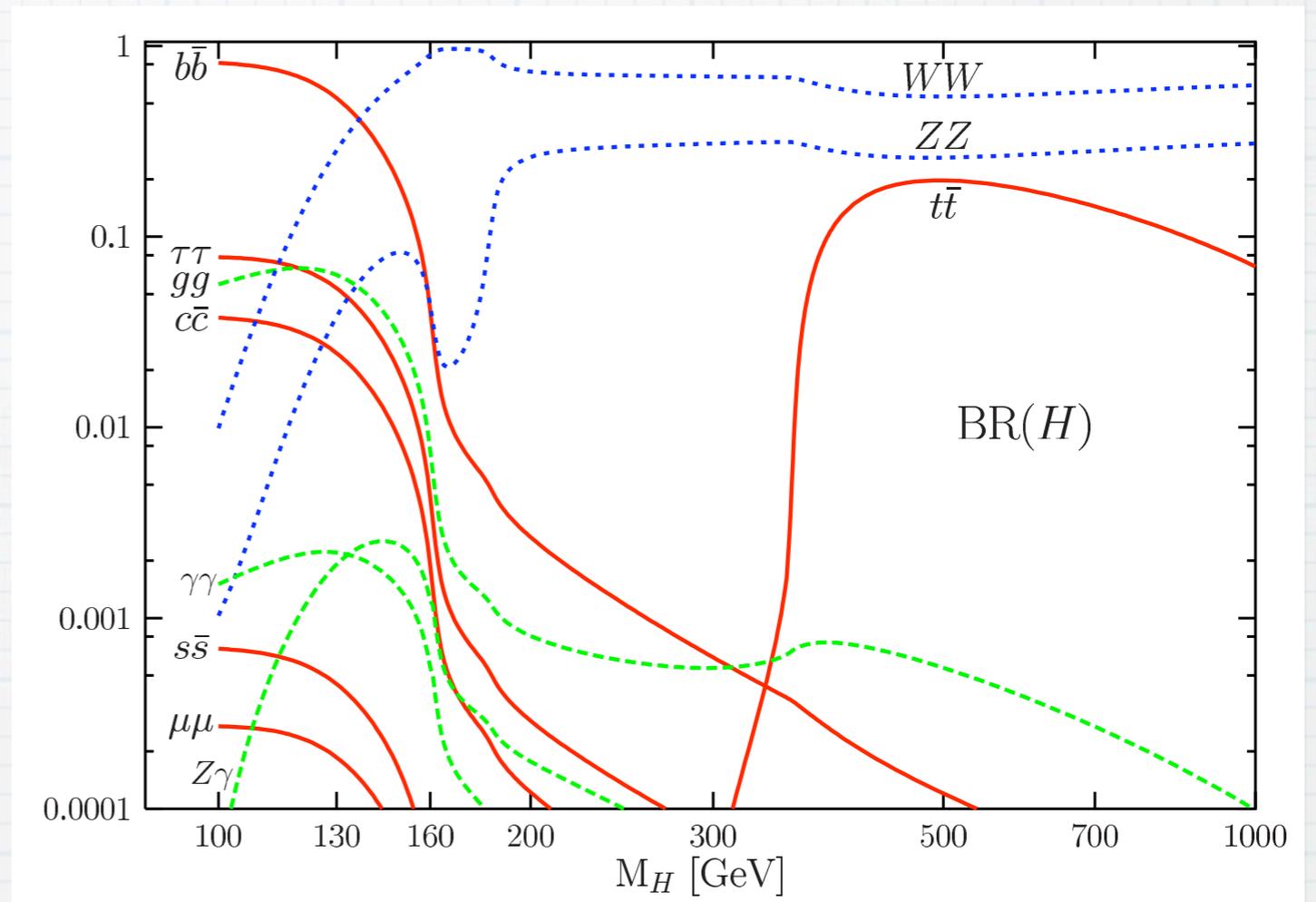
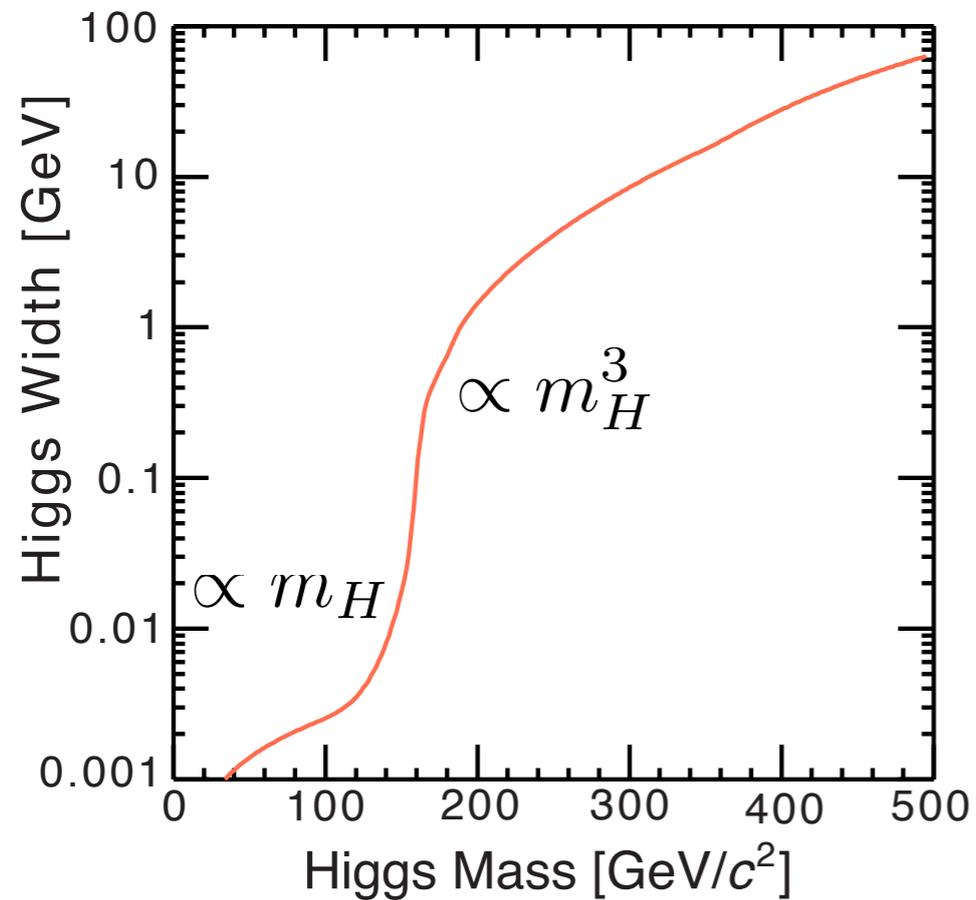
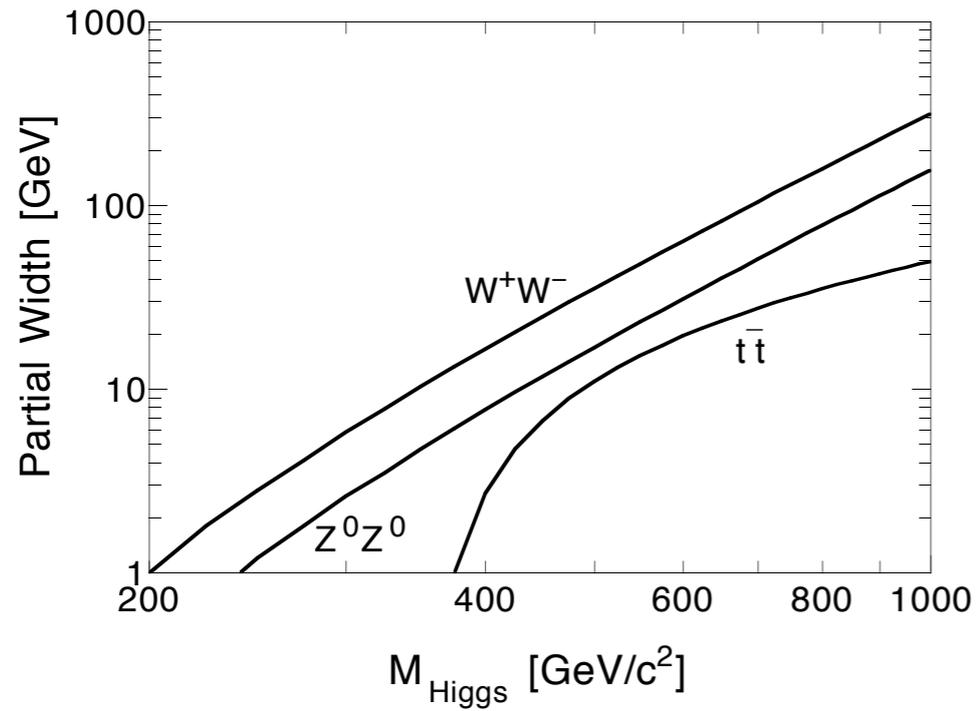
vector boson fusion (VBF)

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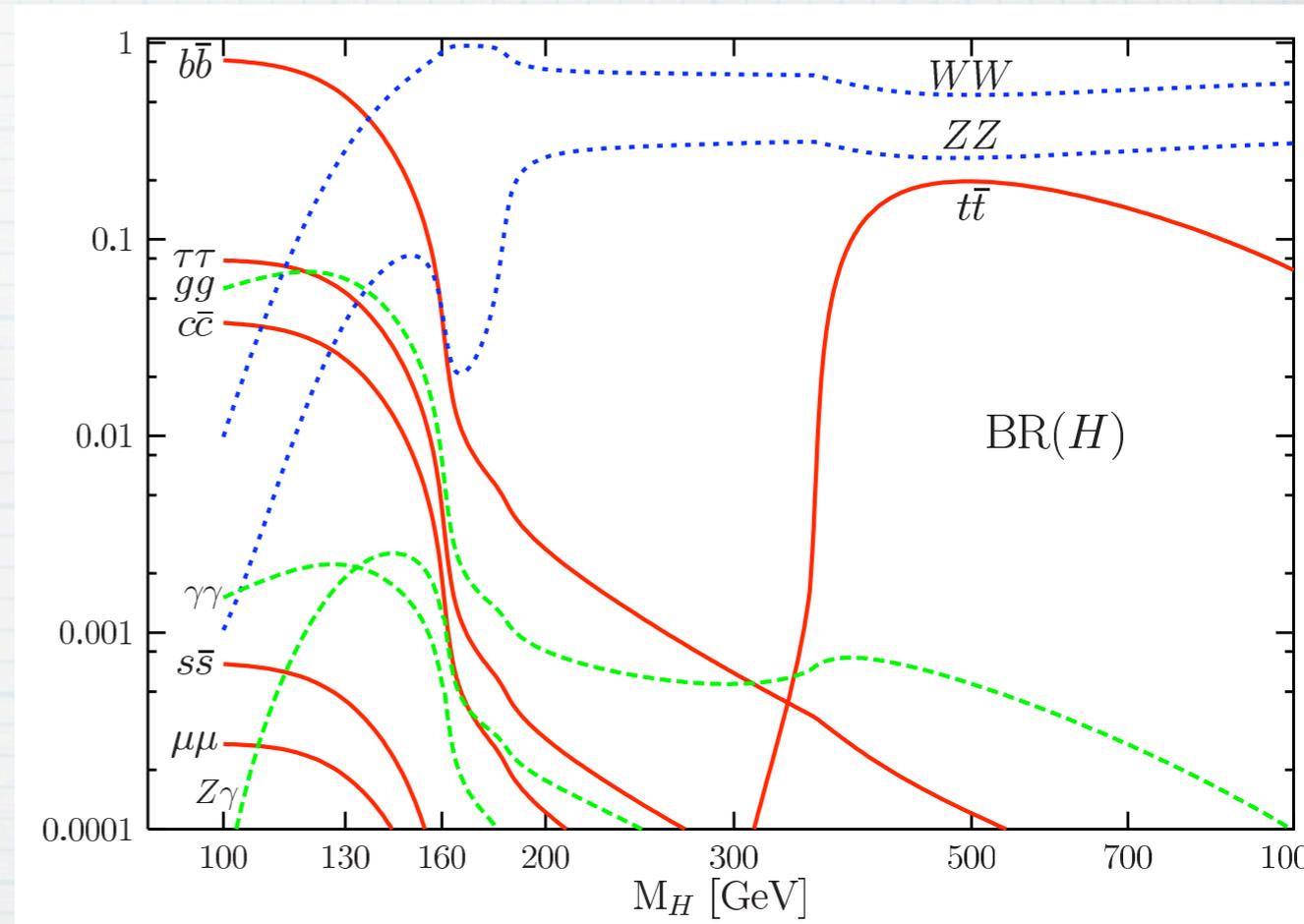
# Decay of Higgs



- ❖  $\Gamma$  (vector boson)  $\propto m_H^3$
- ❖  $\Gamma$  (fermion)  $\propto m_H$

# Rough Strategy

- ❖ From Higgs branching ratio
  - ▶ Light Higgs
    - $H \rightarrow b\bar{b}, \tau\tau$
  - ▶ Heavy Higgs
    - $H \rightarrow WW, ZZ$

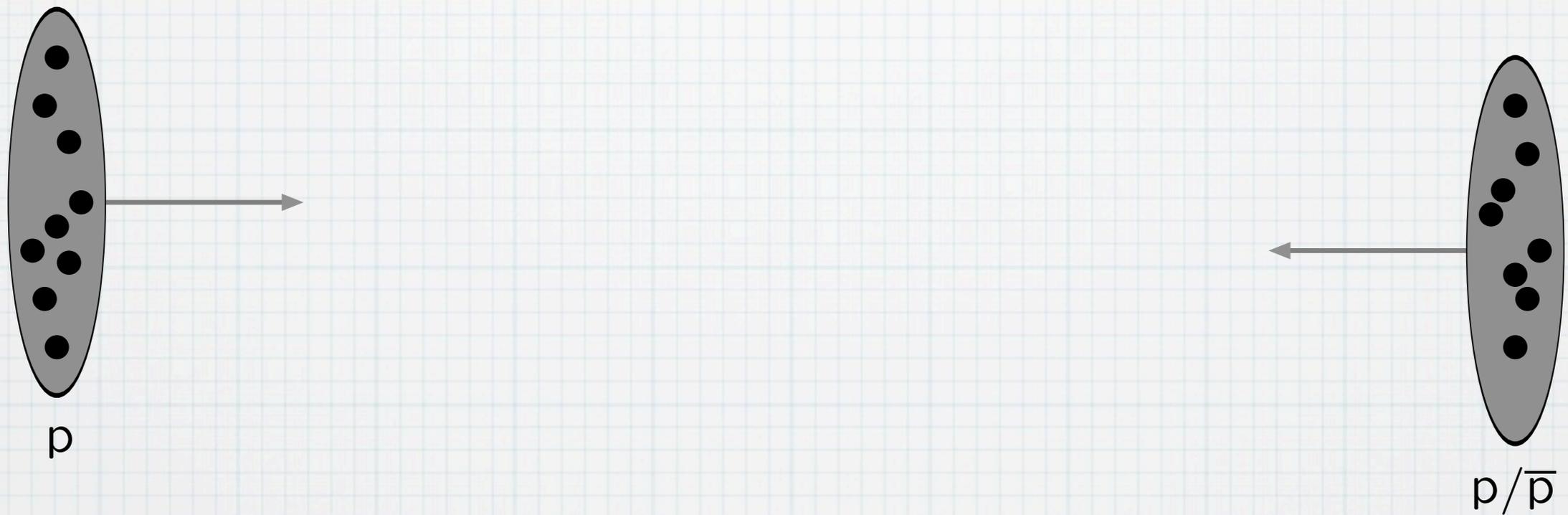


- ❖ With large  $\sigma$  ( $pp \rightarrow H$ )

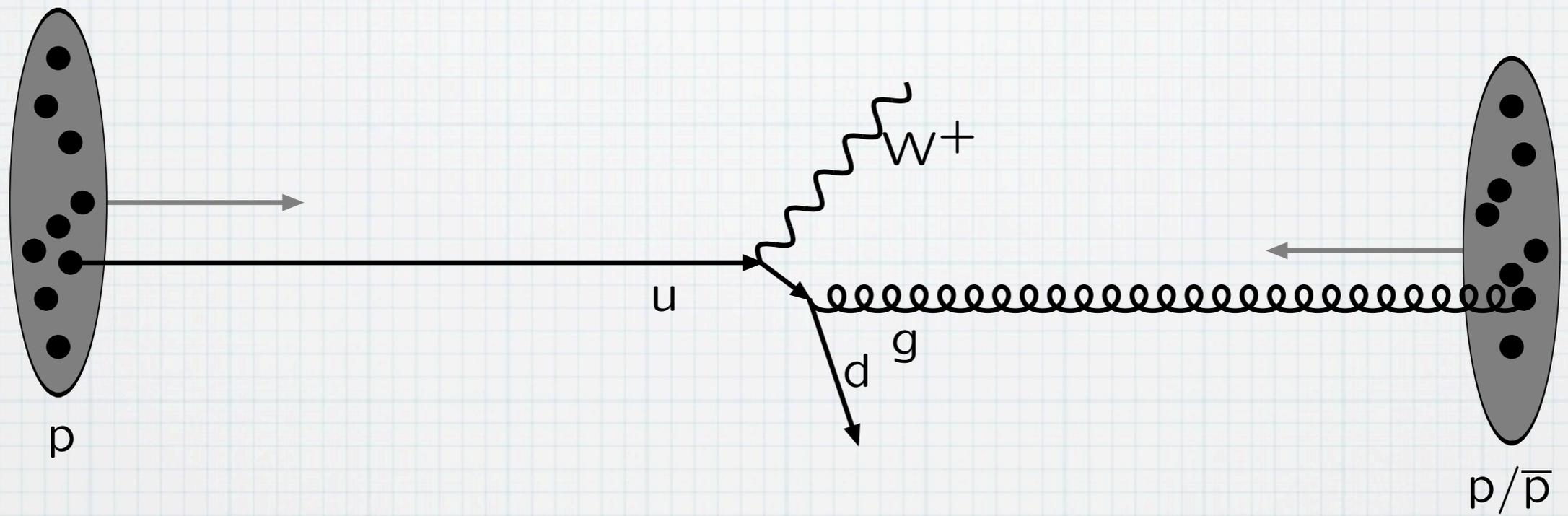
What actually happens  
at hadron collider

# The structure of an event

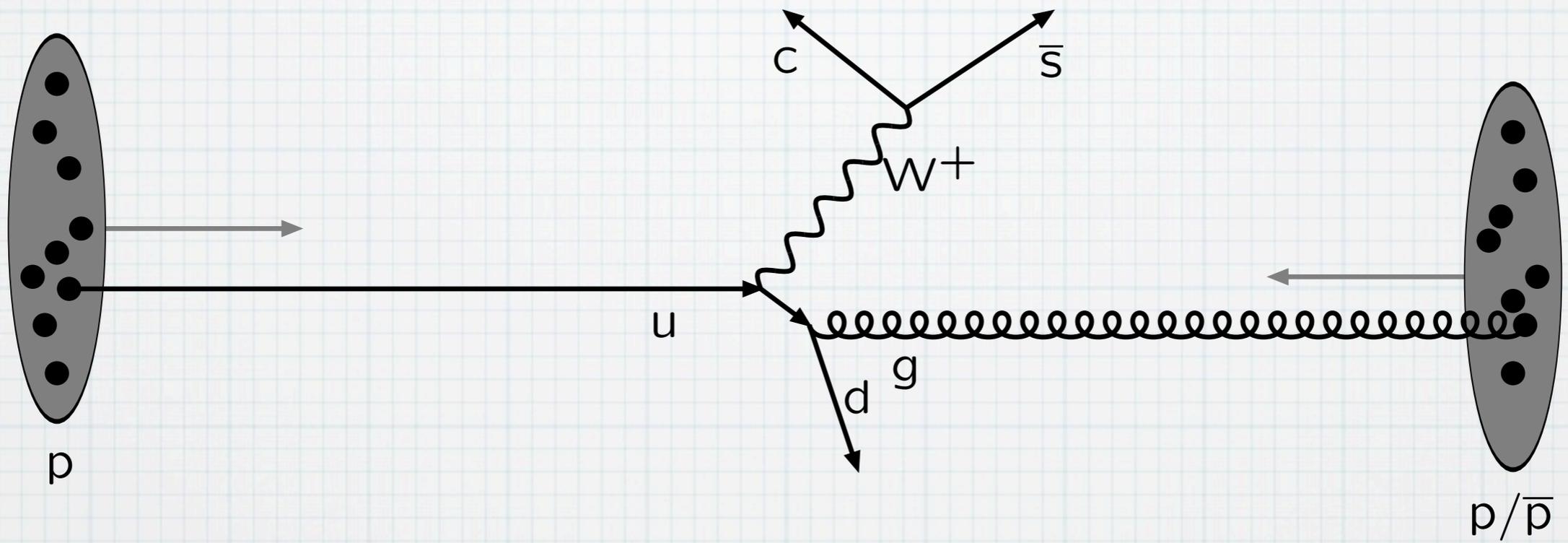
Warning: schematic only, everything simplified, nothing to scale, ...



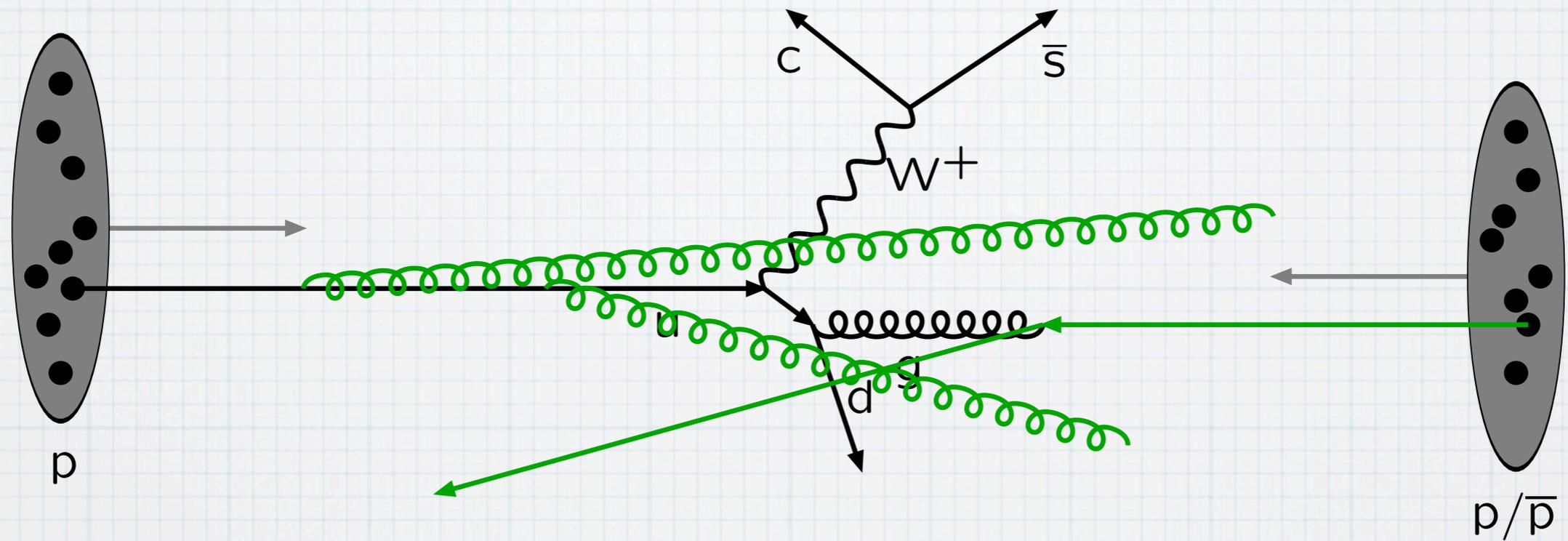
Incoming beams: parton densities



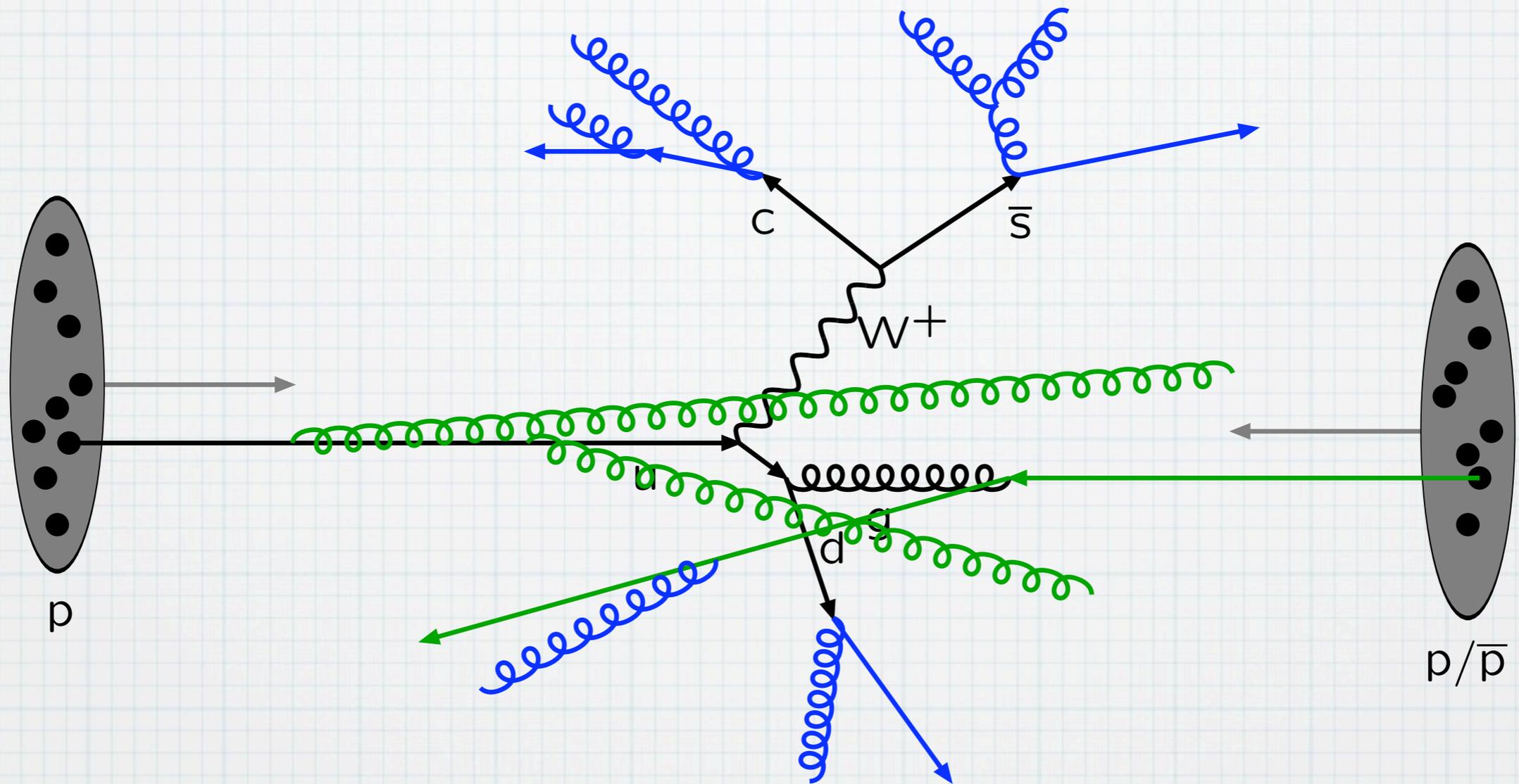
Hard subprocess: described by matrix elements



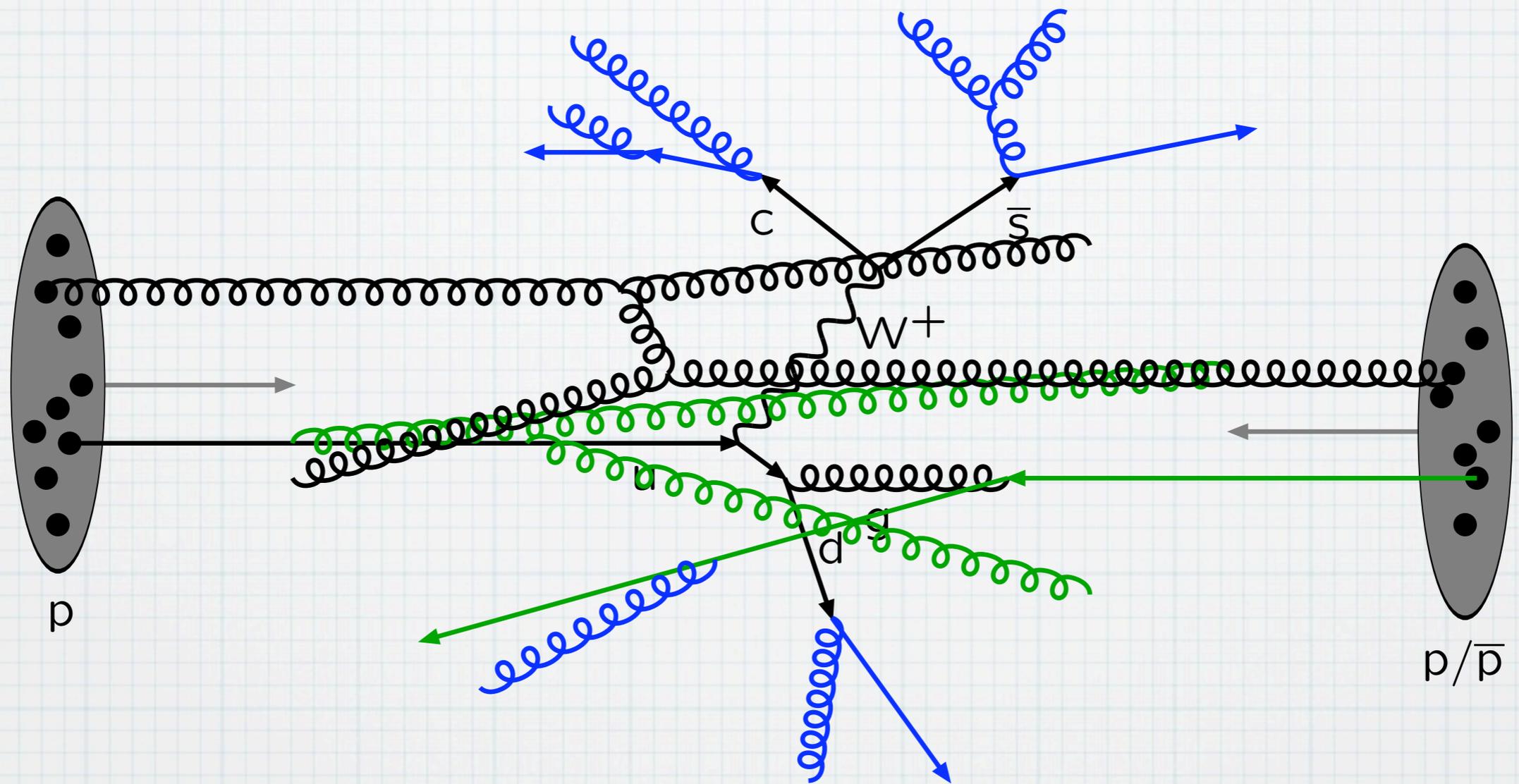
Resonance decays: correlated with hard subprocess



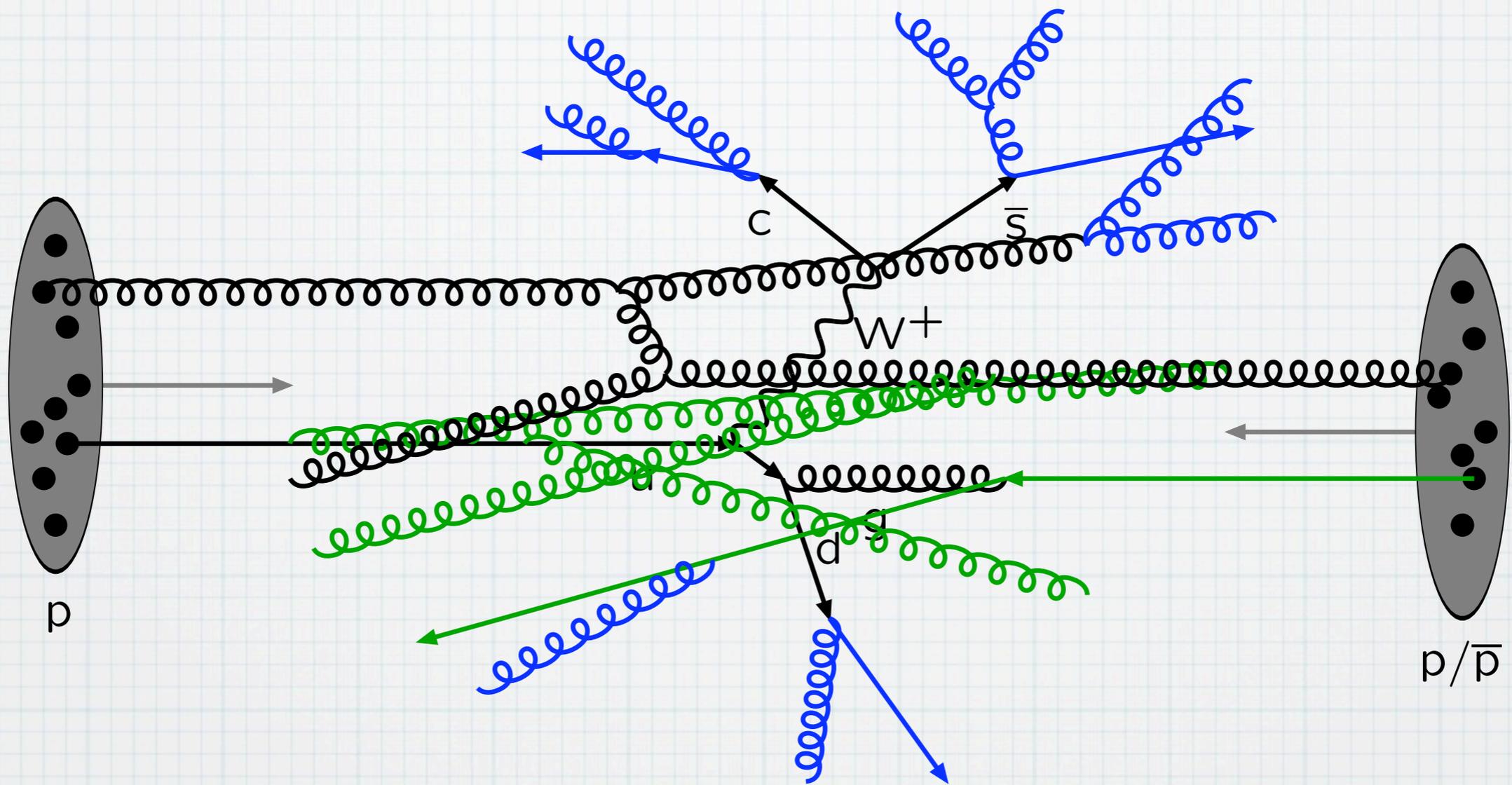
Initial-state radiation: spacelike parton showers



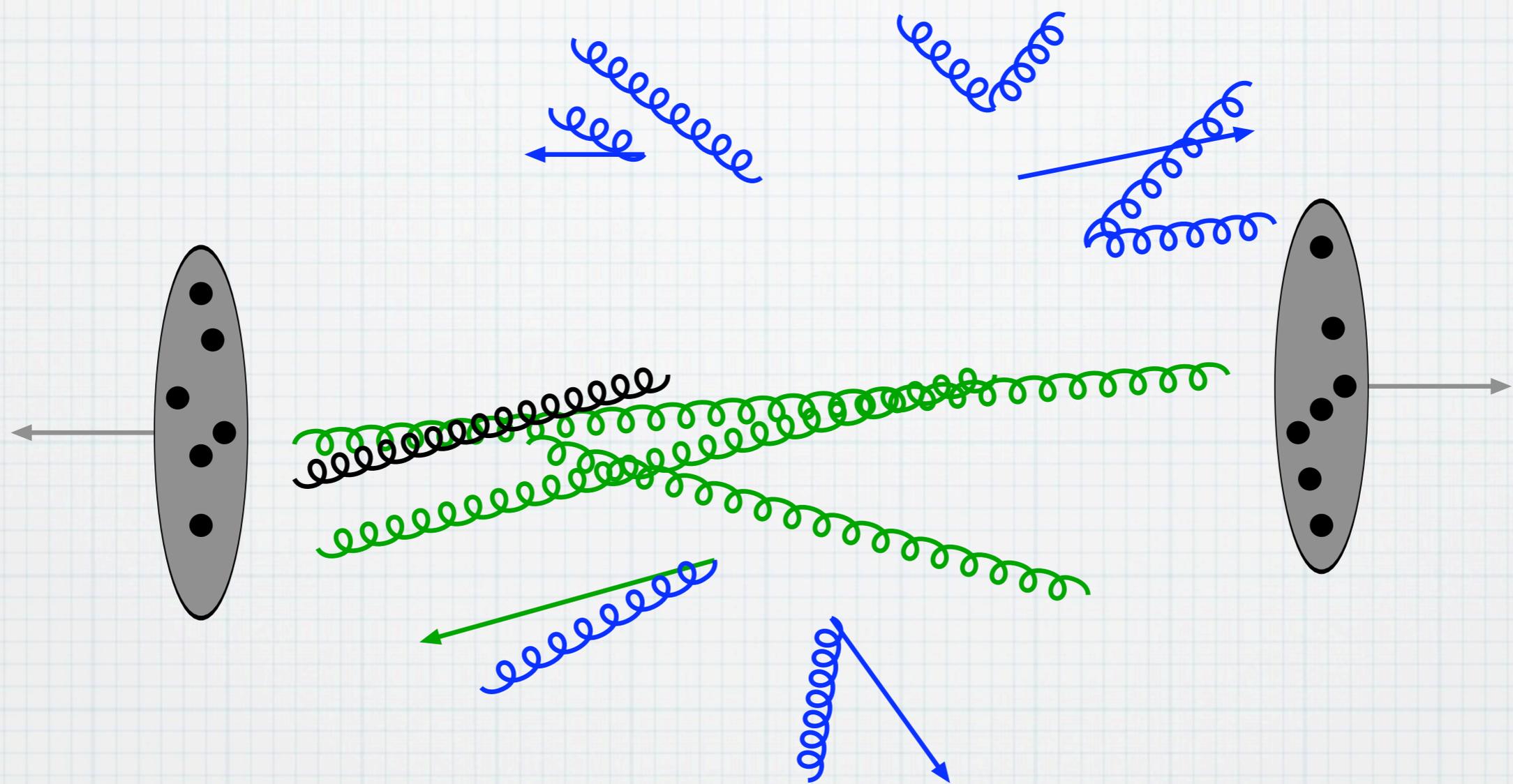
Final-state radiation: timelike parton showers



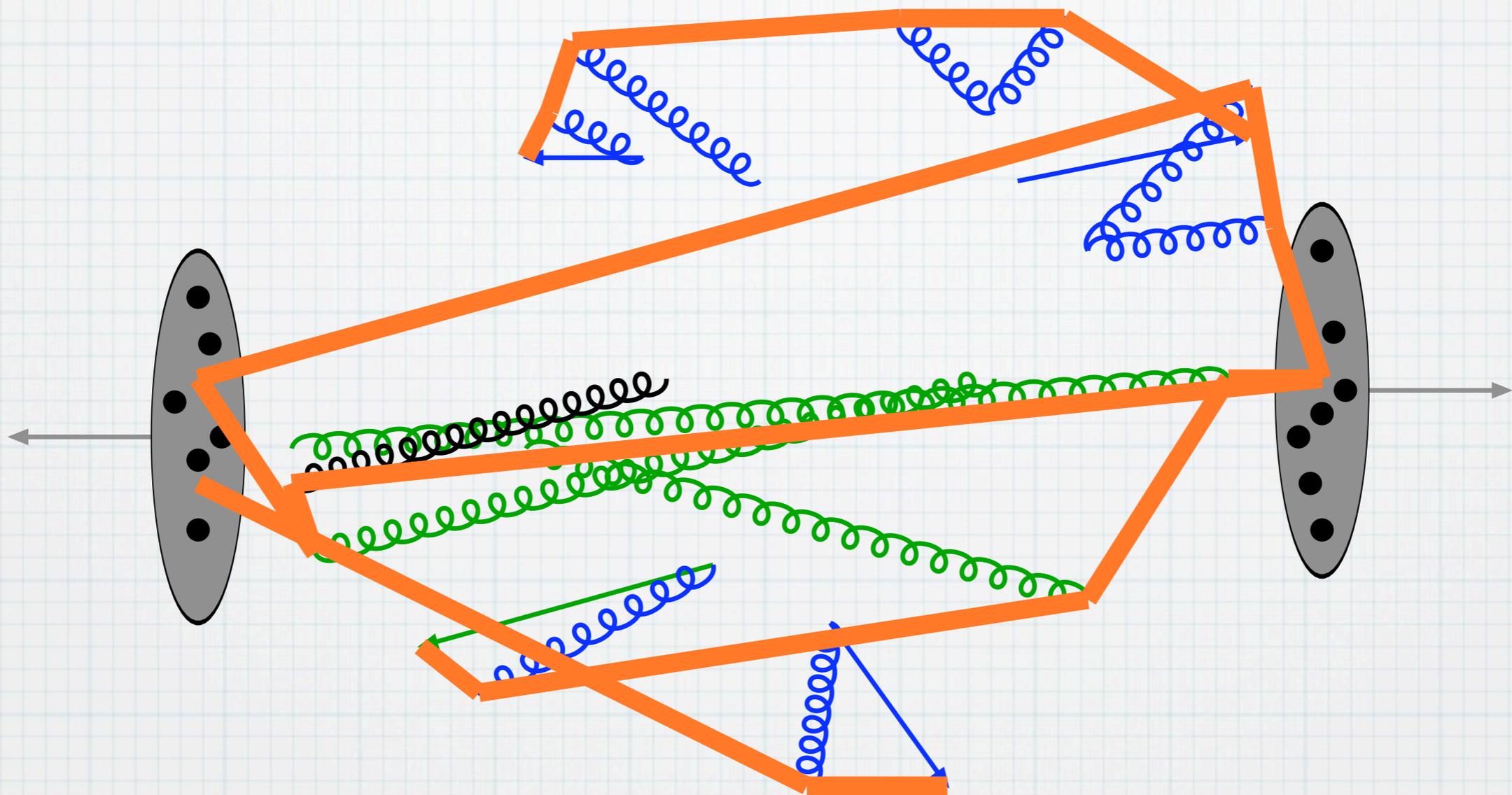
Multiple parton-parton interactions ...



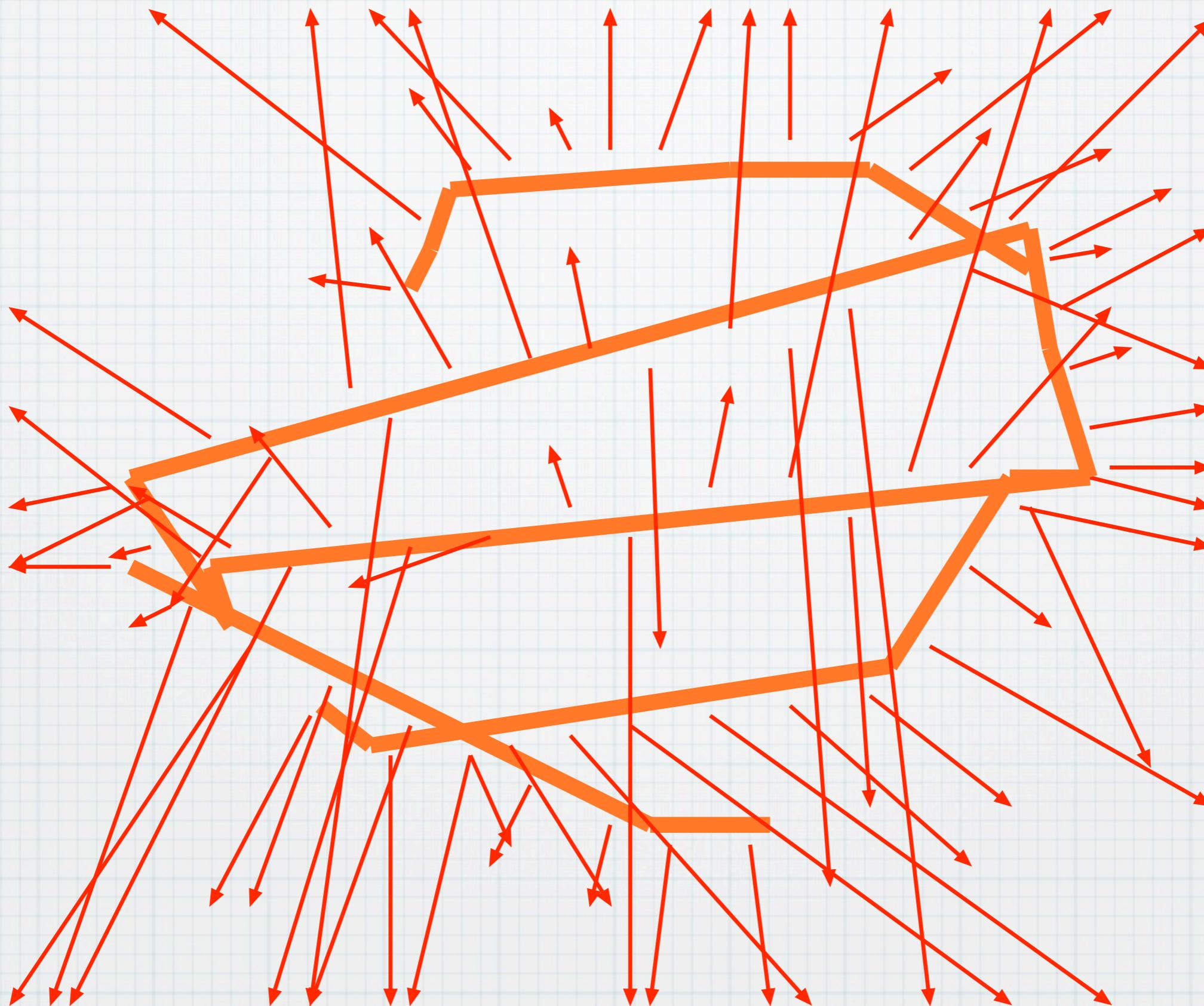
... with its **initial-** and **final-**state radiation



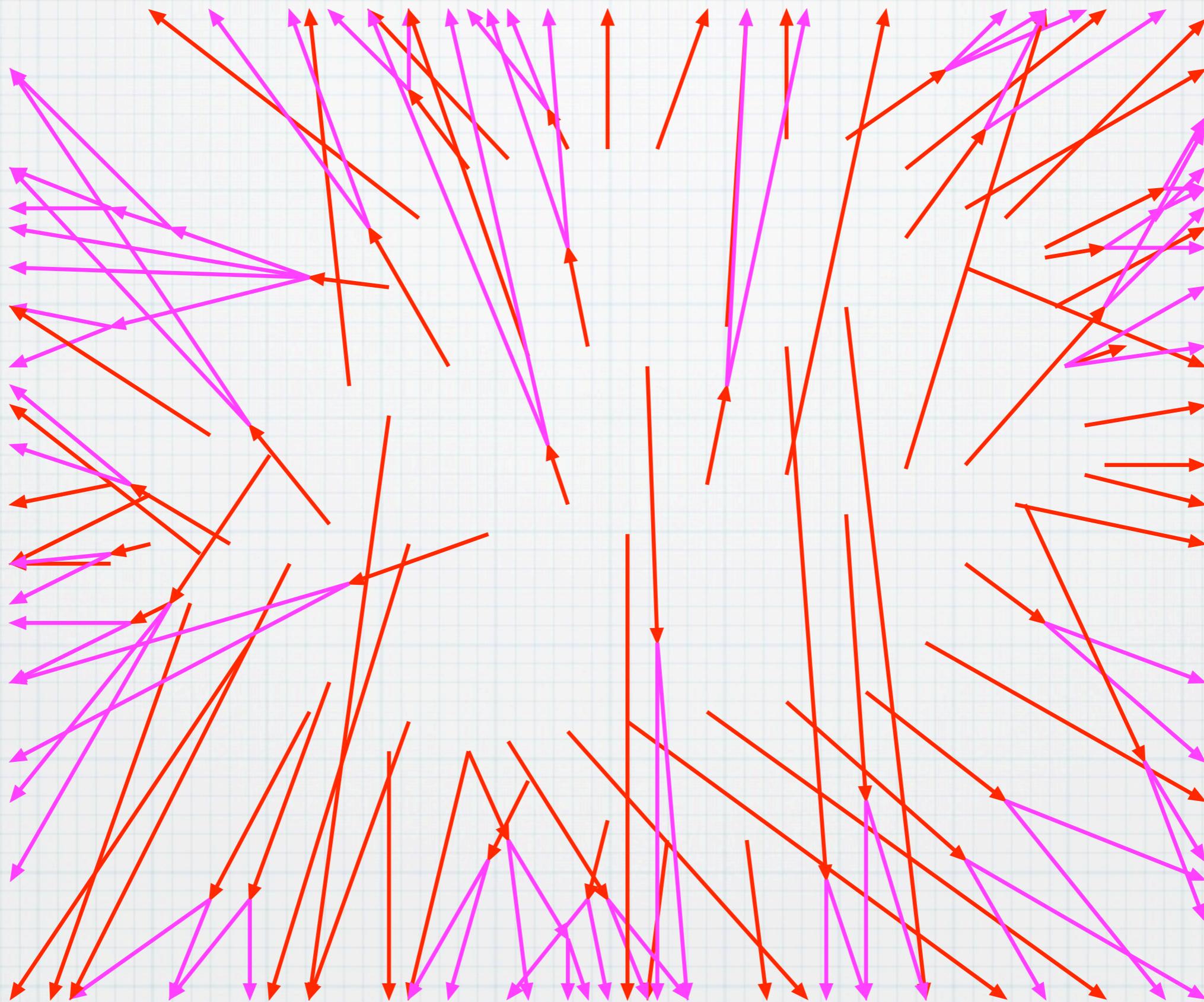
Beam remnants and other outgoing partons



Everything is connected by colour confinement strings  
Recall! Not to scale: strings are of hadronic widths



The strings fragment to produce primary hadrons

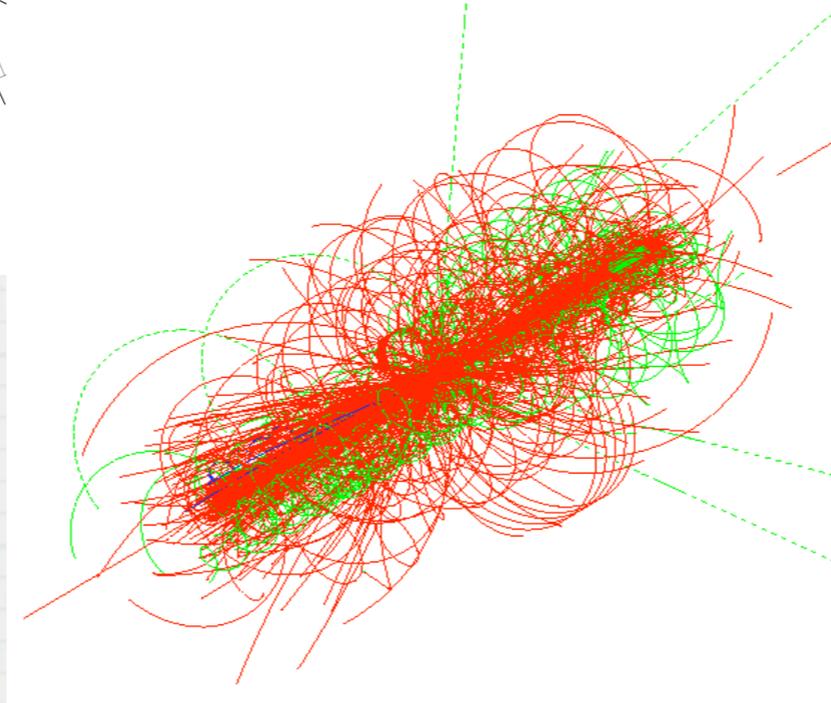
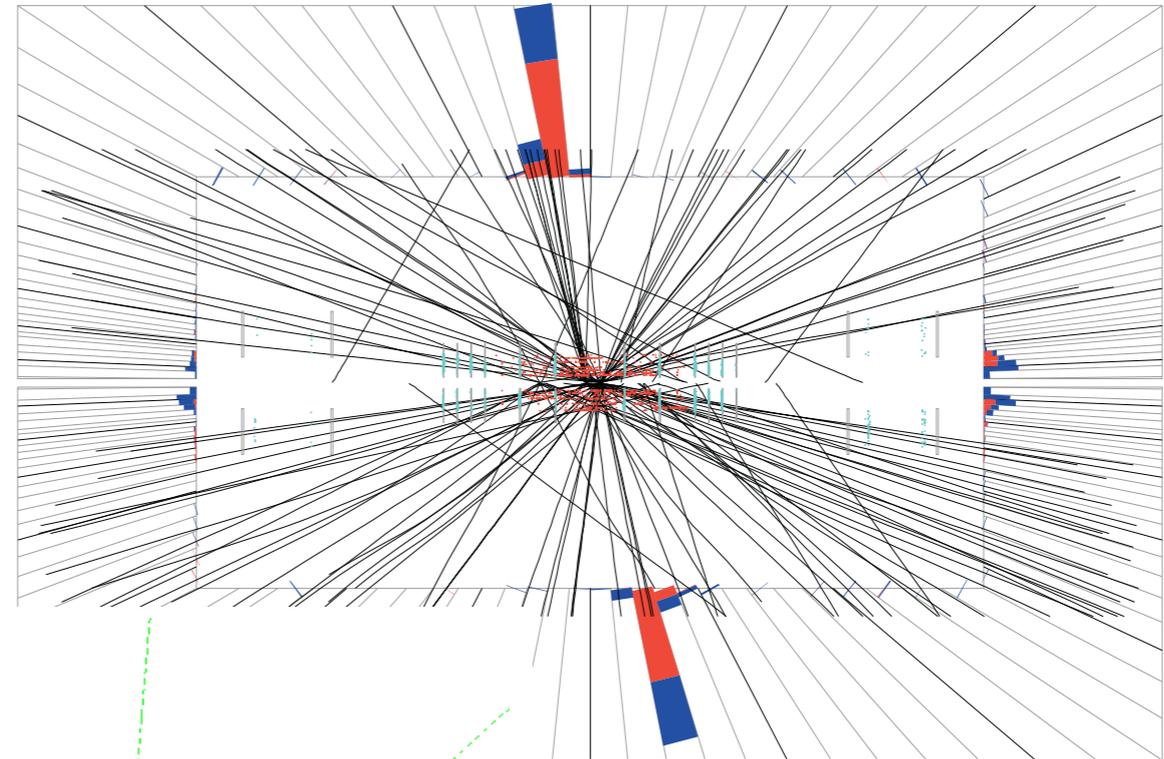
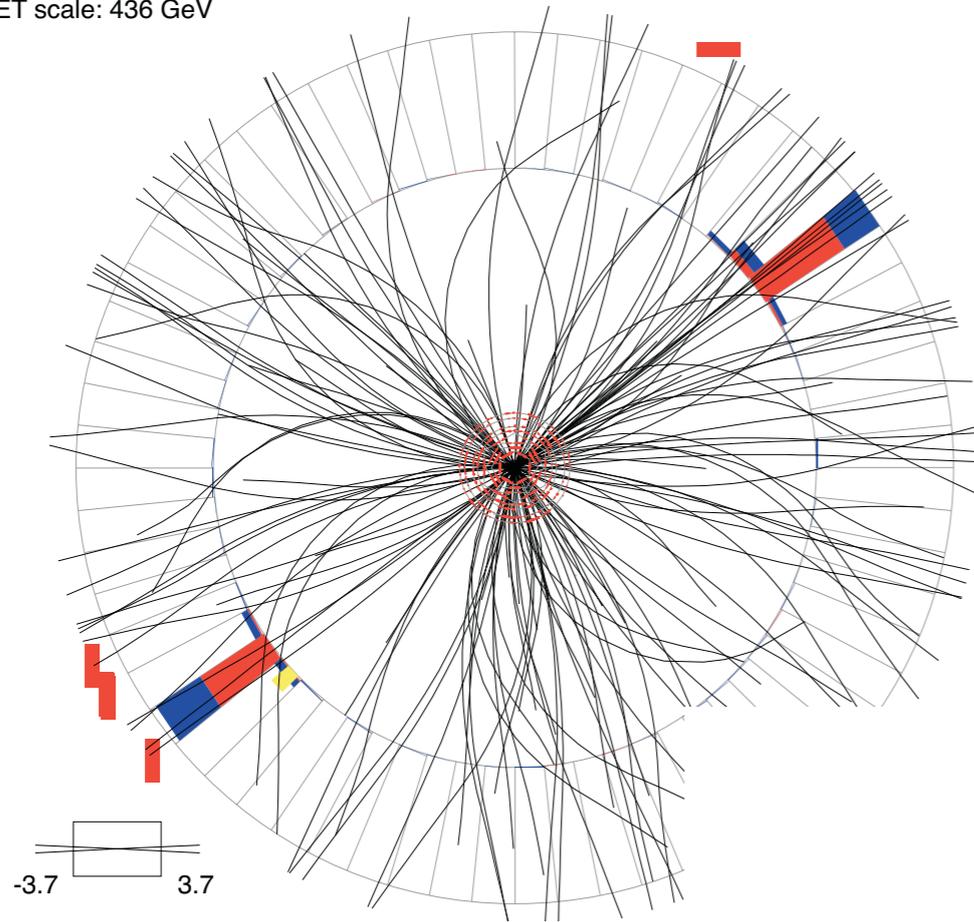


Many hadrons are unstable and decay further

# Real Event at Dzero

E scale: 431 GeV

ET scale: 436 GeV



# Experimental Difficulty

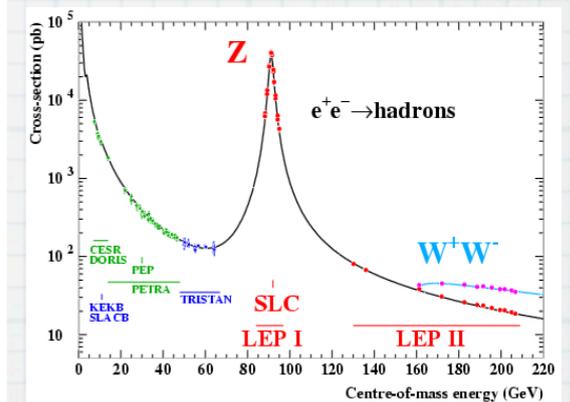
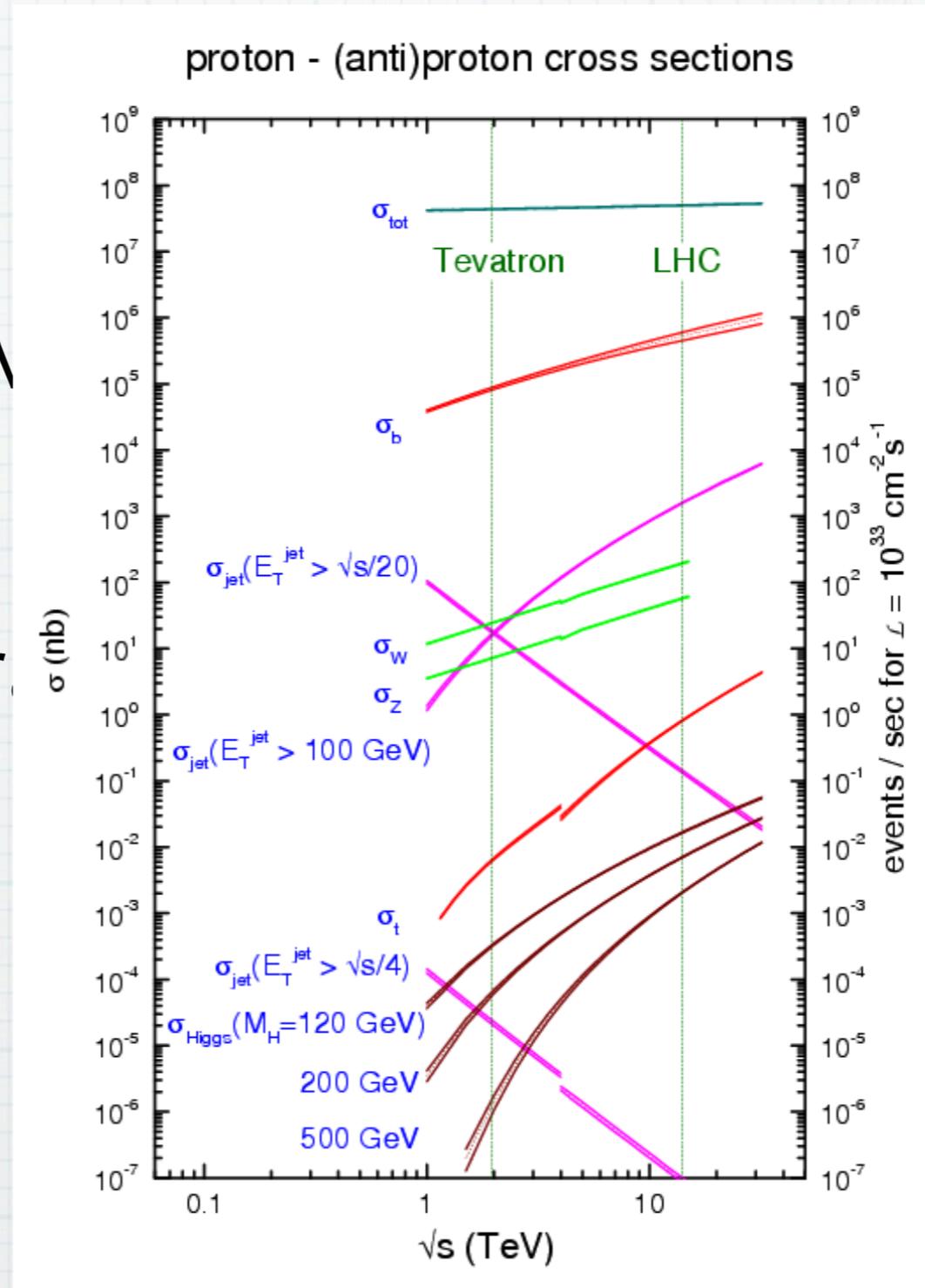
- ❖ Underlying Event
- ❖ Multiple Interactions

# Experimental Difficulty

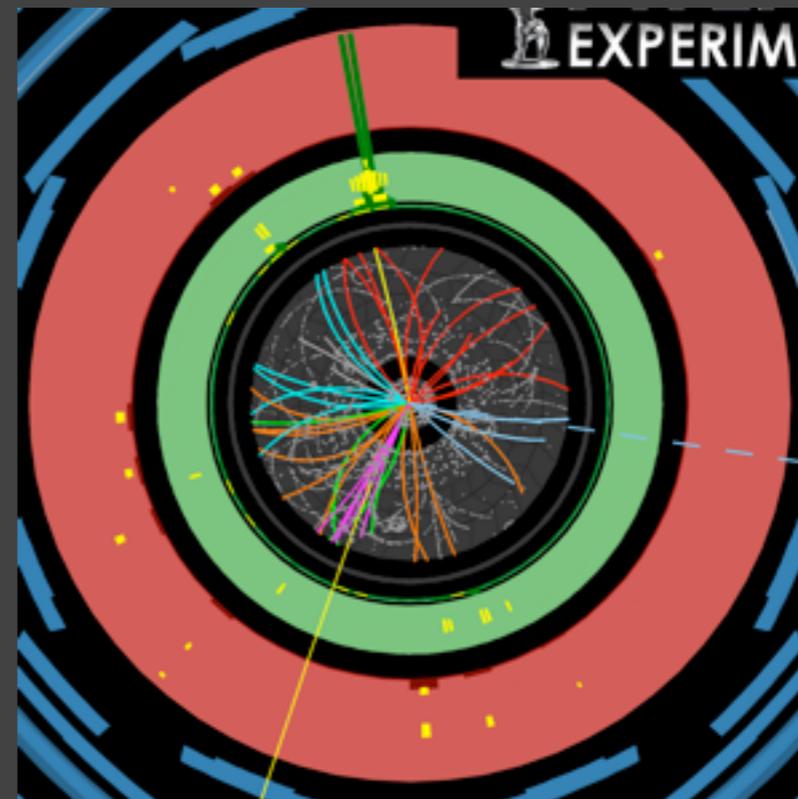
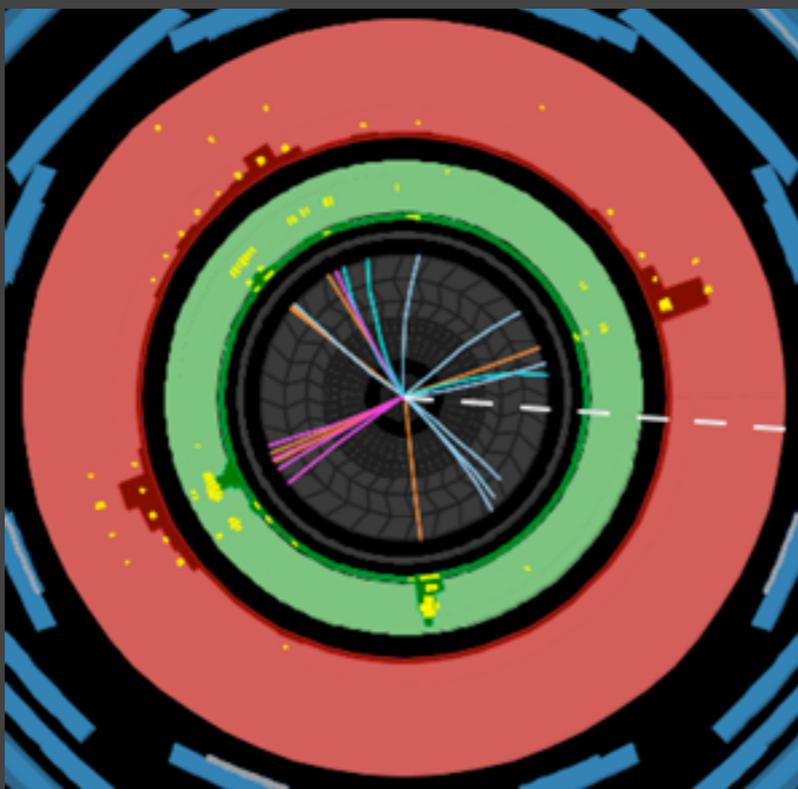
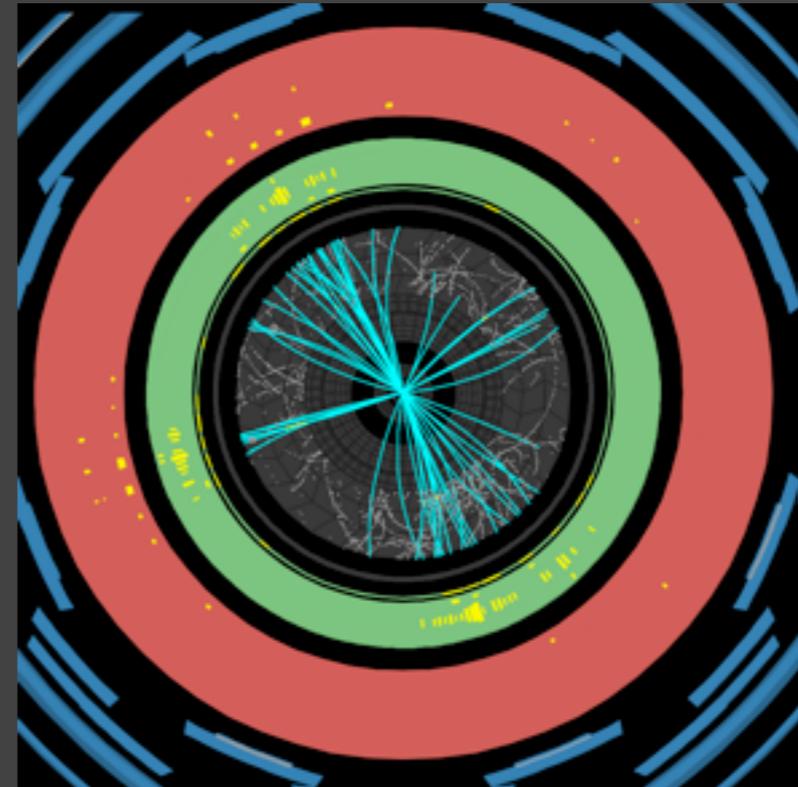
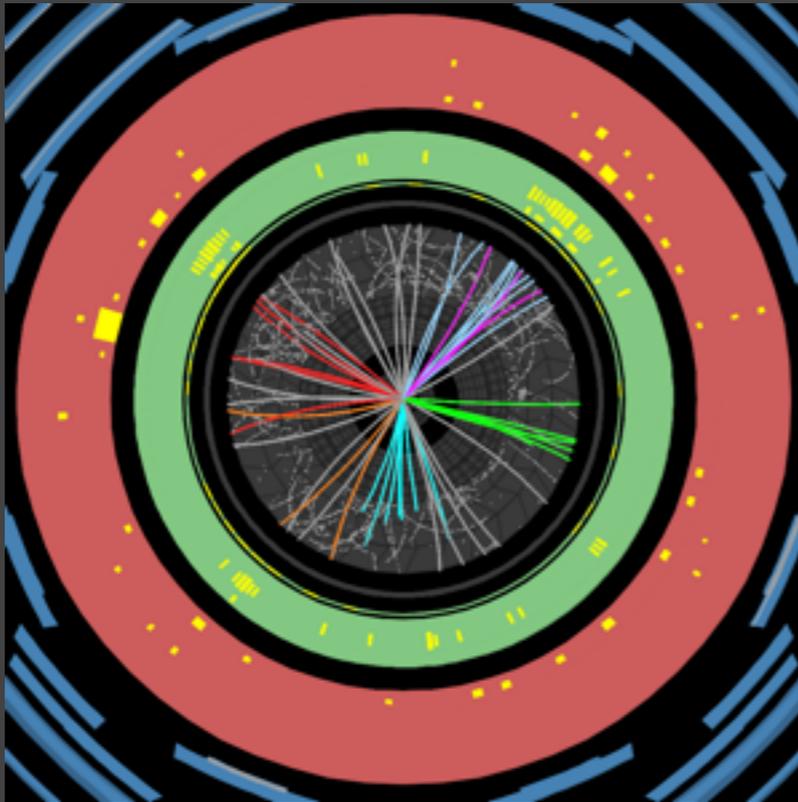
❖ Underlying Events

❖ Multiple Interactions

❖ Low S/N

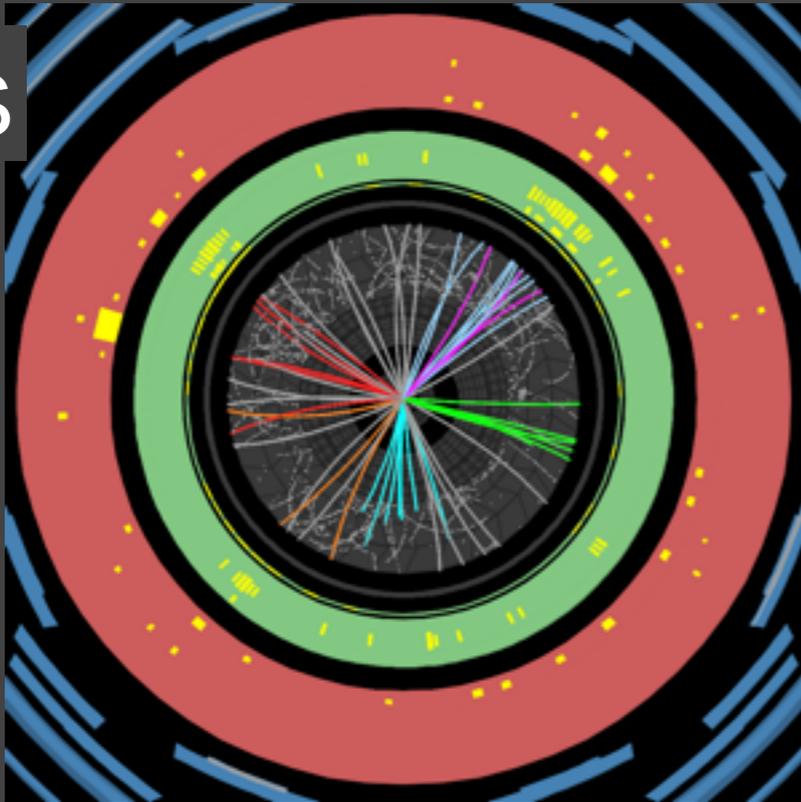


# Can you distinguish?



# Can you distinguish?

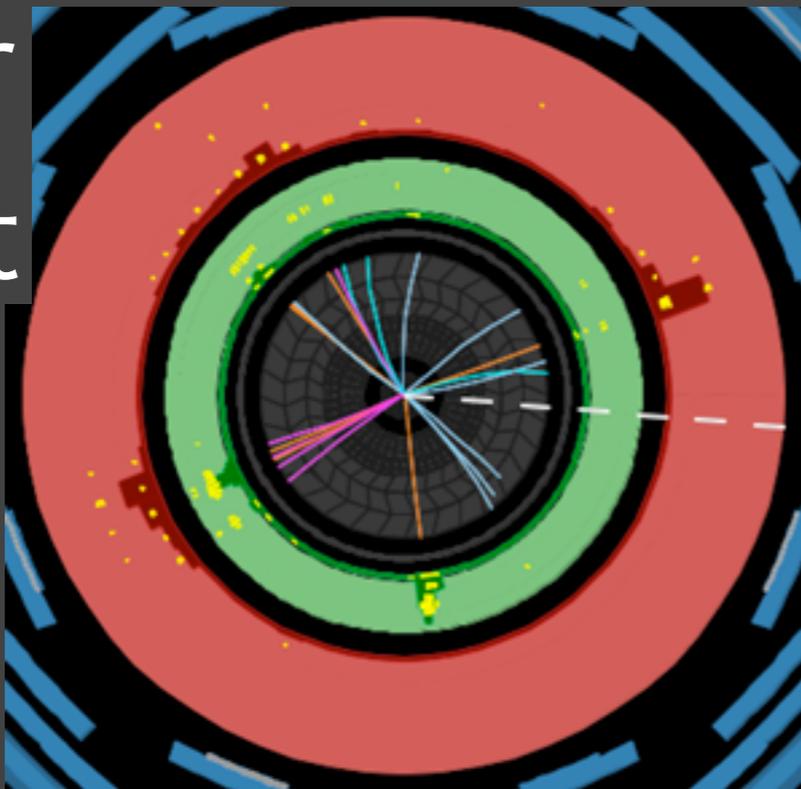
6jets



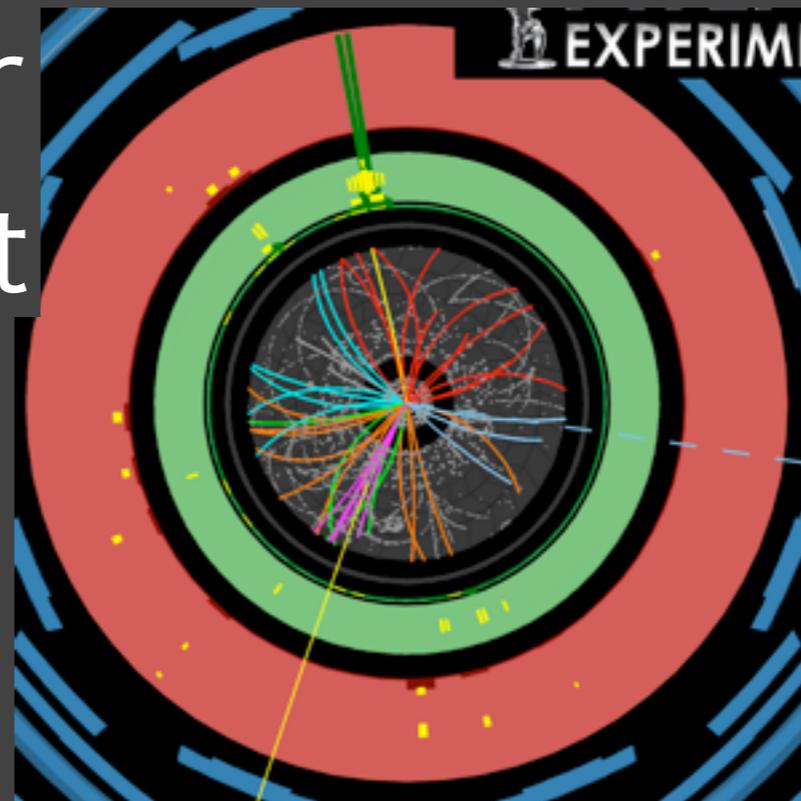
4jets



ttbar  
e+jet



ttbar  
e+jet

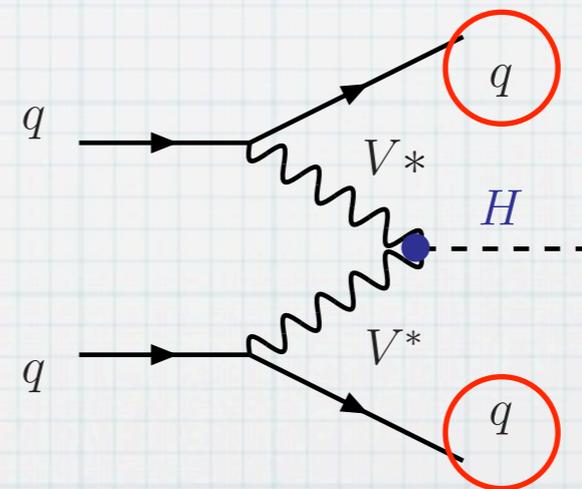
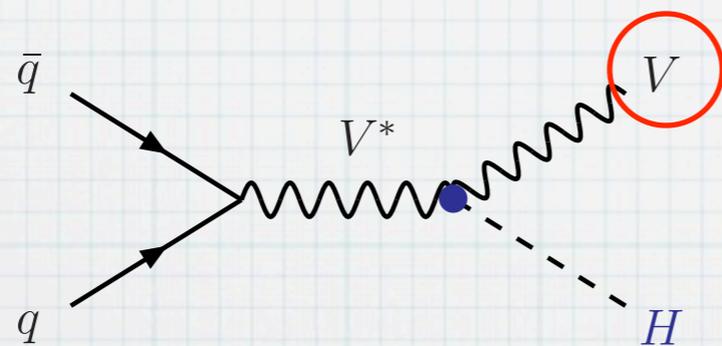


We have to fight for  
huge backgrounds in  
complicated event  
structure

# Clue Experimentalist Needs

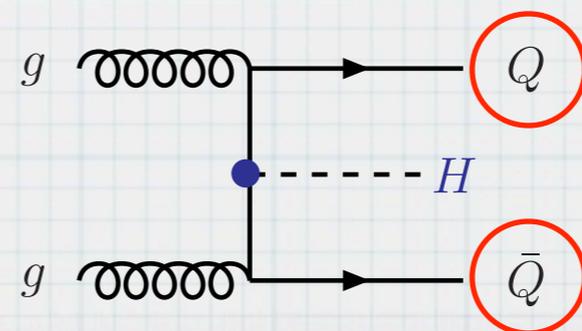
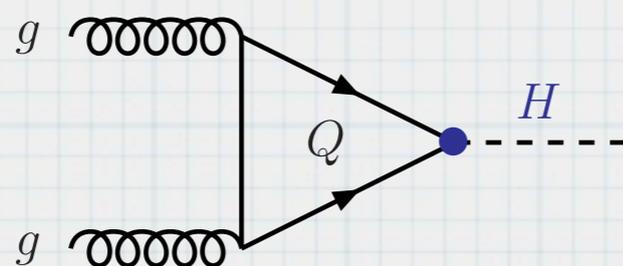
- ❖ Majority of backgrounds
  - ▶ quark/gluon (=jet) production
    - ⇒ we need something else
  - isolated lepton or special topology

associated production of vector boson



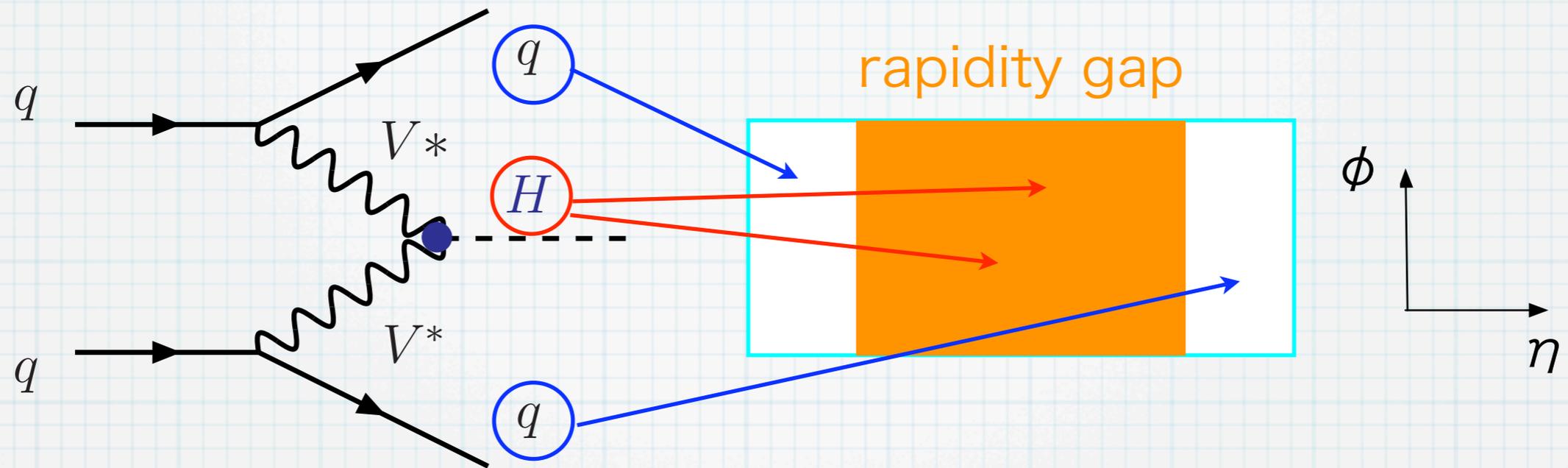
vector boson fusion (VBF)

gluon fusion (GF)

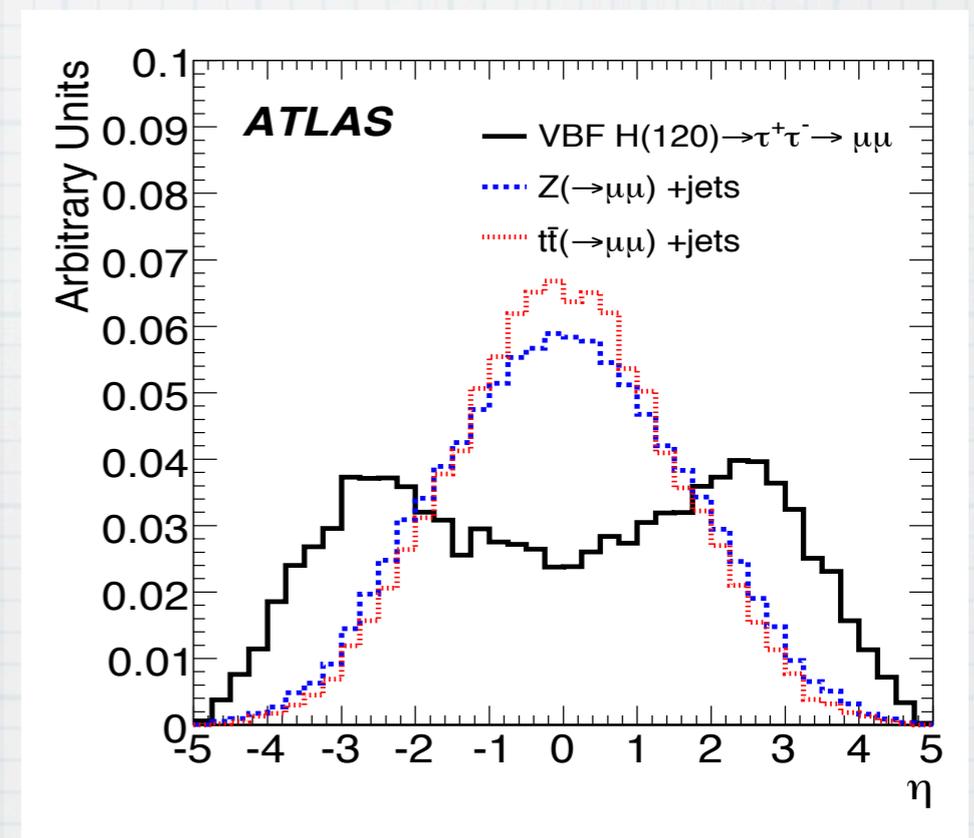


associated production of heavy quark (t, b)

# Vector Boson Fusion

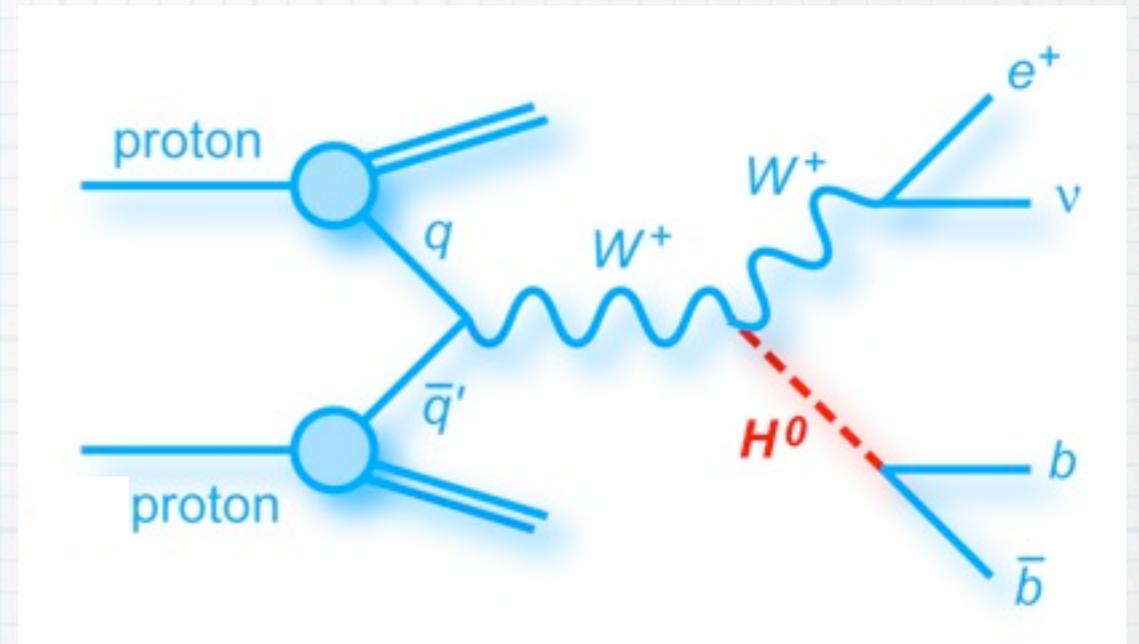


- ❖ Two forward jets
  - ▶ propagator  $\sim 1/(q^2 - m_V^2)$
- ❖ No jet activity in central
  - ▶ no color connection

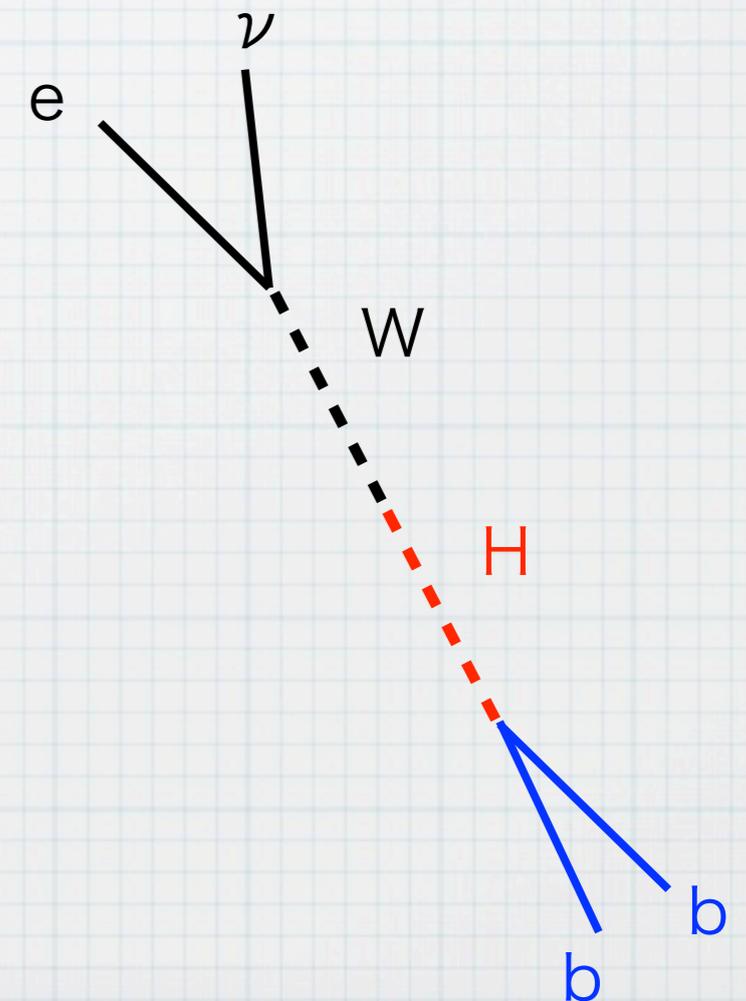


# $W/Z + (H \rightarrow bb)$

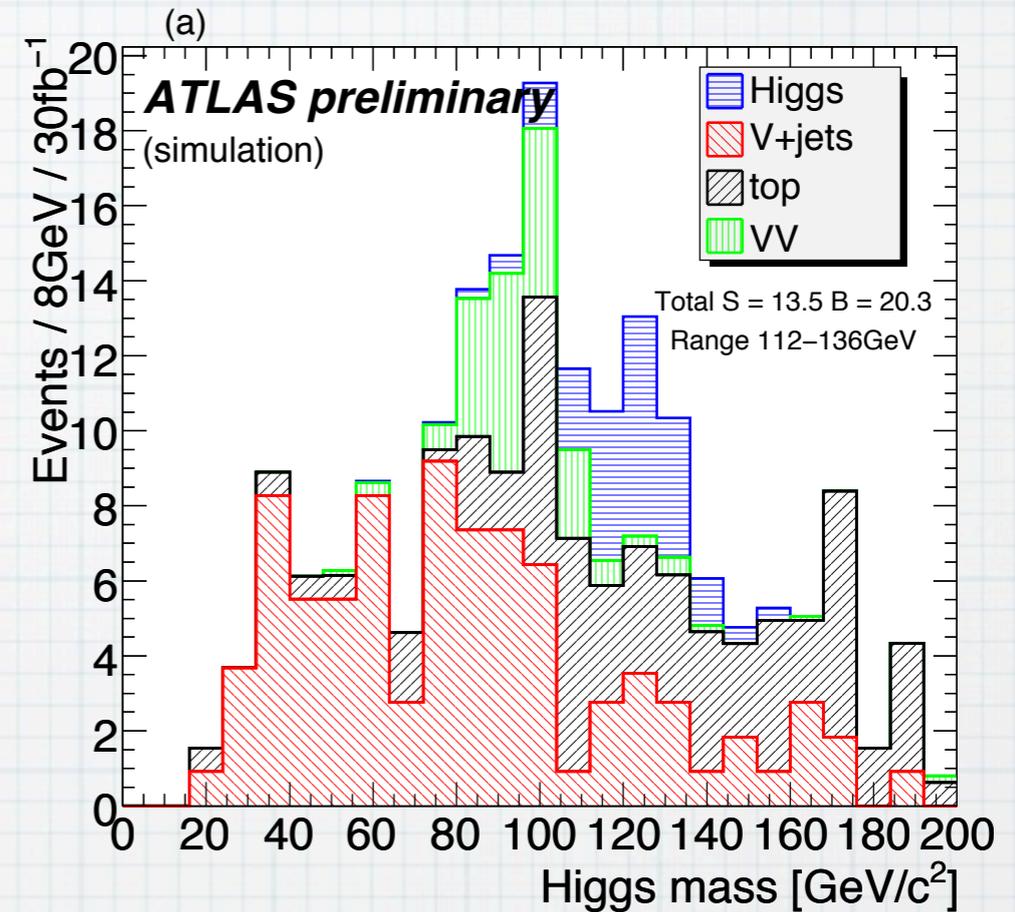
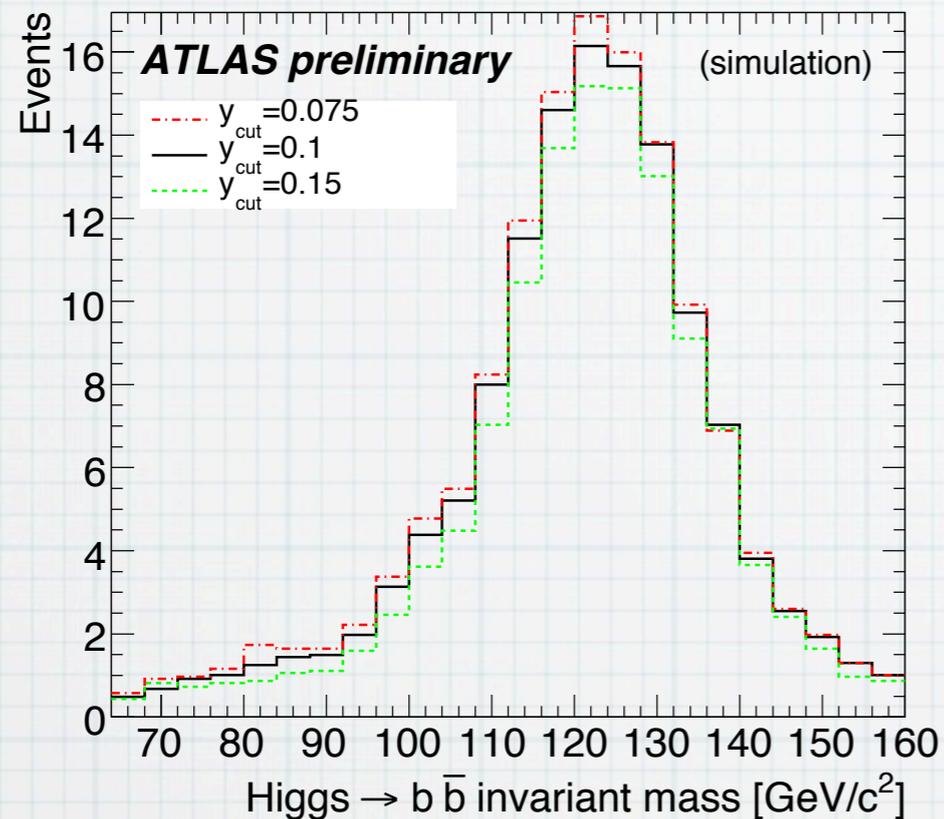
- ❖  $W \rightarrow l\nu$ ,  $Z \rightarrow ll$  works as a “tag”



- ❖ Still large backgrounds  
⇒ highly boosted  $H$  (and  $V$ )
  - typically  $p_T > 200$  GeV
- ▶ need special jet algorithm
  - sub-jet structure

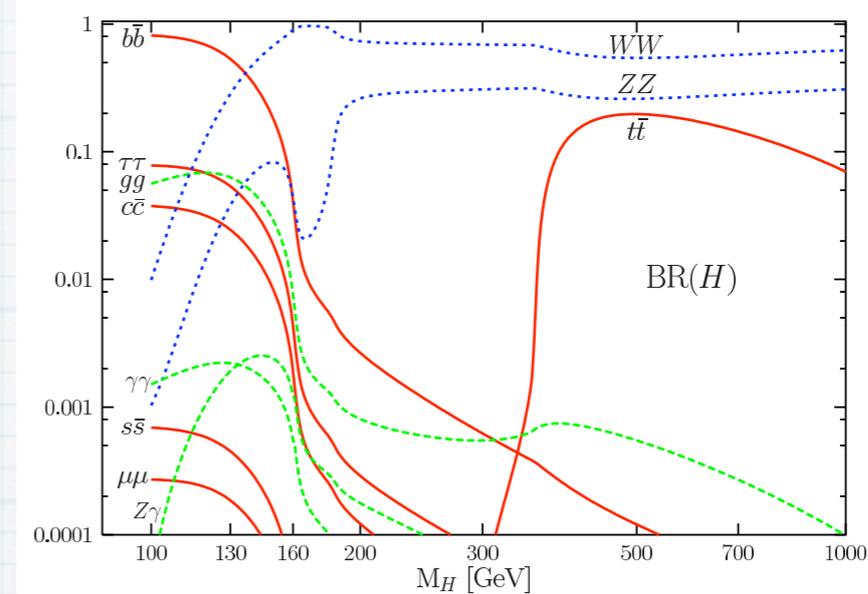
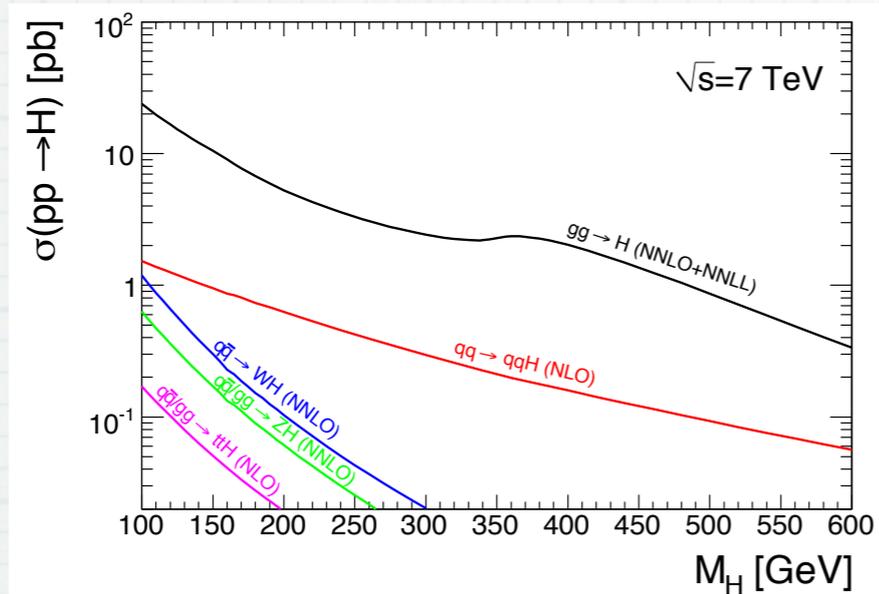


# Low mass $VH \rightarrow bb$



- ❖ Capability to reconstruct H from sub-jet
- ❖ Need high statistics  $\geq 30 \text{ fb}^{-1}$
- ❖ Still important to access  $Y_b$

# Experimental Strategy



## ❖ Light

- ▶ GF (+VBF)  $H \rightarrow \gamma \gamma$
- ▶ VBF  $H \rightarrow \tau \tau$
- ▶  $W/Z + H \rightarrow bb$

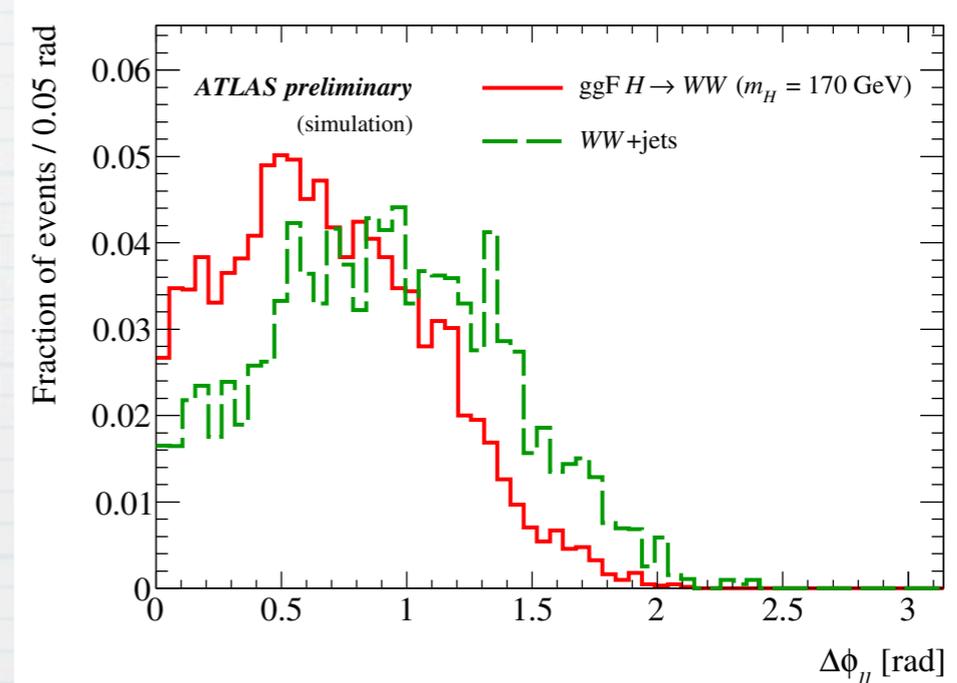
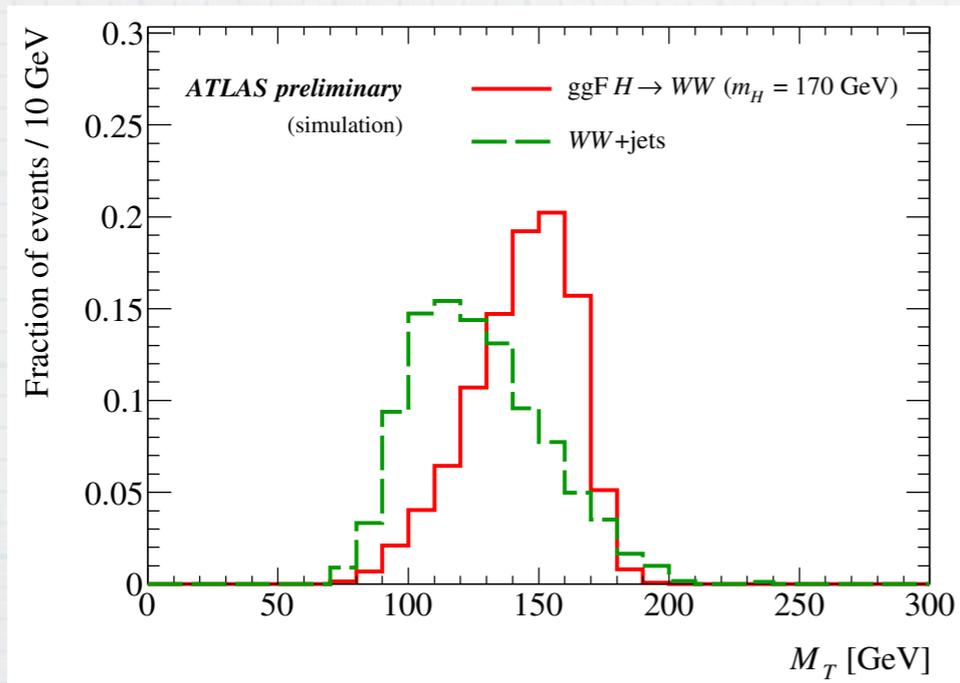
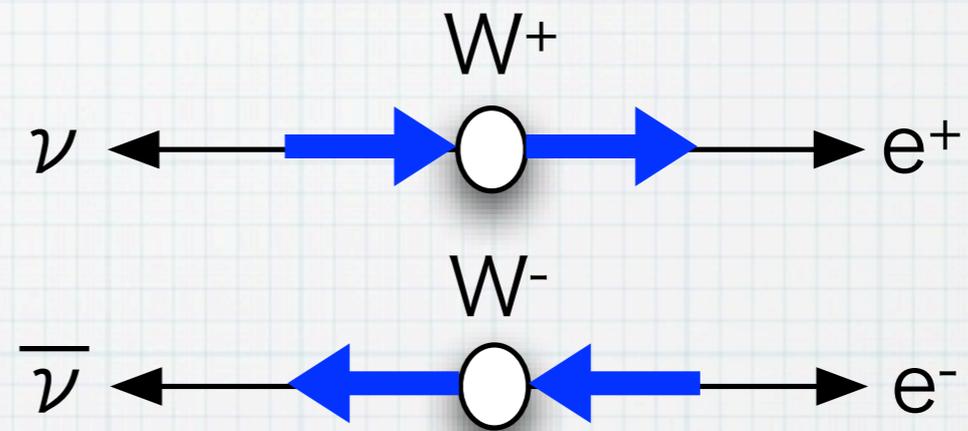
Lepton  
EM object  
Special topology

## ❖ Heavy or wide mass range

- ▶ GF (+VBF)  $H \rightarrow WW(\rightarrow ll+X), ZZ(\rightarrow ll ll)$

$$H \rightarrow WW$$

- ❖ Main search channel for wide mass range
- ❖ Useful topology
  - ▶ Spin correlation
  - ▶ Transverse mass

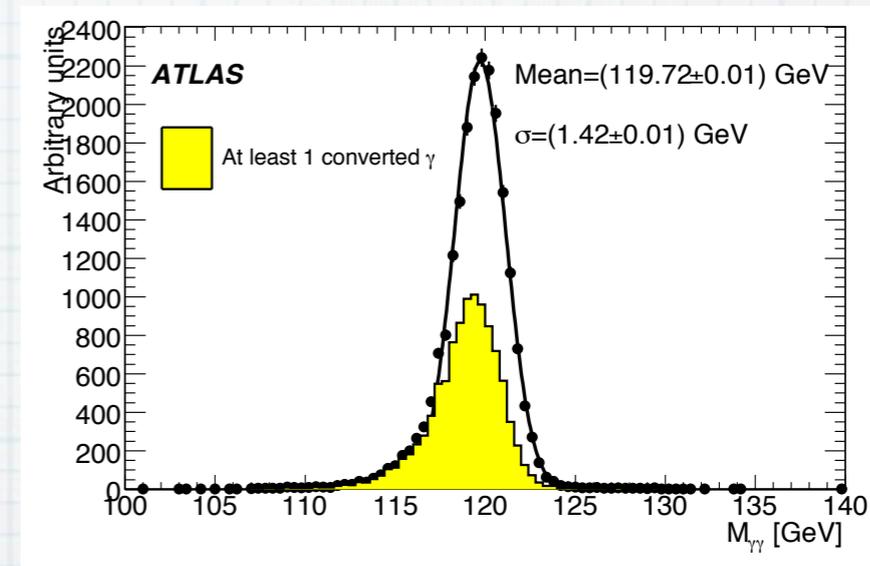


$$H \rightarrow \gamma \gamma$$

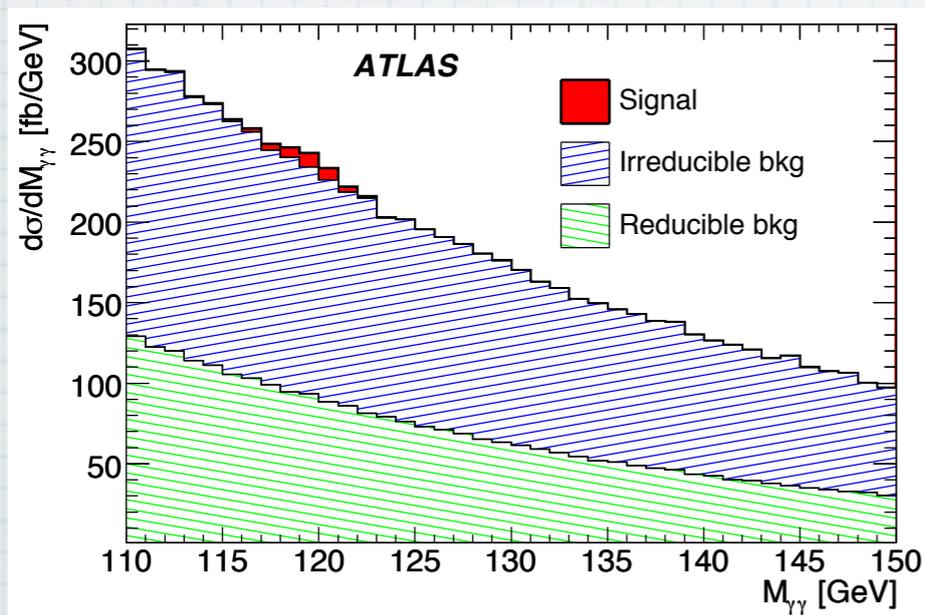
❖ Search for a peak in  $M_{\gamma\gamma}$  over continuous background

► Resolution crucial

(\*) Figures are for 14 TeV simulation



inclusive

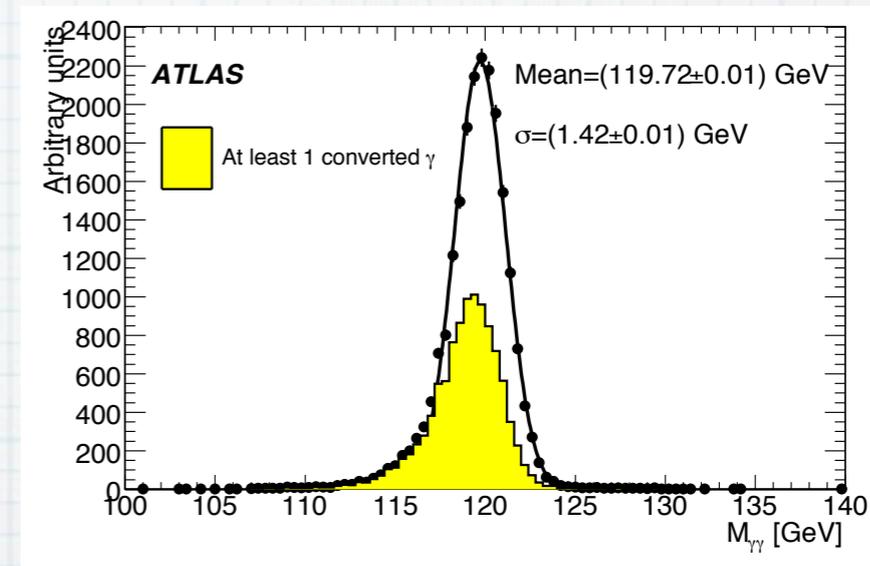


$$H \rightarrow \gamma \gamma$$

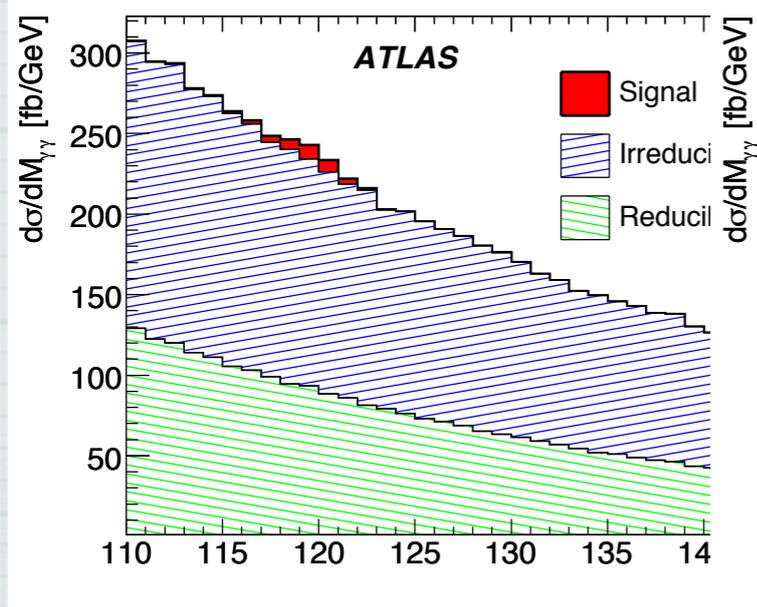
❖ Search for a peak in  $M_{\gamma\gamma}$  over continuous background

► Resolution crucial

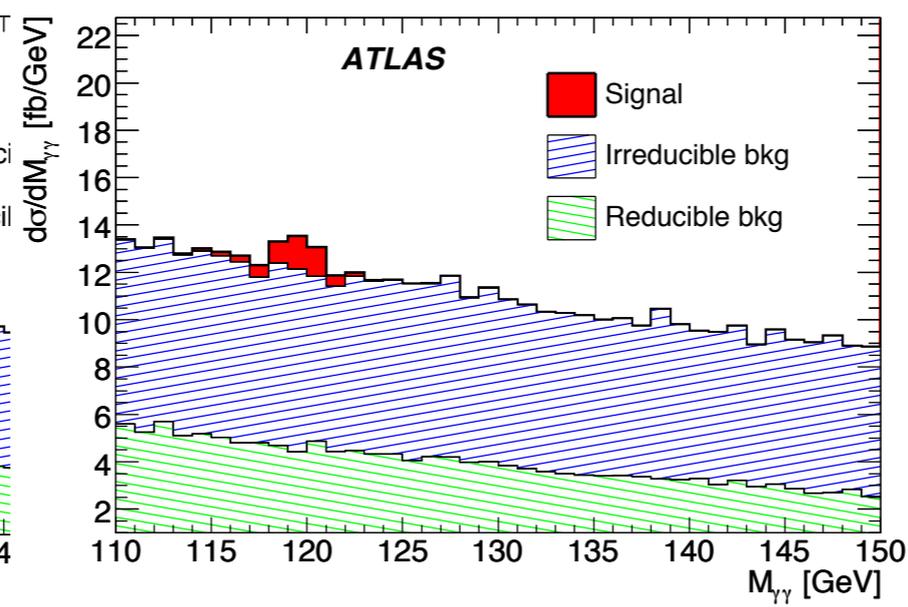
(\*) Figures are for 14 TeV simulation



inclusive



1jet

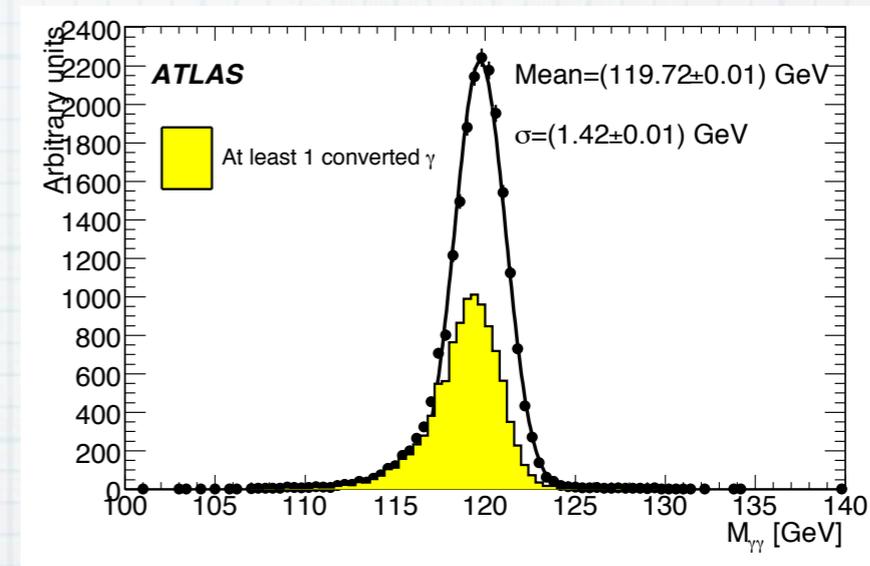


$$H \rightarrow \gamma \gamma$$

❖ Search for a peak in  $M_{\gamma\gamma}$  over continuous background

► Resolution crucial

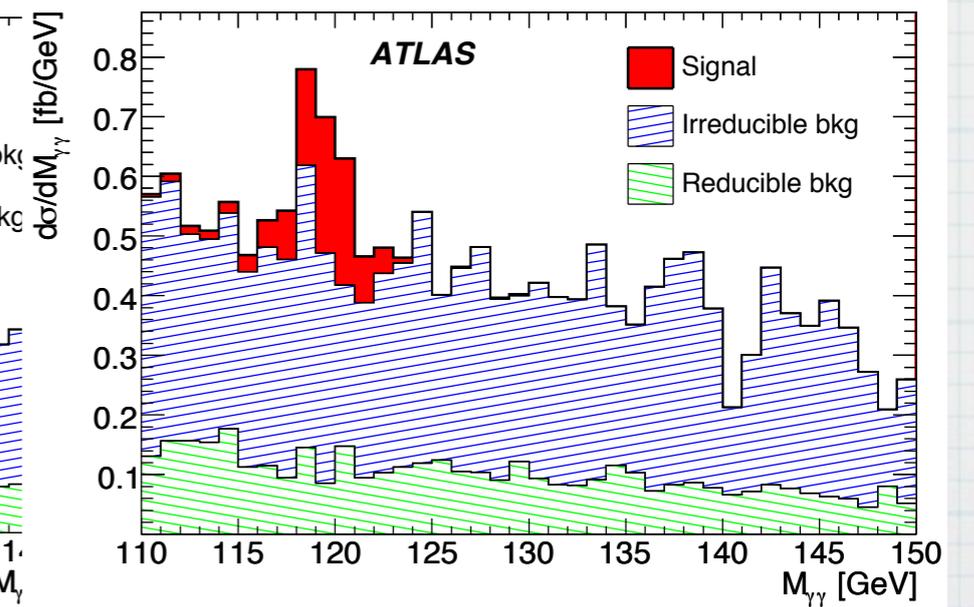
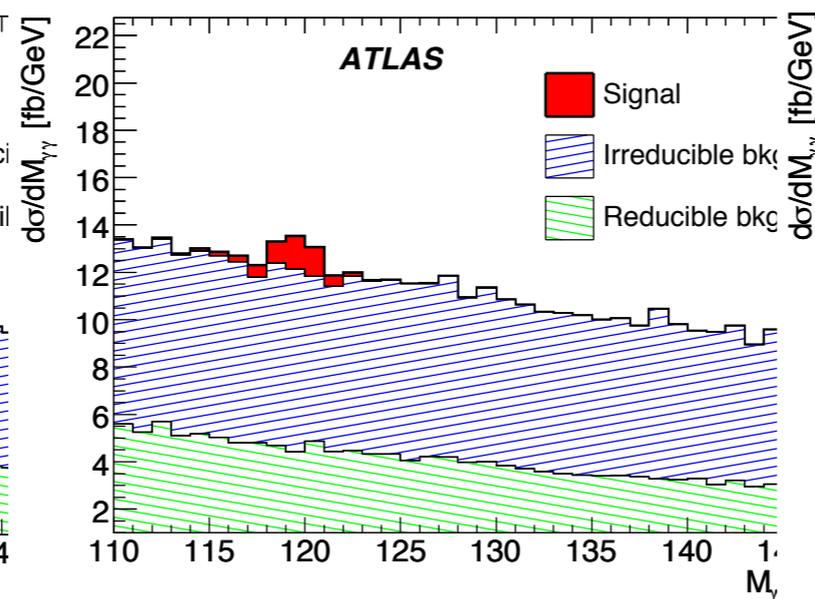
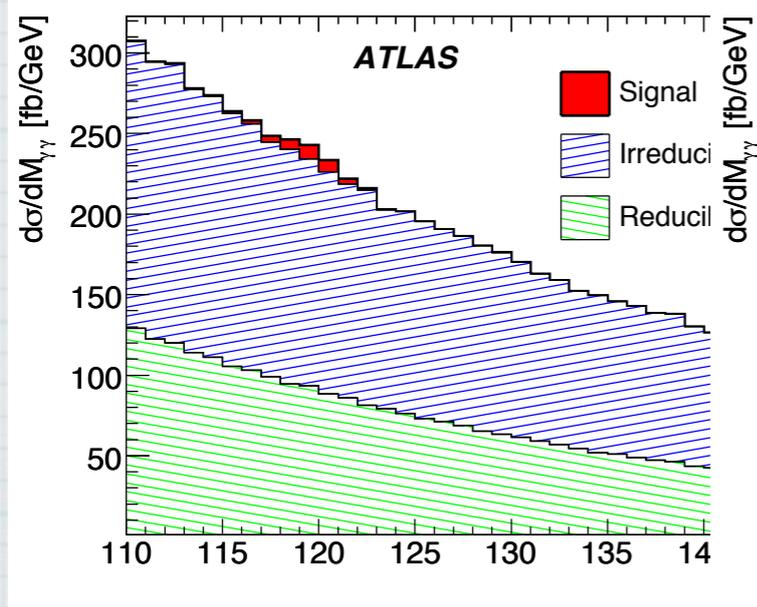
(\*) Figures are for 14 TeV simulation



inclusive

1jet

2jet

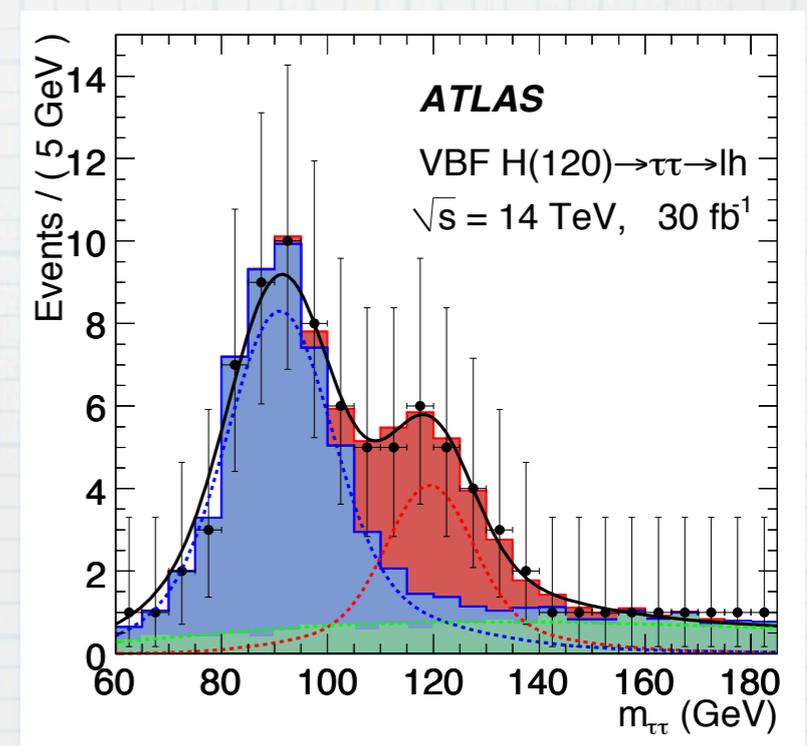
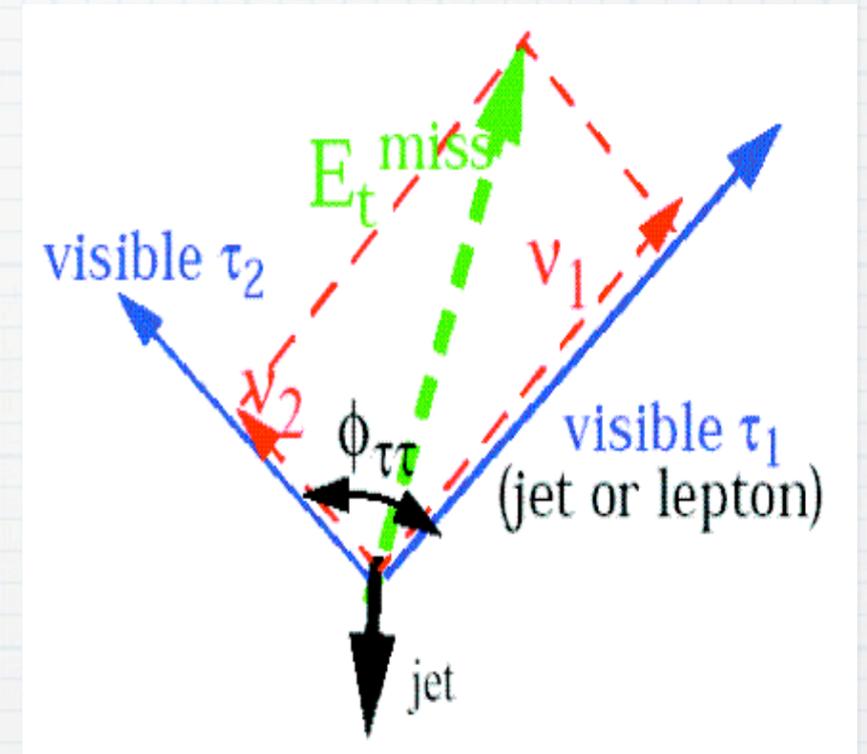


# VBF $H \rightarrow \tau \tau$

- ❖ Can reconstruct  $m_{\tau\tau}$ 
  - ▶  $\nu$  direction assumed to be collinear with the observed object

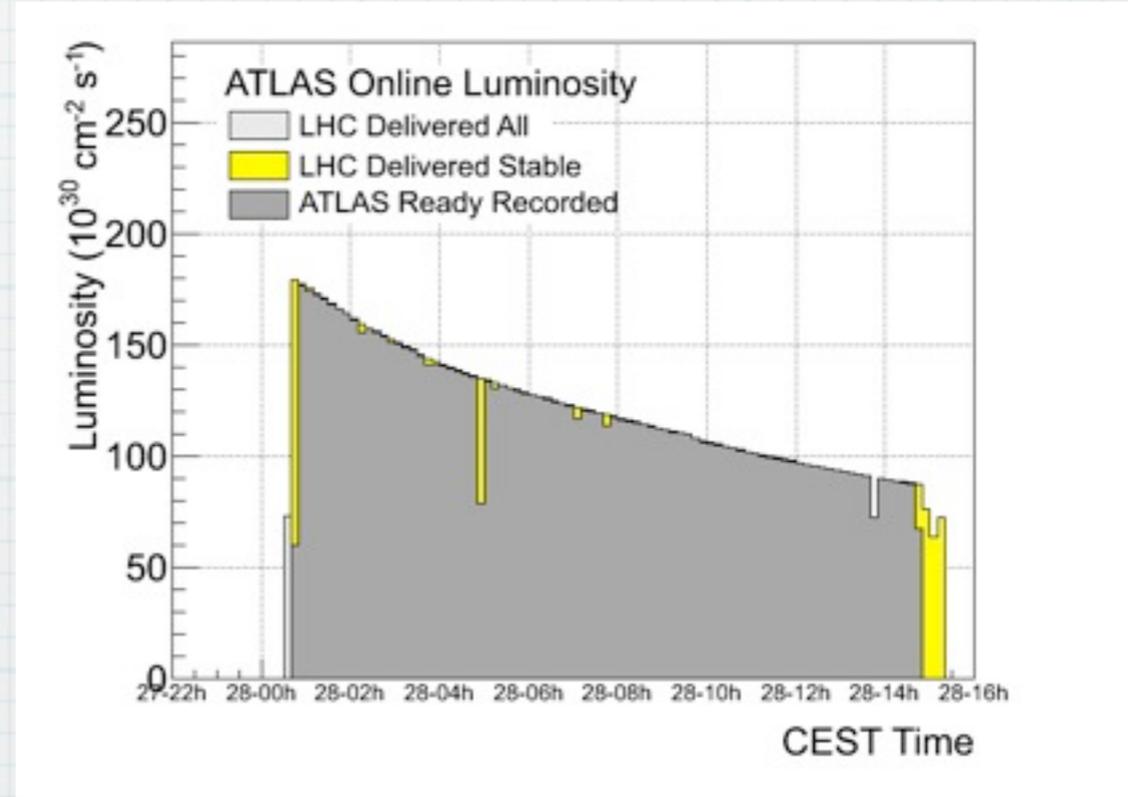
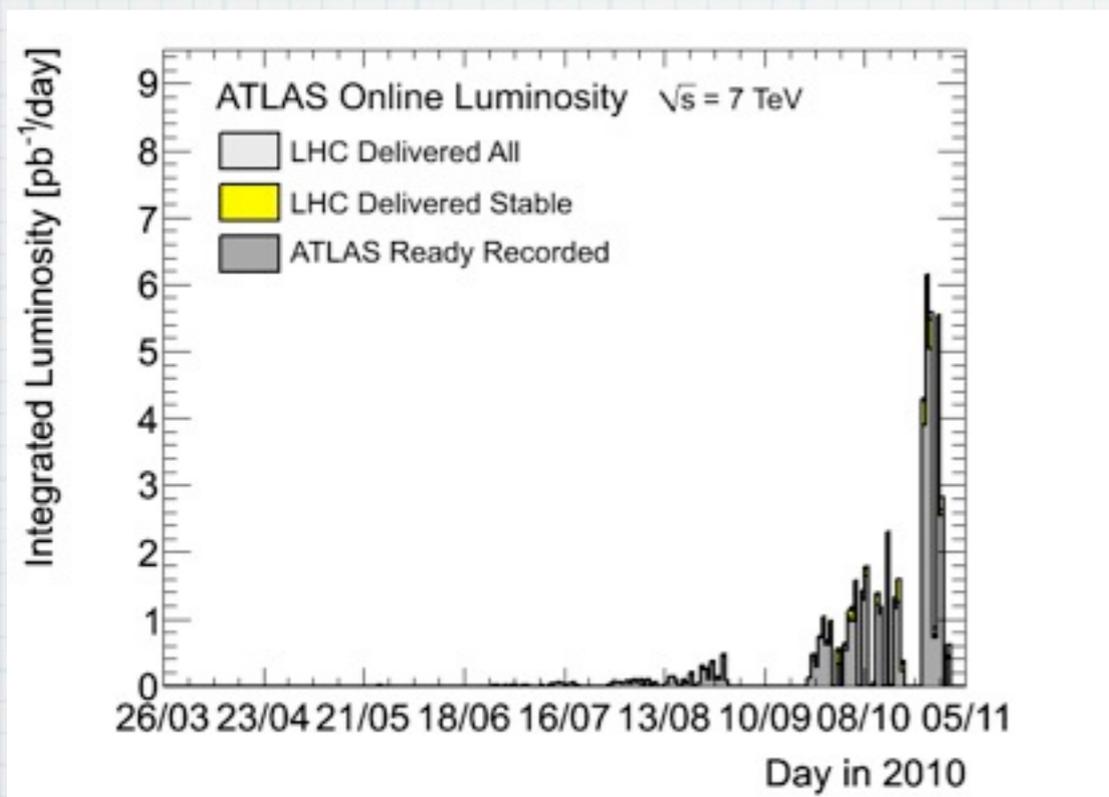
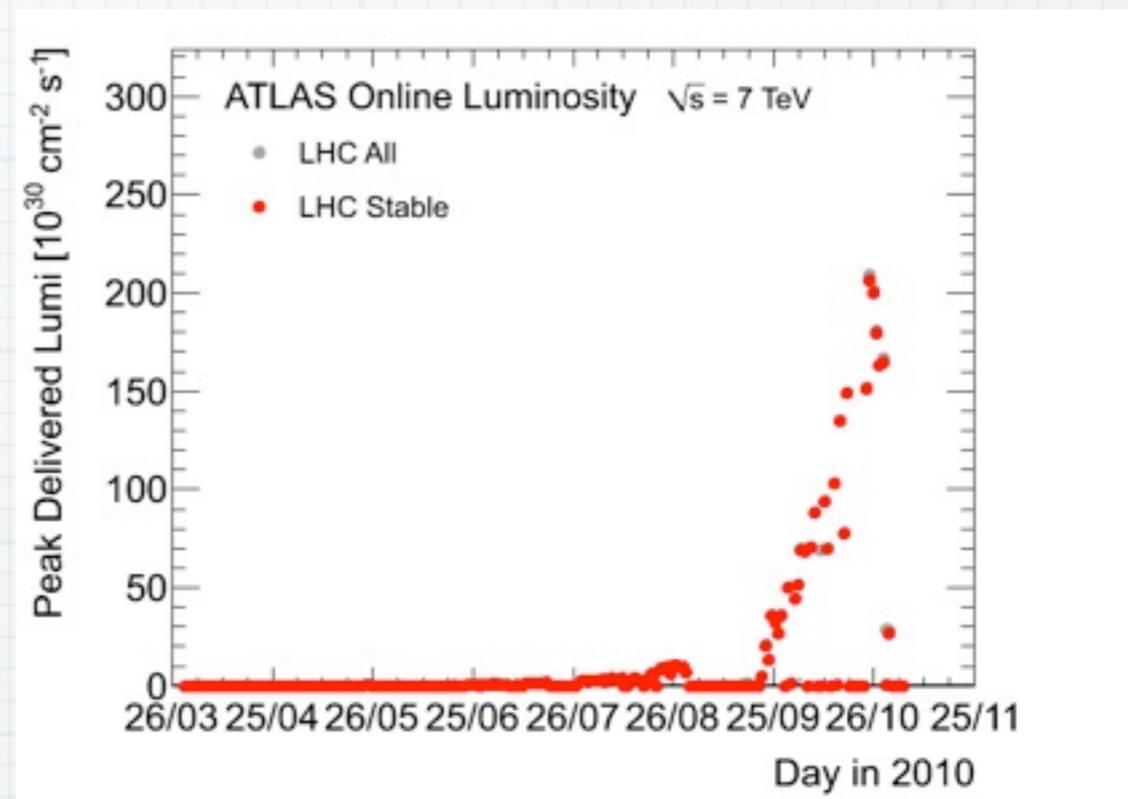
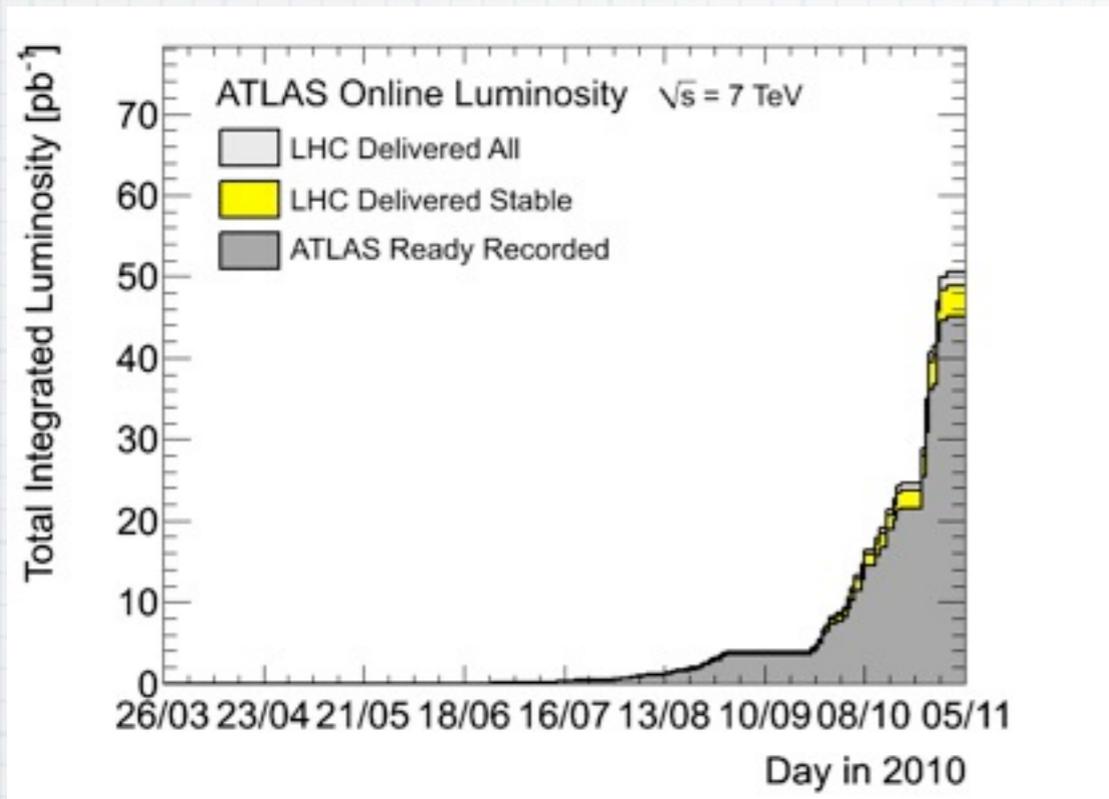
●  $m_H/2 \gg m_\tau$

- ❖ Two forward jets and no central jets

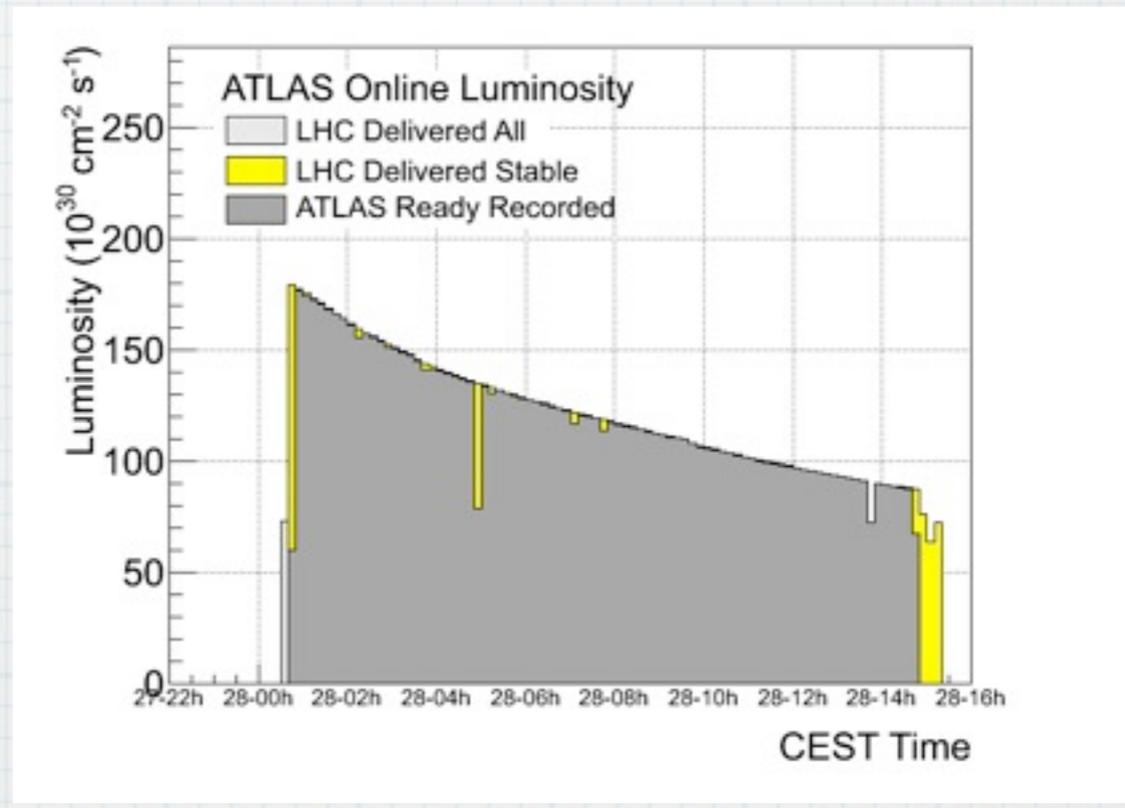
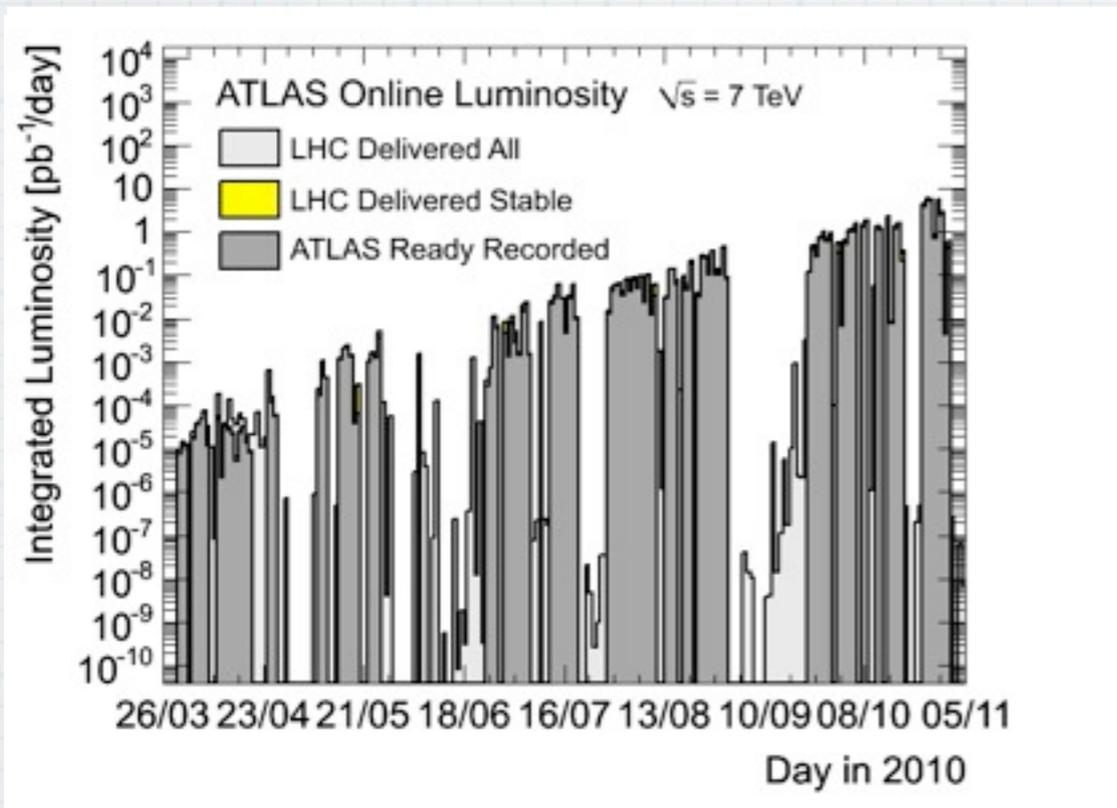
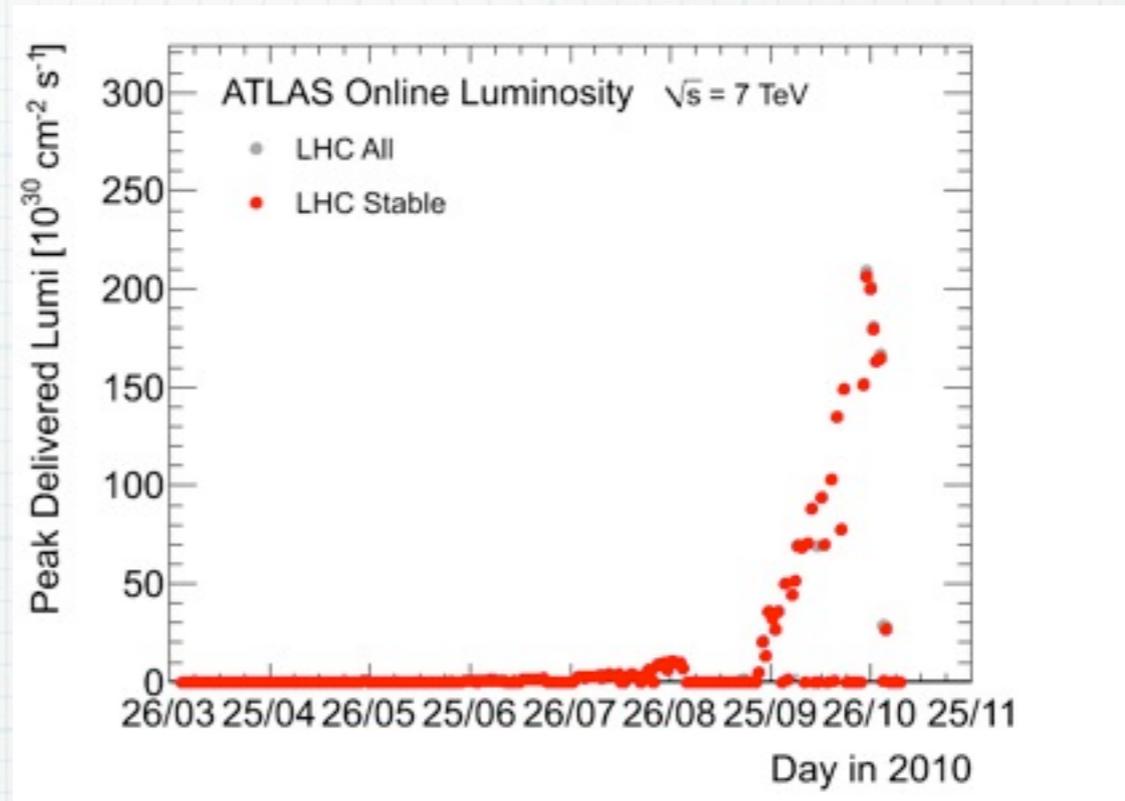
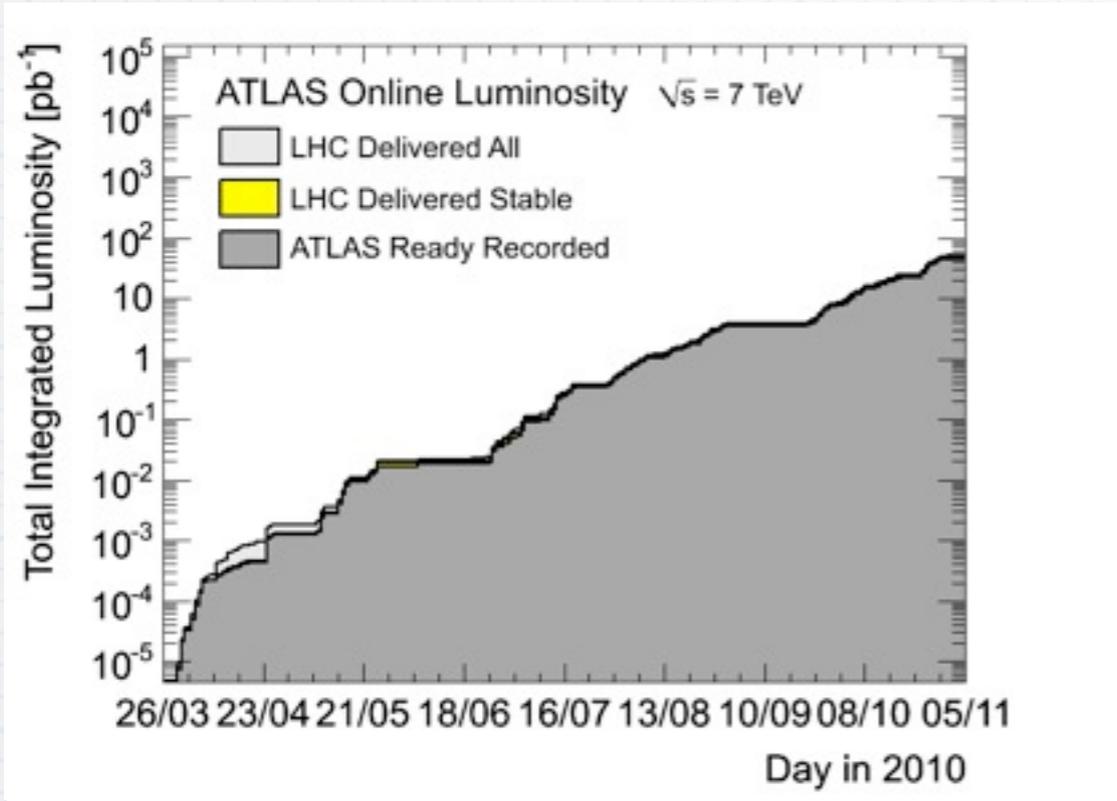


How well we are  
(were) doing

# Data Collection



# Data Collection

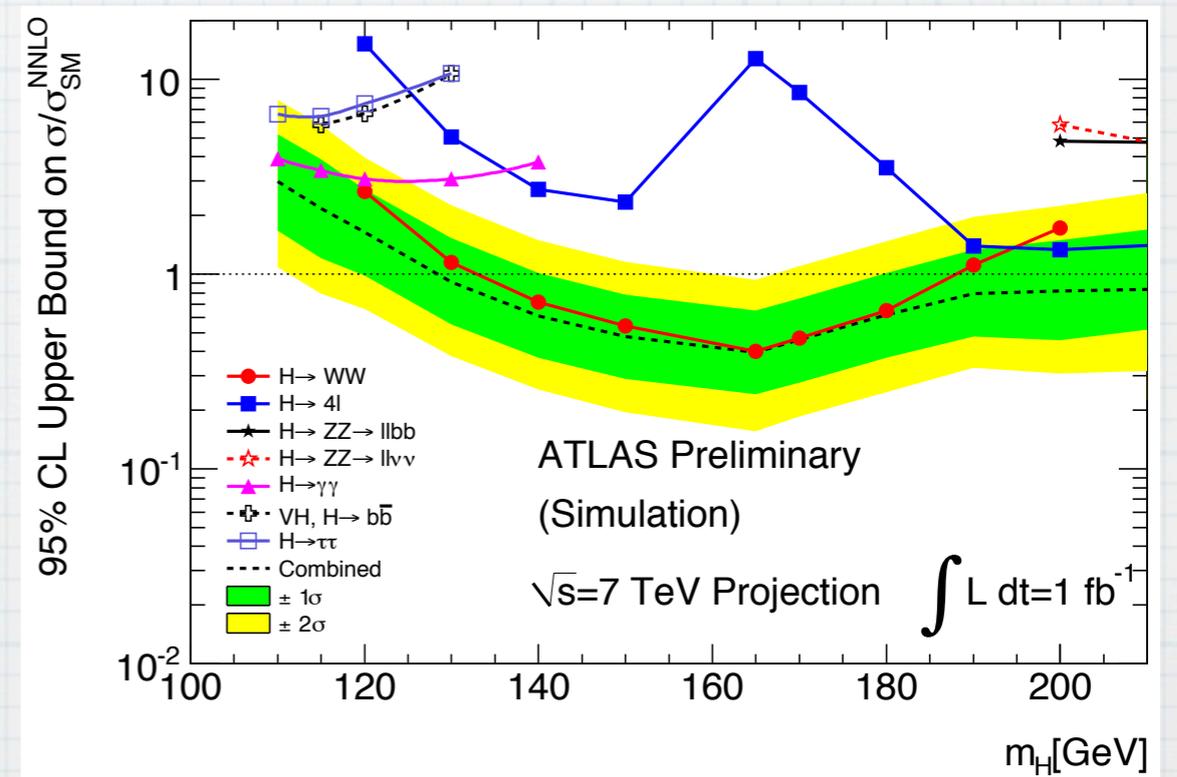
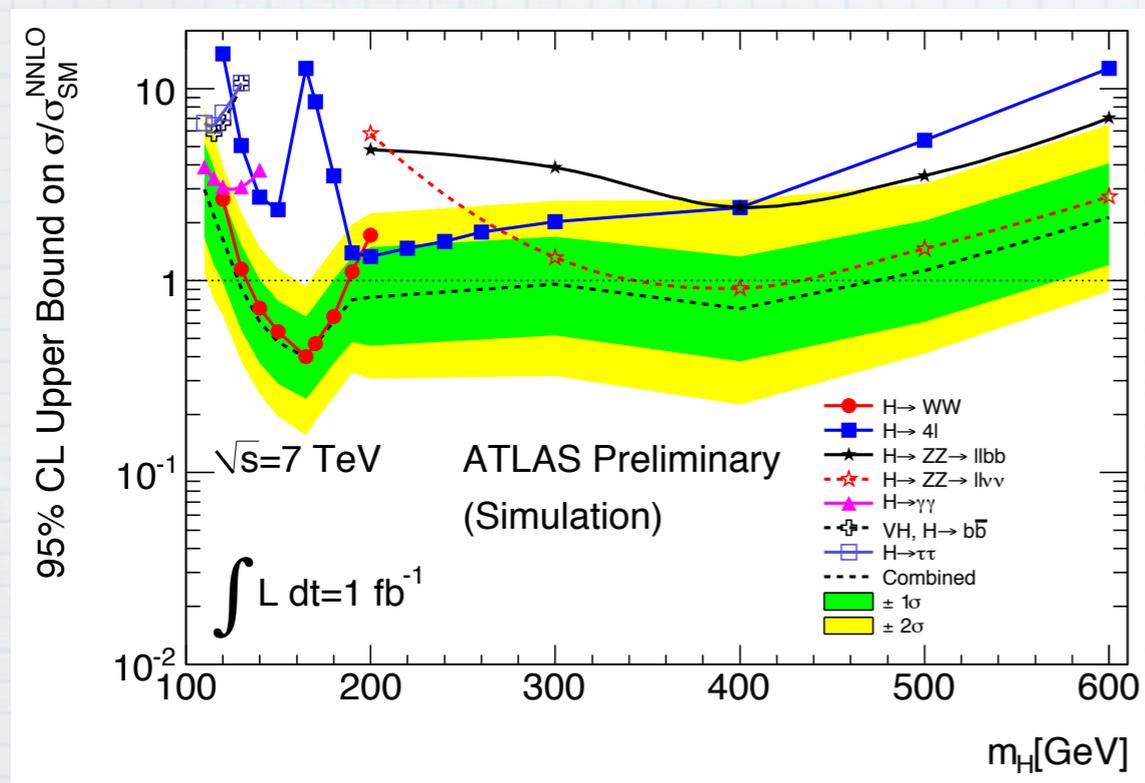


# Run Scenario

- ❖ (was) Default
  - ▶ Run 2011 at  $\sqrt{s}=7\text{TeV}$ , accumulate  $\sim 1\text{fb}^{-1}$ , shutdown 2012 - beginning of 2013
  
- ❖ The other options
  - ▶ Run through 2012 at increased energy (8 or 9 TeV?), shutdown afterwards
    - ⇐ will make a decision at LHCC

# Expected Sensitivity

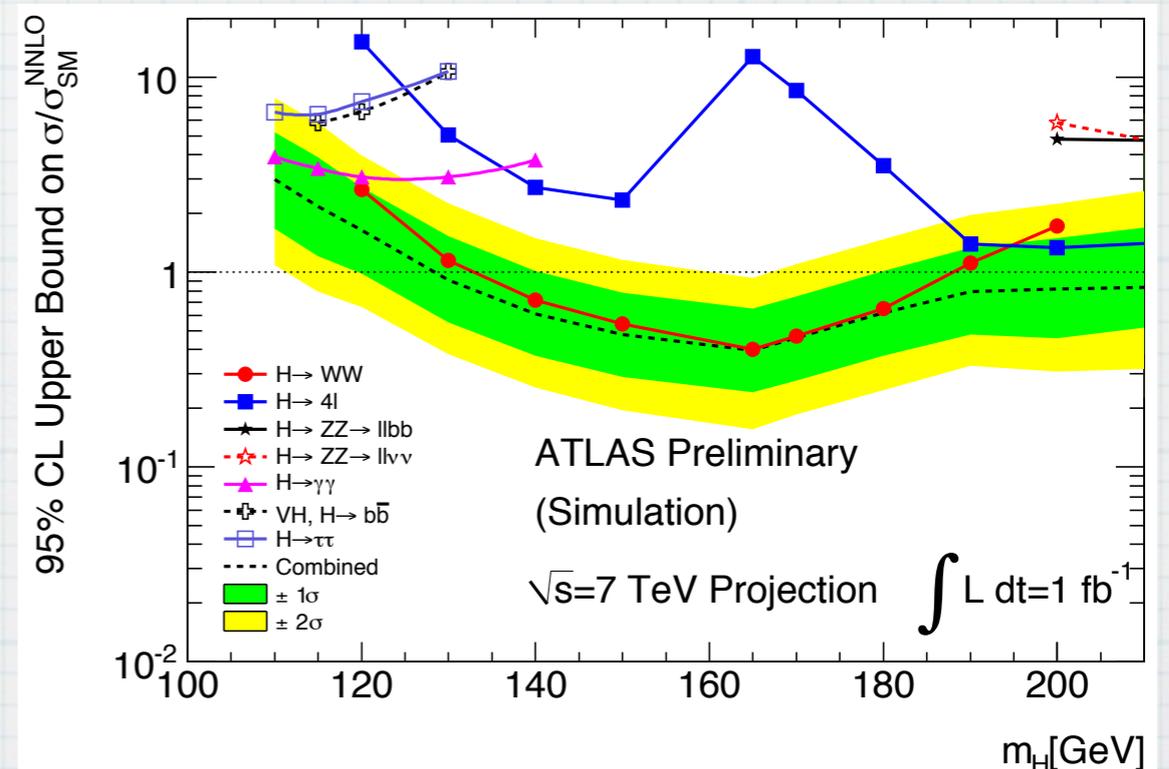
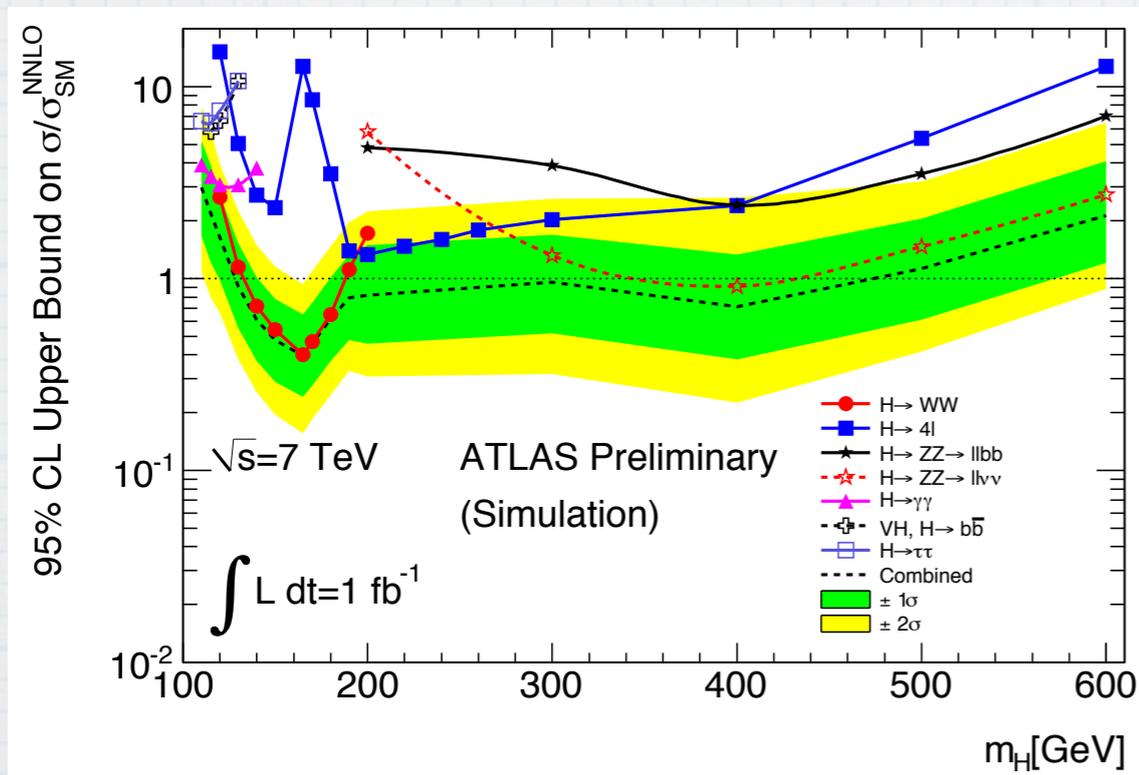
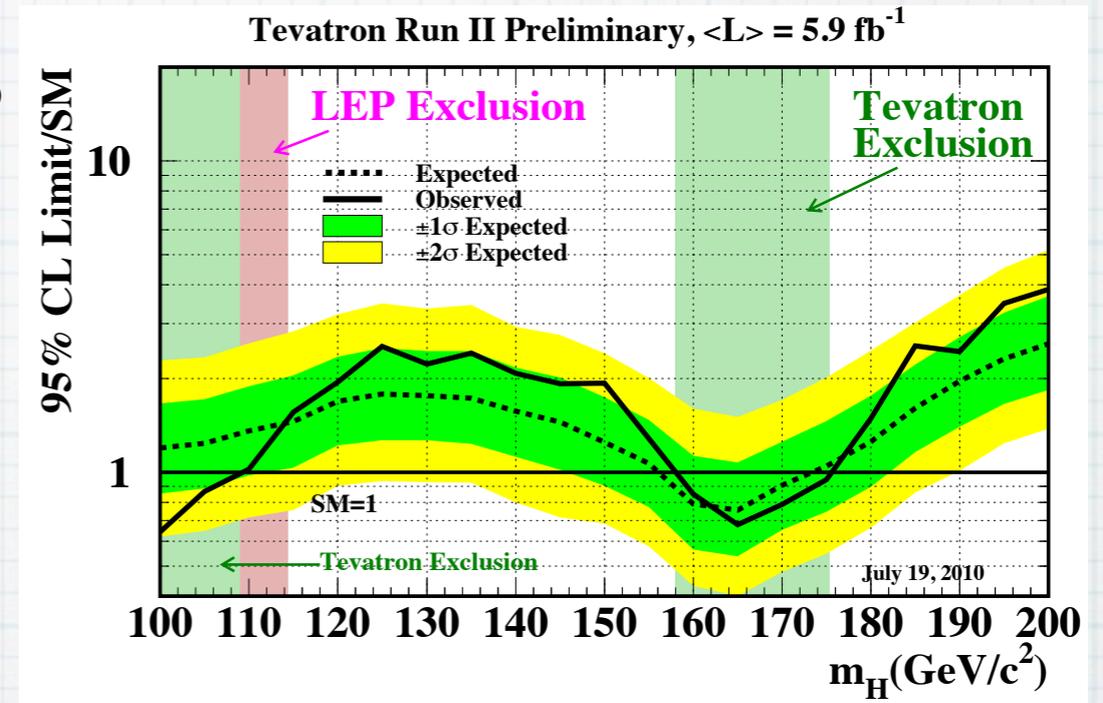
❖  $\sqrt{s} = 7\text{TeV}, 1\text{fb}^{-1}$



# Expected Sensitivity

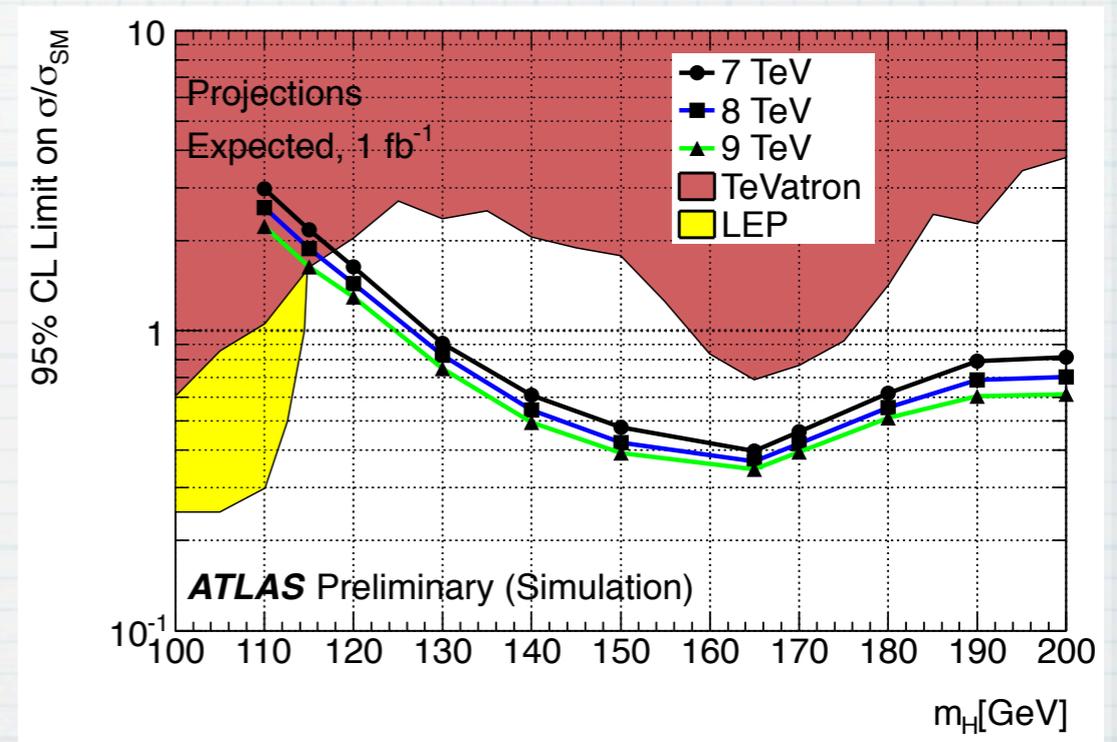
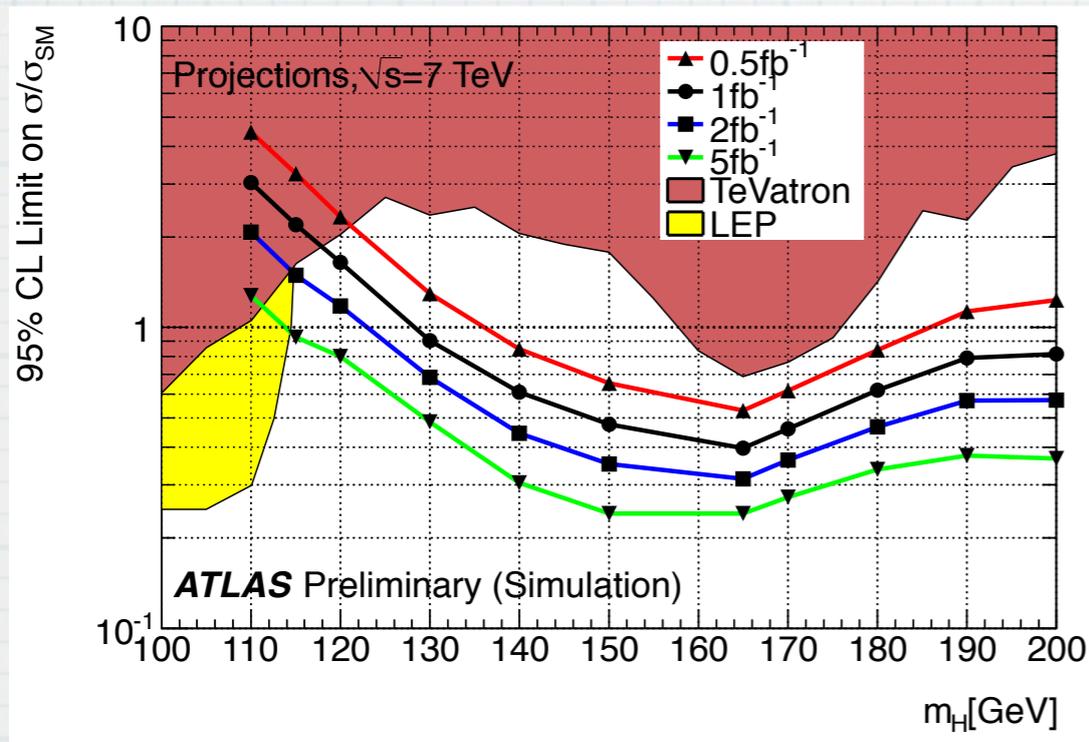
## Tevatron status

❖  $\sqrt{s} = 7\text{TeV}, 1\text{fb}^{-1}$



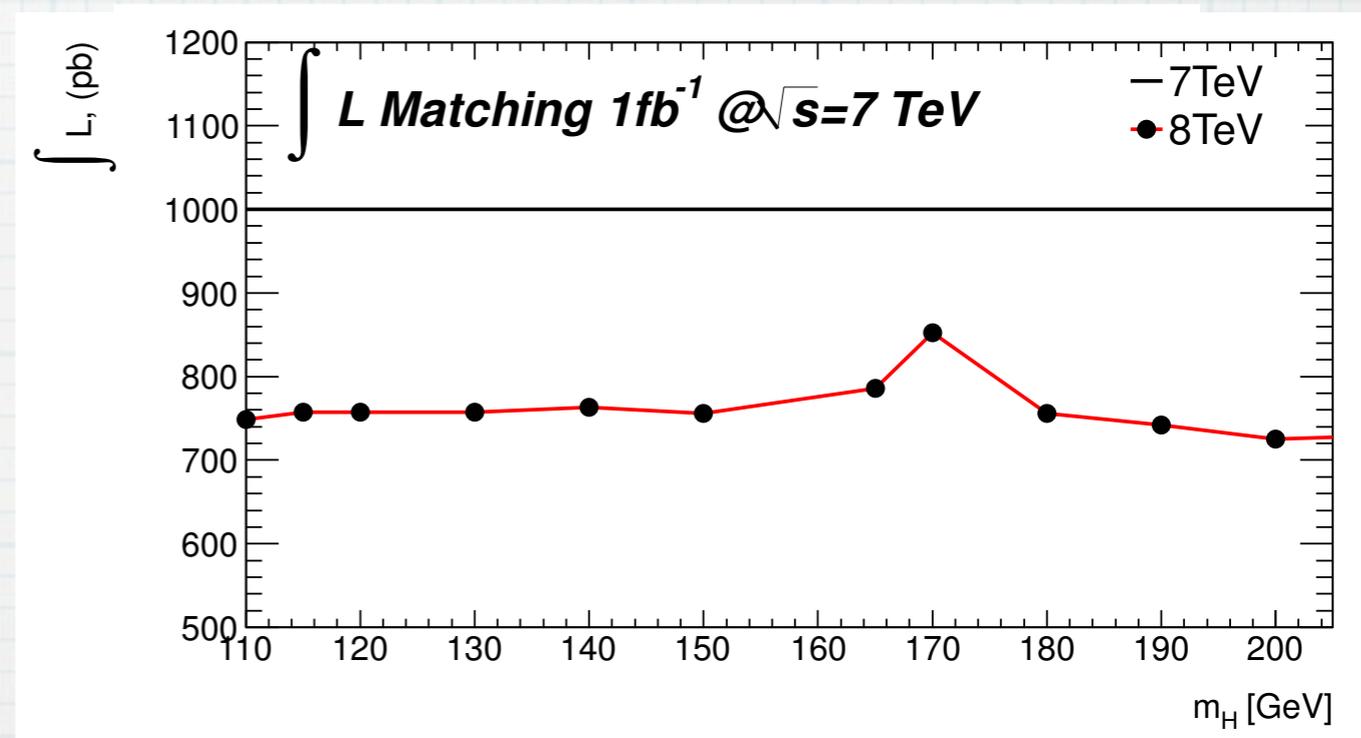
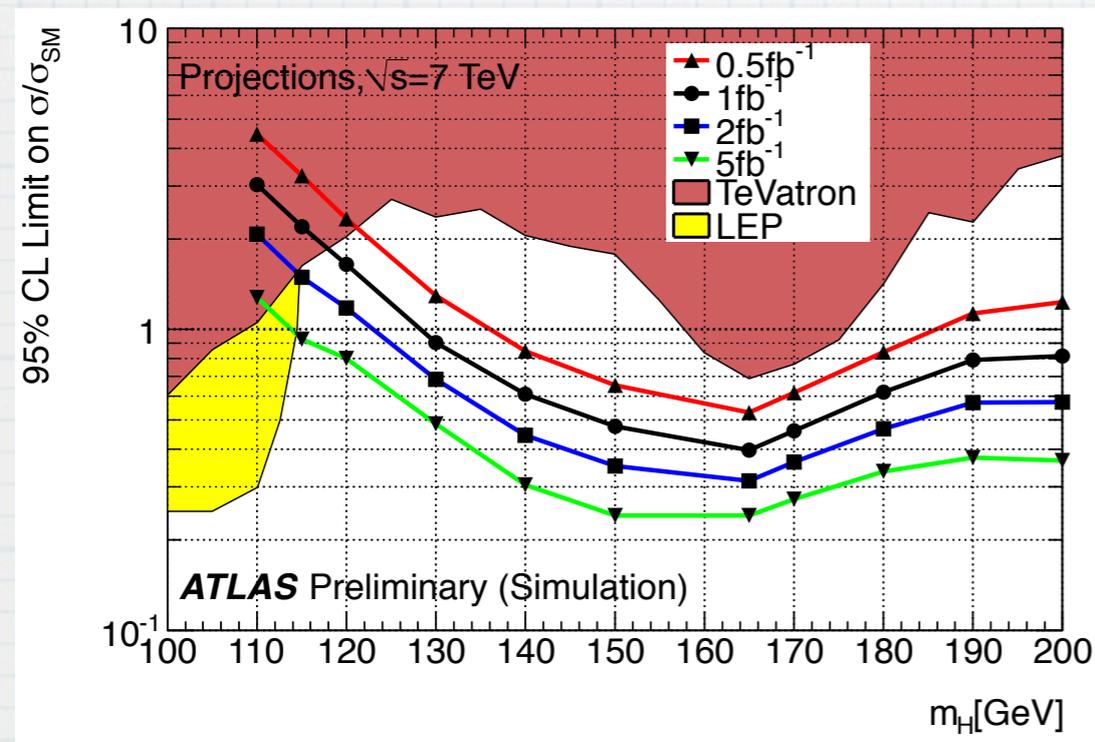
# Comparison of Run Scenarios

- ❖ Different integrated luminosity
- ❖ Different beam energy



# Comparison of Run Scenarios

- ❖ Different integrated luminosity
- ❖ Different beam energy



# SUSY Higgs

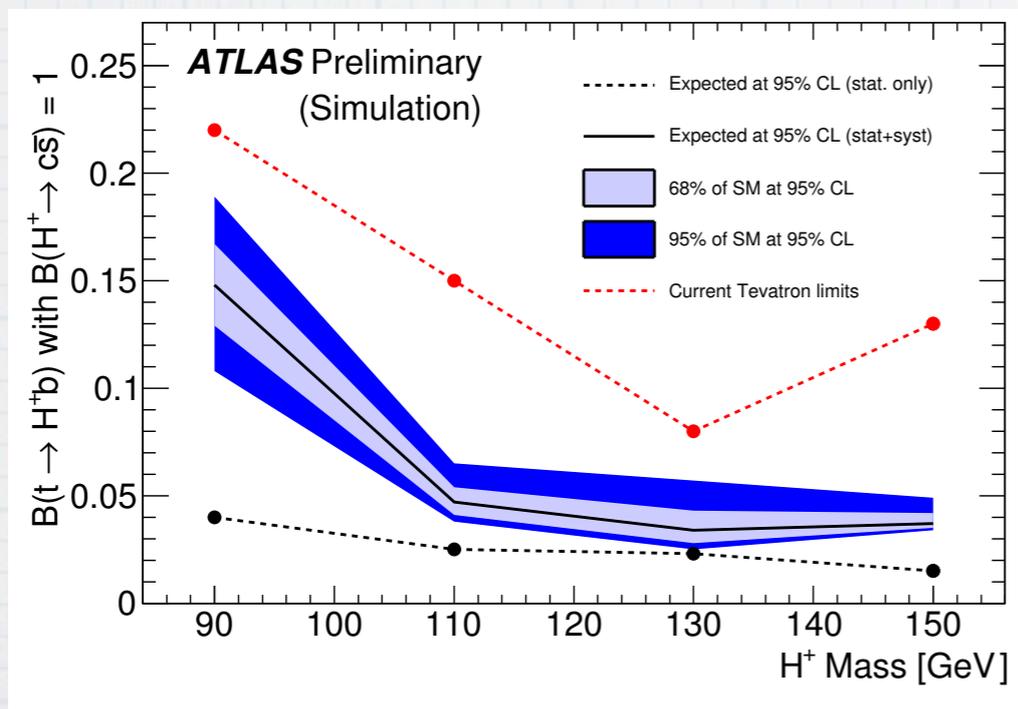
$$\tan \beta = \frac{v_u}{v_d}$$

- ❖ Search strategy (or sensitivity) depends on  $\tan \beta$ 
  - ▶ large (small)  $\tan \beta$ 
    - coupling to down (up) type fermion enhanced

# SUSY Higgs

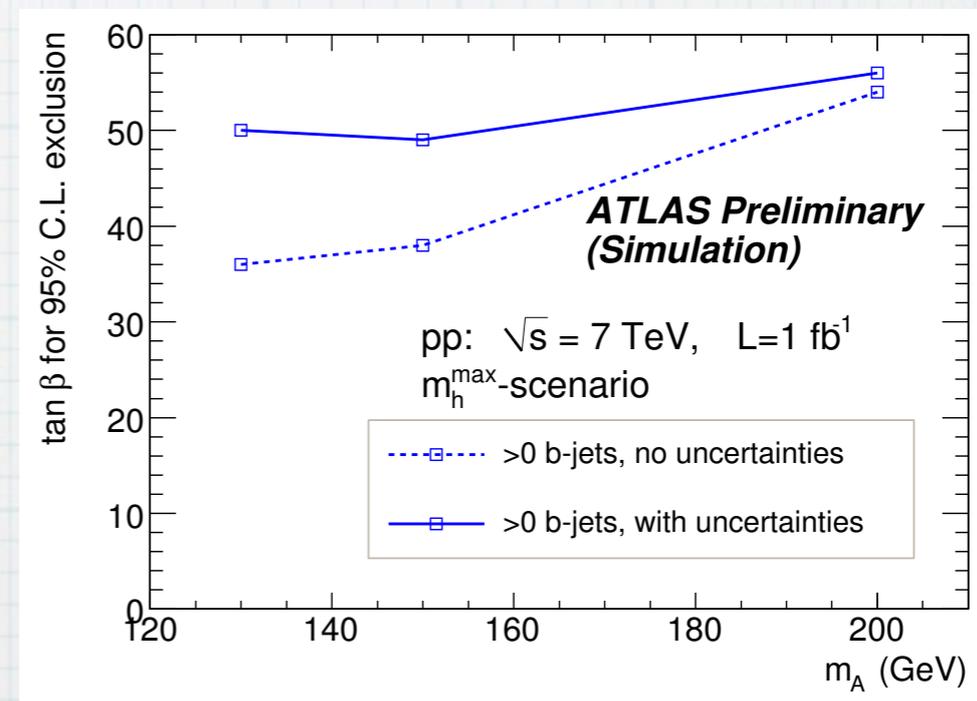
❖ Small  $\tan\beta$   
when  $M_{H^+} < M_t$

$$t\bar{t} \rightarrow bH^+ (\rightarrow c\bar{s})bW^-$$



❖ Large  $\tan\beta$

$$b\bar{b}(h/H/A \rightarrow \mu^+ \mu^-)$$



# Conclusions

- ❖ Electroweak symmetry breaking the most important mystery
- ❖ Possibility of finding Higgs in two years
  - ▶ Running through 2012
  - ▶  $5\sigma$  discovery possible for  $m_H > 130$  GeV
    - $5 \text{ fb}^{-1}$  for both ATLAS & CMS

# Conclusions

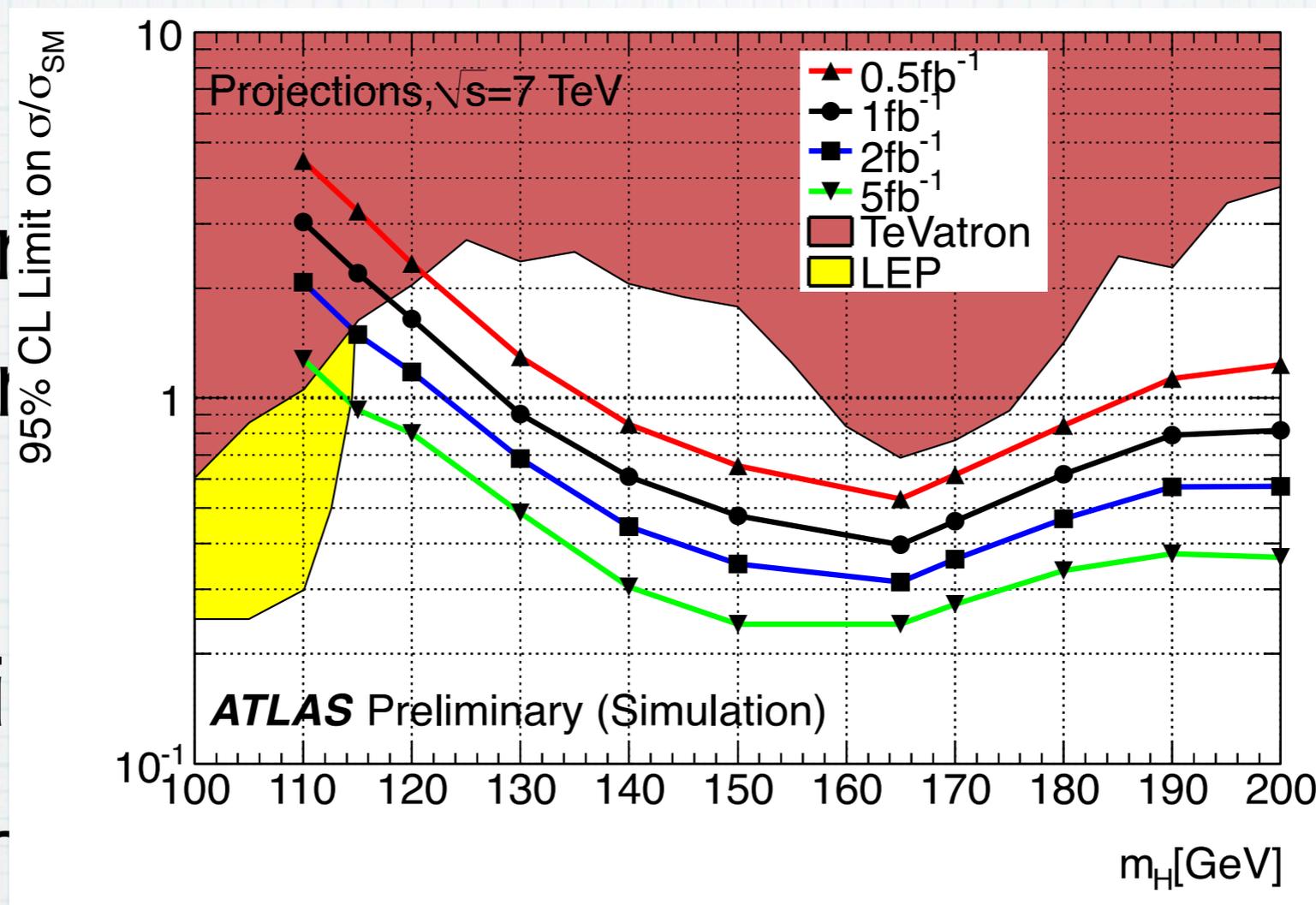
❖ Electri  
impor

❖ Possi

▶ Rur

▶  $5\sigma$  discovery possible for  $m_H > 130$  GeV

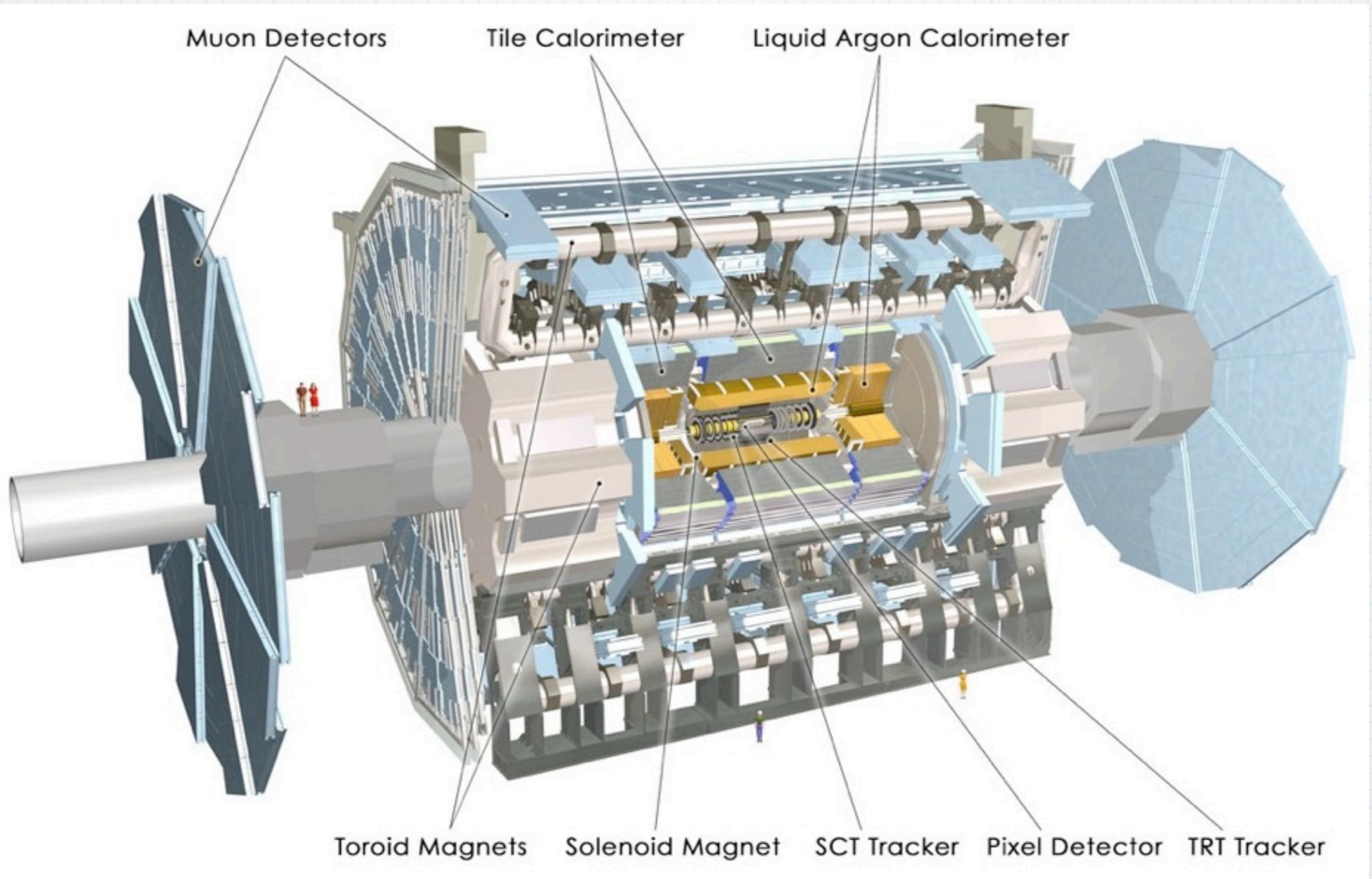
●  $5\text{ fb}^{-1}$  for both ATLAS & CMS



the most

years

# ATLAS Detector



# H $\rightarrow$ WW search

$m_H$ (GeV)	120	130	140	150	165	170	180	190	200
Signal	7.44	19.6	35.3	50.8	76.4	63.8	48.4	30.6	19.7
$t\bar{t}$	5.6	7.3	10.3	13.4	17.6	19.0	20.2	20.9	21.2
WW	32.1	43.3	53.5	61.3	69.9	71.5	74.1	75.4	76.2
$W + jets$	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Z	0.424	0.424	3.13	3.13	3.13	3.13	3.13	3.13	3.13