

# Searches for Exotic Heavy Quarks

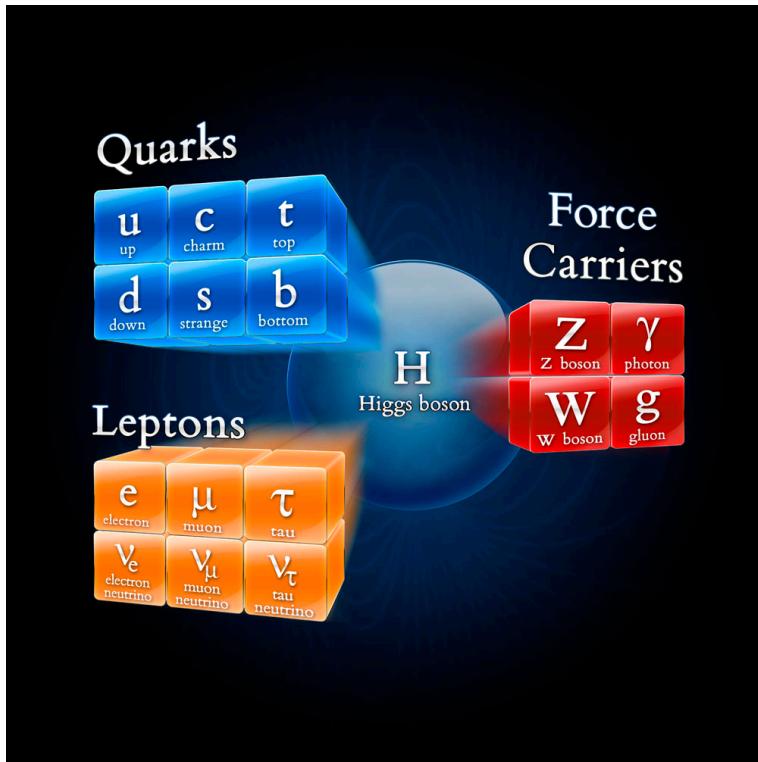
Snežana Nektarijević

15/5/15

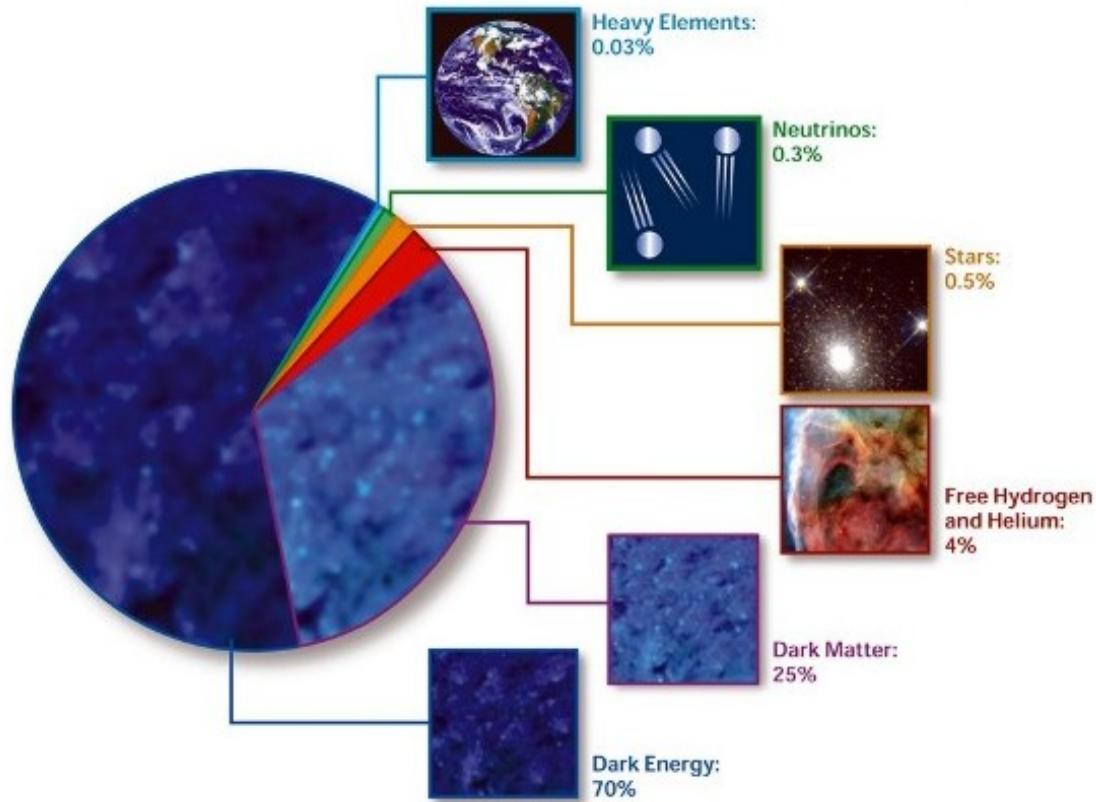
TH Conference Room, CERN, Geneva



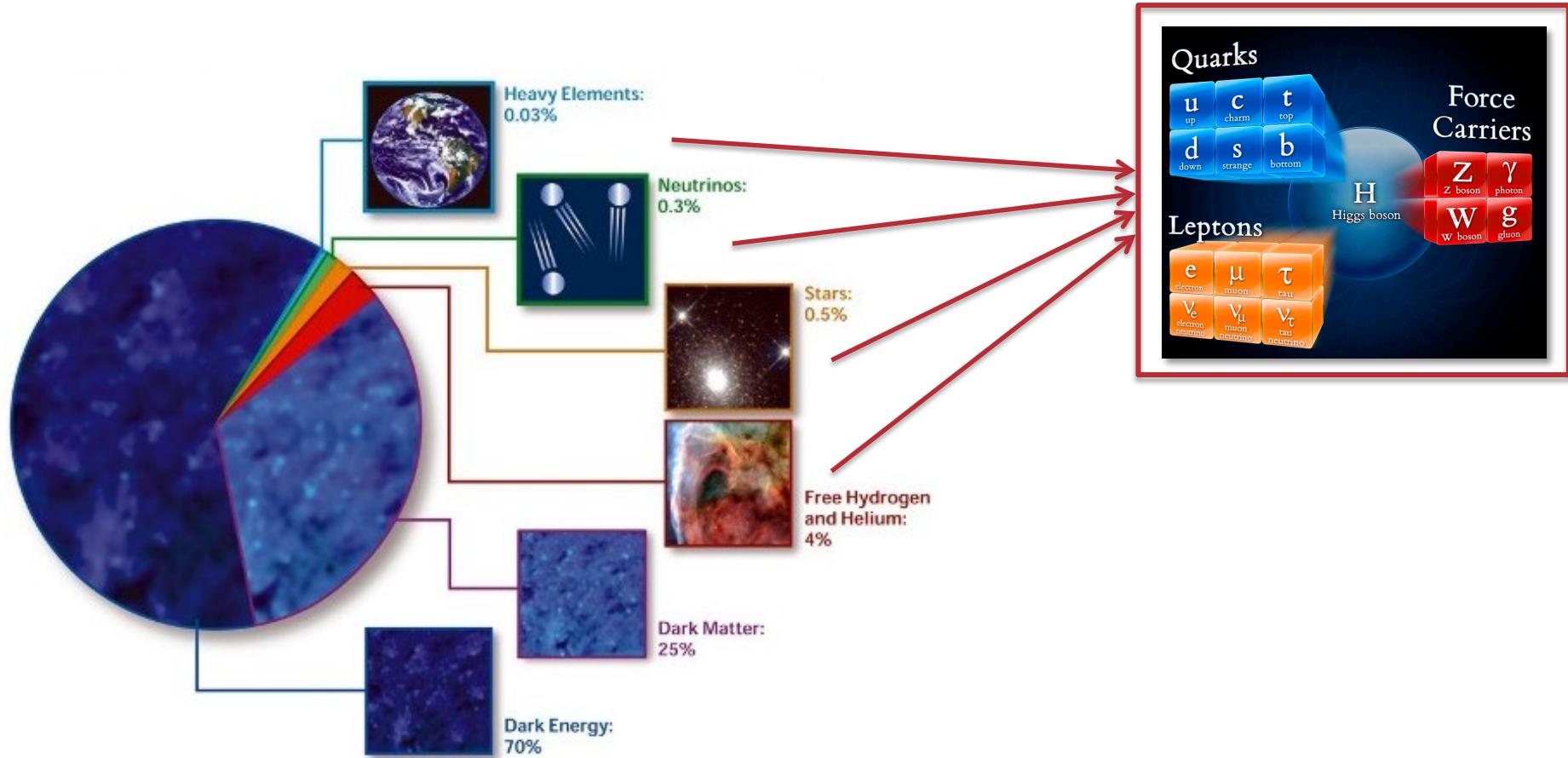
# Standard Model of Particle Physics



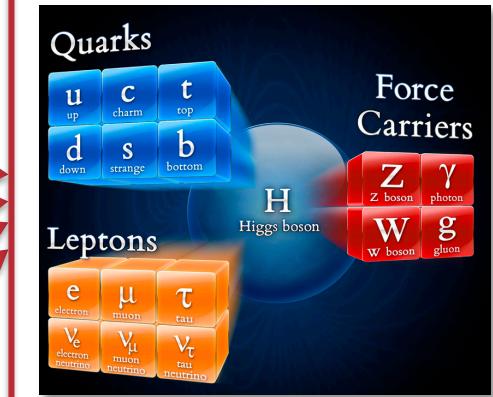
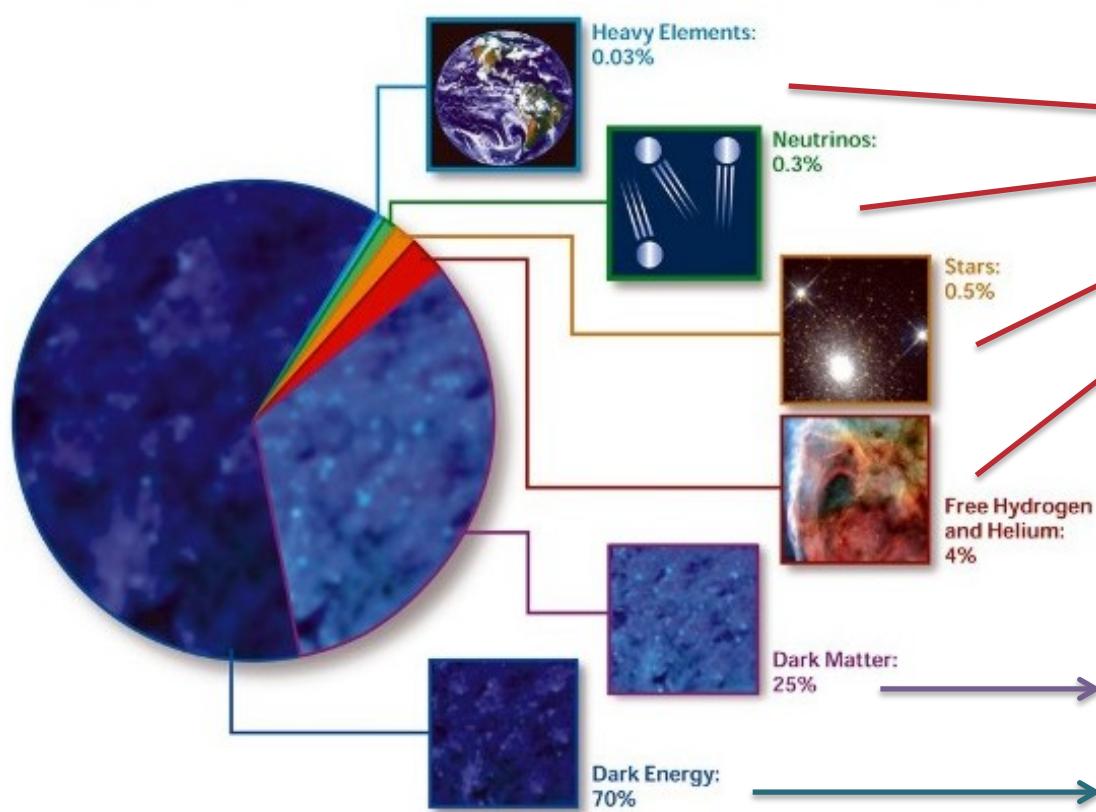
# Composition of the Universe



# Composition of the Universe



# New Physics Models

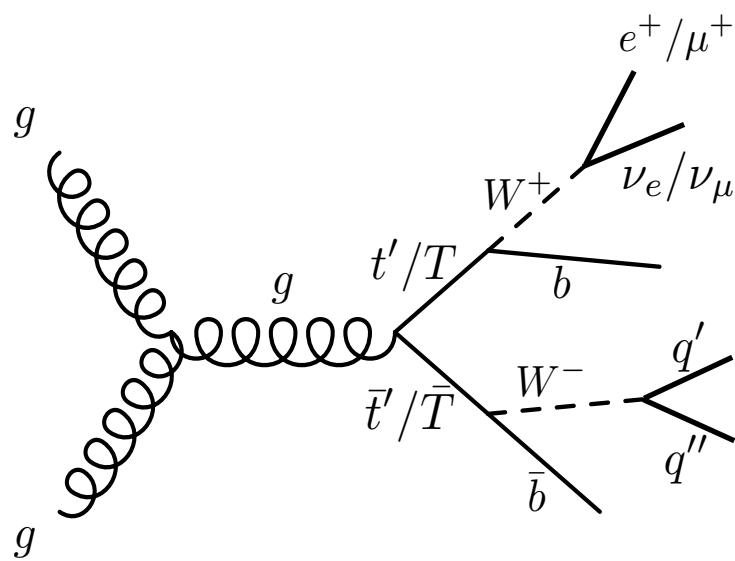


- New physics models:
  - Target one or more shortcomings of the SM
  - Develop a solution
    - Make predictions, phenomenology...
- New physics candidates
  - SUSY
  - Composite Higgs
  - Extra Dimensions

↓  
Exotic Heavy Quarks

# Process Sought

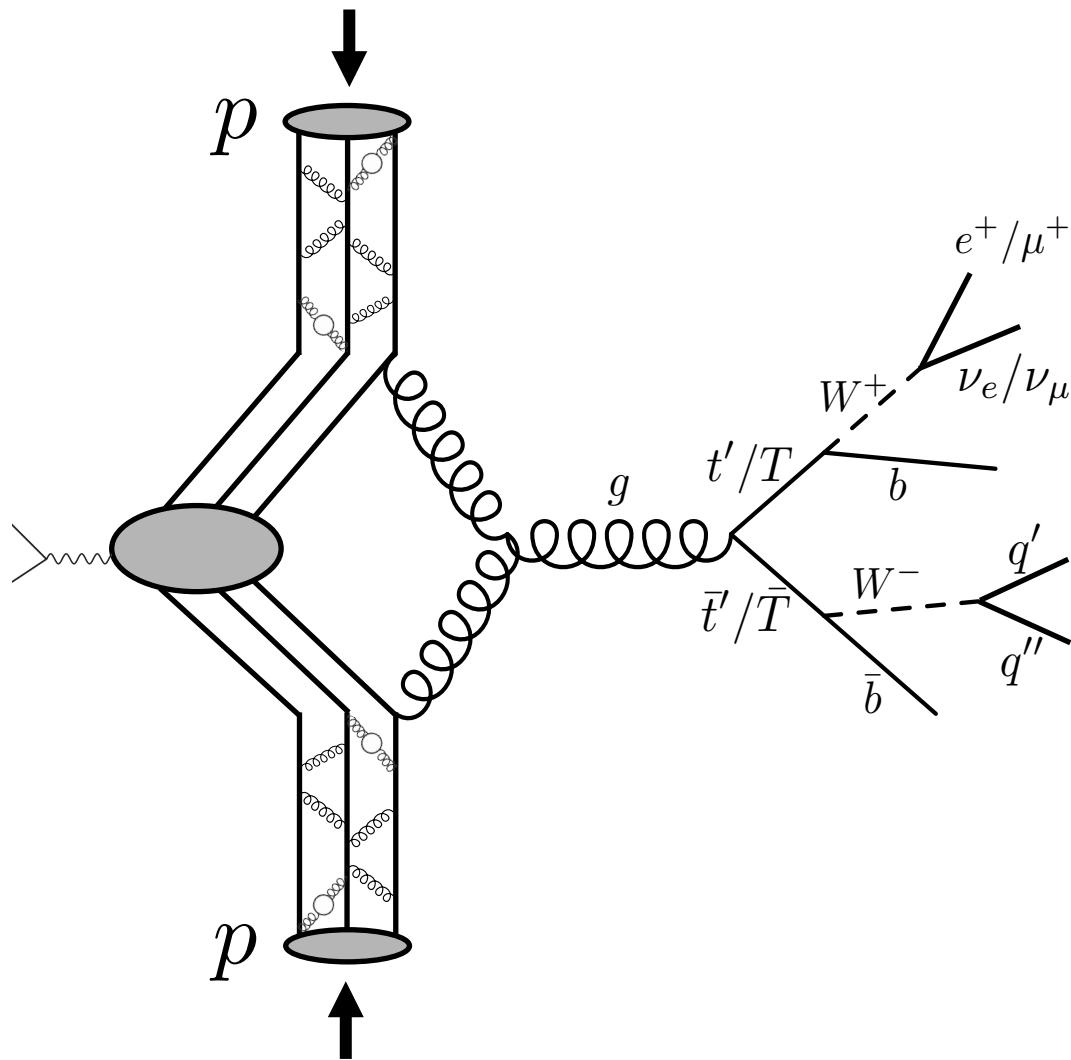
Production and  $t'/T$ -Decay Mode



- ❖ Pair production of the heavy quark  $T$
- ❖ Mass  $> 400$  GeV
- ❖ Decay modes:
  - ❖  $T \rightarrow Wb$
  - ❖  $T \rightarrow Zt$
  - ❖  $T \rightarrow Ht$

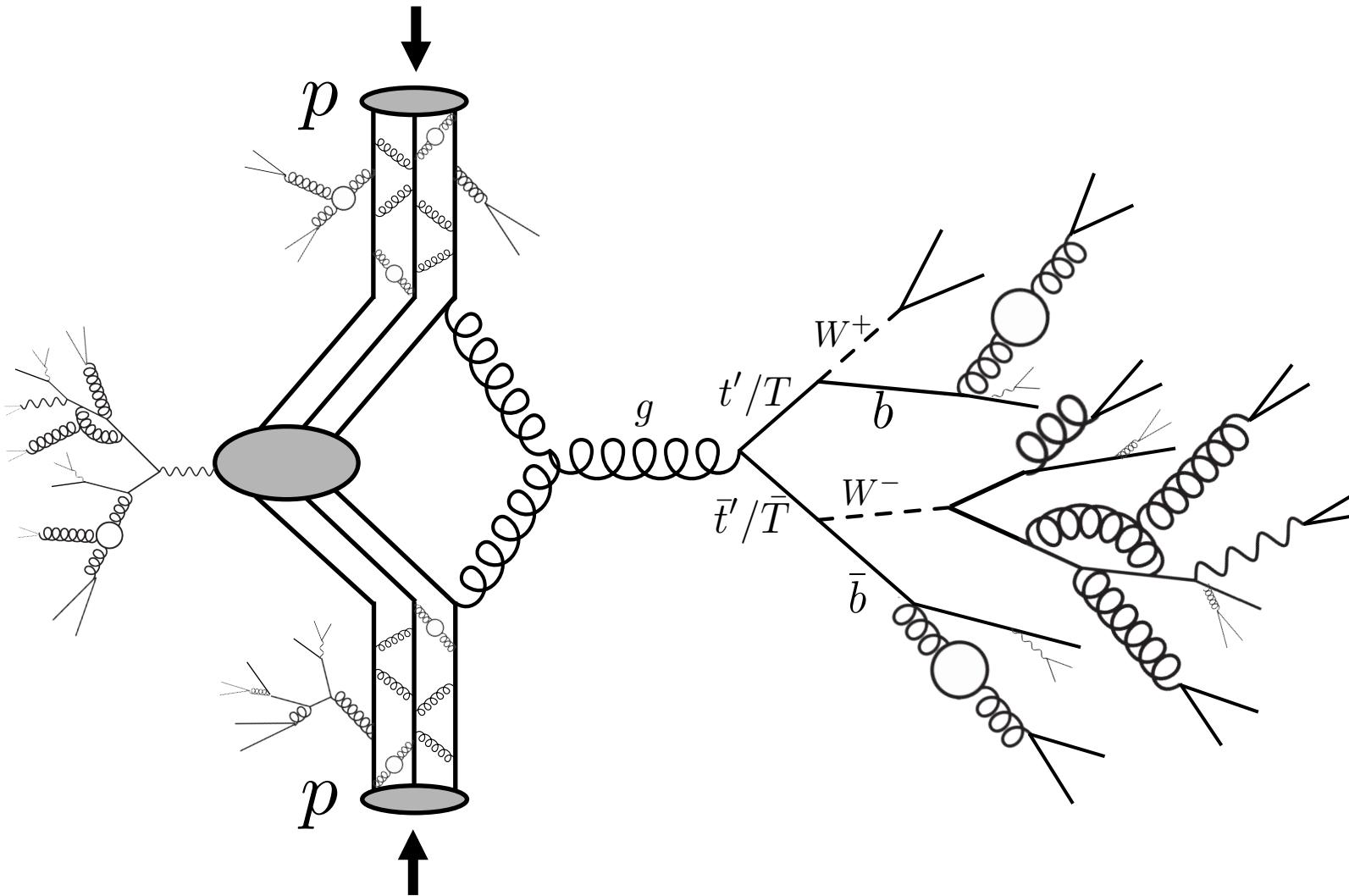
# Event Description

## Proton-proton Collisions



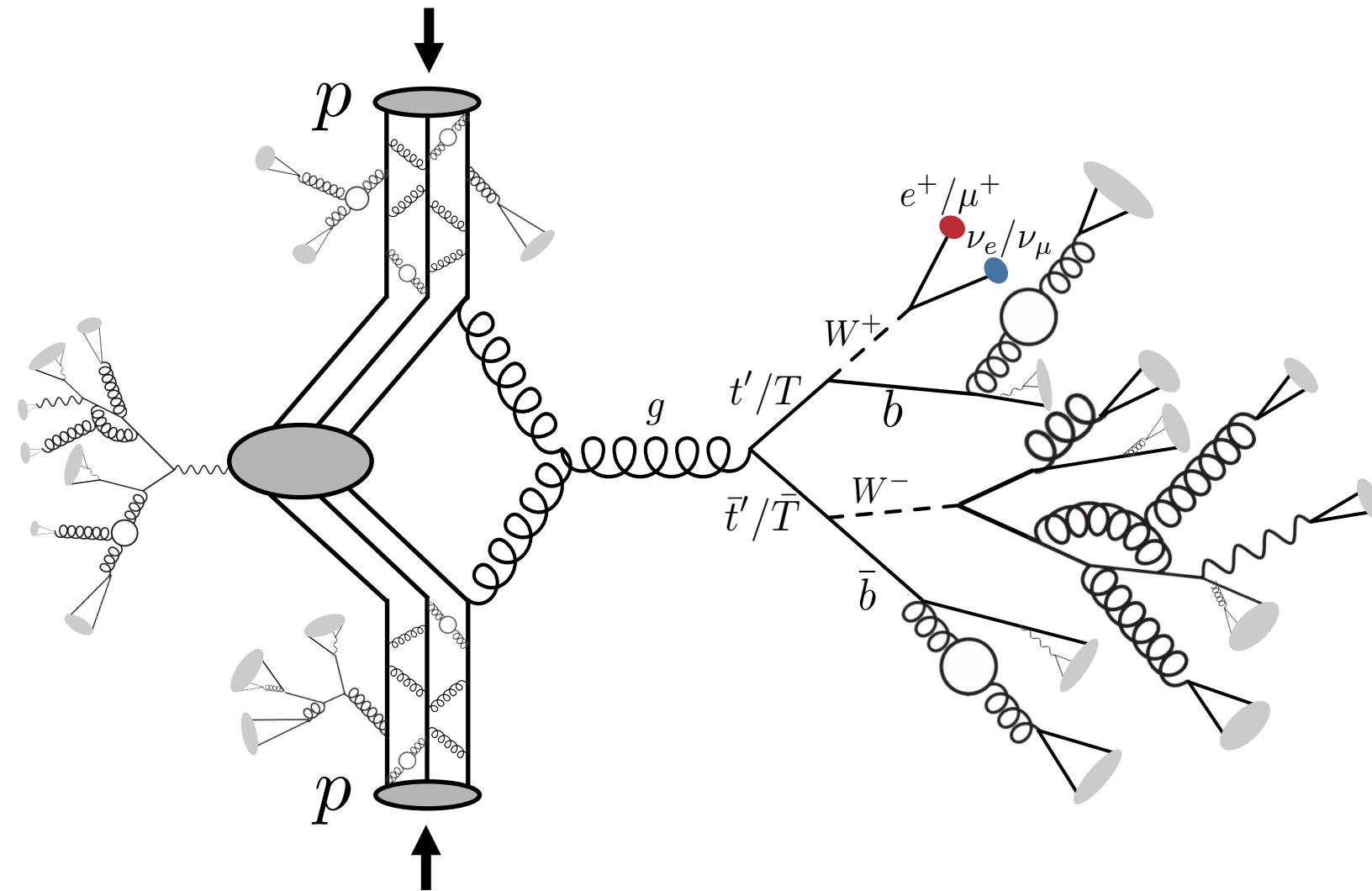
# Event Development

## Parton Shower



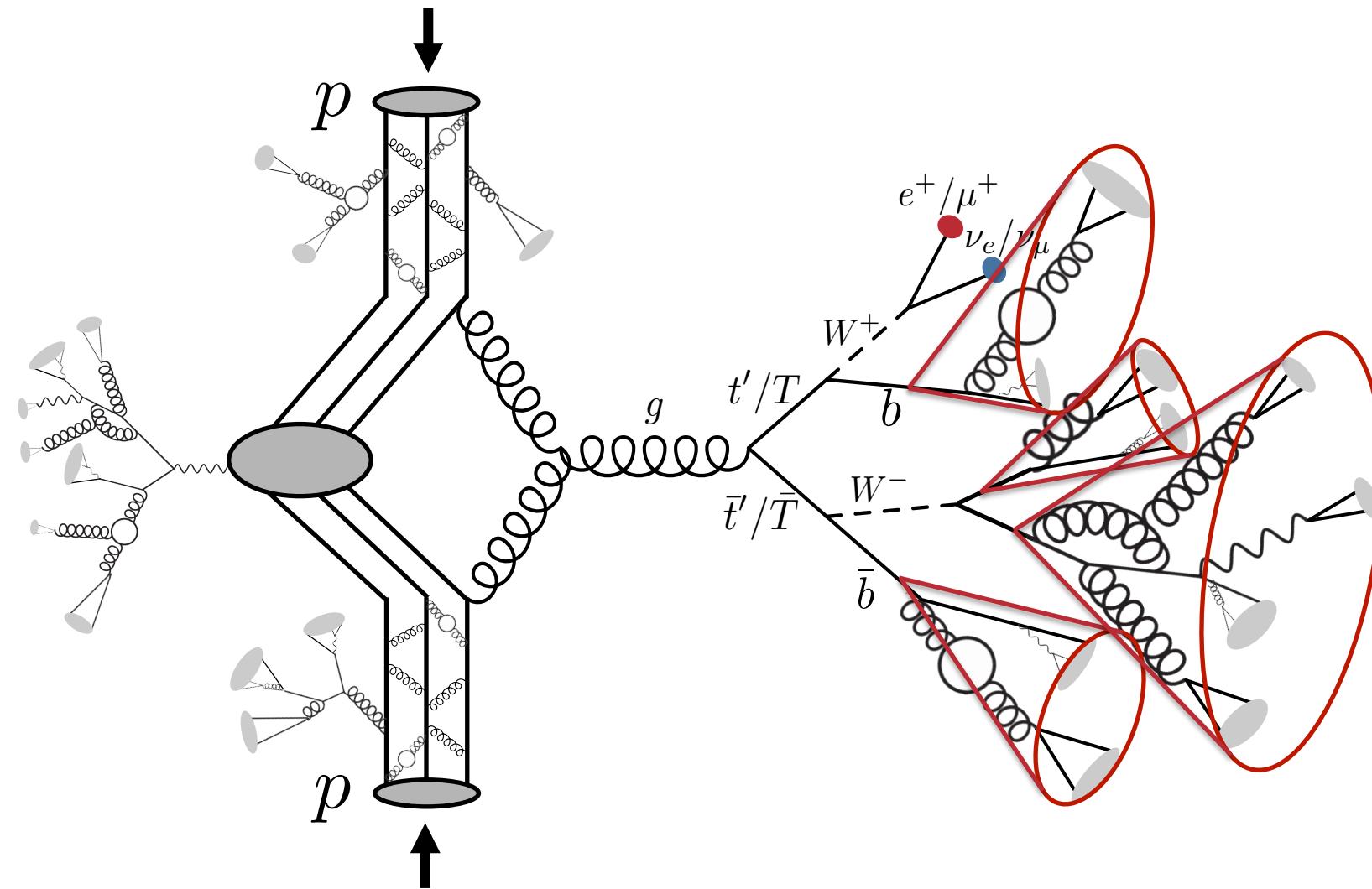
# Event Development

## Hadronisation



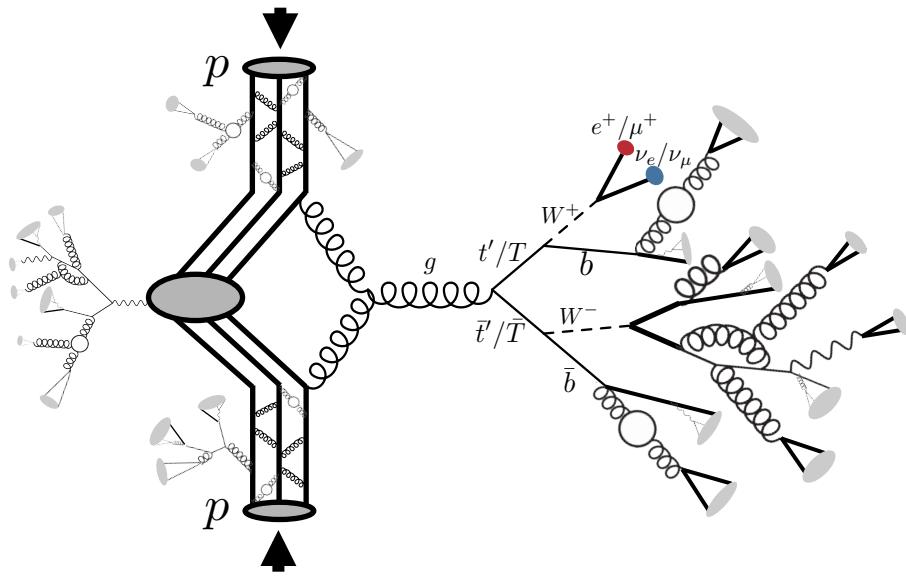
# Event Development

## Jet Reconstruction



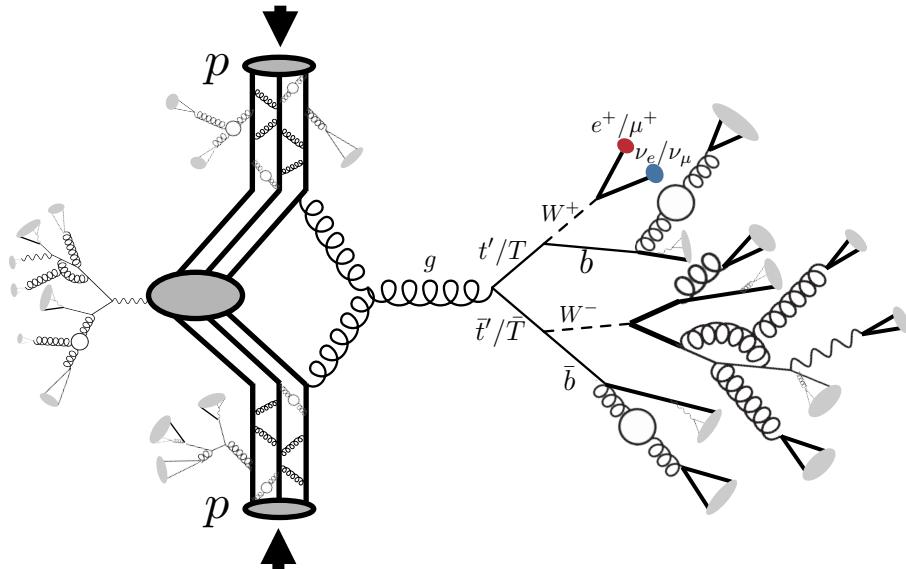
# Event Topology

Particle level

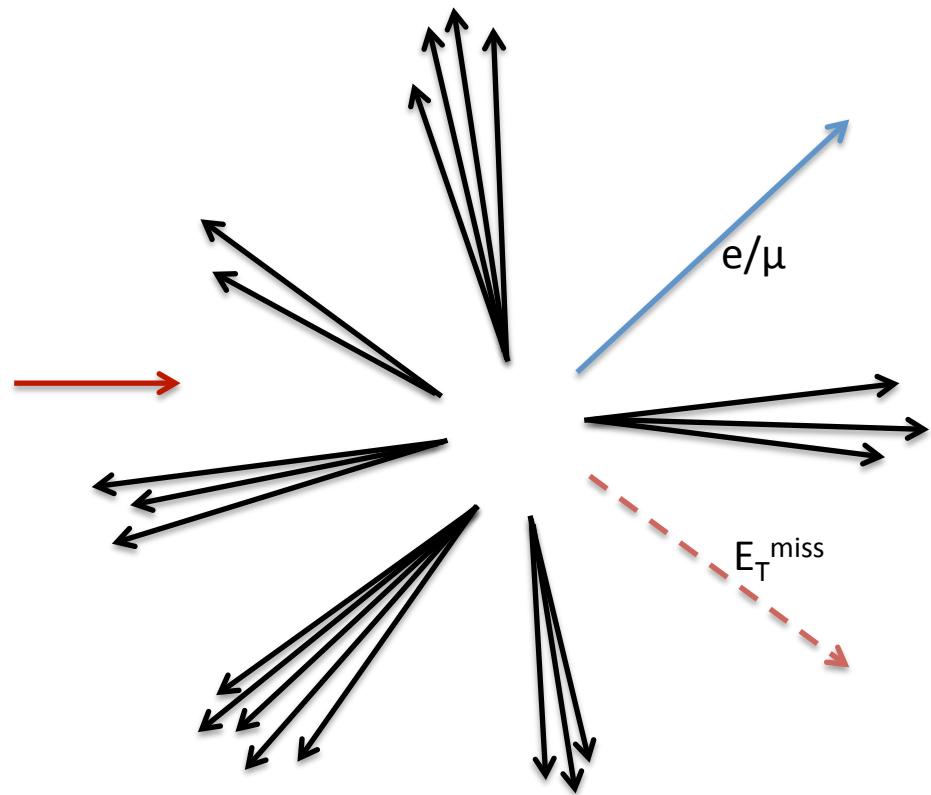


# Event Topology

Particle Level

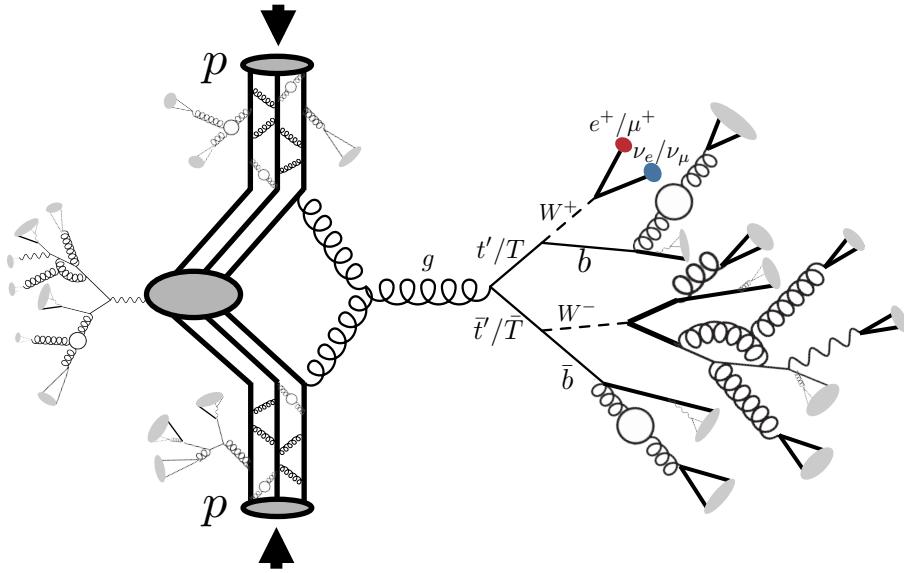


Detector Level

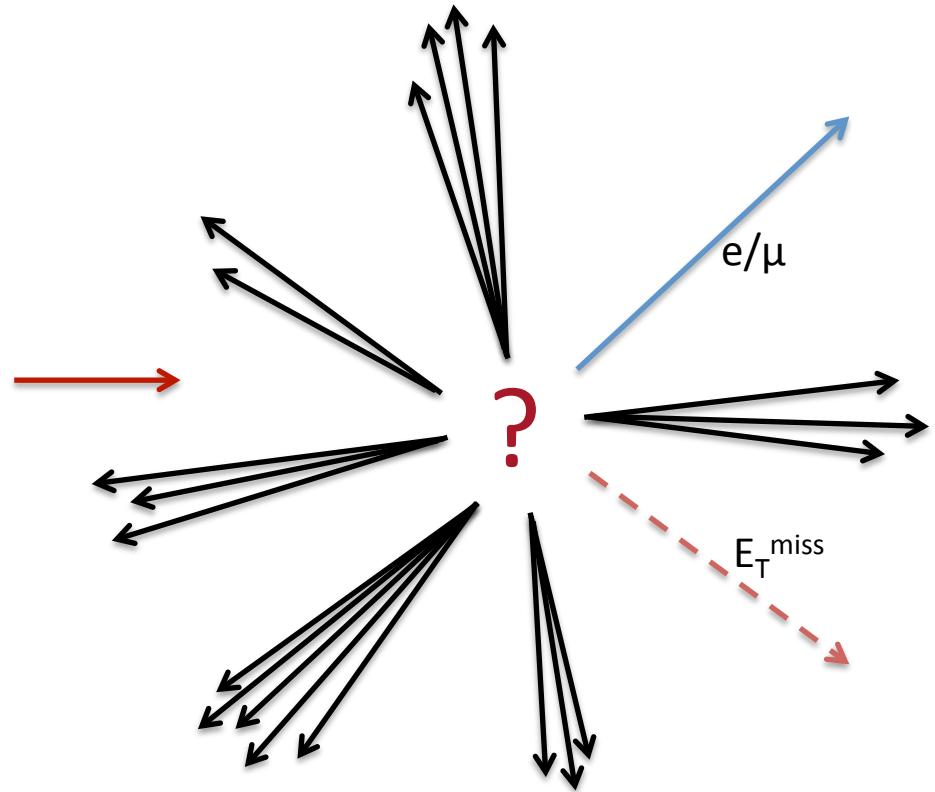


# Event Reconstruction

Particle Level



Detector Level



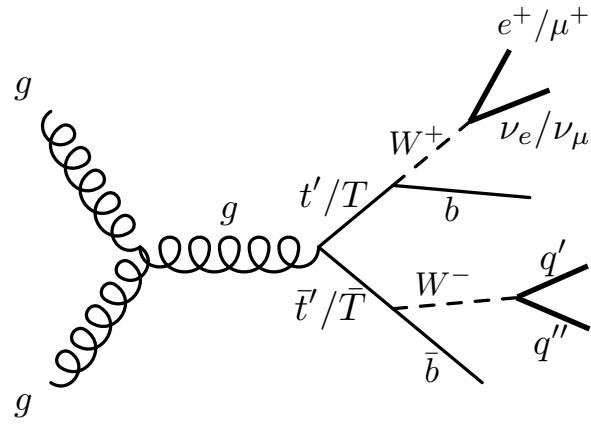




# Signal vs Backgrounds

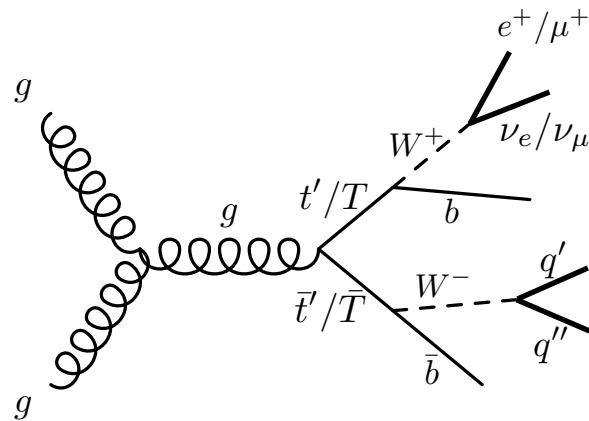
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Signal:

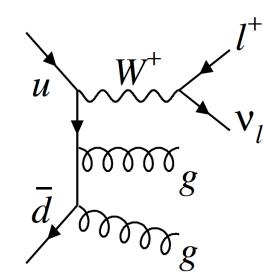
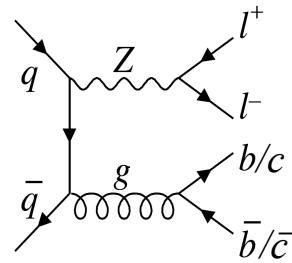
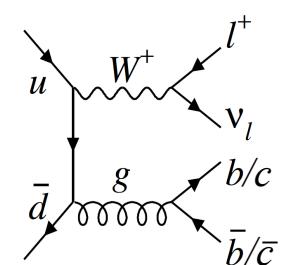
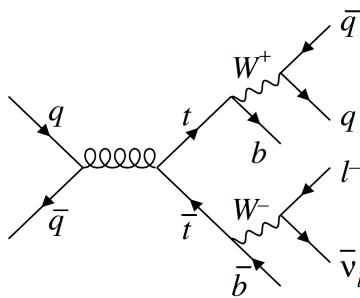


# Signal vs Backgrounds

Signal:



Backgrounds:



~1'000'000 x more background than signal expected

# Classical vs Quantum Physics

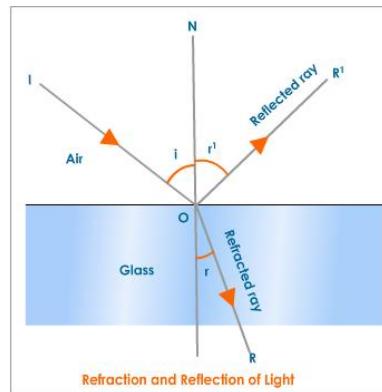
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	Classical Physics	Quantum Physics
Nature	Deterministic	Probabilisitc
Repetitive experiments	Always the same result	Spectrum of results
Measurements	Discrete values	Distributions

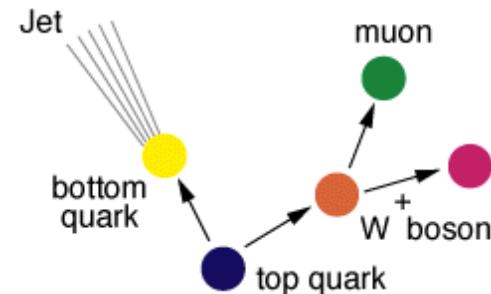
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Classical process



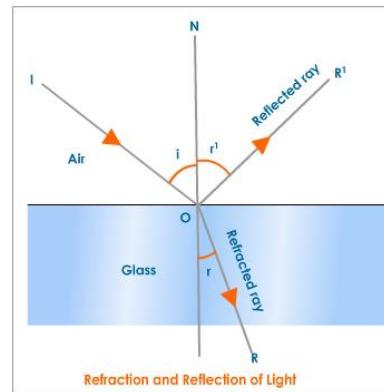
Quantum process



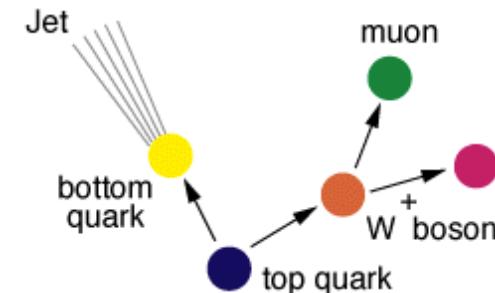
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Quantum process

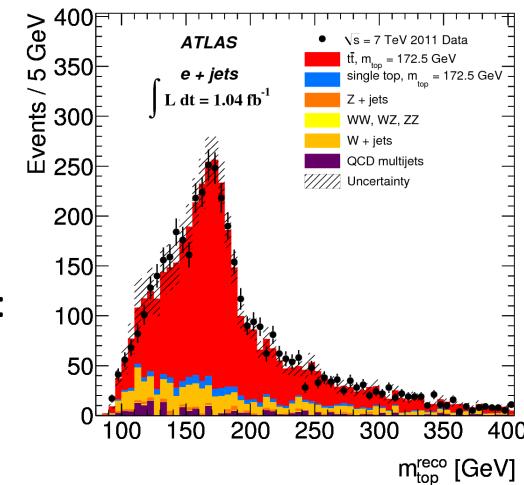


Relativistic mass of a single particle:

$$(mc^2)^2 = E^2 - |\vec{p}|^2 c^2$$

Invariant mass of a system of particles:

$$(Wc^2)^2 = \left( \sum E \right)^2 - \left| \sum \vec{p} \right|^2 c^2$$

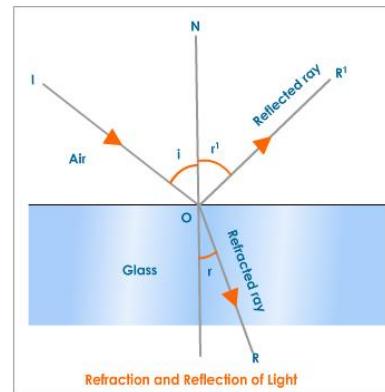


# Classical vs Quantum Physics

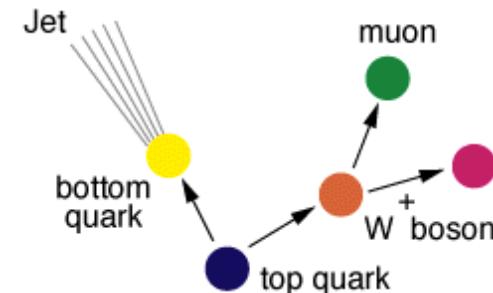
	Classical Physics	Quantum Physics
Nature	Deterministic	Probabilisitc
Repetitive experiments	Always the same result	Spectrum of results
Measurements	Discrete values	Distributions

- Collider physics
  - Many repeated experiments under conditions as similar as possible
  - Measurement of kinetic variables -> distributions

Classical process



Quantum process

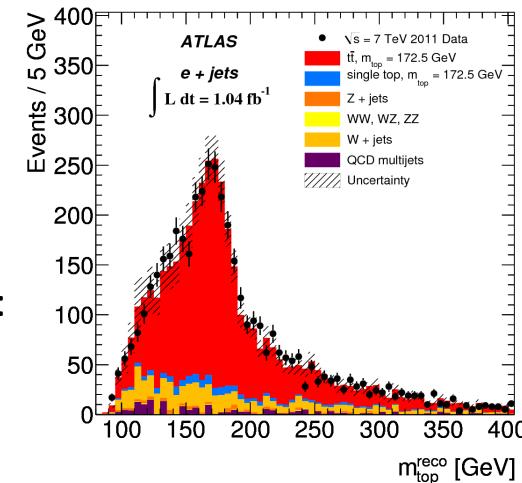


Relativistic mass of a single particle:

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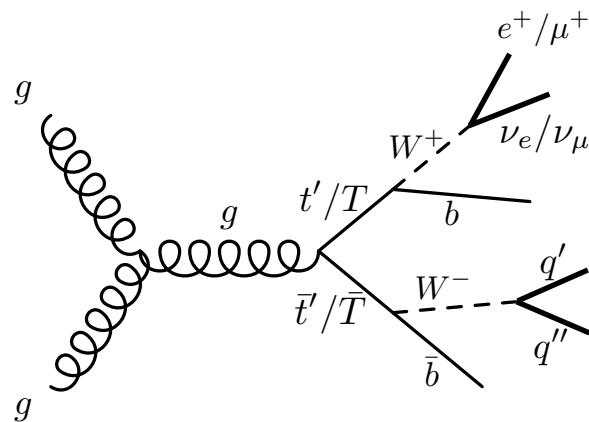
Invariant mass of a system of particles:

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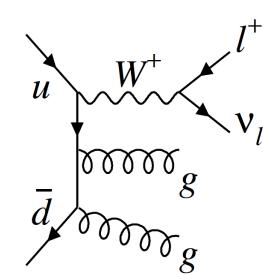
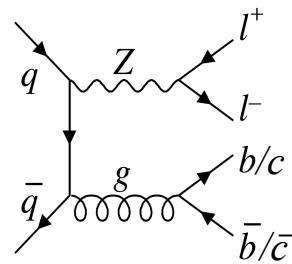
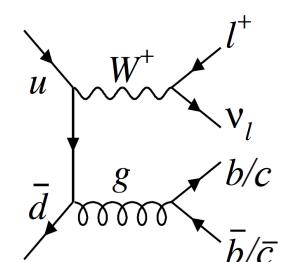
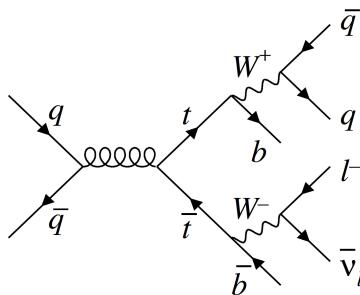


# Signal vs Backgrounds

Signal:



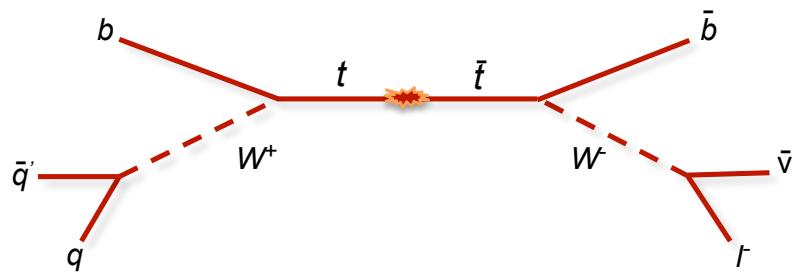
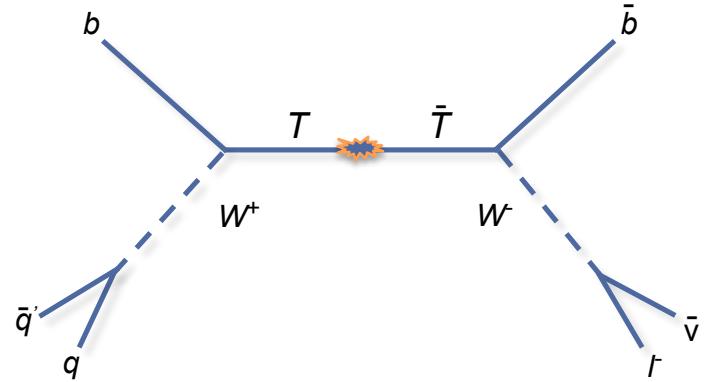
Backgrounds:



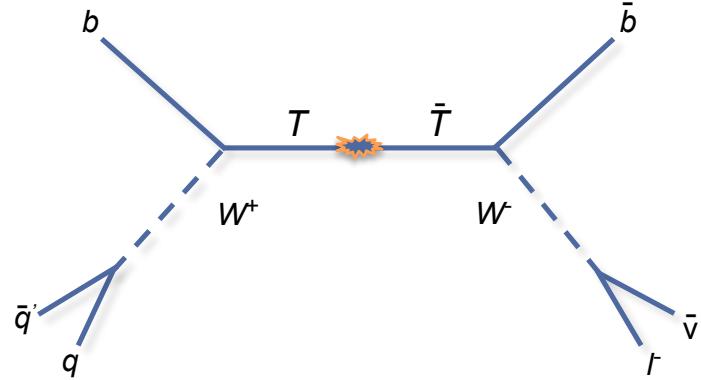
$\sim 1'000'000 \times$  more background than signal expected

# Kinematics: $T\bar{T}$ vs $t\bar{t}$

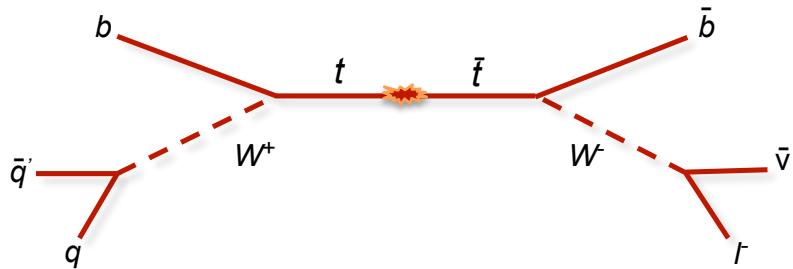
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# Kinematics: $T\bar{T}$ vs $t\bar{t}$



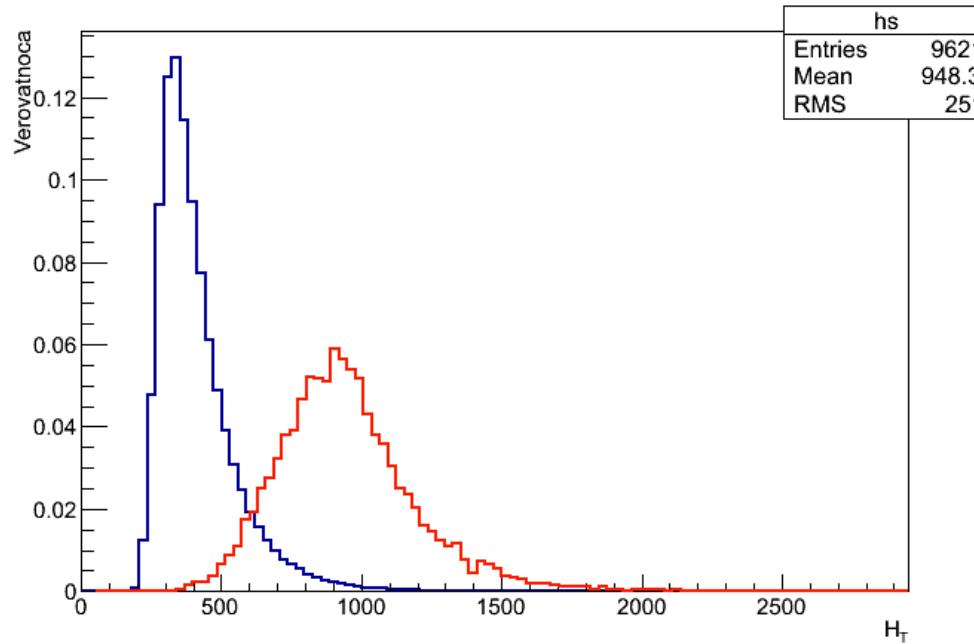
- ❖  $m_T > m_t$ 
  - ⇒ Differences in the **momentum** distributions of the decay products
  - ⇒ Differences in **angles** between decay products



# Signal/Background Discrimination

- Primer:
  - varijabla  $H_T \rightarrow$  suma transferzalnih impulsa objekata od interesa

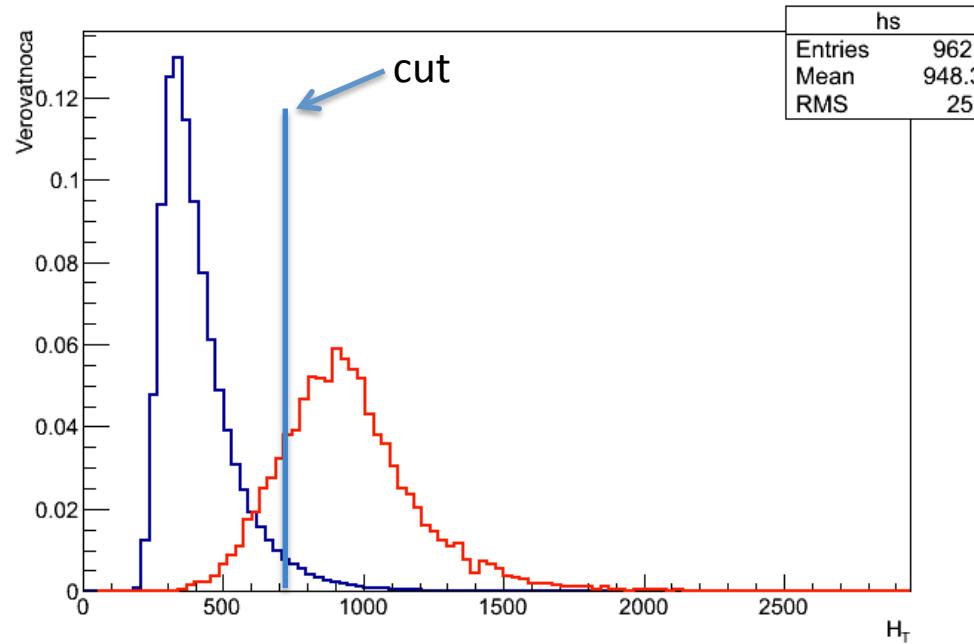
$$H_T = \sum p_T$$



# Signal/Background Discrimination

- Primer:
  - varijabla  $H_T \rightarrow$  suma transferzalnih impulsa objekata od interesa

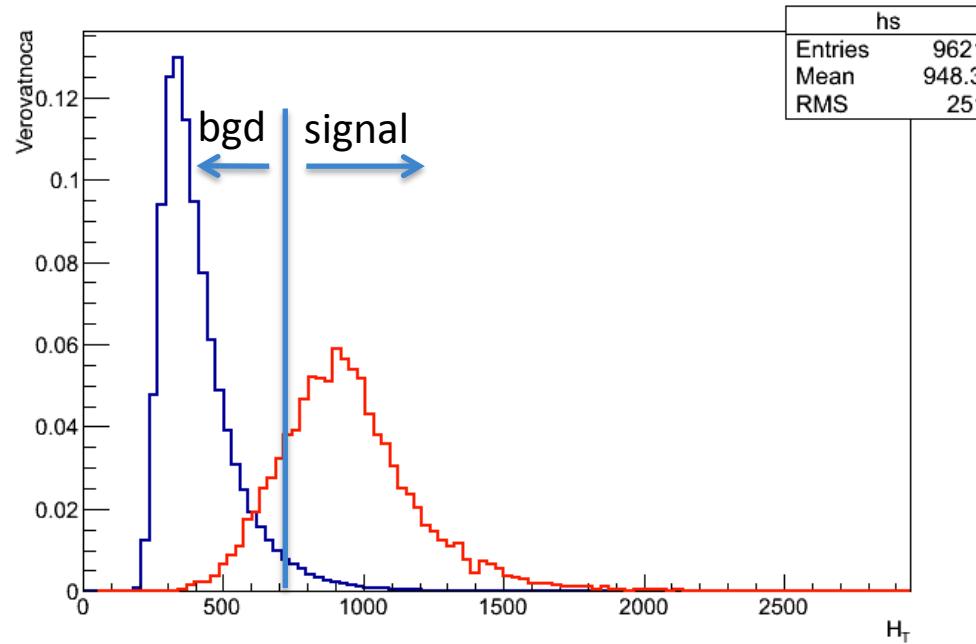
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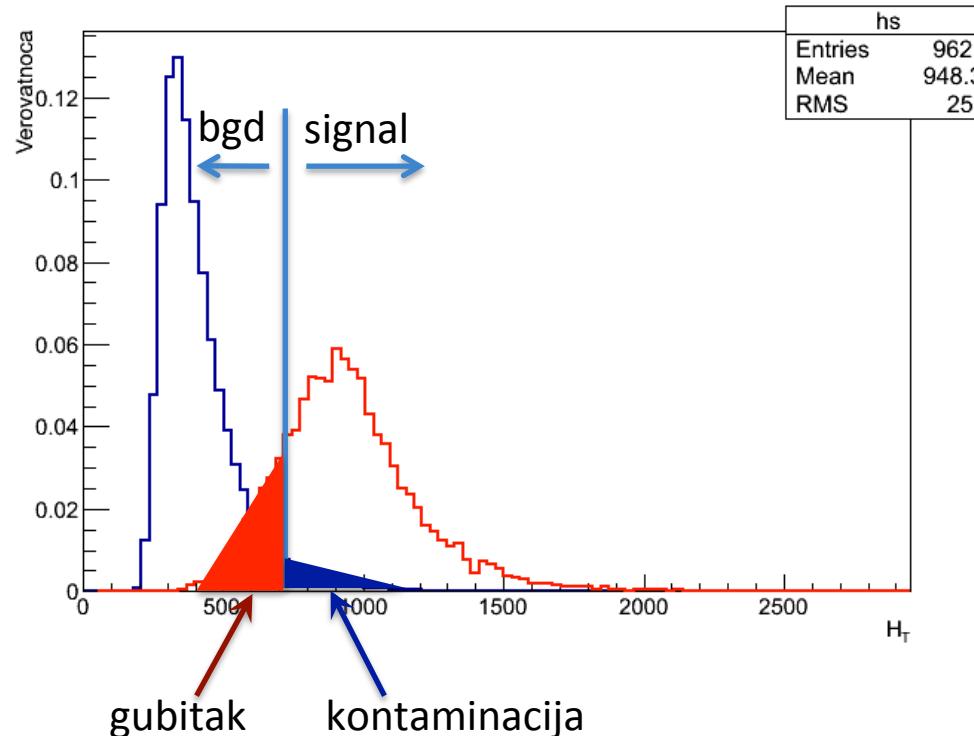
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# Signal/Background Discrimination

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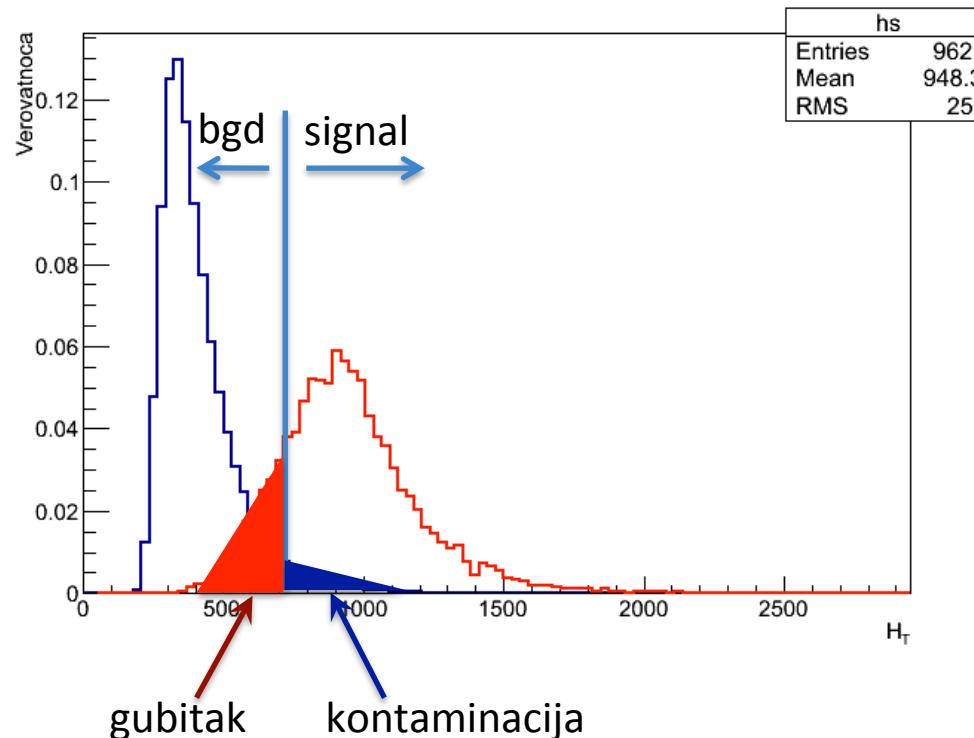


# Signal/Background Discrimination

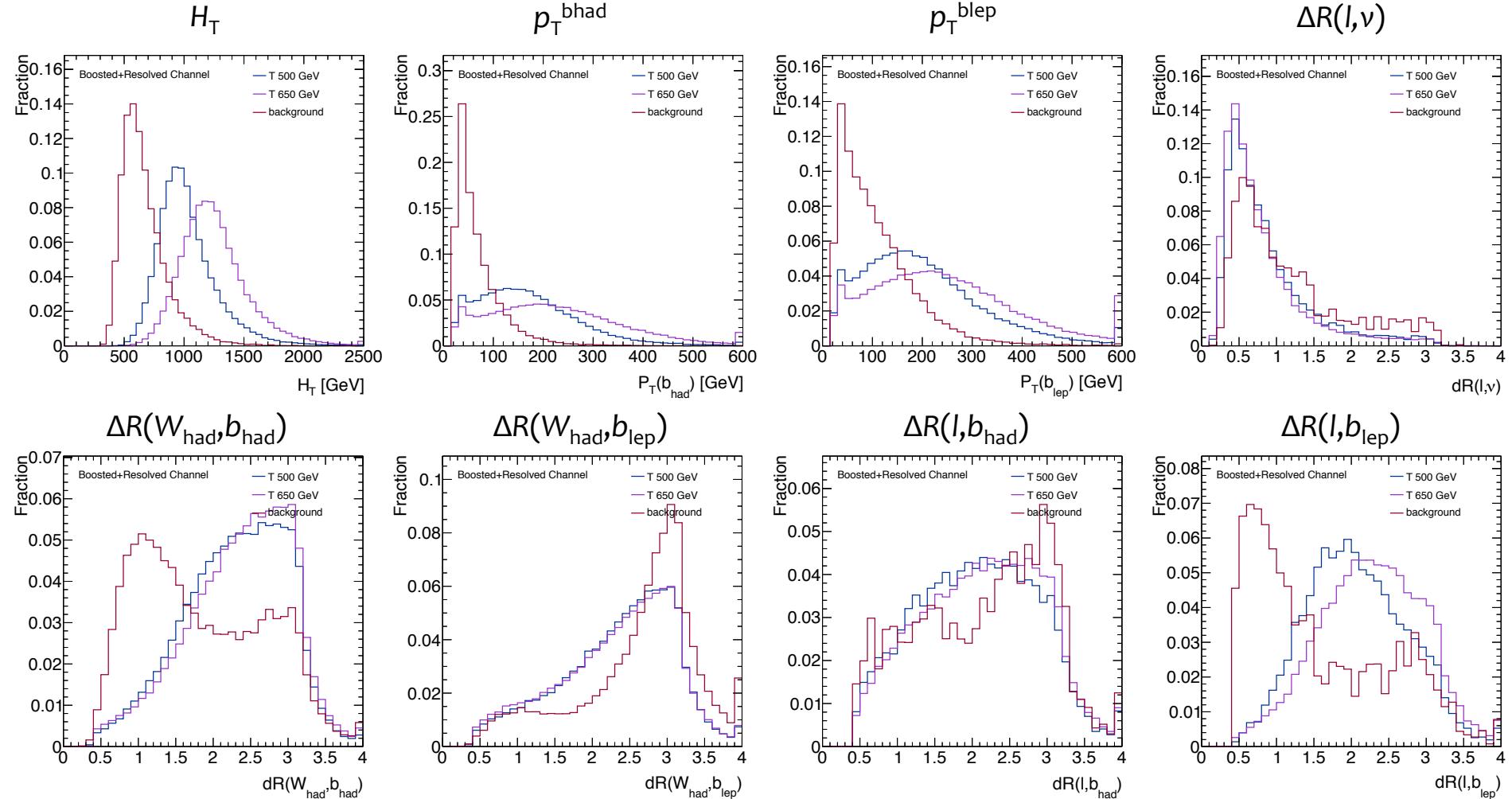
- Primer:
  - varijabla  $H_T \rightarrow$  suma transferzalnih impulsa objekata od interesa

$$H_T = \sum p_T$$

Optimizacija selekcije:  
• Simultana minimizacija kontaminacije i gubitka u više promenljivih

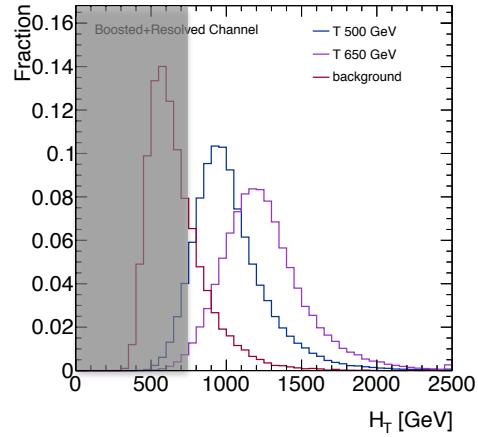


# Discriminating Variables

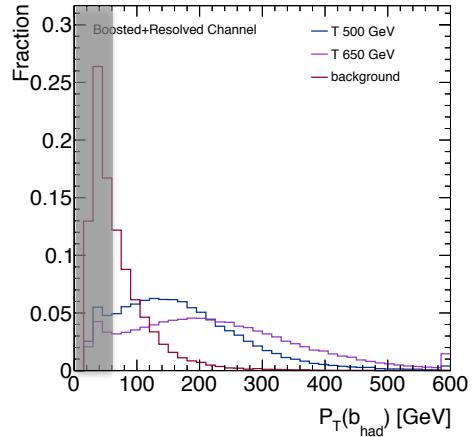


# Cut-based Selection

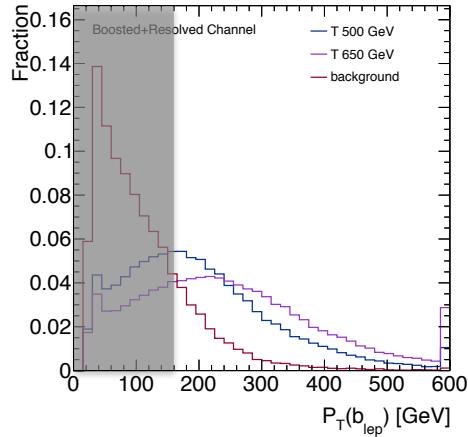
$H_T > 750 \text{ GeV}$



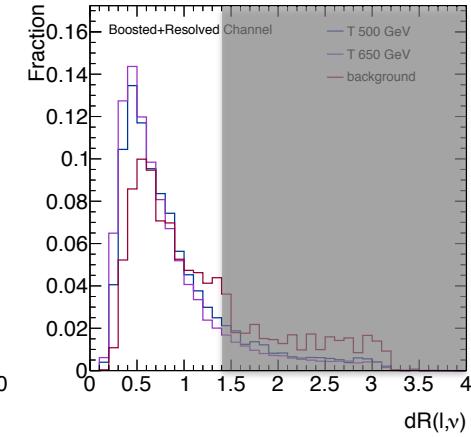
$\min p_T^b > 60 \text{ GeV}$



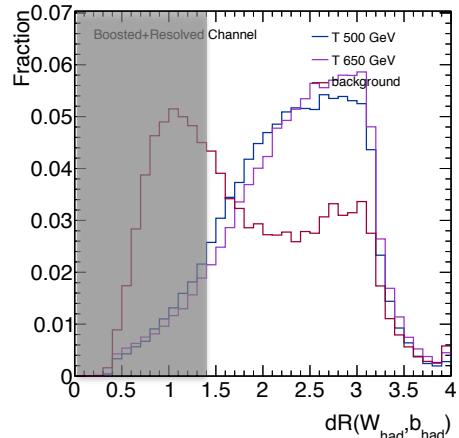
$\max p_T^b > 160 \text{ GeV}$



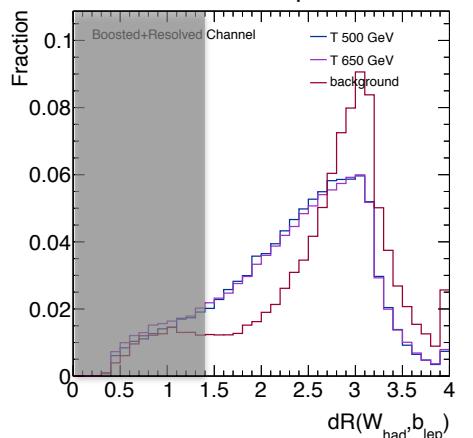
$\Delta R(l, \nu) < 1.4$



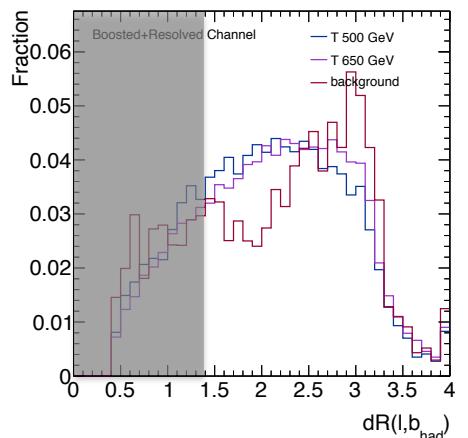
$\Delta R(W_{\text{had}}, b_{\text{had}}) > 1.4$



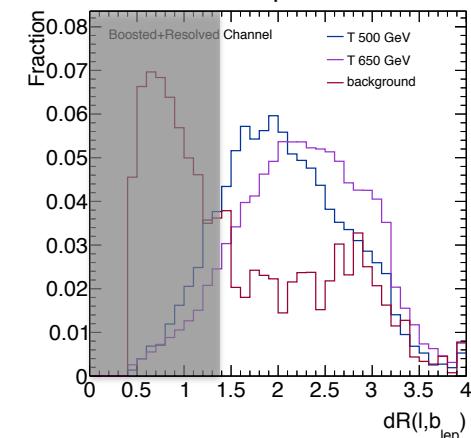
$\Delta R(W_{\text{had}}, b_{\text{lep}}) > 1.4$



$\Delta R(l, b_{\text{had}}) > 1.4$



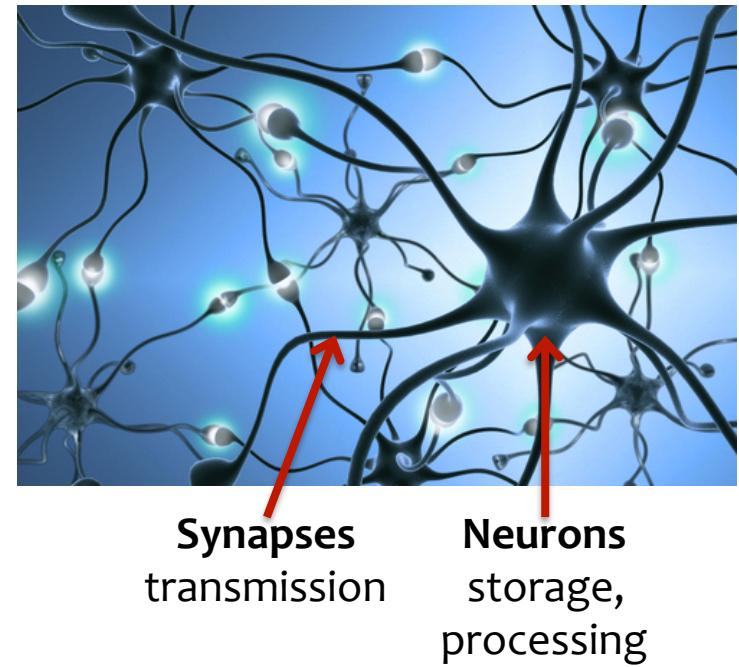
$\Delta R(l, b_{\text{lep}}) > 1.4$



# Multi-Variate Analysis

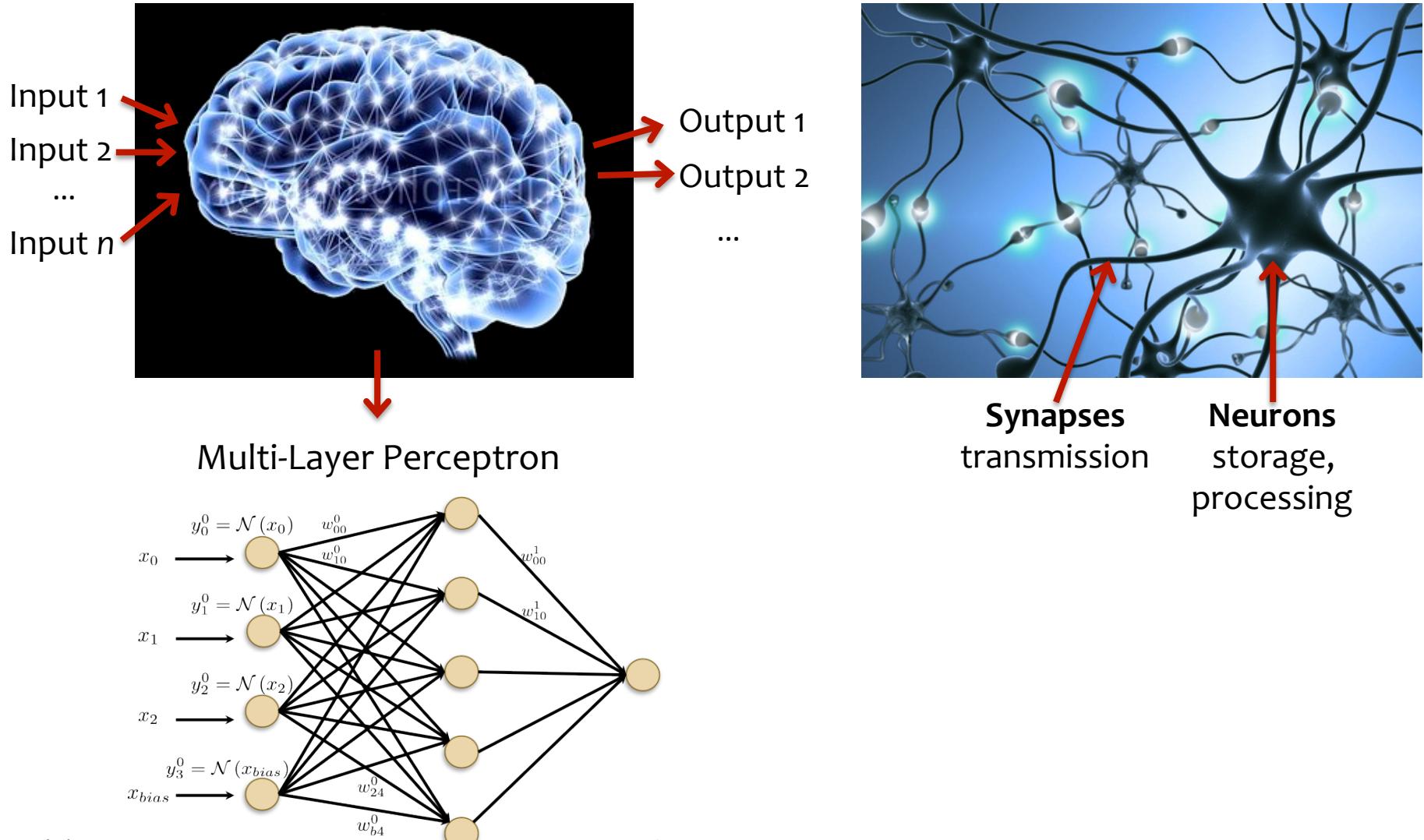
## Motivation

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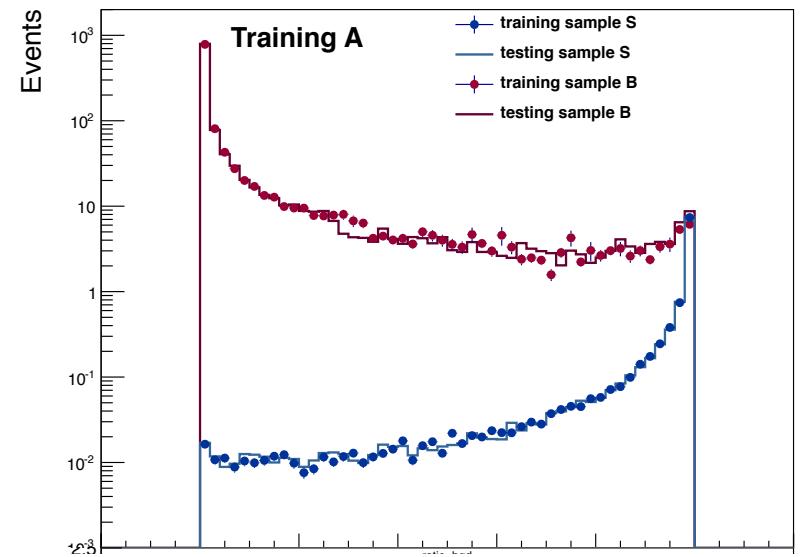
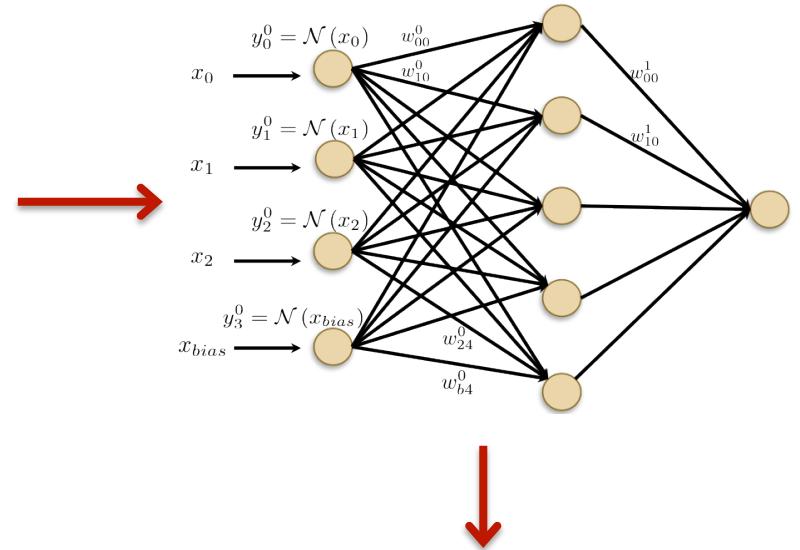
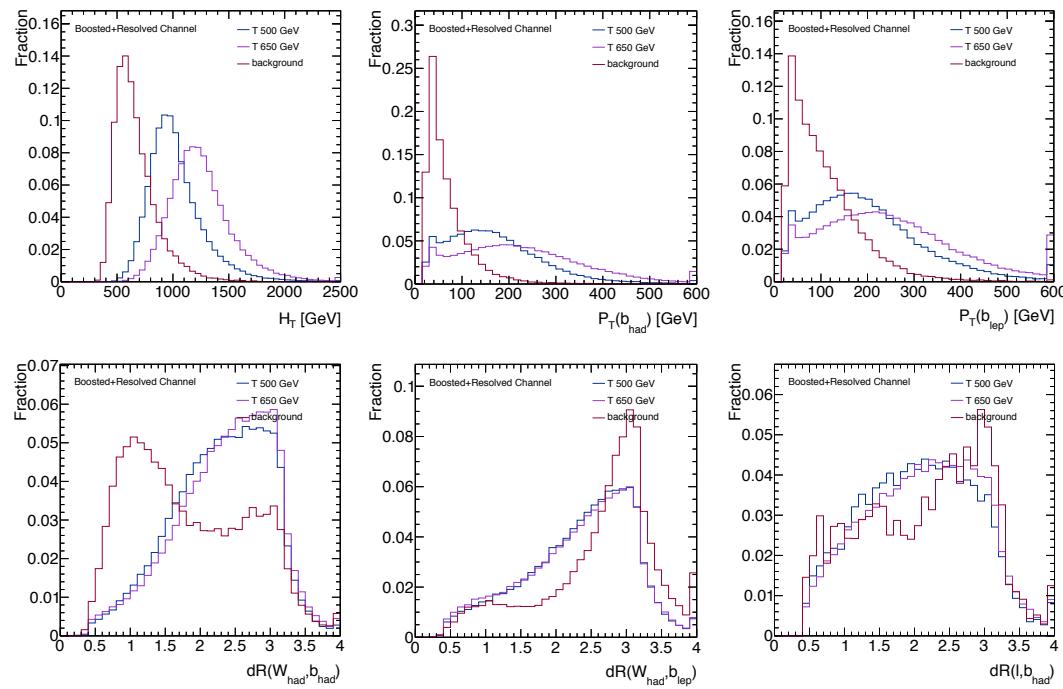


# Multi-Variate Analysis

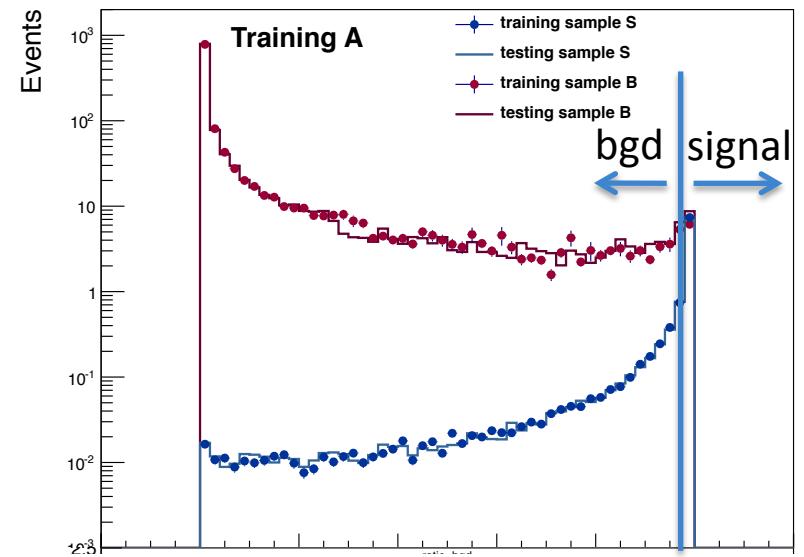
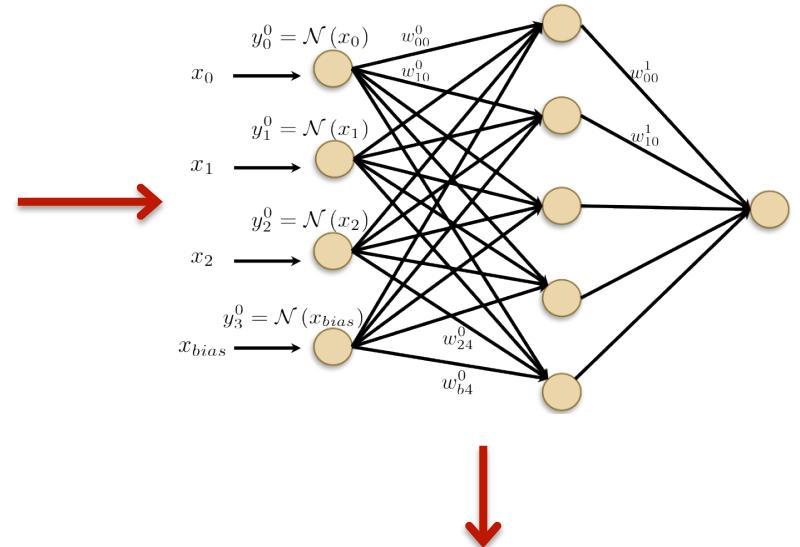
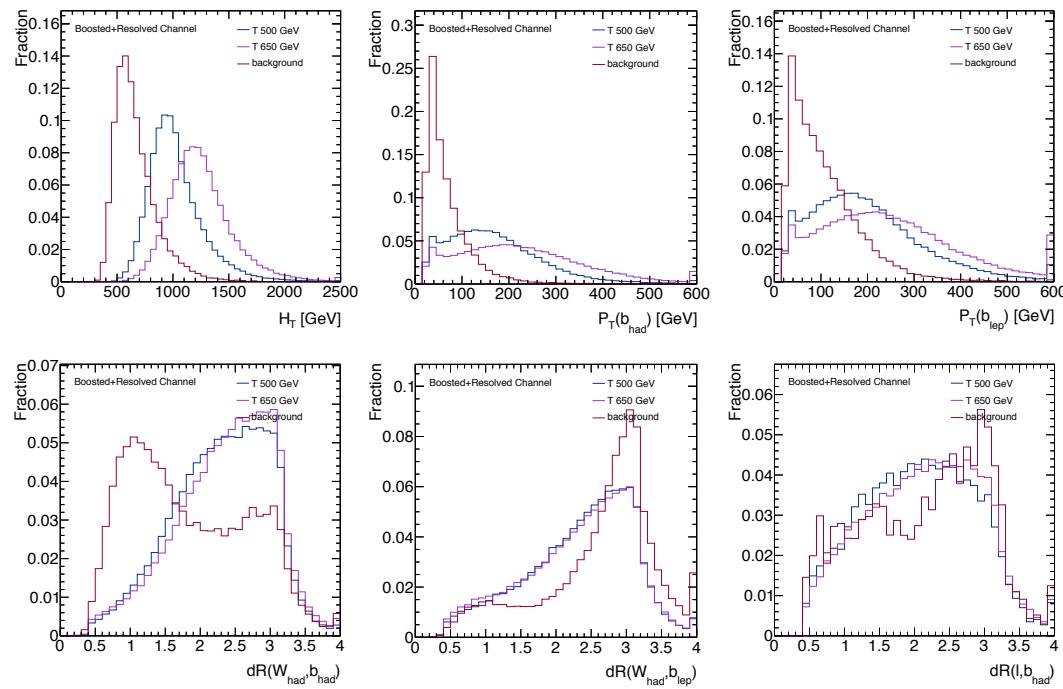
## Artificial Neural Network



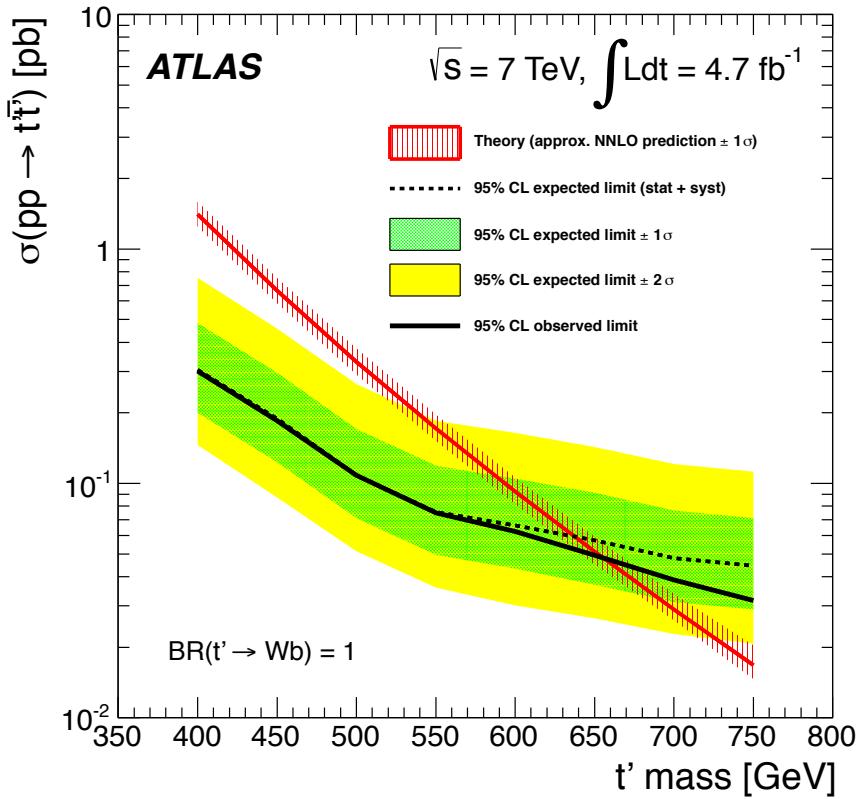
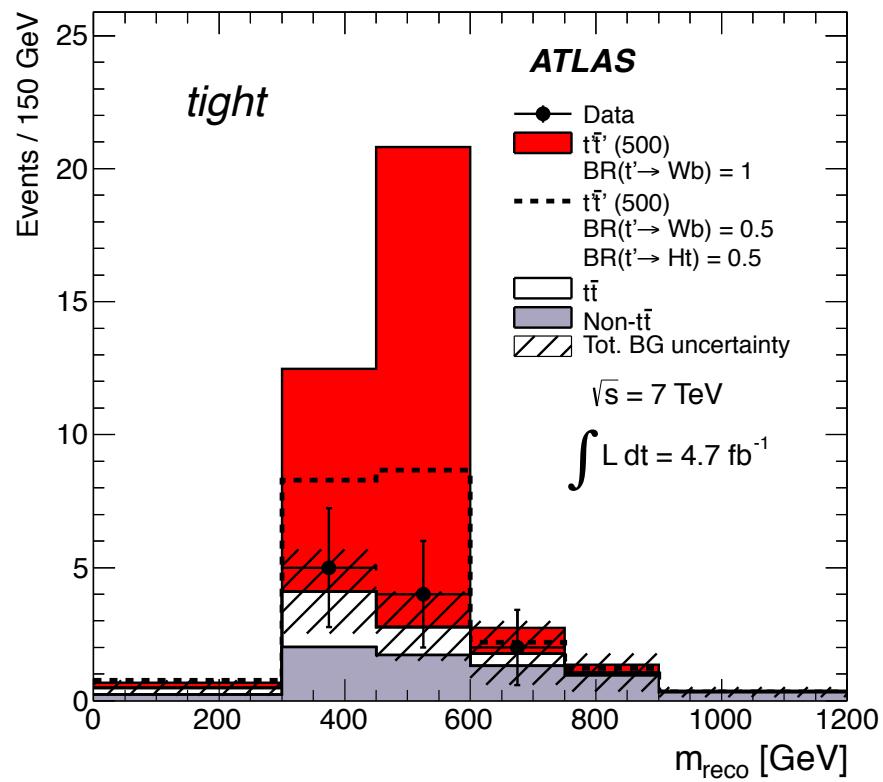
# Neural Network Selection



# Neural Network Selection



# Systematic Uncertainties and Statistical Analysis



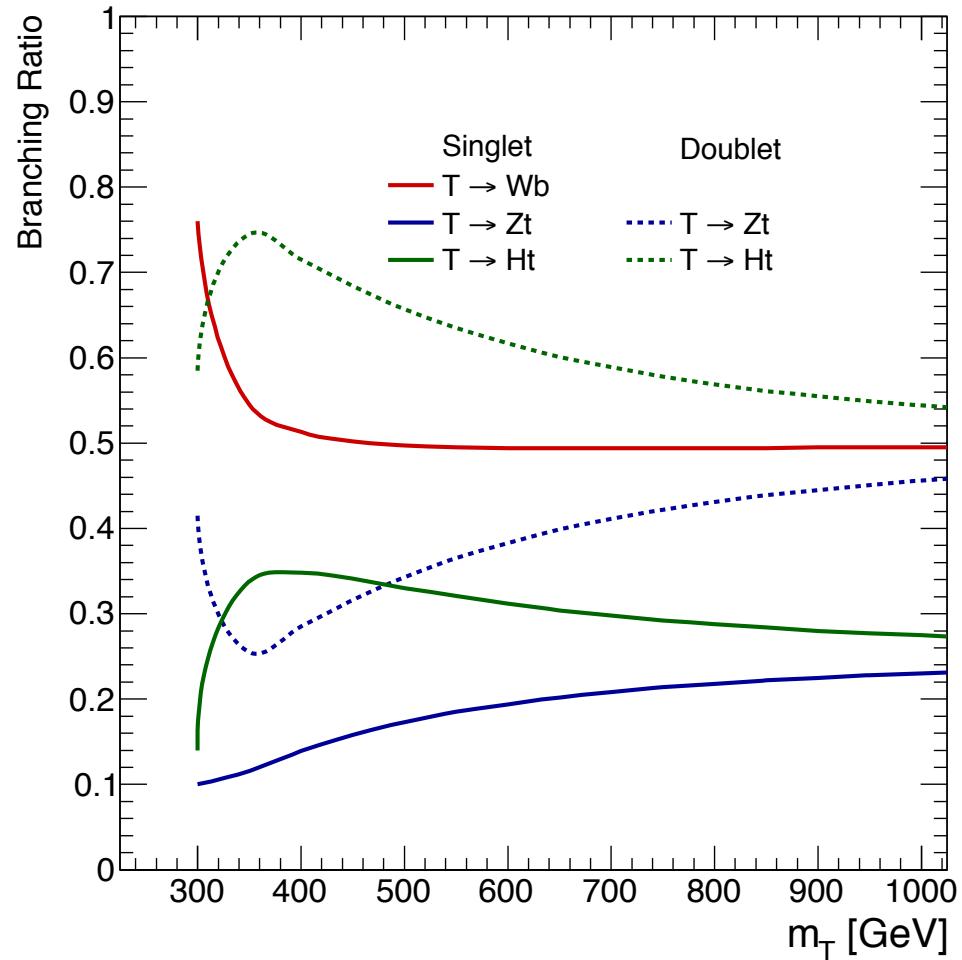
# Don't forget any decay!

T-quark decay modes:

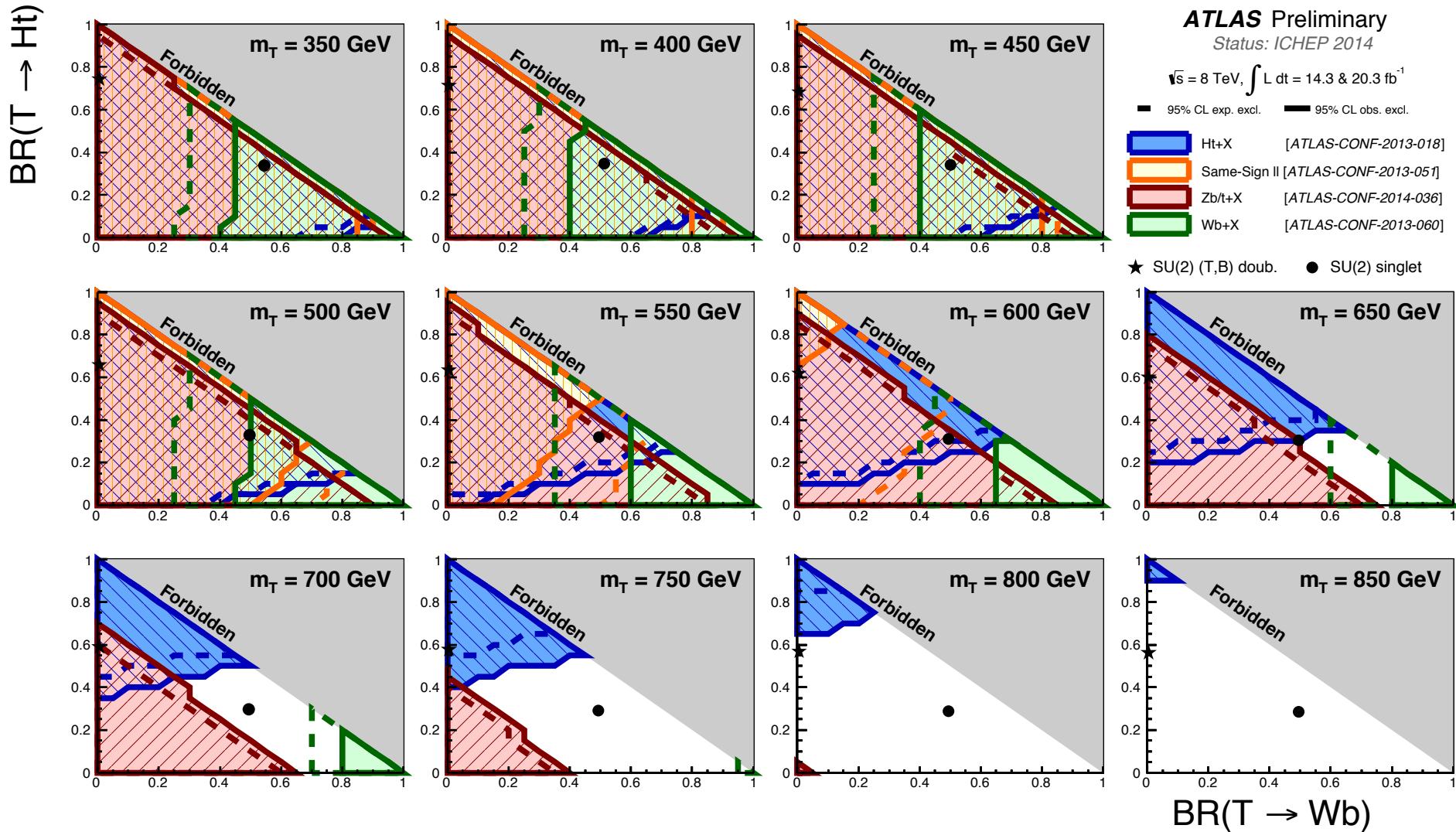
$T \rightarrow Wb$

$T \rightarrow Zt$

$T \rightarrow Ht$



# Exclusion Limits vs Branching Fraction



# Conclusion

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Keep searching because...



# Conclusion

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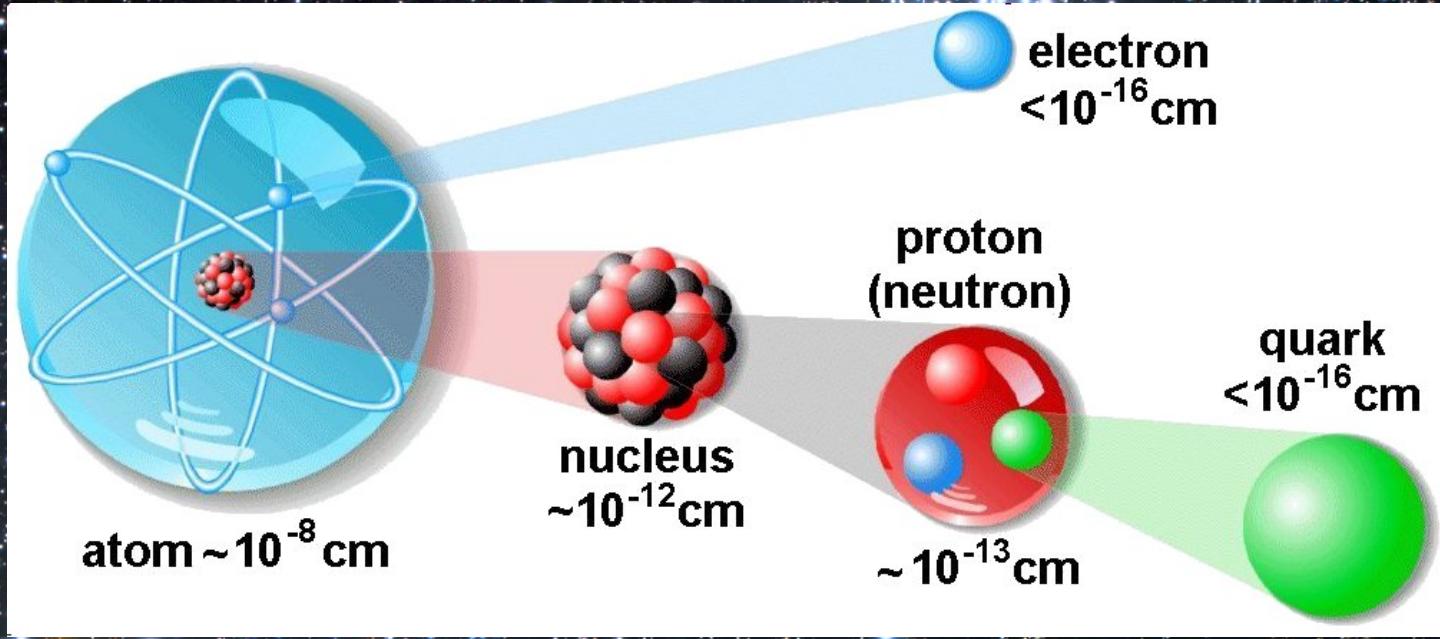
... the neighbours might be curious about the outcome!



# Backup

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# Composition of the Universe



# Composition of the Universe

## Matter Particles

Quarks	
 u	 d
up	down
 t	 b
top	bottom
 s	 c
strange	charm

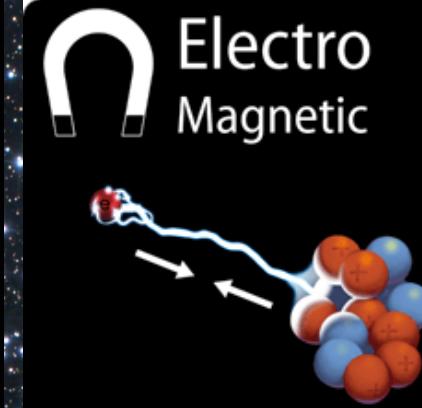
Leptons	
 e	 $\nu_e$
electron	electron neutrino
 $\mu$	 $\nu_\mu$
muon	muon neutrino
 $\tau$	 $\nu_\tau$
tau	tau neutrino

Anti-quarks	
 $\bar{u}$	 $\bar{d}$
 $\bar{t}$	 $\bar{b}$
 $\bar{s}$	 $\bar{c}$

Anti-leptons	
 $e^+$	 $\bar{\nu}_e$
 $\bar{\mu}$	 $\bar{\nu}_\mu$
 $\bar{\tau}$	 $\bar{\nu}_\tau$

## Forces

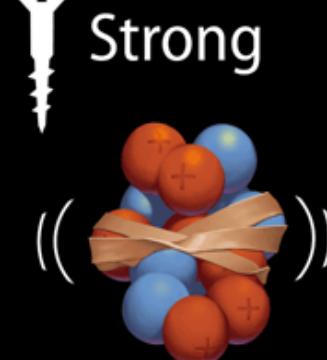
Electro Magnetic



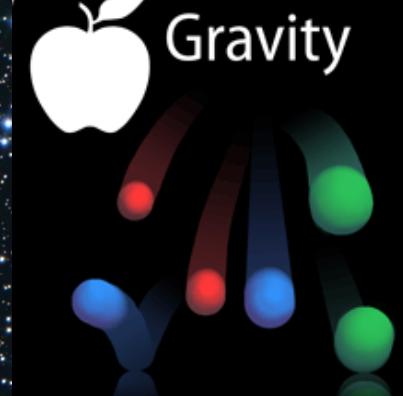
Weak



Strong

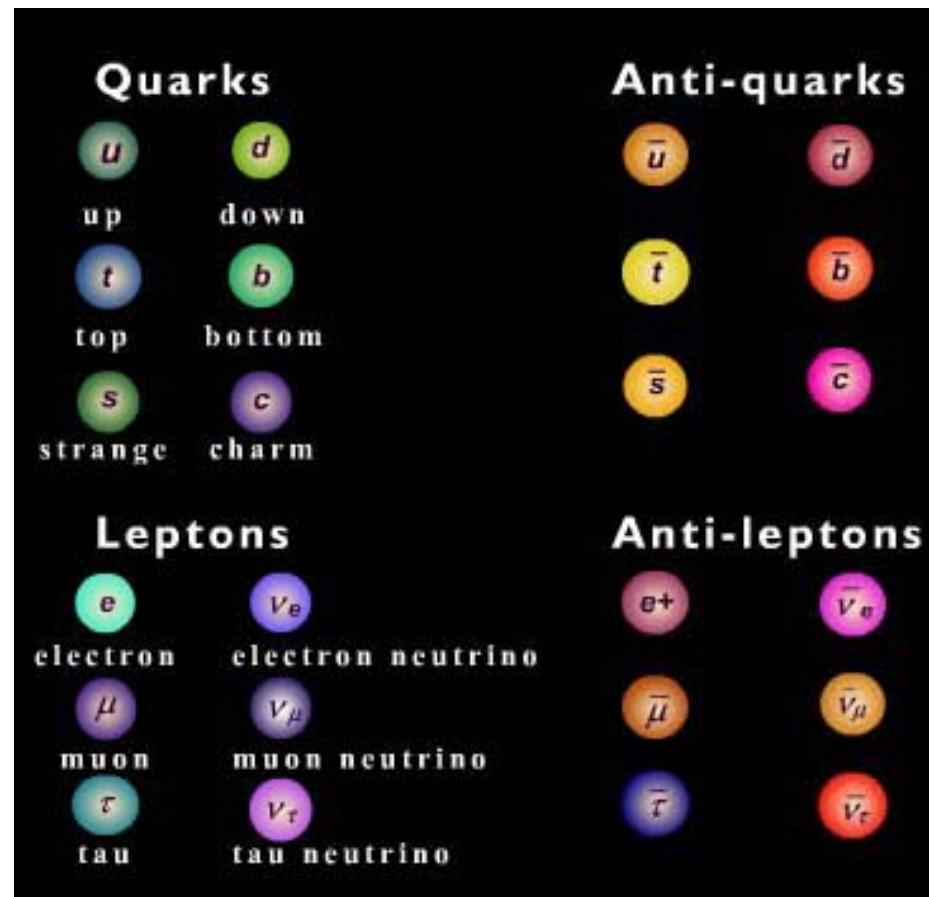


Gravity



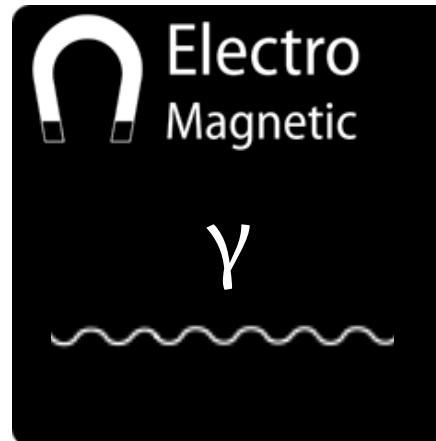
# Standard Model of Particle Physics

- ◊ SM: relativistic quantum field theory in Lagrangian formalism
- ◊ Matter particles: quantum fields
  - + spin-½ fermions



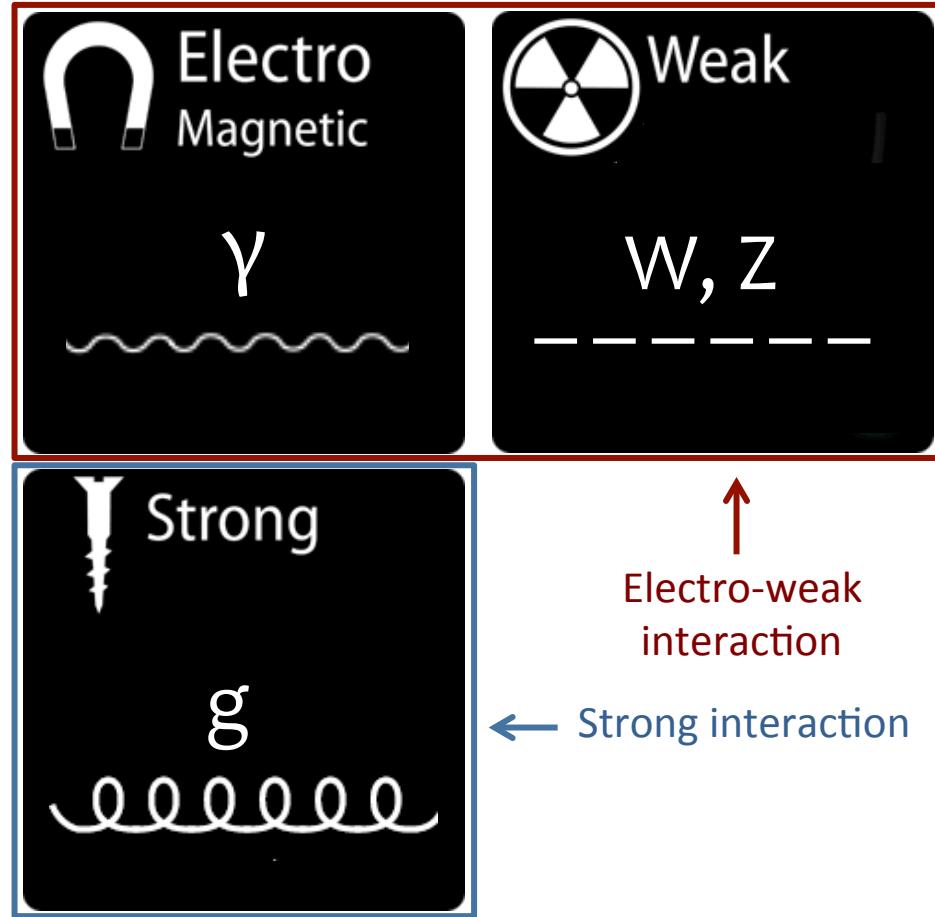
# Standard Model of Particle Physics

- ❖ SM: relativistic quantum field theory in Lagrangian formalism
- ❖ Matter particles: quantum fields
  - + spin-½ fermions
- ❖ Forces: exchange of force mediators
  - + spin-1 bosons



# Standard Model of Particle Physics

- ❖ SM: relativistic quantum field theory in Lagrangian formalism
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  - ❖ Electro-weak unification
  - ❖ Interactions have local symmetries
  - ❖ Force mediators generated as gauge fields to enforce the local symmetry

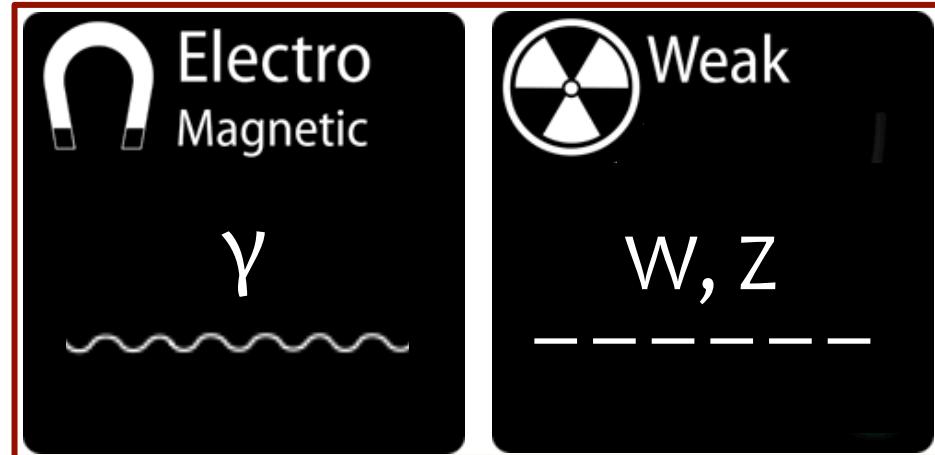


$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

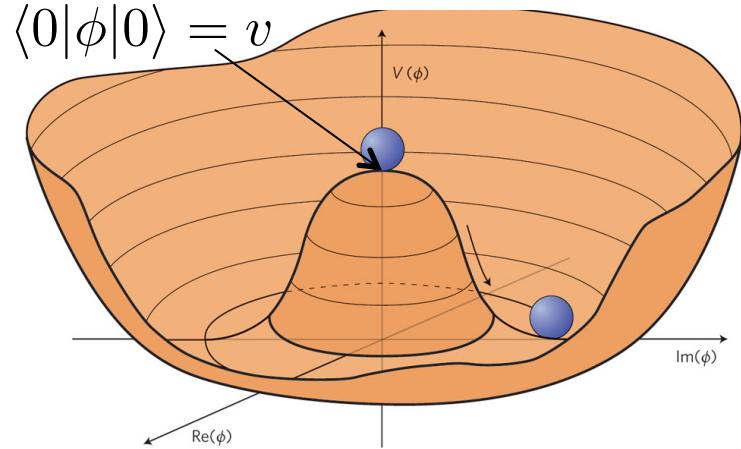
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⇒ electro-weak symmetry is broken
- ❖ Spontaneous symmetry breaking mechanism is caused by a spin-0 Higgs field
  - “Sombrero”-shaped potential with a non-zero vacuum expectation value
  - Yukawa interaction with this field generates masses of all massive fermions

$$m_\psi = y_\psi v / \sqrt{2}$$



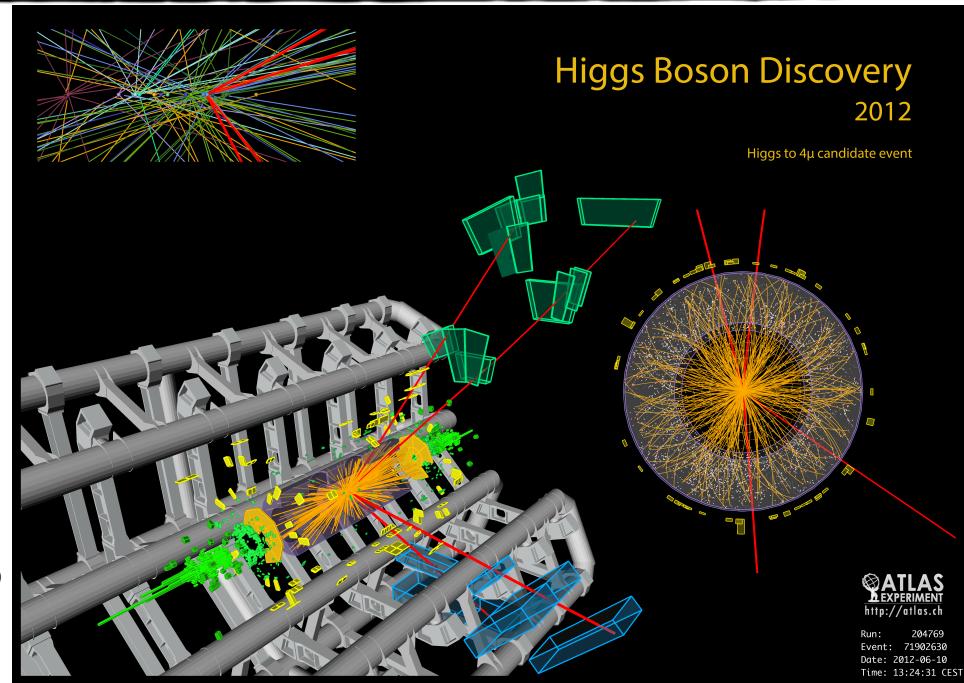
$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$$



$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

# Standard Model of Particle Physics

- ✧ SM: relativistic quantum field theory in Lagrangian formalism
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  - ✧ Yukawa interaction with this field generates masses of all massive fermions
  - ✧ Manifestation of the Higgs field is the spin-0 Higgs boson. A candidate of the Higgs boson has been discovered at CERN in 2012



The Nobel Prize in Physics 2013



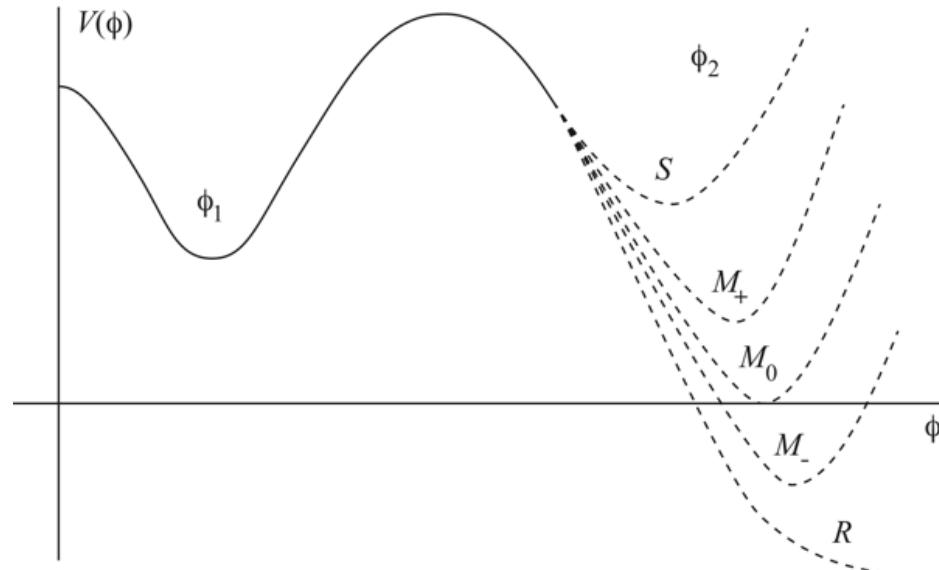
# Standard Model Lagrangian

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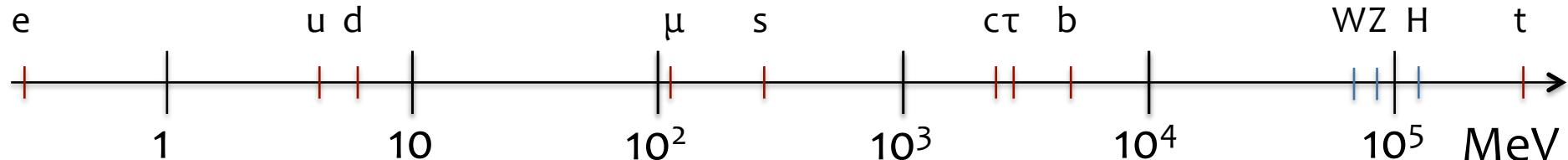
$$\begin{aligned}\mathcal{L}_{SM} = & -\frac{1}{4} \sum_{i=1}^3 W_{\mu\nu}^i W^{i\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} \sum_{i=1}^8 G_{\mu\nu}^i G^{i\mu\nu} \quad \left. \begin{array}{l} \text{gauge fields} \\ \text{kinematics} \end{array} \right\} (2.85) \\ & + \bar{\psi}_L \left( i\partial_\mu - i\frac{g}{2} \sum_{i=1}^3 \sigma^i \cdot W_\mu^i - i\frac{g'Y}{2} B_\mu \right) \psi_L \quad \left. \begin{array}{l} \text{left-handed} \\ \text{weak currents} \end{array} \right\} \\ & + \bar{\psi}_R \left( i\partial_\mu - i\frac{g'Y}{2} B_\mu \right) \psi_R \quad \left. \begin{array}{l} \text{left-handed} \\ \text{weak currents} \end{array} \right\} \\ & - \frac{g_s}{2} \sum_{a=1}^8 \bar{\psi} \gamma^\mu \lambda^a G_\mu^a \psi \quad \left. \begin{array}{l} \text{strong interaction} \end{array} \right\} \\ & - \frac{1}{2} M_H^2 (v + h)^2 - \frac{M_H^2}{v^2} (v + h)^4 \quad \left. \begin{array}{l} \text{Higgs mass and} \\ \text{self-interaction} \end{array} \right\} \\ & + \left| \left( \partial_\mu - i\frac{g}{2} \sum_{i=1}^3 \sigma^i \cdot W_\mu^i - i\frac{g'Y}{2} B_\mu \right) (v + h) \right|^2 \quad \left. \begin{array}{l} \text{gauge fields mass,} \\ \text{self-interaction and} \\ \text{Higgs coupling} \end{array} \right\} \\ & - m \bar{\psi} \psi - \frac{m}{v} \bar{\psi} \psi h \quad \left. \begin{array}{l} \text{fermion mass and} \\ \text{Higgs coupling} \end{array} \right\}\end{aligned}$$

# Limitations of the Standard Model - Inconsistency

## Higgs vacuum stability



## Particle mass / Higgs Yukawa coupling hierarchy

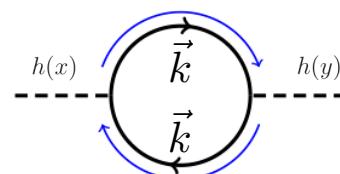


# Higgs Mass Problem – Fine Tuning

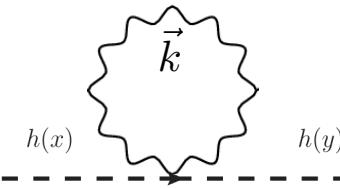
Bare Higgs Prop.

$$h(x) \quad \quad \quad h(y)$$

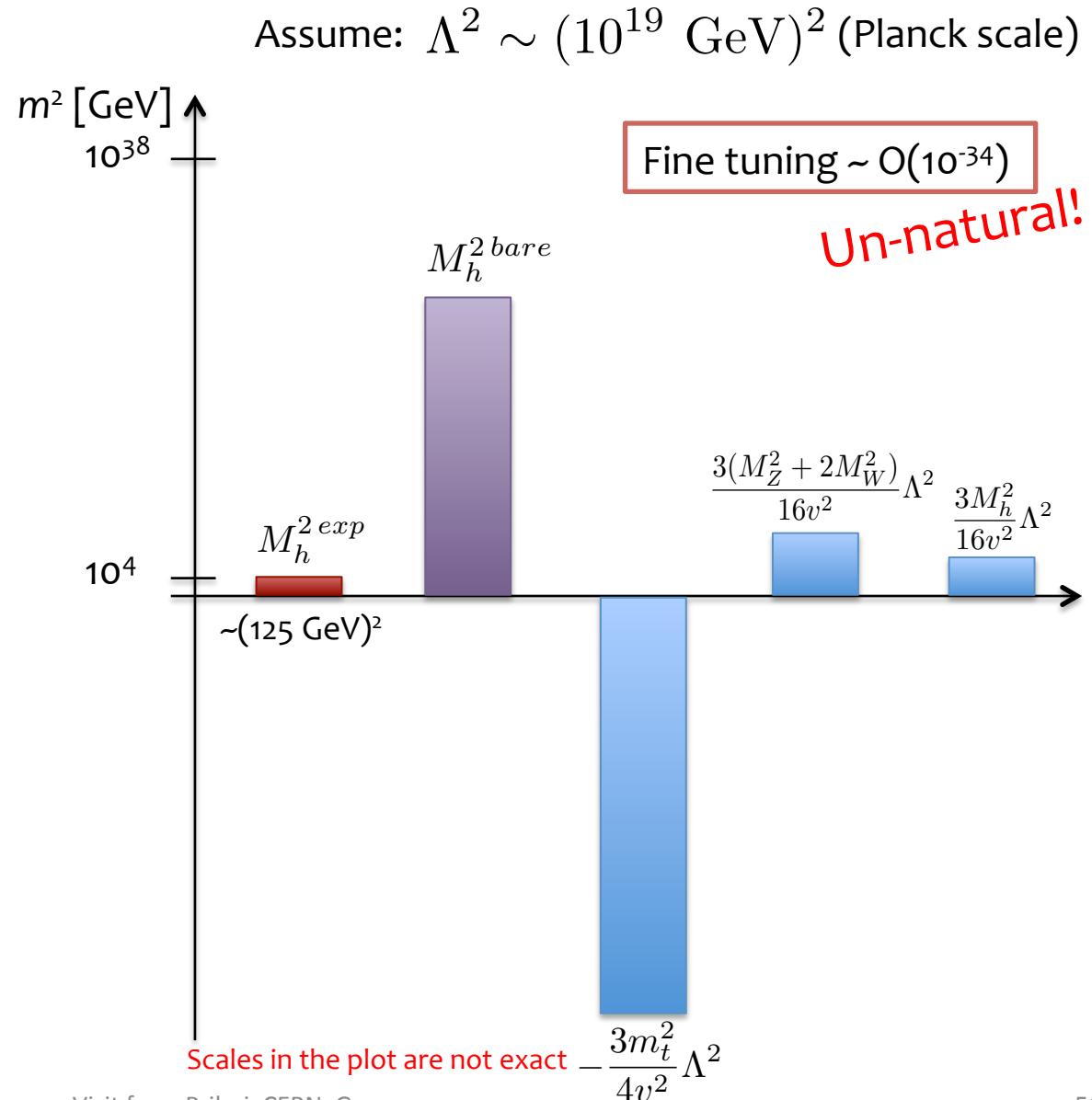
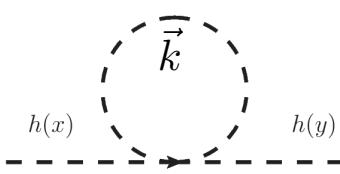
Fermion loop



Vector boson loop

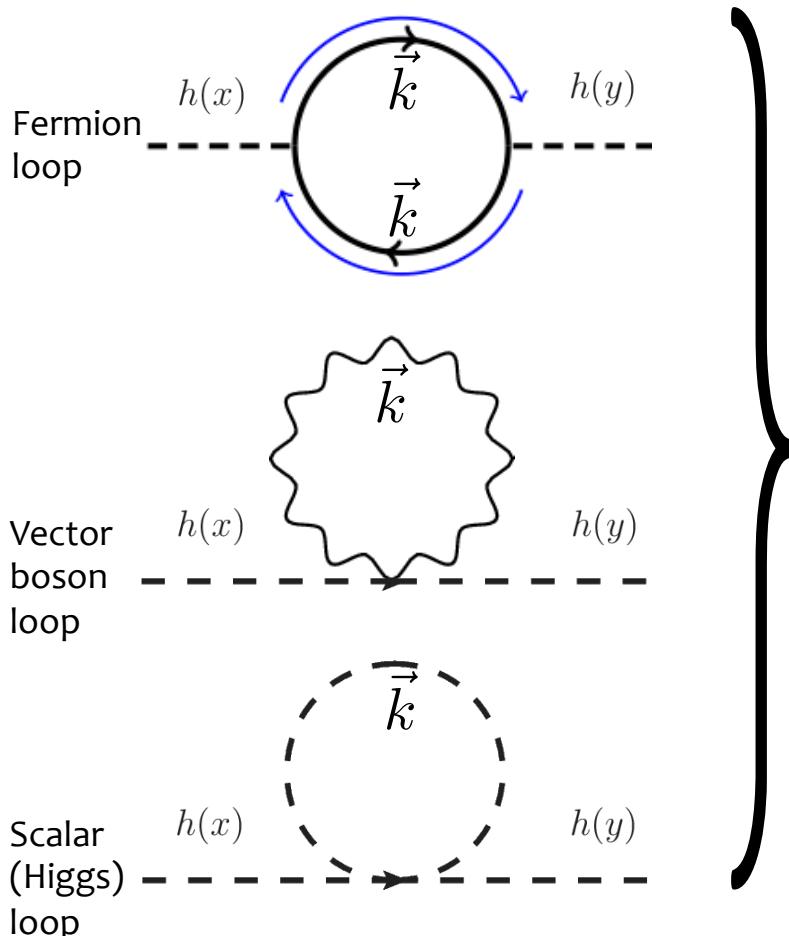


Scalar (Higgs) loop



# Higgs Mass Problem – Quadratic Divergences

Bare Higgs Prop.  $h(x) \rightarrow h(y)$   $M_h^{2\,bare}$



$$\sim \mathcal{C} \int \frac{d^4 k}{k^2} \rightarrow \mathcal{C} \int_p^\Lambda \frac{d^4 k}{k^2} \rightarrow \frac{\mathcal{C}}{16\pi^2} \Lambda^2$$

$\Lambda \rightarrow$  Cutoff scale up to which the SM is valid  
 $\Rightarrow$  at which new physics enters

# Higgs Mass Problem – Quadratic Divergences

Bare Higgs Prop.  $h(x) \rightarrow h(y)$   $M_h^{2\,bare}$

Fermion loop  $h(x) \rightarrow h(y)$

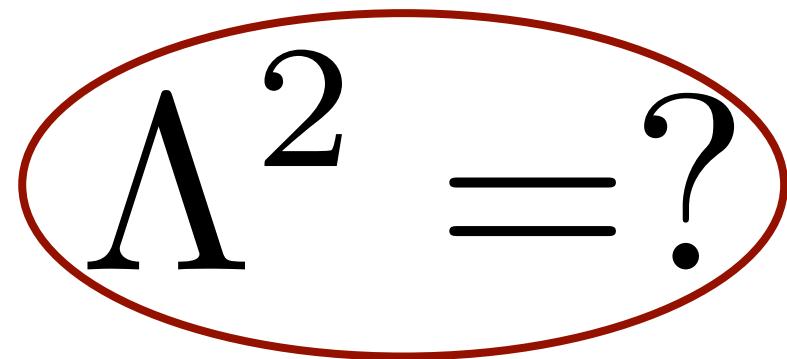
$$\sim -\frac{3y_t^2}{8}\Lambda^2 = -\frac{3m_t^2}{4v^2}\Lambda^2$$

Vector boson loop  $h(x) \rightarrow h(y)$

$$\sim \frac{9g^2 + 3g'^2}{64}\Lambda^2 = \frac{3(M_Z^2 + 2M_W^2)}{16v^2}\Lambda^2$$

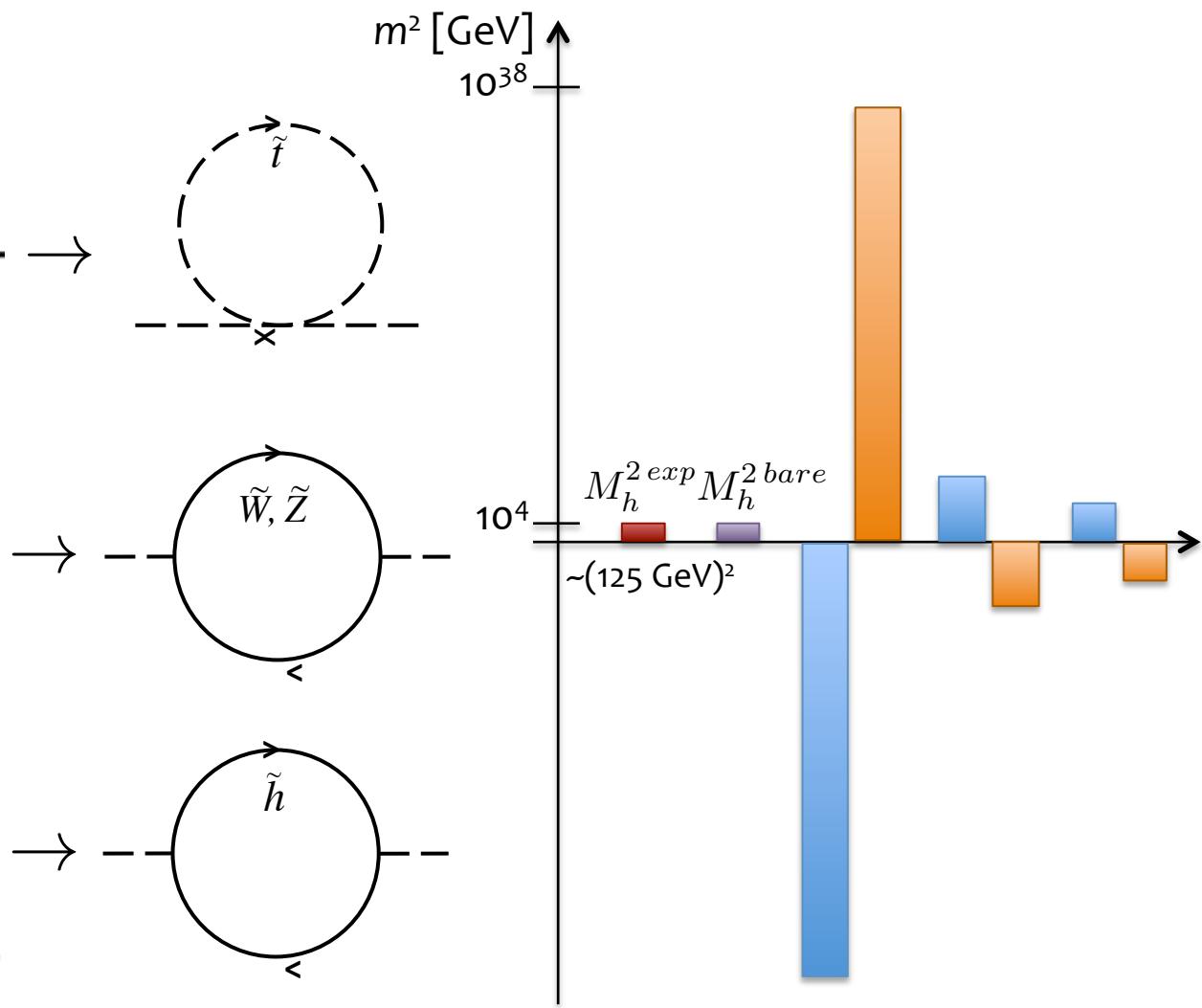
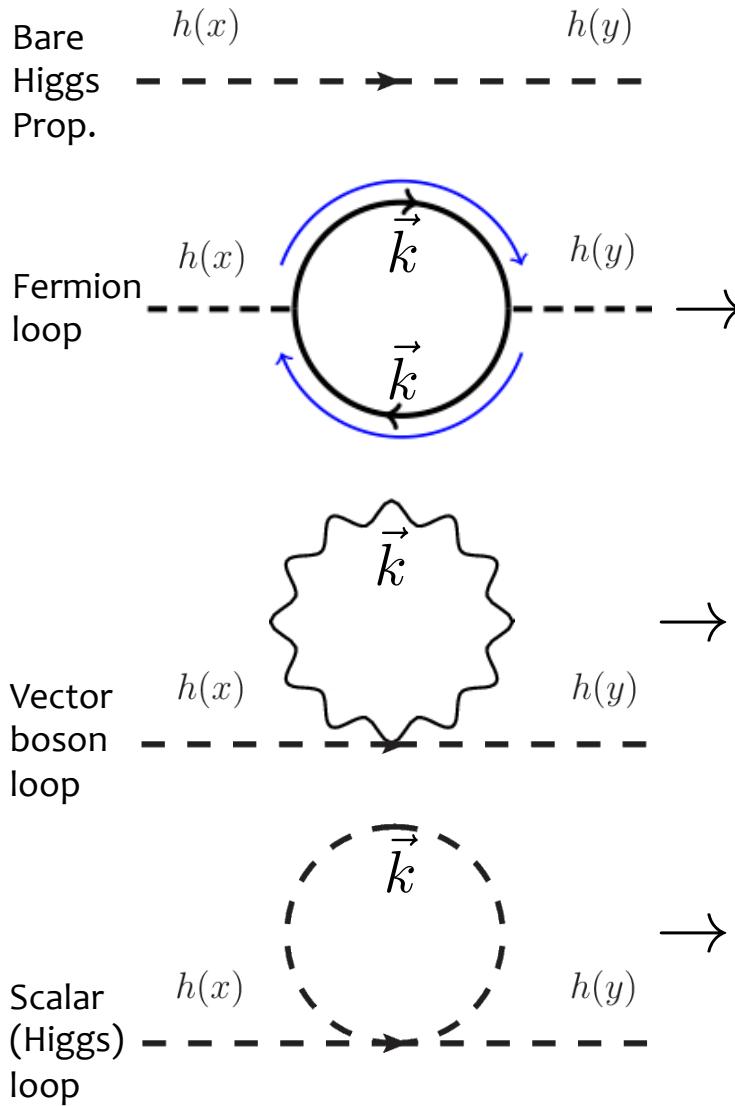
Scalar (Higgs) loop  $h(x) \rightarrow h(y)$

$$\sim \frac{\lambda^2}{16}\Lambda^2 = \frac{3M_h^2}{16v^2}\Lambda^2$$

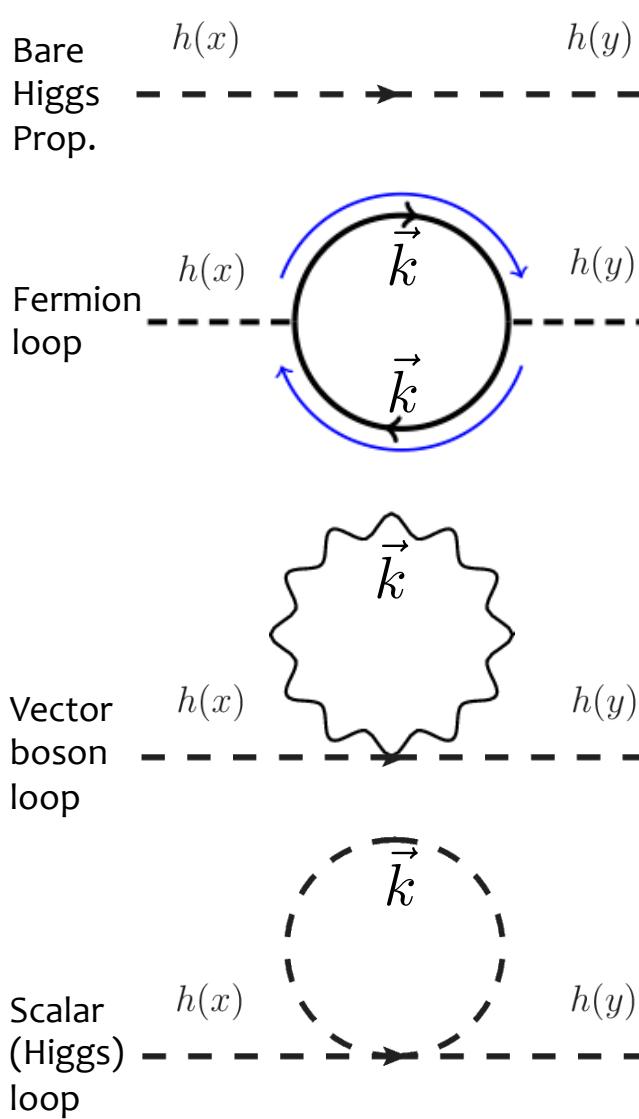


- ✧ Planck scale  $\sim 10^{19}$  GeV ?
  - + Quantum gravity
- ✧ GUT scale  $\sim 10^{15}$  GeV ?
  - + Grand unification (elw+strong)
- ✧ Other BSM physics?

# Higgs Mass Problem Solutions – Supersymmetry

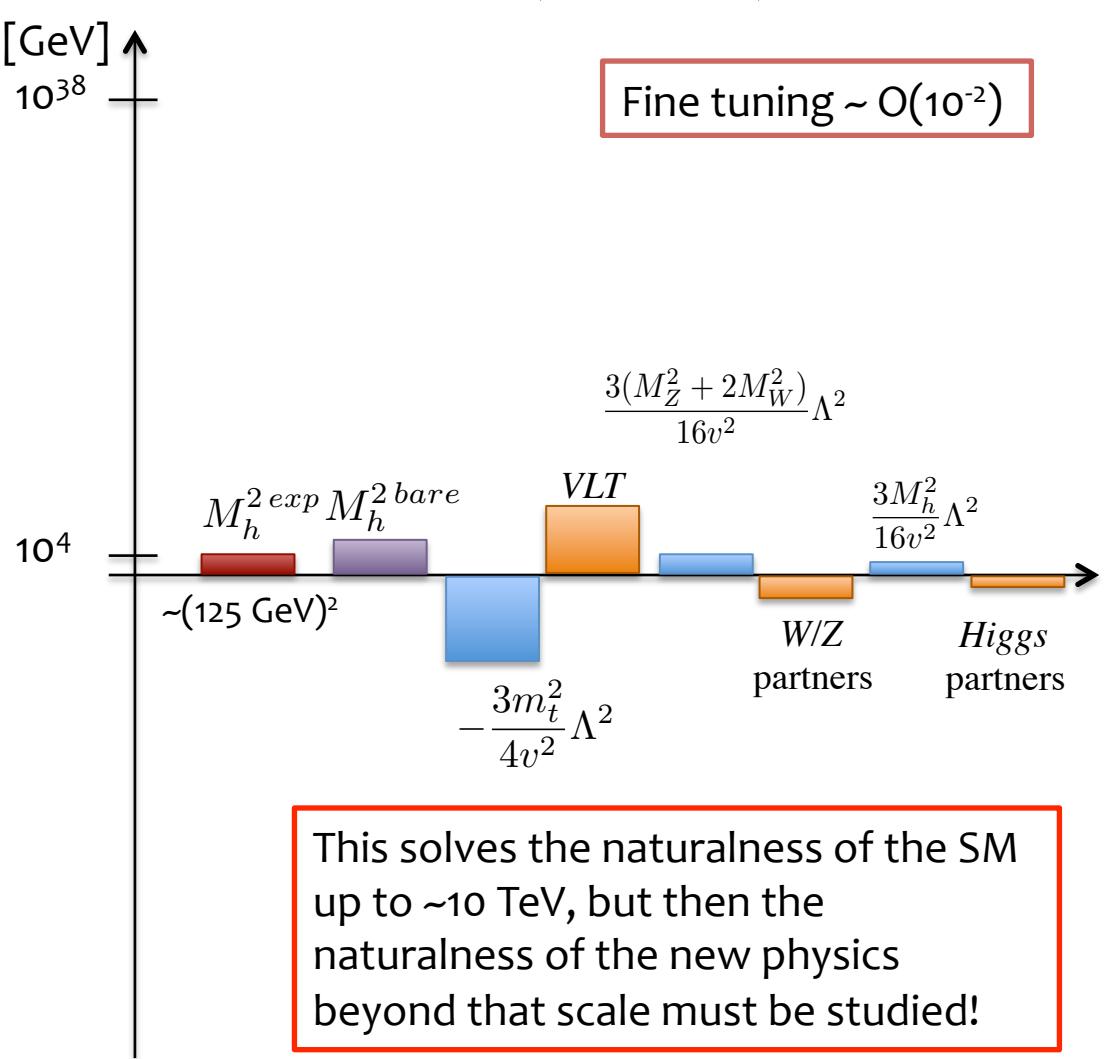


# Higgs Mass Problem Solutions – Vector-like Quarks



Assume:  $\Lambda^2 \sim (10^4 \text{ GeV})^2$

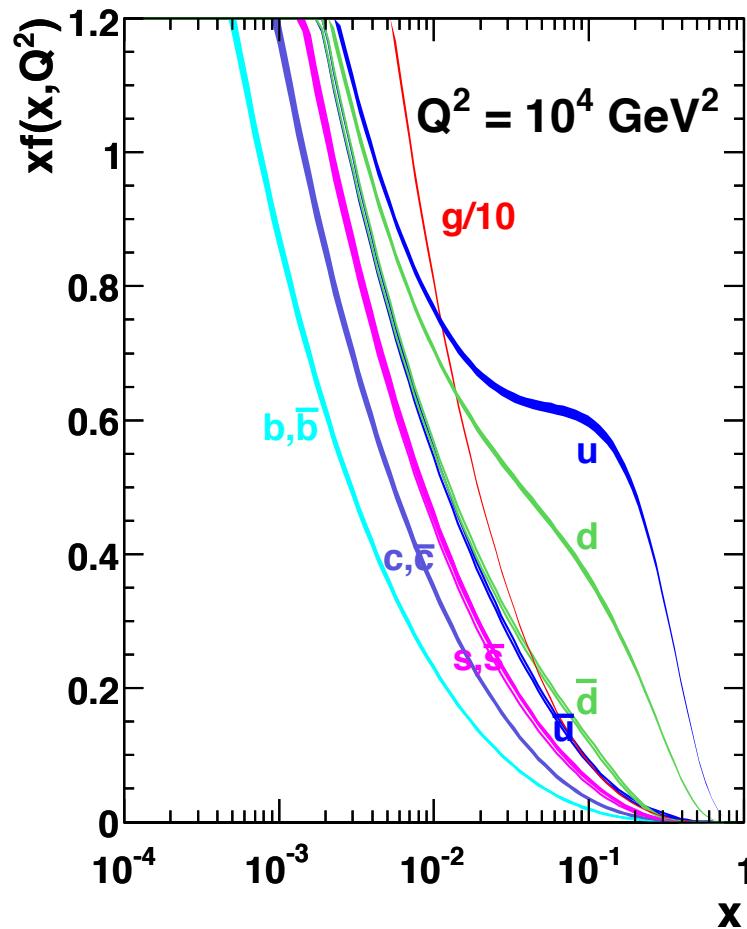
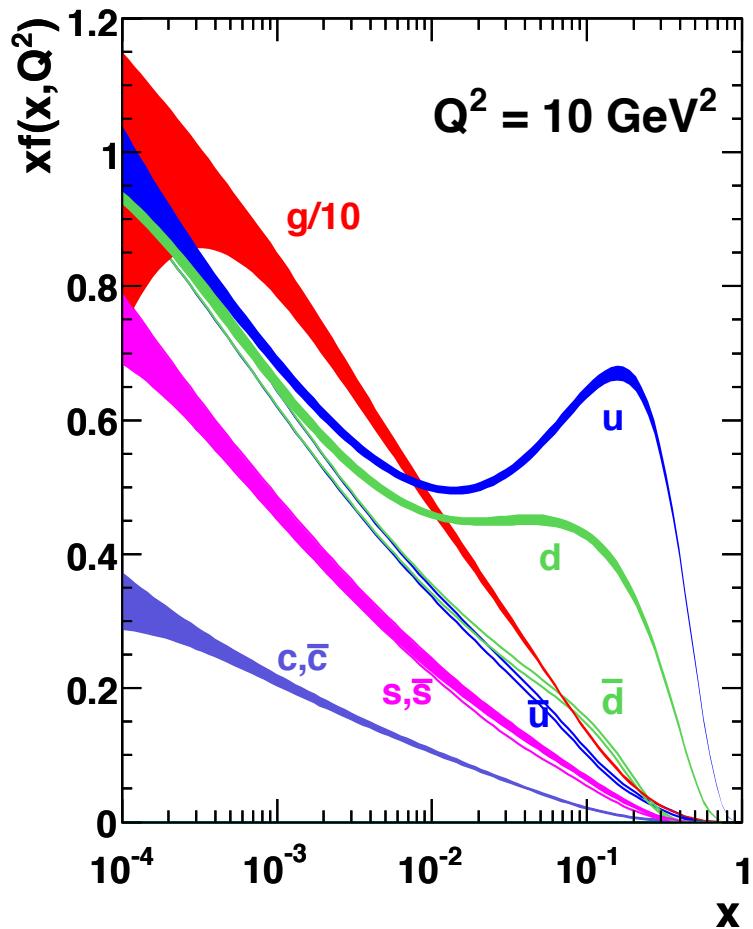
Fine tuning  $\sim O(10^{-2})$



# Event Description

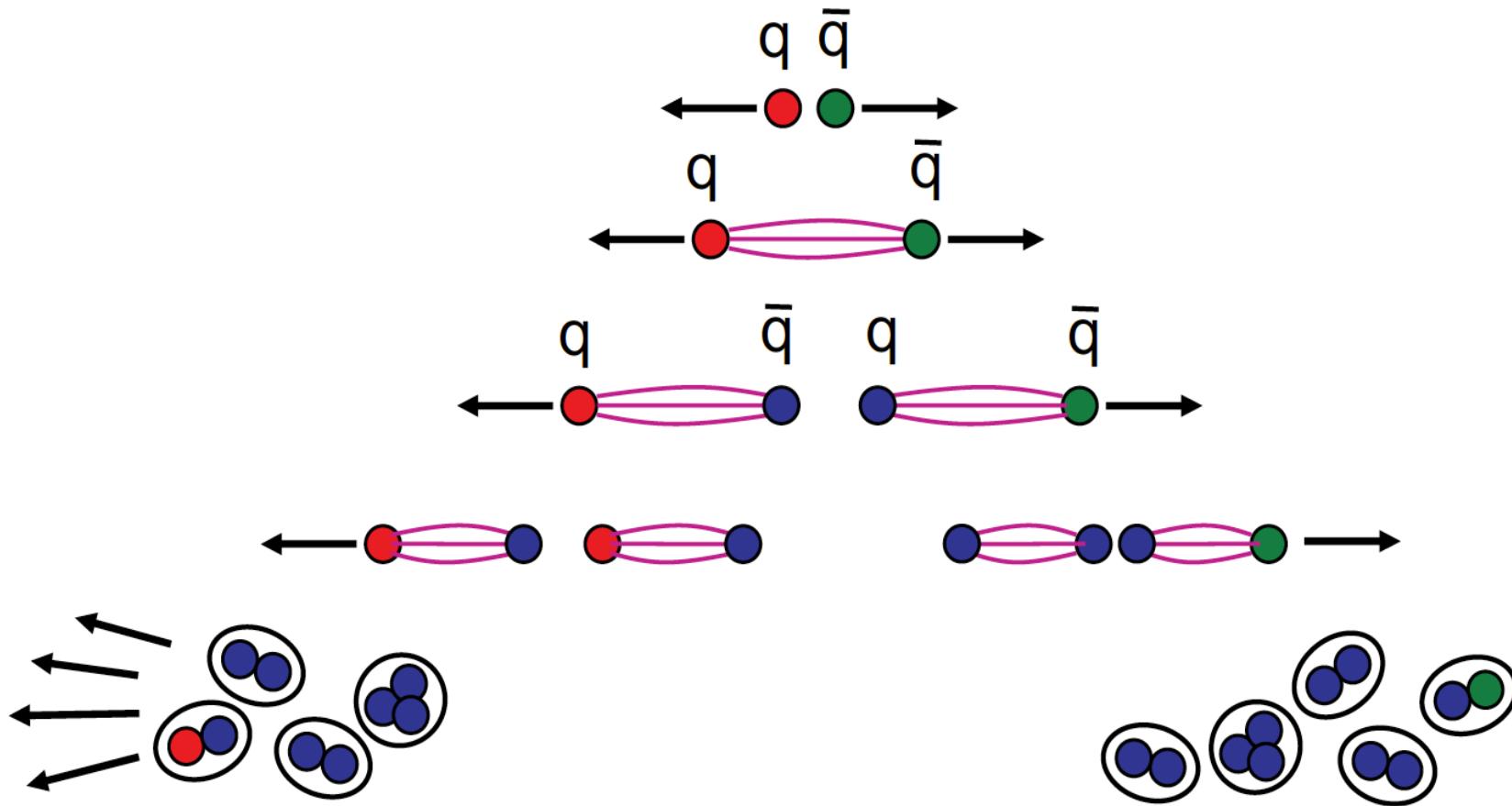
## Parton Distribution Functions

MSTW 2008 NNLO PDFs (68% C.L.)



# Event Description

## Parton Shower



# Event Description

## Particle Detection – Jet Reconstruction

- ❖ Jet reconstruction:

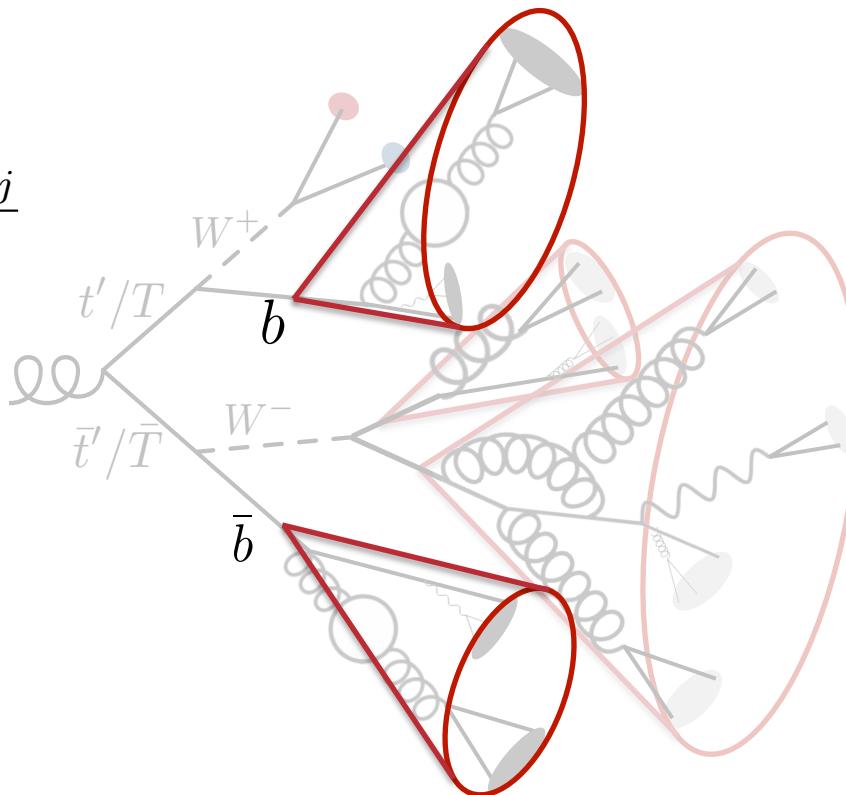
- ❖ Anti-kT clustering algorithm

$$d_{ij} = \min \left( \frac{1}{k_{Ti}^2}, \frac{1}{k_{Tj}^2} \right) \frac{\Delta R_{ij}^2}{R^2}$$

- ❖ Parameter R=0.4

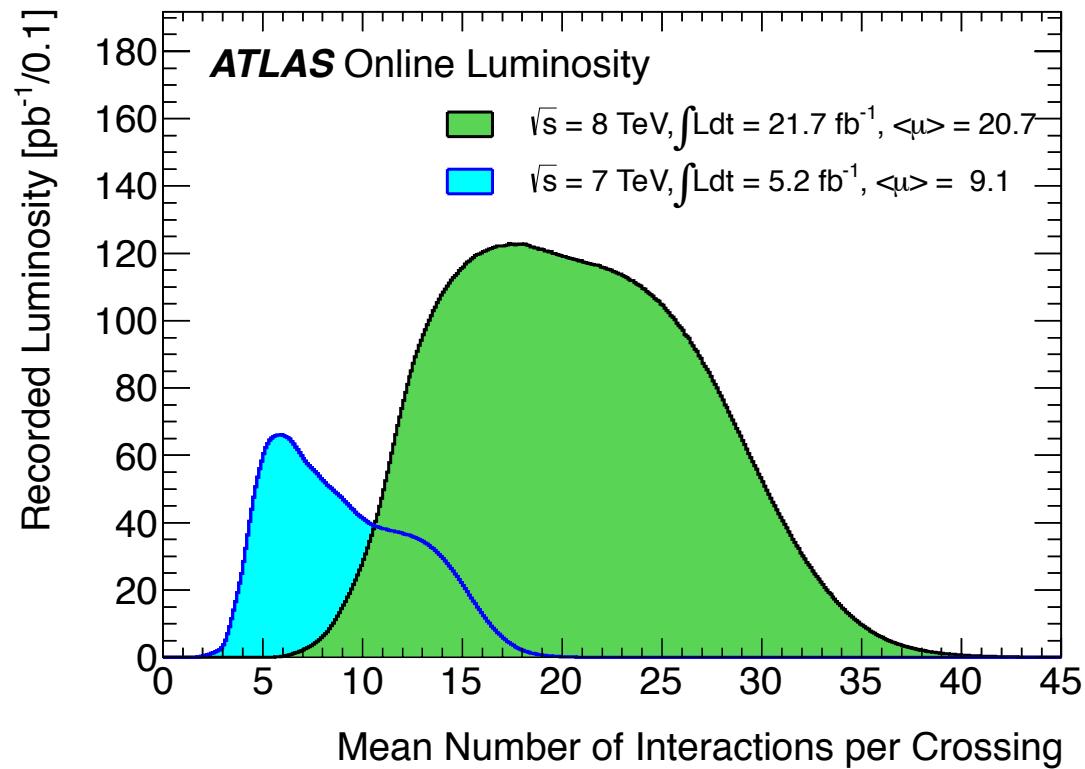
- ❖ Jet energy calibration:

- ❖ Pile-up and origin correction
  - ❖ EM+JES energy calibration



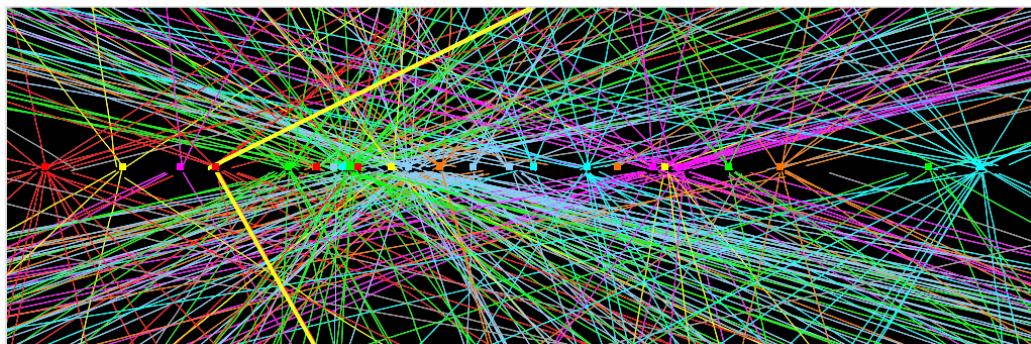
# Experimental Realisation

## Event Production – Pile-up



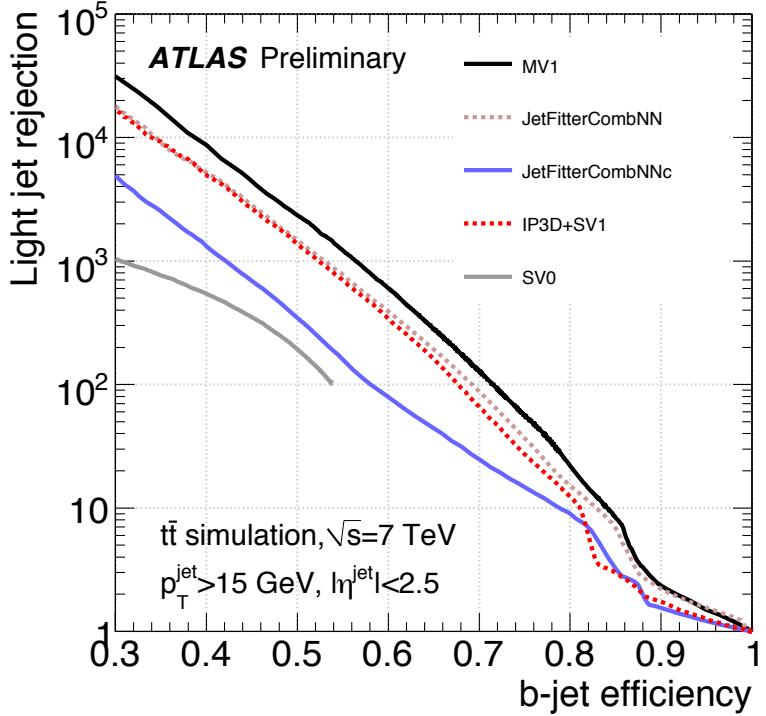
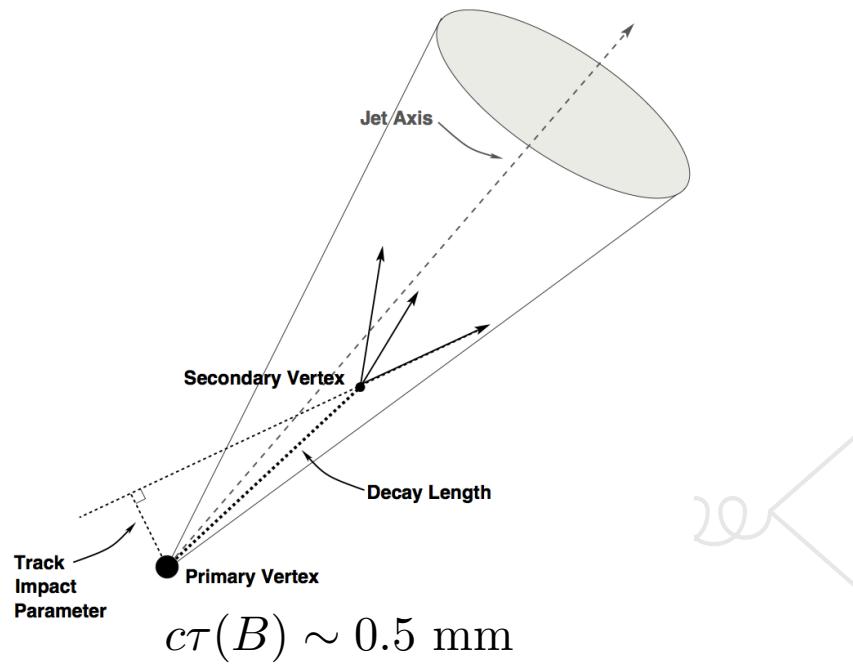
Summary of 2011 data taking campaign

Centre-of mass energy	7 TeV
Bunch spacing	75/50 ns
Peak luminosity	$3.7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
Max $\langle \mu \rangle$	19



# Event Description

## Particle Detection

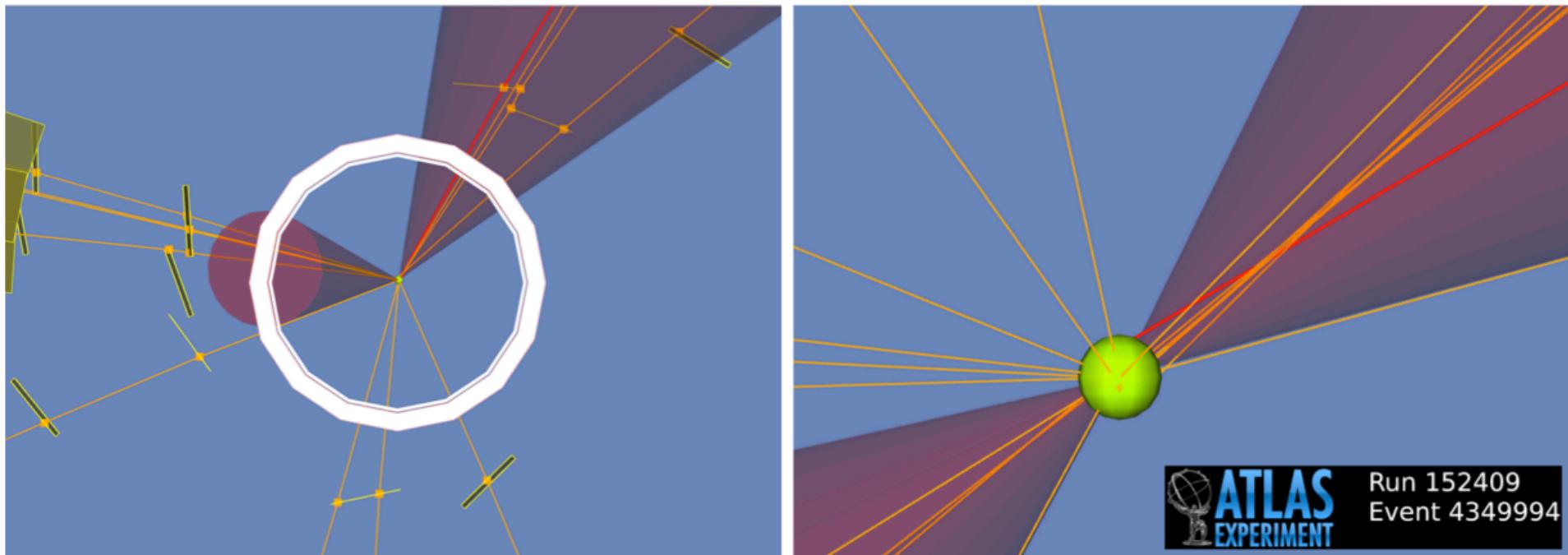


- ❖ B-jet reconstruction algorithms exploit
  - ✚ SV displacement
  - ✚ impact parameter of the jet direction
  - ✚ B-decay chain
- ❖ Results from various approaches combined using a multivariate-technique
- ❖ Calibrated using ttbar event candidates

# Event Description

## Particle Detection

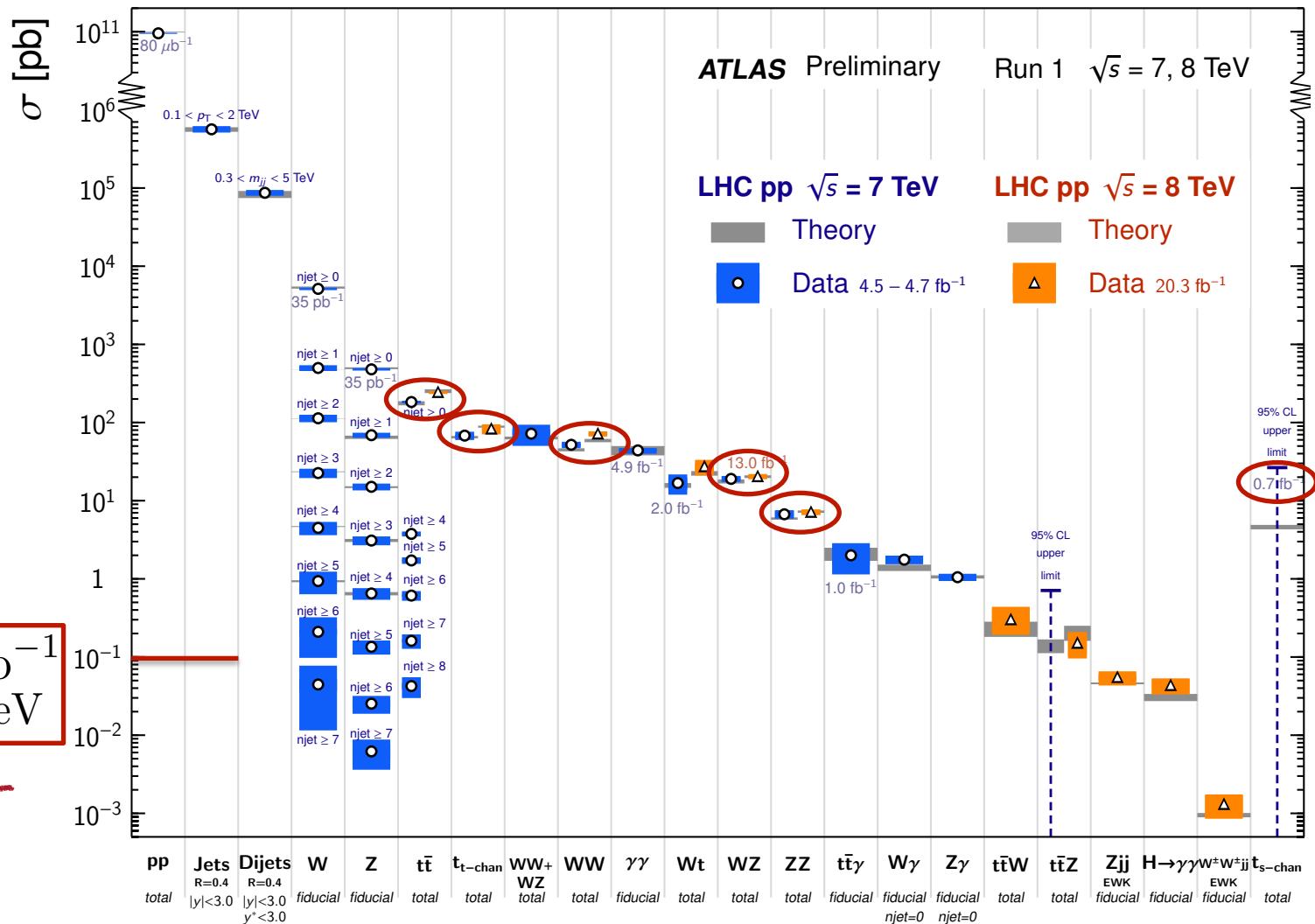
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# SM Backgrounds – Cross Sections

## Standard Model Production Cross Section Measurements

Status: July 2014



# Hypothesis Testing

## CLs method with Binned Log-Likelihood Ratio

$$\begin{aligned} \text{observed } & \quad \text{expected } \\ N_{bins} & \downarrow \quad \downarrow \\ -2 \ln \mathcal{L}(data|H_i) = -2 \sum_{j=1}^{N_{bins}} (n_j \ln \mu_j - \mu_j) \\ LLR = -2 \ln \frac{\mathcal{L}(data|s+b)}{\mathcal{L}(data|b)} \end{aligned}$$

$$\begin{aligned} 1 - CL_b &= p(LLR \leq LLR_{obs}|b) \\ CL_{s+b} &= p(LLR \geq LLR_{obs}|s+b) \\ CL_s &= \frac{CL_{s+b}}{CL_b} \end{aligned}$$

