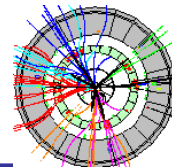


# Physics at hadron colliders

- ◆ **Hadron-hadron interactions**
- ◆ **Top physics**
- ◆ **Higgs**
- ◆ **QCD & electroweak**
- ◆ **Searches**
- ◆ **Future colliders**



# Hadron-hadron interactions

protons complex objects:

partonic

substructure:

quarks & gluons

hard scattering

processes (large

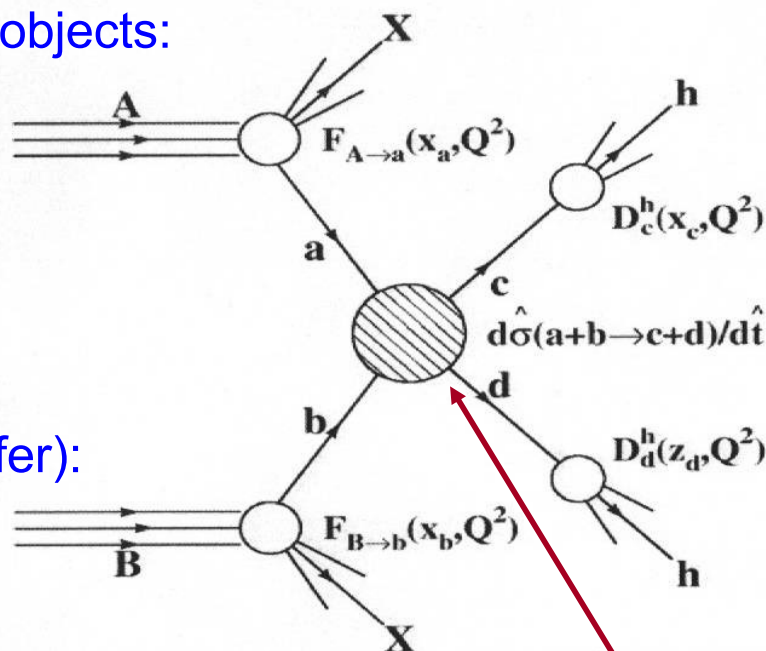
momentum transfer):

quark-quark

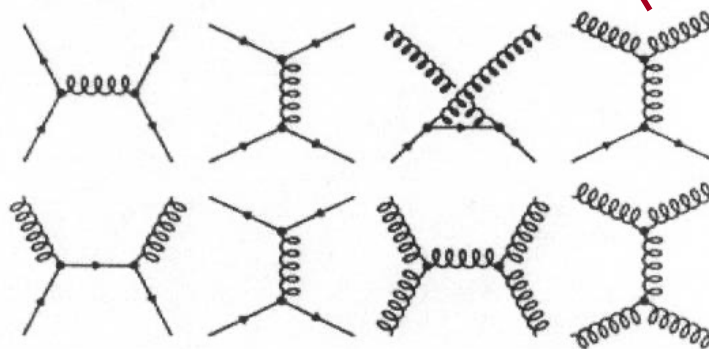
quark-gluon

gluon-gluon

at parton level

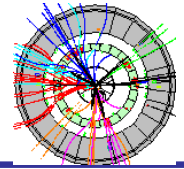


scattering or annihilation



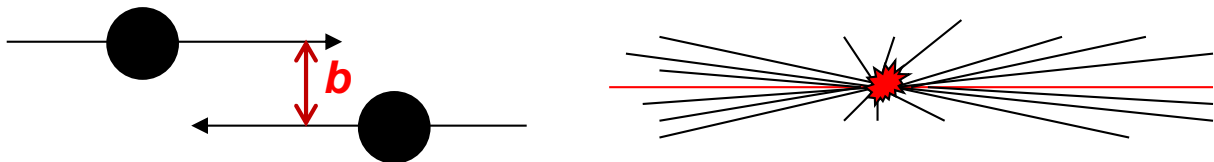
however: hard scattering (high  $p_T$  processes) represent only a tiny fraction of the total inelastic pp cross section. e.g. total inelastic cross section  $\sim 80$  mb at  $\sqrt{s} = 13$  TeV.

Dominated by events with small momentum transfer, in particular by two event types: diffractive (colourless exchange with the quantum numbers of vacuum between the two protons) & minimum-bias (exchange of colour).



## Inelastic low $p_T$ hadron-hadron collisions

Most interactions due to interactions at large distance between incoming protons where protons interact as “a whole” → **small momentum transfer** ( $\Delta p \approx \hbar / \Delta x$ ) / **large impact parameter  $b$**  → particles in final state have large (small) longitudinal (transverse) momentum.



$\langle p_T \rangle \approx 500 \text{ MeV}$  (of charged particles in final state)

$$\frac{dN}{d\eta} \approx 6$$

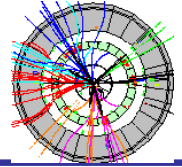
~6 charged particles per pseudorapidity unit in central region of experiment  
(uniform distribution in azimuthal angle)  
(LHC numbers)

most energy escapes down the beam pipe.

Called **minimum-bias events** (“soft” events) & constitute a large fraction of the total cross section e.g.  $\sim 60 \text{ mb}$  of  $\sim 110 \text{ mb}$  at  $\sqrt{s} = 13 \text{ TeV}$ . Perhaps not very interesting in themselves but needs to be understood. Cross section large that they occur multiple times per bunch crossing (e.g. 2024-26:  $\sim 60$  times)  $\Rightarrow$  overlap interesting collisions (“pile-up”) & change measured event quantities.



# Diffraction



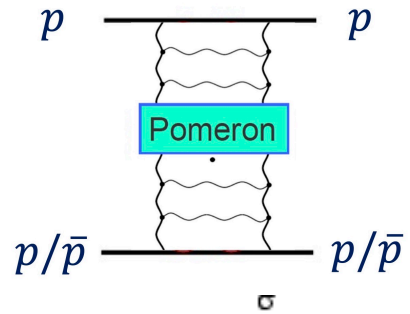
## Diffractive processes

another large part of the total cross section are diffractive processes, where non-colored object(s) are exchanged referred to as "Pomeron(s)". Pomeron is described by a system of two (or even number) of gluons or gluon ladder

diffractive events characterized by "rapidity gaps"  
 (= regions of pseudorapidity without primary particle production)

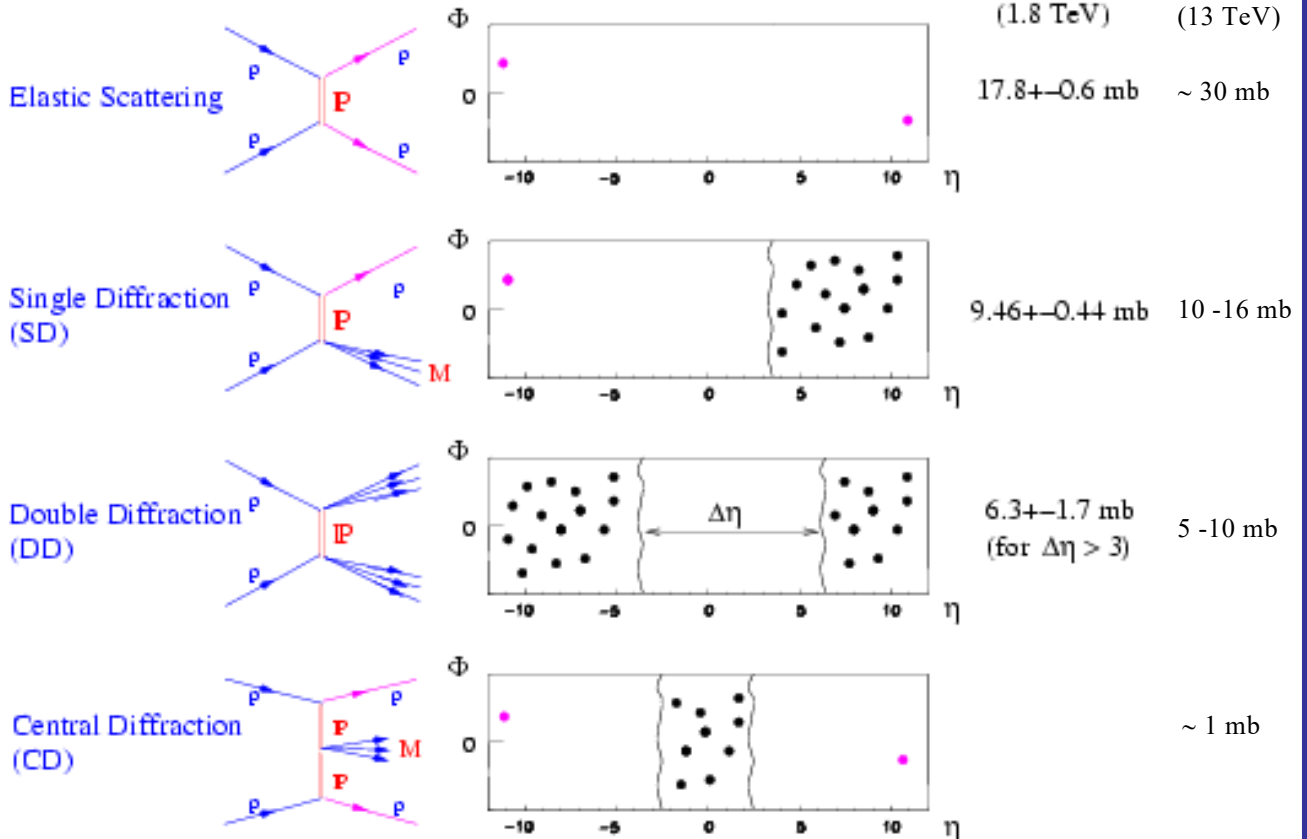
- elastic scattering ~ 30 mb
  - single diffraction 10 – 16 mb
  - double diffraction 5 – 10 mb
  - central diffraction ~ 1 mb
- in total ~ 50 mb @  $\sqrt{s} = 13$  TeV.

e.g. elastic scattering



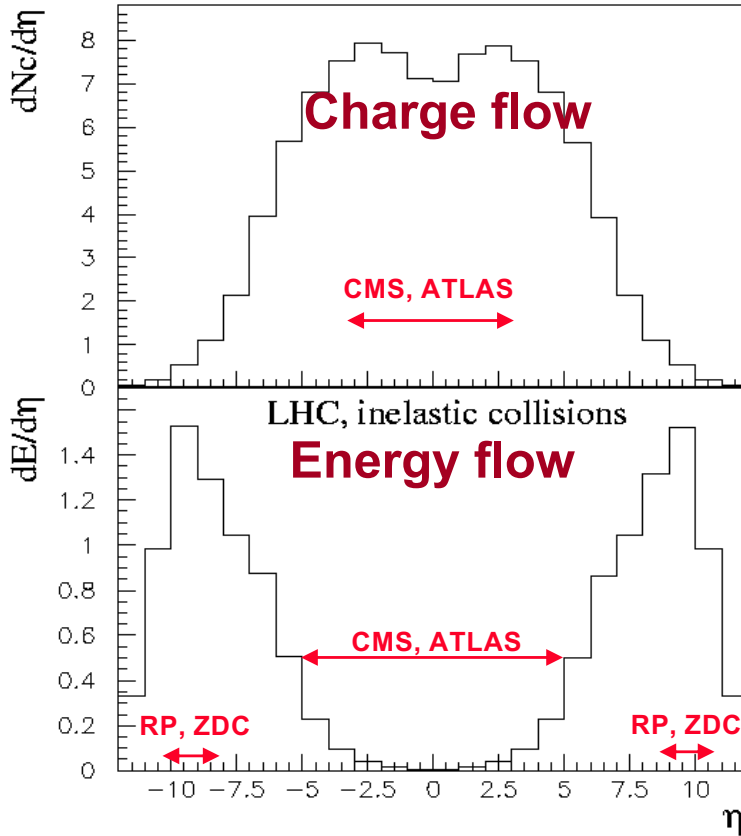
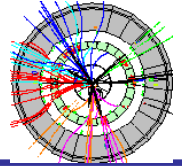
(1.8 TeV) (13 TeV)

17.8+/-0.6 mb ~ 30 mb





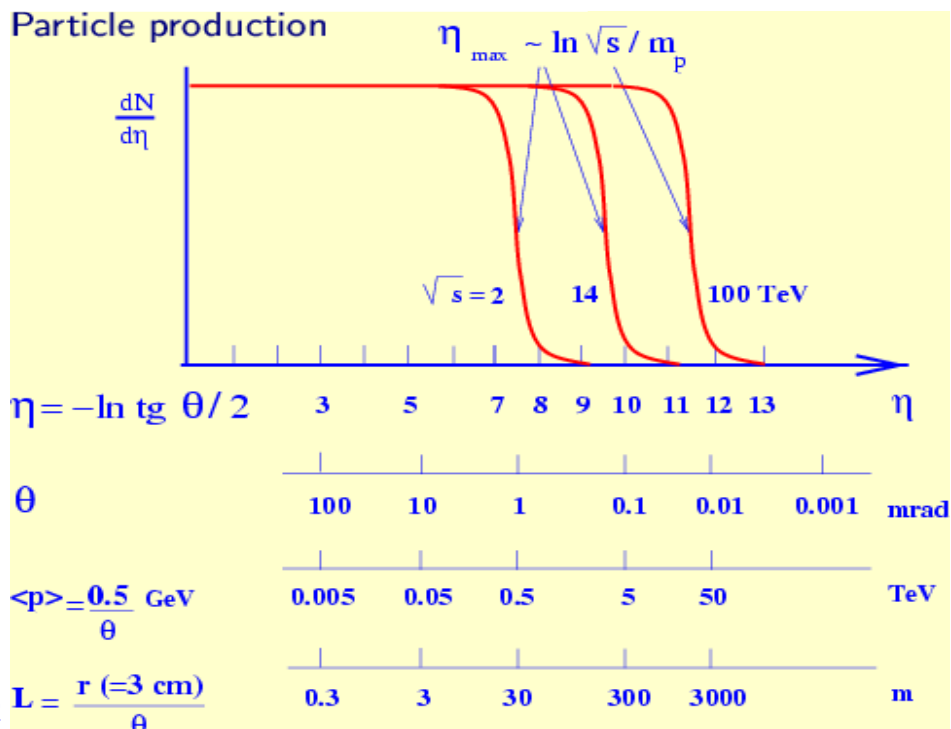
## Hadron-hadron interactions



charged particle & energy flow in an average proton-proton collision at LHC.

The acceptances of baseline ATLAS & CMS experiments are also indicated

RP = Roman Pots (detect intact protons)  
ZDC = Zero Degree Calorimeters (detect neutral particles)



pseudorapidity

$$\eta = -\ln \tan \theta / 2$$

polar angle

$\theta$

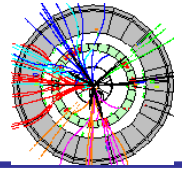
average particle momentum

$$\langle p \rangle = \frac{0.5 \text{ GeV}}{\theta}$$

distance to IP @ LHC vacuum chamber radius

$$L = \frac{r (=3 \text{ cm})}{\theta}$$

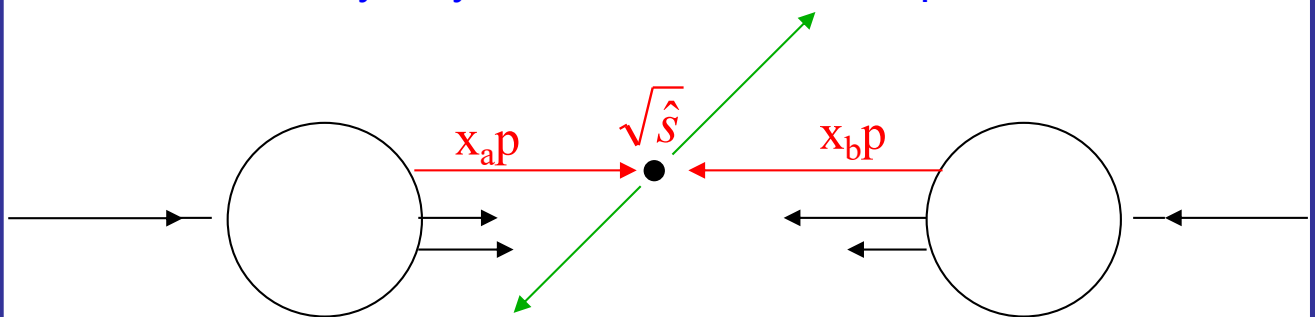
IP = interaction point



### Inelastic high $p_T$ hadron-hadron collisions

proton beam can be seen as a beam of quarks & gluons with a wide band of energies, occasionally occurs hard scattering between constituents of incoming hadrons.

constituents carry only a fraction  $0 < x < 1$  of proton momentum.



$p \equiv$  momentum of incoming hadron

- effective centre-of-mass energy  $\sqrt{\hat{s}}$  smaller than  $\sqrt{s}$  of colliding beams:

if  $x_a \approx x_b$

$$\sqrt{\hat{s}} = \sqrt{x_a x_b s} \approx x \sqrt{s}$$

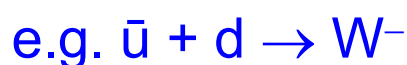
to produce at LHC a mass of:

100 GeV:  $x \sim 0.007$

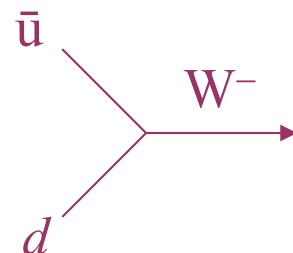
1 TeV:  $x \sim 0.07$

5 TeV:  $x \sim 0.4$

these are interesting physics events but they are rare.

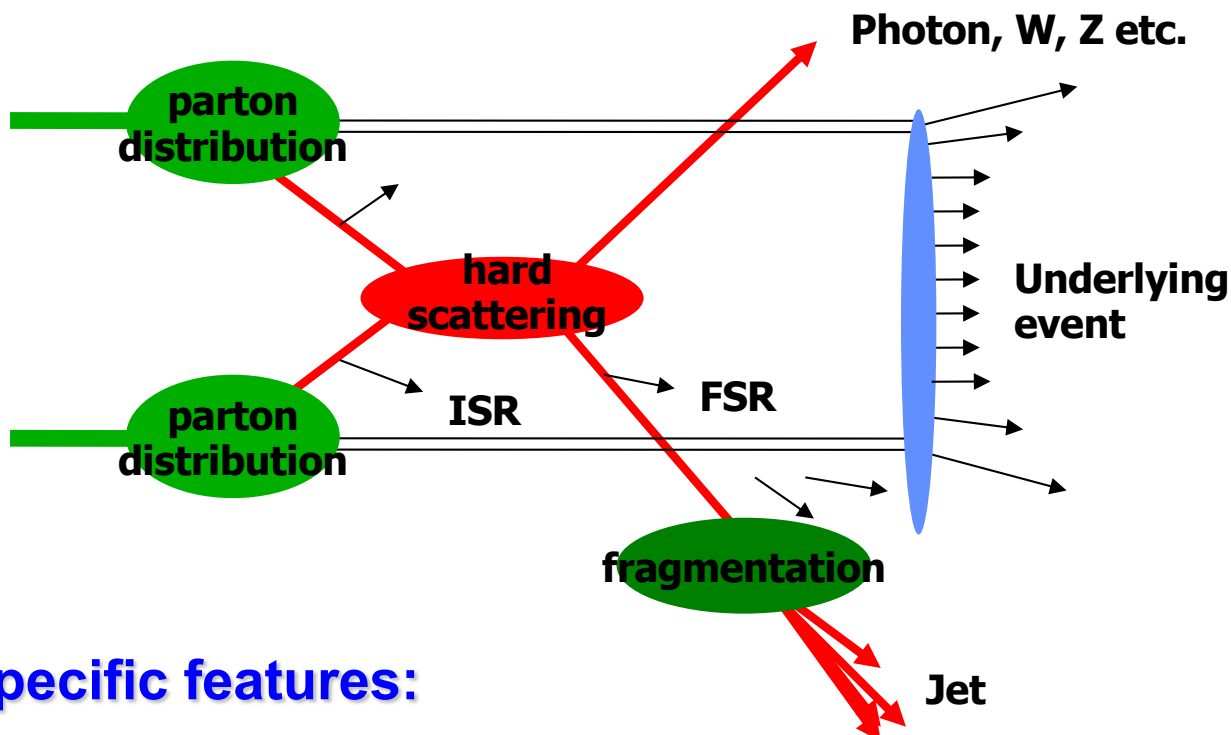
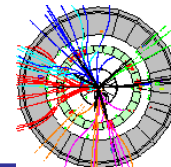


$$\sigma (pp \rightarrow W) \approx 150 \text{ nb} \approx 10^{-6} \sigma_{\text{tot}} (pp)$$





## Hadron-hadron interactions



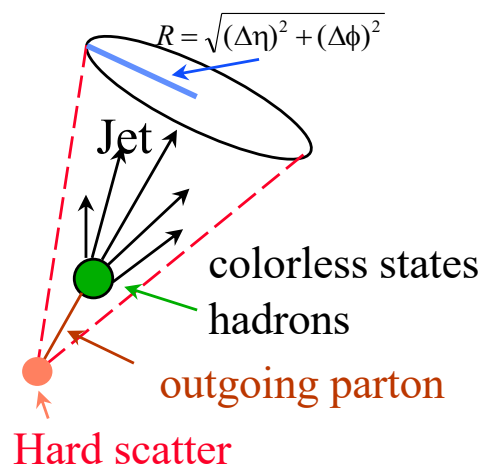
### specific features:

- ◆ hard scattering  $\sigma$  from parton distributions (pdfs)
- ◆ initial and final states can “radiate” gluons (ISR & FSR)
- ◆ colored final states fragment to form “jets”
- ◆ underlying event from proton remnants

### fragmentation (hadronization):

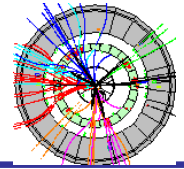
- ◆ quarks/gluons produced give raise to lots of radiation ( $\alpha_S$  is large!) & recombine to form colorless spray of almost collinear hadrons: **a jet**
- ◆ jets = experimental signature of quarks/gluons & observed as localized energy deposits in calorimeters.
- ◆ jet energy  $\neq$  parton energy due to calorimeter response, missing ( $\nu$ 's, low  $p_T$  & out of cone) particles & overlapping particles (from min. bias events). average corrections applied.

at hadron colliders jets usually formed using simple cone algorithms ( $R \approx 0.7$ )





# Hadron-hadron interactions



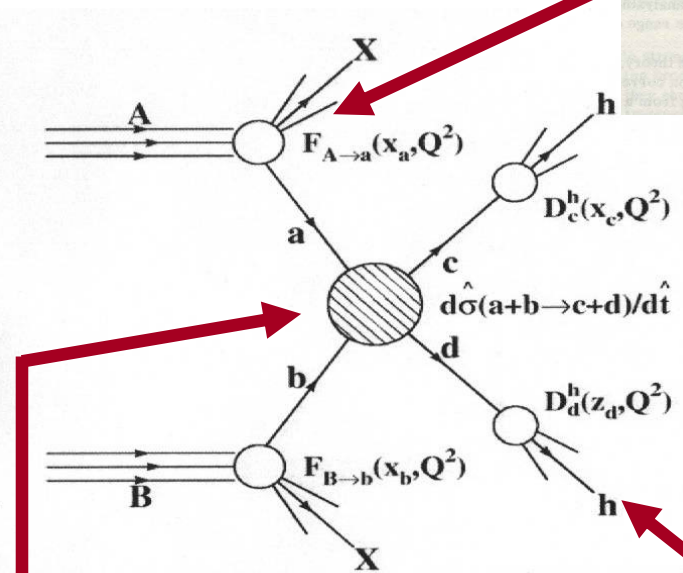
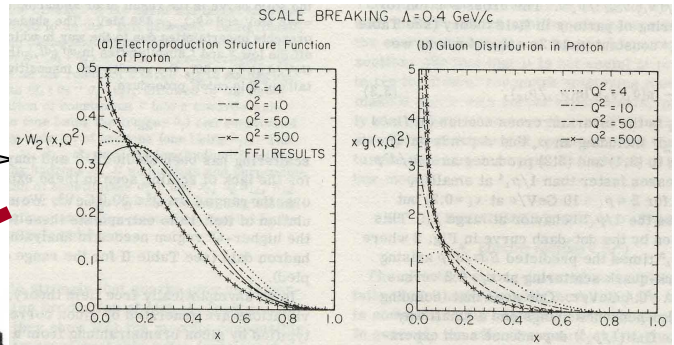
- cross-section :

$$\sigma = \sum_{a,b} \int dx_a dx_b f_a(x_a, Q^2) f_b(x_b, Q^2) \hat{\sigma}_{ab}(x_a, x_b)$$

$\hat{\sigma}_{ab} \equiv$  hard scattering cross-section

$f_i(x, Q^2) \equiv$  parton distribution function

**parton distribution functions**  
measured in DIS & hadron-hadron collisions

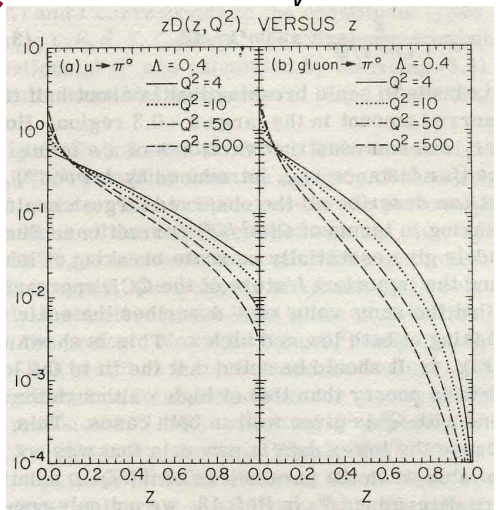


**quark & gluon fragmentation functions**  
measured mostly in e<sup>+</sup>e<sup>-</sup> collisions; modeled by fragmentation MC

TABLE I. Cross sections for the various constituent quark-quark, quark-gluon, and gluon-gluon subprocesses.<sup>a</sup> The differential cross section is given by  $d\hat{\sigma}/d\hat{t} = \pi\alpha_s^2(Q^2)|A|^2/\hat{s}^2$ , where  $\alpha_s(Q^2)$  is the effective coupling given by Eq. (3.1).

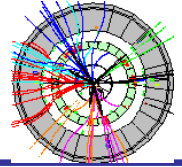
| Subprocess  | $ A ^2$  |
|---|--|
| 1. $q_i q_j \rightarrow q_i q_j$<br>$q_i \bar{q}_j \rightarrow q_i \bar{q}_j$<br>( $i \neq j$ ) | $\frac{4}{9} \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}$  |
| 2. $q_i q_i \rightarrow q_i q_i$  | $\frac{4}{9} \left( \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{s}^2 + \hat{t}^2}{\hat{u}^2} \right) - \frac{8}{27} \frac{\hat{s}^2}{\hat{u}\hat{t}}$ |
| 3. $q_i \bar{q}_i \rightarrow q_i \bar{q}_i$  | $\frac{4}{9} \left( \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2} \right) - \frac{8}{27} \frac{\hat{u}^2}{\hat{s}\hat{t}}$ |
| 4. $q_i \bar{q}_i \rightarrow gg$   | $\frac{32}{27} \left( \frac{\hat{u}^2 + \hat{t}^2}{\hat{u}\hat{t}} \right) - \frac{8}{3} \left( \frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2} \right)$               |
| 5. $gg \rightarrow q_i \bar{q}_i$   | $\frac{1}{6} \left( \frac{\hat{u}^2 + \hat{t}^2}{\hat{u}\hat{t}} \right) - \frac{3}{8} \left( \frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2} \right)$                 |
| 6. $q_i g \rightarrow q_i g$  | $-\frac{4}{9} \left( \frac{\hat{u}^2 + \hat{s}^2}{\hat{u}\hat{s}} \right) + \left( \frac{\hat{u}^2 + \hat{s}^2}{\hat{t}^2} \right)$                            |
| 7. $gg \rightarrow gg$  | $\frac{9}{2} \left( 3 - \frac{\hat{u}\hat{t}}{\hat{s}^2} - \frac{\hat{u}\hat{s}}{\hat{t}^2} - \frac{\hat{s}\hat{t}}{\hat{u}^2} \right)$                        |

**quark & gluon cross-sections**  
calculable in QCD





## Parton fragmentation functions



Parton fragmentation function  $D_i^h(x, Q^2)$  describes the probability to produce certain hadron  $h$  from parton  $i$  ( $= q, \bar{q}, g \dots$ ). Analogous to pdf's obtain from DIS.

In fragmentation function,  $x$  represents fraction of partons momentum carried by produced hadron  $h \leftrightarrow$  In pdf,  $x$  represents fraction of momentum of original hadron carried by interacting parton.  $Q^2$  describes here the energy (scale) of the original parton when produced instead of the momentum transfer as for pdf's in DIS.

Fragmentation functions  $D_i^h(x, Q^2)$  exhibit similar scaling violations as pdf's  $f_i(x, Q^2)$  from DIS. The  $Q^2$  evolution described by similar "DGLAP"-equations:

$$\frac{\partial D_i(x, Q^2)}{\partial \ln Q^2} = \sum_j \int_x^1 \frac{dz}{z} \frac{\alpha_s}{2\pi} P_{ji}(z, \alpha_s) D_j\left(\frac{x}{z}, Q^2\right),$$

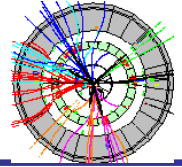
where 
$$P_{ji}(z, \alpha_s) = P_{ji}^{(0)}(z, \alpha_s) + \frac{\alpha_s}{2\pi} P_{ji}^{(1)}(z, \alpha_s) + \dots$$

Lowest-order functions  $P_{ji}^{(0)}(z)$  same as those for pdf's in DIS but higher-order terms different. NB! Splitting function  $P_{ji}$  (& not  $P_{ij}$ ) since  $D_j$  describes fragmentation of final parton.  $P_{ji}$  = probability for parton  $i$  to transfer into parton  $j$ .

Effect of  $Q^2$  evolution same as for DIS pdf's:  $x$ -distribution shifted towards lower values for larger  $Q^2$ 's.  $P_{ji}$ 's contain singularities at  $z = 0$  &  $z = 1$ , which have important effects on fragmentation at small & large  $x$ , for details see O. Biebel, P. Nason & B.R. Webber, hep-ph/0109282.



## Parton fragmentation functions



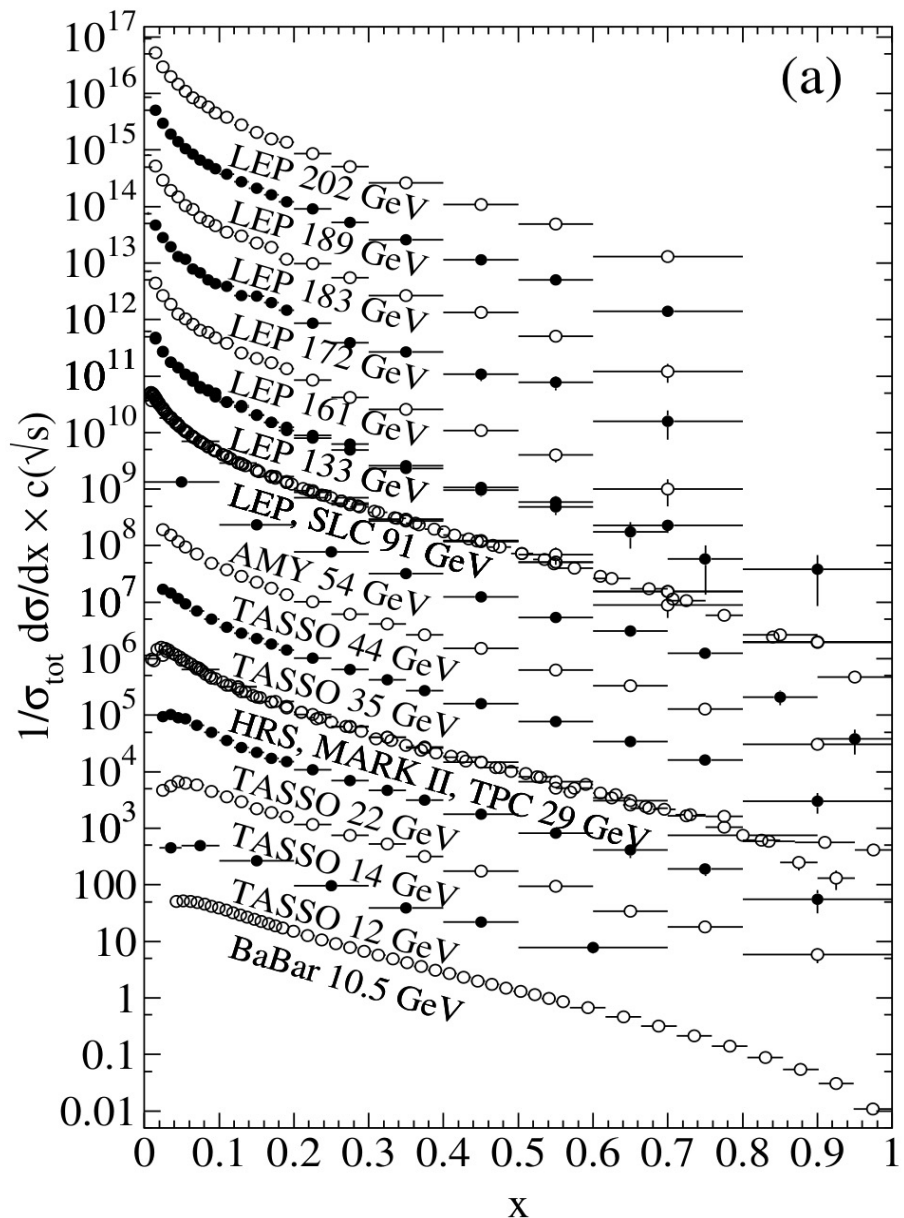
Parton fragmentation function  $D_i^h(x,s)$  usually determined from  $e^+e^-$  fragmentation functions  $F^h(x,s)$ .

$$F^h(x,s) = \frac{1}{\sigma_{\text{tot}}} \frac{d\sigma}{dx} (e^+e^- \rightarrow hX) = \sum_i \int_x^1 \frac{dz}{z} C_i(s; z, \alpha_s) D_i^h\left(\frac{x}{z}, s\right),$$

$$C_q(s; z, \alpha_s) = g_q(s) \delta(1-z) + O(\alpha_s) \quad \& \quad C_g(s; z, \alpha_s) = O(\alpha_s)$$

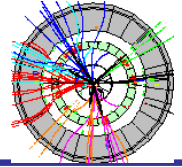
&  $g_i(s)$  appropriate (e.g.  $q$ ) electroweak coupling.

The  $e^+e^-$  fragmentation functions for all charged particles for different  $\sqrt{s}$ . The influence of scaling violations can be seen. Larger  $\sqrt{s}$  shifts the  $x$ -distribution towards smaller  $x$ 's & exponential becomes steeper.





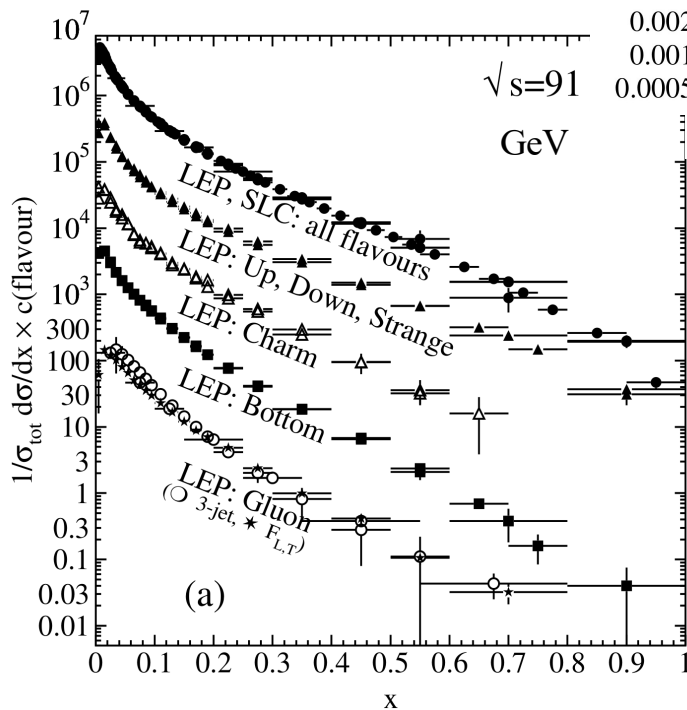
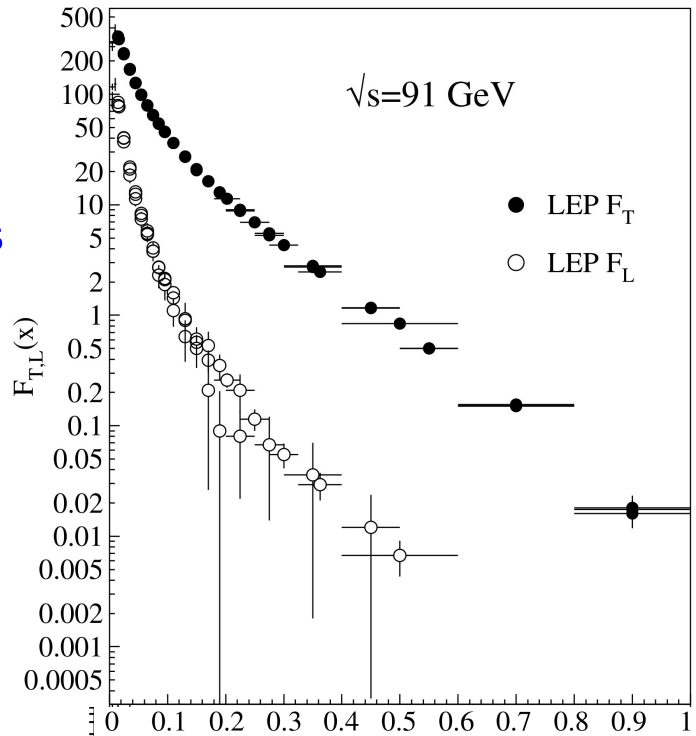
## Parton fragmentation functions



In  $e^+e^- \rightarrow \gamma/Z^0 \rightarrow hX$ , differential  $x$  &  $\cos \theta$  distribution (ignoring parity-violating  $F_A$ -term,  $\theta =$  angle between  $h$  &  $e^+$ ):

$$\frac{1}{\sigma_{\text{tot}}} \frac{d^2\sigma}{dx d\cos\theta} (e^+e^- \rightarrow hX) = \frac{3}{8} (1 + \cos^2 \theta) F_T(x,s) + \frac{3}{4} \sin^2 \theta F_L(x,s),$$

where  $F_L(x,s)$  &  $F_T(x,s)$  longitudinal & transverse fragmentation functions representing contributions from virtual bosons having longitudinal or transversal polarization (w.r.t. direction of motion of hadron).

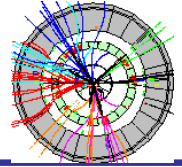


Gluon fragmentation function  $D_g(x)$  can be extracted from measured  $F_T(x)$  &  $F_L(x)$ . Coefficient functions  $C_i$ 's of  $q$  &  $g$  comparable at  $O(\alpha_s)$ .

$$F_L(x,s) = C_F \frac{\alpha_s}{2\pi} \int_x^1 \frac{dz}{z} \left[ F_T(z,s) + 4 \left( \frac{z}{x} - 1 \right) D_g(z,s) \right] + O(\alpha_s^2) \quad \& \quad C_F = \frac{4}{3}$$

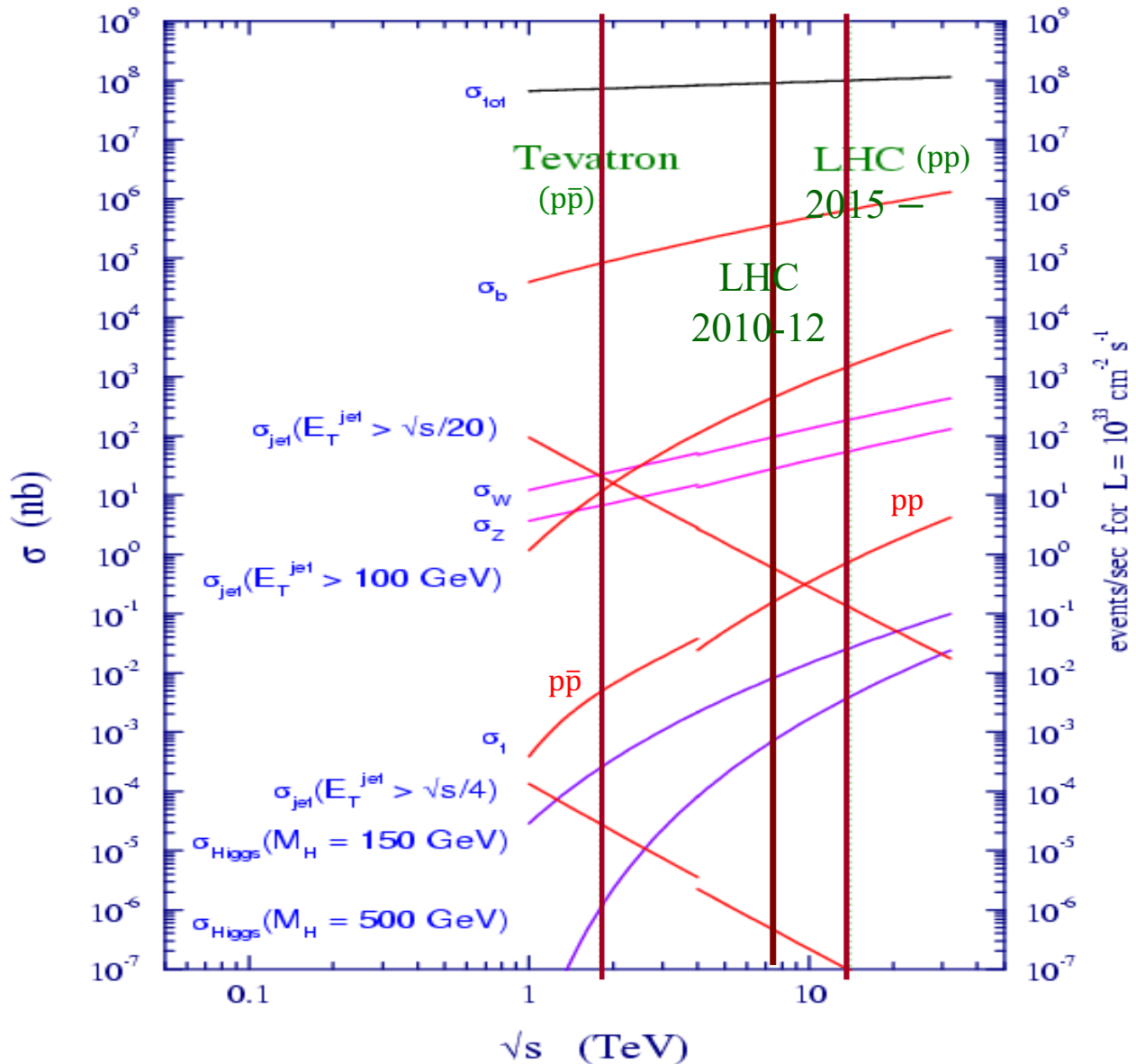


## Hadron-hadron interactions



Most interesting processes are **rare processes**:

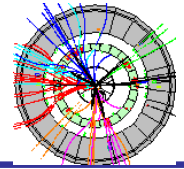
- involve **heavy particles**
- have **small cross-sections** (e.g. W production)



main background: QCD jets  $\rightarrow$  lepton & photon signatures  
important trigger signatures: a)  $\mu$  (charged particle beyond cal.),  
b)  $\gamma/e$  (em. shower) & c) neutrinos (missing transverse energy).  
note: pay a prize for branching ratio i.e.  $\text{BR}(W \rightarrow l\nu) \approx 30\%$



## Trigger



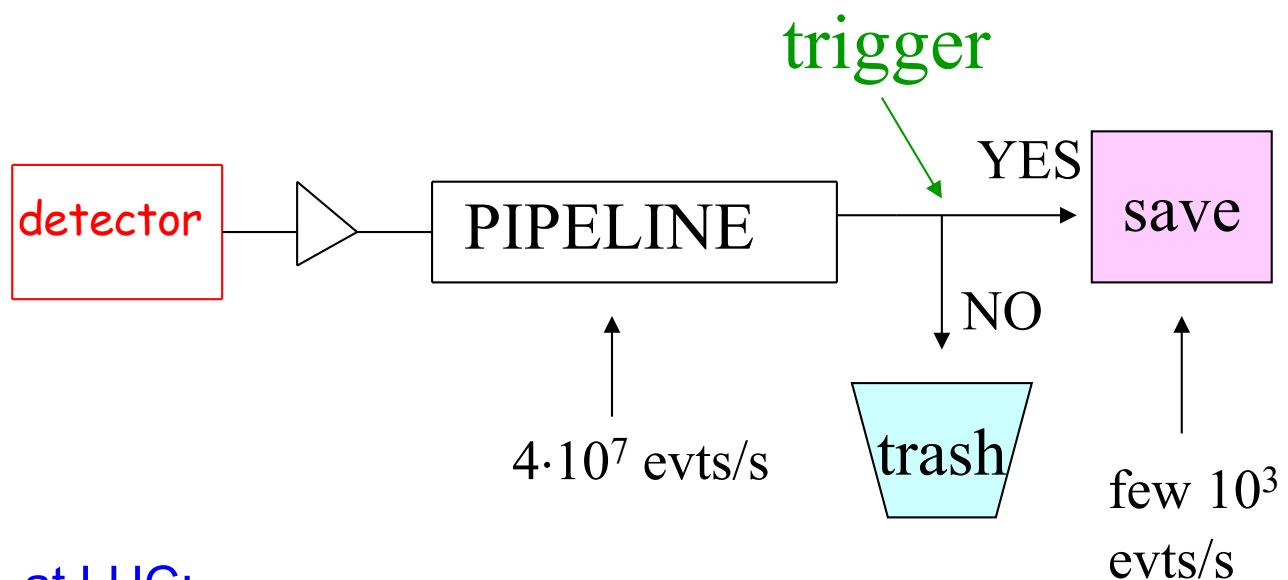
- **trigger**: much more difficult than in  $e^+e^-$  collisions  
(LHC numbers given)

bunch crossing rate:  $\sim 4 \cdot 10^7$  events/second  
can record  $\sim$  few kHz (event size: few MB)

$\Rightarrow$  **trigger rejection  $\sim 10^4$**

**trigger decision  $\approx \mu\text{s}$**   $\rightarrow$   $>$  interaction rate (of 25 ns)

store massive amount of data in **pipelines** while special trigger processors performs calculations

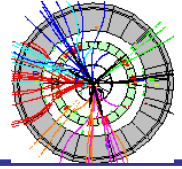


at LHC:

- low level (1<sup>st</sup>) trigger based (mostly) on calorimetry & muons chamber info  $\Rightarrow$  change for high lumi LHC
- high level trigger (HLT) software based using a (crude) full event reconstruction.
- exceptions: LHCb triggerless (online analysis)



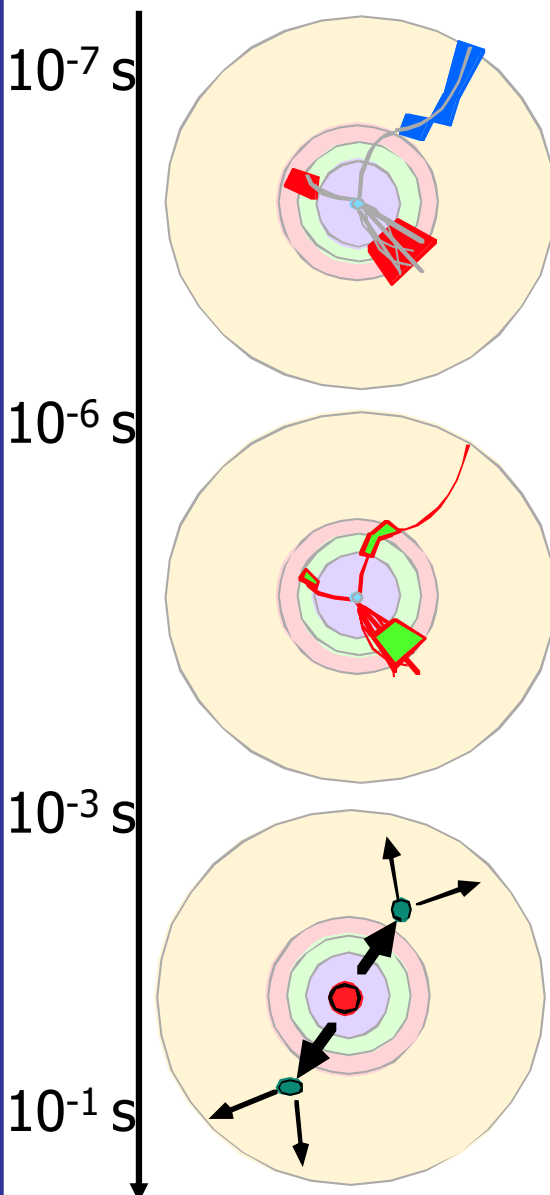
## Trigger



Trigger decision taken on several levels with increasing complexity & selectivity ('divide et impera'). Start with coarse information & refine as you go along. Employ parallelism as much as possible in search of relevant info.

All data of previous level must be stored until subsequent trigger decision has been taken.

**Level "0":** Event rate:  $4 \cdot 10^7$  Hz. Detector channels:  $10^7 - 10^8$   
DAQ running constantly at 40 MHz. Data flow  $\approx 10^{14}$  B/s



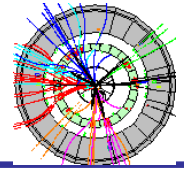
**Level-1 trigger:** coarse selection of interesting candidate events within a few  $\mu$ s. L1-trigger output rate  $\approx 100$  kHz. Implementation: specific hardware (ASICs, FPGA, DSP)

**High Level Trigger (HLT):** full event reconstruction based on cruder information. Writing data to storage medium. Output rate: a few kHz. Total event size: few MB. Implementation: fast processor farms.

**New paradigm: Triggerless readout** implemented by LHCb. Possible due to zero suppression on detectors & comparatively small total event size ( $\sim 100$  kB).



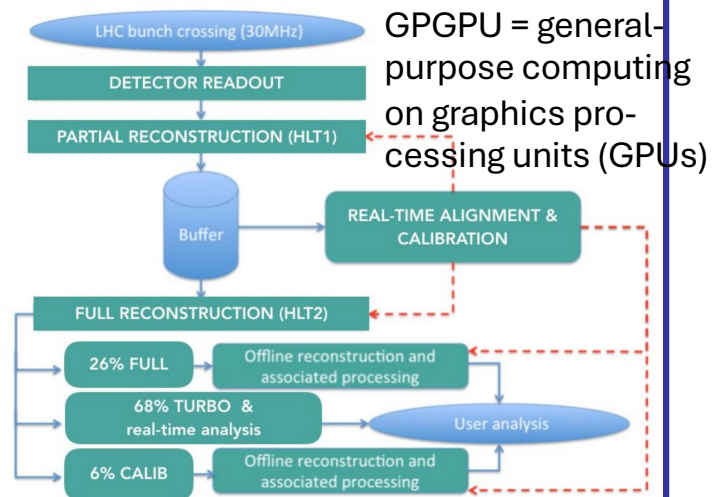
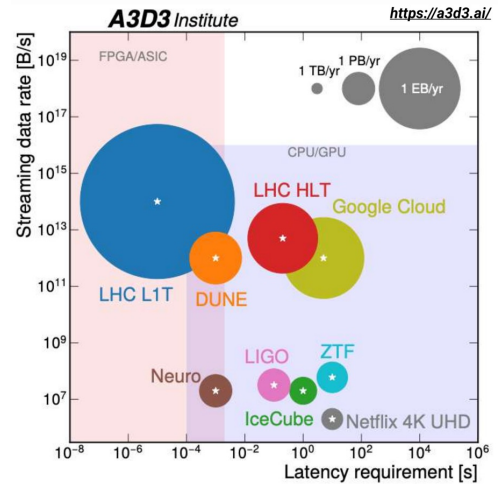
# Trigger



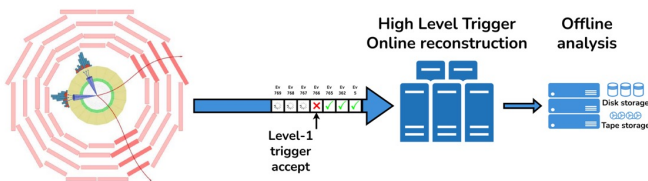
- Limiting factor is bandwidth = maximal output data rate.
- Employ machine learning techniques to make trigger selection more "efficient"

## LHCb triggerless readout

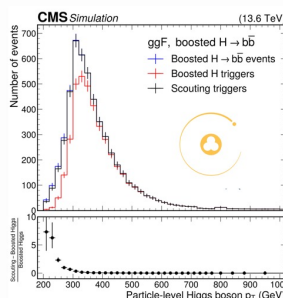
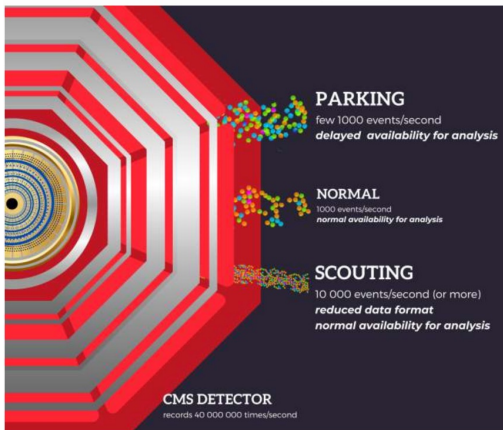
- Two stages of software filtering:
  - 1) "HLT1" on GPGPUs
  - 2) "HLT2" on CPUs
- Large storage buffer to decouple the two
- Calibration and alignment are performed "semi-live", while the data are buffered



## CMS HLT data streams



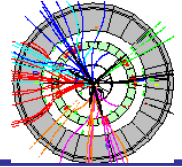
- In the second step, CMS software trigger, **High Level Trigger** (HLT), reconstructs the events selected by L1T
- Capacity increased by 20% in 2024
- GPU-accelerated reconstruction in O(100 ms) per event
- Increasingly ML-based object identification



- **Record-high rates of events stored in 2024:**
  - ~2 kHz for prompt reconstruction (twice the design value)
  - ~5 kHz for opportunistic reconstruction ("parking")
  - ~27 kHz for HLT Scouting i.e. analysis with HLT-reconstructed events and objects
- 2025:**
  - ~3 kHz
  - ~6 kHz
  - ~30 kHz

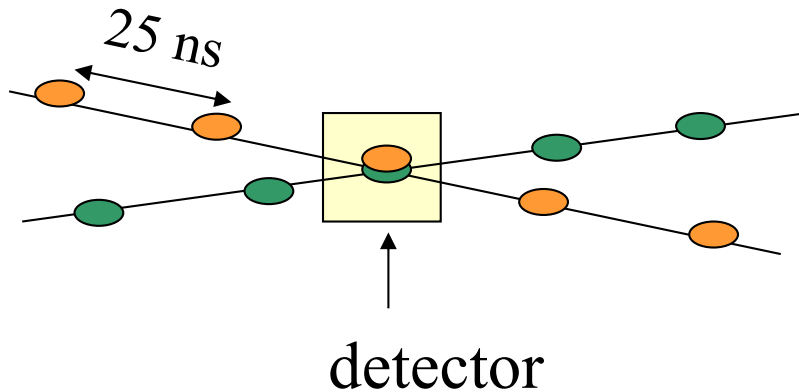


## Pileup



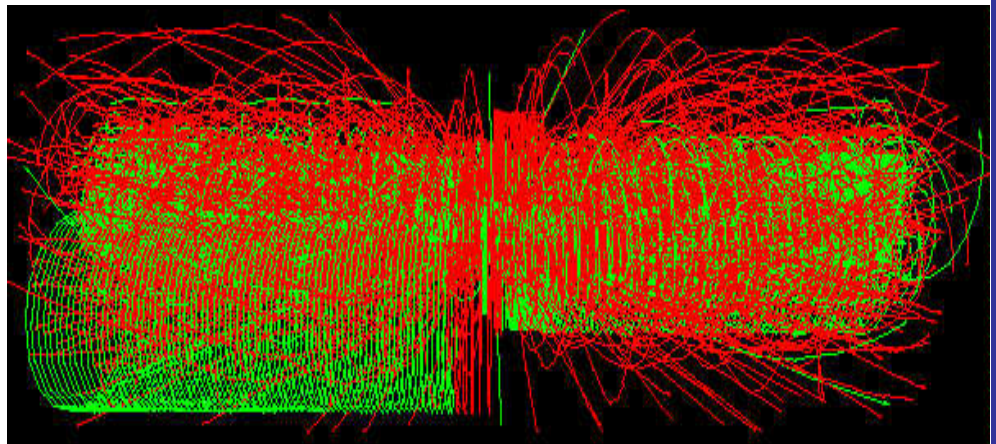
### Typical of LHC:

protons grouped in bunches (of  $\sim$  few  $10^{11}$  protons)  
crossing each other at the interaction points every **25 ns**



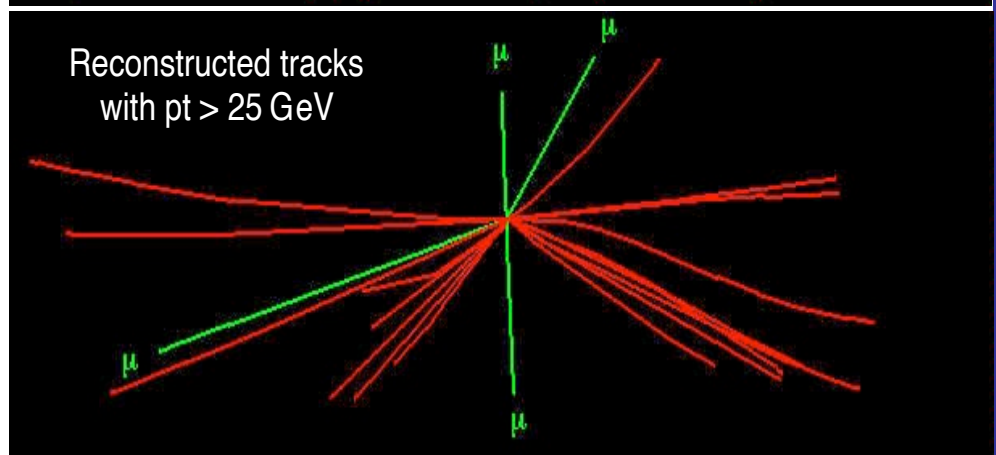
$\Rightarrow$  at each beam crossing  $\sim$  **50-60 minimum-bias** events are produced at  $L \approx$  few  $10^{34}$   $\text{cm}^{-2}\text{s}^{-1}$ . these overlap with high  $p_T$  physics events, giving rise to so-called **pile-up**

$\sim$  3000  
charged  
particles in  
the detectors  
however most  
particles have  
low  $p_T$



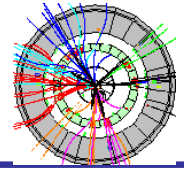
example:  
a  $H \rightarrow ZZ$ ;  
 $Z \rightarrow \mu^+ \mu^-$  at  
 $L = 10^{34}$   
 $\text{cm}^{-2}\text{s}^{-1}$

trick: focus  
on high  $p_T$   
particles





## Pile-up



### Pile-up, a very serious experimental difficulty at LHC

Large impact on detector design:

- LHC detectors must have **fast response**, otherwise integrate over many bunch crossings → too large pile-up

Typical response time : **15-50 ns** → integrate over 1-2 bunch crossings → pile-up of ~ 50-120 minimum bias ⇒ **very challenging for readout electronics**

- LHC detectors must be **highly granular** to minimize probability that pile-up particles are in the same sensitive detector element as interesting object (e.g.  $\gamma$  from  $H \rightarrow \gamma\gamma$ ) → **large number of electronic channels** ⇒ **high cost**

- LHC detectors must be **radiation resistant**: high flux of particles from pp collisions → high radiation environment

Fluence of different type of particles in 1 year at  $10^{34}$

$\text{cm}^{-2} \text{s}^{-1}$  in ATLAS

silicon tracker as function

of distance to collision

vertex. Innermost pixel

layer (at 4 cm) survives

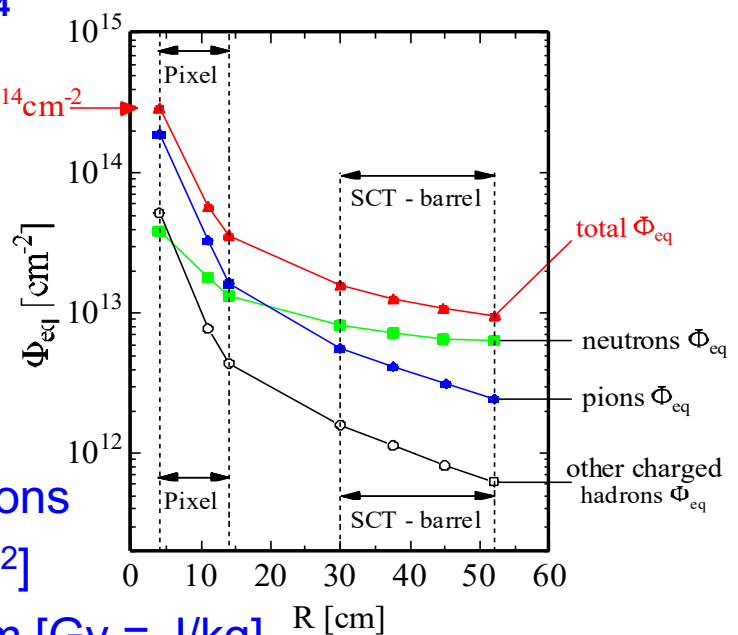
~3 years with current

technology. Some definitions

- fluence:  $\Phi = N_{\text{part}}/A [\text{cm}^{-2}]$

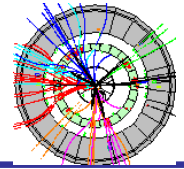
- dose:  $D = \text{deposited } E/m [\text{Gy} = \text{J/kg}]$

#### ATLAS - Inner Detector





## Event rates at LHC



### Keyword: large event statistics

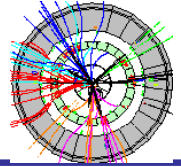
Expected event rates in ATLAS & CMS for representative (both known & new) physics processes at current high luminosity running ( $\mathcal{L} \approx 2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ )

| Process   | Events/s | Events/year    | Other machines (total statistics) |
|---|----------|----------------|-----------------------------------|
| $W \rightarrow e\nu$  | 300      | $10^9$         | $10^4$ LEP / $10^7$ Tev.          |
| $Z \rightarrow ee$  | 30       | $10^8$         | $10^7$ LEP                        |
| $t\bar{t}$  | 16       | $5 \cdot 10^7$ | $10^4$ Tevatron                   |
| $b\bar{b}$  | $10^6$   | few $10^{12}$  | $10^8$ B-factories                |
| $\tilde{g}\tilde{g}$<br>( $m_{\text{gluino}} = 1 \text{ TeV}$ ) | 0.02     | $5 \cdot 10^4$ | —                                 |
| H<br>( $m_{\text{H}} = 125 \text{ GeV}$ )                       | $\sim 1$ | few $10^6$     | $10^4$ Tevatron                   |
| QCD jets<br>$p_{\text{T}} > 200 \text{ GeV}$                    | $10^3$   | few $10^9$     | $10^7$ Tevatron                   |

High lumi LHC ( $\sim 5 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ ): statistics 2.5 times larger

→ LHC is a B-factory, top factory, W/Z factory, Higgs factory, etc.... (the difficult challenge is to extract the signal)

# Top quark



top quark (t) discovered by the CDF and DØ experiments at the Tevatron in 1995 (SU(2)<sub>L</sub> partner of the b quark)  
 a most intriguing fermion :  $m_{\text{top}} \approx 172.6 \text{ GeV}$  (heaviest known fundamental particle,  $\times 40$  heavier than b quark)  $\rightarrow$  clues about origin of particle masses ( $h_{\text{top}} = m_{\text{top}}/v_{\text{EW}} \sim 1$ )  
 top decays instantaneously and almost exclusively to Wb  
 $\Gamma(t \rightarrow Wb) \sim 1.5 \text{ GeV} \gg \Lambda_{\text{QCD}}$   
 - top decay a (almost?) pure electroweak process  
 - no hadronization (no T mesons, “toponium”?)

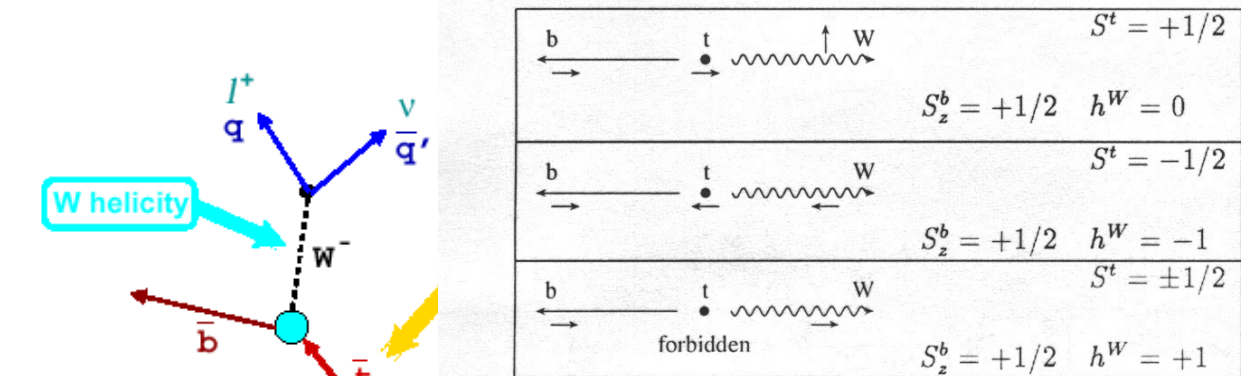
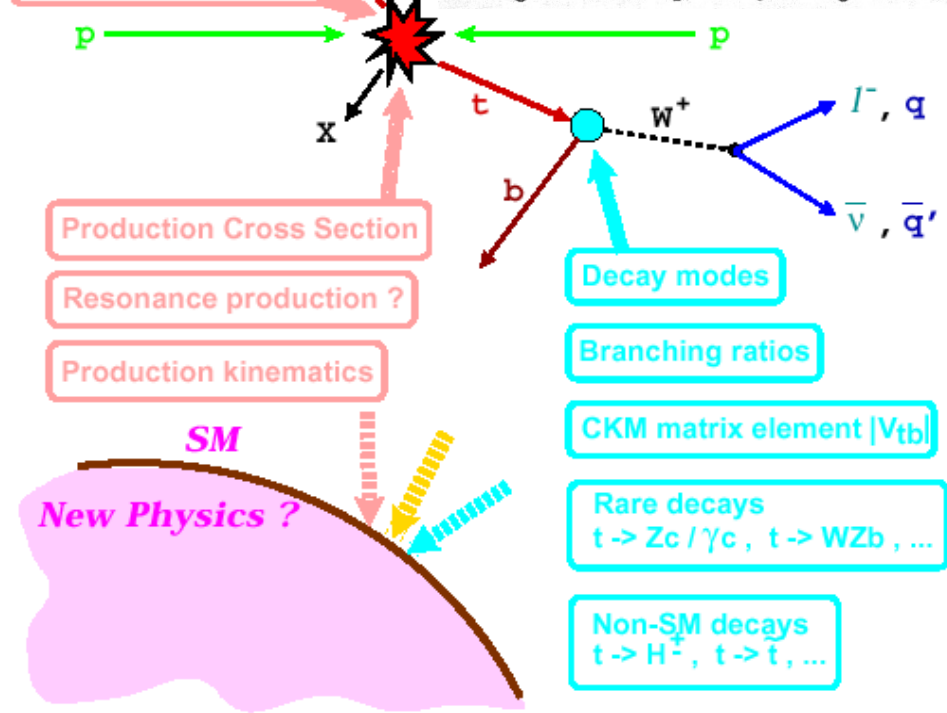


Figure 1.6: Top decays: angular momentum conservation

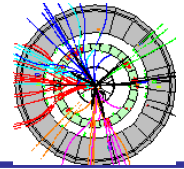


polarisation of the top quark transmitted to the W-boson

“toponium” = a bound state of a top and antitop quark



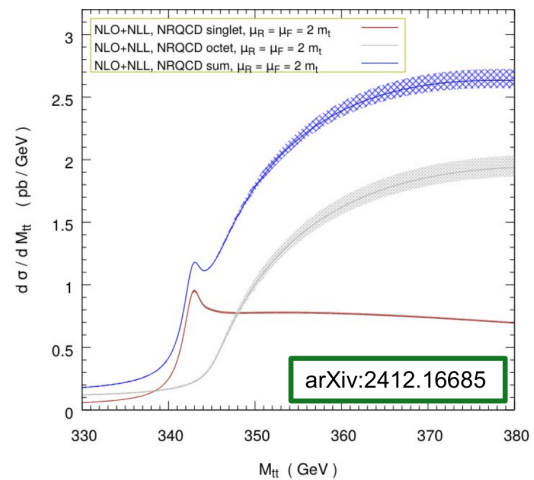
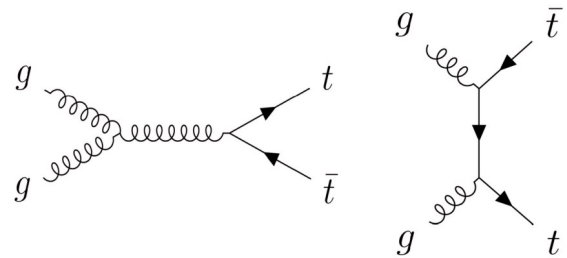
# Top pair production & decay



## Top Quark QCD Production

Top quark production @ LHC dominated by pair production via QCD diagrams: 830-880 pb @  $\sqrt{s} = 13-13.6$  TeV

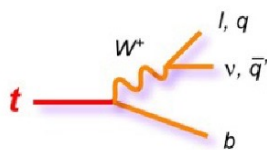
- ◆ color octet ( $^1S_0[8]$  or  $^3S_1[8]$ ) - repulsive  
→ contributions small below threshold
- ◆ color singlet ( $^1S_0[1]$ ) - attractive  
→ peak below the  $t\bar{t}$  threshold



## Top Pair Decay Channels

In the SM the top quark decays exclusively into a W boson and a b quark

$$B(t \rightarrow Wb) \simeq 100\%$$

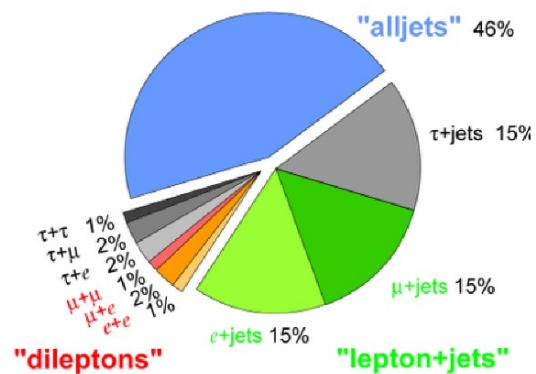


the branching fractions of the t-tbar final states depend on the W boson branching fractions

Top Pair Decay Channels

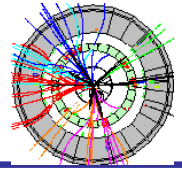
|                |               |           |          |               |            |
|----------------|---------------|-----------|----------|---------------|------------|
| $c\bar{s}$     | electron+jets | muon+jets | tau+jets | all-hadronic  |            |
| $\bar{u}d$     |               |           |          |               |            |
| $\tau^+\tau^-$ | dileptons     |           |          | tau+jets      |            |
| $\mu^+\mu^-$   |               |           |          | muon+jets     |            |
| $e^+e^-$       |               |           |          | electron+jets |            |
| W decay        | $e^+$         | $\mu^+$   | $\tau^+$ | $u\bar{d}$    | $c\bar{s}$ |

Top Pair Branching Fractions

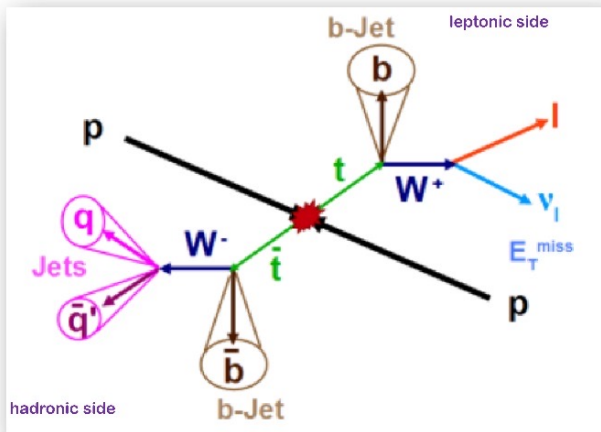




# Top decays: leptons + jets



## Lepton+Jets

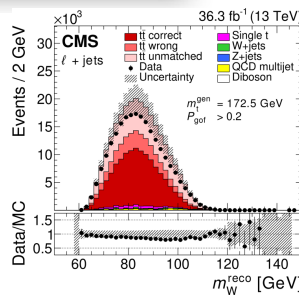
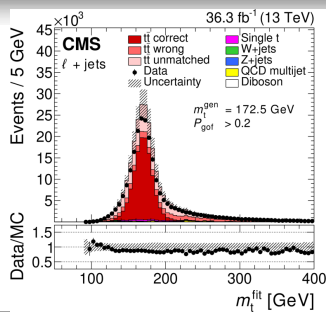


### Golden mode at the LHC

- High rate: 30% of top pairs
- Low backgrounds:  $S/B > 1$
- W reconstructed in hadronic channel in situ constraint of jet energy scale
- full reconstruction of the top quark on the hadronic side
- direct mass measurement

### But

- large combinatorics reduced by efficient b-tagging and good di-jet mass resolution

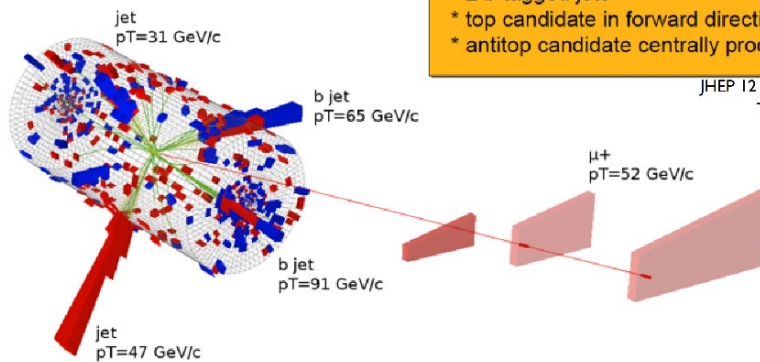


Reconstructed top mass improved significantly by profile likelihood fit

## Lepton+Jets Event Selection



CMS Experiment at LHC, CERN  
Data recorded: Mon May 2 10:44:23 2011 CEST  
Run/Event: 163817 / 685608658



### Top quark pair candidate event

- \* high probability to be  $t\bar{t}$  event
- \* 2 b-tagged jets
- \* top candidate in forward direction
- \* antitop candidate centrally produced

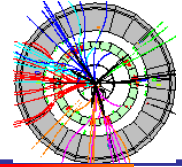
JHEP 12 (2012) 105  
TOP-14-001

### Typical event selection

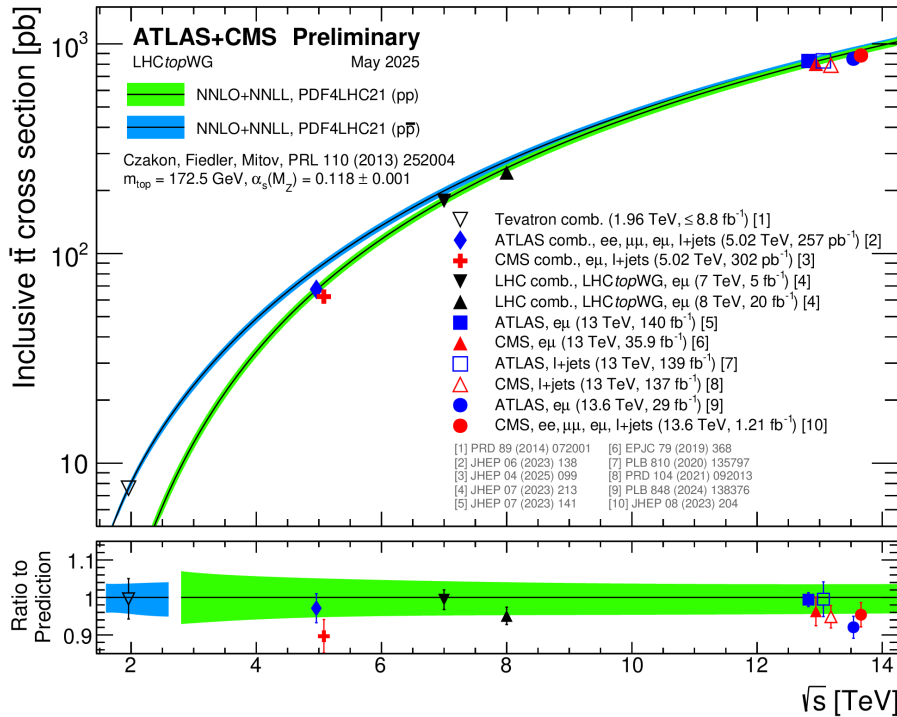
- trigger lepton + jets
- exactly one lepton  $p_T > 30$  GeV and  $|\eta| < 2.1$
- $\geq 4$  jets with  $p_T > 30$  GeV and  $|\eta| < 2.4$
- 2 b-tagged jets among the 4 leading jets



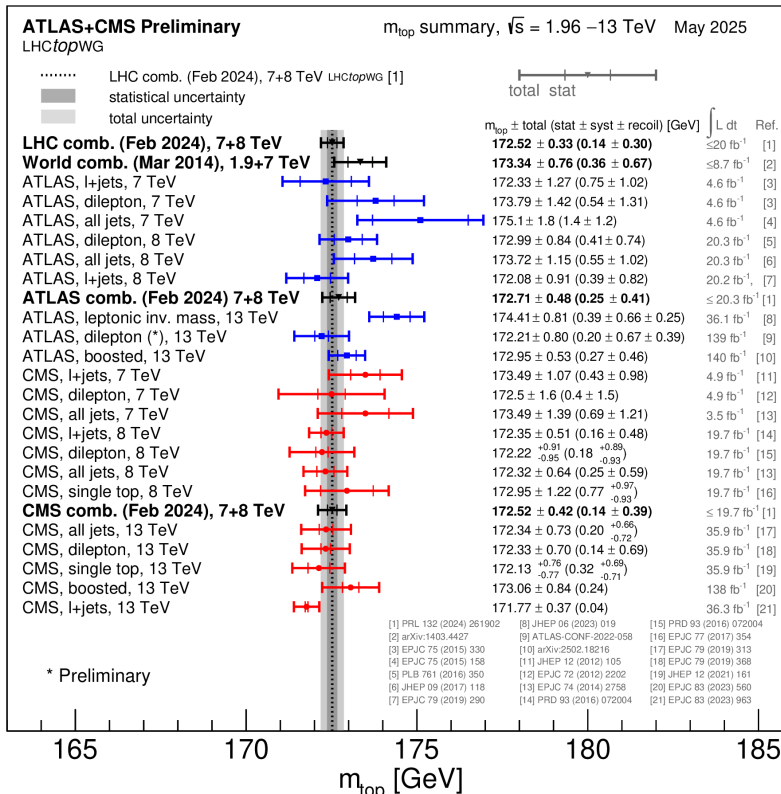
# Top quark mass



## Production cross section



## Summary of Mass Measurements



**PDG:**

$$m_t = 172.56 \pm 0.31 \text{ GeV}$$

**ATLAS:**

$$m_t = 172.71 \pm 0.48 \text{ GeV}$$

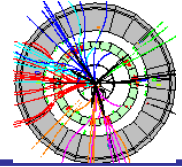
**CMS:**

$$m_t = 172.52 \pm 0.42 \text{ GeV}$$

- excellent agreement between ATLAS and CMS



# Top quark mass

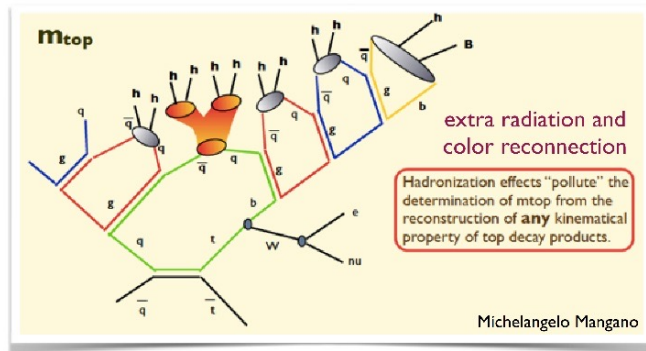


## What Mass for the EW fit?

The definition of the mass of the top quark is **ill-defined**

- the mass measured from **bW decay products** is assumed to be close from pole  $m_{pole}$
- problem:  $m_{pole}$  for a **coloured particle** cannot be determined with accuracy better than  $\Lambda_{QCD}$  ( $\approx 0.2$  GeV)
- the top quark decays before hadronising but still the b quark has to hadronise

Which final state particles to assign to the original top quark?



- Importance of measuring the mass using alternate techniques
  - mass and end point of  $b\ell$  spectrum
  - decay length (boost) of B hadrons

theoretically a good approach is to extract the mass from measurements of the cross section

## Mass from Cross Section

- use the best x-section measurement (**dilepton**)
- use most recent NNLO calculations of top pair x-section to extract  $m_t$
- also provide a measurement of the strong coupling constant at  $m_t$

ATLAS+CMS Preliminary LHCtopWG  $m_{top}$  from cross-section measurements November 2023

|   | total | stat | $m_{top} \pm \text{tot (stat} \pm \text{syst} \pm \text{theo) [GeV]}$ | $\int L dt$                 | Ref.                     |                           |
|---|-------|------|---|-----------------------------|--------------------------|---------------------------|
| <b><math>\sigma(t\bar{t})</math> inclusive, NNLO+NNLL</b> |       |      |   |                             |                          |                           |
| ATLAS, 7+8 TeV  |       |      | $172.9^{+2.5}_{-2.6}$   | $\leq 20 \text{ fb}^{-1}$   | [1]                      |                           |
| CMS, 7+8 TeV  |       |      | $173.8^{+1.7}_{-1.8}$   | $\leq 19.7 \text{ fb}^{-1}$ | [2]                      |                           |
| CMS, 13 TeV   |       |      | $169.9^{+1.9}_{-2.1} (0.1 \pm 1.5^{+1.2}_{-1.5})$                     | $35.9 \text{ fb}^{-1}$      | [3]                      |                           |
| ATLAS, 13 TeV   |       |      | $173.1^{+2.0}_{-2.1}$   | $36.1 \text{ fb}^{-1}$      | [4]                      |                           |
| LHC comb., 7+8 TeV  |       |      | $173.4^{+1.8}_{-2.0}$   | $\leq 20 \text{ fb}^{-1}$   | [5]                      |                           |
| <b><math>\sigma(t\bar{t}+1j)</math> differential, NLO</b> |       |      |   |                             |                          |                           |
| ATLAS, 7 TeV  |       |      | $173.7^{+2.3}_{-2.1} (1.5 \pm 1.4^{+1.0}_{-0.5})$                     | $4.6 \text{ fb}^{-1}$       | [6]                      |                           |
| ATLAS, 8 TeV  |       |      | $171.1^{+1.2}_{-1.0} (0.4 \pm 0.9^{+0.7}_{-0.3})$                     | $20.2 \text{ fb}^{-1}$      | [7]                      |                           |
| CMS, 13 TeV   |       |      | $172.1^{+1.4}_{-1.3} (1.3^{+0.5}_{-0.4})$                             | $36.3 \text{ fb}^{-1}$      | [8]                      |                           |
| <b><math>\sigma(t\bar{t})</math> n-differential, NLO</b>  |       |      |   |                             |                          |                           |
| ATLAS, n=1, 8 TeV   |       |      | $173.2 \pm 1.6 (0.9 \pm 0.8 \pm 1.2)$                                 | $20.2 \text{ fb}^{-1}$      | [9]                      |                           |
| CMS, n=3, 13 TeV  |       |      | $170.5 \pm 0.8$   | $35.9 \text{ fb}^{-1}$      | [10]                     |                           |
| <b><math>m_{top}</math> from top quark decay</b>          |       |      |   |                             |                          |                           |
|   |       |      |   | [1] EPJC 74 (2014) 3109     | [5] JHEP 2307 (2023) 213 | [9] EPJC 77 (2017) 804    |
|   |       |      |   | [2] JHEP 08 (2016) 029      | [6] JHEP 10 (2015) 121   | [10] EPJC 80 (2020) 658   |
|   |       |      |   | [3] EPJC 79 (2019) 368      | [7] JHEP 11 (2019) 150   | [11] PRD 93 (2016) 072004 |
|   |       |      |   | [4] EPJC 80 (2020) 528      | [8] JHEP 07 (2023) 077   | [12] EPJC 79 (2019) 290   |

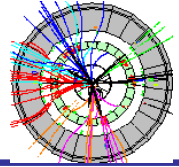
Legend:   
 Pink: CMS, 7+8 TeV comb. [11]   
 Cyan: ATLAS, 7+8 TeV comb. [12]

X-axis:  $m_{top}$  [GeV] (155 to 190)

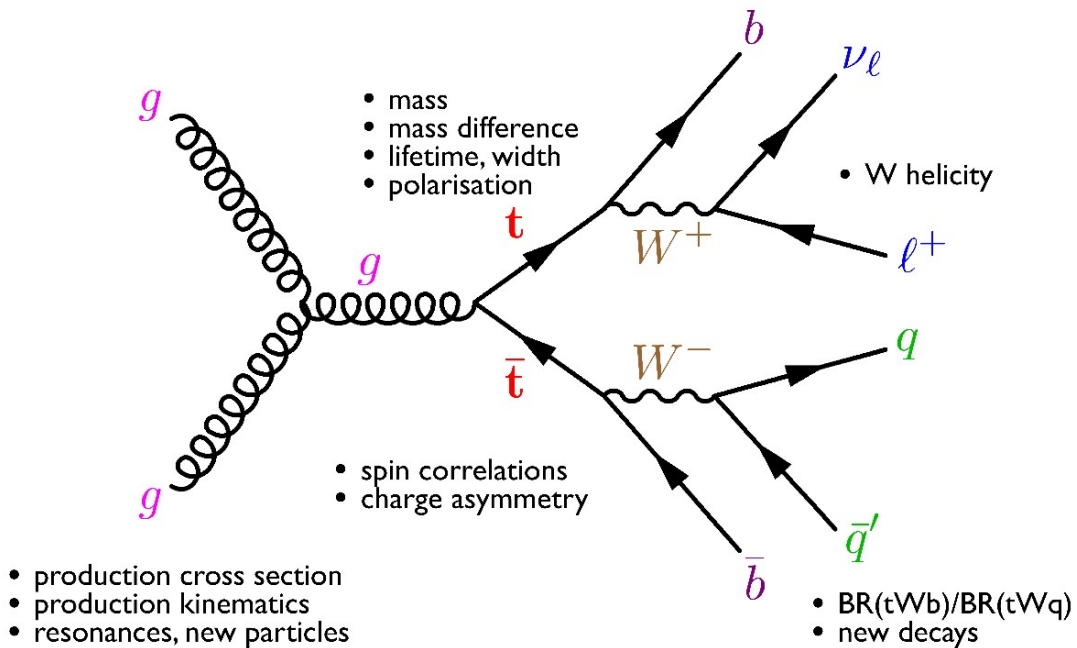
PDG:  $m_t = 172.4 \pm 0.7$  GeV



# Top properties

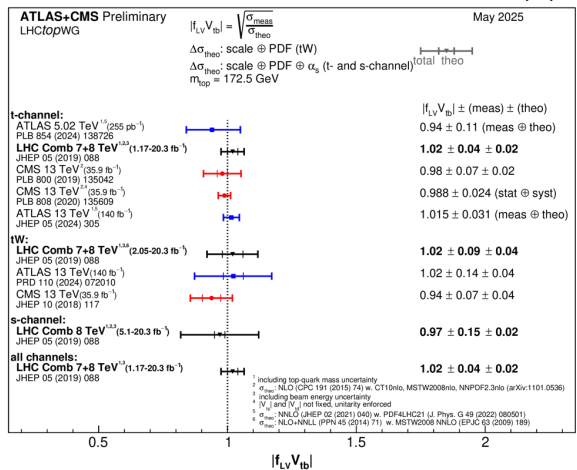
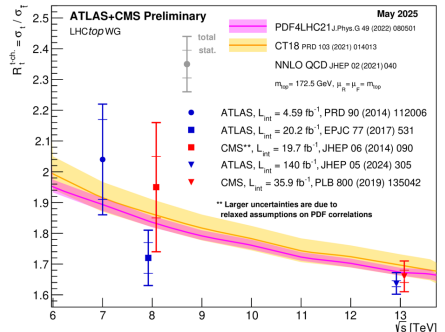
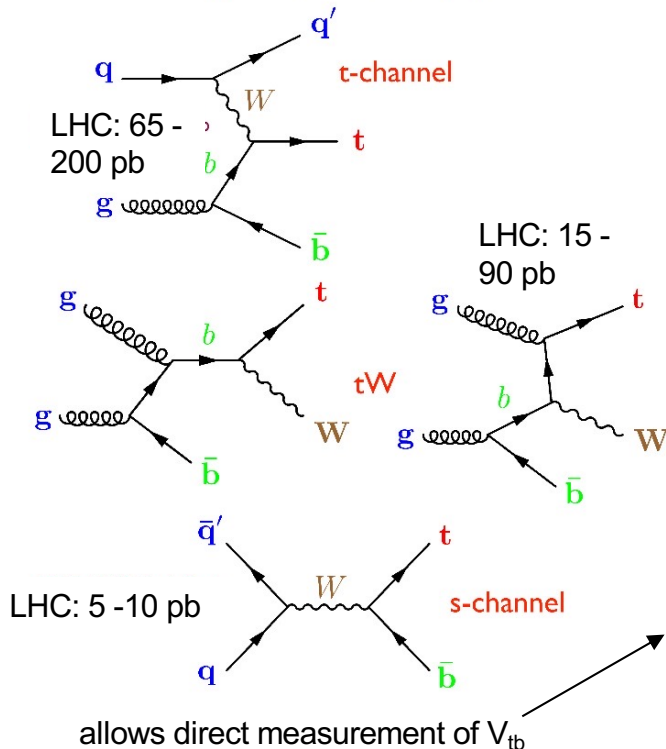


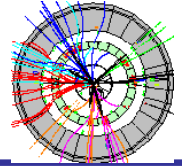
## Top Quark Properties



## Electroweak Production: Single Top

EW production of a top quark





### Electroweak precision measurements:

$$m_W = \left( \frac{\pi \alpha_{EM}}{\sqrt{2} G_F} \right)^{1/2} \frac{1}{\sin \theta_W \sqrt{1 - \Delta r}} \leftarrow \propto m_{top}^2 \text{ \& } \ln(m_H^2)$$

since  $G_F$ ,  $\alpha_{em}$ ,  $\sin\theta_W$  are known with high precision,  
 precise measurements of  $m_{top}$  &  $m_W$  constrain radiative  
 corrections & Higgs mass (weakly due logarithmic dependence)

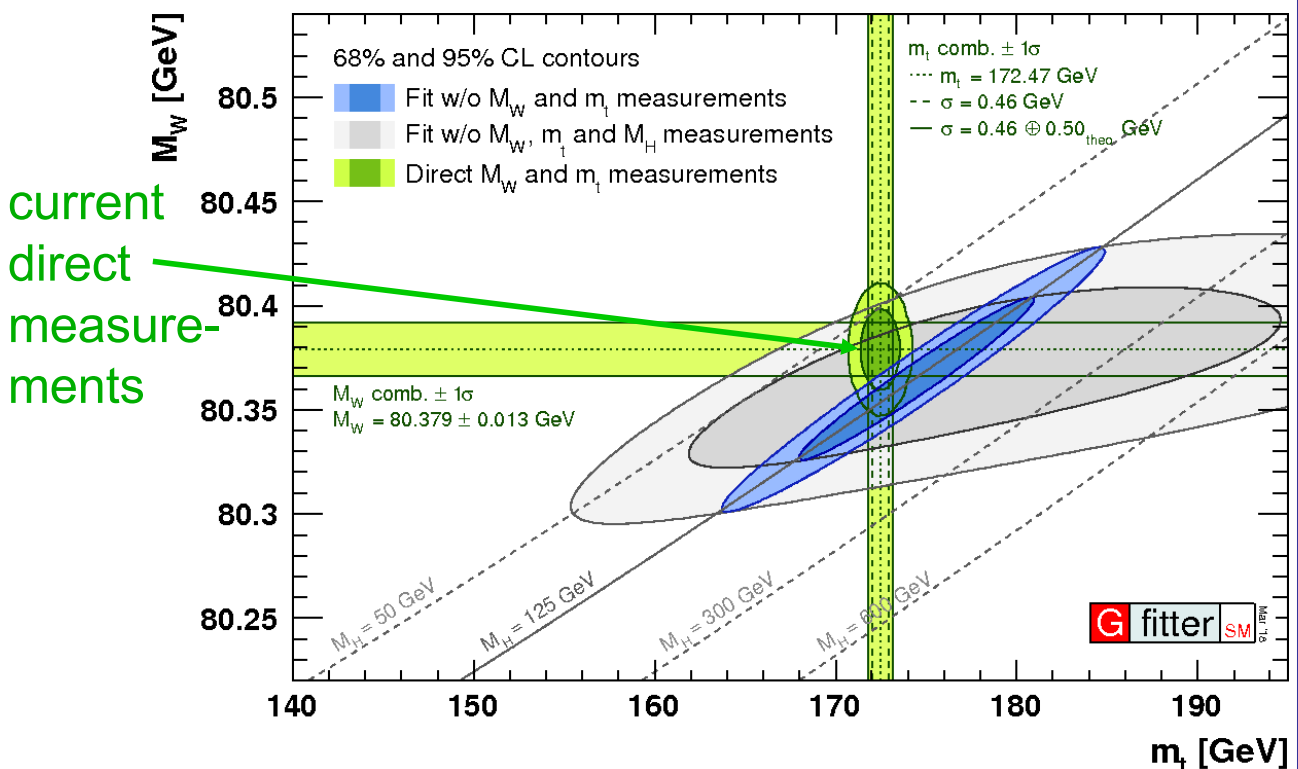
$$m_W \text{ (LEP2/Tevatron/LHC)} = 80.369 \pm 0.013 \text{ GeV}$$

$2 \cdot 10^{-4}$

$$m_{top} \text{ (Tevatron/LHC)} = 172.52 \pm 0.33 \text{ GeV}$$

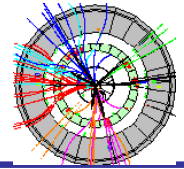
$3 \cdot 10^{-3}$

ultimate Standard Model test: compare direct  
 Higgs mass with radiative correction prediction.





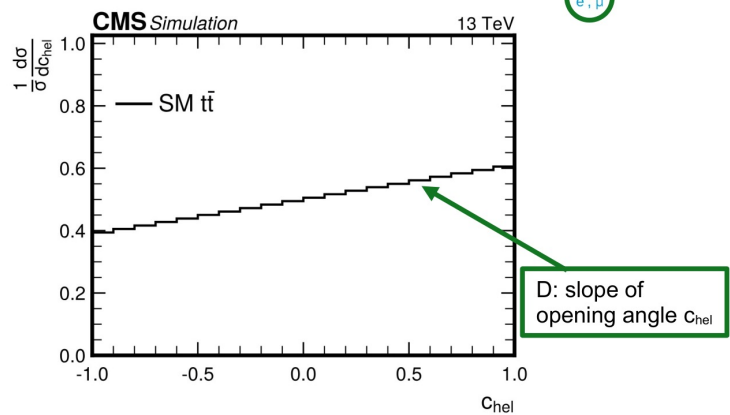
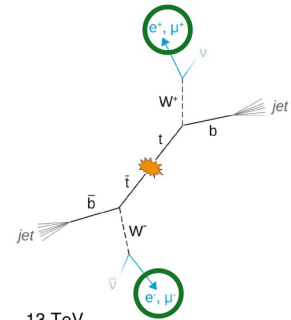
# Quantum entanglement



## Quantum entanglement at $t\bar{t}$ threshold

idea:

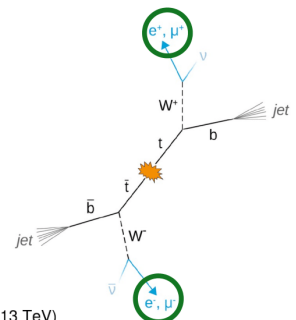
- lepton directions perfectly correlated with top spin
- measure spin correlation strength (D) from cosine of opening angle ( $c_{hel}$ ) of charged leptons in parent top rest frames



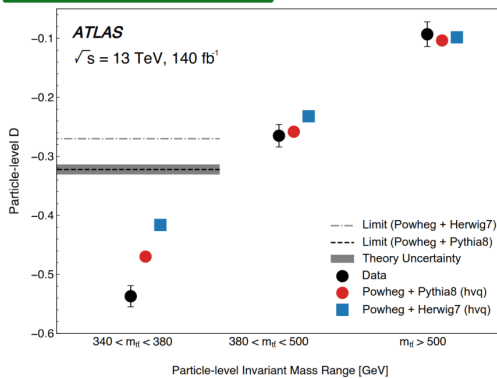
## Quantum entanglement at $t\bar{t}$ threshold

idea:

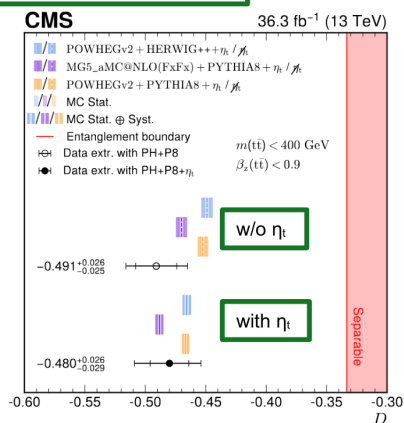
- lepton directions perfectly correlated with top spin
- measure spin correlation strength (D) from cosine of opening angle ( $c_{hel}$ ) of charged leptons in parent top rest frames
- Peres-Horodecki-Criterion:  
D < -1/3 proofs entangled tops (assuming QM)



Nature 633 (2024) 542



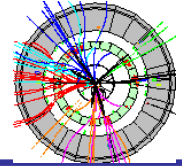
RPP 87 (2024) 117801



Improved description of data considering  $t\bar{t}$  quasi-bound states

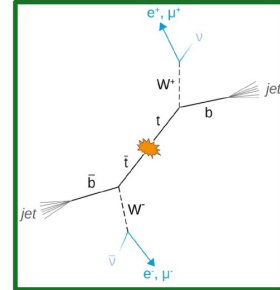
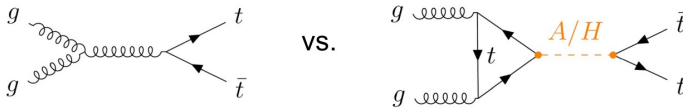


# Toponium



## A closer look at the $t\bar{t}$ threshold

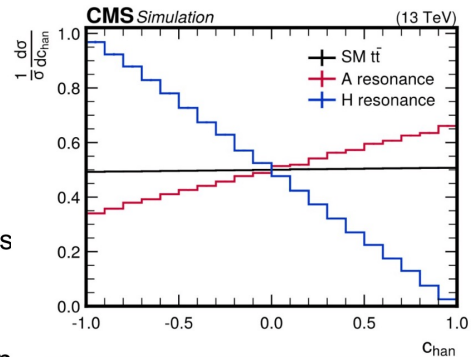
- ◆ explore differences in production mode
  - distinguish  $t\bar{t}$  continuum from pure (pseudo)scalar states



- distinguish  $^1S_0 (A/\eta_t)$  from  $^3P_0 (H)$   $t\bar{t}$  states

→ spin correlation observables!

- direction of down-type fermion fully correlated with parent top quark spin
- easiest in the dilepton channel



- ◆  $C_{hel}$ : cosine of opening angle between charged leptons in parent top quark rest frames

- ◆  $C_{chan}$ : as  $C_{hel}$  but inverted component along top direction

3 search variables:  $m_{t\bar{t}} \times C_{hel} \times C_{chan}$

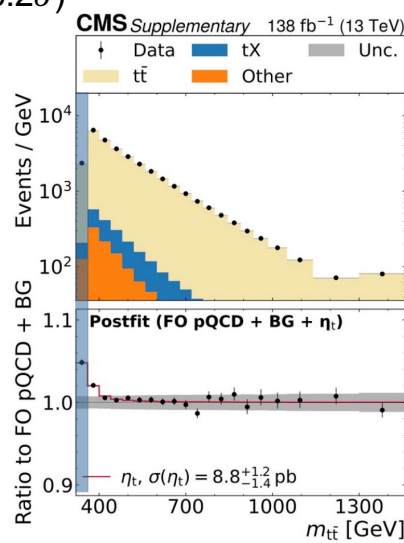
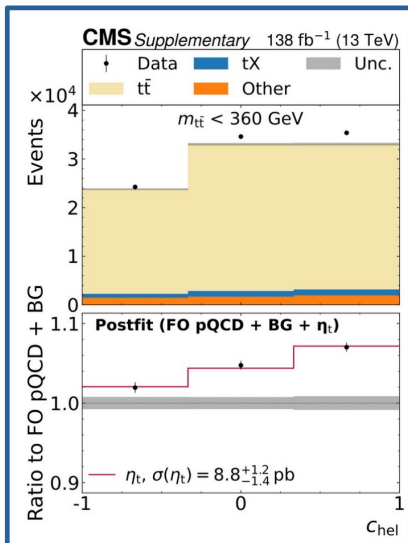
## Extracting $\eta_t$ cross section

RPP 88 (2025) 087801

- ◆ profile-likelihood fit to 20 bins of  $m_{t\bar{t}}$  x 3 bins of  $C_{hel}$  x 3 bins of  $C_{chan}$

Confirmed by ATLAS

$$\sigma(\eta_t) = 8.8 \pm 0.5 \text{ (stat)}^{+1.1}_{-1.3} \text{ (syst)} \text{ pb} = 8.8^{+1.2}_{-1.4} \text{ pb} \quad (> 6.2\sigma)$$

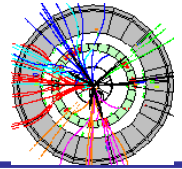


Toponium or new pseudo-scalar? Indistinguishable but SM explanation (toponium) seems more plausible.

Excess from  $t\bar{t}$  in  $^1S_0$  state

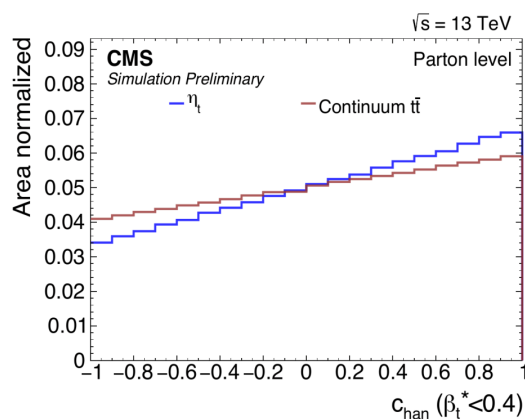
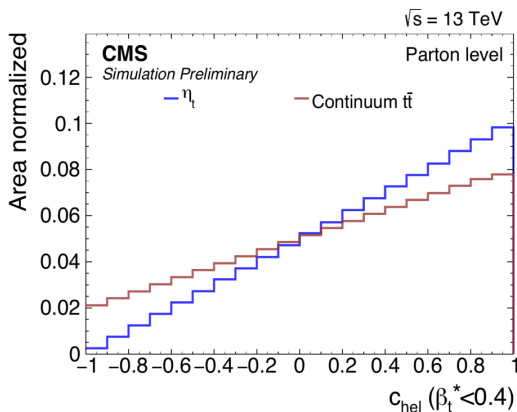
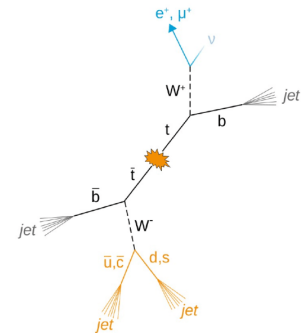


# Toponium



## First studies of the $t\bar{t}$ threshold in lepton+jets final states

- ◆ results based on  $138 \text{ fb}^{-1}$  of  $e/\mu$  + jets events recorded at 13 TeV
- ◆ probe relative velocity  $\beta_t^*$ :
  - $|\mathbf{p}|/E$  of leptonic top in ZMF of hadronic top
- ◆ combine with spin and parity sensitive observables  $c_{\text{hel}}$  and  $c_{\text{han}}$

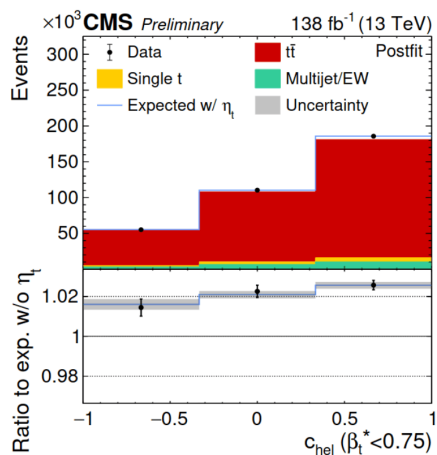
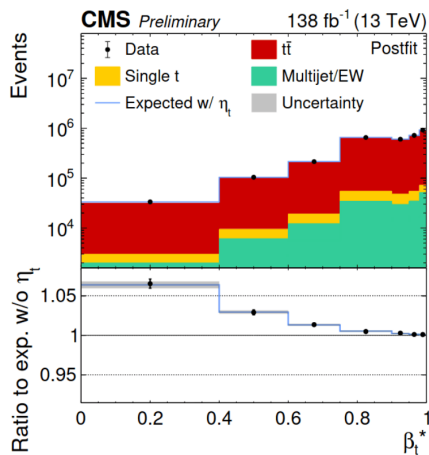


## Signal extraction

CMS-PAS-TOP-25-002

- ◆ perform fit in 16 categories
  - one or two b-tagged jets
  - low or high value of  $S_{\text{NN}}$
  - four data taking periods
- ◆ use  $7 \beta_t^* \times 3 c_{\text{hel}} \times 3 c_{\text{han}}$  bins

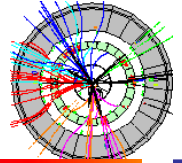
$$\sigma(\eta_t) = 5.1 \pm 0.9 \text{ pb } (> 6 \sigma \text{ SD})$$



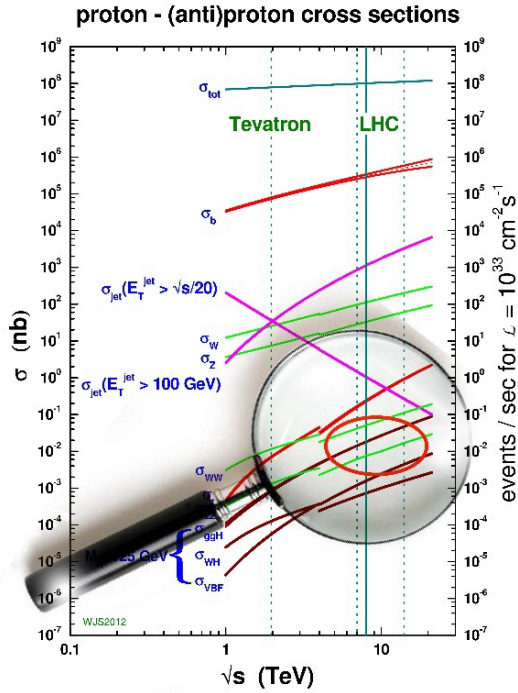
Spin correlation well described



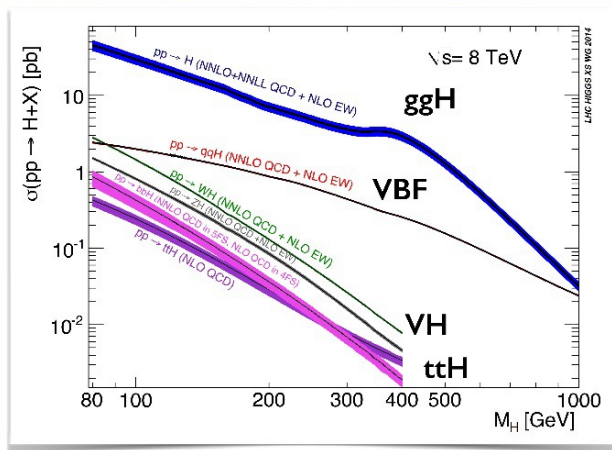
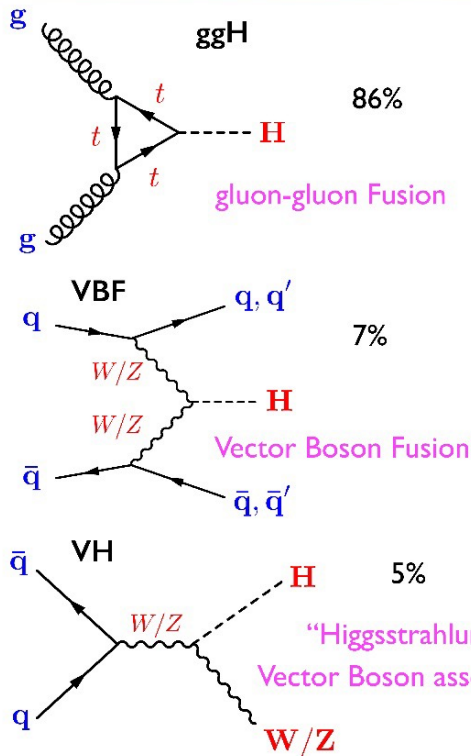
# Higgs physics



## Higgs Physics

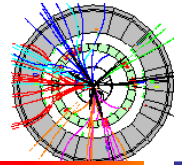


## Production of the Higgs Boson

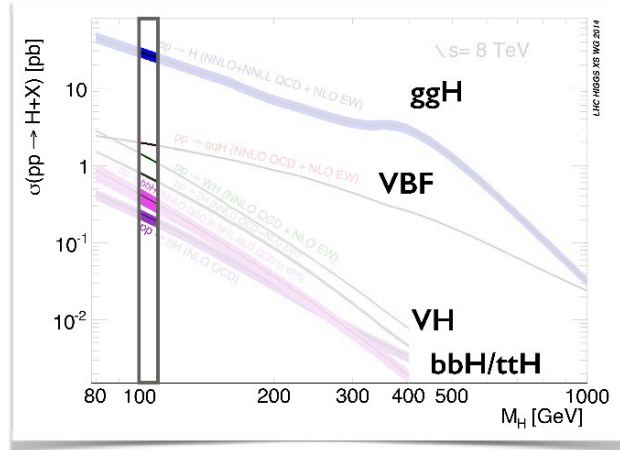
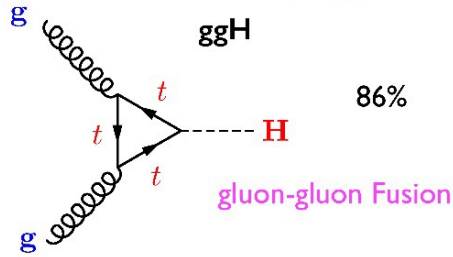




# Higgs production & decay



## Production of the Higgs Boson



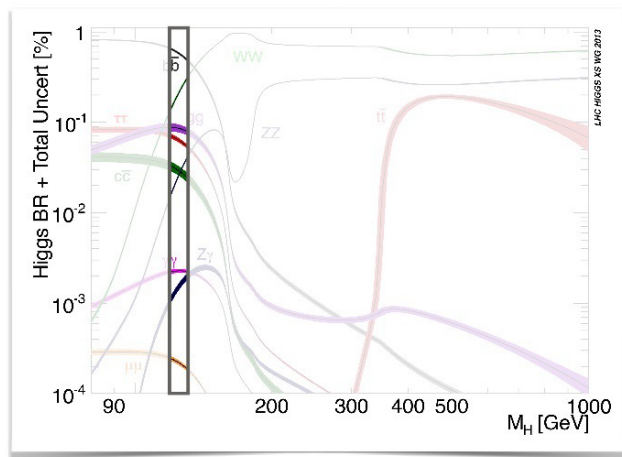
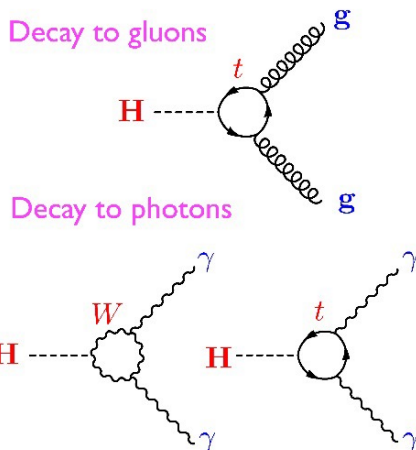
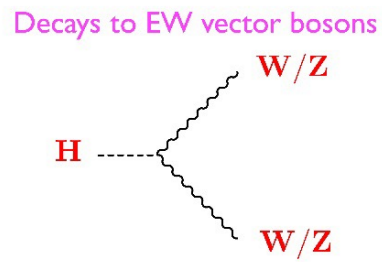
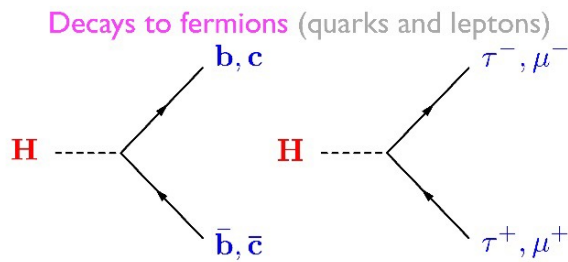
Cross sections ( $m_H = 125$  GeV)

- **Tevatron 1.96 TeV**  
1.2 pb  
ggH=78% VH=17% VBF=5%
- **LHC 8 TeV**  
23 pb  
ggH=86% VBF=7% VH=5% ttH<1%
- **LHC 13 TeV**  
51 pb  
ggH=86% VBF=7% VH=4% ttH=1%

Typical theory uncertainties

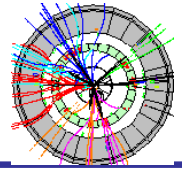
- **ggH** 15% NNnLO
- **VBF** 5% NLO
- **VH** 5% NNLO
- **ttH** 15% LO

## Decays of the Higgs Boson



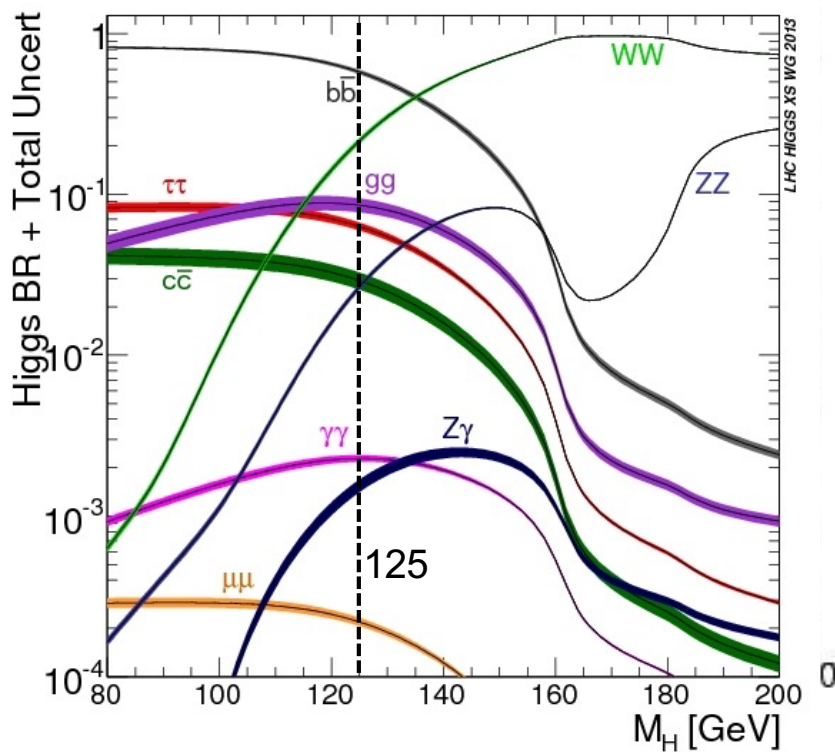


# Higgs decay



## Higgs decay branching ratios

"Higgs couples to mass"



| BR(%)          | Higgs 125 GeV   | Z boson |
|----------------|-----------------|---------|
| q $\bar{q}$    |                 | 70      |
| b $\bar{b}$    | 58.2            | 15      |
| c $\bar{c}$    | 2.9             | 12      |
| gg             | 8.2             | 0       |
| $l^+l^-$       | 0.022 ( $\mu$ ) | 10      |
| $\tau^+\tau^-$ | 6.3             | 3       |
| $\gamma\gamma$ | 0.23            |         |
| W*W*           | 21.4            |         |
| Z*Z*           | 2.6             |         |

at 1<sup>st</sup> order: 
$$\Gamma(H \rightarrow f\bar{f}) = \frac{N_C^f G_F m_f^2}{4\sqrt{2}\pi} m_H \beta_f,$$

where  $\beta_f$  is the fermion velocity in the decay.