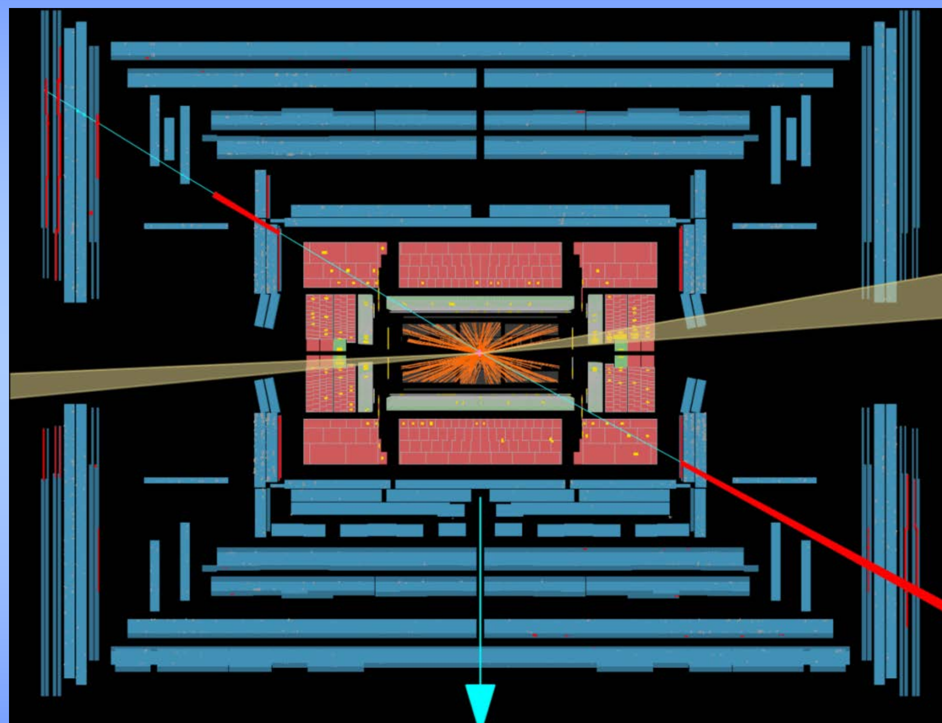
Measuring Weak Boson Scattering with ATLAS



Marc-André Pleier

BNL

DESY Physics Seminar, April 14/15 2015

Why?

Fundamental Questions

Fundamental Questions

Fundamental Questions

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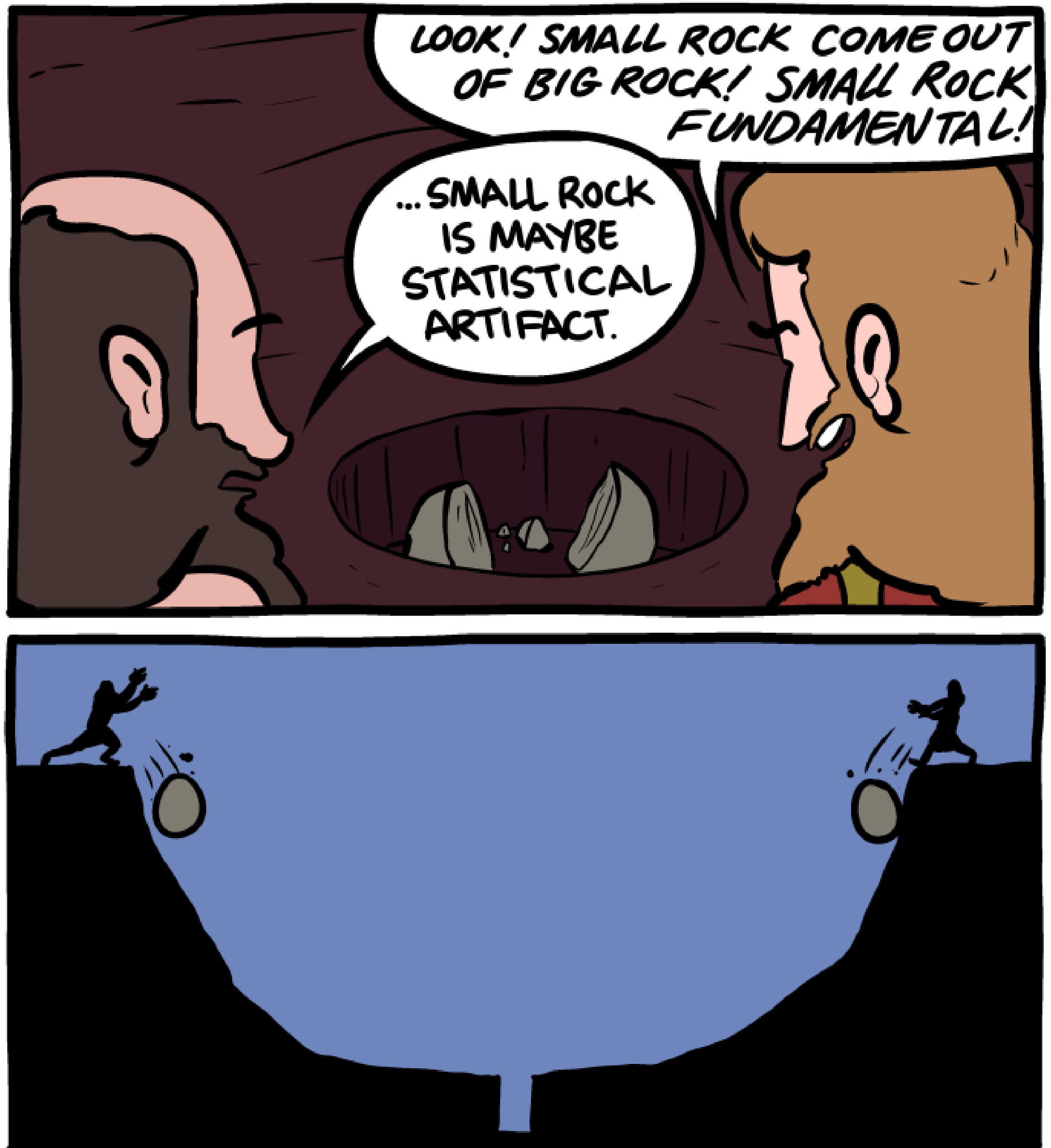
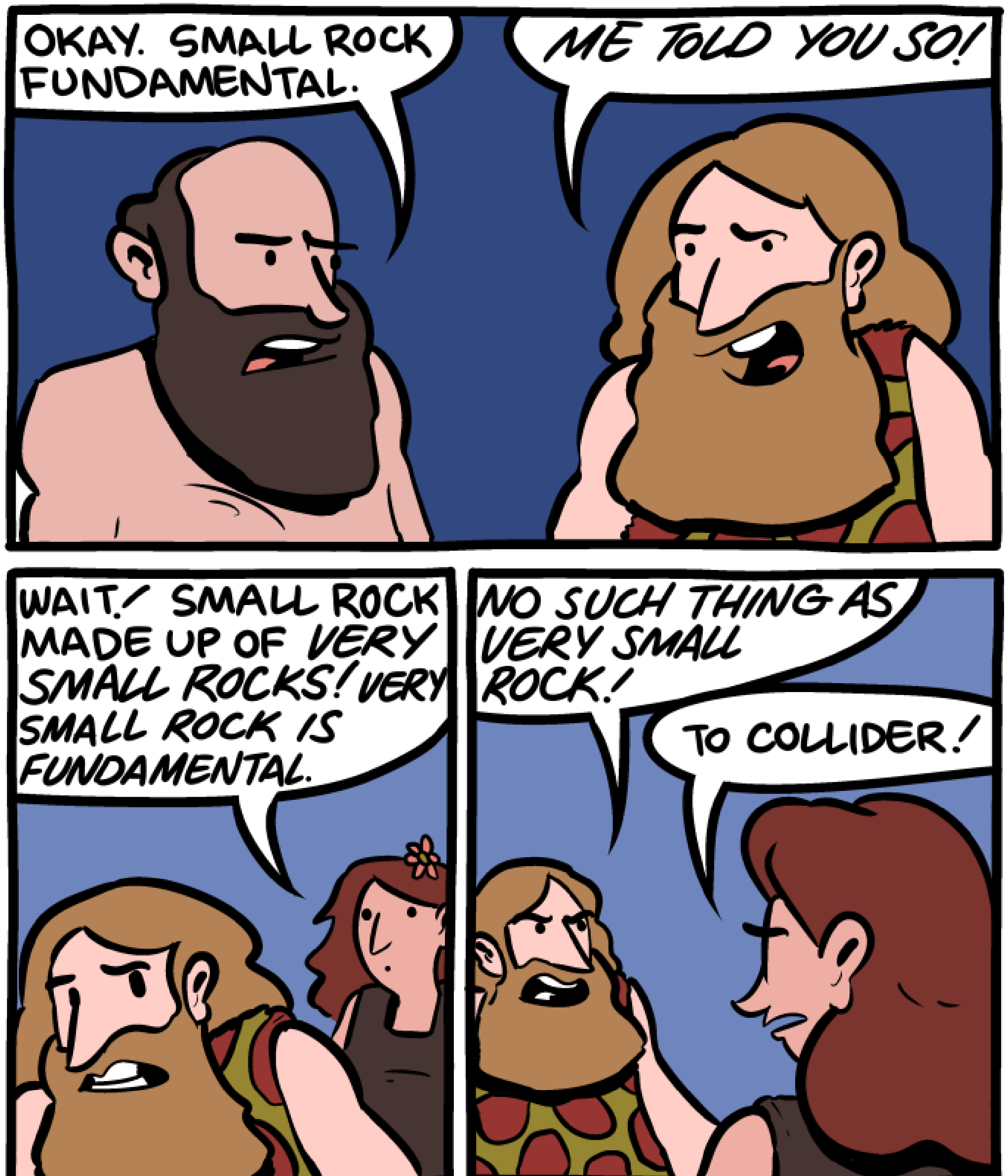
No historical accuracy is implied.



Fundamental Questions



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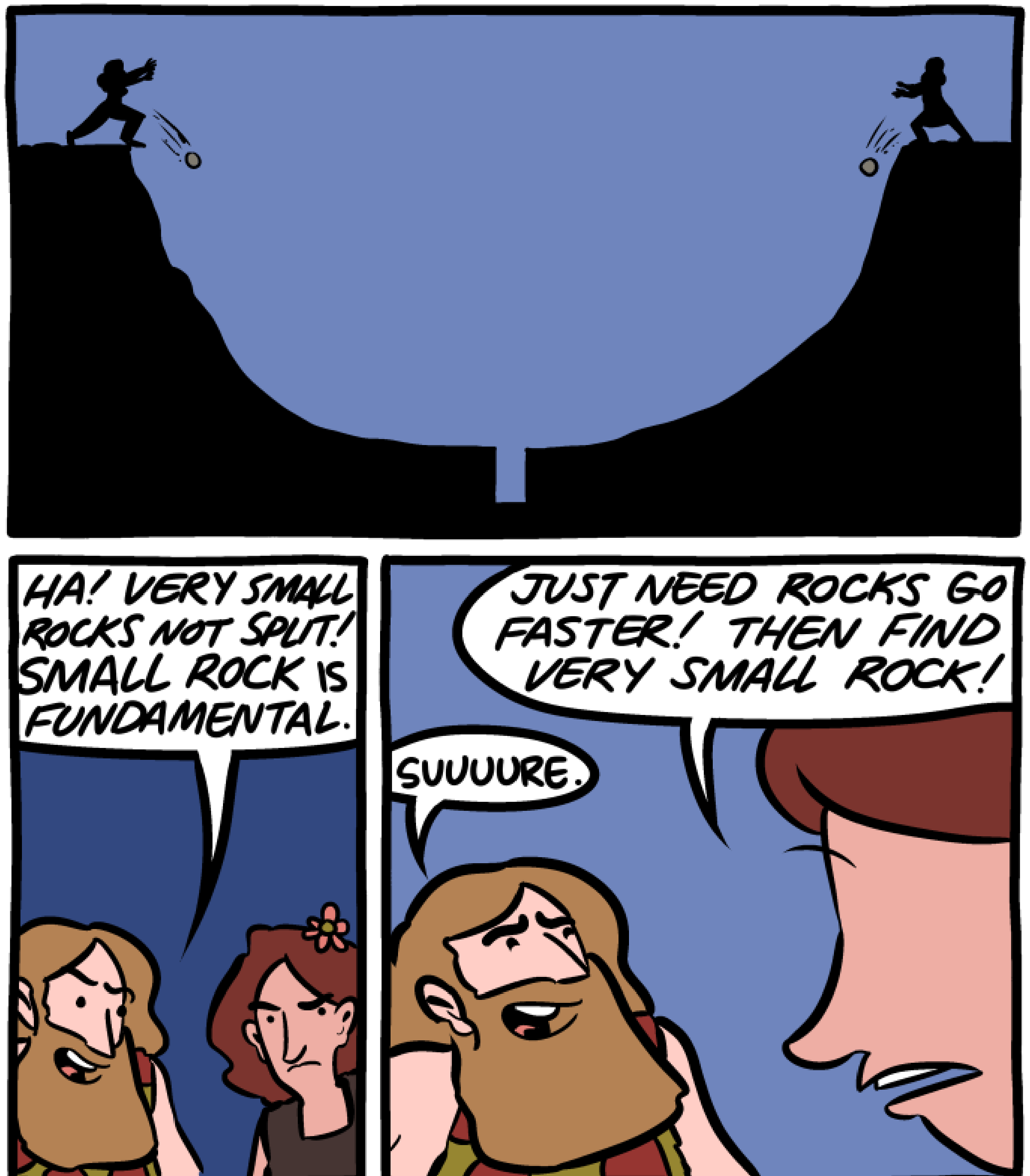
Fundamental Questions



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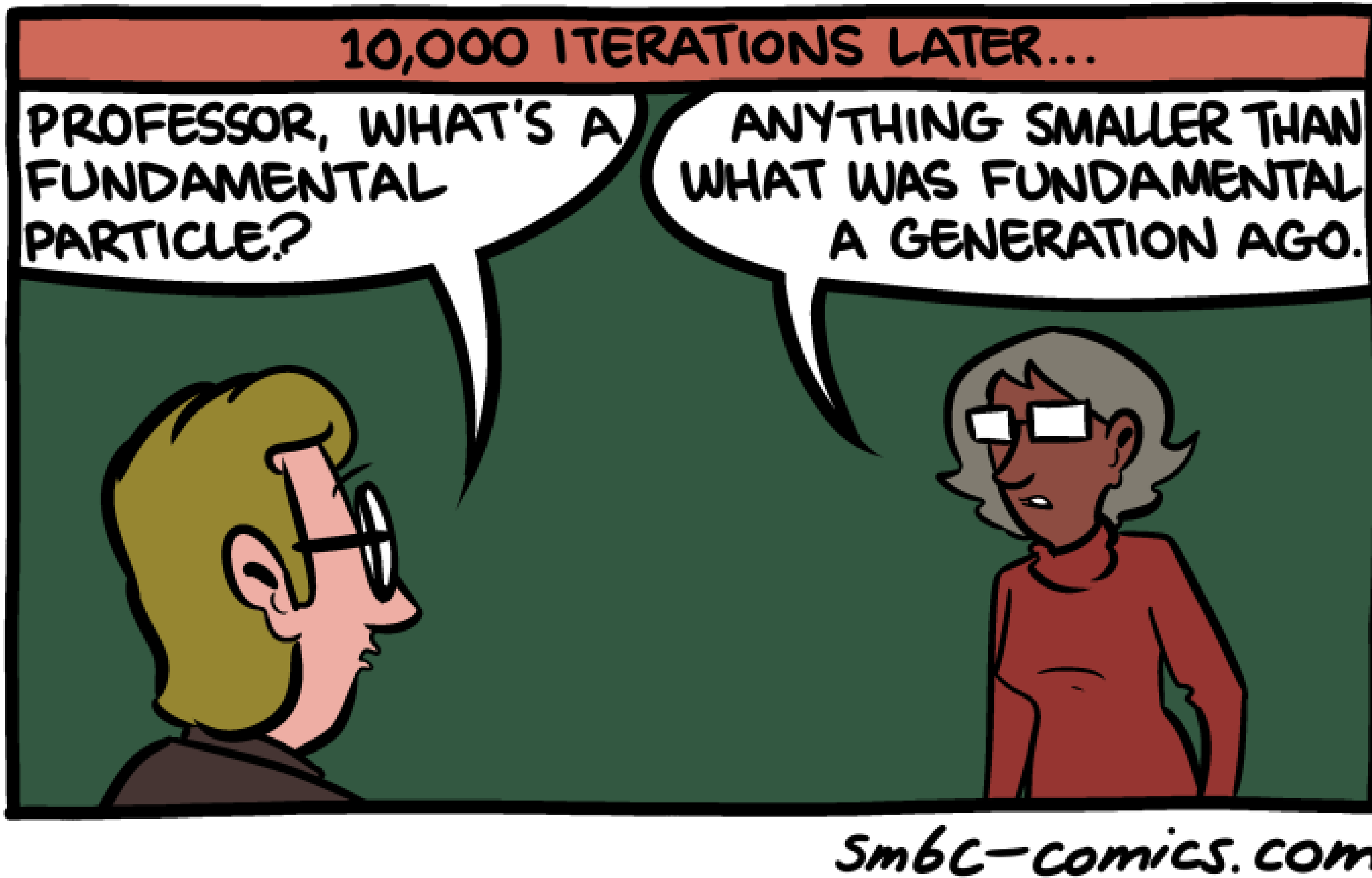
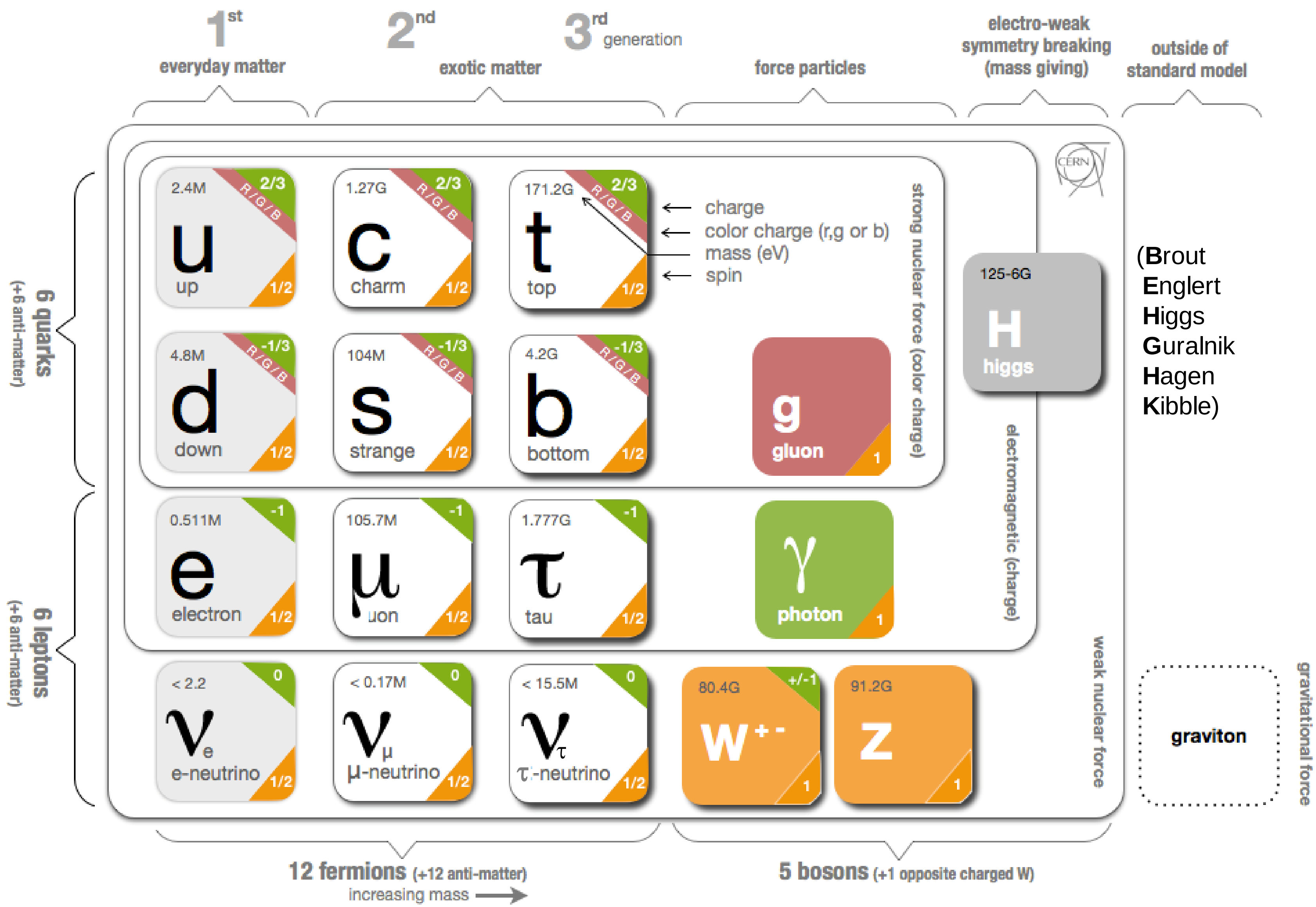
Fundamental Questions

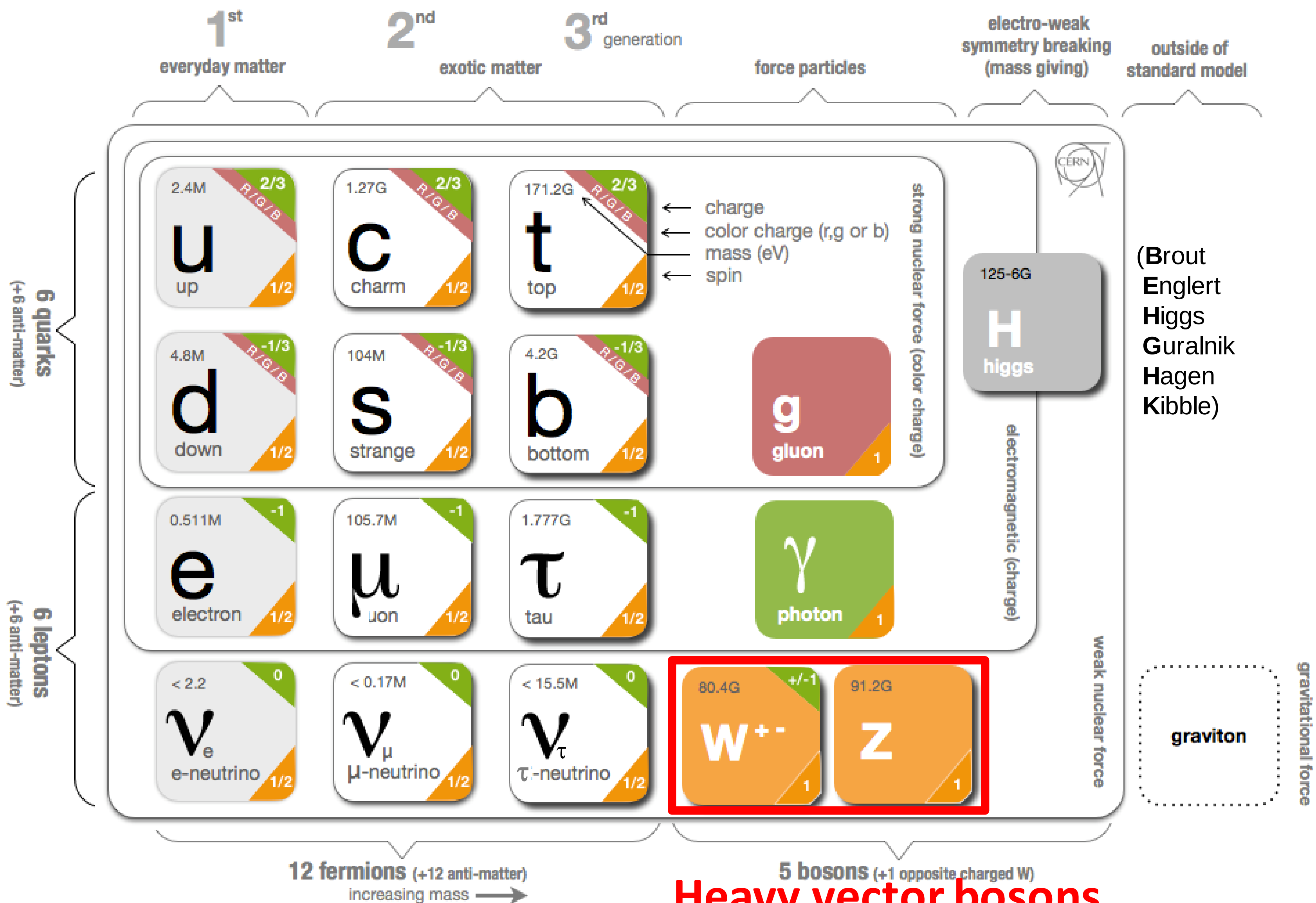


Building Blocks of Matter & their interactions



(**B**rout
Englert
Higgs
Guralnik
Hagen
Kibble)

Building Blocks of Matter & their interactions



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Heavy vector bosons

Higgs-Search until...

July 4th 2012: DISCOVERY!

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updated 10:42 AM EDT, Wed July 4, 2012

FERMILAB/DEPT. OF ENERGY

Scientists may have found 'God particle'

The Washington Post

84° Washington, DC | July 4, 2012 | Edition: U.S. | Regional | Make us your homepage

Scientists discover particle consistent with Higgs boson

Brian Vastag and Joel Achenbach

(Scientists listen to an update on the Higgs boson in Geneva. | Reuters)

Scientists announce the discovery of a particle theorized to be so fundamental that without it, nothing would exist.

- Why Higgs boson is a big deal | Photos: "God particle" hunt

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Erfolg bei Suche nach Higgs-Teilchen

„Eine wissenschaftliche Sensation"

Wissenschaftler im Teilchenforschungszentrum Cern in Genf glauben, das jahrzehntelang gesuchte Higgs-Teilchen gefunden zu haben. Monatelang war im weltgrößten Teilchenbeschleuniger danach gefahndet worden – jetzt liegen die bahnbrechenden Ergebnisse vor. Mehr › 41 15

Higgs: Jagd nach einem Phantom ›

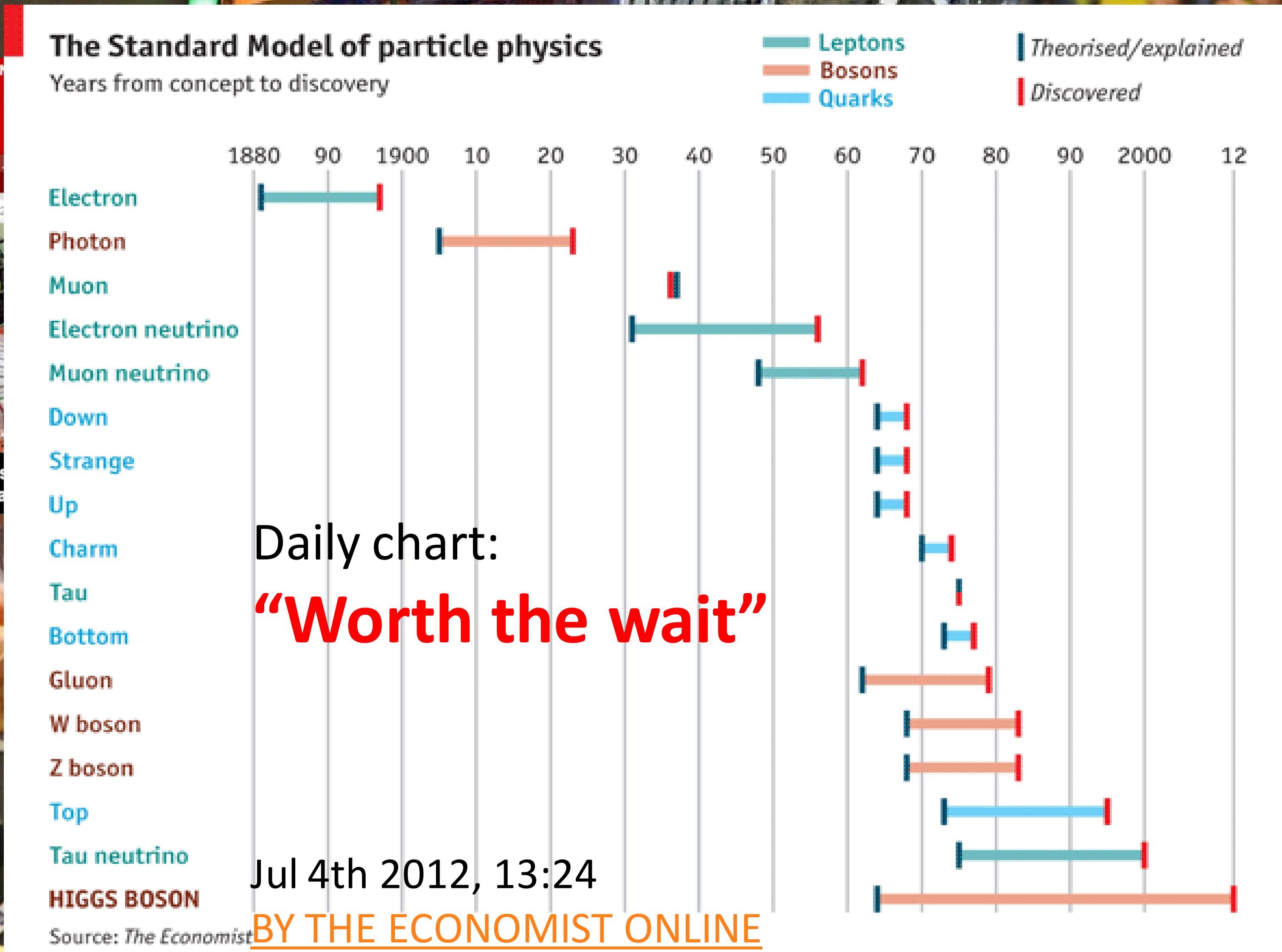
Nobelpreisträger im Interview

„Ich denke, wir haben es"

Die Entdeckung des Higgs-Teilchens ist ein historischer Moment auch für vier Nobelpreisträger, die mit der F.A.Z. auf der Nobelpreisträger-Tagung in Lindau gesprochen haben. Sehen Sie ihre Erläuterungen im Video. Mehr ›

July 4th 2012: DISCOVERY!

July 4th 2012: DISCOVERY!



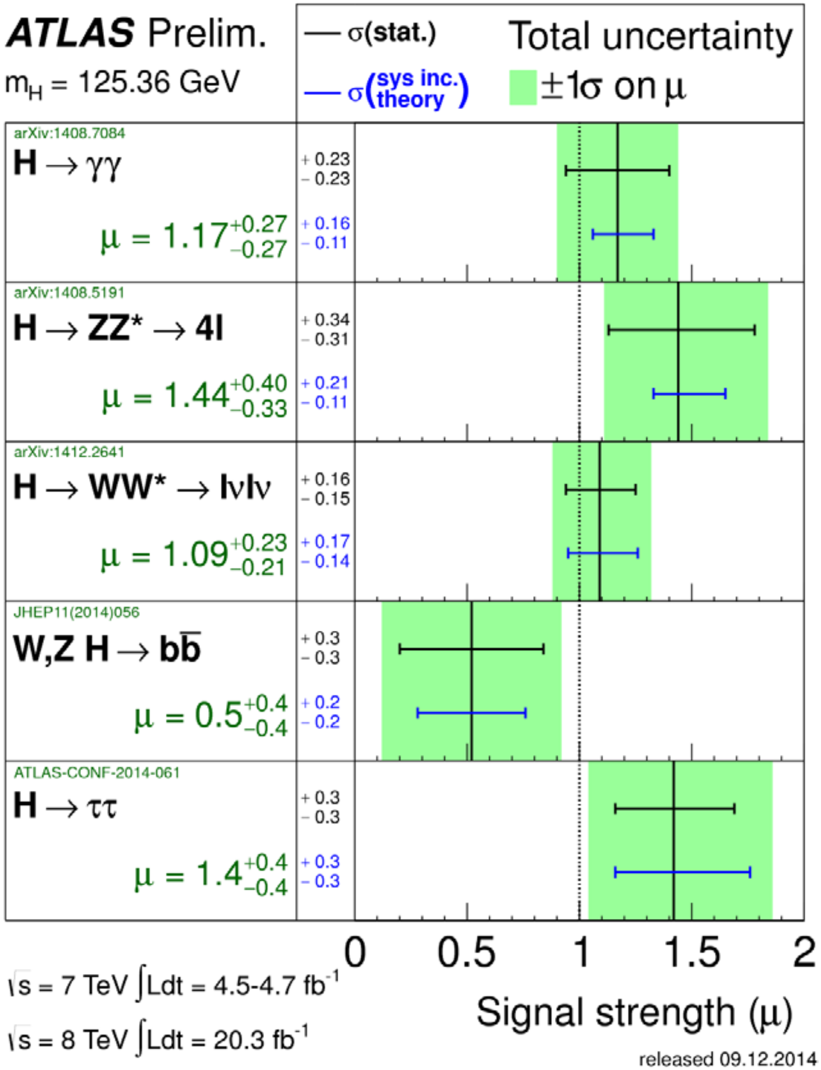
Daily chart:

"Worth the wait"

Jul 4th 2012, 13:24

BY THE ECONOMIST ONLINE

Back to work…



ATLAS Prelim.
m_H = 125.36 GeV
σ(stat.)
σ(sys inc. theory)
Total uncertainty
±1σ on μ
arXiv:1408.7084
H → γγ
μ = 1.17 +0.27 −0.27
+0.23 −0.23
+0.16 −0.11
arXiv:1408.5191
H → ZZ* → 4l
μ = 1.44 +0.40 −0.33
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JHEP11(2014)056
W,Z H → bb̄
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+0.3 −0.3
+0.2 −0.2
ATLAS-CONF-2014-061
H → ττ
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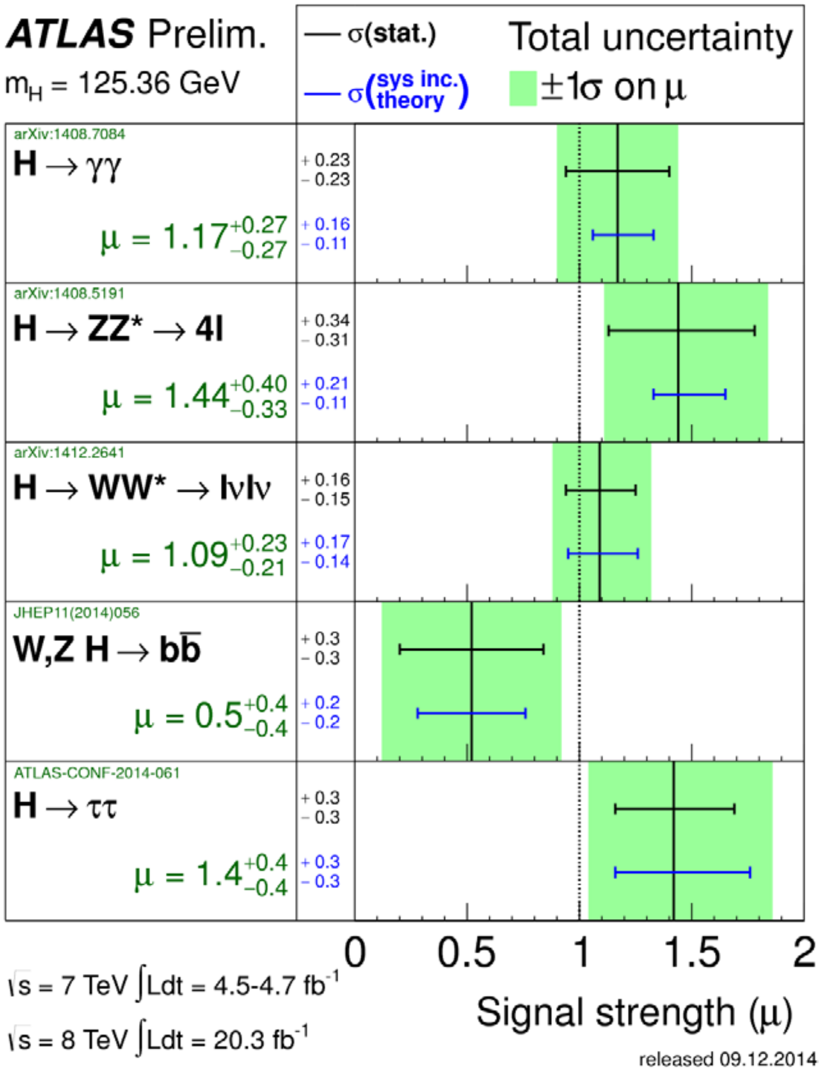
+0.3 −0.3
+0.3 −0.3
0
0.5
1
1.5
2
Signal strength (μ)
√s = 7 TeV ∫Ldt = 4.5-4.7 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
released 09.12.2014

Back to work…



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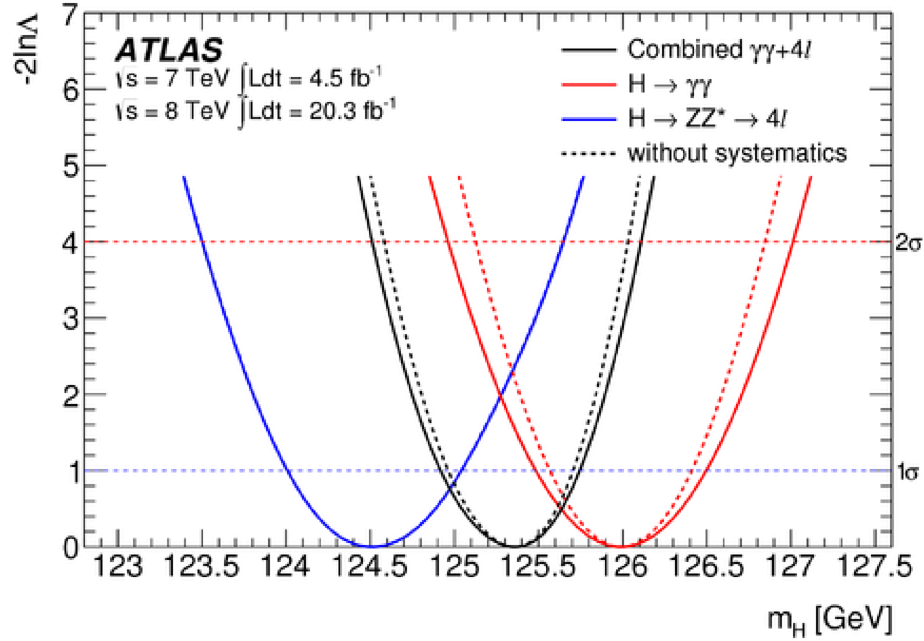

ATLAS
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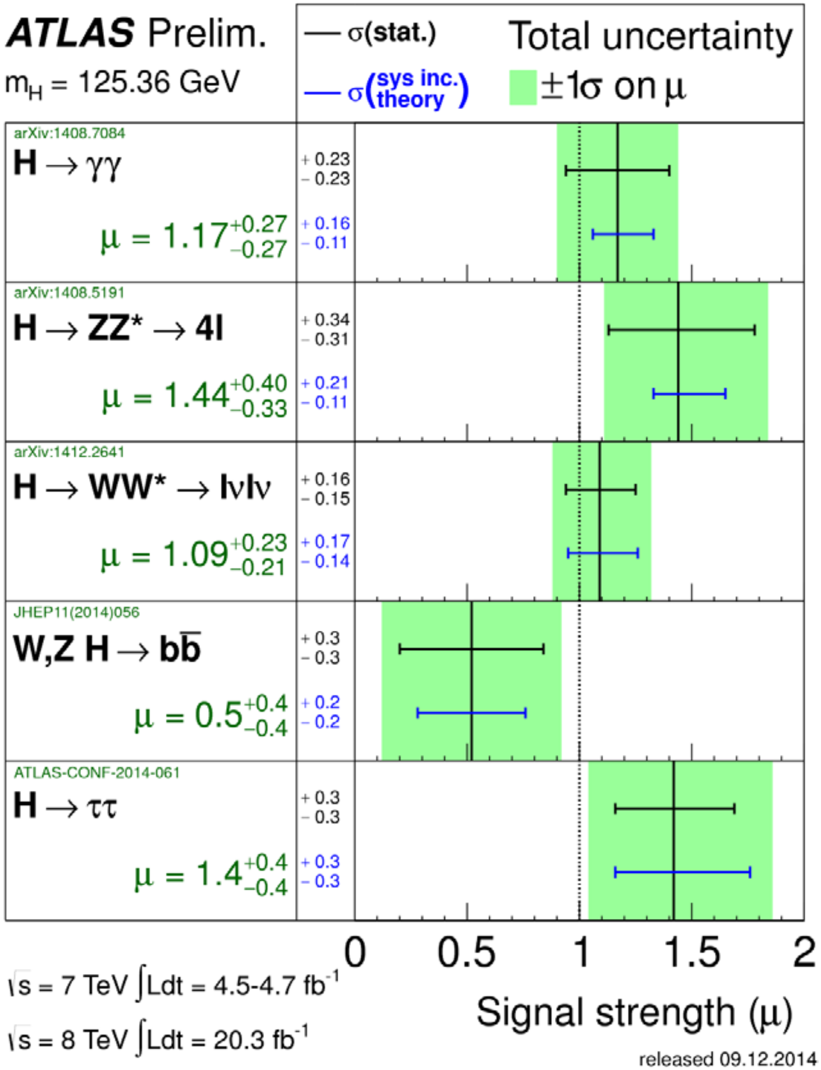
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
Combined γγ+4l
H → γγ
H → ZZ* → 4l
without systematics
-2lnΛ
2σ
1σ
123 123.5 124 124.5 125 125.5 126 126.5 127 127.5
m_H [GeV]

Back to work…



[PRD 90, 052004 (2014)]

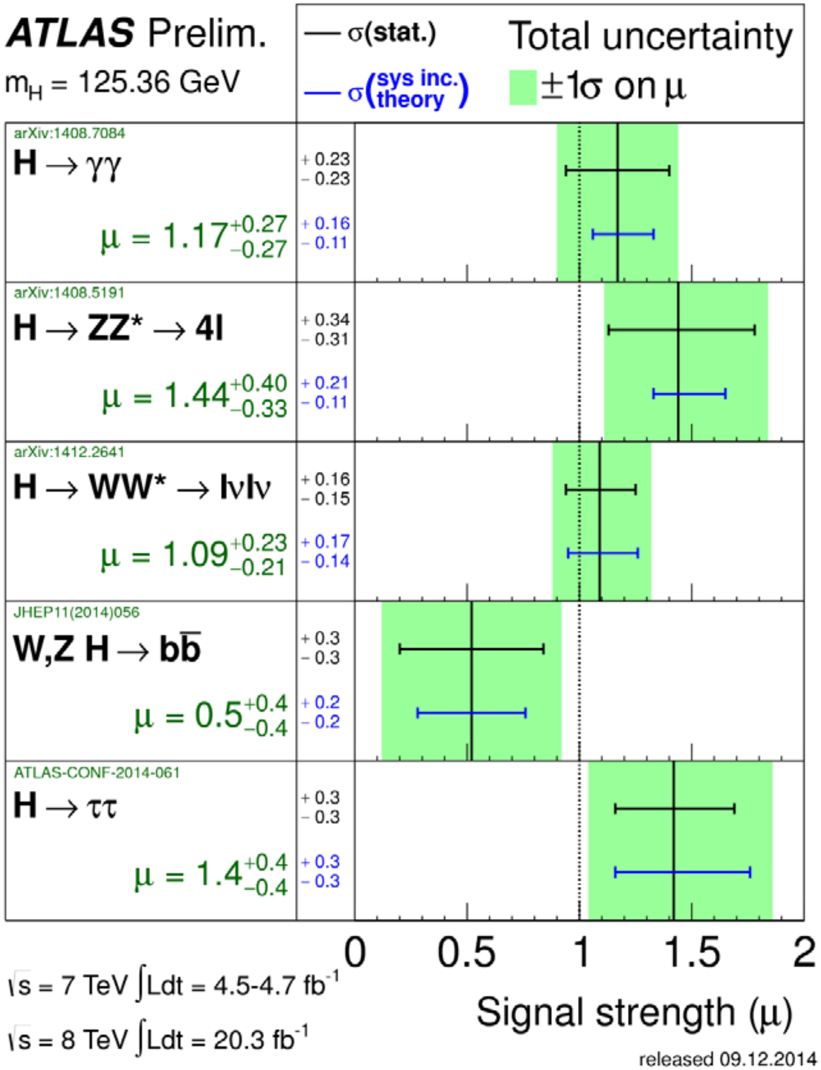
$$m_H^{\gamma\gamma} = 125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{syst})\ \text{GeV}$$

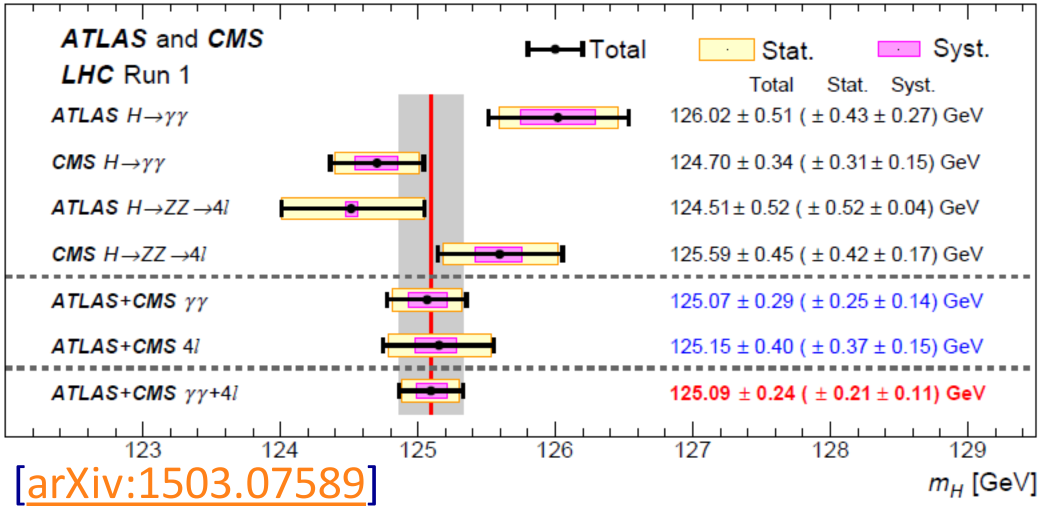
$$m_H^{ZZ^*} = 124.51 \pm 0.52\ (\text{stat}) \pm 0.06\ (\text{syst})\ \text{GeV}$$

$$\Delta m_H = \quad 1.47 \pm 0.67\ (\text{stat}) \pm 0.28\ (\text{syst})\ \text{GeV}$$

$$m_H^{\text{comb}} = 125.36 \pm 0.37\ (\text{stat}) \pm 0.18\ (\text{syst})\ \text{GeV}$$

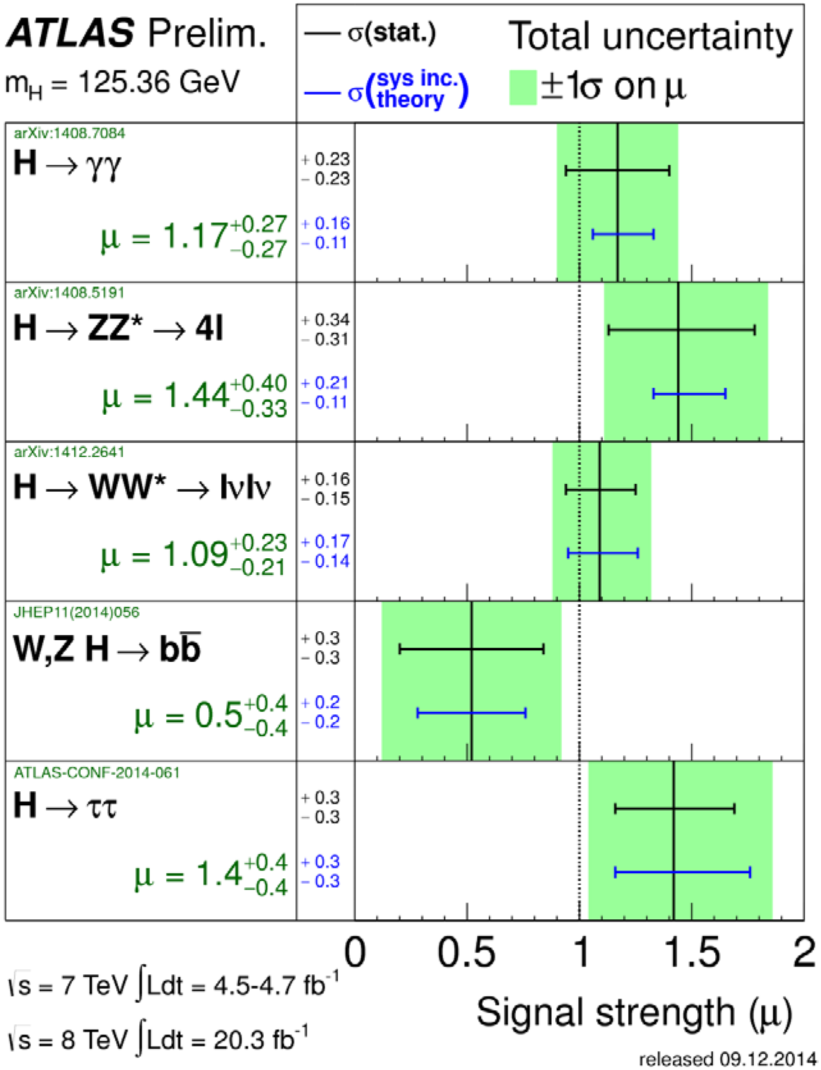
Back to work…

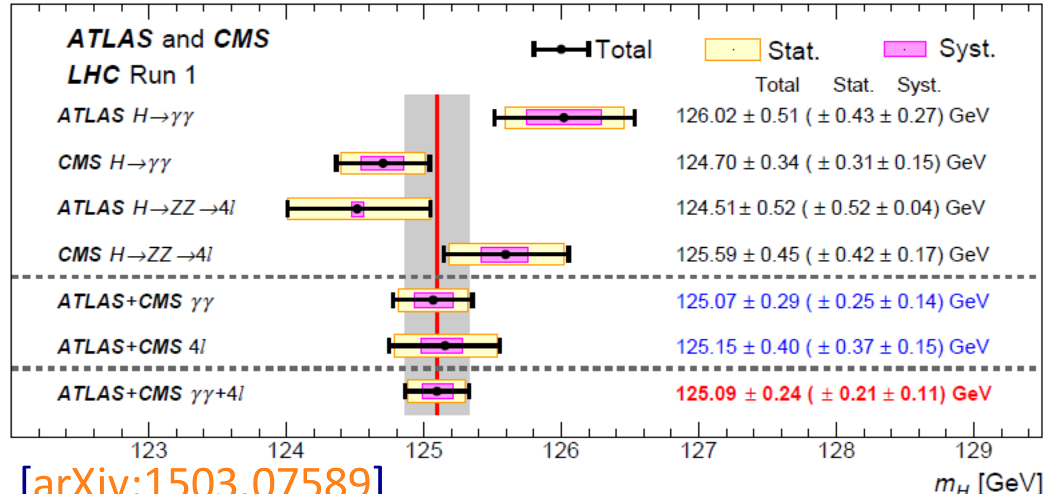




[arXiv:1503.07589]

Back to work…





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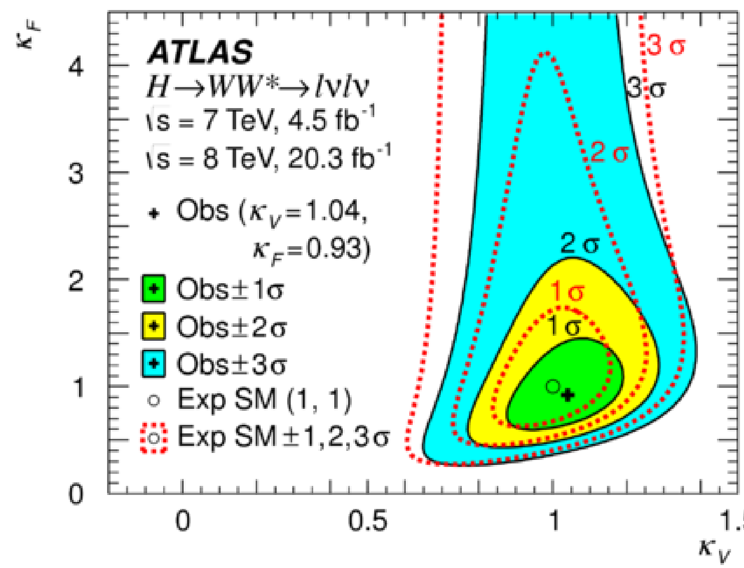
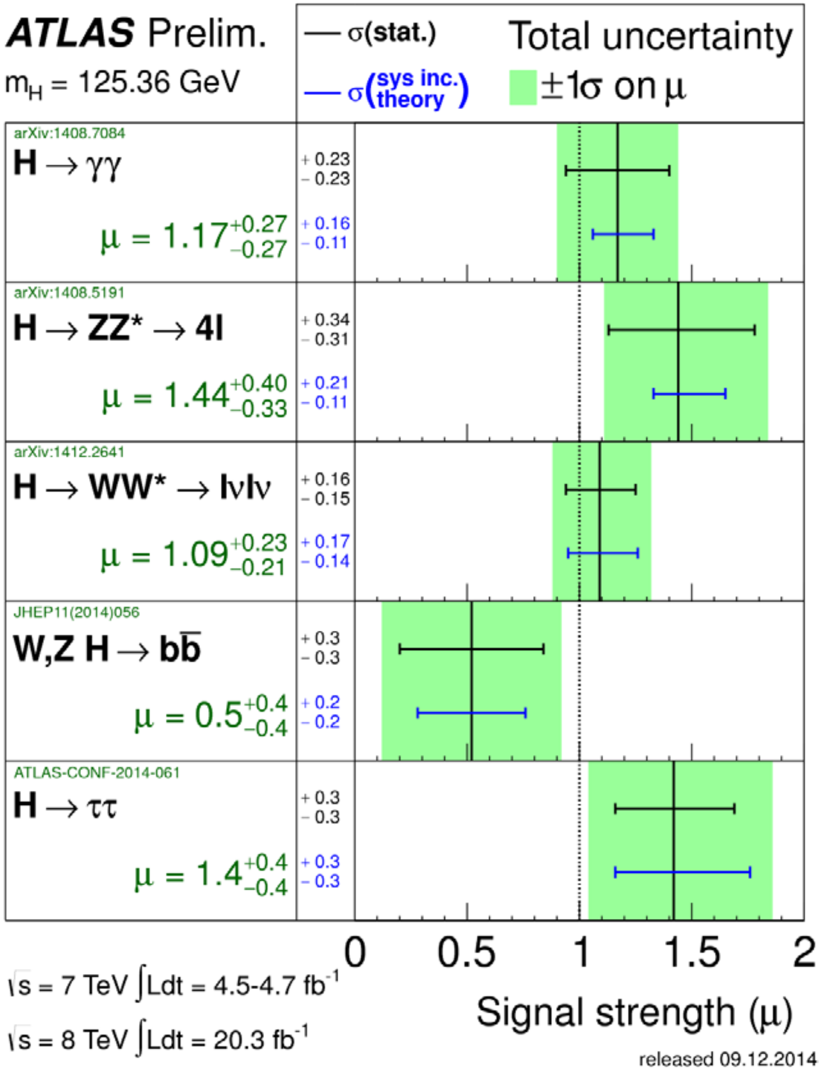
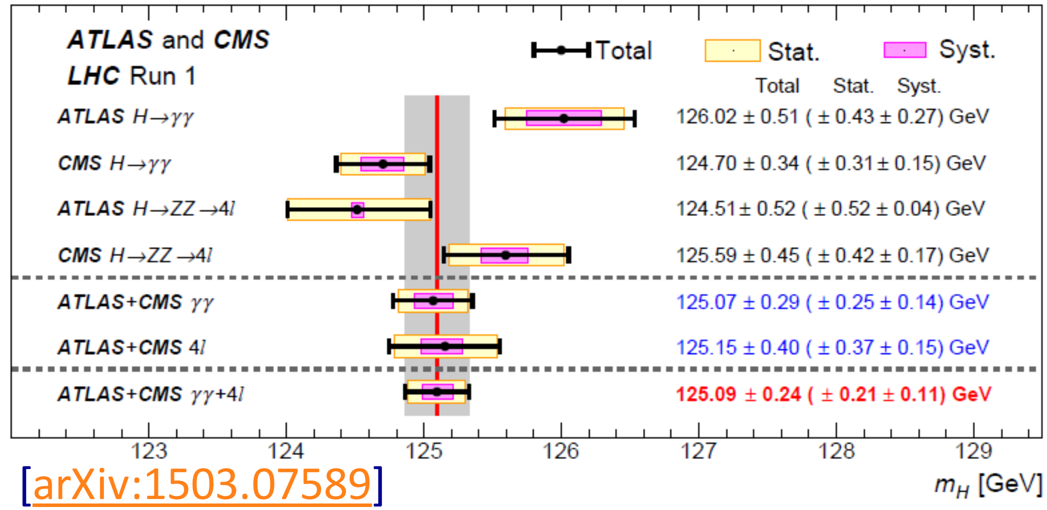


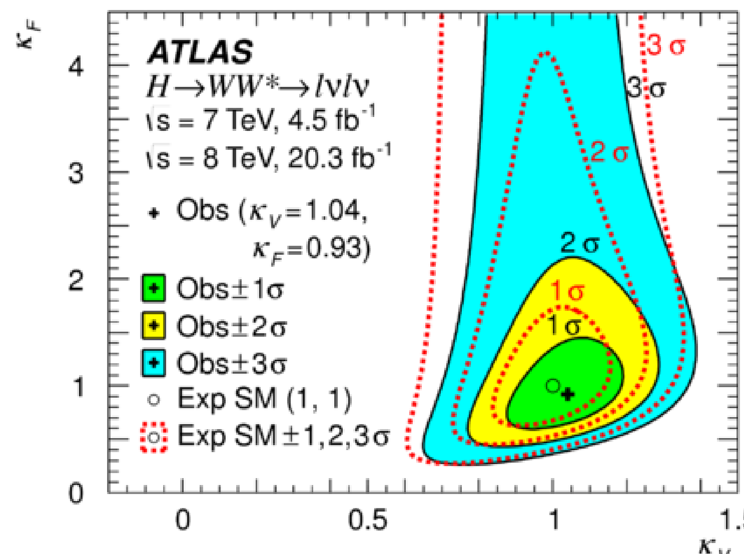
[arXiv:1412.2641]

Back to work…





[arXiv:1503.07589]



[arXiv:1412.2641]

- Test of spin/parity J^P using angular distributions: 0^+ vs. 0^-, 1^+, 1^-, 2^+ : compatible with SM expectation (0^+). [PLB 726 (2013) 120]

Is it "THE" Higgs?

- Does the Higgs play by the "Standard Model Rule-Book"?
- Can depict particle interactions in simple pictures: "Feynman diagrams". **The cast:**


Quarks (q), electrons, muons, …


Photon (γ), W & Z bosons


Gluon (g)


Higgs (H)

- The Standard Model of particle physics dictates how above lines can be put together: who can interact with whom?

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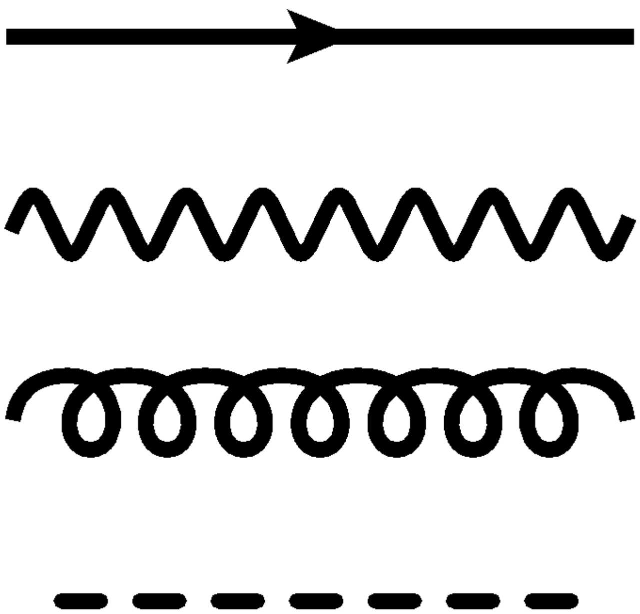

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Heavy vector bosons

Gluon (g)

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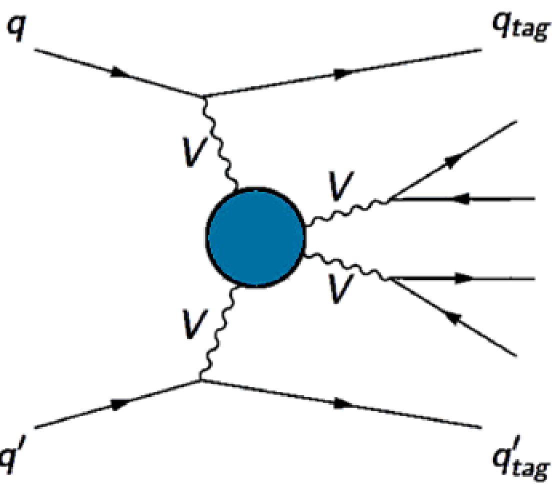
Vector Boson Scattering



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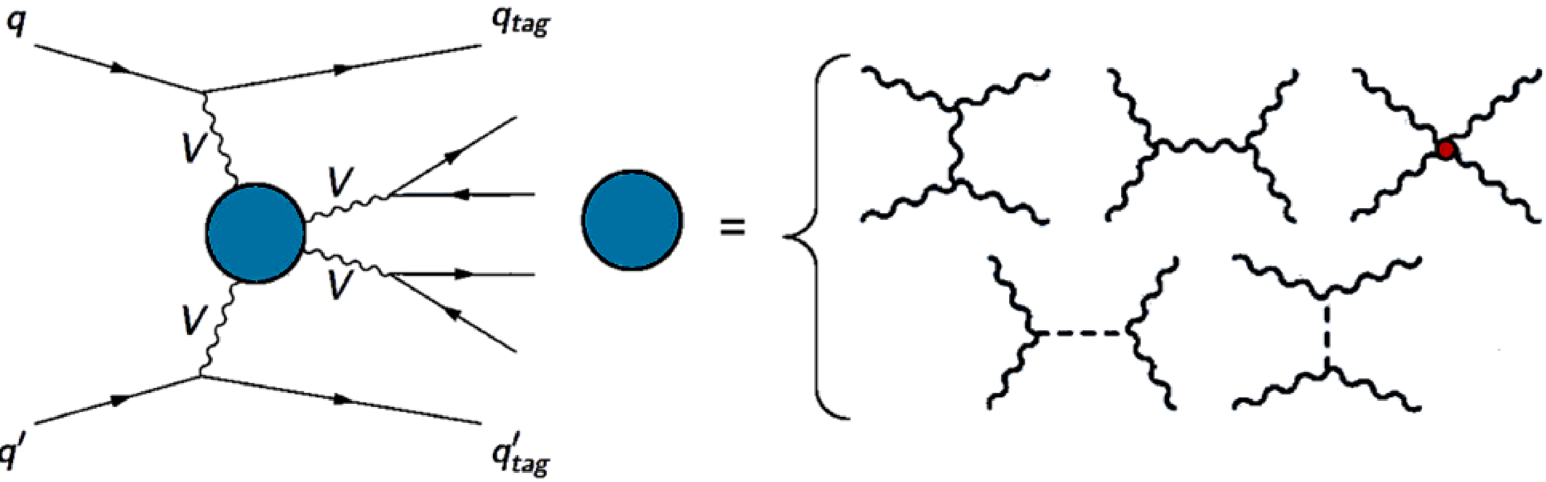

V=W/Z self-interactions

V-Higgs interactions

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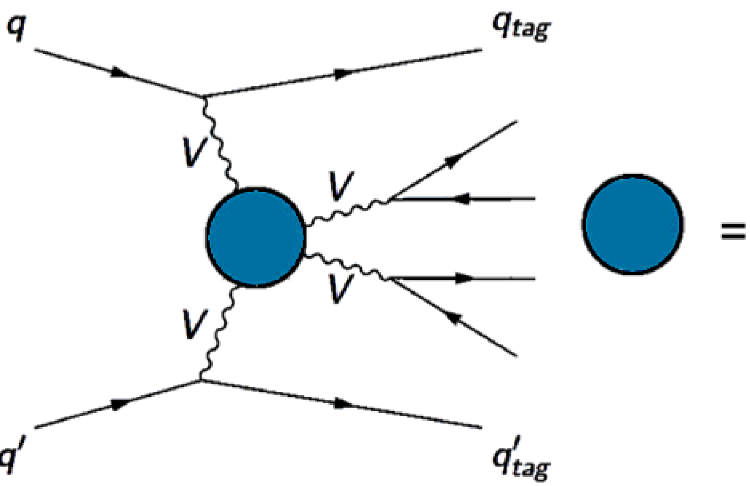
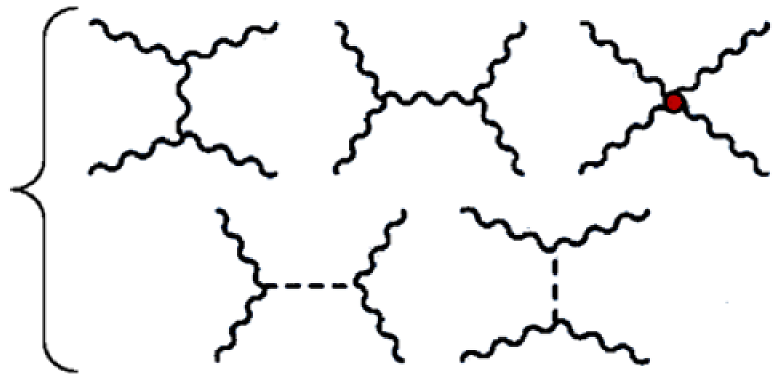
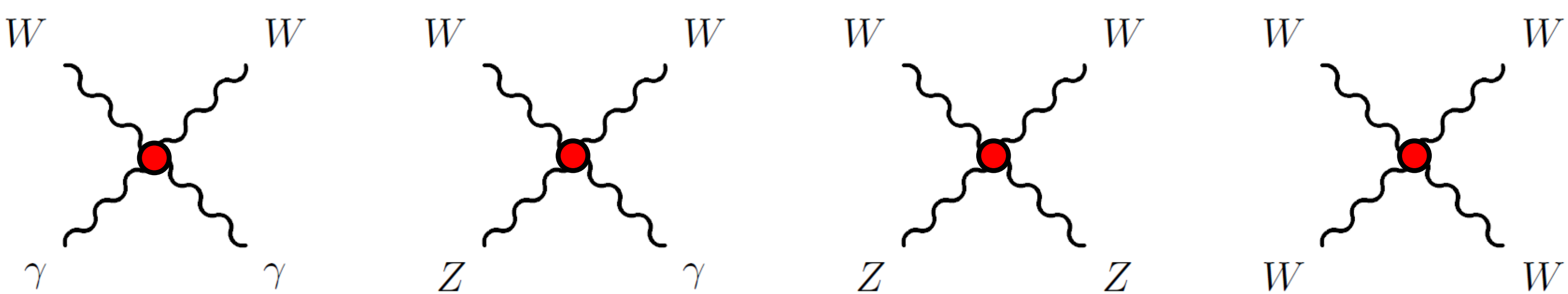




V=W/Z self-interactions

V-Higgs interactions

- **Quartic self-interactions of W/Z never observed before – untested territory!**



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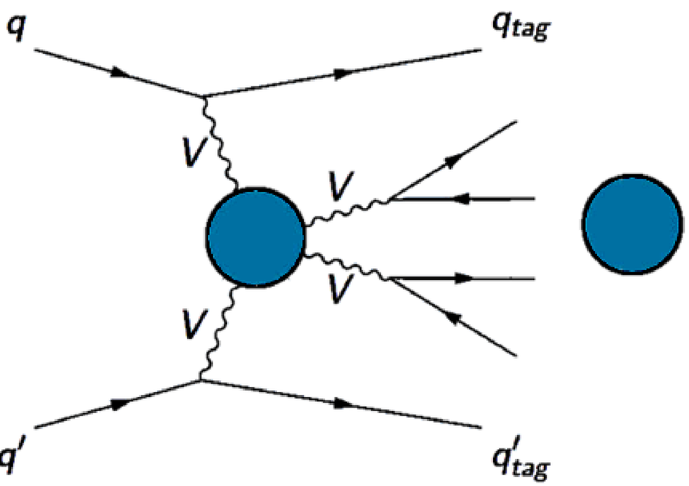

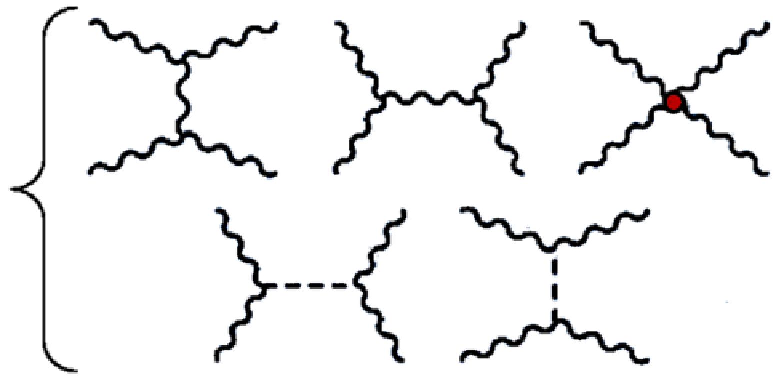

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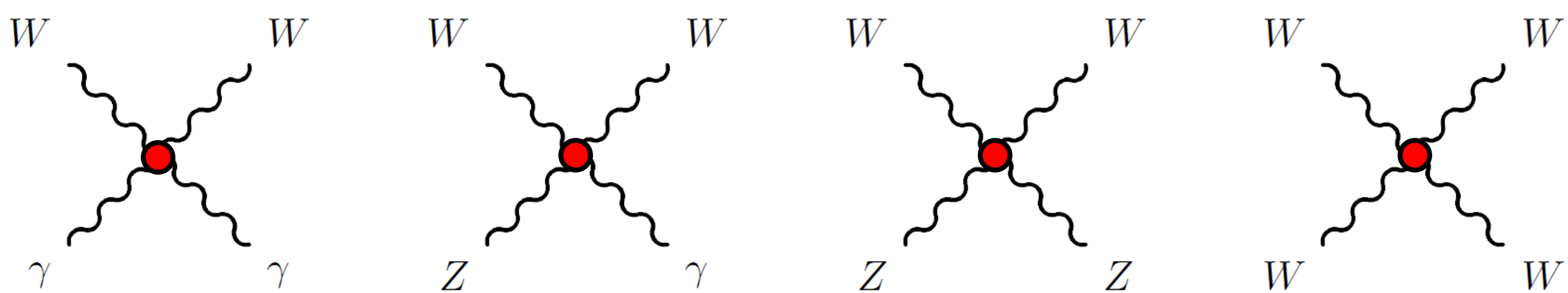
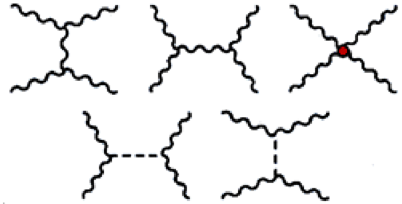


- ❖ Quartic self interactions just involving γ/Z forbidden…

Why the Higgs part matters

- ❖ No Higgs: 

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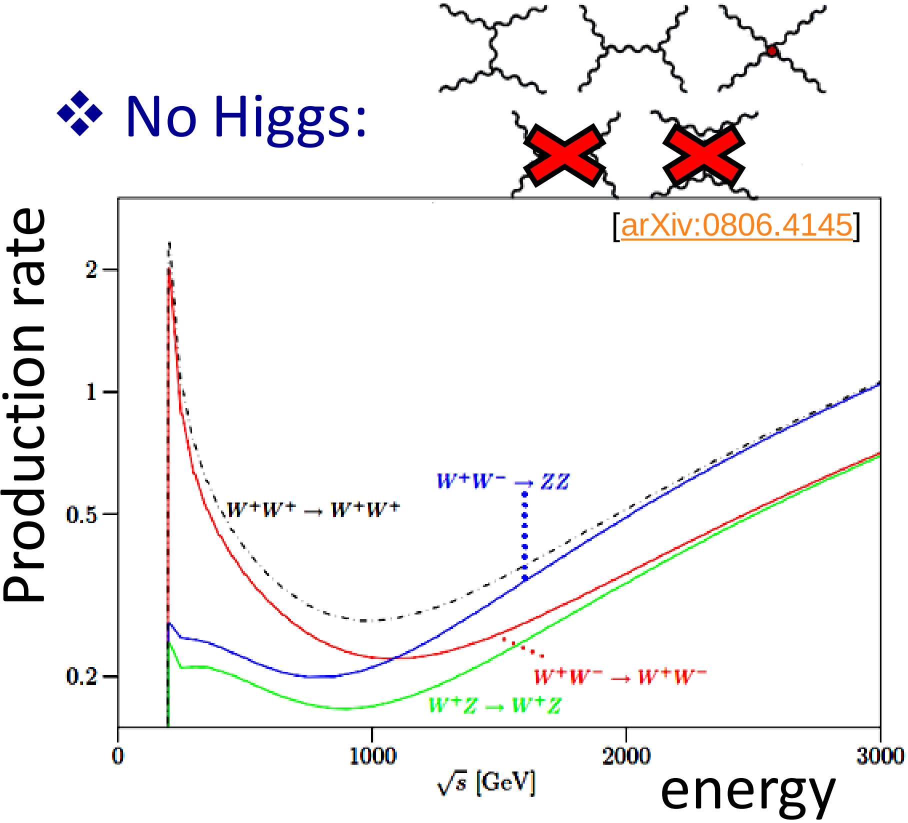

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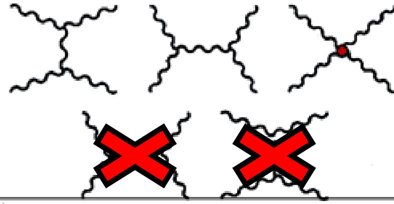

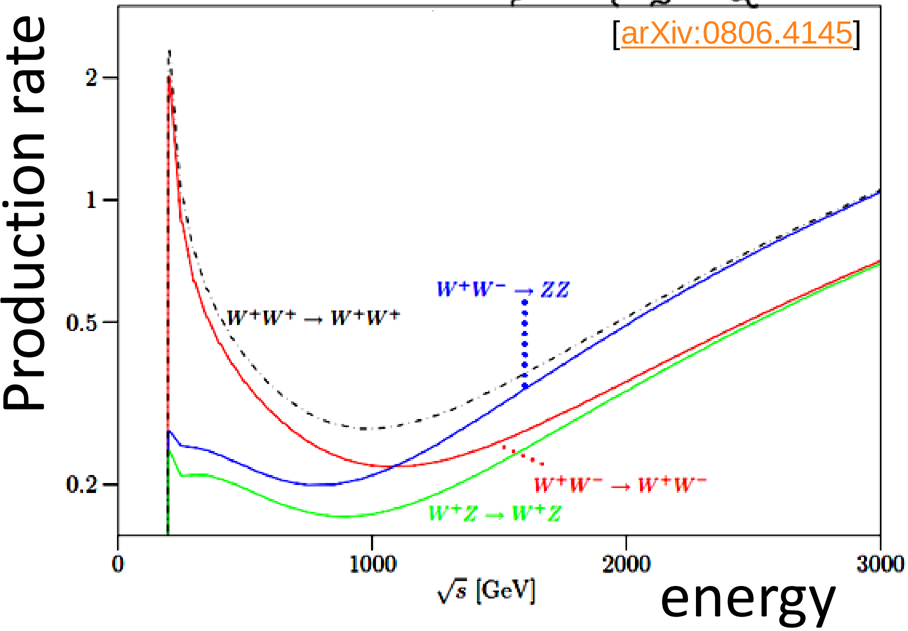

- Production rate **in**creases with energy

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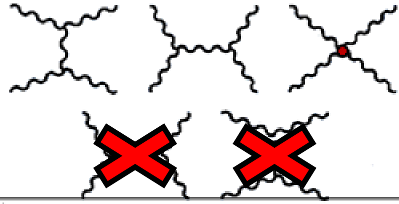

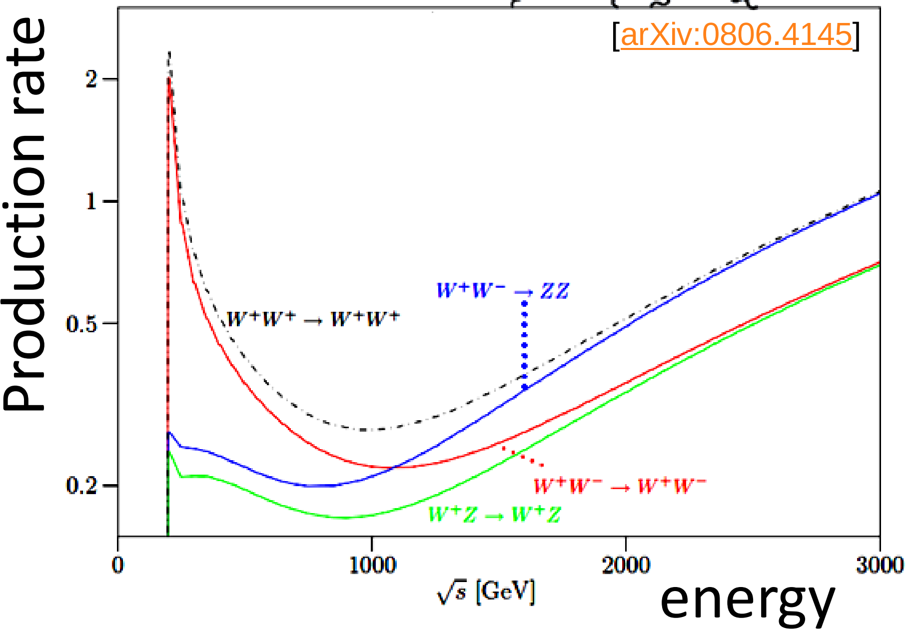

❖ Production rate **in**creases with energy

❖ Probabilities > 1 at high energies

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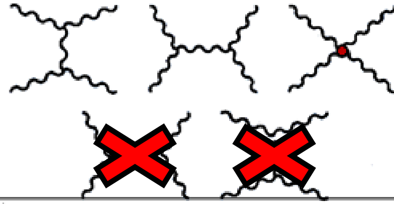

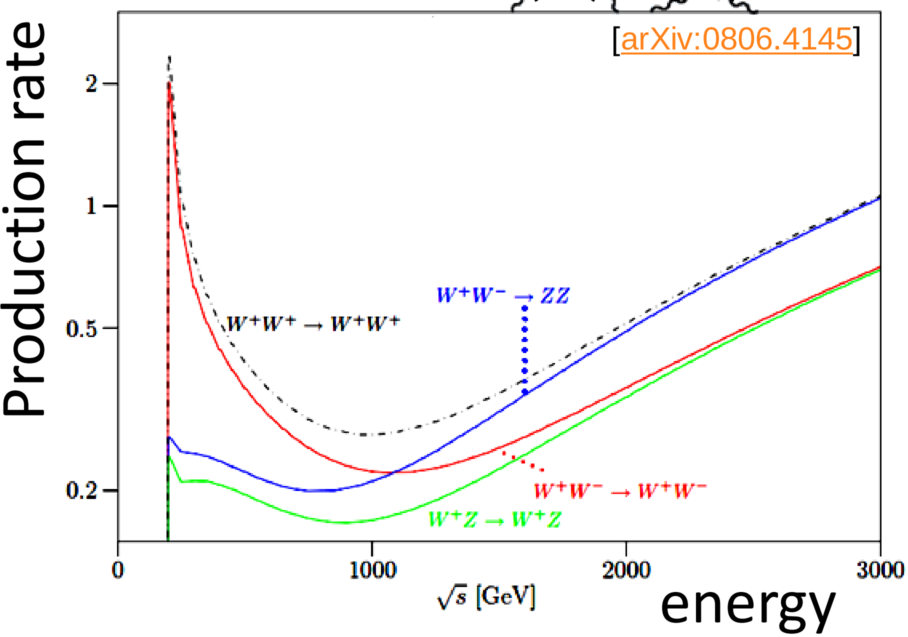

- Production rate **in**creases with energy
- Probabilities > 1 at high energies
- Standard Model breaks down!

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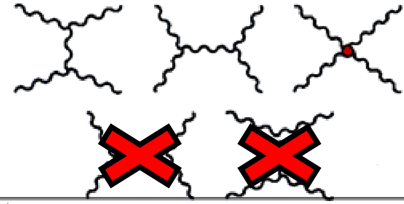

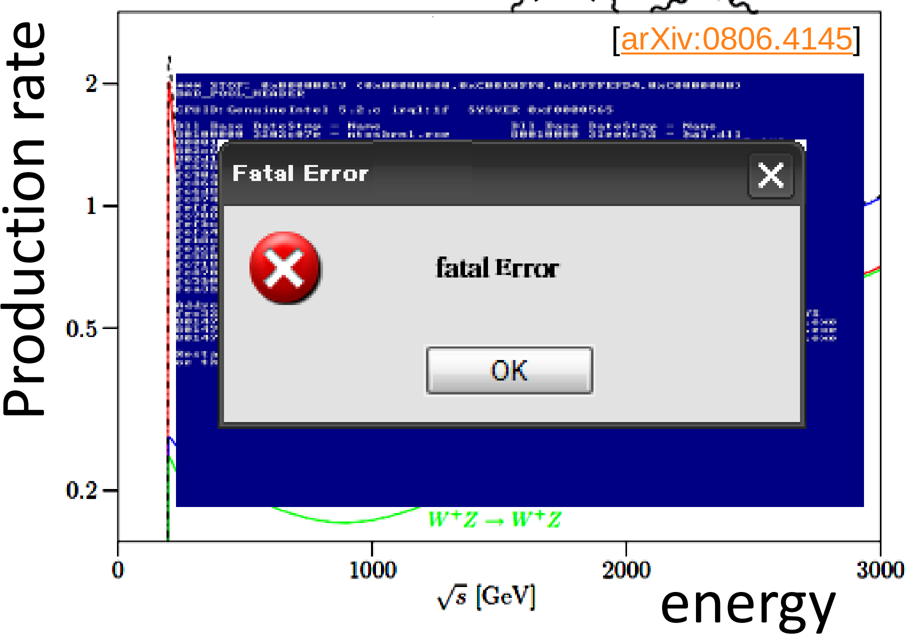

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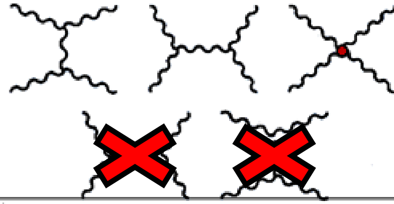

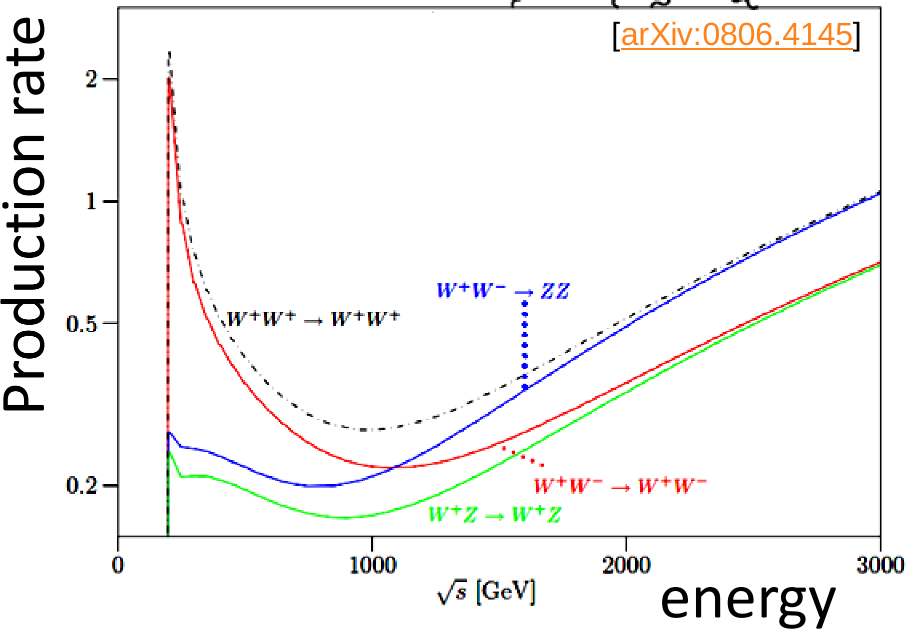

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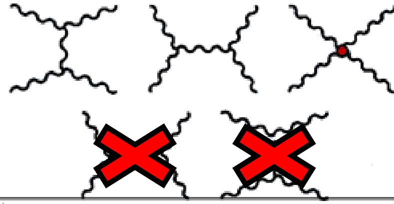

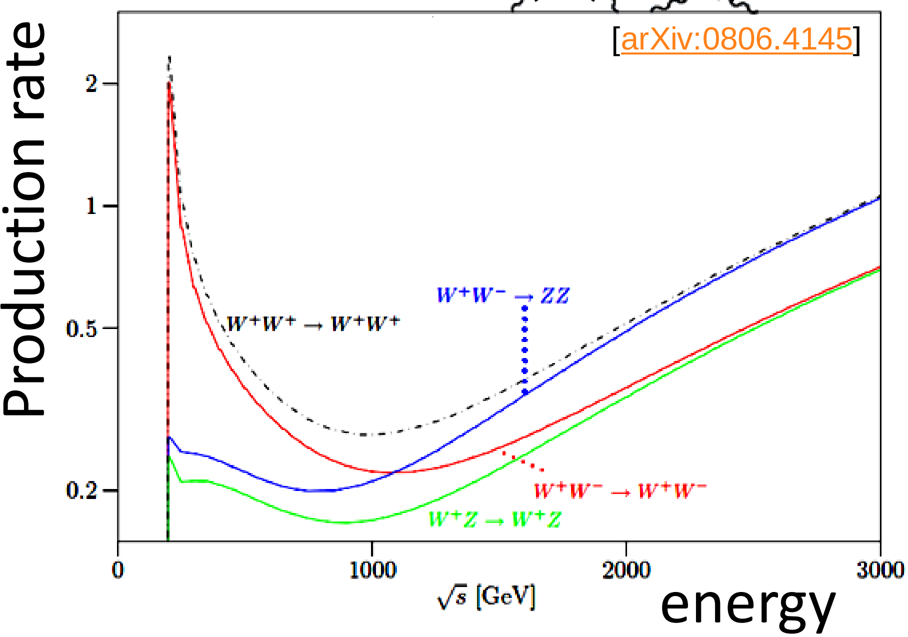

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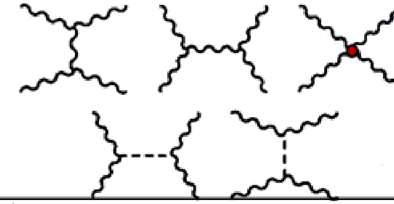

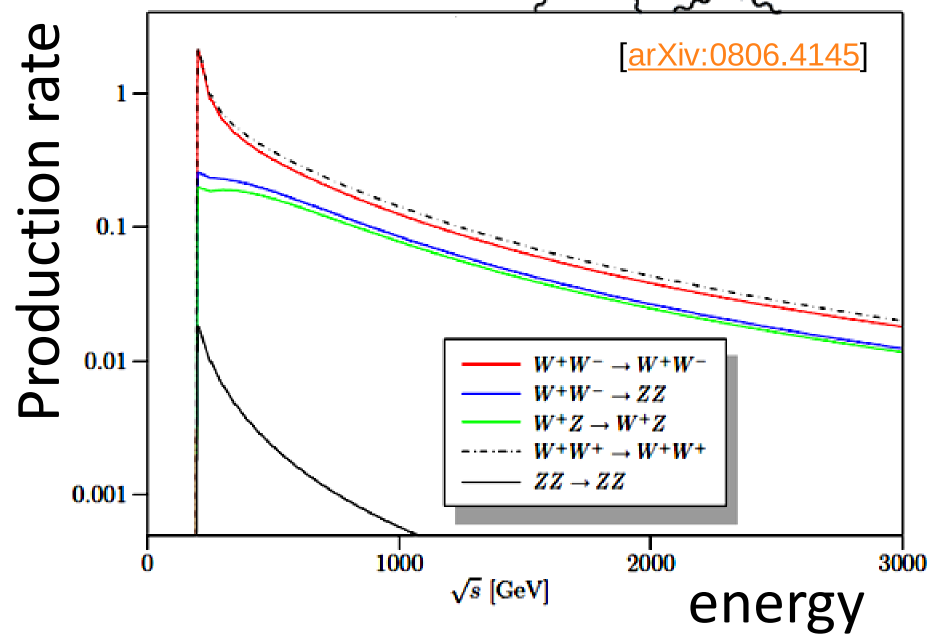

❖ Production rate **in**creases with energy

❖ Probabilities > 1 at high energies

❖ Standard Model breaks down!

❖ Production rate **de**creases with energy

❖ Probabilities < 1 for all energies

❖ Standard Model alive & kicking!

Why the Higgs part matters

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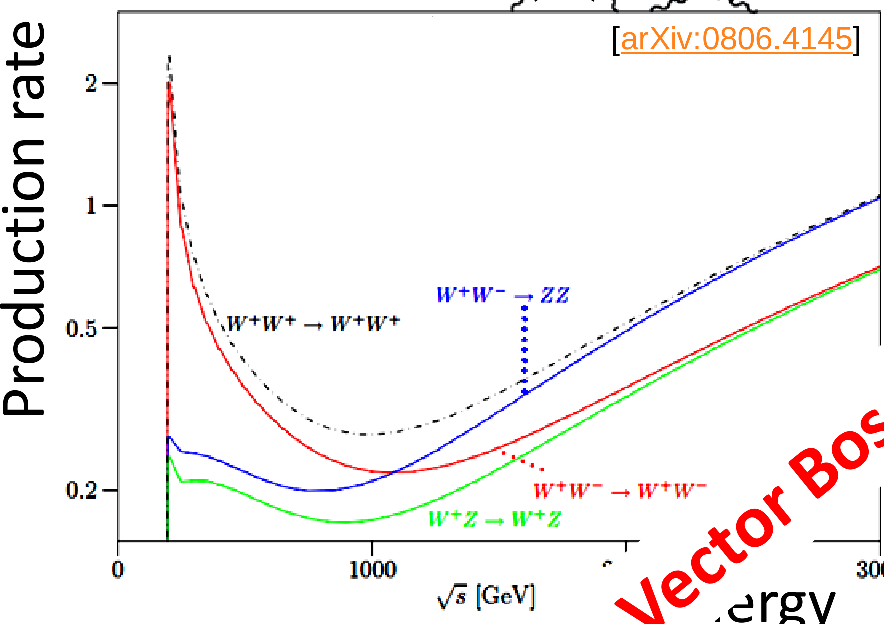
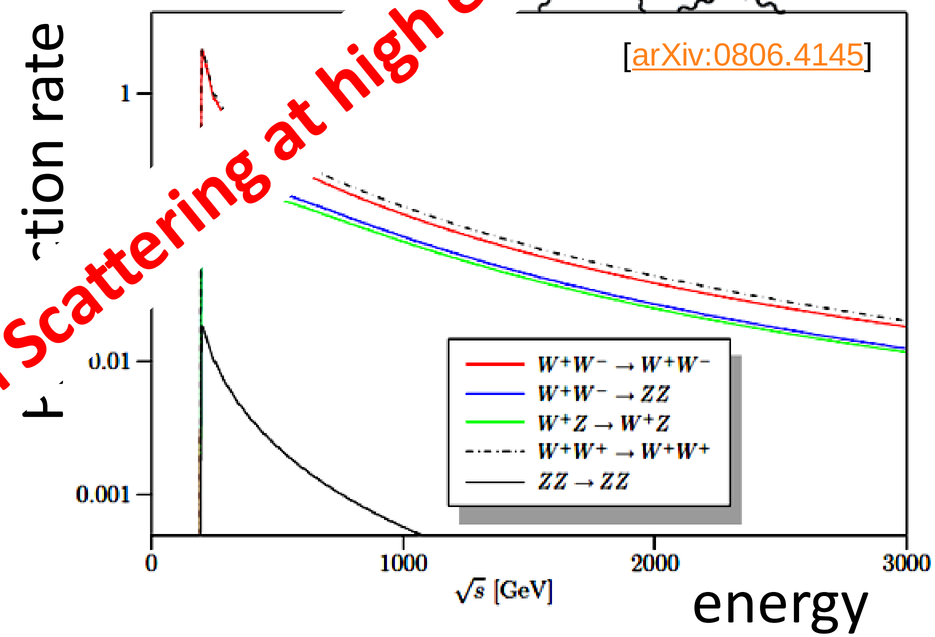


- With Higgs:



Need to measure Vector Boson Scattering at high energies!

- Production ra eases with energy
- Proba > 1 at high energies
- St d Model breaks down!

- Production rate **de**creases with energy
- Probabilities < 1 for all energies
- Standard Model alive & kicking!

How?

The Large Hadron Collider (LHC)

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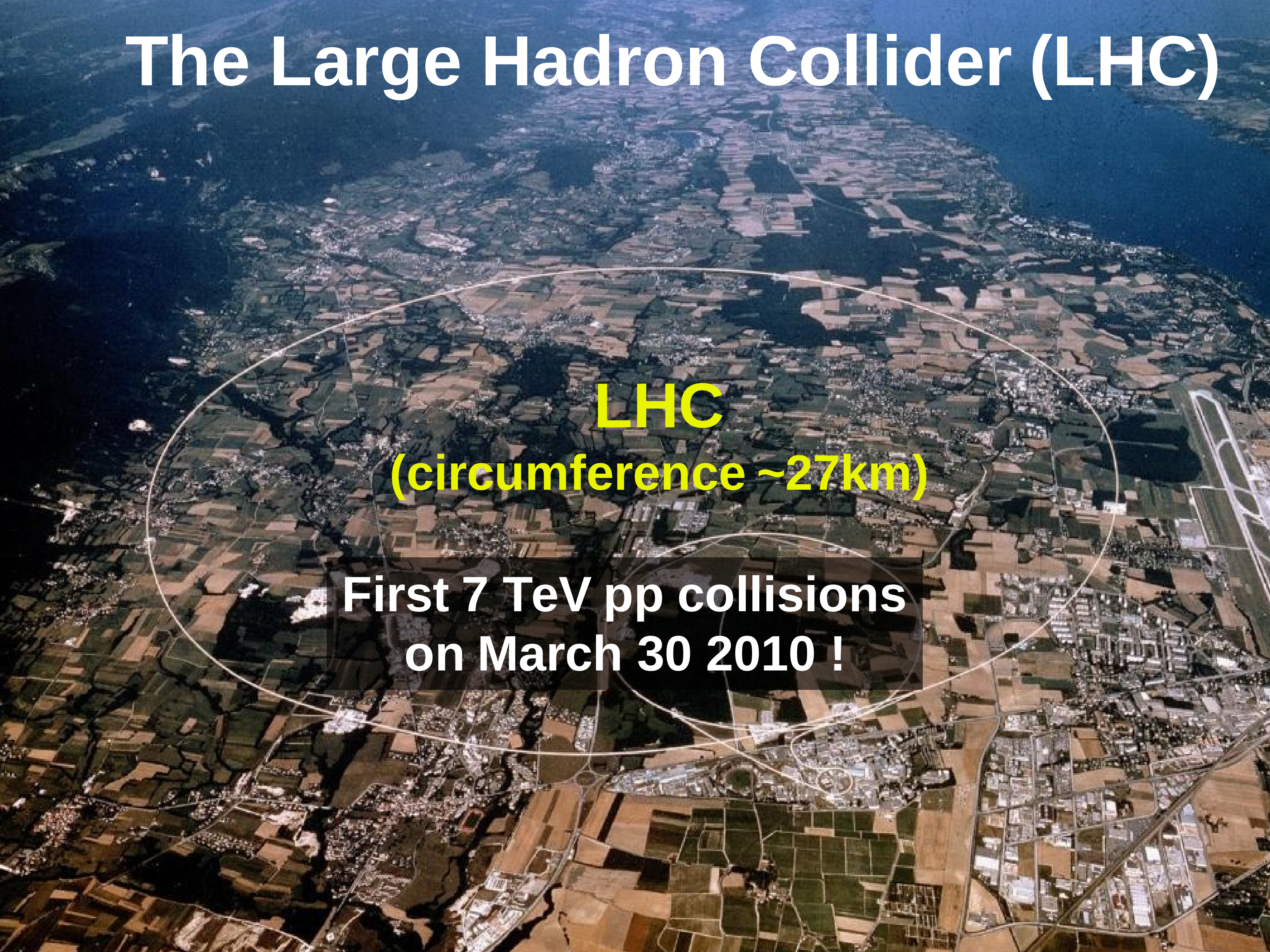

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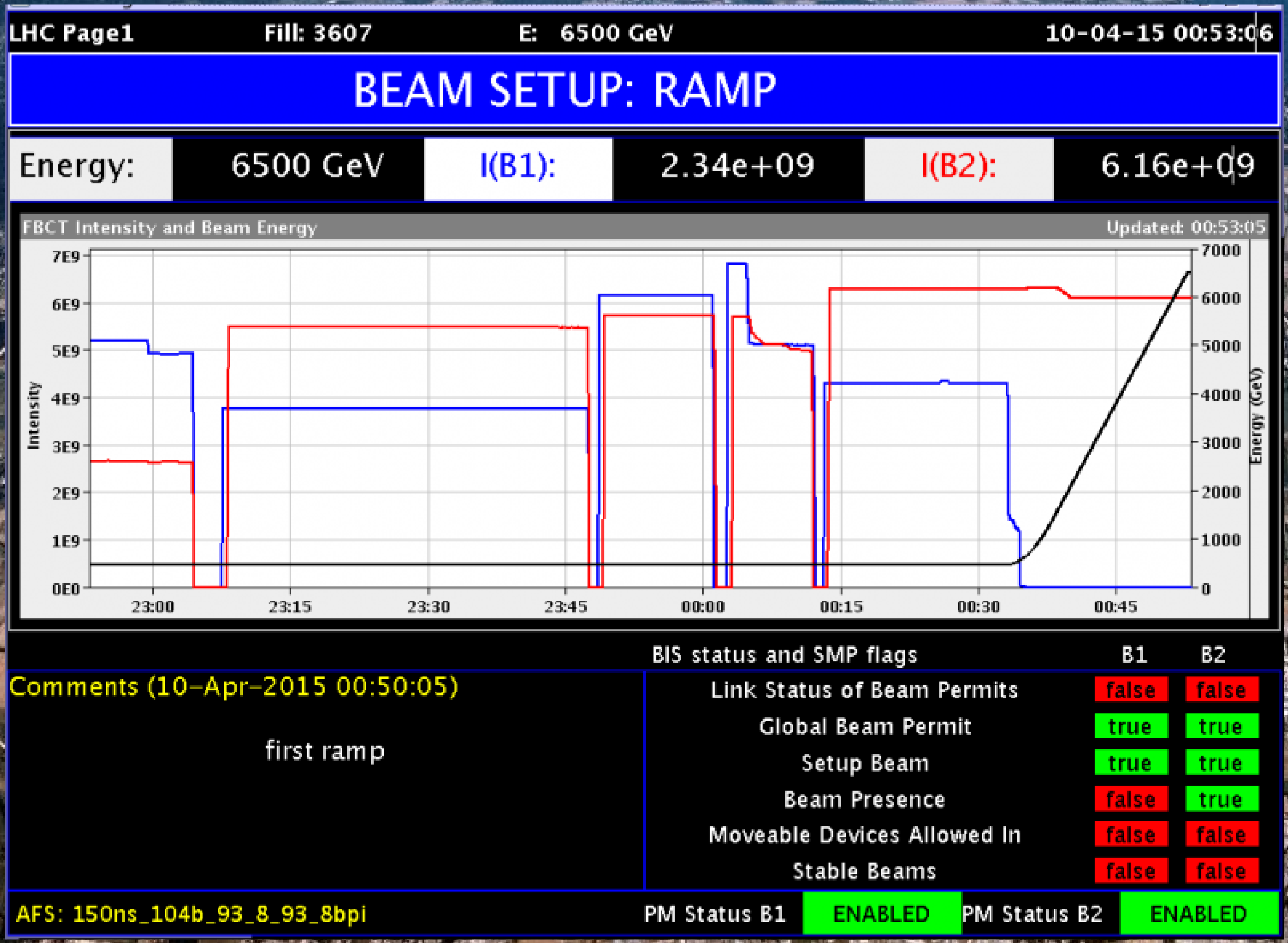
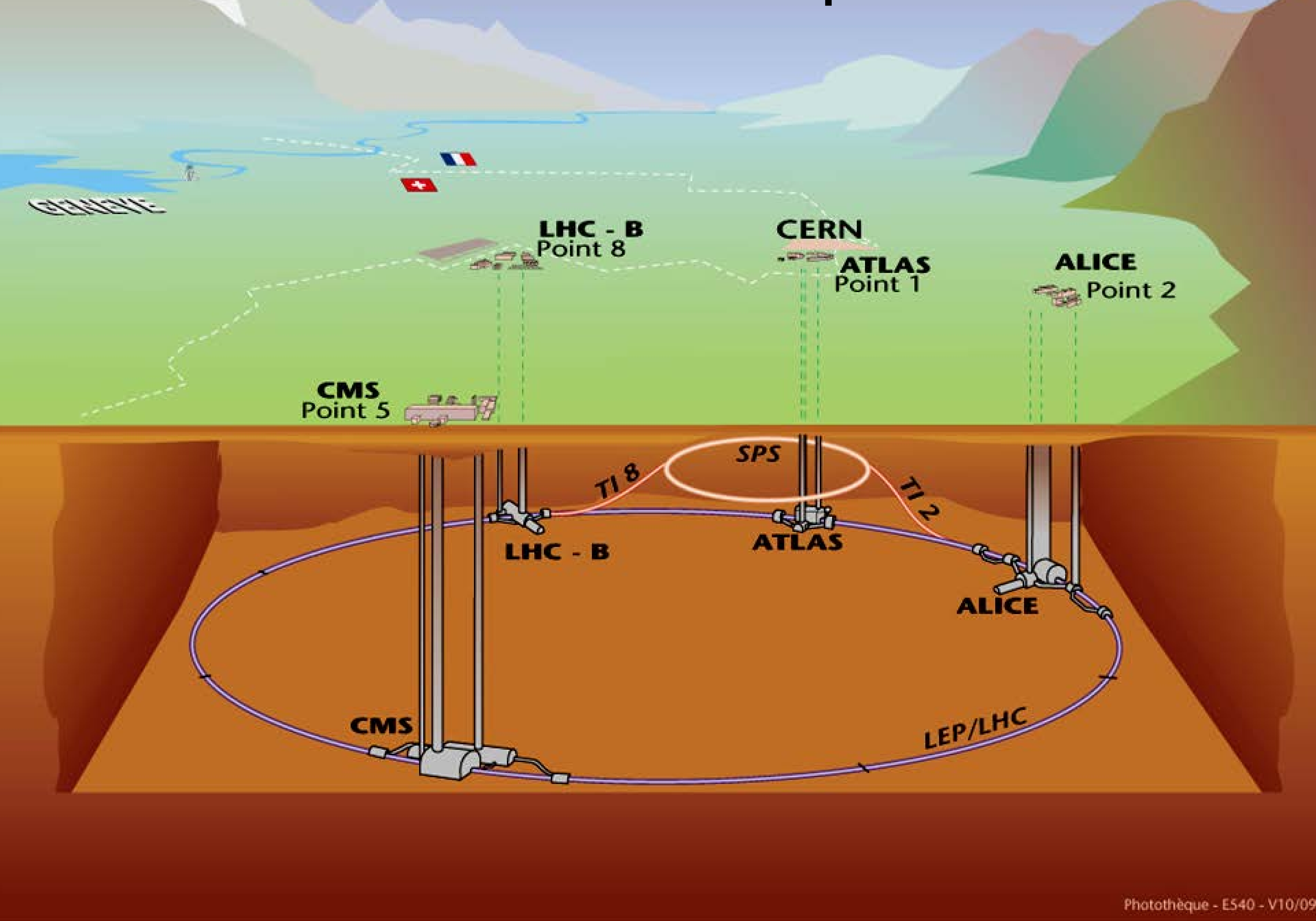
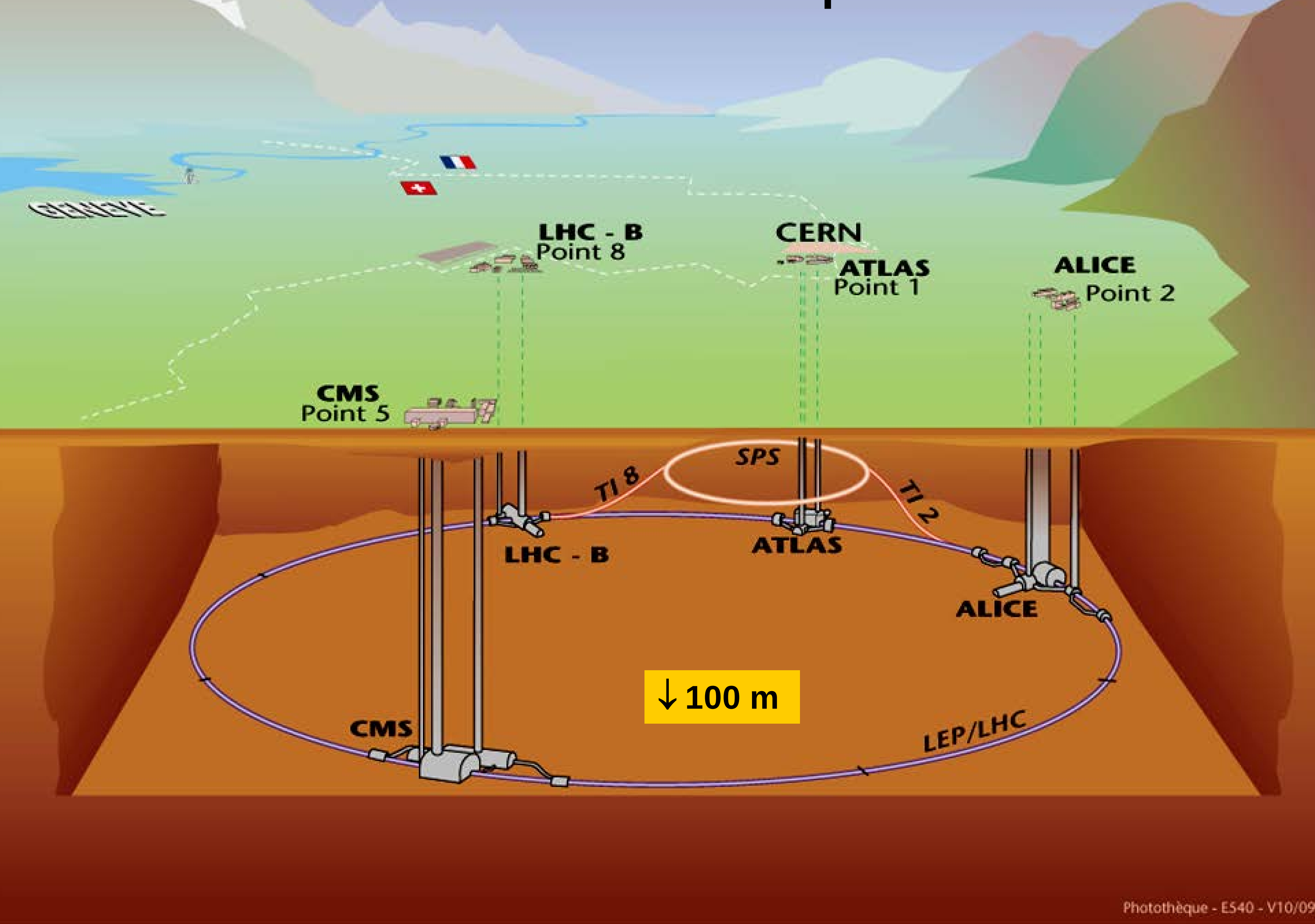


The LHC and its Experiments

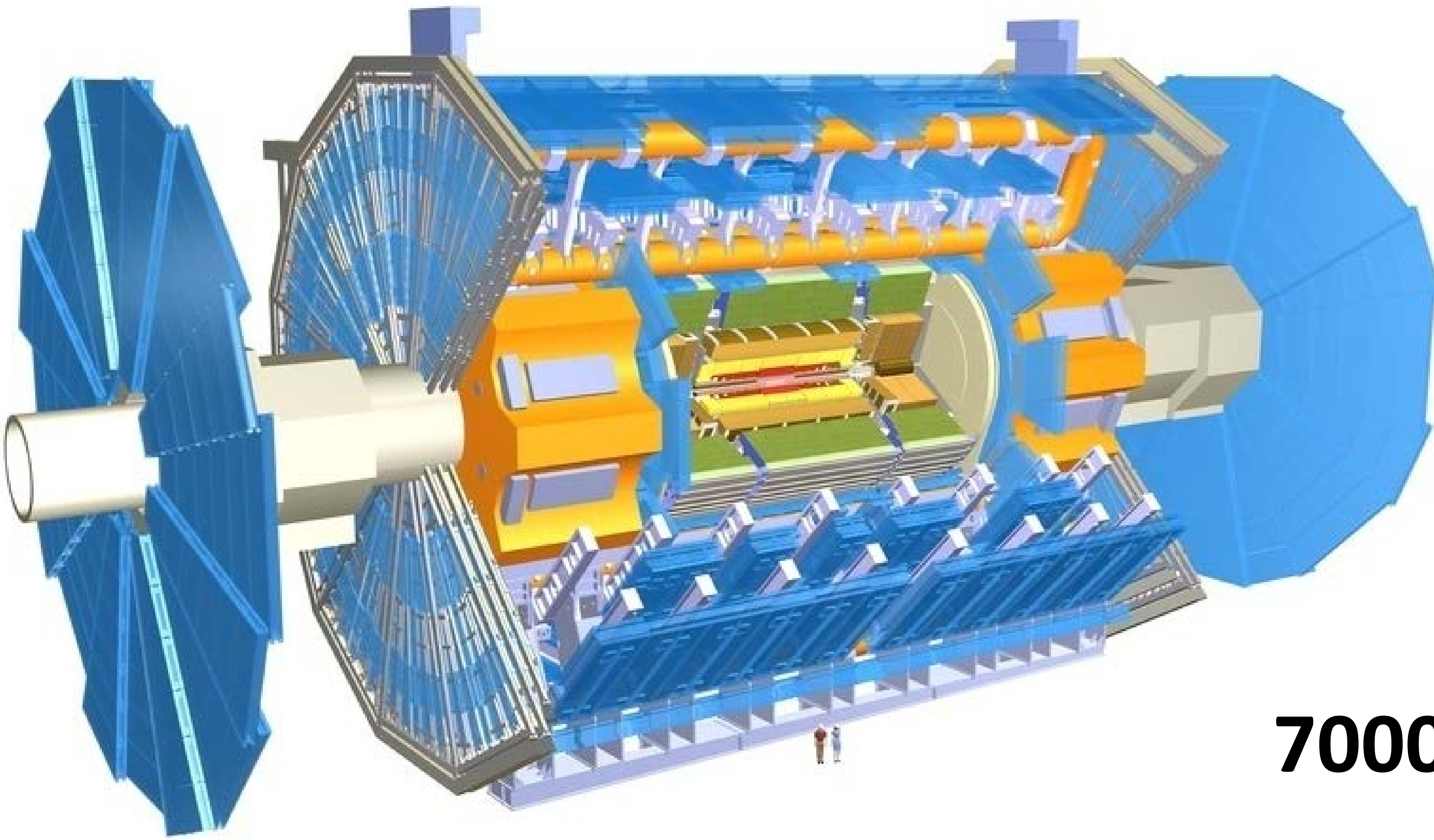


The LHC and its Experiments



The ATLAS-Detector

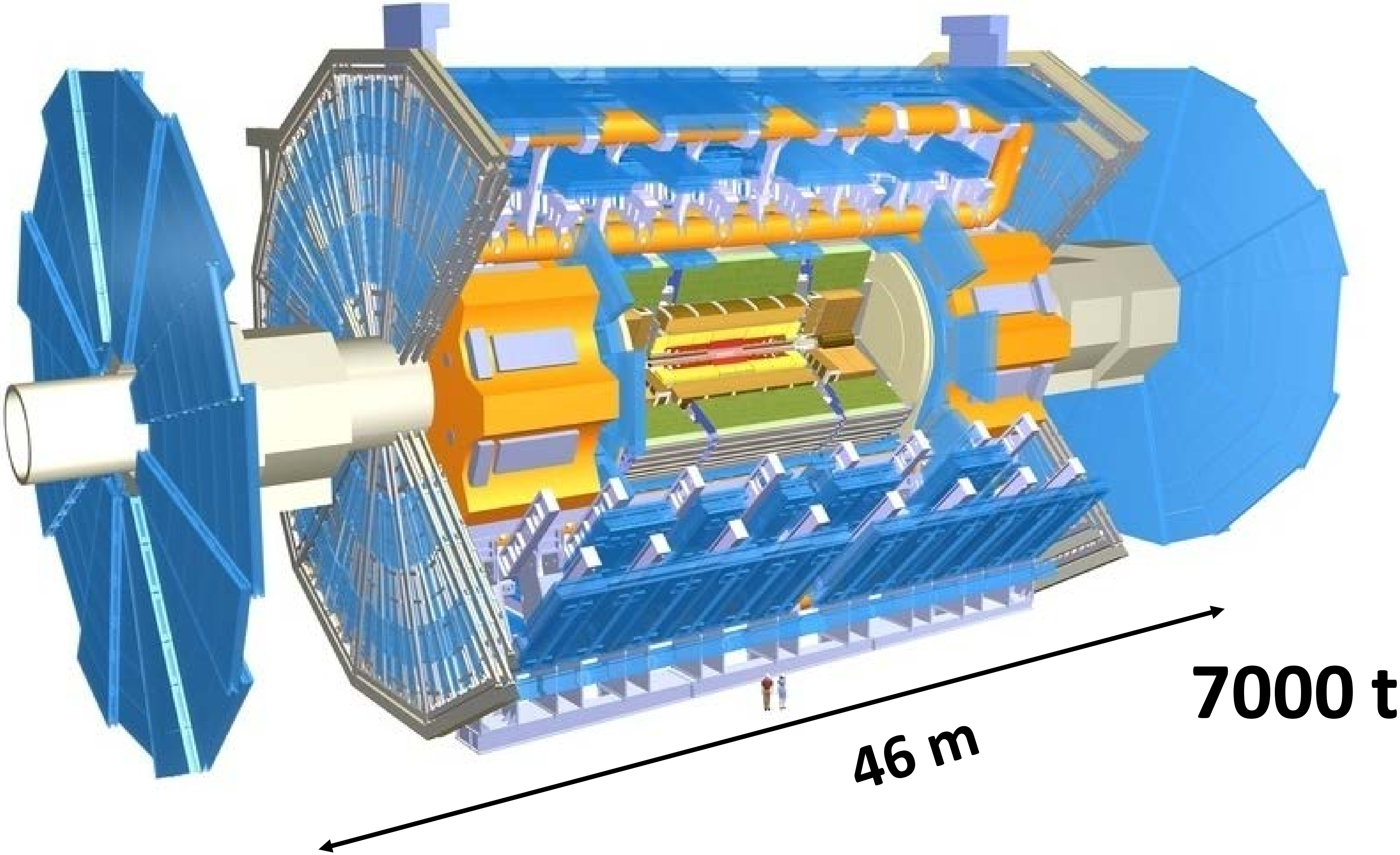
(A Toroidal LHC ApparatuS)



7000 t

The ATLAS-Detector

(A Toroidal LHC ApparatuS)



The ATLAS-Detector

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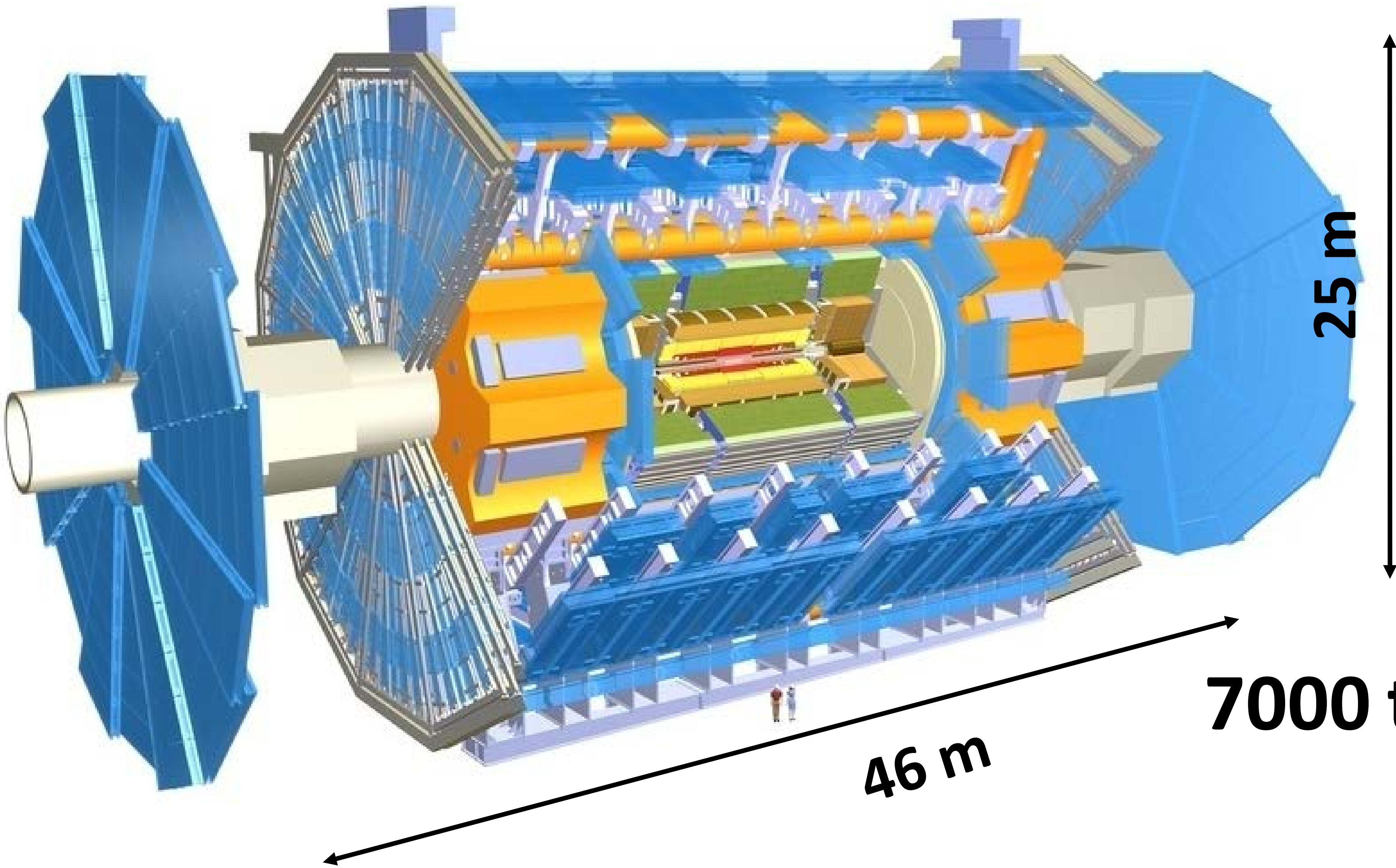

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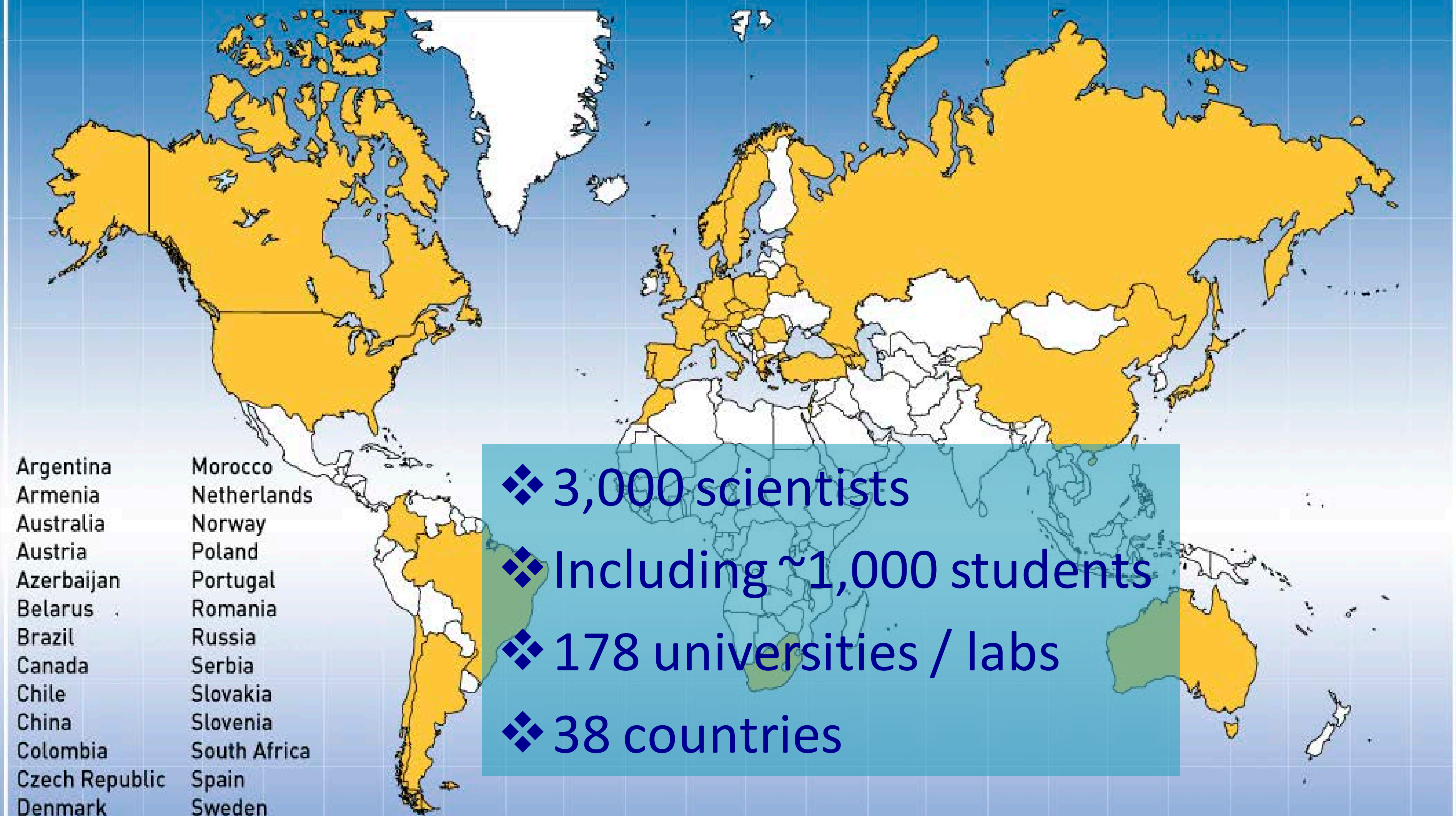


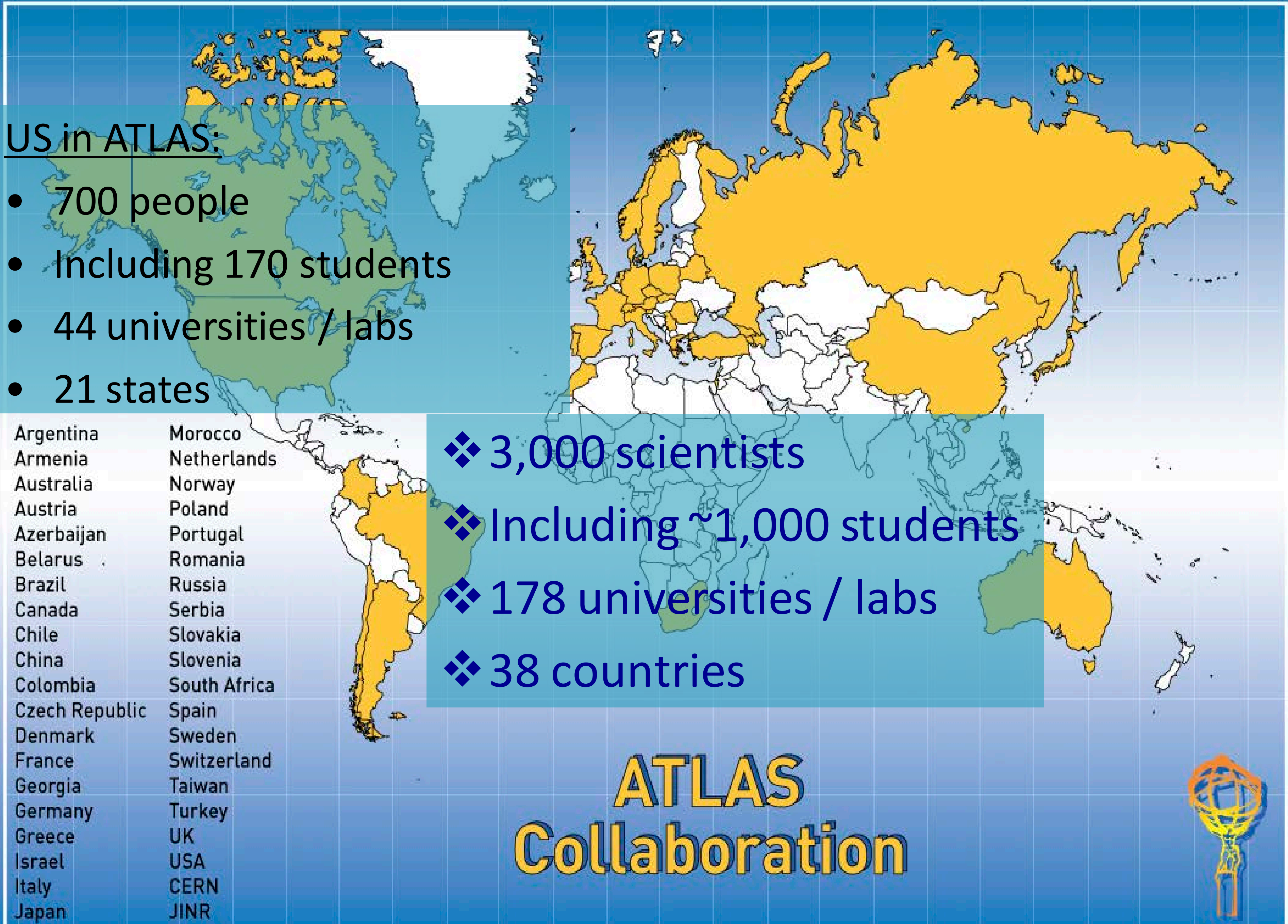
ATLAS Collaboration

- 3,000 scientists
- Including ~1,000 students
- 178 universities / labs
- 38 countries

Argentina	Morocco
Armenia	Netherlands
Australia	Norway
Austria	Poland
Azerbaijan	Portugal
Belarus	Romania
Brazil	Russia
Canada	Serbia
Chile	Slovakia
China	Slovenia
Colombia	South Africa
Czech Republic	Spain
Denmark	Sweden
France	Switzerland
Georgia	Taiwan
Germany	Turkey
Greece	UK
Israel	USA
Italy	CERN
Japan	JINR

US in ATLAS:

- 700 people
- Including 170 students
- 44 universities / labs
- 21 states



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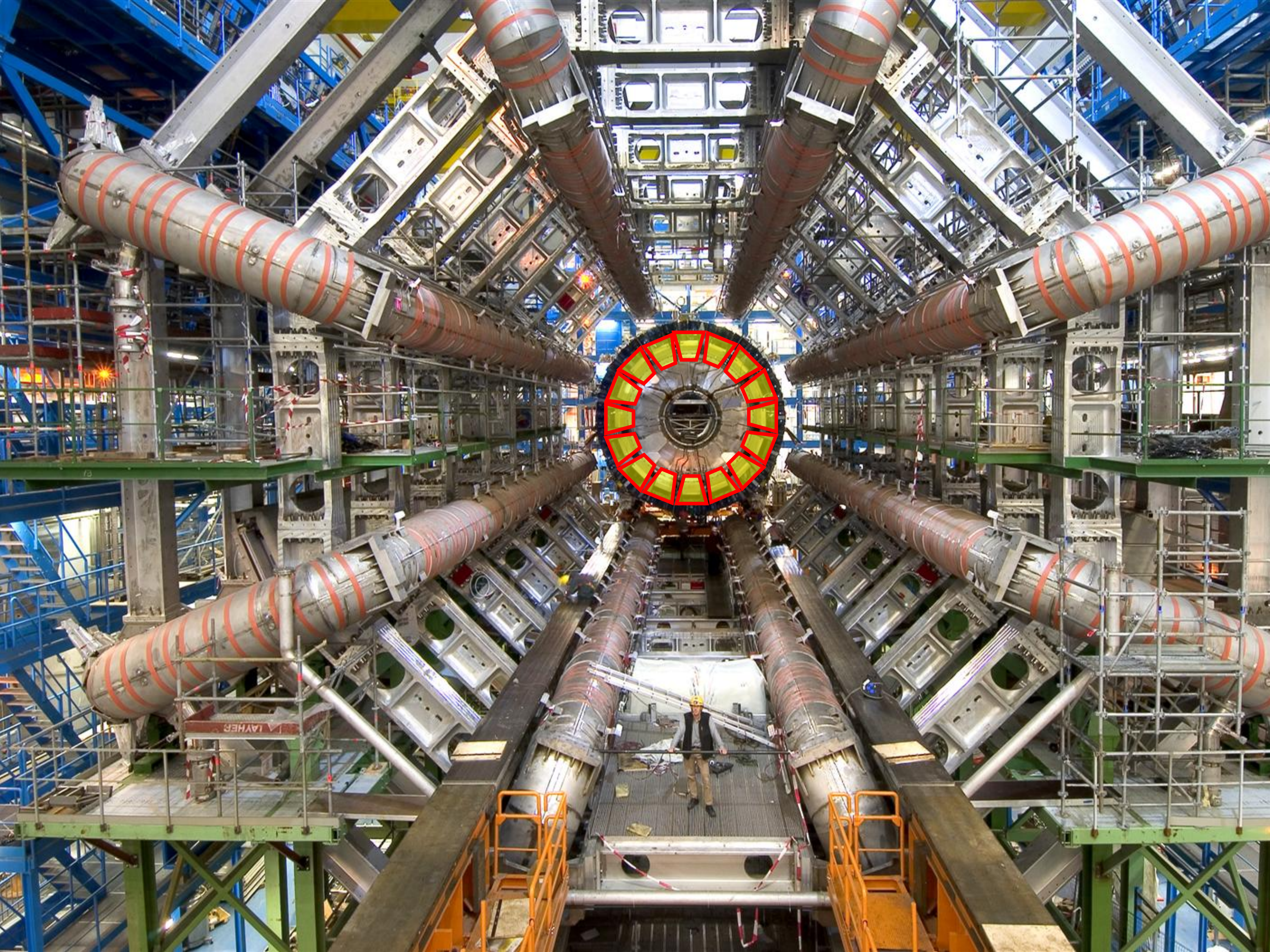
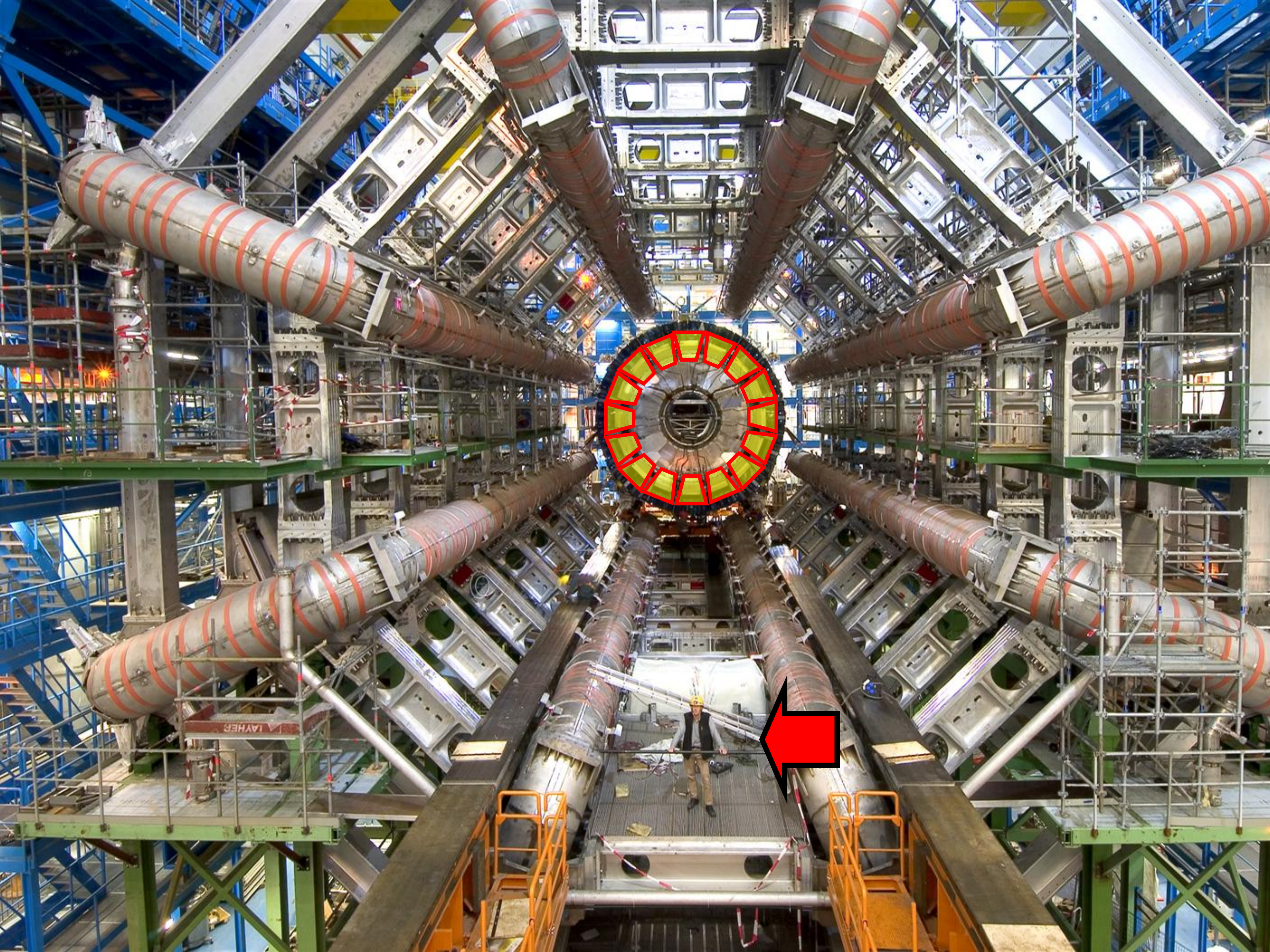
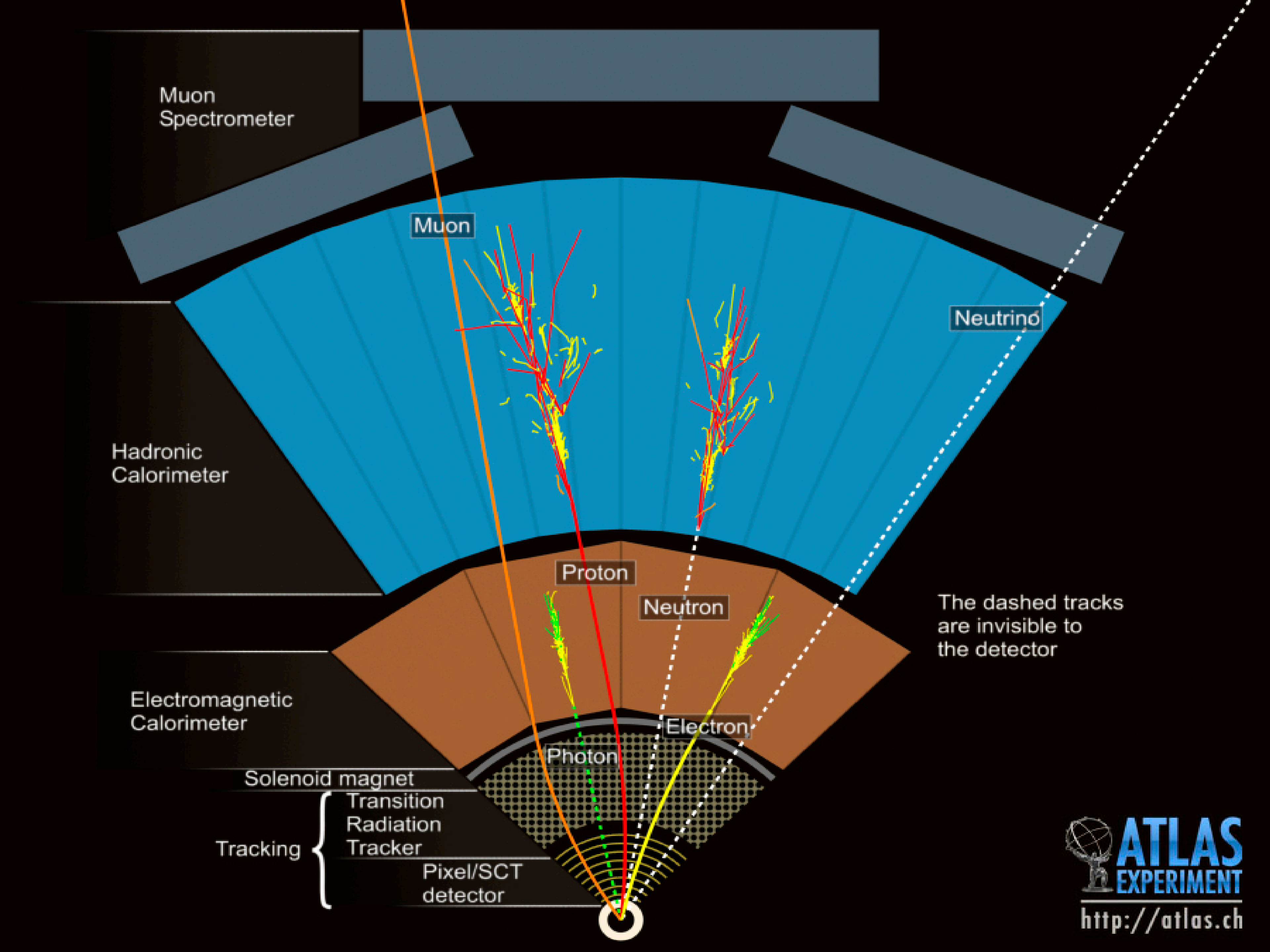
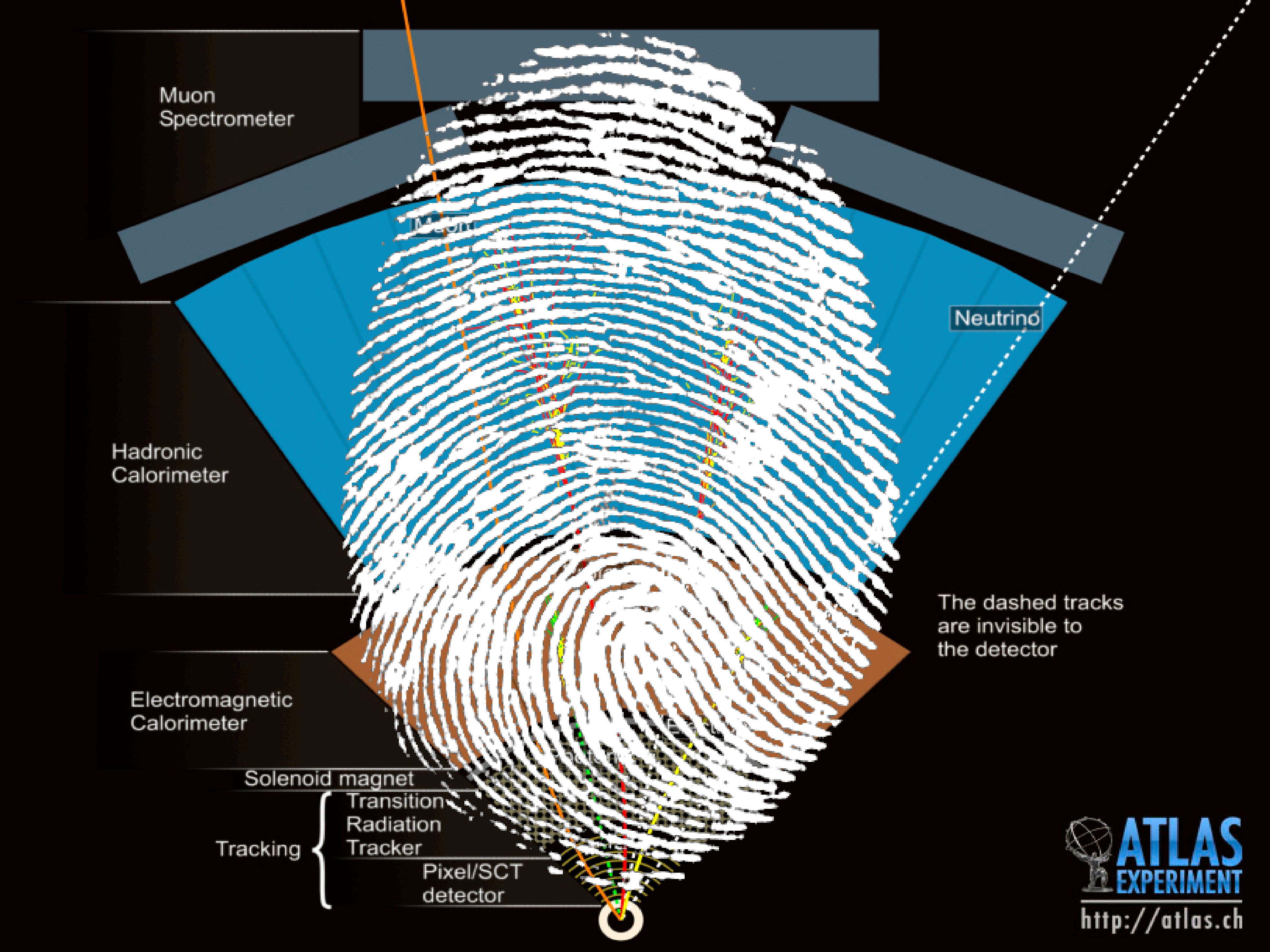





Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks are invisible to the detector
http://atlas.ch



Muon Spectrometer
Hadronic Calorimeter
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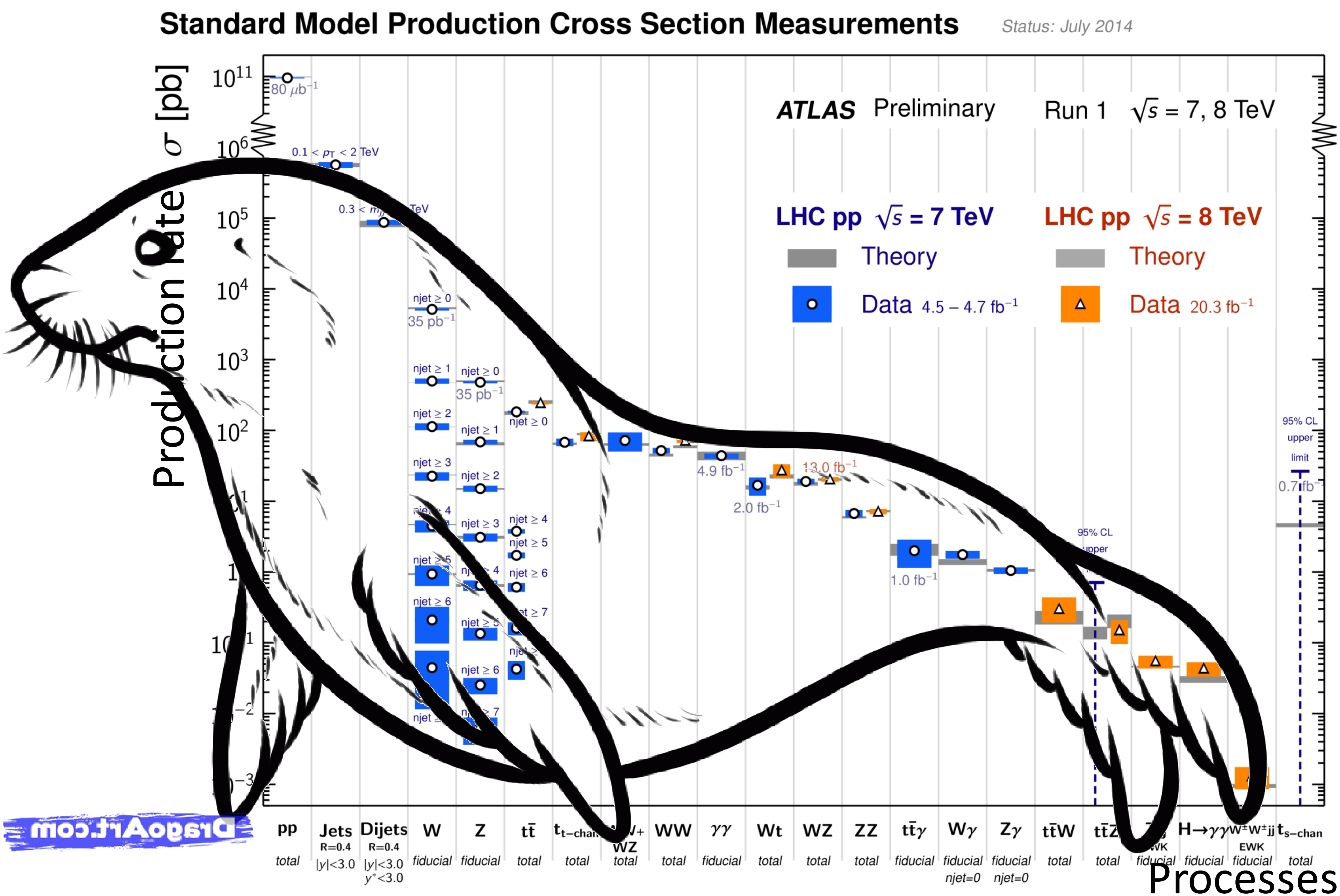
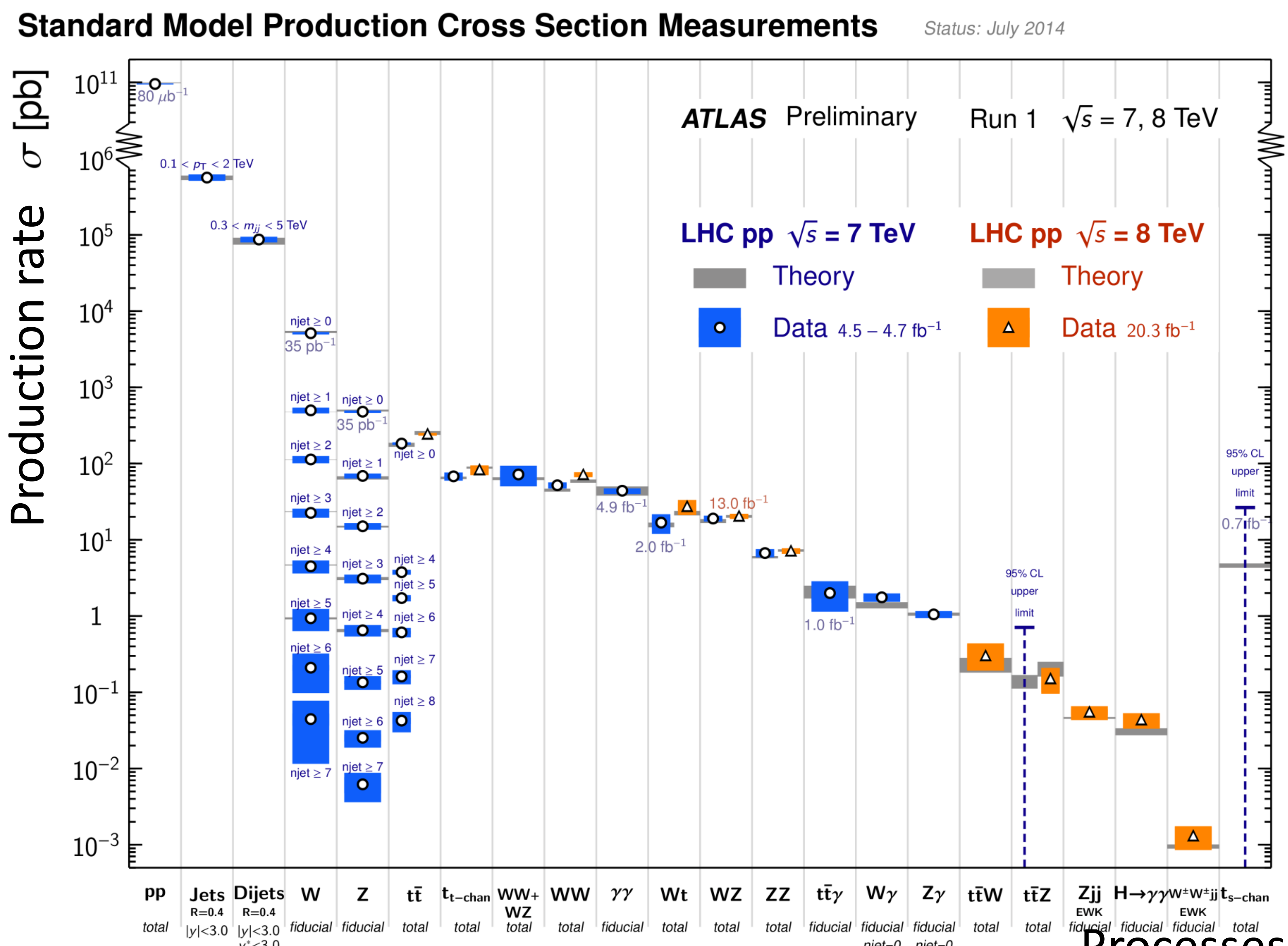
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch

What we measure in ATLAS…



What we measure in ATLAS…



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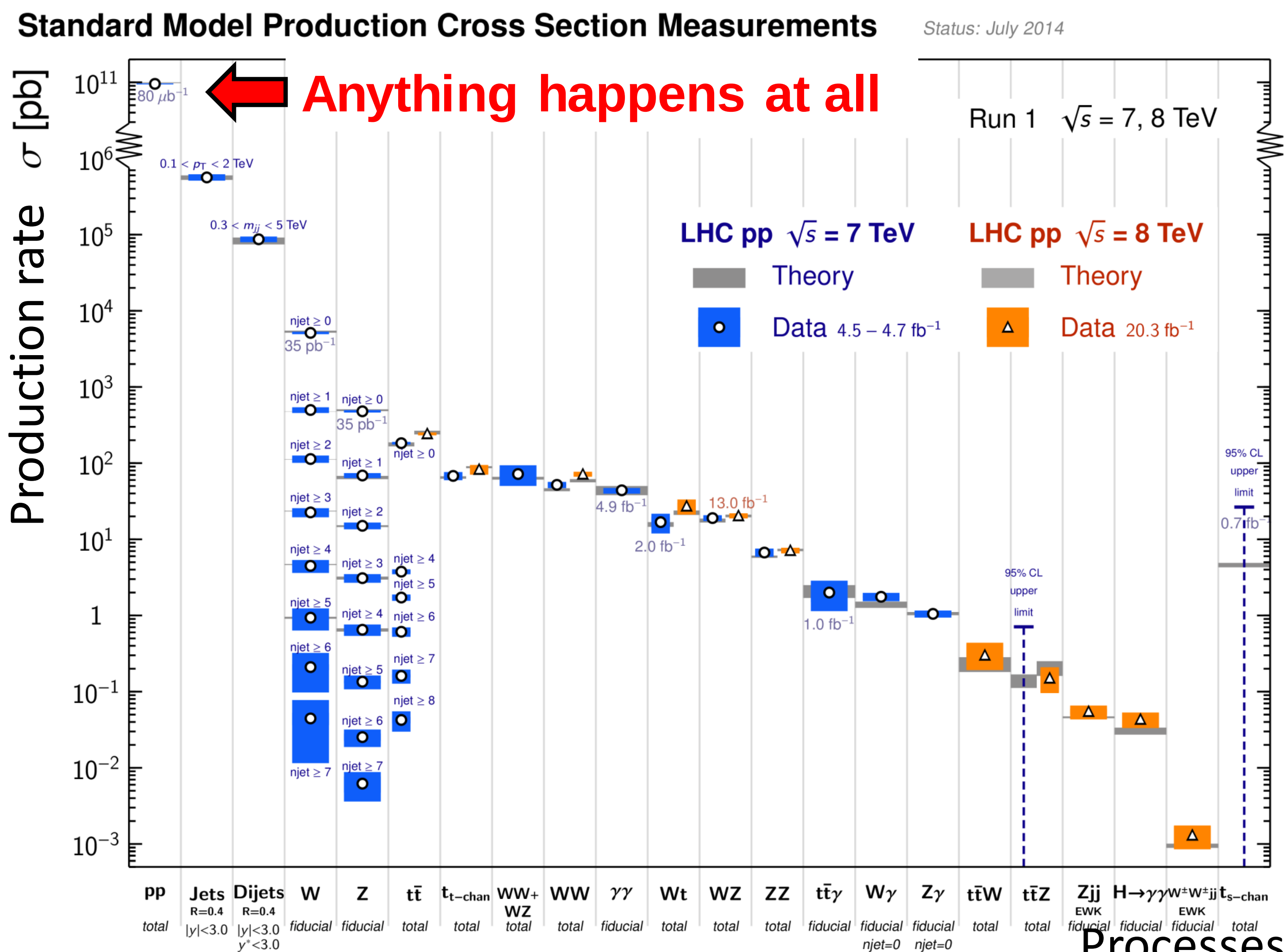

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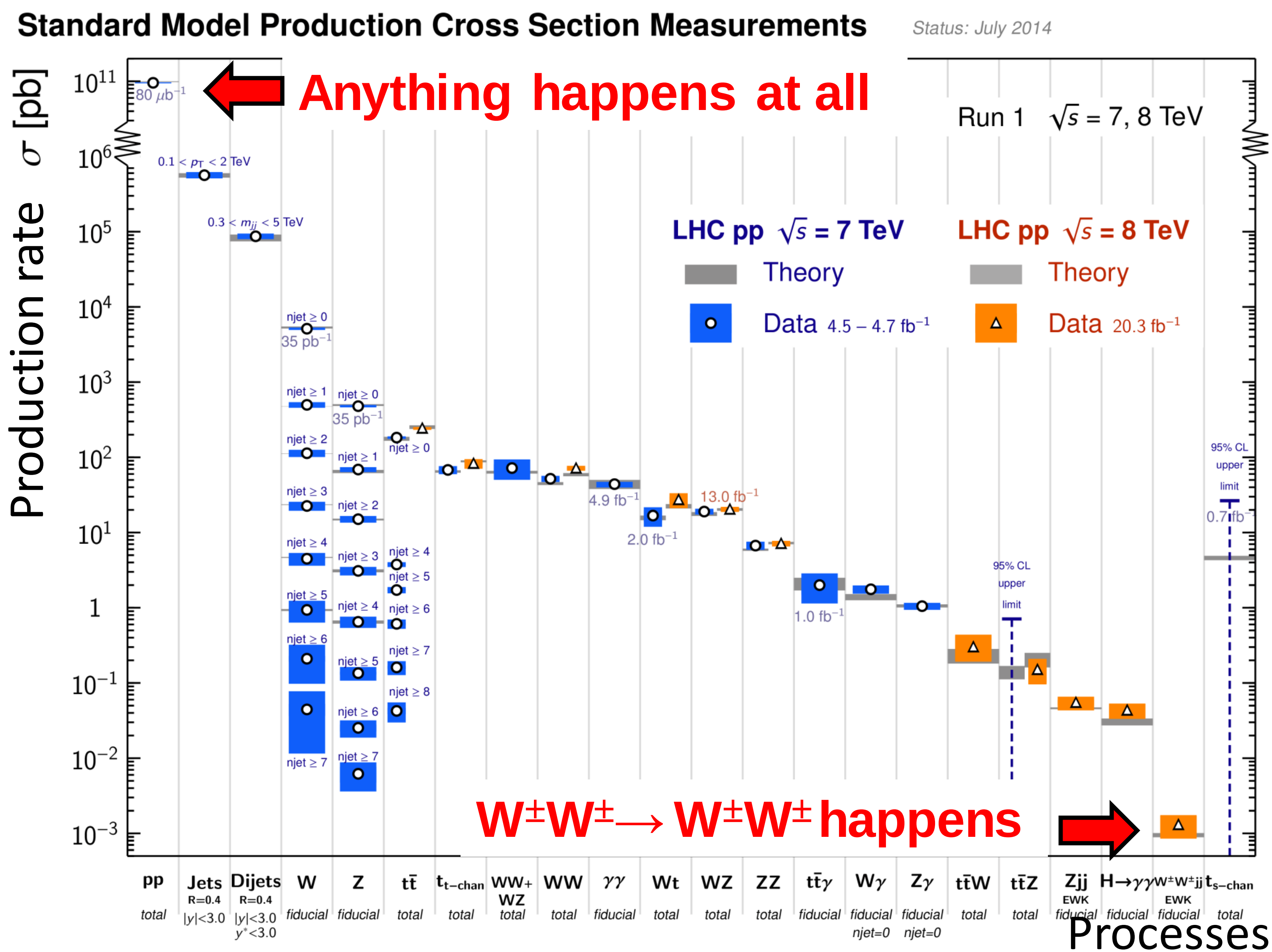
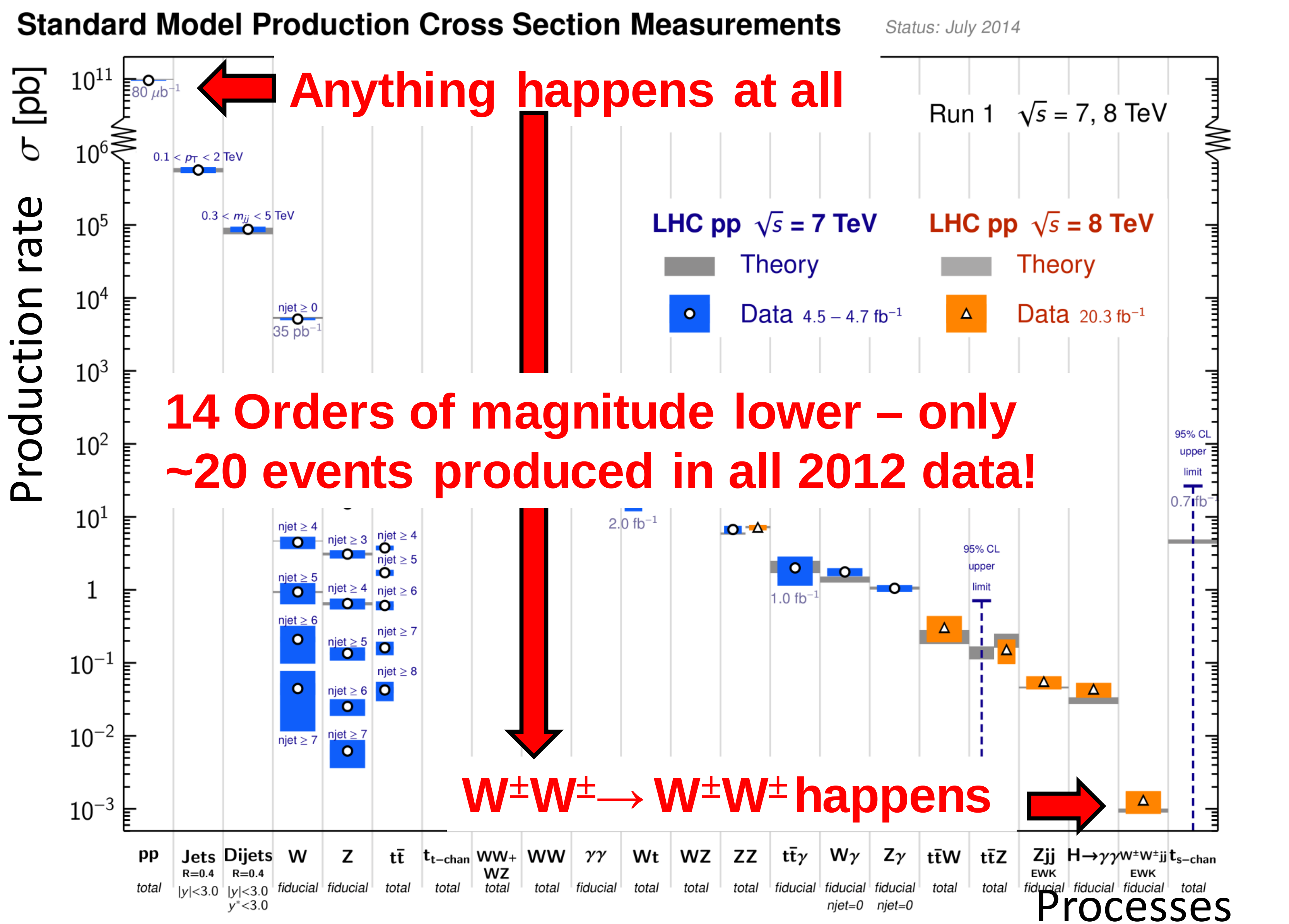


What we measure in ATLAS…



Data selection

Looking for extremely rare processes:

$W^{\pm}W^{\pm} \rightarrow W^{\pm}W^{\pm}$ happens every ~100,000,000,000,000 collisions!

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(still need to **detect** them!)

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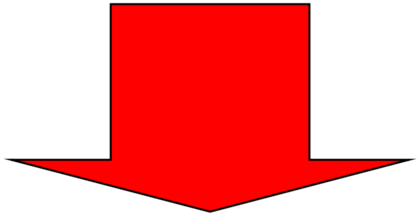

Need high proton-proton collision rate: Up to 1,000,000,000 per second!

Data selection

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$W^{\pm}W^{\pm} \rightarrow W^{\pm}W^{\pm}$ happens every
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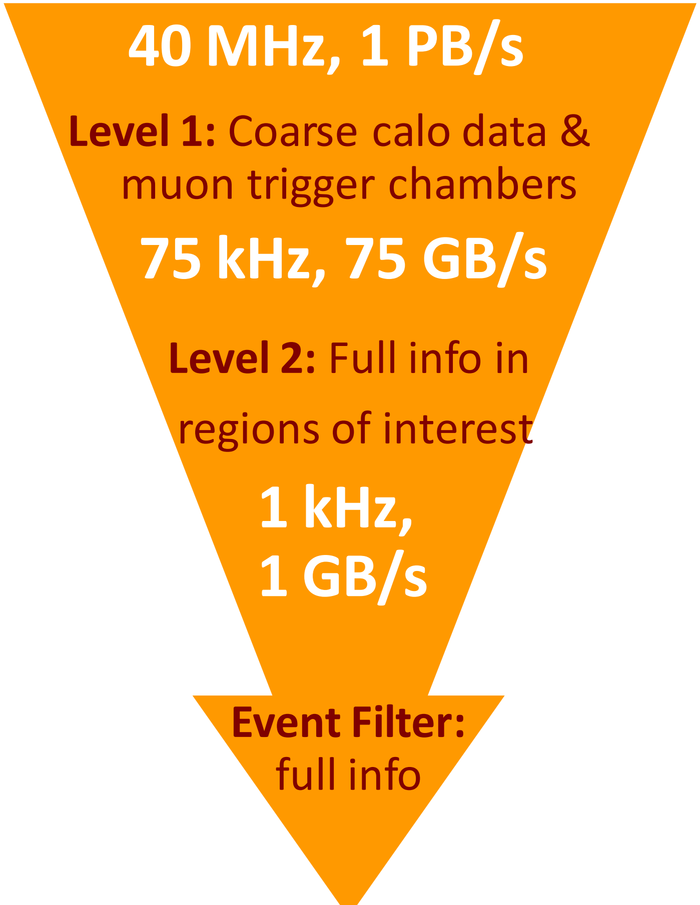
Data selection

Selection of 100 'best' events/s:



~100 Hz, ~100 MB/sec

~10 TB/day, 1 PB/yr recorded data

Data selection

Selection of 100 'best' events/s:

40 MHz, 1 PB/s

Level 1: Coarse calo data & muon trigger chambers

75 kHz, 75 GB/s

Level 2: Full info in regions of interest

1 kHz, 1 GB/s

Event Filter: full info

~100 Hz, ~100 MB/sec

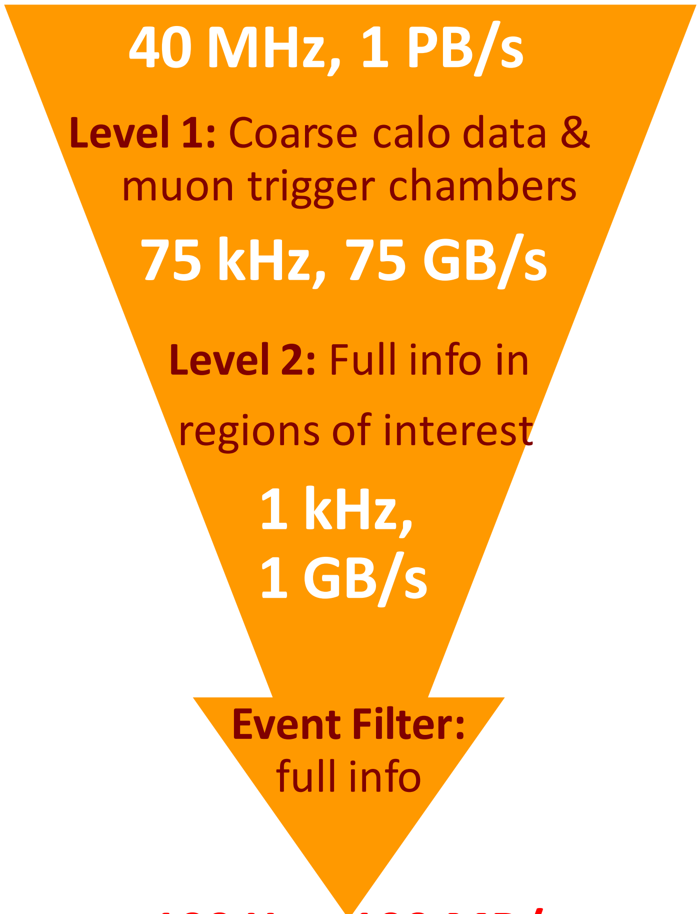
~10 TB/day, 1 PB/yr recorded data

LHC data volume:
10-15 PB/yr

One CD: 650 MB
1 PB = 10^9 MB

Data selection

Selection of 100 'best' events/s:



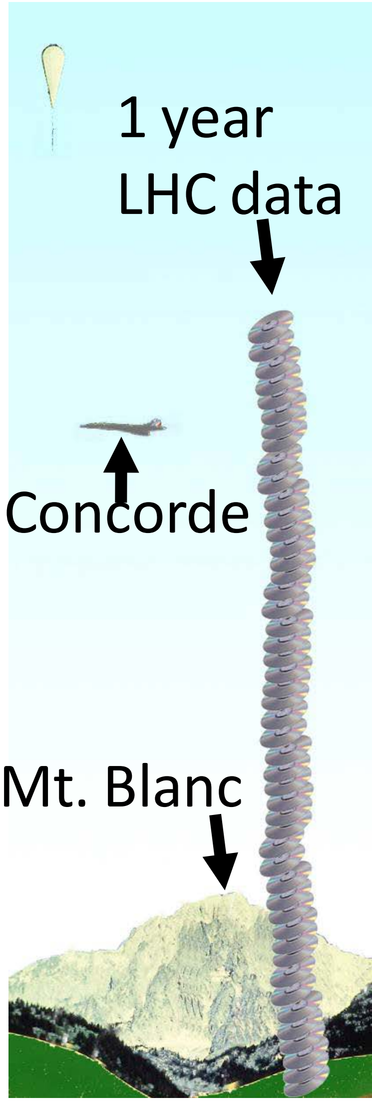
~100 Hz, ~100 MB/sec

~10 TB/day, 1 PB/yr recorded data

LHC data volume:
10-15 PB/yr

One CD: 650 MB
1 PB = 10^9 MB

12-mile-high stack of CDs!

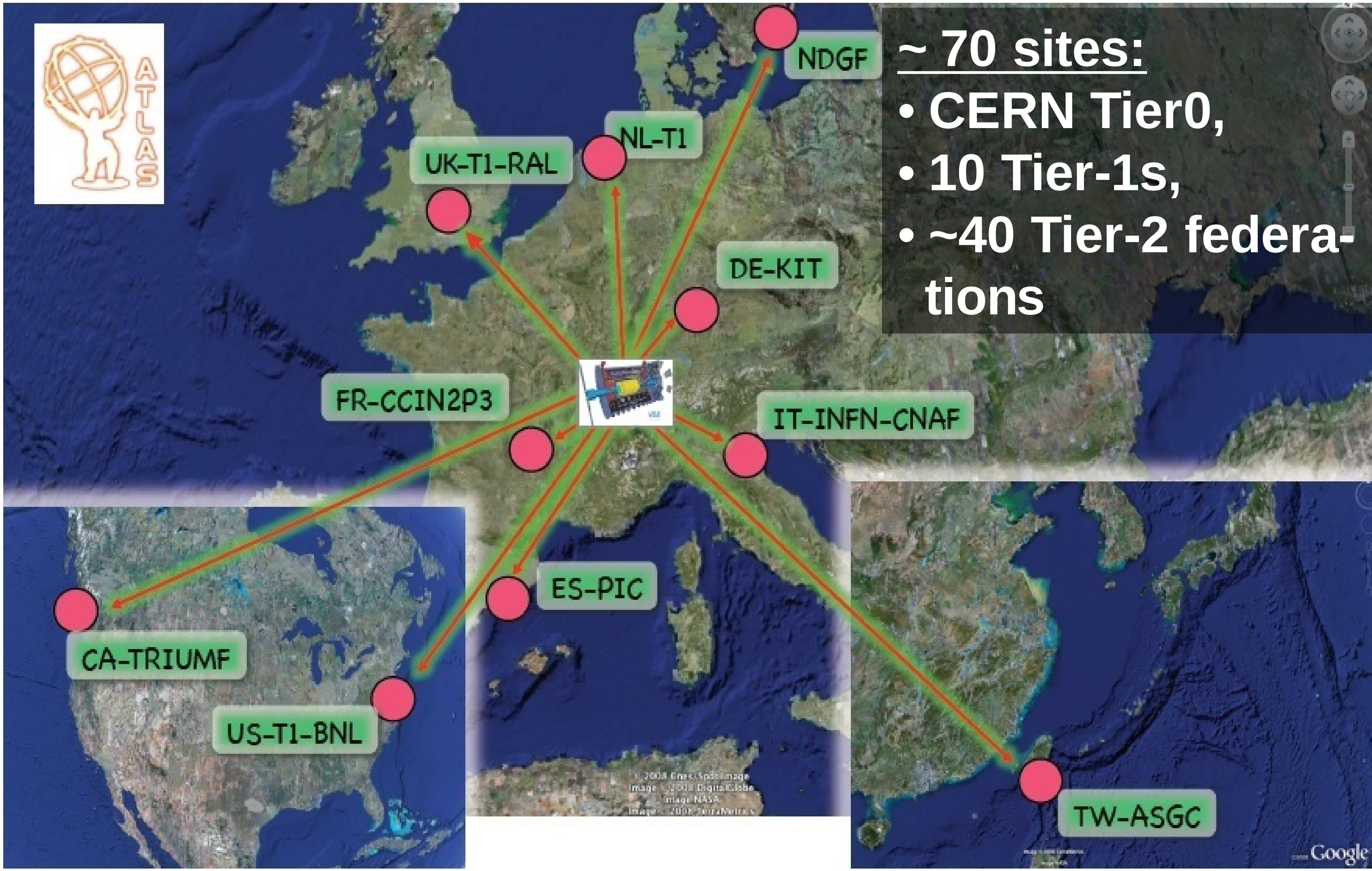


A Global Computing System

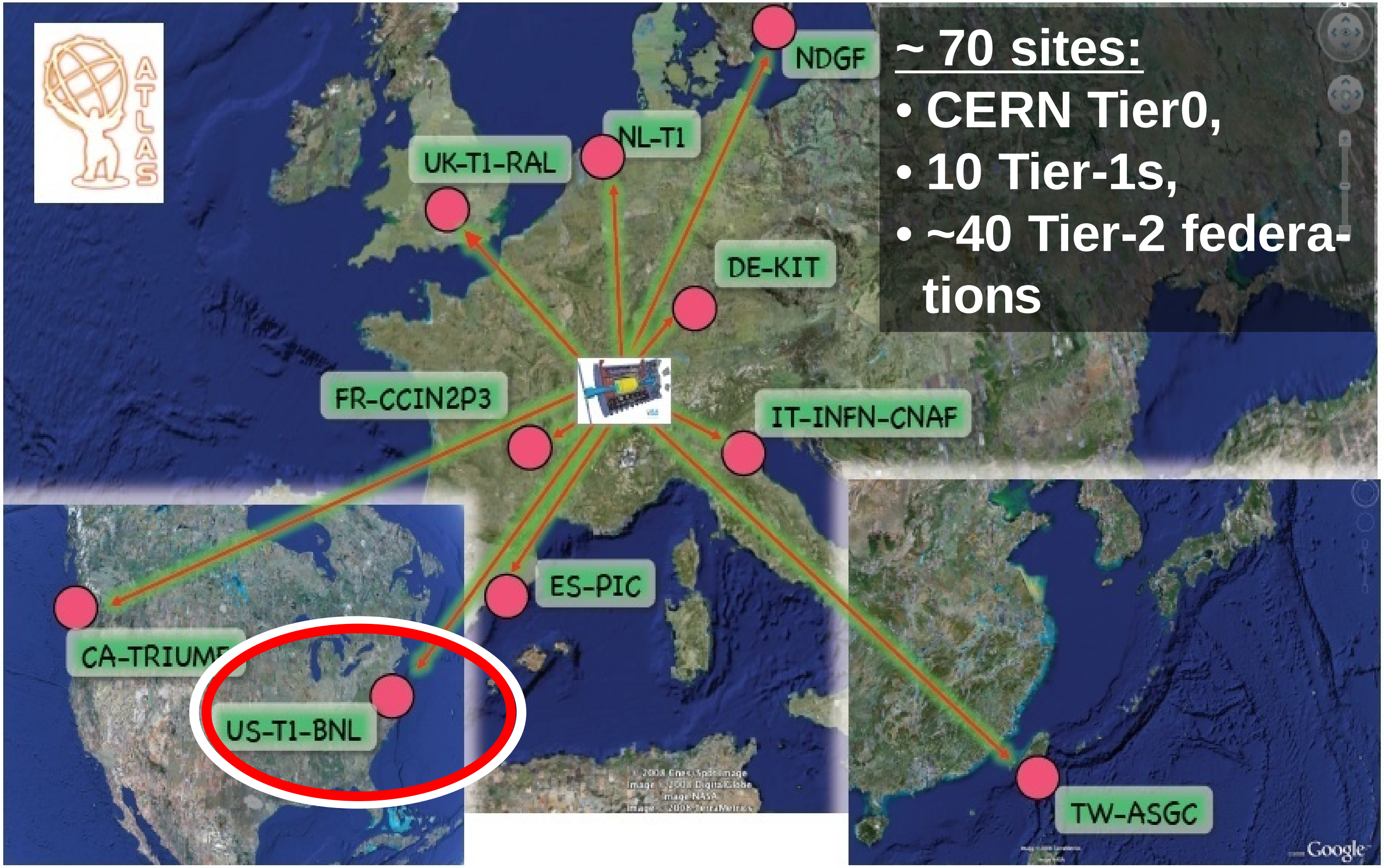
- Worldwide LHC **Computing Grid**
- 170 computing centers
- 40 countries
- National and international grid computing projects
- 2 million jobs run every day

© GridPP/Imperial College London

ATLAS World-Wide Computing Grid

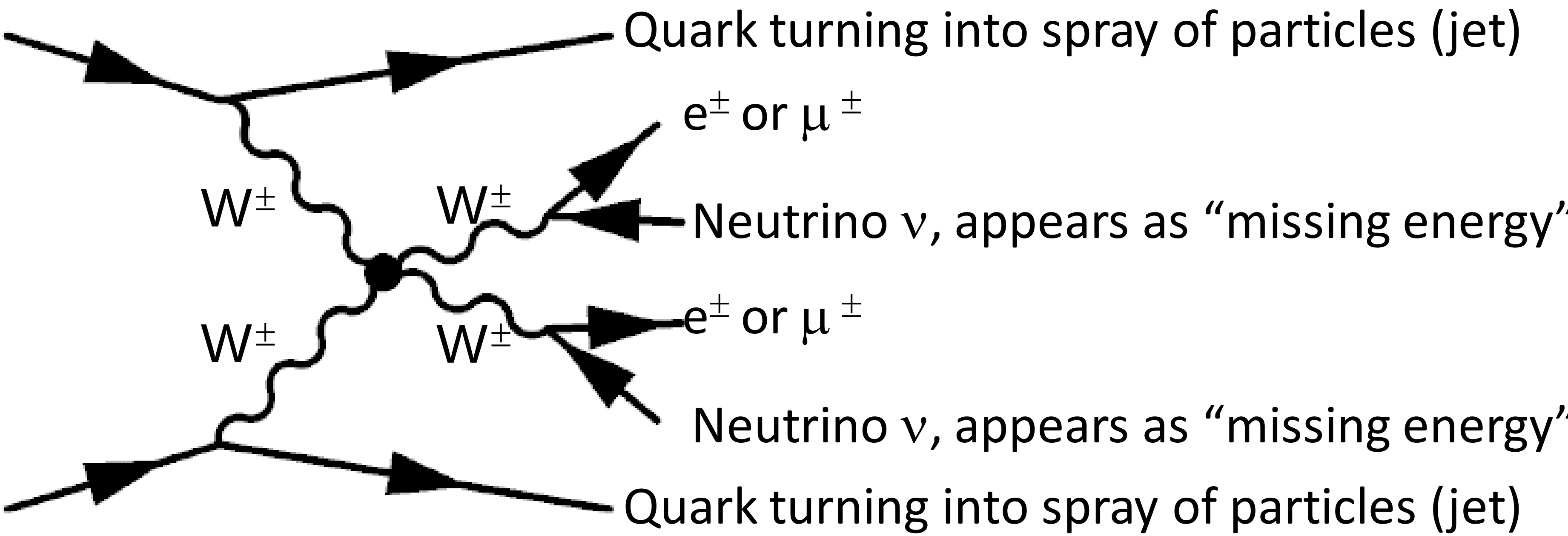


ATLAS World-Wide Computing Grid



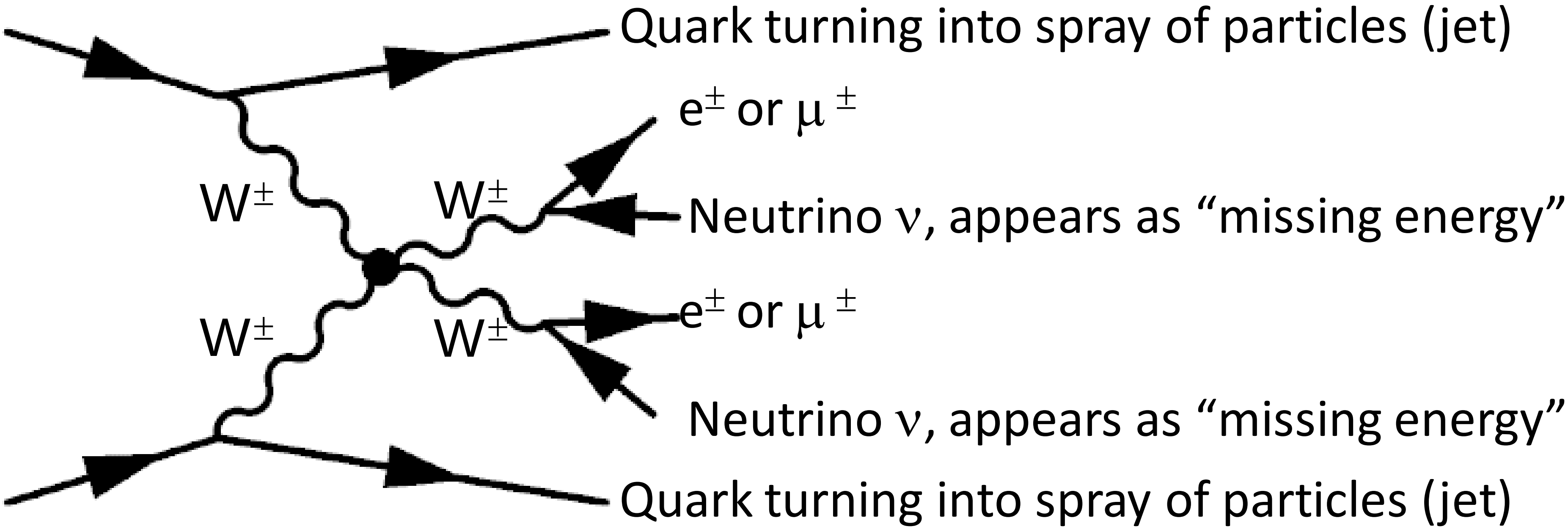
<u>~ 70 sites:</u>
- CERN Tier0,
- 10 Tier-1s,
- ~40 Tier-2 federations

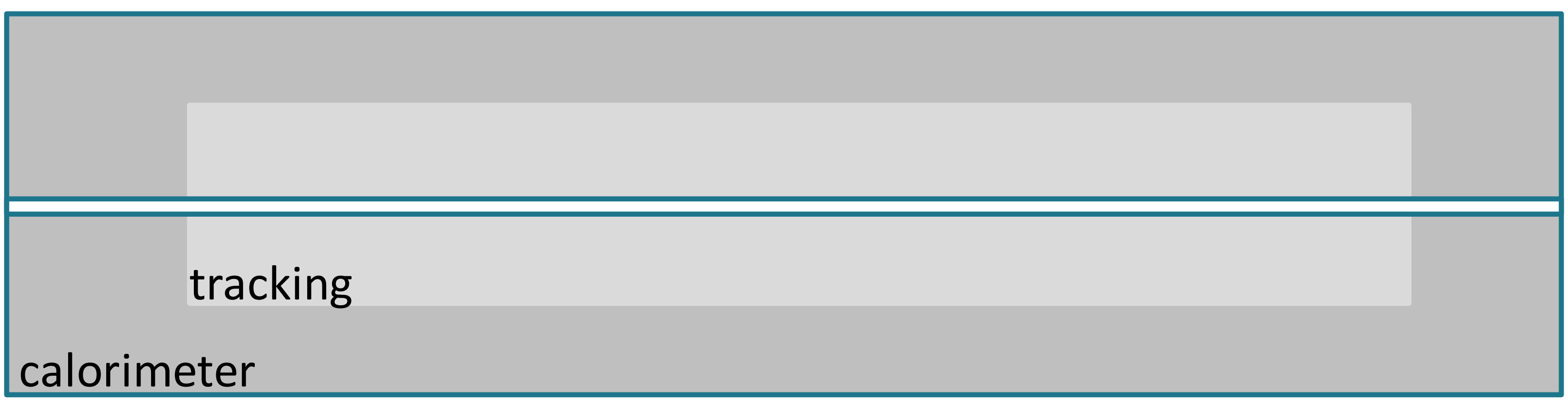
$W^{\pm}W^{\pm} \rightarrow W^{\pm}W^{\pm}$ Fingerprint



- Two jets in forward-backward constellation in detector
- Two energetic leptons ($e^{\pm}$ or $\mu^{\pm}$) of same electric charge
- "Missing energy" due to neutrinos escaping undetected

$W^{\pm}W^{\pm} \rightarrow W^{\pm}W^{\pm}$ Fingerprint





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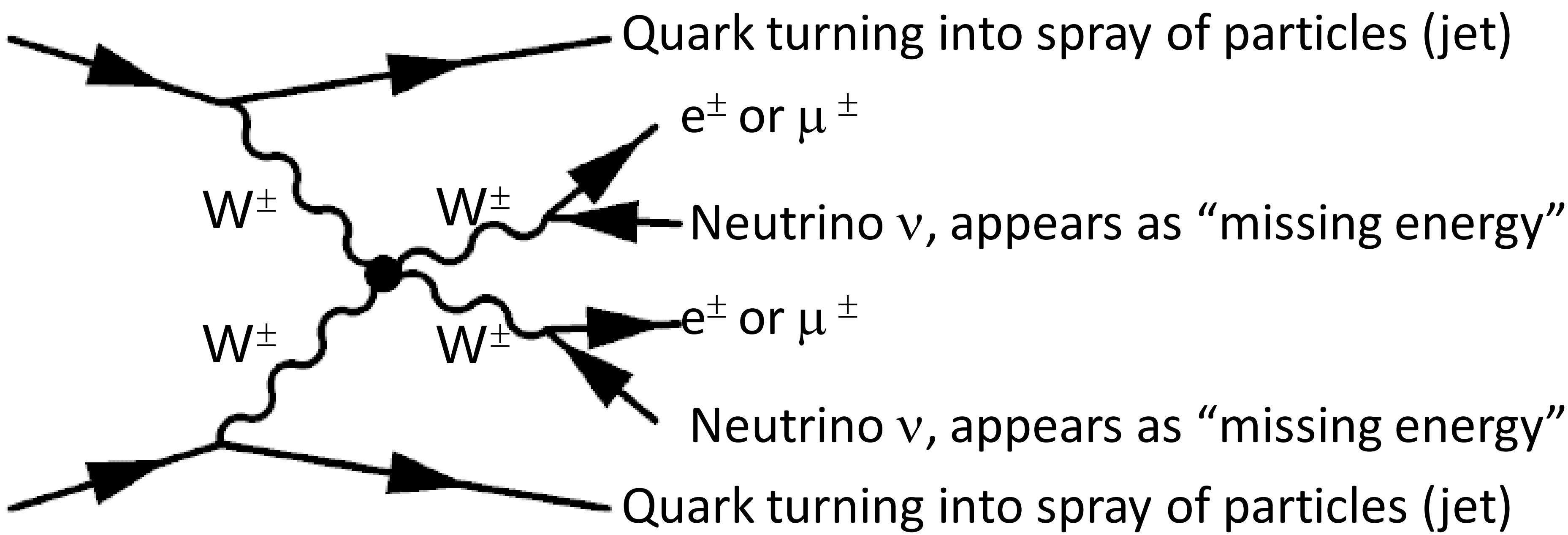
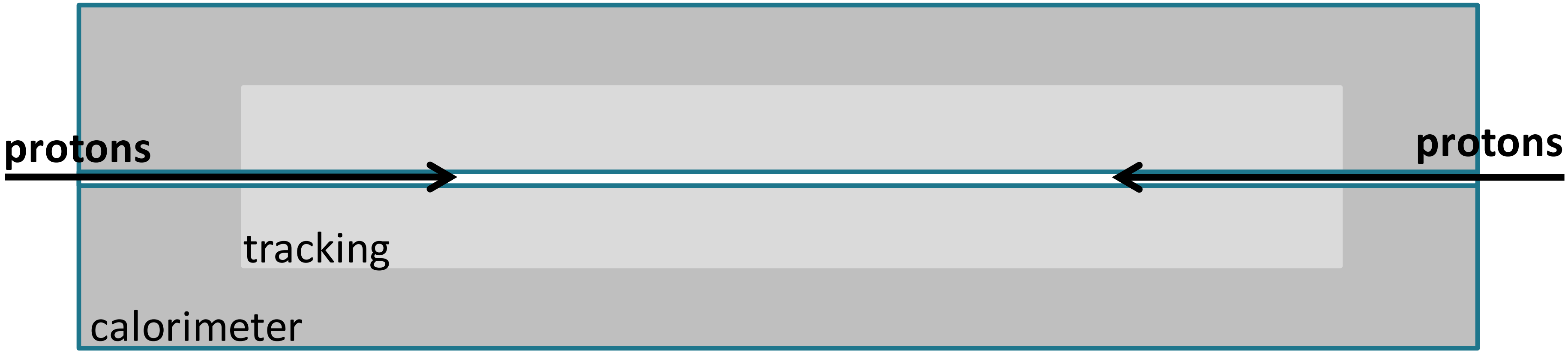
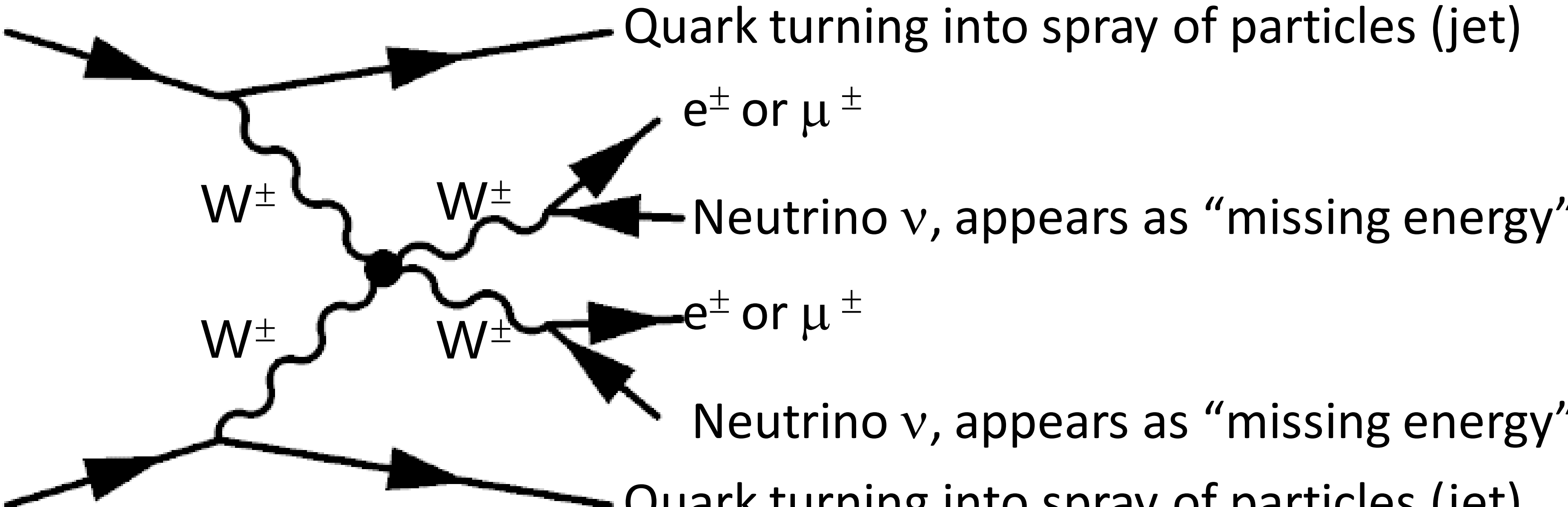
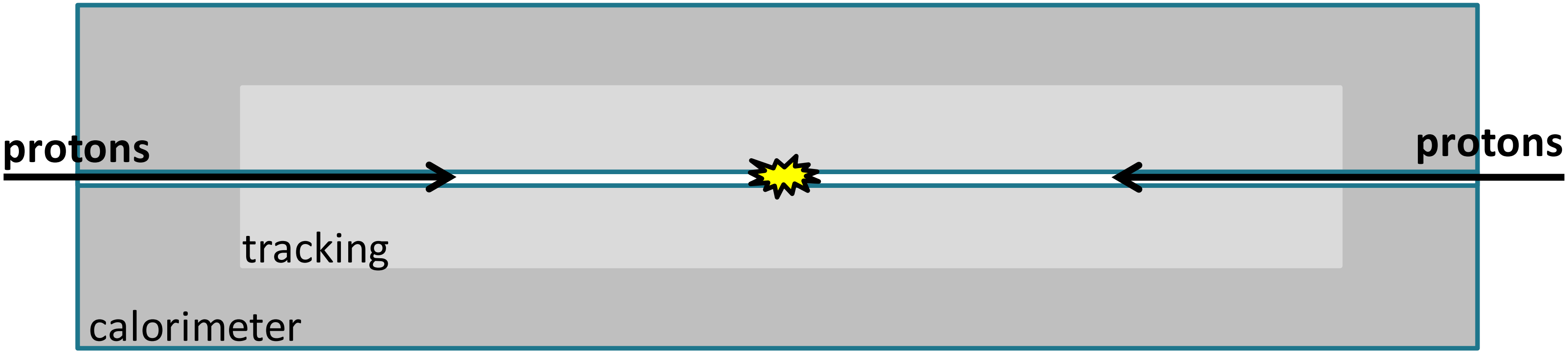




$W^\pm W^\pm \rightarrow W^\pm W^\pm$ Fingerprint





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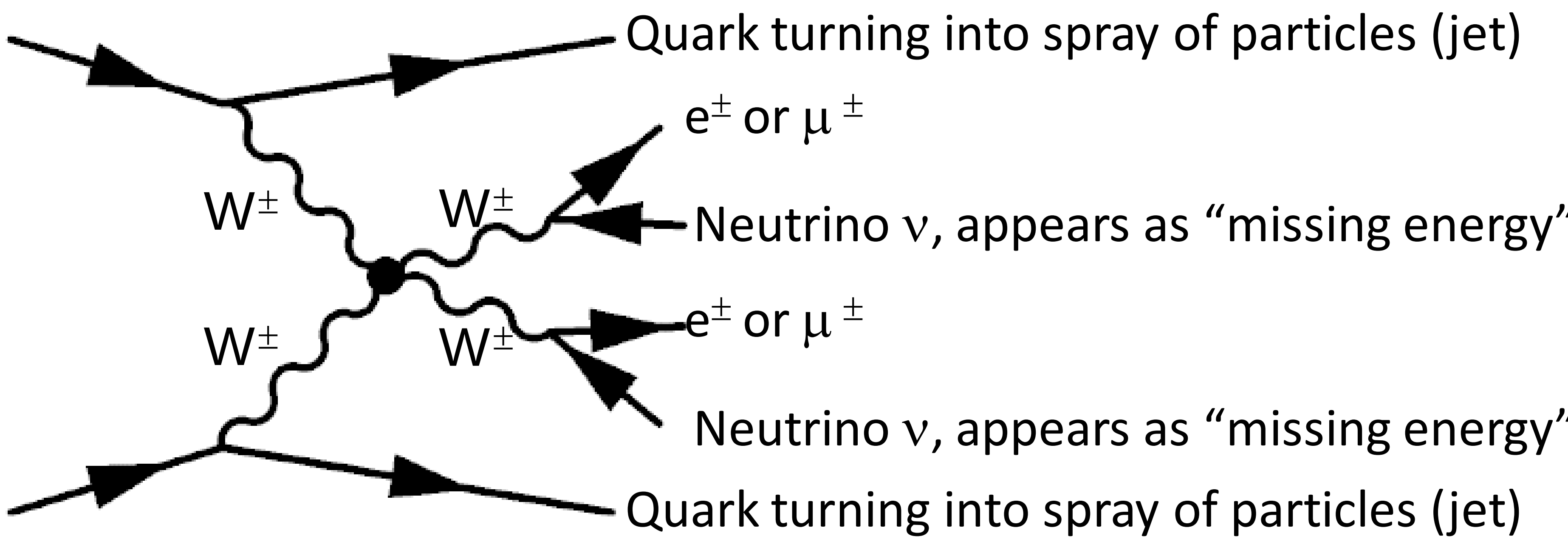
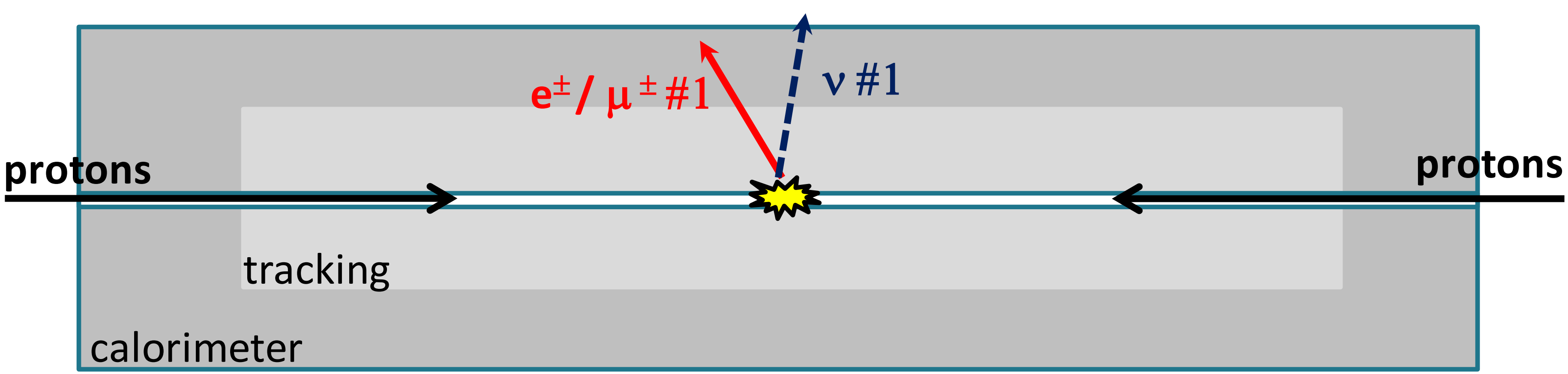
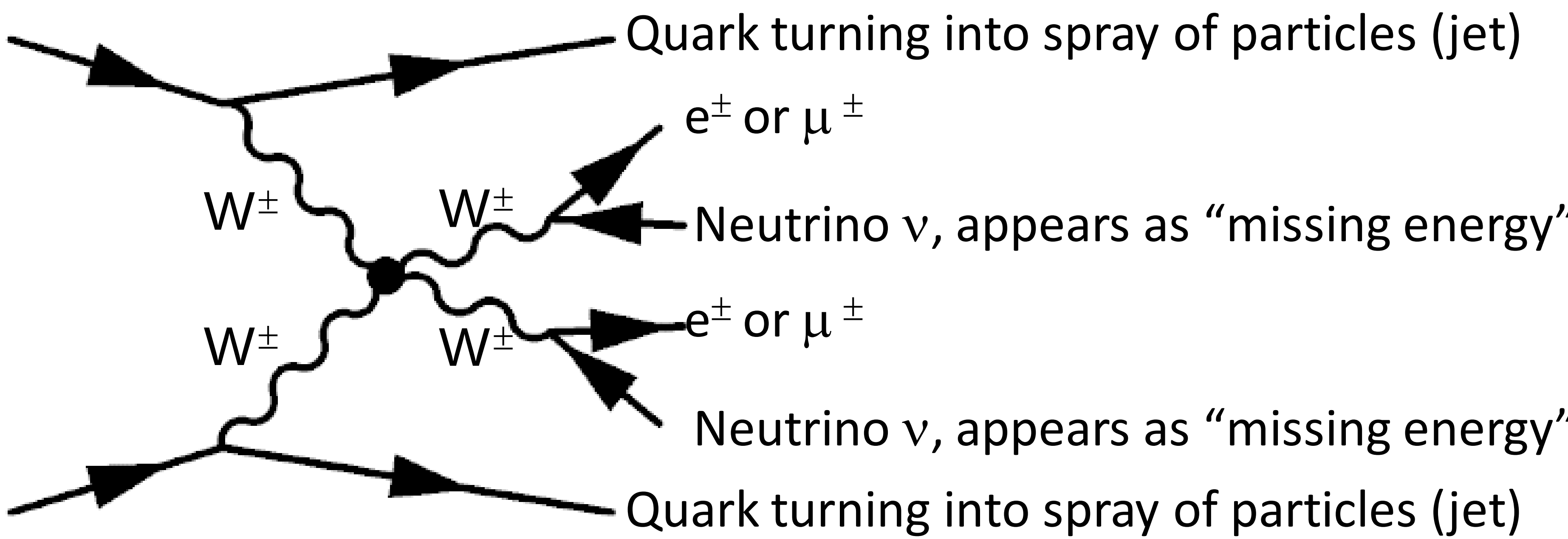
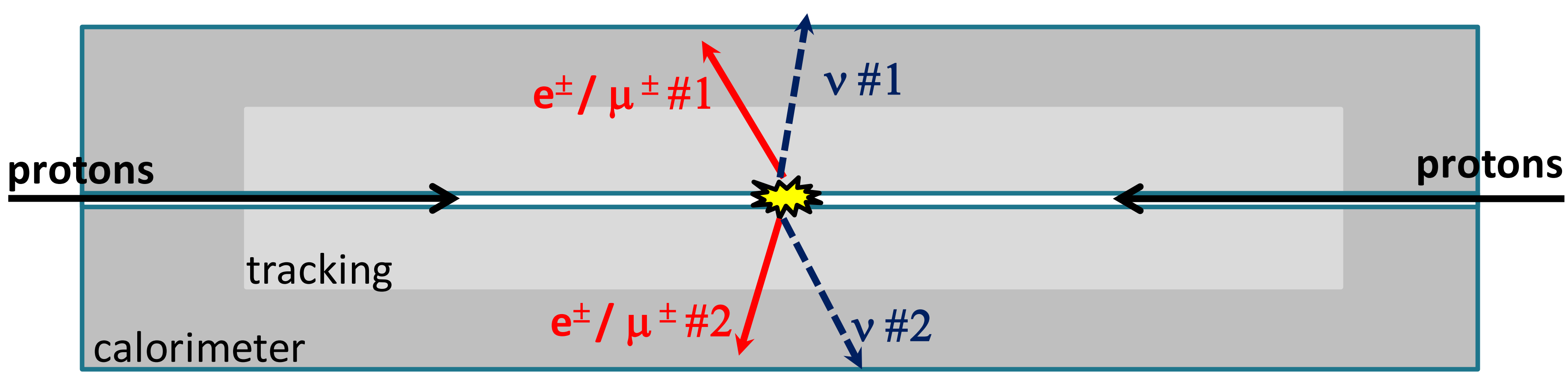


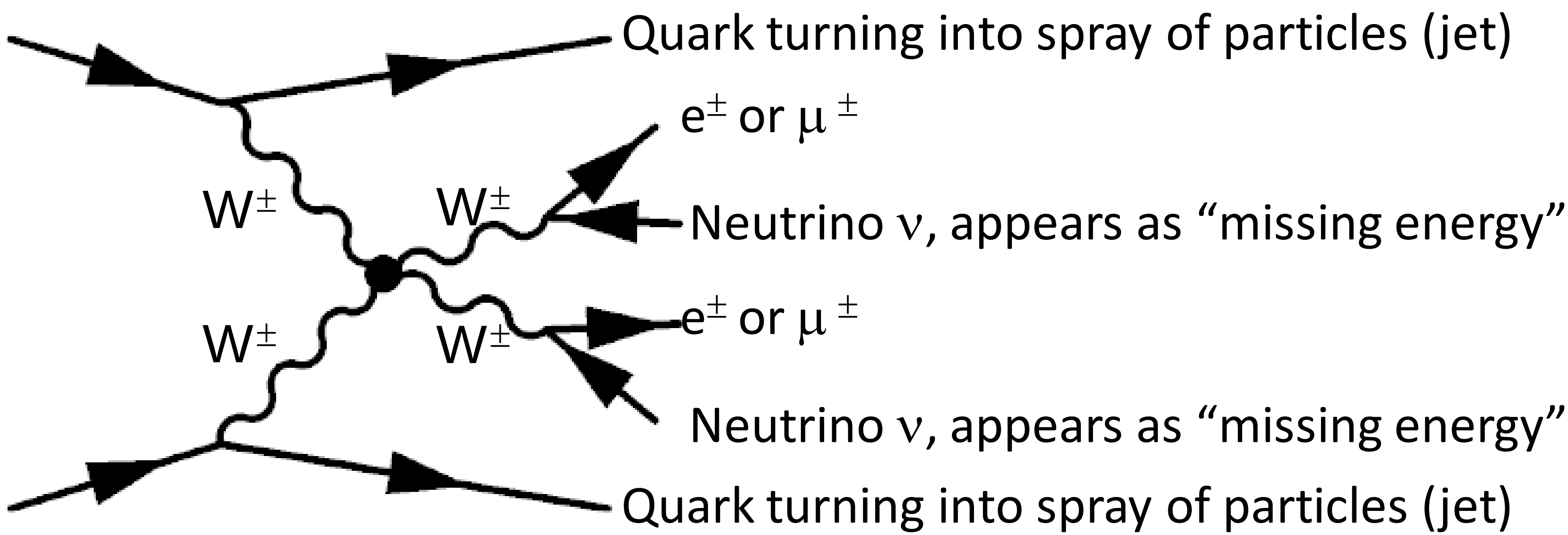


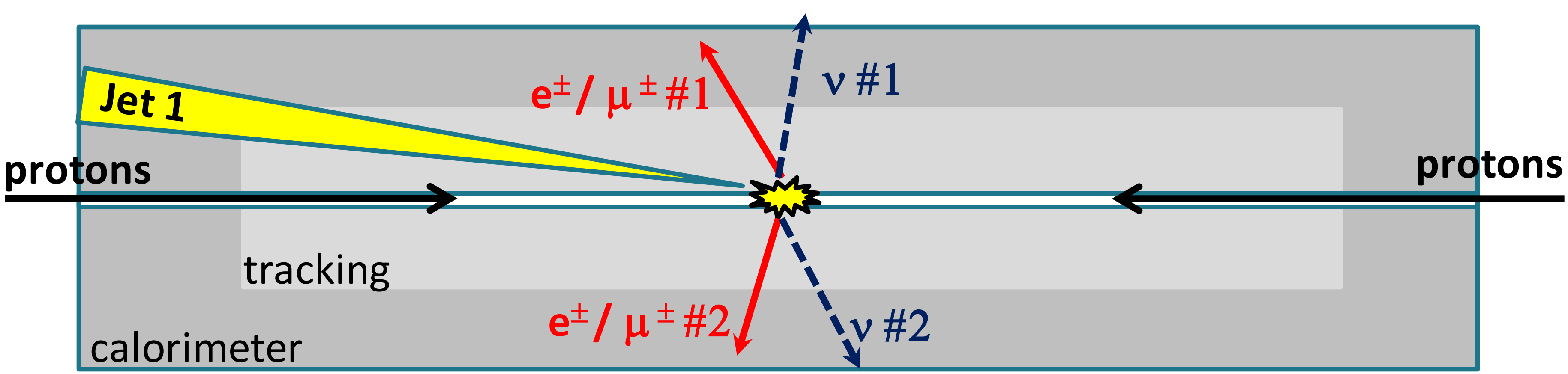
$W^\pm W^\pm \rightarrow W^\pm W^\pm$ Fingerprint



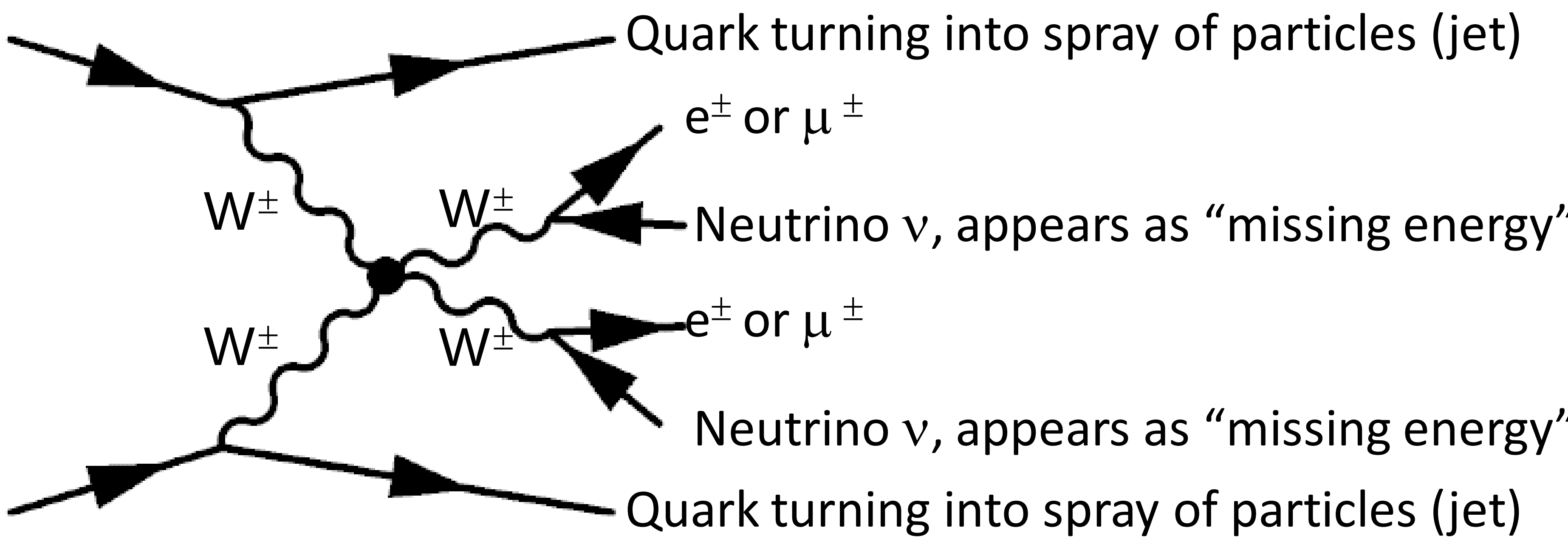


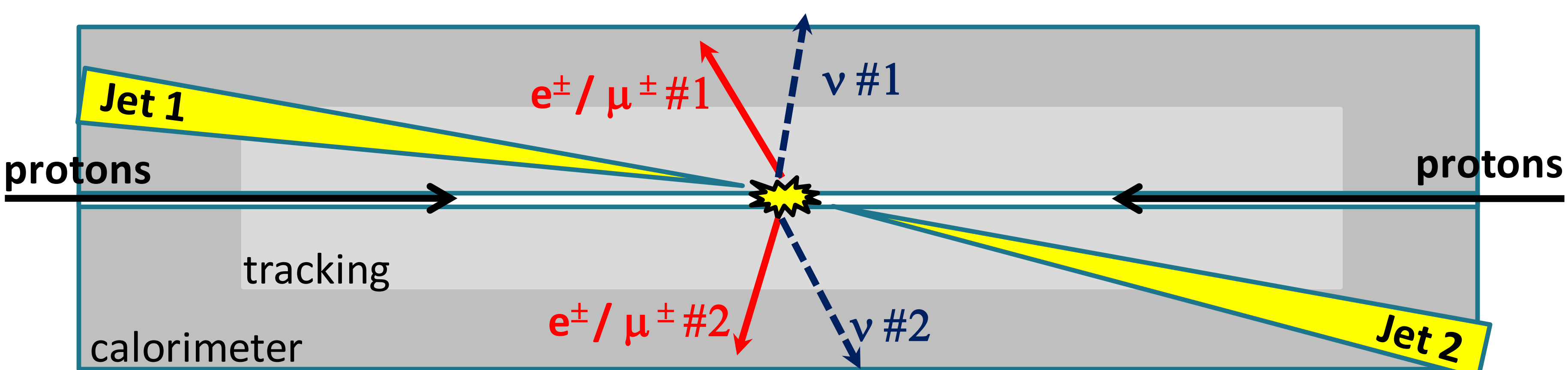
$W^{\pm}W^{\pm} \rightarrow W^{\pm}W^{\pm}$ Fingerprint





$W^{\pm}W^{\pm} \to W^{\pm}W^{\pm}$ Fingerprint

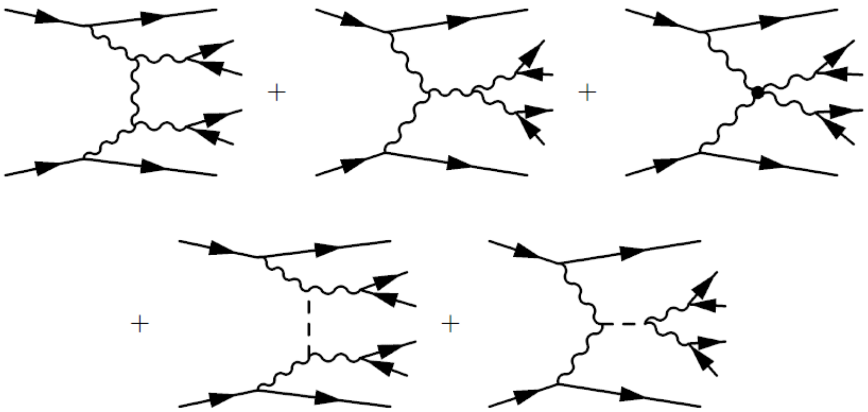




VVjj classification

- pure electroweak VV jj production:

VBS diagrams (what we're after):



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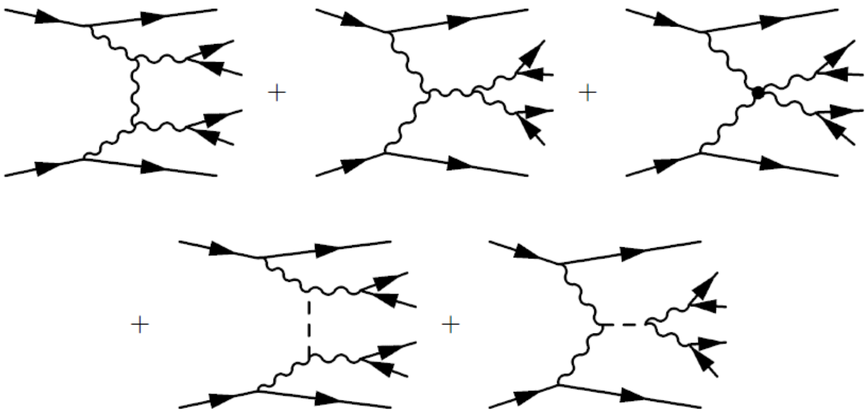
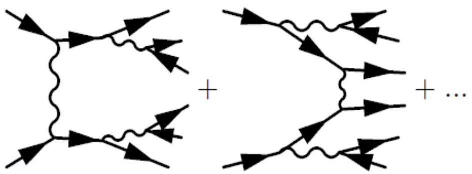


non-VBS diagrams, gauge invariantly

not separable:



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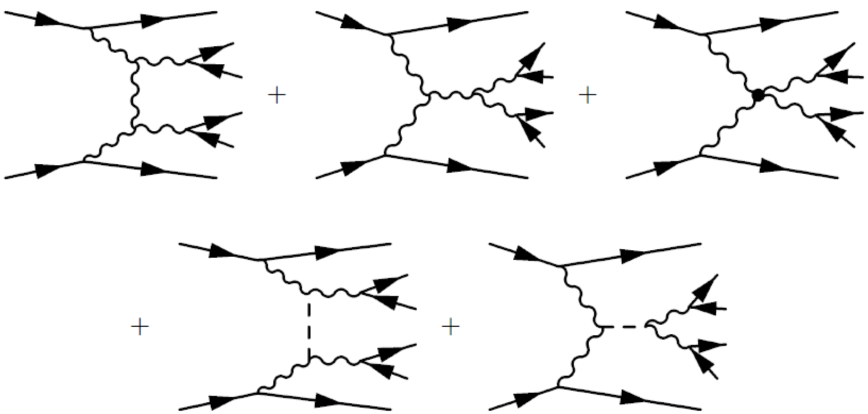

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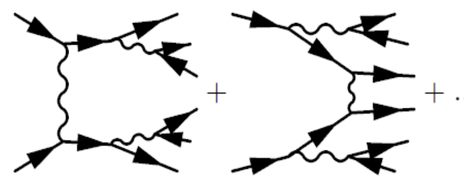
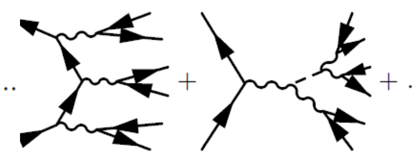


separable:



suppressed by kinematic cuts

VVjj classification

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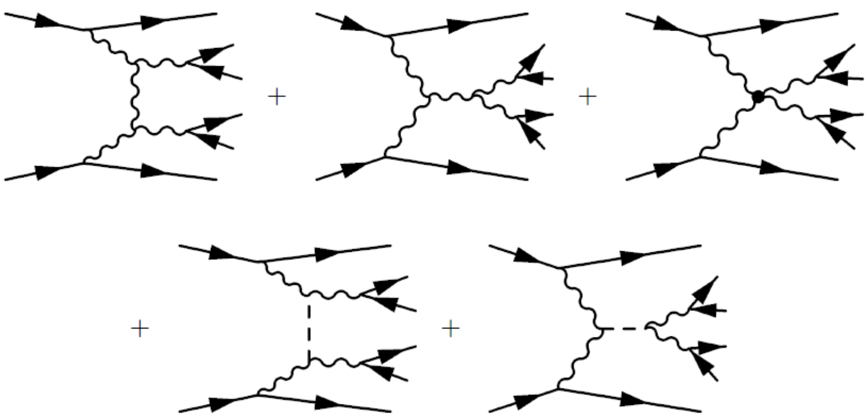
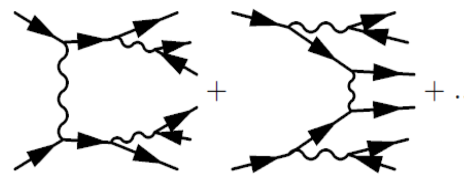
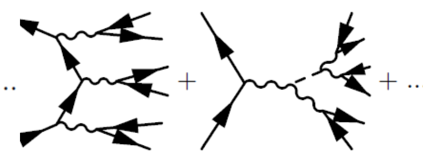


non-VBS diagrams, gauge invariantly

not separable:



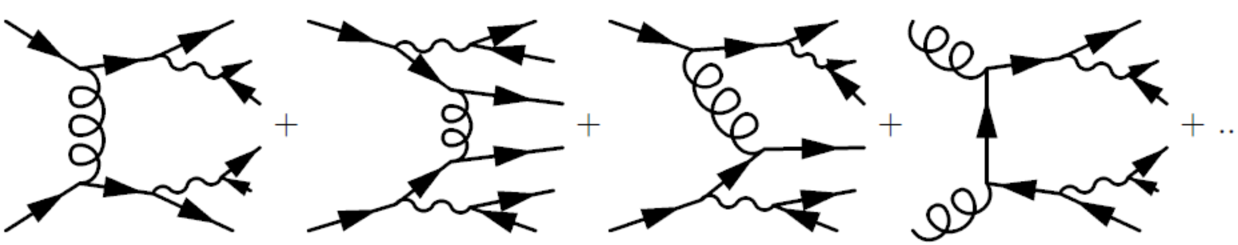
separable:



suppressed by kinematic cuts

- "strong" VV jj production:

gauge invariantly separable, suppressed by kinematic cuts



WBS Channels to Study

- LO WBS cross sections for pp collisions at 8 TeV, split by final state, EW and QCD contributions (SHERPA w/ p_T (l) > 5 GeV, m_{ll} > 4 GeV, p_T (j) > 10 GeV)

Final state	VV	σ_{VVjj} (EW) [fb]	σ_{VVjj} (QCD) [fb]
$\ell^+\nu\ \ell^-\nu$ jj (opposite sign)	W^+W^- + ZZ	94	3192
$\ell^+\ell^-\ \ell^\pm\nu$ jj	$W^\pm Z$	30	687
$\ell^+\ell^-\ \ell^+\ell^-$ jj	ZZ	2	106
$\ell^\pm\nu\ \ell^\pm\nu$ jj (same sign)	$W^\pm W^\pm$	20	19

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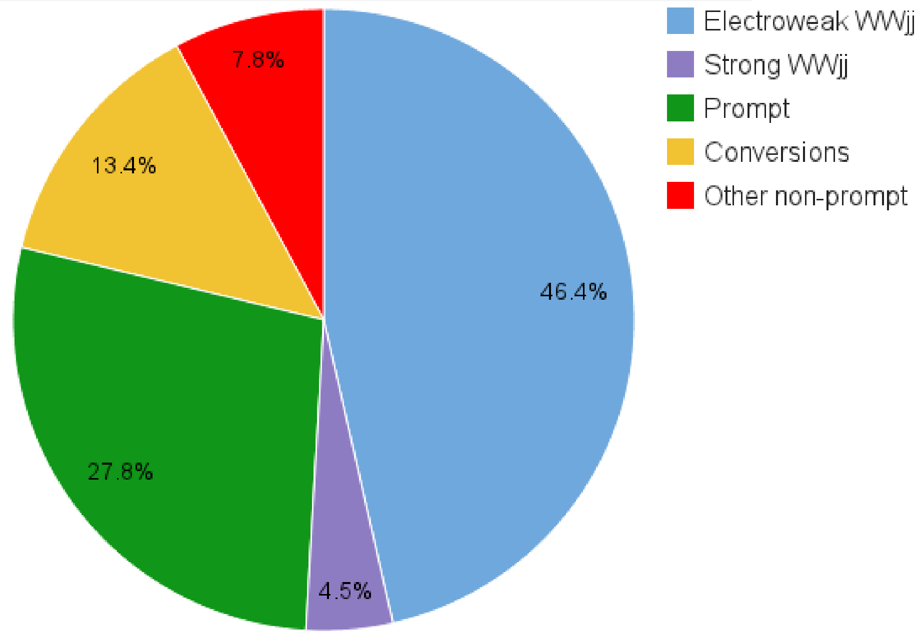
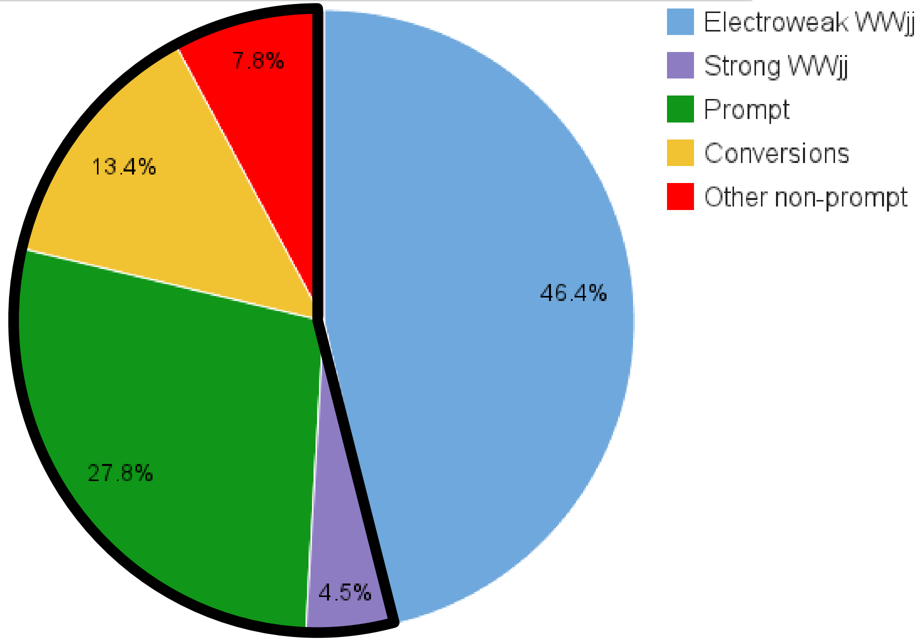
$\ell^+\ell^-\ \ell^+\ell^-$ jj	ZZ	2	106
$\ell^\pm\nu\ \ell^\pm\nu$ jj (same sign)	$W^\pm W^\pm$	20	19

+ Same-sign requirement suppresses Z, top backgrounds
+ Greatly reduced QCD background
- Understand charge-mis-ID, jets faking leptons

$W^{\pm}W^{\pm}jj$ Background Sources

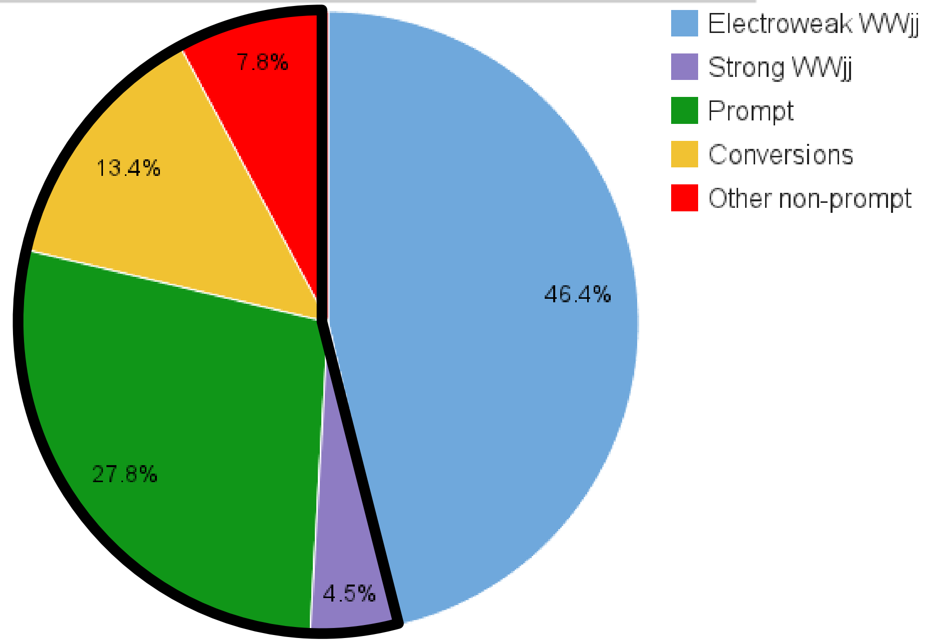


$W^{\pm}W^{\pm}jj$ Background Sources

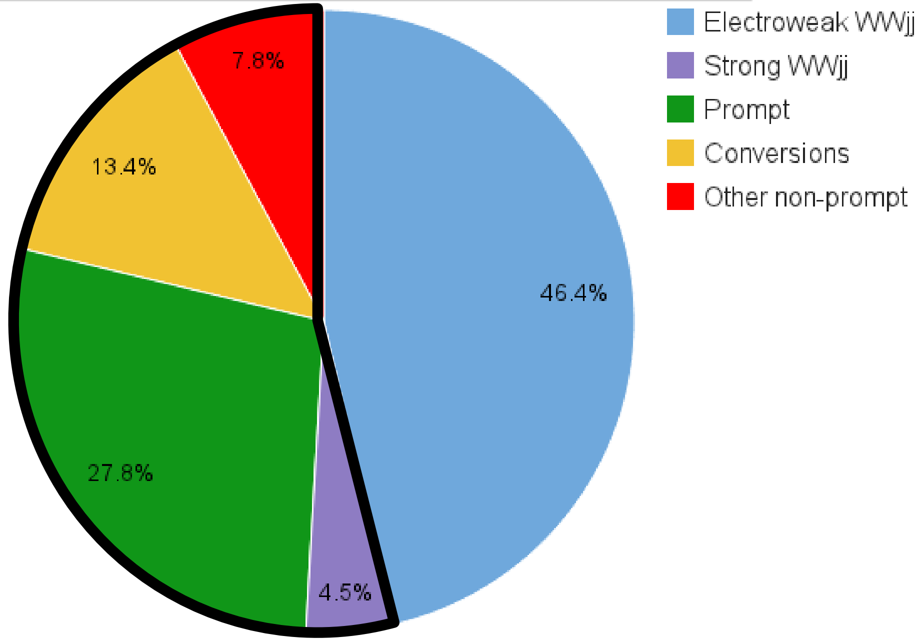


$W^{\pm}W^{\pm}jj$ Background Sources

❖ prompt background (28%):
  - 3 or more prompt leptons:
    - o WZ/γ*+jets
    - o ZZ+jets
    - o $t\bar{t}$+W/Z
    - o tZj

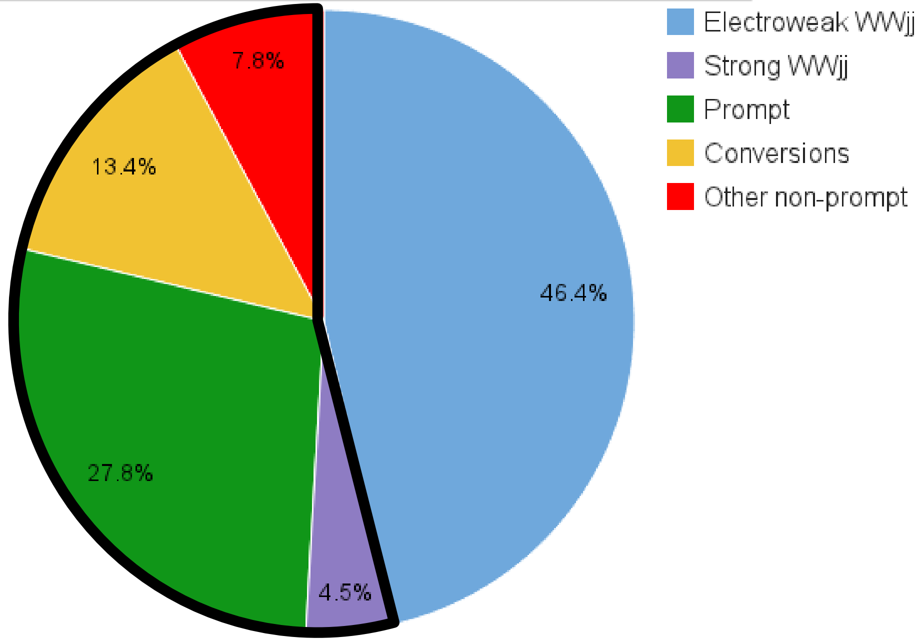


$W^{\pm}W^{\pm}jj$ Background Sources



- **prompt background (28%):**
  - 3 or more prompt leptons:
    - o WZ/γ^*+jets
    - o ZZ+jets
    - o $t\bar{t}$+W/Z
    - o tZj
- **conversions (13%):**
  - prompt photon conversion
    - o $W\gamma$
  - charge mis-ID due to bremsstrahlung with conversion (data driven)
    - o Z/γ^*+jets, di-leptonic $t\bar{t}$ decays, W^+W^-

$W^{\pm}W^{\pm}jj$ Background Sources



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    - WZ/γ^*+jets
    - ZZ+jets
    - $t\bar{t}$+W/Z
    - tZj
- conversions (13%):
  - prompt photon conversion
    - $W\gamma$
  - charge mis-ID due to bremsstrahlung with conversion (data driven)
    - Z/γ^*+jets, di-leptonic $t\bar{t}$ decays, W^+W^-
- other non-prompt background (8%):
  - leptons from hadron decays in jets (data driven)
    - W+jets, semi-leptonic $t\bar{t}$ decays, multi-jet events

$W^{\pm}W^{\pm}jj$ Background Sources

- prompt background (28%):
  - 3 or more prompt leptons:
    - WZ/γ^*+jets
    - ZZ+jets
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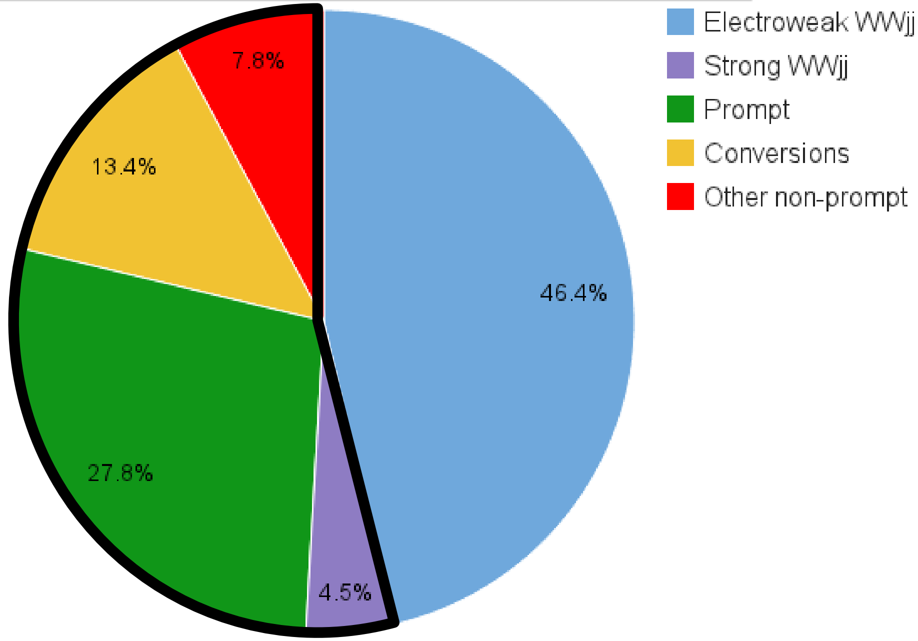
    - $W\gamma$
  - charge mis-ID due to bremsstrahlung with conversion (data driven)
    - Z/γ^*+jets, di-leptonic $t\bar{t}$ decays, W^+W^-
- other non-prompt background (8%):
  - leptons from hadron decays in jets (data driven)
    - W+jets, semi-leptonic $t\bar{t}$ decays, multi-jet events
- WW jj strong (5%)



Background Control Regions

- Test background modelling with dedicated control regions
  - prompt background: trilepton control region (invert 3rd lepton veto, drop cuts on m_{jj}, Δy_{jj})
  - conversion and prompt backgrounds: control region with at most one jet ("≤ 1 jet")
  - non-prompt leptons from top: at least one jet identified as b-jet
  - combined background model: invert m_{jj} selection

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Control Region		Trilepton	≤ 1 jet	b-tagged	Low m_{jj}
$e^{\pm}e^{\pm}$	exp.	36 ± 6	278 ± 28	40 ± 6	76 ± 9
	data	40	288	46	78
$e^{\pm}\mu^{\pm}$	exp.	110 ± 18	288 ± 42	75 ± 13	127 ± 16
	data	104	328	82	120
$\mu^{\pm}\mu^{\pm}$	exp.	60 ± 10	88 ± 14	25 ± 7	40 ± 6
	data	48	101	36	30

Background Control Regions

❖ Test backg... ...rol regions

- promp... ...rd lepton veto,
  drop c...
- conver... ...with at most one
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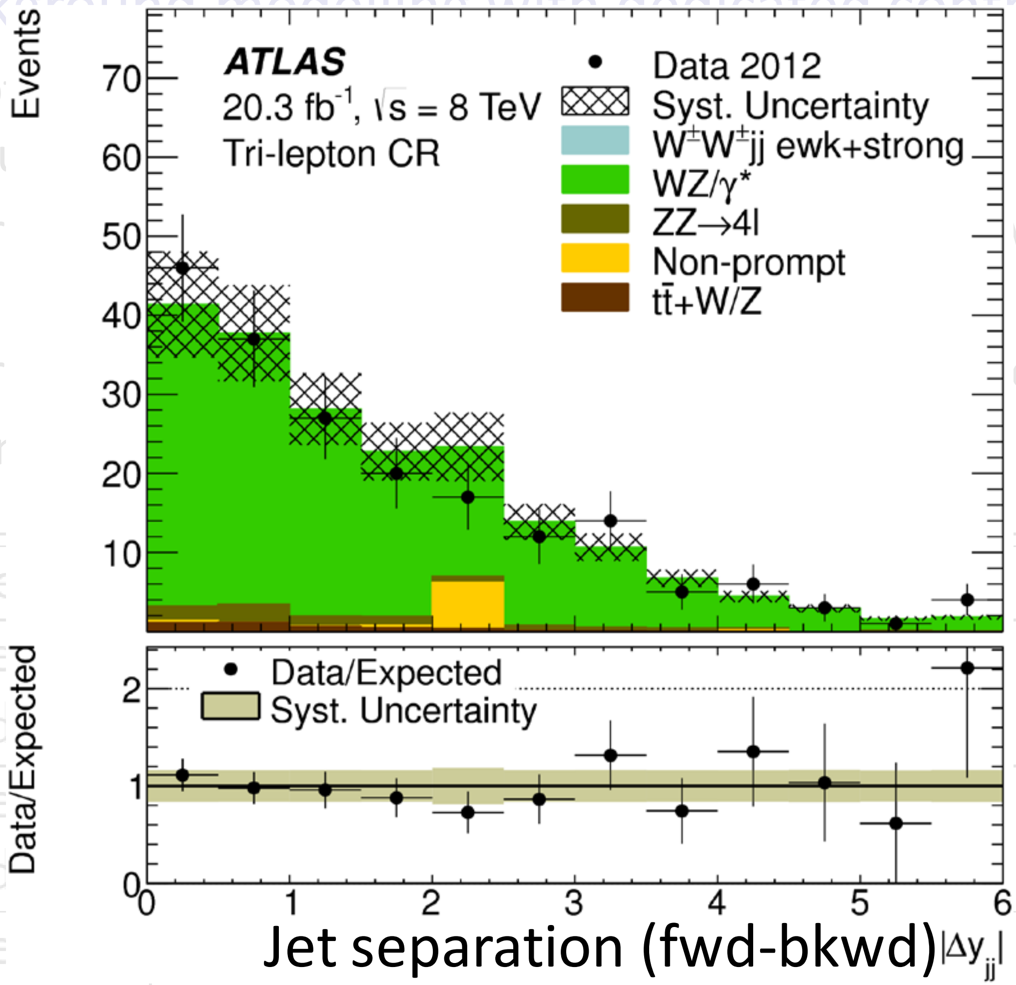
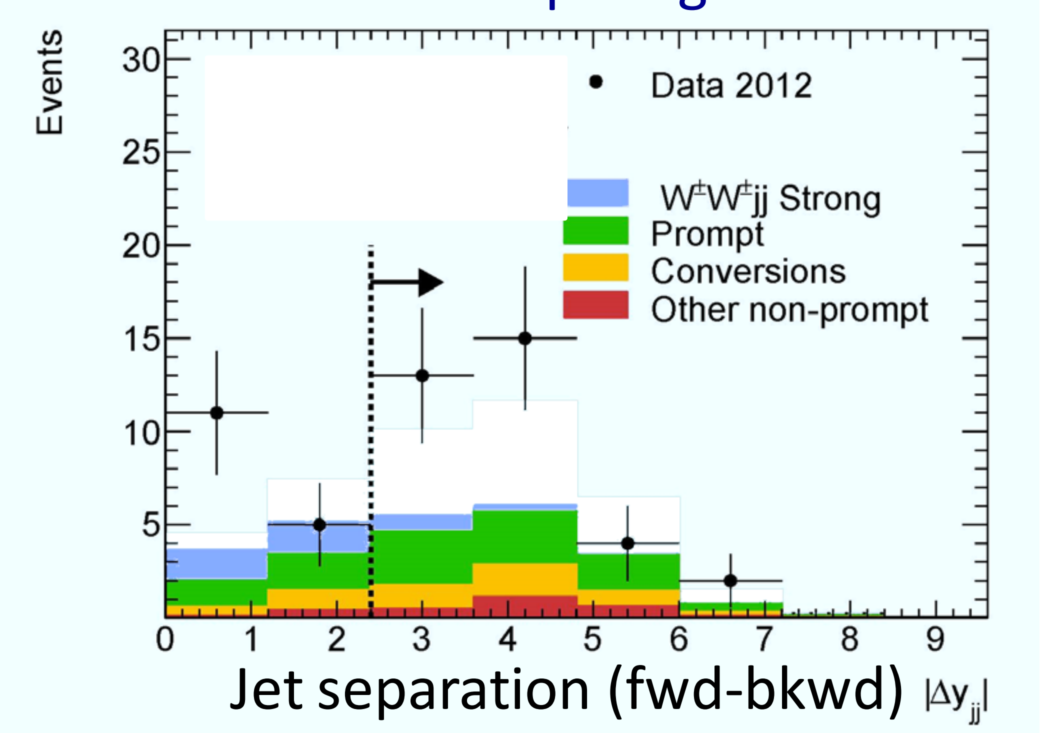


Control Re...				Low m_{jj}
$e^{\pm}e^{\pm}$	e...			76 ± 9
	d...			78
$e^{\pm}\mu^{\pm}$	e...			127 ± 16
	d...			120
$\mu^{\pm}\mu^{\pm}$	e...			40 ± 6
data	48	101	36	30

What do we see?

❖ Final selection – requiring forward-backward jets:



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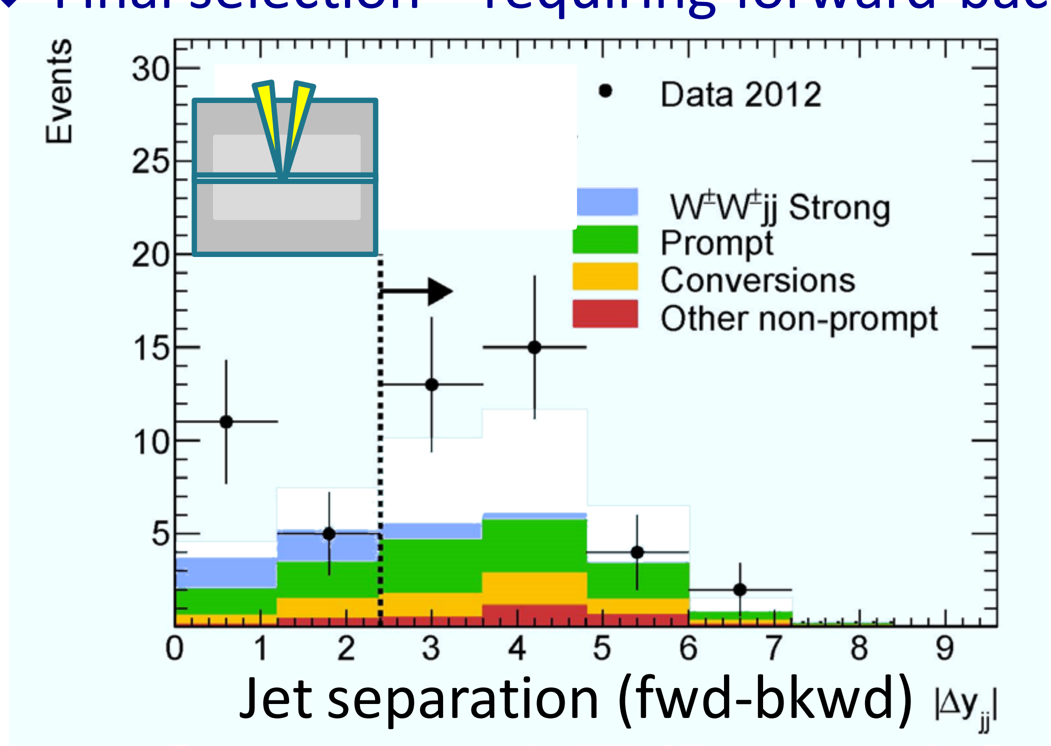

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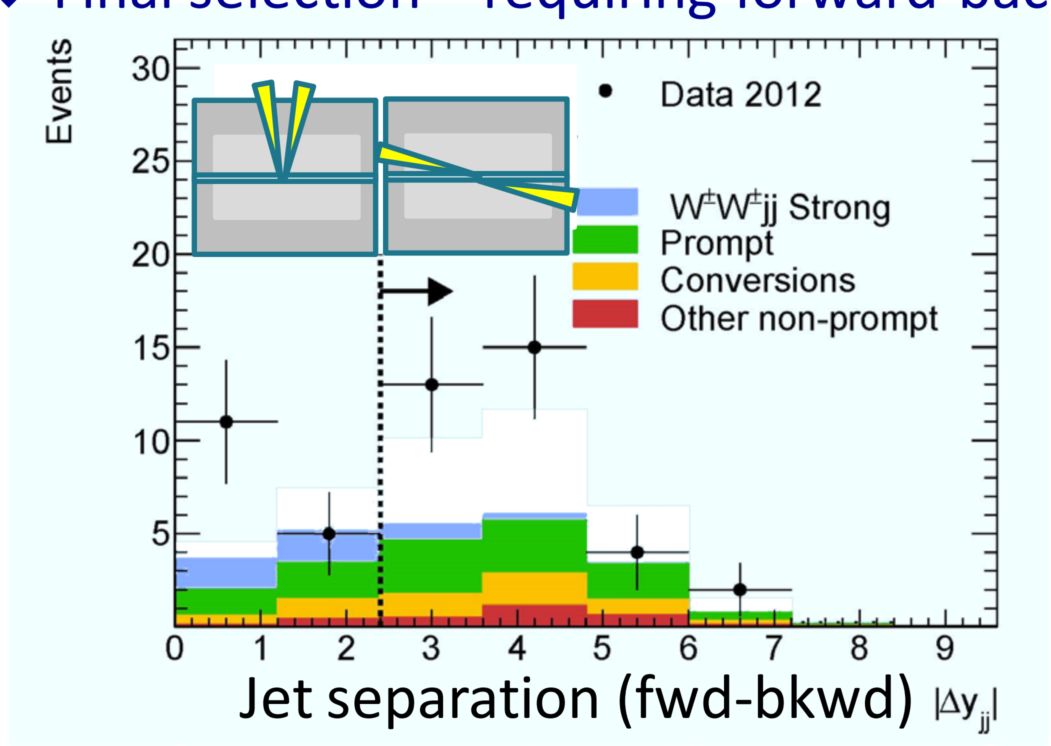

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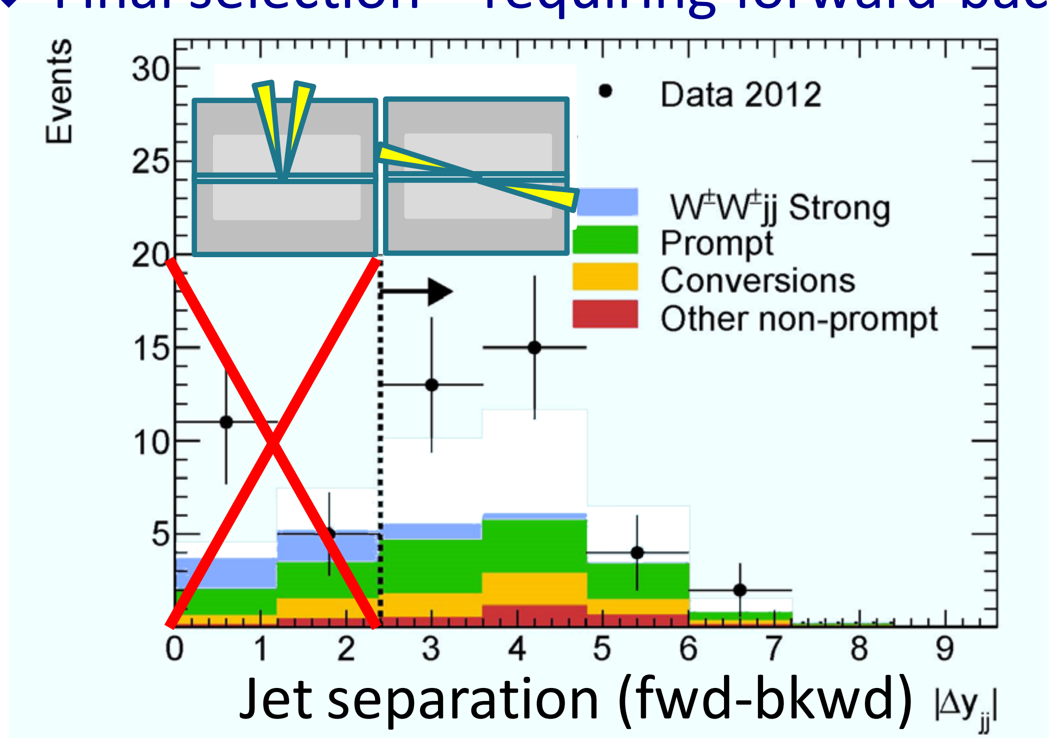

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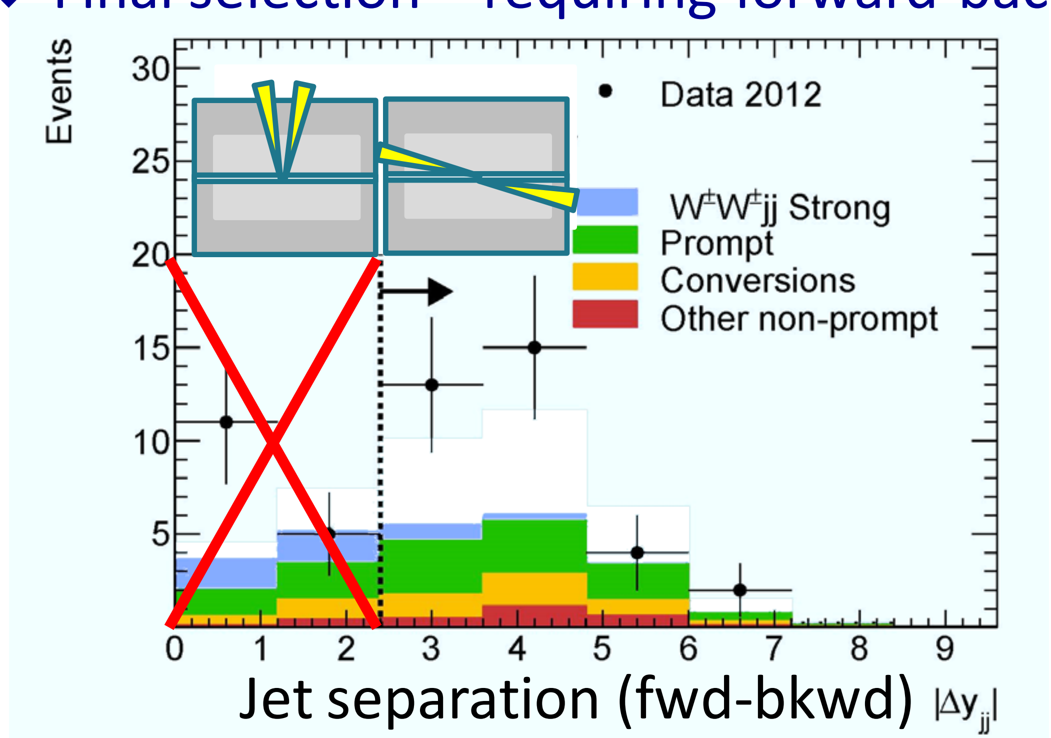

Predicted background	**15.9±1.9**
Observed events	**34**

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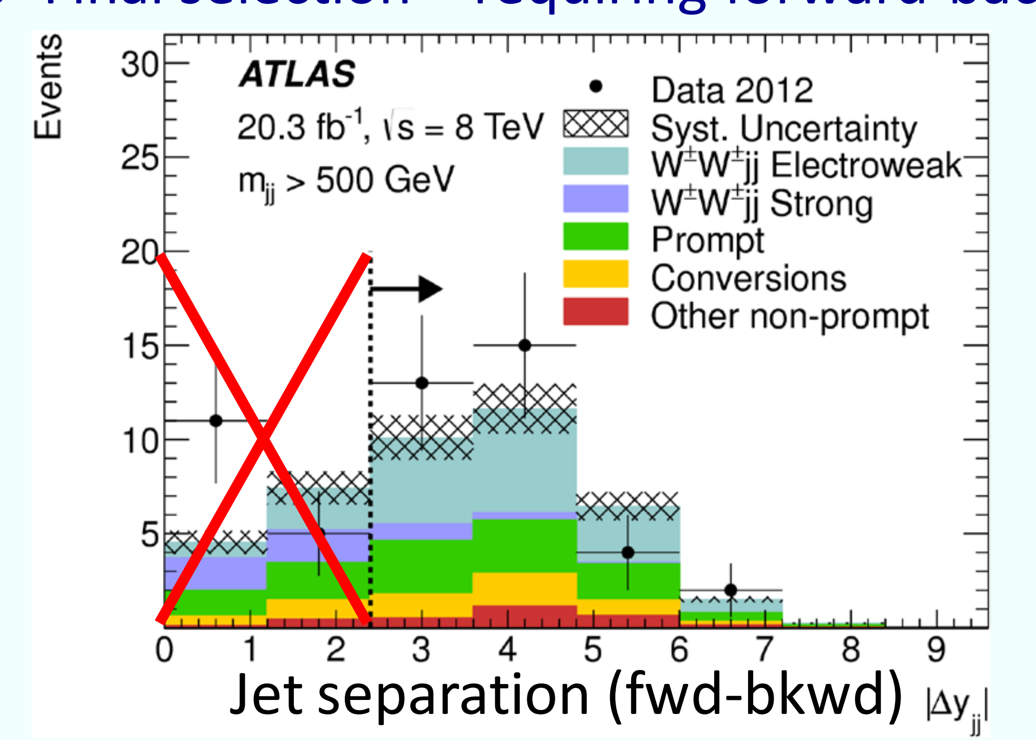

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Predicted signal	**13.9±0.8**
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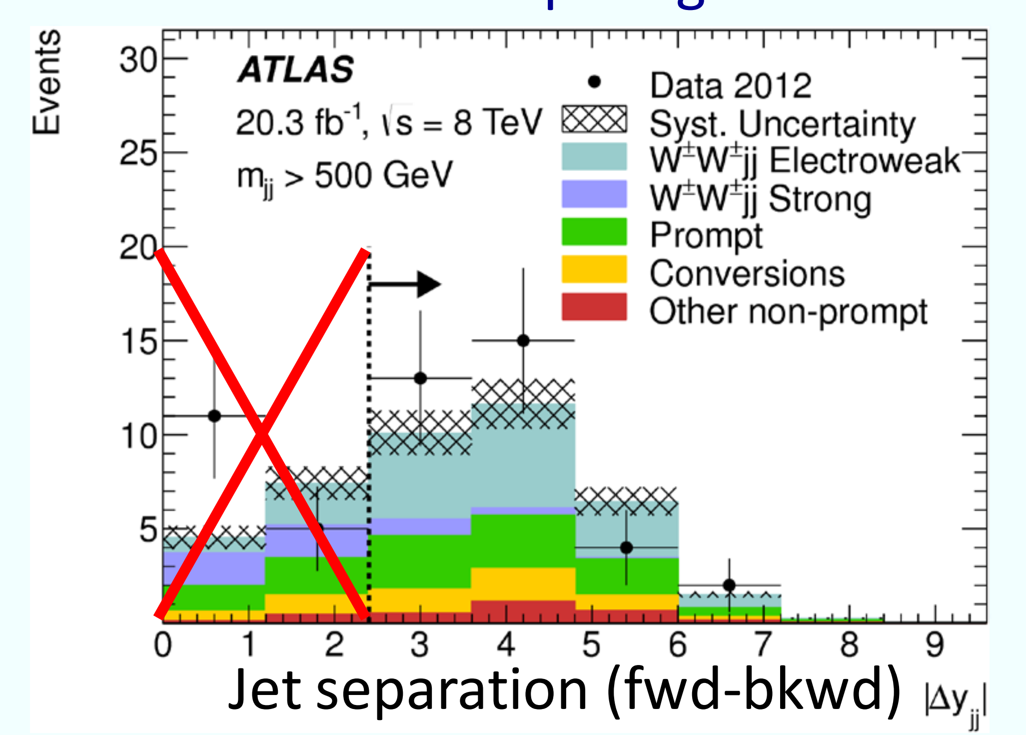

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Published in PRL:
Phys. Rev. Lett. 113 (2014) 141803

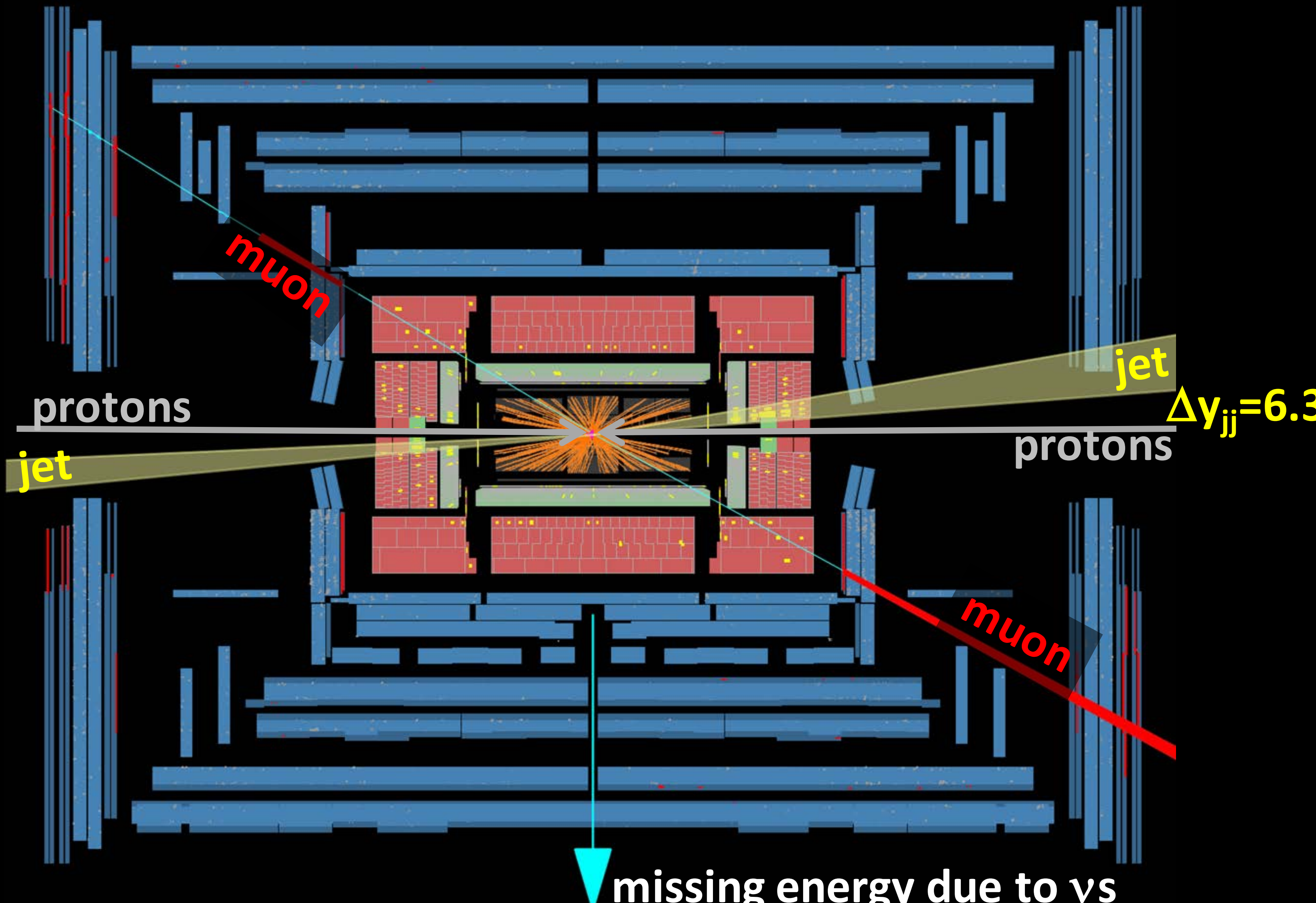
❖ **First evidence** (3.6 σ) for EW WWjj production

$$\sigma^{EW}_{W^\pm W^\pm jj} = 1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})\ \text{fb} \quad \text{SM}: \sigma^{EW}_{W^\pm W^\pm jj}(\text{NLO}) = 0.95 \pm 0.06\ \text{fb}$$

❖ **First access** to WWWW vertex

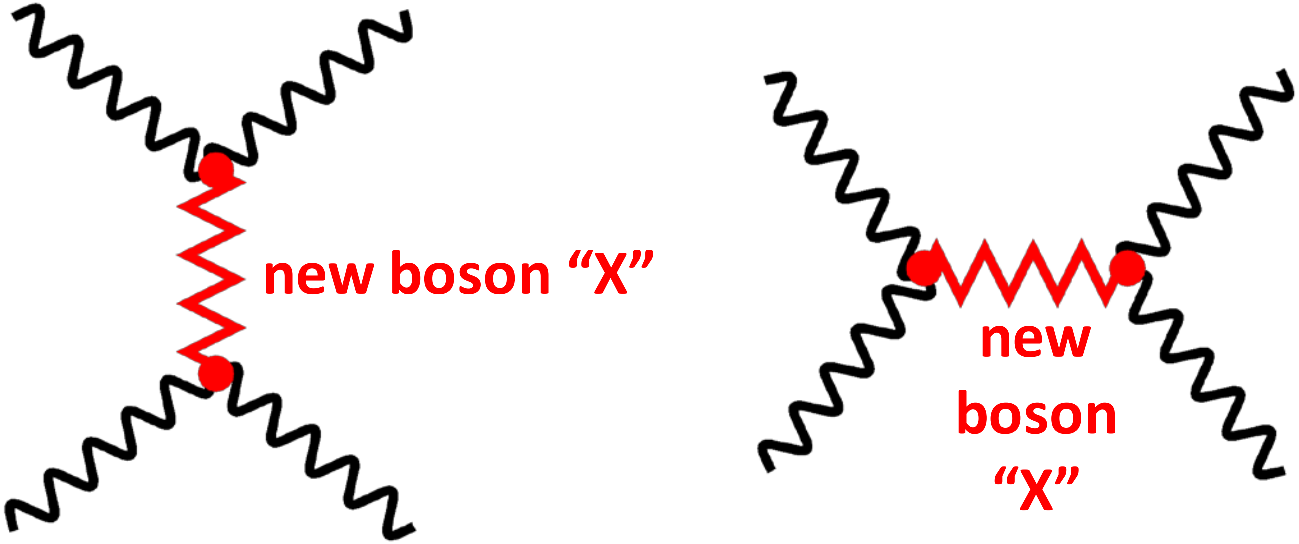
❖ **Starting point** of VBS program at LHC!

$W^{\pm}W^{\pm}jj \rightarrow \ell\nu\ell\nu jj$ candidate event



Exploring the unknown

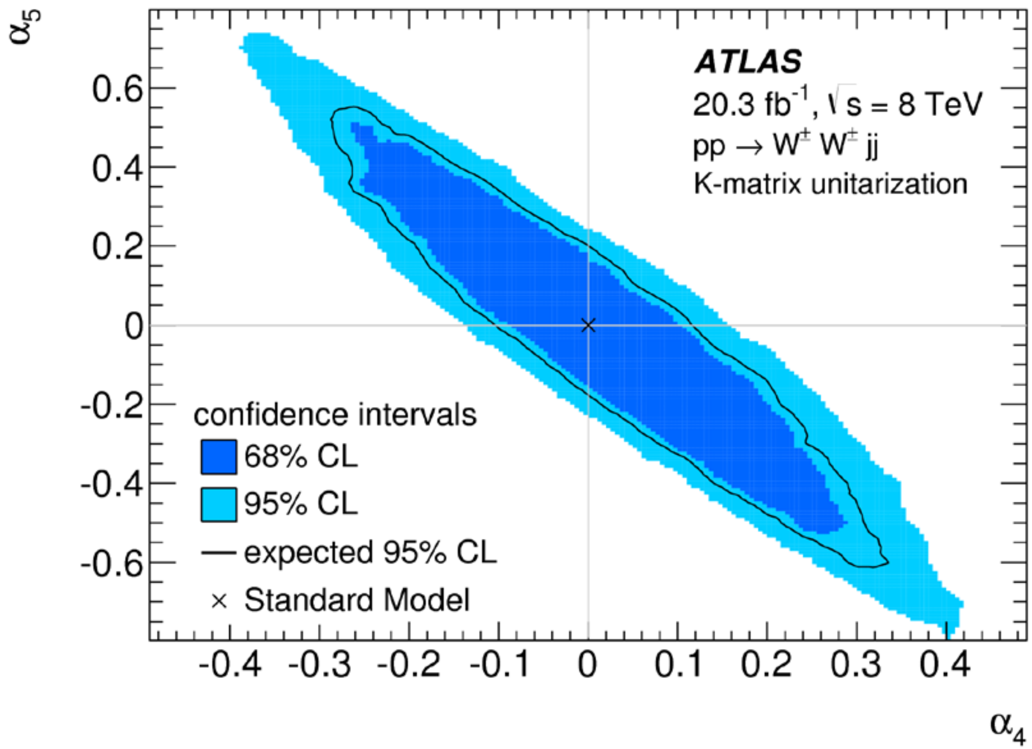
- Wealth of models propose extensions to Standard Model (which is known to be incomplete):



- Can search for specific models, or do a model-independent search for modifications from the Standard Model: "Effective Field Theory"
- "New Physics" will modify production rate and kinematics of decay products

First constraints on New Physics

- Use our measurement to constrain admixture of anomalous couplings α_4, α_5 (both = 0 in Standard Model):



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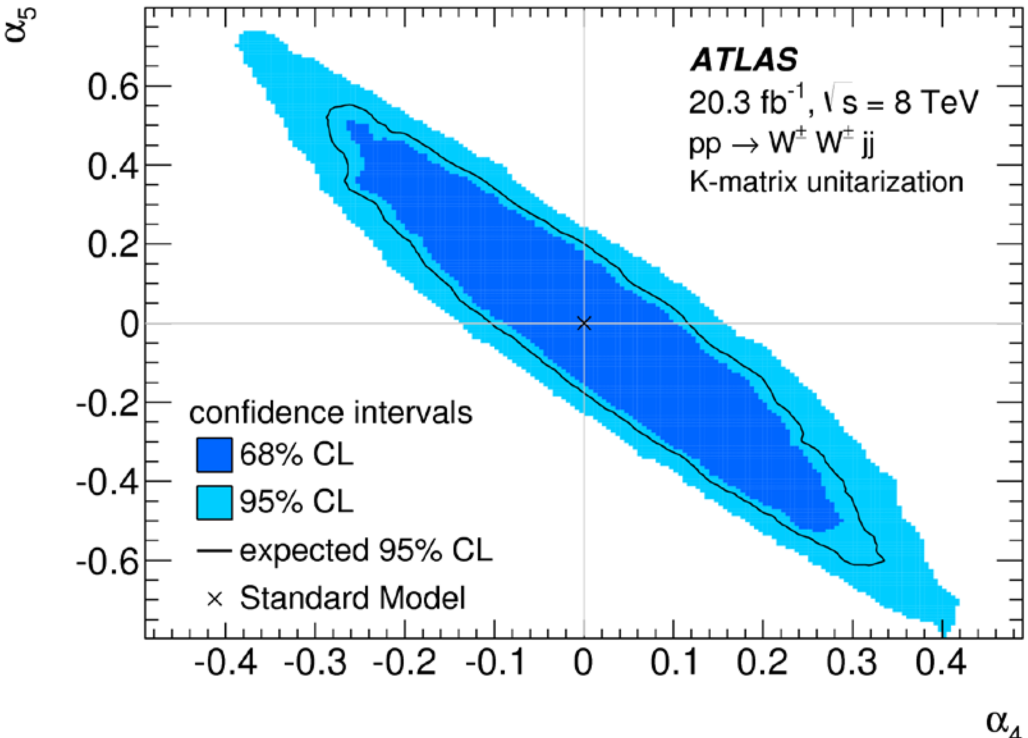

1D 95% CL intervals

expected:

$-0.10 < \alpha_4 < 0.12$

$-0.18 < \alpha_5 < 0.20$

observed:

$-0.14 < \alpha_4 < 0.16$

$-0.23 < \alpha_5 < 0.24$

(respective other $\alpha_i = 0$)

- **First** limits on anomalous quartic couplings

First constraints on New Physics

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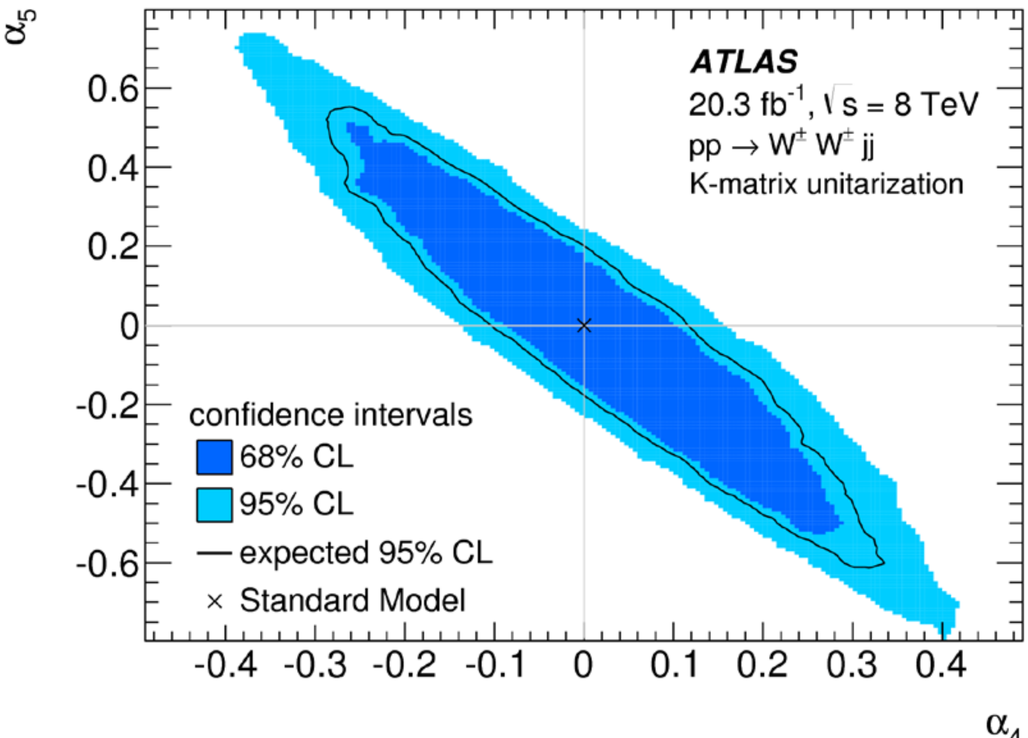

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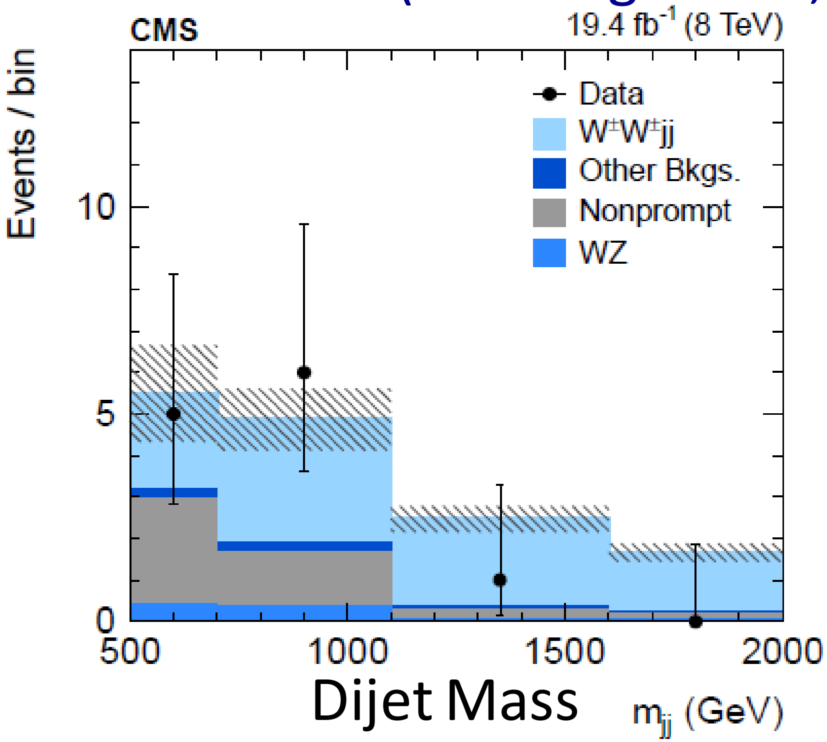
- ❖ **First** limits on anomalous quartic couplings
- ❖ Scale of new physics: Λ > 500 - 650 GeV

CMS $W^{\pm}W^{\pm}jj$ result

❖ Final selection (same signature, different cuts): [PRL 114 (2015) 051801]



Dijet Mass

❖ Significance for EW WWjj production: 2.9σ (exp), **1.9σ (obs)**

❖ $\sigma^{EW}_{W^{\pm}W^{\pm}jj} = 4.0^{+2.4}_{-2.0}(\text{stat})^{+1.1}_{-1.0}(\text{syst})\ \text{fb} \quad \text{SM}: \sigma^{EW}_{W^{\pm}W^{\pm}jj}(\text{NLO}) = 5.8 \pm 1.2\ \text{fb}$

CMS W±W±jj result

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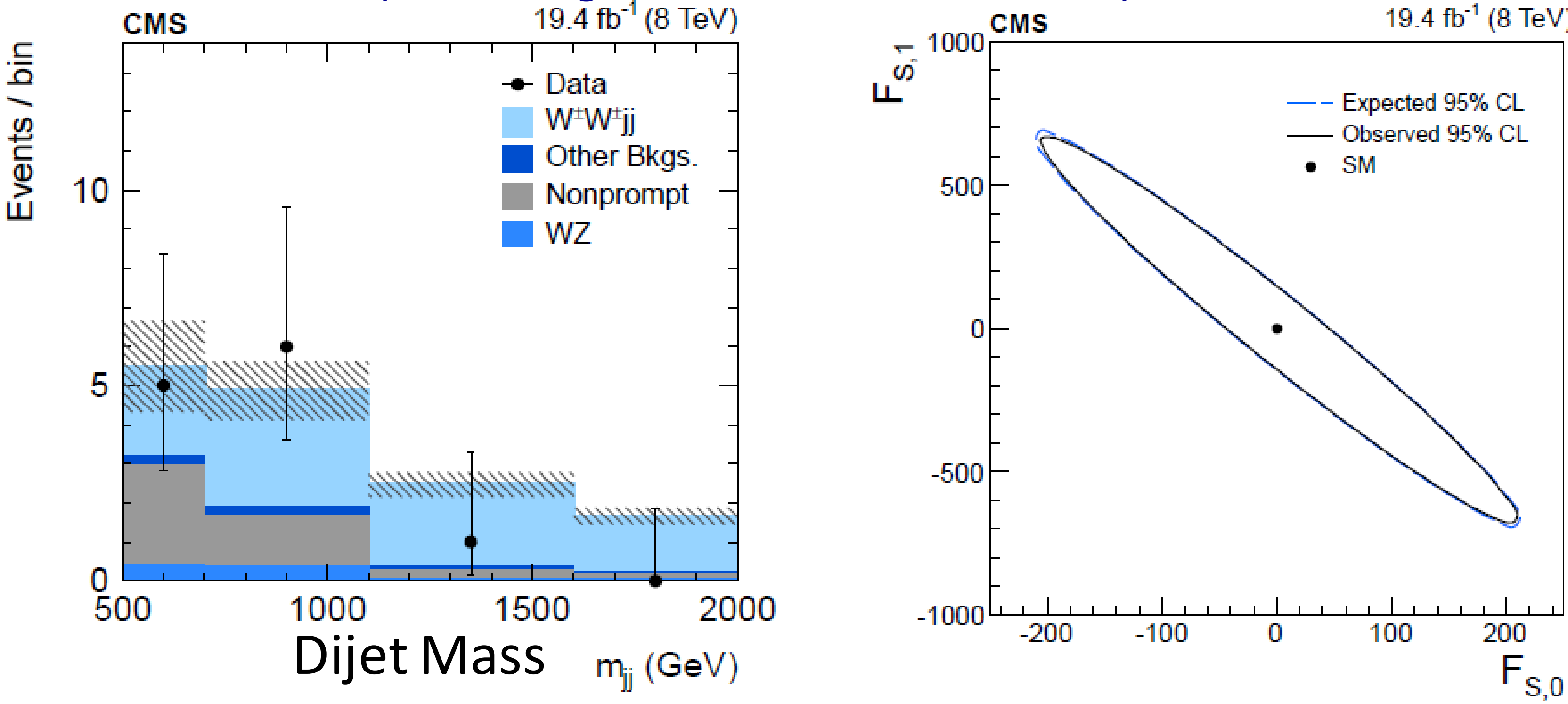

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❖ Limits on anomalous quartic gauge couplings (EFT model)

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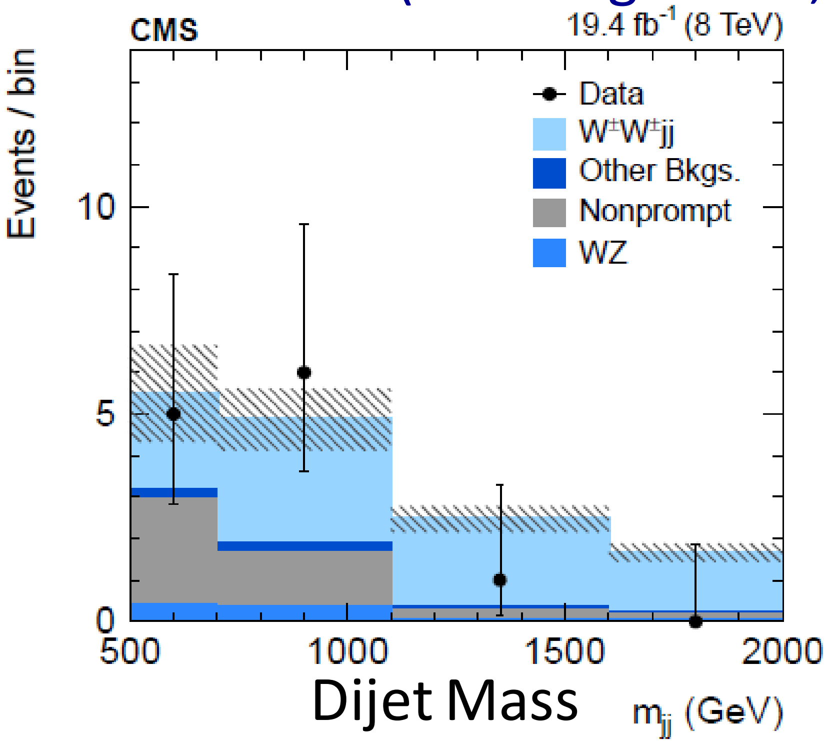

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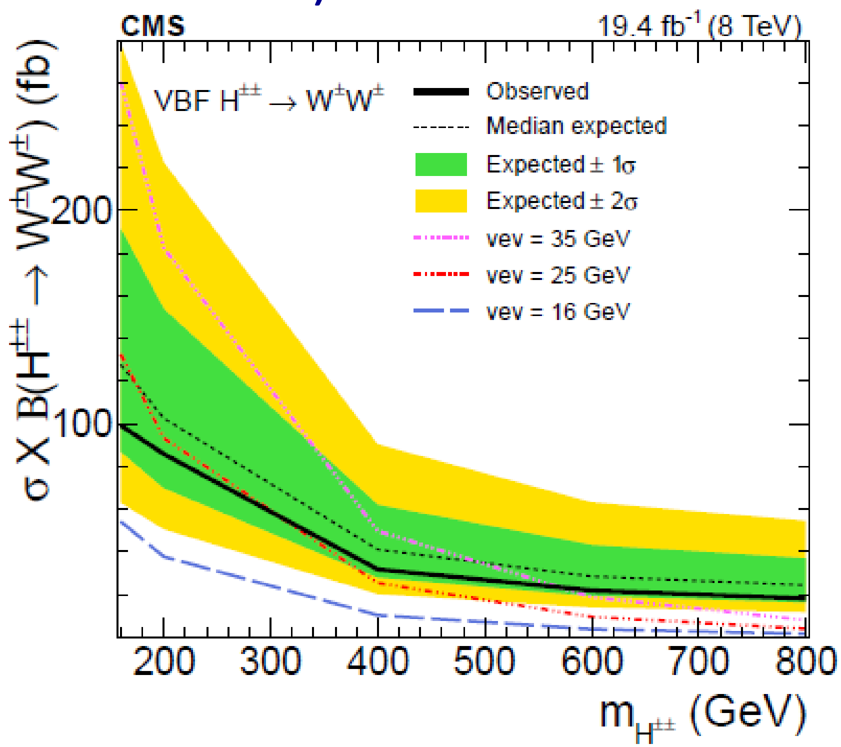

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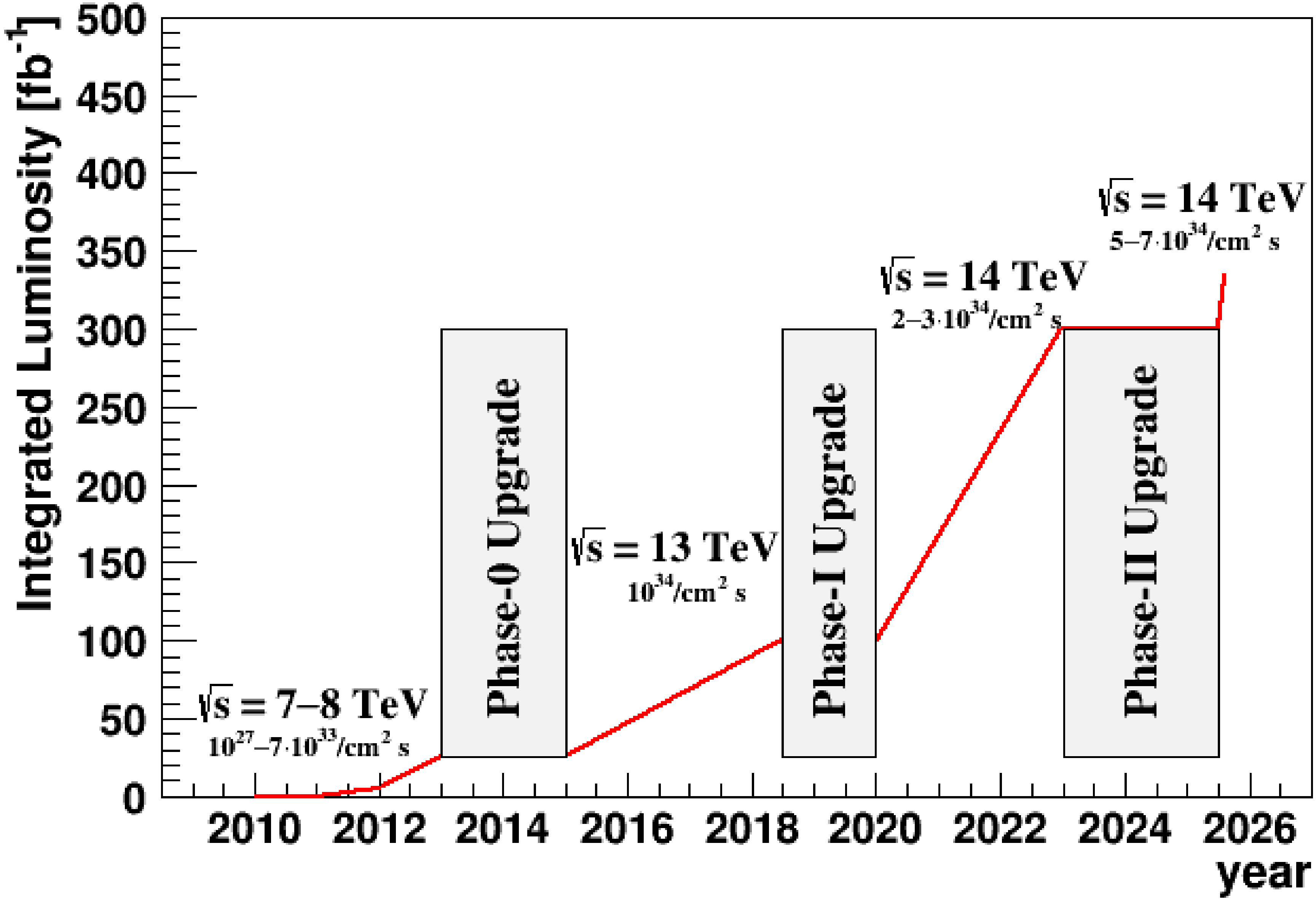
❖ Limits on anomalous quartic gauge couplings (EFT model)

❖ **Explicit BSM (Georgi-Machacek) model test: doubly-charged Higgs**

LHC Run Plan



Integrated Luminosity [fb^{-1}]
500
450
400
350
300
250
200
150
100
50
0
2010
2012
2014
2016
2018
2020
2022
2024
2026
year
$\sqrt{s}$ = 7–8 TeV
10^{27}–$7\cdot10^{33}$/cm^2 s
Phase-0 Upgrade
$\sqrt{s}$ = 13 TeV
10^{34}/cm^2 s
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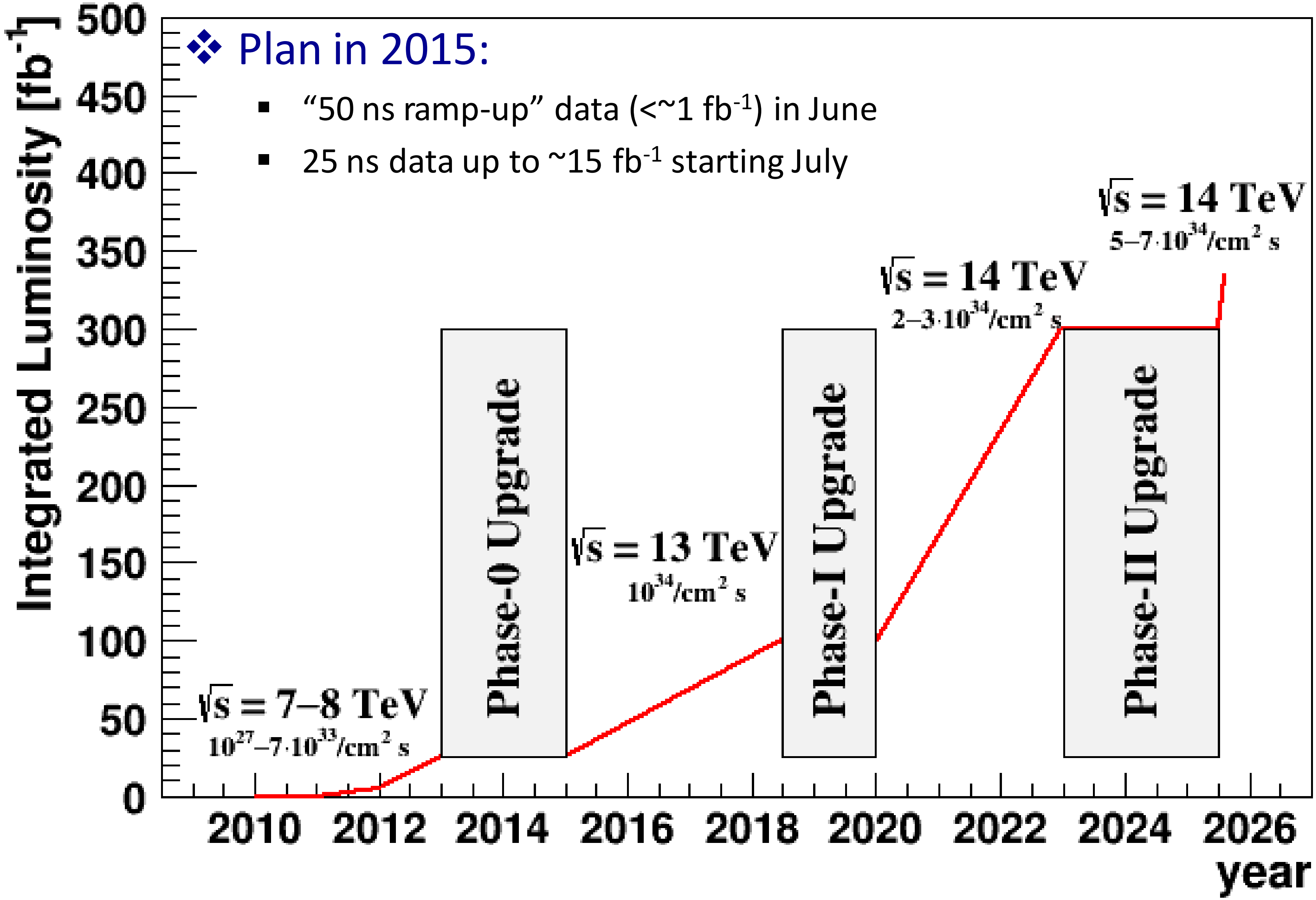
LHC Run Plan

❖ Plan in 2015:

- “50 ns ramp-up” data (<~1 fb^{-1}) in June
- 25 ns data up to ~15 fb^{-1} starting July



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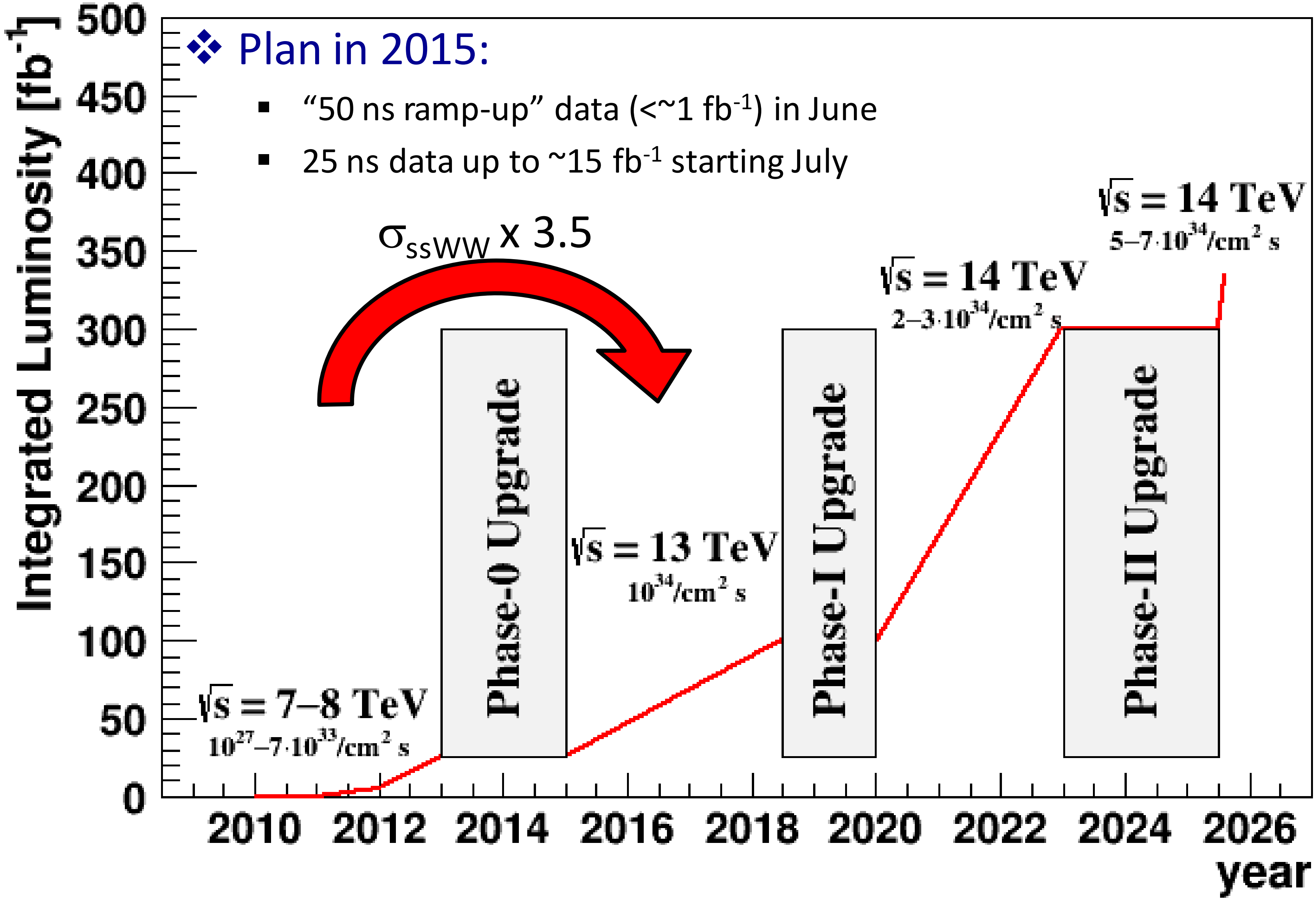
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$\sqrt{s}$ = 7–8 TeV
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50
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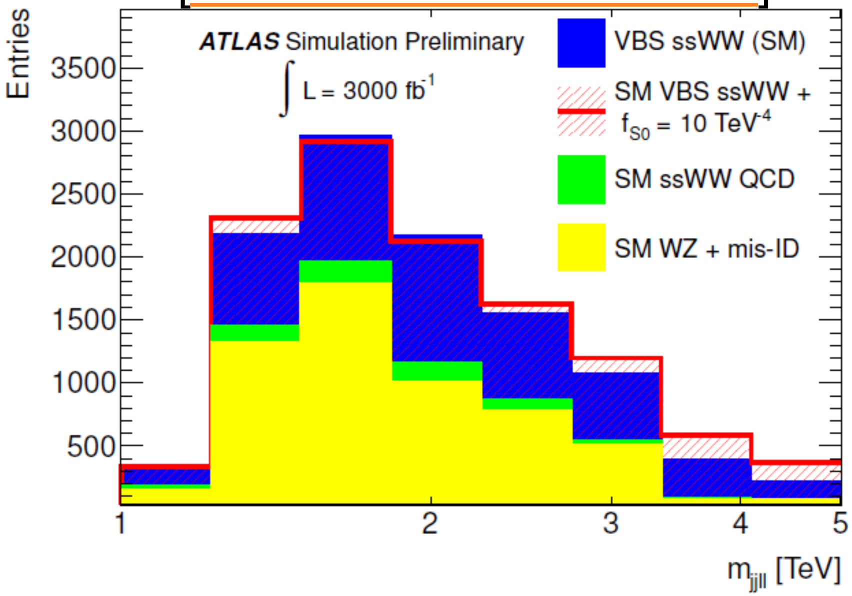
2026
year

Looking forward

- What could we see w/ 15 vs. 150 times the current dataset?

[ATL-PHYS-PUB-2013-006]



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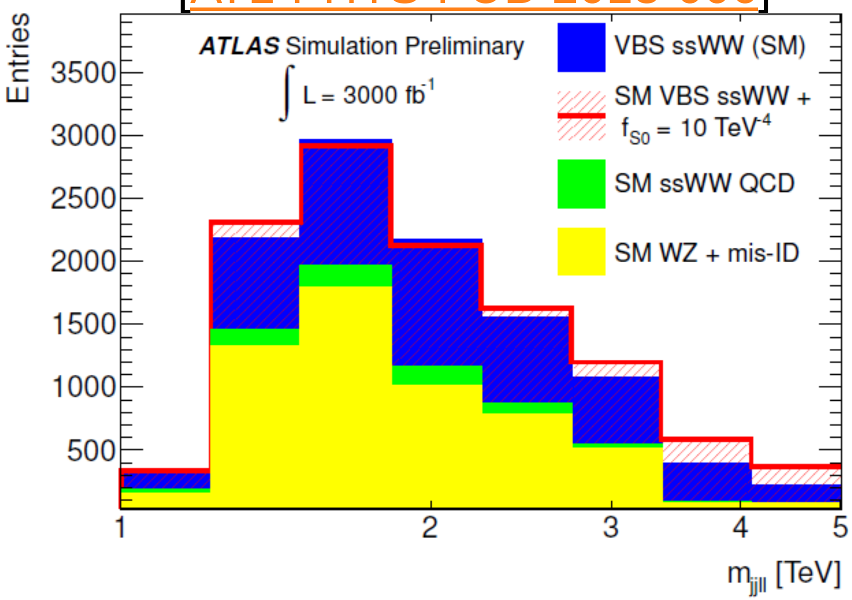


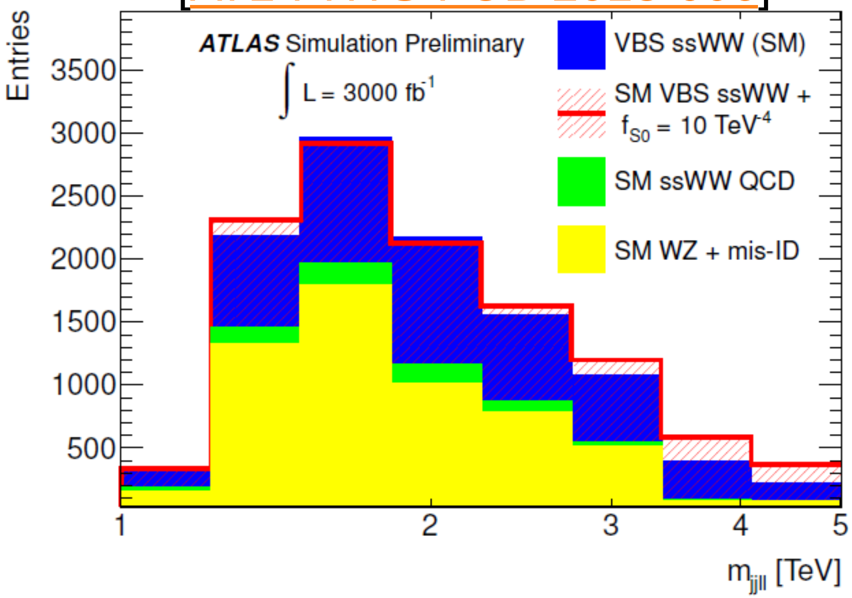
- Gain in sensitivity (5σ aQGC discovery) for HL-LHC: **factor of two.**

Looking forward

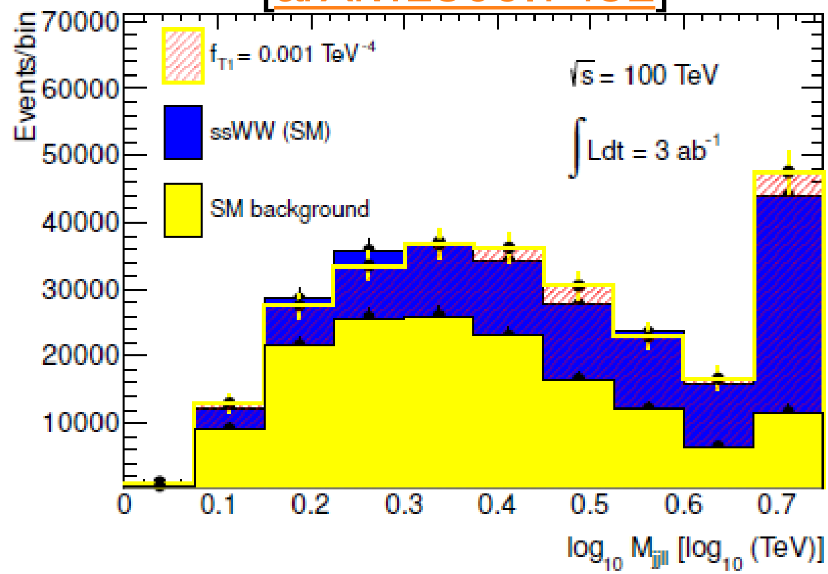
❖ What could we see w/ 15 vs. 150 times the current dataset?

❖ What could we gain running at 100 TeV rather than 14 TeV?

[ATL-PHYS-PUB-2013-006]



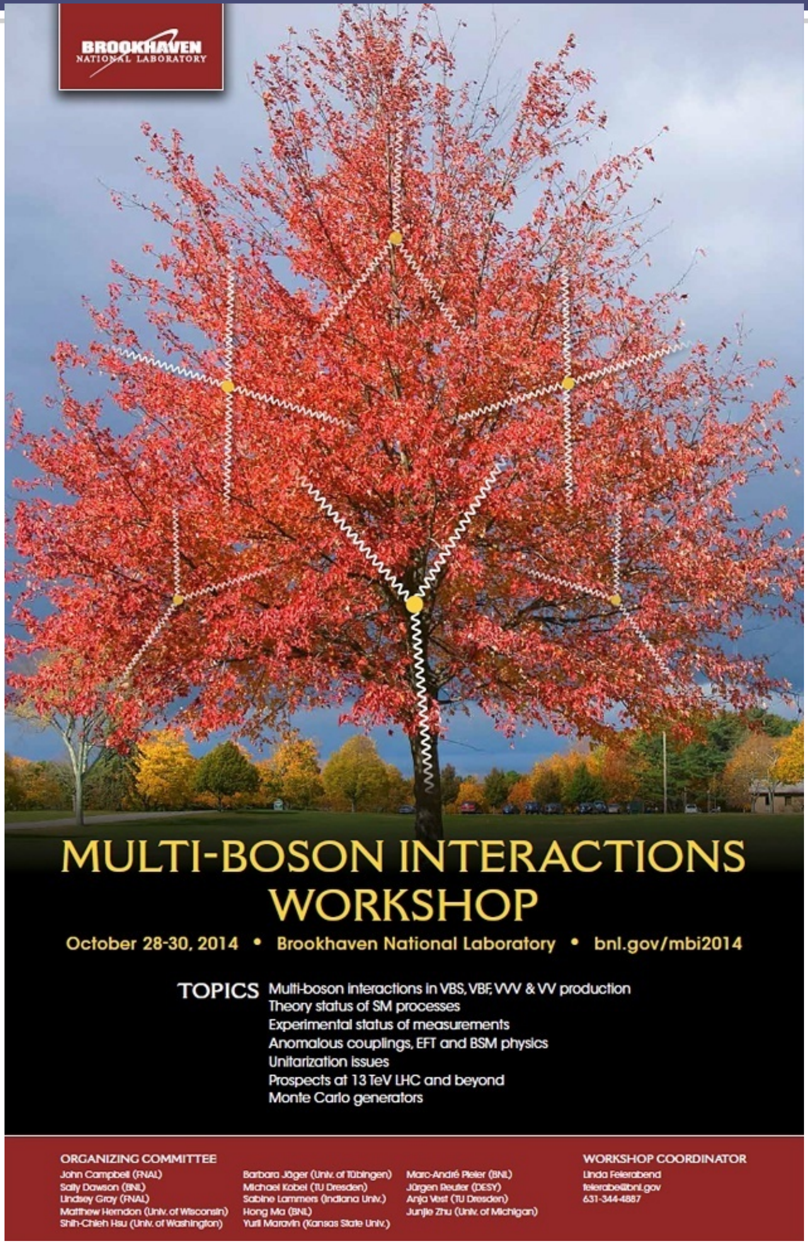
[arXiv:1309.7452]



❖ Gain in sensitivity (5σ aQGC discovery) for HL-LHC: **factor of two.**

❖ Gain in sensitivity (5σ aQGC discovery) for 14→100 TeV: **factor of one hundred.**

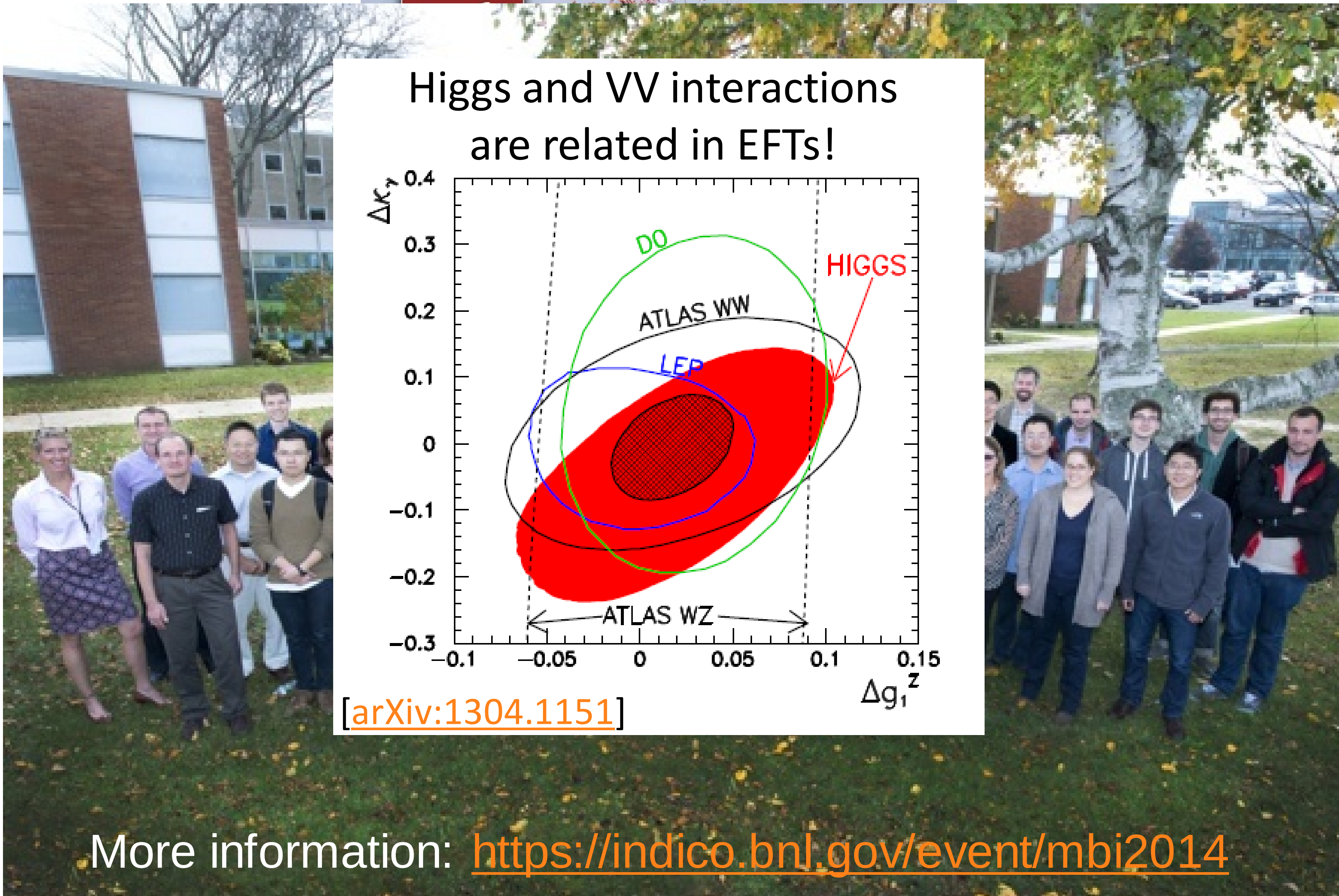
October 2014 @ BNL



October 2014 @ BNL

More information: https://indico.bnl.gov/event/mbi2014

October 2014 @ BNL

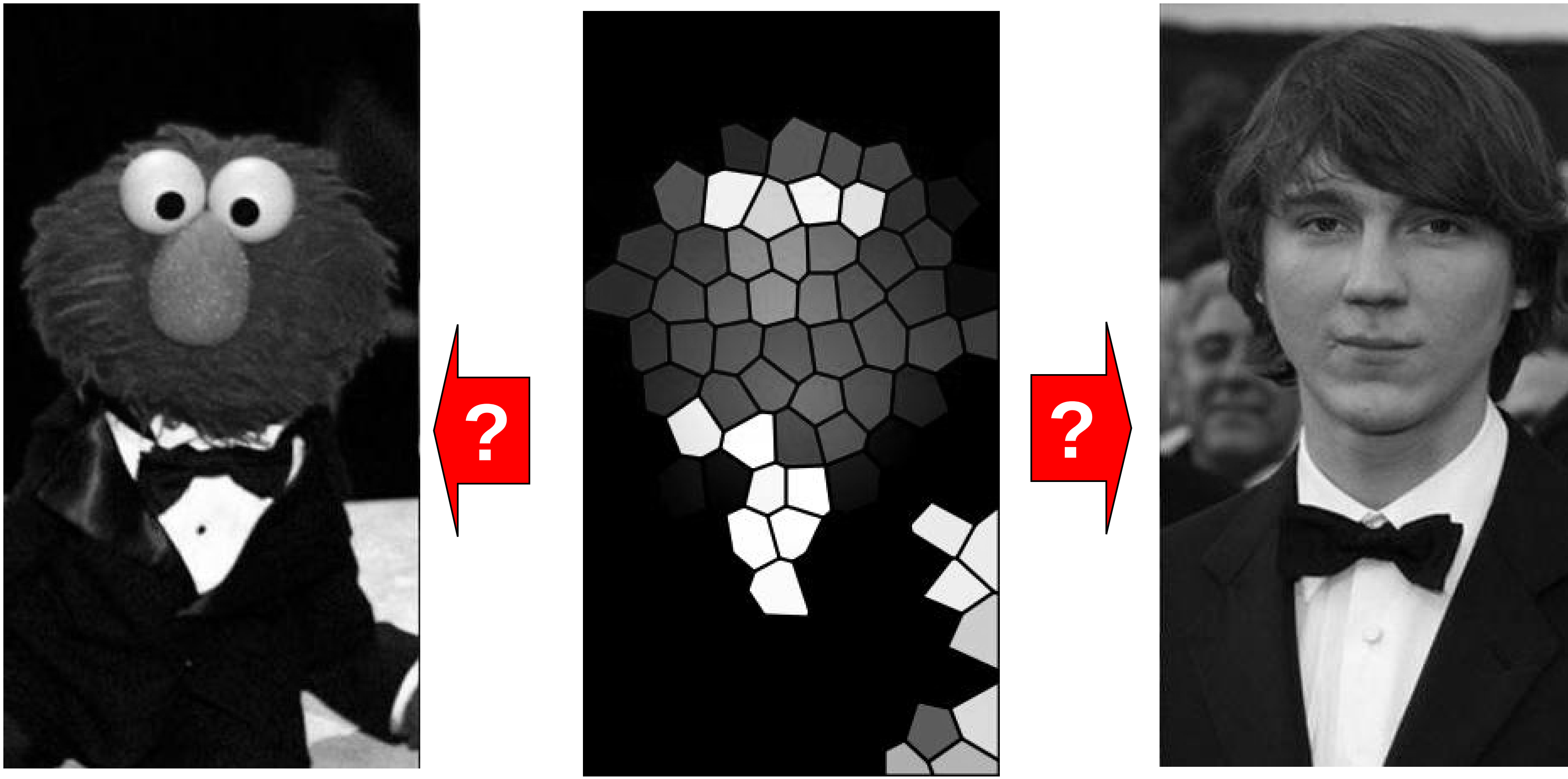


Higgs and VV interactions are related in EFTs!

[arXiv:1304.1151]

More information: https://indico.bnl.gov/event/mbi2014

What we see so far…



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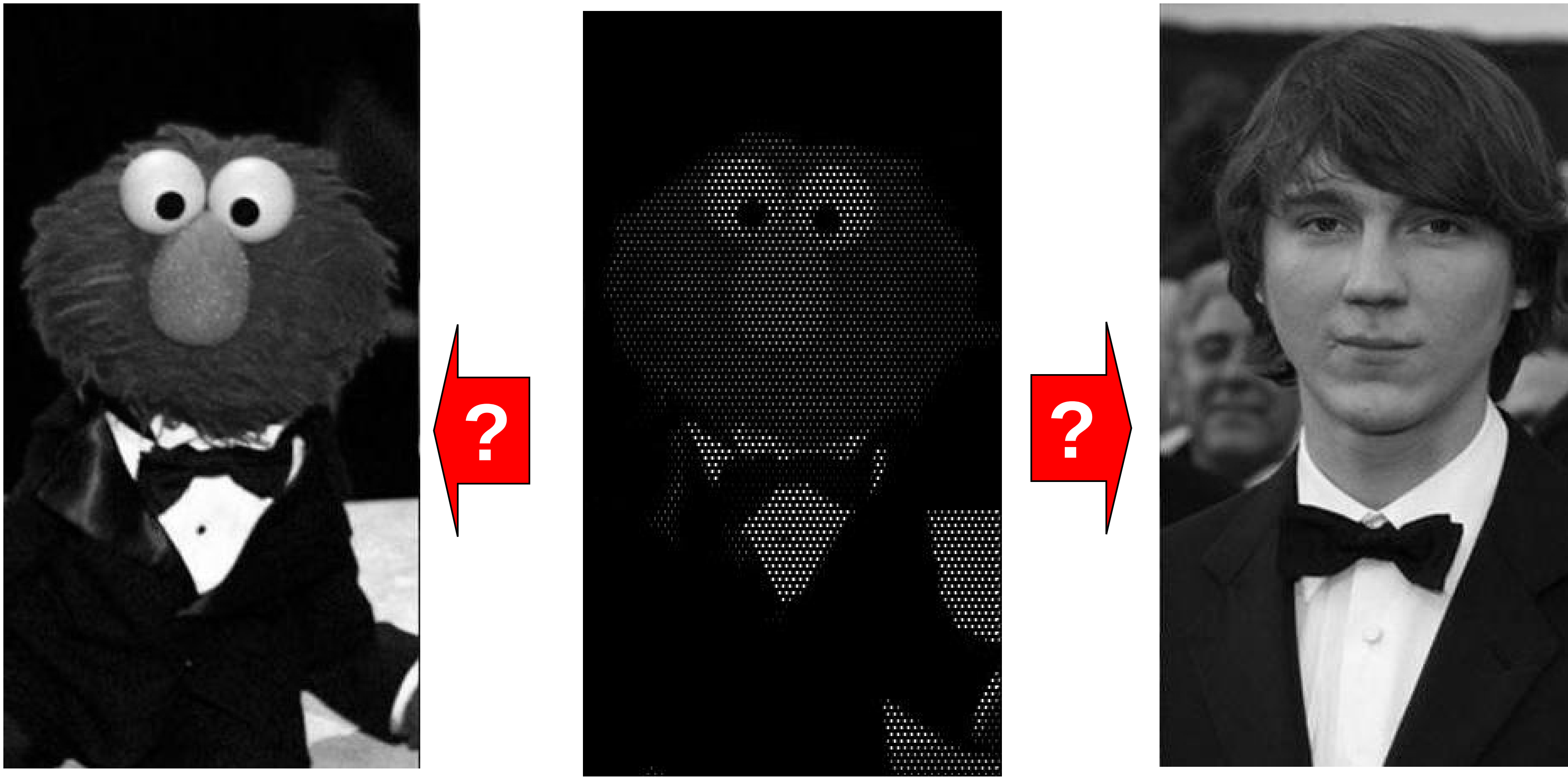

… more data will help …

Summary

- Many open fundamental questions in physics, today:
    - ***Does the Higgs do its job as expected in WBS?***

- First ever results on WBS, involving a WWWW vertex

- 13/14 TeV data will allow more detailed study of quartic vertex

Summary

- Many open fun… …s, today:
  - ***Does the Hi… …WBS?***
- First ever result… …W vertex
- 13/14 TeV data … …y of quartic vertex

What we know is a drop, what we don't know is an ocean.

Isaac Newton (1643 - 1727)