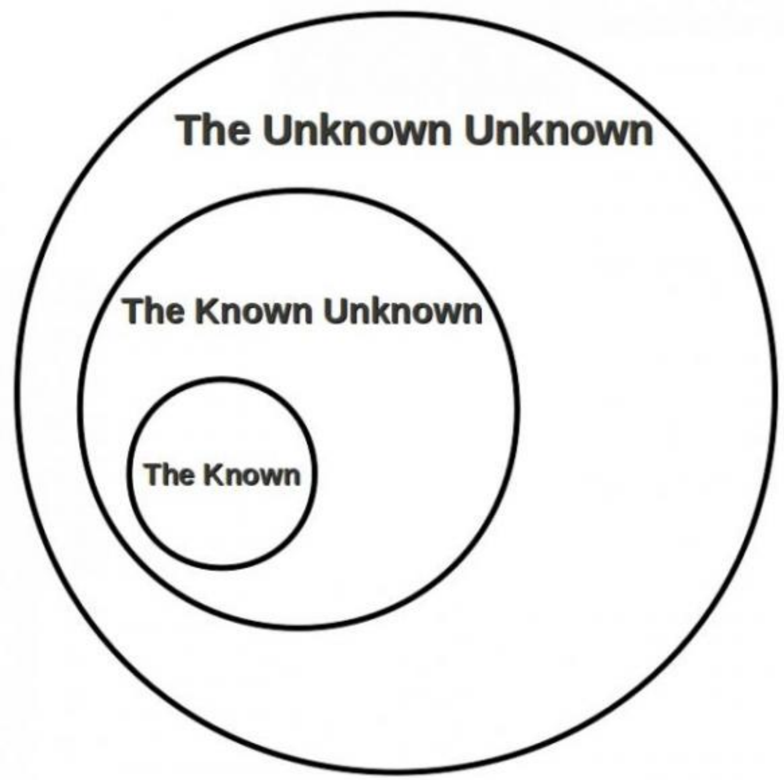
Particle Physics



Lecturer: Deepak Kar
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WITS UNIVERSITY 100 1922 2022

National Research Foundation

CERN

ATLAS EXPERIMENT

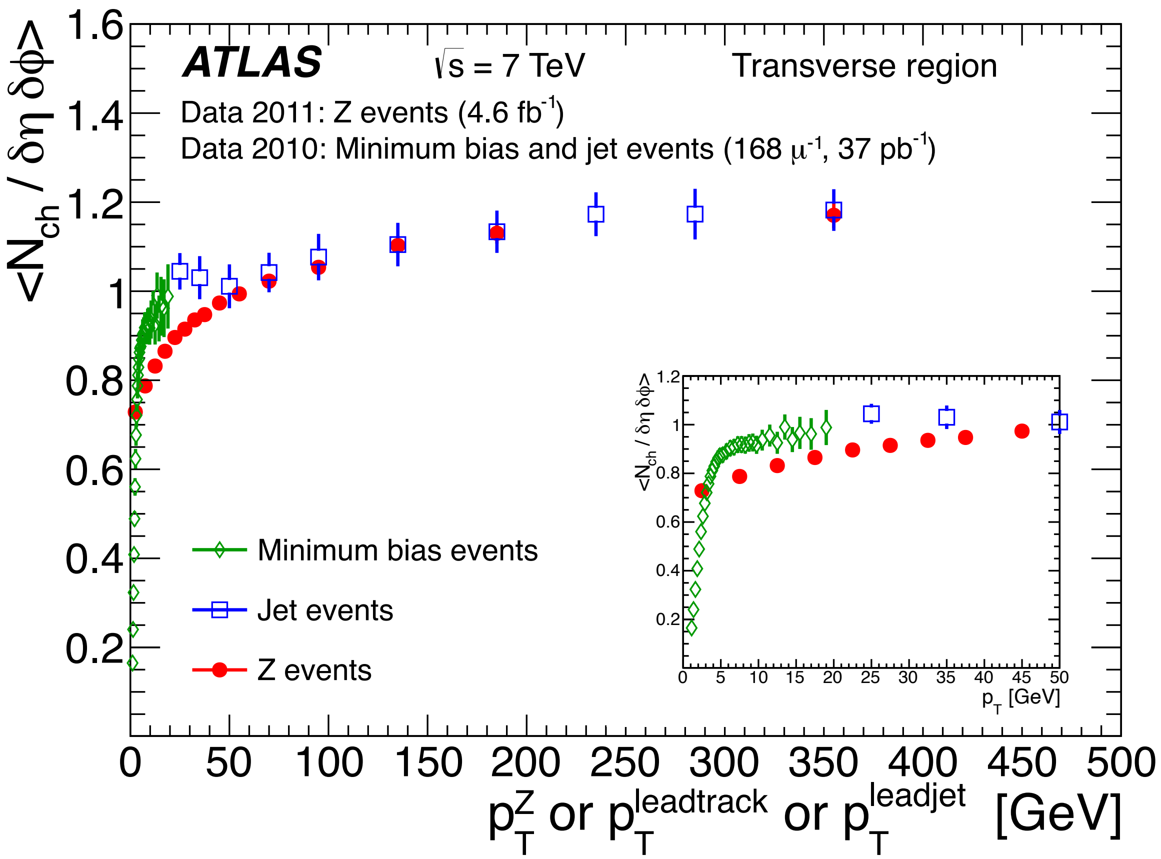
Session 1:
Setting the Scene

Who am I?


Gainesville, FL, USA
2003-2008
Glasgow, UK
2012-2014
Dresden, Germany
2009-2011
Calcutta, India
till 2003
Geneva, Switzerland
2011-2012
Johannesburg, SA
2015 -

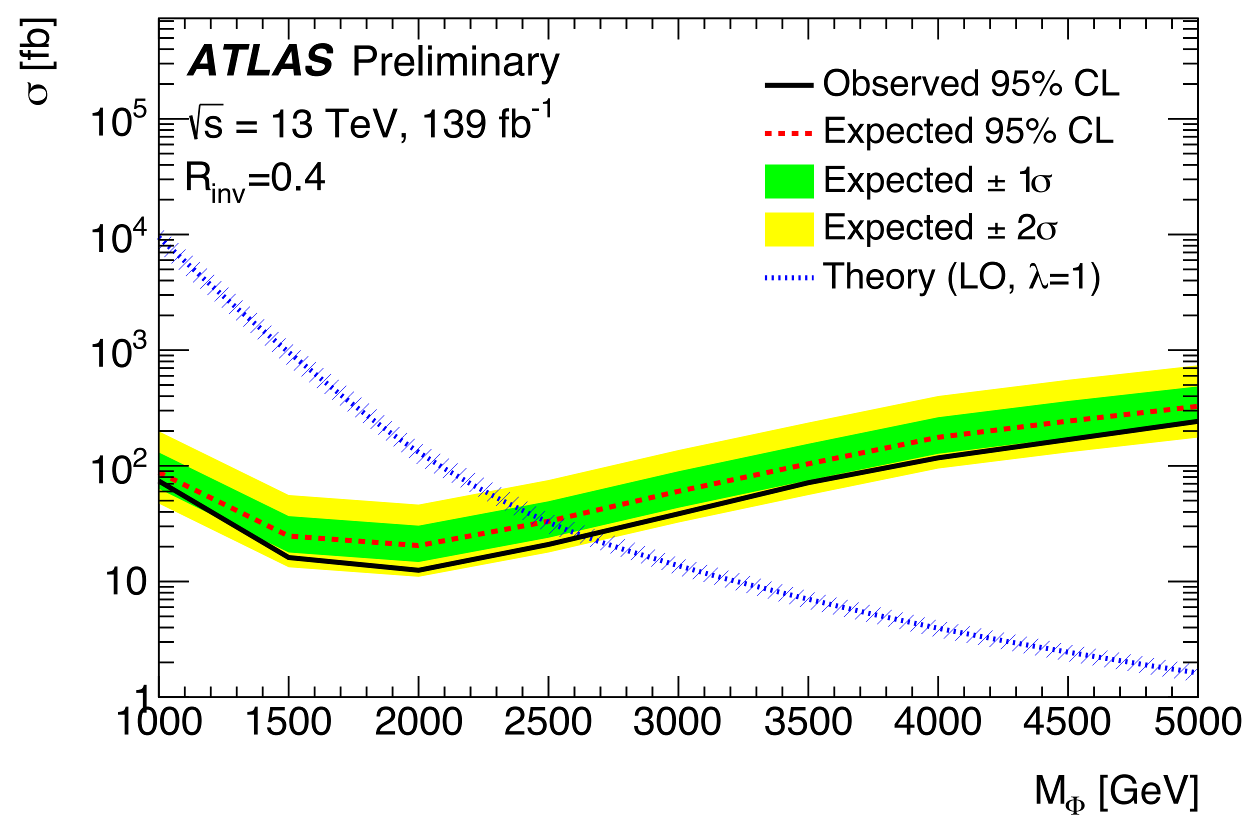
Two results I am most proud of …

Measurement of Underlying Event

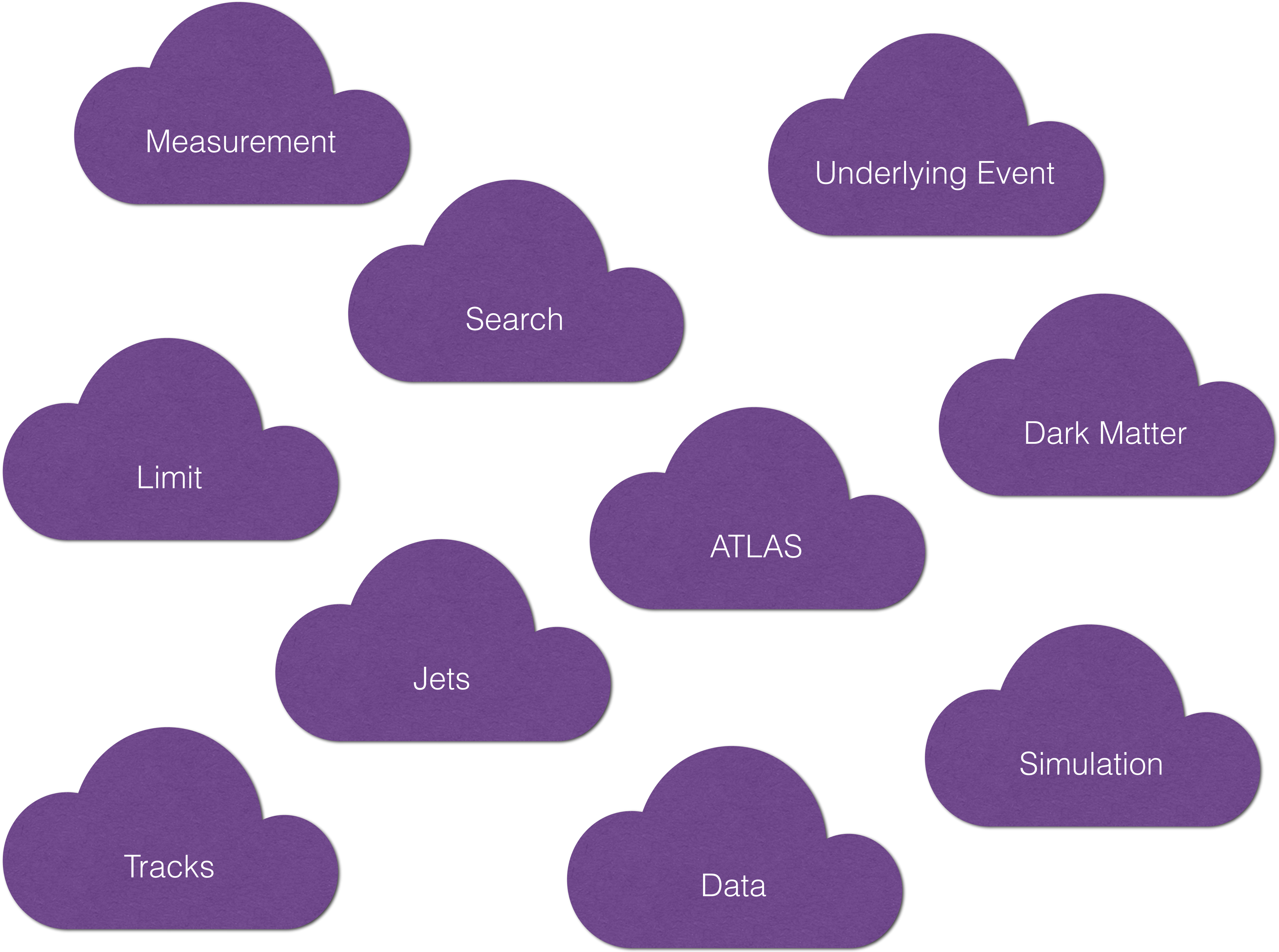


…using charged particle/tracks

Semi-visible jets search



…setting first limits on this strongly interacting dark matter scenario


Measurement
Underlying Event
Search
Dark Matter
Limit
ATLAS
Jets
Simulation
Tracks
Data

At the end of these set of lectures, all of these should make sense to you :)

At the end of these set of lectures, all of these should make sense to you :)

Already

Detectors: Sally

Standard Model (measurements): James

Beyond the Standard model (search): Nikolina

Dark Matter: Gopolang

Limits (and a lot more!): Harrison

A bit of jets: Mario

Machine Learning: Claire

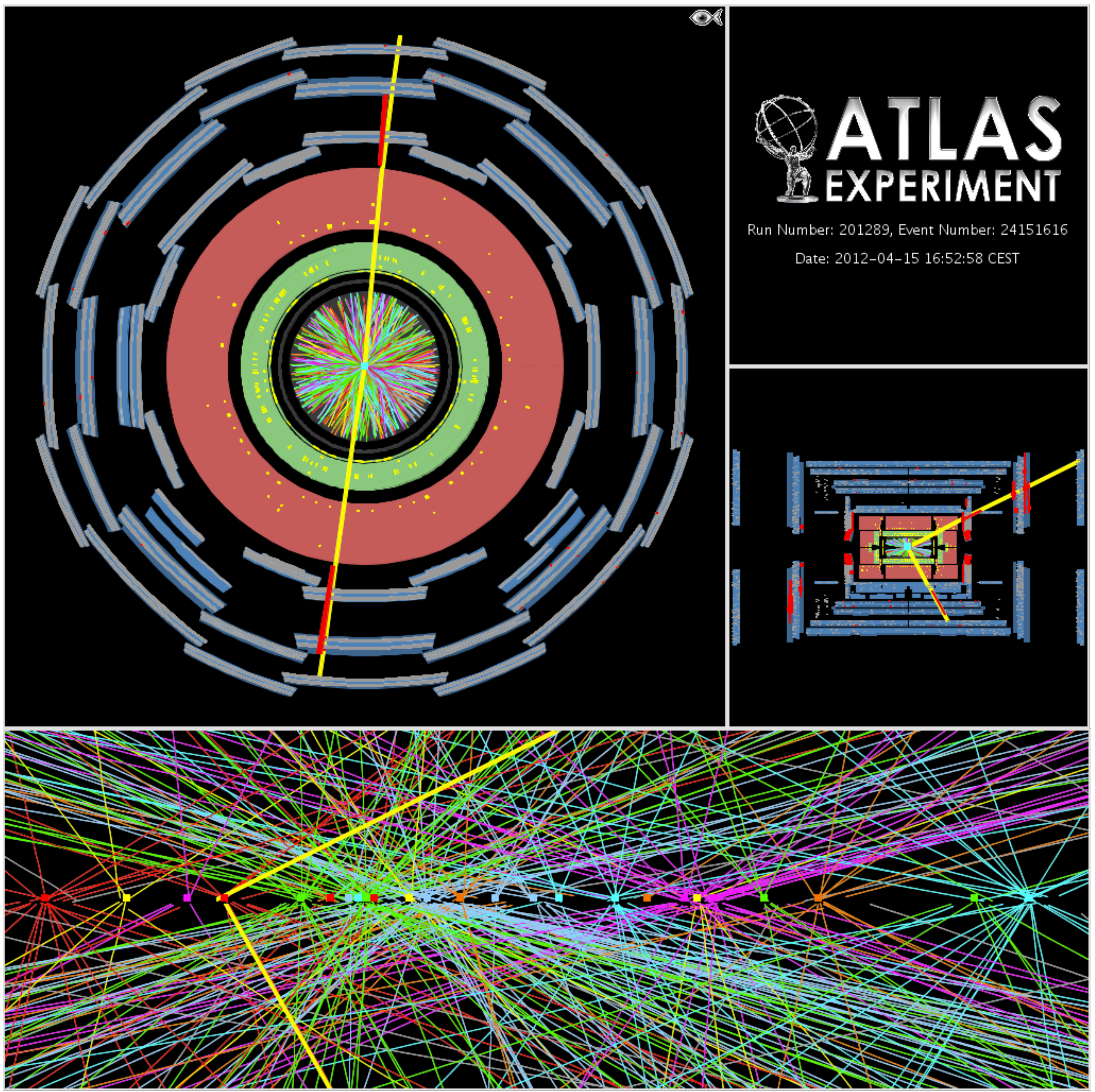
Collisions

Time for some fun
and games…

What have we learnt?

- It is hard to collide single protons …
- Need bunches of them!
- But can have more than one collision, leading to *pile-up*

Pile-up (PU)



We collide proton bunches, so overlap between different collisions is inevitable!

Increases with higher luminosity

What have we learnt?

- It is hard to collide single protons …
- Need bunches of them!
- But can have more than one collision, leading to *pile-up*

One collision == EVENT

Outcome of the collisions is probablistic, no exhaustive list of possibilities!

Collision rate

- **Cross-section**: how often a particular process occurs.
- Measured as an effective area the target particle presents to projectile particles.
- Unit: Barn = 10^{-28} m^2
- Mostly used with prefixes.

Unit		Prefix	
Barn (b)		1	
Unit	Prefix	Unit	Prefix
Mili (mb)	10^{-3}	Pico (pb)	10^{-12}
Micro (μb)	10^{-6}	Femto (fb)	10^{-15}
Nano (nb)	10^{-9}	Atto (ab)	10^{-18}

For colliding beams

Actual number for a process: $N_{process} = \sigma_{process} \int L dt$

Physics

Accelerator

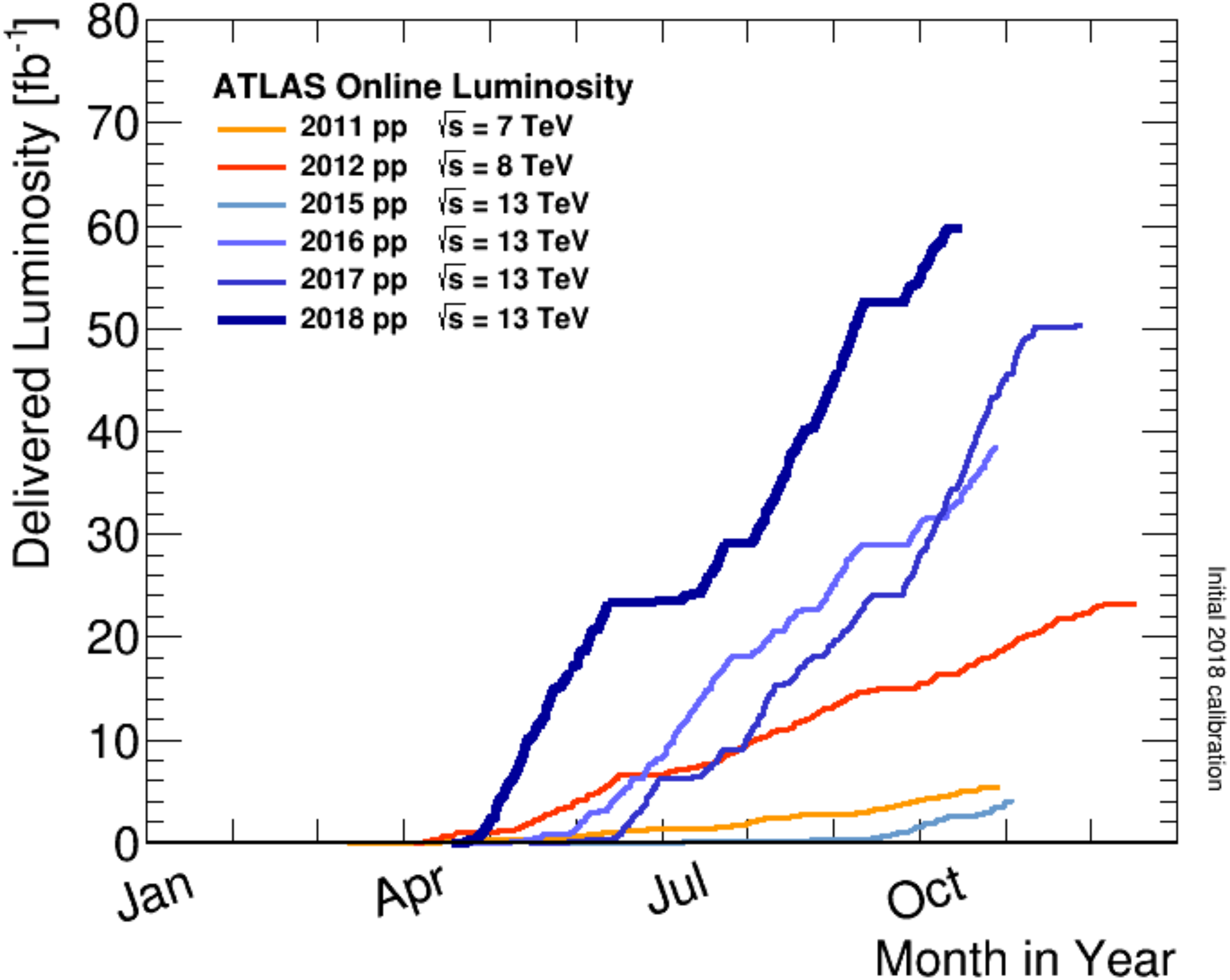
Luminosity

Luminosity measured in units of 1/area

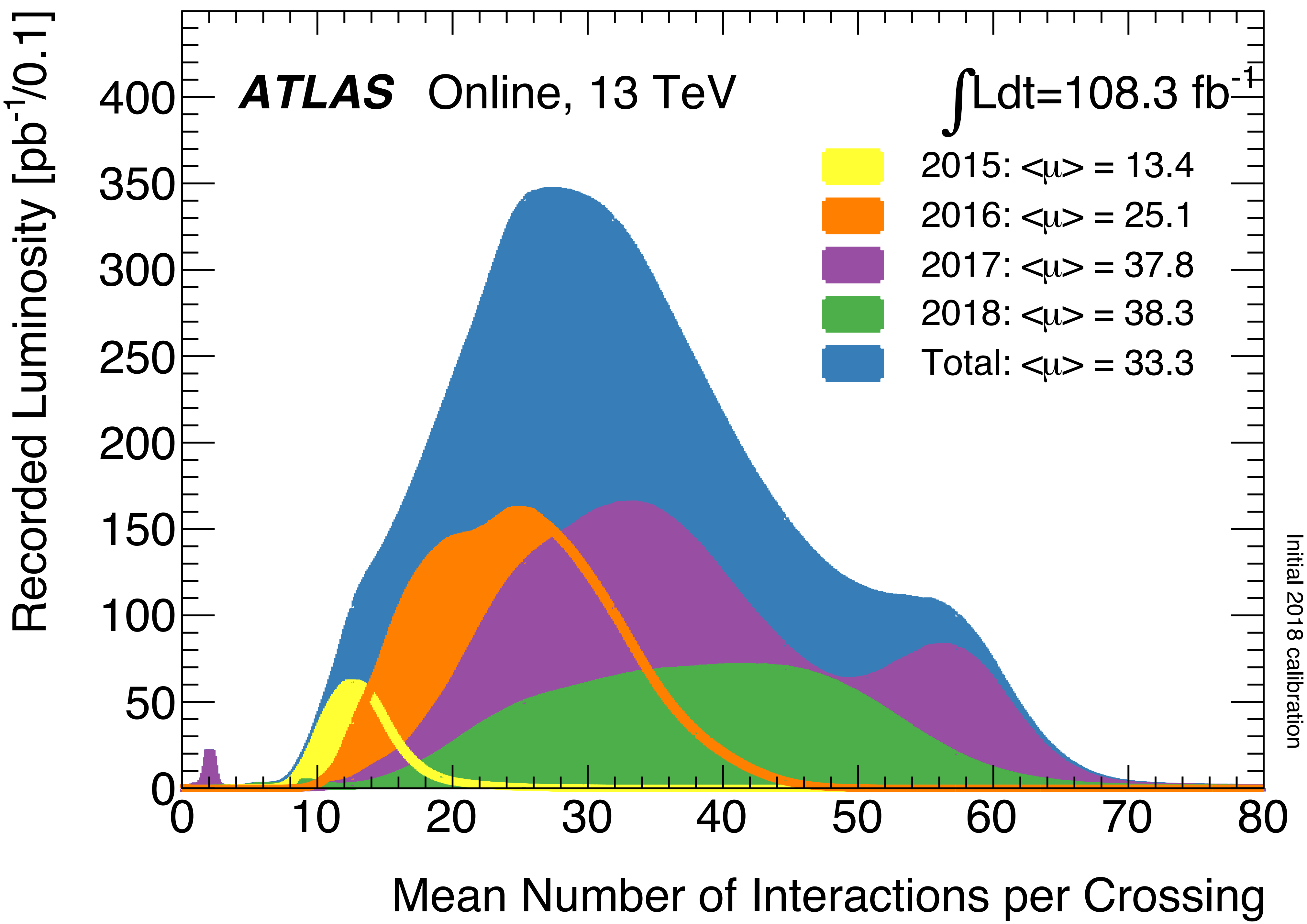
So now you you what 139 fb^{-1} in LHC papers mean!

Some numbers

- Design frequency of LHC: 40 MHz = 25 ns bunch spacing.
- 1 bunch contains ~1.15 x 10^{11} protons, 2808 bunches per beam.
- 1 inverse fb = ~ 10^{12} pp collisions at LHC
- ATLAS records ~300 Hz, i.e 300 events per second.
- Size of event ~1.5 MB, so 1 fb^{-1} means ~500 TB of data.



ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
2017 pp √s = 13 TeV
2018 pp √s = 13 TeV
Delivered Luminosity [fb-1]
0
10
20
30
40
50
60
70
80
Jan
Apr
Jul
Oct
Month in Year
Initial 2018 calibration

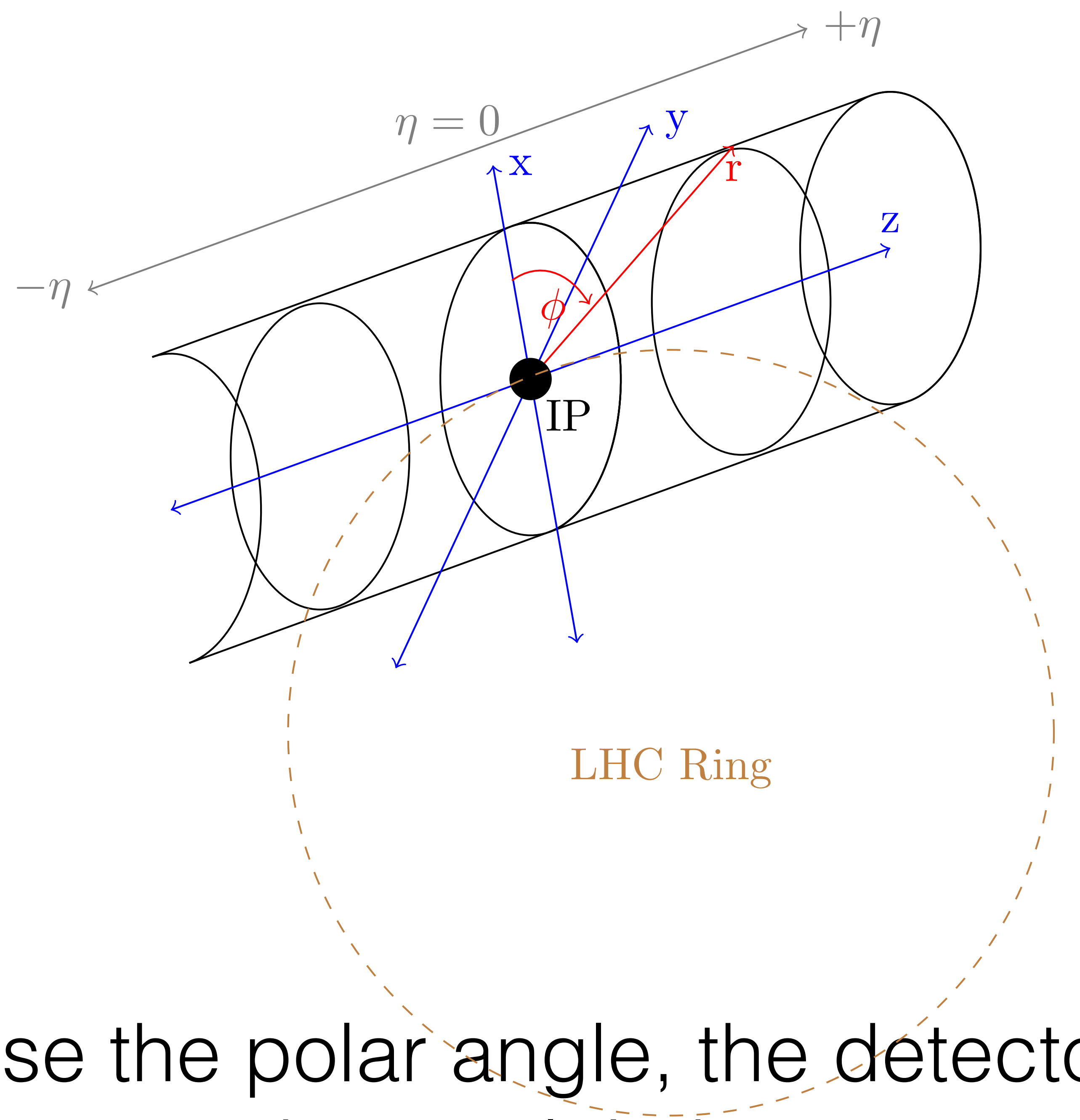


ATLAS Online, 13 TeV
∫Ldt=108.3 fb^-1
2015: <μ> = 13.4
2016: <μ> = 25.1
2017: <μ> = 37.8
2018: <μ> = 38.3
Total: <μ> = 33.3
Recorded Luminosity [pb^-1/0.1]
Mean Number of Interactions per Crossing
0
50
100
150
200
250
300
350
400
0
10
20
30
40
50
60
70
80
Initial 2018 calibration

Coordinates

- Only transverse plane (x-y) is relevant
- Coordinates encoding both energy and position information
- Lorentz boost invariant!

Coordinates



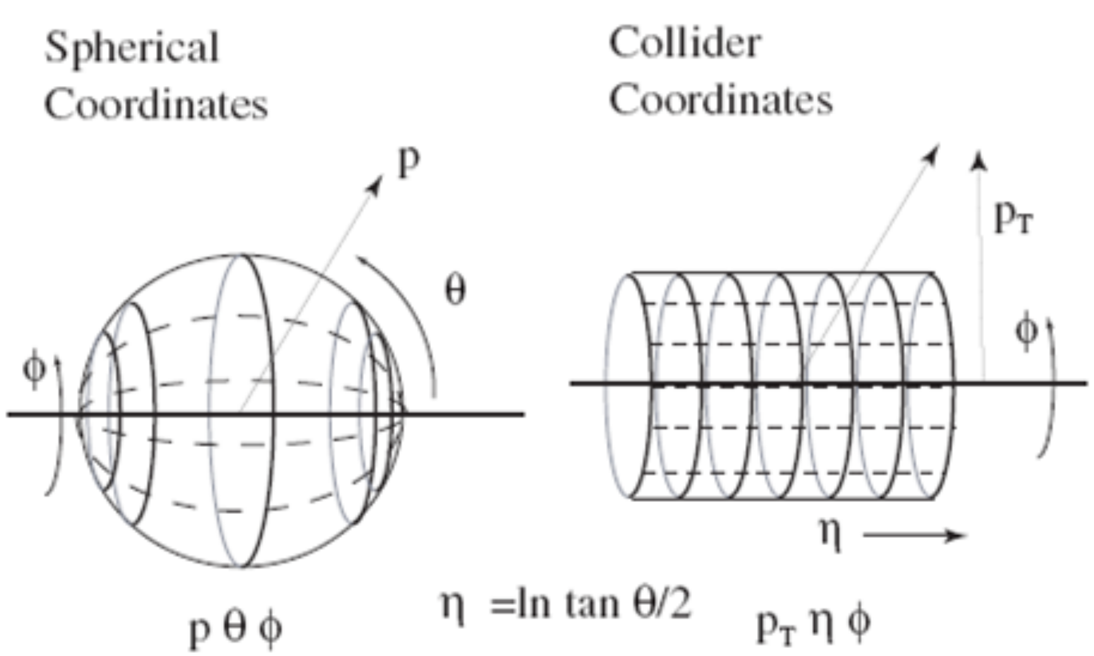
We do not use the polar angle, the detector is cylindrical, so need to exploit that symmetry.

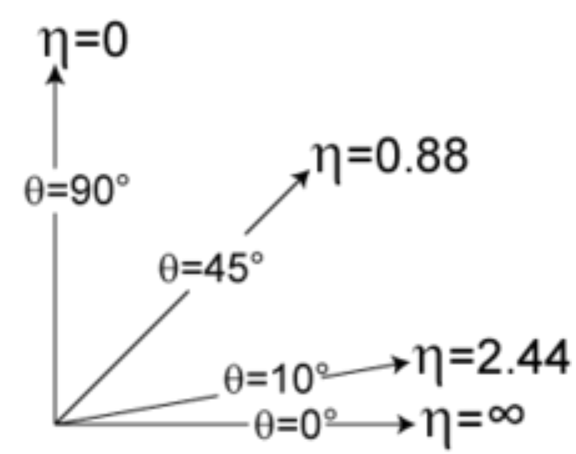
Pseudo-rapidity

Rapidity: $y = \frac{1}{2}\ln(\frac{E+p_z}{E-p_z})$

Difference of rapidity is invariant under Lorentz boost (along z-axis).
But hard to measure, since only transverse momentum is measured.

Pseudo-rapidity: $\eta = -\ln\tan\theta/2$ Identical for massless particles





Distance:

Transverse Momentum: $p_{\mathrm{T}} = \sqrt{p_x^2 + p_y^2}$

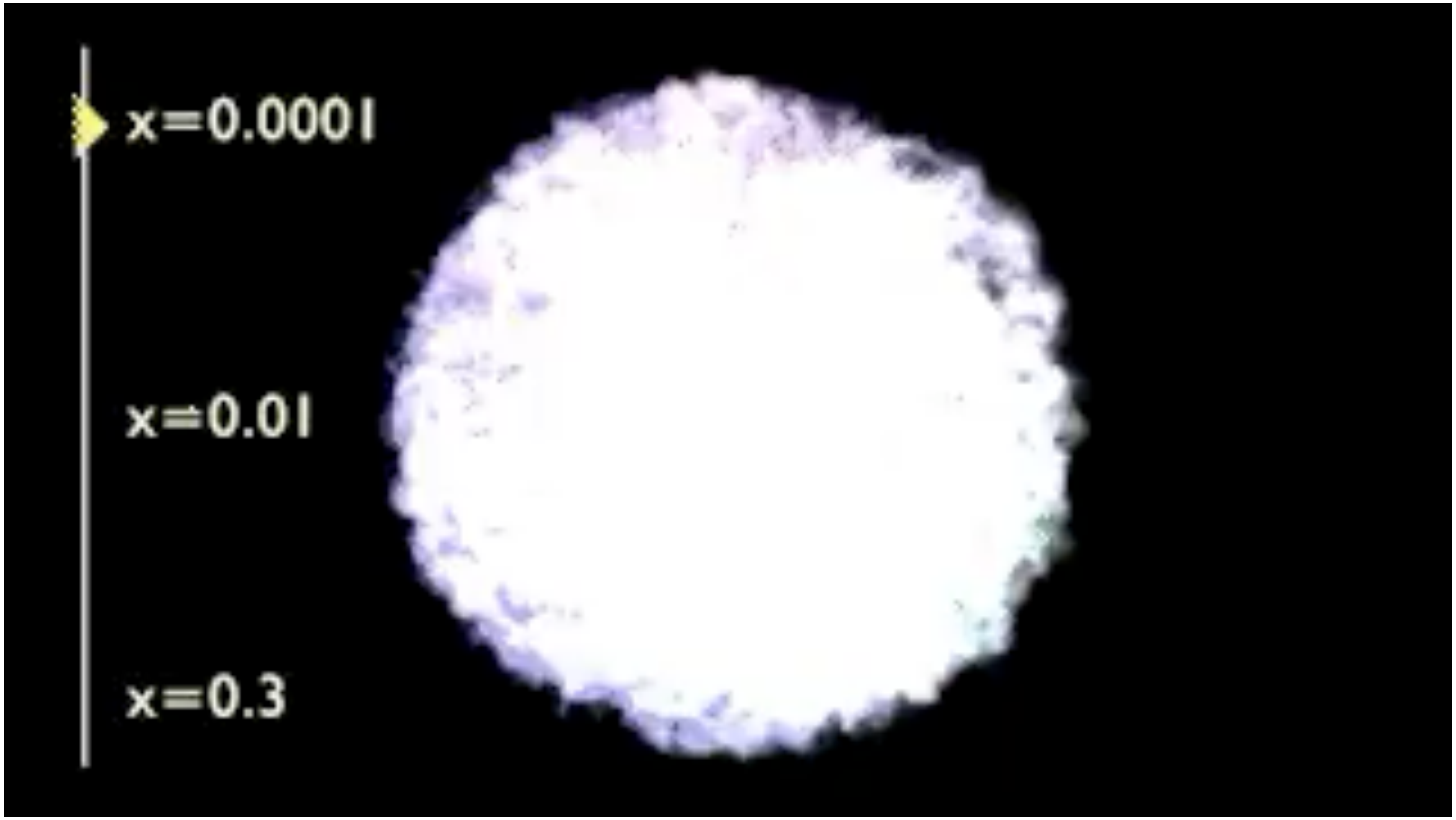
$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

So we collide protons against protons …

MCQ

What's inside a proton?

- A. Duh, we all know its u-u-d!
- B. Not just u-u-d, but a whole *sea* of quarks
- C. Nobody knows, really.

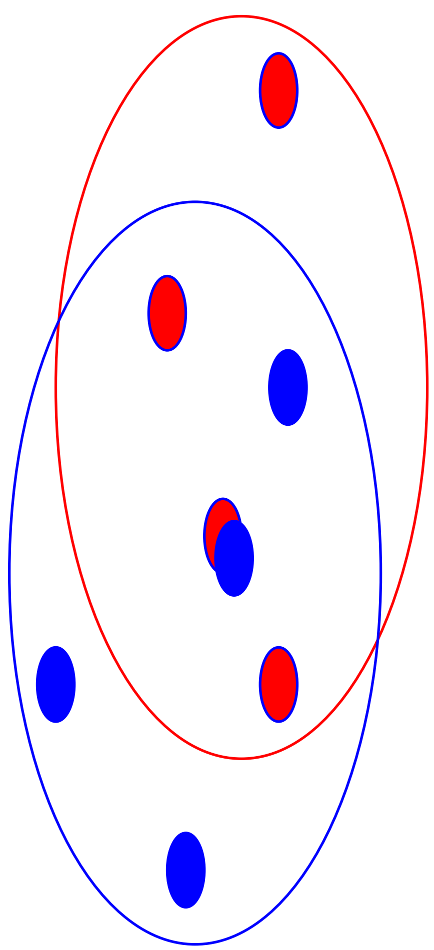


x = momentum fraction carried by quarks

Quarks and Gluons are collectively termed as patrons

Anatomy of Collisions

Proton-proton overlap:

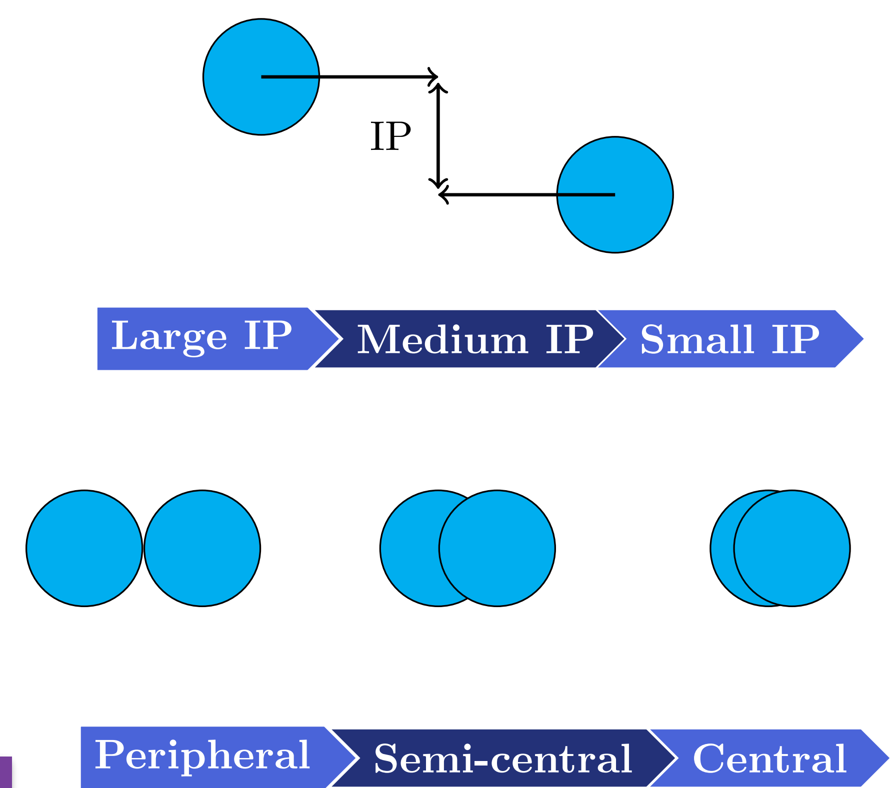


Elongated at relativistic speeds

… only the “partons” collide!

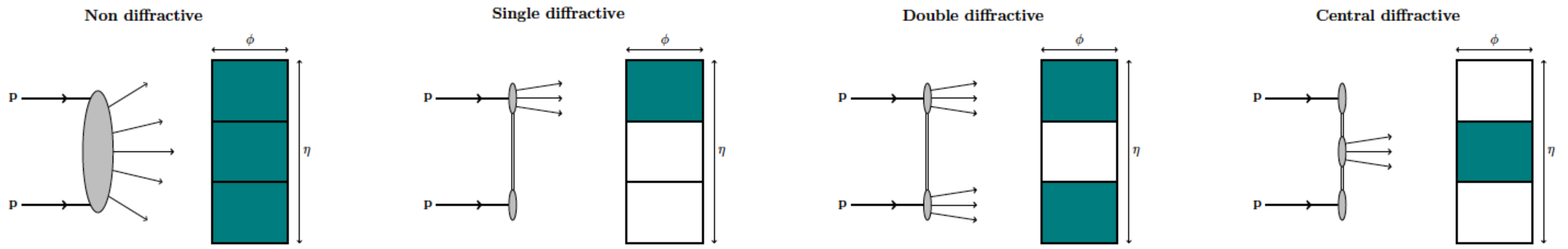
… with probabilistic energy distribution!

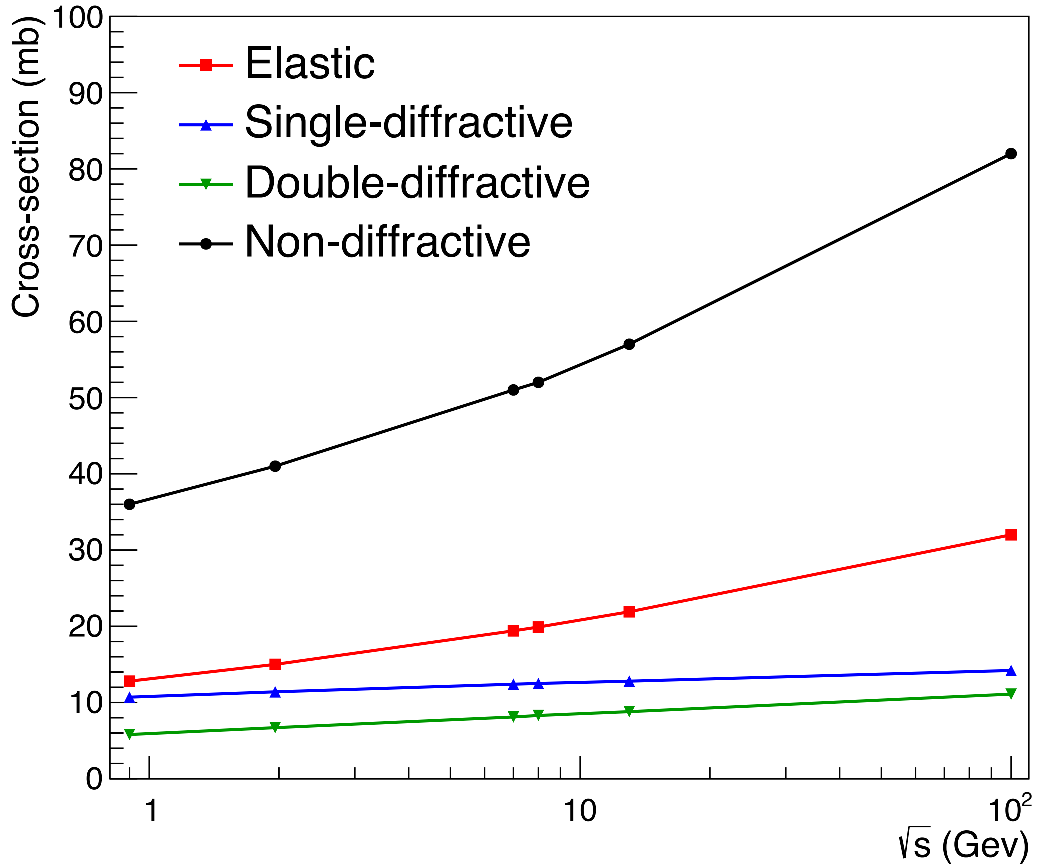
Definition of Impact Parameter (IP):



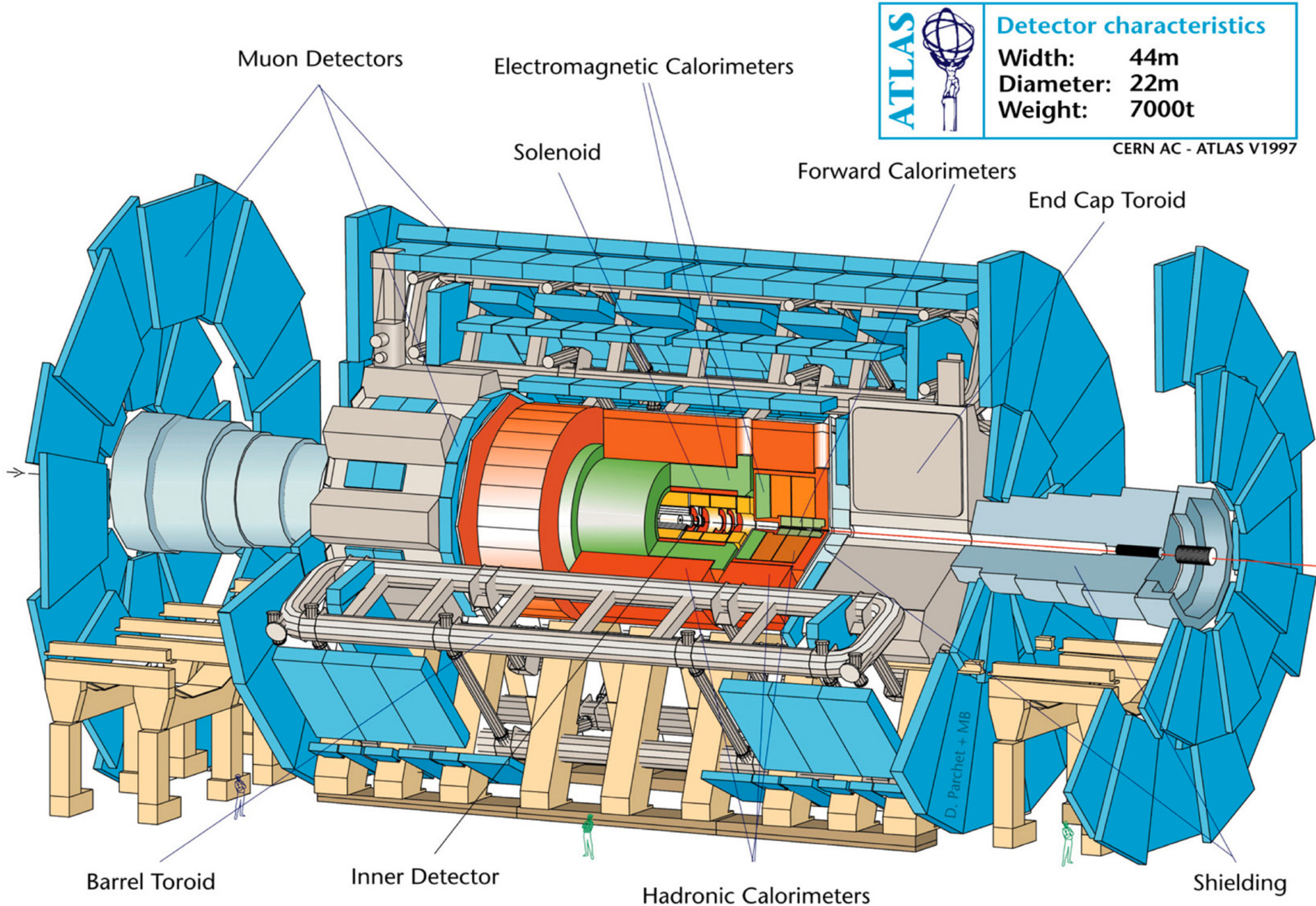
More peripheral collisions, less energy to share!

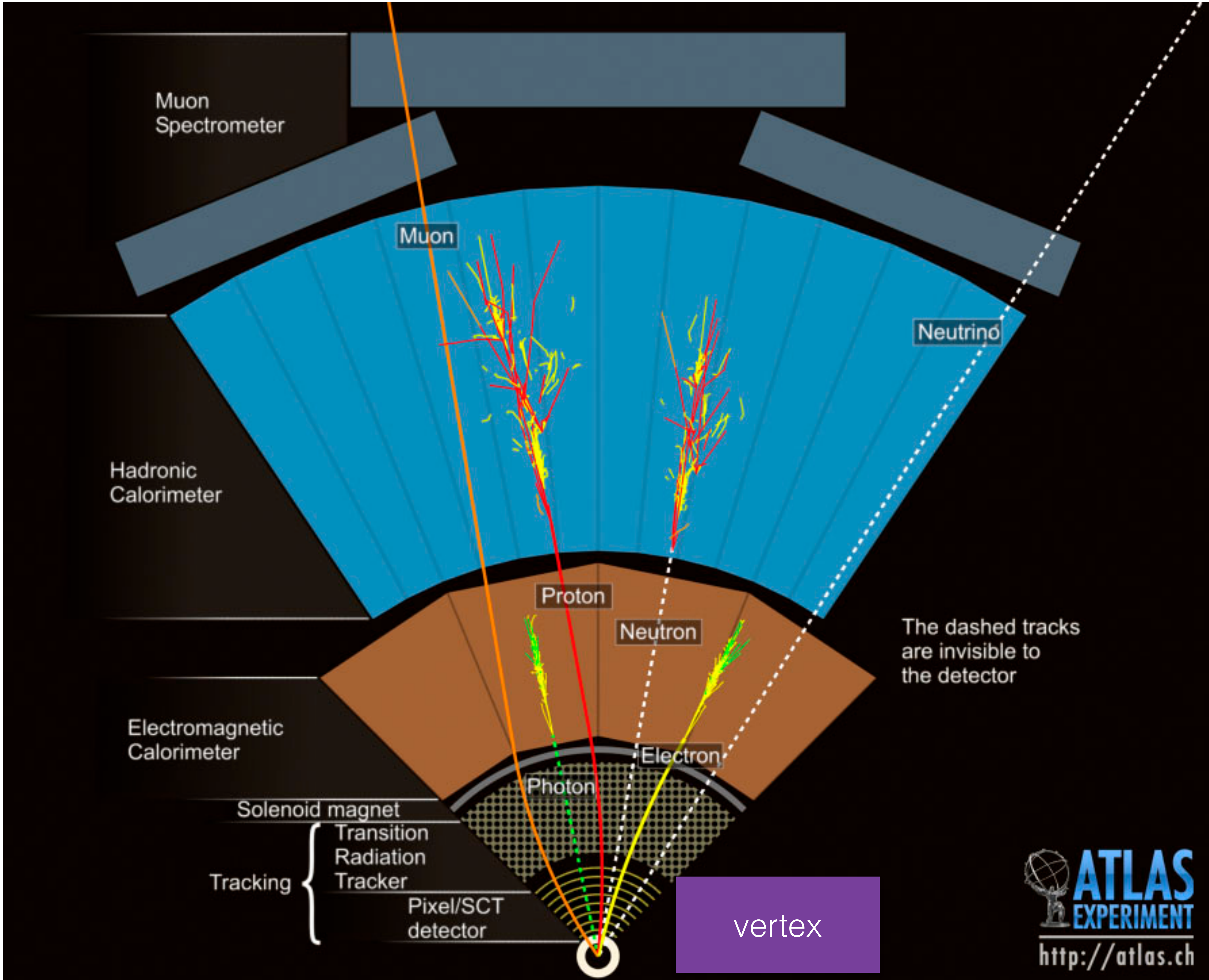
Anatomy of Collisions



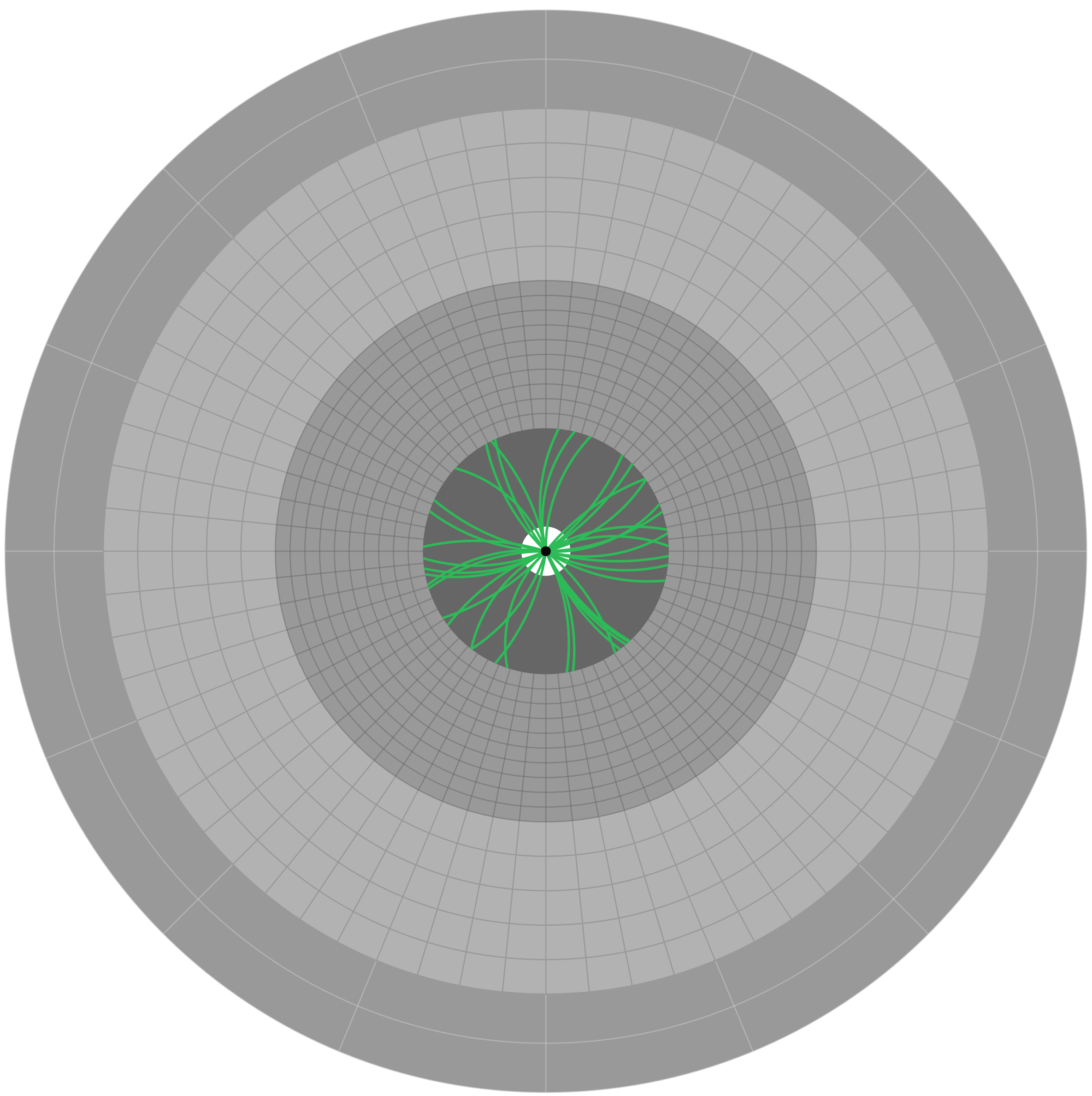


Particle Detection


Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB


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
ATLAS
EXPERIMENT
http://atlas.ch
vertex

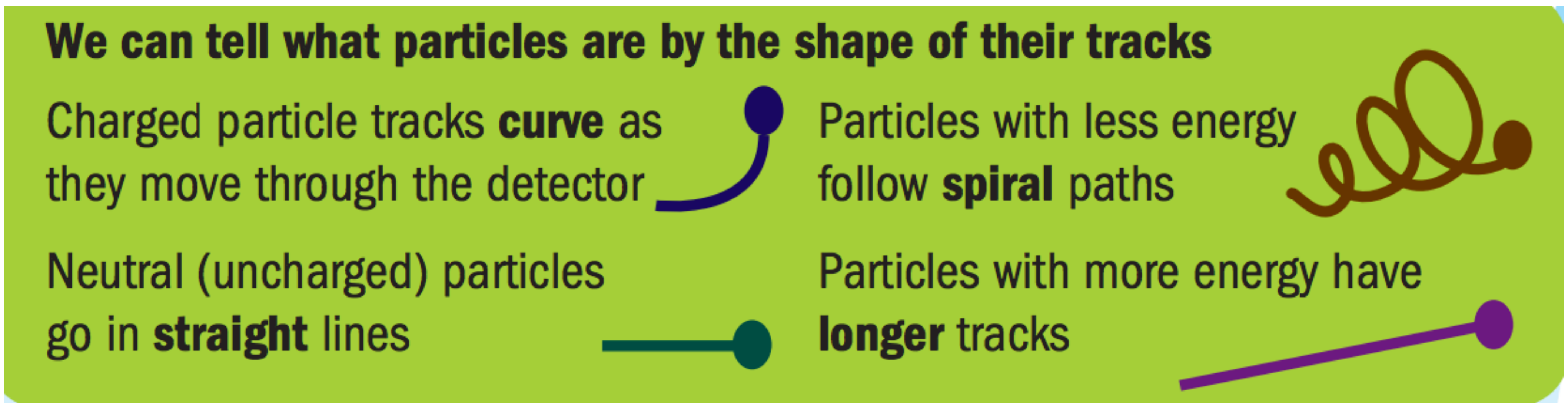
Tracks

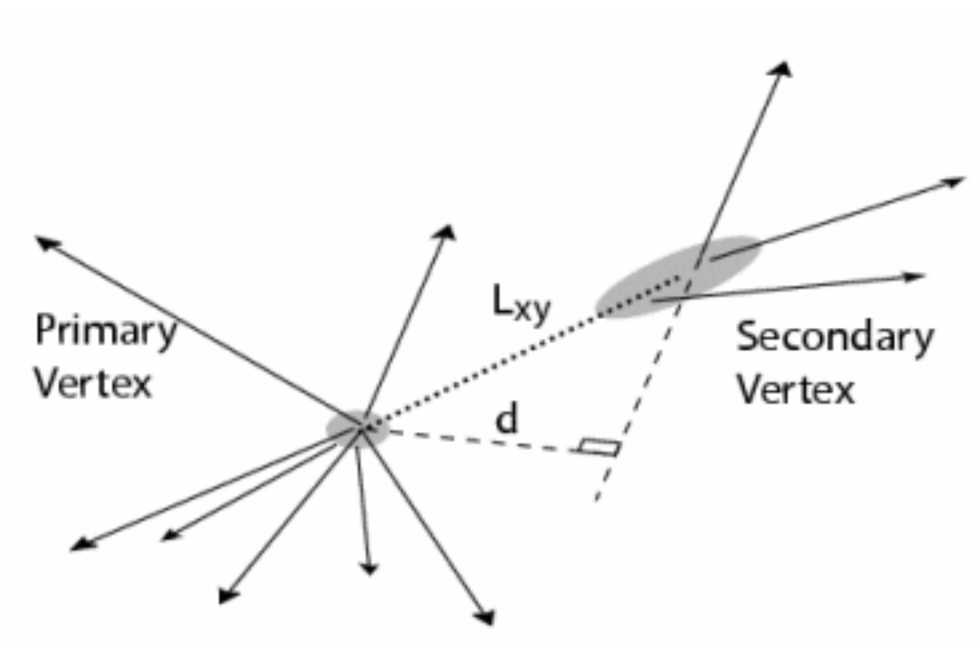


Identify charge
and momentum
from the curvature

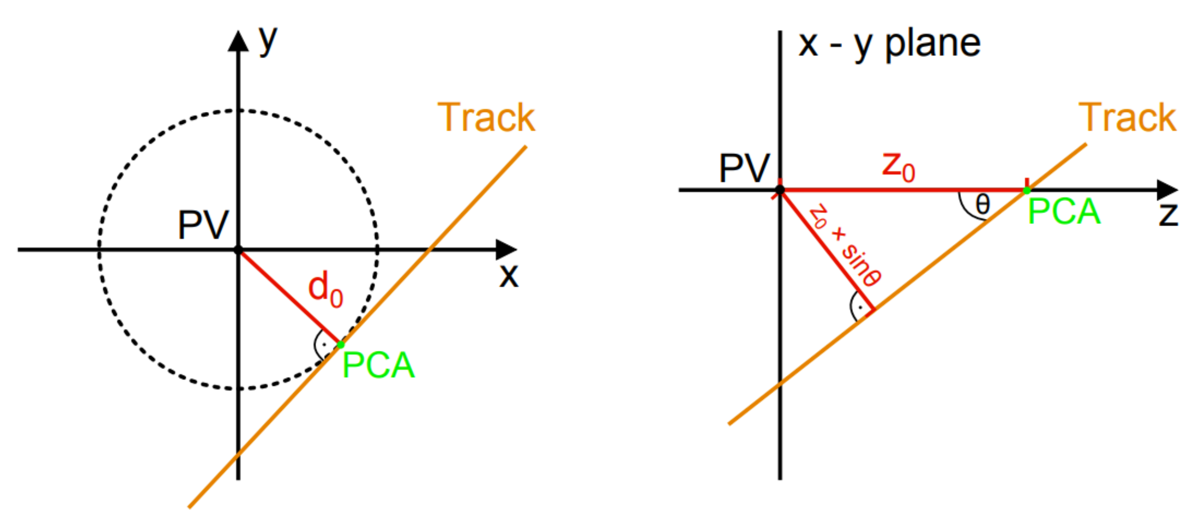
Electrons, muons,
charged hadrons
(mostly pions, kaons)

Tracks



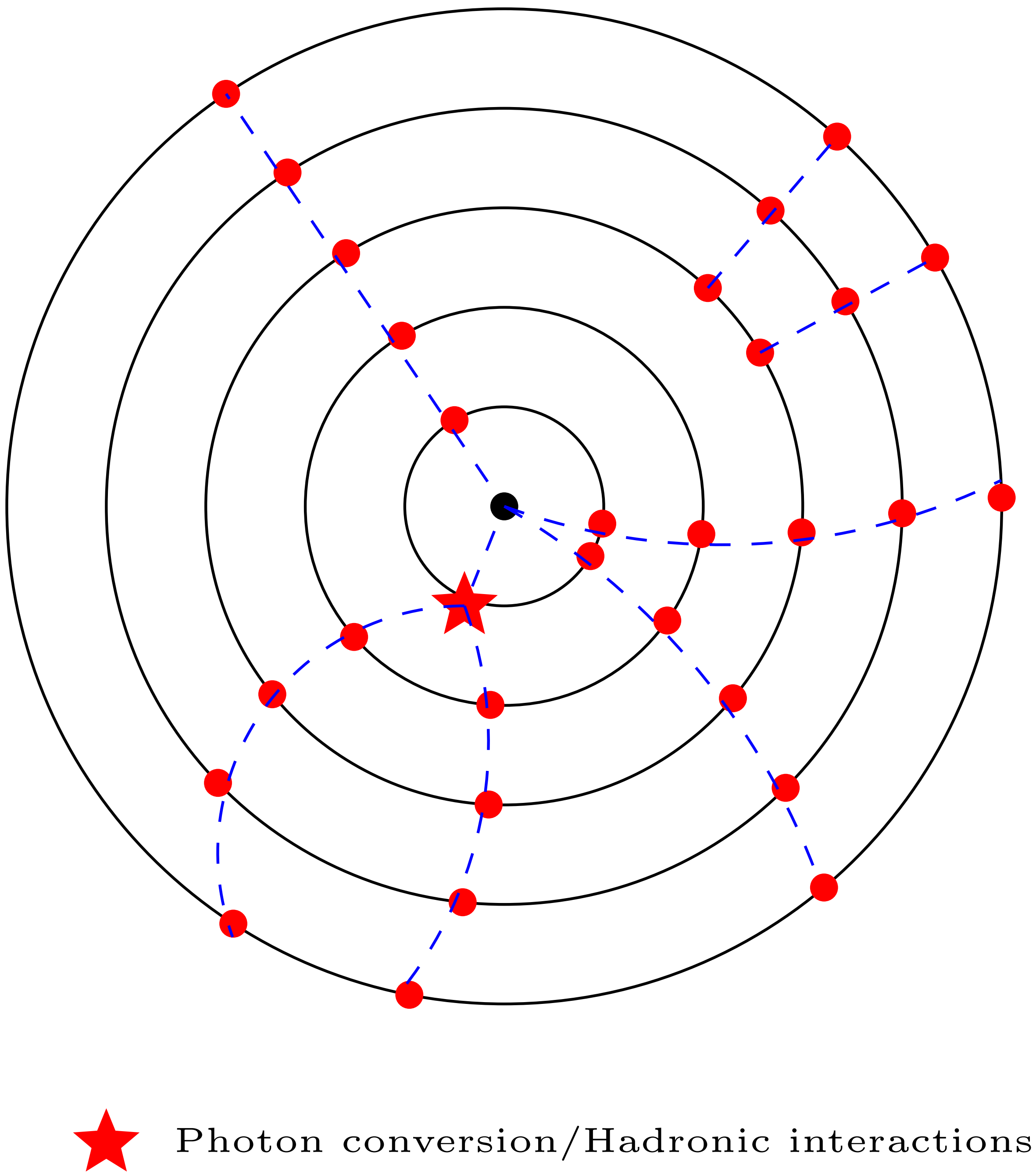


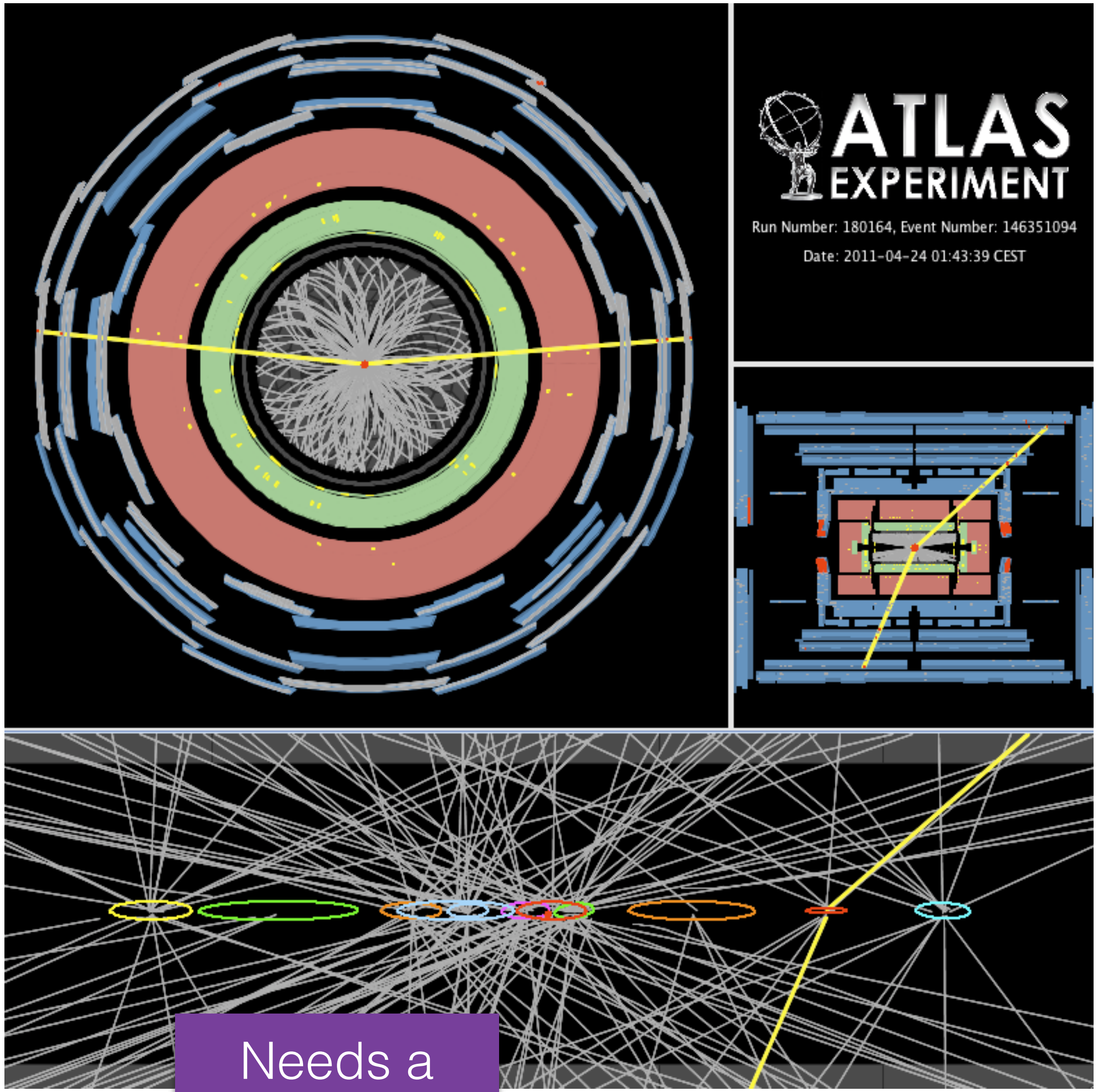
PV, SV



Impact parameters

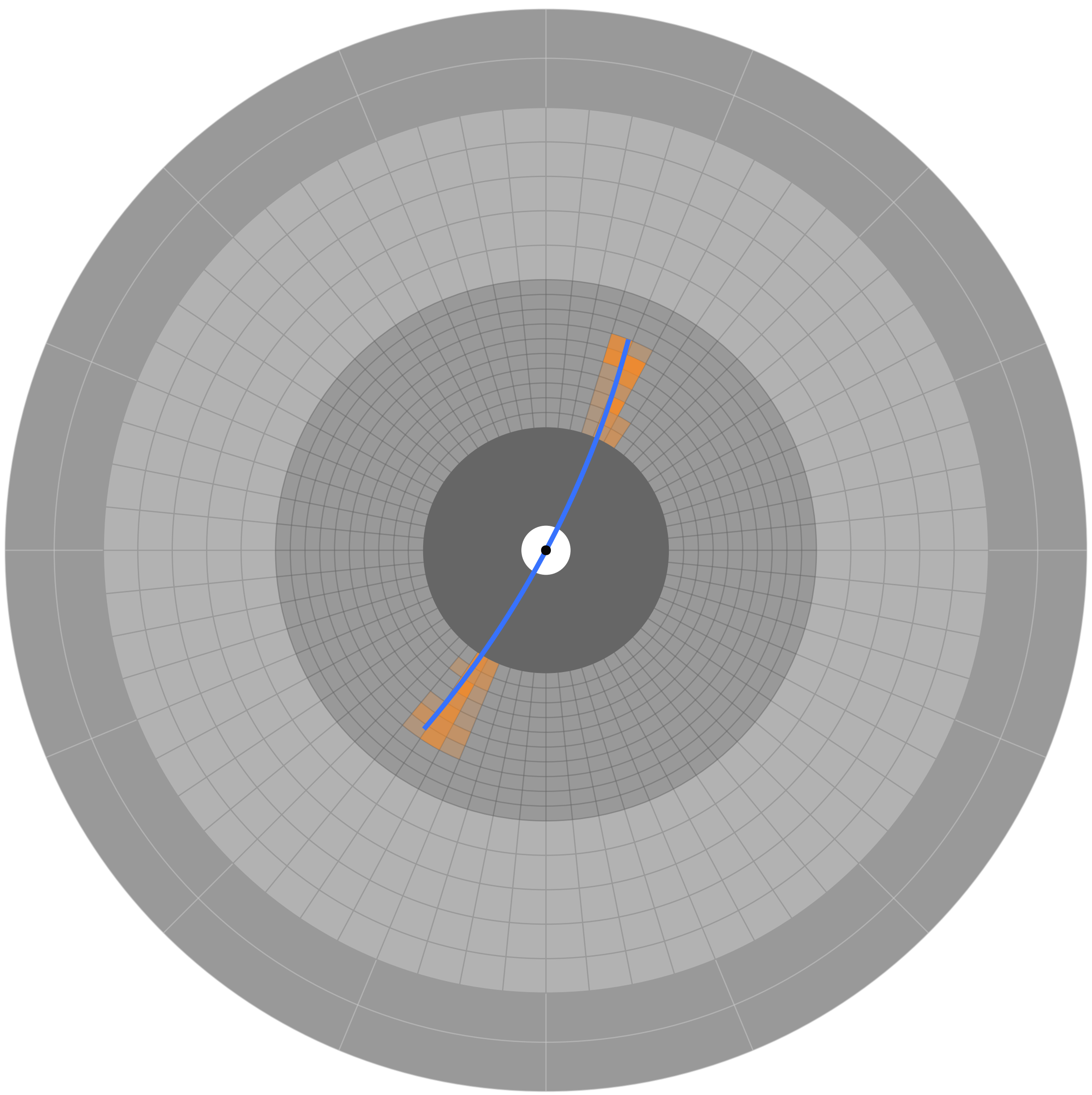
Tracks





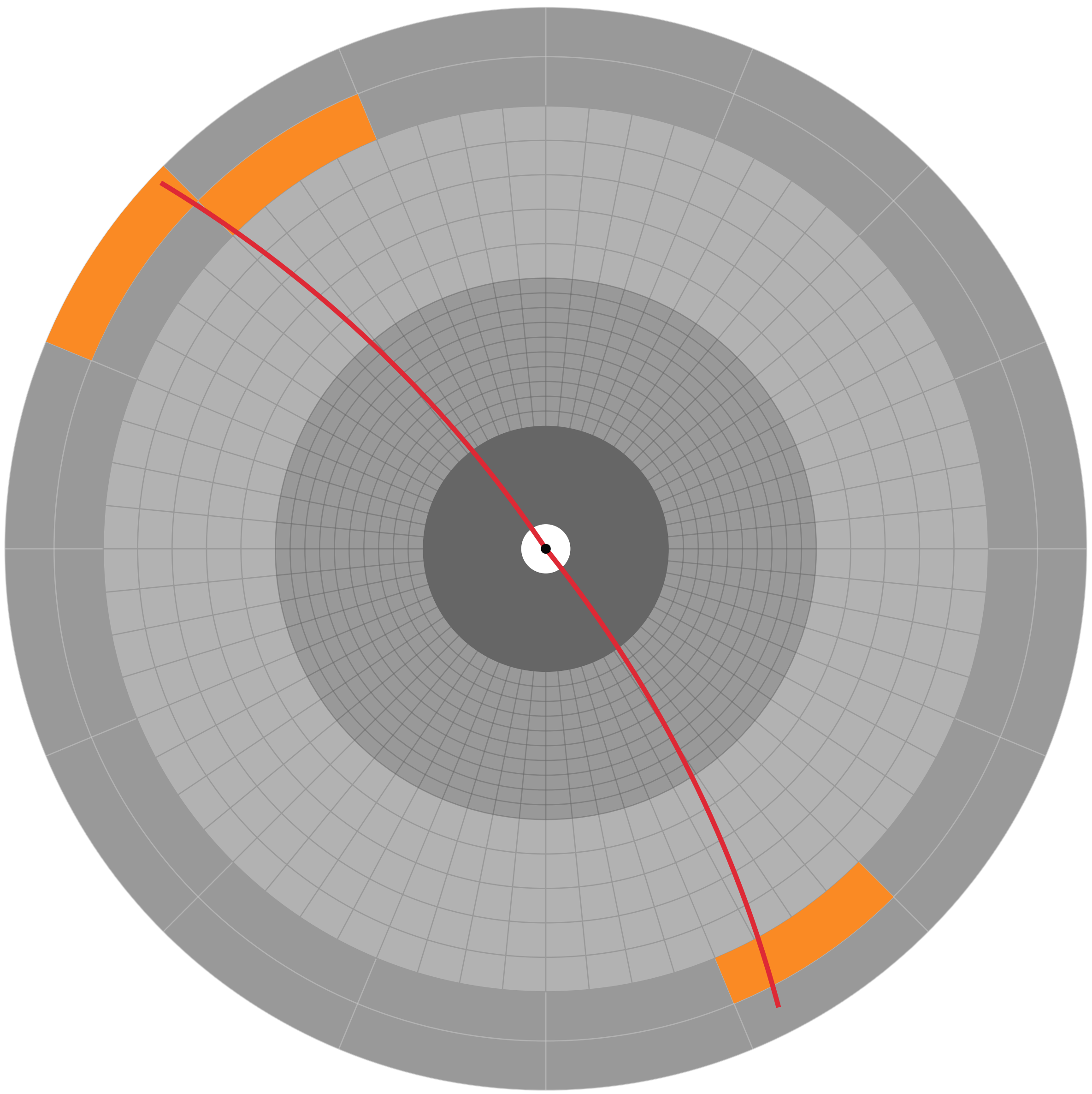
Needs a series of hits

Electrons



Tracks+
energy deposit
in EM calorimeter

Muons



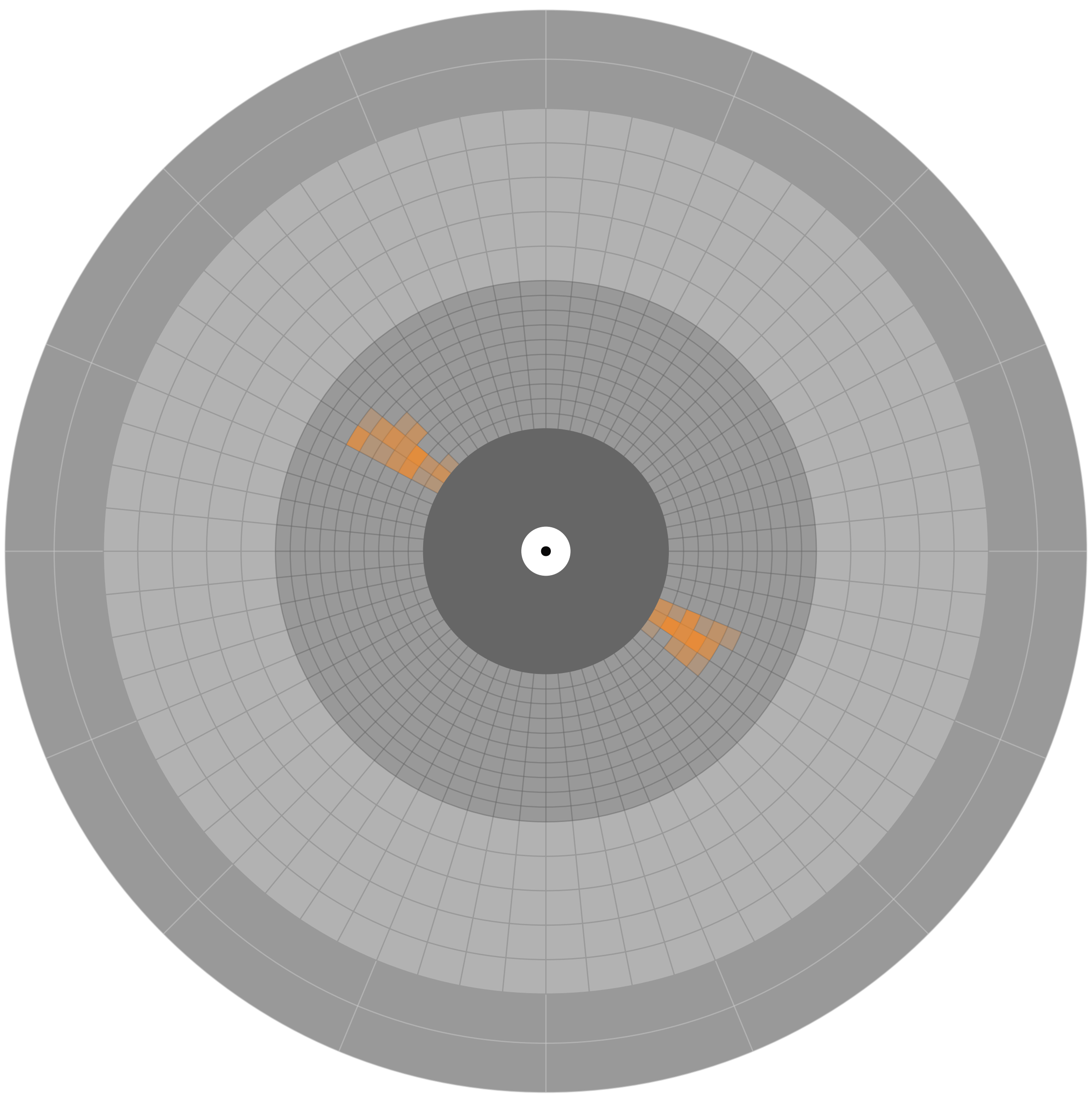
Heavier!

Stops in
muon chamber

Tracks+
energy deposit in
calorimeters

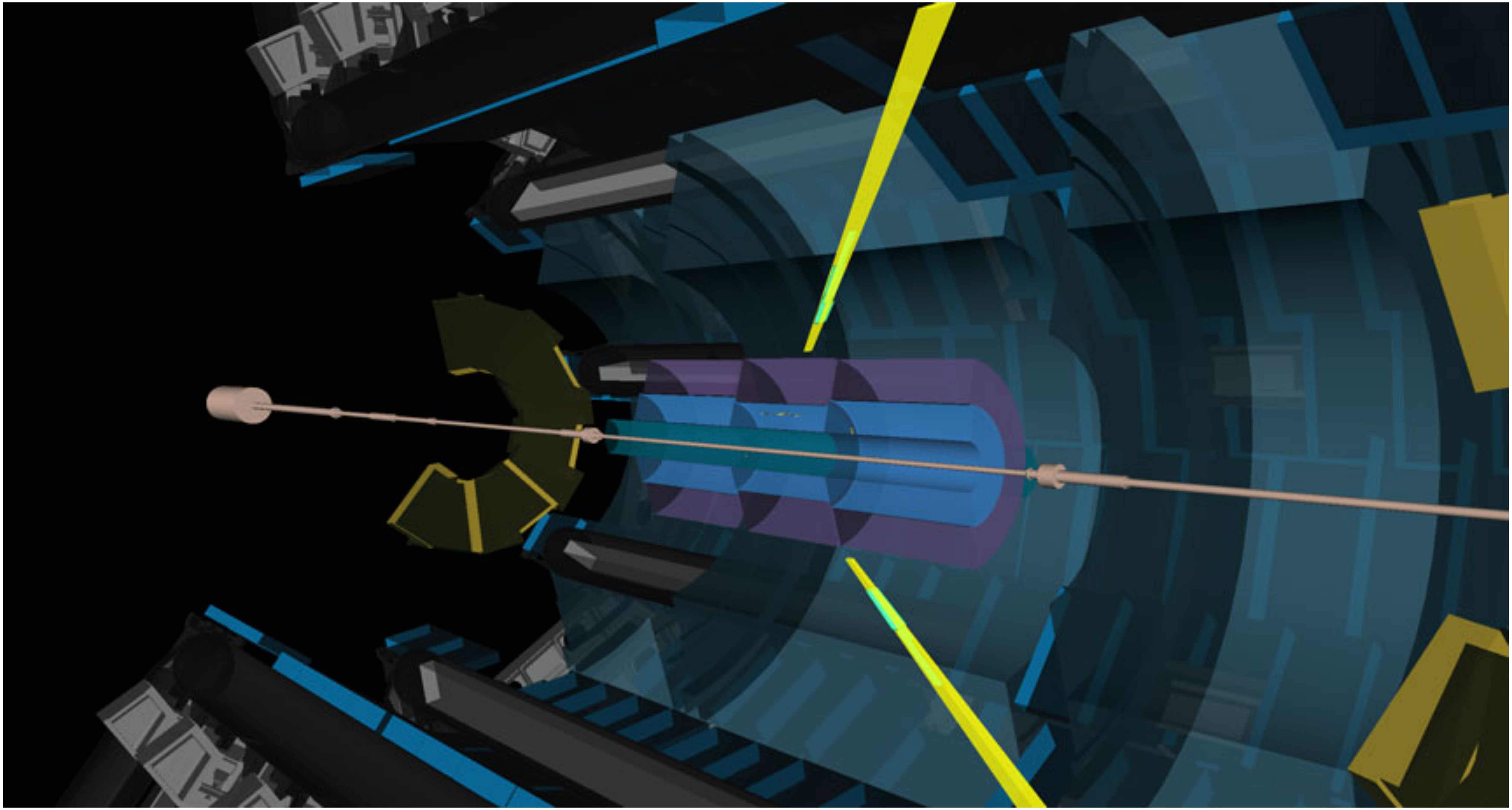
Very less energy in
calorimeters

Photons

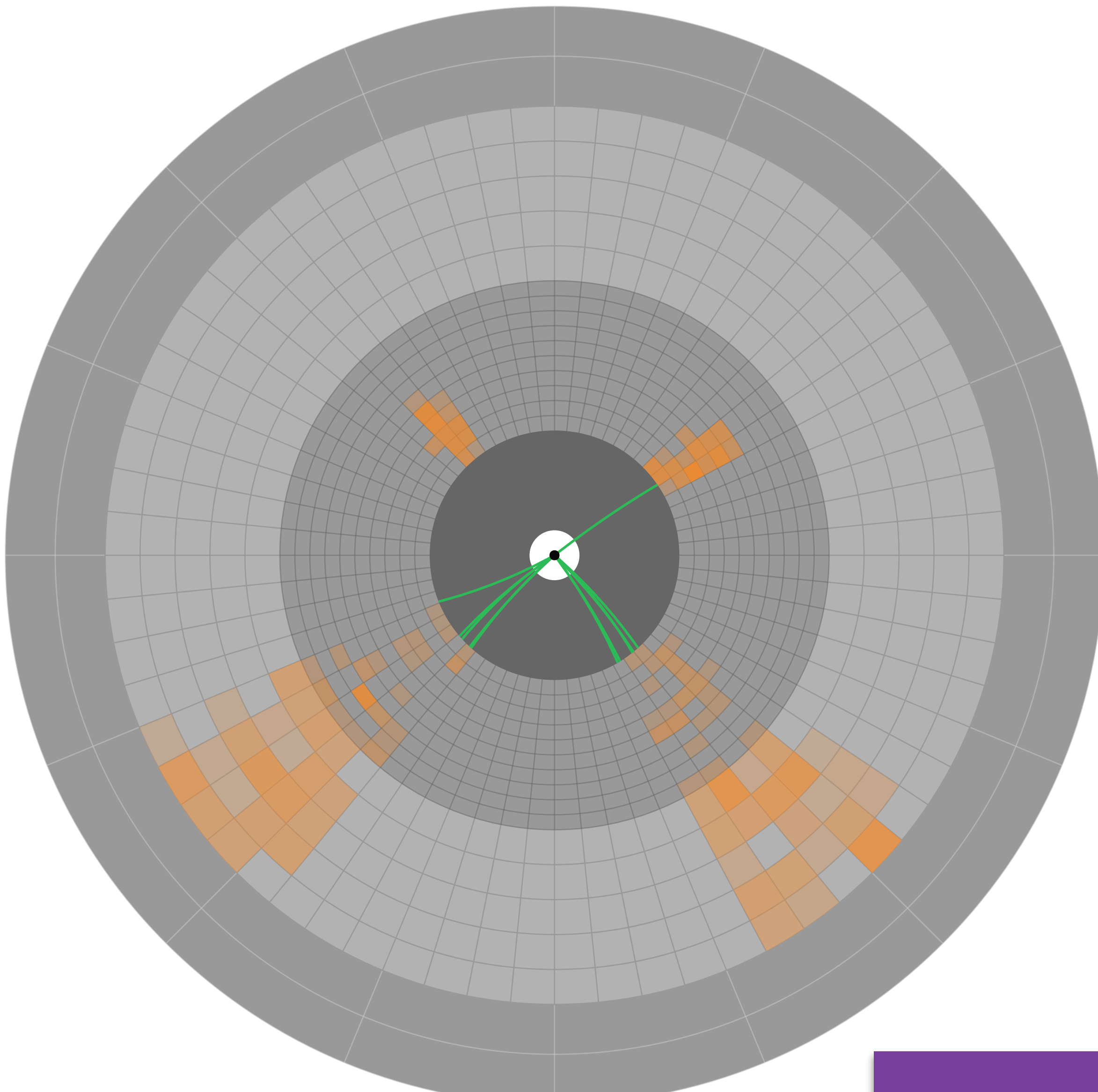


No tracks+
energy deposit
in EM calorimeter

Photons



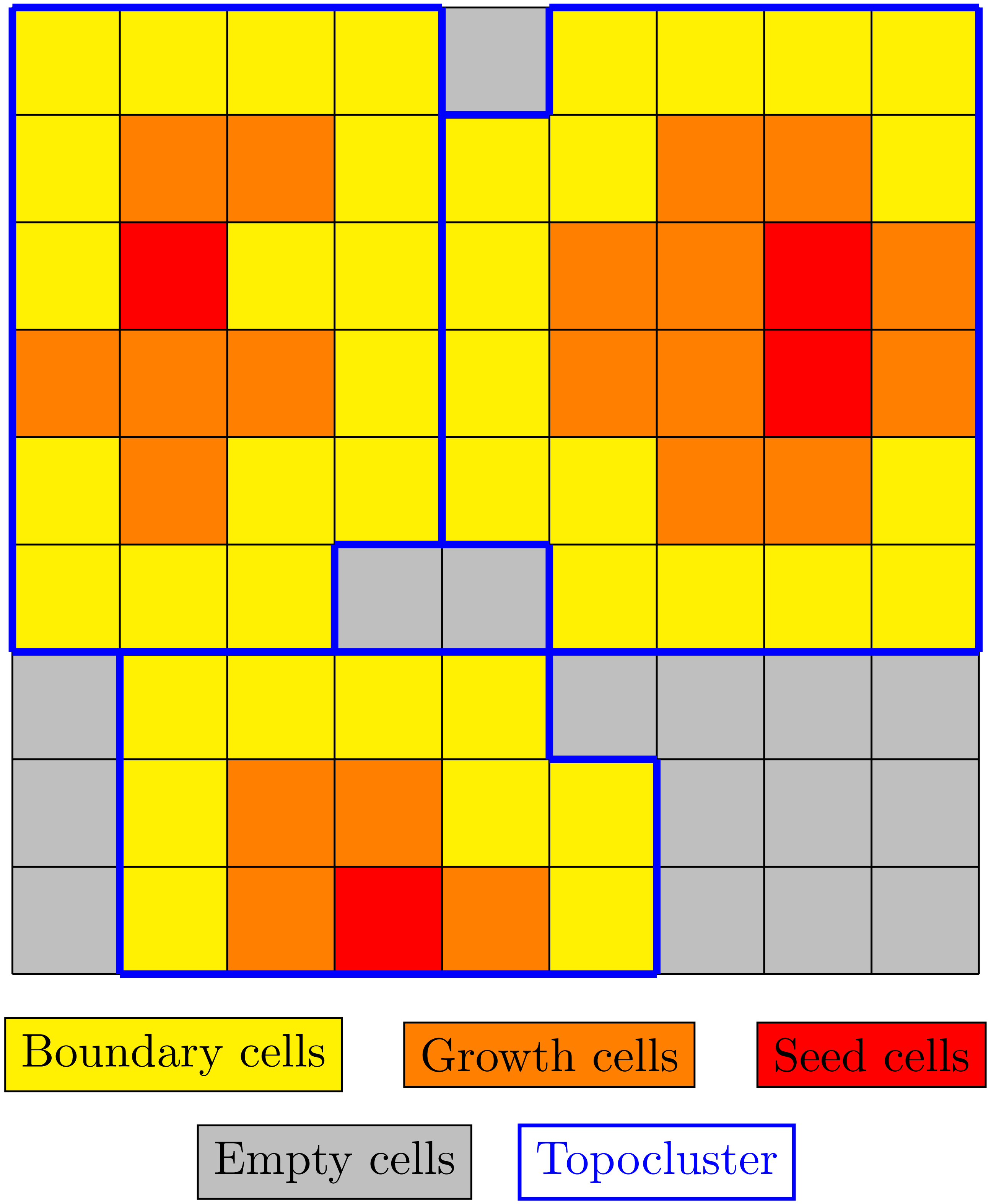
Hadrons



No tracks (neutral)+ energy deposit in hadronic calorimeter

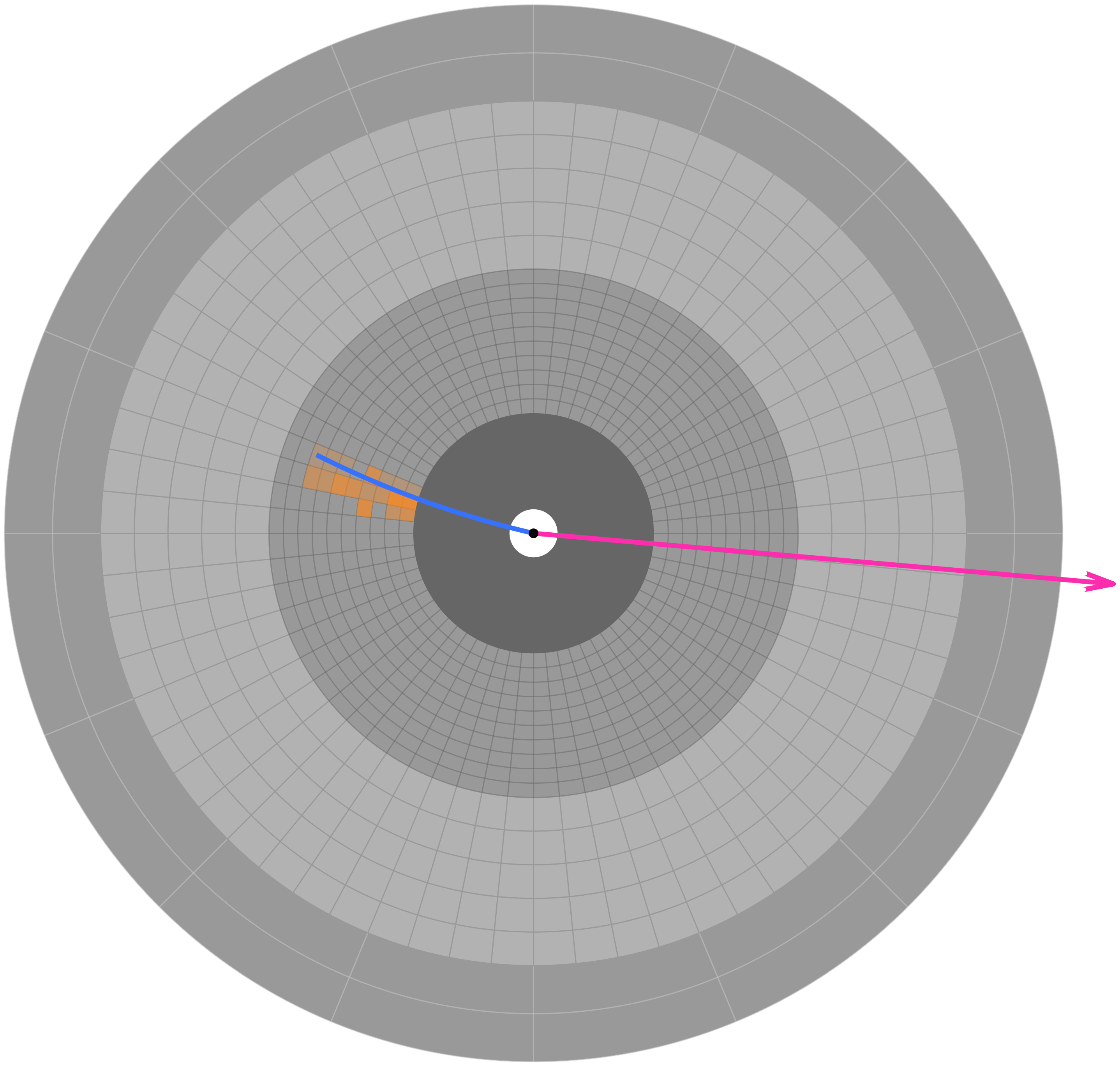
Is everything stopped in the detector?
Almost …

Neutral Hadrons



No tracks+
energy deposit
in hadronic
calorimeter

Neutrinos



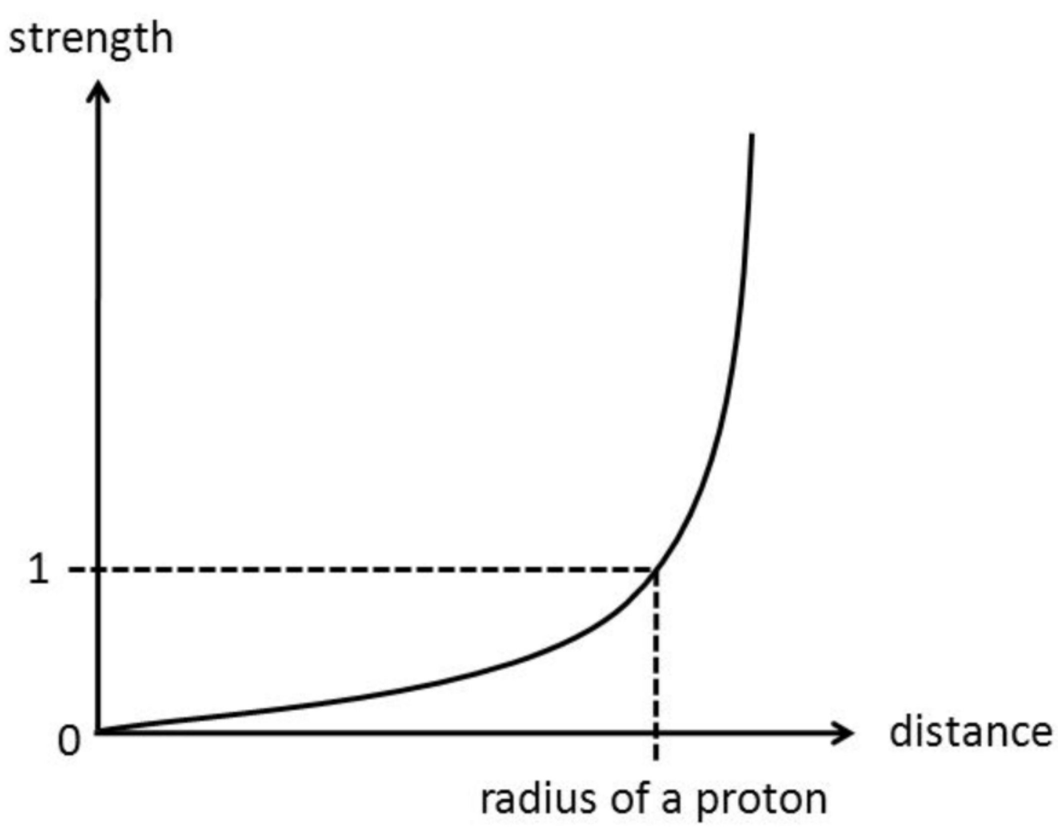
Missing Energy

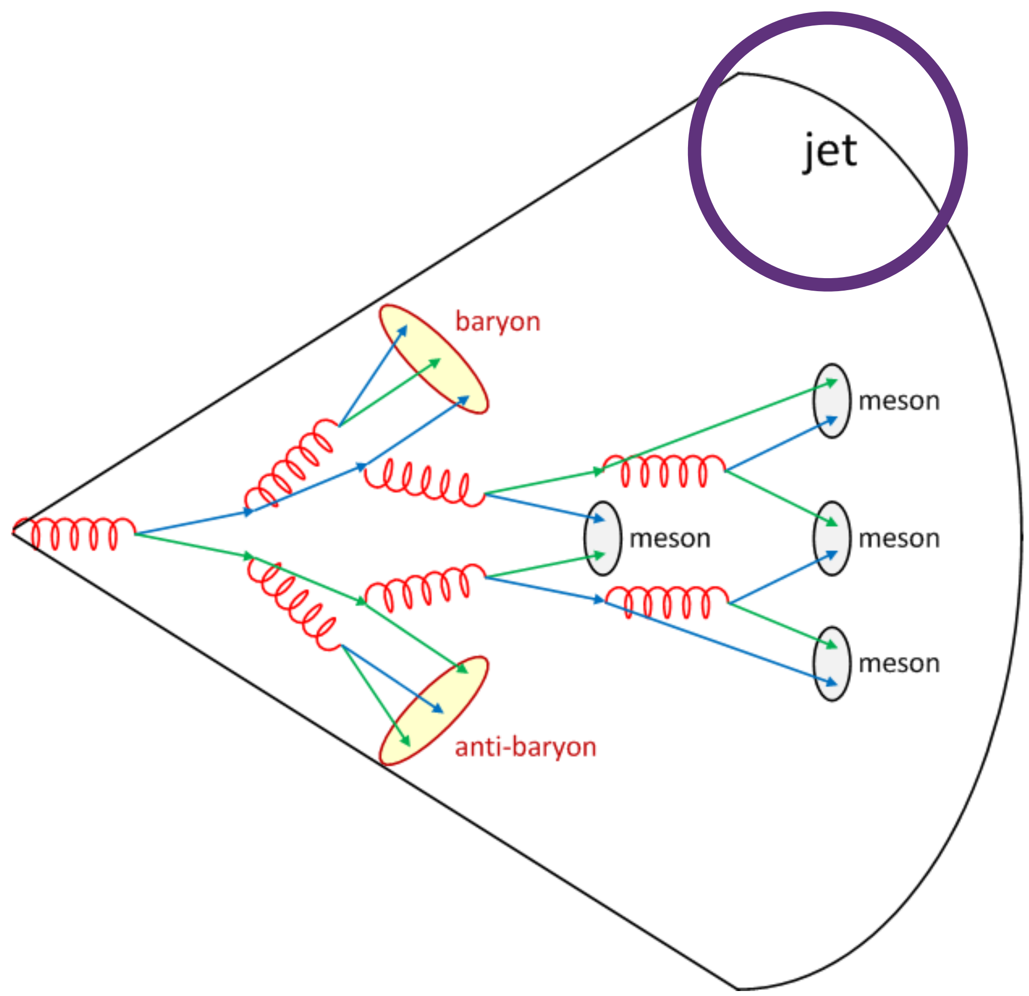
- Do not interact with the detector
- Imbalance of p_T
- Can be signs of new physics as well!

Only invisible SM particles are the neutrinos. DM, SUSY particles have not been seen yet!

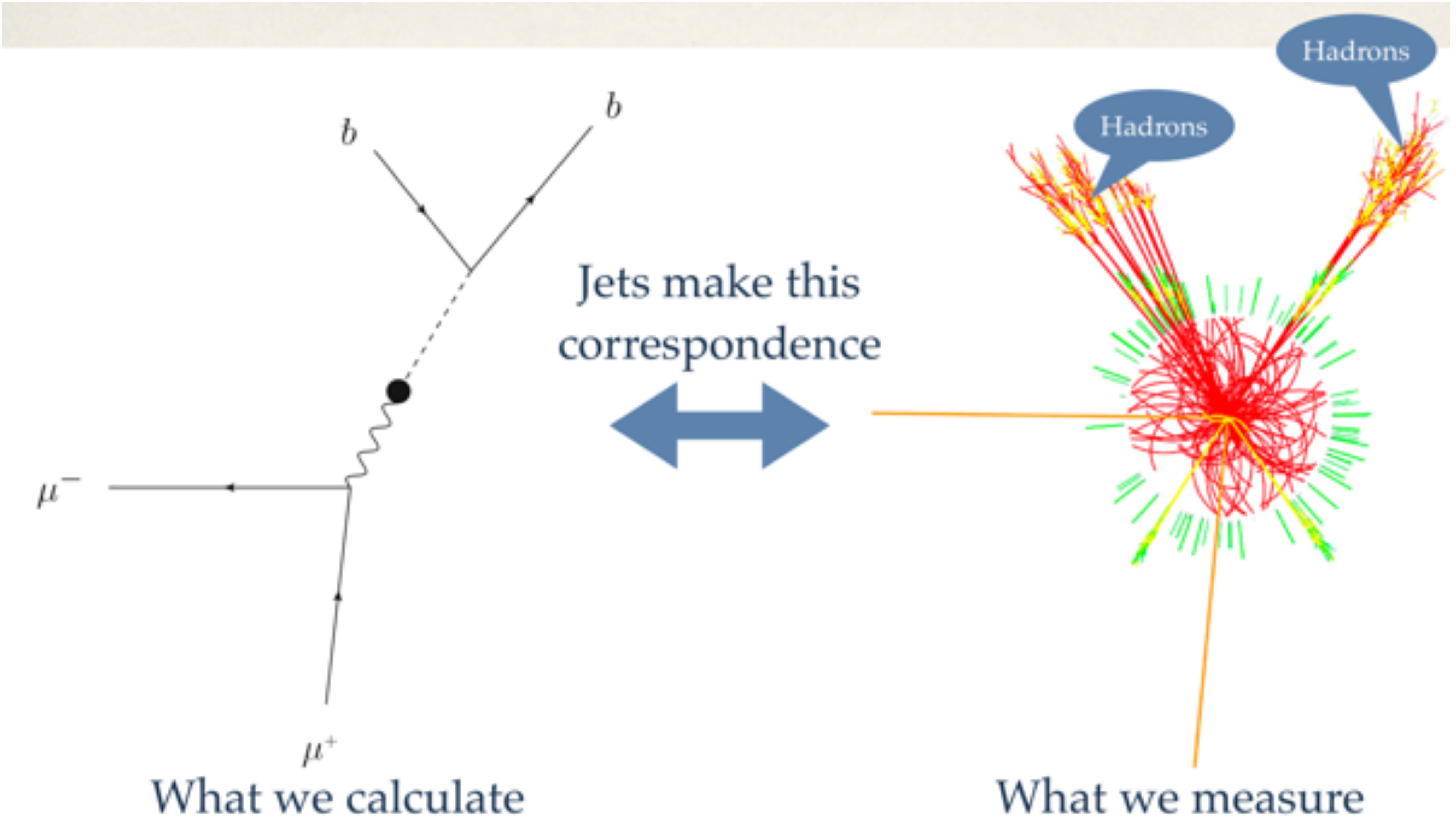
No free partons

- Strong interaction works like a rubber band!
- Only in composite (colourless) hadrons



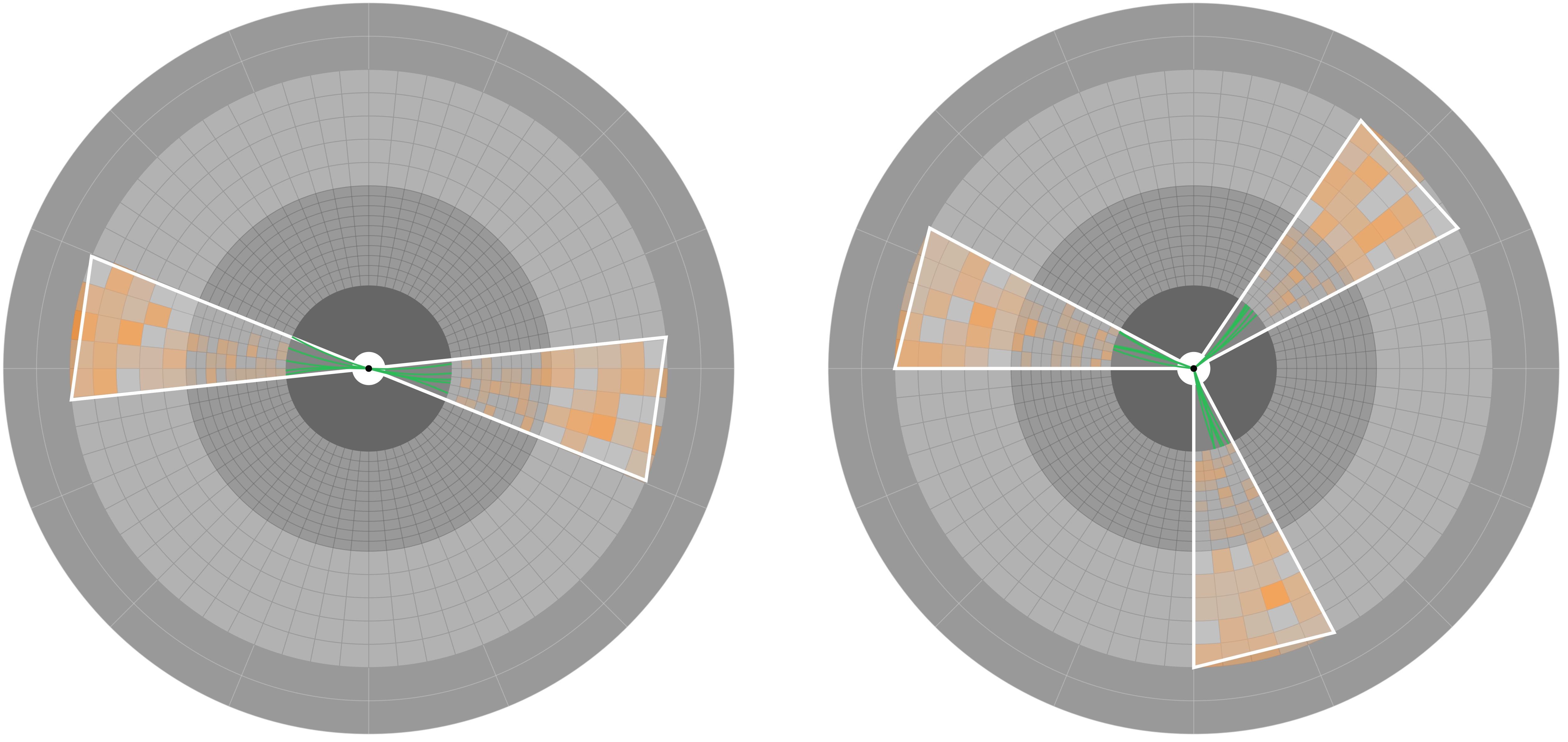


Jets



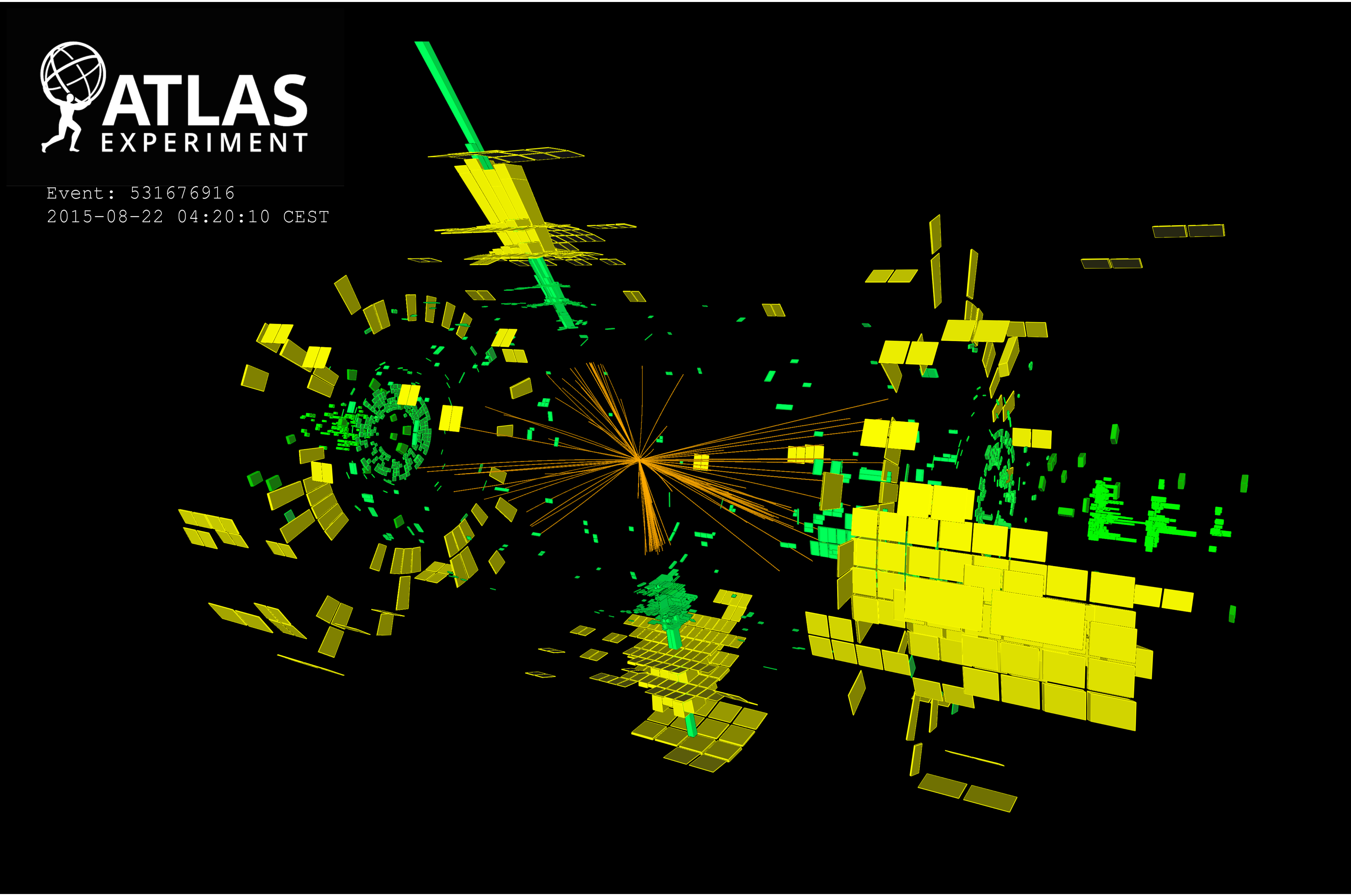
Jets are defined by how it is formed (algorithm), and the (cone) size/radius.

Jets

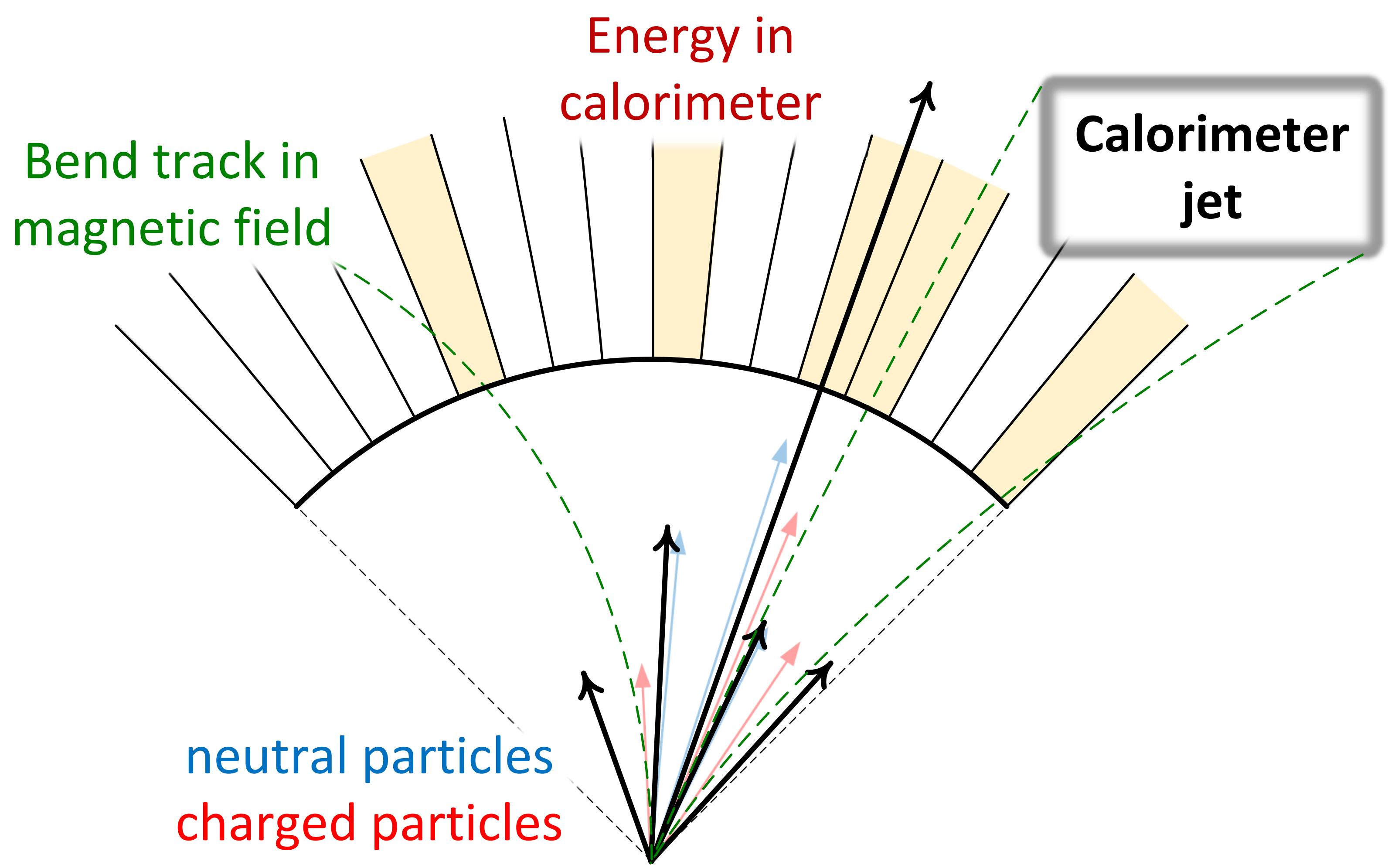


Jet Making

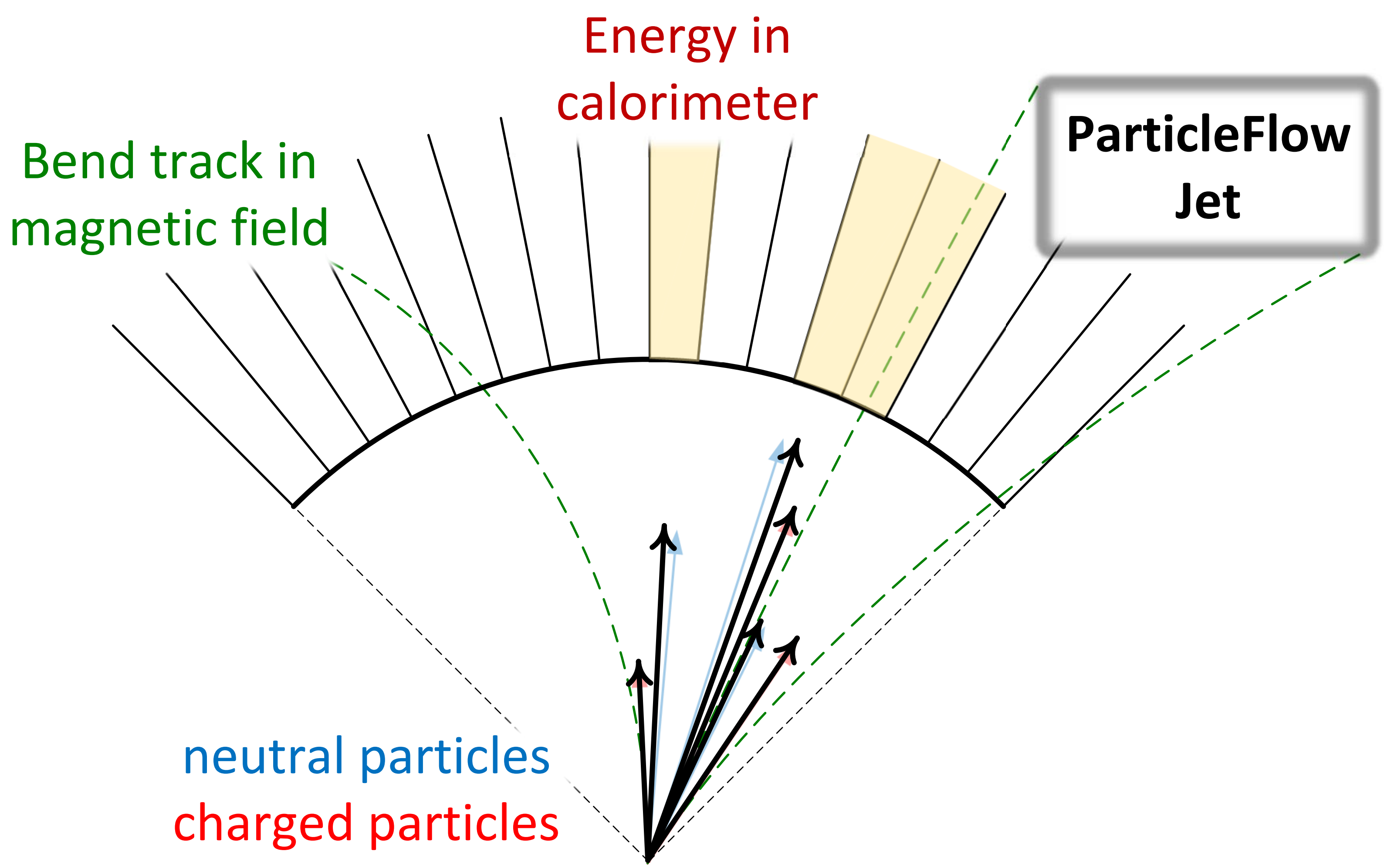
- Defined by input objects, combination algorithm, and the radius.
- Usual algorithm in LHC experiments: anti-k_t algorithm, which combines inputs in momentum-space, starting with *hardest* inputs.
- Algorithms need to be theoretically robust!


ATLAS
EXPERIMENT
Event: 531676916
2015-08-22 04:20:10 CEST

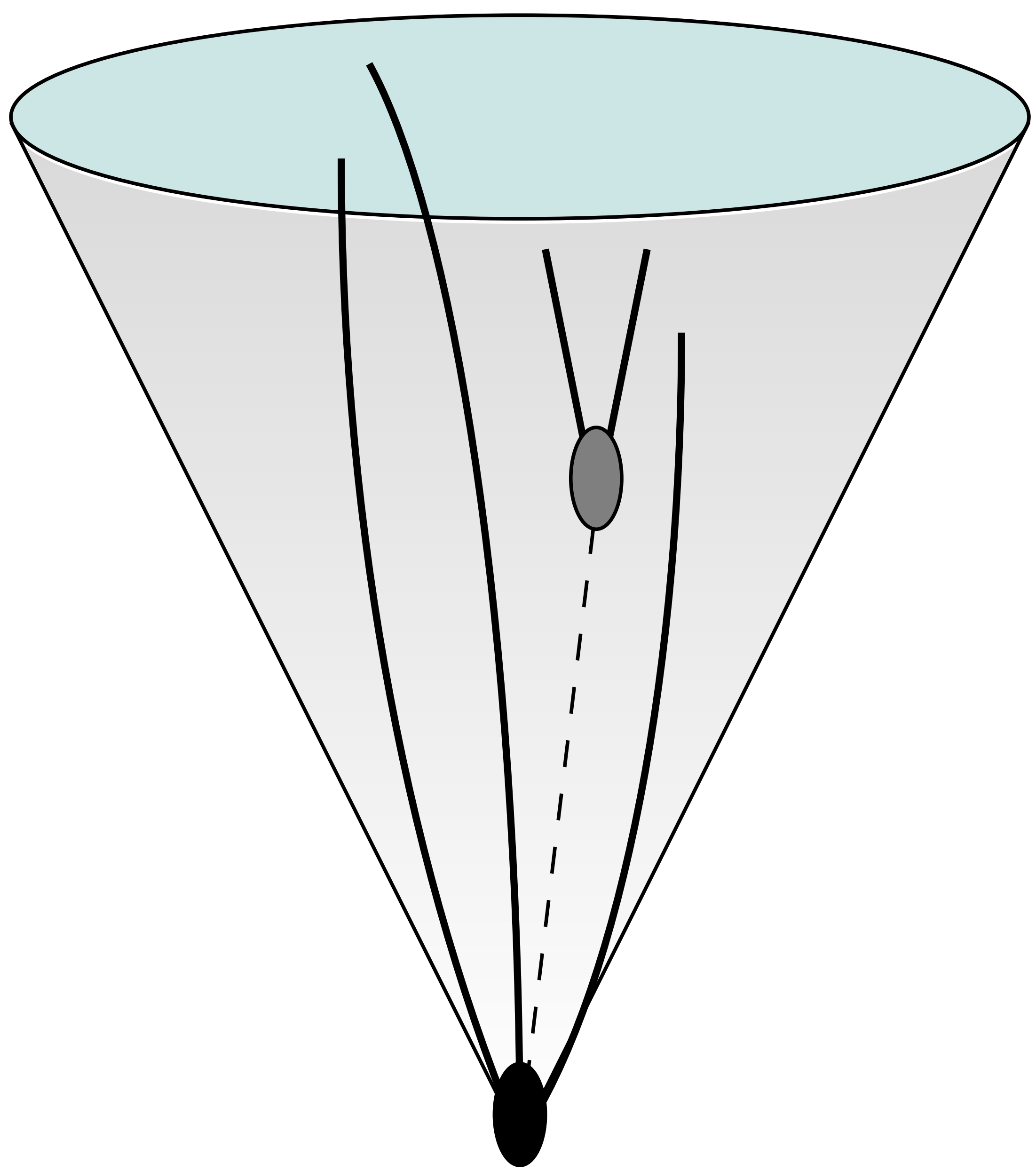
Calorimeter Objects



ParticleFlow Objects



B-tagging



Displaced vertex

Usually other criteria used as well

Session 2:
A Pinch of Theory

Common process at hadron colliders …

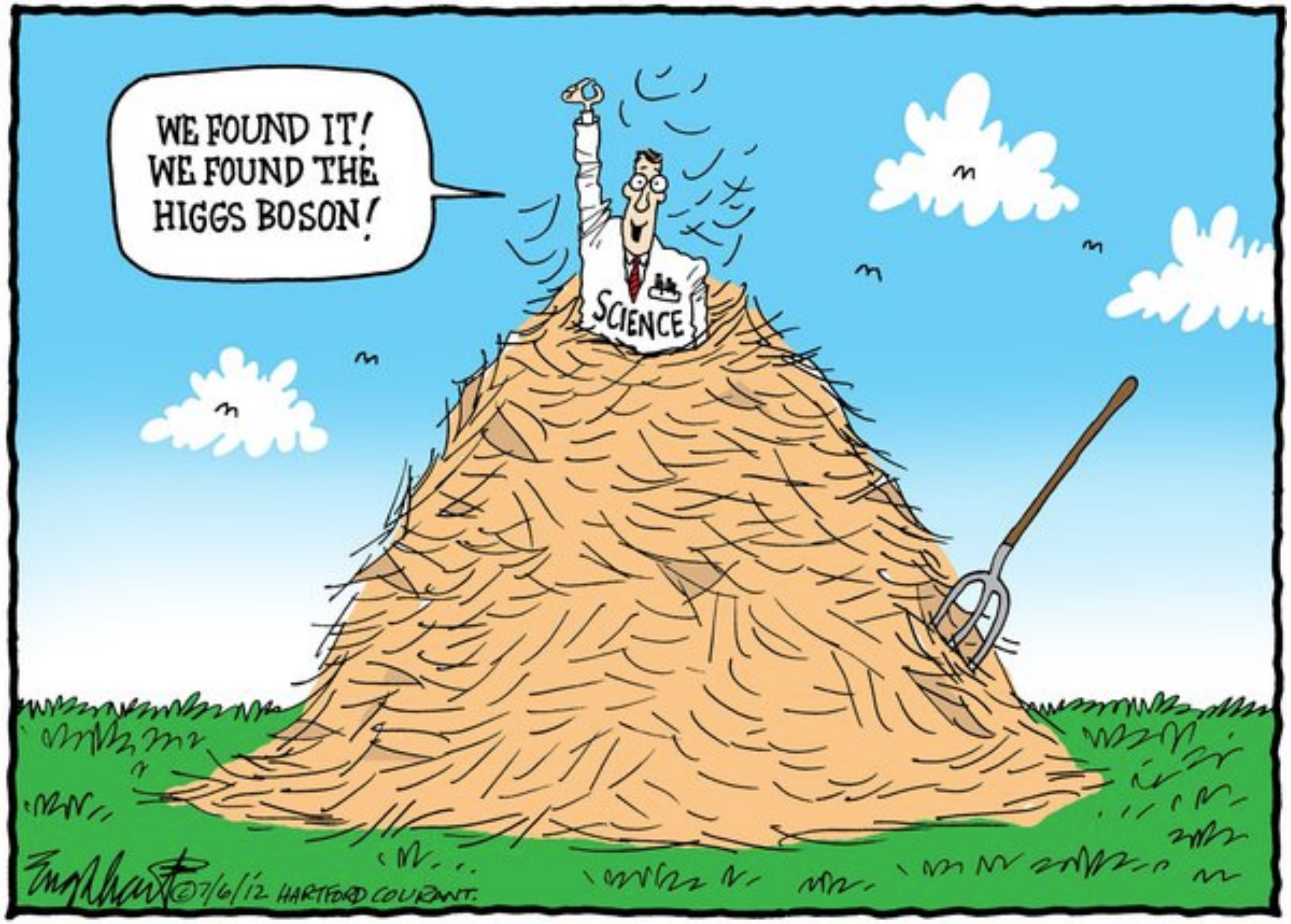
At 13 TeV collision energy:

Inclusive jet:
somewhere here

Process		Cross-section (in pb)	
Total Inelastic		8×10^{10}	
Process	Cross-section (in pb)	Process	Cross-section (in pb)
W^+, W^-	$1.2 \times 10^4, 8.8 \times 10^3$	Wt	94
Z	2×10^3	H	43
$t\bar{t}$	820	WZ	40
Single $t, \bar{t}$	136, 80	ZZ	15
W^+W^-	142	HH	0.03

Particle	Decay modes	BF (in %)
Z	$\ell^+\ell^-$	10 (equally divided into three flavours)
	$\nu\nu$	20 (equally divided into three flavours)
	$q\bar{q}$	70
W	$\ell^\pm\nu$	33 (equally divided into three flavours)
	$q\bar{q}$	70
Top	Wb	100
$t\bar{t}$	$\ell\nu b$, $q\bar{q}b$	14.8 (equally divided into three flavours)
	$\ell\nu b$, $\ell\nu b$	2.5 (equally divided into three flavours, mixed)
	$\ell\nu b$, $\ell\nu b$	1.25 (equally divided into three flavours, same)
	$q\bar{q}b$, $q\bar{q}b$	44.4
Higgs	$b\bar{b}$	60
	W^+W^-	21
	gg	9
	$\tau^+\tau^-$	5
	$c\bar{c}$	2.5
	ZZ	2.5
	$\gamma\gamma$	0.2
	$Z\gamma$	0.15
τ	$e\nu_e\nu\tau$	17.8
	$\mu\nu_\mu\nu\tau$	17.4
	$\pi^-\nu\tau$	10.8
	$\pi^-\pi^0\nu\tau$	25.5
	$\pi^-\pi^0\pi^0\nu\tau$	10.3
	$\pi^-\pi^0\pi^0\pi^0\nu\tau$	1.1

What do we do?


WE FOUND IT! WE FOUND THE HIGGS BOSON!
SCIENCE
©7/6/12 HARTFORD COURANT.

What you see is not what you have!

- We don't get what is coming out of the collisions.
- Finite lifetime of particles, decays before reaching the detector.
- Detectors have finite resolution, less than perfect response and efficiency.

Hard Objects

- We are *mostly* interested in discovering new particles, which have high mass or p_T.
- These processes mostly result in production of jets, photons, top quarks, W/Z/Higgs bosons, etc.
- The SM BF for these production modes are very small, so mostly swamped by *background* processes described so far.

Analysis is the procedure by which we extract physics information from data (with a lot of help from simulation). Measurements are designed to verify standard model predictions, while the searches are designed to look for beyond the standard model signatures.

Analysis is the procedure by which we extract physics information from data (with a lot of help from simulation). Measurements are designed to verify standard model predictions, while the searches are designed to look for beyond the standard model signatures.

Modelling the collisions

Event Generators

- We want realistic simulation of the collision events. Why? Devise analysis strategy, background model, study/remove detector effect, etc.
- The hard scattering part can be calculated theoretically (in some order) .
- The soft part is not calculable, so we use phenomenological models implemented in generators

Actually two step process, but not going to discuss detector simulation!

Useful terms

- Strong coupling constant (α_s): QCD interaction strength.

- Scales: hard scattering scale (momentum transfer), renormalisation scale (subtracts uv divergence), factorisation scale (separates non-perturbative physics)

- PDF: probability of a quark and gluon carrying a certain fraction of proton energy.

Useful terms

- Strong coupling constant (α_s): QCD intera strength.

- Scales: hard scattering scale (momentum transfer) renorm factori physic

- PDF: probability of a quark and gluo certain fraction of proton energy.

Neg amplitudes: think as of as destructive interference

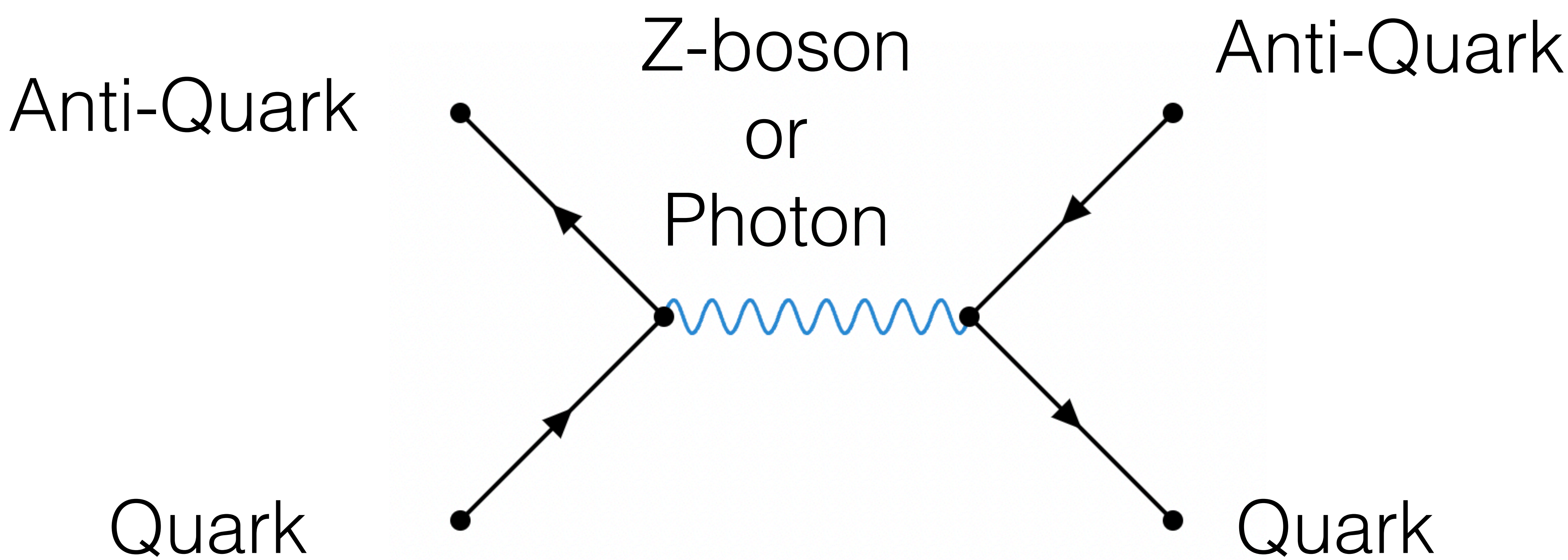
Scale setting and variations are ad-hoc, sensible/educated guesses at best. Scale variations at LO should cover NLO effects.

If the k-factor is too large, probably worth going to NLO! We usually have ~20% effect.

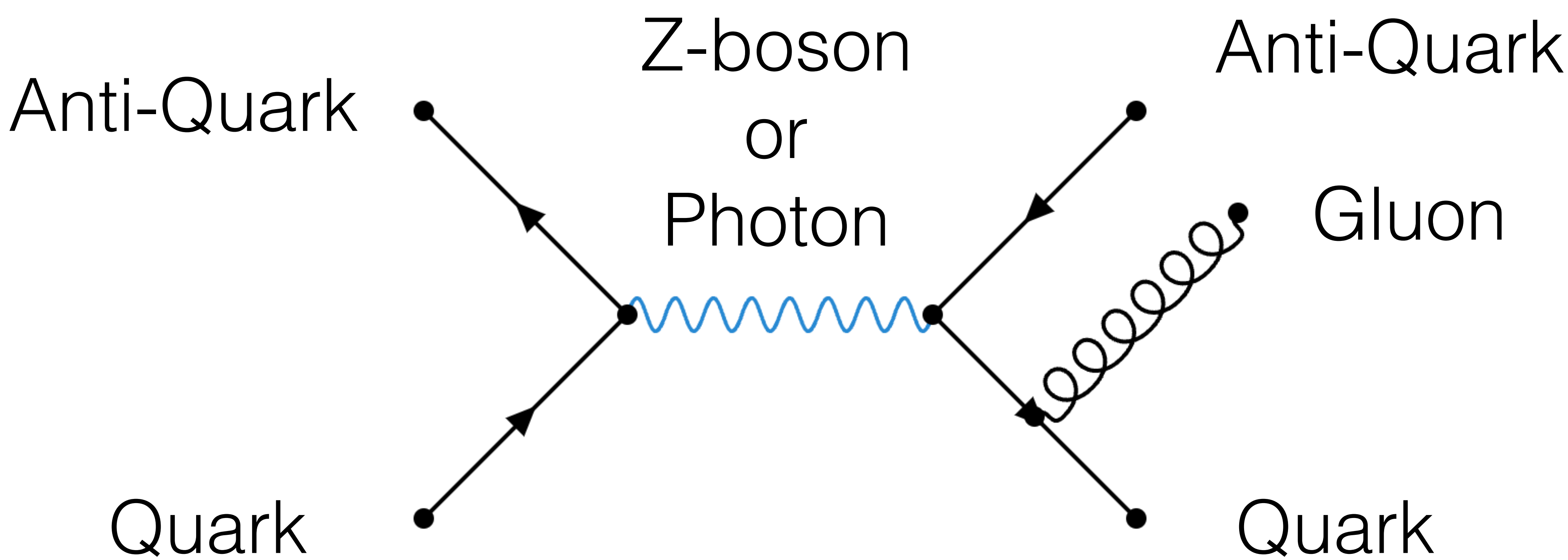
Small distance scale, undefined number of partons -> uncertainty on energy fraction

Feynman Diagrams

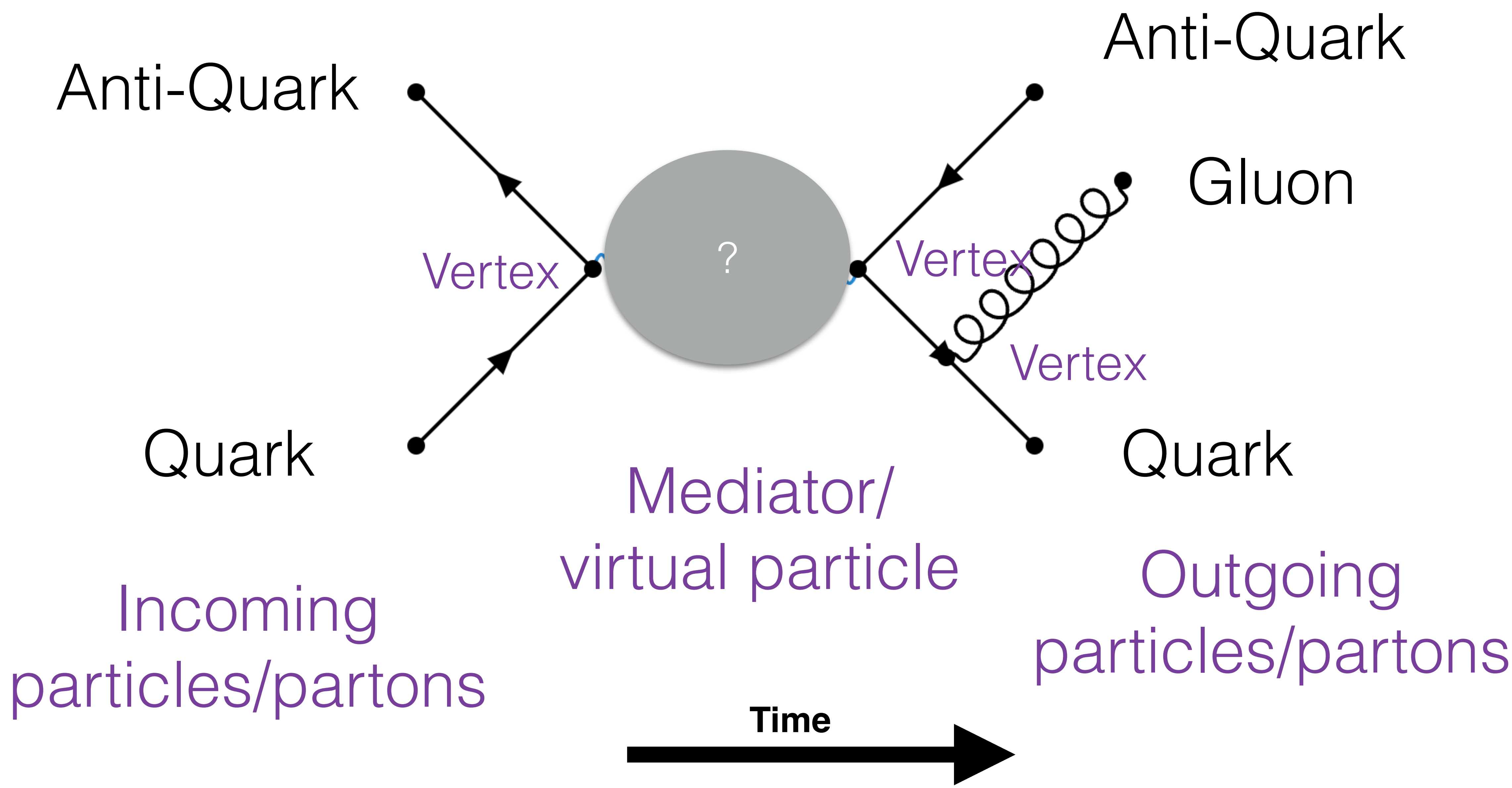
Feynman diagrams



Feynman diagrams



Feynman diagrams

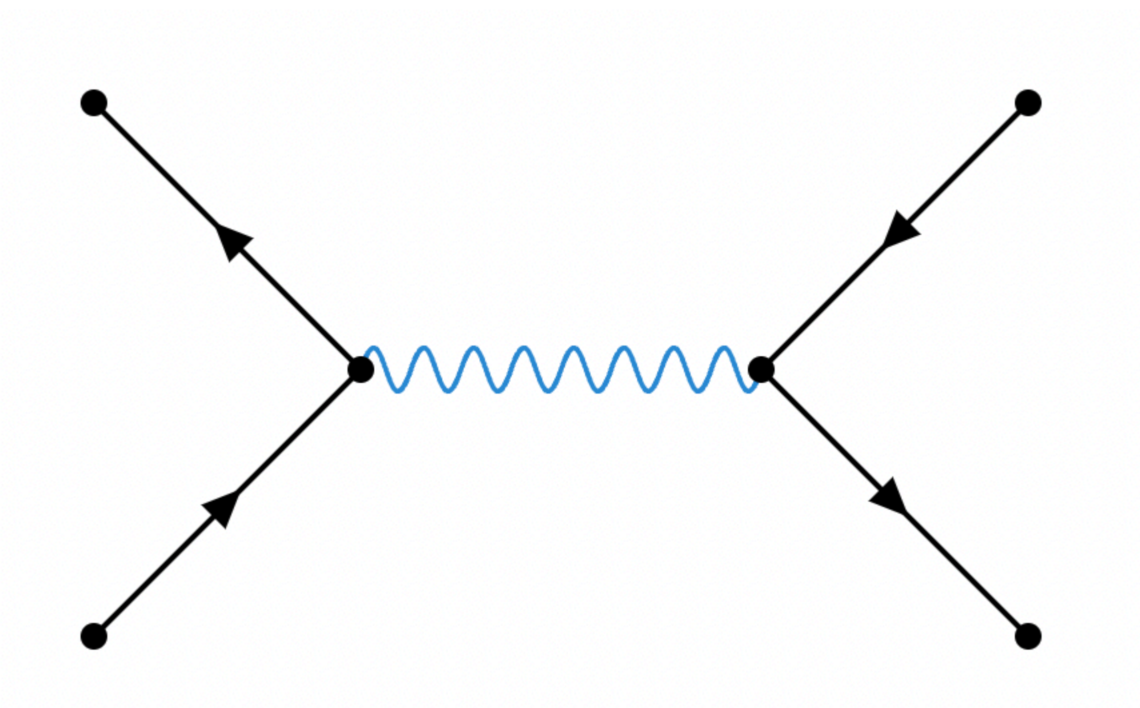


The lines are NOT particle trajectories

Shorthand to calculate scattering amplitudes …

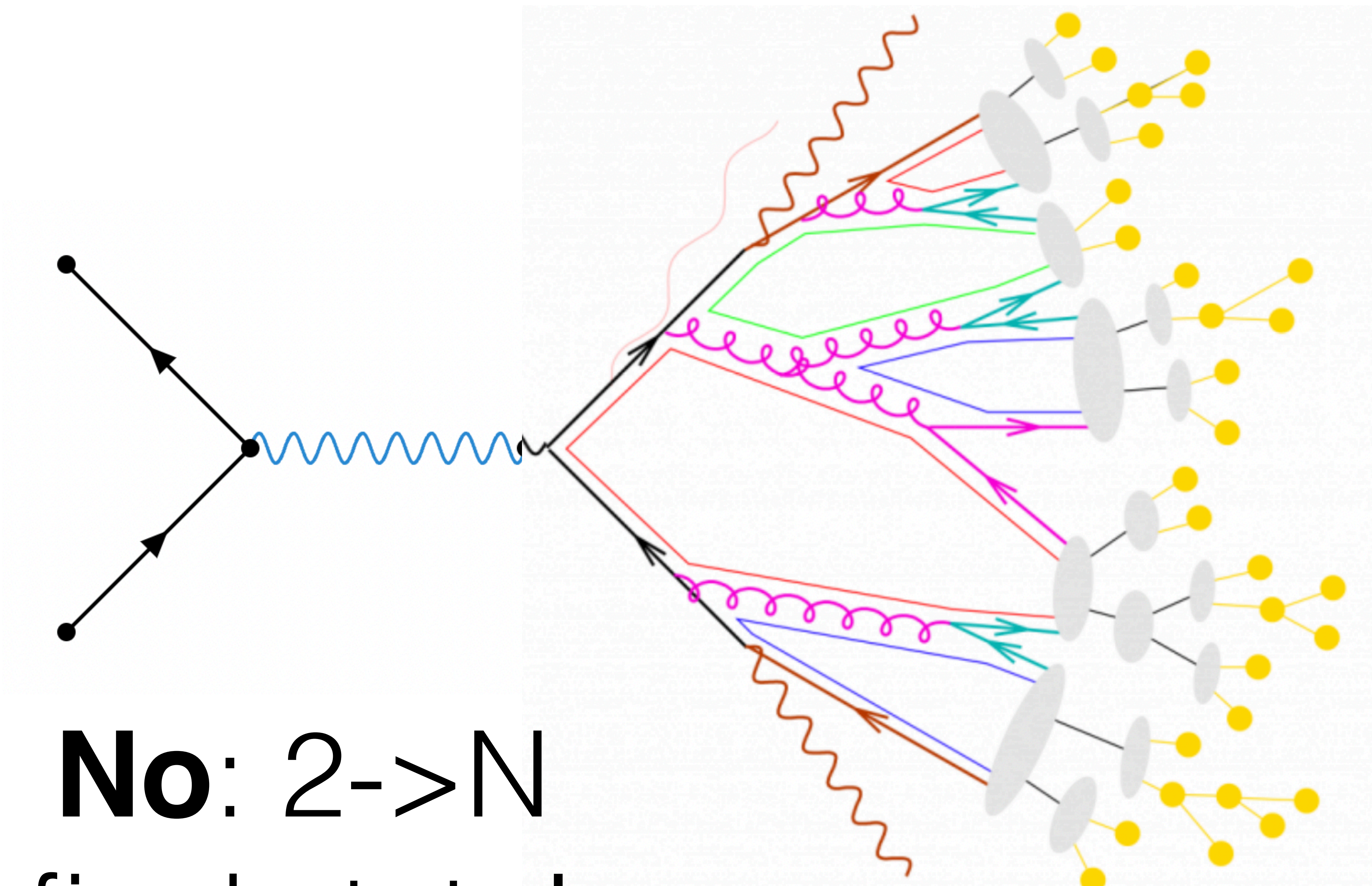
- We want to calculate probabilities for relativistic scattering processes.
- Initial and final states: particles with well defined momenta
- Each graph represents one way that process can happen

Simulation of Events



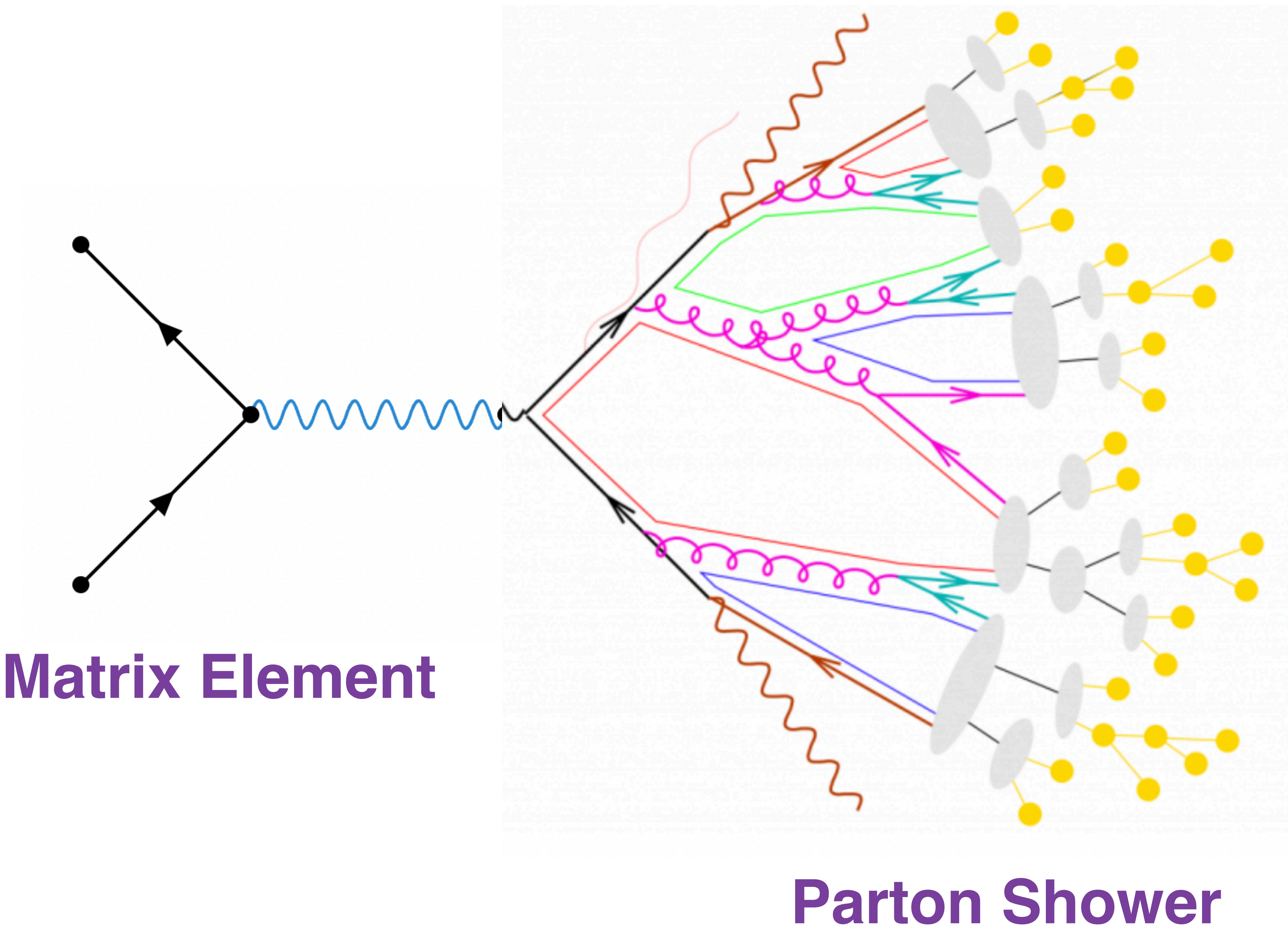
Is that all?

Simulation of Events



No: 2->N
final state!

Simulation of Events



Monte Carlo?!

It is impossible to calculate and integrate the matrix elements for a large numbers of particles

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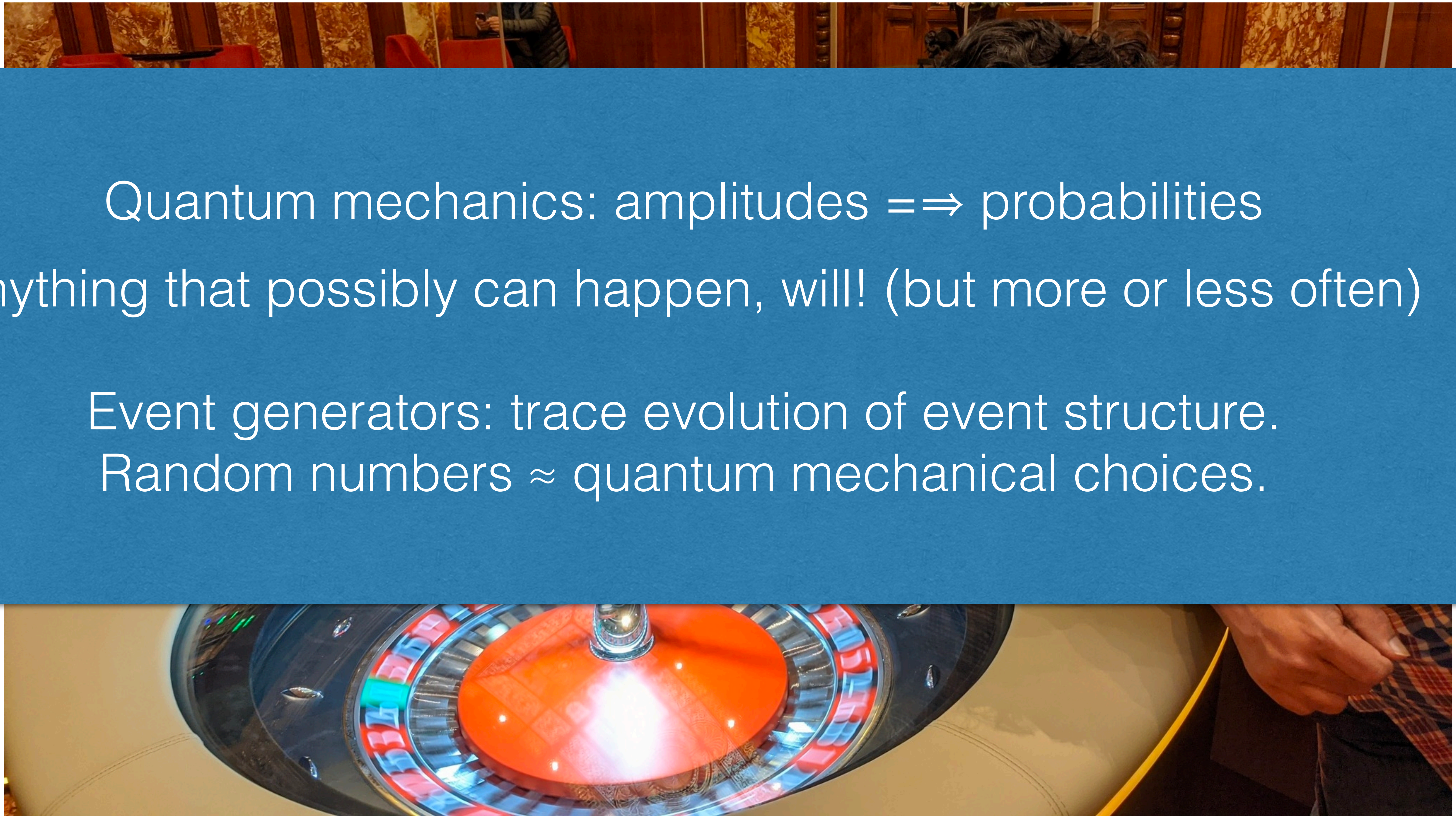


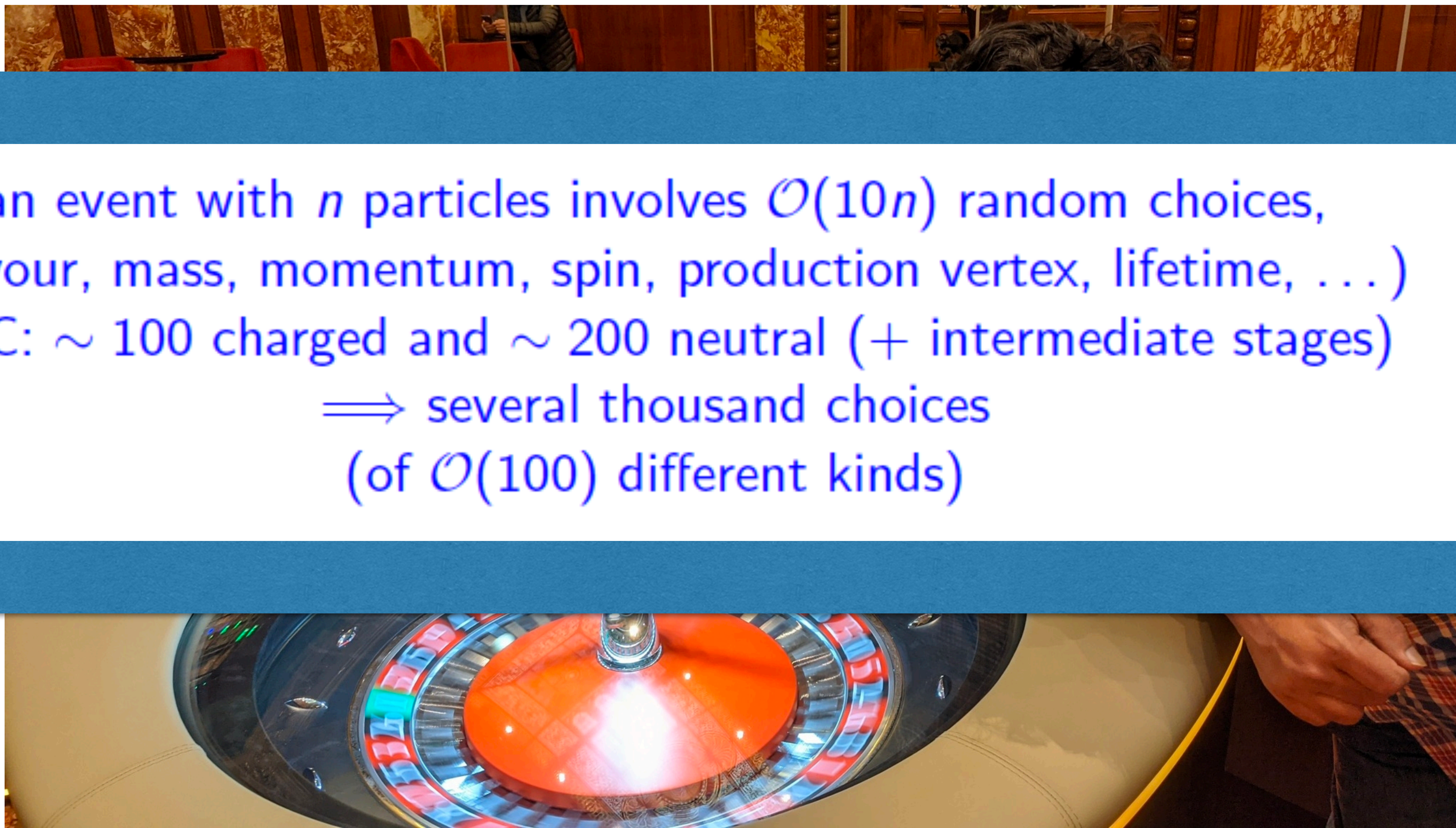
Quantum mechanics: amplitudes $\Longrightarrow$ probabilities

Anything that possibly can happen, will! (but more or less often)

Event generators: trace evolution of event structure.
Random numbers $\approx$ quantum mechanical choices.

Monte Carlo?!

It is impossible to calculate and integrate the matrix elements for a large numbers of particles

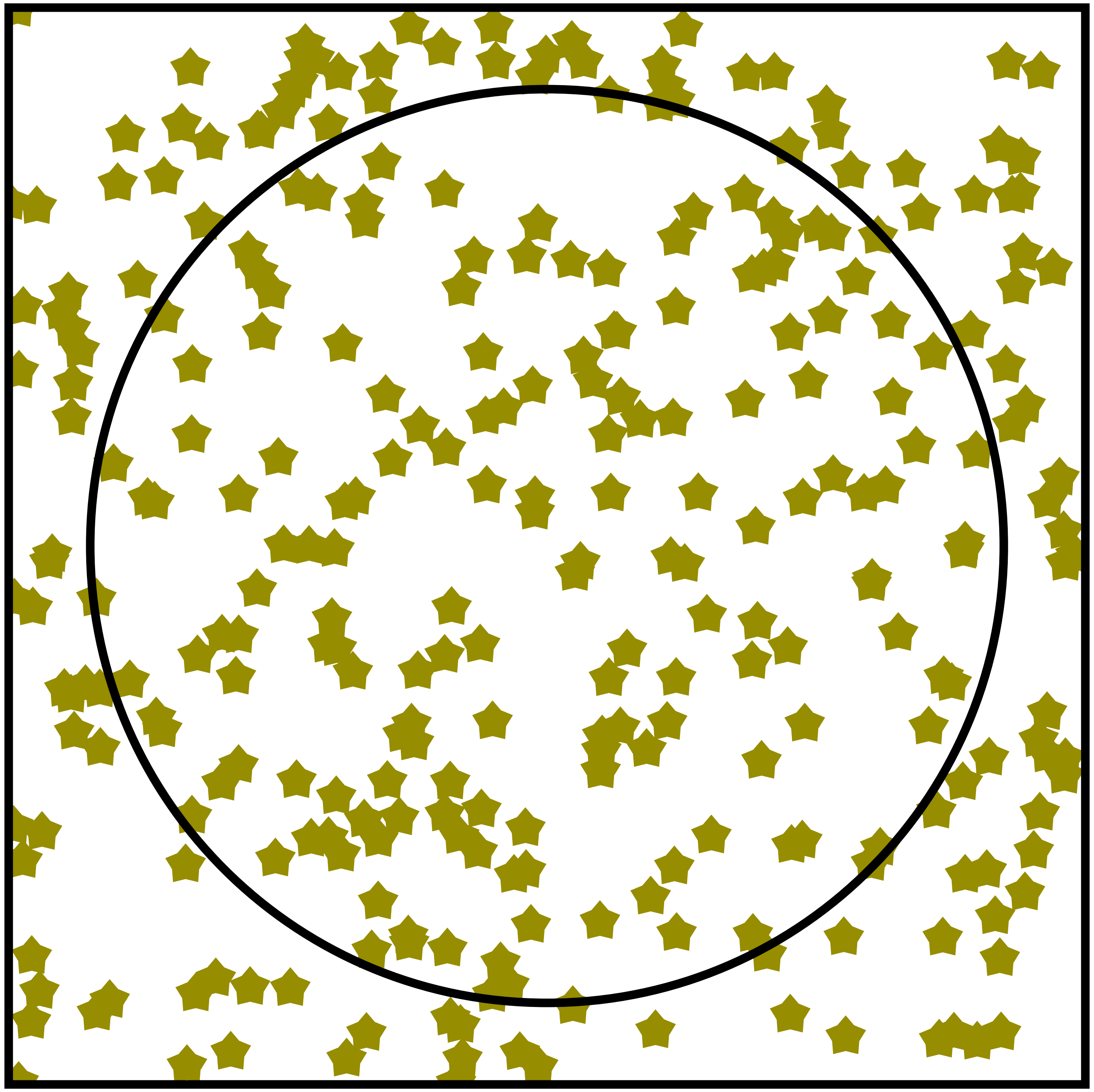


an event with n particles involves $\mathcal{O}(10n)$ random choices,
(flavour, mass, momentum, spin, production vertex, lifetime, . . .)
LHC: $\sim$ 100 charged and $\sim$ 200 neutral (+ intermediate stages)
$\Longrightarrow$ several thousand choices
(of $\mathcal{O}(100)$ different kinds)

Monte Carlo Method

Find the area of a circle?

Monte Carlo Method

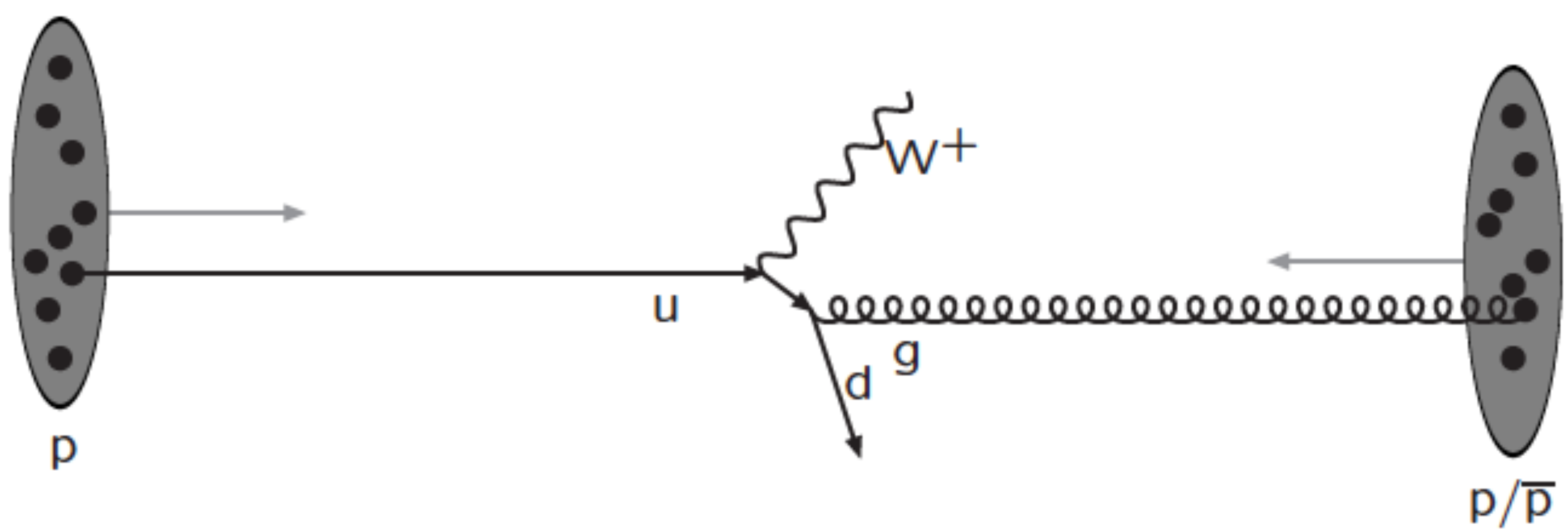


The structure of an event – 1

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

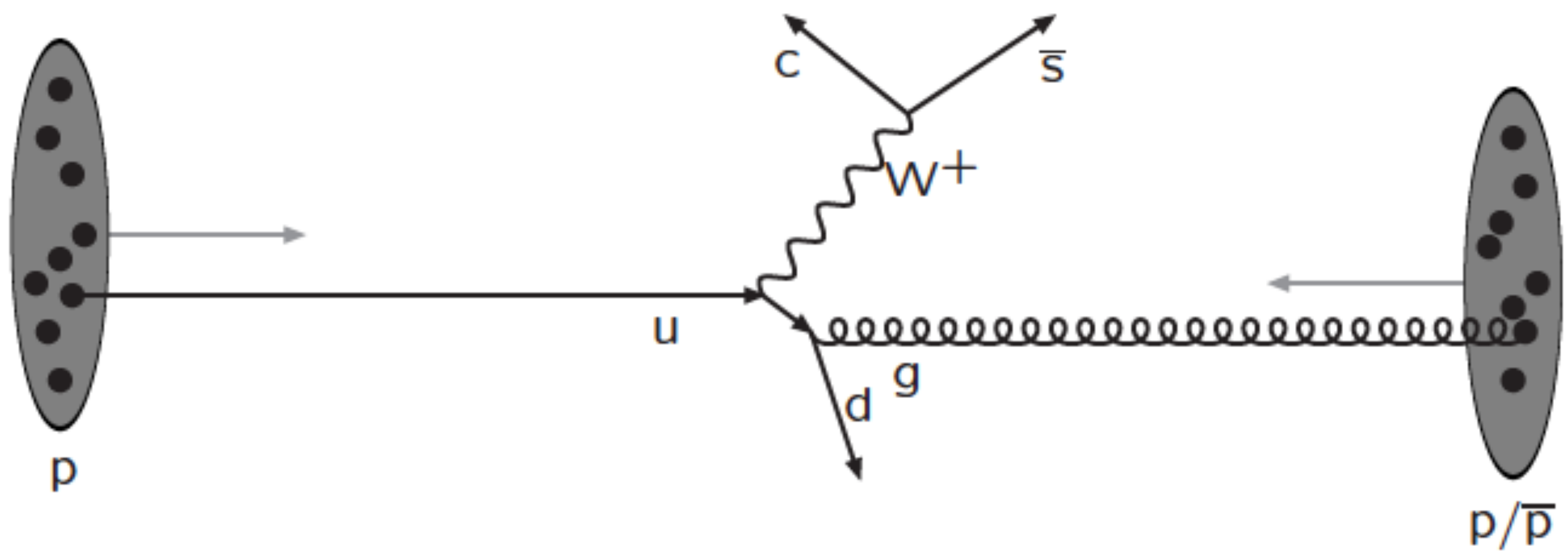
Incoming beams: parton densities

The structure of an event – 2



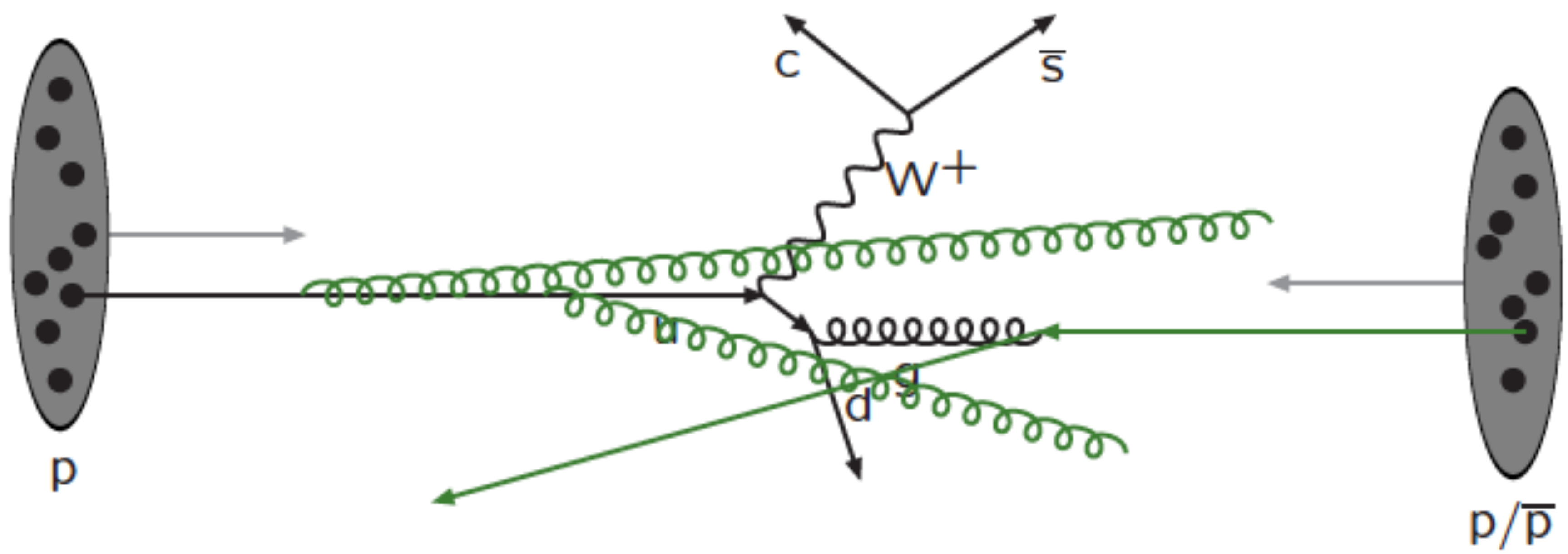
Hard subprocess: described by matrix elements

The structure of an event – 3



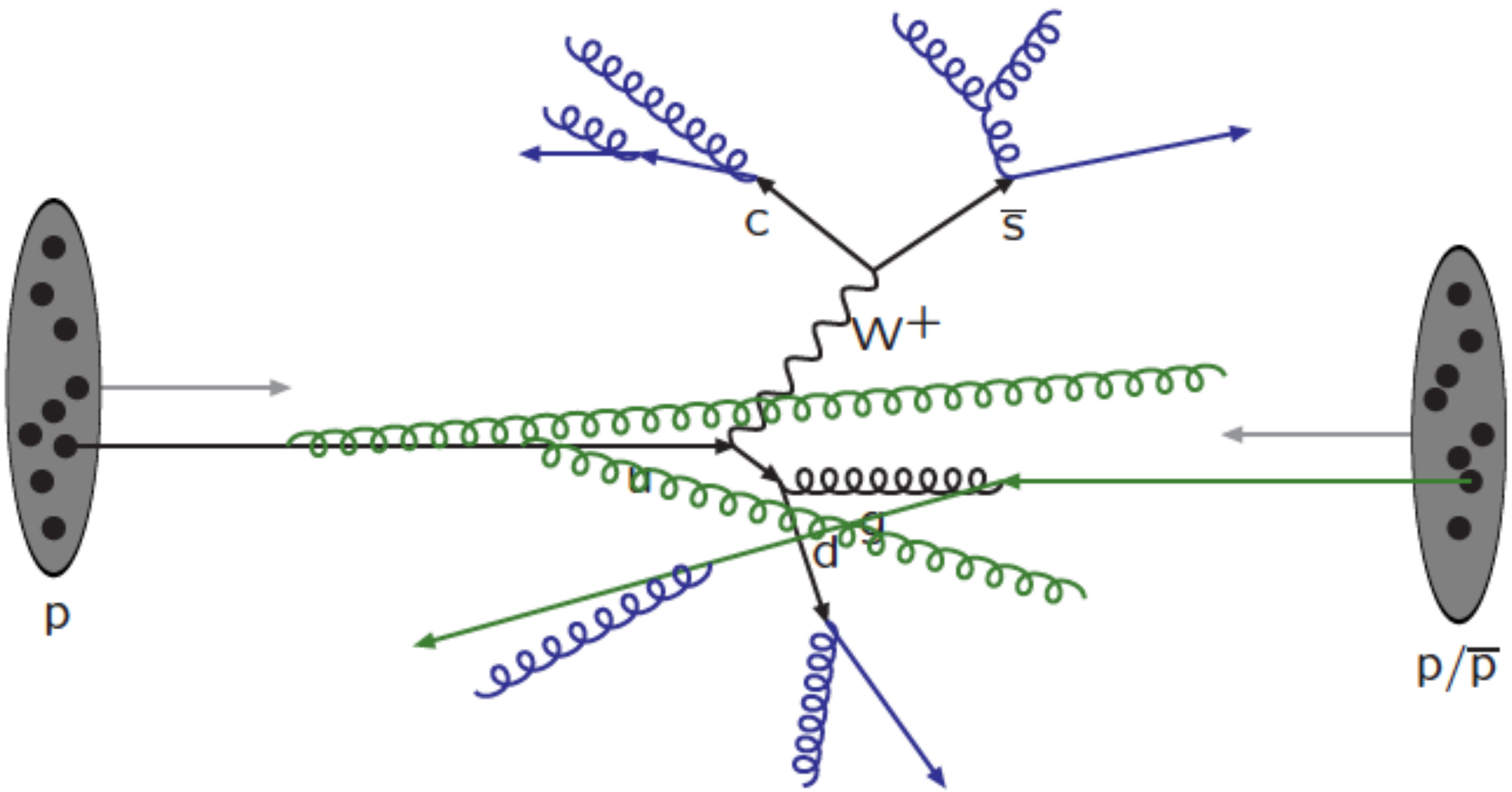
Resonance decays: correlated with hard subprocess

The structure of an event – 4



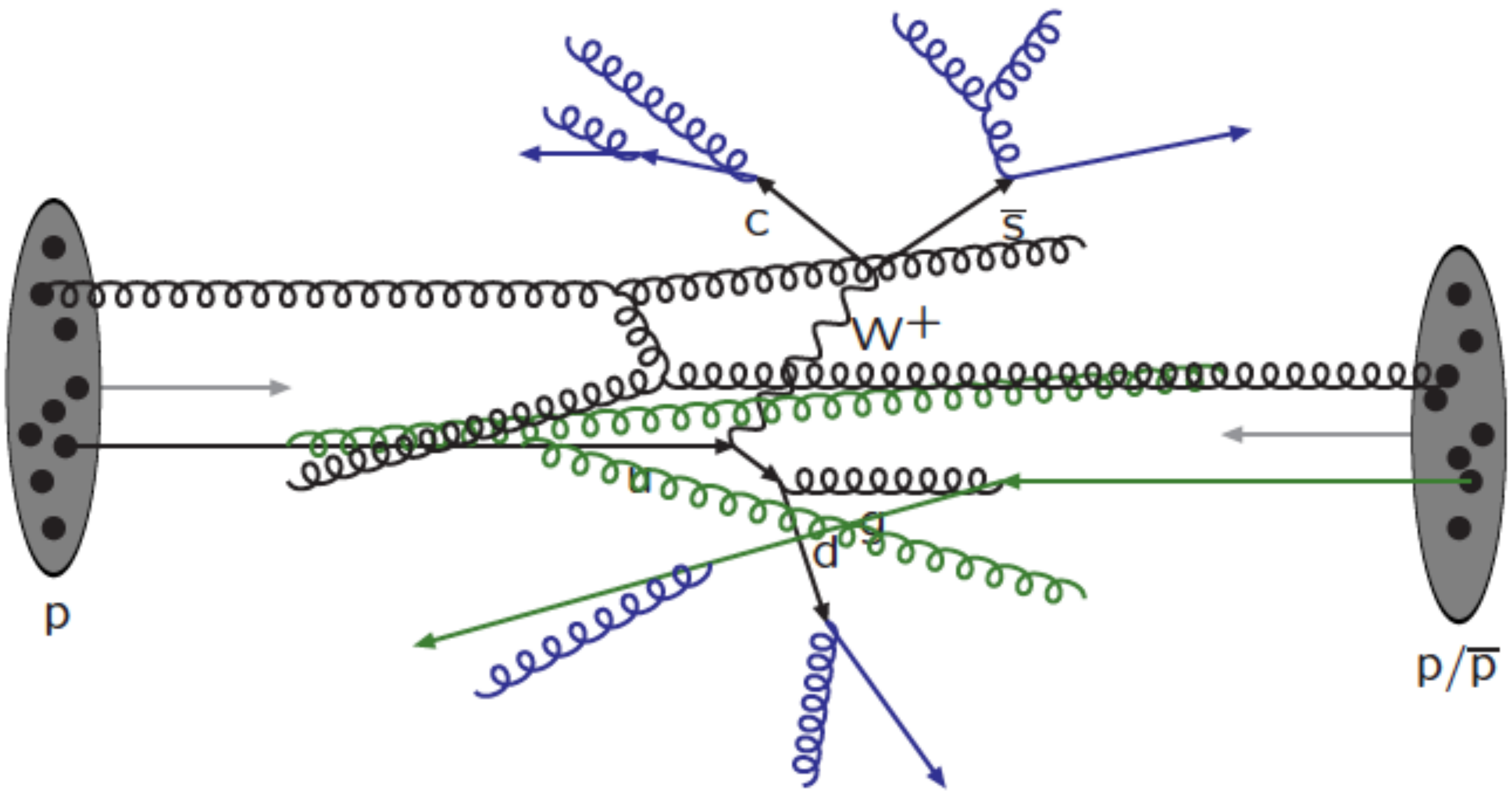
Initial-state radiation: spacelike parton showers

The structure of an event – 5



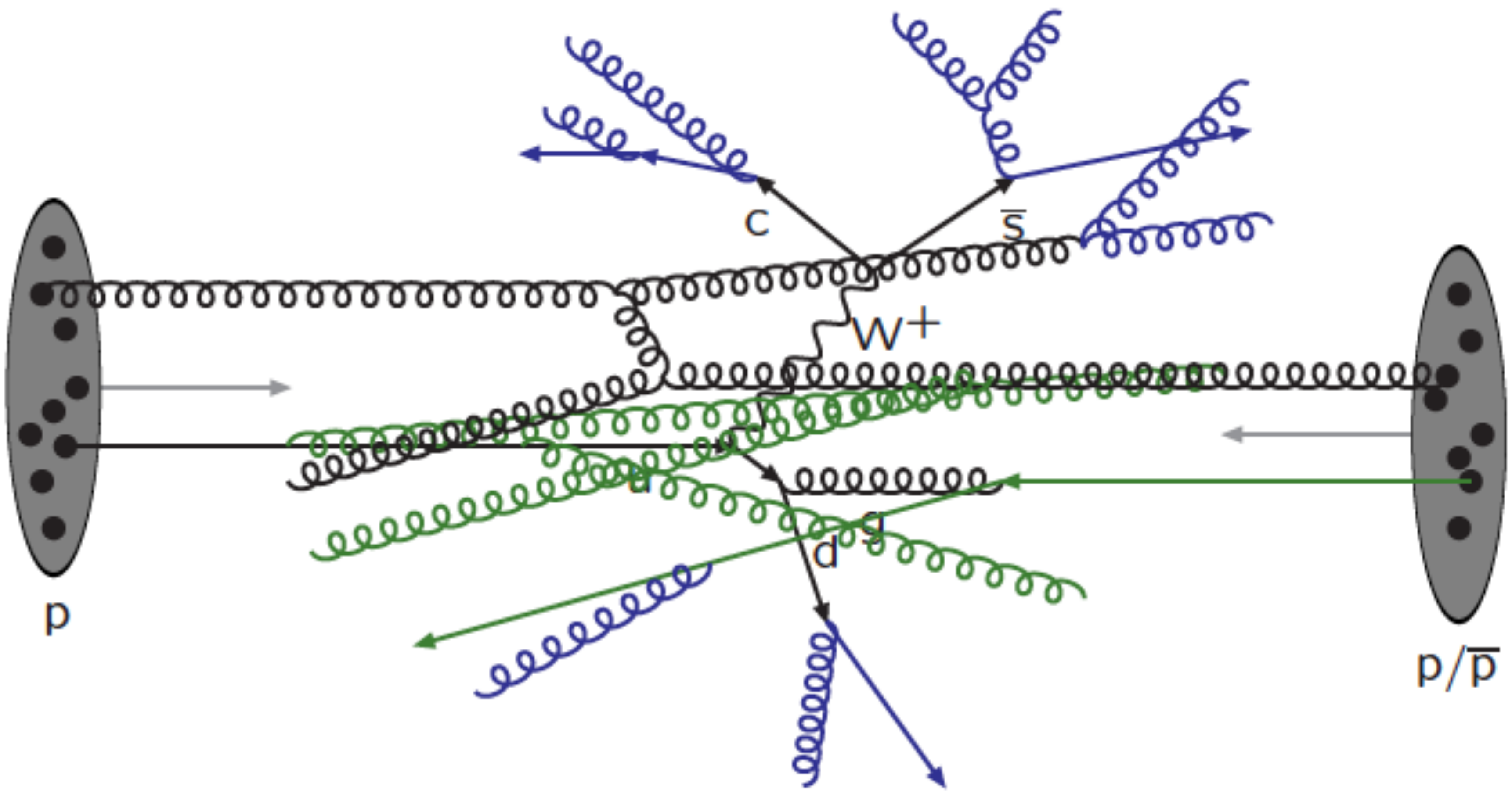
Final-state radiation: timelike parton showers

The structure of an event – 6



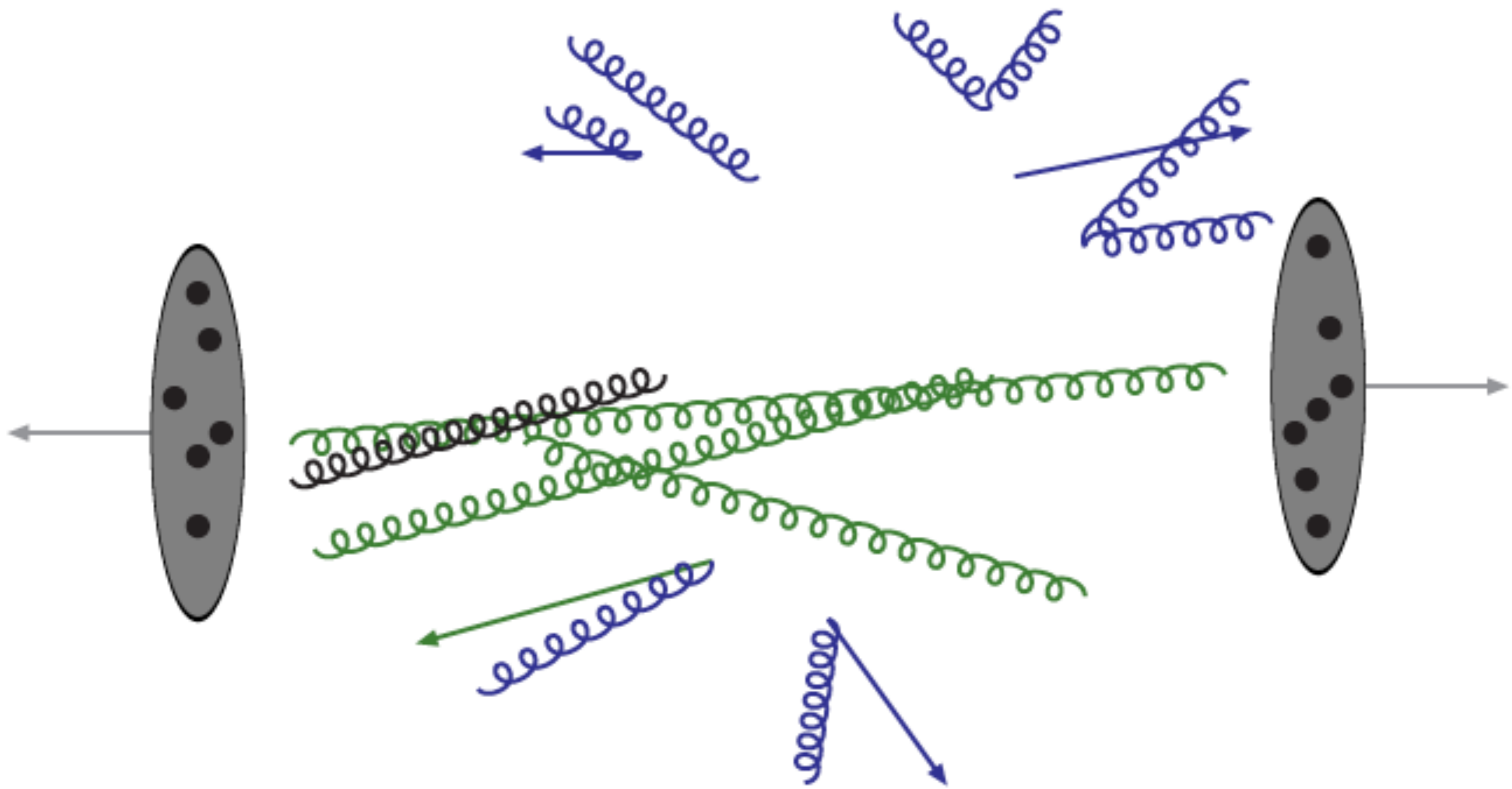
Multiple parton–parton interactions . . .

The structure of an event – 7



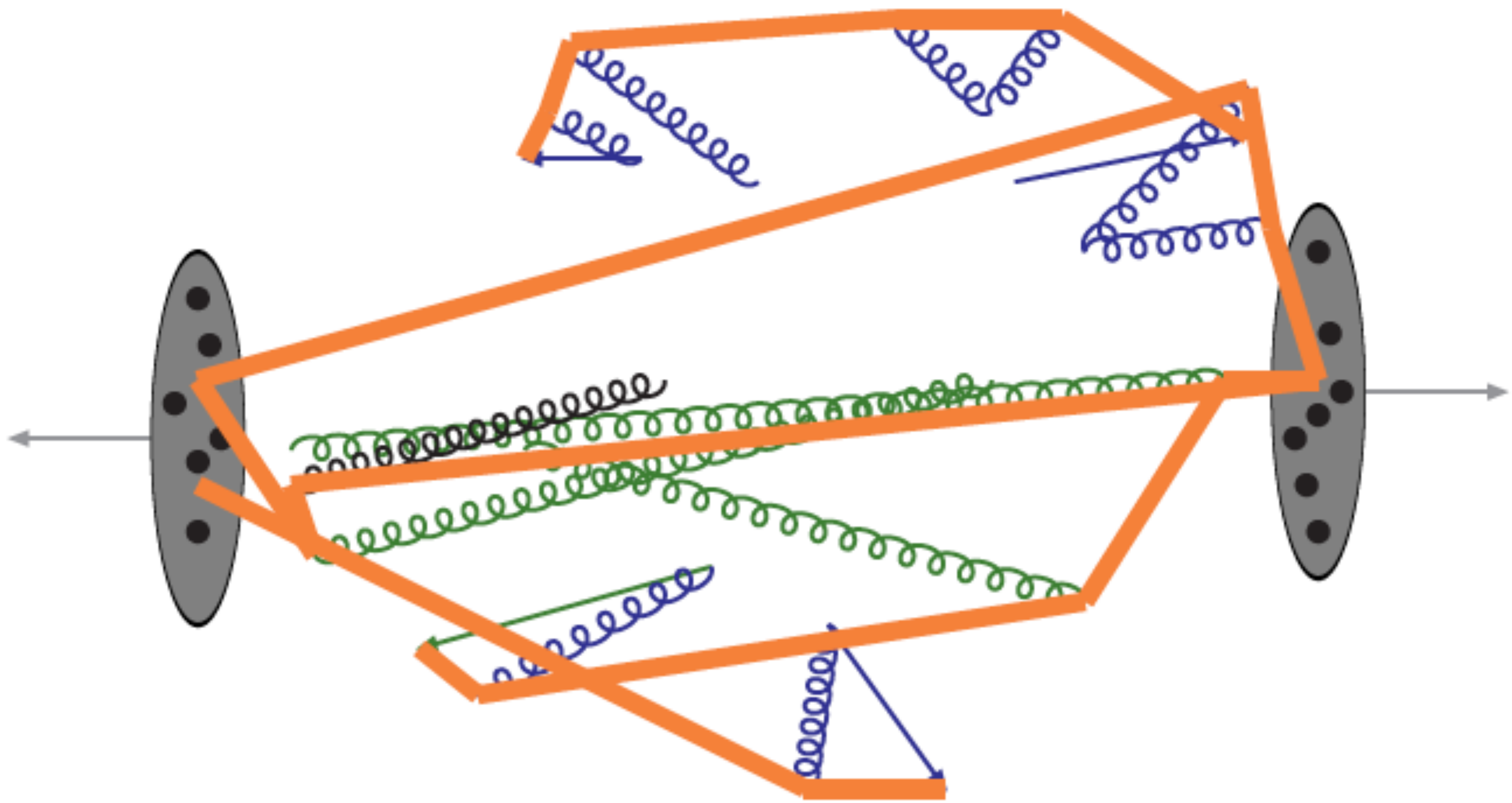
...with its initial- and final-state radiation

The structure of an event – 8



Beam remnants and other outgoing partons

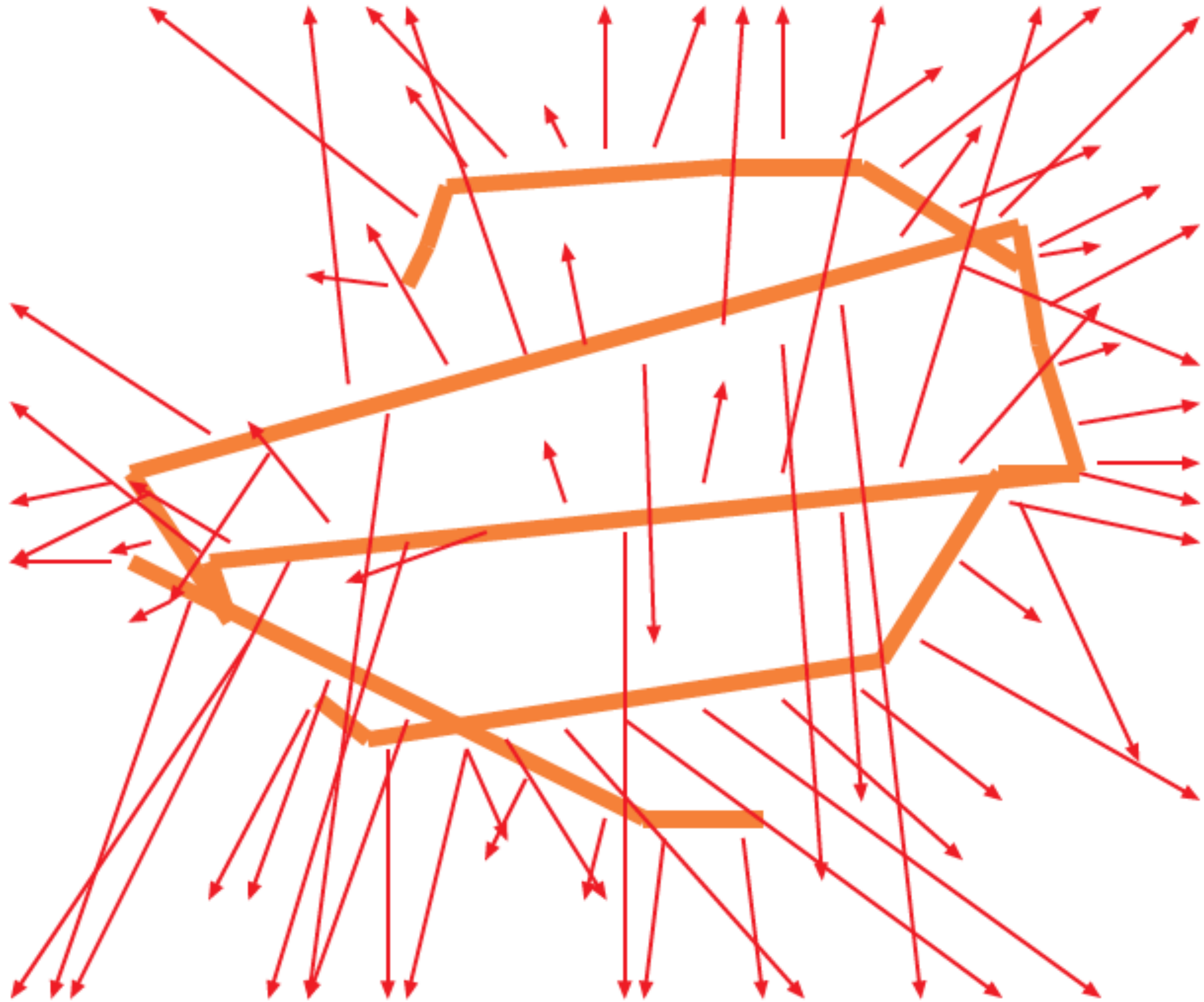
The structure of an event – 9



Everything is connected by colour confinement strings

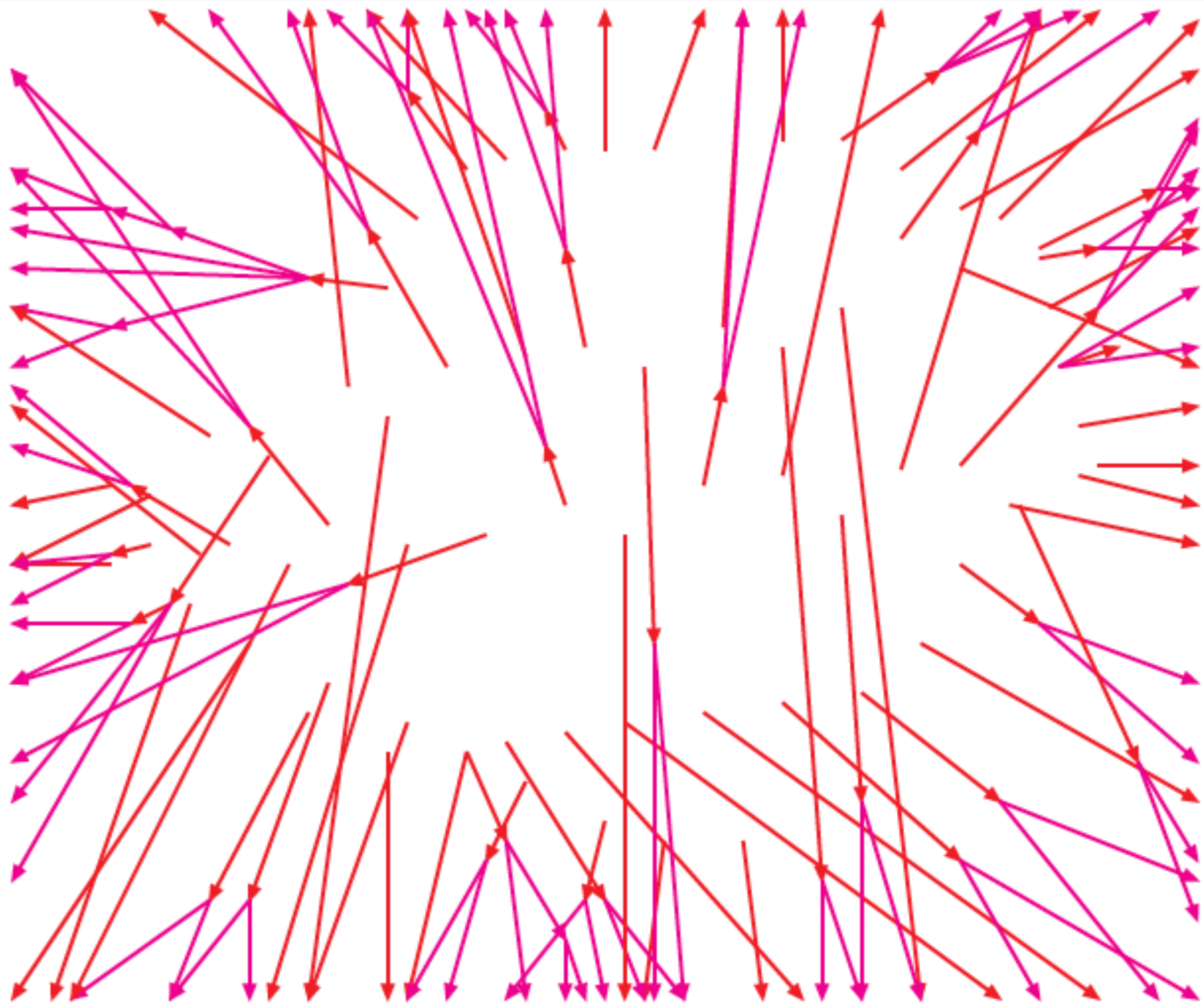
Recall! Not to scale: strings are of hadronic widths

The structure of an event – 10

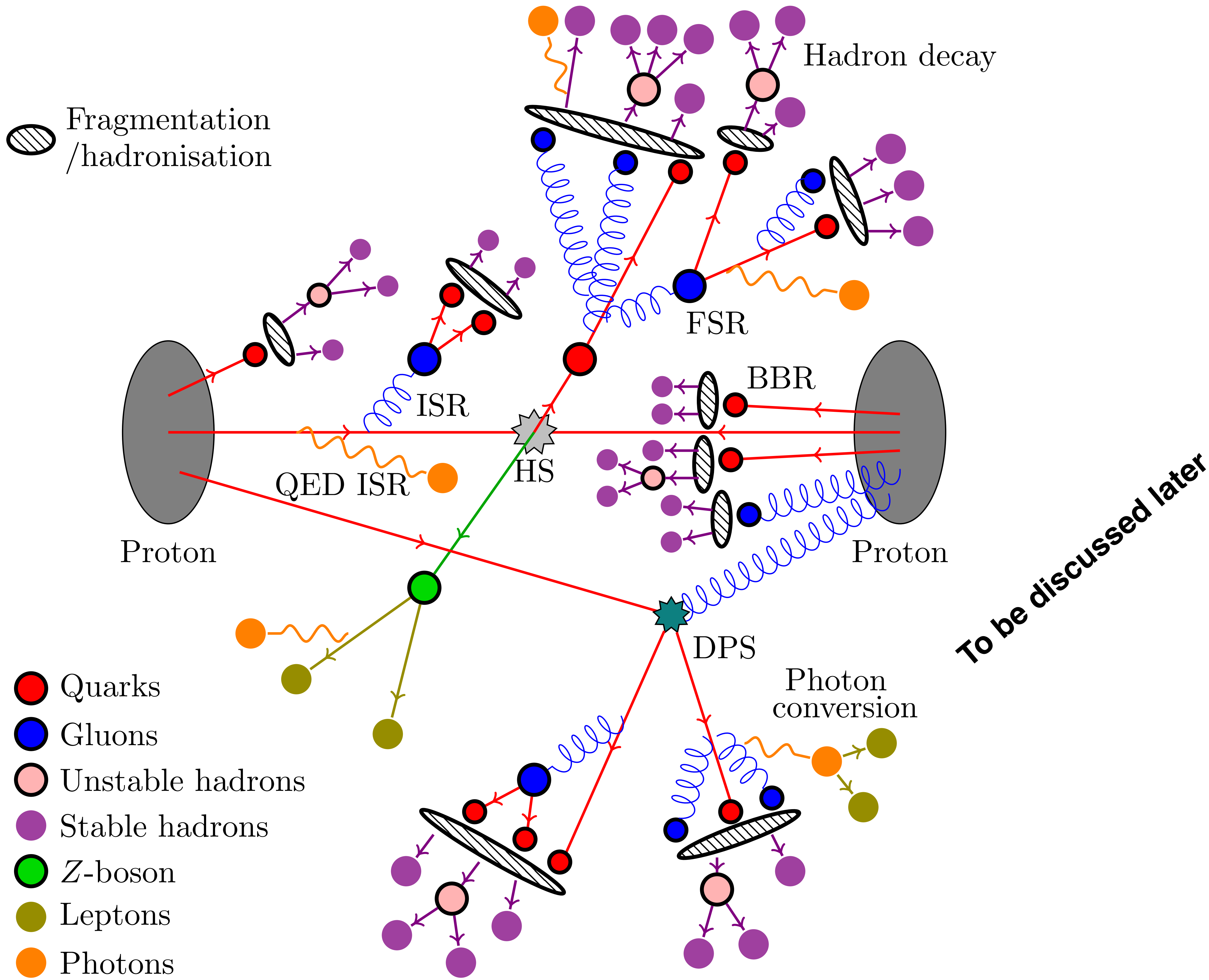


The strings fragment to produce primary hadrons

The structure of an event – 11



Many hadrons are unstable and decay further


Hadron decay
Fragmentation
/hadronisation
FSR
BBR
ISR
QED ISR
HS
Proton
Proton
DPS
Photon
conversion
To be discussed later
Quarks
Gluons
Unstable hadrons
Stable hadrons
Z-boson
Leptons
Photons

Common Event Generators

- **All-in-one:** Pythia, Herwig, Sherpa (LO/NLO in ME, PS is LO so far)
- **ME-only:** Madgraph/aMC@NLO, Powheg

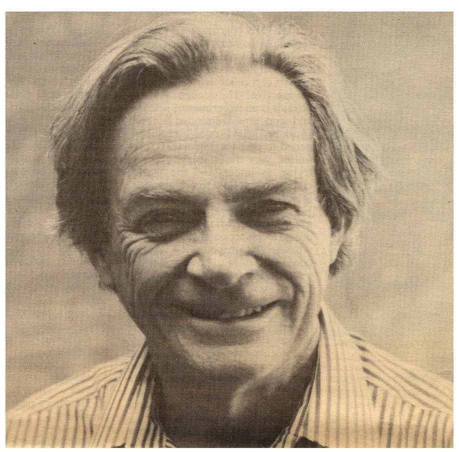
Tuning

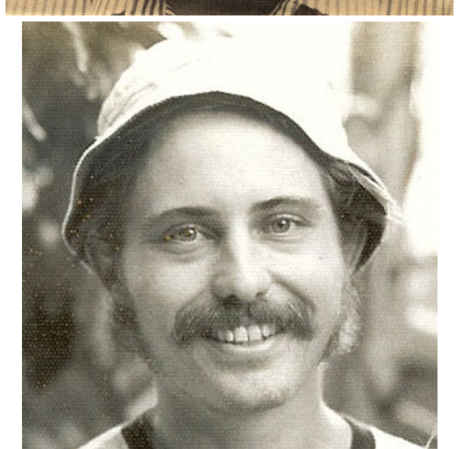
- Ultimate goal: models need to describe real data.
- “Free” parameters control all these aspects of the models, which cannot be derived analytically.
- A bunch of correlated (or anti-correlated) parameters describe one aspect, so have to change them simultaneously.

Like turning knobs on your (dad’s) radio!

Tune: A particular optimized parameter setting in a particular MC generator to match the simulation with available data. Differ according to which datasets are included.

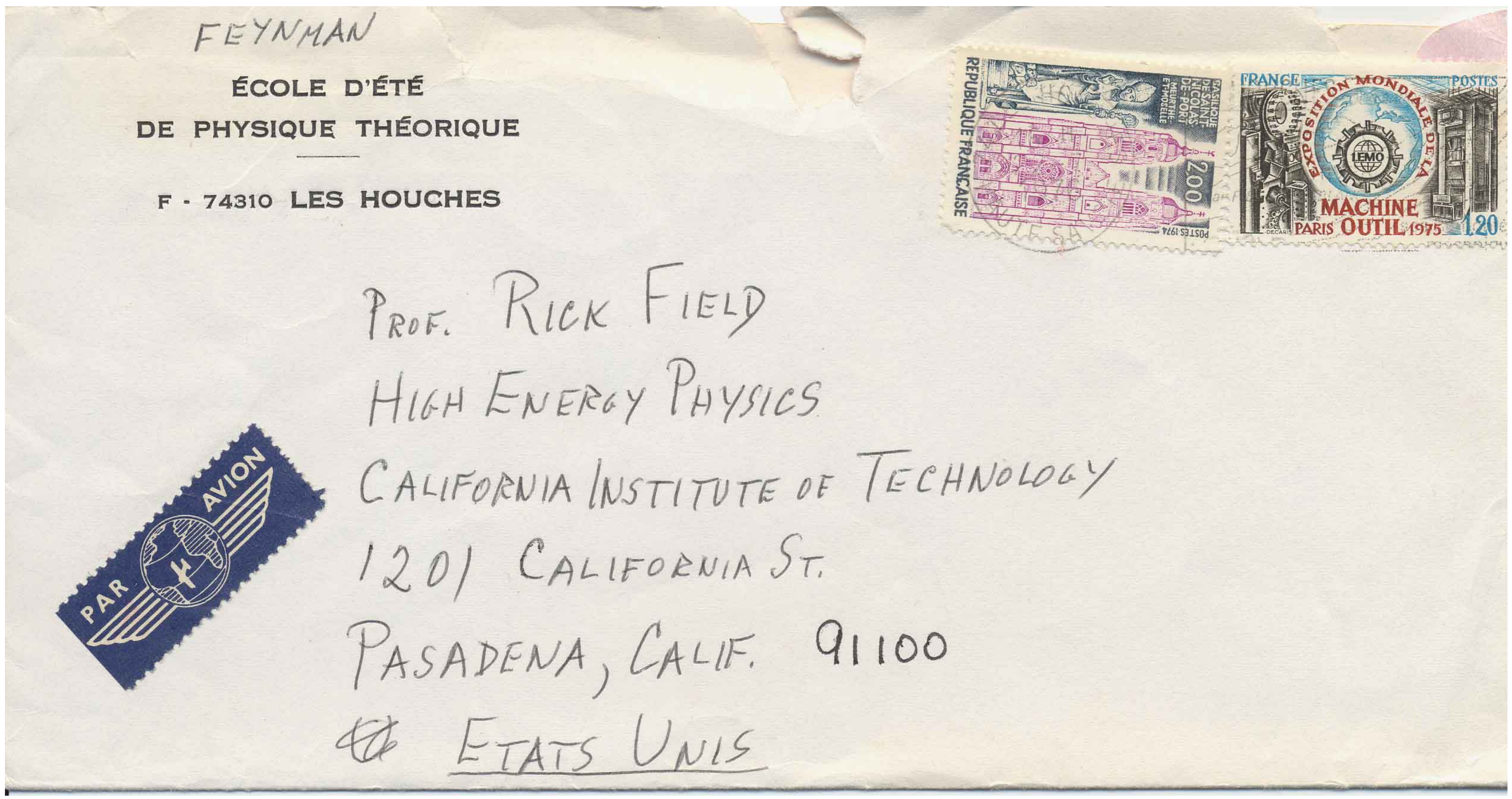
J. D. Bjorken: But it often happens that the physics simulations provided by the the MC generators carry the authority of data itself. They look like data and feel like data, and if one is not careful they are accepted as if they were data.



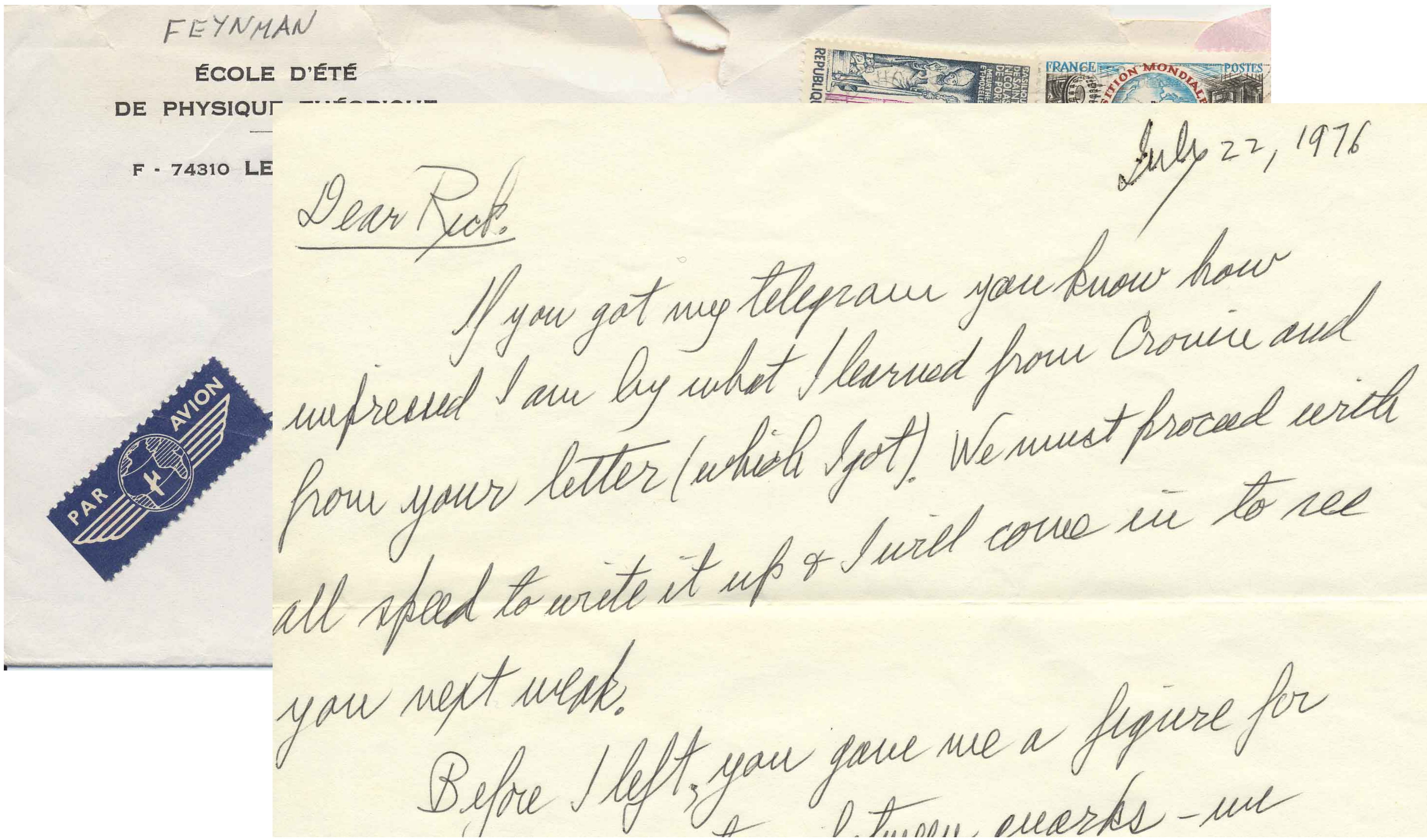


Field and Feynman: The predictions of the model are reasonable enough physically that we expect it may be close enough to reality to be useful in designing future experiments and to serve as a reasonable approximation to compare to data. We do not think of the model as a sound physical theory .

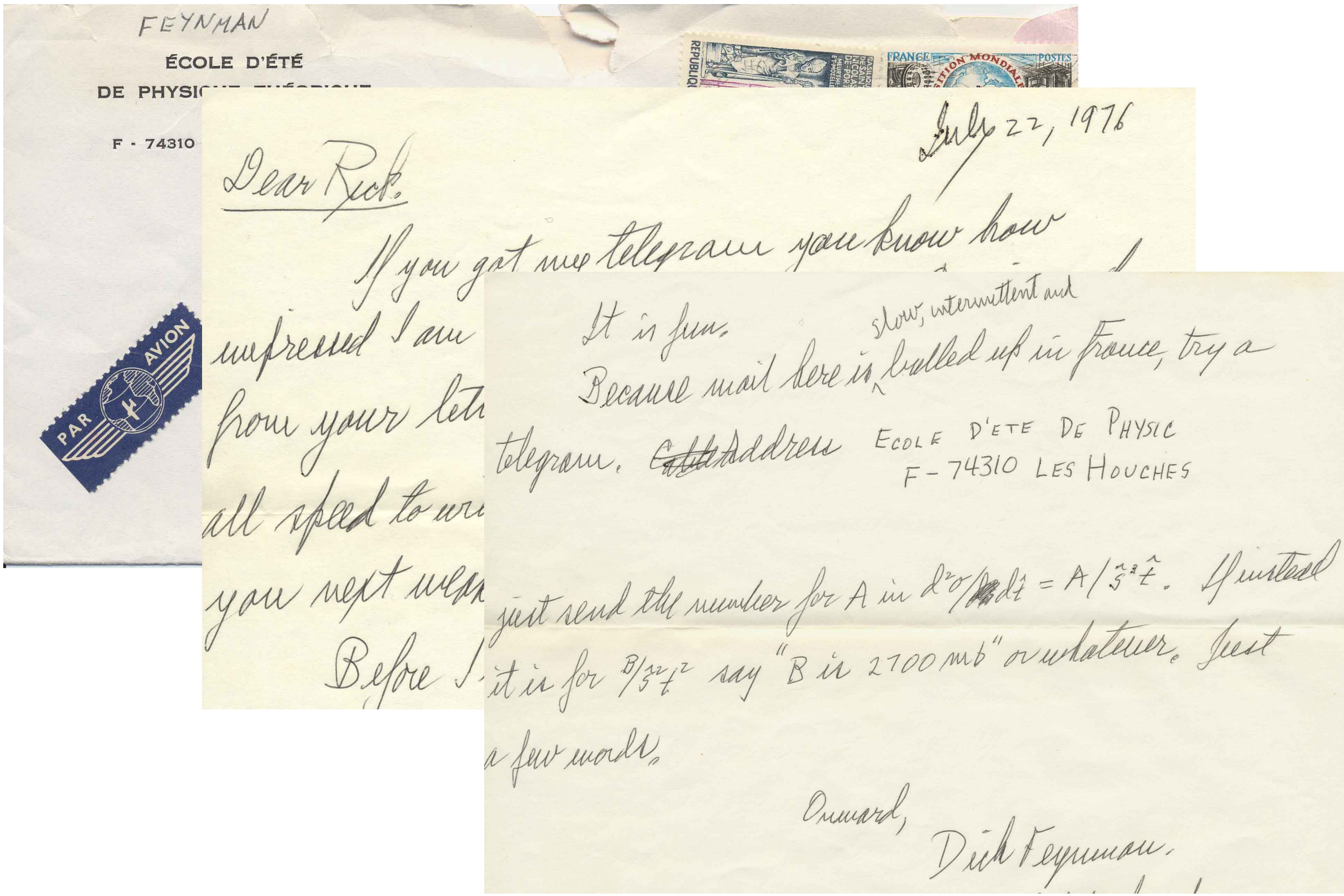
Some History!



Some History!

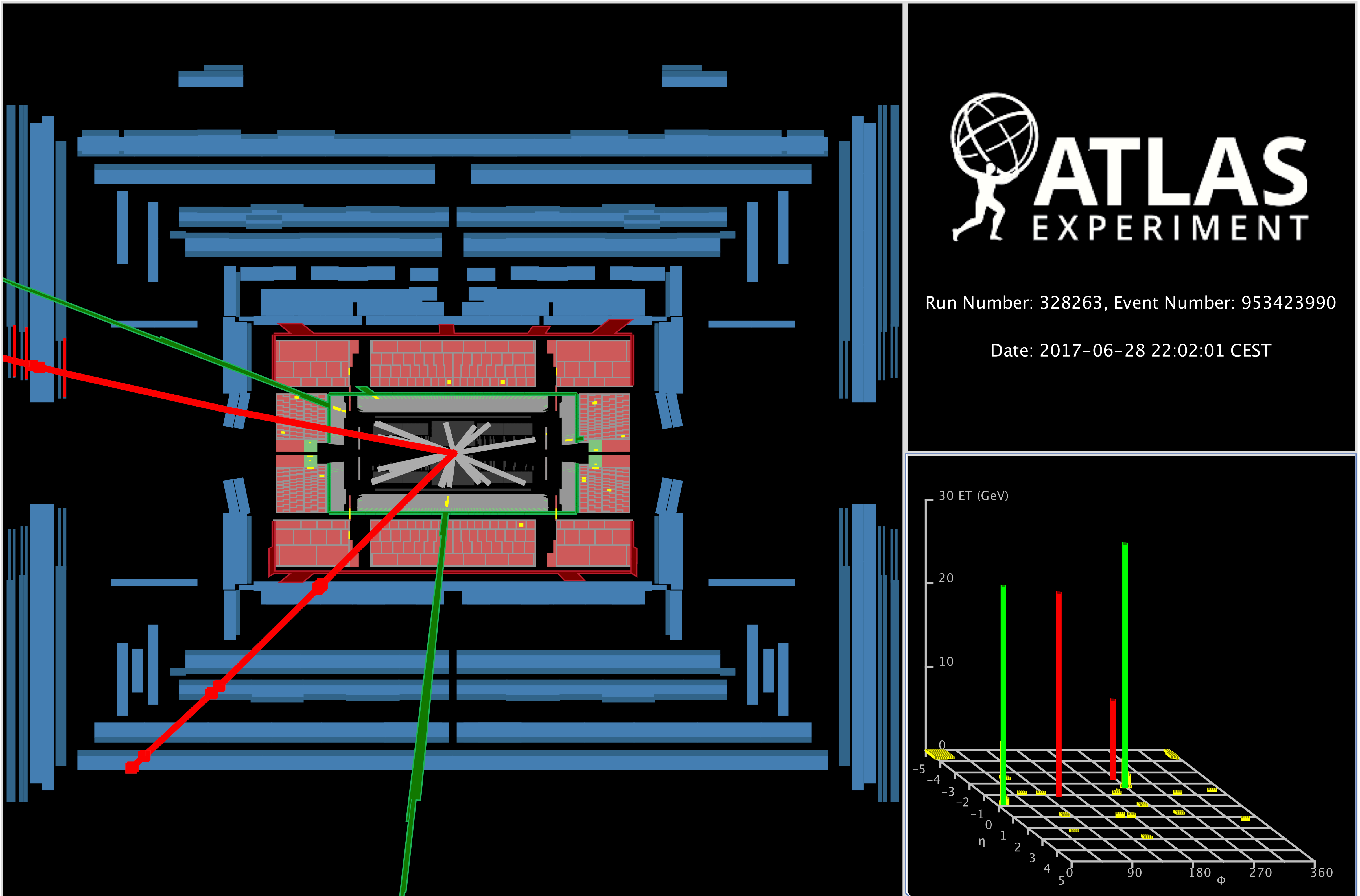


Some History!

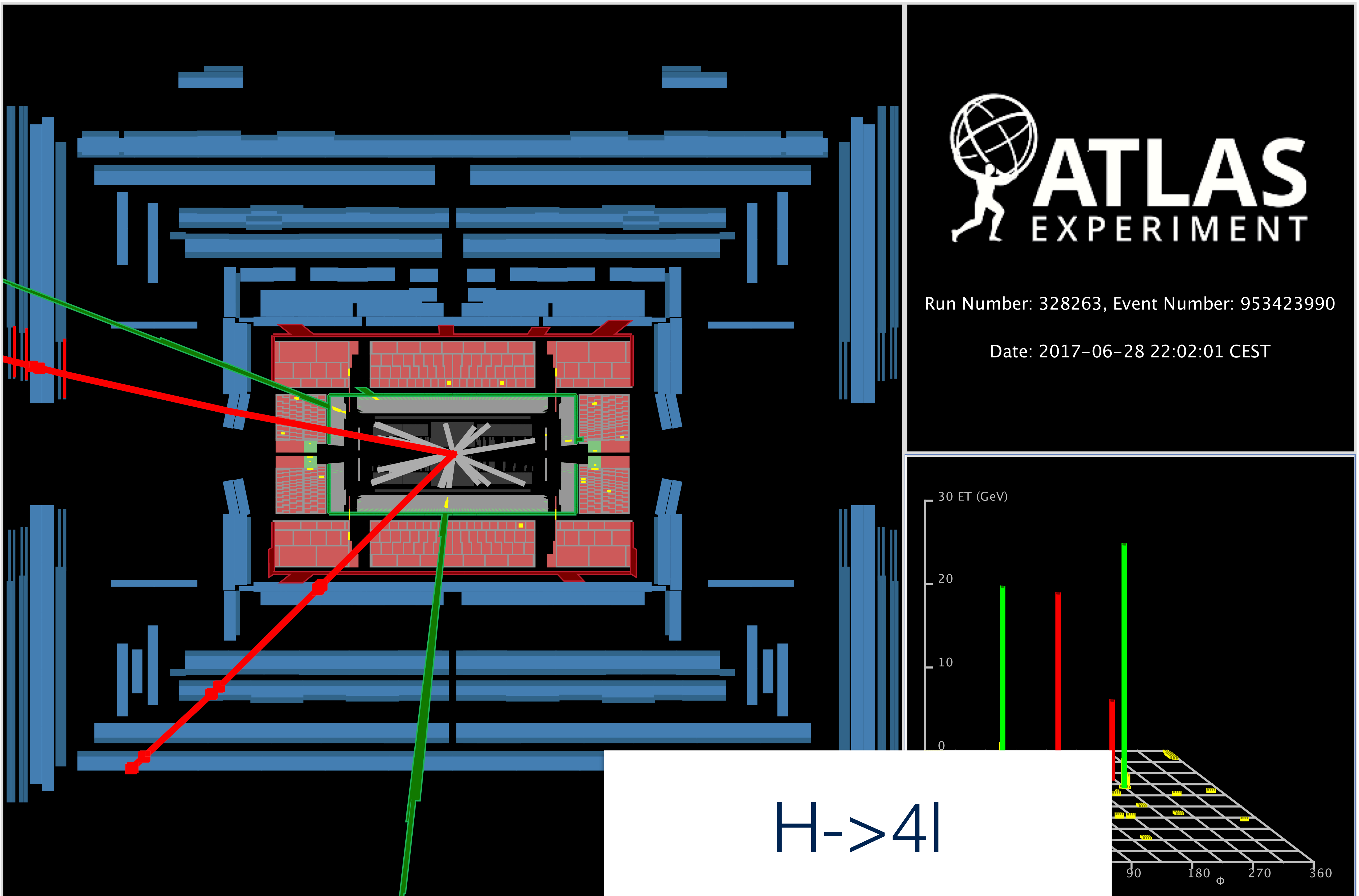


Session 3:
Handpicking the Events

Event Displays

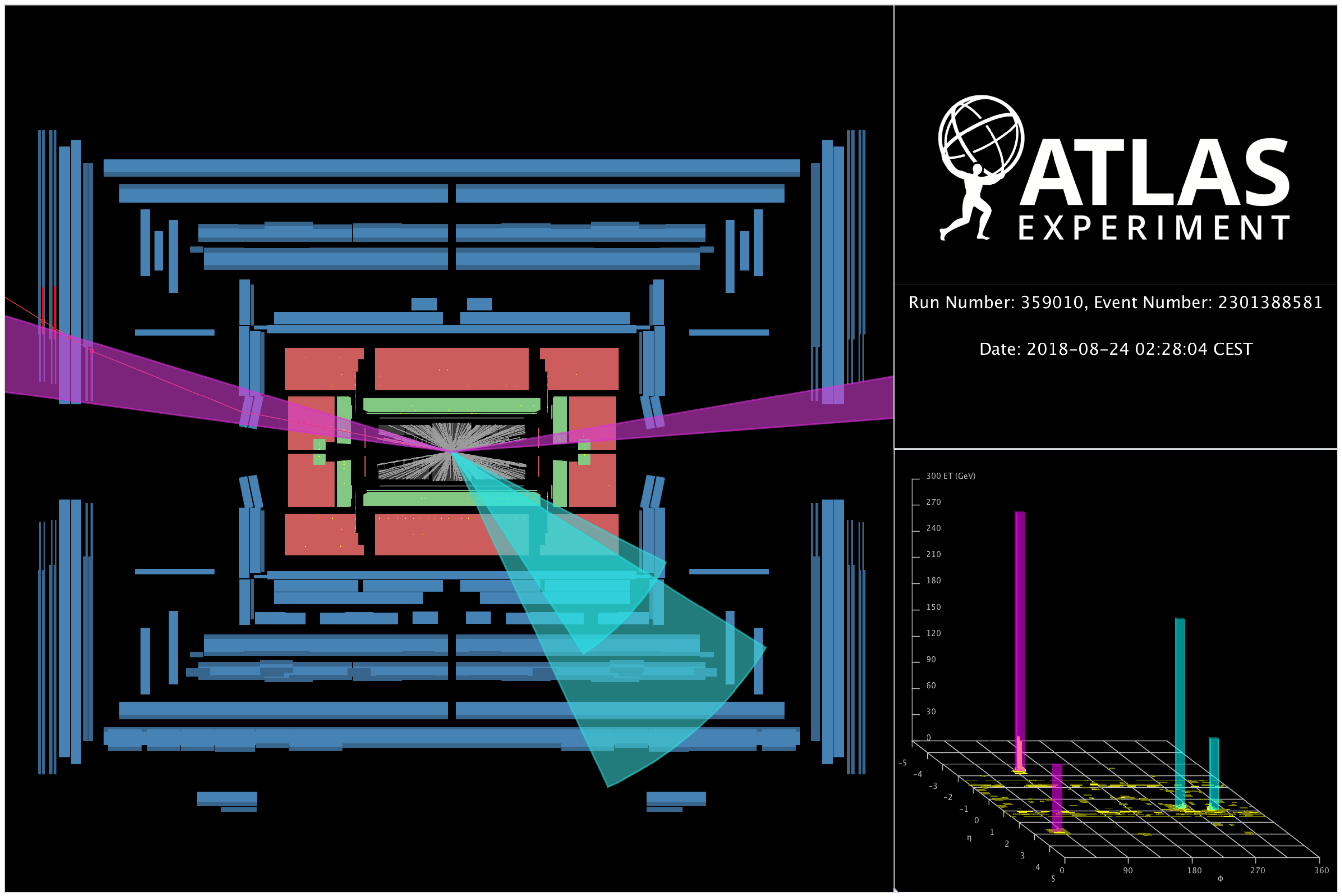


Event Display 1



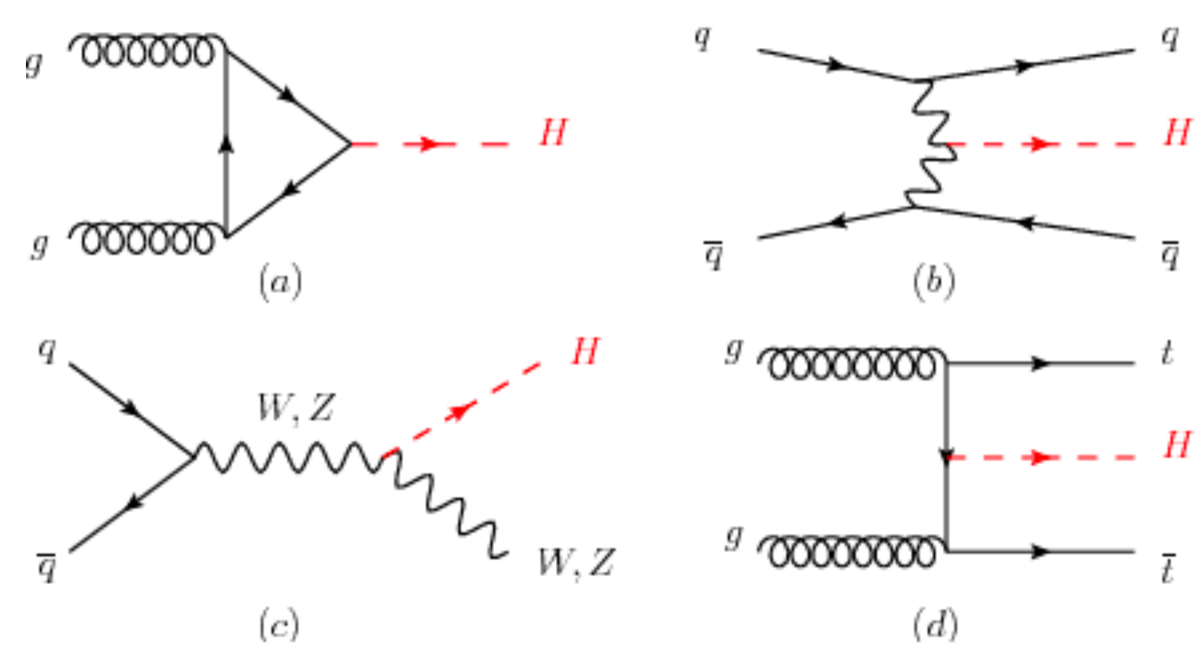
H->4l

Event Display 2



Event display with two b-tagged jets in blue. The two other jets are shown in purple.
The invariant mass of the two b-tagged jets is 124.6 GeV and of the two other jets is 1.9 TeV

- 124.6 GeV -> Higgs decaying to bb, most prominent decay channel.
- Two other jets, clearly very energetic, so definitely coming from hard scattered partons.
- Which Higgs boson production mode that may be?



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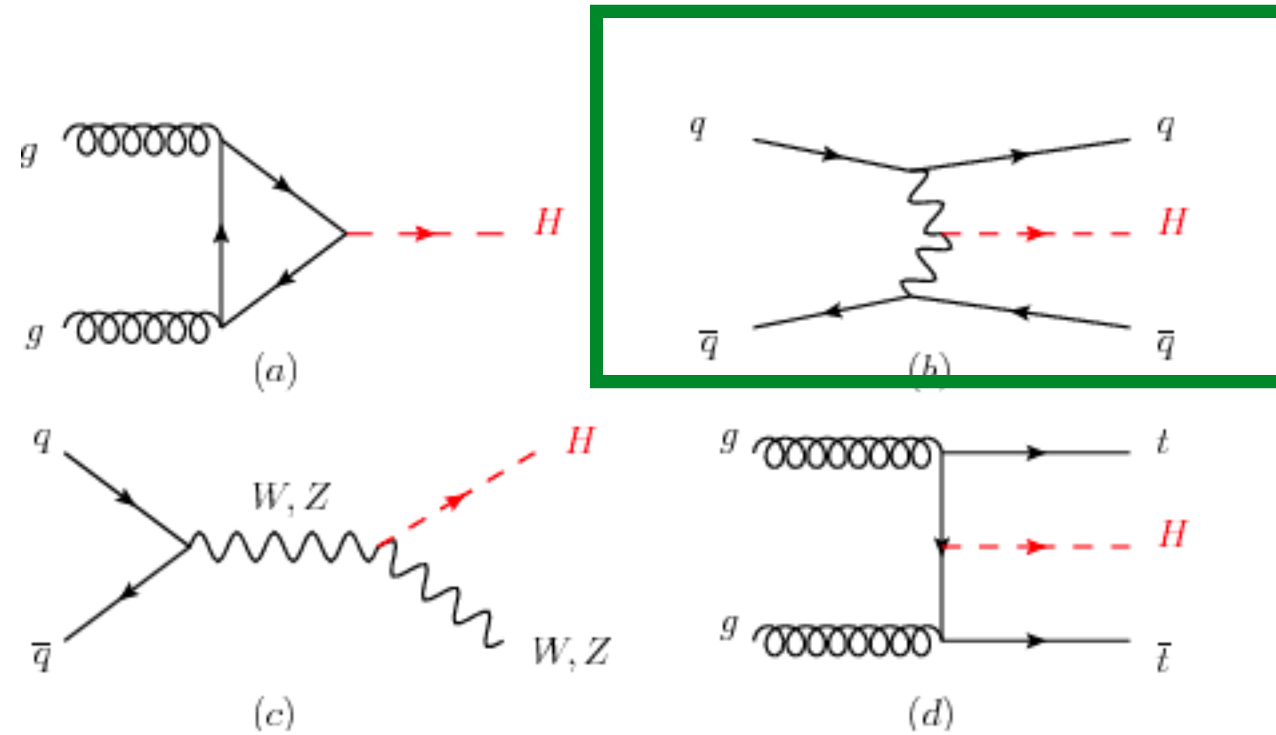
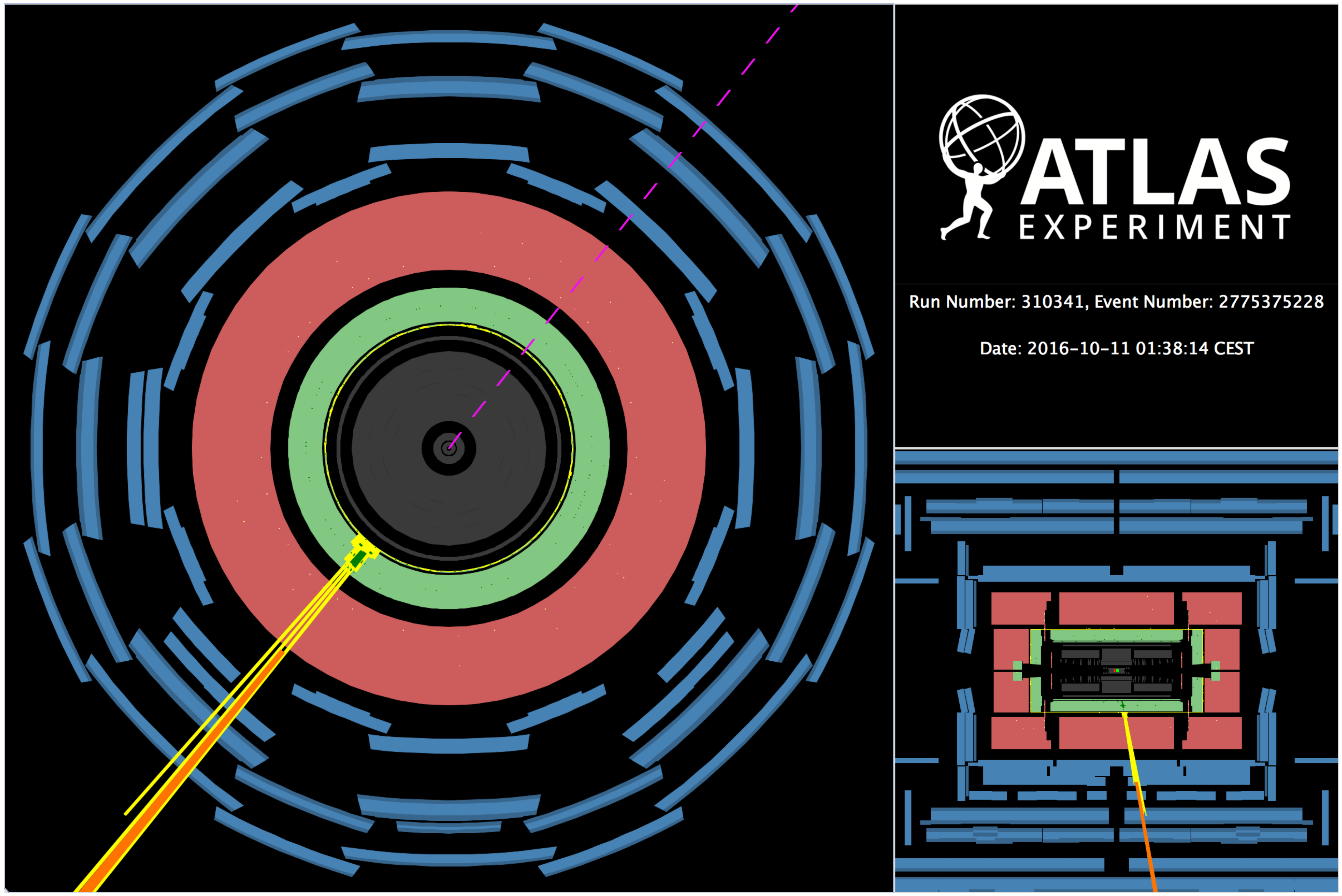


Event Display 3



Event display with photon, shown in yellow/orange with transverse energy of 661 GeV.The missing transverse momentum of 660 GeV is indicated by pink dashed line. No tracks with transverse momentum of 10 GeV or more are found in the inner detector for this event

- Single photon, so cannot come from a 2 body decay (i.e Higgs)

- Significant MET, so one or more real neutrino

- MET balances the photon, so must be coming from decay of a heavy particle

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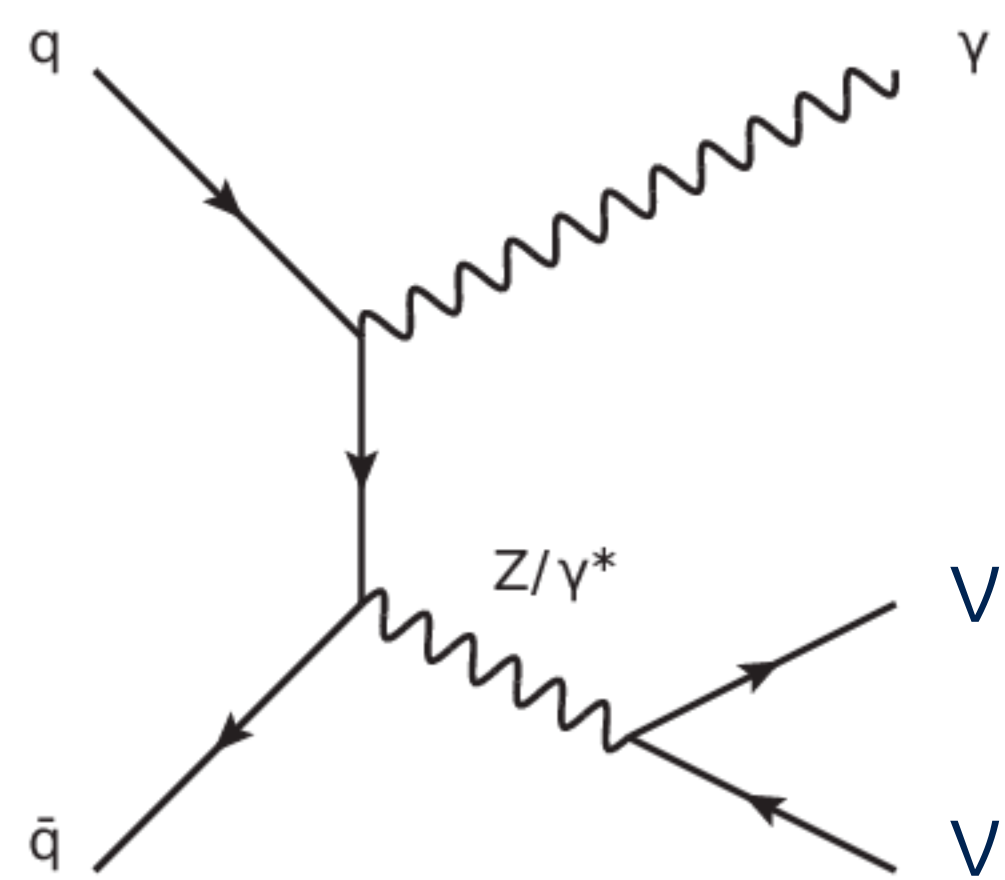


Other possible diagrams as well…

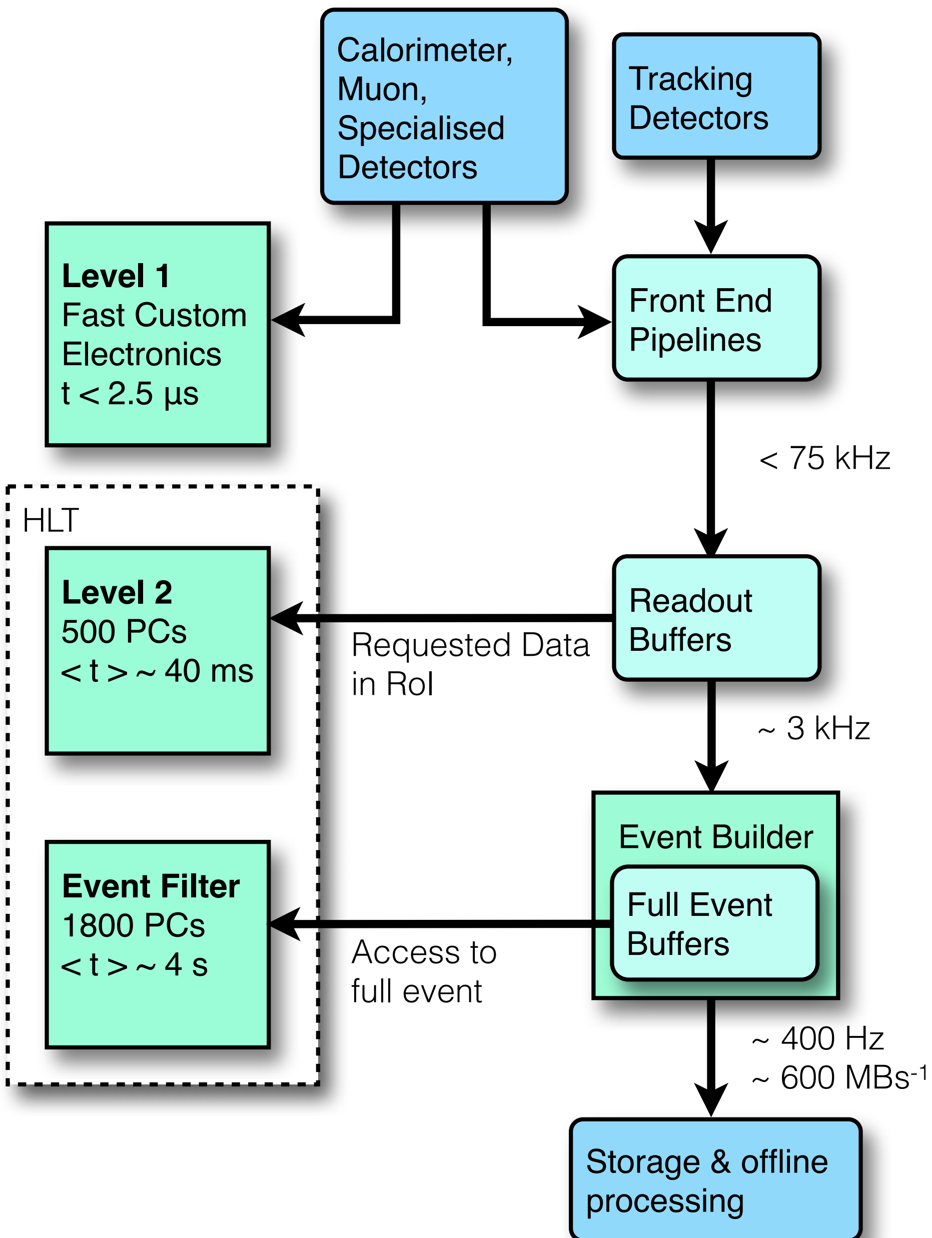
But in order to get to such pretty clean signal events, some (a lot?) of effort is still needed …

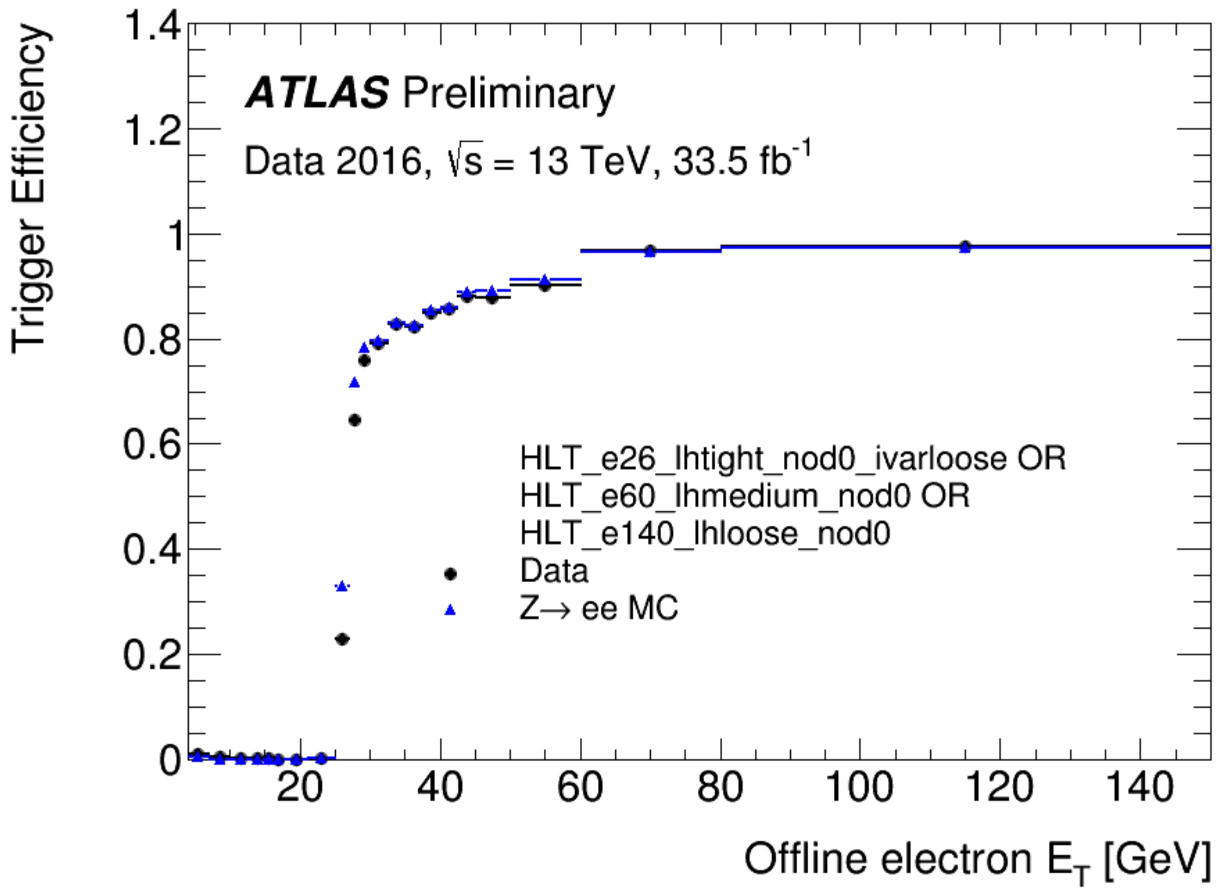
MC Normalisation

Normalisation factor:

$$
\begin{aligned}
N &= Lumi_{\text{data}}/Lumi_{\text{mc}} \\
&= Lumi_{\text{data}} \times \text{cross} - \text{section} \times \text{efficiency} \times k\text{-factor}/\text{sum-weights}
\end{aligned}
$$

Trigger





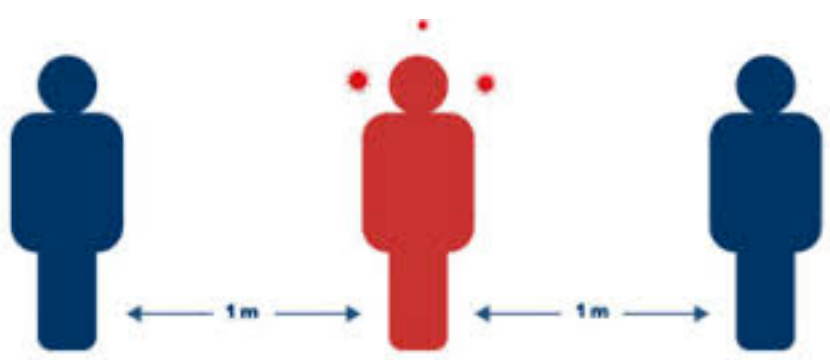
Identify the interesting events to store, hundreds of events/sec from ~100 millions

Isolation

- Prompt leptons (i.e from PV) or photons should not have a lot of activity close to them.
- Not the same for non-prompt or misidentified ones. Semileptonic b/c decays can give leptons, QED radiation can result in photons.
- Sum of energy in a transverse cone around the object must be less than some threshold

Fakes/Overlap Removal

- Object reconstruction algorithms run independent of one another



we followed it before it was cool …

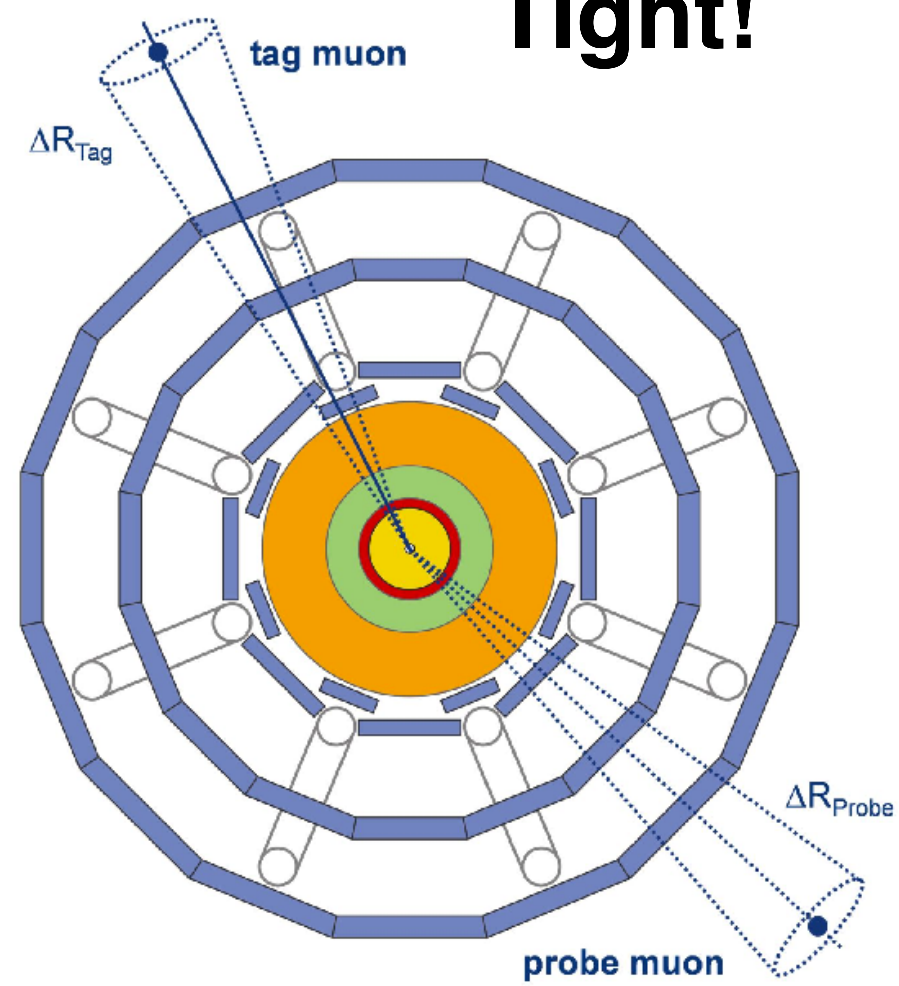
Fakes/Overlap Removal

- Object reconstruction algorithms run independent of one another
- Same detector signature can result in multiple objects being reconstructed, results in fakes!
- Electrons as jets, and vice versa (jets contain neutral pions!)
- Overlap removal to address the double counting

Calibration and efficiency

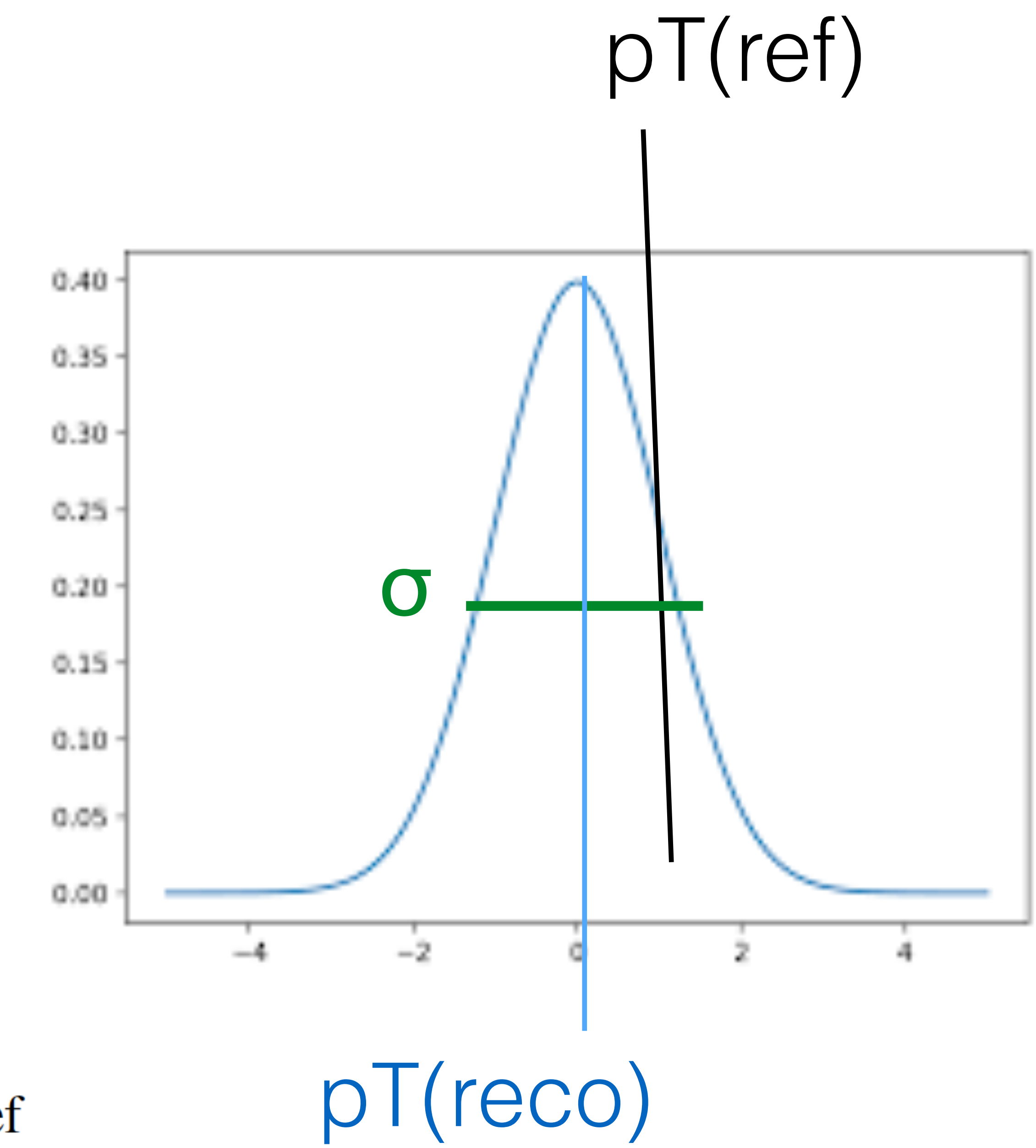
- Calibration: mostly selecting a pure sample of known events, and comparing with them.

- Efficiency: correct for losses due to detector imperfection and geometric acceptance. Sometimes by tag-and-probe method.



Jet energy scale and resolution

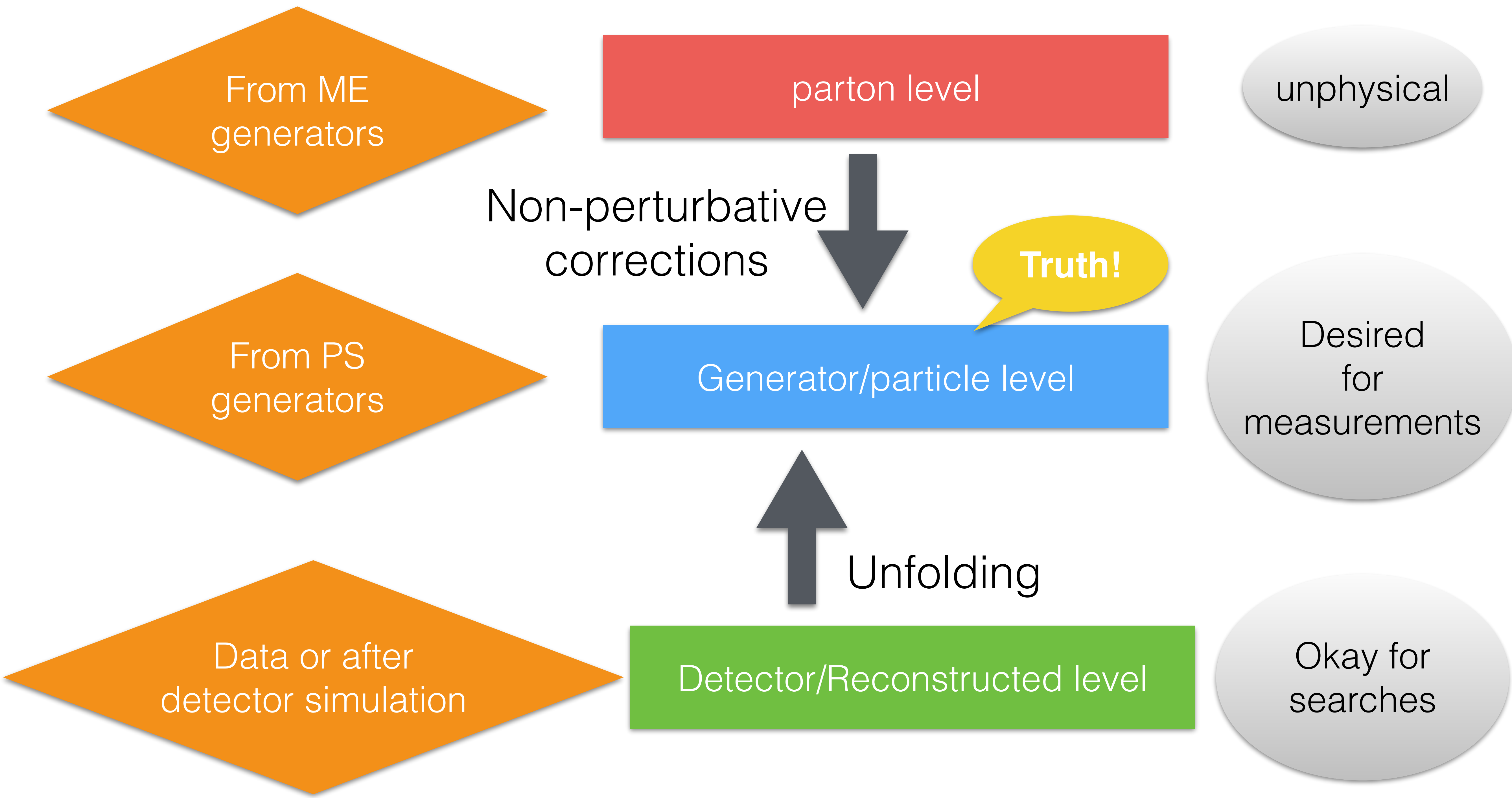
- Measured value in the detector can be shifted, and not identical for all jets.
- Random fluctuations -> Gaussian!



Scale: $\mu = p_{\mathrm{T}}^{\mathrm{reco}} / p_{\mathrm{T}}^{\mathrm{ref}}$

Resolution: **σ**

Analysis objects



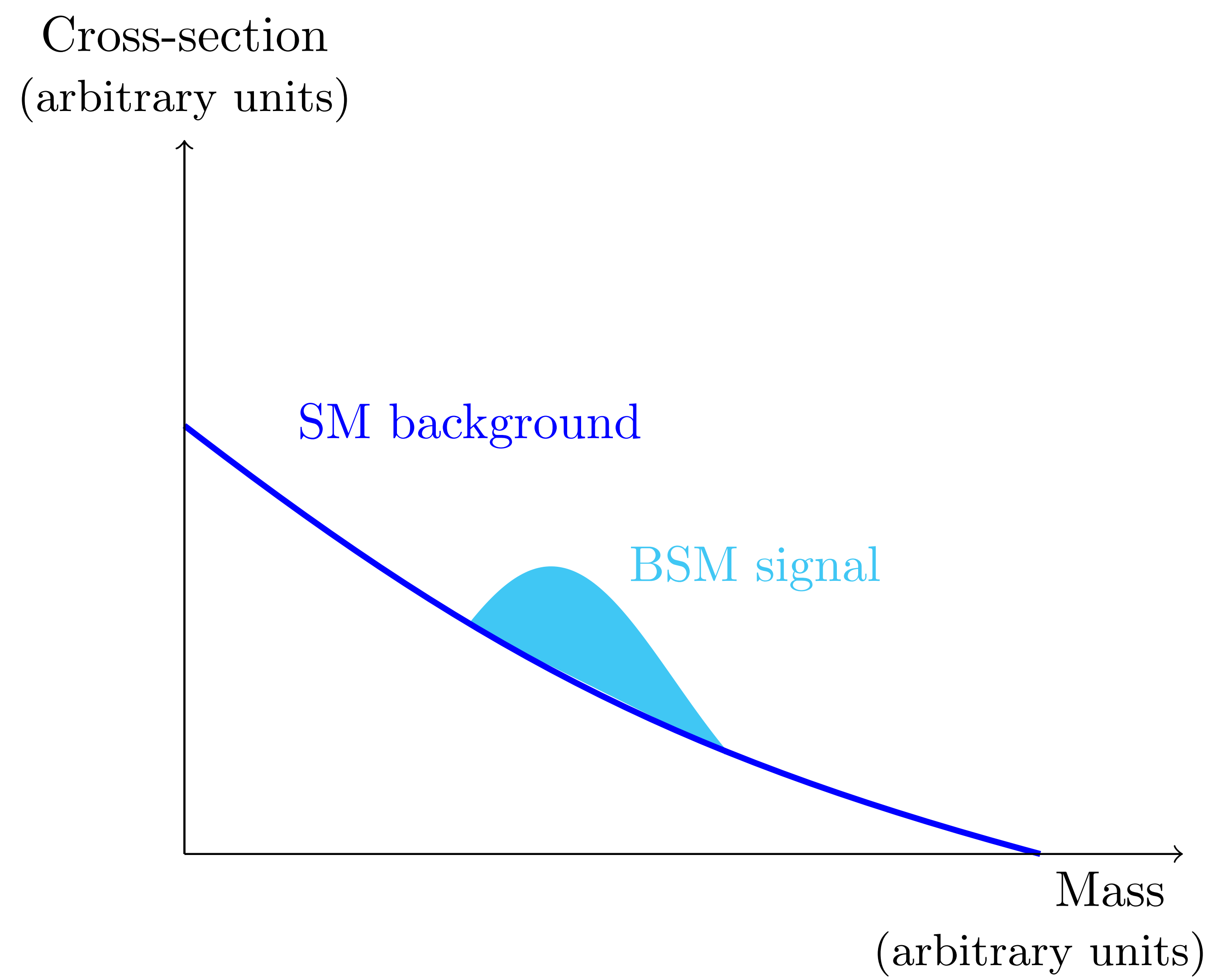
Session 4: Analysis

Measurements

- To validate Standard Model (in a new energy regime)
- Measure the free parameters of SM (often indirectly)
- To test the predictions of MC generators
- Background for searches

Searches

- Resonance searches: bumphunting
- Cut and count
- Excess of MET: DM
- Signal strength



Cross-section

$$N = L\sigma\varepsilon A + B,$$

Cross-section

No of events — Efficiency — Acceptance

$$N = L\sigma\varepsilon A + B$$

Integrated luminosity — Cross-section — No of background events

Leads to: $\sigma = (N - B)/L\varepsilon A$

- **Acceptance**: usually geometric or threshold
- **Efficiency**: due to detector imperfections

How do we find these? Thats the whole challenge ;)

Analysis

- A particular physics signal has a specific final state
- Other SM processes can produce same or similar final states (background)
- Apply cuts on observables to retain most of the signal, reject most of the background
- Object and event selection!

Every search is different, so no best technique!

- Objects cuts, usually fairly standard, not much of a choice … like η, p_T, OL, isolation, quality criteria etc.

Event level cuts

- Trigger, GRL
- Object multiplicity, topology
- Higher p_T of objects
- Angular separation
- MET direction and magnitude
- More high-level observables

Decided by signal to background discrimination power, and by right balance!

Significance:

$$S/\sqrt{N} = S/\sqrt{S+B} \approx S/\sqrt{B},$$

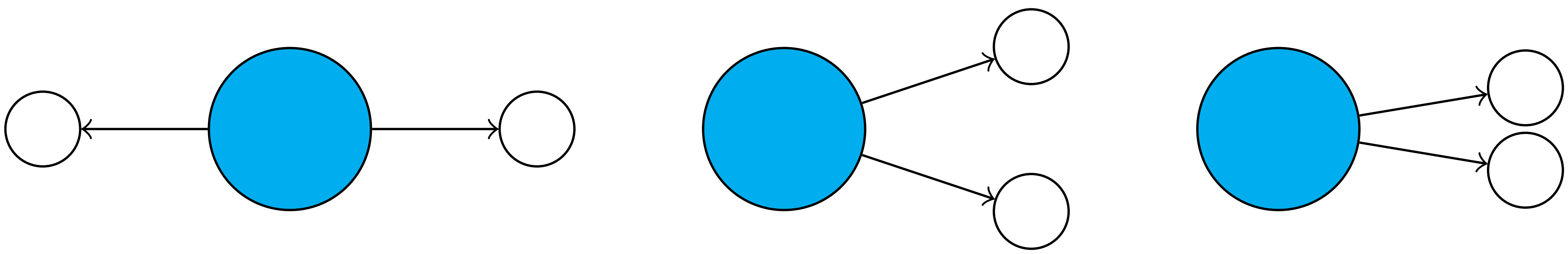
Observables

- So we have charged tracks, jets, electrons, muons, photons, and MET.

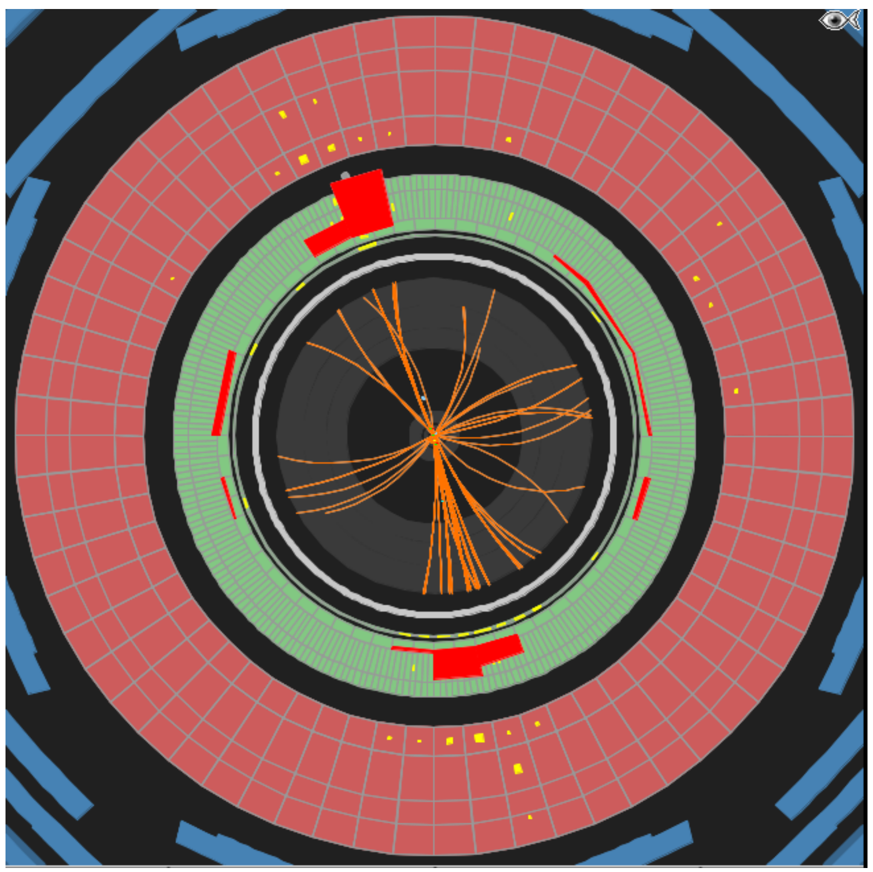
- From these, we need to form observables which will tell us about either what process occurred during collisions, or whether our simulation programmes can describe the event topology correctly.

Two body decay

Decay of a particle:



Track Multiplicity



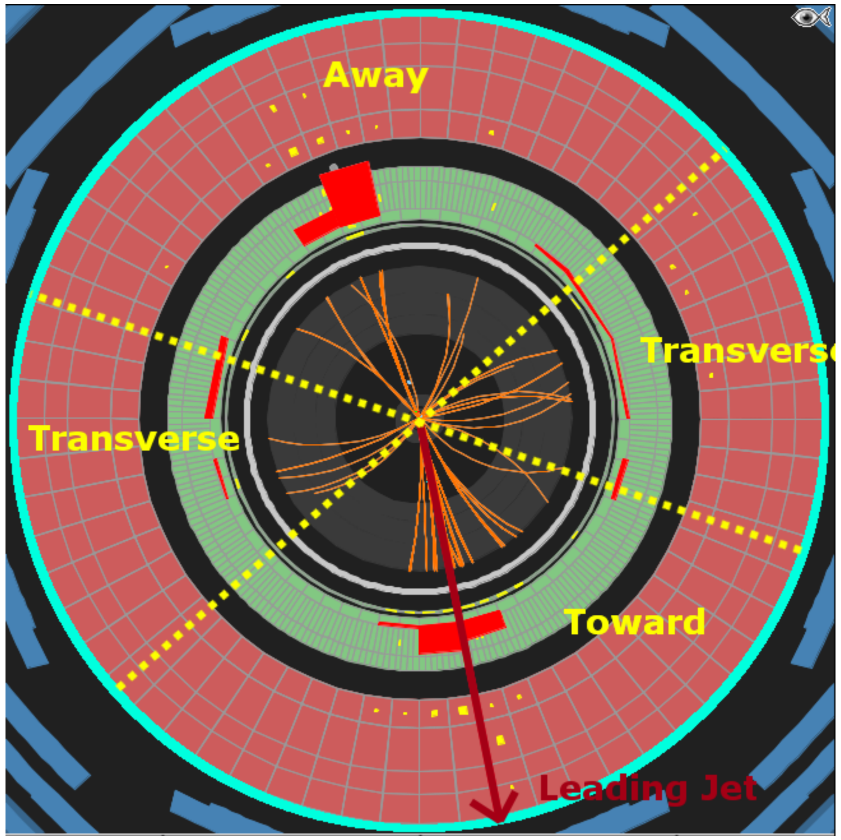
Leading Jet:

$p_T = 69.7$ GeV

$\eta = 1.3$ iRad

$\phi = -1.4$ rad

Track Multiplicity



Leading Jet:

$p_T = 69.7$ GeV

$\eta = 1.3$ iRad

$\phi = -1.4$ rad

Transverse:

$N_{chg} = 9$

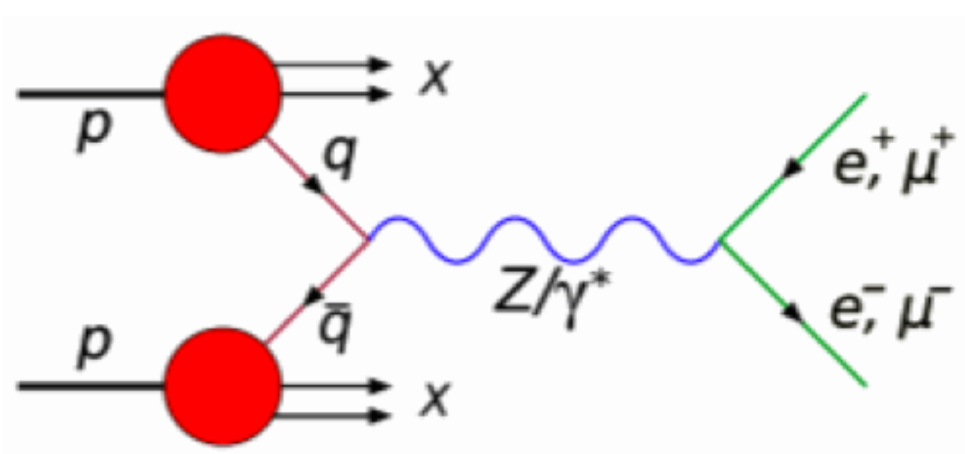
$\sum p_T^{chg} \cong 10$ GeV

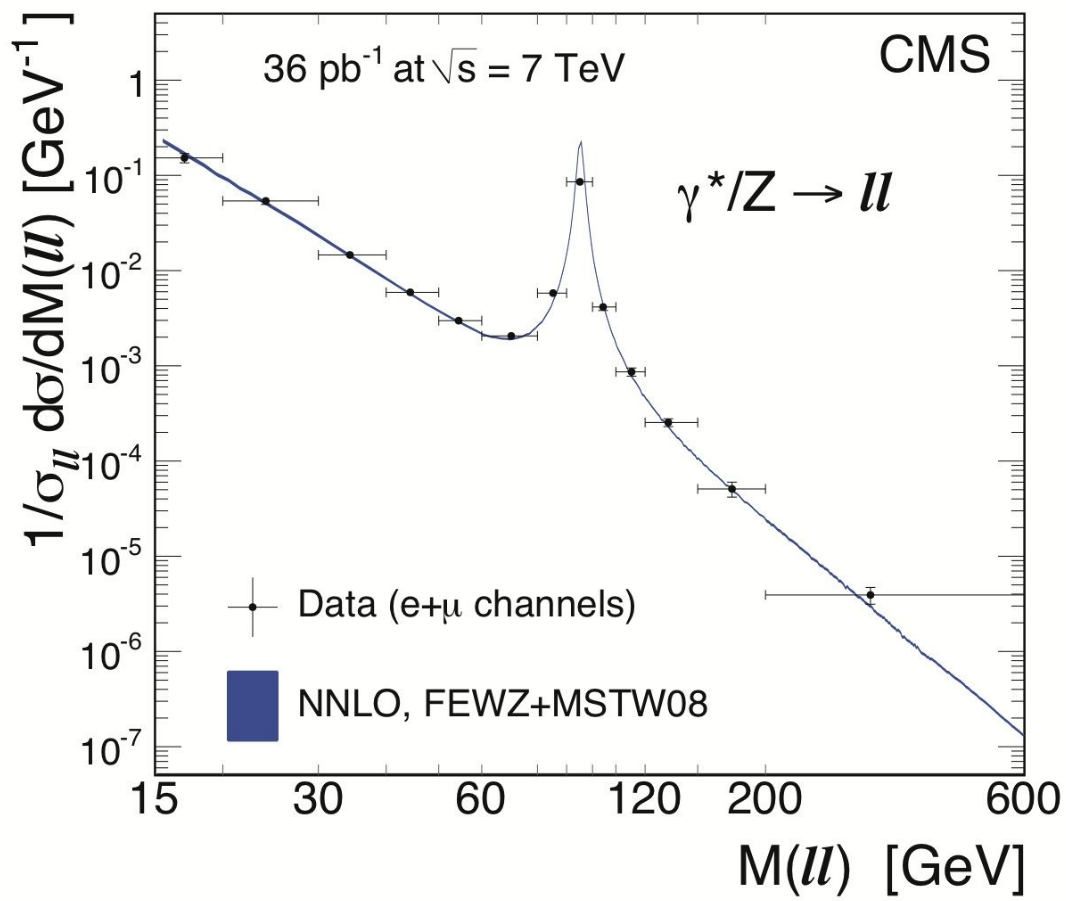
$\bar{p_T} \cong 1.1$ GeV

Generalise to…

- Lepton, photon, jet multiplicities.
- Angles between them …
- Form “mother particles”….

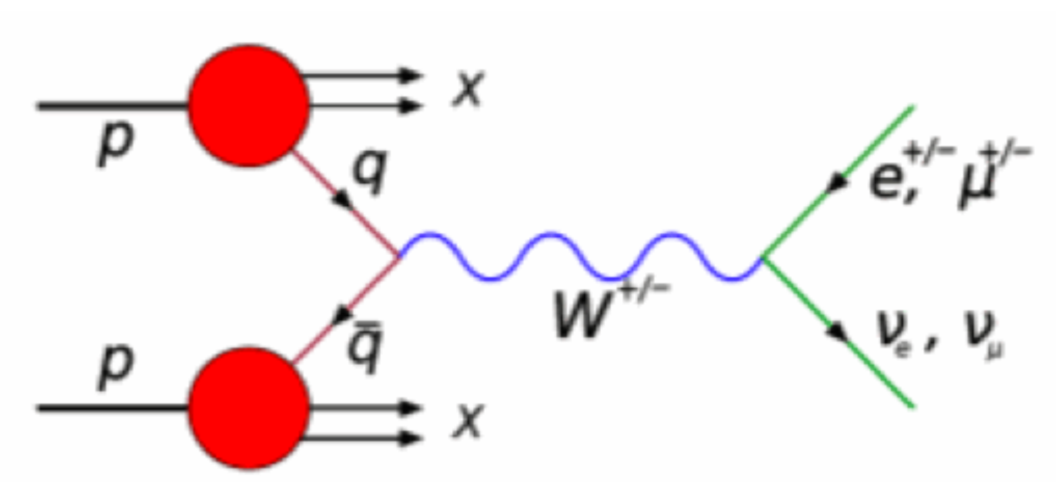
Invariant Mass





Adding four momenta of all decay products

Not So Simple for W



Electron or muon can be measured with precision, but not the missing energy!

So how to get W boson mass?

W Mass

- We measure the MET and that is (ideally) equivalent to pT of the neutrino.
- Can be done by subtracting the hadronic recoil from lepton pT.
- Then calculate transverse mass as:

$$m_T \equiv \sqrt{2(p_{\mathrm{T}}^{l} p_{\mathrm{T}}^{miss} - \vec{p_{\mathrm{T}}^{l}} \cdot \vec{p_{\mathrm{T}}^{\mathrm{miss}}})} = \sqrt{2 p_{\mathrm{T}}^{l} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}$$

W Mass

In W-boson rest frame:

$$\vec{p^l} \equiv \frac{M_W}{2}(1, \sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$

$$p^{\vec{miss}} \equiv \frac{M_W}{2}(1, -\sin\theta\cos\phi, -\sin\theta\sin\phi, -\cos\theta)$$

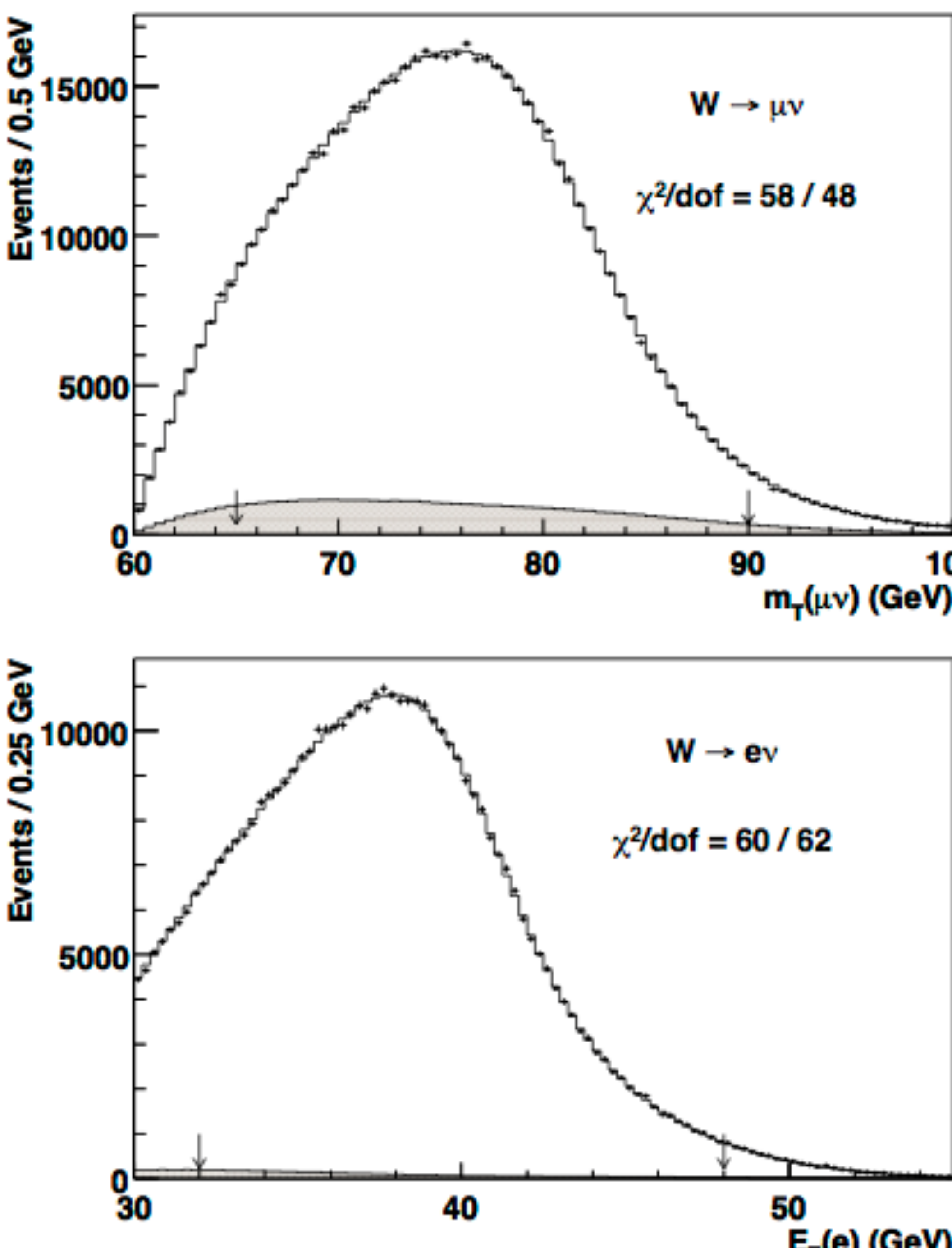
Leads to:

$$m_T^2 \equiv 2\frac{m_W^2}{4}(1 - \sin^2\theta\cos^2\phi - \sin^2\theta\sin^2\phi - \cos^2\theta)$$

$$= \frac{m_W^2}{2}(2\sin^2\theta) = m_W^2\sin^2\theta$$

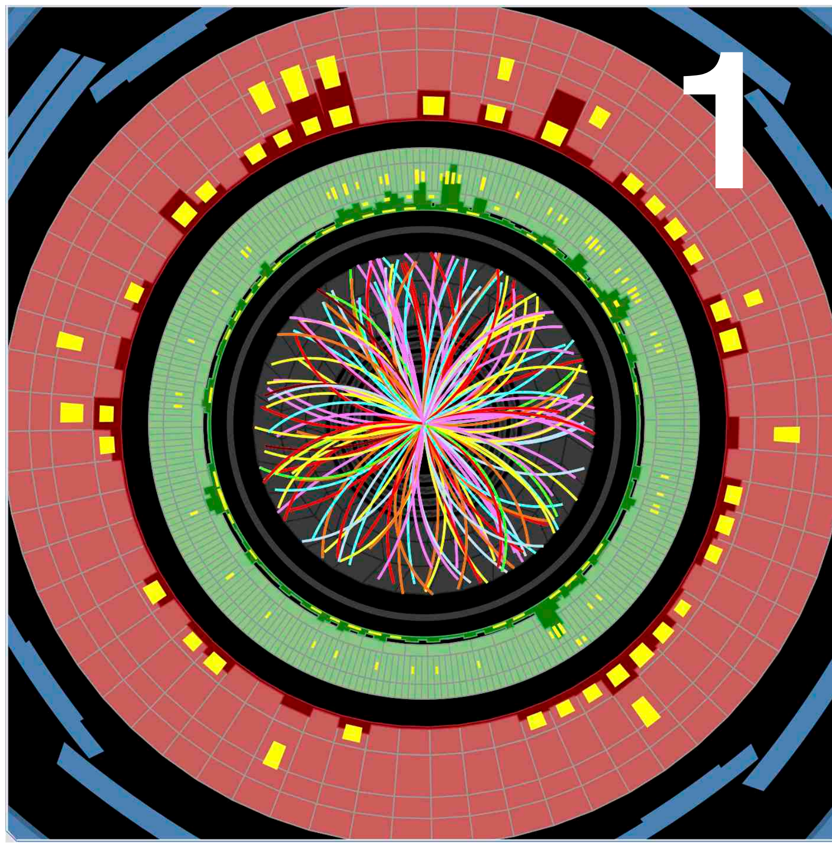
Implies: $m_T^2 \leq m_W^2$

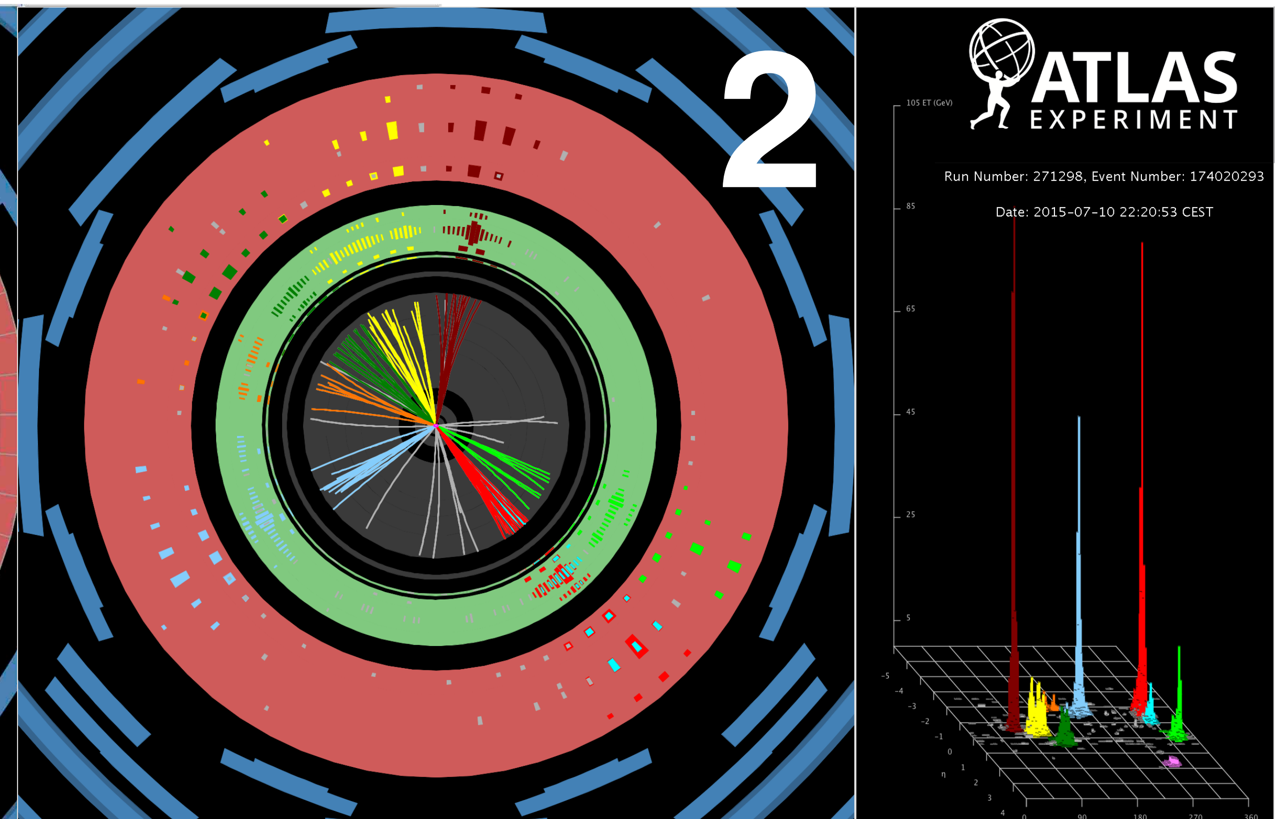
W Mass

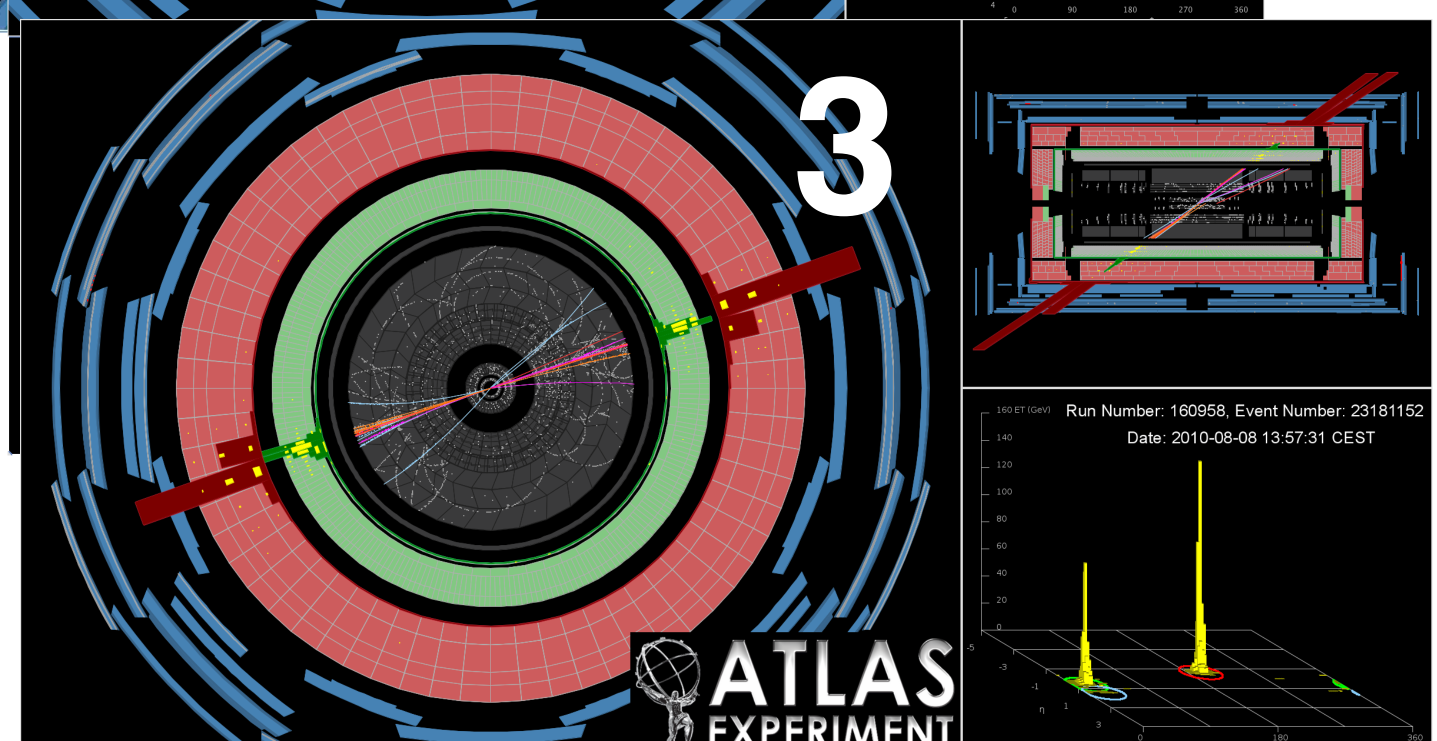


Jacobian peak

Event Shapes

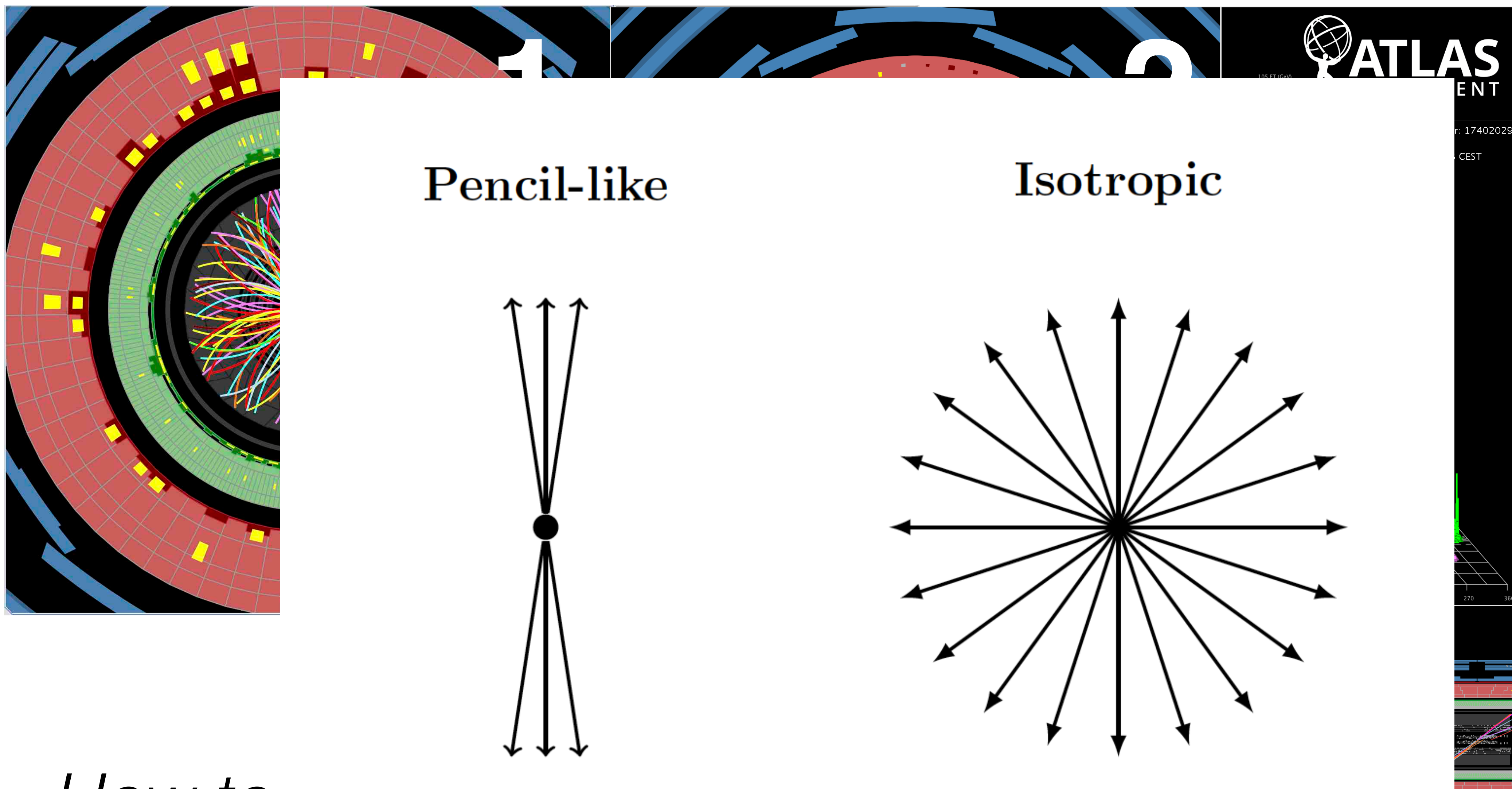


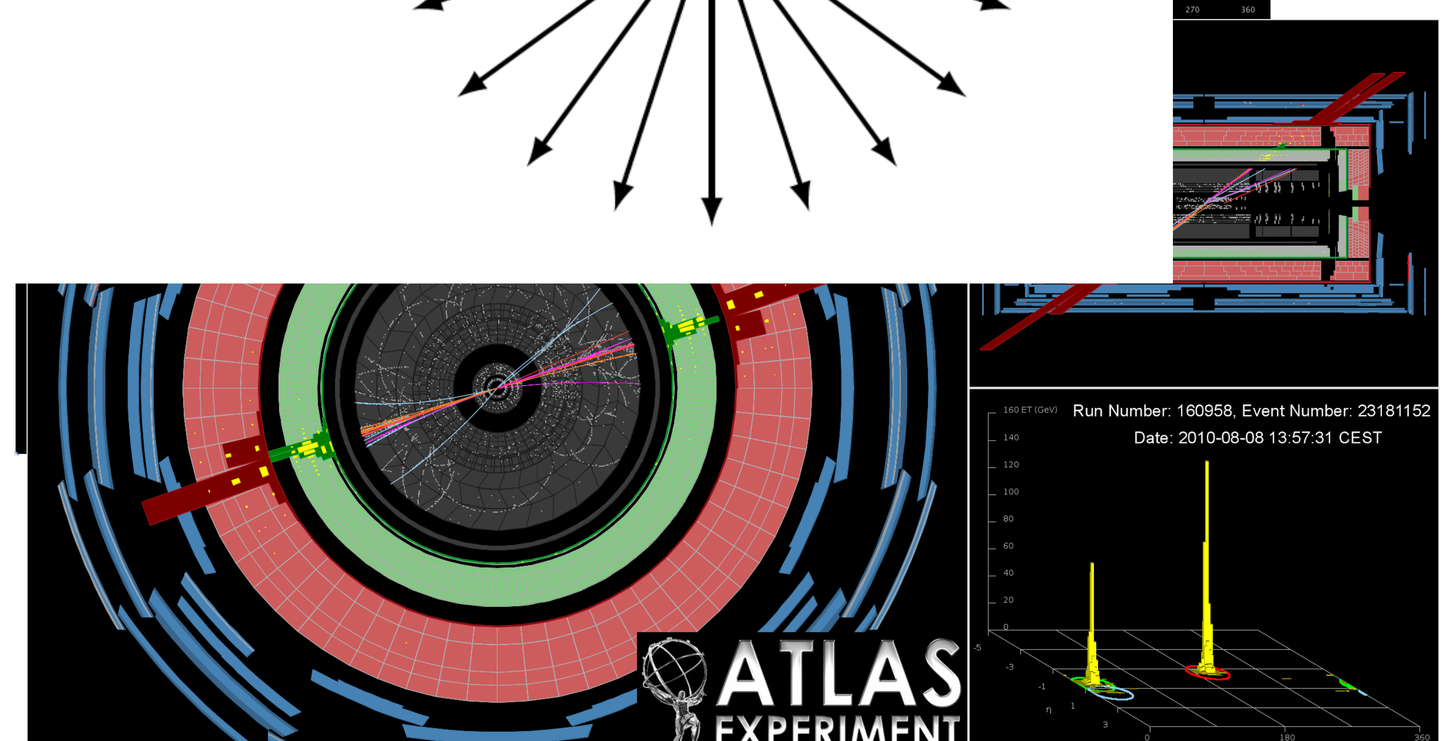




How to distinguish?

Event Shapes





How to distinguish?

Event Shape Observables

Transverse thrust $\tau_\perp$

$$\tau_\perp = \tau_T = 1 - \max_{\hat{n}_T} \frac{\sum_i |\mathbf{p}_{T,i} \cdot \hat{n}_T|}{\sum_i |\mathbf{p}_{T,i}|} \qquad |\hat{n}_T| = 1$$

Transverse momentum flow along the thrust axis
$0 \leq \tau_\perp \leq 1 - \frac{2}{\pi} \approx 0.36$

Thrust Minor T_M

$$T_M = \frac{\sum_i |\mathbf{p}_{T,i} \times \hat{n}_M|}{\sum_i |\mathbf{p}_{T,i}|} \qquad \hat{n}_M = \hat{n}_T \times \hat{z}$$

Out-of-eventplane transverse momentum flow
$0 \leq T_M \leq 1$

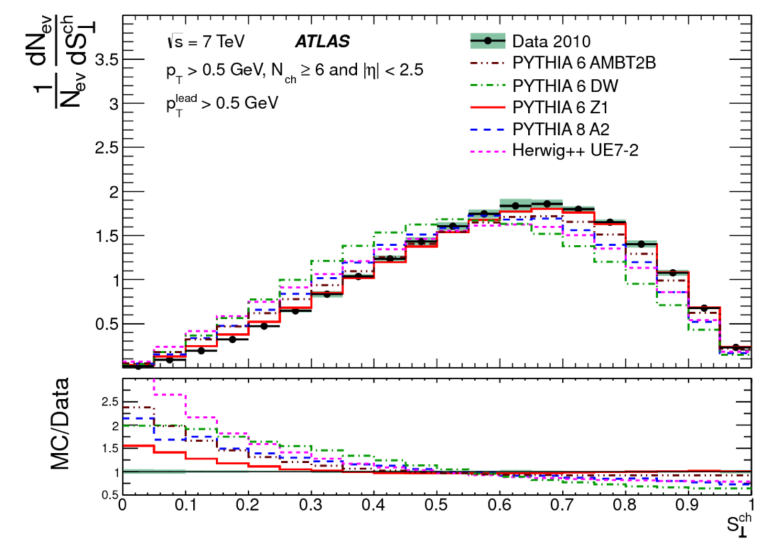
Transverse sphericity $S_\perp$

$$S_{xy} = \sum_i \begin{bmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} \\ p_{x,i}p_{y,i} & p_{y,i}^2 \end{bmatrix} \qquad \lambda_2^{xy} > \lambda_1^{xy} = \text{Eigenvalues of } S_{xy}$$

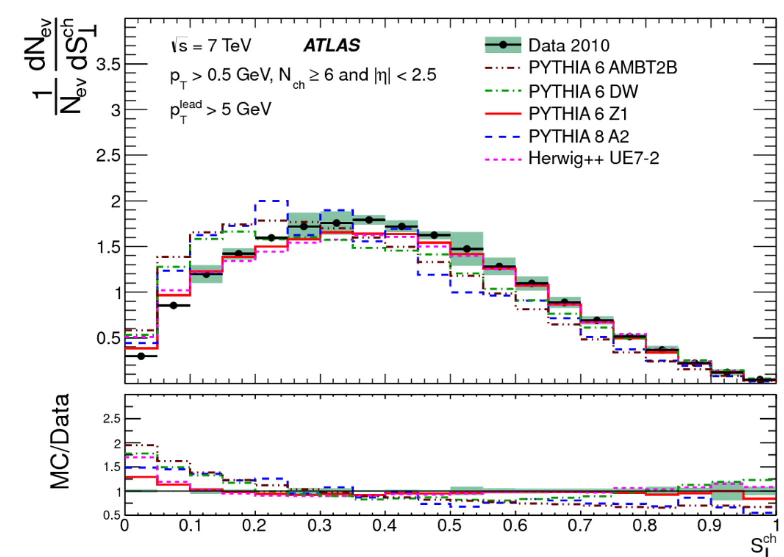
and

$$S_\perp = \frac{2\lambda_2^{xy}}{\lambda_1^{xy} + \lambda_2^{xy}}$$

Isotropy of transverse momentum flow
$0 < S_\perp \leq 1$



More isotropic



More dijet-like

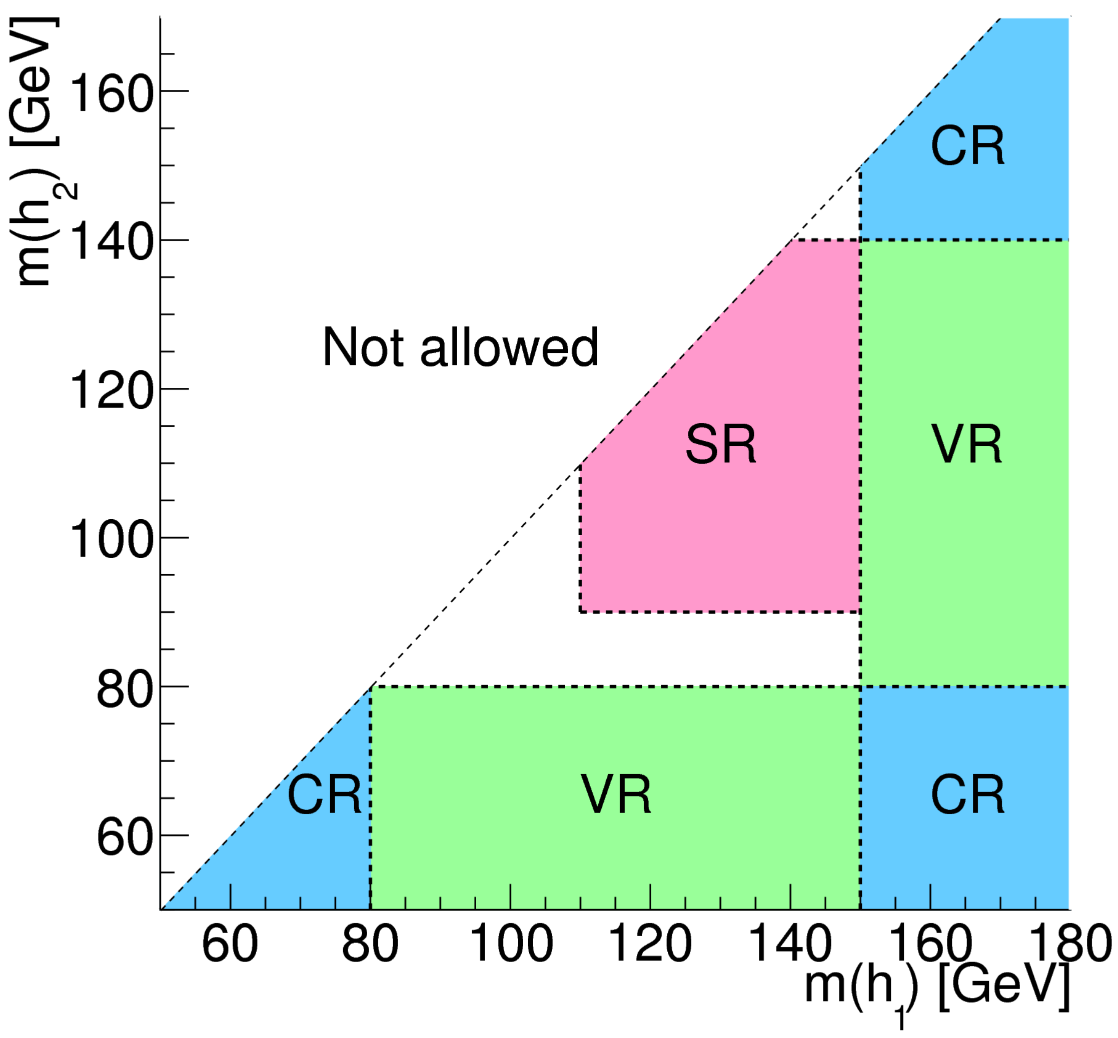
Types of backgrounds

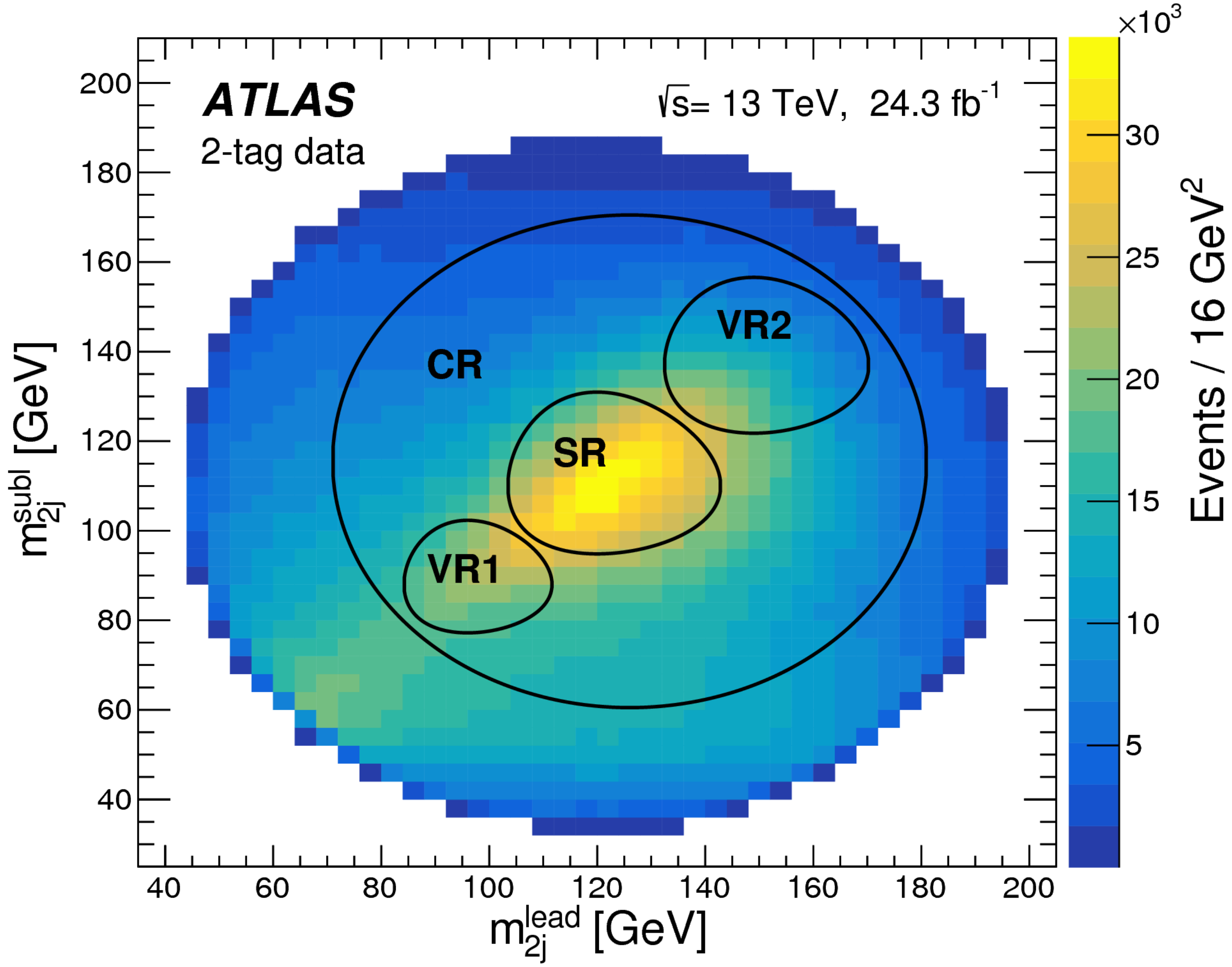
- Irreducible: same final state. SM ZZ for H to ZZ.
- Reducible: not the same final state, resulting from misreconstructed processes or misidentified objects. W(lnu)+jets for Z(ll)+jets.
- Combinatorial: random combination of objects looking like the signal. All hadronic ttbar.

Signal and control regions

- We apply selection *cuts* on the objects and event topology to maximise signal and minimise background.
- However, when searching for a new physics signal, we do not want to bias ourselves.
- So divide the events into signal region, where data is blinded when we fix analysis strategies, and control region by inverting one (or more signal cuts), where we can check data-MC agreement and estimate background contribution.
- Unblinded after cuts are optimised and **fixed.**

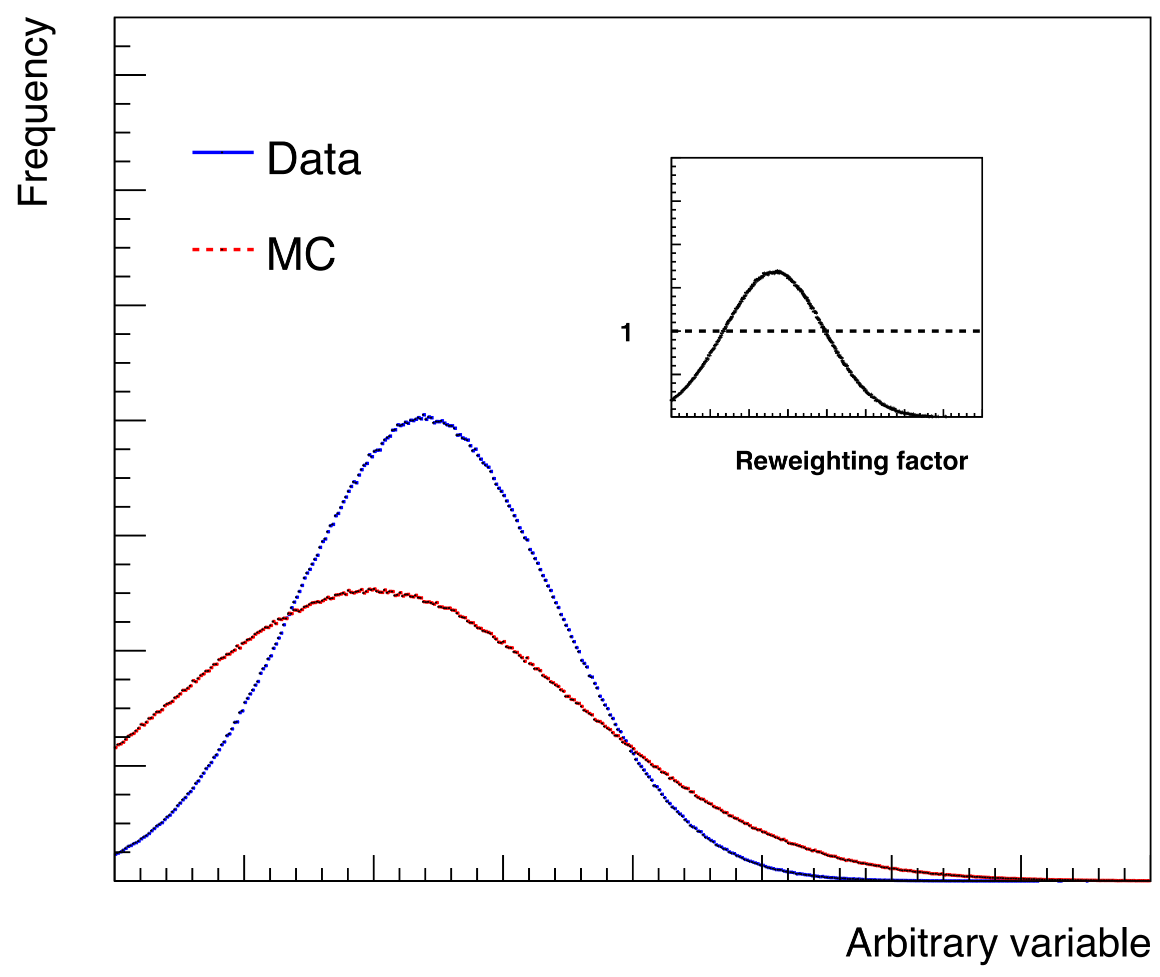
SR and CR


m(h2) [GeV]
160
140
120
100
80
60
Not allowed
CR
SR
VR
VR
CR
CR
60
80
100
120
140
160
180
m(h1) [GeV]


ATLAS
√s= 13 TeV, 24.3 fb-1
2-tag data
CR
VR2
SR
VR1
200
180
160
140
120
100
80
60
40
m2j subl [GeV]
40
60
80
100
120
140
160
180
200
m2j lead [GeV]
×10³
30
25
20
15
10
5
Events / 16 GeV²

Data-MC agreement in CR

- What if simulation does not describe the data in CR?
- Modelling?
- Calibration/efficiency estimates wrong?
- Reweight :-(

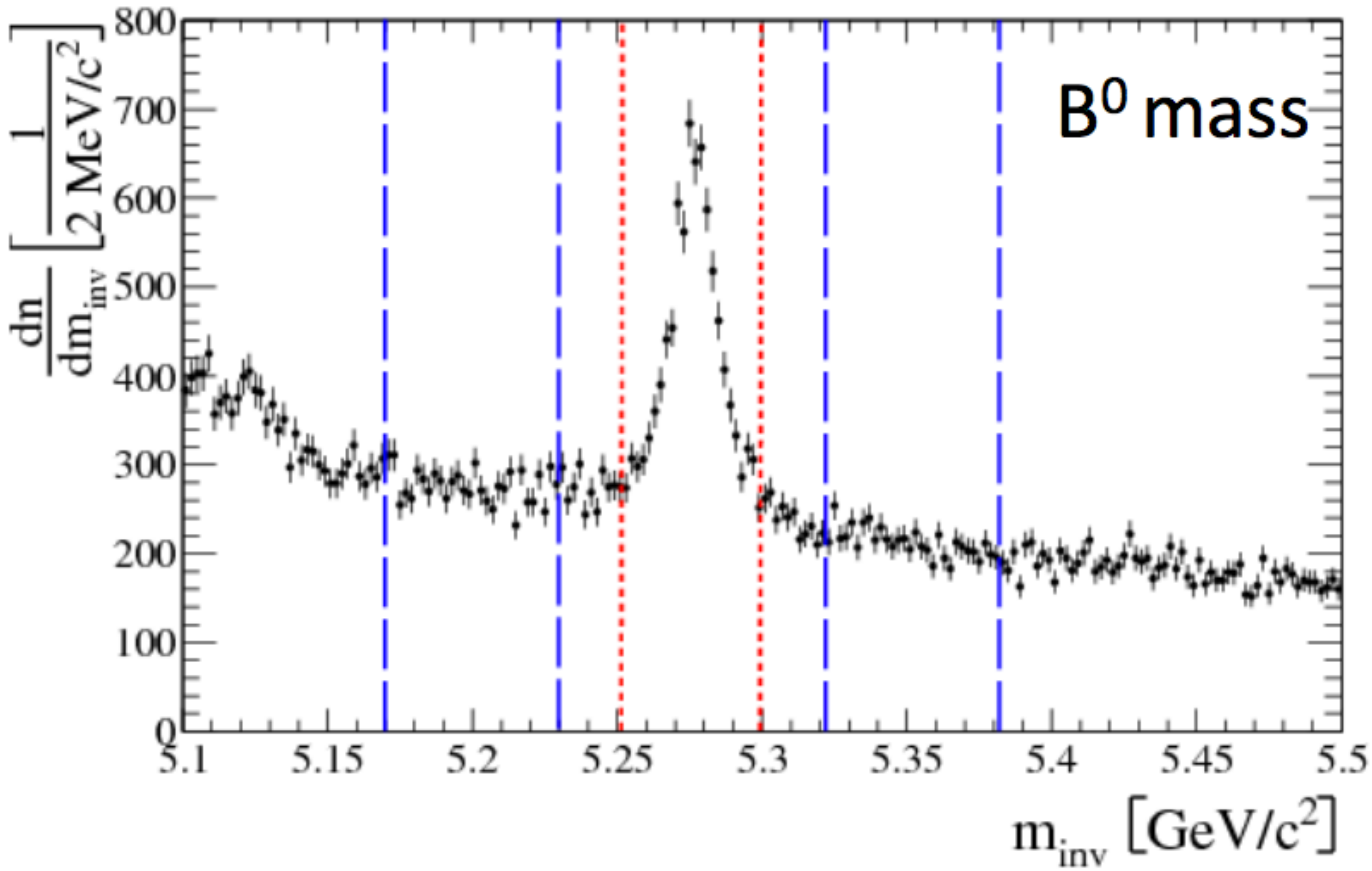


Estimate the backgrounds

Data and/or simulation driven

- Anti-selection/inversion of cuts
- Side-bands/shape extraction by fit
- ABCD method
- …

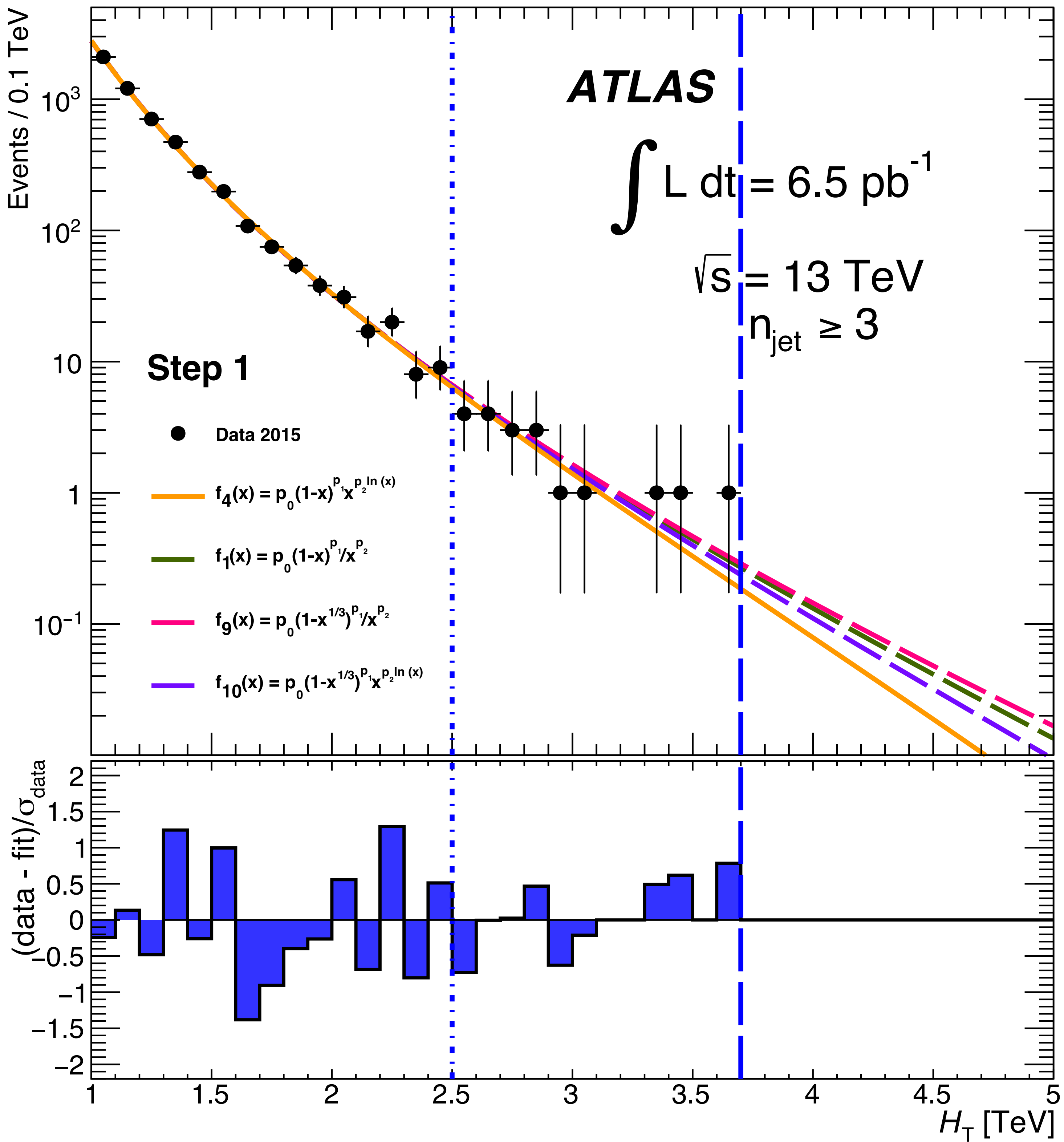
Sidebands



Estimate background under a resonance peak

With or without fitting

Sidebands

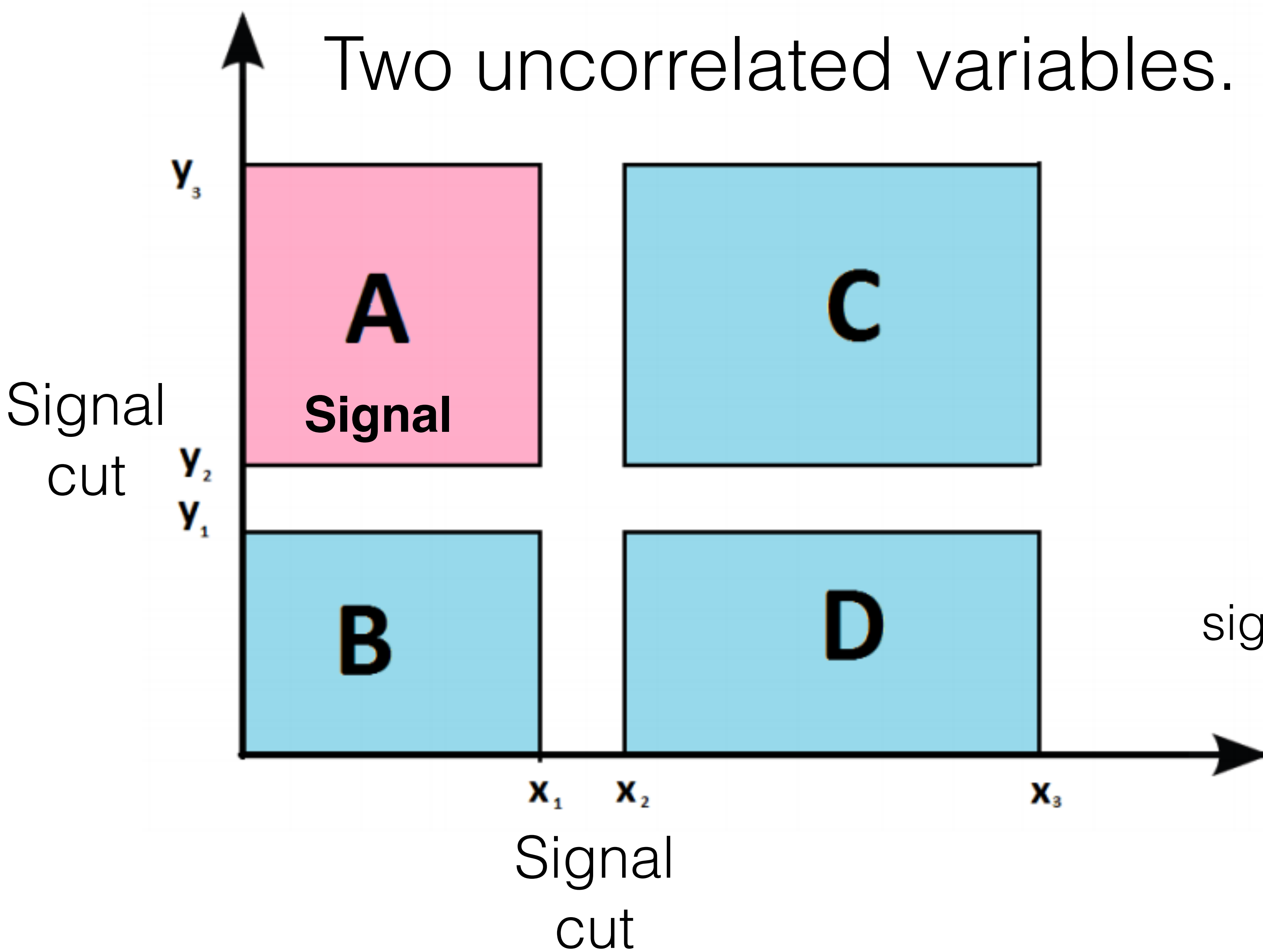


Estimate background under a resonance peak

With or without fitting

ABCD method

Two uncorrelated variables.



Estimate by:

$$N_A = \frac{N_B \times N_C}{N_D}$$

b.g in
signal region

Unfolding

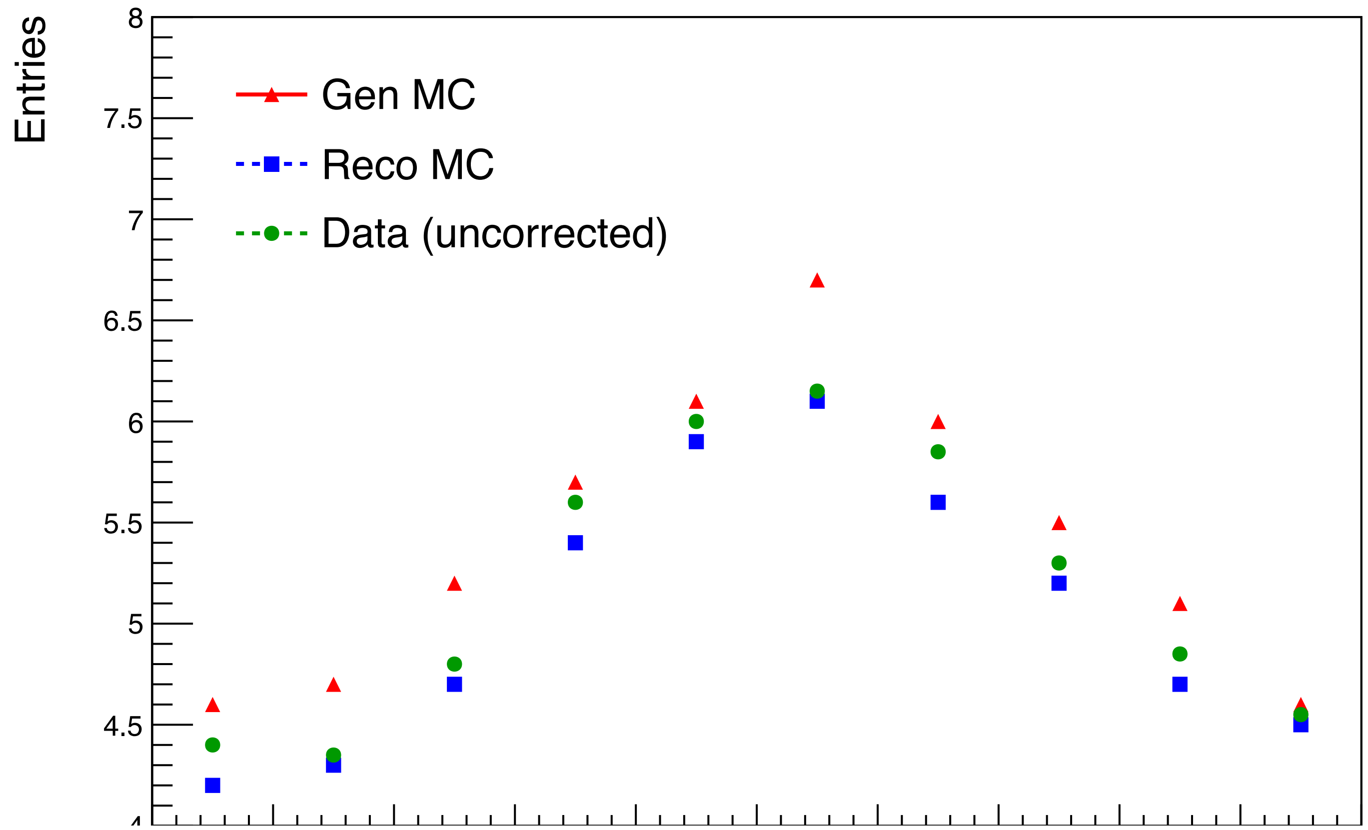
- We measure at detector level.
- But each detector is different!
- Unfold the detector effect to arrive at generator level.
- Mathematically: $m_i = \sum_j \alpha_{ij} t_j$, which is an ill-posed problem!
- Bin-by-bin or (iterative) Bayesian method.

Unfolding

- We measure at detector leve...
- But each detector is di...
- Unfold the detec... ...rrive at generator level.
- Mathemat... ...$a_{ij}t_j$, which is an ill-posed proble...
- Bin-by-... (iterative) Bayesian method.

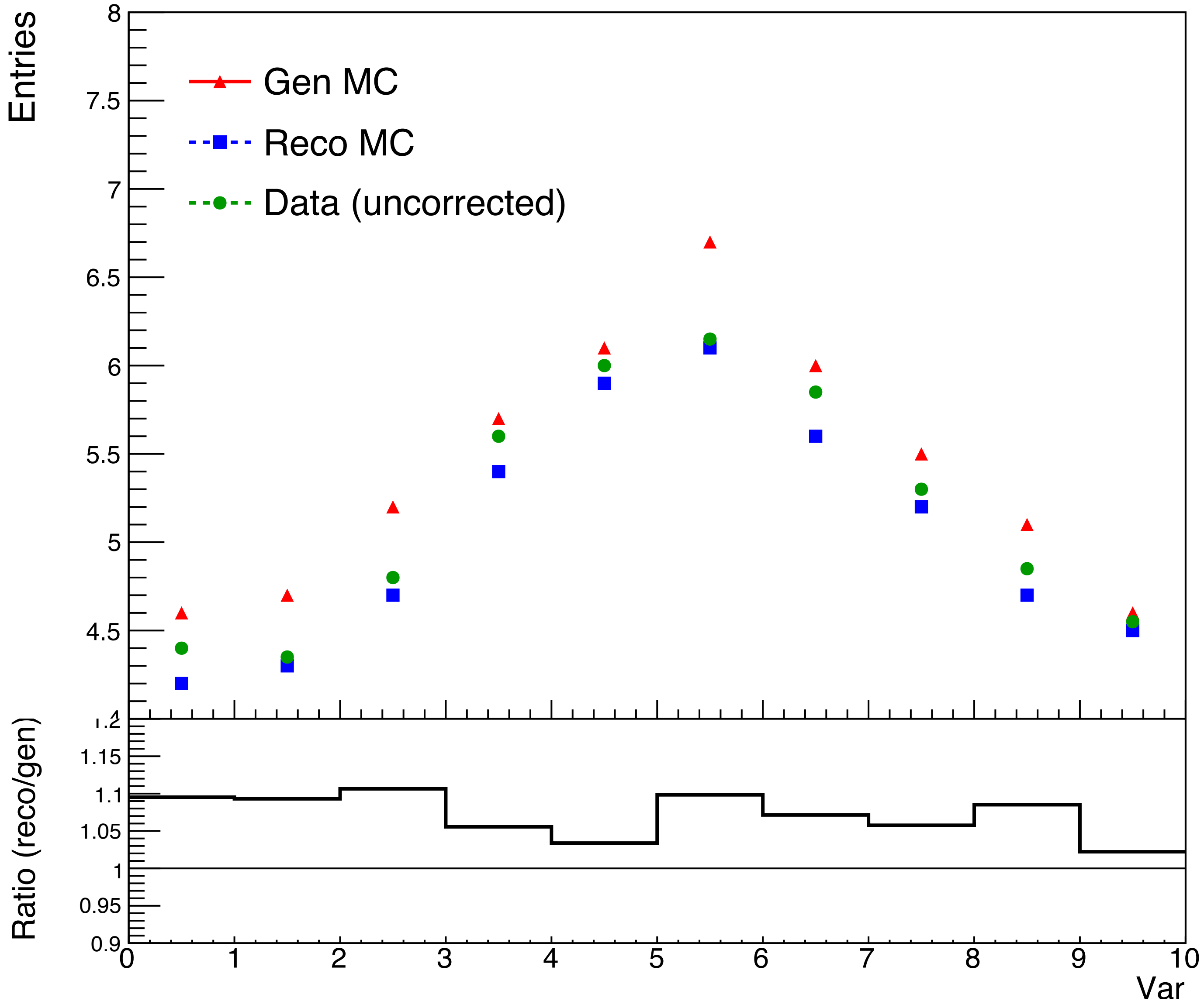
Also measure in a model independent fiducial phase space

Bin-by-bin unfolding



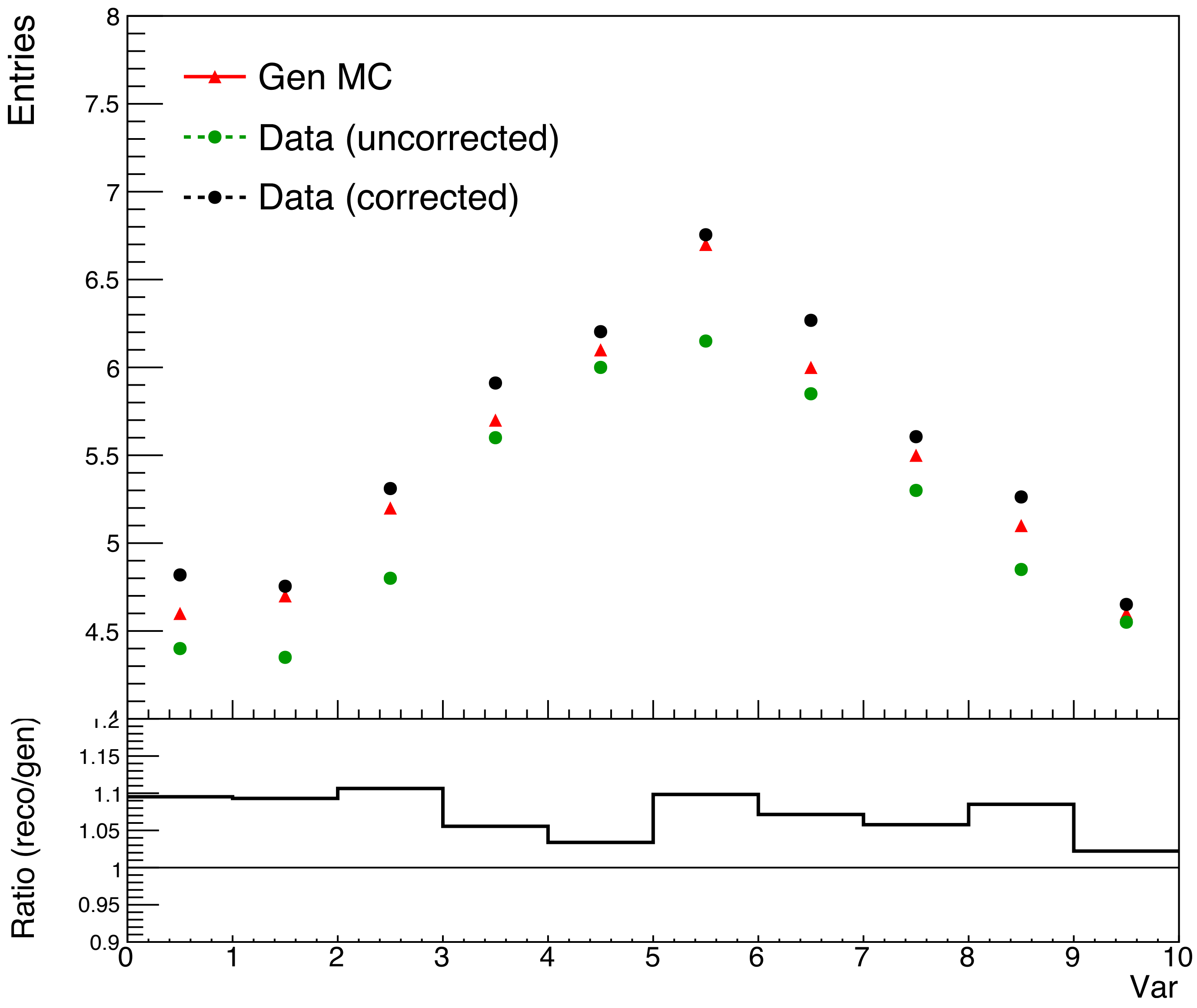
1. Start with the distributions we have

Bin-by-bin unfolding



2. Calculate the reco/gen ratio for each bin

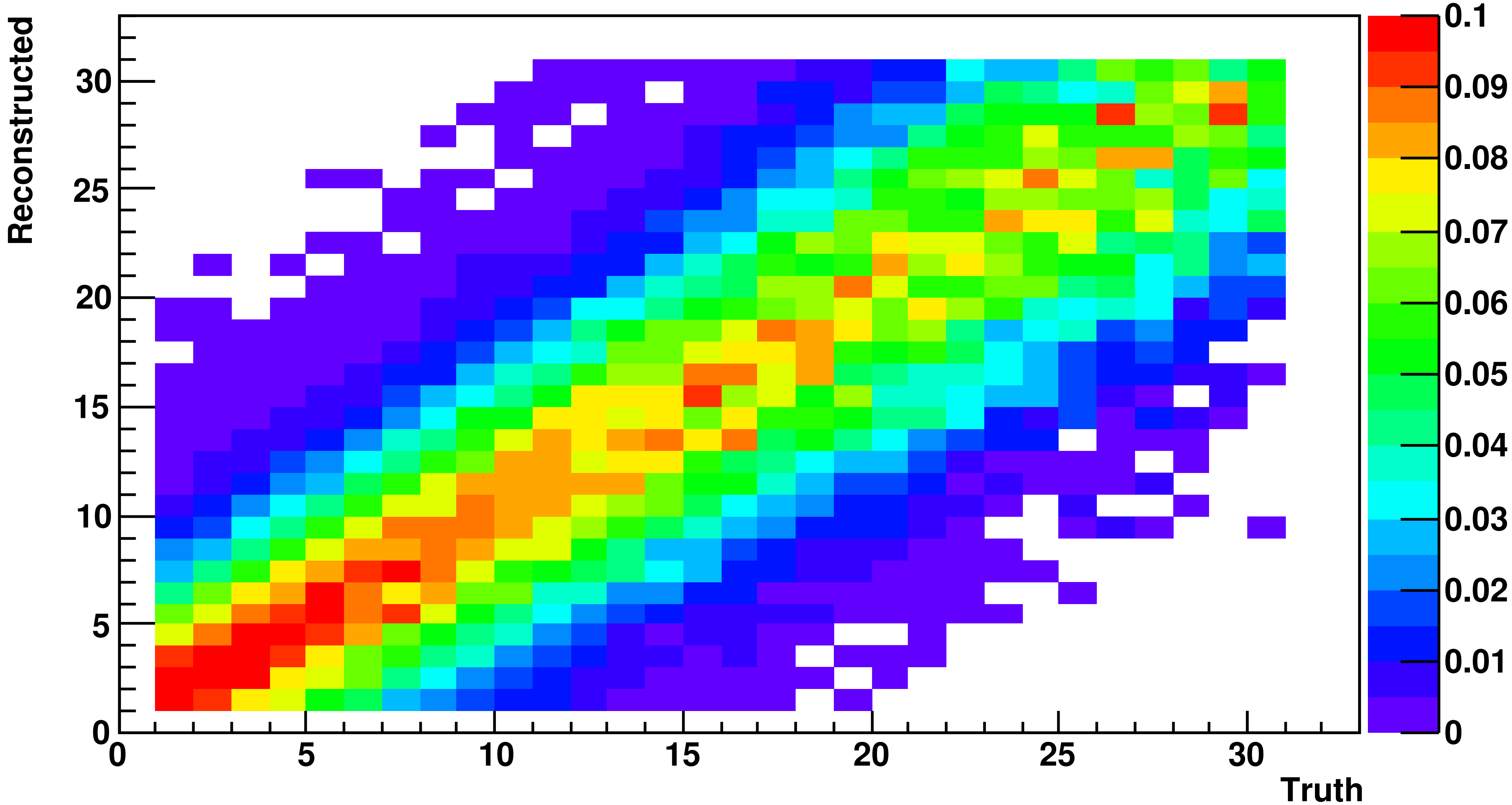
Bin-by-bin unfolding



3. Multiply data in each bin by the ratio in each bin

Not adequate for steeply rising/falling distributions as do not account for bin migrations

Bayesian Iterative unfolding



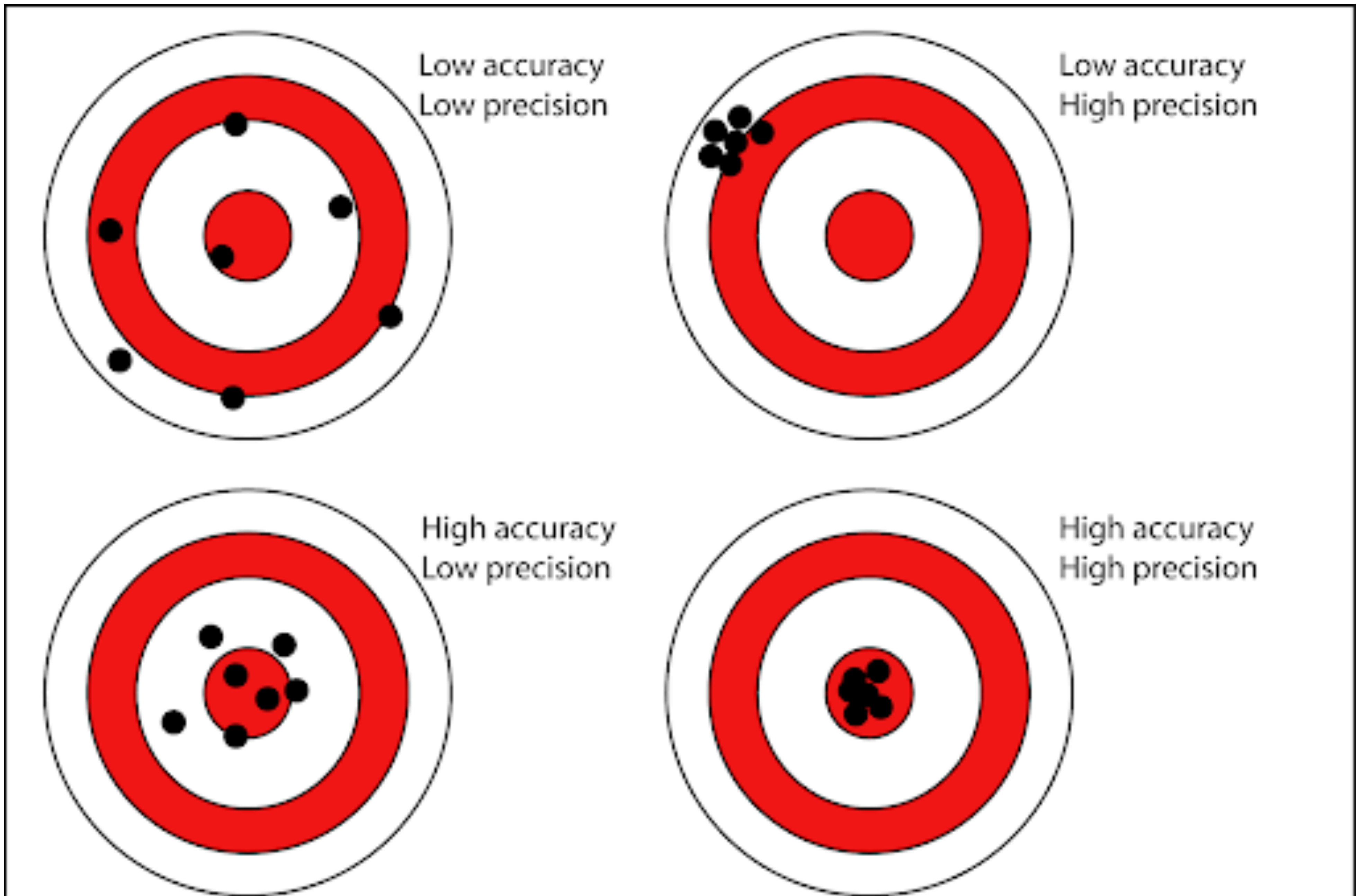
Smearing matrix
Diagonal: good!

Session 5:
Uncertainties and Plots

Accuracy and Precision

?

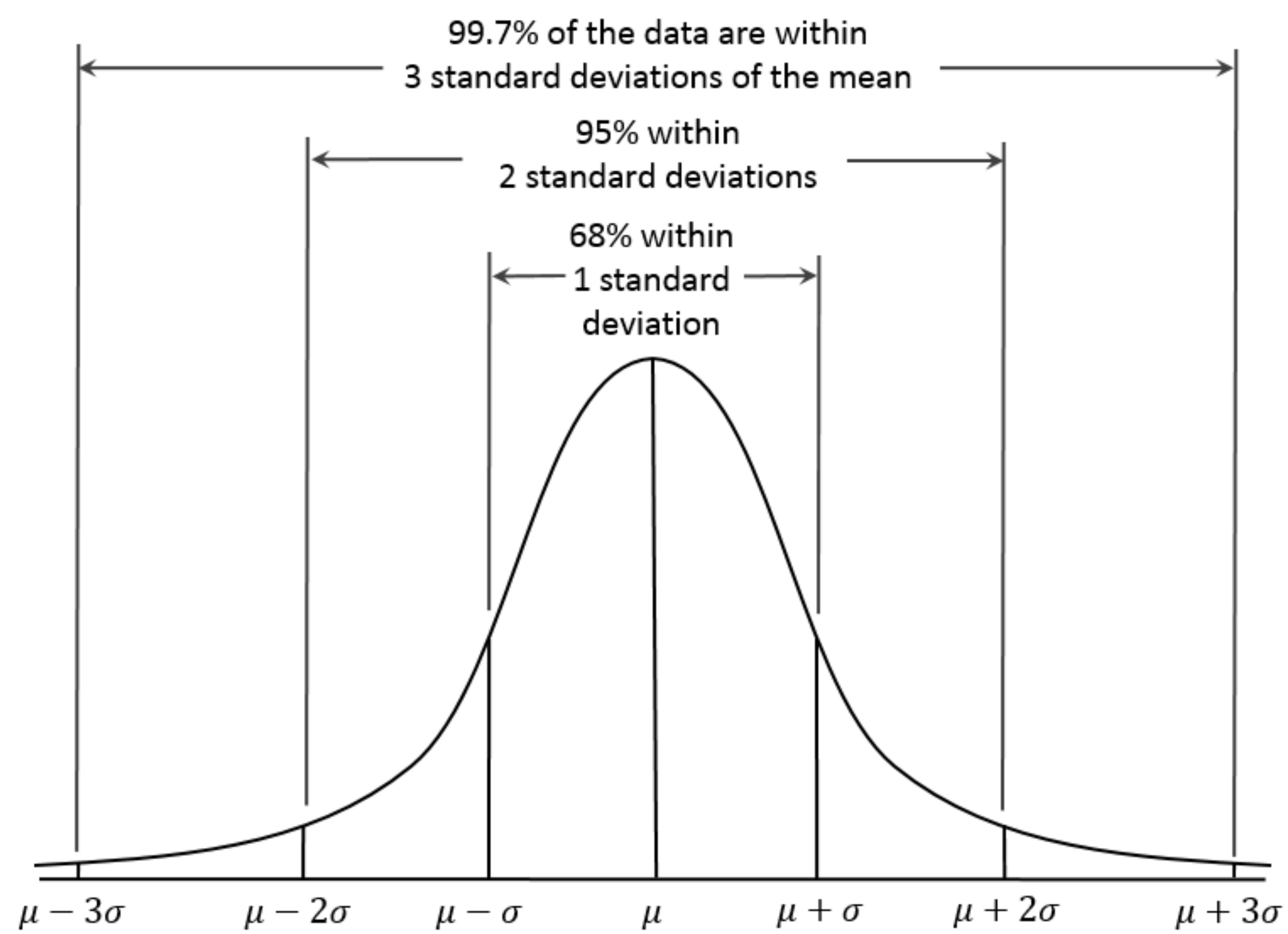
Accuracy and Precision



Uncertainties

- Statistical: random fluctuations, improves with more data. Goes as 1/sqrt(N) (assumed Gaussian)

- Systematic: bias in the measurement, challenging to estimate well.



Results presented as:

$$m_W = 80370 \pm 7(stat.) \pm 11(exp.syst.) \pm 14(mod.syst.) MeV = 80370 \pm 19 MeV$$

Sources of Systematic Uncertainties

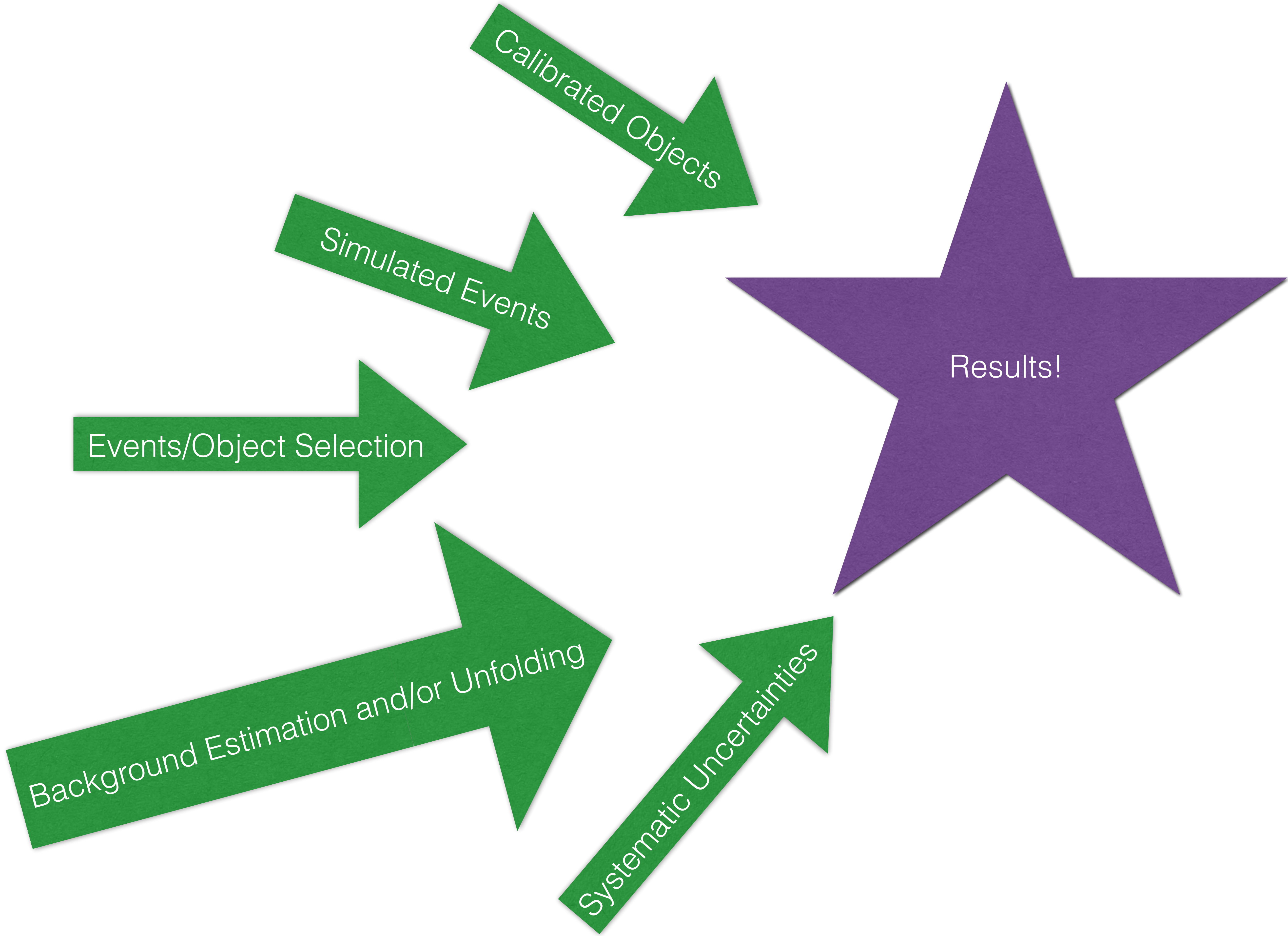
- Luminosity
- Detector (calibration, efficiency …)
- Trigger (efficiency)
- Theoretical inputs/simulation
- Background estimation
- Unfolding

	Measurement	Search
Uncertainty on:	Data	MC simulation
How?	Unfold data distributions, corresponding to each variation	Recalculate final results, corresponding to each variation
Finally:	Differences from the nominal are the uncertainties. Combine them in quadrature or otherwise	

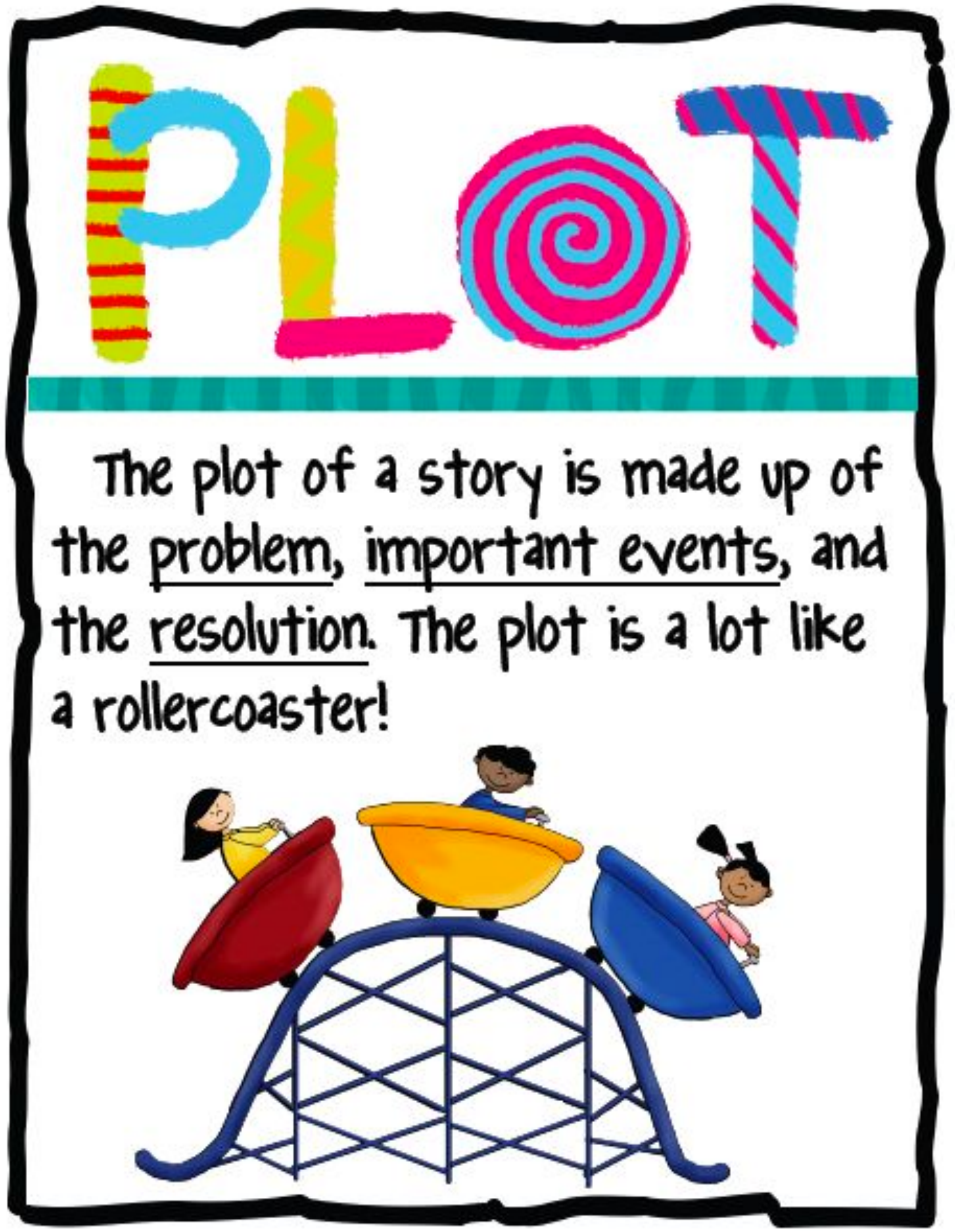
Estimation

- Data-MC comparison
- Varying correction factors
- Alternative methods
- Generator comparisons

Cut variation is usually not systematic uncertainty!


Calibrated Objects
Simulated Events
Events/Object Selection
Background Estimation and/or Unfolding
Systematic Uncertainties
Results!

Plots

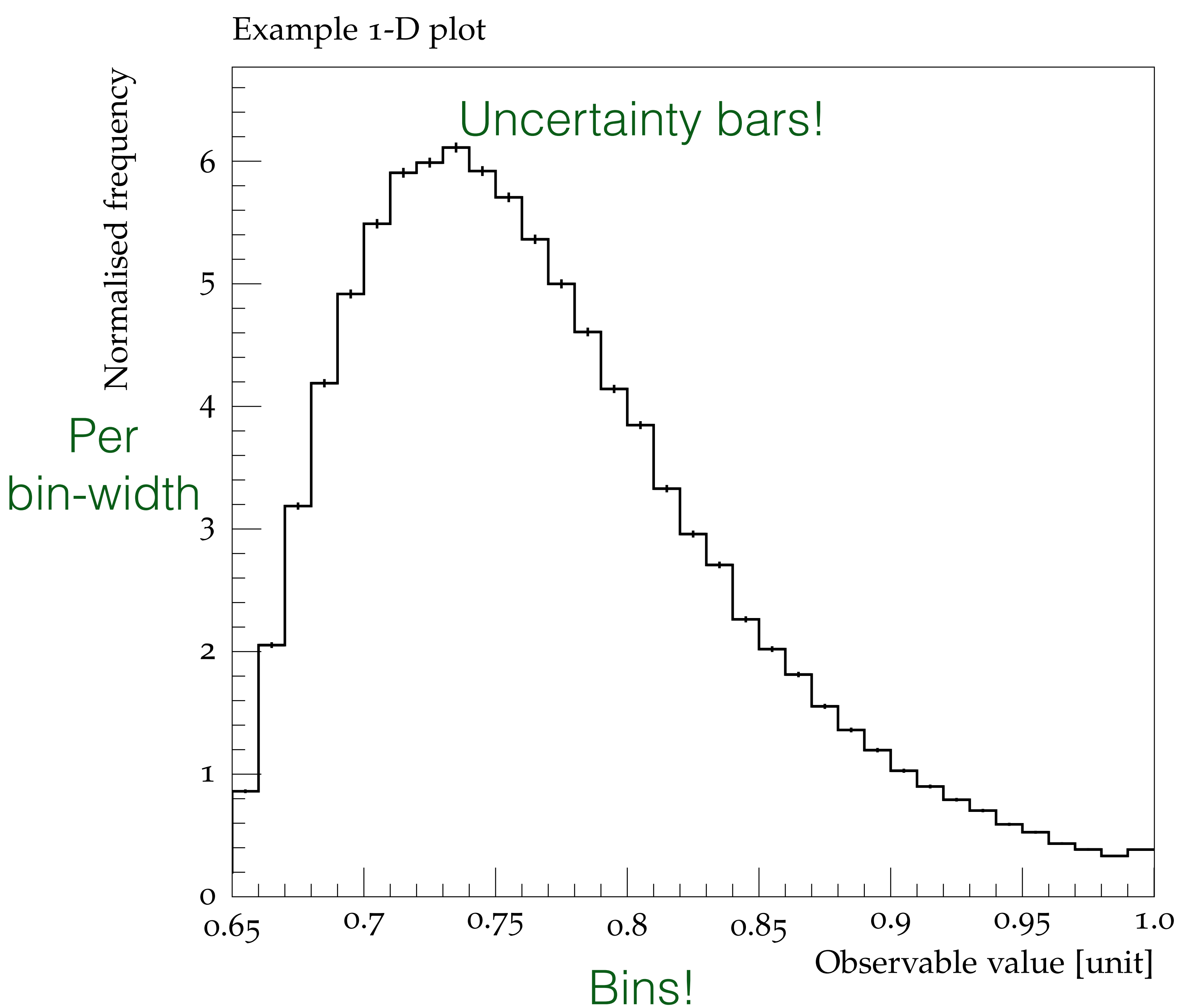


Well, somewhat!

Common types of plots

- Frequency/cross-section plots
- Profile plots
- Two-dimensional correlation plots
- Limit plots
- ROC curves

Frequency Distributions



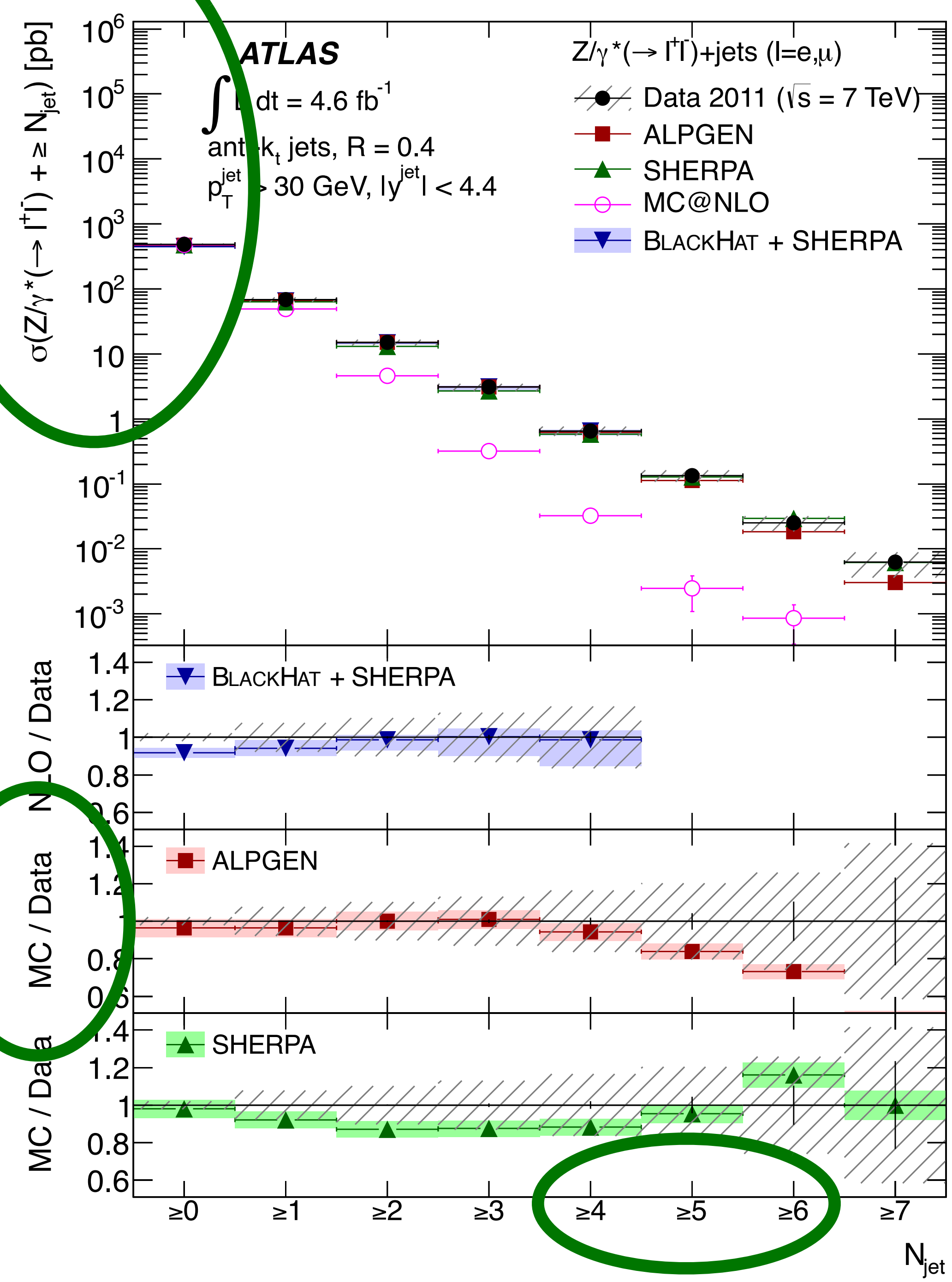
Cross-section plot

Log scale!

Cross-section
for the process
(sometime normalised
by some factors)

(single) differential:
binned in one observable

double differential: binned in two



Ratio
to help
comparison

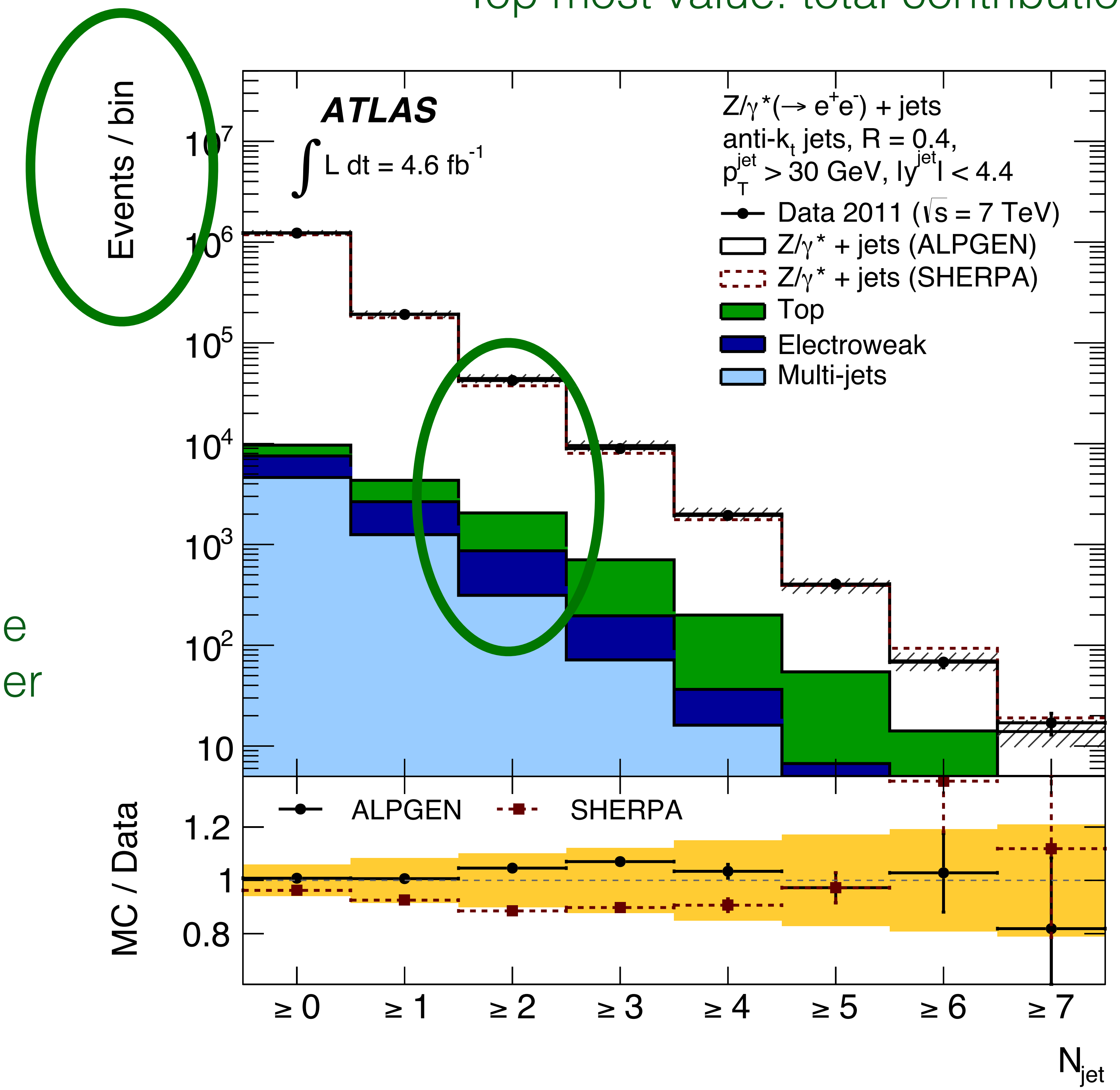
Bins should
be stable
statistically

Stat uncertainty ~sqrt(N)

Cross-section plot (stacked)

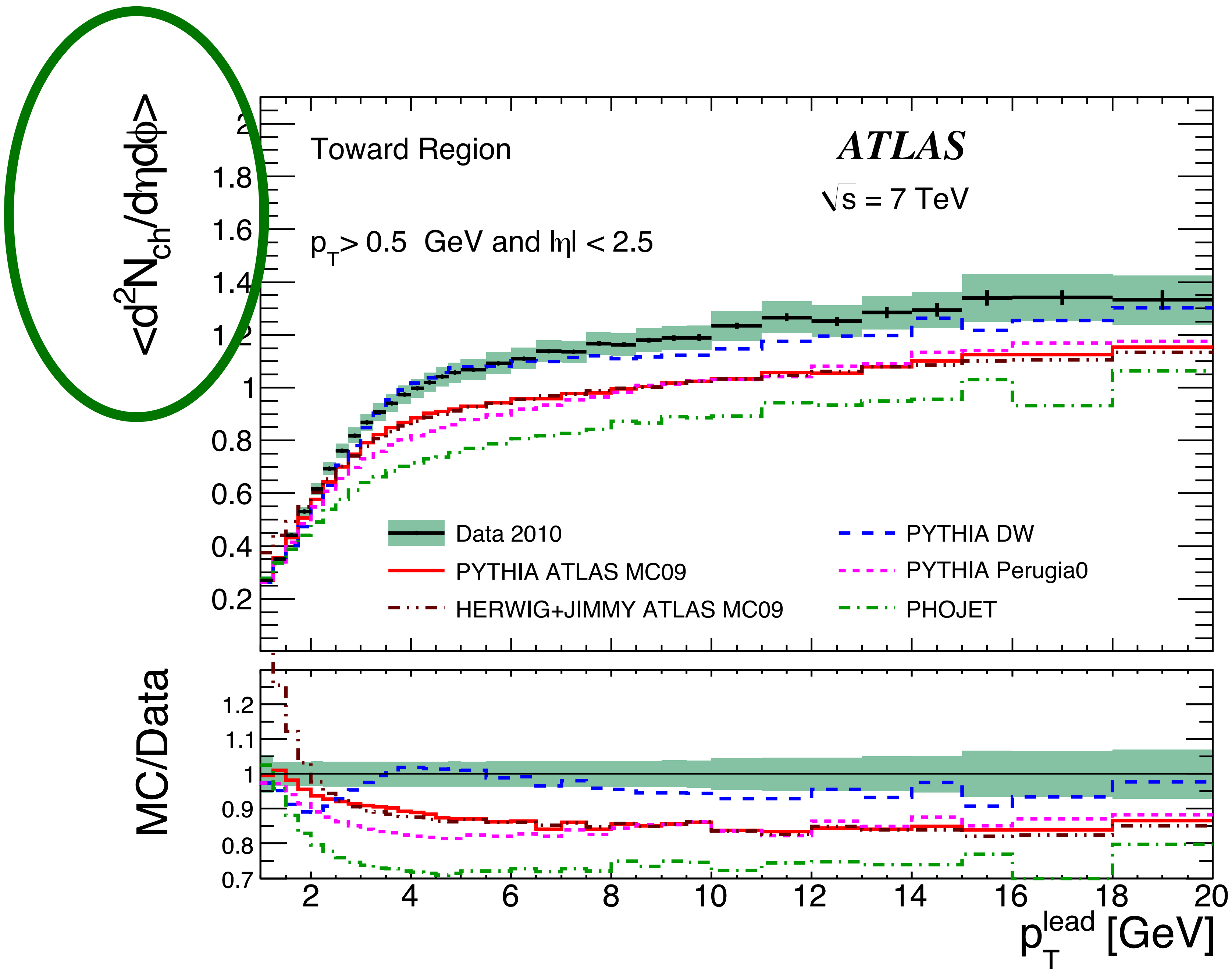
Top most value: total contribution

Each SM process stacked one over the other



Profile

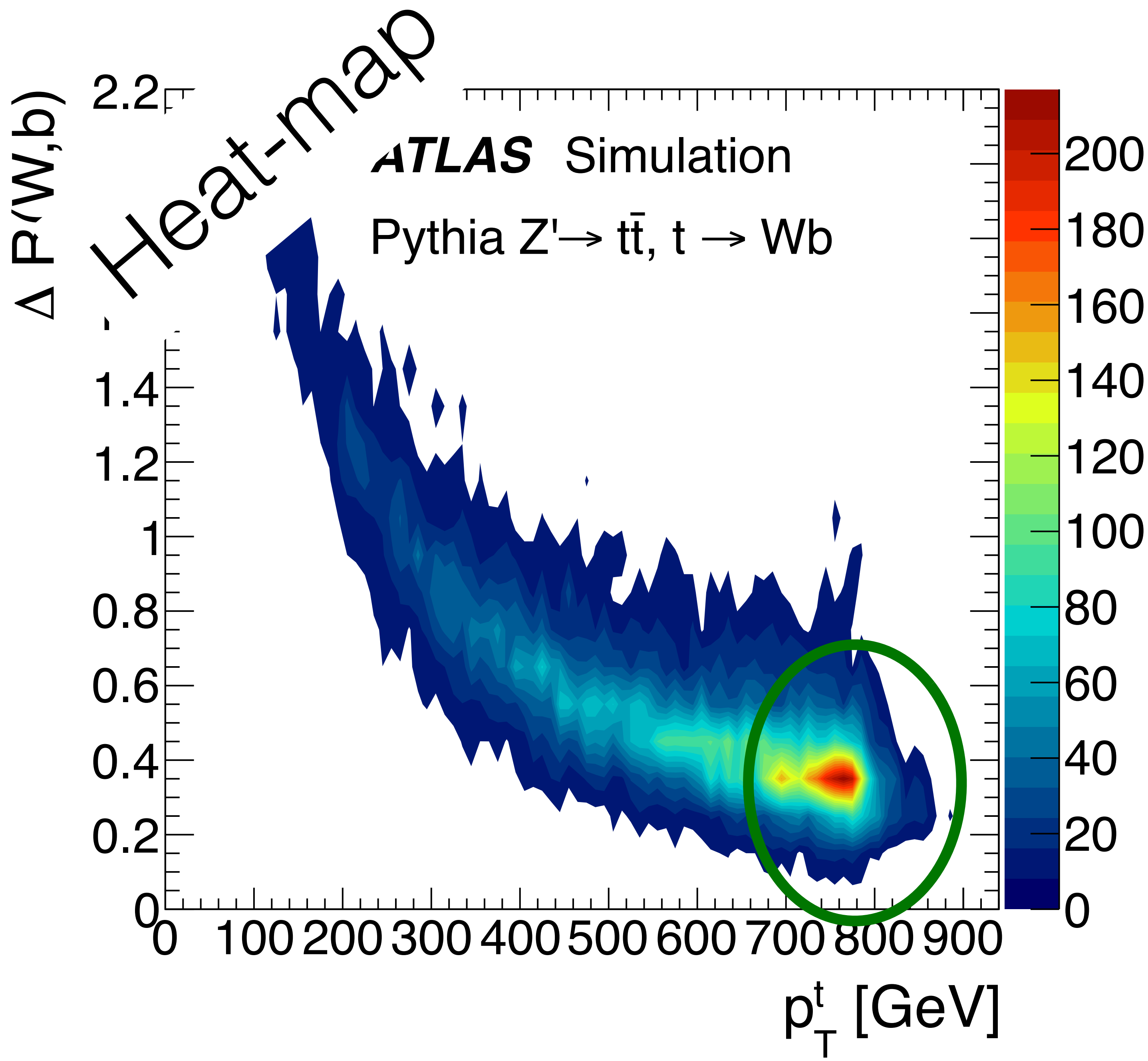
Mean value



Useful to asses the overall trend, but not details

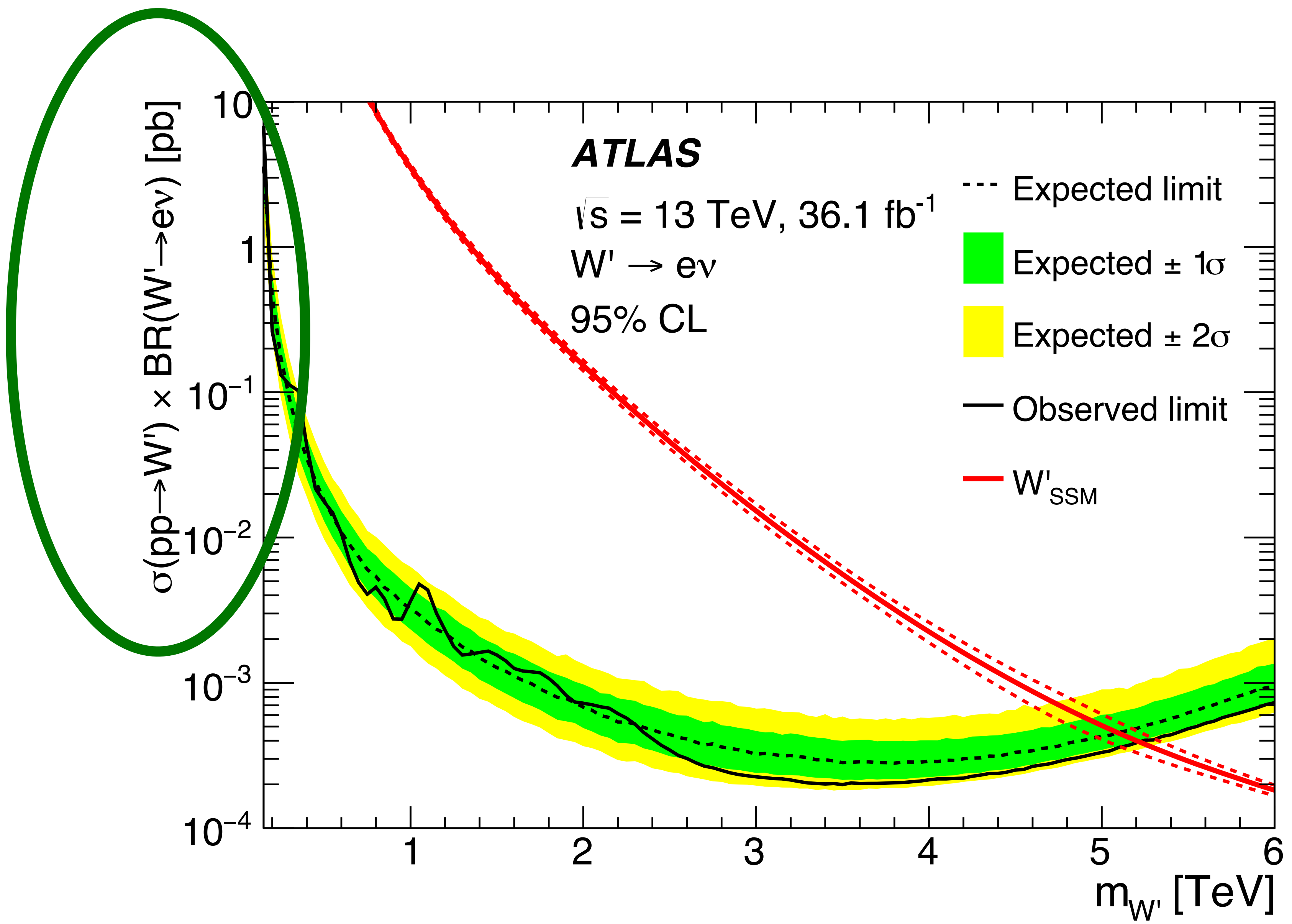
2D Correlation

Hidden 3rd axis corresponding to frequency



Largest correlation

Limit plot



When signature of a new model is not found, the model is excluded up to a certain parameter value

Presented in terms of 95% confidence level, which the associated probability of that observation being correct 95% of the time. In other words, if the measurement is made repeatedly on independent datasets, the measured value will be obtained at least 95% of the time.

Components of a limit plot

- Expected line: from MC simulation (SM), usually using same luminosity as data. The 1 and 2 σ bands are from MC uncertainty. (Brazil plot!)

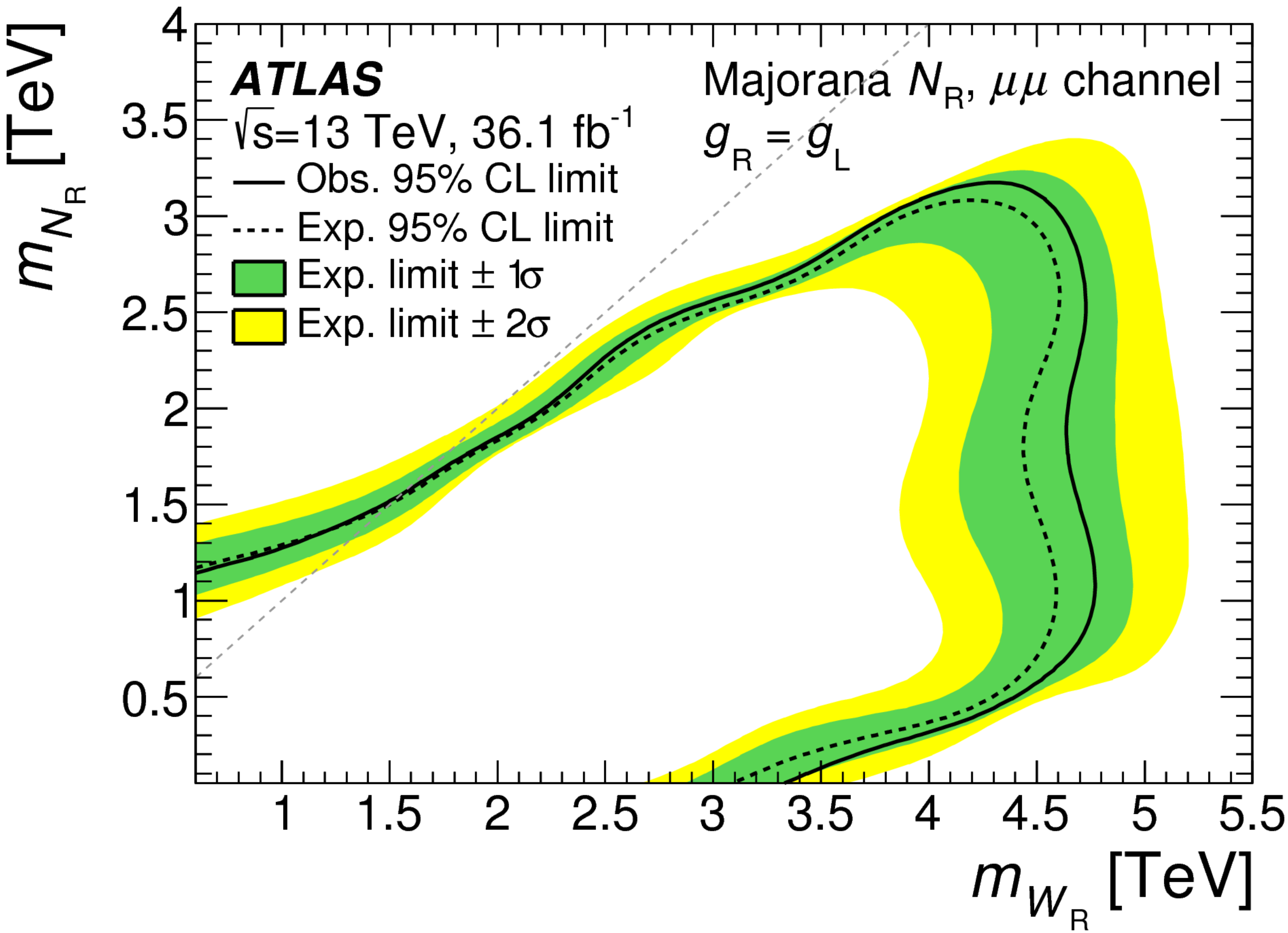
- Observed line: from data, actual number of events seen, with statistical uncertainties. It is expected to stay within the expected bands if the simulation is accurate.

- Theory line: calculated from new model, often with associated systematic uncertainties.

Interpreting a limit plot

- As long as the expected and observed lines are below the theory prediction, the conclusion is no evidence of the new particle is seen. By this argument, the expected and observed limits are respectively 5.1 and 5.2 TeV, from where the theory prediction line intersects the expected and observed lines. If at any point, the observed line goes beyond the expected brazil-bands, that may indicate data contains more events than SM predicts. However, the threshold for an observation is 3σ and a discovery is 5σ. Only in the region where observed is higher than the theory line, and beyond the statistically allowed deviations from expected, this particular new model can be confirmed.

2D Limits



ATLAS
√s=13 TeV, 36.1 fb-1
Obs. 95% CL limit
Exp. 95% CL limit
Exp. limit ± 1σ
Exp. limit ± 2σ
Majorana N_R, μμ channel
g_R = g_L
m_{N_R} [TeV]
m_{W_R} [TeV]
4
3.5
3
2.5
2
1.5
1
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5

An Aside: Why Limits?

We all want to find new physics.

An Aside: Why Limits?

We all want to find new physics.

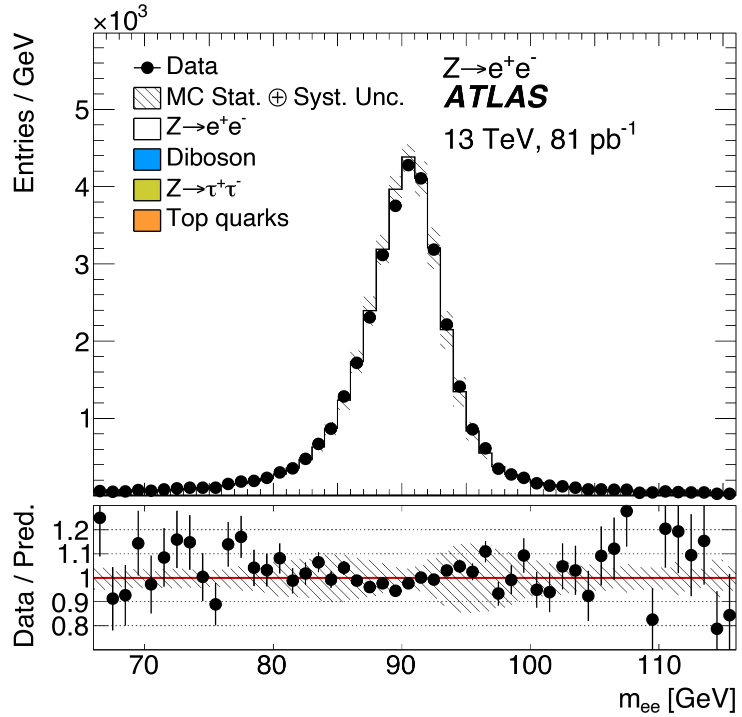
But out of 100 new physics models, at least 99 are wrong, possibly all 100 are!

So null results also tell us a lot.

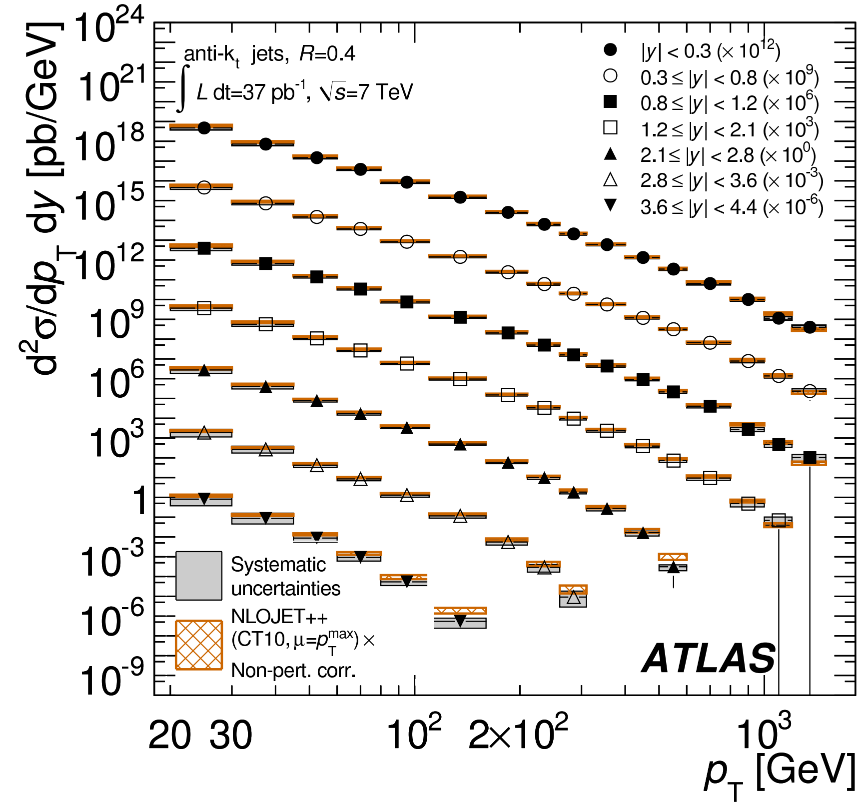
And techniques/methods developed can help in a future discovery!

Session 6:
The Full Circle

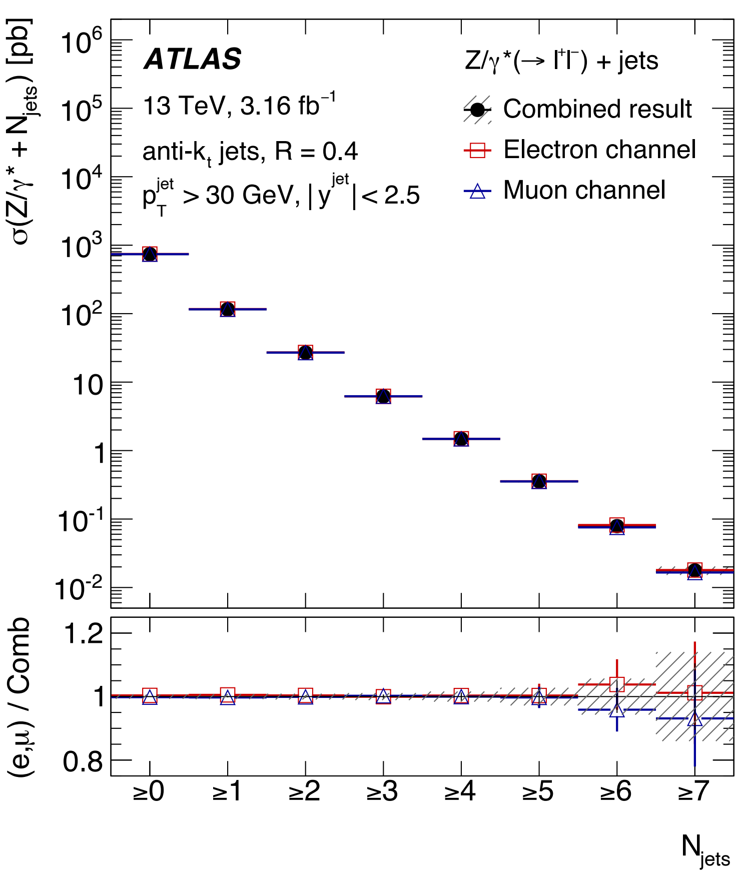
Results!



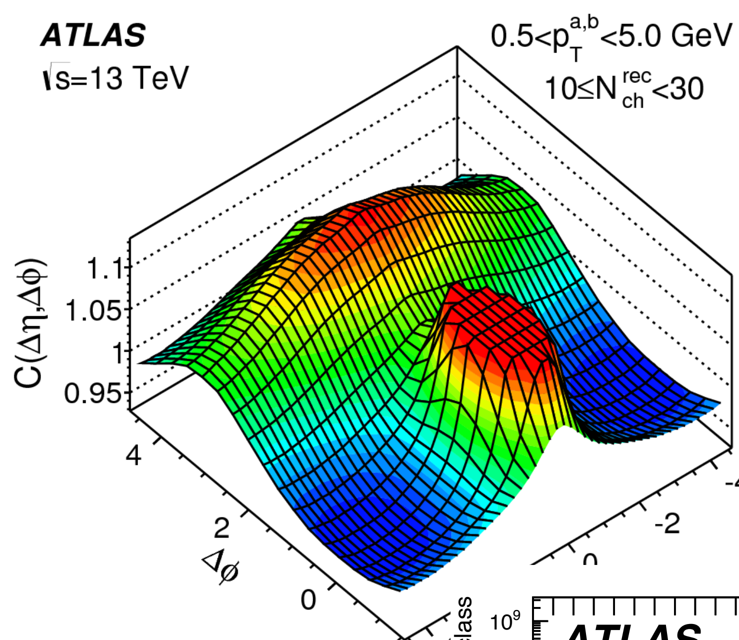
Entries / GeV
×10³
Data
MC Stat. ⊕ Syst. Unc.
Z→e⁺e⁻
Diboson
Z→τ⁺τ⁻
Top quarks
Z→e⁺e⁻
ATLAS
13 TeV, 81 pb⁻¹
Data / Pred.
m_ee [GeV]



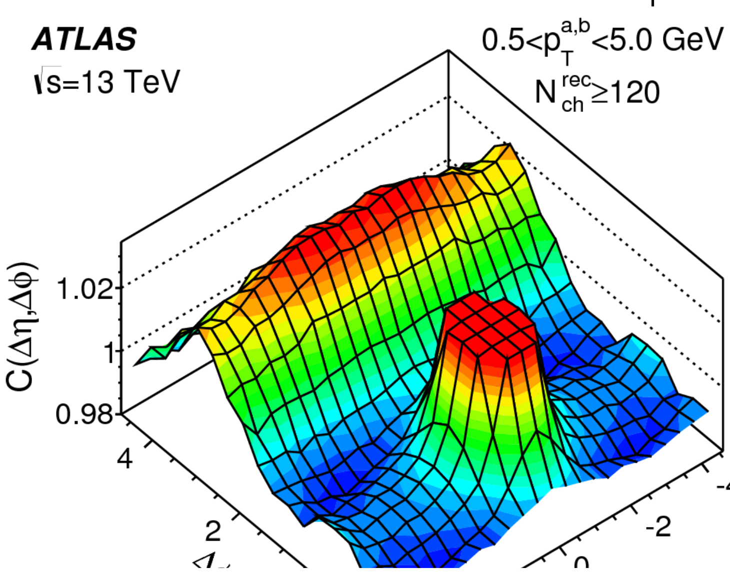
d²σ/dp_T dy [pb/GeV]
anti-k_t jets, R=0.4
∫ L dt=37 pb⁻¹, √s=7 TeV
|y| < 0.3 (× 10¹²)
0.3 ≤ |y| < 0.8 (× 10⁹)
0.8 ≤ |y| < 1.2 (× 10⁶)
1.2 ≤ |y| < 2.1 (× 10³)
2.1 ≤ |y| < 2.8 (× 10⁰)
2.8 ≤ |y| < 3.6 (× 10⁻³)
3.6 ≤ |y| < 4.4 (× 10⁻⁶)
Systematic uncertainties
NLOJET++ (CT10, μ=p_T^max) × Non-pert. corr.
ATLAS
p_T [GeV]



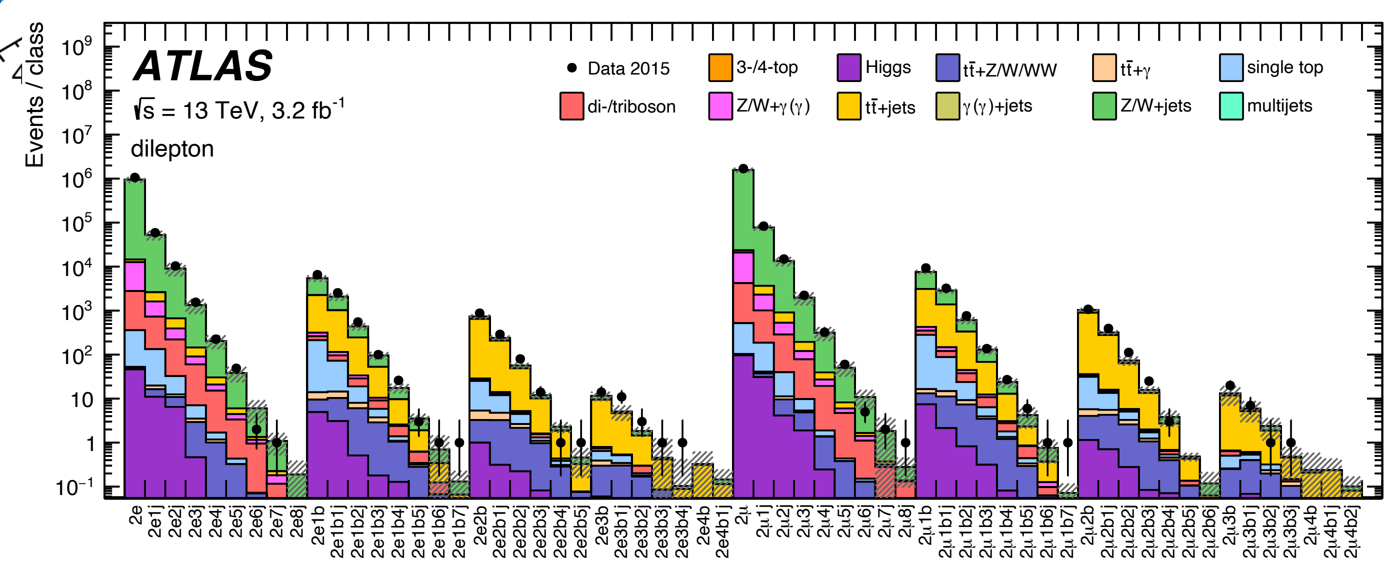
σ(Z/γ* + N_jets) [pb]
ATLAS
13 TeV, 3.16 fb⁻¹
anti-k_t jets, R = 0.4
p_T^jet > 30 GeV, |y^jet| < 2.5
Z/γ*(→ l⁺l⁻) + jets
Combined result
Electron channel
Muon channel
(e,μ) / Comb
N_jets



ATLAS
√s=13 TeV
0.5<p_T^a,b<5.0 GeV
10≤N_ch^rec<30
C(Δη,Δφ)
Δφ



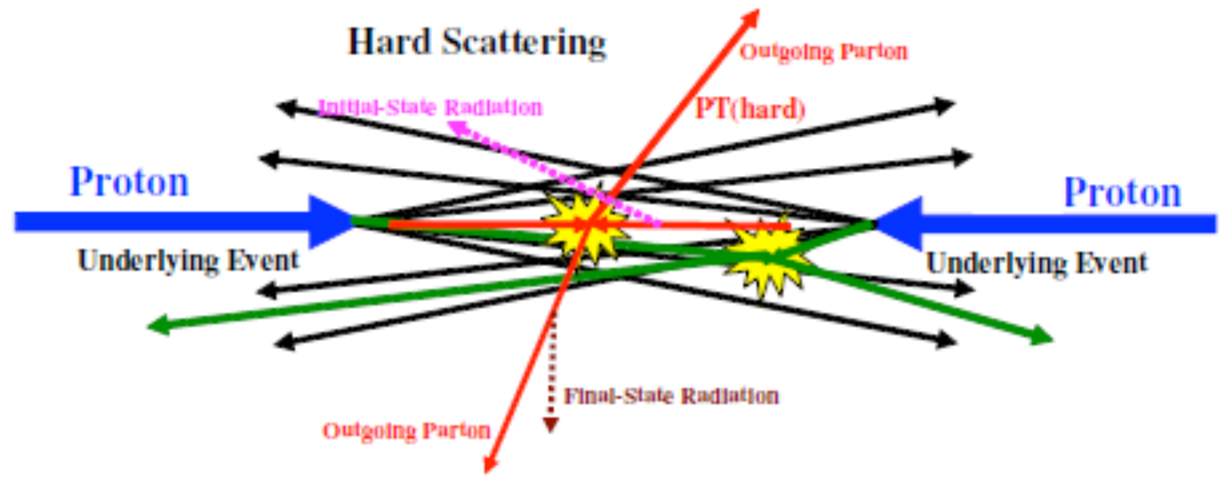
ATLAS
√s=13 TeV
0.5<p_T^a,b<5.0 GeV
N_ch^rec≥120
C(Δη,Δφ)



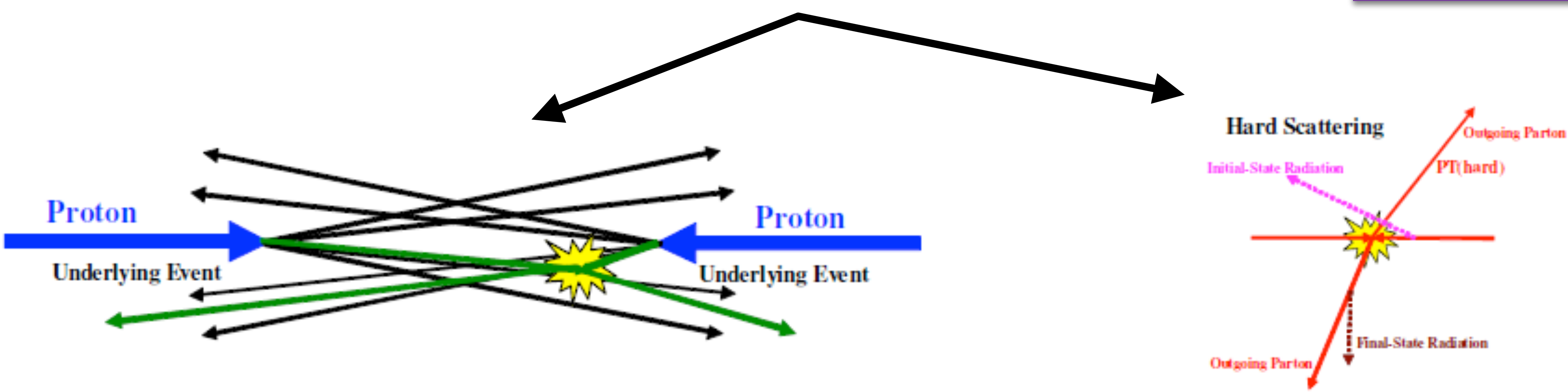
ATLAS
√s = 13 TeV, 3.2 fb⁻¹
dilepton
Events / class
Data 2015
3-/4-top
Higgs
tt̄+Z/W/WW
tt̄+γ
single top
di-/triboson
Z/W+γ(γ)
tt̄+jets
γ(γ)+jets
Z/W+jets
multijets

Example Measurement!

Components



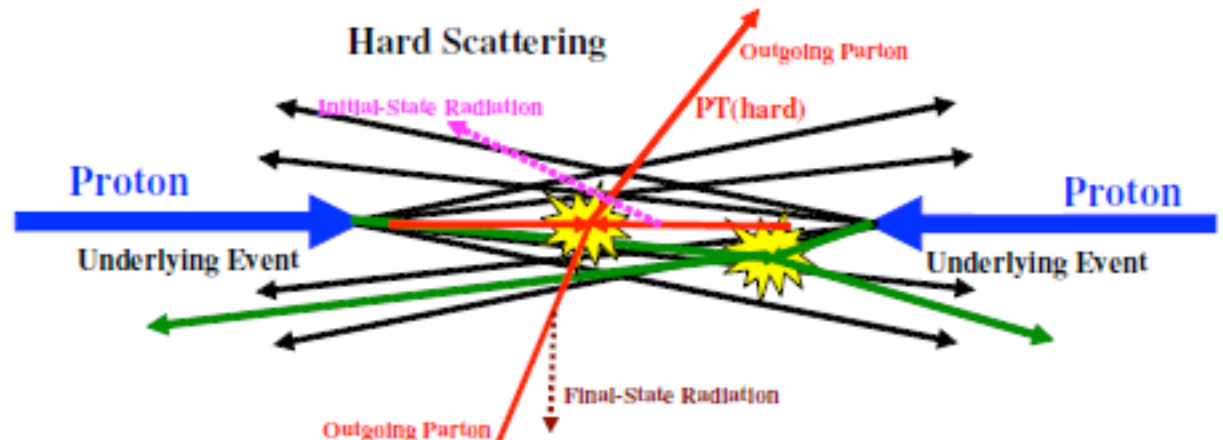
How many MPIs? No limit, but the xs falls off…

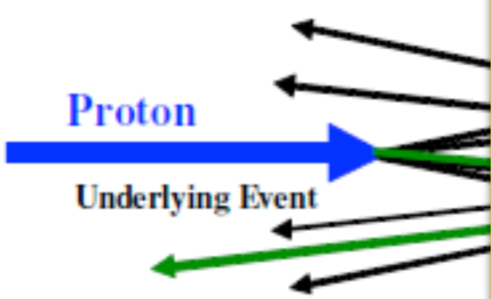


Underlying event (UE) = BBR+ MPI+ (ISR+FSR)

BBR: Beam-beam remnants
MPI: Multiple Parton interactions
ISR/FSR: Initial/Final state radiation

Components





Plus fragmentation and hadronisation (free quarks can not exist in nature!)

Underl ... R+FSR)

BBR: Beam-beam remnants
MPI: Multiple Parton interactions
ISR/FSR: Initial/Final state radiation

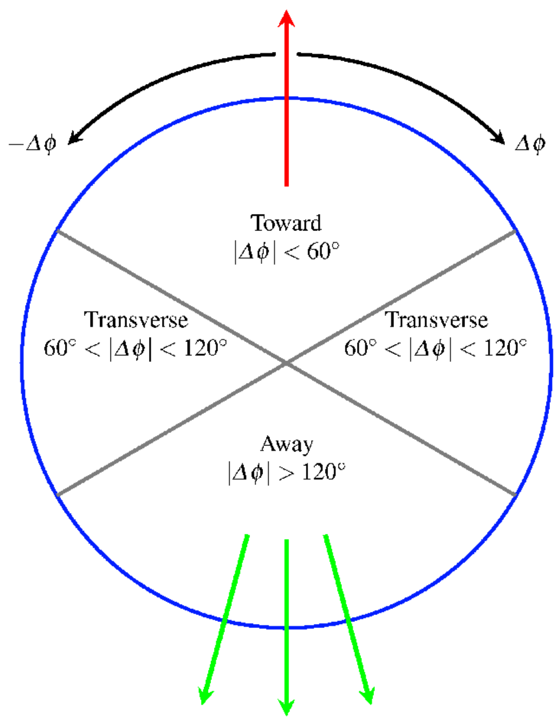
Underlying event

Minimum Bias (MB)

- Pretty much everything, exact definition trigger dependent.
- Large fraction of inelastic cross-section, proportional to natural production rate.
- Characterised by very few high p_T objects
- Not the same as UE or PU!

Measurement of UE

Leading jet or Z boson



Observable	Definition
p_T^Z	Transverse momentum of the Z-boson
$N_{ch}/\delta\eta\,\delta\phi$	Number of stable charged particles per unit η–ϕ
$\Sigma p_T/\delta\eta\,\delta\phi$	Scalar p_T sum of stable charged particles per unit η–ϕ
Mean p_T	Average p_T of stable charged particles

Jet or single lepton trigger.

Leading jet with $p_T > 25$ GeV or reconstructed Z-boson from oppositely charged lepton pairs with $p_T > 20$ GeV. Z mass window.

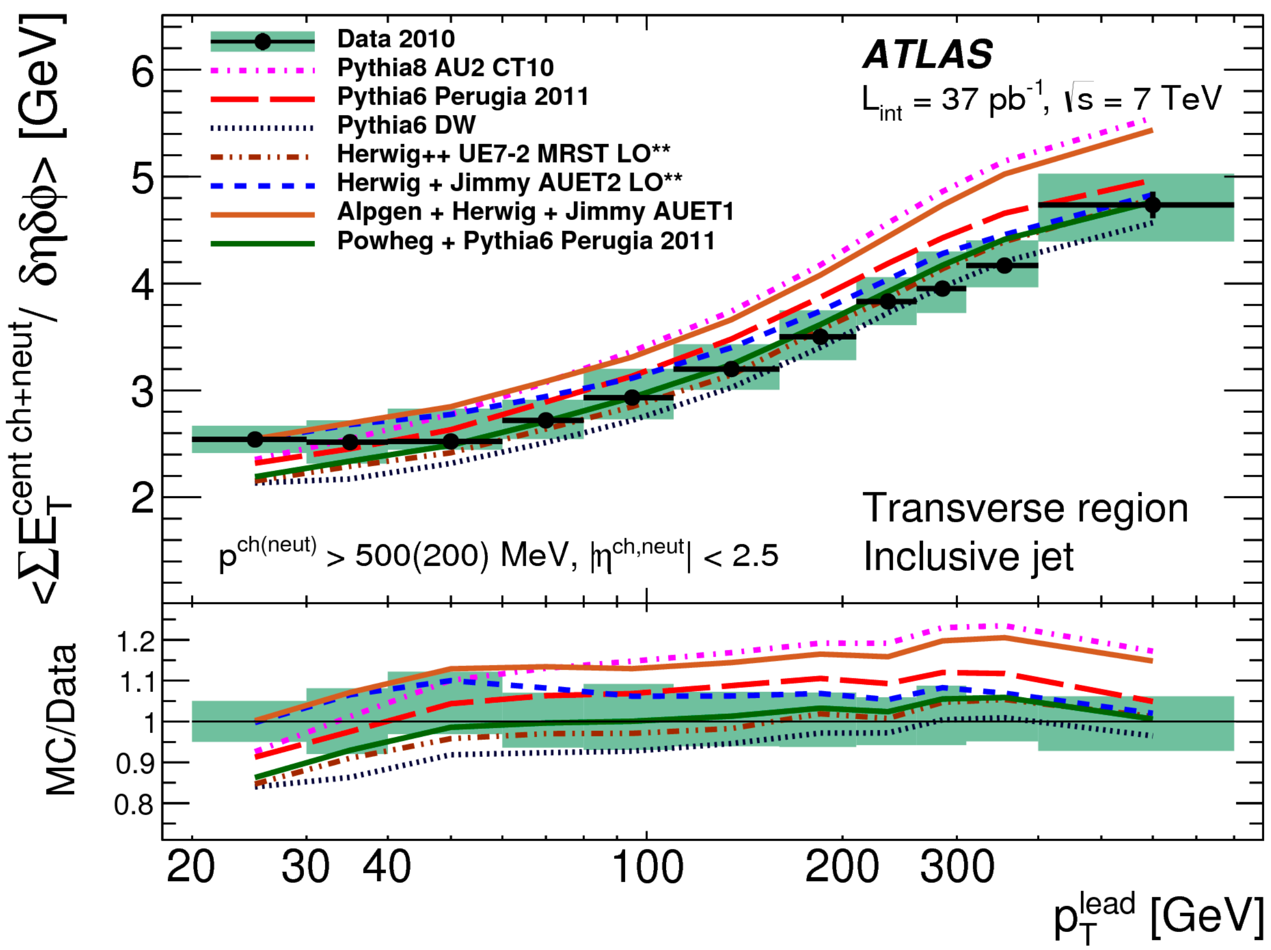
Tracks with $p_T > 0.5$ GeV.

Negligible background.

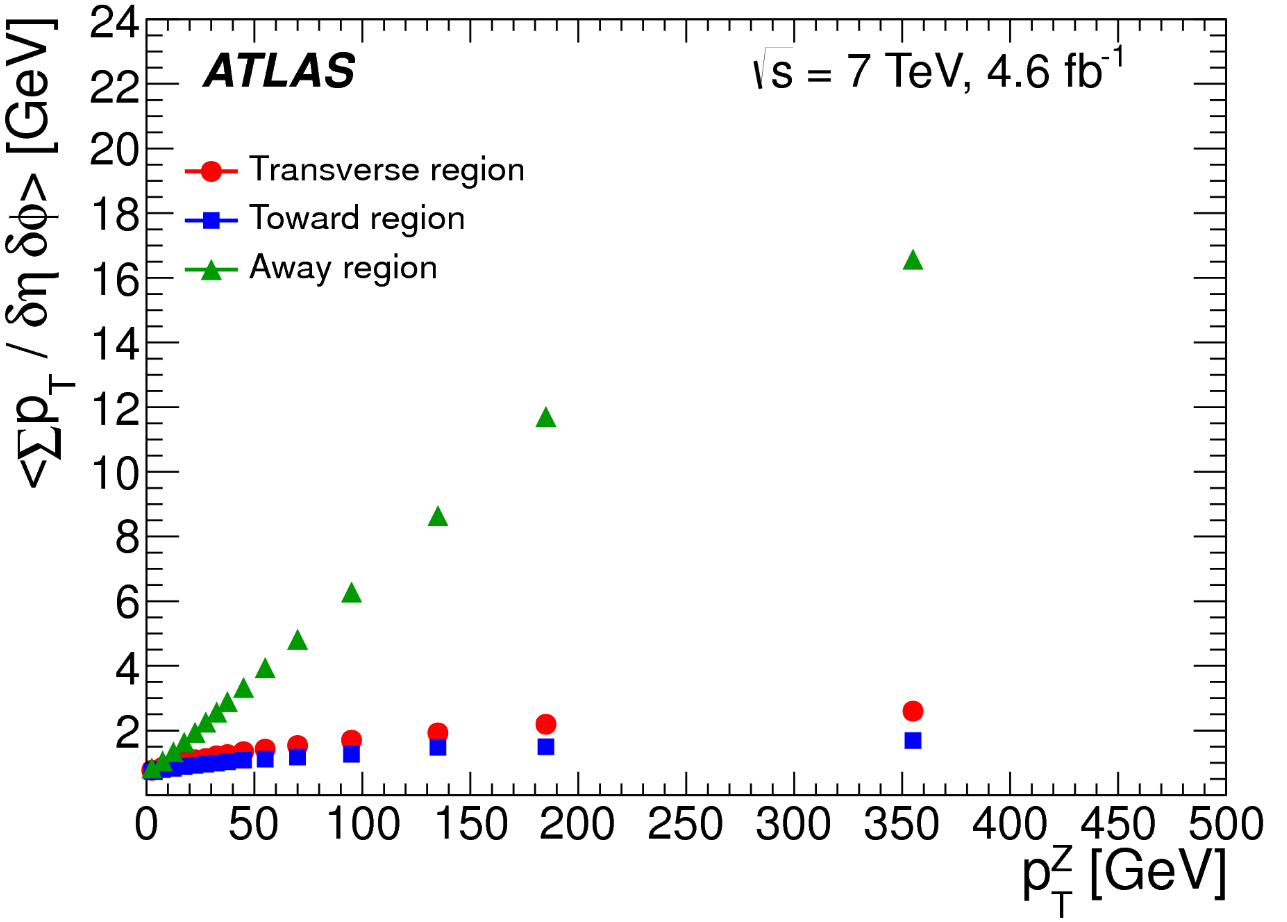
Detector level distributions unfolded to particle level.

Largest uncertainty from track reconstruction efficiency and unfolding.

Results

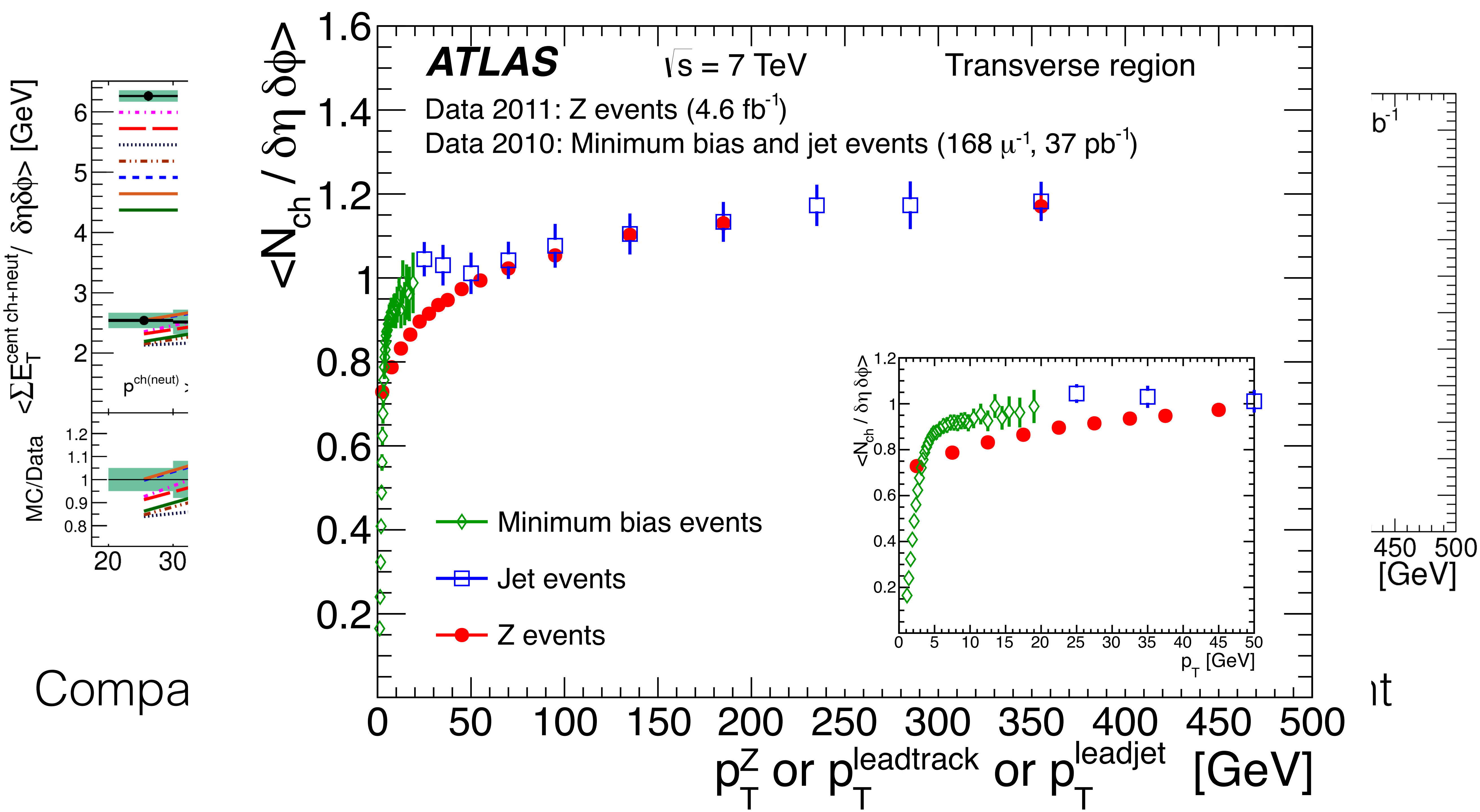


Comparison of model predictions with data



Comparison of different Regions

Results



Compa ... nt

Example Search!

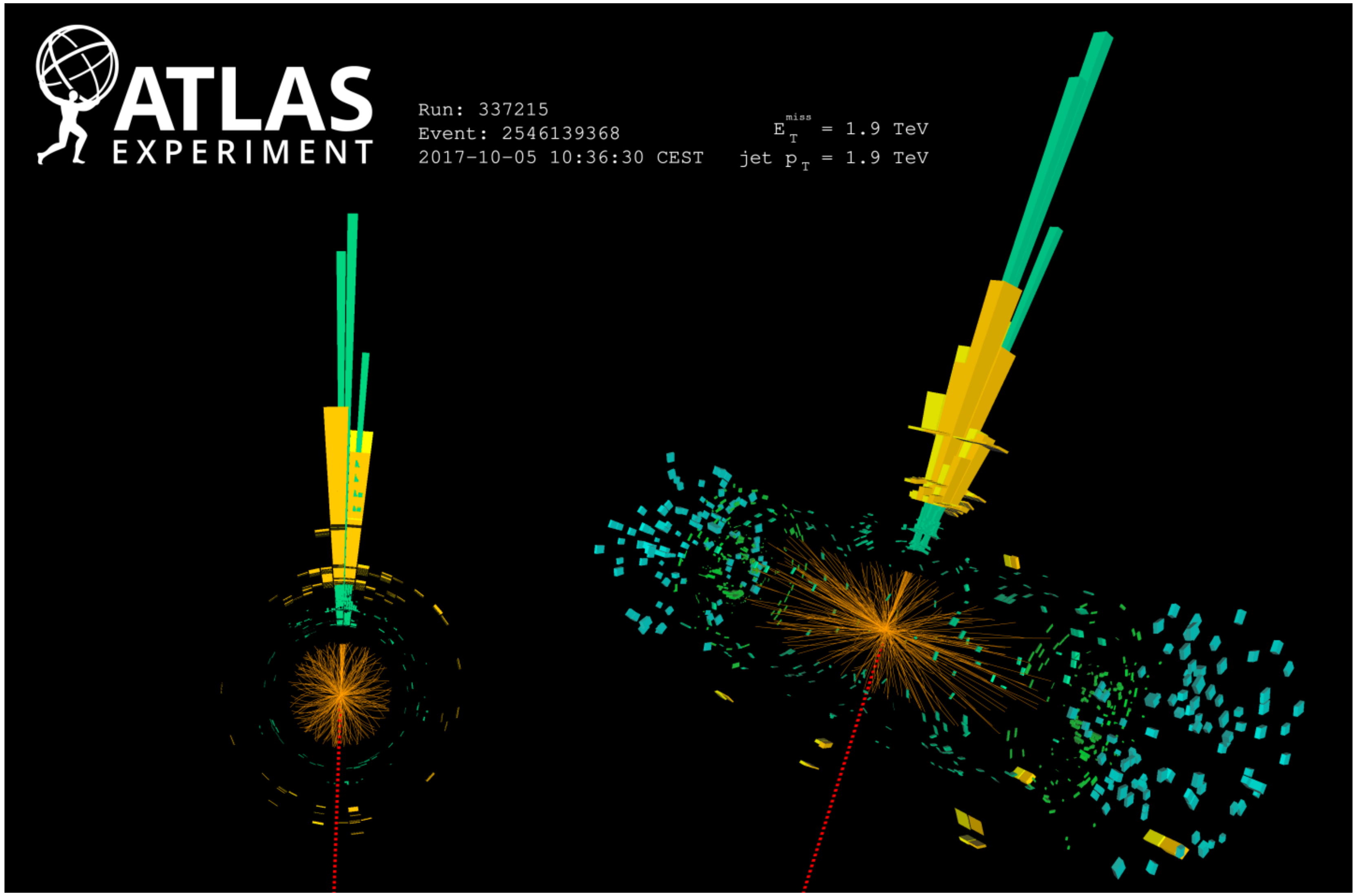
Semi-visible jets Se

Why this is novel?

So far, almost all dark matter searches in colliders are for WIMPs

So called mono-X signatures, X being any SM particle or object.

Large MET on one side!

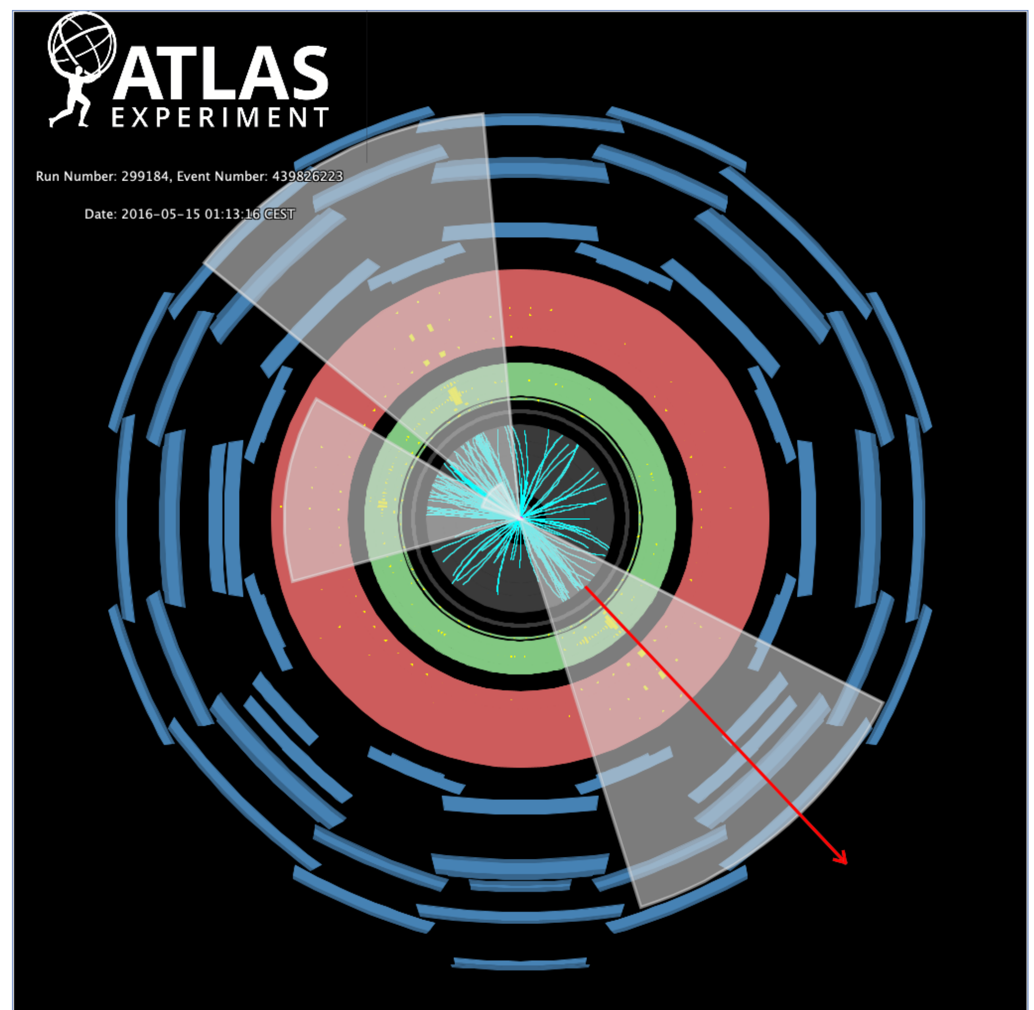


Semi-visible jets Se

Why this is novel?

So far, almost all dark matter searches in colliders are for WIMPs

We are looking for SIMPs, where the dark sector is considered A replica of QCD

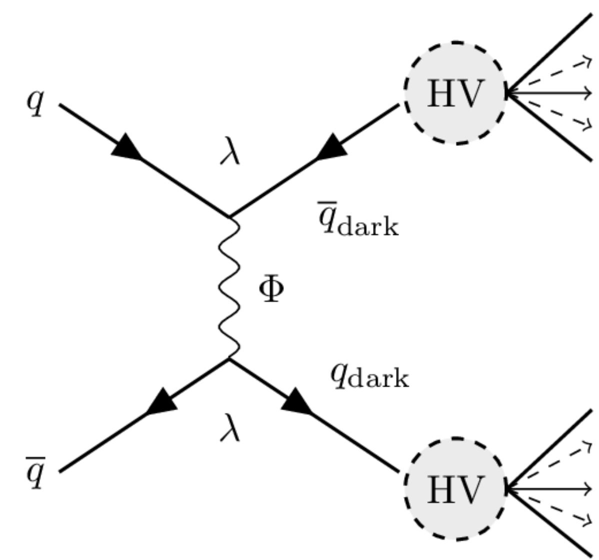


Semi-visible jets Search

Strongly interacting dark sector: bifundamental mediator acts as a portal!

Ratio of the rate of stable dark hadrons over the total number of hadrons in the event is termed R_{inv}

Simulated in Pythia Hidden Valley Module



Results in jets interpersed with dark hadrons, with missing transverse momentum direction aligned with one of the SVJs in leading order. Not so for events with extra jets and large boost.

Events with two central jets, MET trigger, leading jet $p_T > 250$ GeV, $H_T > 600$ GeV, MET 600 > GeV, jet closest to MET with $\Delta\Phi<2$

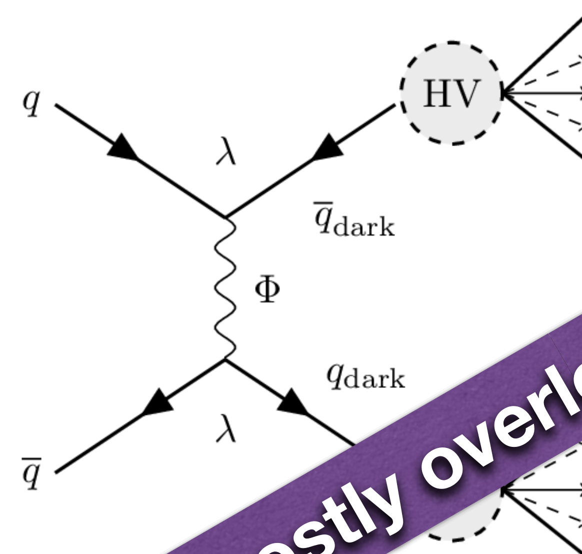
Define: SR (muon veto), and three CRs, 1L, 1L1B, 2L (with muons and b-tagged jets)

Semi-visible jets Search

Strongly interacting dark sector: bifundamental mediator acts as a portal!

Ratio of the rate of stable dark hadrons over the total number of hadrons in the [illegible] is term[illegible] r_{inv}

Si[illegible]ated in Pythia Hidden Valley Module



Results in je[illegible] interperse[illegible] dark hadro[illegible] missing tr[illegible]rse momentum [illegible]ection aligned with one of the SVJs in leading order. Not so for events with extra jets and large boost.

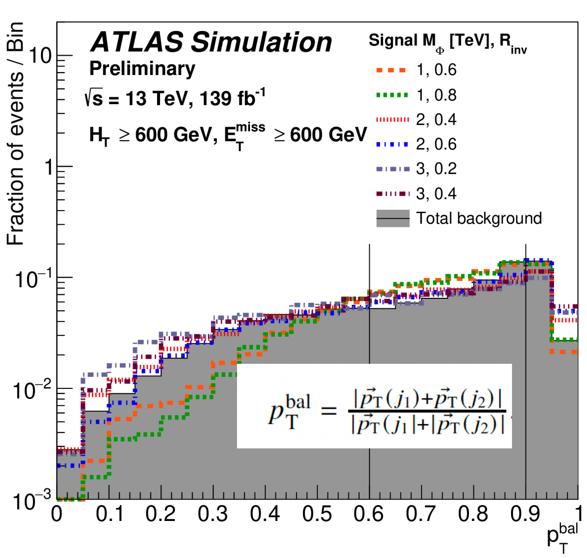
Unique collider topology - mostly overlooked in searches!

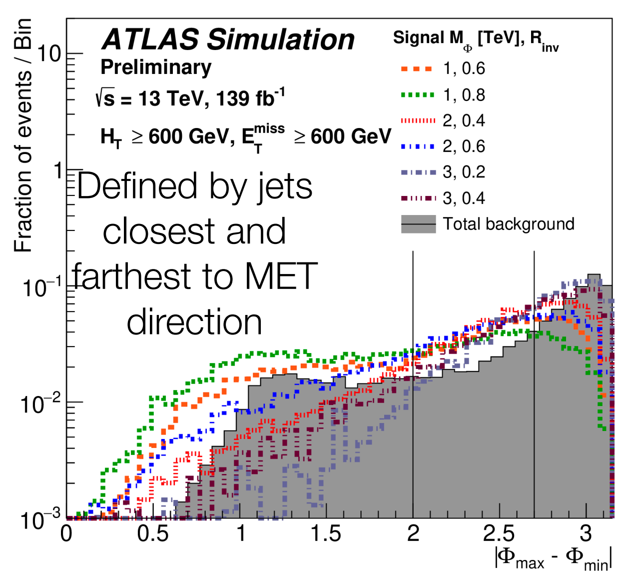
Events with two central jets, MET trigger, leading jet p_T > 250 GeV, H_T > 600 GeV, MET 600 > GeV, jet closest to MET with $\Delta\Phi$<2

Define: SR (muon veto), and three CRs, 1L, 1L1B, 2L (with muons and b-tagged jets)

Background Estimate

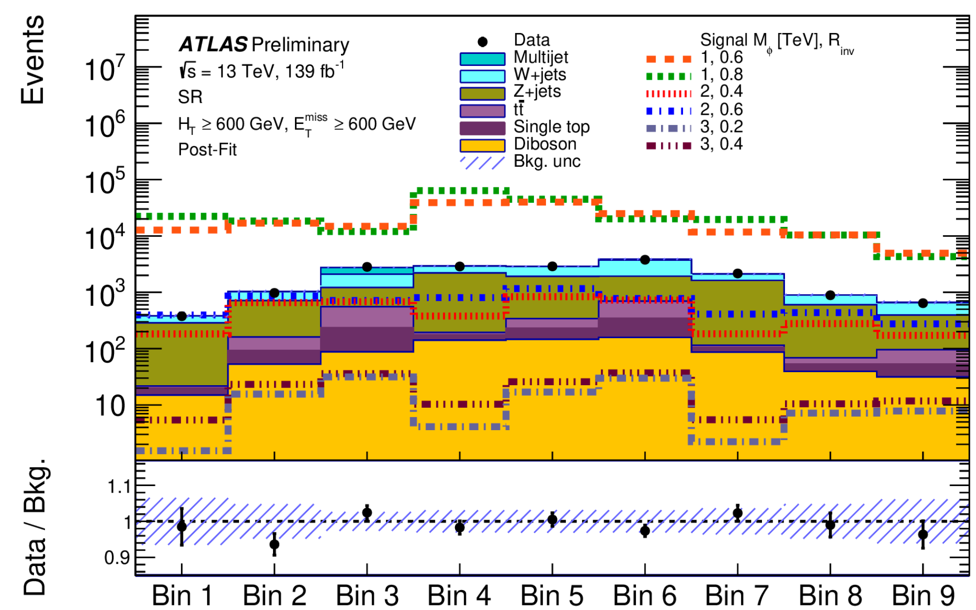
Two sensitive observables:





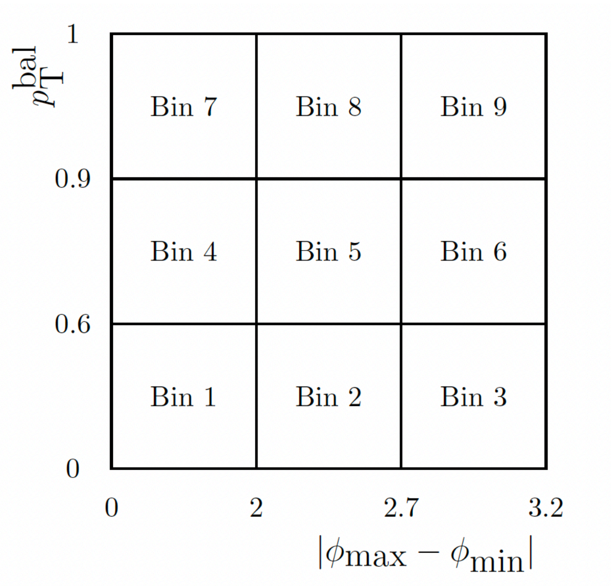
Defined by jets closest and farthest to MET direction

Partially data-driven method, simultaneously fit SR and three CRs to obtain scale factors for each bg process:



Process	k^{SF}
Z+jets	1.18 ± 0.05
W+jets	1.09 ± 0.04
Top processes	0.64 ± 0.04
Multijet	1.10 ± 0.04

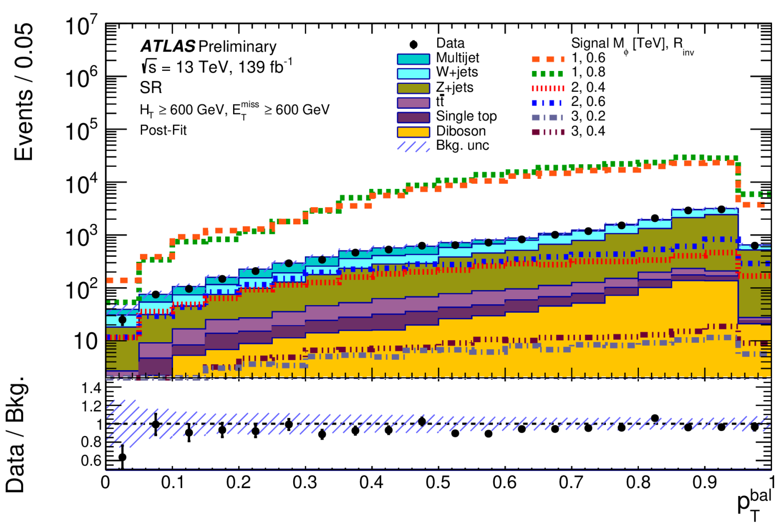
Used to Form a 9-bin grid, with yields in each bin treated as observables:

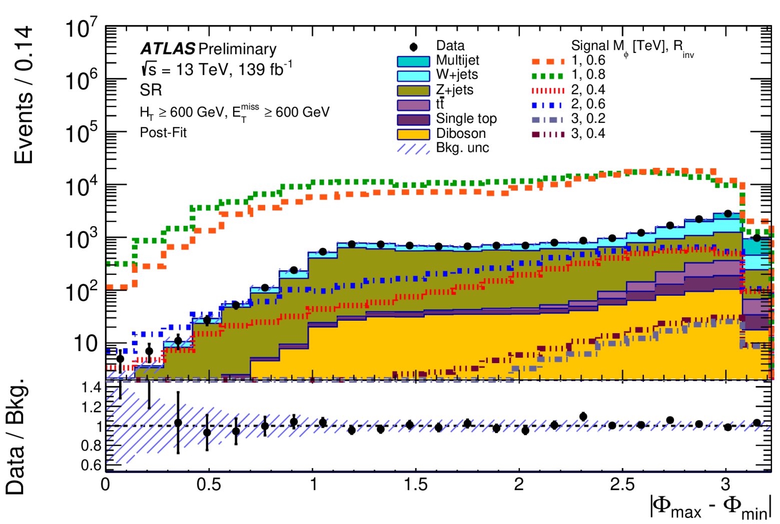


Absence of signal, good post-fit agreement :(

Multijet reweighed in using a dedicated VR given by MET within 250 to 300 GeV, then fitted

Results

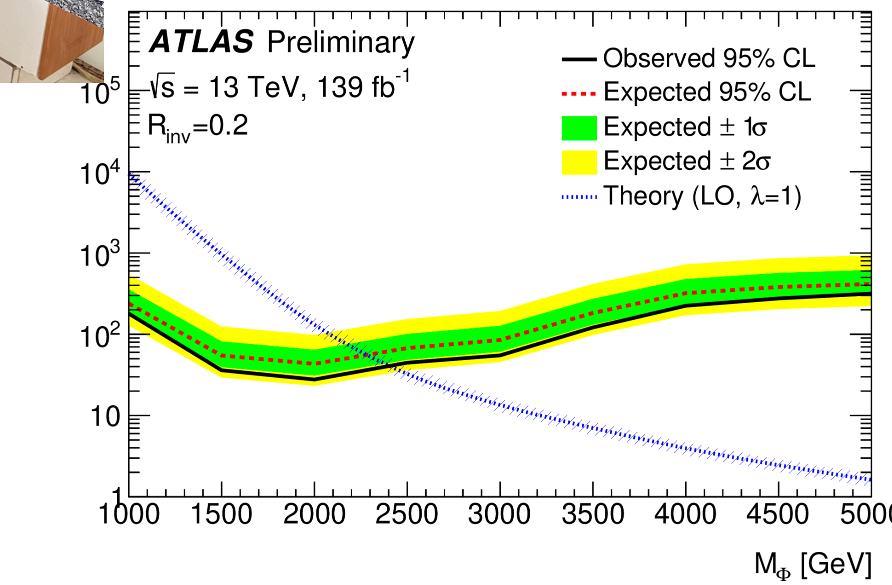


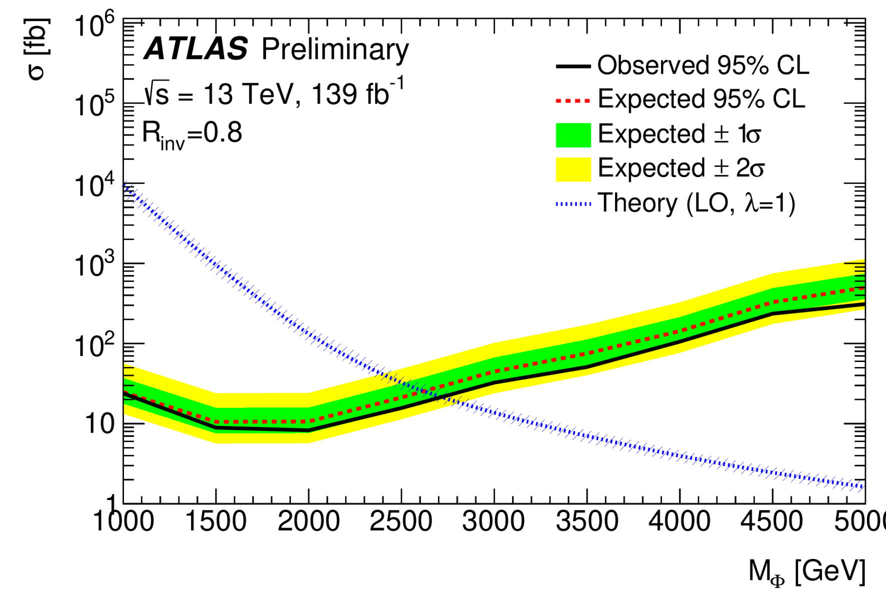


Excellent agreement between data and background prediction

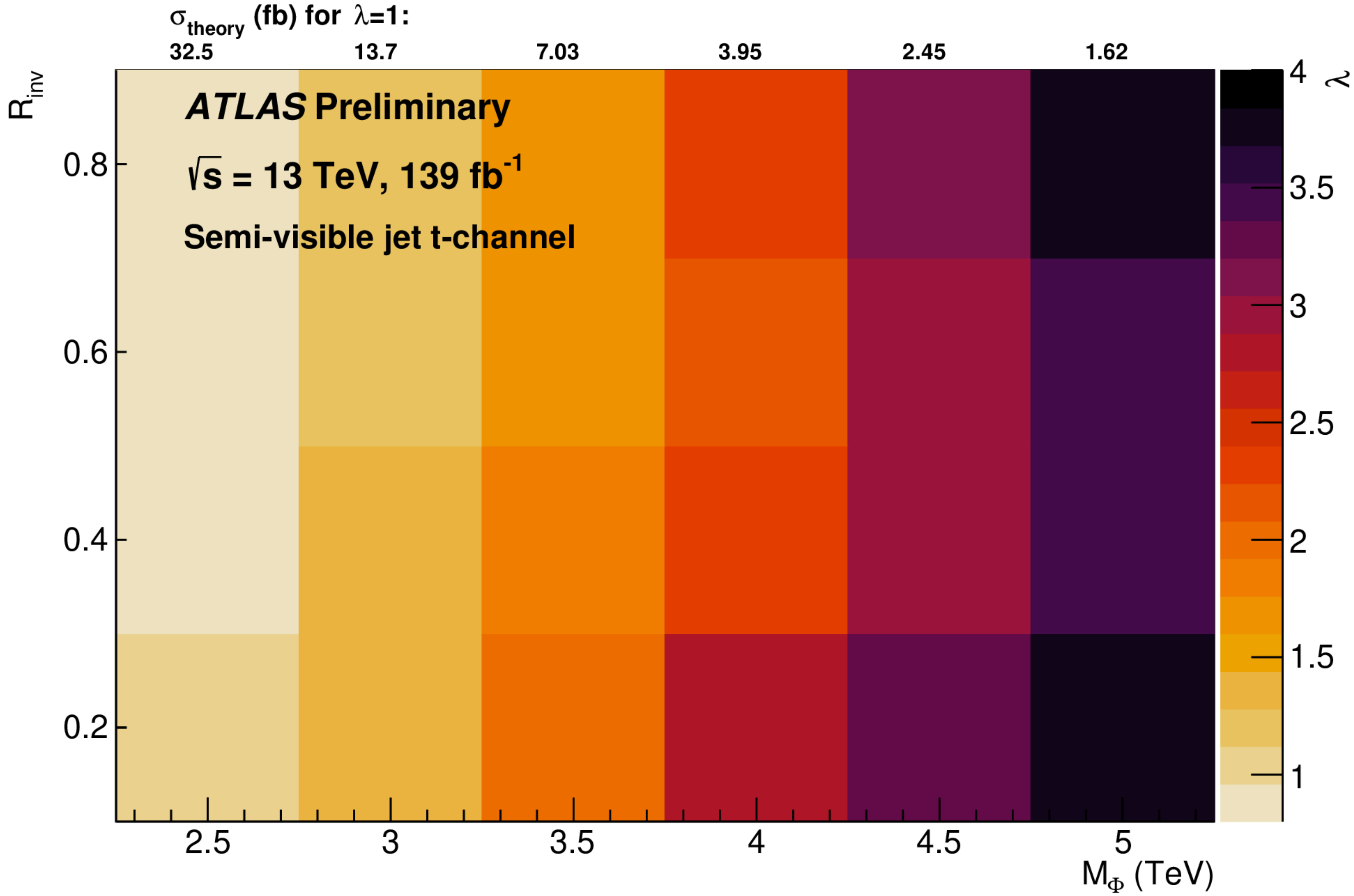
Limits on mediator mass separately for each $\boldsymbol{R}_{\text{inv}}$

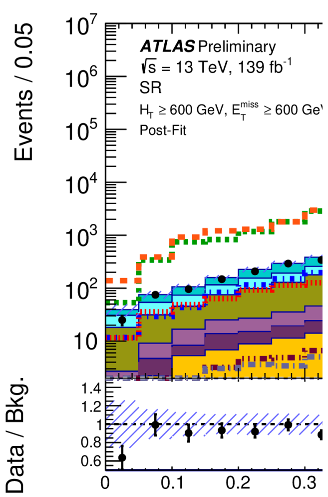
For mediator mass of 2.5 TeV or higher can also express the limits in terms of the q-q_d-ϕ vertex coupling strength λ, with the XS scaling as λ^4

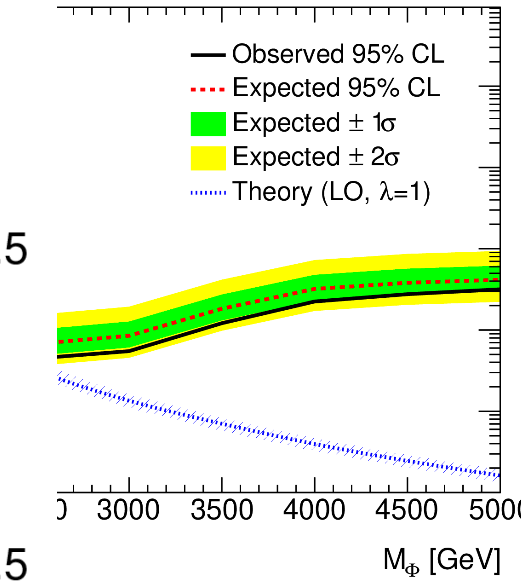


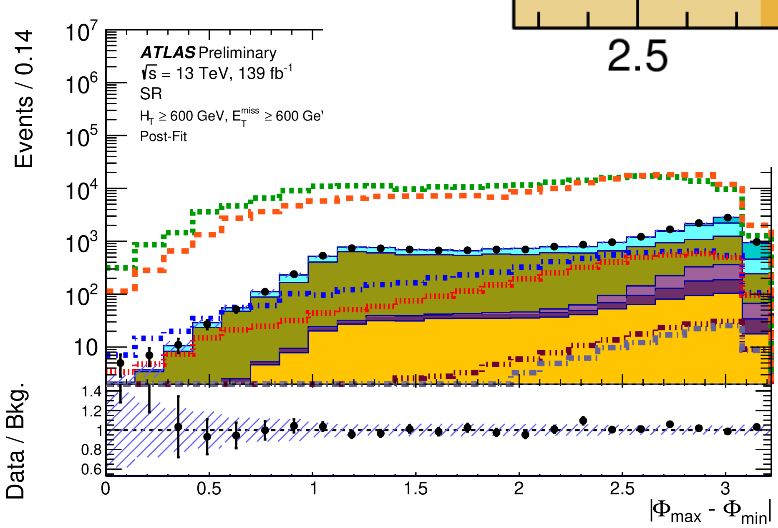


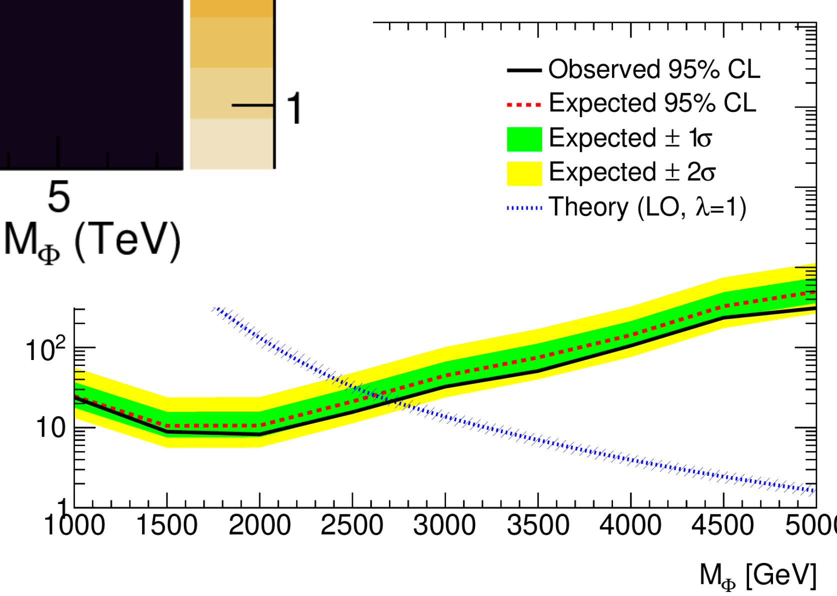
95% CL upper limits on λ





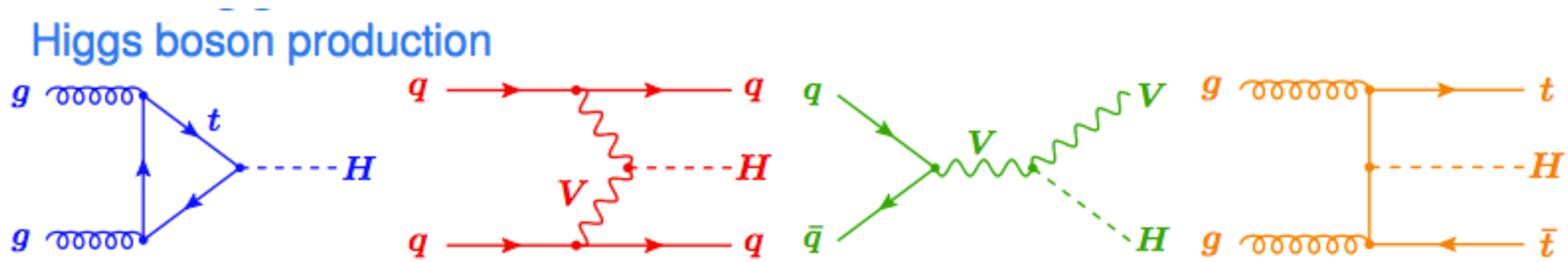






express the limits in terms of the q-q_d-ϕ vertex coupling strength λ, with the XS scaling as λ^4

Searches: Higgs at the LHC

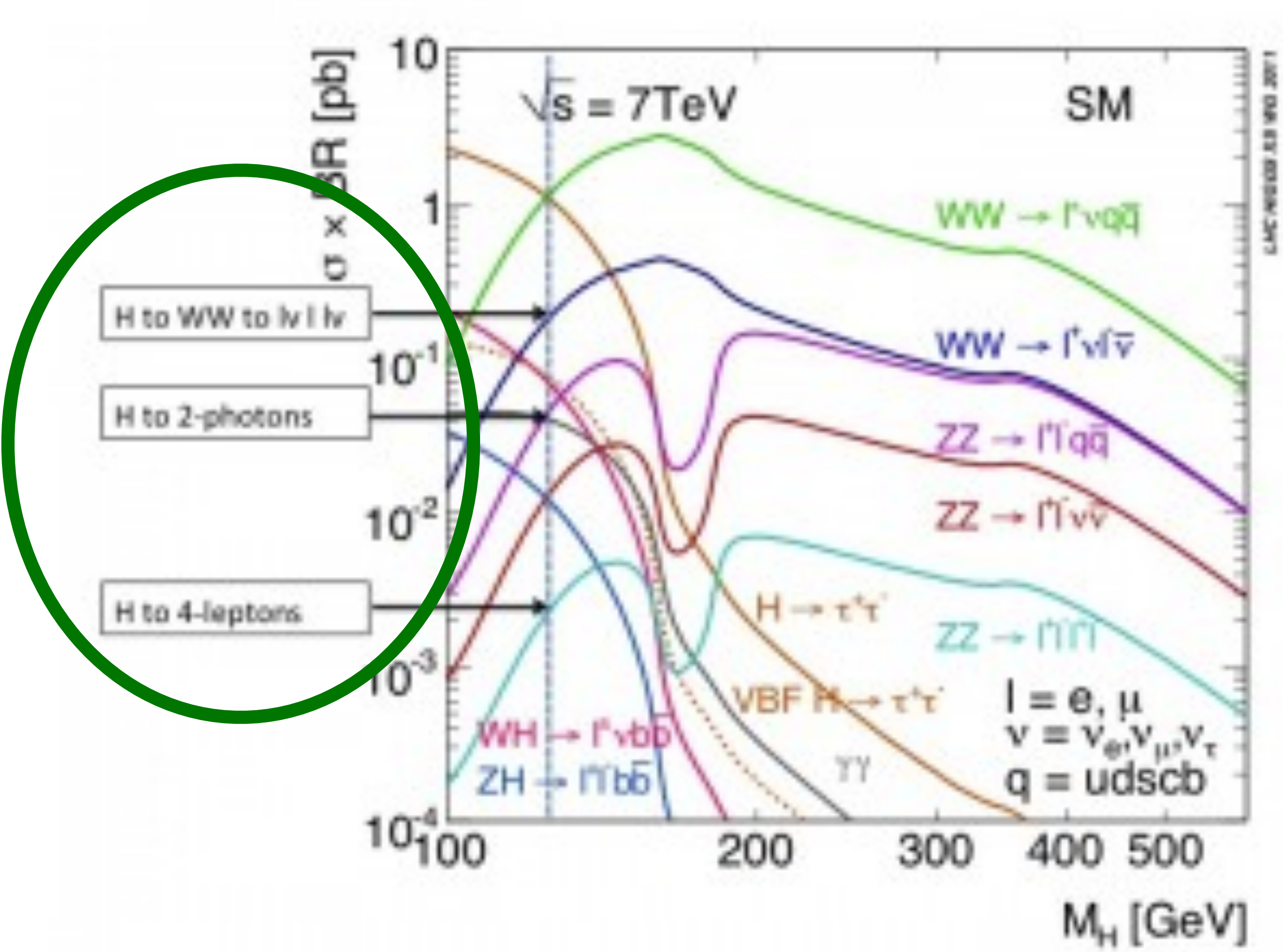


Main production channel

2 forward jets, little hadronic activity in between

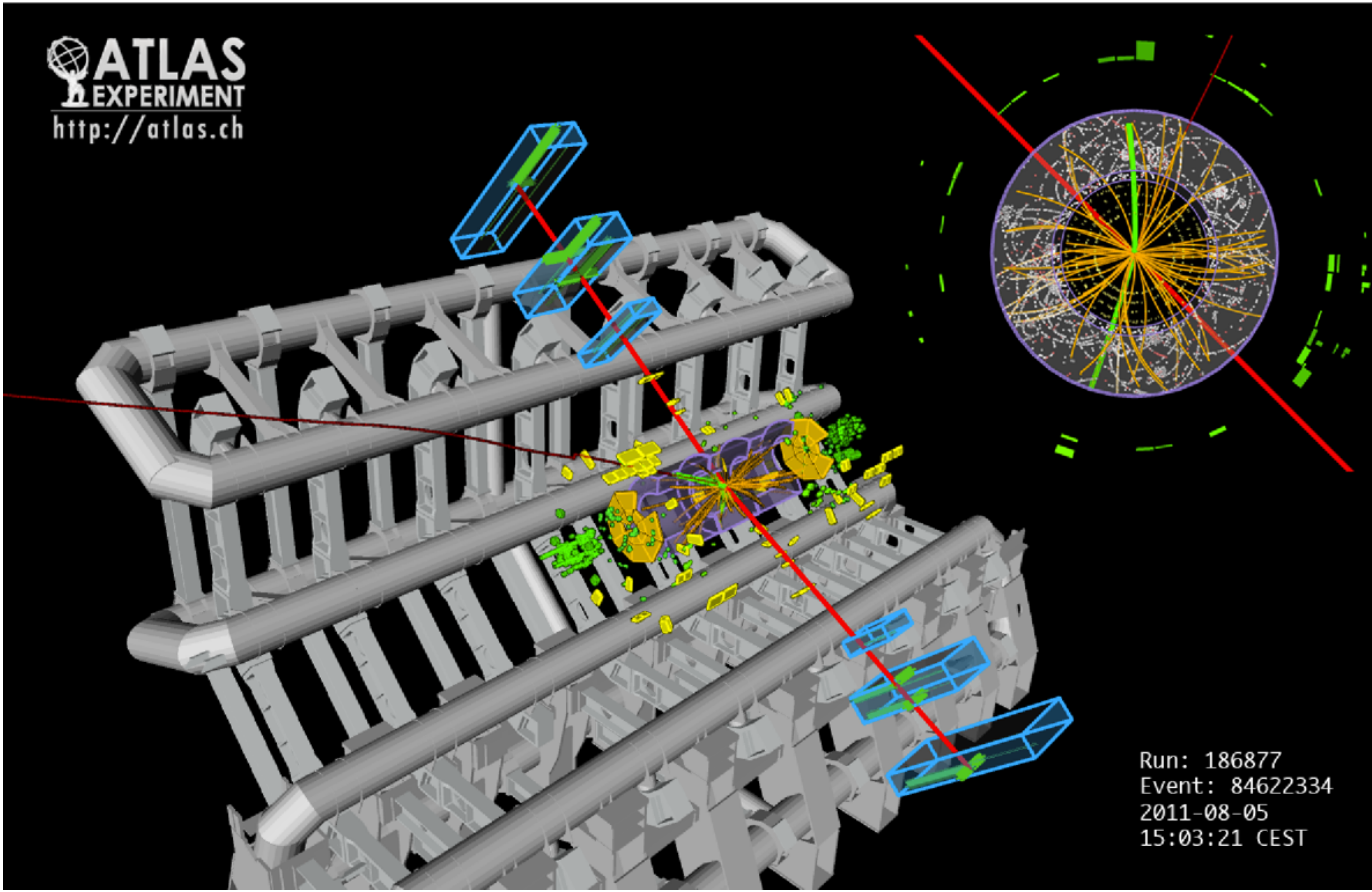
Tag *W* and *Z* leptonic and hadronic decays

Tag 2 top quarks



Final states with leptons or photons are easier to distinguish, measure.

Decays to jets are more difficult to separate from multijet background.


ATLAS
EXPERIMENT
http://atlas.ch
Run: 186877
Event: 84622334
2011-08-05
15:03:21 CEST

H->$\gamma\gamma$

Find two photons

Background:
(irreducible)
$\gamma\gamma$ by mass

(reducible)
γ-jet or jet-jet
using detector

Fitted by 4th order poly

H->ZZ->4l

Find four leptons

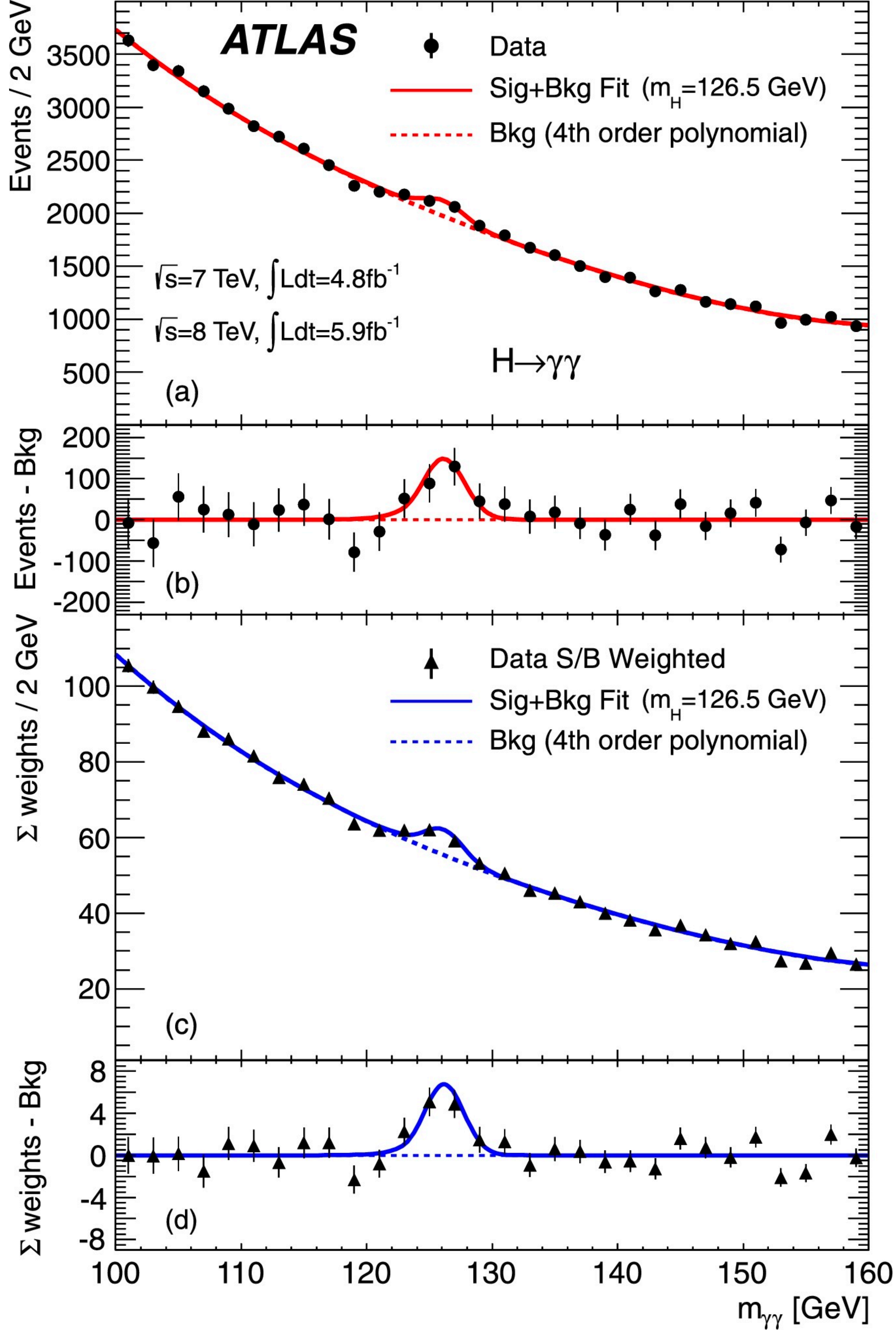
Background:
(irreducible)
ZZ by mass

(reducible)
Zbb or ttbar
by lepton isolation or b-tagging (for leptons from b decay)

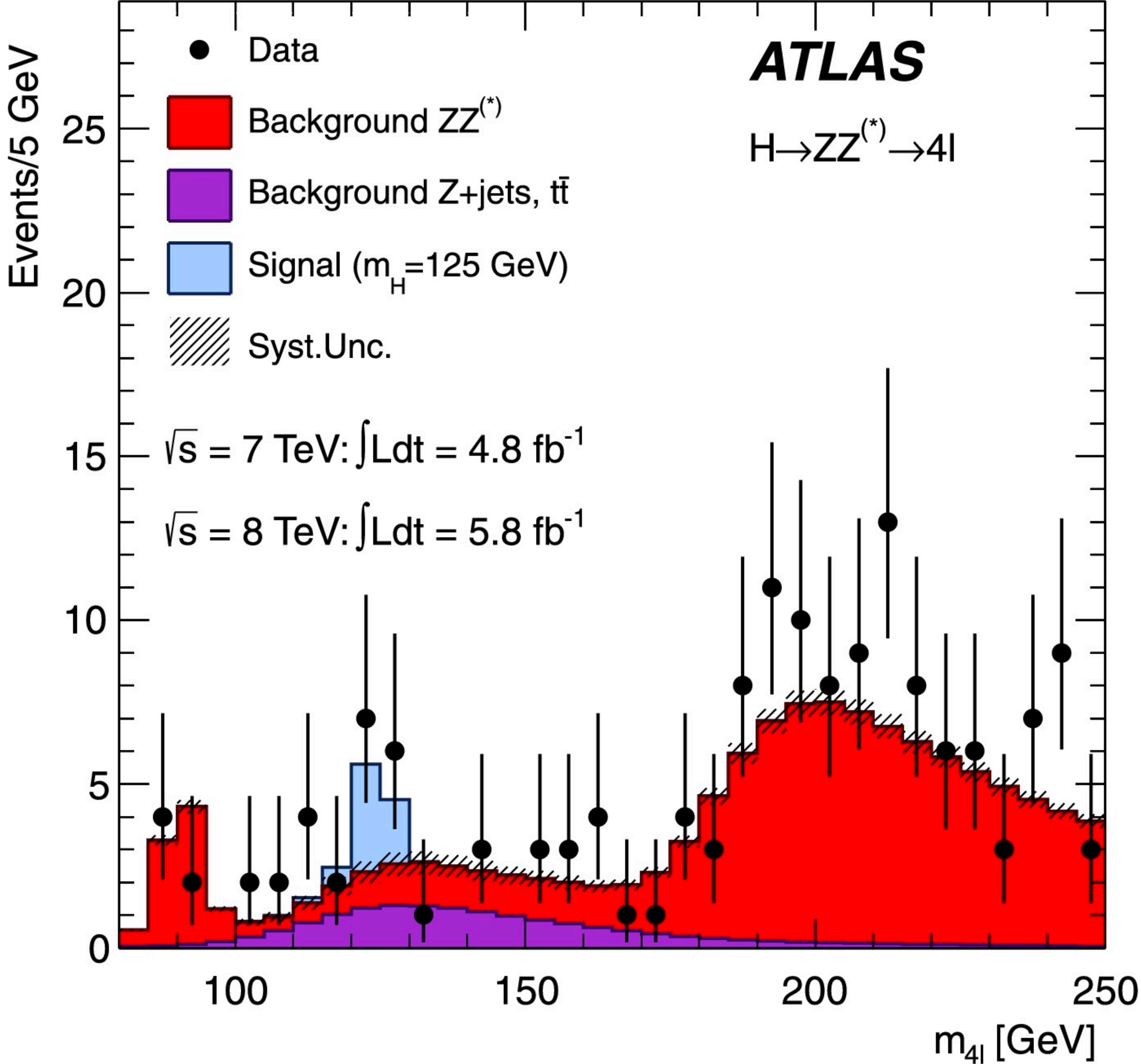
H->WW->2l2v

Find two leptons and missing energy

Background:
WW by mass
W+jets, Wt, ttbar by lepton angular correlation, jet veto



ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
√s=7 TeV, ∫Ldt=4.8fb-1
√s=8 TeV, ∫Ldt=5.9fb-1
H→γγ
Events / 2 GeV
(a)
Events - Bkg
(b)
Data S/B Weighted
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
Σ weights / 2 GeV
(c)
Σ weights - Bkg
(d)
m_γγ [GeV]



Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (mH=125 GeV)
Syst.Unc.
ATLAS
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Events/5 GeV
0
5
10
15
20
25
100
150
200
250
m4l [GeV]

How to confirm?

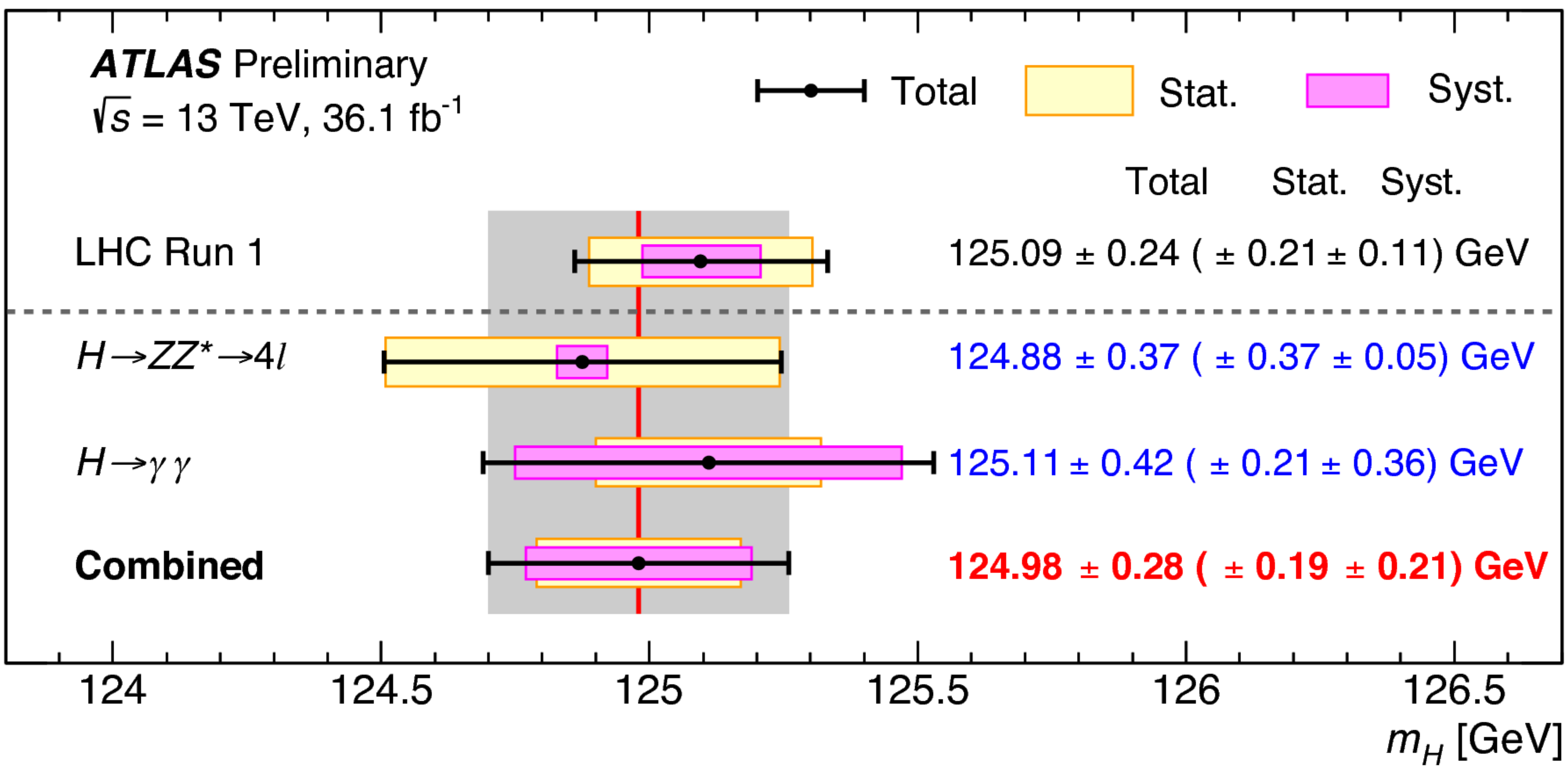
- Significant deviation from the background-only hypothesis: new peak in a mass-distribution or more events than expected in some kinematic distribution
- Significant: $N_S/\mathrm{sqrt}(N_B) > 5$ (of course not so simple, combine channels accounting for all systematics, and look elsewhere effect)

5 sigma: if the experiment was done 3.5 million times, only once the background fluctuation will result in the signal.

SM Higgs?

- Obvious question: how do we know it is the SM Higgs?
- Many extensions of the SM predict additional Higgs bosons (with one SM-like Higgs), rule out or find!
- Precisely measure the properties.

Mass measurements

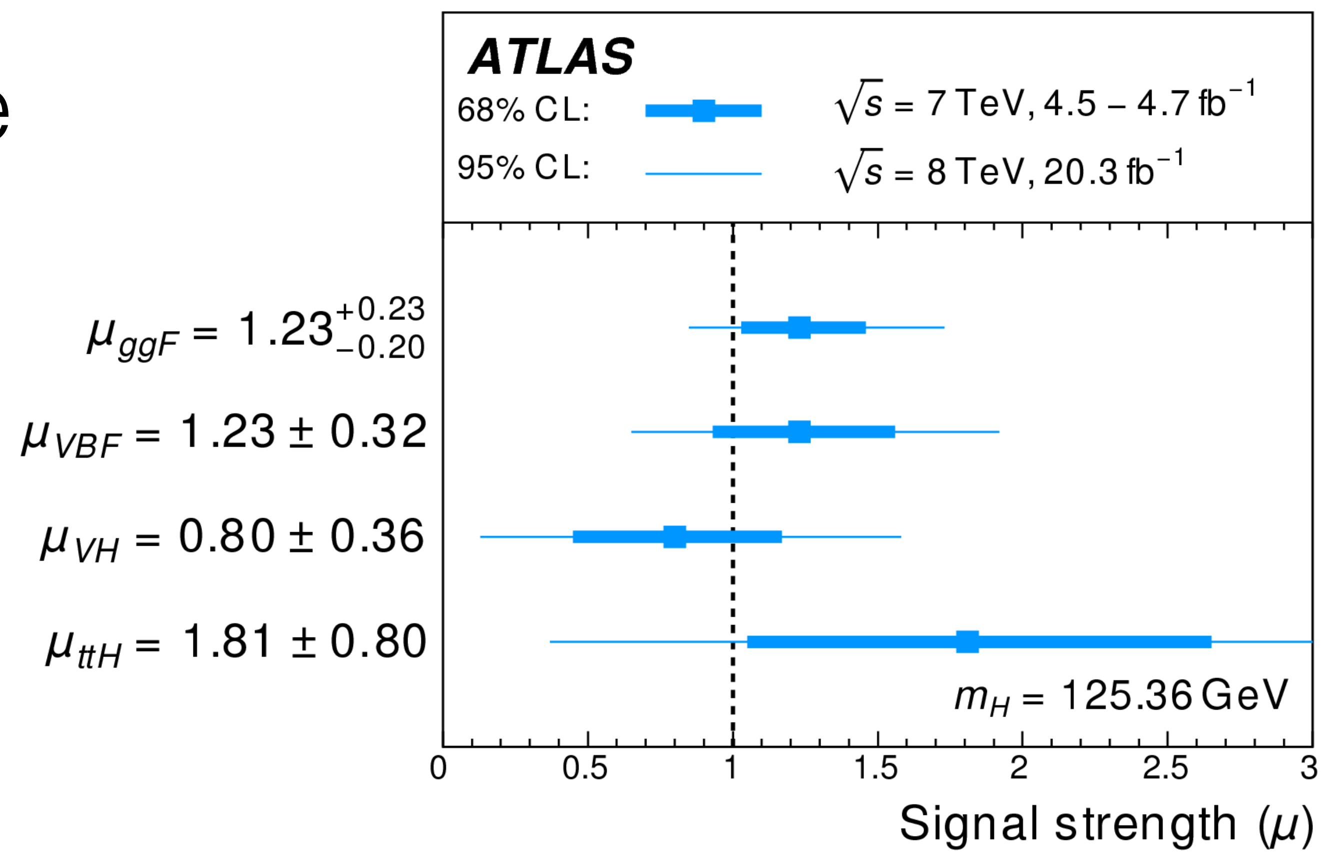


Measured in high resolution channels, $\boldsymbol{\gamma\gamma}$ and 4l

Signal strength

- Defined as **μ**: how many signal events were detected in all possible production and decay channels compared to the expectations in the Standard Model.

- Deviation from unity: interesting!



Also measured spin, couplings…

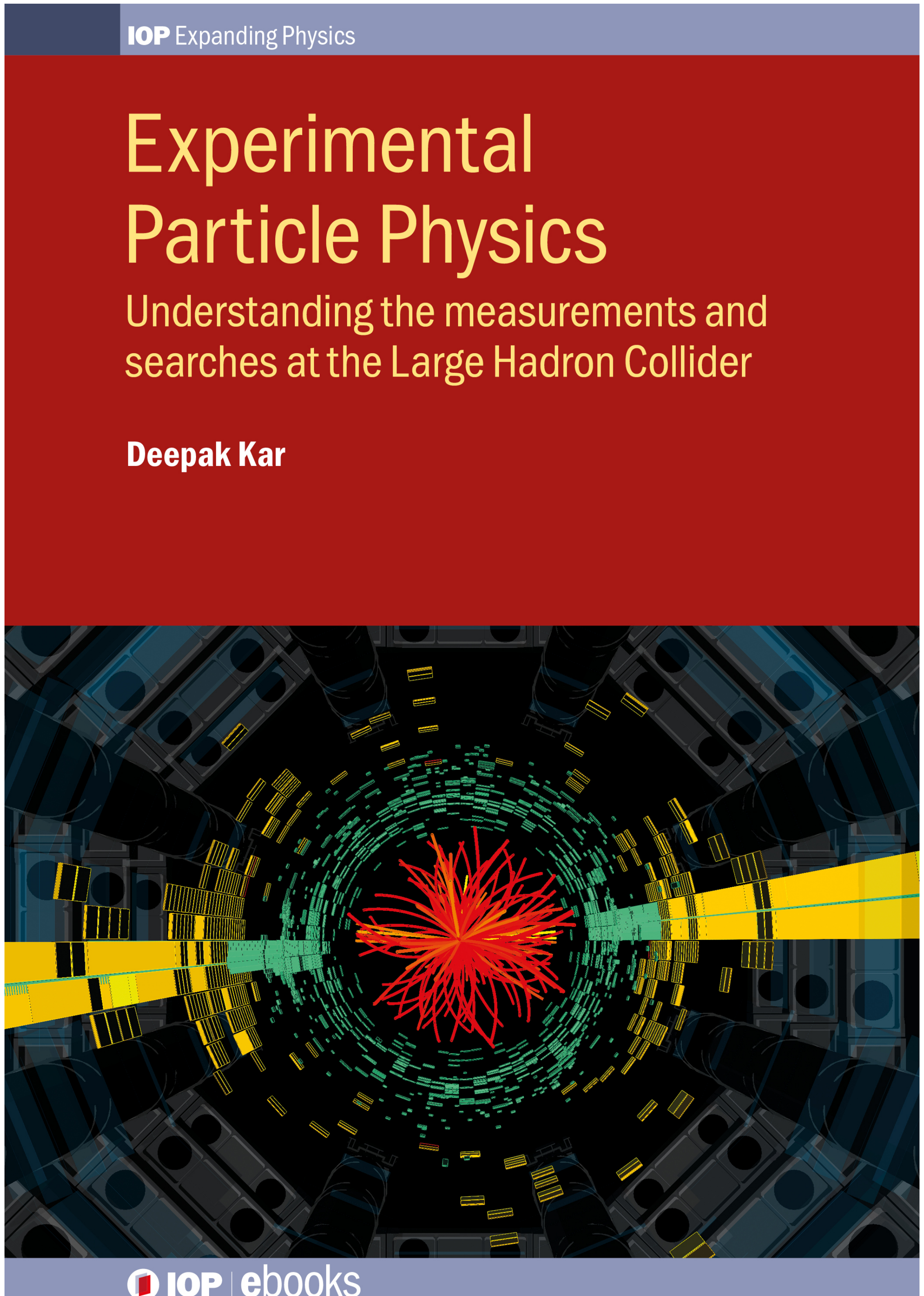
Top down view of the subject

NEW PREDICTIONS (10 years)

1. QCD tests & applications will greatly improve, incorporating NLO, NNLO,...and a theory of fragmentation and hadronization.
2. Atlas and CMS will discover a candidate Higgs particle.
3. There will be convincing evidence for Susy particles.
4. Plans will be underway to build a LC (at Cern) to explore the superworld and the US will join CERN.
5. There will be direct detection of the Dark Matter wind.
6. Alice will see a crossover to the perturbative quark-gluon plasma.
7. Some new Z mesons will be discovered.
8. Gravitational waves and B modes will be observed.
9. String theory will start to be a **theory** with predictions.
10. We will have a plausible explanation of why Λ is so small.

David Gross: EPS 2011

Want to learn more?



If you can’t access online, ask me ;-)

Want to work on these fascinating topics for your masters or PhD?

If you are from SA, you should have applied for NRF bursary

For our other African friends:

https://twas.org/opportunity/twas-nrf-doctoral-programme

https://owsd.net/career-development/phd-fellowship

A Non-Exhaustive List of References

- My book, duh!
- Andy’s excellent/complementary book
- UE Result: Eur. Phys. J. C (2014) 74:3195
- SVJ Result: ATLAS-CONF-2022-038

Fin.