Lund University
Faculty of Science

ATP common seminar
14 March 2012

Status of the LHC
and
Anatomy of LHC events

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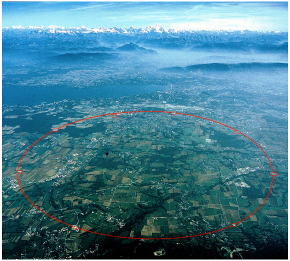
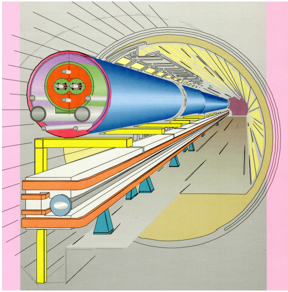
What is happening at CERN/LHC in general?
How is Lund theory involved and affected?

A Brief LHC History

- mid-70'ies: plans a new 27 km ring tunnel at CERN, with space for separate $e^{\pm}$ and p beams
- 1979–1989–2000 design/construction and running of the LEP $e^{\pm}$ machine, $E_{\rm cm}^{\rm max} = 209$ GeV limited by synchrotron radiation
- 1984: first LHC physics workshop
- 1990: full-scale studies begin; aim for start 1998
- 1995: LHC project approved
- 2000: civil engineering begins
- 1990–2008: drawn-out design & construction process

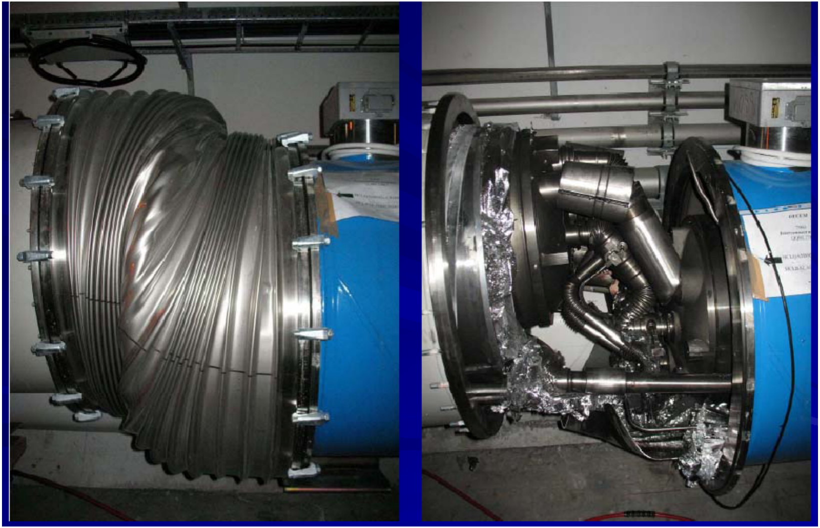




LHC Tunnel View

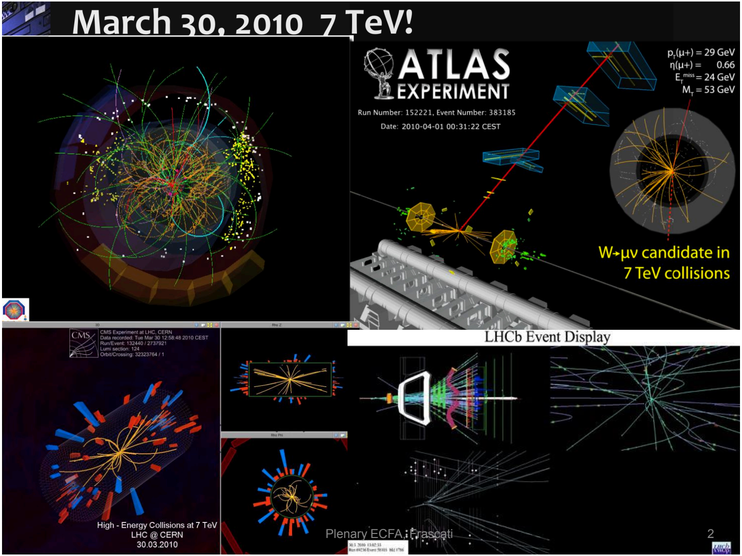
2008: machine and detectors ready to go – commissioning

The "Incident": 19 September 2008

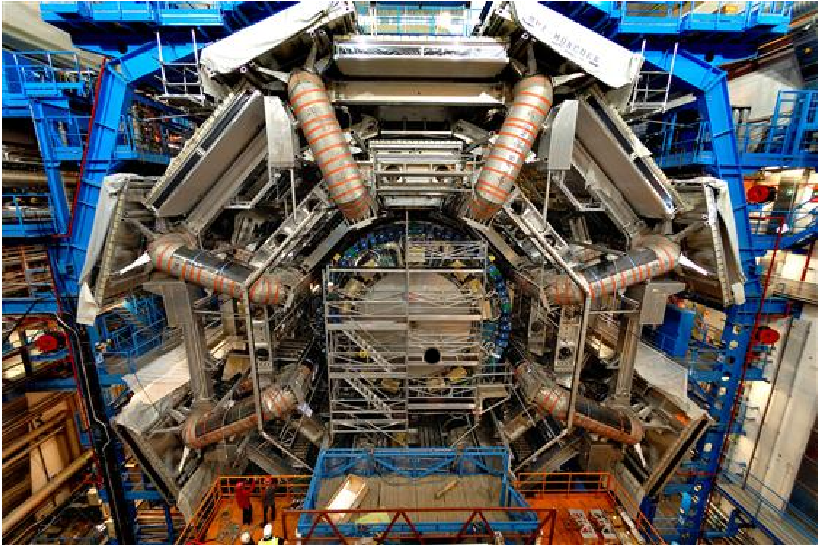


one year of repair work, start out at 900 GeV in November 2009

First 7 TeV Collisions

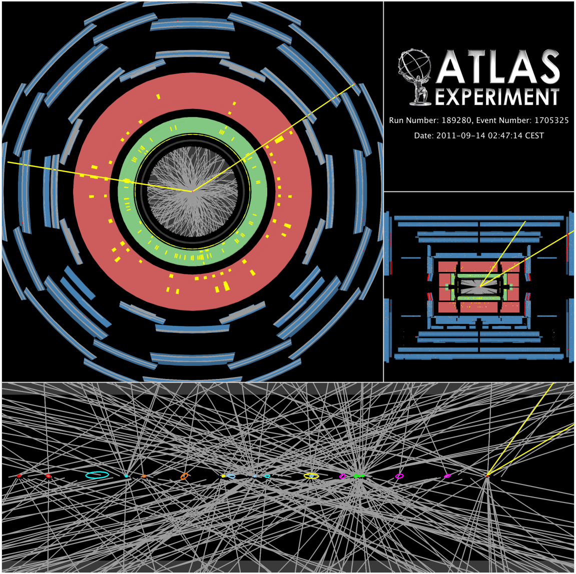


The ATLAS Detector



25 m high, 45 m long, 7 000 tons, lots of electronics, . . .

Final 2011 Running Conditions



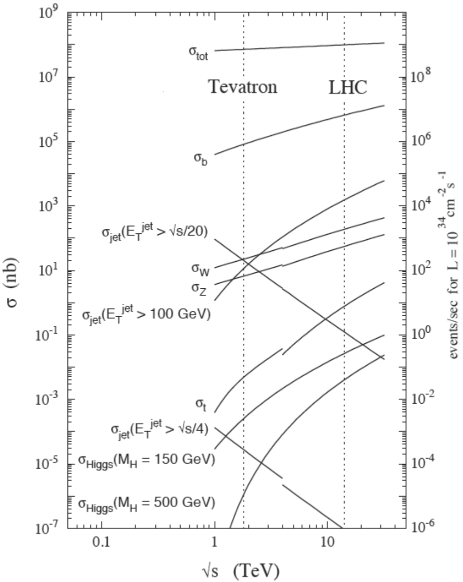
still 7 TeV
CM energy

20 000 000
bunch crossings
per second

$\sim$ 10 pp collisions
per crossing

$\sim$ 400 saved
per second

Cross Sections



master formulae

$\langle n \rangle = \sigma \int \mathcal{L}\, \mathrm{d}t$

$\mathcal{L} \approx f n_1 n_2 / A$

$\sigma_{\mathrm{tot}} \approx 100$ mb
$= 10$ fm$^2 = 10^{-29}$ m^2

2011: $\int \mathcal{L}\, \mathrm{d}t = 5$ fb^{-1}
$= 5 \cdot 10^{43}$ m^{-2}

so $n_{\mathrm{tot}} = 5 \cdot 10^{14}$
in each of ATLAS/CMS

lower in ALICE/LHCb

$$\frac{\sigma_{H(m=125\ \mathrm{GeV})}}{\sigma_{\mathrm{tot}}} \approx 10^{-10}$$

Event Generator Reasons

An event generator is intended to simulate various event kinds as accurately as possible.

It uses random numbers to represent quantum mechanical choices.

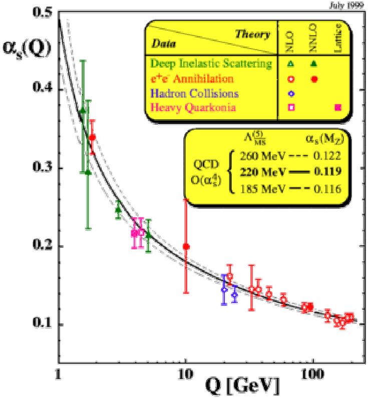
It can be used to

- predict event rates and topologies
  ⇒ estimate feasibility
- simulate possible backgrounds
  ⇒ devise analysis strategies
- study detector requirements
  ⇒ optimize detector/trigger design
- study detector imperfections
  ⇒ evaluate acceptance corrections

```
// Pick pT2 (in overestimated z range) for fixed alpha_strong.
if (alphaSorder == 0) {
  dip.pT2 = dip.pT2 * pow( rndmPtr->flat(),
    1. / (alphaS2pi * emitCoefTot) );

// Ditto for first-order alpha_strong.
} else if (alphaSorder == 1) {
  dip.pT2 = Lambda2 * pow( dip.pT2 / Lambda2,
    pow( rndmPtr->flat(), b0 / emitCoefTot) );

  // For second order reject by second term in alpha_strong expression.
} else {
  do dip.pT2 = Lambda2 * pow( dip.pT2 / Lambda2,
    pow( rndmPtr->flat(), b0 / emitCoefTot) );
  while (alphaS.alphaS2OrdCorr(dip.pT2) < rndmPtr->flat()
    && dip.pT2 > pT2min);
}
wt = 0.;

// If crossed c or b thresholds: continue evolution from threshold.
if (nFlavour == 5 && dip.pT2 < m2b) {
  mustFindRange = true;
  dip.pT2       = m2b;
} else if ( nFlavour == 4 && dip.pT2 < m2c) {
  mustFindRange = true;
  dip.pT2       = m2c;

// Abort evolution if below cutoff scale, or below another branching.
} else {
  if ( dip.pT2 < pT2endDip) { dip.pT2 = 0.; return; }

  // Pick kind of branching: X -> X g or g -> q qbar.
  dip.flavour  = 21;
  dip.mFlavour = 0.;
  if (colTypeAbs == 2 && emitCoefQqbar > rndmPtr->flat()
    * emitCoefTot) dip.flavour = 0;

  // Pick z: either dz/(1-z) or flat dz.
  if (dip.flavour == 21) {
    dip.z = 1. - zMinAbs * pow( 1. / zMinAbs - 1., rndmPtr->flat() );
  } else {
    dip.z = zMinAbs + (1. - 2. * zMinAbs) * rndmPtr->flat();
  }

  // Do not accept branching if outside allowed z range.
  double zMin = 0.5 - sqrtpos( 0.25 - dip.pT2 / dip.m2DipCorr );
  if (zMin < SIMPLIFYROOT) zMin = dip.pT2 / dip.m2DipCorr;
  dip.m2 = dip.m2Rad + dip.pT2 / (dip.z * (1. - dip.z));
```

Event Generator Challenges

- Structure of LHC events impossible to "solve" from first principles;
  e.g. QCD in perturbative and nonperturbative regimes. (Perturbation theory helpful; lattice QCD not much help.)
- Even if calculable somehow, need 1000-body expressions and phase space sampling.
- Immense variability, with "typical events" and "rare corners".
- Several competing mechanisms contribute.



Need to

- combine theory with models
- divide and conquer

Who was Pythia?

The Oracle of Delphi:
ca. 1000 B.C. — 390 A.D.

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The Oracle of Delphi:
ca. 1000 B.C. — 390 A.D.

What is PYTHIA?

Generator development begun in Lund in 1978, for own physics studies.

Increasingly tool for experimentalists, to "sell" our physics.

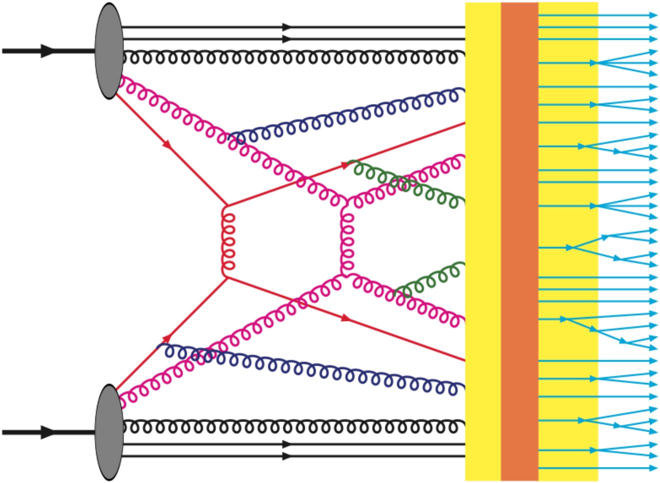
PYTHIA (+JETSET) general-purpose "core".

Other special programs interfaced to PYTHIA.

Most used generator at LEP and LHC.

Lots of Lund people involved over the years.

The Main Physics Components (in PYTHIA)

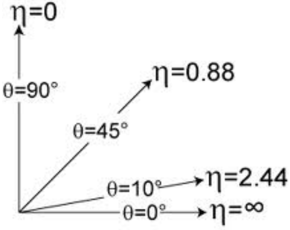


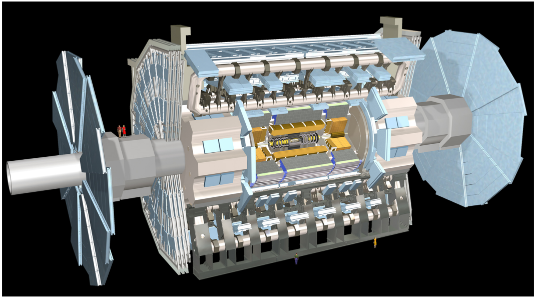
Hides further layers of complexity, e.g. > 200 different ME's, > 400 different particles, $> 6\,000$ different decay channels, ...

Cylindrical Phase Space

Collision along z axis: wide variation of produced particles in p_z, but limited in p_x, p_y. Therefore often use

$$
\begin{aligned}
y &= \frac{1}{2}\ln\frac{E+p_z}{E-p_z} \\
y \approx \eta &= \frac{1}{2}\ln\frac{|\mathbf{p}|+p_z}{|\mathbf{p}|-p_z} = -\ln\tan(\theta/2) \\
p_\perp &= \sqrt{p_x^2+p_y^2}
\end{aligned}
$$

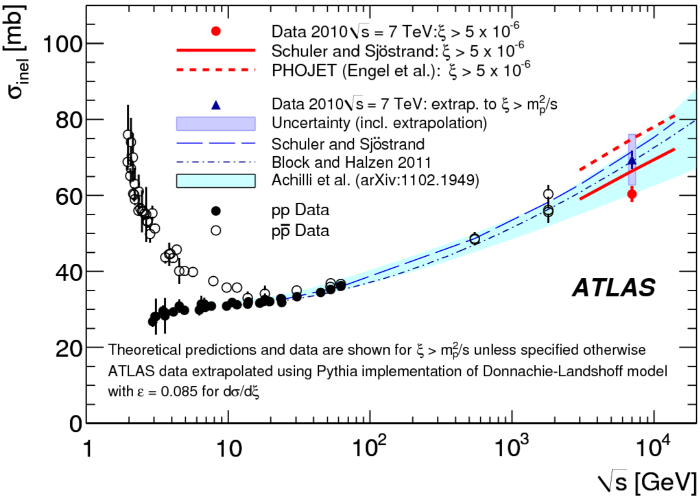




$(\eta, \varphi, p_\perp)$ standard coordinate choice:

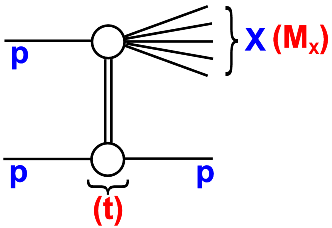
$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} \approx \frac{\mathrm{d}^3\sigma}{\mathrm{d}\eta\,\mathrm{d}\varphi\,\mathrm{d}p_\perp^2}$$

Total Inelastic Cross Section



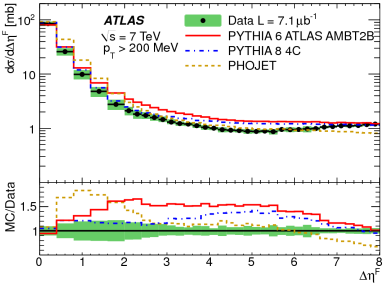
Proton is getting bigger with energy: wavefunction tails find it easier to interact (multiparton interactions).
In line with expectations; if anything then below.

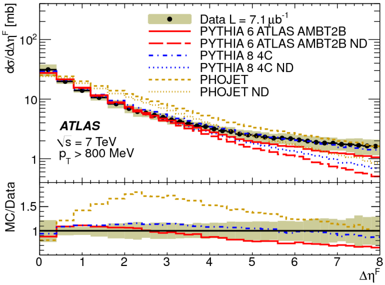
Diffractive Cross Section and Properties



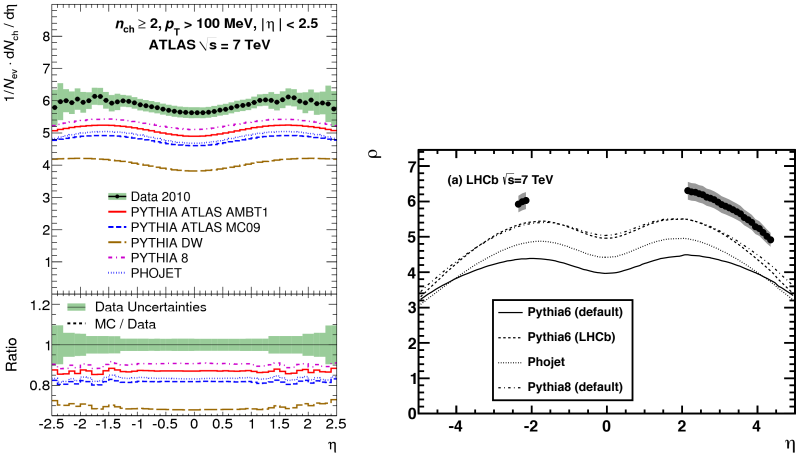
If only one proton breaks up, then part of detector empty.
$\Delta\eta$ = largest empty region counted from detector edge at $\eta \approx 5$.
Expect $\mathrm{d}M_x^2/M_x^2 \approx \mathrm{d}\Delta\eta$.
Deviations from mass spectrum or hadronization modelling.

Using particles with $p_\perp > 0.2$ GeV or $p_\perp > 0.8$ GeV:



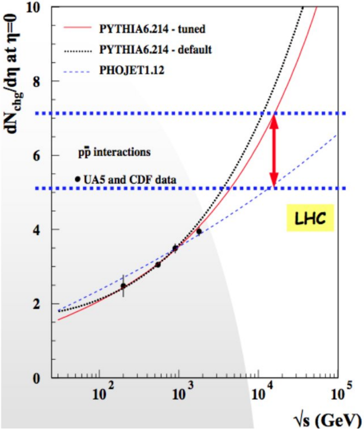


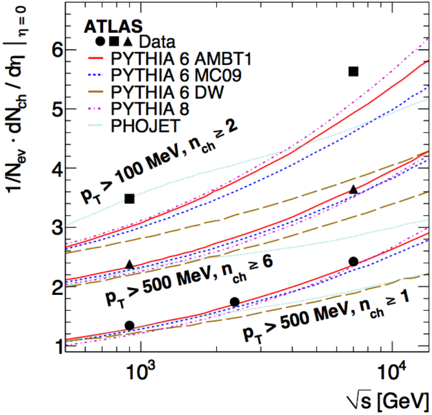
Charged Rapidity Distribution



Dip around $\eta = 0$ artefact; absent if using y instead.

Charged Rapidity Plateau



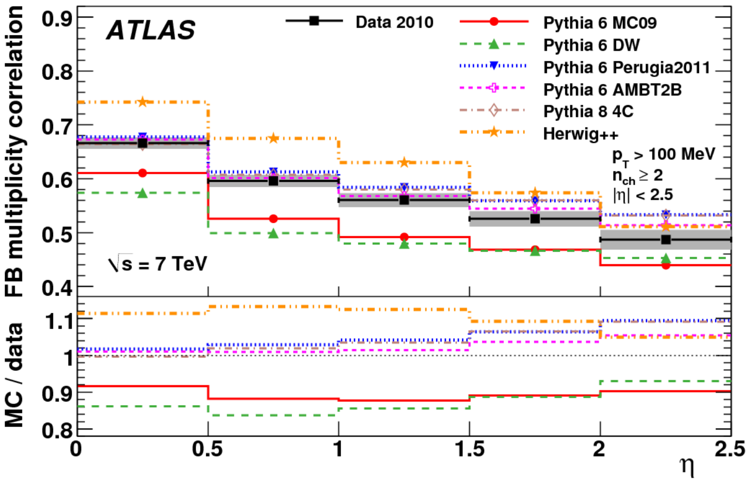


How does $\mathrm{d}n_{\mathrm{ch}}/\mathrm{d}\eta$ grow with energy? $\propto \ln E$ or $\propto \ln^2 E$?

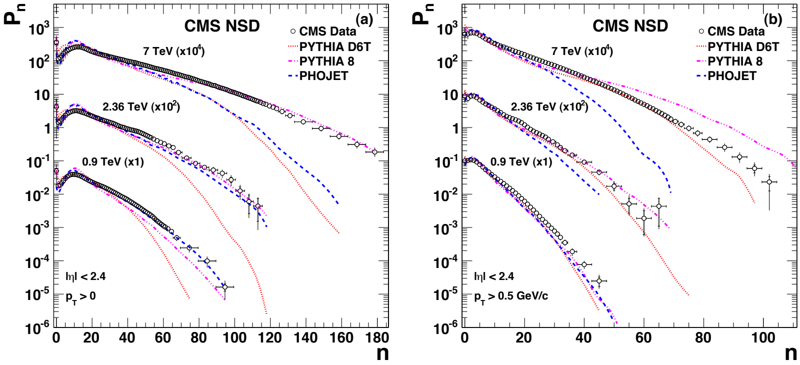
Provides information on several simultaneous subcollisions!

MPI = MultiParton Interactions.

Rapidity Plateau Correlations

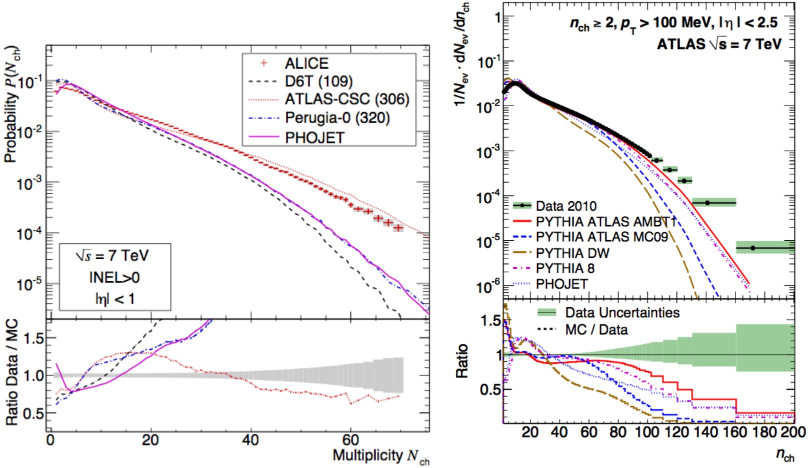


Charged Multiplicity Distribution – 1



- We need to understand both average and spread.
- "Ankle": transition from one to ≥ 2 interactions?
- High multiplicity tail driven by abundant MPI rate.
- Broad spectrum of tunes even within given model.

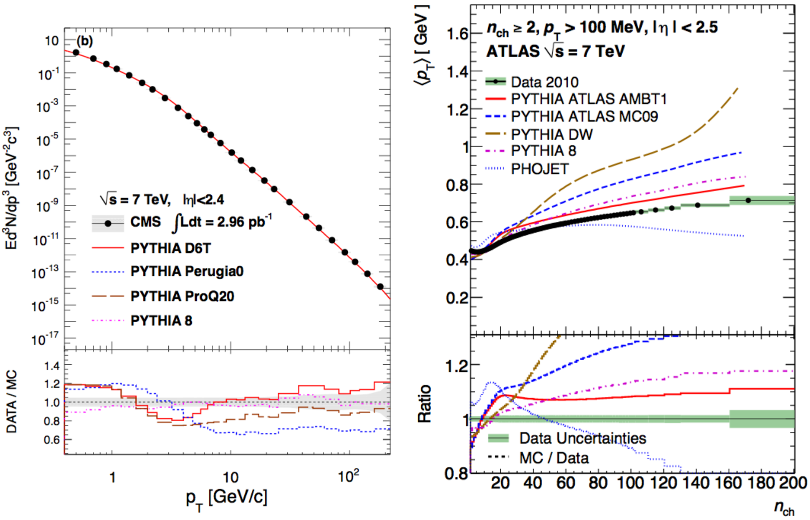
Charged Multiplicity Distribution – 2



"Ankle" also present in ALICE and ATLAS data.

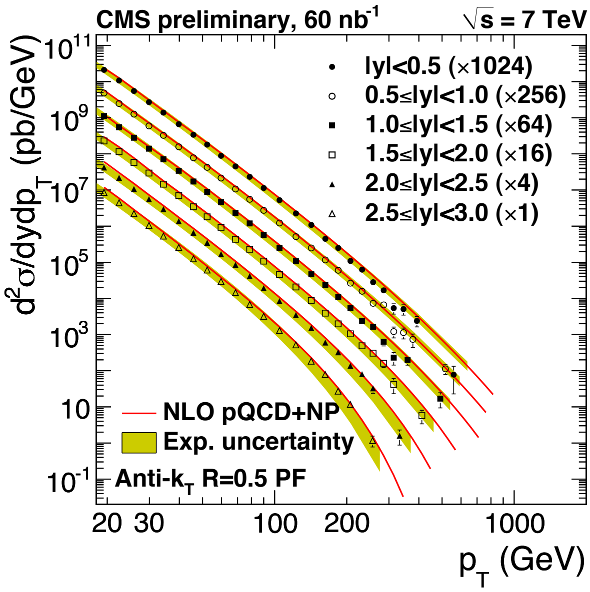
Benchmark comparisons ALICE/ATLAS/CMS generally successful.

Charged Transverse Momentum Distribution

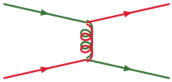


$\langle p_\perp \rangle$ sensitive to colour correlations between MPIs!

Jet Transverse Momentum Distribution



Dominated by QCD $2 \rightarrow 2$

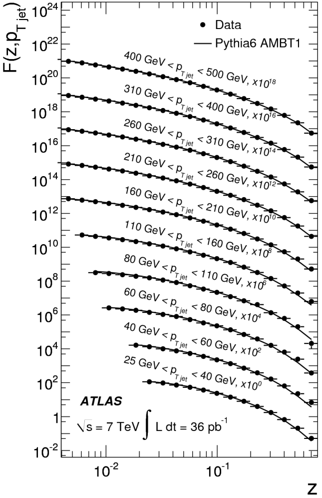


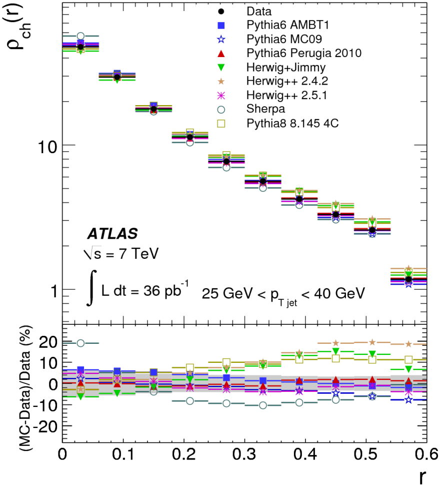
$$qq' \longrightarrow qq'$$
$$q\bar{q} \longrightarrow q'\bar{q}'$$
$$q\bar{q} \longrightarrow gg$$
$$qg \longrightarrow qg$$
$$gg \longrightarrow gg$$
$$gg \longrightarrow q\bar{q}$$

$$\frac{d\sigma}{dp_\perp^2} \propto \frac{1}{p_\perp^4}$$

$\otimes$ PDFs

Jet Fragmentation Profile

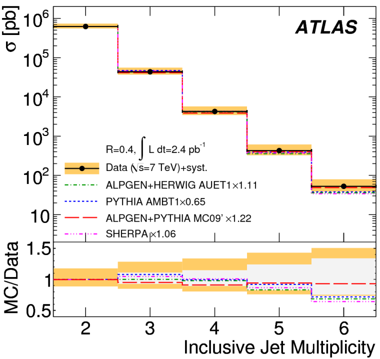


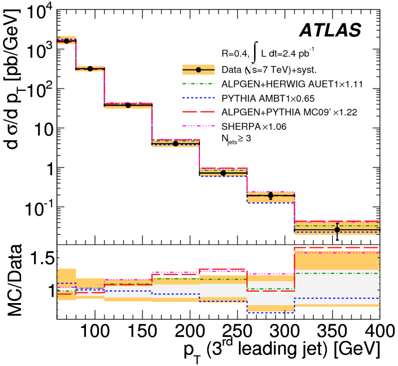


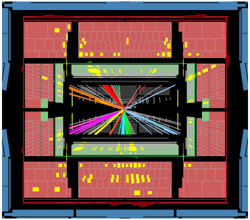
$$z \approx \frac{p_{\perp \mathrm{had}}}{p_{\perp \mathrm{jet}}} \approx \frac{E_{\mathrm{had}}}{E_{\mathrm{jet}}}$$

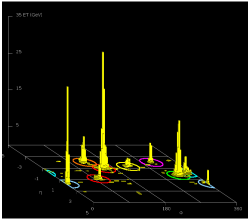
$$r = \sqrt{(\eta_{\mathrm{had}} - \eta_{\mathrm{jet}})^2 + (\varphi_{\mathrm{had}} - \varphi_{\mathrm{jet}})^2}$$

Number of Jets — QCD Events

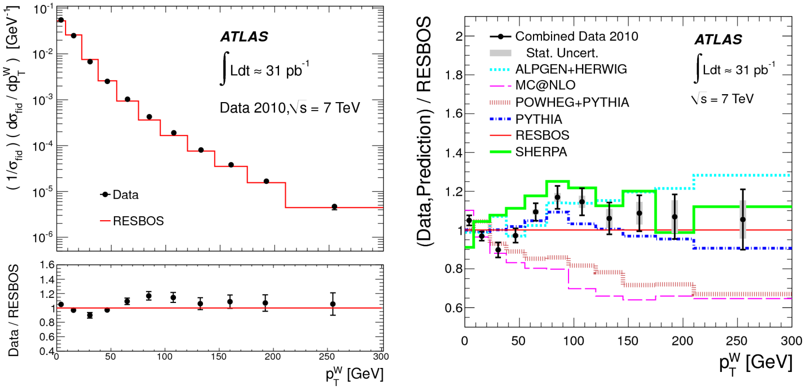






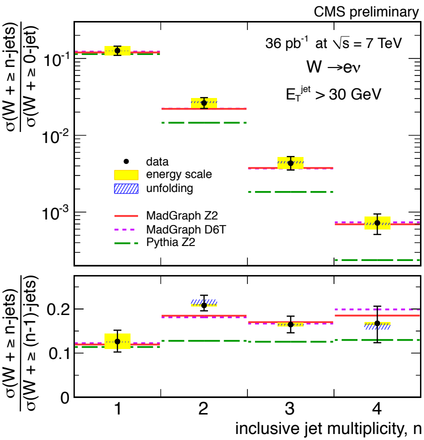


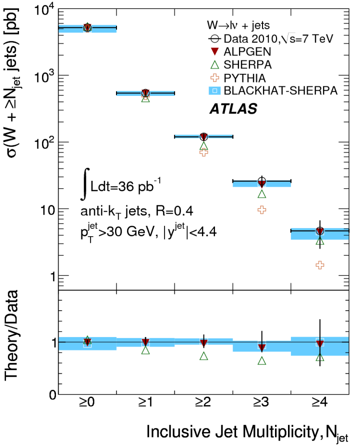
W/Z Transverse Momentum



Here next-to-leading approaches do worse than leading ones!?

Number of Jets — W/Z Events





PYTHIA showers do much worse for W + multijets than for QCD multijets!

Need for matching to higher-order matrix elements (S. Prestel, L. Lönnblad)

Tuning

RIVET: collection of experimental data, together with matching analysis routines. Can be applied to generator events for comparison with data.

PROFESSOR: parameter tuning in multidimensional parameter space.

- Generate large event samples at $\mathcal{O}(n^2)$ *random* points in (reasonable) parameter space. Slow!
- Analyze events and fill relevant histograms.
- For each bin of each histogram parametrize

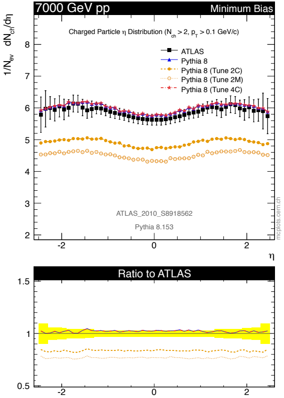
$$X_{MC} = A_0 + \sum_{i=1}^{n} B_i p_i \sum_{i=1}^{n} C_i p_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} D_{ij} p_i p_j$$

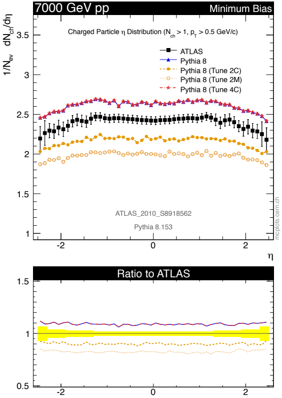
- Do minimization of χ^2 to parametrized results. Fast!

MCPLOTS

Repository of comparisons between various tunes and data, mainly based on RIVET for data analysis, see `http://mcplots.cern.ch/`.
Part of the LHC@home 2.0 platform for home computer participation.

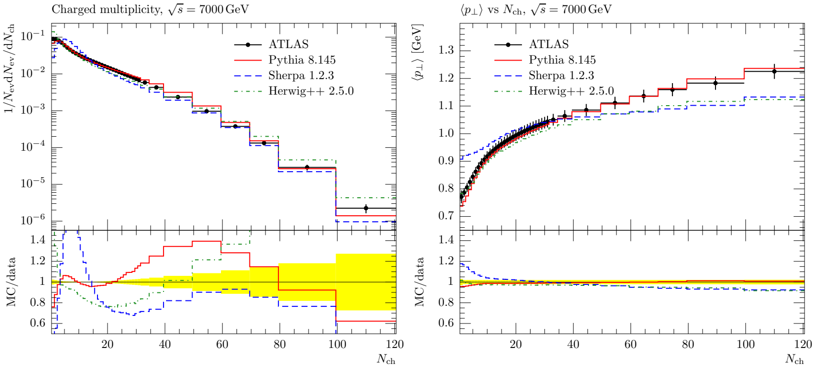
Generator	Version
alpgenherwigjimmy	
alpgenpythia6	
herwig++	
herwig++powheg	
pythia6	
pythia8	
sherpa	
vincia	





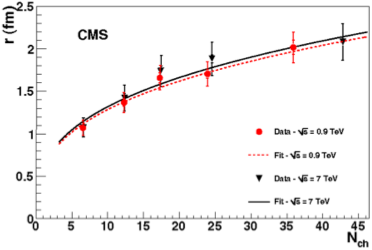
State of New Generators

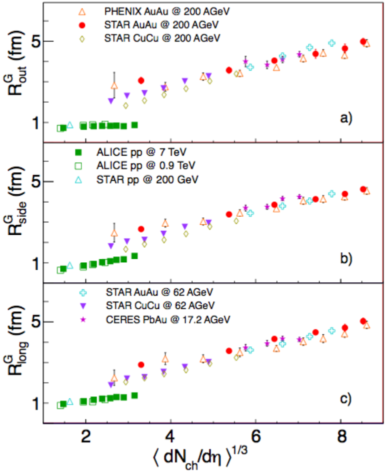
New data leads to new tunes, even if progress is slow.
Also good way to find bugs and other problems.
State of new C++ generators early 2011:



A. Buckley et al., Phys. Rep. 504 (2011) 145 [arXiv:1101.2599[hep-ph]]

Bose-Einstein $r(N_{\text{ch}}) \propto N_{\text{ch}}^{1/3}$
cannot be accommodated
in PYTHIA effective description
that worked at LEP

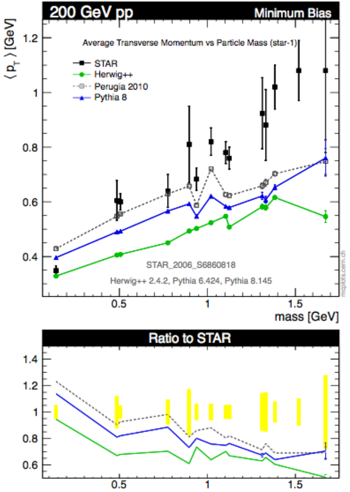


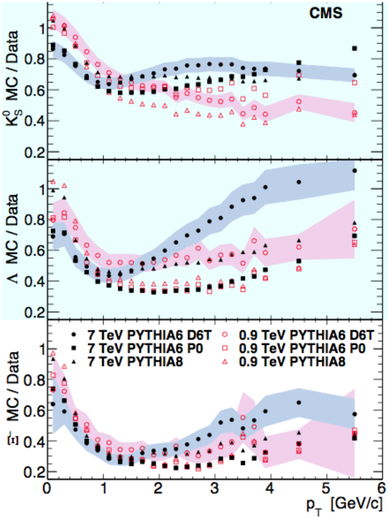


Multiple overlapping fragmenting strings ⇒ dense hadron gas!

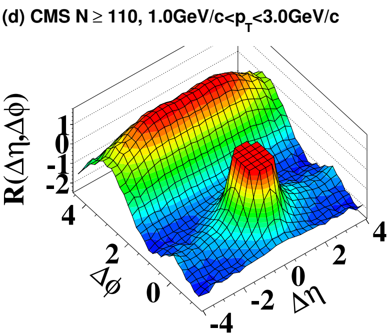
Cloud #2: Flavour Composition

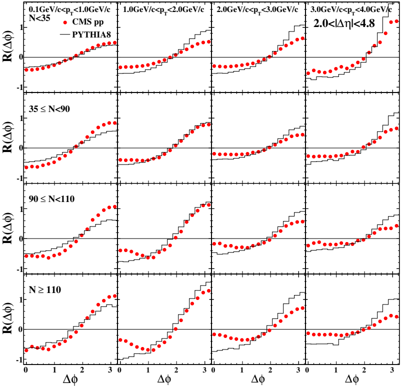
Need more $p_\perp$ for K, p, Λ, . . . , relative to $\pi^\pm$:





Cloud #3: The Ridge





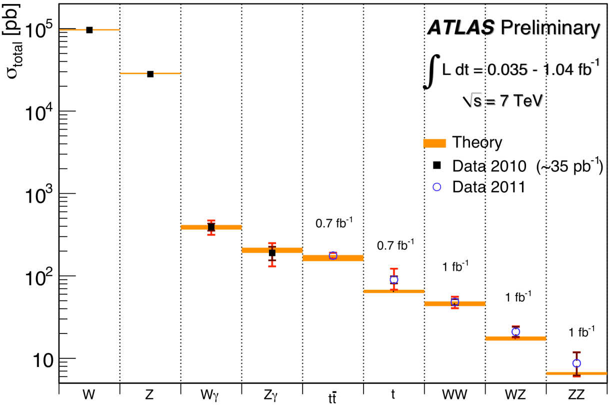
Geometry of colliding protons (non-symmetric shapes)?
Collective phenomena?

Results Galore

\# of papers

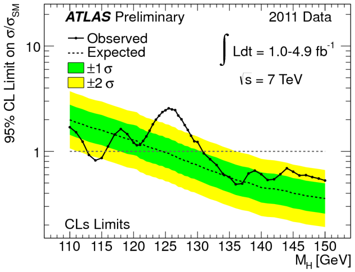
134	CMS
126	ATLAS
39	LHCb
28	ALICE

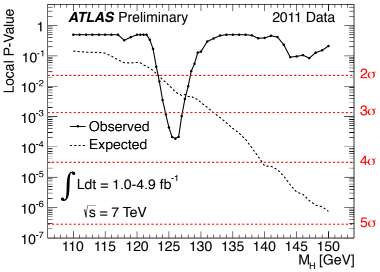
\+ conference
\+ "internal"
\+ theses
\+ . . .

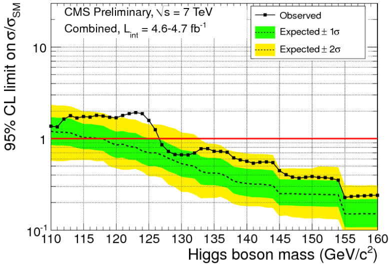


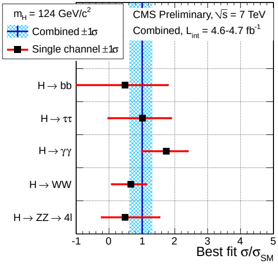
Typical Working groups: QCD, EW, B, quarkonia, top, Higgs, SUSY, Exotics, Heavy Ions

Higgs Results, December 2011

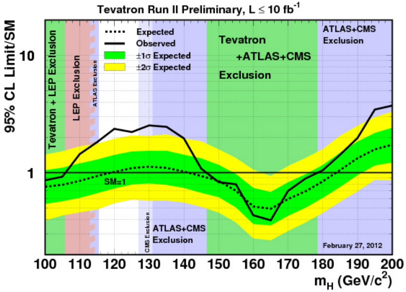


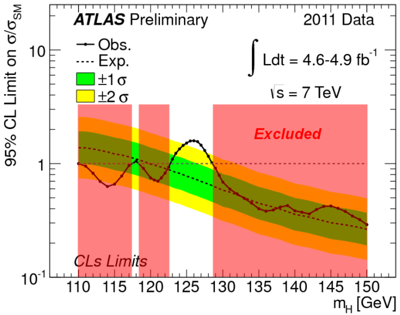


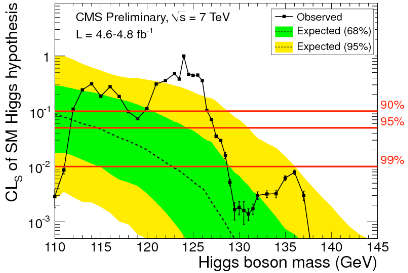




Higgs Results, March 2012

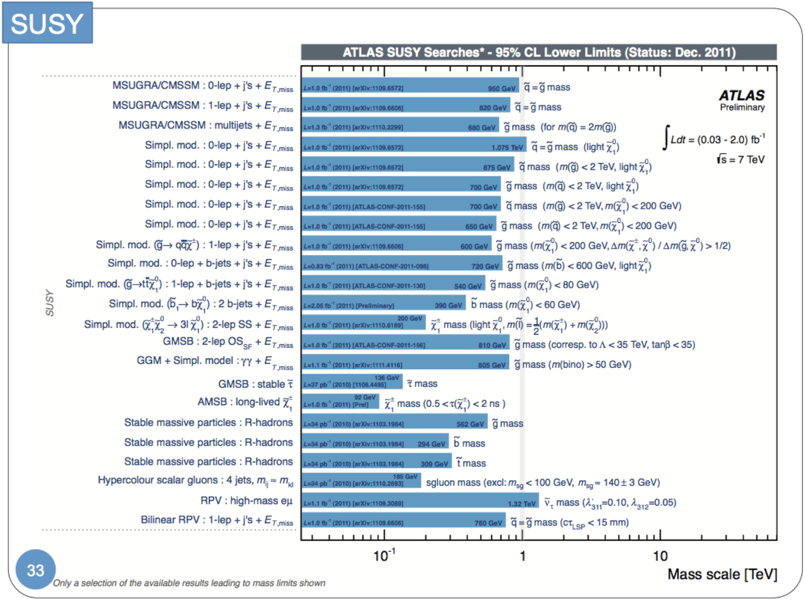




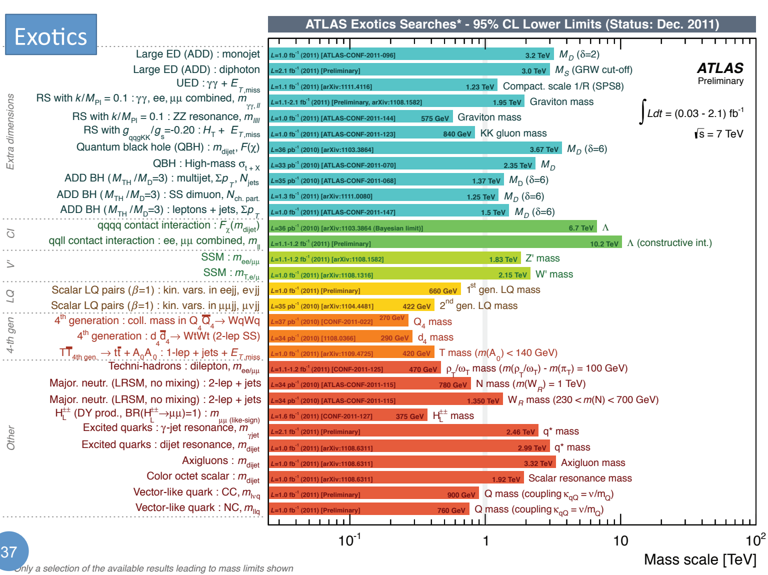


Drifting terminology:
"SM Scalar Boson"
"Brout–Englert–Higgs Boson"
"BEH Boson"
"BEH Mechanism"
... but still "Higgs Boson" as well, and only $gg \to H$, m_H

Limits Galore – 1



Limits Galore – 2



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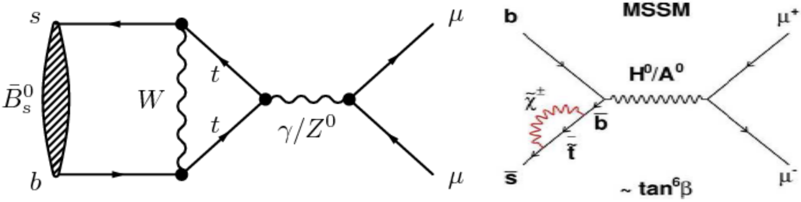
Rare Decays – Another Set of Limits



	$\text{BR}(B_s^0 \to \mu^+\mu^-)$	$\text{BR}(B^0 \to \mu^+\mu^-)$
Standard Model	$(3.2 \pm 0.2) \cdot 10^{-9}$	$(0.11 \pm 0.01) \cdot 10^{-9}$
CDF	$10^{+8}_{-6} \cdot 10^{-9}$	–
CDF 95% CL limit	$< 40 \cdot 10^{-9}$	$< 6.0 \cdot 10^{-9}$
D0 95% CL limit	$< 51 \cdot 10^{-9}$	–
CMS 95% CL limit	$< 7.7 \cdot 10^{-9}$	$< 1.8 \cdot 10^{-9}$
LHCb 95% CL limit	$< 4.5 \cdot 10^{-9}$	$< 1.03 \cdot 10^{-9}$

Only one example where BSM is being restricted from B physics.

QCD and BSM Physics

QCD understanding crucial also for studies of "exotic" physics, since

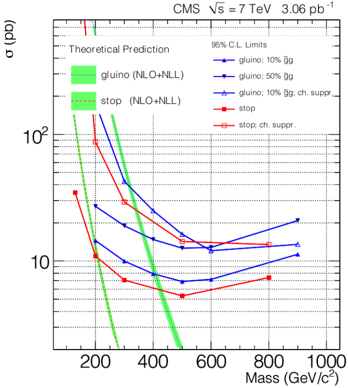
- incoming protons ⇒ production involves strong interactions
- production of new coloured states favourable (squarks, Kaluza-Klein quarks/gluons, excited quarks, . . .)

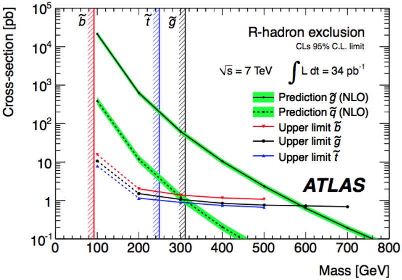
Several different possibilities studied, e.g.

1. Gravitational scattering and black hole formation (G. Gustafson, L. Lönnblad, M. Sjödahl)
2. Baryon number violation in SUSY decays (P. Skands, TS)
3. Hadronization and decay of long-lived SUSY particles (A. Kraan, TS)
4. Parton showers and hadronization in Hidden Valleys (L. Carloni, J. Rathsman, TS)

R-Hadrons

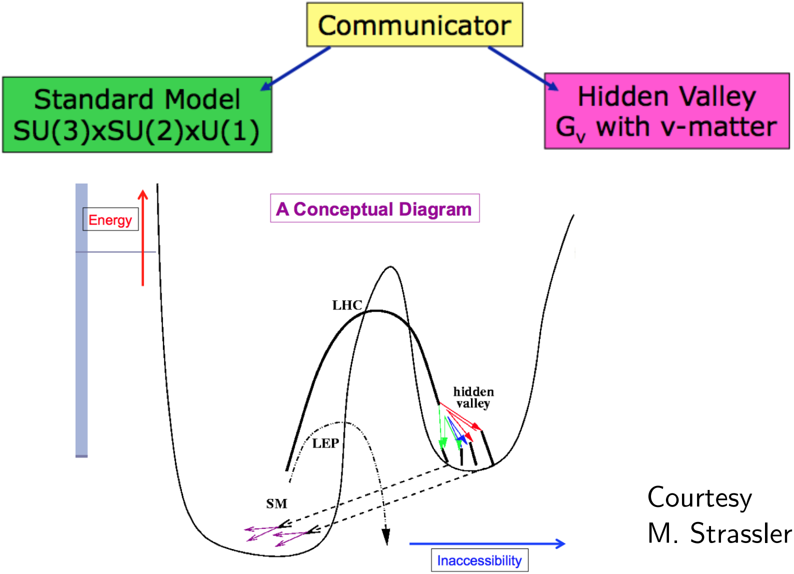
Long-lived coloured particle will hadronize, e.g. $R^-(\tilde{g}d\bar{u})$.
Particle can flip charge and baryon number by exhanging quarks with normal matter: $R^-(\tilde{g}d\bar{u}) + p(uud) \to R^+(\tilde{g}duu) + \pi^-(d\bar{u})$.
Decays may or may not happen inside detector.
PYTHIA framework standard for LHC searches:





But, again, only limits.

Hidden Valleys: Motivation



Courtesy
M. Strassler

Hidden Valleys: Setup

Hidden Valleys (secluded sectors) experimentally interesting
if they can give observable consequences at the LHC:

- coupling not-too-weakly to our sector, and
- containing not-too-heavy particles.

Here: no attempt to construct a specific model,
but to set up a reasonably generic framework.

Either of two gauge groups,

1. Abelian $U(1)$, unbroken or broken (massless or massive γ_v),
2. non-Abelian $SU(N)$, unbroken ($N^2 - 1$ massless g_v's),

with matter q_v's in fundamental representation.

Times three alternative production mechanisms

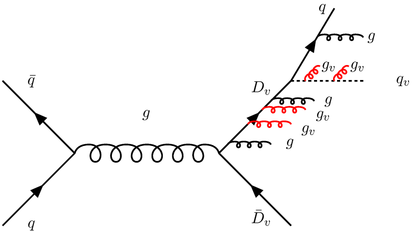
1. massive Z': $\mathrm{q}\overline{\mathrm{q}} \to \mathrm{Z}' \to \mathrm{q}_v\overline{\mathrm{q}}_v$,
2. kinetic mixing: $\mathrm{q}\overline{\mathrm{q}} \to \gamma \to \gamma_v \to \mathrm{q}_v\overline{\mathrm{q}}_v$,
3. massive F_v charged under both SM and hidden group, so e.g. $\mathrm{gg} \to \mathrm{F}_v\overline{\mathrm{F}}_v$. Subsequent decay $\mathrm{F}_v \to \mathrm{f}\mathrm{q}_v$.

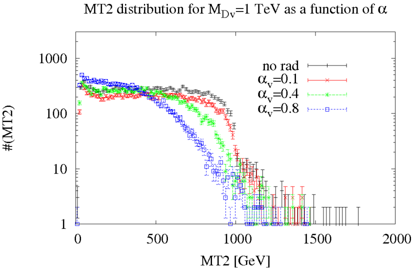
Hidden Valleys: Showers

Interleaved shower in QCD, QED and HV sectors:
emissions arranged in one common sequence of decreasing emission $p_\perp$ scales.

HV $U(1)$: add $\mathrm{q}_v \to \mathrm{q}_v\gamma_v$ and $\mathrm{F}_v \to \mathrm{F}_v\gamma_v$.

HV $SU(N)$: add $\mathrm{q}_v \to \mathrm{q}_v\mathrm{g}_v$, $\mathrm{F}_v \to \mathrm{F}_v\mathrm{g}_v$ and $\mathrm{g}_v \to \mathrm{g}_v\mathrm{g}_v$.





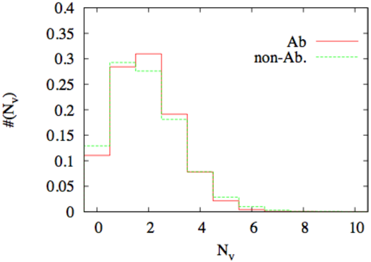
Recoil effects in visible sector also of invisible emissions!

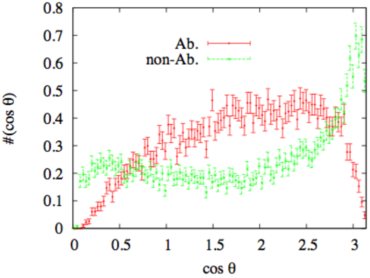
Hidden Valleys: Decays

Hidden Valley particles may remain invisible, or

- Broken $U(1)$: γ_v acquire mass, radiated γ_vs decay back, $\gamma_v \to \gamma \to \mathrm{f}\bar{\mathrm{f}}$ with BRs as photon ($\Rightarrow$ lepton pairs!)
- $SU(N)$: hadronization in hidden sector, with full string fragmentation setup, giving
  - off-diagonal "mesons", flavour-charged, stable & invisible
  - diagonal "mesons", can decay back $\mathrm{q}_v\bar{\mathrm{q}}_v \to \mathrm{f}\bar{\mathrm{f}}$

Even when tuned to same average activity, hope to separate





LHC Scheduled Future

2012 $7 \to 8$ TeV, $5 \to 15$ fb^{-1}

2013–14 shutdown to improve safety system (+ retrain magnets); slow restart likely

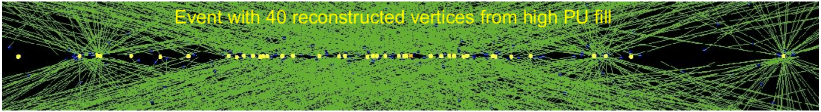
2015–17 run at 13–14 TeV, slowly increasing luminosity

2018 shutdown, preparing for upgrade

2019–21 continue to run at 14 TeV, collect 100 fb^{-1}/year

2022–23 shutdown, luminosity upgrade, slow restart

2024–30 high-luminosity run to collect 3000 fb^{-1}



Long-term future options:

- (Re)install electron ring for *ep*/*eA* collisions.
- New ~ 20 T magnets to double the LHC energy.
- ~ 3 TeV e^+e^- linear collider.

Summary

- After many delays/disappointments LHC is now doing well.
- Flood of new results; impossible to keep track of all.
- Signs of a 125 GeV Higgs, consistent with Standard Model.
- No signs of physics Beyond the Standard Model.
- Event generators continue to play a central role.
- Qualitatively main features of data successfully predicted,
  in some cases over ten orders of magnitude.
- Quantitatively many $\mathcal{O}(20\%)$ discrepancies,
  and a few real bad ones.
- Push towards higher precision: theory $\leftrightarrow$ generators $\leftrightarrow$ data.
- Increasing luminosity smears many observables.

We live in interesting times!