39th John Hopkins Workshop
Theory Challenges in the LHC era
Gothenburg, Sweden
August 12–14, 2015

QCD and BSM

Torbjörn Sjöstrand

Department of Astronomy and Theoretical Physics
Lund University
Sölvegatan 14A, SE-223 62 Lund, Sweden

Contents

QCD at LHC

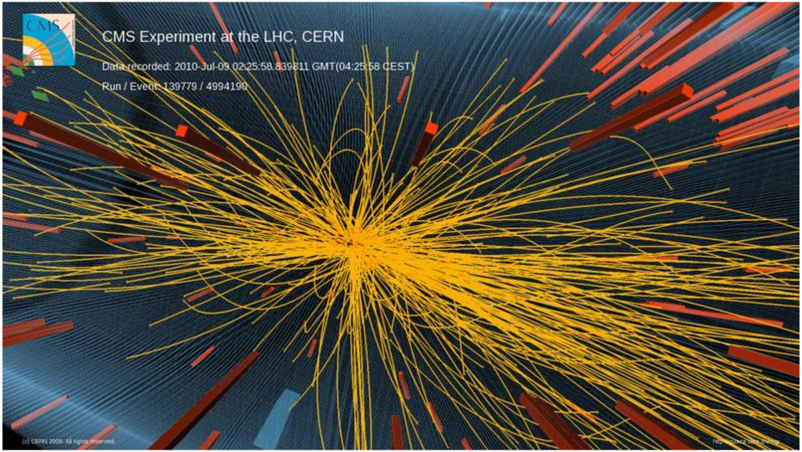
LHC is a QCD machine:

- hard processes initiated by partons (quarks, gluons),
- associated with initial-state QCD corrections (showers etc.),
- underlying event by QCD mechanisms (MPI, colour flow),
- even in scenarios for physics Beyond the Standard Model (BSM) production of new coloured states often favoured (squarks, KK gluons, excited quarks, leptoquarks, . . .).

In addition, BSM physics can raise "new", specific QCD aspects:

- new production mechanisms
- new parton-shower aspects
- new decay channels
- new hadronization phenomena
- new correlations with rest of the event

Event topologies

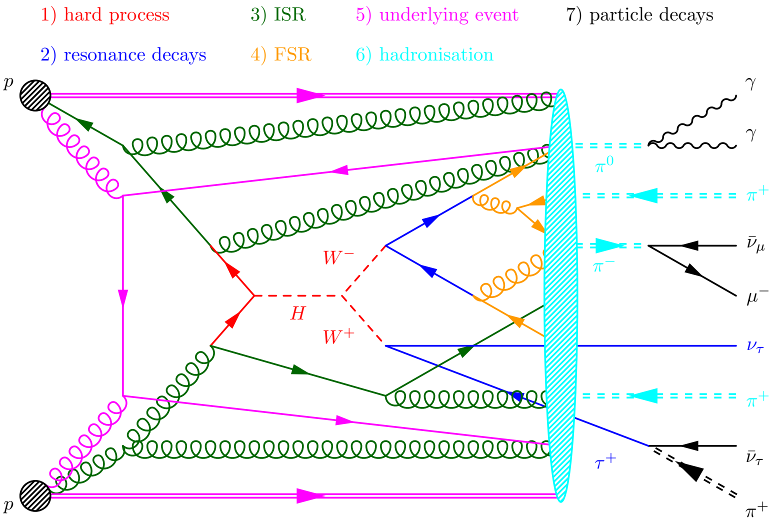


Expect and observe high multiplicities at the LHC.

What are production mechanisms behind this?

How deal with complexity?

Dissection of an Event



(from Philip Ilten, PhD thesis)

Sketch hides many further layers of complexity!

What is PYTHIA? Who was Pythia?

QCD is unsolved.
No perfect description.
Do the best you can!

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

Use random numbers to represent quantum mechanical choices.

Experimentalists use it at various stages of planning and analysis.

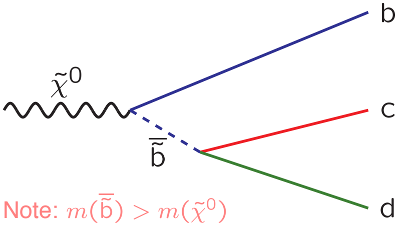
Generator development in Lund began in 1978.

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

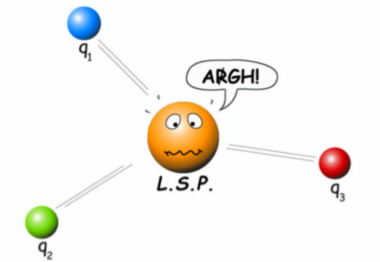
Currently at PYTHIA 8.210:
code $\sim$ 100 000 lines; documentation a further $\sim$ 50 000 lines.

1. R-parity violation in SUSY

Baryon number violation (BNV) is allowed in SUSY superpotential.
Alternatively lepton number violation, but proton unstable if both.
BNV couplings should not be too big, or else large loop corrections
$\Rightarrow$ relevent for LSP (Lightest Supersymmetric Particle).



Note: $m(\overline{\tilde{b}}) > m(\tilde{\chi}^0)$



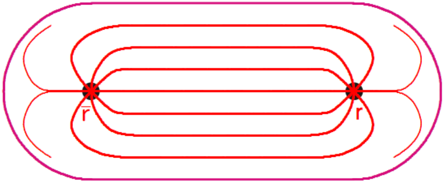
What about showers and hadronization in decays?

P. Skands & TS, Nucl. Phys. B659 (2003) 243;

N. Desai & P. Skands, arXiv:1109.5852 [hep-ph]

The Lund string

In QCD, for large charge separation, field lines seem to be compressed to tubelike region(s) $\Rightarrow$ **string(s)**

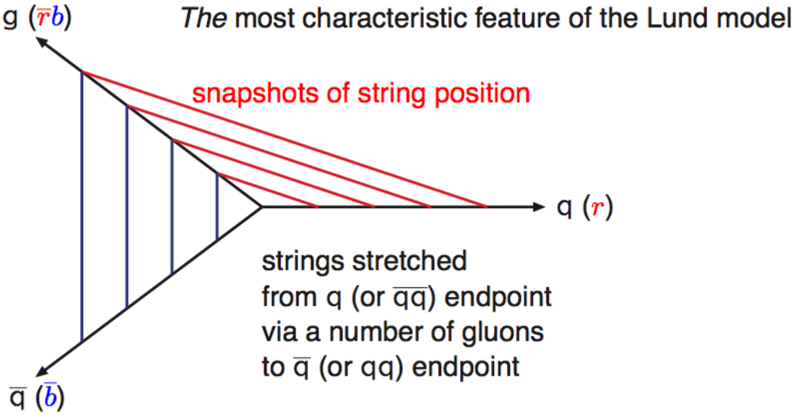


by self-interactions among soft gluons in the "vacuum".

Gives linear confinement with string tension:
$F(r) \approx \mathrm{const} = \kappa \approx 1\ \mathrm{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$

Separation of transverse and longitudinal degrees of freedom
$\Rightarrow$ simple description as 1+1-dimensional object – **string** – with Lorentz invariant formalism

The Lund gluon picture

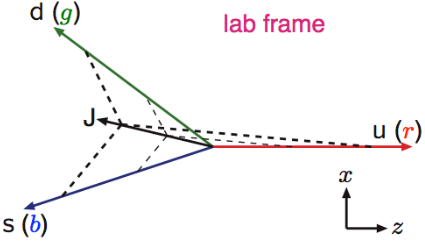


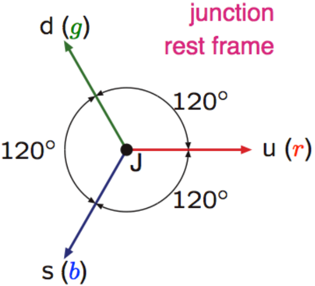
Gluon = kink on string, carrying energy and momentum

Force ratio gluon/ quark = 2,
cf. QCD $N_C/C_F = 9/4$, $\rightarrow 2$ for $N_C \rightarrow \infty$

The junction

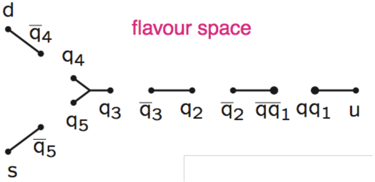
What string topology for 3 quarks in overall colour singlet?
One possibility is to introduce a **junction** (Artru, 't Hooft, . . .).

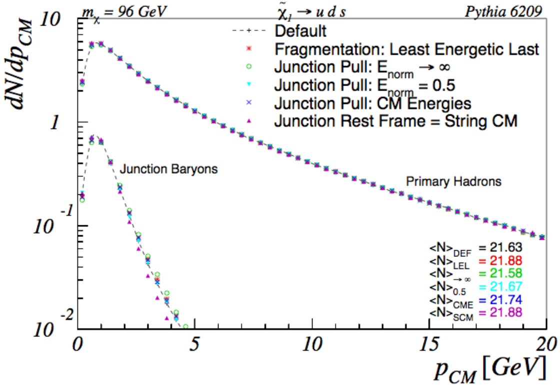




Junction rest frame = where string tensions $\mathbf{T}_i = \kappa\, \mathbf{p}_i / |\mathbf{p}_i|$ balance
$= 120^\circ$ separation between quark directions.
This is not the CM frame where momenta $\mathbf{p}_i$ balance,
but in BNV decay no collinear singularity between quarks,
so normally junction is slowly moving in LSP rest frame.

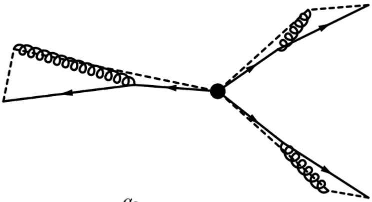
Each string piece can break, mainly to give mesons. Always one baryon around junction; junction "carries" baryon number.



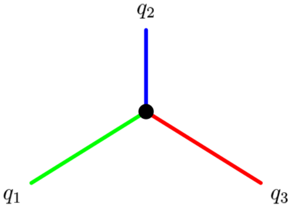


Junction baryon slow $\Rightarrow$ "smoking-gun" signal.

The junction and dipole showers



Normal showers:
each parton can radiate.



Dipole showers: each *pair* of partons, with matching colour–anticolour, can radiate, with recoil inside system.
But here no simply matching colours!

Solution: let each three possible dipoles radiate, but with half normal strength.
Gives correct answer collinear to each parton, and reasonable interpolation in between.

2. *R*-hadron motivation

Now different tack: *R*-parity conserved.

Conventional SUSY: LSP is neutralino, sneutrino, or gravitino.
Squarks and gluinos are unstable and decay to LSP,
e.g. $\tilde{\mathrm{g}} \to \tilde{\mathrm{q}}\overline{\mathrm{q}} \to \mathrm{q}\tilde{\chi}\overline{\mathrm{q}}$.

Alternative SUSY: gluino LSP, or long-lived for another reason.

E.g. Split SUSY (Dimopoulos & Arkani-Hamed):
scalars are heavy, including squarks $\Rightarrow$ gluinos long-lived.

2. *R*-hadron motivation

Now different tack: *R*-parity conserved.

Conventional SUSY: LSP is neutralino, sneutrino, or gravitino.
Squarks and gluinos are unstable and decay to LSP,
e.g. $\tilde{\mathrm{g}} \to \tilde{\mathrm{q}}\overline{\mathrm{q}} \to \mathrm{q}\tilde{\chi}\overline{\mathrm{q}}$.

Alternative SUSY: gluino LSP, or long-lived for another reason.

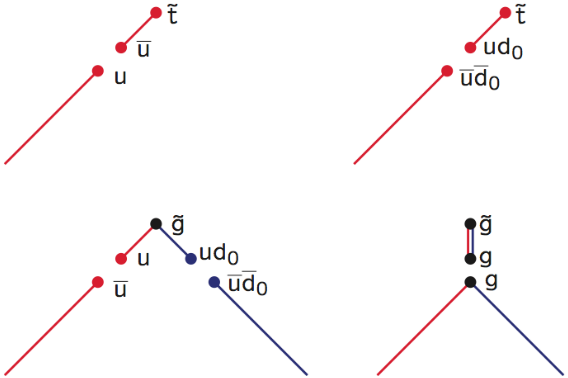
E.g. Split SUSY (Dimopoulos & Arkani-Hamed):
scalars are heavy, including squarks $\Rightarrow$ gluinos long-lived.

More generally, many BSM models contain colour triplet or octet particles that can be (pseudo)stable: extra-dimensional excitations with odd KK-parity, leptoquarks, excited quarks, ...

$\Rightarrow$ PYTHIA allows for hadronization of 3 generic states:

- colour octet uncharged, like $\tilde{\mathrm{g}}$, giving $\tilde{\mathrm{g}}\mathrm{u}\overline{\mathrm{d}}$, $\tilde{\mathrm{g}}\mathrm{uud}$, $\tilde{\mathrm{g}}\mathrm{g}$, ...,
- colour triplet charge $+2/3$, like $\tilde{\mathrm{t}}$, giving $\tilde{\mathrm{t}}\overline{\mathrm{u}}$, $\tilde{\mathrm{t}}\mathrm{ud}_0$, ...,
- colour triplet charge $-1/3$, like $\tilde{\mathrm{b}}$, giving $\tilde{\mathrm{b}}\overline{\mathrm{c}}$, $\tilde{\mathrm{b}}\mathrm{su}_1$, ...

R-hadron formation



Squark fragmenting to meson or baryon

Gluino fragmenting to baryon or glueball

Most hadronization properties by analogy with normal string fragmentation, but
glueball formation new aspect, assumed $\sim$ 10% of time (or less).

R-hadron interactions

R-hadron interactions with matter involve interesting aspects:

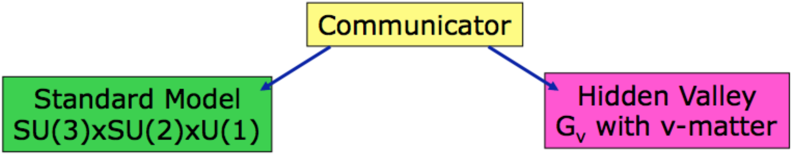
- $\tilde{\mathrm{b}}/\tilde{\mathrm{t}}/\tilde{\mathrm{g}}$ massive $\Rightarrow$ slow-moving, $v \sim 0.7c$.
- In R-hadron rest frame the detector has $v \sim 0.7c$
  $\Rightarrow E_{\mathrm{kin,p}} \sim 1$ GeV: low-energy (quasi)elastic processes.
- Cloud of light quarks and gluons interact with hadronic rate;
  sparticle is inert reservoir of kinetic energy.
- Charge-exchange reactions allowed, e.g.
  $R^+(\tilde{\mathrm{g}}\mathrm{u}\overline{\mathrm{d}}) + \mathrm{n} \to R^0(\tilde{\mathrm{g}}\mathrm{d}\overline{\mathrm{d}}) + \mathrm{p}$.
  Gives alternating track/no-track in detector.
- Baryon-exchange predominantly one way,
  $R^+(\tilde{\mathrm{g}}\mathrm{u}\overline{\mathrm{d}}) + \mathrm{n} \to R^0(\tilde{\mathrm{g}}\mathrm{udd}) + \pi^+$,
  since (a) kinematically disfavoured (π exceptionally light)
  and (b) few pions in matter.

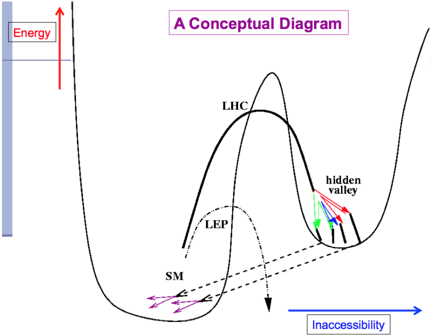
. . . but part of detector simulation (GEANT), not PYTHIA.

A.C. Kraan, Eur. Phys. J. C37 (2004) 91; M. Fairbairn et al., Phys. Rep. 438 (2007) 1

3. Hidden Valleys: motivation

M. Strassler, K. Zurek, Phys. Lett. B651 (2007) 374; . . .





Courtesy
M. Strassler

L. Carloni & TS, JHEP 1009, 105; L. Carloni, J. Rathsman & TS, JHEP 1104, 091

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.

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

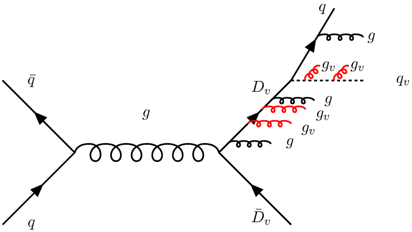
1. massive Z': $\mathrm{q}\overline{\mathrm{q}} \to \mathrm{Z}' \to \mathrm{q}_v\overline{\mathrm{q}}_v$,
2. kinetic mixing: $\mathrm{q}\overline{\mathrm{q}} \to \gamma \to \gamma_v \to \mathrm{q}_v\overline{\mathrm{q}}_v$,
3. massive F_v charged under both SM and hidden group, so e.g. $\mathrm{gg} \to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

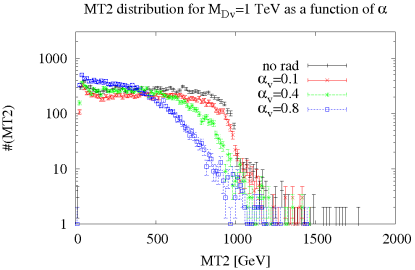
Hidden Valleys showers

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 $\mathrm{g}_v \to \mathrm{g}_v\mathrm{g}_v$.





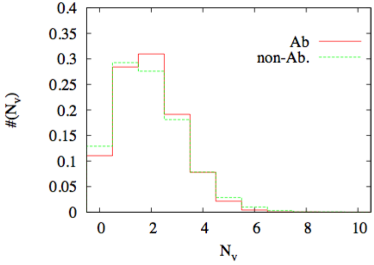
Recoil effects in visible sector also of invisible emissions!

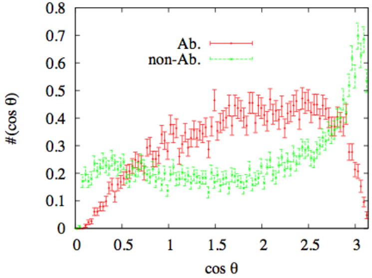
Hidden Valleys decays

Hidden Valley particles may remain invisible, or

- Broken $U(1)$: γ_v acquire mass, radiated γ_vs decay back, $\gamma_v \to \gamma \to \mathrm{f}\overline{\mathrm{f}}$ 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 $\mathrm{q}_v\overline{\mathrm{q}}_v \to \mathrm{f}\overline{\mathrm{f}}$

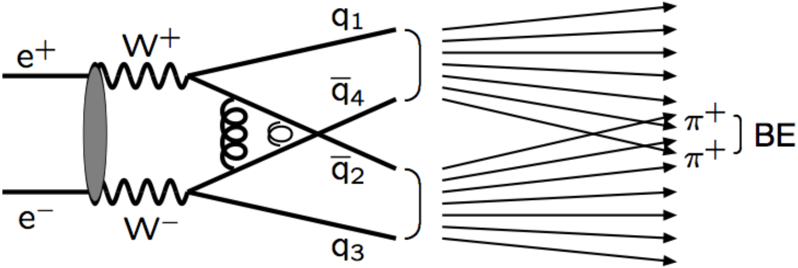
Even when tuned to same average activity, hope to separate





4. Interconnection at LEP 2

$\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to \mathrm{q_1\overline{q}_2\, q_3\overline{q}_4}$ reconnection limits m_{W} precision!



- perturbative $\langle \delta M_{\mathrm{W}} \rangle \lesssim 5$ MeV : negligible!
  (killed by dampening from off-shell W propagators)
- nonperturbative $\langle \delta M_{\mathrm{W}} \rangle \sim 40$ MeV :
  favoured; no-effect option ruled out at 2.8σ
  (but more extreme models from other authors ruled out)
- Bose-Einstein $\langle \delta M_{\mathrm{W}} \rangle \lesssim 100$ MeV : full effect ruled out.
  (but models with ~ 20 MeV barely acceptabe)

Colour reconnection models for LEP 2

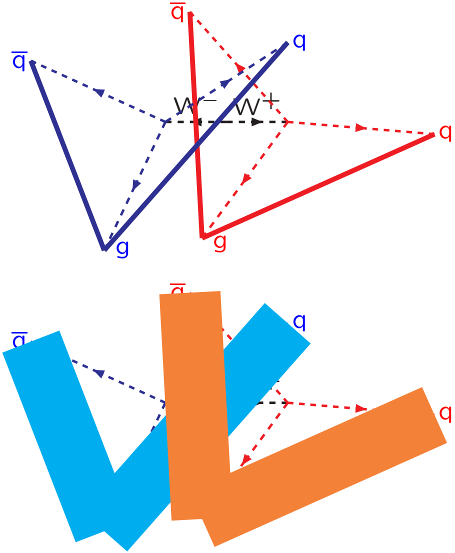
Colour rearrangement studied in several models, e.g.

Scenario II: vortex lines.
Analogy: type II superconductor.
Strings can reconnect only if central cores cross.

Scenario I: elongated bags.
Analogy: type I superconductor.
Reconnection proportional to space–time overlap.

In both cases favour reconnections that reduce total string length.

LEP 2 data agrees with scenario I with $\sim$ 50% of all events reconnected.

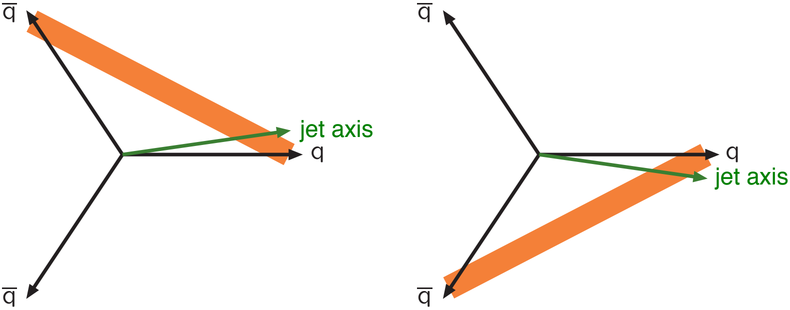


(schematic only; nothing to scale)

Higgs *CP* Violation

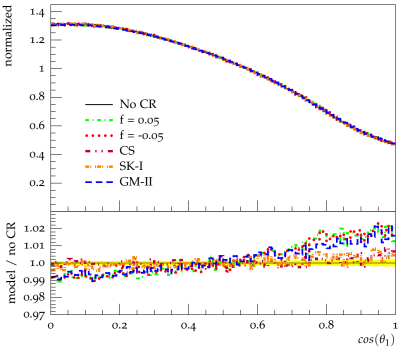
Is the 125 GeV Higgs a pure *CP*-even state? Any odd admixture?

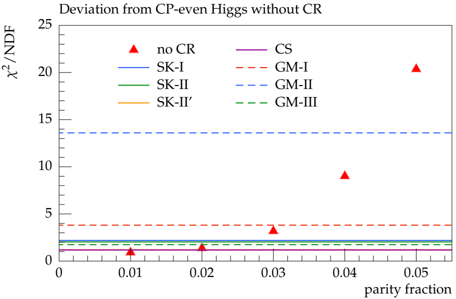
For LHC and future $\mathrm{e}^+\mathrm{e}^-$ (& $\mu^+\mu^-$?) colliders to probe.
One possibility is $\mathrm{H}^0 \to \mathrm{W}^+\mathrm{W}^- \to \mathrm{q}_1\overline{\mathrm{q}}_2\mathrm{q}_3\overline{\mathrm{q}}_4$.
Angular correlations put limits on odd admixture.



But: colour reconnection $\Rightarrow$ shifted jet directions
$\Rightarrow$ shifted angular correlations.

Higgs CP Violation – 2





$$f = \frac{\int \text{odd} + |\text{interference}|}{\int \text{all}}$$

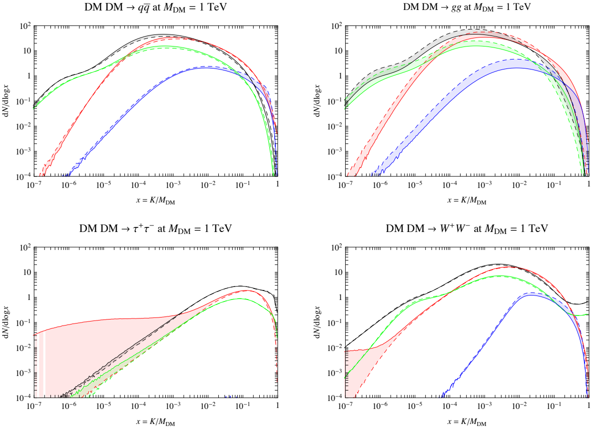
Conclusion 1: only problem for constraints $f < 0.03 - 0.05$.

Conclusion 2:

precision physics is not only a matter of higher orders.

5. Dark Matter annihilation

Common question: in my model DM particles annihilate pairwise. Given the mass and the two-body branching ratios, what is the spectrum of γ, $\mathrm{e}^{\pm}$, $\mathrm{p}/\overline{\mathrm{p}}$, ν?



photons

$\mathrm{e}^{\pm}$

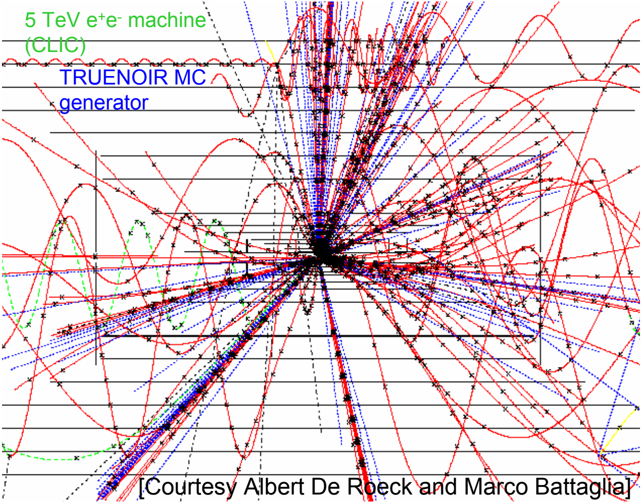
$\overline{\mathrm{p}}$

neutrinos

PYTHIA continuous
HERWIG dashed

M. Cirelli et al.,
JCAP 1103 (2011) 051,
JCAP 1210 (2012) E01

6. Black Hole evaporation

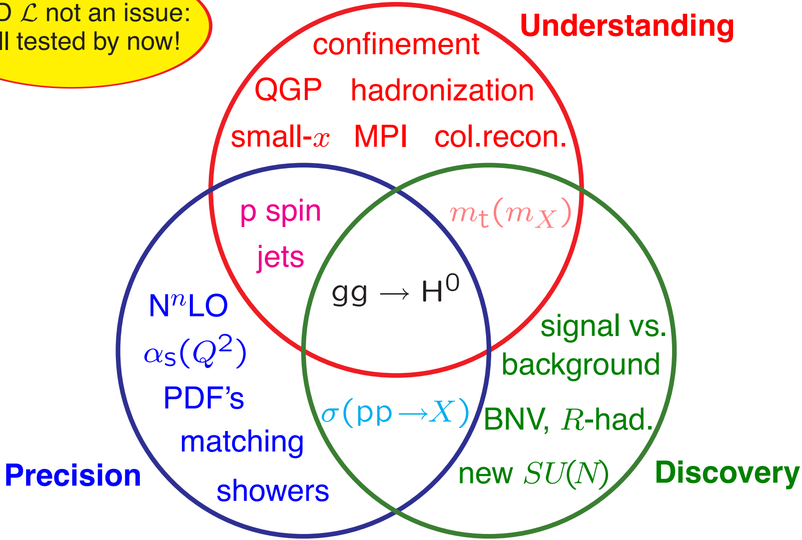


(in presentation by G. Landsberg, 2002)

- production
- spin-down
- Hawking radiation
- final evaporation
- remnants
- showers
- hadronization

The Three Frontiers of QCD

QCD $\mathcal{L}$ not an issue:
well tested by now!



QCD Precision

- LO MEs solved for all practical applications;
  bottleneck in efficient phase space selection
- NLO MEs now automatized: MadGraph5_aMC@NLO
- NNLO MEs current calculational frontier
- NNNLO MEs for $\mathrm{gg} \to \mathrm{H}$
- Parton distributions: NLO norm, but NNLO up and coming
- Match&Merge: different approaches to combine topologies
- Parton showers: formally LL, in reality NLL (partly tuning).
  - $p_\perp$-ordered dipole showers dominate; simpler match to MEs.
  - Provides Sudakov factors to remove M&M doublecounting.
  - Describes copious semisoft radiation, e.g. jet substructure.

Big, healthy community! Steady progress!

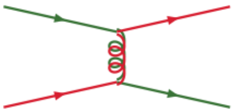
QCD Understanding

Smaller community for many topics. Slower progress.

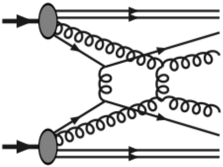
- Heavy Ions and QGP studies: doing fine.
- Parton showers:
  - Several new algorithms written.
  - Understanding maturing by comparison with MEs.
  - Better precision also for standalone use without M&M.
- Several areas with slow progress, by the usual suspects:
  - Hadronization: string vs. cluster fragmentation since 35 years.
  - Multiparton interactions: major ideas $>$ 25 years old.
  - Colour reconnection: major ideas $>$ 20 years old.
  - Beam remnants: standard approaches $>$ 10 years old.
  - Diffraction: Ingelman–Schlein Pomeron $>$ 30 years old.
- Other areas with essentially no progress:
  - Bose-Einstein: role still not understood;
    e.g.: does BE effects change multiplicity distribution?
  - Beginnings of a QGP in central LHC pp collisions?
  - Initially dense hadron gas: rescattering?

A proton is a bunch of partons: several parton-parton collisions per proton-proton one is unavoidable.

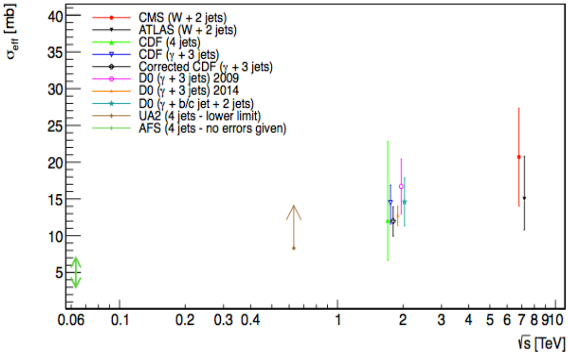
Normal QCD $2 \rightarrow 2$



supplemented by Double Parton Scattering (DPS)



and beyond (MPI)



$$\sigma_{AB} = \frac{1}{1+\delta_{AB}} \frac{\sigma_A \sigma_B}{\sigma_{\mathrm{eff}}}$$

so $\sigma_{\mathrm{eff}} \approx \sigma_{\mathrm{non-diff}}/2 \Rightarrow$ twice naive rate

The divergence of the QCD cross section

Cross section for $2 \to 2$ interactions is dominated by t-channel gluon exchange, so diverges like $\mathrm{d}\hat{\sigma}/\mathrm{d}p_{\perp}^2 \approx 1/p_{\perp}^4$ for $p_{\perp} \to 0$.
Also, $\int \mathrm{d}x\, f(x, p_{\perp}^2) = \infty$, i.e. infinitely many partons, so

$$\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) = \iiint_{p_{\perp\mathrm{min}}} \mathrm{d}x_1\, \mathrm{d}x_2\, \mathrm{d}p_{\perp}^2\, f_1(x_1, p_{\perp}^2)\, f_2(x_2, p_{\perp}^2)\, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_{\perp}^2}$$

diverges for $p_{\perp} \to 0$: unphysical!

MPIs half of solution, since then $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) > \sigma_{\mathrm{non-diff}}$ allowed, but not enough. Need regularization e.g. like

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_{\perp}^2} \propto \frac{\alpha_{\mathrm{s}}^2(p_{\perp}^2)}{p_{\perp}^4} \to \frac{\alpha_{\mathrm{s}}^2(p_{\perp 0}^2 + p_{\perp}^2)}{(p_{\perp 0}^2 + p_{\perp}^2)^2}$$

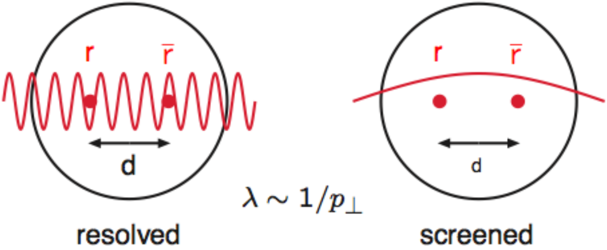
with $p_{\perp 0} \approx 2 - 3$ GeV to describe data.

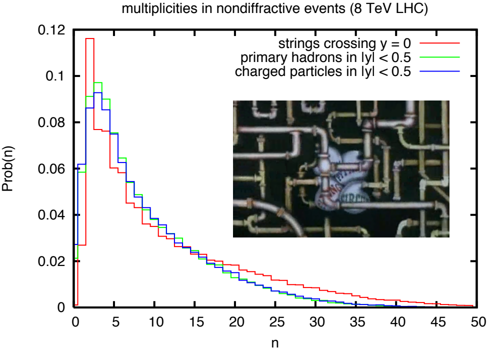
Other half of solution is that perturbative QCD is not valid at small $p_\perp$ since q, g are not asymptotic states (confinement!).

Naively breakdown at

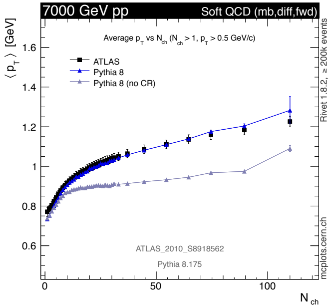
$$p_{\perp\mathrm{min}} \simeq \frac{\hbar}{r_\mathrm{p}} \approx \frac{0.2\ \mathrm{GeV} \cdot \mathrm{fm}}{0.7\ \mathrm{fm}} \approx 0.3\ \mathrm{GeV} \simeq \Lambda_\mathrm{QCD}$$

. . . but better replace r_p by (unknown) colour screening length d in hadron:





$\langle p_\perp \rangle (n_{\mathrm{ch}})$ effect:



String width $\sim$ hadronic width

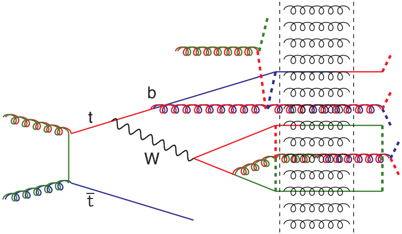
$\Rightarrow$ Overlap factor $\sim$ 10!

Larger for hard collisions
(small impact parameter)

Colour reconnection (CR):
reduce total string length
$\Rightarrow$ reduce hadronic multiplicity

$$\left.\begin{array}{l}\Gamma_{\mathrm{t}} \approx 1.5\ \mathrm{GeV} \\ \Gamma_{\mathrm{W}} \approx 2\ \mathrm{GeV} \\ \Gamma_{\mathrm{Z}} \approx 2.5\ \mathrm{GeV}\end{array}\right\} \Rightarrow c\tau \approx 0.1\ \mathrm{fm}:$$

p "pancakes" have passed,
MPI/ISR/FSR for $p_\perp \geq 2$ GeV,
inside hadronization colour fields.

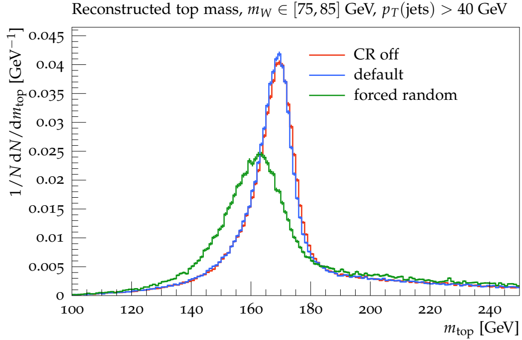


Experiment	m_{top} [GeV]	Error due to CR	Reference
World comb.	173.34±0.76	310 MeV (**40%**)	arXiv:1403.4427
CMS	172.22±0.73	150 MeV (**20%**)	CMS-PAS-TOP-14-001
D0	174.98±0.76	100 MeV (**13%**)	arXiv:1405.1756

(S. Argyropoulos)

1. Great job in reducing the errors.
2. CR is one of the dominant systematics.
3. Why is the CR uncertainty going down when there are
   - no advances in theoretical understanding, and
   - no measurements to constrain it?

Effects on top mass before tuning



Δm_{top} relative to no CR:

model	Δm_{top} [GeV]	Δm_{top} rescaled
default (late)	-0.415	$+0.209$
default early	$+0.381$	$+0.285$
forced random	-6.970	-6.508

Asymmetric spread:
$\Delta m_{top} < 0$ easy,
$\Delta m_{top} > 0$ difficult.

Parton showers already prefer minimal λ.

Main effect from jet broadening, some from jet–jet angles.

Effects on top mass after tuning

No publicly available measurements of UE in top events.

- Afterburner models tuned to ATLAS jet shapes in $\mathrm{t\bar{t}}$ events
  $\Rightarrow$ high CR strengths disfavoured.
- Early-decay models tuned to ATLAS minimum bias data
  $\Rightarrow$ maximal CR strengths required to (almost) match $\langle p_\perp \rangle(n_{\mathrm{ch}})$.

model	Δm_{top} rescaled
default (late)	$+0.239$
forced random	-0.524
swap	$+0.273$

Δm_{top} relative to no CR

$$\mathbf{m_{top}^{max} - m_{top}^{min} \approx 0.80\ \mathrm{GeV}}$$

Excluding most extreme (unrealistic) models down to

$$\mathbf{m_{top}^{max} - m_{top}^{min} \approx 0.50\ \mathrm{GeV}}$$

(in line with Sandhoff, Skands & Wicke)

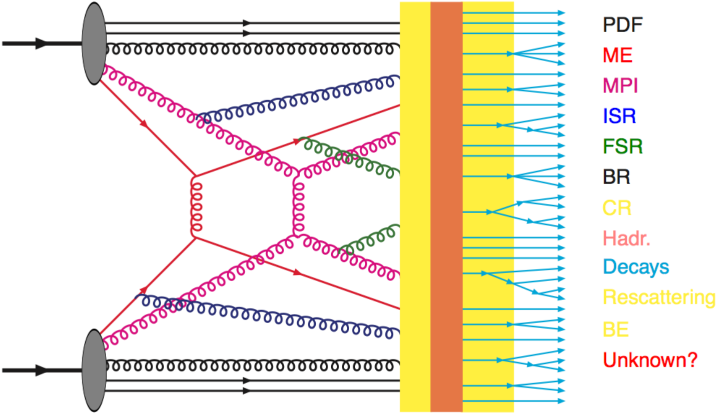
Studies of top events could help constrain models:

- jet profiles and jet pull (skewness)
- underlying event

Event Generators

Daunting complexity of LHC event.

General-purpose event generators: currently only way to break down the problem into manageable subtasks:



Better (alternative to) event generators?

The Workhorses: What are the Differences?

HERWIG, PYTHIA and SHERPA offer convenient frameworks for LHC physics studies, but with slightly different emphasis:

PYTHIA (successor to JETSET, begun in 1978):
- originated in hadronization studies: the Lund string
- leading in development of MPI for MB/UE
- pragmatic attitude to showers & matching

HERWIG (successor to EARWIG, begun in 1984):
- originated in coherent-shower studies (angular ordering)
- cluster hadronization & underlying event pragmatic add-on
- large process library with spin correlations in decays

SHERPA (APACIC++/AMEGIC++, begun in 2000):
- own matrix-element calculator/generator
- extensive machinery for CKKW ME/PS matching
- hadronization & min-bias physics under development

MCnet: combined projects, meetings & summer schools

Other Relevant Software

Some examples (with apologies for many omissions):

- Other event/shower generators: PhoJet, Ariadne, Dipsy, Cascade, Vincia
- Matrix-element generators: MadGraph/MadEvent, CompHep, CalcHep, Helac, Whizard, Sherpa, GoSam, aMC@NLO
- Matrix element libraries: AlpGen, POWHEG BOX, MCFM, NLOjet++, VBFNLO, BlackHat, Rocket
- Special BSM scenarios: Prospino, Charybdis, TrueNoir
- Mass spectra and decays: SOFTSUSY, SPHENO, HDecay, SDecay
- Feynman rule generators: FeynRules
- PDF libraries: LHAPDF
- Resummed ($p_\perp$) spectra: ResBos
- Approximate loops: LoopSim
- Jet finders: anti-$k_\perp$ and FastJet
- Analysis packages: Rivet, Professor, MCPLOTS
- Detector simulation: GEANT, Delphes
- Constraints (from cosmology etc): DarkSUSY, MicrOmegas
- Standards: PDG id's, LHA, LHEF, SLHA, LHAPDF, HepMC, Binoth, ...

Can be meaningfully combined and used for LHC physics!

Summary

QCD physics understanding and tools essential for BSM@LHC

- Matrix elements & PDFs: obvious & straightforward
- Parton showers: SUSY, Hidden Valley, Dark Matter
- MPI & Colour Reconnection: Higgs, mass of colored particles
- Hadronization: RPV, R-hadrons, HV, Higgs, DM, BH

In addition, QCD challenges in its own right

- Precision MEs, PDFs and showers
- Hadronization mechanisms
- Multiparton interactions
- Colour reconnections

QCD physics understanding and tools essential for BSM@LHC

- Matrix elements & PDFs: obvious & straightforward
- Parton showers: SUSY, Hidden Valley, Dark Matter
- MPI & Colour Reconnection: Higgs, mass of colored particles
- Hadronization: *R*PV, *R*-hadrons, HV, Higgs, DM, BH

In addition, QCD challenges in its own right

- Precision MEs, PDFs and showers
- Hadronization mechanisms
- Multiparton interactions
- Colour reconnections