QCD and BSM

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Intro: QCD, LHC and generators

BSM meets QCD
1. R-parity violation in SUSY
2. R-hadron phenomenology
3. Hidden Valleys
4. Higgs decays
5. Dark Matter annihilation
6. Black Hole evaporation

QCD and event generators
- The frontiers of QCD
- Multiparton Interactions and Colour Reconnection
- The top mass
- Event generators and other software

Outlook
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
Expect and observe high multiplicities at the LHC.

What are production mechanisms behind this?

How deal with complexity?
Dissection of an Event

1) hard process
2) resonance decays
3) ISR
4) FSR
5) underlying event
6) hadronisation
7) particle decays

Figure 2.12: Schematic of an example proton-proton to SM Higgs boson event produced by a general purpose Monte Carlo generator such as Pythia. The process begins with a $q\bar{q}$ hard process and then proceeds with resonance decays, FSR, ISR, the underlying event, hadronisation, and finally, particle decays.

Generators are publicly available, each with advantages and disadvantages, but the three primary general purpose generators are Pythia, Herwig++, and Sherpa.

A schematic of an example event produced by a general purpose Monte Carlo generator is provided in Fig. 2.12. This schematic is a simplification of the process, but attempts to provide all the salient features. The event generation begins with the calculation of the hard process by performing Monte Carlo integration of the cross-section formula of Eq. 2.65, where the matrix element is built from the elements of Sect. 2.1.2. In this example, the hard process is the production of an SM Higgs boson from a quark pair decaying into two $W$ bosons.

Next, resonance decays are performed, again using perturbative QFT and Monte Carlo integration. Resonance decays occur on a time-scale shorter than the hadronisation of quarks and gluons, and are primarily decays of $W$, $Z$, or Higgs bosons, or $t$-quarks. In Fig. 2.12, the $W^-$ from the hard process decays into a quark pair, and the $W^+$ into a lepton and neutrino.

After the hard process and resonance decays are simulated, the initial and final state quarks and gluons are dressed with parton showers which probabilistically simulate the radiation of gluons and quarks as determined by perturbative theory. The parton shower on the final state particles is labelled final state radiation (FSR) and the shower on the initial state particles is initial state radiation (ISR). Here, FSR is only performed on the decay products of the $W^-$ as the $W^+$ has not decayed to quarks or gluons. At this point electromagnetic final state radiation may also be

Sketch hides many further layers of complexity!
What is **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.

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

Who was Pythia?

The Oracle of Delphi:  
ca. 1000 B.C. — 390 A.D.
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 ⇒ relevant for LSP (Lightest Supersymmetric Particle).

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

What about showers and hadronization in decays?

The Lund string

In QCD, for large charge separation, field lines seem to be compressed to tubelike region(s) ⇒ string(s)

by self-interactions among soft gluons in the “vacuum”.

Gives linear confinement with string tension:
\[ F(r) \approx \text{const} = \kappa \approx 1 \text{ GeV/fm} \quad \iff \quad V(r) \approx \kappa r \]

Separation of transverse and longitudinal degrees of freedom ⇒ 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 $N_C \rightarrow \infty$
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 $T_i = \kappa \frac{p_i}{|p_i|}$ balance = 120° separation between quark directions.

This is not the CM frame where momenta $p_i$ 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
⇒ "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.
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. \( \tilde{g} \rightarrow \tilde{q}\bar{q} \rightarrow q\tilde{\chi}\bar{q} \).

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

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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, \ldots.

\( \Rightarrow \) Pythia allows for hadronization of 3 generic states:
- colour octet uncharged, like \( \tilde{g} \), giving \( \tilde{g}u\bar{d}, \tilde{g}uud, \tilde{g}g, \ldots \),
- colour triplet charge \( +2/3 \), like \( \tilde{t} \), giving \( \tilde{t}\bar{u}, \tilde{t}ud_0, \ldots \),
- colour triplet charge \( -1/3 \), like \( \tilde{b} \), giving \( \tilde{b}\bar{c}, \tilde{bsu}_1, \ldots \).
$R$-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:

- $\tilde{b}/\tilde{t}/\tilde{g}$ massive $\Rightarrow$ slow-moving, $\nu \sim 0.7c$.
- In $R$-hadron rest frame the detector has $\nu \sim 0.7c$ $\Rightarrow E_{\text{kin},p} \sim 1$ 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.
  \[
  R^+(\tilde{g}u\bar{d}) + n \rightarrow R^0(\tilde{g}d\bar{d}) + p.
  \]
  Gives alternating track/no-track in detector.
- Baryon-exchange predominantly one way,
  \[
  R^+(\tilde{g}u\bar{d}) + n \rightarrow R^0(\tilde{g}udd) + \pi^+,
  \]
  since (a) kinematically disfavoured ($\pi$ exceptionally light) and (b) few pions in matter.

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

3. Hidden Valleys: motivation

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

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

Torbjörn Sjöstrand QCD and BSM slide 16/39
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

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Either of two gauge groups,

1. Abelian $U(1)$, unbroken or broken (massless or massive $\gamma_V$),
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 $Z'$: $q\bar{q} \rightarrow Z' \rightarrow q_V\bar{q}_V$,
2. kinetic mixing: $q\bar{q} \rightarrow \gamma \rightarrow \gamma_V \rightarrow q_V\bar{q}_V$,
3. massive $F_V$ charged under both SM and hidden group, so e.g. $gg \rightarrow F_V\bar{F}_V$. Subsequent decay $F_V \rightarrow fq_V$.  

Torbjörn Sjöstrand QCD and BSM slide 17/39
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 $q_v \rightarrow q_v \gamma_v$ and $F_v \rightarrow F_v \gamma_v$.
HV $SU(N)$: add $q_v \rightarrow q_v g_v$, $F_v \rightarrow F_v g_v$ and $g_v \rightarrow g_v g_v$.

Recoil effects in visible sector also of invisible emissions!
Hidden Valley particles may remain invisible, or

- **Broken $U(1)$**: $\gamma_v$ acquire mass, radiated $\gamma_v$s decay back, $\gamma_v \rightarrow \gamma \rightarrow ff$ 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 $q_v \overline{q}_v \rightarrow ff$

Even when tuned to same average activity, hope to separate
4. Interconnection at LEP 2

\[ e^+e^- \rightarrow W^+W^- \rightarrow q_1q_2q_3q_4 \] reconnection limits \( m_W \) precision!

- **perturbative** \( \langle \delta M_W \rangle \lesssim 5 \text{ MeV} \): negligible!
  (killed by dampening from off-shell W propagators)

- **nonperturbative** \( \langle \delta M_W \rangle \sim 40 \text{ MeV} \):
  - favoured; no-effect option ruled out at 2.8\( \sigma \)
  (but more extreme models from other authors ruled out)

- **Bose-Einstein** \( \langle \delta M_W \rangle \lesssim 100 \text{ MeV} \): full effect ruled out.
  (but models with \( \sim 20 \text{ MeV} \) barely acceptable)
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.
Is the 125 GeV Higgs a pure \( CP \)-even state? Any odd admixture?

For LHC and future \( e^+e^- \) (\& \( \mu^+\mu^- \)) colliders to probe. One possibility is \( H^0 \rightarrow W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4 \).

Angular correlations put limits on odd admixture.

But: colour reconnection \( \Rightarrow \) shifted jet directions \( \Rightarrow \) shifted angular correlations.
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 $\gamma$, $e^\pm$, $p/\bar{p}$, $\nu$?

**DM DM $\rightarrow q\bar{q}$ at $M_{DM} = 1$ TeV**

**DM DM $\rightarrow gg$ at $M_{DM} = 1$ TeV**

**DM DM $\rightarrow \tau^+\tau^-$ at $M_{DM} = 1$ TeV**

**DM DM $\rightarrow W^+W^-$ at $M_{DM} = 1$ TeV**

**Comparison between Monte Carlo results**

**Photons**

**$e^\pm$**

**$p/\bar{p}$ neutrinos**

**Pythia continuous line**

**Herwig dashed line**

6. Black Hole evaporation

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

![Black Hole Event Display](image)

5 TeV $e^+e^-$ machine (CLIC)
TRUENOIR MC generator

[Courtesy Albert De Roeck and Marco Battaglia]

(in presentation by G. Landsberg, 2002)
The Three Frontiers of QCD

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

Understanding
- Confinement
- QGP hadronization
- Small-$x$ MPI col. recon.

Precision
- $N^n_{LO}$
- $\alpha_s(Q^2)$
- PDF’s matching showers

Discovery
- $gg \rightarrow H^0$
- $m_t(m_X)$
- Signal vs. background
- BNV, $R$-had.
- New $SU(N)$

Precision
- $\sigma(pp \rightarrow X)$
- $m_t(m_X)$
- Signal vs. background
- BNV, $R$-had
- New $SU(N)$
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 $gg \rightarrow H$
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!
Small 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)

\[ \sigma_{AB} = \frac{1}{1 + \delta_{AB}} \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \]

so $\sigma_{\text{eff}} \approx \sigma_{\text{non-diff}} / 2 \Rightarrow$ 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 $d\hat{\sigma}/dp_\perp^2 \approx 1/p_\perp^4$ for $p_\perp \to 0$. Also, $\int dx f(x, p_\perp^2) = \infty$, i.e. infinitely many partons, so

$$\sigma_{\text{int}}(p_{\perp \text{min}}) = \int \int \int_{p_{\perp \text{min}}} dx_1 dx_2 dp_\perp^2 f_1(x_1, p_\perp^2) f_2(x_2, p_\perp^2) \frac{d\hat{\sigma}}{dp_\perp^2}$$

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

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

$$\frac{d\hat{\sigma}}{dp_\perp^2} \propto \alpha_s^2(p_\perp^2) \frac{p_\perp^4}{p_\perp^4} \to \alpha_s^2(p_{\perp 0}^2 + p_\perp^2) \frac{p_\perp^4}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

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

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

$$p_{\perp\text{min}} \approx \frac{\hbar}{r_p} \approx \frac{0.2 \text{ GeV} \cdot \text{fm}}{0.7 \text{ fm}} \approx 0.3 \text{ GeV} \approx \Lambda_{\text{QCD}}$$

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

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

multiplicities in nondiffractive events (8 TeV LHC)

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

String width $\sim$ hadronic width
$\Rightarrow$ Overlap factor $\sim 10!$
A top mass puzzle

\[
\begin{aligned}
\Gamma_t &\approx 1.5 \text{ GeV} \\
\Gamma_W &\approx 2 \text{ GeV} \\
\Gamma_Z &\approx 2.5 \text{ GeV}
\end{aligned}
\] \Rightarrow c\tau \approx 0.1 \text{ fm}:

p “pancakes” have passed, MPI/ISR/FSR for \( p_\perp \geq 2 \text{ GeV} \), inside hadronization colour fields.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( m_{\text{top}} ) [GeV]</th>
<th>Error due to CR</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>World comb.</td>
<td>173.34±0.76</td>
<td>310 MeV (40%)</td>
<td>arXiv:1403.4427</td>
</tr>
<tr>
<td>CMS</td>
<td>172.22±0.73</td>
<td>150 MeV (20%)</td>
<td>CMS-PAS-TOP-14-001</td>
</tr>
<tr>
<td>D0</td>
<td>174.98±0.76</td>
<td>100 MeV (13%)</td>
<td>arXiv:1405.1756</td>
</tr>
</tbody>
</table>

(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

Reconstructed top mass, $m_W \in [75, 85]$ GeV, $p_T(\text{jets}) > 40$ GeV

<table>
<thead>
<tr>
<th>model</th>
<th>$\Delta m_{\text{top}}$ [GeV]</th>
<th>$\Delta m_{\text{top}}$ rescaled</th>
</tr>
</thead>
<tbody>
<tr>
<td>default (late)</td>
<td>$-0.415$</td>
<td>$+0.209$</td>
</tr>
<tr>
<td>default early</td>
<td>$+0.381$</td>
<td>$+0.285$</td>
</tr>
<tr>
<td>forced random</td>
<td>$-6.970$</td>
<td>$-6.508$</td>
</tr>
</tbody>
</table>

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

Parton showers already prefer minimal $\lambda$.

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

<table>
<thead>
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<th>$\Delta m_{\text{top}}$ rescaled</th>
</tr>
</thead>
<tbody>
<tr>
<td>default (late)</td>
<td>+0.239</td>
</tr>
<tr>
<td>forced random swap</td>
<td>−0.524</td>
</tr>
<tr>
<td></td>
<td>+0.273</td>
</tr>
</tbody>
</table>

$\Delta m_{\text{top}}$ relative to no CR

$\frac{m_{\text{top}}^{\text{max}} - m_{\text{top}}^{\text{min}}}{m_{\text{top}}^{\text{max}} - m_{\text{top}}^{\text{min}}} \approx 0.80$ GeV

Excluding most extreme (unrealistic) models down to

$\frac{m_{\text{top}}^{\text{max}} - m_{\text{top}}^{\text{min}}}{m_{\text{top}}^{\text{max}} - m_{\text{top}}^{\text{min}}} \approx 0.50$ GeV

(in line with Sandhoff, Skands & Wicke)

Studies of top events could help constrain models:

- jet profiles and jet pull (skewness)
- underlying event
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?
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, S Decay
- **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, MC PLOTS
- **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
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Thank you!