QCD and BSM

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Matter: quarks, leptons

Forces: electromagnetic, weak, strong

Higgs
The Standard Model of Particle Physics – 2

\[ \mathcal{L} = \sum_f \overline{\psi}_f \gamma^\mu iD_\mu \psi_f - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^i_{\mu\nu} W^i_{\mu\nu} - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} \]

\[ + (D_\mu \phi)\dagger (D_\mu \phi) - \mu^2 \phi\dagger \phi - \lambda (\phi\dagger \phi)^2 \]

\[ - \frac{\sqrt{2} \mu^2}{\lambda} \sum_{f,f'} M_{ff'} (\overline{\psi}_{L_f} \phi \psi_{R_{f'}} + \overline{\psi}_{R_{f'}} \phi\dagger \psi_{L_f}) , \]

\[ D_\mu = \partial_\mu + ig_1 \frac{Y}{2} B_\mu + ig_2 \frac{\tau^i}{2} W^i_\mu + ig_3 \frac{\lambda^a}{2} G^a_\mu , \]

\[ F^{a}_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu \quad (f^{abc} = 0 \text{ for } U(1)) . \]

Nonlinear equations, mathematically too complex to "solve".
Perturbation theory: expansion e.g. in orders of \( \alpha_{\text{em}} \).

\[ E_n = a_1 \alpha_{\text{em}} + a_2 \alpha_{\text{em}}^2 + a_3 \alpha_{\text{em}}^3 + \cdots \]
Strong interactions: Quantum ChromoDynamics (QCD)

\[ \alpha_s(M_Z) = 0.1185 \pm 0.0006 \]

\[ Q \text{ pole fit} \]

\[ \begin{align*}
\alpha_s(Q) & \quad 1 \quad 10 \quad 100 \\
Q [\text{GeV}] & \end{align*} \]

- \[ \alpha_s \gg \alpha_{\text{em}} \]
- \[ \alpha_s \rightarrow \infty \text{ for small scales} \]
- \[ \text{triple-gluon vertex: gluon self-interaction} \]
- \[ \text{quarks + gluons confined inside hadrons} \]

\[ \text{QCD } \alpha_s(M_Z) = 0.1185 \pm 0.0006 \]

- \( \tau \) decays (N^{3\text{LO}})
- Lattice QCD (NNLO)
- DIS jets (NLO)
- Heavy Quarkonia (NLO)
- e^{+}e^{-} jets & shapes (res. NNLO)
- Z pole fit (N^{3\text{LO}})
- pp \rightarrow \text{jets (NLO)} \]
High-energy collisions at the LHC

Strong interactions: observe high multiplicities at the LHC.
A scattered quark or gluon appers as a jet of particles — somehow.
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 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\[10,\,11,\,12\], Herwig\[72,\,73\], and Sherpa\[74,\,75\].

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 performed.

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.

Long-term development project.

Currently at Pythia 8.215:
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.
The Standard Model (SM) is successful, but flawed:

- Describes 5% of the energy content of the Universe.
- Dark Matter is 27% — new particle(s) to be found!
- Gravity not part of the SM; Dark Energy 68%.
- Divergences e.g. in Higgs mass $\Rightarrow$ extreme fine-tuning
  \[ (\delta m_e/m_e \sim \alpha_{em} \ln(m_{Pl}^2/m_e^2); \ \delta m_H^2 \sim m_{Pl}^2) \]
- $\sim 25$ free parameters, much arbitrariness
- How come $Q_e + Q_p \equiv 0$?
- (Matter-antimatter asymmetry of the Universe)
- (Neutrino masses)
- \ldots

**Anthropic principle:** we only exist because the Universe is flawed.
“Mirror” world, (more than) doubling up particle content. A SUSY partner for each SM particle, offset by spin 1/2. Cancels divergences, e.g. for Higgs mass.

Not without problems, e.g. \( \sim 100 \) more parameters. Intense multi-decade hunt unsuccessful.
Examples of other BSM physics

Superstrings requires big groups like $E_8 \times E_8$, where e.g. $E_8 \rightarrow E_6 \rightarrow SU(5) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$

- Unification of SM gauge groups.
- Many new matter and interaction particles.
- Weakly coupled “hidden” sectors, e.g. other $E_8$.
- Large extra dimensions.

Each topic can stand on its own.

Also many other possibilities, like

- a fourth generation,
- compositeness, or
- left–right symmetry.

Unknown which is right track, if any.
BSM at the LHC

BSM particles usually short-lived, or weakly interacting (like DM). Then visible final state consists of hadrons, leptons and photons, just like ordinary processes.

As easy to model as SM processes.
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As easy to model as SM processes.
Original structure hidden, but traces of it may be left in terms of invariant masses and angular distributions.

Discovery requires detailed understanding of rare signals and huge backgrounds.
LHC is a QCD machine:

- hard processes initiated by quarks and gluons,
- final state almost always dominated by hadrons,
- underlying event by QCD mechanisms (showers, MPIs, ...),
- 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
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: \( m(\tilde{b}) > m(\tilde{\chi}^0) \)

What about showers and hadronization in decays?

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 \( N_C/C_F = 9/4 \), → 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 $T_i = \kappa |p_i|/|p_i|$ balance $= 120^\circ$ 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 \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. \( \tilde{g} \rightarrow \tilde{q}\bar{q} \rightarrow q\tilde{\chi}\bar{q} \).

**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.
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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, . . . .

$\Rightarrow$ **Pythia** allows for hadronization of 3 generic states:

- colour octet uncharged, like $\tilde{g}$, giving $\tilde{g}u\bar{d}$, $\tilde{g}uud$, $\tilde{g}g$, . . . ,
- colour triplet charge $+2/3$, like $\tilde{t}$, giving $\tilde{t}\bar{u}$, $\tilde{t}ud_0$, . . . ,
- colour triplet charge $-1/3$, like $\tilde{b}$, giving $\tilde{b}\bar{c}$, $\tilde{bsu_1}$, . . . .
$R$-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 with matter involve interesting aspects:

- $\tilde{b}/\tilde{t}/\tilde{g}$ massive $\Rightarrow$ slow-moving, $v \sim 0.7c$.
- In $R$-hadron rest frame the detector has $v \sim 0.7c$ $\Rightarrow E_{\text{kin},p} \sim 1$ 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.
  \[ R^+(\tilde{g}\bar{u}\bar{d}) + n \rightarrow R^0(\tilde{g}\bar{d}\bar{d}) + p. \]
  Gives alternating track/no-track in detector.
- Baryon-exchange predominantly one way,
  \[ R^+(\tilde{g}\bar{u}\bar{d}) + n \rightarrow R^0(\tilde{g}udd) + \pi^+, \]
  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
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 $\gamma$),
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 $Z'$: $q^v q^v \rightarrow Z' \rightarrow q^v q^v$,
2. kinetic mixing: $q^v q^v \rightarrow \gamma \rightarrow \gamma q^v \rightarrow q^v q^v$,
3. massive $F^v$ charged under both SM and hidden group, so e.g. $gg \rightarrow F^v F^v$. Subsequent decay $F^v \rightarrow fq^v$.
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3. massive $F_v$ charged under both SM and hidden group, so e.g. $gg \rightarrow F_v \bar{F}_v$. Subsequent decay $F_v \rightarrow f q_v$. 
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 Valleys decays

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 $q_v \bar{q}_v \rightarrow ff$

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

\[ e^+ e^- \rightarrow W^+ W^- \rightarrow q_1 \bar{q}_2 q_3 \bar{q}_4 \] 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.

(schematic only; nothing to scale)
Is the 125 GeV Higgs a pure $CP$-even state? Any odd admixture?

For LHC and future $e^+e^-$ (and $\mu^+\mu^-$?) 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.
Common question: in my model DM particles annihilate pairwise. Given the mass and the two-body branching ratios, what is the spectrum of $\gamma$, $e^\pm$, $p/\bar{p}$, $\nu$?

- **photons**
- $e^\pm$
- **$\bar{p}$**
- **neutrinos**

**Pythia** continuous

**Herwig** dashed

6. Black Hole evaporation

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

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

[Courtesy Albert De Roeck and Marco Battaglia]

(in presentation by G. Landsberg, 2002)
QCD is not an issue: well tested by now!

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

Understanding

- $gg \rightarrow H^0$
- Precision
  - $N^nLO$
  - $\alpha_s(Q^2)$
  - PDF's
  - Matching
  - Showers
- Discovery
  - $\sigma(pp \rightarrow X)$
  - $m_t(m_X)$
  - Signal vs. background
  - BNV, $R$-had.
  - New $SU(N)$

- Torbjörn Sjöstrand QCD and BSM slide 34/42
Multiparton Interactions (MPIs)

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

Normal QCD $2 \to 2$

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
Cross section for $2 \rightarrow 2$ interactions is dominated by $t$-channel gluon exchange, so diverges like $d\hat{\sigma}/dp_{\perp}^2 \approx 1/p_{\perp}^4$ for $p_{\perp} \rightarrow 0$.

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 $p_{\perp} \rightarrow 0$: 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

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

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

\begin{align*}
\text{resolved} & \quad \lambda \sim \frac{1}{p_\perp} \\
\text{screened} & \quad d
\end{align*}
Colour reconnection (CR): reduce total string length ⇒ reduce hadronic multiplicity

String width ∼ hadronic width
⇒ Overlap factor ∼ 10!
Larger for hard collisions (small impact parameter)
A top mass puzzle

\[ \Gamma_t \approx 1.5 \text{ GeV} \]
\[ \Gamma_W \approx 2 \text{ GeV} \]
\[ \Gamma_Z \approx 2.5 \text{ GeV} \]

\[ \Rightarrow c\tau \approx 0.1 \text{ fm} : \]

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>

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

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.

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

<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>
No publicly available measurements of UE in top events.

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

<table>
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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

**Additional Information**

\[ m_{\text{top}}^{\text{max}} - m_{\text{top}}^{\text{min}} \approx 0.80 \text{ GeV} \]

Excluding most extreme (unrealistic) models down to

\[ m_{\text{top}}^{\text{max}} - m_{\text{top}}^{\text{min}} \approx 0.50 \text{ GeV} \]

(in line with Sandhoff, Skands & Wicke)

Studies of top events could help constrain models:

- jet profiles and jet pull (skewness)
- underlying event
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
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Thank you!