Mainly taken from presentations at “QCD, EW and tools at 100 TeV”, CERN, 7–9 October 2015, https://indico.cern.ch/event/437912 (report on arXiv within next few days) + some slides by Jesper Roy Christiansen
The kinematical range at 100 TeV (Juan Rojo)

Kinematics of a 100 TeV FCC

Plot by J. Rojo, Dec 2013

FCC 100 TeV

LHC 14 TeV

20 TeV Z’

2 TeV squarks

Higgs, top

W, Z

DY, low-pt jets

y=-8

y=-4

y=0

y=4

y=8
The role of small $x$ (Juan Rojo)

Small-$x$, small-$Q$ PDFs are required for the description of soft and semi-hard physics in MC generators. Can be quantified by sampling of Bjorken-$x$ in Pythia8 at 7 and 100 TeV.

At the LHC, small-$x$ PDFs are required down to $10^{-6}$ while at the FCC we require $10^{-8}$. 

P. Skands

Pythia8 Monash Tune: Skands, Carrazza, JR, 1404.5630
Small $x$ at small $Q^2$ (Juan Rojo)
Inelastic cross section (David d’Enterria)

\[ \sigma_{\text{tot}} = \sigma_{\text{elastic}} + \sigma_{\text{inel}} \]

- Non-computable from QCD Lagrangian (lattice?), but constrained by fundamental QM relations: Froisart bound, optical th., dispersion relations
- Similar MC predictions of \( \sigma_{\text{inel}} \) evolution, in agreement with LHC data:
  - (Interestingly, deviations seem to appear at energies above 100 TeV)

Models indicate: \( \sigma_{\text{inel}} (100 \text{ TeV}) = 103 \pm 3 \text{ mb} \)
Inelastic Cross Section = ND + SD + DD (+CD)

\[ \sigma_{ND}^{pp}(s) = \sigma_{INEL}^{pp}(s) - \int \left( d\sigma_{SD}^{pp \rightarrow Xp}(s) + d\sigma_{SD}^{pp \rightarrow pX}(s) + d\sigma_{DD}^{pp}(s) + d\sigma_{CD}^{pp}(s) \right) \]

Can in principle interfere

\[ \Rightarrow \text{model-dependent classification} \]

Define physical observables

(large gaps, identified protons, ...)

Too many large-gap events

Diffractive parameters in need of updating.

**Spectra: 5 different possibilities. Default is Schuler-Sjöstrand:**

\[ \frac{d\sigma_{SD}^{pp \rightarrow Xp}(s)}{dt \, dM_X^2} = \frac{g_{3p}^3 \beta_{pp}^3}{16\pi \, M_X^2} F_{SD}(M_X) \exp \left( B_{SD}^{Xp} t \right), \]

\[ \frac{d\sigma_{DD}^{pp}(s)}{dt \, dM_1^2 \, dM_2^2} = \frac{g_{3p}^2 \beta_{pp}^2}{16\pi \, M_1^2 \, M_2^2} F_{DD}(M_1, M_2) \exp \left( B_{DD} t \right) \]
solid curves: $M^{2}_X/s < 0.05$, dashed all diffraction

More on this tomorrow!
QCD jet cross section (Peter Skands)

Consider the inclusive-jet cross section in QCD

At LO = perturbative parton-parton (2→2) QCD cross section (tree-level)

$\sigma_{2\to 2} > \sigma_{pp}$ interpreted as consequence of each pp containing several 2→2 interactions: MPI
Interleaved Evolution (FSR + ISR + MPI)

Perturbative MPI evolution regulated by colour-screening scale $p_{T0}$

$$\frac{d\sigma_{2\rightarrow2}}{dp_{\perp}^2} \propto \frac{\alpha_s^2(p_{\perp}^2)}{p_{\perp}^4} \rightarrow \frac{\alpha_s^2(p_{\perp}^2 + p_{\perp 0}^2)}{(p_{\perp}^2 + p_{\perp 0}^2)^2}$$

$p_{T0}$ scales with CM energy: $p_{T0}^2(s) \propto s^\gamma$

- Old Default (4C) : $\gamma = 0.19$
- Monash 2013 : $\gamma = 0.215$
- New “Monash Slow” : $\gamma = 0.23$ (cutoff increases faster $\rightarrow N_{ch}$ grows slower)

Event structure (e.g., $N_{ch}$ distributions) further significantly affected by:

- Proton $b$ profile; Low-x PDFs; Colour Reconnections; Other collective effects?

Hadronization: Lund String Model

Jet Universality: fundamental parameters constrained by LEP data

No additional parameters for gluon jets, nor for pp collisions (modulo dynamics)
Central charged-track density (Peter Skands)

**Best measured: INEL > 0**
(at least one charged particle inside |eta| < 1)

A VERY SENSITIVE E-SCALING PROBE: relative increase in the central charged-track multiplicity from 0.9 to 2.36 and 7 TeV

**INEL > 0 |eta| < 1**

Data from ALICE EPJ C68 (2010) 345

![Graph showing data and models for INEL > 0](image)

INEL > 0
100 TeV: \( \frac{<N_{ch}>}{\Delta \eta \Delta \varphi} = 1.75 \pm 0.15 \)

drops to 1.5 ± 0.15 including all inelastic
 Cosmic Ray Scales (David d’Enterria)

- CR energy & identity for $E_{CR} = 10^{15} - 10^{21}$ eV determined using atmosphere as "calorimeter" and comparing shower to hadronic MCs:
  - CR+Air collisions: QCD interactions at c.m. energies up to $\sqrt{s_{GZK}} \sim 300$ TeV

Extended Air Showers (EAS)

- CR energy & identity for $E_{CR} = 10^{15} - 10^{21}$ eV determined using atmosphere as "calorimeter" and comparing shower to hadronic MCs:
  - CR+Air collisions: QCD interactions at c.m. energies up to $\sqrt{s_{GZK}} \sim 300$ TeV

Extended Air Showers (EAS)
Reggeon-Field-Theory models (David d’Enterria)

- **Soft interactions via Reggeons & Pomerons:**
  Elastic/Diffractive/Inelastic scatts. consistently treated through unitarity/analyticity/crossing

- **Perturbative interactions via**
  “cut (hard) Pomerons” (≈ LO pQCD)

- **Semi-hard dynamics:**
  - eikonal (multi)parton ladders (p-A, A-A possible)
  - parton saturation via enhanced $|P|$ diags, or running $p_{T,0} \sim Q_{\text{sat}}$ (as PYTHIA/HERWIG)

- **Non-perturbative ingredients:**
  - string fragmentation (Lund model)
  - beam-remnants

- **Model parameters:**
  - Tuned with accelerator data.
  - $O(20)$, much less than in std collider MCs
~50% of charged-hadron production due to semihard MPI activity:

- EPOS, QGSJET-II and PYTHIA 8 very similar results:
  \[ \frac{dN_{\text{ch}}}{d\eta}(\text{NSD})=11\pm0.5, \; \frac{dN_{\text{ch}}}{d\eta}(\text{inel})=9.5\pm1.0 \]

- PYTHIA 6 & PHOJET “thinner” distributions (impact of low-x PDFs). PHOJET lower by ~40% (wrong \( Q_s \) running? not enough MPIs?).
Per-event charged multiplicity at $\eta=0$ for low & large $N_{\text{ch}}$:

- Multiplicity peak (dominated by diffractive processes)
- High-multiplicity tails (dominated by MPIs)

P(large $N_{\text{ch}}$): EPOS/QGSJET-II similar, PYTHIA $\sim$smaller, PHOJET off

$>1\%$ probability of $N_{\text{ch}}>100$ within $|\eta|<1$

P(low $N_{\text{ch}}$): PYTHIA/PHOJET less soft/diffractive activity.
\(<p_T>\) is sensitive to pQCD x-sections, gluon saturation and possible final-state collective flow:

- CRs MCs predict slower \(<p_T>\) evolution than PYTHIA (less minijets).
- At FCC-100 TeV: \(<p_T> = 0.65–0.75\text{ GeV/c}\) (PYTHIA: \(<p_T> = 0.8\text{ GeV/c}\)
The ridge effect (David d’Enterria)

- Long-range (over $\Delta \eta \sim 8$) near-side hadron correlations “ridge” in central (high multiplicity) $pp$, $pPb$ and $PbPb$ collisions at LHC:

  - **Pb+Pb 2.76 TeV**
  - **p+Pb 5.02 TeV**
  - **p+p 7 TeV**

- **Initial-state?** Correlated gluons around saturation scale:
  - Multiparton interactions enhance the near-side diagrams

- **Final-state?** Collective parton-flow:
  - Hydro calculations (EPOS) reproduce well the details of such structure
Colour Reconnection (CR)

CR needed to explain e.g. $\langle p_{\perp} \rangle(n_{ch})$, 1987 and now:

**FIG. 27.** Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings only; dotted line, $gg$ scatterings with “maximal” string length; solid line $gg$ scatterings with “minimal” string length.

CR reduces total string length
⇒ reduces hadronic multiplicity
The new QCD-based CR model (Christiansen + Skands)

New model relies on two main principles

- **SU(3)** colour rules give allowed reconnections

<table>
<thead>
<tr>
<th>Ordinary string reconnection</th>
<th>Double junction reconnection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q \quad \bar{q} \quad \bar{q}$</td>
<td>$q \quad \bar{q} \quad \bar{q}$</td>
</tr>
<tr>
<td>$q \quad \bar{q}$</td>
<td>$q \quad \bar{q}$</td>
</tr>
<tr>
<td>$q \quad \bar{q}$</td>
<td>$q \quad \bar{q}$</td>
</tr>
<tr>
<td>$(q\bar{q}: 1/9, \text{gg: } 1/8, \text{model: } 1/9)$</td>
<td>$(qq: 1/3, \text{gg: } 10/64, \text{model: } 2/9)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Triple junction reconnection</th>
<th>Zipping reconnection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q \quad \bar{q} \quad \bar{q}$</td>
<td>$q \quad g \quad g \quad q \quad \bar{q}$</td>
</tr>
<tr>
<td>$q \quad \bar{q}$</td>
<td>$q \quad \bar{q}$</td>
</tr>
<tr>
<td>$q \quad \bar{q}$</td>
<td>$q \quad \bar{q}$</td>
</tr>
<tr>
<td>$(q\bar{q}: 1/27, \text{gg: } 5/256, \text{model: } 2/81)$</td>
<td>(Depends on number of gluons)</td>
</tr>
</tbody>
</table>

- minimal $\lambda$ measure gives preferred reconnections

$$\lambda \approx \sum_{\text{dipoles}} \ln(1 + \frac{m_{ij}^2}{m_0^2}) \text{ measure of string length, } \propto n_{\text{hadronic}}$$
The new QCD-based CR model (Christiansen + Skands)

Comparison with LHC data:

- $\Lambda/K^0_S$ versus transverse momentum at $\sqrt{s} = 7$ TeV

![Graph showing comparison of data, new model, and Monash model](image)

(arXiv:1102.4282)

- Many baryons from junctions, but few from regular strings (big-mass string systems cut up!)

![Graph showing multiplicity and string masses](image)
A top mass puzzle (Spyros Argyropoulos)

\[ \begin{align*}
\Gamma_t & \approx 1.5 \text{ GeV} \\
\Gamma_W & \approx 2 \text{ GeV} \\
\Gamma_Z & \approx 2.5 \text{ GeV}
\end{align*} \]

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

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( \pm )0.76</td>
<td>310 MeV (40%)</td>
<td>arXiv:1403.4427</td>
</tr>
<tr>
<td>CMS</td>
<td>172.22( \pm )0.73</td>
<td>150 MeV (20%)</td>
<td>CMS-PAS-TOP-14-001</td>
</tr>
<tr>
<td>D0</td>
<td>174.98( \pm )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?
• Afterburner models tuned to ATLAS jet shapes in $t\bar{t}$ events ⇒ high CR strengths disfavoured.
• Early-decay models tuned to ATLAS minimum bias data ⇒ maximal CR strengths required to (almost) match $\langle p_\perp \rangle(n_{ch})$.

Excluding most extreme (unrealistic) models

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

(in line with Sandhoff, Skands & Wicke)

New: $\Delta m_{\text{top}} \approx 0$ in QCD-based model

Studies of top events could help constrain models:
• jet profiles and jet pull (skewness)
• underlying event

Impacts any future precision measurement involving (partly) hadronic final state.
Weak correction to QCD 2 jets has log enhancement of form $\alpha_{\text{weak}} \ln^2 \left( \frac{p_T^2}{m_W^2} \right)$.
PYTHIA QCD shower starting from $q\bar{q} \rightarrow Z^0$ underestimates $Z + n$ jet rate.
Implement W/Z emission as part of standard shower.
Add contribution to W/Z production from QCD $2 \to 2$. 

$\sigma(\geq N_{\text{jet}}, Z \to \mu^+\mu^-, p_{\perp}(\text{jet}) > 30 \text{ GeV}, |y_{\text{jet}}| < 4.4)$

<table>
<thead>
<tr>
<th>$N_{\text{jet}}$</th>
<th>MC/data</th>
<th>MC/Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>4</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>5</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td>6</td>
<td>1.8</td>
<td>2.0</td>
</tr>
<tr>
<td>7</td>
<td>2.0</td>
<td>2.2</td>
</tr>
</tbody>
</table>

$\frac{d\sigma}{dp_{\perp}} [\text{ pb/GeV}]$

<table>
<thead>
<tr>
<th>$p_{\perp}$</th>
<th>ATLAS data</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.6</td>
</tr>
<tr>
<td>60</td>
<td>0.8</td>
</tr>
<tr>
<td>80</td>
<td>1.0</td>
</tr>
<tr>
<td>100</td>
<td>1.2</td>
</tr>
<tr>
<td>120</td>
<td>1.4</td>
</tr>
<tr>
<td>140</td>
<td>1.6</td>
</tr>
<tr>
<td>160</td>
<td>1.8</td>
</tr>
<tr>
<td>180</td>
<td>2.0</td>
</tr>
</tbody>
</table>

$\sigma_{\text{Combined}}$
Angular distributions still not great: $\varphi$ selection too simple.
Input for merging, with broader range of shower histories.