Monte Carlo Generators and Soft QCD

3. MultiParton Interactions and Hadronization

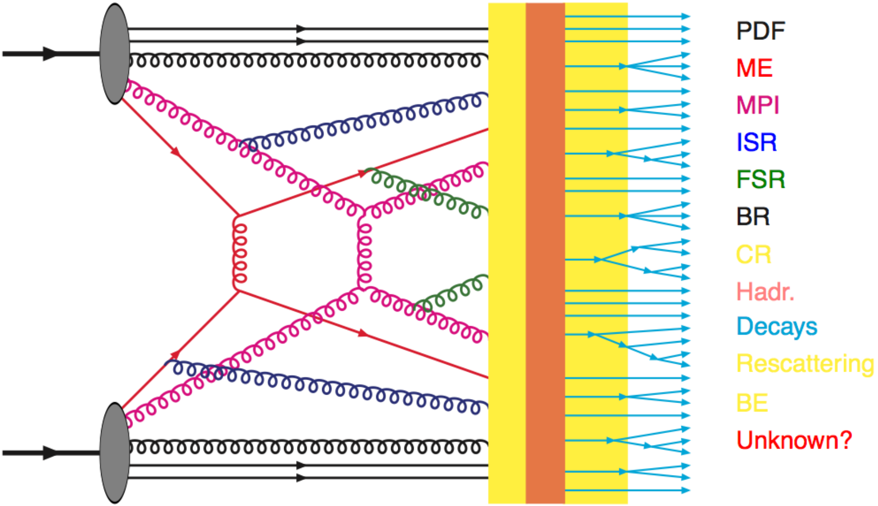
Torbjörn Sjöstrand

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

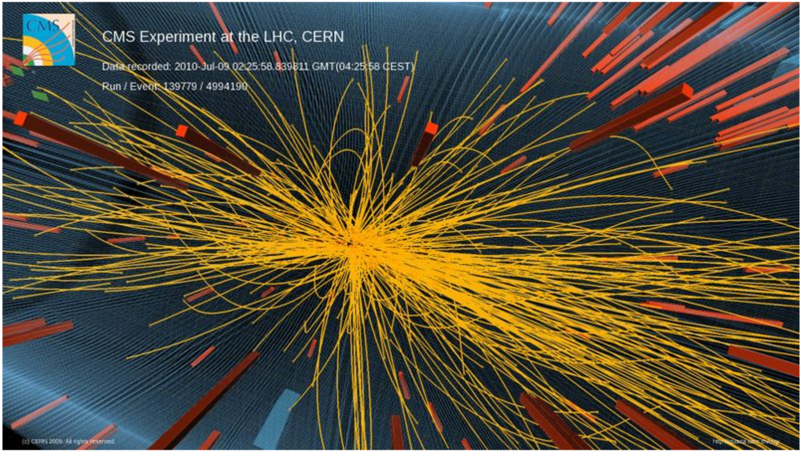
CERN, 3 September 2013

Event Generators Reminder

An event consists of many different physics steps, which have to be modelled by event generators:



Event topologies



Expect and observe high multiplicities at the LHC.

What are production mechanisms behind this?

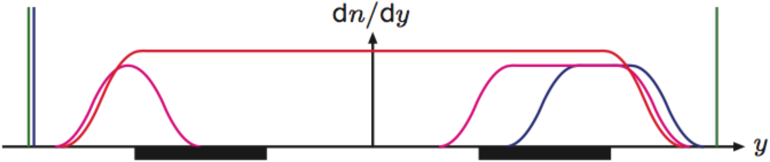
What is minimum bias (MB)?

MB ≈ "all events, with no bias from restricted trigger conditions"

$\sigma_{\text{tot}} =$

$\sigma_{\text{elastic}} + \sigma_{\text{single-diffractive}} + \sigma_{\text{double-diffractive}} + \cdots + \sigma_{\text{non-diffractive}}$

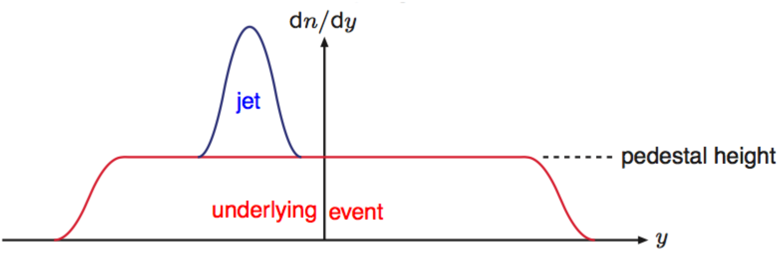
Schematically:



Reality: can only observe events with particles in central detector: no universally accepted, detector-independent definition

$\sigma_{\text{min-bias}} \approx \sigma_{\text{non-diffractive}} + \sigma_{\text{double-diffractive}} \approx 2/3 \times \sigma_{\text{tot}}$

What is underlying event (UE)?

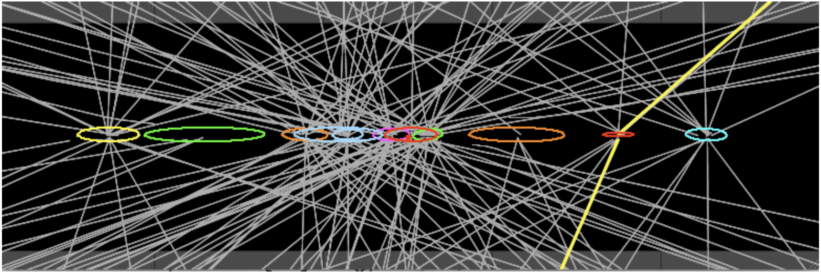


In an event containing a jet pair or another hard process, how much further activity is there, that does not have its origin in the hard process itself, but in other physics processes?

Pedestal effect: the UE contains more activity than a normal MB event does (even discarding diffractive events).

Trigger bias: a jet "trigger" criterion $E_{\perp \mathrm{jet}} > E_{\perp \mathrm{min}}$ is more easily fulfilled in events with upwards-fluctuating UE activity, since the UE $E_{\perp}$ in the jet cone counts towards the $E_{\perp \mathrm{jet}}$. *Not enough!*

What is pileup?



$\langle n \rangle = \overline{\mathcal{L}}\,\sigma$

where $\overline{\mathcal{L}}$ is machine luminosity per bunch crossing, $\overline{\mathcal{L}} \sim n_1 n_2 / A$ and $\sigma \sim \sigma_{\mathrm{tot}} \approx 100$ mb.

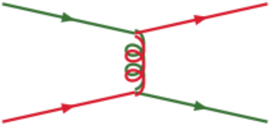
Current LHC machine conditions $\Rightarrow \langle n \rangle \sim 10 - 20$.

Pileup introduces no new physics, and is thus not further considered here, but can be a nuisance.

However, keep in mind concept of bunches of hadrons leading to multiple collisions.

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 $p_{\perp} \to 0$.



Integrate QCD $2 \to 2$

$\mathrm{qq}' \to \mathrm{qq}'$

$\mathrm{q\overline{q}} \to \mathrm{q}'\overline{\mathrm{q}}'$

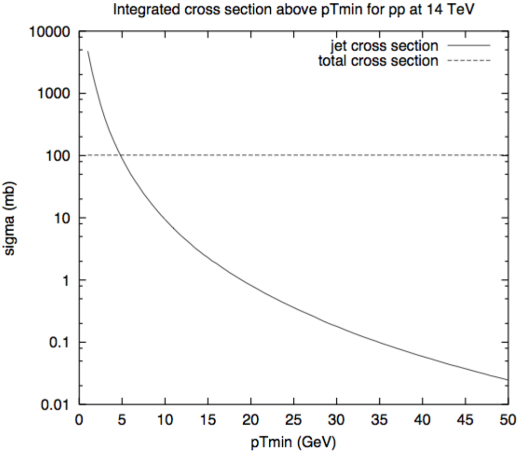
$\mathrm{q\overline{q}} \to \mathrm{gg}$

$\mathrm{qg} \to \mathrm{qg}$

$\mathrm{gg} \to \mathrm{gg}$

$\mathrm{gg} \to \mathrm{q\overline{q}}$

(with CTEQ 5L PDF's)



What is multiple partonic interactions (MPI)?

Note that $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}})$, the number of ($2 \to 2$ QCD) interactions above $p_{\perp\mathrm{min}}$, involves integral over PDFs,

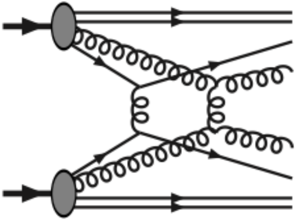
$$\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) = \iiint_{p_{\perp\mathrm{min}}} \mathrm{d}x_1 \, \mathrm{d}x_2 \, \mathrm{d}p_{\perp}^2 \, f_1(x_1, p_{\perp}^2) \, f_2(x_2, p_{\perp}^2) \, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_{\perp}^2}$$

with $\int \mathrm{d}x \, f(x, p_{\perp}^2) = \infty$, i.e. infinitely many partons.

So half a solution to $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) > \sigma_{\mathrm{tot}}$ is

many interactions per event: MPI (historically MI or MPPI)

$$\begin{aligned} \sigma_{\mathrm{tot}} &= \sum_{n=0}^{\infty} \sigma_n \\ \sigma_{\mathrm{int}} &= \sum_{n=0}^{\infty} n \, \sigma_n \\ \sigma_{\mathrm{int}} &> \sigma_{\mathrm{tot}} \iff \langle n \rangle > 1 \end{aligned}$$



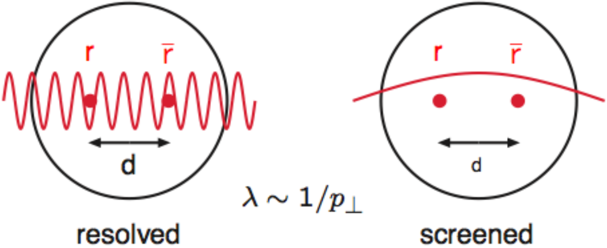
Colour screening

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

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

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

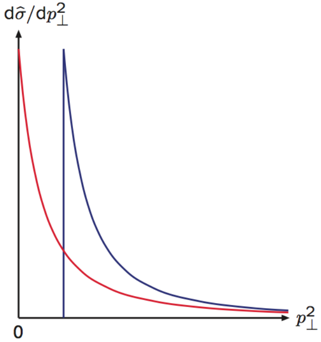


Regularization of low-$p_\perp$ divergence

so need $\boxed{\textbf{nonperturbative regularization for } p_\perp \to 0}$, e.g.

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \quad \to \quad \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4}\,\theta\left(p_\perp - p_{\perp\mathrm{min}}\right) \qquad \text{(simpler)}$$

$$\text{or} \quad \to \quad \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2} \qquad \text{(more physical)}$$

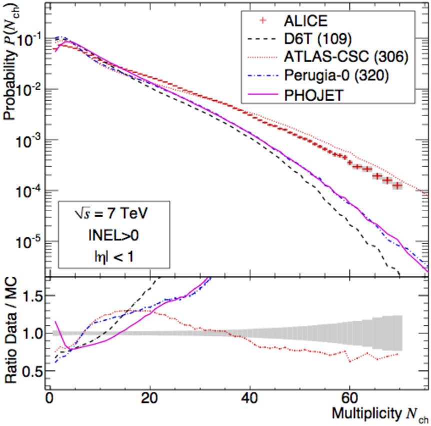


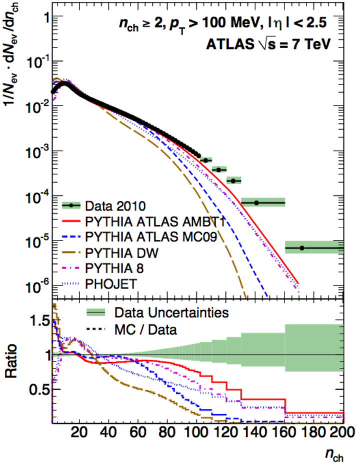
where $p_{\perp\mathrm{min}}$ or $p_{\perp 0}$ are free parameters, empirically of order **2 GeV**.

Typically 2 – 3 interactions/event at the Tevatron, 4 – 5 at the LHC, but may be more in "interesting" high-$p_\perp$ ones.

MPI effects

By now several direct tests of back-to-back jet pairs and similar.
However, only probes high-$p_\perp$ tail of effects.
More direct and dramatic are effects on multiplicity distributions:





MPI and event generators

All modern general-purpose generators are built on MPI concepts.

PYTHIA implementation main points:

- MPIs are gererated in a falling sequence of $p_\perp$ values; recall Sudakov factor approach to parton showers.
- Multiparton PDFs: energy, momentum and flavour are subtracted from proton by all “previous” collisions.
- Protons modelled as extended objects, allowing both central and peripheral collisions, with more or less activity.
- (Partons at small x more broadly spread than at large x.)
- Colour screening increases with energy, i.e. $p_{\perp 0} = p_{\perp 0}(E_{\mathrm{cm}})$, as more and more partons can interact.
- (Rescattering: one parton can scatter several times.)
- Colour connections: each interaction hooks up with colours from beam remnants, but also correlations inside remnants.
- Colour *re*connections: many interaction “on top of” each other $\Rightarrow$ tightly packed partons $\Rightarrow$ colour memory loss?

Interleaved evolution

- Transverse-momentum-ordered parton showers for ISR and FSR.
- MPI also ordered in $p_\perp$.

⇒ Allows interleaved evolution for ISR, FSR and MPI:

$$\begin{aligned}\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} &= \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_\perp}\right) \\ &\times \quad \exp\left(-\int_{p_\perp}^{p_{\perp\mathrm{max}}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_\perp}\right) \mathrm{d}p'_\perp\right)\end{aligned}$$

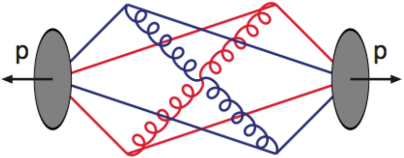
Ordered in decreasing $p_\perp$ using "Sudakov" trick.

Corresponds to increasing "resolution":
smaller $p_\perp$ fill in details of basic picture set at larger $p_\perp$.

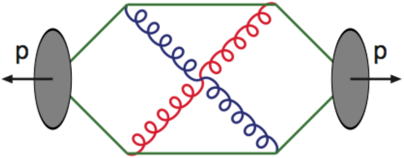
- Start from fixed hard interaction ⇒ underlying event
- No separate hard interaction ⇒ minbias events
- Possible to choose two hard interactions, e.g. $\mathrm{W}^-\mathrm{W}^-$

Colour correlations and $\langle p_\perp \rangle (n_{\mathrm{ch}})$ – 1

$\langle p_\perp \rangle (n_{\mathrm{ch}})$ is very sensitive to colour flow



long strings to remnants ⇒ much n_{ch}/interaction ⇒ $\langle p_\perp \rangle (n_{\mathrm{ch}}) \sim$ flat



short strings (more central) ⇒ less n_{ch}/interaction ⇒ $\langle p_\perp \rangle (n_{\mathrm{ch}})$ rising

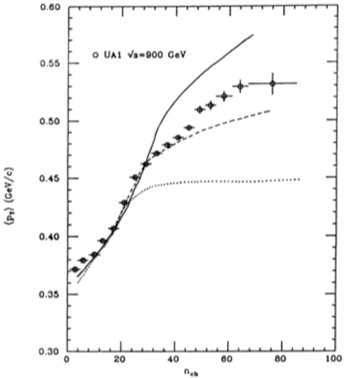
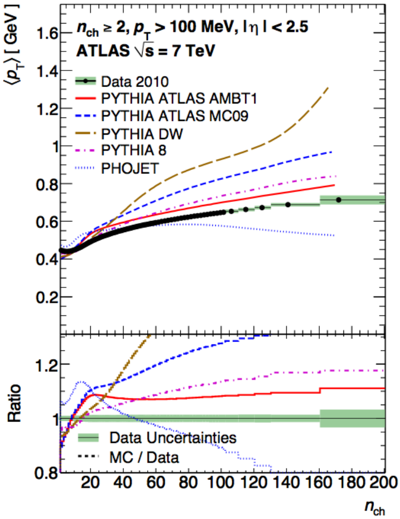
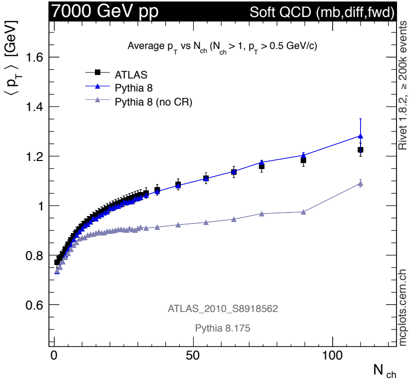


FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings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

Colour correlations and $\langle p_\perp \rangle (n_{\mathrm{ch}})$ – 2

Comparison with data, generators before and after LHC data input:



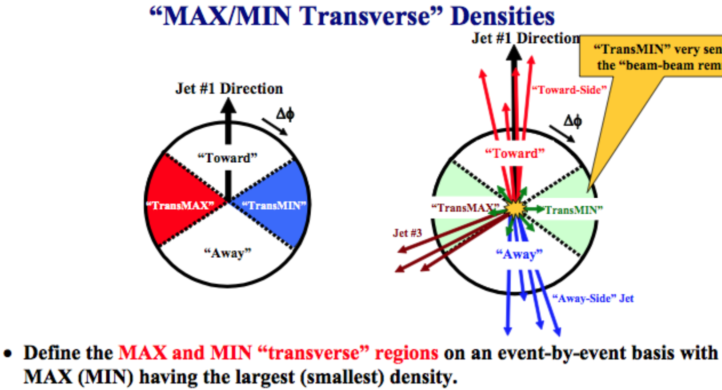


see also A. Buckley et al., Phys. Rep. 504 (2011) 145 [arXiv:1101.2599[hep-ph]]

Jet pedestal effect – 1

Events with hard scale (jet, W/Z) have more underlying activity!
Events with *n* interactions have *n* chances that one of them is hard,
so "trigger bias": hard scale ⇒ central collision
⇒ more interactions ⇒ larger underlying activity.

Studied in particular by Rick Field, with CDF/CMS data:

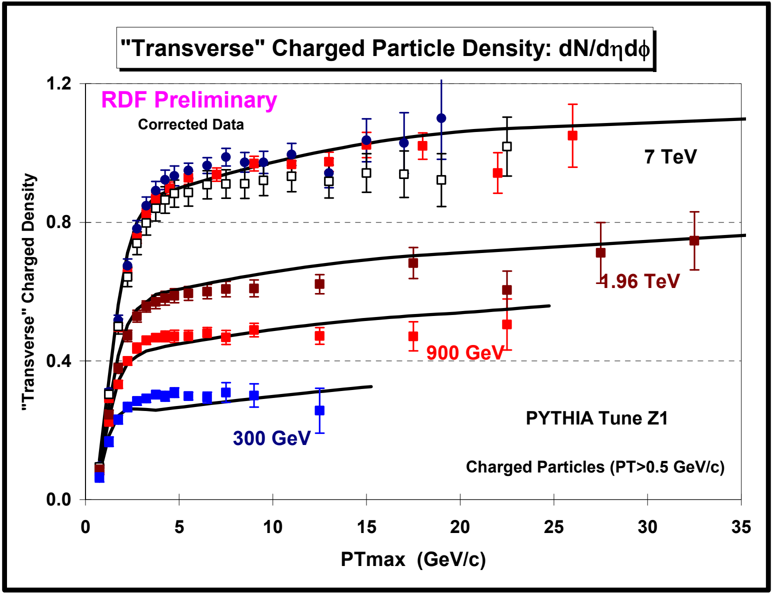


"MAX/MIN Transverse" Densities

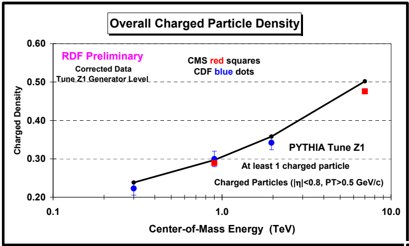
"TransMIN" very sensitive to the "beam-beam remnants"!

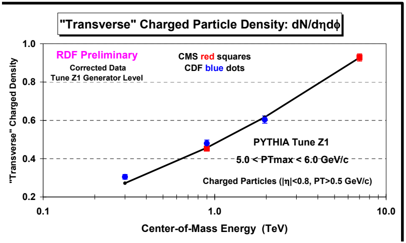
- **Define the MAX and MIN "transverse" regions on an event-by-event basis with MAX (MIN) having the largest (smallest) density.**

Jet pedestal effect – 2

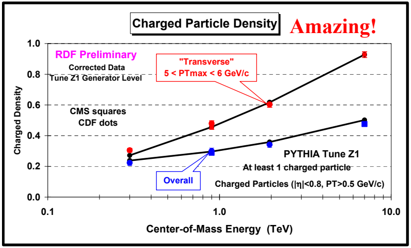


Jet pedestal effect – 3





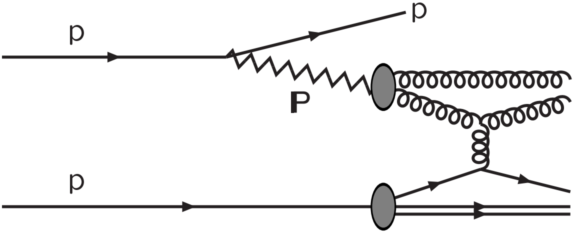
- **Corrected CDF and CMS data on the overall density of charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ for events with at least one charged particle with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ and on the charged particle density, in the "transverse" region as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ with 5 < PTmax < 6 GeV/c. The data are plotted versus the center-of-mass energy (*log scale*).**



Conclusion: "transMIN" (MPI+BBR) increases much faster with E_{cm} than "transDIF" (ISR+FSR), proportionately speaking.

Diffraction

Ingelman-Schlein: Pomeron as hadron with partonic content
Diffractive event = (Pomeron flux) × ($\mathbb{P}$p collision)



Used e.g. in
POMPYT
POMWIG
PHOJET

1) σ_{SD} and σ_{DD} taken from existing parametrization or set by user.

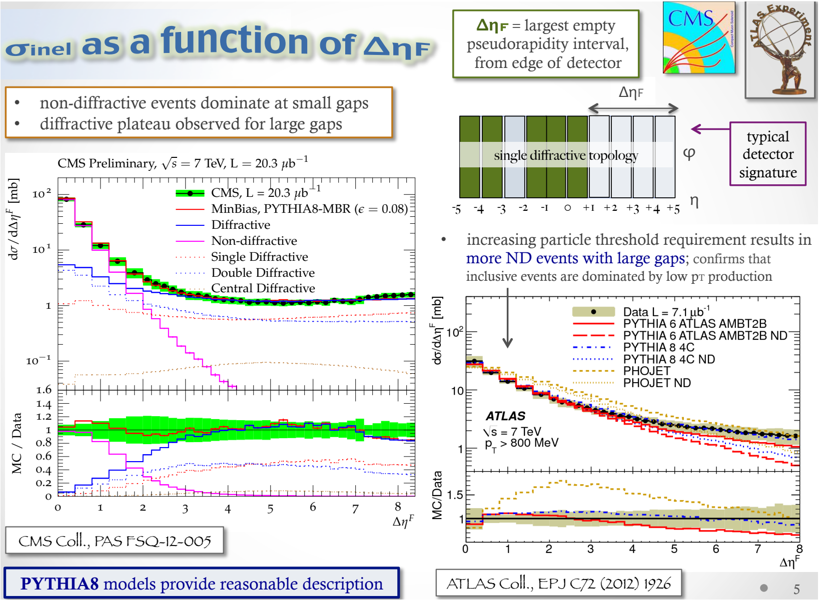
2) $f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t) \Rightarrow$ diffractive mass spectrum, $p_{\perp}$ of proton out.

3) Smooth transition from simple model at low masses to $\mathbb{P}$p with full pp machinery: multiple interactions, parton showers, etc.

4) Choice between 5 Pomeron PDFs.

5) Free parameter $\sigma_{\mathbb{P}\mathrm{p}}$ needed to fix $\langle n_{\mathrm{interactions}} \rangle = \sigma_{\mathrm{jet}}/\sigma_{\mathbb{P}\mathrm{p}}$.

Diffraction data



σ_{inel} as a function of $\Delta\eta_F$

- non-diffractive events dominate at small gaps
- diffractive plateau observed for large gaps

CMS Coll., PAS FSQ-12-005

PYTHIA8 models provide reasonable description

$\Delta\eta_F$ = largest empty pseudorapidity interval, from edge of detector

typical detector signature

- increasing particle threshold requirement results in more ND events with large gaps; confirms that inclusive events are dominated by low p_T production

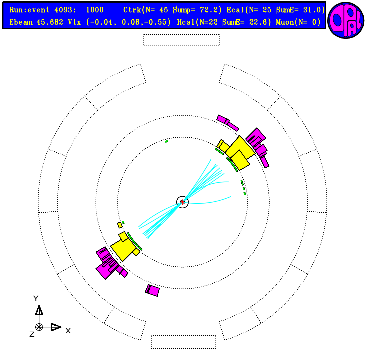
ATLAS Coll., EPJ C72 (2012) 1926

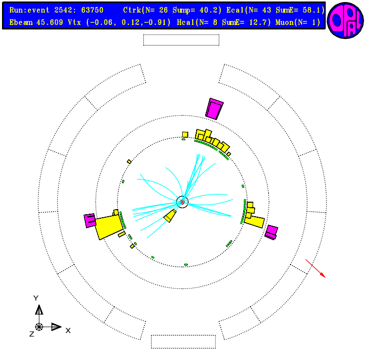
(C. Gwenlan, EPSHEP 2013)

Hadronization

Hadronization/confinement is nonperturbative ⇒ only models.

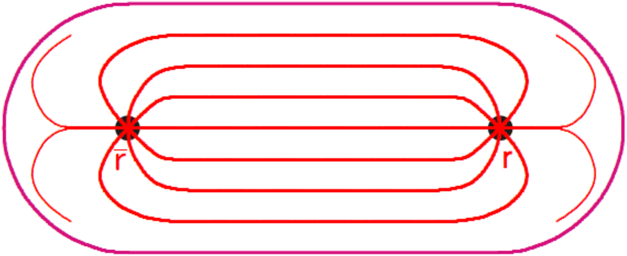
Begin with $\mathrm{e}^+\mathrm{e}^- \to \gamma^*/\mathrm{Z}^0 \to \mathrm{q}\overline{\mathrm{q}}$ and $\mathrm{e}^+\mathrm{e}^- \to \gamma^*/\mathrm{Z}^0 \to \mathrm{q}\overline{\mathrm{q}}\mathrm{g}$:





The QCD potential – 1

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



Gives force/potential between a q and a $\overline{\mathrm{q}}$:

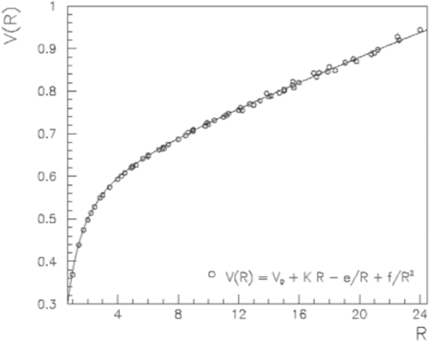
$F(r) \approx \mathrm{const} = \kappa \quad \Longleftrightarrow \quad V(r) \approx \kappa r$

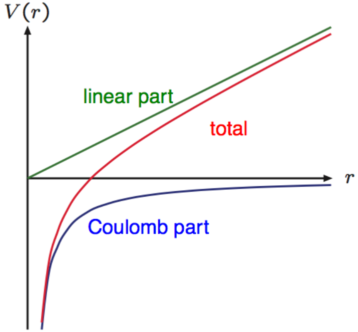
$\kappa \approx 1\ \mathrm{GeV/fm}$ ≈ potential energy gain lifting a 16 ton truck.

Flux tube parametrized by center location as a function of time ⇒ simple description as a 1+1-dimensional object – a string.

The QCD potential – 2

Linear confinement confirmed e.g. by lattice QCD calculation of gluon field between a static colour and anticolour charge pair:

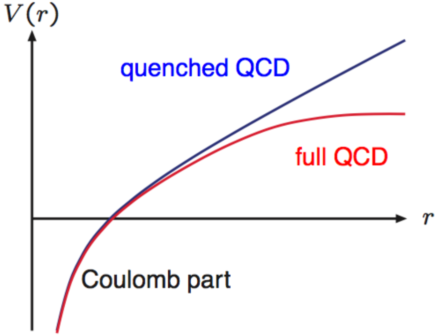


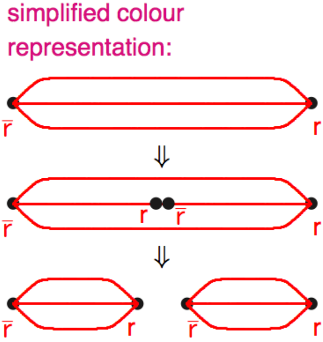


At short distances also Coulomb potential, important for internal structure of hadrons, but not for particle production (?).

The QCD potential – 3

Full QCD = gluonic field between charges ("quenched QCD")
plus virtual fluctuations $\mathrm{g} \rightarrow \mathrm{q}\overline{\mathrm{q}}\,(\rightarrow \mathrm{g})$
$\Longrightarrow$ nonperturbative string breakings $\mathrm{gg}\ldots \rightarrow \mathrm{q}\overline{\mathrm{q}}$





String motion

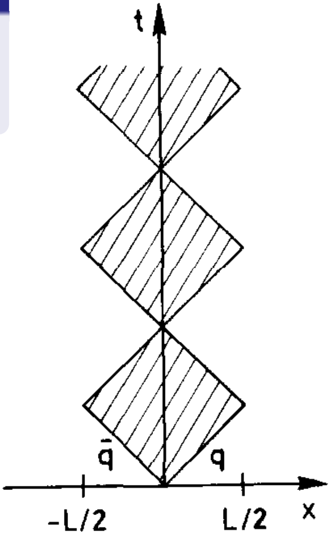
The Lund Model: starting point

Use only linear potential $V(r) \approx \kappa r$ to trace string motion, and let string fragment by repeated $\mathrm{q\overline{q}}$ breaks.

Assume negligibly small quark masses. Then linearity between space–time and energy–momentum gives

$$\left|\frac{\mathrm{d}E}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}E}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}t}\right| = \kappa$$

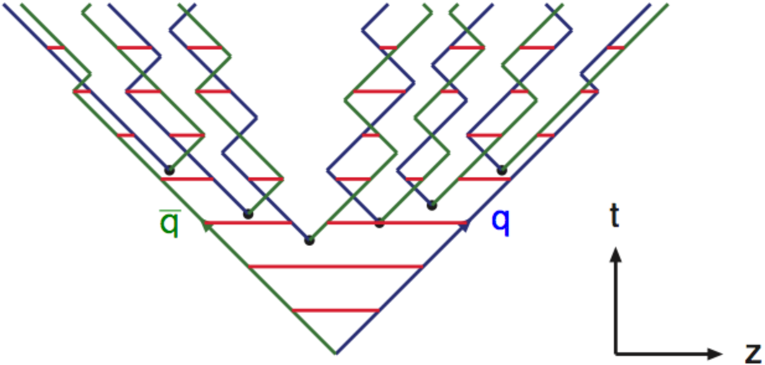
$(c = 1)$ for a $\mathrm{q\overline{q}}$ pair flying apart along the $\pm z$ axis.
But signs relevant: the q moving in the $+z$ direction has $\mathrm{d}z/\mathrm{d}t = +1$ but $\mathrm{d}p_z/\mathrm{d}t = -\kappa$.



The Lund Model

Combine yo-yo-style string motion with string breakings!

Motion of quarks and antiquarks with intermediate string pieces:

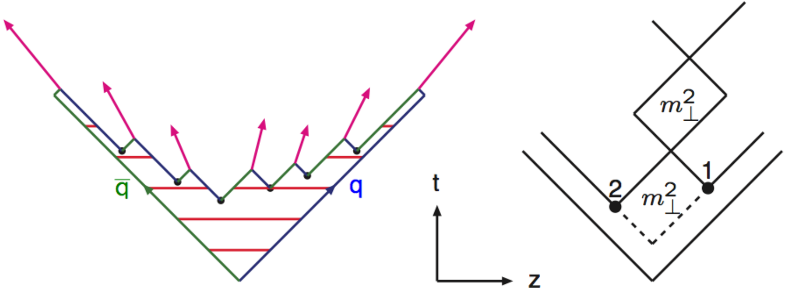


A q from one string break combines with a $\overline{q}$ from an adjacent one.

Gives simple but powerful picture of hadron production.

Where does the string break?

Fragmentation starts in the middle and spreads outwards:



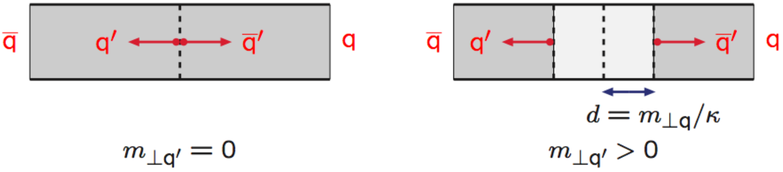
Corresponds to roughly same invariant time of all breaks,
$\tau^2 = t^2 - z^2 \sim$ constant,
with breaks separated by hadronic area $m_\perp^2 = m^2 + p_\perp^2$.

Hadrons at outskirts are more boosted.

Approximately flat rapidity distribution, $\mathrm{d}n/\mathrm{d}y \approx$ constant

$\Rightarrow$ total hadron multiplicity in a jet grows like $\ln E_{\mathrm{jet}}$.

How does the string break?



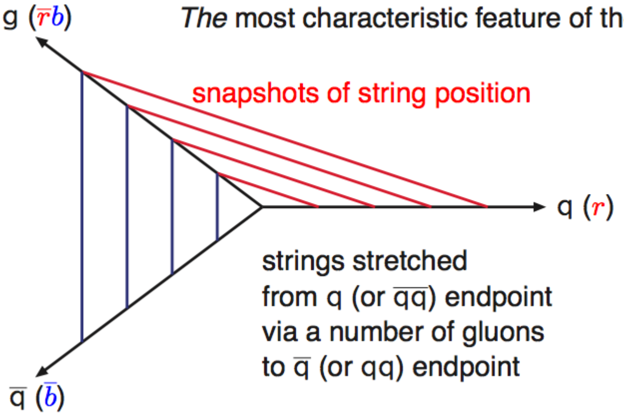
String breaking modelled by tunneling:

$$\mathcal{P} \propto \exp\left(-\frac{\pi m_{\perp \mathrm{q}}^2}{\kappa}\right) = \exp\left(-\frac{\pi p_{\perp \mathrm{q}}^2}{\kappa}\right) \exp\left(-\frac{\pi m_{\mathrm{q}}^2}{\kappa}\right)$$

- Common Gaussian $p_\perp$ spectrum, $\langle p_\perp \rangle \approx 0.4$ GeV.
- Suppression of heavy quarks, $\mathrm{u\overline{u}} : \mathrm{d\overline{d}} : \mathrm{s\overline{s}} : \mathrm{c\overline{c}} \approx 1 : 1 : 0.3 : 10^{-11}$.
- Diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production.

String model unpredictive in understanding of hadron mass effects $\Rightarrow$ many parameters, 10–20 depending on how you count.

The Lund gluon picture – 1



The most characteristic feature of the Lund model

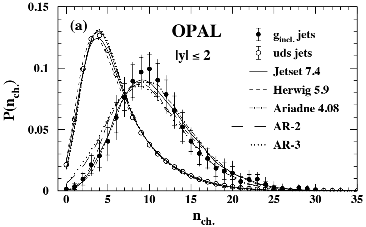
strings stretched
from q (or $\overline{\mathrm{qq}}$) endpoint
via a number of gluons
to $\overline{\mathrm{q}}$ (or qq) endpoint

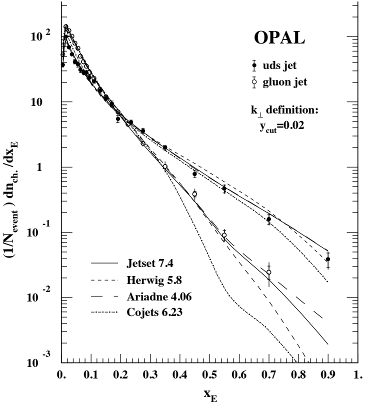
Gluon = kink on string

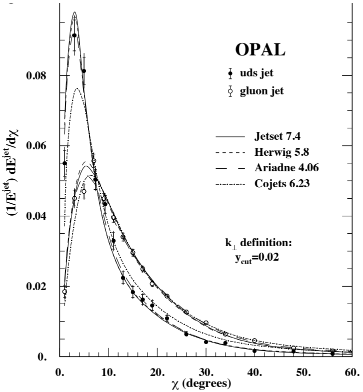
Force ratio gluon/ quark = 2,
cf. QCD $N_C/C_F = 9/4$, → 2 for $N_C \to \infty$
No new parameters introduced for gluon jets!

The Lund gluon picture – 2

Energy sharing between two strings makes hadrons in gluon jets softer, more and broader in angle:

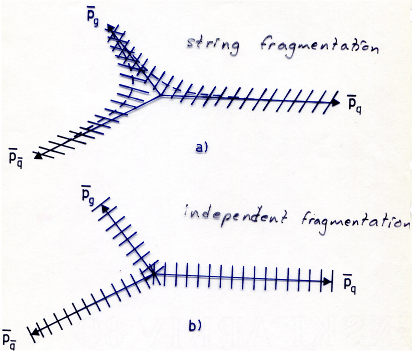


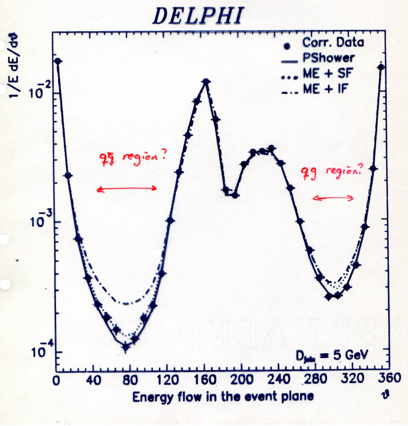




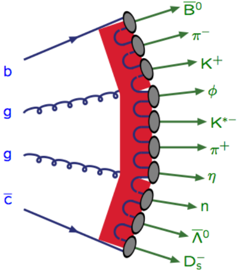
The Lund gluon picture – 3

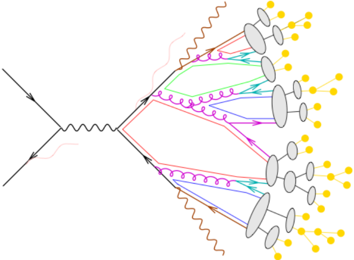
Particle flow in the $\mathrm{q\overline{q}g}$ event plane depleted in q–$\mathrm{\overline{q}}$ region owing to boost of string pieces in q–g and g–$\mathrm{\overline{q}}$ regions:





String vs. Cluster

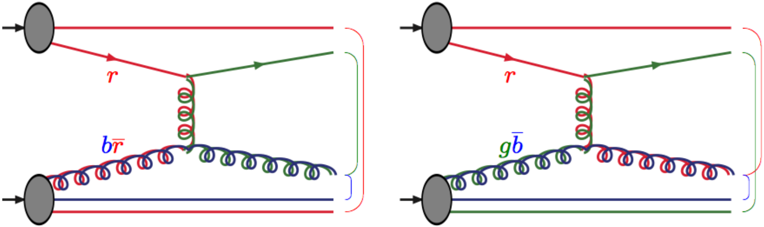




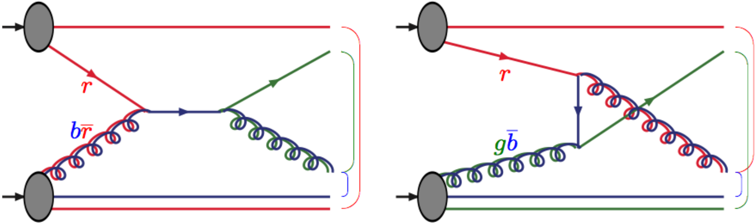
program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

Colour flow in hard processes – 1

One Feynman graph can correspond to several possible colour flows, e.g. for $\mathrm{qg} \to \mathrm{qg}$:



while other $\mathrm{qg} \to \mathrm{qg}$ graphs only admit one colour flow:



Colour flow in hard processes – 2

so nontrivial mix of kinematics variables $(\hat{s}, \hat{t})$
and colour flow topologies I, II:

$$\begin{aligned} |\mathcal{A}(\hat{s},\hat{t})|^2 &= |\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t}) + \mathcal{A}_{\mathrm{II}}(\hat{s},\hat{t})|^2 \\ &= |\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t})|^2 + |\mathcal{A}_{\mathrm{II}}(\hat{s},\hat{t})|^2 + 2\,\mathcal{R}e\left(\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t})\mathcal{A}^*_{\mathrm{II}}(\hat{s},\hat{t})\right) \end{aligned}$$

with $\mathcal{R}e\left(\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t})\mathcal{A}^*_{\mathrm{II}}(\hat{s},\hat{t})\right) \neq 0$
⇒ indeterminate colour flow, while
- showers *should* know it (coherence),
- hadronization *must* know it (hadrons singlets).

Normal solution:

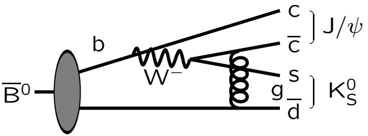
$$\frac{\mathrm{interference}}{\mathrm{total}} \propto \frac{1}{N_{\mathrm{C}}^2 - 1}$$

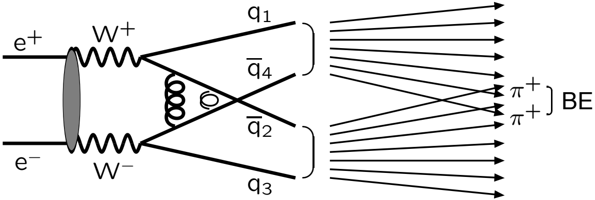
so split $\mathrm{I}:\mathrm{II}$ according to proportions in the $N_{\mathrm{C}} \to \infty$ limit, i.e.

$$\begin{aligned} |\mathcal{A}(\hat{s},\hat{t})|^2 &= |\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t})|^2_{\mathrm{mod}} + |\mathcal{A}_{\mathrm{II}}(\hat{s},\hat{t})|^2_{\mathrm{mod}} \\ |\mathcal{A}_{\mathrm{I(II)}}(\hat{s},\hat{t})|^2_{\mathrm{mod}} &= |\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t}) + \mathcal{A}_{\mathrm{II}}(\hat{s},\hat{t})|^2 \left(\frac{|\mathcal{A}_{\mathrm{I(II)}}(\hat{s},\hat{t})|^2}{|\mathcal{A}_{\mathrm{I}}(\hat{s},\hat{t})|^2 + |\mathcal{A}_{\mathrm{II}}(\hat{s},\hat{t})|^2} \right)_{N_{\mathrm{C}} \to \infty} \end{aligned}$$

Colour Reconnection Revisited

Colour rearrangement well established e.g. in B decay.





At LEP 2 search for effects in $e^+e^- \to W^+W^- \to q_q\overline{q}_2\, q_3\overline{q}_4$:

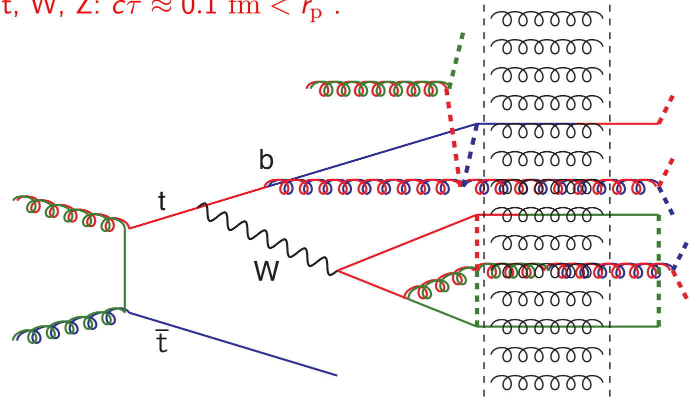
- perturbative $\langle \delta M_W \rangle \lesssim 5$ MeV : negligible!
- nonperturbative $\langle \delta M_W \rangle \sim 40$ MeV : signs but inconclusive.
- Bose-Einstein $\langle \delta M_W \rangle \lesssim 100$ MeV : full effect ruled out.

Hadronic collisions with MPI's: many overlapping colour sources. Reconnection established by $\langle p_\perp \rangle(n_{ch})$, but details unclear.

The Mass of Unstable Coloured Particles – 1

MC: close to pole mass, in the sense of Breit–Wigner mass peak.

t, W, Z: $c\tau \approx 0.1\ \mathrm{fm} < r_{\mathrm{p}}$.



At the Tevatron: $m_{\mathrm{t}} = 173.20 \pm 0.51 \pm 0.71$ GeV = `PMAS(6,1)`

At the LHC: $m_{\mathrm{t}} = 173.4 \pm 0.4 \pm 0.9$ GeV (CMS) = `6:m0` ?

Need better mass definition for coloured particles?

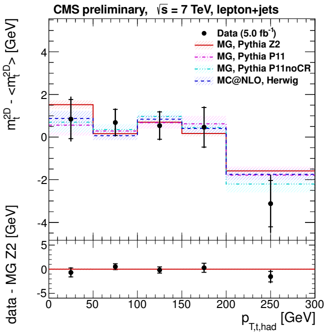
The Mass of Unstable Coloured Particles – 2

Dependence of Top Mass on Event Kinematics

CMS-PAS-TOP-12-029

NEW

	Fig.	Observable
color recon.	1	$\Delta R_{q\bar{q}}$
	2	$\Delta\phi_{q\bar{q}}$
	3	$p_{T,t,had}$
	4	$\lvert\eta_{t,had}\rvert$
ISR/FSR	5	H_T
	6	$m_{t\bar{t}}$
	7	$p_{T,t\bar{t}}$
	8	Jet multiplicity
b-quark kin.	9	$p_{T,b,had}$
	10	$\lvert\eta_{b,had}\rvert$
	11	$\Delta R_{b\bar{b}}$
	12	$\Delta\phi_{b\bar{b}}$

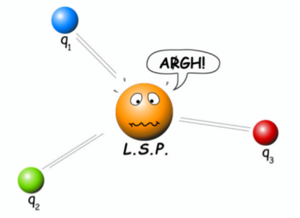


- *First top mass measurement binned in kinematic observables.*
- Additional validation for the top mass measurements.
- With the current precision, no mis-modelling effect due to
  - color reconnection, ISR/FSR, b-quark kinematics, difference between pole or MS~ masses.

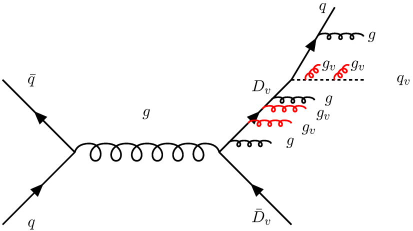
E. Yazgan

(Moriond 2013)

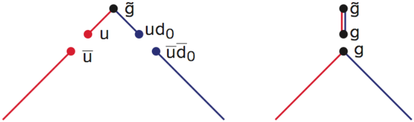
QCD and BSM physics



BNV ⇒ junction topology
⇒ special handling of
showers and hadronization



Hidden valleys:
showers potentially interleaved
with normal ones;
hadronization in hidden sector;
decays back to normal sector



R-hadrons: long-lived $\tilde{g}$ or $\tilde{q}$;
new: hadronization of massive object “inside” the string

Summary

- Multiparton interactions well establihed by now.
- Detailed modelling differs between generators.
- Decent description of many kinds of data.
- Some progress on modelling of diffraction.
- Hadronization: string model most sophisticated.
- Slow/no evolution of core hadronization models.
- Colour reconnection highly relevant but unclear.
- QCD is relevant for many aspects of SM & BSM physics.

The Road Ahead – 1

What will be the role of the LHC?

- to study a rich set of new particles predominantly decaying to leptons, photons and invisible particles?
- to study a rich set of new particles predominantly decaying to partons, i.e. jets?
- to study a SM Higgs in boring detail, but do little else (cf. top at the Tevatron)?
- ~~to become a QCD machine for lack of better (cf. HERA)?~~

Either way, generators will always be needed, but to a varying degree.

Many obvious evolutionary steps for generators:

- automated NLO ⇒ POWHEG calculations
- UNLOPS: combining CKKW-L–style matching with NLO
- parton showers with complete NLL accuracy
- improved MPI and hadronization frameworks

The Road Ahead – 2

And some revolutionary ones:

- automated multiloops for complete N^{n}LO calculations, e.g. formalism with inherent Sudakov form factors
- lattice QCD describes hadronization

But what is progress (in the eyes of experimentalists)?

- more complicated models with more tunable parameters, giving better agreement with data?
- more sophisticated/predictive models with fewer tunable parameters, giving *worse* agreement with data?