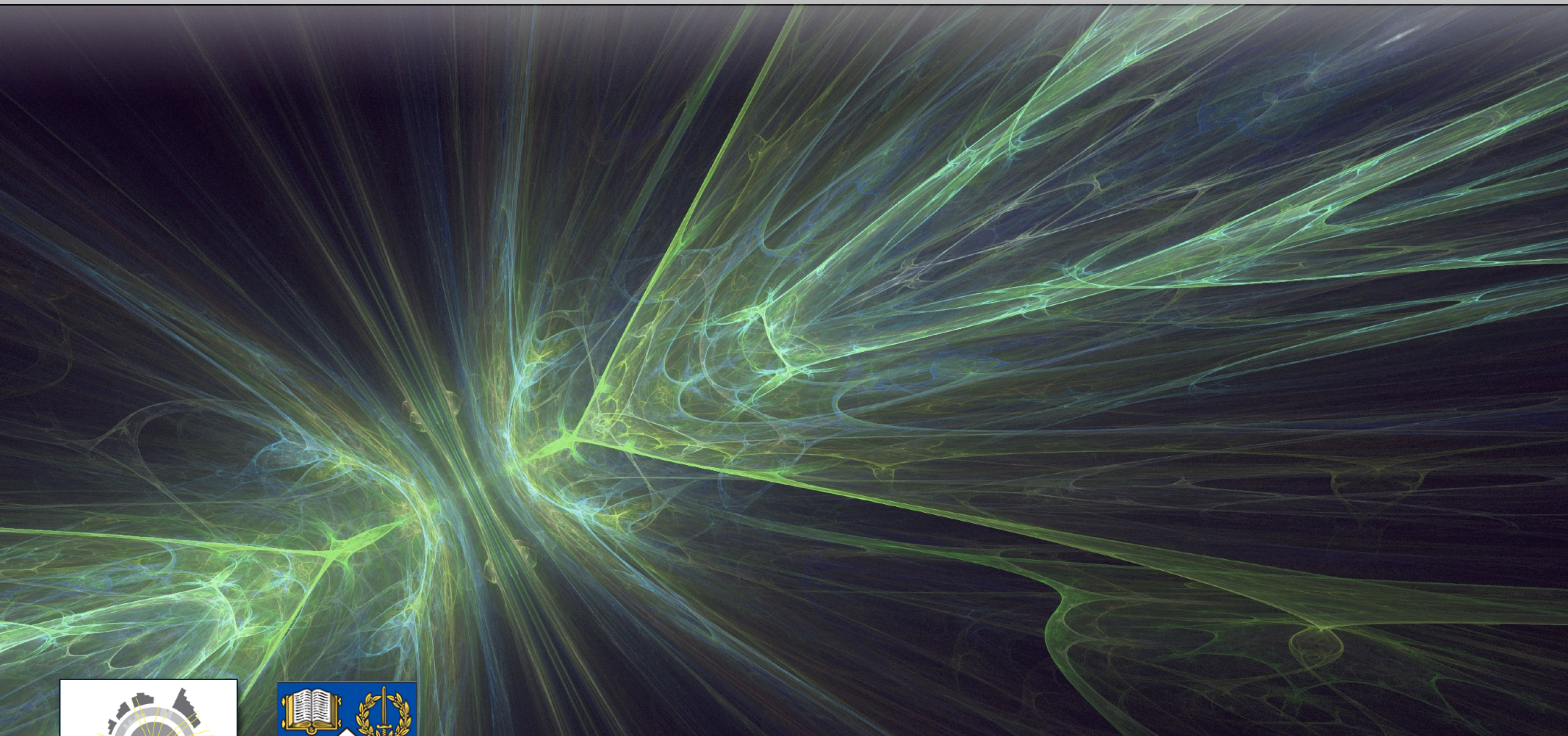
Introduction to Event Generators

Lecture 4: Physics at Hadron Colliders



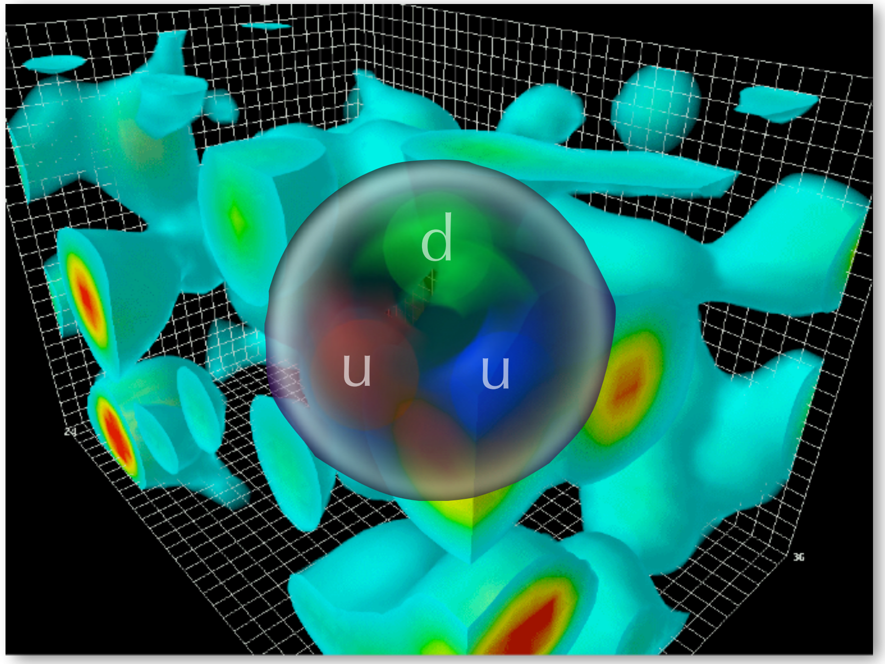
Peter Skands (Monash University)

11th MCnet School, Lund 2017

What are we really colliding?

Hadrons are composite, with time-dependent structure

Partons within clouds of further partons, constantly being emitted and absorbed



Lattice simulation, D. Leinweber (Adelaide)

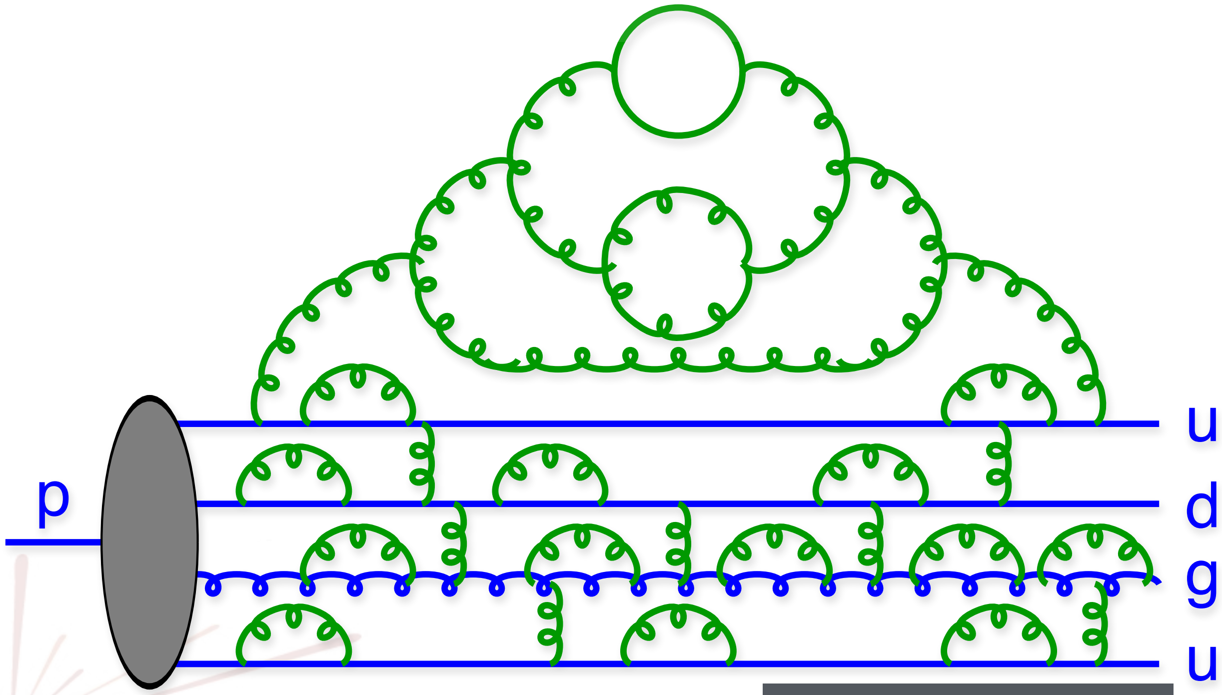


illustration by T. Sjöstrand

(for hadron to remain intact, virtualities $k^2 < M_h^2$
High-virtuality fluctuations suppresed by powers of:

$$\frac{\alpha_s M_h^2}{k^2}$$

M_h : mass of hadron
k^2 : virtuality of fluctuation

SUCH STUFF AS BEAMS ARE MADE OF

Lifetime of typical fluctuation ~ r_p/c (=time it takes light to cross a proton)

~ 10^{-23} s; Corresponds to a frequency of ~ 500 billion THz

To the LHC, that's slow! (reaches "shutter speeds" thousands of times faster)

$E=h\nu \rightarrow \nu_{LHC}$ = 13 TeV/h = 3.14 million billion THz

➜ Protons look "frozen" at moment of collision

But they have a lot more than just two "u" quarks and a "d" inside

Hard to calculate (non-perturbative), so use statistics to parametrise the structure: **parton distribution functions** (PDFs)

@LO: Every so often I will pick a gluon, every so often a quark (antiquark)

Measured at previous colliders (+ now at LHC), as function of energy fraction

Hard scattering knows nothing of the target hadron apart from the fact that it contained the struck parton → **factorisation**

[M. Seymour]

Simple question: what does the ***average*** LHC collision look like?

First question: how many are there?

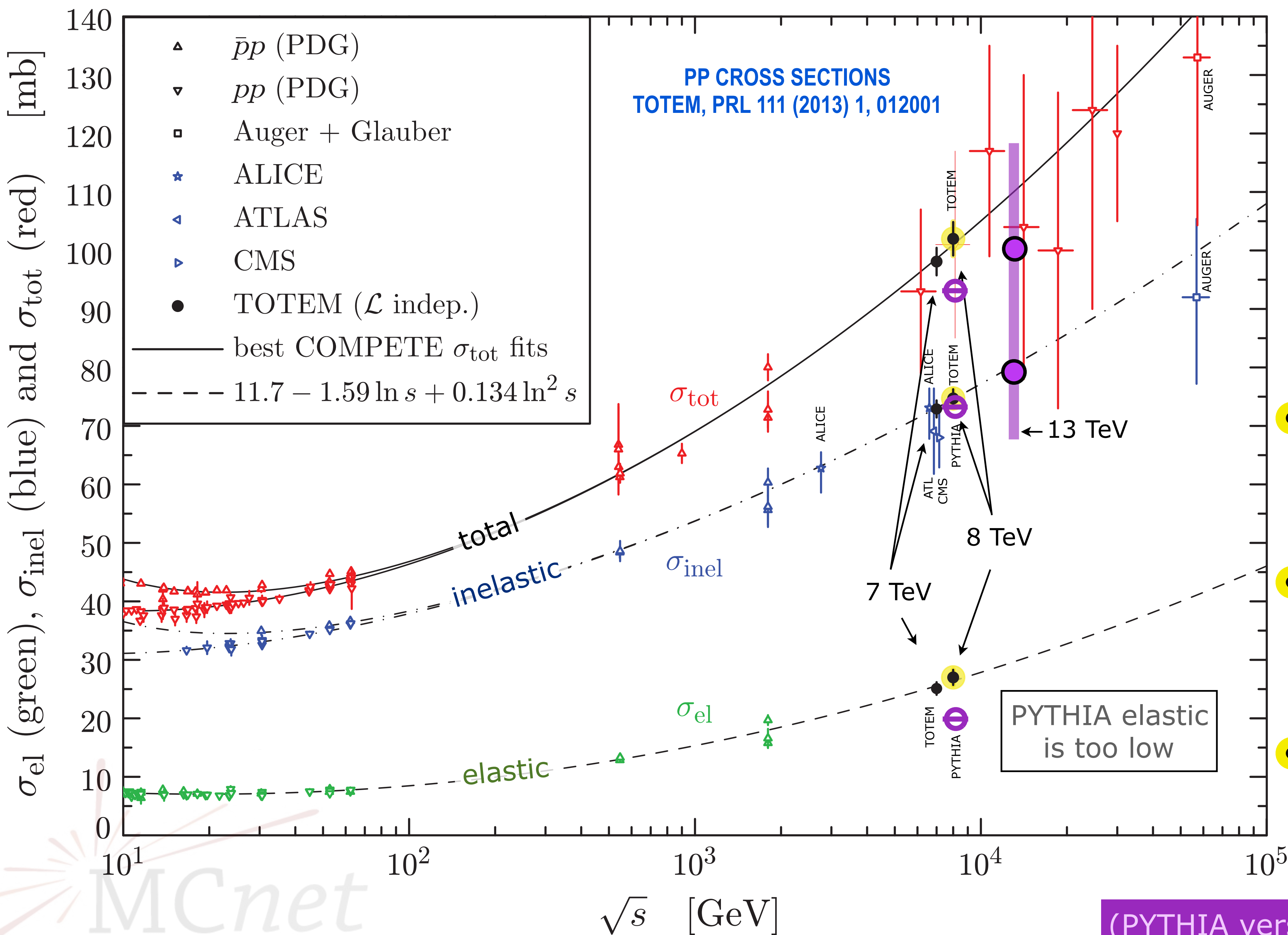
What is $\sigma_{tot}(pp)$ at LHC ?

(could we compute it in perturbation theory?)

THE TOTAL CROSS SECTION

$$\sigma_{\mathrm{tot}}(s) = \sigma_{\mathrm{el}}(s) + \sigma_{\mathrm{inel}}(s) \propto s^{0.08} \text{ or } \ln^2(s) \ ?$$

Donnachie-Landshoff   Froissart-Martin Bound



$\sigma_{\mathrm{tot}}(13\ \mathrm{TeV}) \sim 110 \pm 6$ mb

PYTHIA: 100 mb

$\sigma_{\mathrm{inel}}(13\ \mathrm{TeV}) \sim 80 \pm 3.5$ mb

PYTHIA: 78 mb

(2.9%)

$\sigma_{\mathrm{tot}}(8\ \mathrm{TeV}) = 101 \pm 2.9$ mb

PYTHIA: 93 mb

(2.3%)

$\sigma_{\mathrm{inel}}(8\ \mathrm{TeV}) = 74.7 \pm 1.7$ mb

PYTHIA: 73 mb

(5.1%)

$\sigma_{\mathrm{el}}(8\ \mathrm{TeV}) = 27.1 \pm 1.4$ mb

PYTHIA: 20 mb

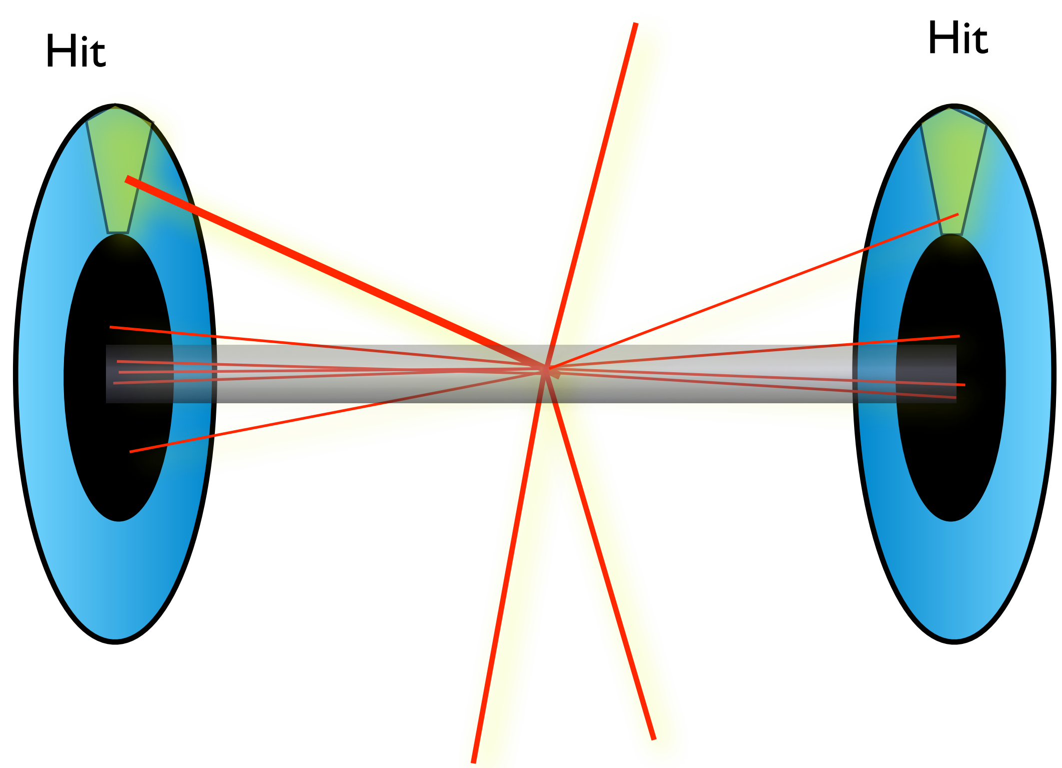
(PYTHIA versions: 6.4.28 & 8.1.80)

Simple question: what does the ***average*** LHC collision look like?

First question: how many are there? What is $\sigma_{tot}(pp)$ at LHC ?

Around 100mb (of which about half is "inelastic, non-diffractive")

Example of "Minimum Bias Trigger"



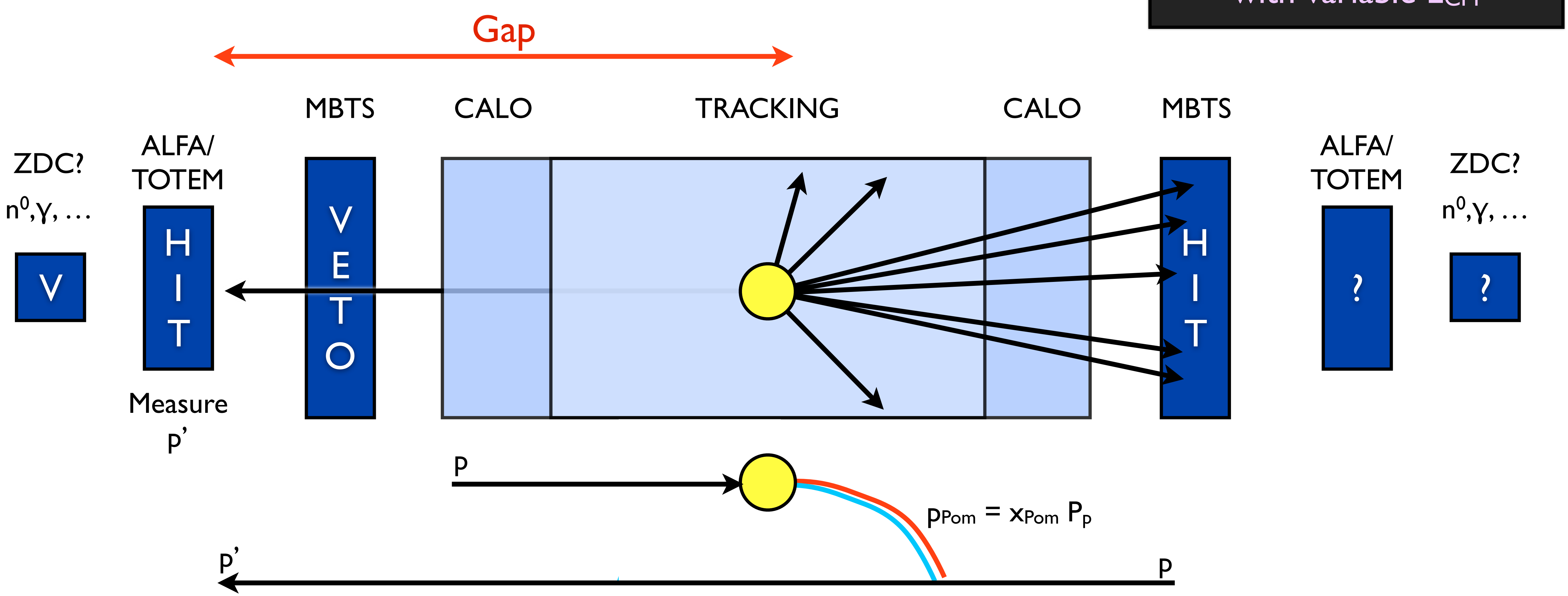
Minimal trigger requirement

At least one hit in some simple and efficient hit counters (typically at large η)

(Double-sided trigger requirement suppresses "single diffraction")

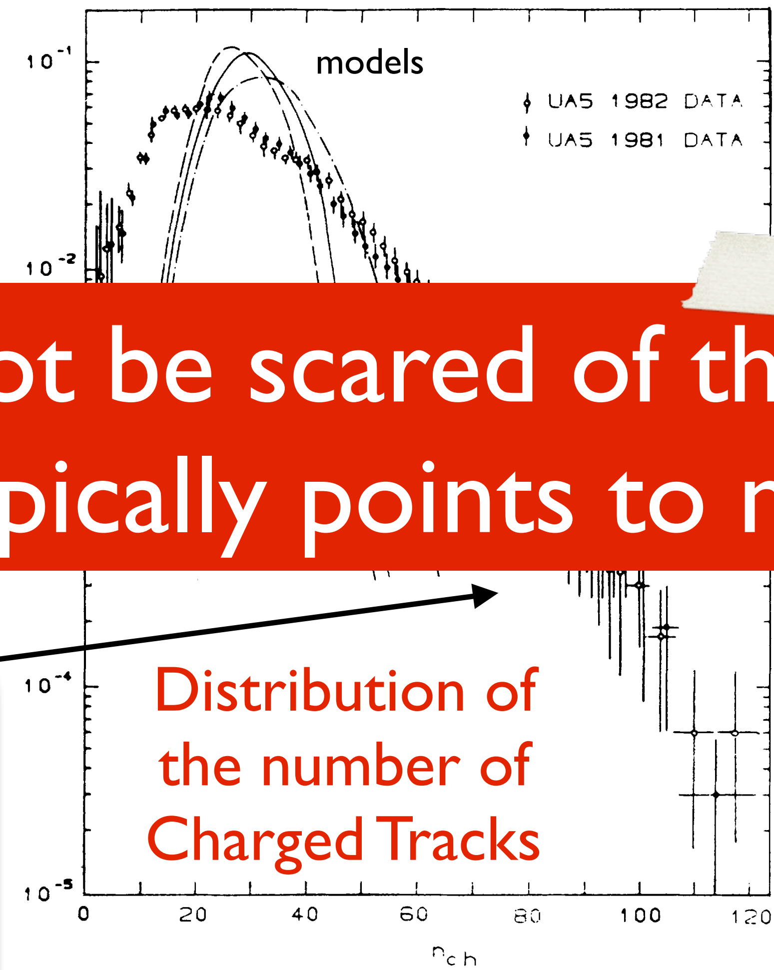
Single Diffraction

Glueball-Proton Collider
with variable E_{CM}



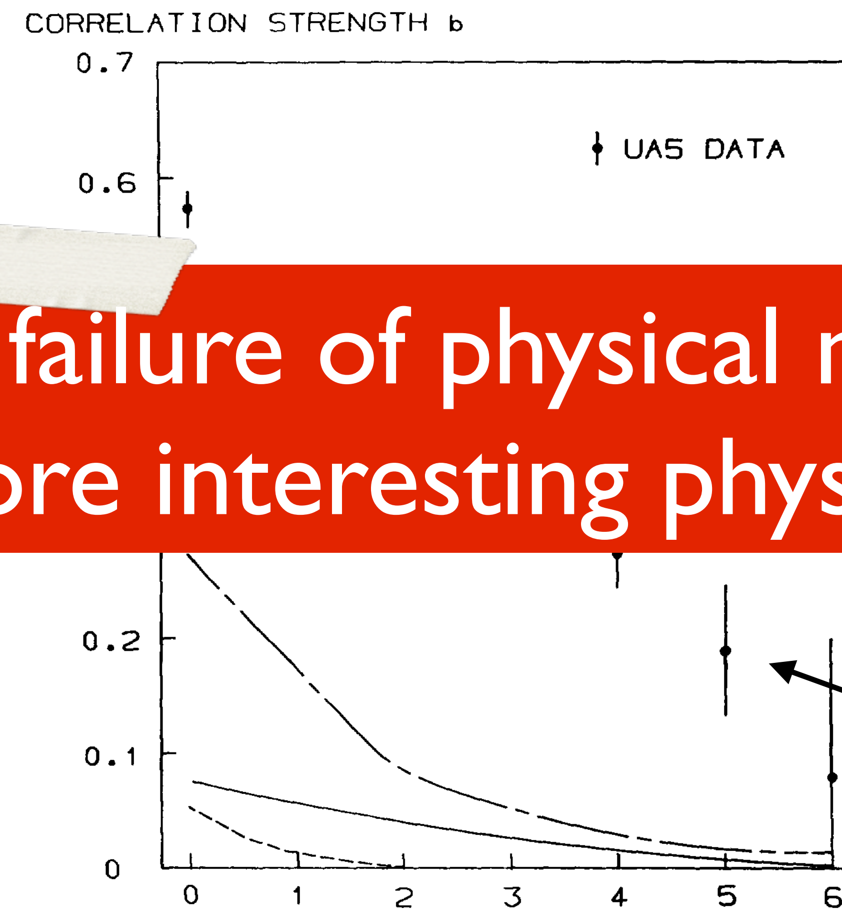
Also:
"Double Diffraction": both protons explode; defined by gap inbetween
"Central Diffraction": two protons + a central (exclusive) system

MC vs Hadron Collisions



Distribution of the number of Charged Tracks

FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 [r]esults (Ref. 32) vs simple models: dashed low p_T only, full in[clu]ding hard scatterings, dash-dotted also including initial- and [fina]l-state radiation.



Correlation Strength (forward-backward)

Do not be scared of the failure of physical models (typically points to more interesting physics)

some mechanism for generating much bigger fluctuations in multiplicity
(here: of charged tracks)

some global (quantum) number tells the entire event to fluctuate up or down ?

Sjöstrand & v. Zijl, Phys.Rev.D36(1987)2019

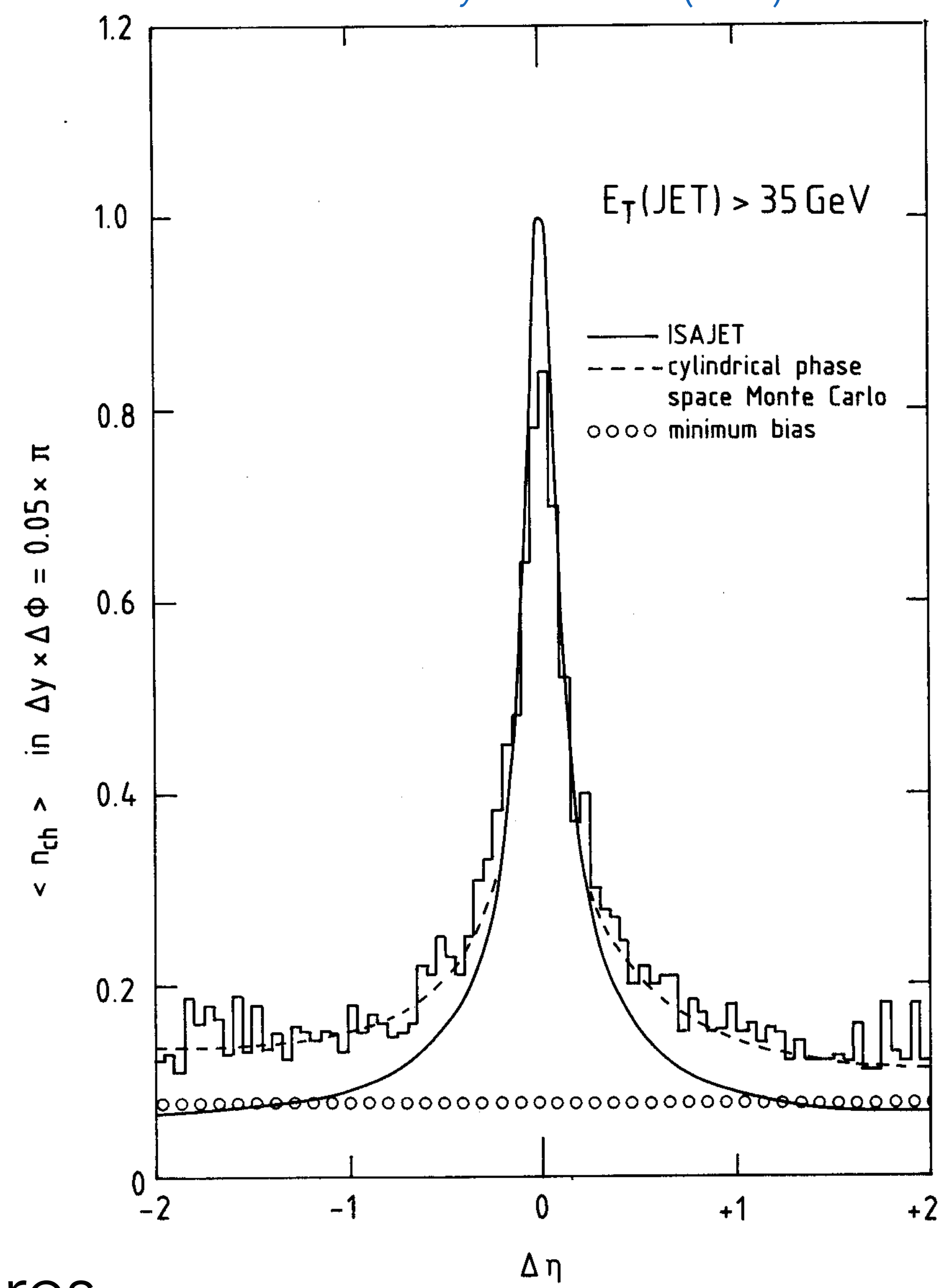
1983: the "Pedestal Effect"

UA1: $p\bar{p}$ at $\sqrt{s} = 540\,\mathrm{GeV}$

Studies of jets with E_T up to 100 GeV

> "Outside the [jet], a constant E_T plateau is observed, whose height is independent of the jet E_T. Its value is substantially higher than the one observed for minimum bias events."

Phys. Lett. B 132 (1983) 214-222

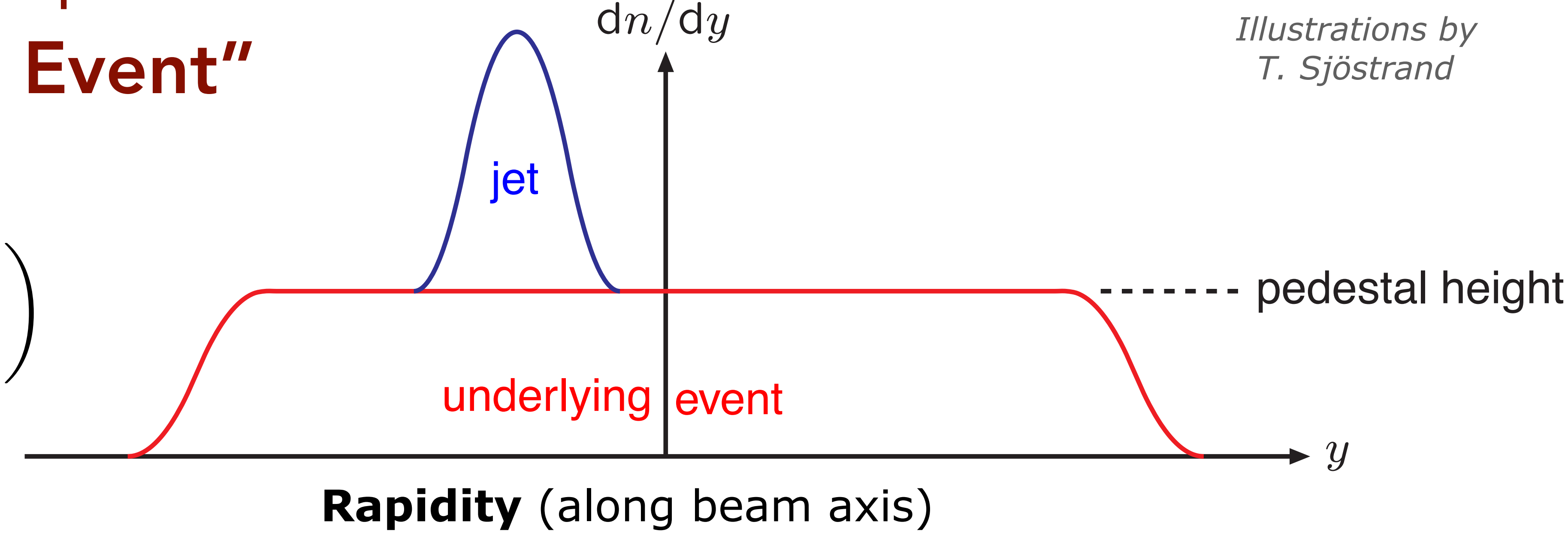


In hadron collisions, hard jets sit on "pedestals" of increased particle production extending far from the jet cores.

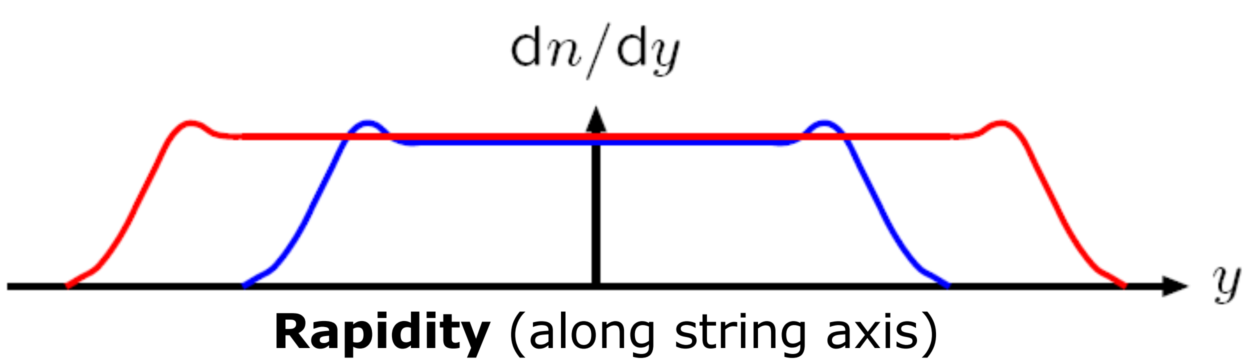
Today, we call the pedestal
"the Underlying Event"

Illustrations by T. Sjöstrand

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$



Looks like something we've seen before … ?



(but pedestal too high to be just one string …)

FROM HARD TO SOFT

Factorisation and IR safety

Main tools for jet calculations

Corrections suppressed by powers of Λ_{QCD}/Q_{Hard}

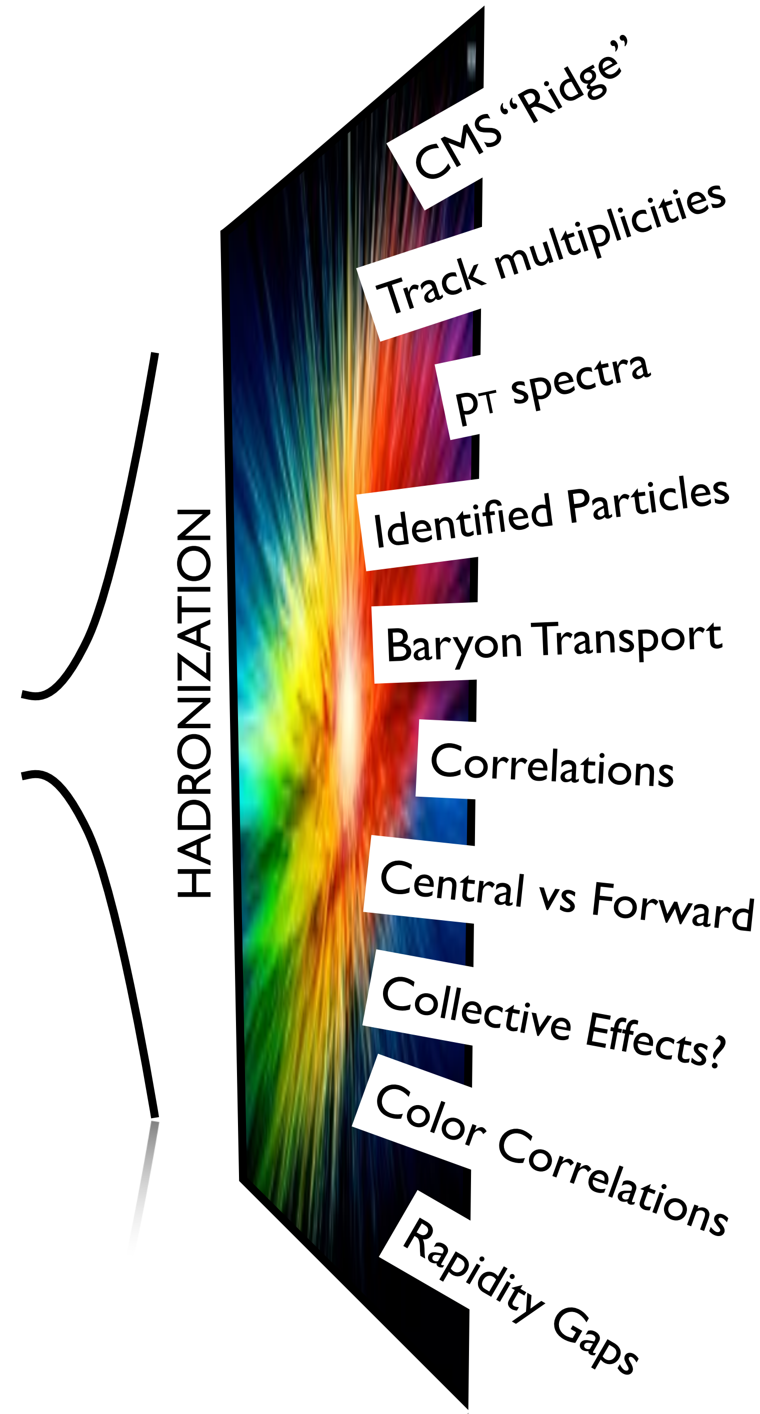
Soft QCD / Minimum-Bias

NO HARD SCALE
Typical Q scales ~ Λ_{QCD}
Extremely sensitive to IR effects
→ Excellent LAB for studying IR effects

~ ∞ statistics for min-bias

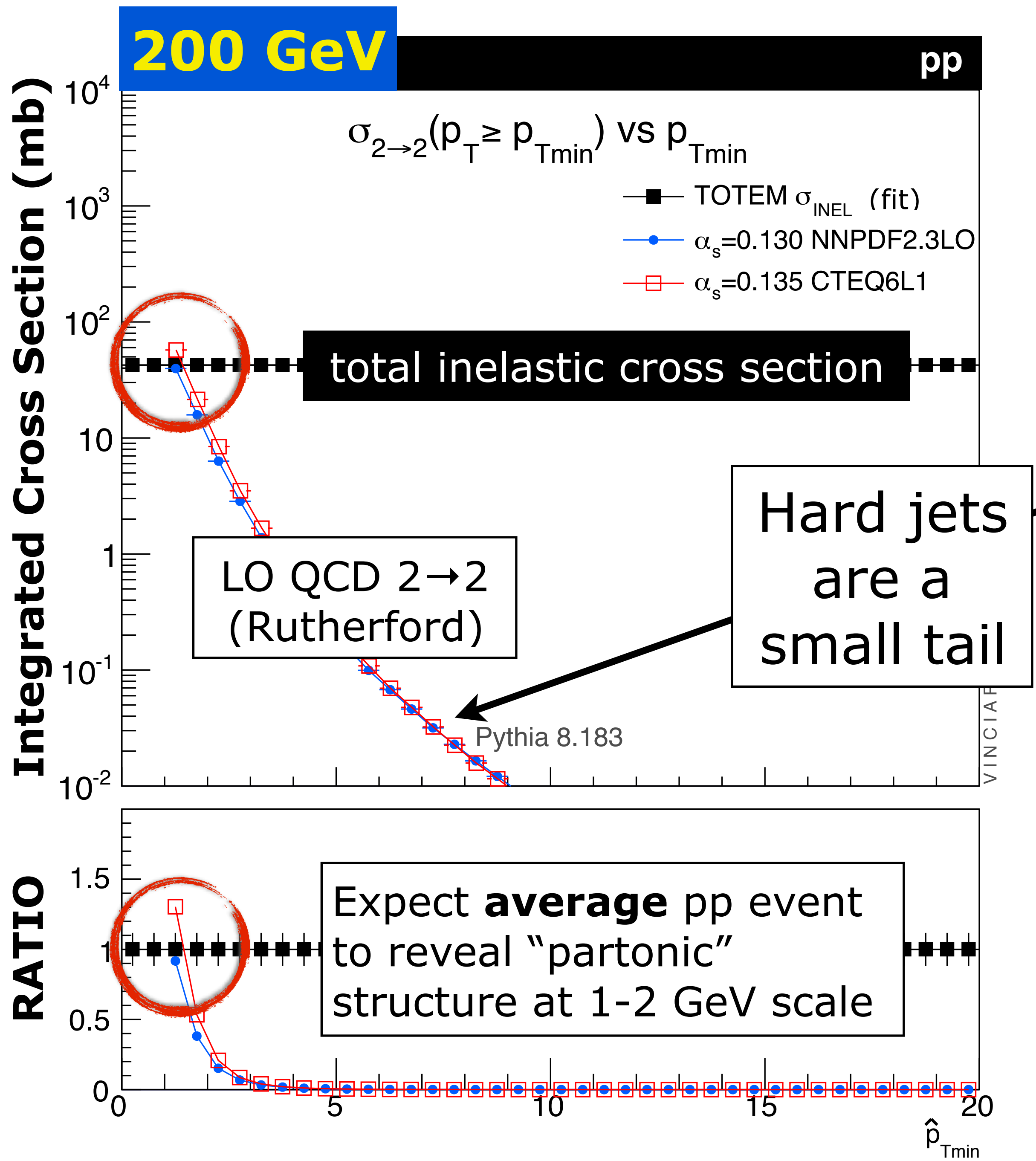
→ Access tails, limits

Universality: Recycling PU ↔ MB ↔ UE



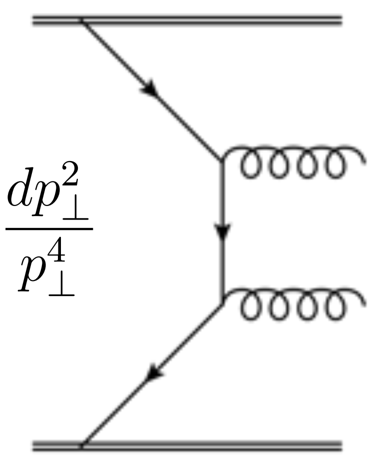
IS THERE NO HARD SCALE?

Compare total (inelastic) hadron-hadron cross section to calculated parton-parton (LO QCD 2→2) cross section



Leading-Order pQCD

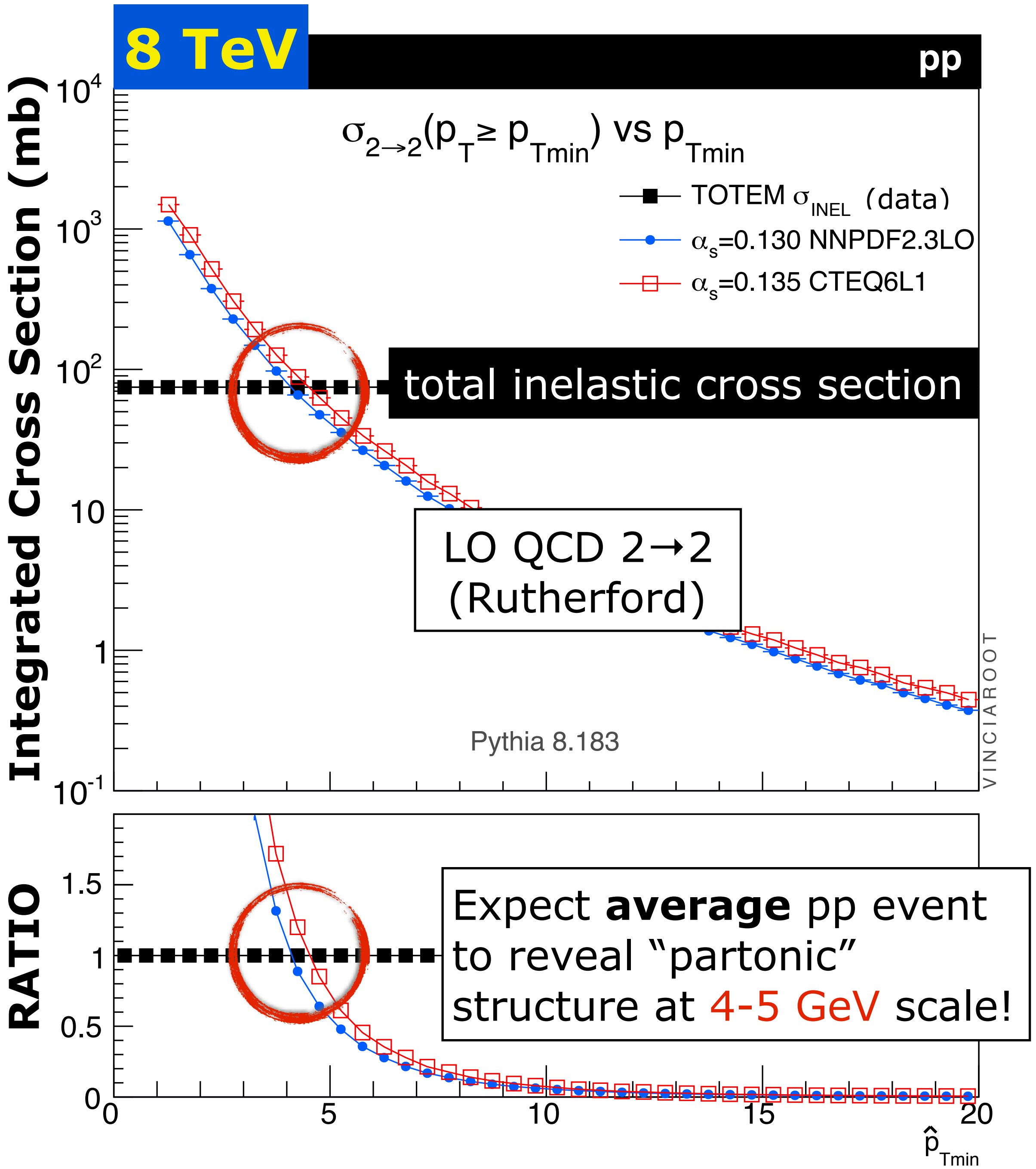
$$\int_{p^2_{\perp,\mathrm{min}}} dp^2_\perp \frac{d\sigma_{\mathrm{Dijet}}}{dp^2_\perp}$$

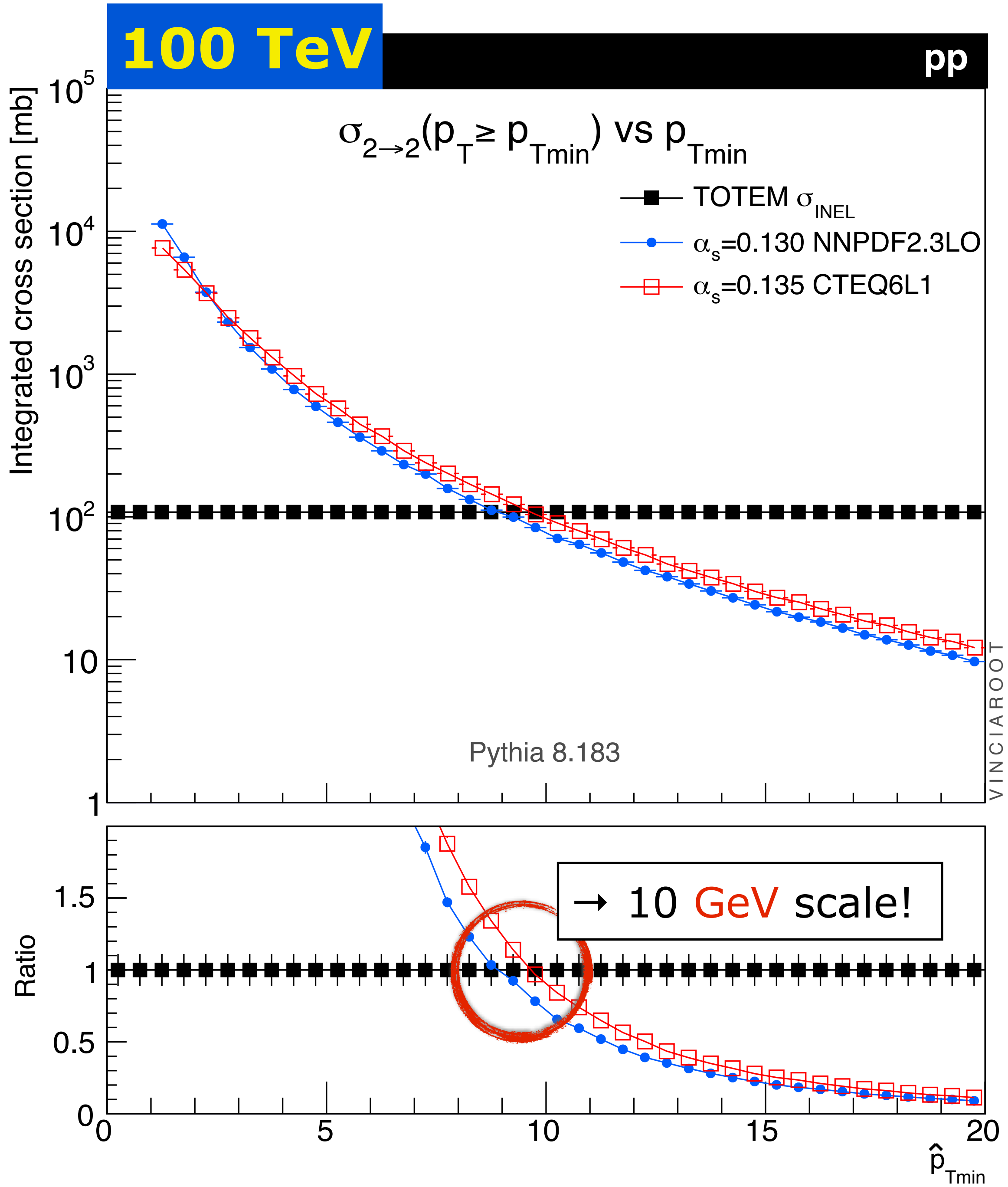


$$d\sigma_{2\to2} \propto \frac{dp^2_\perp}{p^4_\perp} \otimes \mathrm{PDFs}$$

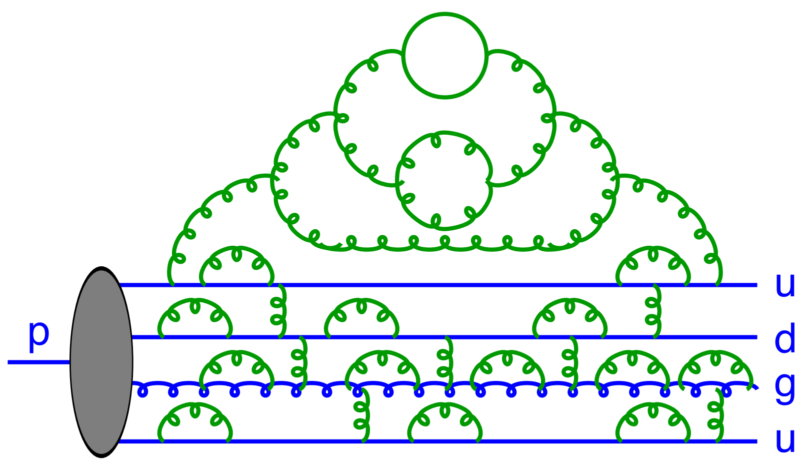
→ 8 TEV → 100 TEV

→ Trivial calculation indicates hard scales in min-bias





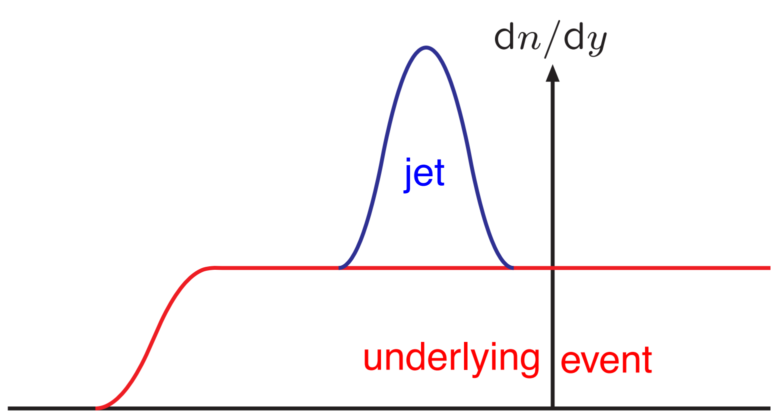
SUMMARY FOR NOW: WE KNOW 3 THINGS



1) Hadrons are composite

Factorisation: hard interaction picks out a single parton; what about the rest?

At some level, multiple-parton-interactions must occur (only a question of how often)



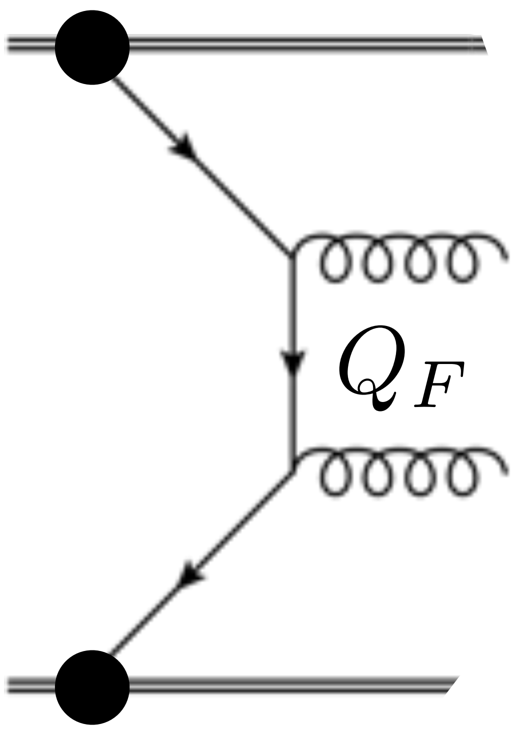
2) Events with a hard trigger are accompanied by an "underlying event"

Looks too high to be just one string

Multiple colour exchanges ?

3) Simple calculations indicate the presence of (semi)hard scales even when no hard trigger is imposed ("minimum bias")

Factorisation: Subdivide Calculation



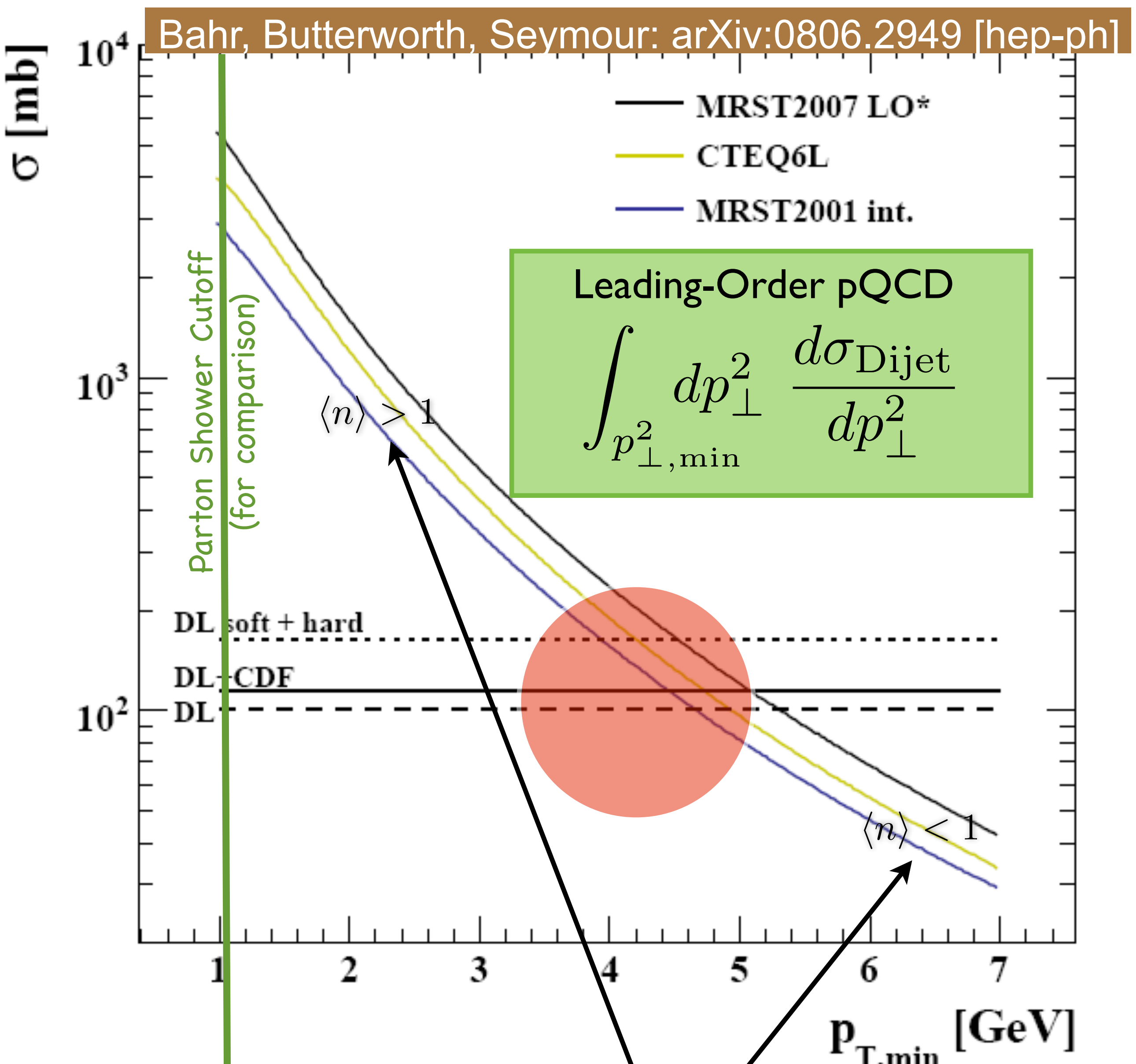
Multiple Parton Interactions go beyond existing theorems

→ perturbative short-distance physics in Underlying Event

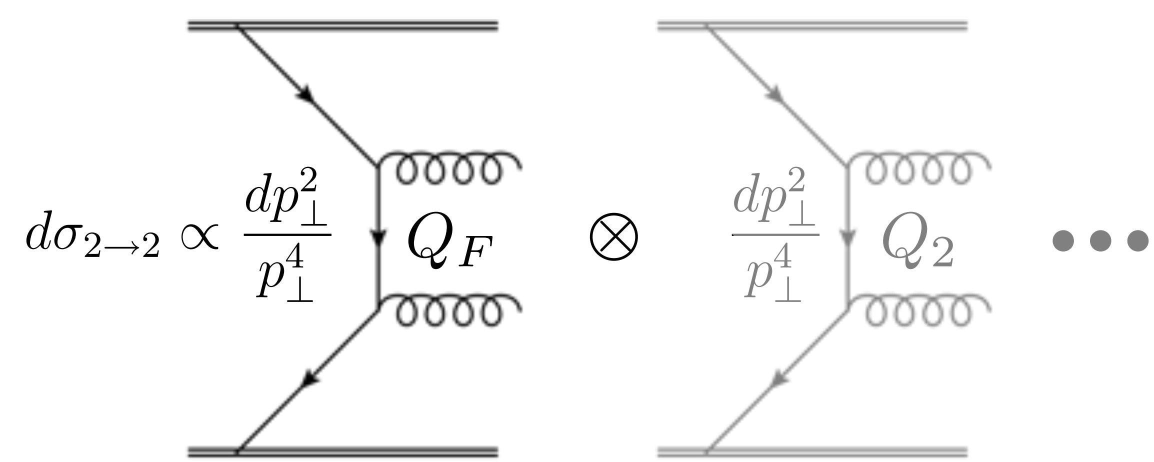
→ Need to generalize factorisation to MPI

Multiple Parton Interactions

= Allow several parton-parton interactions per hadron-hadron collision. Requires extended factorization ansatz.



Earliest MC model ("old" PYTHIA 6 model)
Sjöstrand, van Zijl PRD36 (1987) 2019



Lesson from bremsstrahlung in pQCD: divergences → fixed-order breaks down
Perturbation theory still ok, with resummation (unitarity)

→ Resum dijets?
Yes → MPI!

$$\sigma_{2\to2}(p_{\perp\min}) = \langle n \rangle (p_{\perp\min})\ \sigma_{\text{tot}}$$

Parton-Parton Cross Section

Hadron-Hadron Cross Section

HOW MANY?

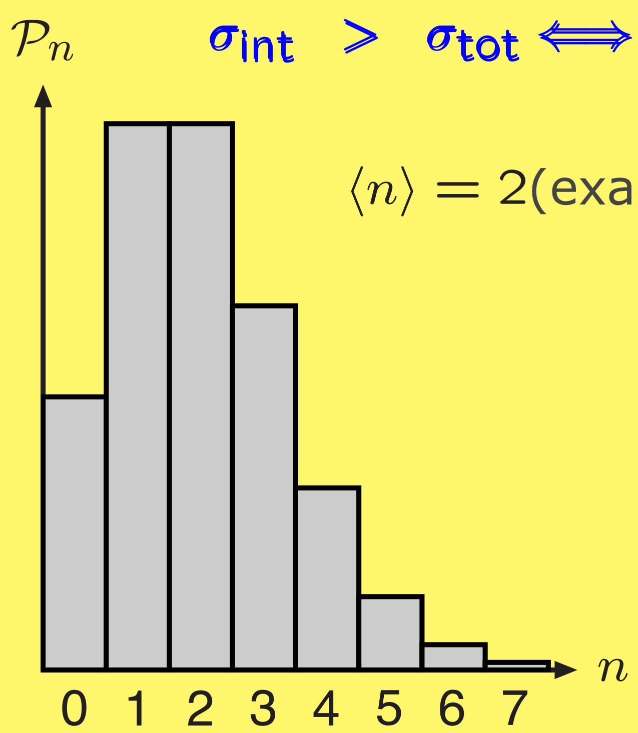
Naively $\langle n_{2\to2}(p_{\perp\mathrm{min}})\rangle = \dfrac{\sigma_{2\to2}(p_{\perp\mathrm{min}})}{\sigma_{\mathrm{tot}}}$

If the interactions are assumed ~ independent (naive factorisation) → Poisson

$$\sigma_{\text{tot}} = \sum_{n=0}^{\infty} \sigma_n$$

$$\sigma_{\text{int}} = \sum_{n=0}^{\infty} n\,\sigma_n$$

$$\boldsymbol{\sigma_{\text{int}} > \sigma_{\text{tot}}} \iff \langle n\rangle > 1$$



$$\mathcal{P}_n = \frac{\langle n\rangle^n}{n!}\, e^{-\langle n\rangle}$$

Real Life

Color screening: $\sigma_{2\to2}\to0$ for $p_\perp\to0$

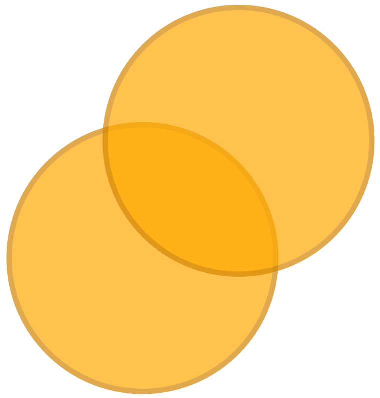
Momentum conservation suppresses high-n tail

Impact-parameter dependence

+ physical correlations

→ not simple product

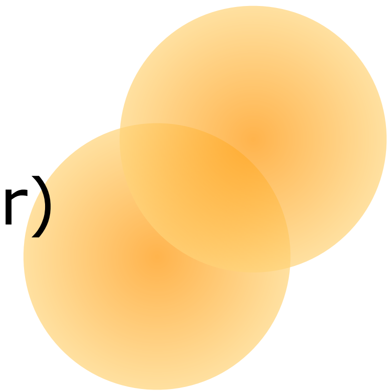
IMPACT PARAMETER



1. **Simple Geometry** (in impact-parameter plane)

Simplest idea: smear PDFs across a uniform disk of size πr_p^2
→ simple geometric overlap factor ≤ 1 in dijet cross section
Some collisions have the full overlap, others only partial
→ Poisson distribution with different mean <n> at each b

2. More realistic **Proton b-shape**



Smear PDFs across a non-uniform disk
E.g., Gaussian(s), or **more**/less peaked (e.g., EM form factor)
Overlap factor = convolution of two such distributions

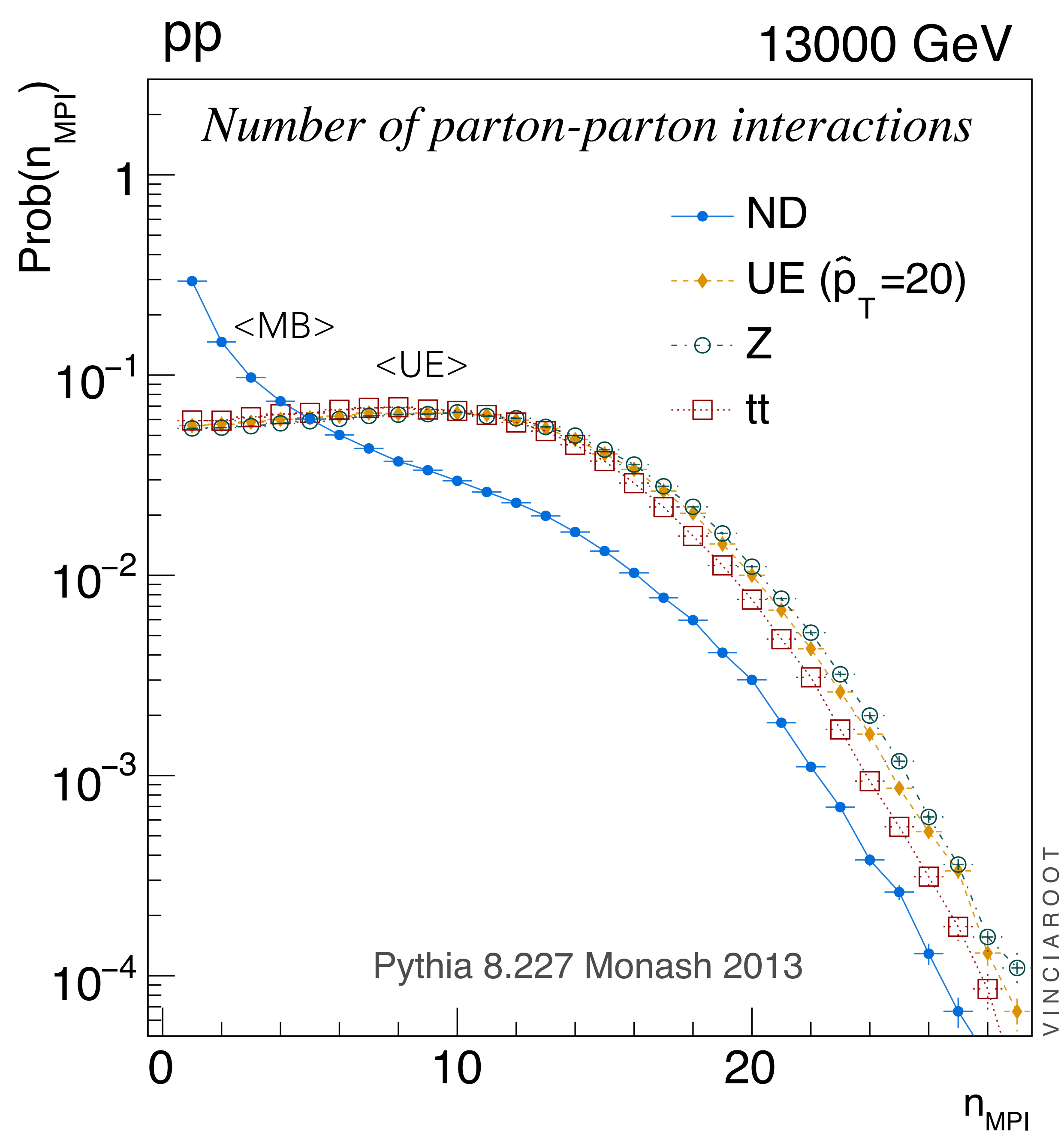
→ Poisson distribution with different mean <n> at each b
"Lumpy Peaks" → large matter overlap enhancements, higher <n>

Note: this is an *effective* description. Not the actual proton mass density.
E.g., peak in overlap function (≫1) can represent unlikely configurations with huge overlap enhancement. Typically use total σ_{inel} as normalization.

Minimum-Bias pp collisions at 7 TeV

Averaged over all pp impact parameters

(Really: averaged over all pp overlap enhancement factors)



*note: can be arbitrarily soft

1: A SIMPLE MODEL

A minimal model incorporating single-parton factorization, perturbative unitarity, and energy-and-momentum conservation

Take literally $\sigma_{2\to2}(p_{\perp\min}) = \langle n\rangle(p_{\perp\min})\ \sigma_{\mathrm{tot}}$

Parton-Parton Cross Section — Hadron-Hadron Cross Section

1. Choose $p_{T\min}$ cutoff
   = main tuning parameter

2. Interpret $<n>(p_{T\min})$ as mean of Poisson distribution
   Equivalent to assuming all parton-parton interactions equivalent and independent ~ each take an instantaneous "snapshot" of the proton

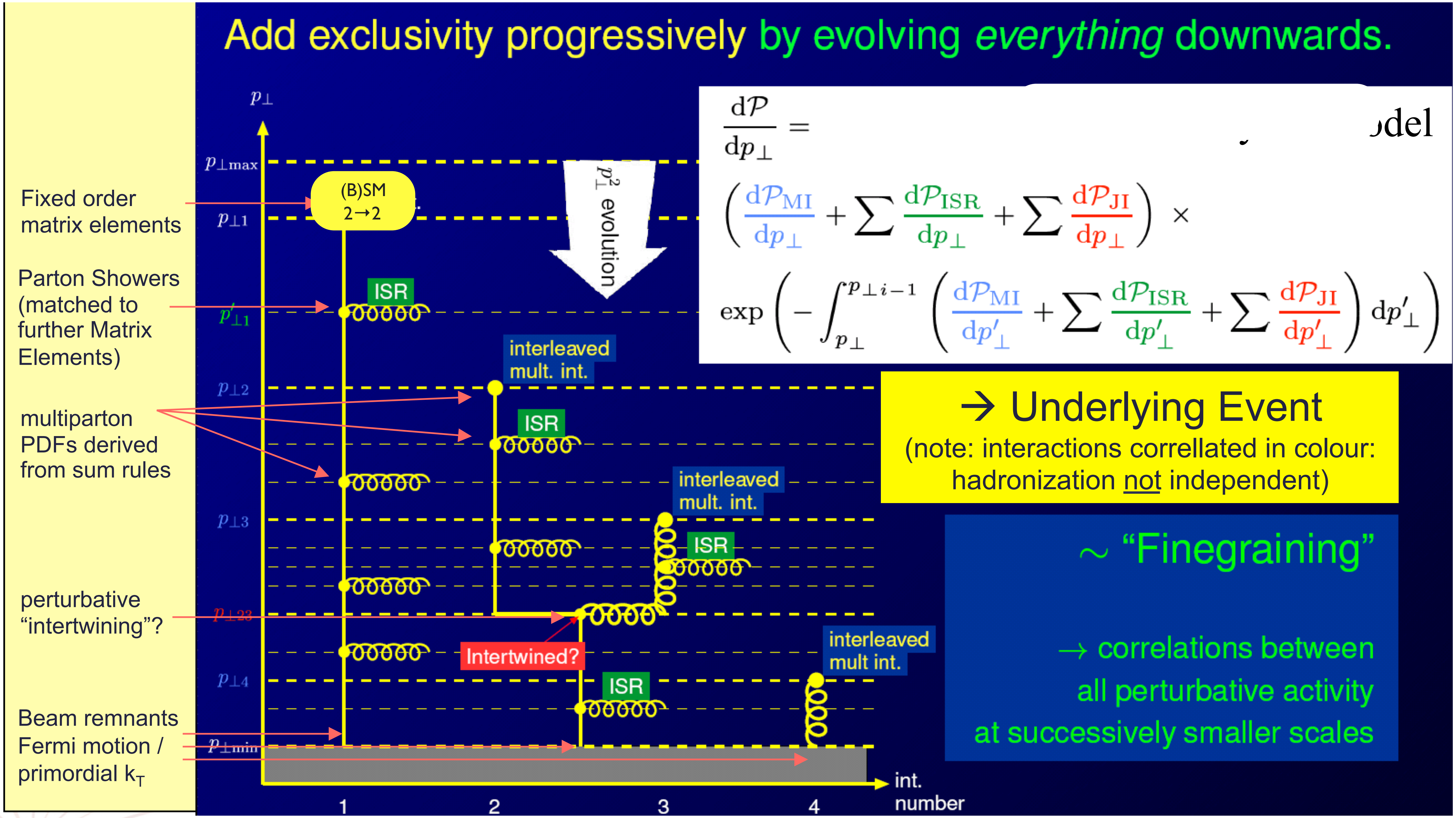
3. Generate n parton-parton interactions (pQCD 2→2)
   Veto if total beam momentum exceeded → overall (E,p) cons

4. Add impact-parameter dependence → $<n> = <n>(b)$
   Ordinary CTEQ, MSTW, NNPDF, …
   Assume factorization of transverse and longitudinal d.o.f., → PDFs : $f(x,b) = f(x)g(b)$
   b distribution ∝ EM form factor → JIMMY model (F77 Herwig) ← Butterworth, Forshaw, Seymour Z.Phys. C72 (1996) 637
   Constant of proportionality = second main tuning parameter

5. Add separate class of "soft" (zero-p_T) interactions representing interactions with $p_T < p_{T\min}$ and require $\sigma_{\mathrm{soft}} + \sigma_{\mathrm{hard}} = \sigma_{\mathrm{tot}}$
   → **Herwig 7 model** Bähr et al, arXiv:0905.4671

The model in Pythia 8

Sjöstrand, P.S., JHEP 0403 (2004) 053; EPJ C39 (2005) 129



MC vs Hadron Collisions

Fluctuations in n_{mpi} → Bigger (global) fluctuations

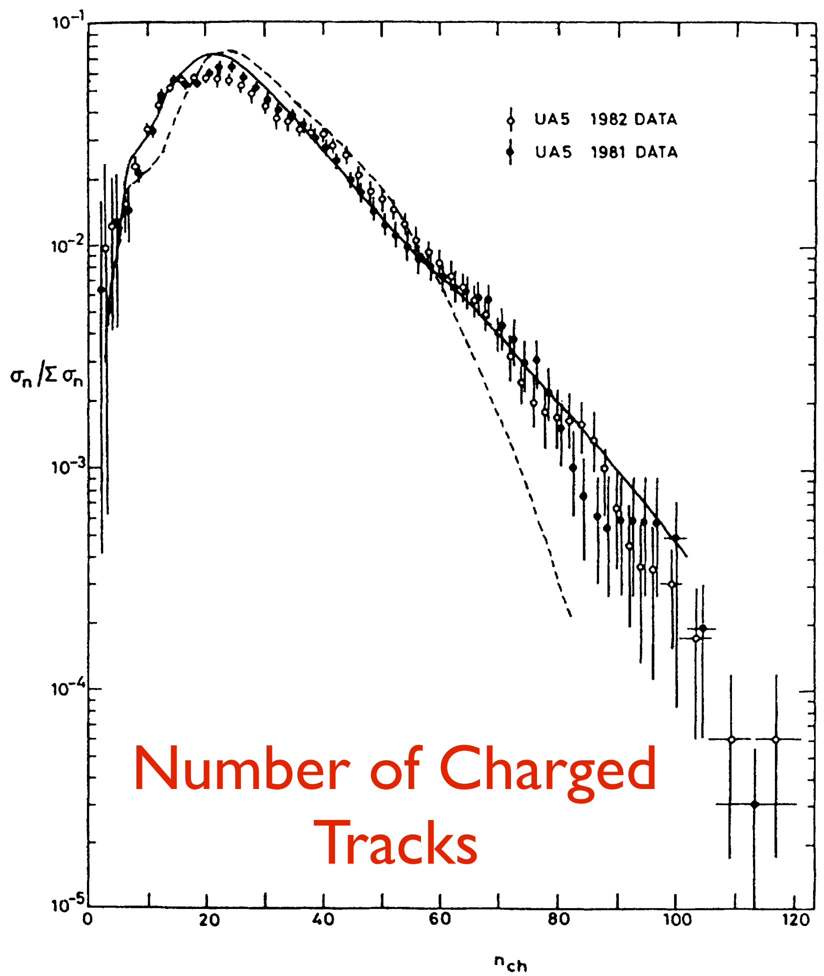
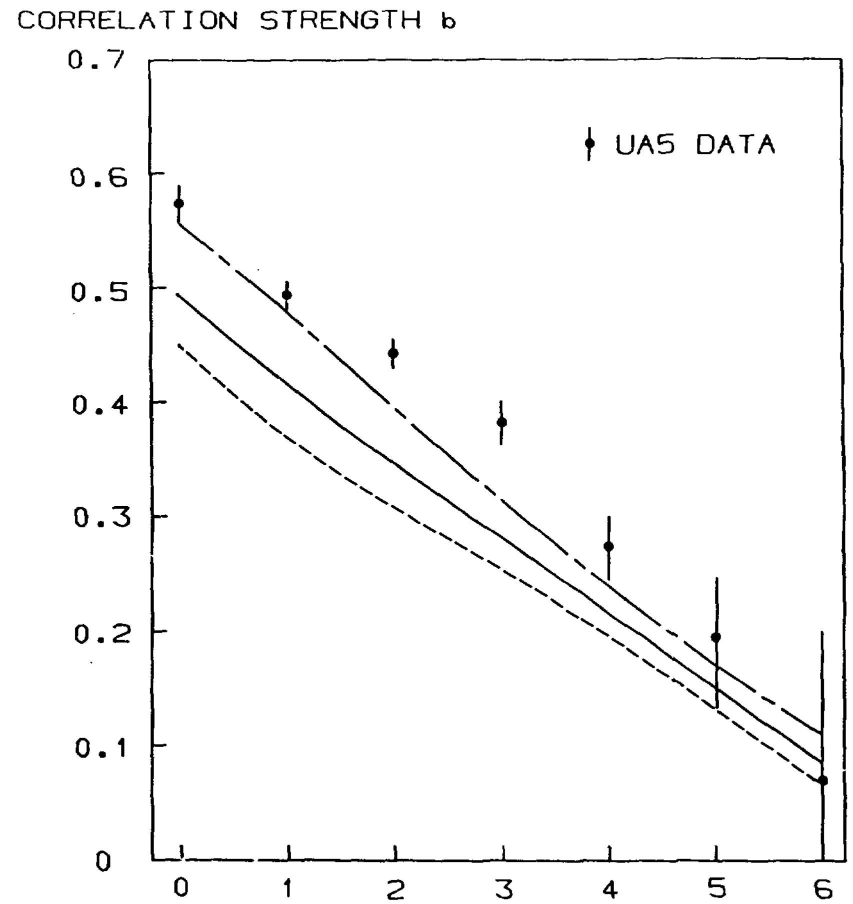
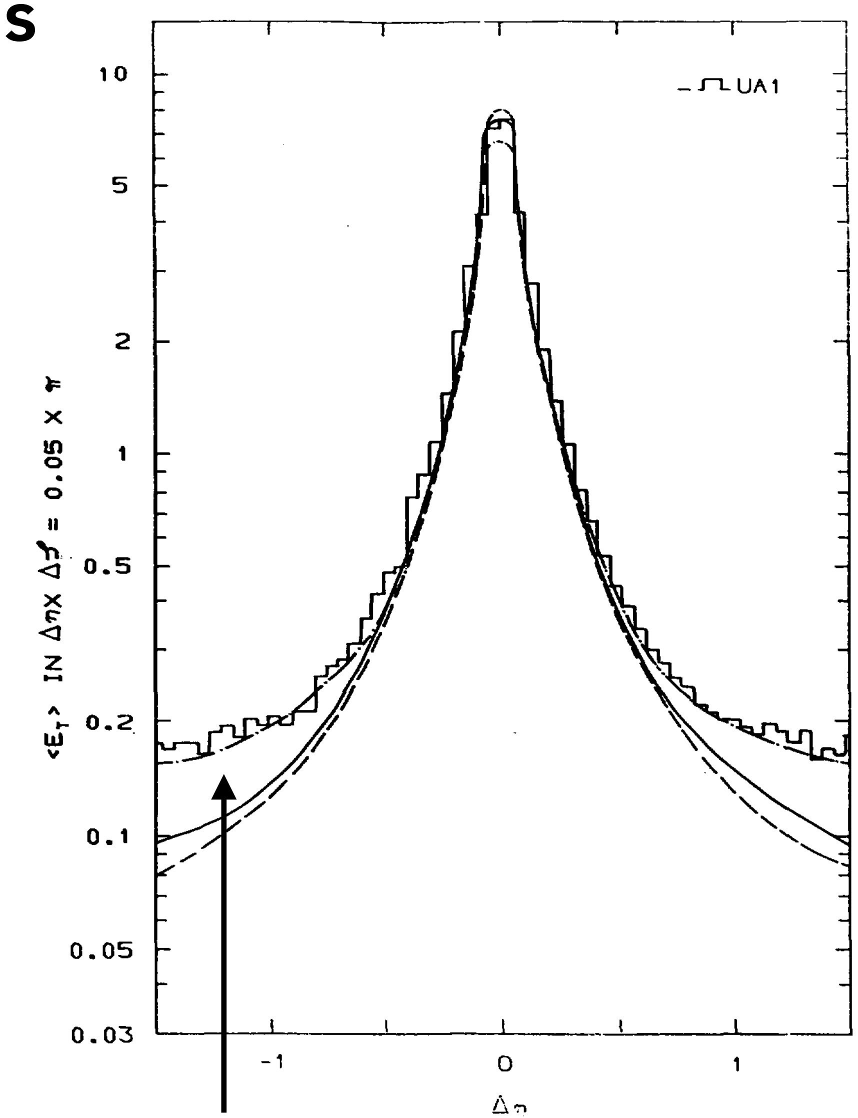


FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\tilde{O}_0(b)$].





Impact-parameter dependence → UE

Sjöstrand & v. Zijl, Phys.Rev.D36(1987)2019

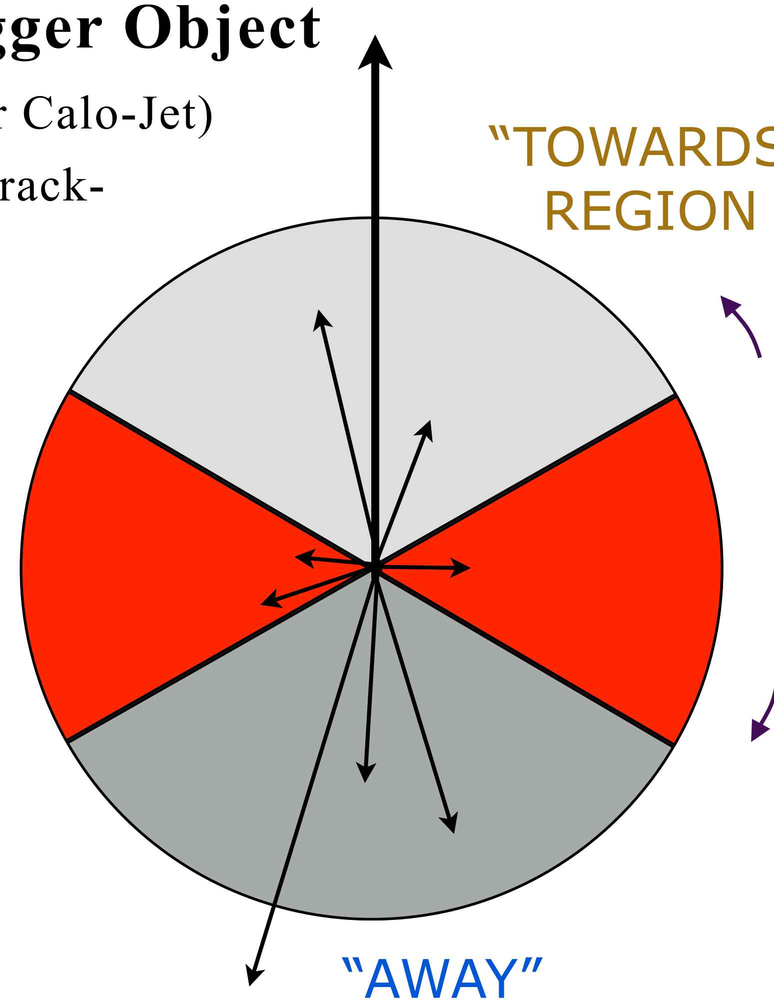
CHARACTERISING THE UNDERLYING EVENT

(The "Rick Field" UE Plots - the same Field as in Field-Feynman)

There are many UE variables.
The most important is $<\Sigma p_T>$ in the "Transverse Region"

Leading Trigger Object

(e.g., hardest track, Track-Jet, or Calo-Jet)
(more inclusive to use jets, but track-based analyses also useful)



~ Recoil Jet

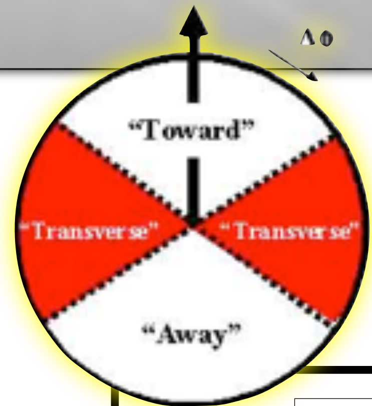
"Transverse Region" (TRNS)

Sensitive to activity at right angles to the hardest jets

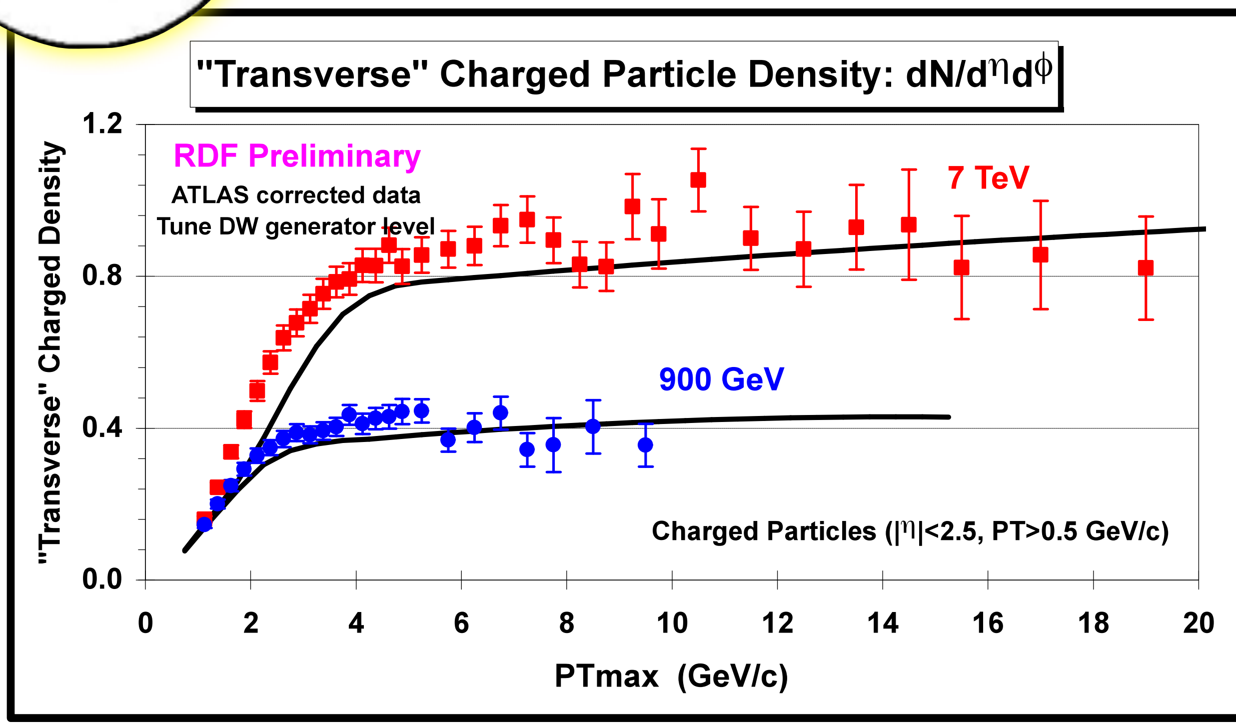
➜ Useful definition of Underlying Event

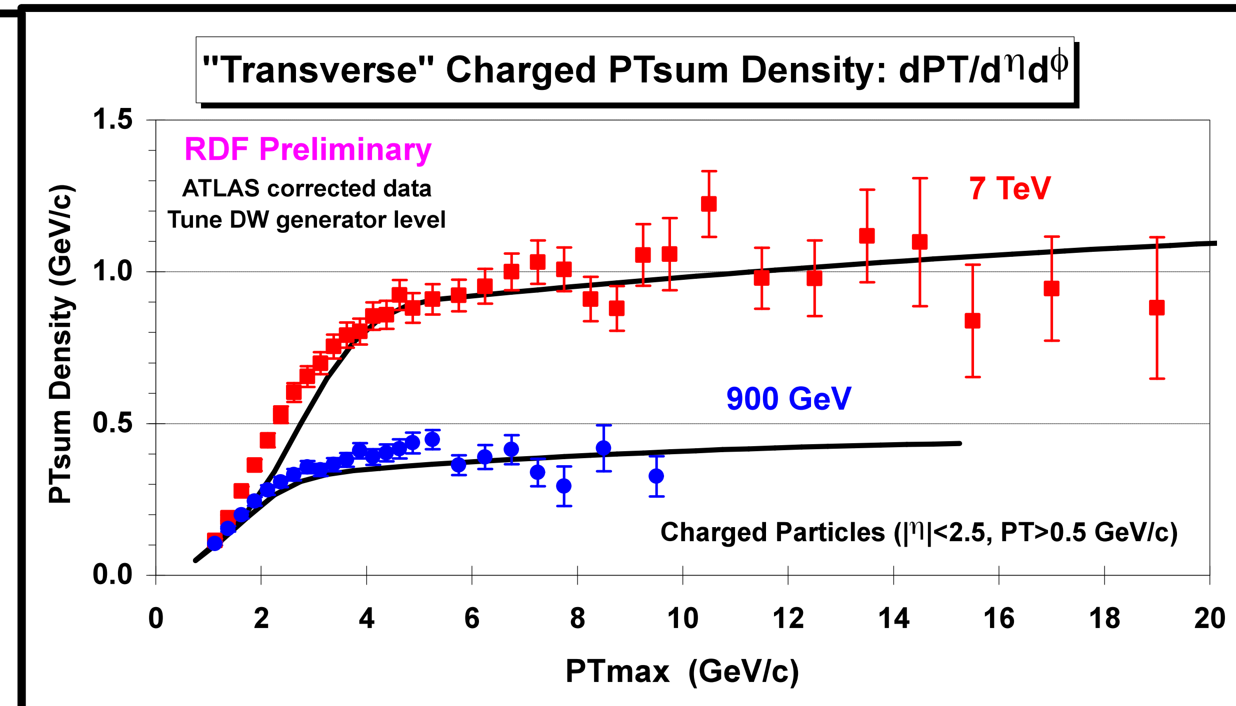
THE PEDESTAL

(NOW CALLED THE UNDERLYING EVENT)



LHC from 900 to 7000 GeV - ATLAS





Track Density (TRANS)

(Not Infrared Safe)

Large Non-factorizable Corrections

Prediction off by ≈ 10%

Sum(pT) Density (TRANS)

(more) Infrared Safe

Large Non-factorizable Corrections

Prediction off by < 10%

Truth is in the eye of the beholder:

R. Field: "See, I told you!"

Y. Gehrstein: "they have to fudge it again"

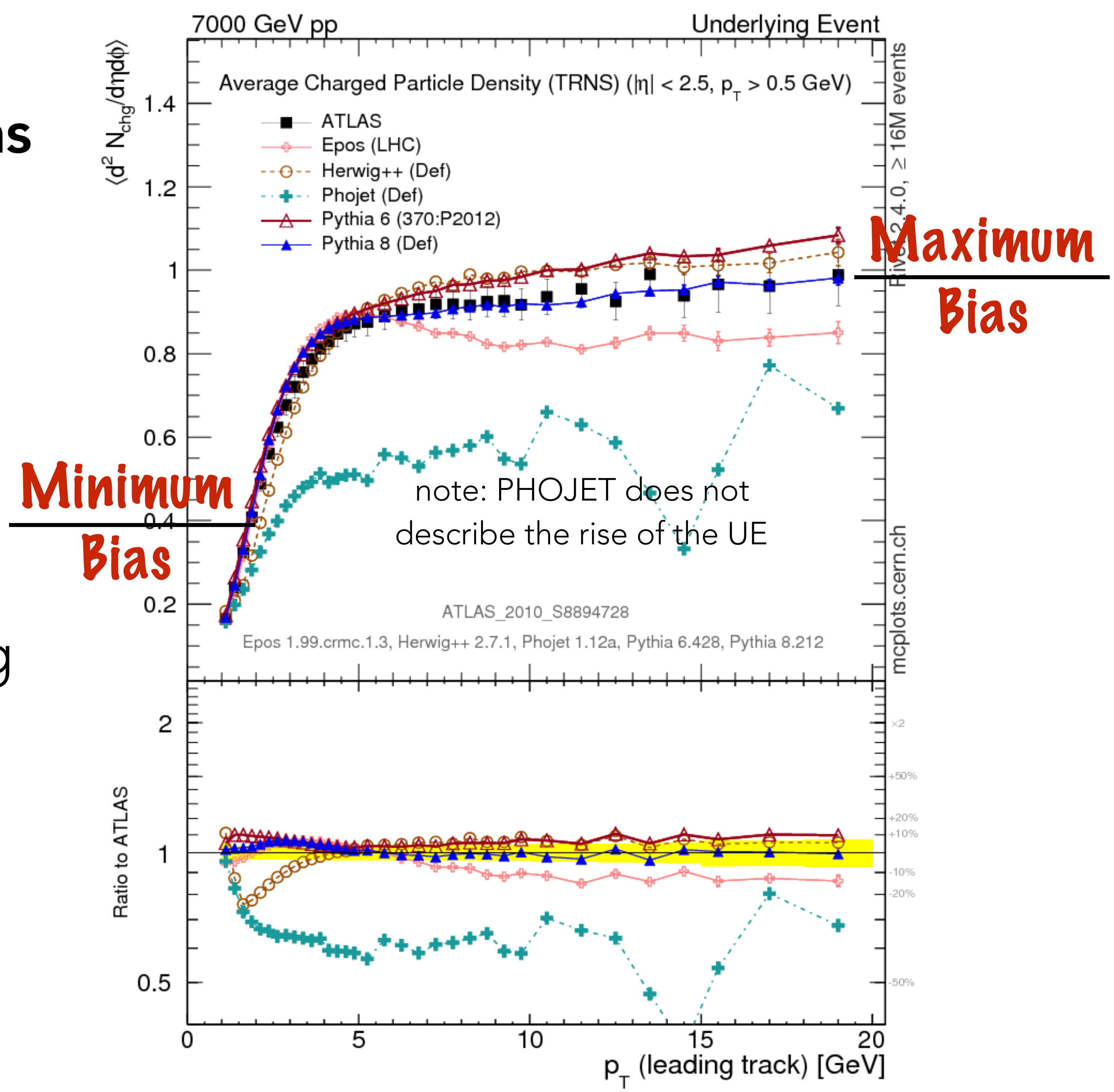
Tautology:

A jet trigger provides a bias
(→subsample of minimum-bias)

Pedestal effect:

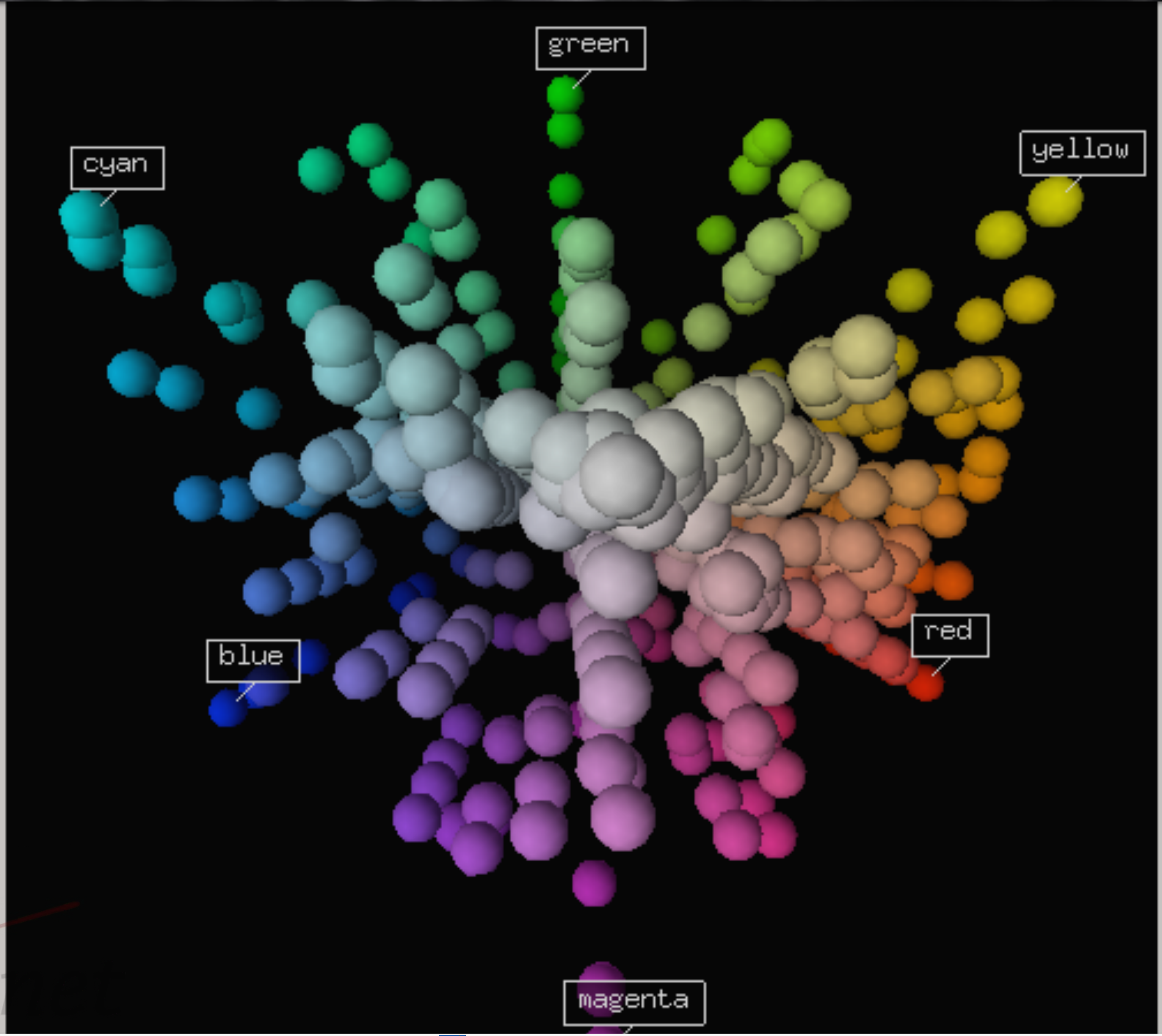
Events with a hard jet trigger are accompanied by a higher plateau of ambient activity

MPI: interpreted as a biasing effect. Small pp impact parameters → larger matter overlaps → more MPI → higher chances for a hard interaction



Plot from mcplots.cern.ch

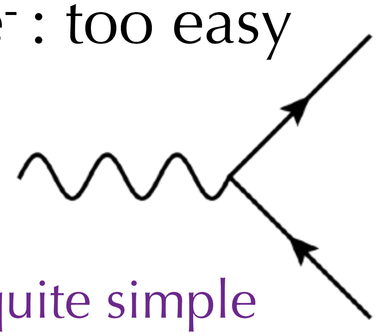
COLOUR SPACE
IN HADRON COLLISIONS



COLOUR CONFUSION

Between which partons do confining potentials arise?

e^+e^- : too easy



(still quite simple even after including bremsstrahlung etc.)

At e^+e^- colliders (eg LEP) : generally good agreement between **measured** particle spectra and **models** based on parton/antenna showers + strings

Basically a single **3-3bar** system, very close to the original lattice studies motivating the string model.

(+ extensions to WW reasonable to ~$O(1/N_c^2)$)

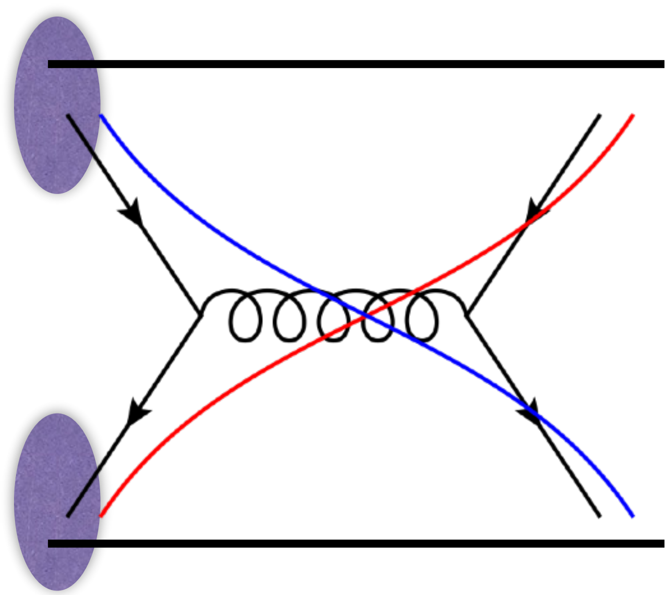
→ re-use same models as input for LHC (universality) ?

Proton-Proton (LHC)

A lot more colour kicked around (& also colour in initial state)

Include “Beam Remnants”

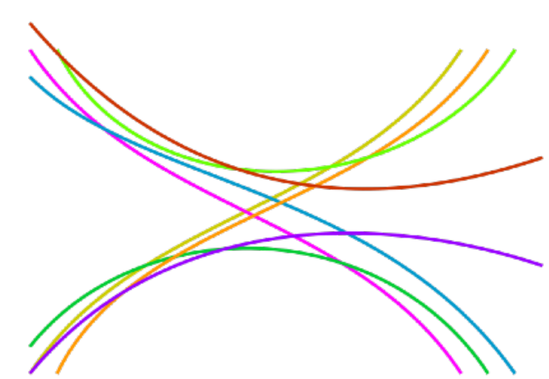
Still might look relatively simple, to begin with



(+baryon beam remnants → “string junctions”)

String-fragmentation of junctions: Sjöstrand & Skands **Nucl.Phys. B659 (2003) 243**

Now add MPI:



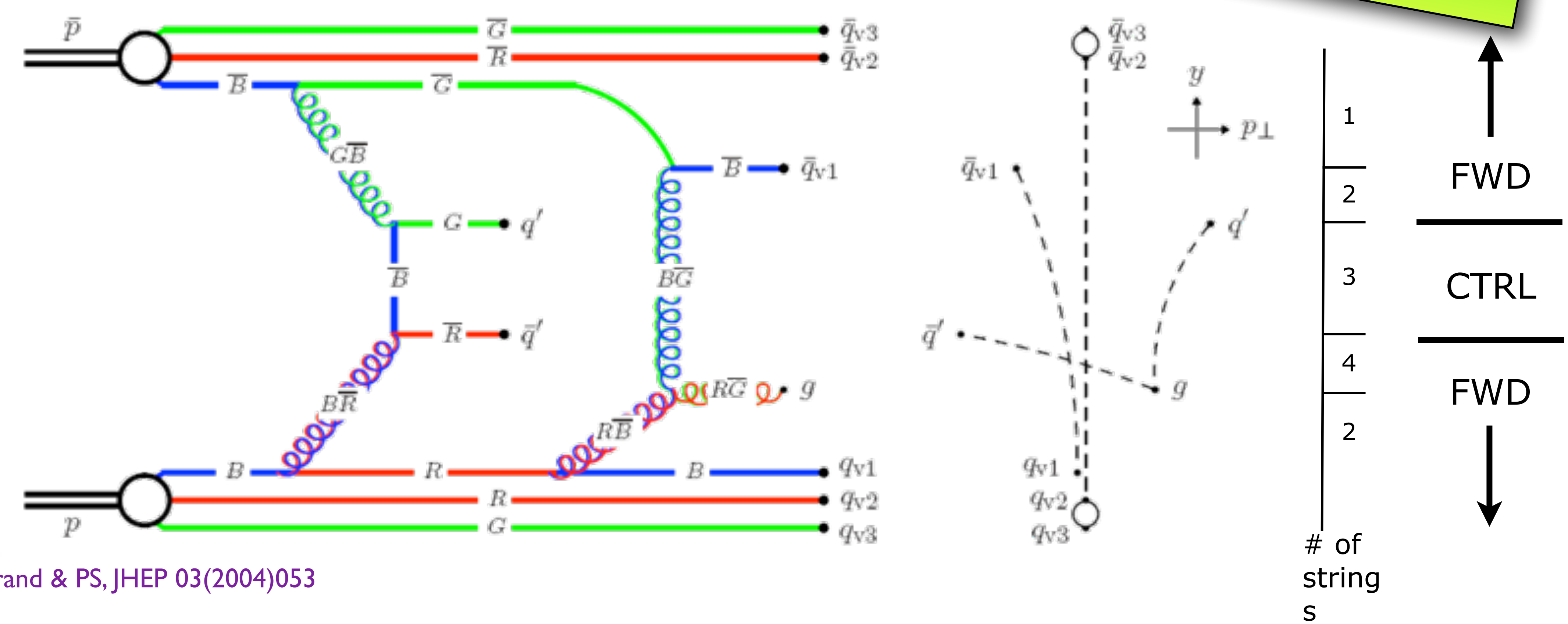
Included in all (modern) Monte Carlo models
But how to make sense of the colour structure?

COLOR CORRELATIONS

Each MPI (or cut Pomeron) exchanges color between the beams

- ▶ The colour flow determines the hadronizing string topology
  - Each MPI, even when soft, is a color spark
  - Final distributions <u>crucially</u> depend on color space

Different models make different ansätze



Sjöstrand & PS, JHEP 03(2004)053

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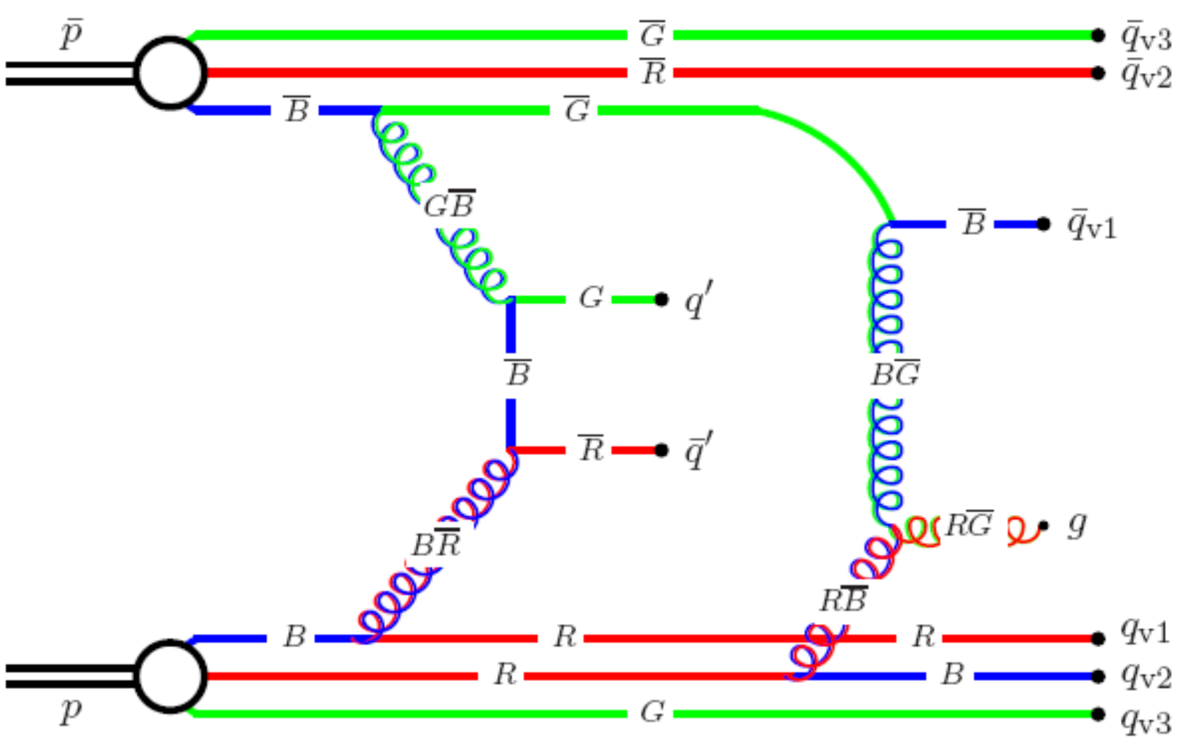
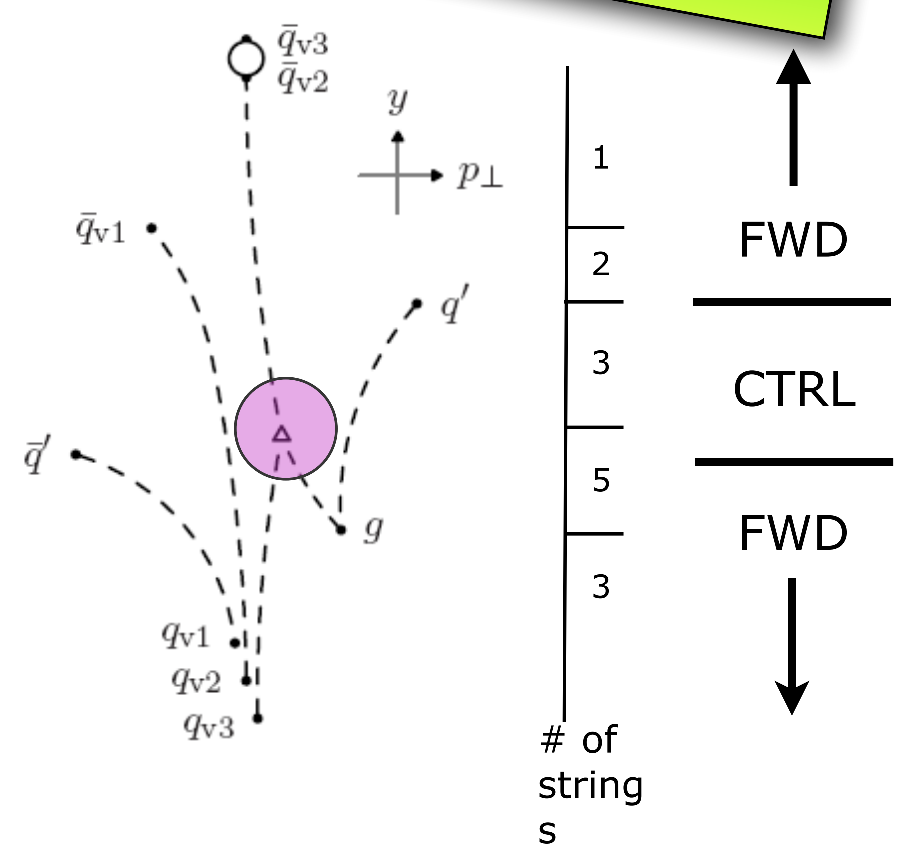
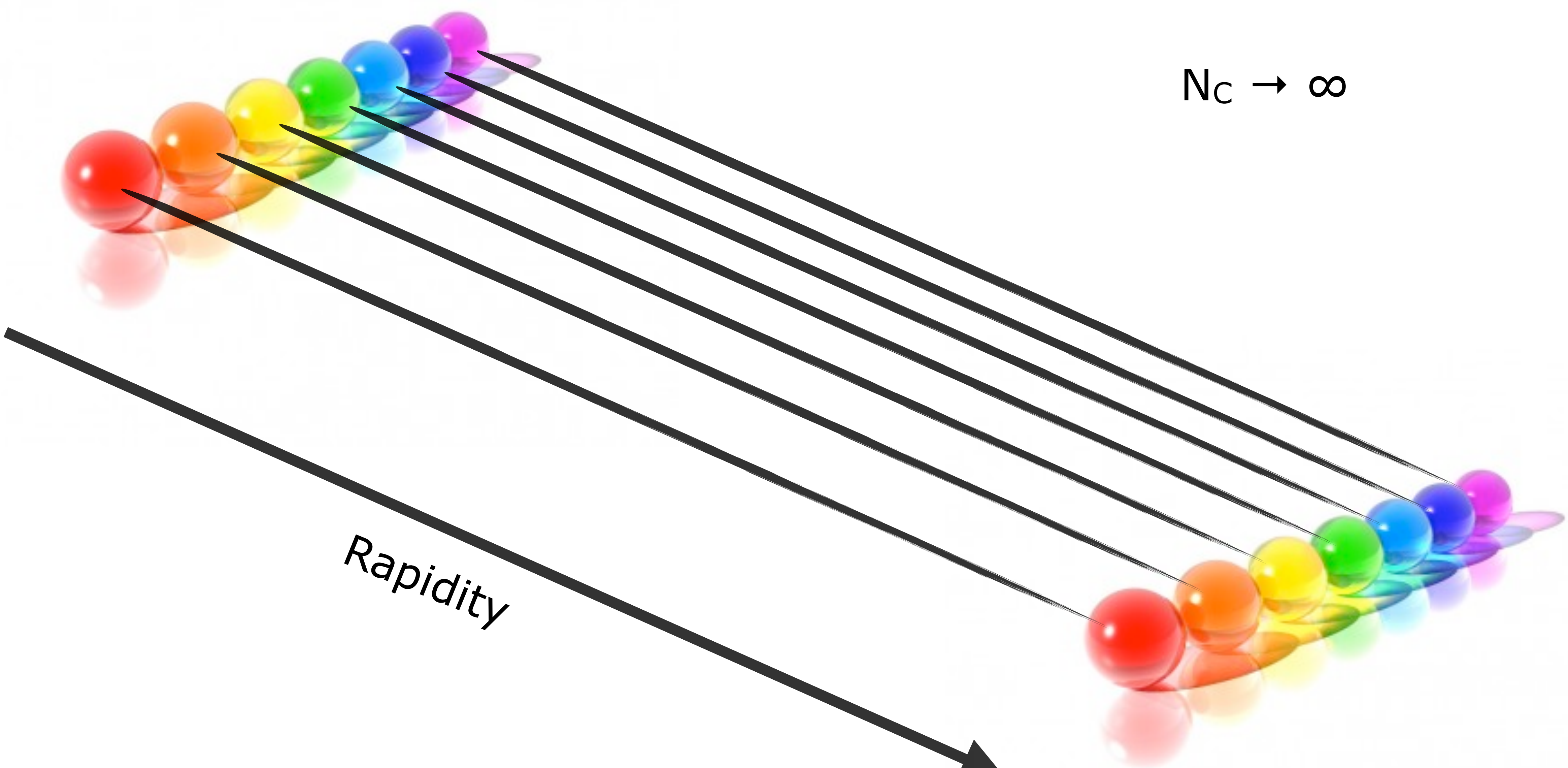


Sjöstrand & PS, JHEP 03(2004)053



COLOR CONNECTIONS

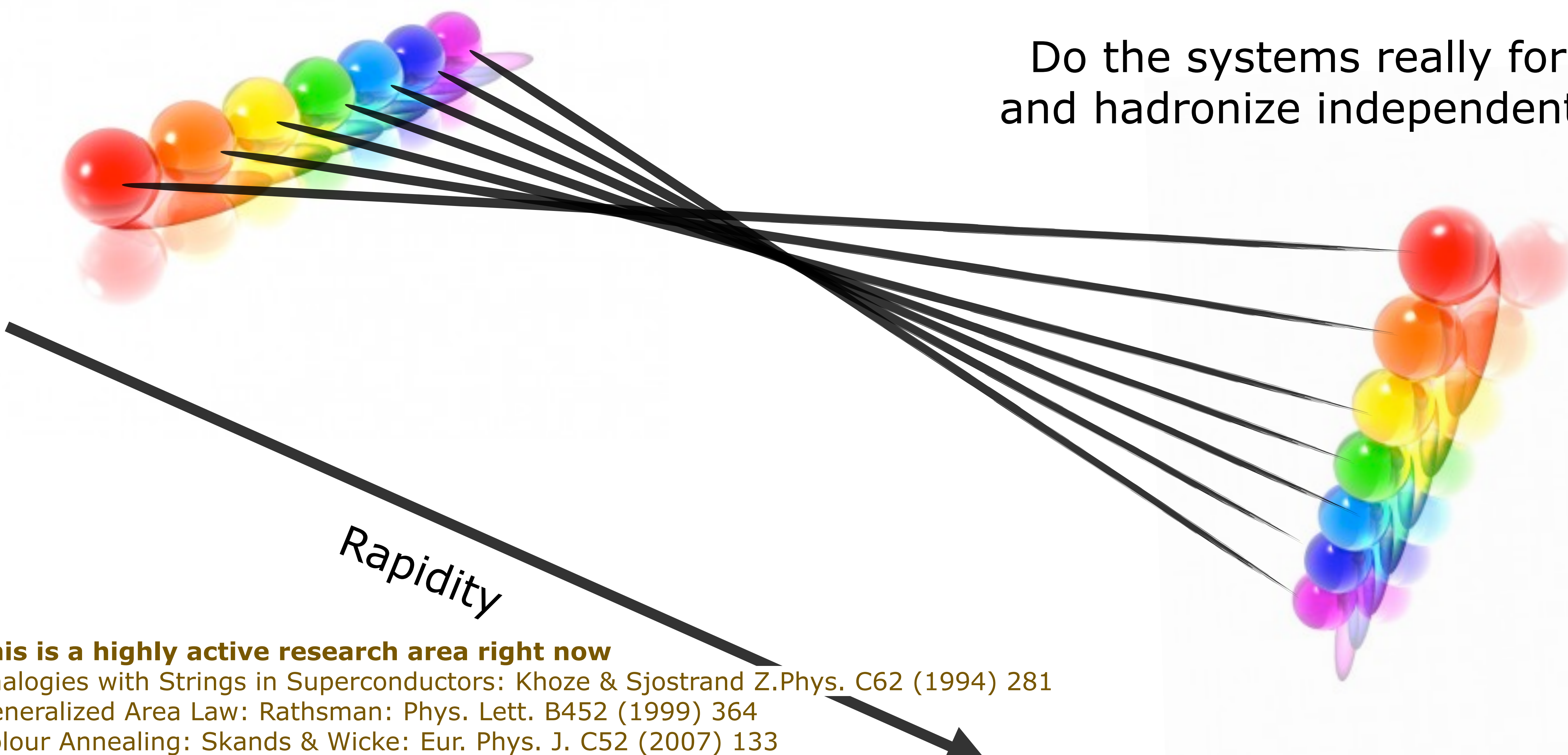
Better theory models needed



COLOR RECONNECTIONS?

Better theory models needed

Do the systems really form and hadronize independently?



This is a highly active research area right now

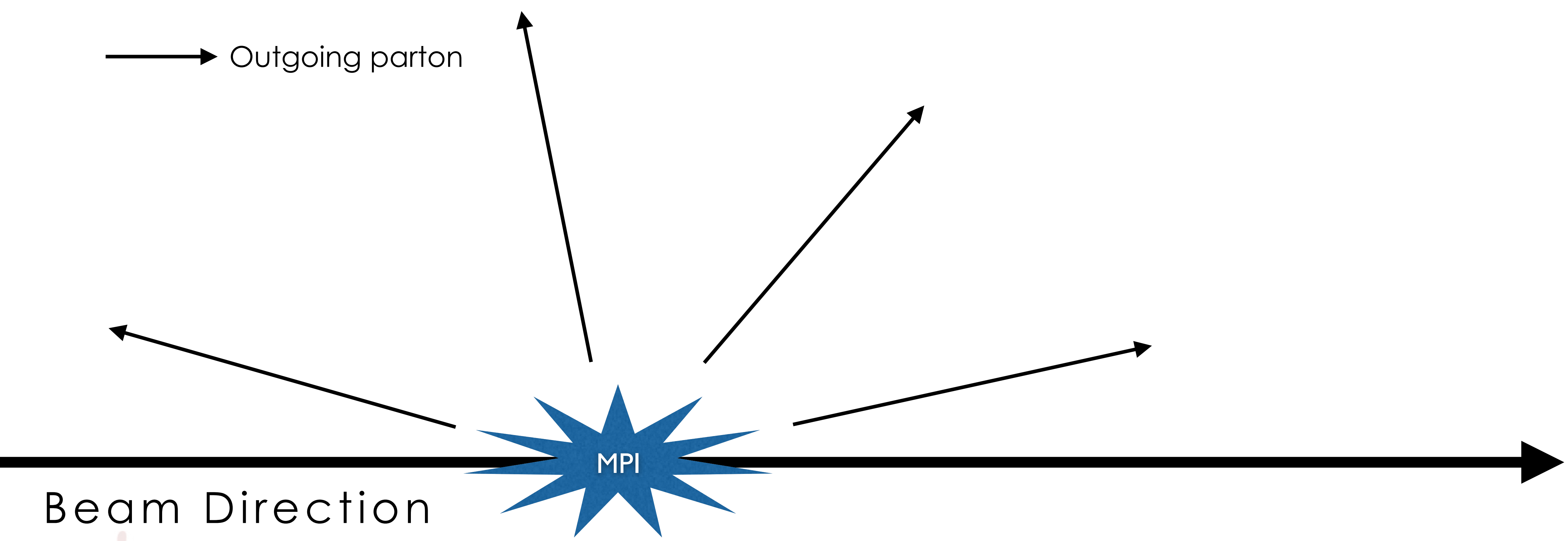
Analogies with Strings in Superconductors: Khoze & Sjostrand Z.Phys. C62 (1994) 281
Generalized Area Law: Rathsman: Phys. Lett. B452 (1999) 364
Colour Annealing: Skands & Wicke: Eur. Phys. J. C52 (2007) 133
Cluster-based models: e.g. Gieseke et al., Eur.Phys.J. C72 (2012) 2225
Dipole Swing, Lonnblad et al.
Gluon Move Model, Sjostrand et al.
Colour Ropes: Bierlich et al, JHEP 1503 (2015) 148
String Formation Beyond Leading Colour: Christensen & Skands: arXiv:1505.01681
String interactions? Hydrodynamics (EPOS: Werner et al.,)? Collective flow? Pressure? Rescatterings?

Multiplicity $\overset{<}{\cancel{\propto}}$ N_{MPI}

COLOUR: WHAT'S THE PROBLEM?

(including **MPI:** Multiple Parton-Parton Interactions ~ the "underlying event")

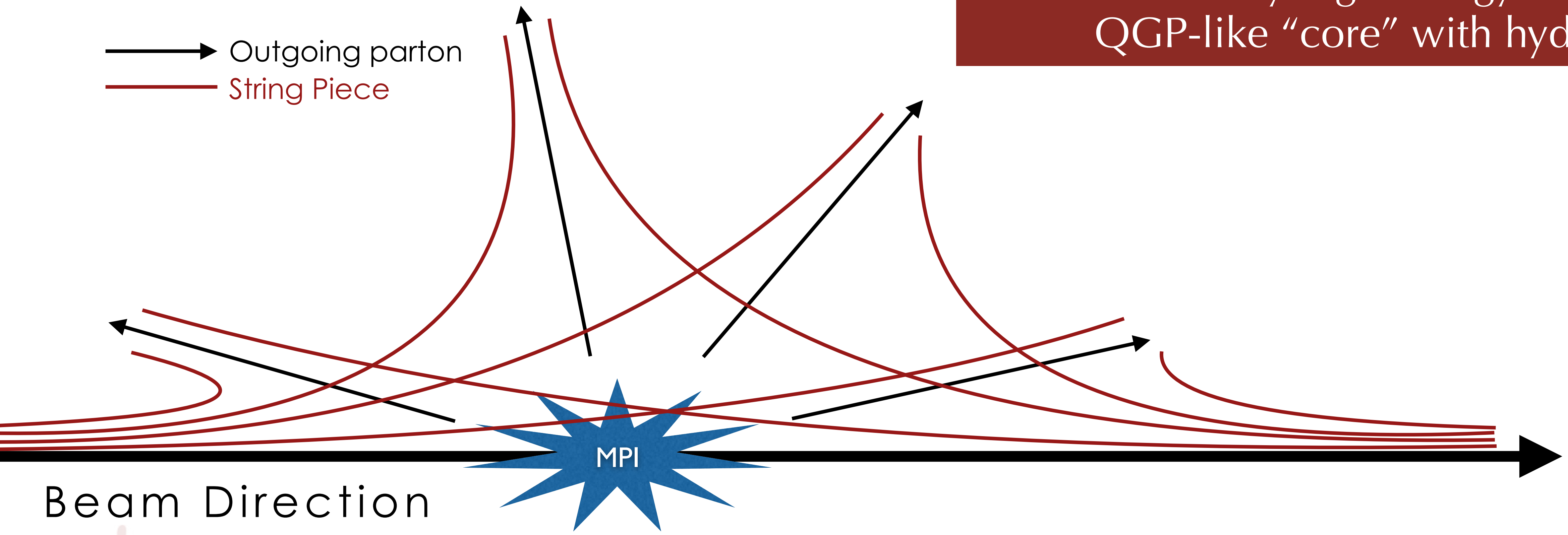
Without Colour Reconnections
Each MPI hadronizes **independently** of all others



(including **MPI:** Multiple Parton-Parton Interactions ~ the "underlying event")

Without Colour Reconnections
Each MPI hadronizes **independently** of all others

So many strings in so little space
If true → Very high energy densities
QGP-like "core" with hydro?



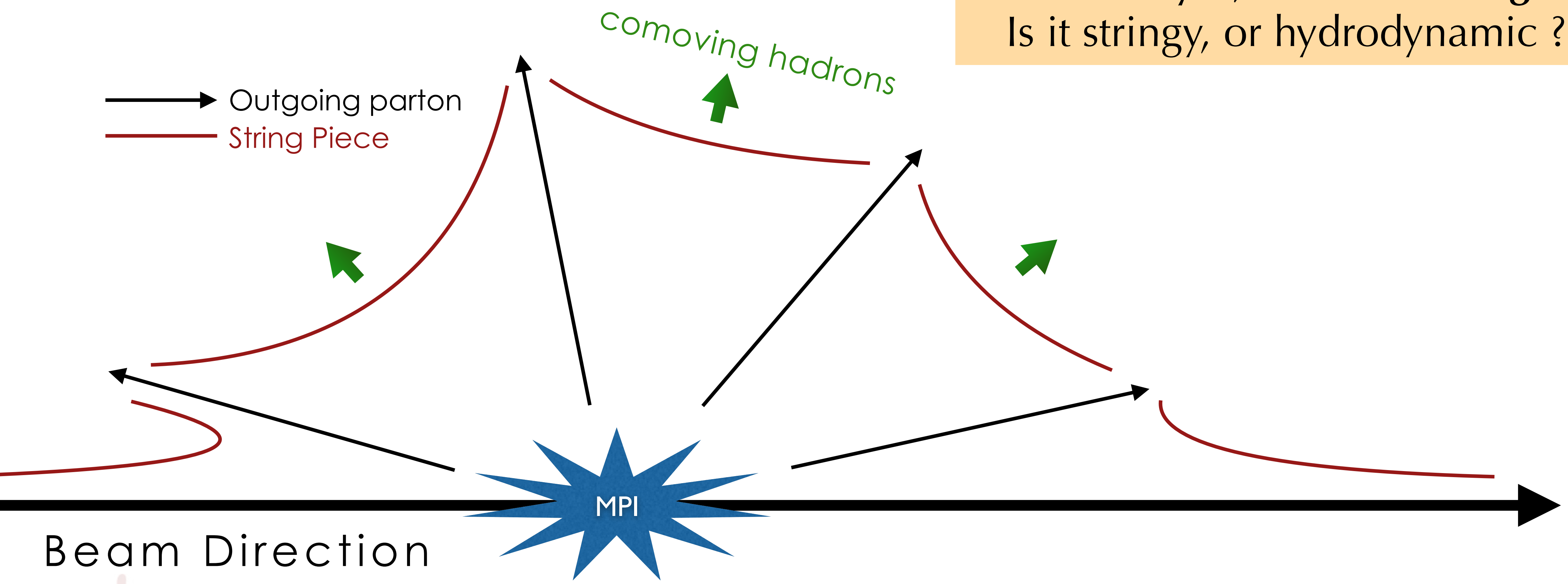
→ Thermal? E.g., EPOS

(including **MPI:** Multiple Parton-Parton Interactions ~ the "underlying event")

With Colour Reconnections
MPI hadronize **collectively**

See also Ortiz et al., Phys.Rev.Lett. 111 (2013) 4, 042001

Highly interesting theory questions now.
Is there collective flow in pp? Or not?
If yes, what is its origin?
Is it stringy, or hydrodynamic ? (or …?)



String-Length Minimisation E.g., PYTHIA, HERWIG

Or Hydro? E.g., EPOS

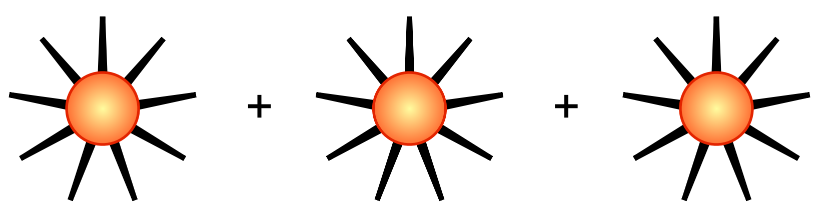
Or Higher String Tension? E.g., DIPSY rope

COLLECTIVE EFFECTS?

A rough indicator of how much colour gets kicked around, should be the number of particles produced

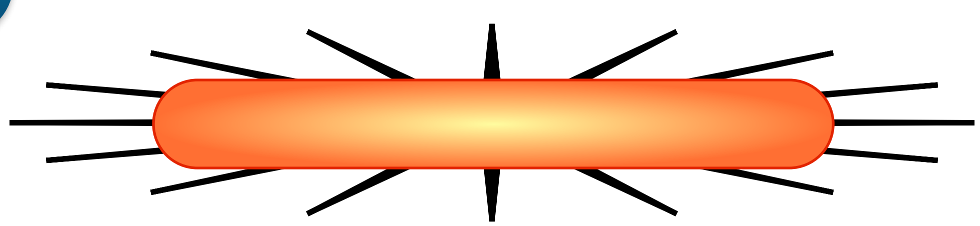
So we study event properties as a function of "N_{ch}" = N_{tracks}

A

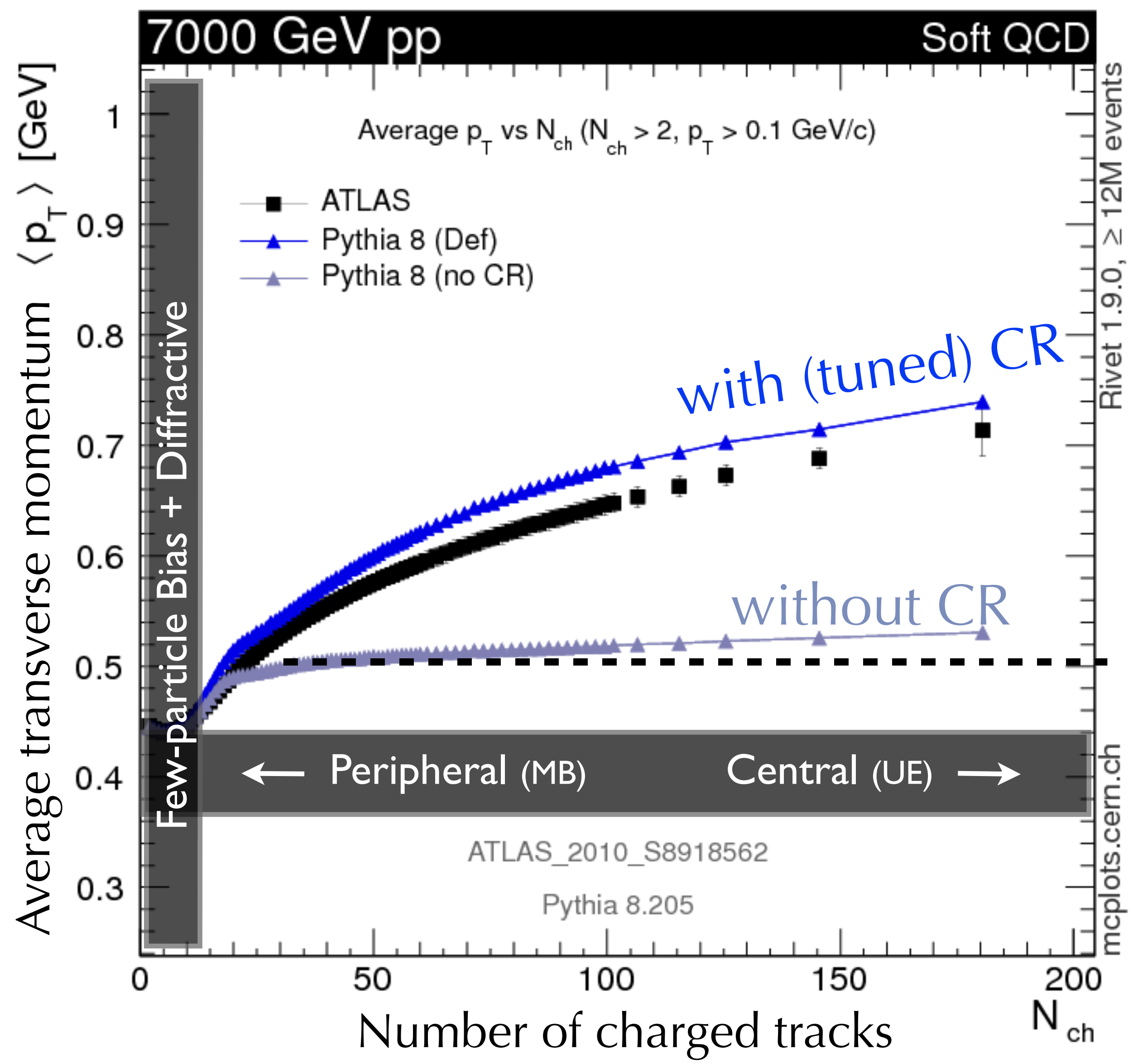


Independent Particle Production:
→ **averages stay the same**

B

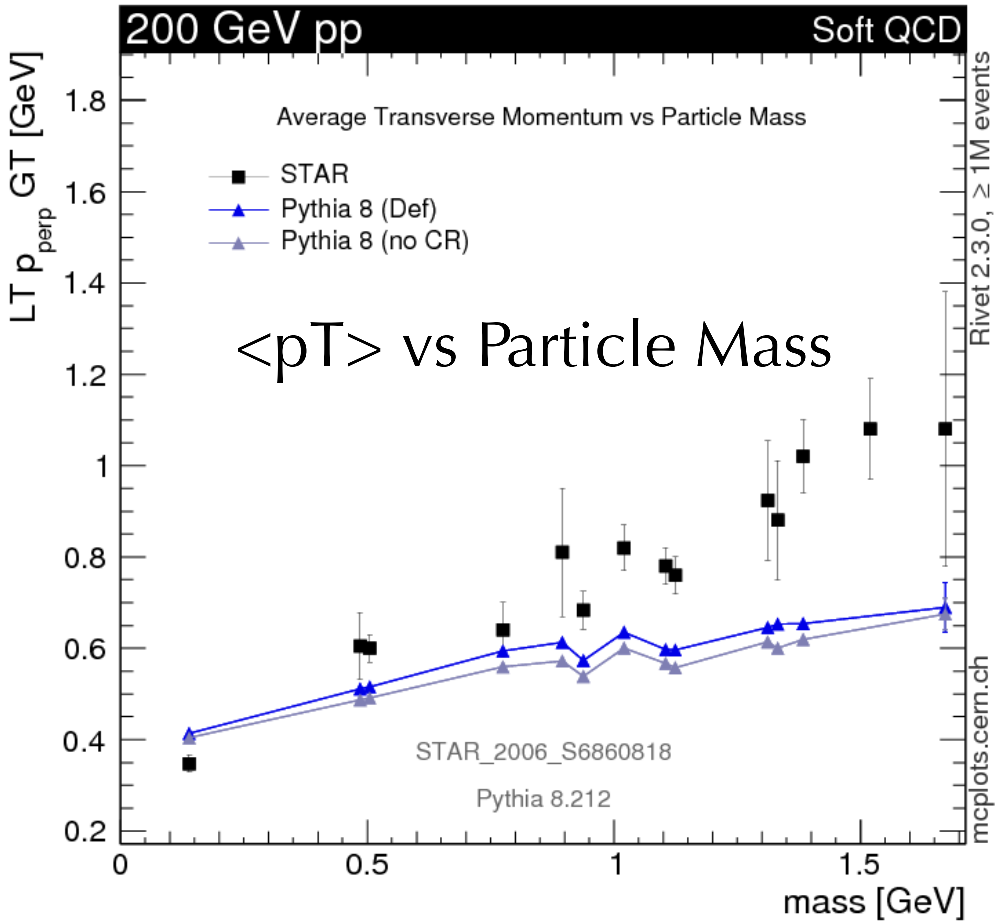


Correlations / Collective effects:
→ **averages depend on N_{ch}**

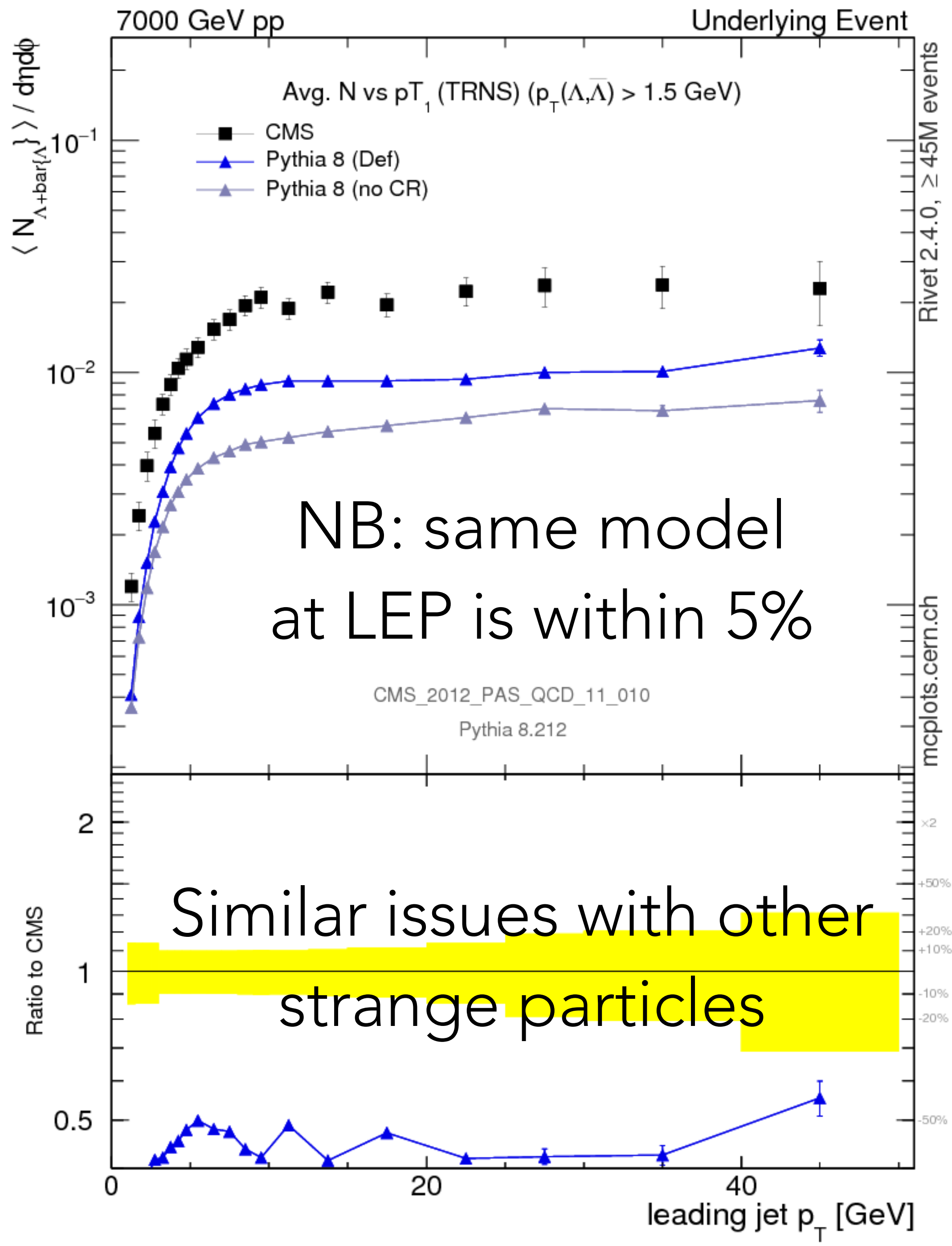


Plots from mcplots.cern.ch

Heavier particles are harder

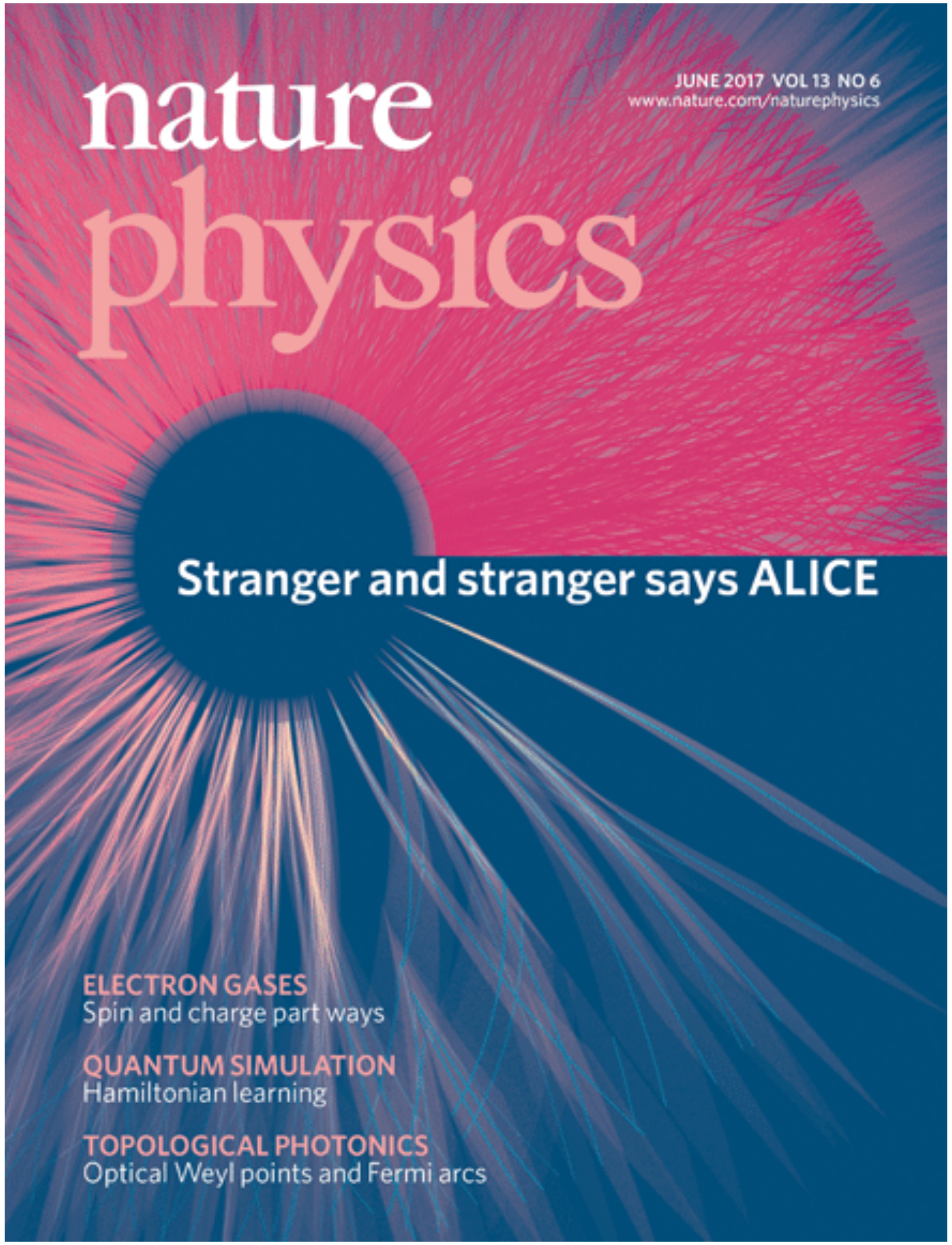


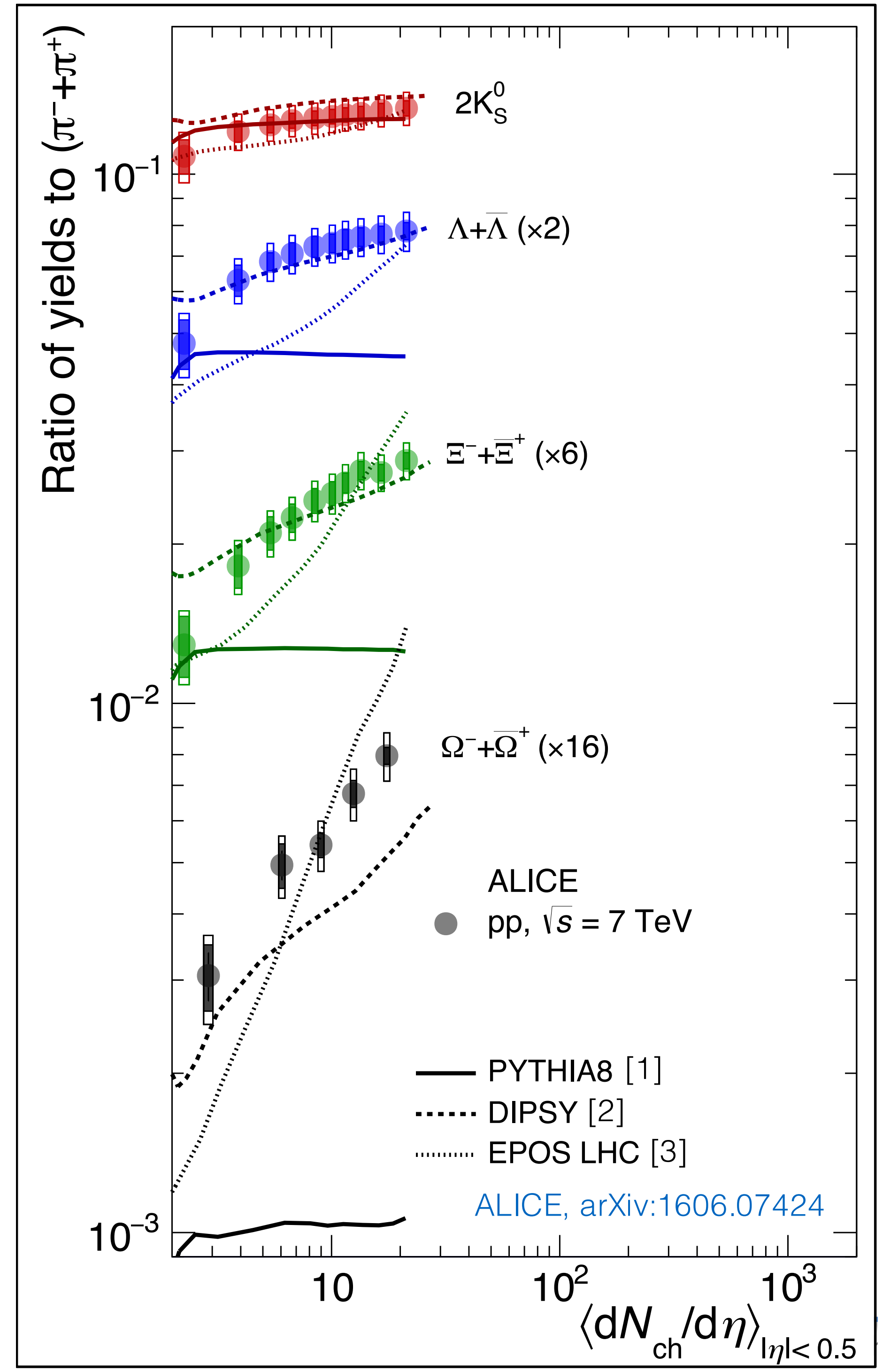
Where have all the Λ gone?



Plots from mcplots.cern.ch

… and then there was this …





SUMMARY: MCS & PARTON SHOWERS

Aim: generate events in as much detail as mother nature

→ Make stochastic choices ~ as in Nature (Q.M.) → Random numbers

Factor complete event probability into separate universal pieces, treated independently and/or sequentially (Markov-Chain MC)

Improve Born-level theory with 'most significant' corrections

Resonance decays (e.g., $t \to bW^+$, $W \to qq'$, $H^0 \to \gamma^0\gamma^0$, $Z^0 \to \mu^+\mu^-$, …)

Bremsstrahlung (FSR and ISR, exact in collinear and soft* limits)

Hard radiation (matching)

Hadronization (strings/clusters, discussed tomorrow)

Additional Soft Physics: multiple parton-parton interactions, Bose-Einstein correlations, colour reconnections, hadron decays, …

MCnet

MCs can be treated as black boxes, without knowing what's in them.

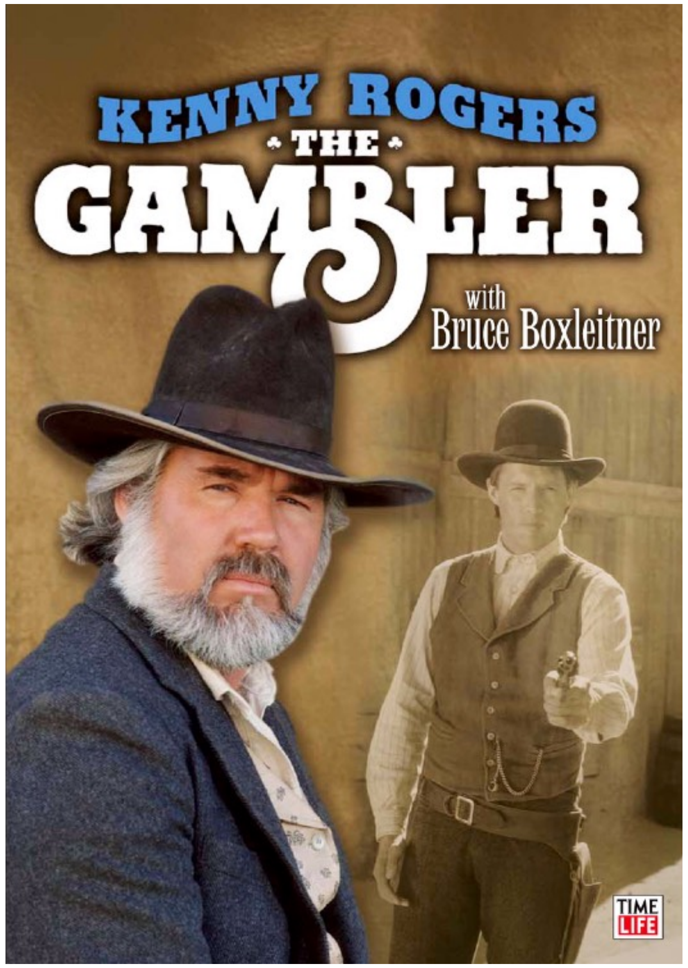
Best Case: Limited Sophistication

Worst Case: Not your lucky day

The secret to successful MC is:

Knowing what to throw away

Knowing what to keep



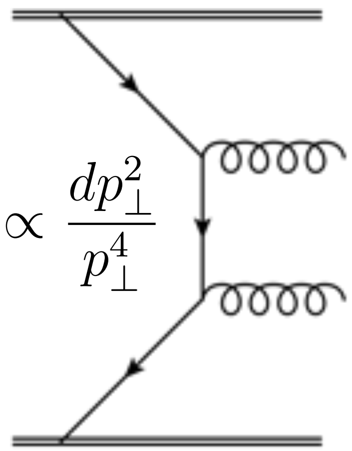
Kenny Rogers "The Gambler", first recorded in 1978

Same year as the first version of PYTHIA (JETGEN)

Extra Slides

(SOME CAVEATS OF MPI-BASED MODELS)

Main applications of factorisation: Central Jets/EWK/top/ Higgs/New Physics

$$d\sigma_{2\to 2} \propto \frac{dp_\perp^2}{p_\perp^4}$$  $\otimes$ PDFs

High Q^2 and finite x

Extrapolation to soft scales delicate.

Impressive successes with MPI-based models but still far from ‘problem solved’

Form of PDFs at small x and Q^2 — “Saturation” ?

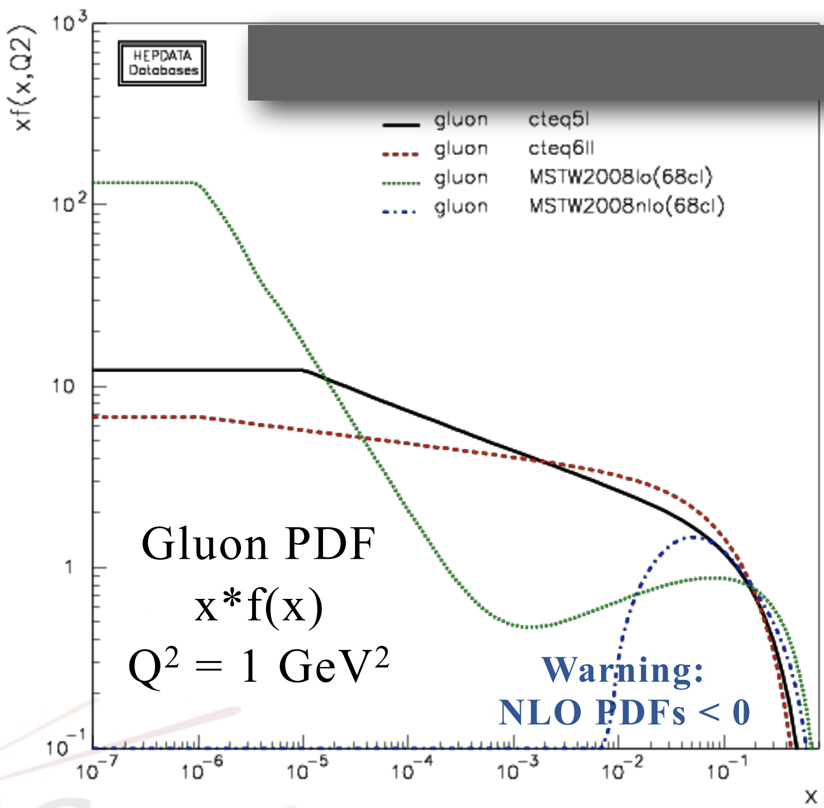
Form and E_{cm} dependence of p_{T0} regulator

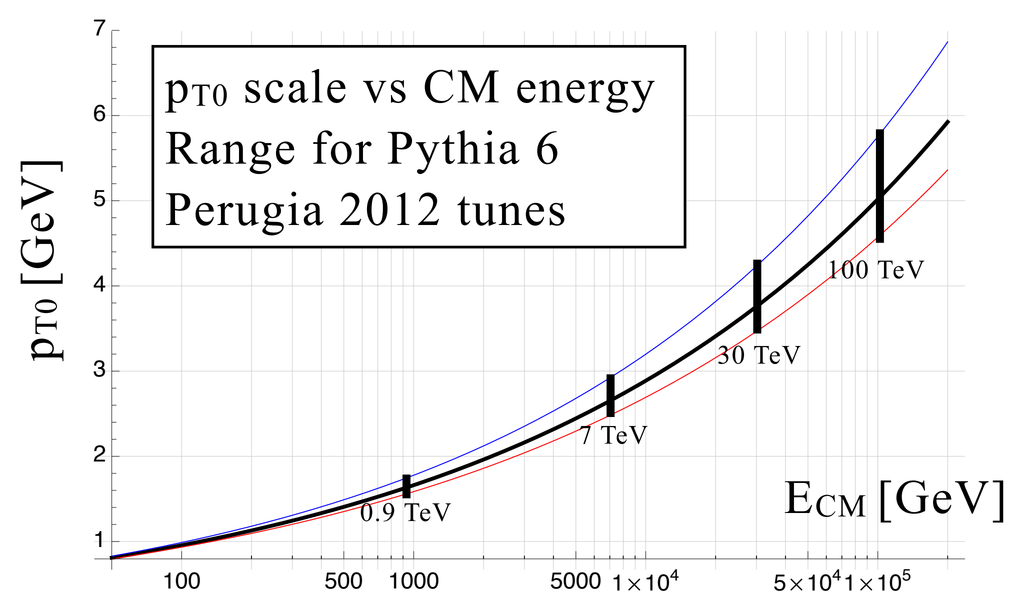
Modeling of the diffractive component

Proton transverse mass distribution

Colour Reconnections, Collective Effects

Poor Man’s Saturation





See also Connecting hard to soft: KMR, EPJ C71 (2011) 1617 + PYTHIA “Perugia Tunes”: PS, PRD82 (2010) 074018 + arXiv:1308.2813

First try: decompose $\sigma_{\mathrm{inel}} = \sigma_{\mathrm{sd}} + \sigma_{\mathrm{dd}} + \sigma_{\mathrm{cd}} + \sigma_{\mathrm{nd}}$

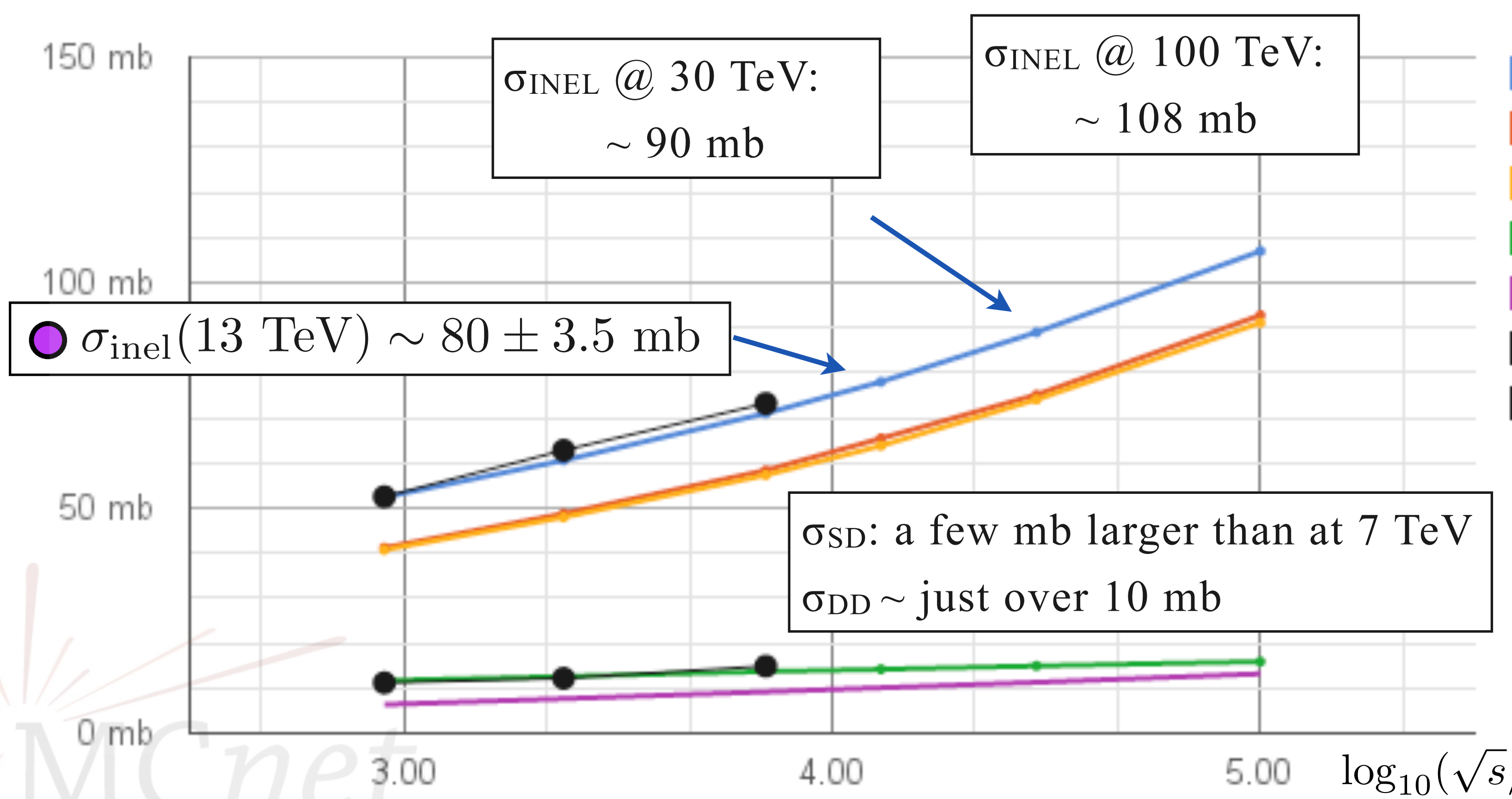
+ Parametrizations of diffractive components: dM^2/M^2

PYTHIA:

$$\frac{\mathrm{d}\sigma_{\mathrm{sd}(AX)}(s)}{\mathrm{d}t\,\mathrm{d}M^2} = \frac{g_{3\mathbb{P}}}{16\pi}\,\beta_{A\mathbb{P}}^2\,\beta_{B\mathbb{P}}\,\frac{1}{M^2}\,\exp(B_{\mathrm{sd}(AX)}t)\,F_{\mathrm{sd}}\ ,$$

$$\frac{\mathrm{d}\sigma_{\mathrm{dd}}(s)}{\mathrm{d}t\,\mathrm{d}M_1^2\,\mathrm{d}M_2^2} = \frac{g_{3\mathbb{P}}^2}{16\pi}\,\beta_{A\mathbb{P}}\,\beta_{B\mathbb{P}}\,\frac{1}{M_1^2}\,\frac{1}{M_2^2}\,\exp(B_{\mathrm{dd}}t)\,F_{\mathrm{dd}}\ .$$

+ Integrate and solve for σ_{nd}



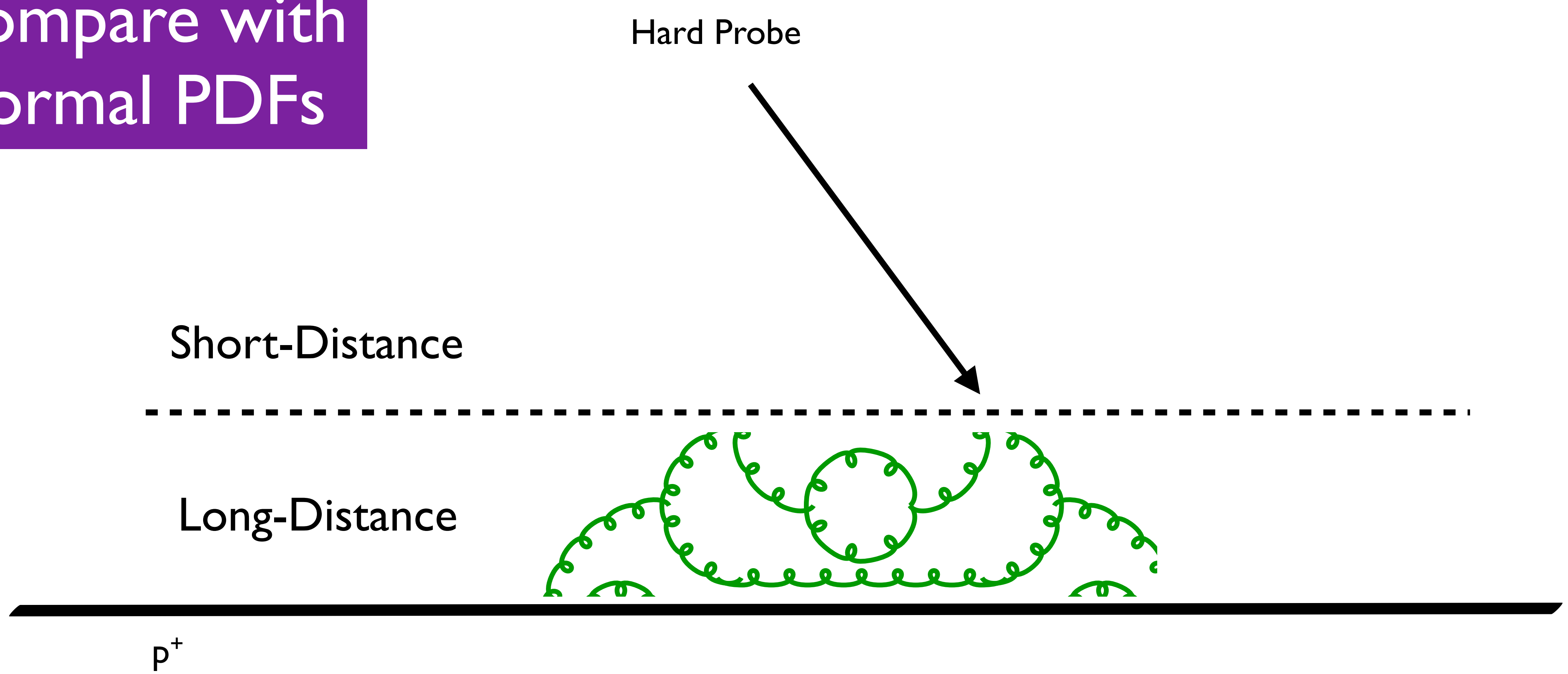
What Cross Section?

INEL	Total Inelastic
INEL>0	Fraction with one charged particle in $\lvert\eta\rvert<1$
NSD	Ambiguous Theory Definition
SD	Ambiguous Theory Definition
DD	Ambiguous Theory Definition
ALICE INEL	Observed fraction corrected to total
ALICE SD	ALICE def : SD has MX<200

Note problem of principle: Q.M. requires **distinguishable final states**

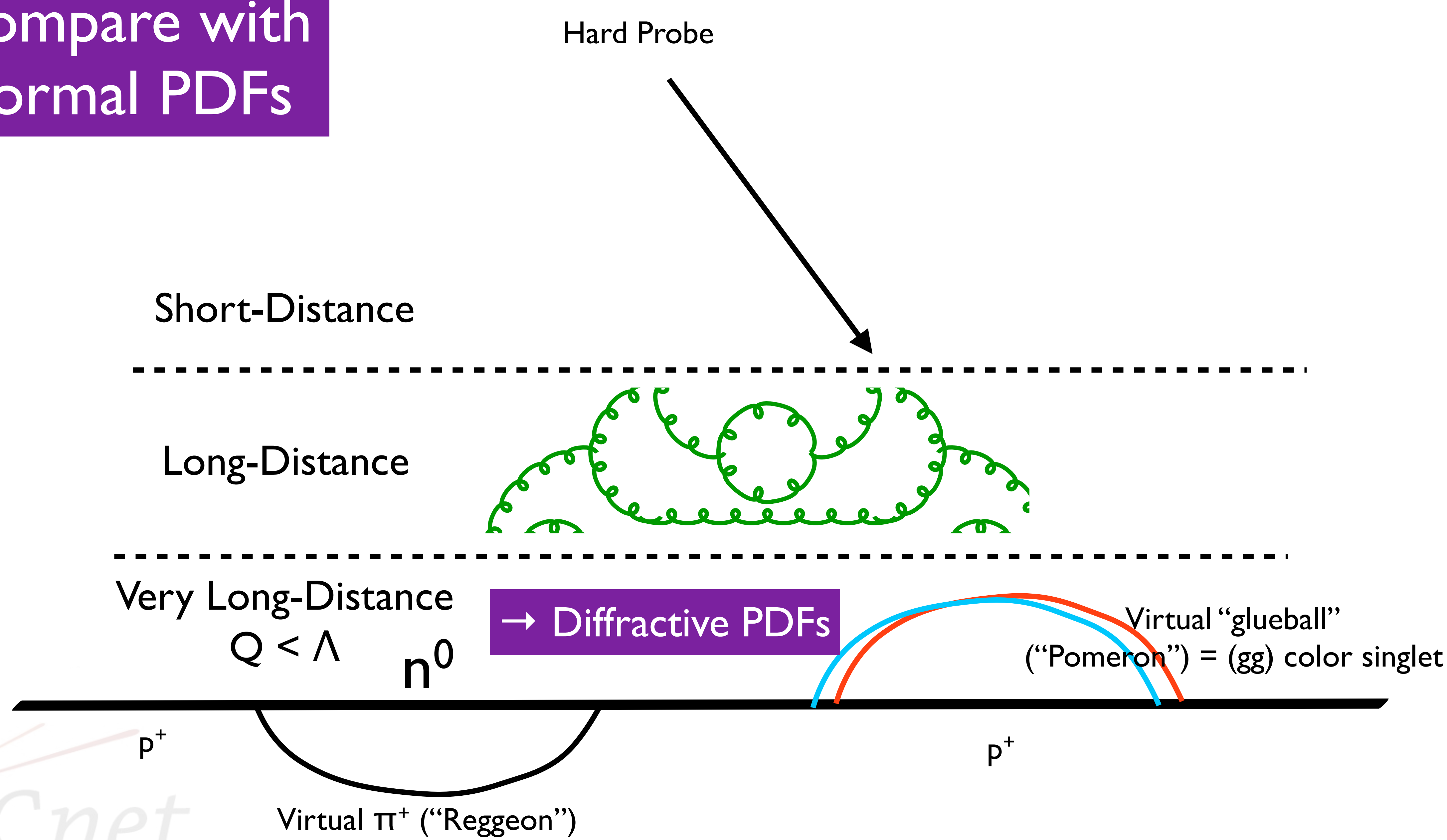
"Intuitive picture"

Compare with normal PDFs



"Intuitive picture"

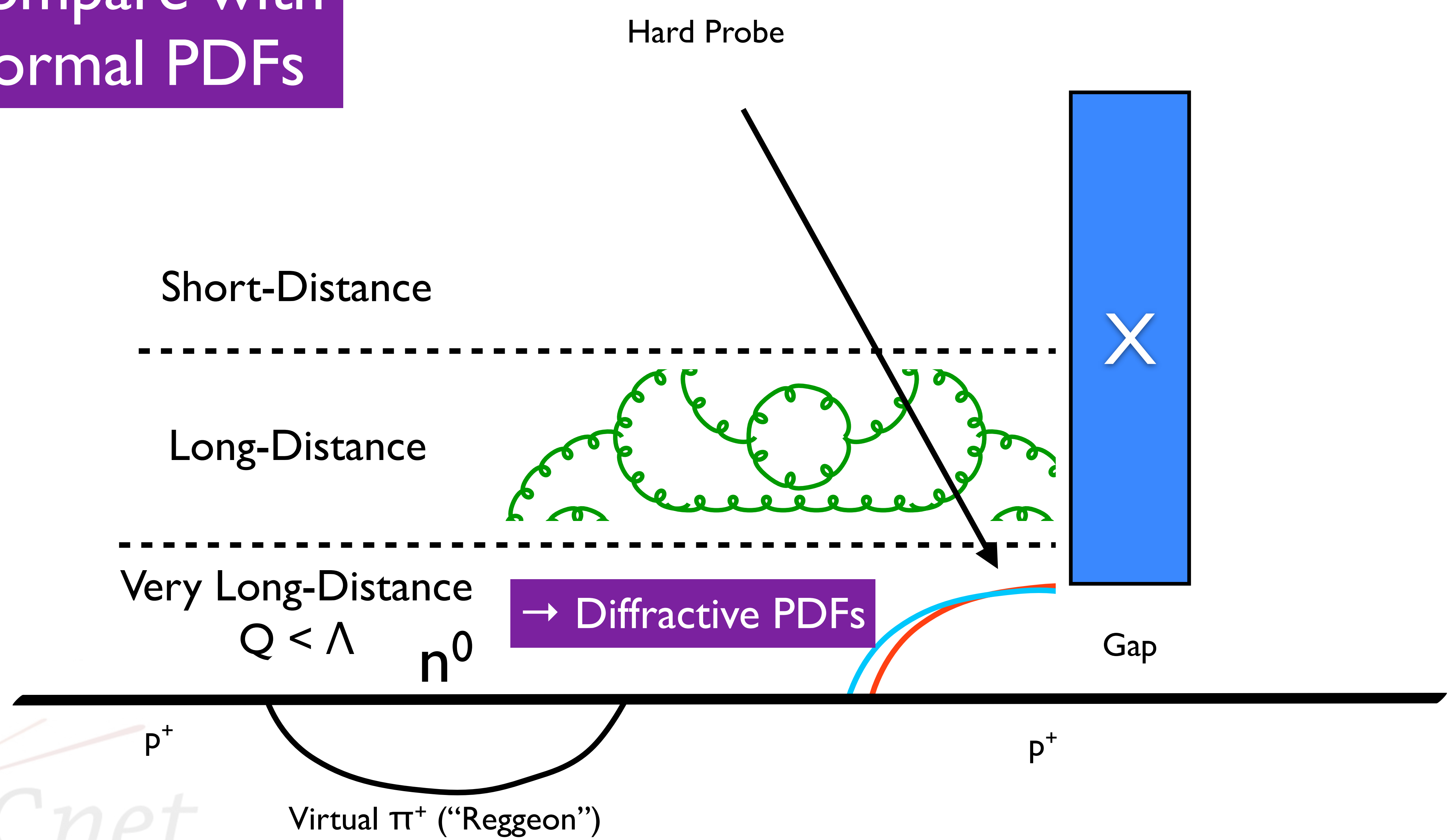
Compare with normal PDFs



(+ DIFFRACTION)

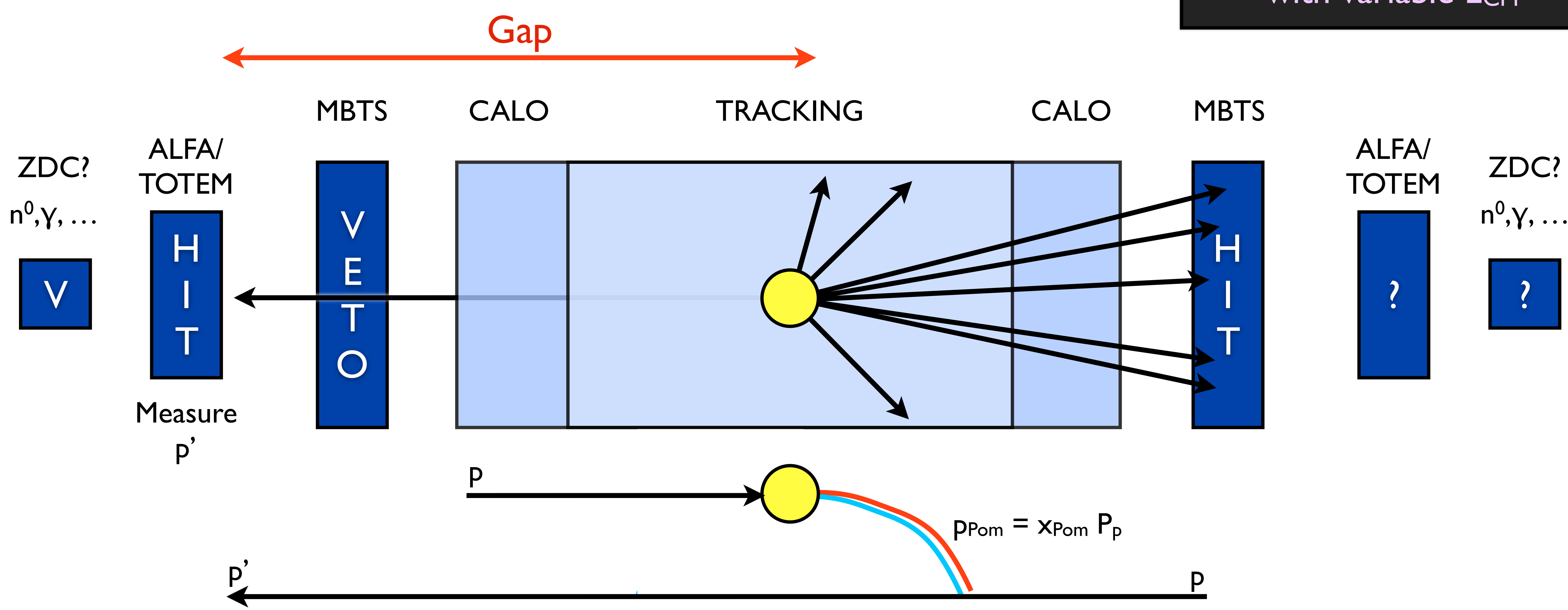
“Intuitive picture”

Compare with normal PDFs



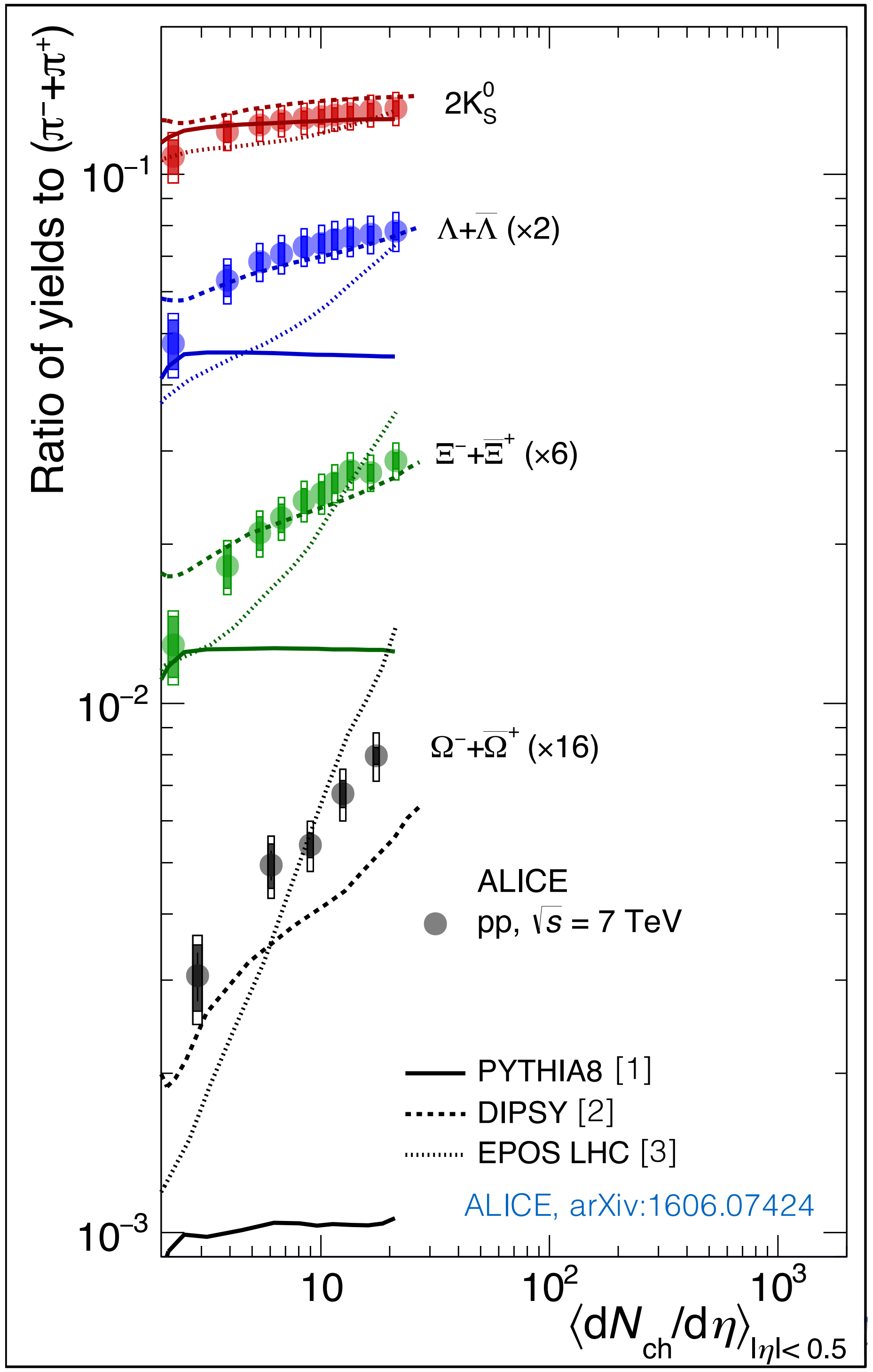
Single Diffraction

Glueball-Proton Collider with variable E_{CM}



Double Diffraction: both protons explode; gap inbetween
Central Diffraction: two protons + a central (exclusive) system

Recent news from ALICE (ICHEP 2016)



D.D. Chinellato – 38th International Conference on High Energy Physics

A clear enhancement of strangeness with (pp) event multiplicity is observed

Especially for multi-strange baryons

No corresponding enhancement for protons (not shown here but is in ALICE paper)

→ this really must be a strangeness effect

Cross-check measurements of the phi meson are now underway

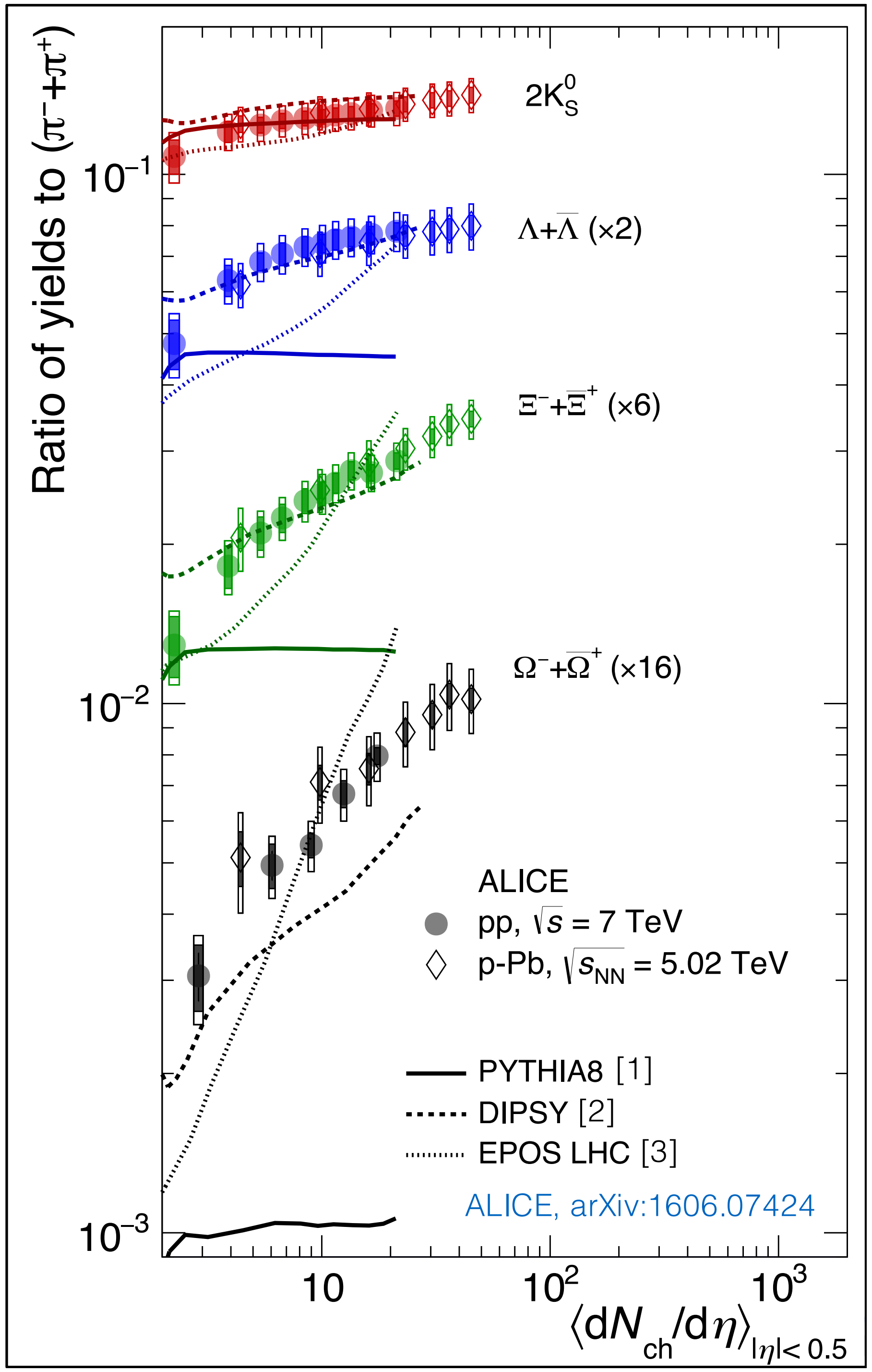
Jet universality: jets at LHC modelled the same as jets at LEP

→ Flat line ! (cf PYTHIA)

DIPSY includes "colour ropes" with higher effective string tension

EPOS includes hydrodynamic "core" with higher effective temperature

The Plot Thickens



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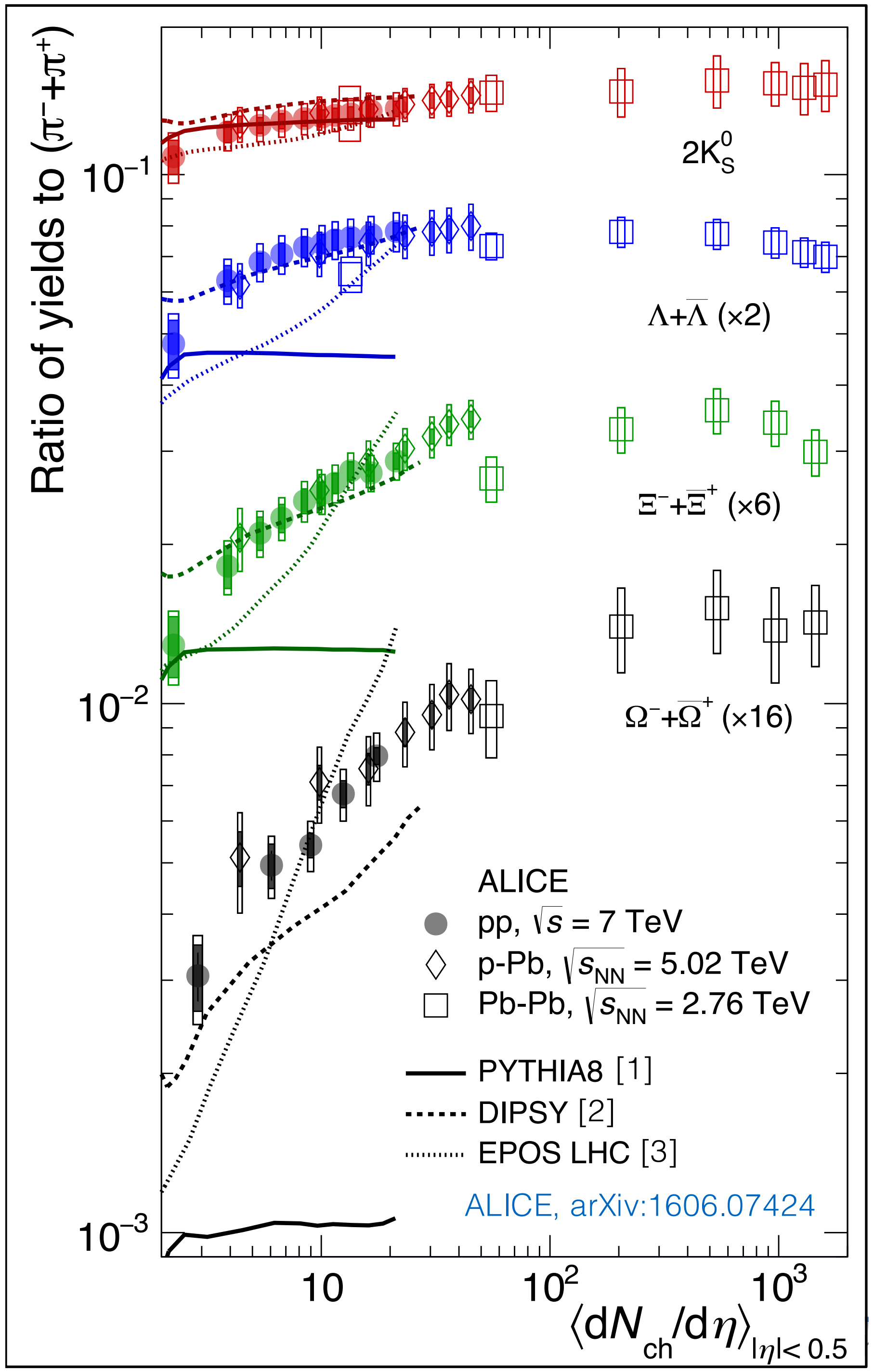
Looks like the effect, whatever it is, continues smoothly into p-Pb

The Plot Thickens



D.D. Chinellato – 38th International Conference on High Energy Physics

Looks like the effect, whatever it is, continues smoothly into p-Pb

… and into Pb-Pb !

Unexpected.

Looks like jet universality and hadronisation in pp is up for revision.

Is it thermal? Stringy? Both?

Collective? Flowy? …

Physics must explain smooth transition to heavy ions. No abrupt "phase transition" seen in these observables