The Effective Energy in QCD

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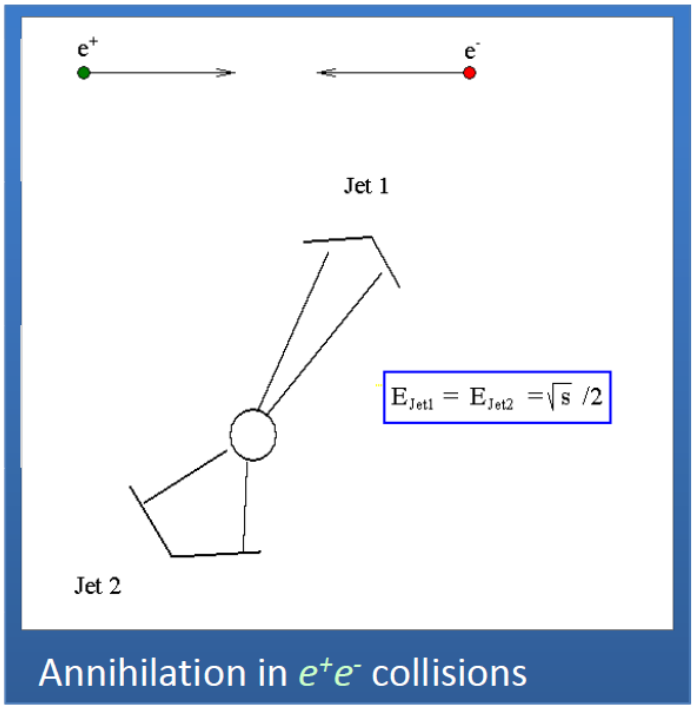
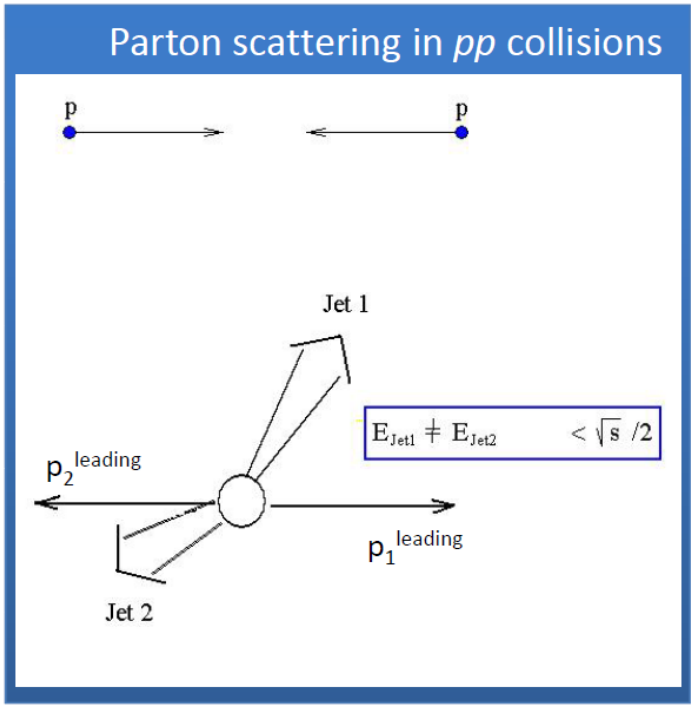
Why the "effective energy"?





***e*⁺*e*⁻ and *pp* collisions cannot be simply compared in terms of the centre-of-mass energy** since in *pp* collisions the quantum number flow conservation (from leading baryons) doesn't allow all the centre-of-mass energy available in the interaction.

→ We need to quantify the real effective energy available for particle production which is ruled by universal QCD properties!

Quantum number flow (QNF)

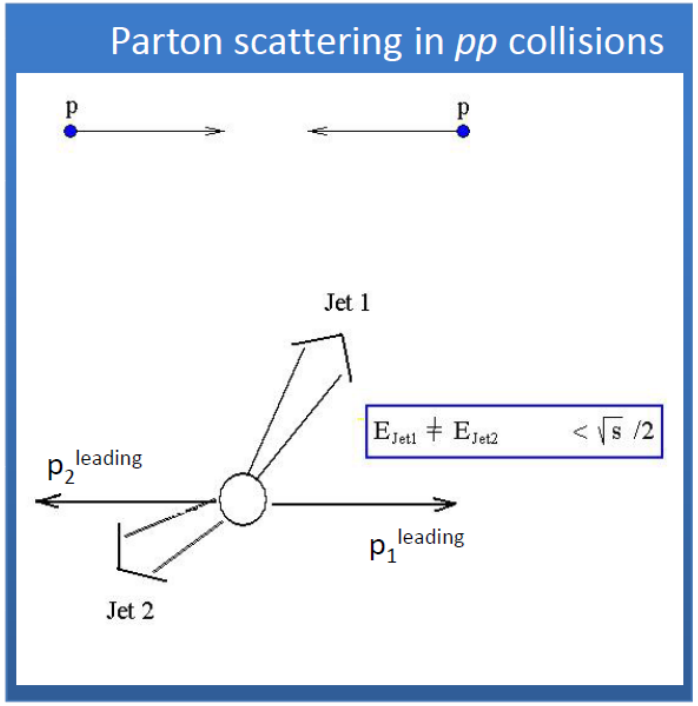
- The quantum number flow (QNF) effect:

  If initial state colliding particles don't annihilate and Quantum Numbers have to be conserved → The whole centre-of-mass energy is not available for particle production since a fraction of energy is taken from the emerging particles conserving the QNF

- Emerging QNF particles carry away a large fraction of the initially available energy/momentum and only what is left remains for fragmentation & hadronization for the associate multihadron system produced → ***Effective Energy***

QNF effect in *pp*

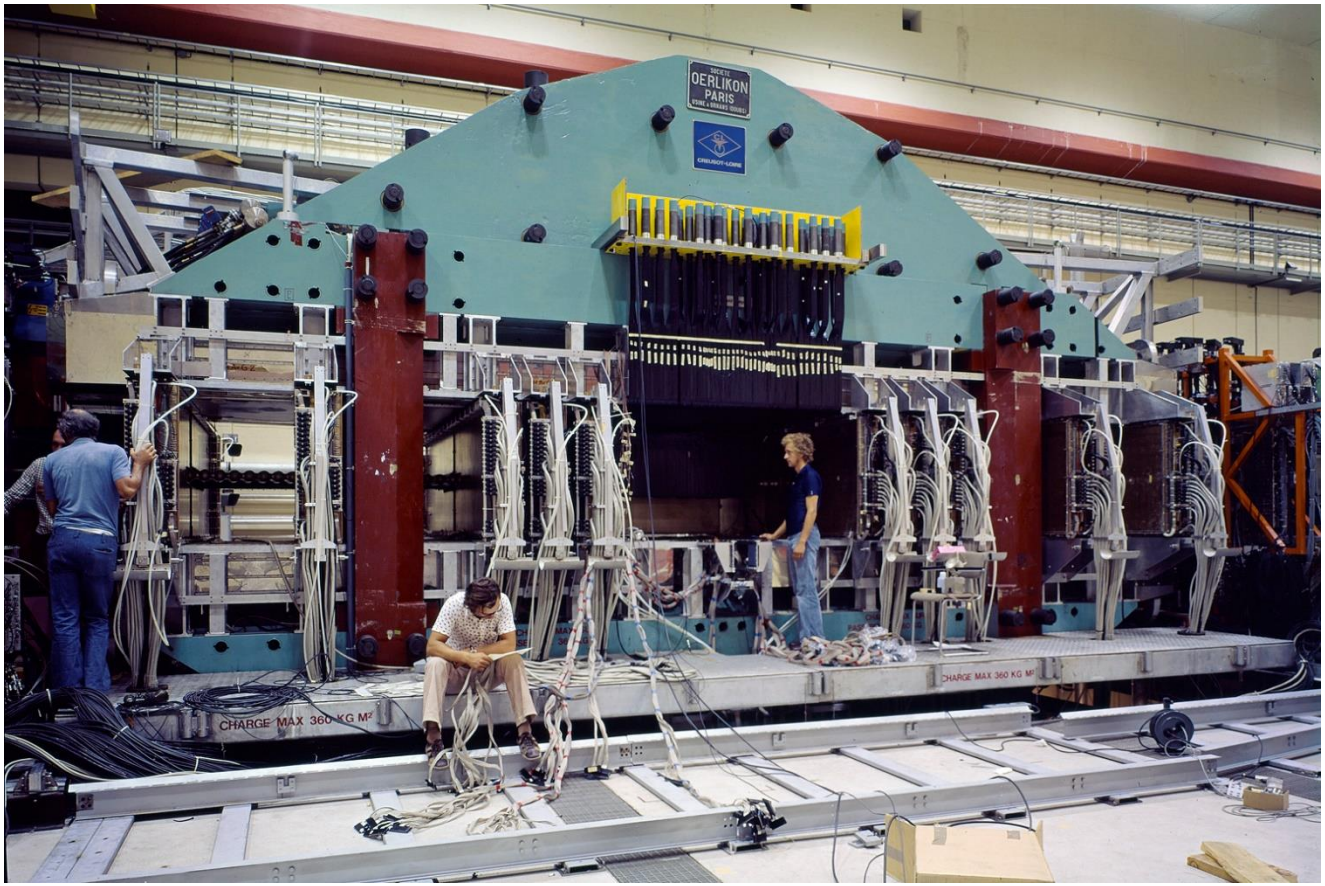
- QNF effect appears in "minimum bias" events, i.e. in the bulk of *pp* final states
- In principle, two outgoing QNF baryons needed to define the effective energy for multihadron production in the final state



i.e. if we are able to measure the energy of the two leading baryons we can subtract it to the centre-of-mass energy to reconstruct the effective energy, event-by-event.

→ This was tested for the first time at the ISR (Intersecting Storage Rings) with the first *pp* accelerator

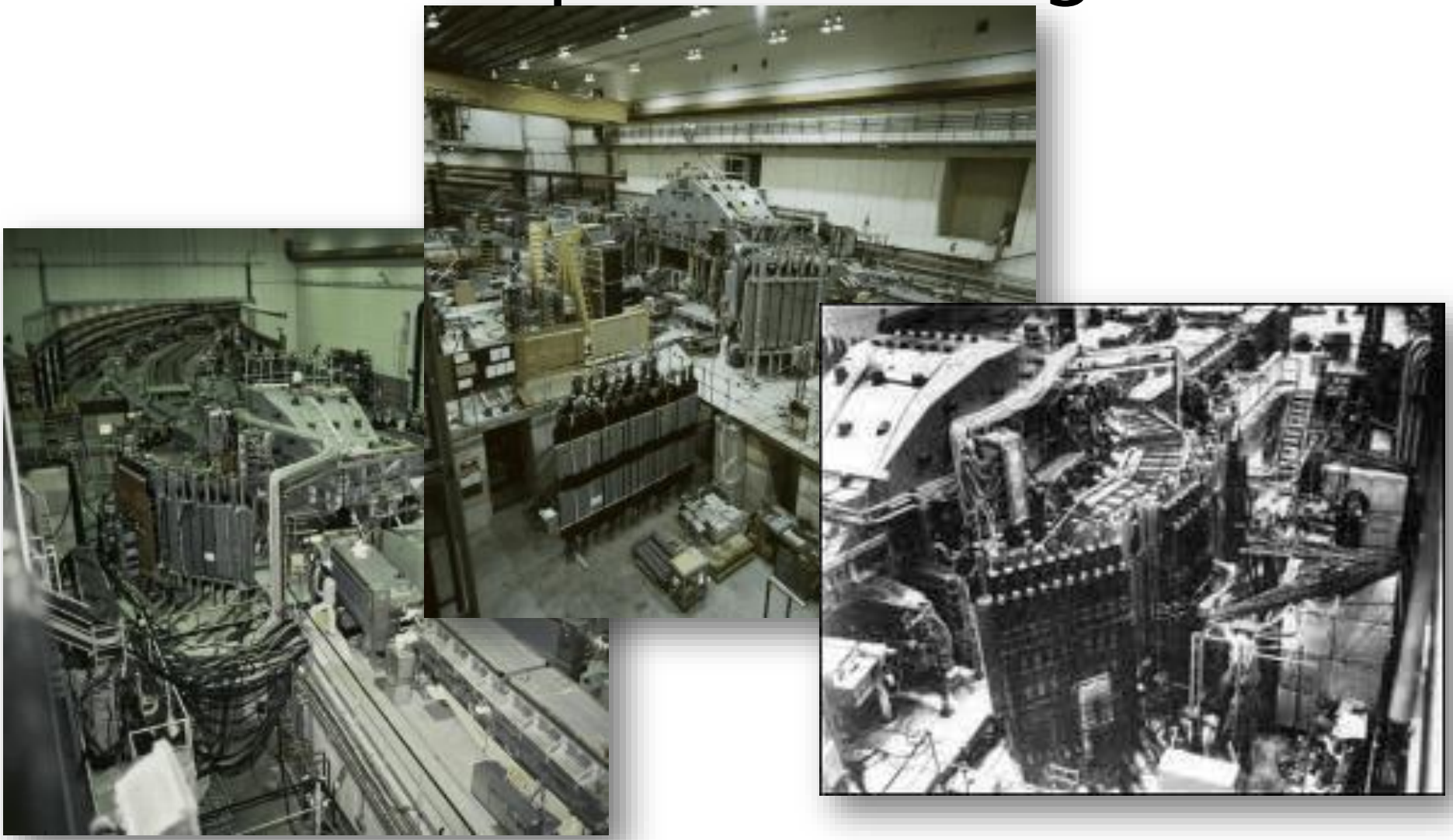
CERN ISR



Some details on the Intersecting Storage Rings:

- On 27 January 1971, two beams of protons collided in the ISR
- It ran until 1984, holding the luminosity record for hadron colliders until 2004
- It was composed of two interlaced rings each with a diameter of 300 metres
- and with a maximum centre-of-mass energy of 62 GeV.

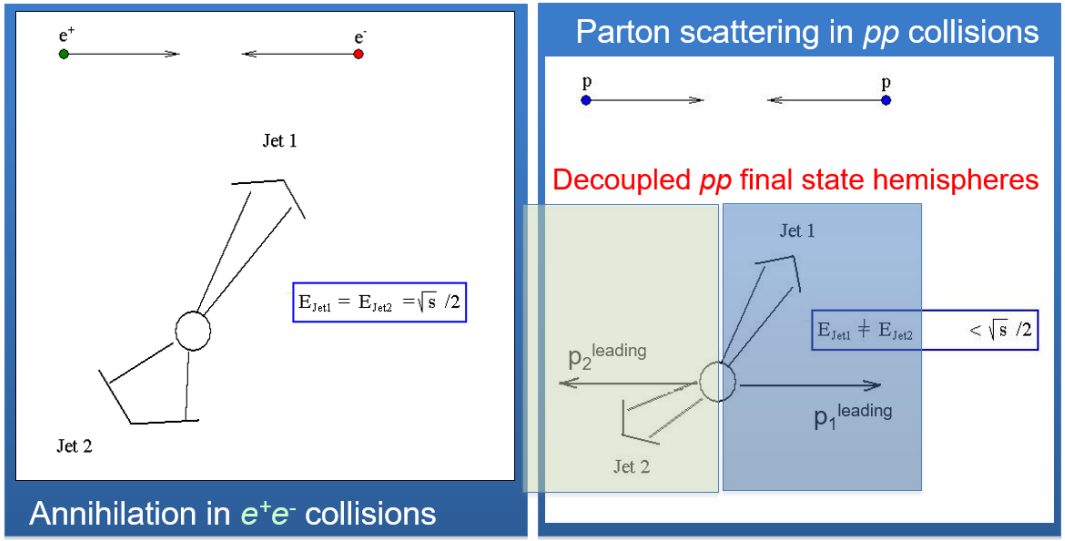
CERN ISR Split Field Magnet



Discoveries at ISR

Discovery of ***QNF baryon independency*** in *pp* interactions at ISR

- If two QNF baryons independent:
  - ✓ two final-state hemispheres decoupled
  - ✓ each hemisphere independently analysed @ its appropriate effective energy
  - ✓ High gain in statistics (depending on √s) for detailed measurements

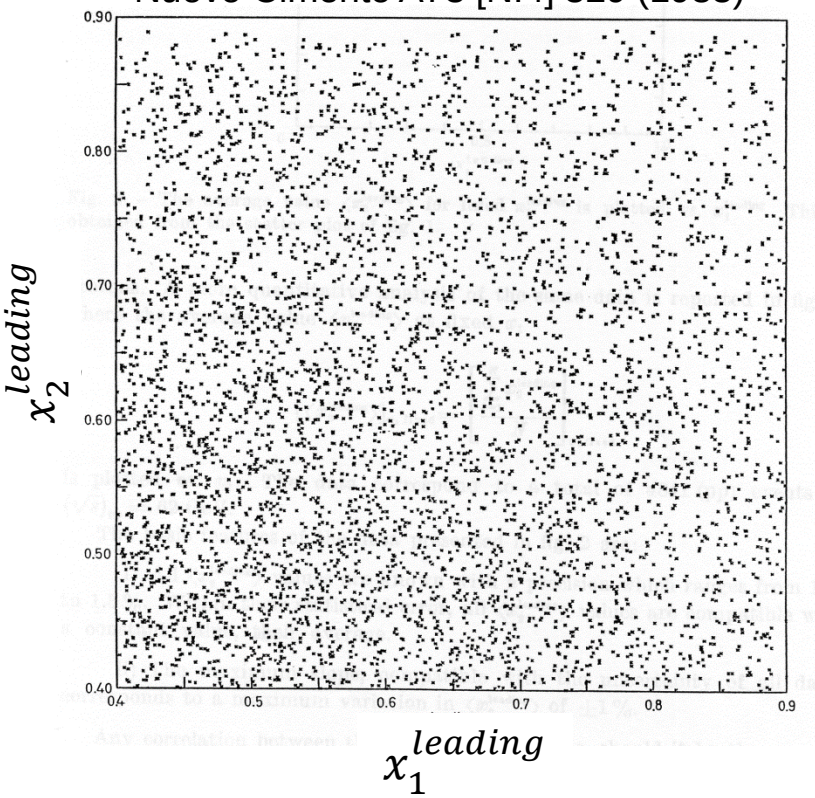


→Discovery of ***Universality Features*** of multihadron production in different kinds of interactions ***Hadronic – Electromagnetic – Weak***

Results from ISR

ISR *pp*@62 GeV

Nuovo Cimento A73 [N.4] 329 (1983)



Independency of the two hemispheres as seen in pp at ISR

The ***QNF effect*** has no long-range correlations

- ✓ It is flavour independent
  (e.g. in *pp* interactions it holds true for *p*, *n*, Λ_s, Λ_c, Λ_b …)
- ✓ It exists no matter the initial interaction

Once the correct ***effective energy*** is taken into account in *pp*, e^+e^-, *DIS:*

→ Study of ***universality features*** in multihadron production in terms of 8 variables among which the most popular is $\langle n_{ch} \rangle$

→ *Multiparticle production proven to be the same no matter the nature of the pairs of interacting particles*

Effective Energy in *pp* collisions

The effective energy available for particle production can be estimated when the QNF particle is reconstructed in the event

- In a single hemisphere (*pp*): $E_{eff} = \left(\frac{\sqrt{s}}{2} - p^{leading} \right)$
- When considering both hemispheres, it can be defined as:

$$\sqrt{\left(q_{tot}^{had}\right)^2} = \sqrt{(1 - x_1^{leading})(1 - x_2^{leading})s}$$

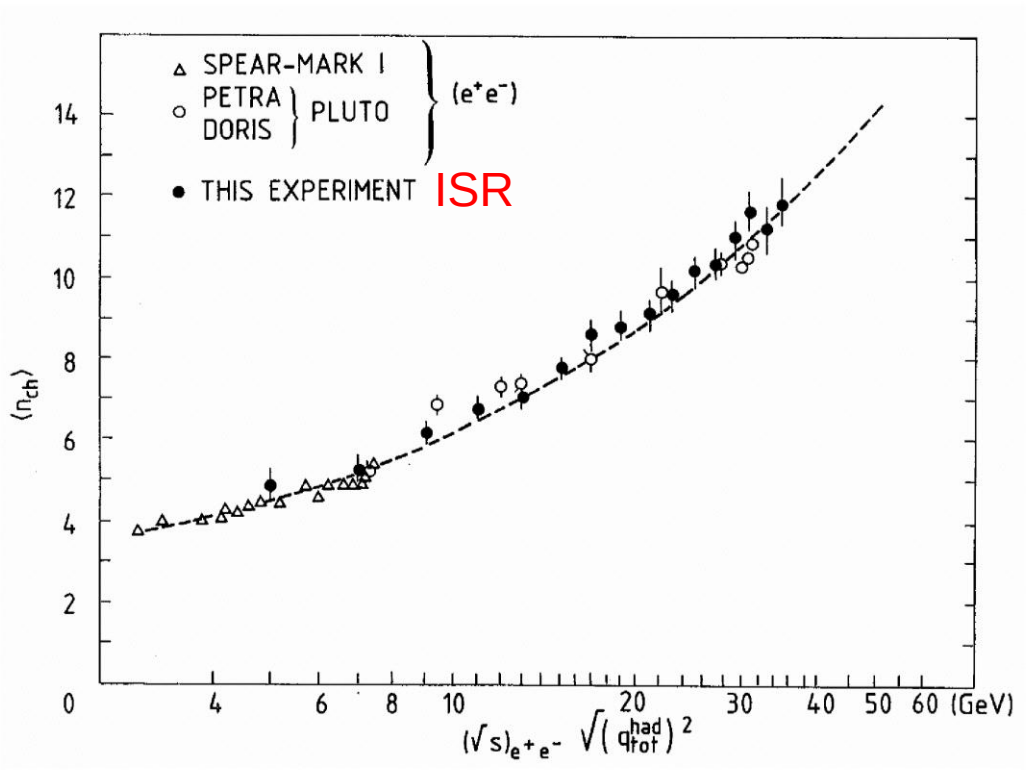
$$\text{with: } x_i^{leading} = \frac{2\,p_i^{leading}}{\sqrt{s}}$$

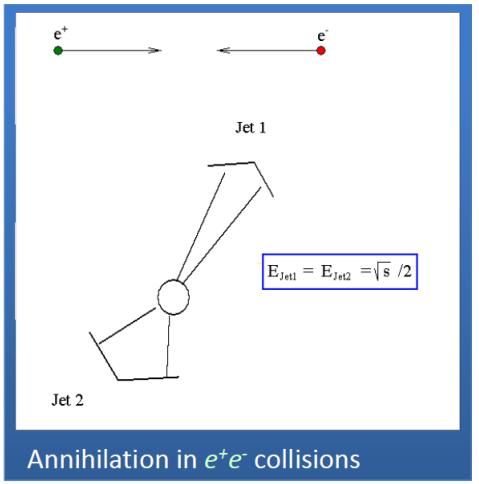
Due to the independency of hemispheres,

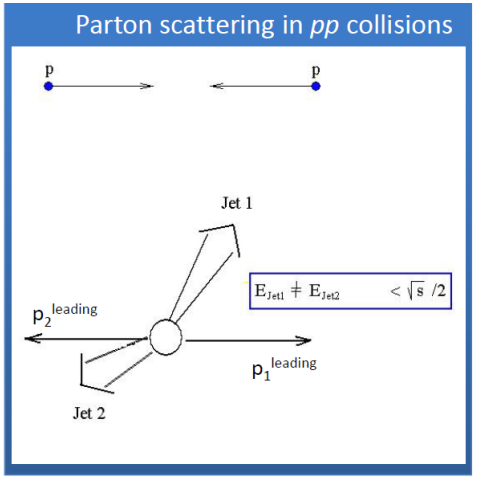
it turns out that in a large $x_i^{leading}$ range this quantity is

$\approx 2E_{eff} < \sqrt{s}$

Effective energy universality







$$q_{tot}^{had} = \sqrt{\left(\sqrt{s}/2 - p_1^{leading}\right)\left(\sqrt{s}/2 - p_2^{leading}\right)}$$

Particle production mechanism is ruled by QCD in non-perturbative regime.
It looks independent of the nature of colliding systems once the real "effective energy" is taken into account as demonstrated at ISR

TOTALLY UNEXPECTED RESULTS FROM THE ISR

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INFN and University of Bologna, Italy
Enrico Fermi Centre, Rome, Italy

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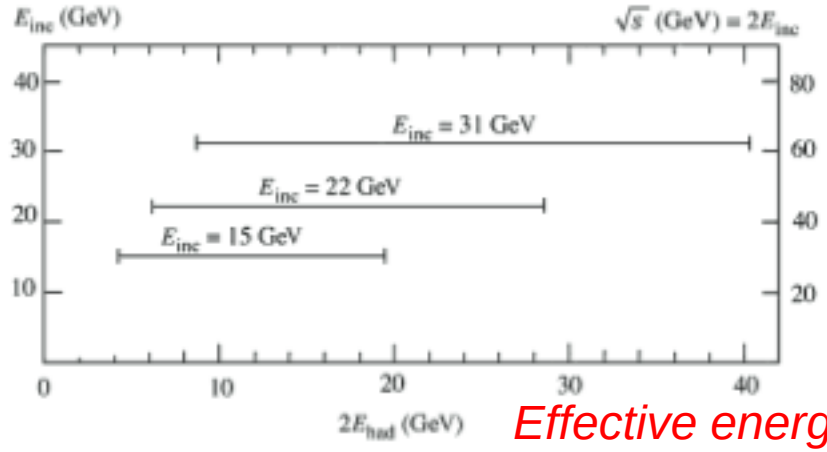
(see also CERN Courier July/August 2011)

On the occasion of the 40th anniversary of ISR



Effective energy

Fig. 1 In the abscissa the "effective" hadronic energy $2E_{had}$ (GeV) available for particle production. In the vertical axis on the left the beam energy, E_{inc}, on the right the total "nominal" energy of the ISR, $\sqrt{s} = 2E_{inc}$.

in 1981

References

[1] M. Basile, G. Cara Romeo, L. Cifarelli, A. Contin, G. D'Ali, P. Di Cesare, B. Esposito, P. Giusti, T. Massam, R. Nania, F. Palmonari, V. Rossi, G. Sartorelli, M. Spinetti, G. Susinno, G. Valenti, L. Votano and A. Zichichi, *"The Leading-Particle Effect in Hadron Physics"*, *Nuovo Cimento A*, 66 (1981) 129; see also *"The Method of Removing the Leading Protons in the Study of High-Energy pp Reactions, Compared with the Standard Analysis"*, *Nuovo Cimento A*, 65 (1981) 414.

[2] M. Basile, G. Cara Romeo, L. Cifarelli, A. Contin, G. D'Ali, P. Di Cesare, B. Esposito, P. Giusti, T. Massam, R. Nania, F. Palmonari, V. Rossi, G. Sartorelli, M. Spinetti, G. Susinno, G. Valenti, L. Votano and A. Zichichi, *"The Leading-Baryon Effect in Strong, Weak, and Electromagnetic interactions"*, *Lett. Nuovo Cimento*, 32 (1981) 321.

[3] M. Basile, G. Cara Romeo, L. Cifarelli, A. Contin, G. D'Ali, P. Di Cesare, B. Esposito, P. Giusti, T. Massam, F. Palmonari, G. Sartorelli, G. Valenti and A. Zichichi, *"Evidence of the Same Multiparticle Production Mechanism in p-p Collisions as in e^+e^- Annihilation"*, *Phys. Lett. B*, 92 (1980) 367.

[4] M. Basile, J. Berbiers, G. Cara Romeo, L. Cifarelli, A. Contin, G. D'Ali, C. Del Papa, P. Giusti, T. Massam, R. Nania, F. Palmonari, G. Sartorelli, M. Spinetti, G. Susinno, L. Votano and A. Zichichi, *"The End of a Myth: High-P_T Physics"*, Opening Lecture in *Proceedings of the XXII Course of the "Ettore Majorana" International School of Subnuclear Physics, Erice, Italy, 5-15 August 1984: "Quarks, Leptons, and their Constituents"* (Plenum Press, New York-London) 1988, p. 1.

[5] M. Basile, G. Cara Romeo, L. Cifarelli, A. Contin, G. D'Ali, P. Di Cesare, B. Esposito, P. Giusti, T. Massam, F. Palmonari, G. Sartorelli, G. Valenti and A. Zichichi, *"The Leading Effect in Λ_c^+ production at $(\sqrt{s}) = 62$ GeV in proton-proton Collisions"*, *Lett. Nuovo Cimento*, 30 (1981) 487.

[6] M. Basile, G. Bonvicini, G. Cara Romeo, L. Cifarelli, A. Contin, G. D'Ali, P. Di Cesare, B. Esposito, P. Giusti, T. Massam, R. Nania, F. Palmonari, G. Sartorelli, G. Valenti and A. Zichichi, *"Evidence for a New Particle with Naked "beauty" and for its Associated Production in high-energy (pp) Interactions"*, *Lett. Nuovo Cimento*, 31 (1981) 97.

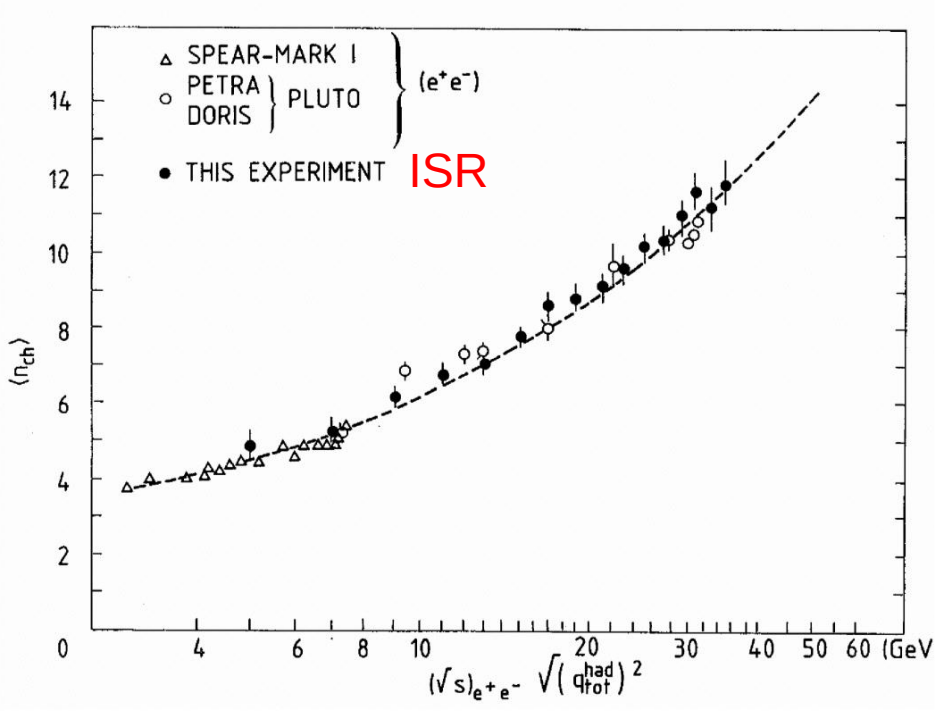
[7] M. Basile, G. Bonvicini, G. Cara Romeo, L. Cifarelli, A. Contin, G. D'Ali, P. Di Cesare, B. Esposito, P. Giusti, T. Massam, R. Nania, F. Palmonari, G. Sartorelli, G. Valenti and A. Zichichi, *"The Leading-baryon Effect in Λ_b^0 production in Proton-Proton Interactions at $(\sqrt{s}) = 62$ GeV"*, *Nuovo Cimento A*, 65 (1981) 408.

[8] V. N. Gribov, G. 't Hooft, G. Veneziano and V. F. Weisskopf, *"The Creation of Quantum ChromoDynamics and the Effective Energy"* in honour of A. Zichichi on the occasion of the Galvani Bicentenary celebrations, edited by L. N. Lipatov, *"World Scientific Series in 20th Century Physics"*, Vol. 25 (World Scientific) 2000 p. 343.

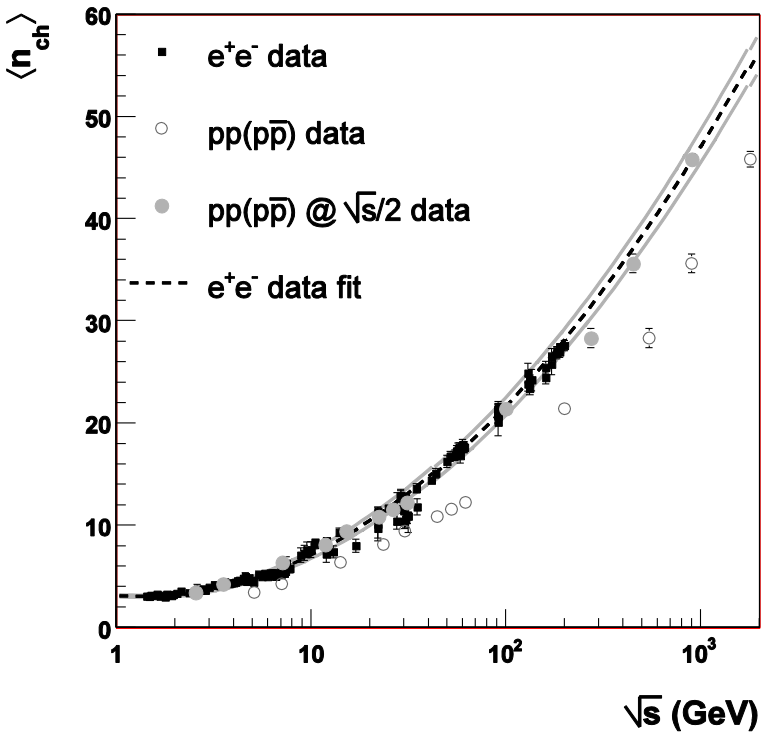
From ISR to the TeV scale

Compilation of results from e^+e^-, pp, $p\bar{p}$ experiments

Nuovo Cimento A73 [N.4] 329 (1983)



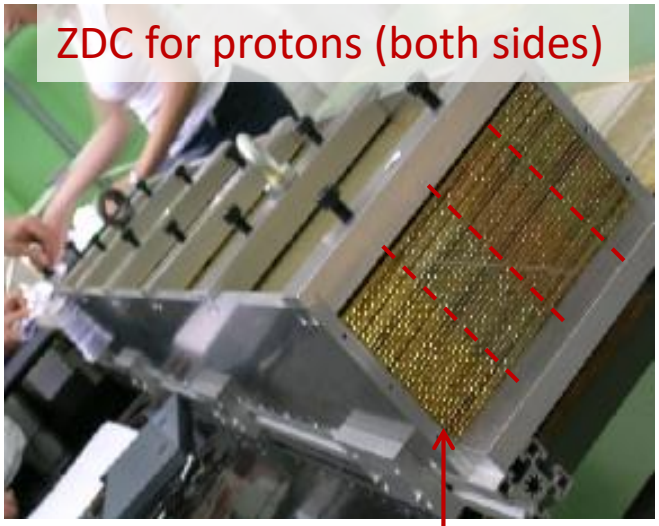
Eur. Phys. J. C50 341 (2007)



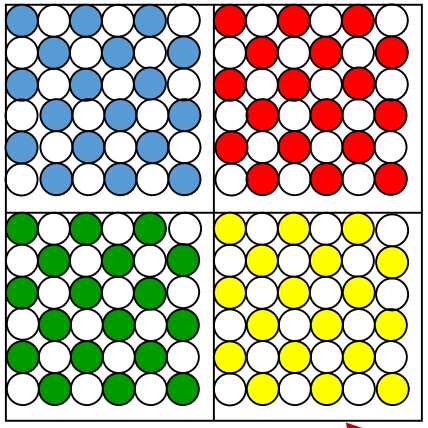
Particle production mechanism is ruled by QCD in non-perturbative regime.
It looks independent of the nature of colliding systems once the real "effective energy" is taken into account as demonstrated at ISR

The Zero Degree Calorimeter (ZDC)

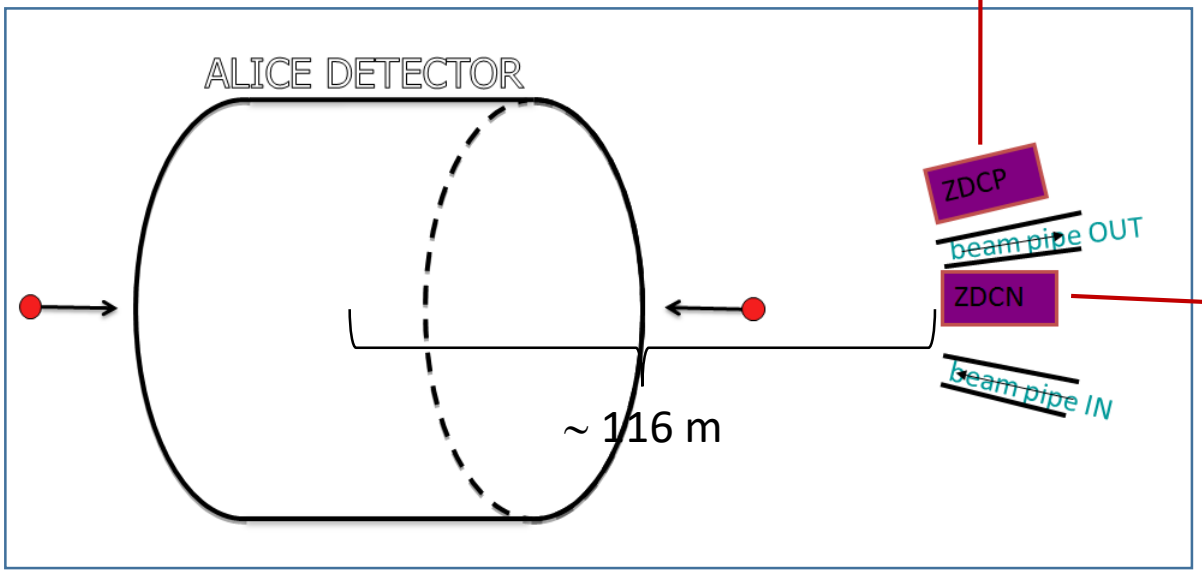
The **ZDC** was designed to measure the number of spectators (nucleons don't interact) in *PbPb* collisions. In *pp* collisions → able to reconstruct the energy of leading nucleons (proton or neutron).

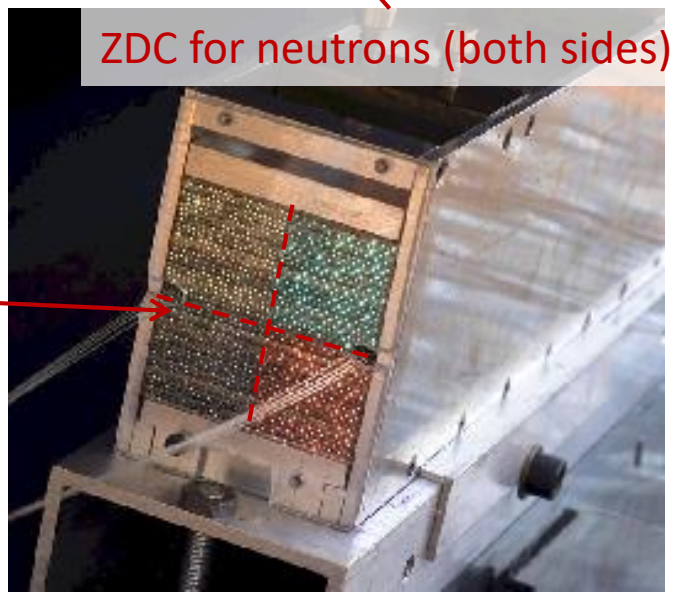


4 towers per calorimeter



PMT 1
PMT 2
PMT 3
PMT 4
PMT c

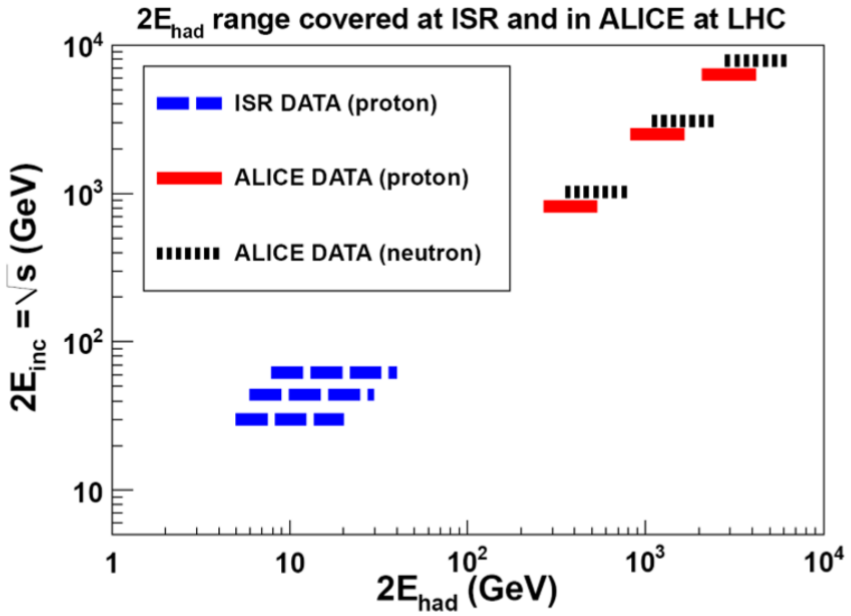




Subnuclear Physics: Past, Present and Future
Pontifical Academy of Sciences, Scripta Varia 119, Vatican City 2014
www.pas.va/content/dam/accademia/pdf/sv119/sv119-cifarelli.pdf

An Interesting Result in pp Collisions at 7 TeV

A. Agostinelli[1,4], A. Alici[3], P.Antonioli[2], S. Arcelli[1], R. Baldini Ferroli[3], F. Bellini[1,4], G. Cara Romeo[2], L. Cifarelli[1,3,4], M. Colocci1, A. De Caro[3], D. De Gruttola[4,5], S. De Pasquale[5], M. Fusco Girard[5], B. Guerzoni[1,4], D. Hatzifotiadou[2], A. Margotti[2], R. Nania[2], F. Noferini[3], P. Pagano[5], A. Pesci[2], R. Preghenella[3], E. Scapparone[2], G. Scioli[1,4], M.C.S. Williams[2,4], C. Zampolli[2,4], A. Zichichi[1,4]



Effective energy studies are feasible at the LHC energy → to extend ISR QCD studies to high-energy regimes

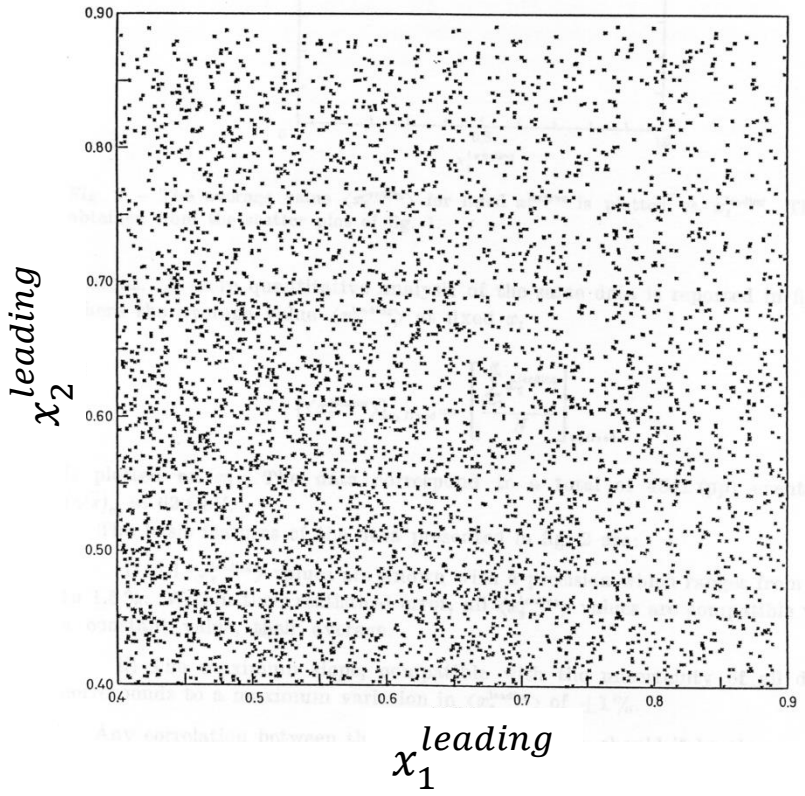
→ ISR lesson is still topical nowadays

Fig. 3. Effective energy range (here indicated as $2E_{had}$ range) covered at ISR and LHC as a function of $\sqrt{s}$.

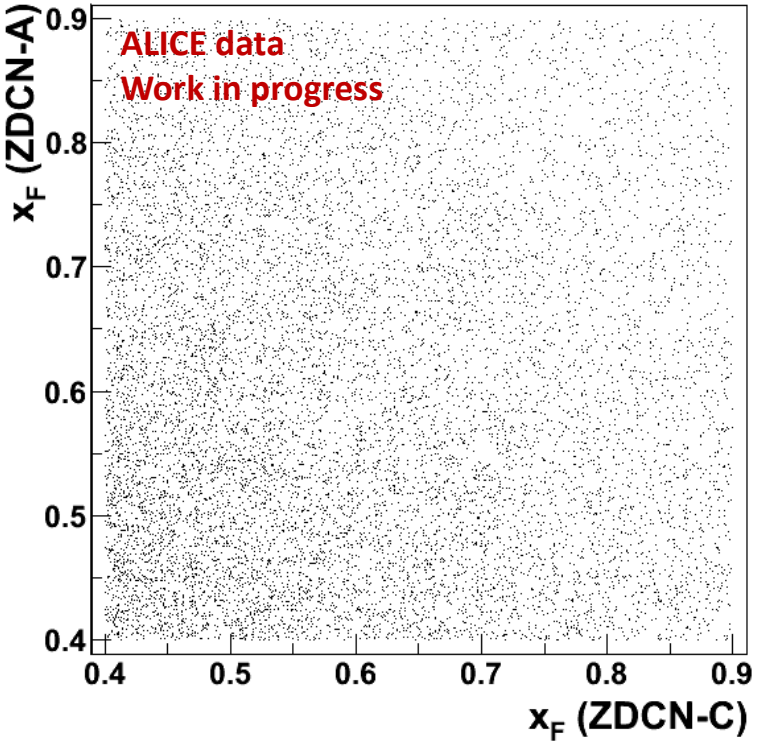
Independency of hemispheres

$$x_F = \frac{E_{ZDC}}{p^{inc}}$$

ISR *pp*@62 GeV



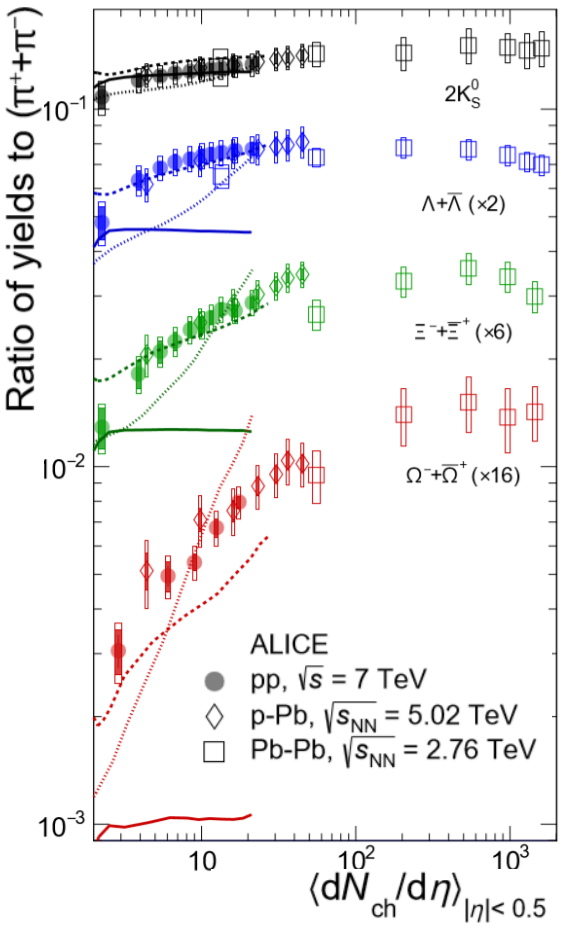
LHC pp@7 TeV



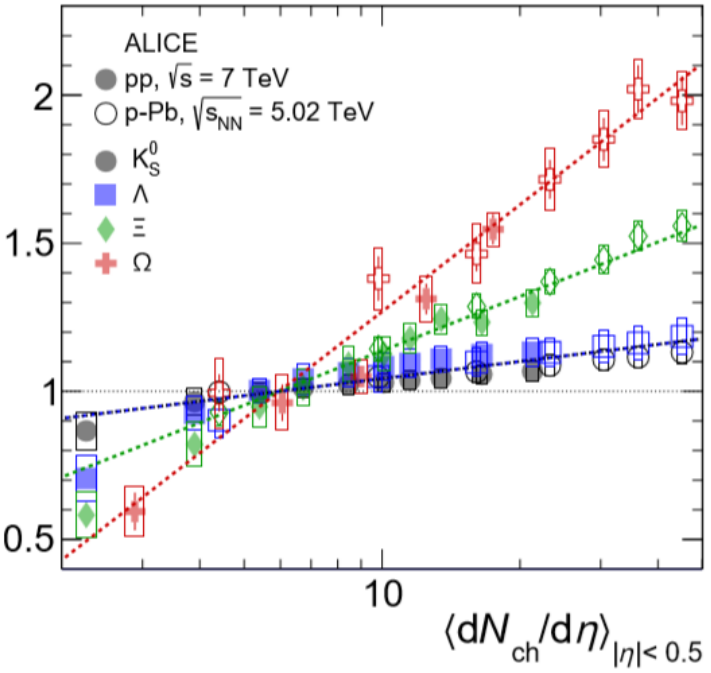
The independency of hemispheres was tested for leading neutron in the same x_F range of ISR: (ZDCN-A vs ZDCN-C) @ 7 TeV.

(ALICE) Nature Physics 13 (2017) 535-539

Interesting observation in pp high multiplicity events



$(h/\pi) / (h/\pi)^{pp}_{INEL>0}$



A strangeness enhancement was observed with the multiplicity in pp collisions → similar trend if compared to p-Pb and Pb-Pb collisions.
How to interpret this result?
As mentioned there is a direct link between multiplicity and the effective energy.

About interpretations

One of the main questions concerns the possibility to ascribe the observation to:

- Initial state effects: Effective Energy (EE), multi-parton interactions, …

or

- Final state effects: High particle density environment/“medium effect” …

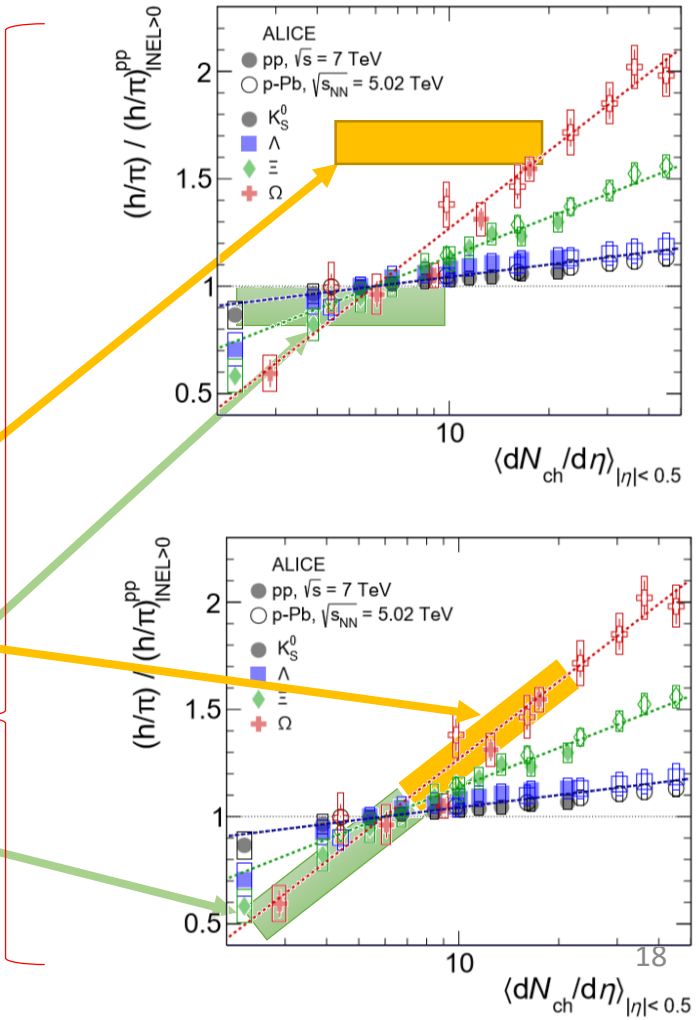
Do we have a way to test the two different scenarios?

Differential analyses vs multiplicity

Repeating measurements after selecting events with two different effective energies, the multiplicity dependence of strangeness production probes two different possible scenarios for the initial / final status effects

Higher effective energy

Lower effective energy



Scenario 1
If strangeness enhancement is an initial state effect (effective energy)
→ Multiplicity dependence has to disappear!

Scenario 2
If strangeness enhancement is a final state effect (just depends on multiplicity)
→ no change!

Final remarks

Particle production mechanism is ruled by QCD in non-perturbative regime. Many effective models are available in the marked but not a complete theory.

Effective energy universality was demonstrated at ISR when two beams of protons collided for the first time (almost 50 years ago).

The lesson learned at ISR is still actual, and effective energy in QCD represent a further interesting frontier of the LHC research programme