Fragmentation and Monte Carlo generators at Belle II

Work in progress.

Ami Rostomyan
(for the Belle II collaboration)

Excited QCD 2017
7-13 May 2017
Sintra, Portugal

HELMHOLTZ ASSOCIATION

DESY

Belle II @ SuperKEKB

New facility to search for physics beyond the SM by studying B, D and τ decays and the major player for precise studies of fragmentation

Tsukuba, Japan

SuperKEKB – major upgrade of the KEKB B-factory at KEK

Belle II detector – upgraded Belle detector

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- ➡ increased currents
- ➡ collisions at Υ(nS)
  - ➡ $E(e^+) = 4$ GeV, $E(e^-) = 7$ GeV

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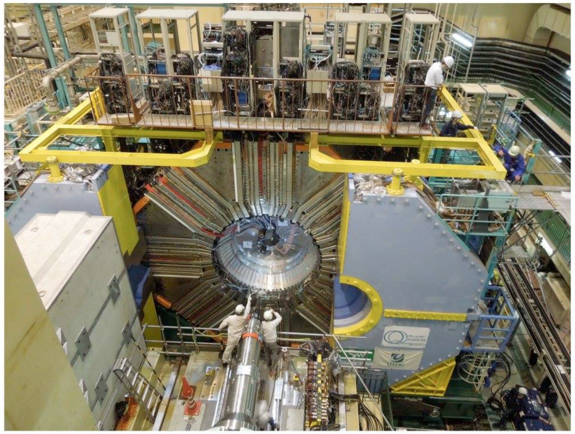

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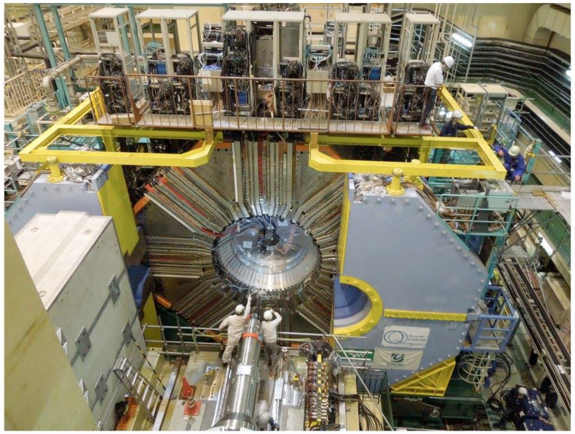
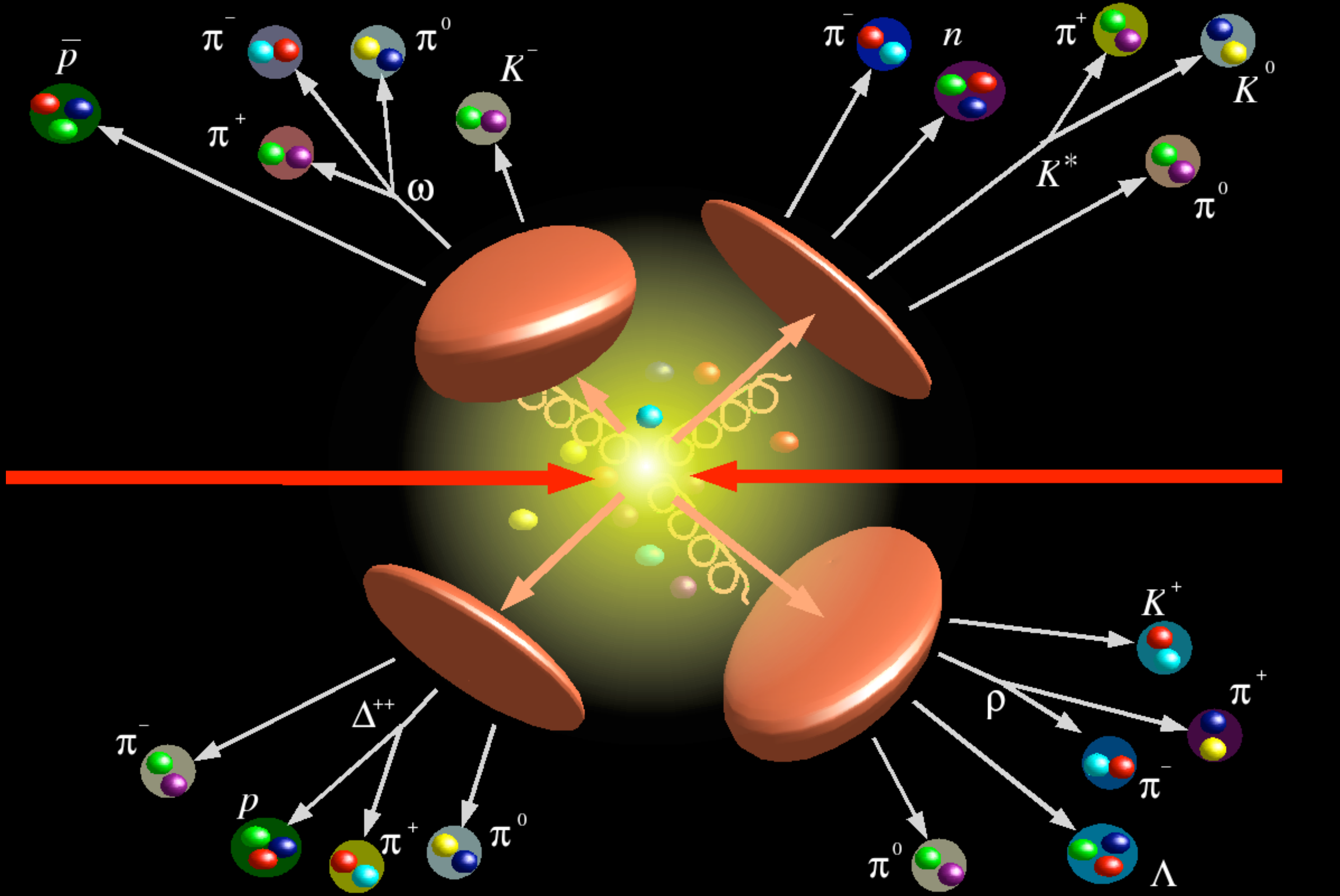


SuperKEKB luminosity projection

Hadronisation or fragmentation

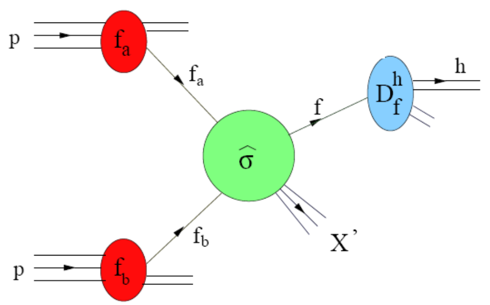


The fragmentation functions

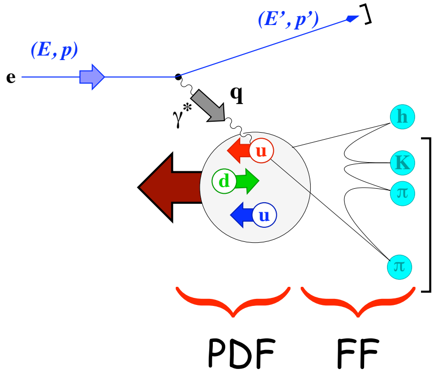
Field, Feynman (1977): Fragmentation functions describe the process of hadronization

- non-perturbative but universal objects of QCD
- $D_q^h(z)$ is the probability that the parton q fragments into a hadron h carrying a fraction z of the parton's momentum

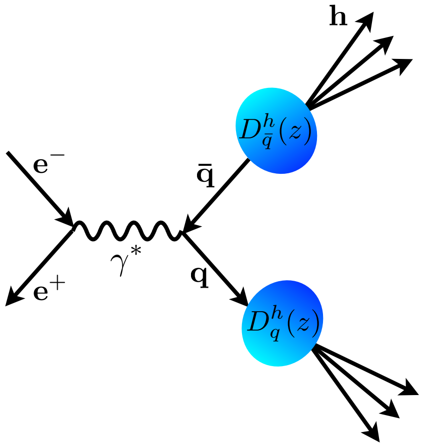
- proton-proton scattering



- lepton-hadron scattering



- e^+e^- annihilation



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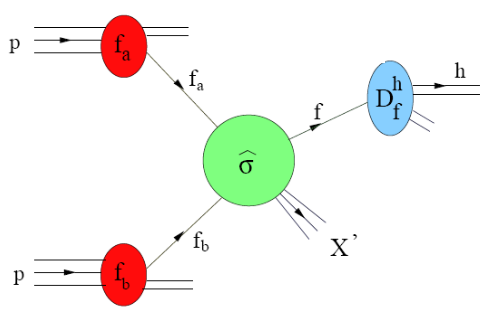
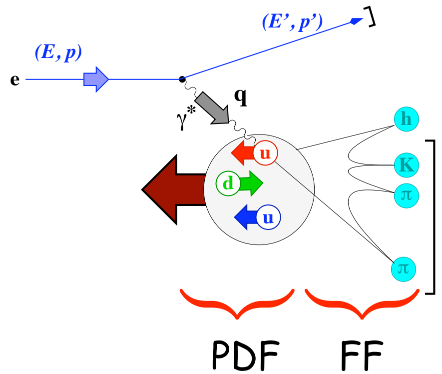
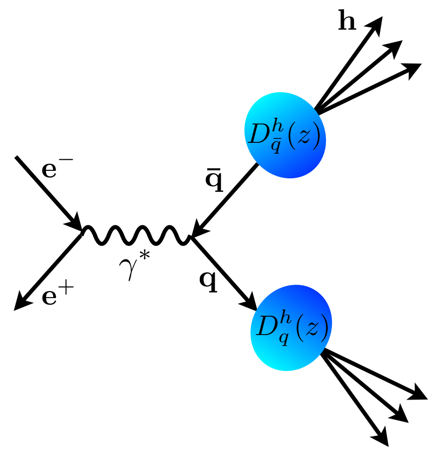




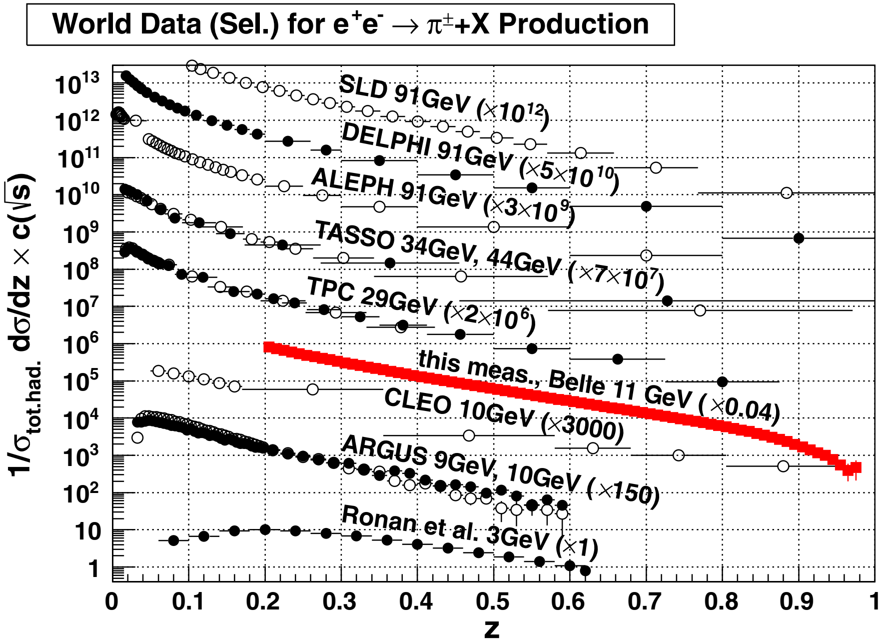


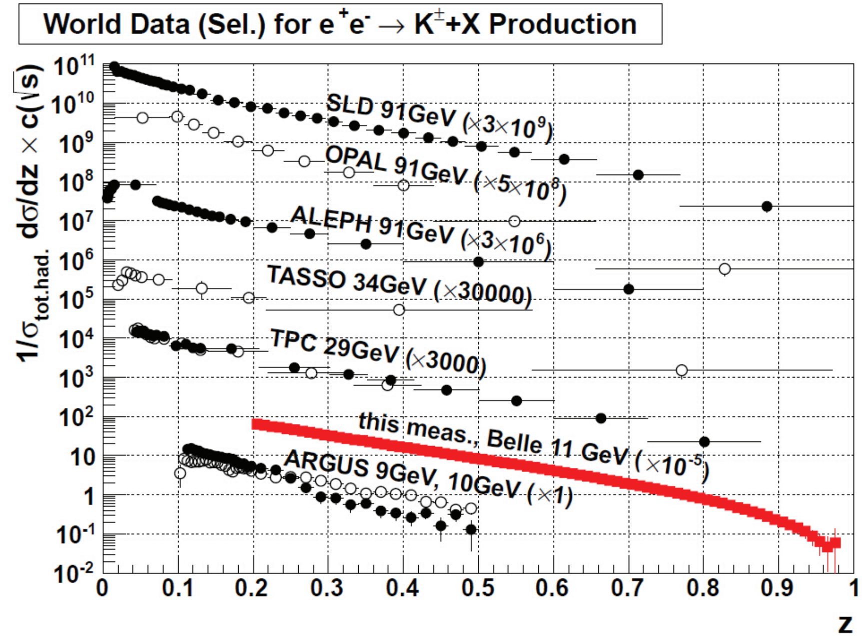
Measurements of fragmentation functions in lepton-hadron, proton-proton scattering and e^+e^- annihilation are complementary

$$\sigma^{e^+e^- \to hX} \propto \sum_q \sigma^{e^+e^- \to q\bar{q}} \otimes (D_q^h + D_{\bar{q}}^h)$$

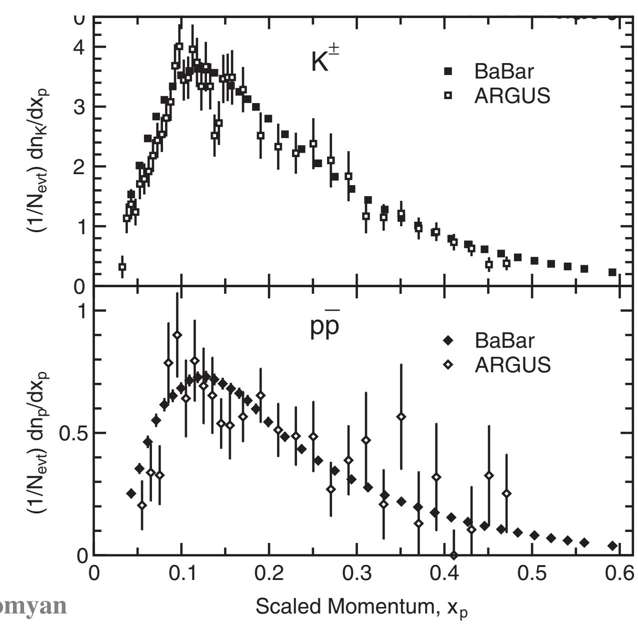
- e^+e^- annihilation:
  - direct probe in clean environment
  - stringent constraints on the combinations $D_q^h + D_{\bar{q}}^h$
  - insensitive to quark-antiquark separation
  - far less sensitive to D_g^h

Measurements from e^+e^- annihilation





– *Belle collaboration. - Phys Rev D 111 062002 (2013)* –

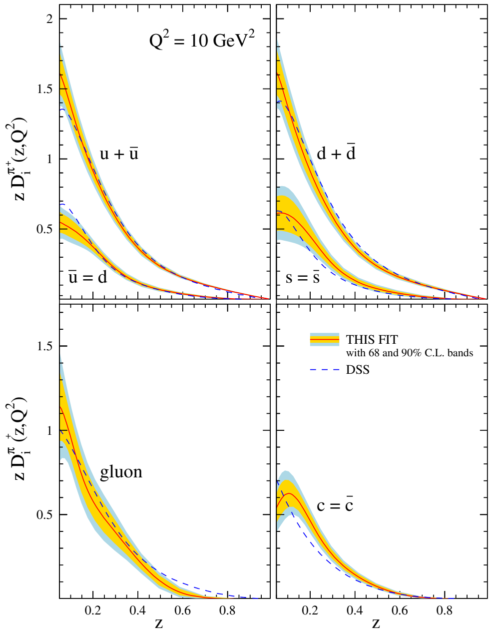


- ➡ large amount of cross section measurements at high $\sqrt{s}$, near Z^0 mass
- ➡ the region around $\sqrt{s} \sim 10$ GeV remained until recently poorly investigated
- ➡ precise measurements from Belle and BaBar
  - ➡ differential cross-section for $\pi^\pm$, $K^\pm$ and $p/\bar{p}$

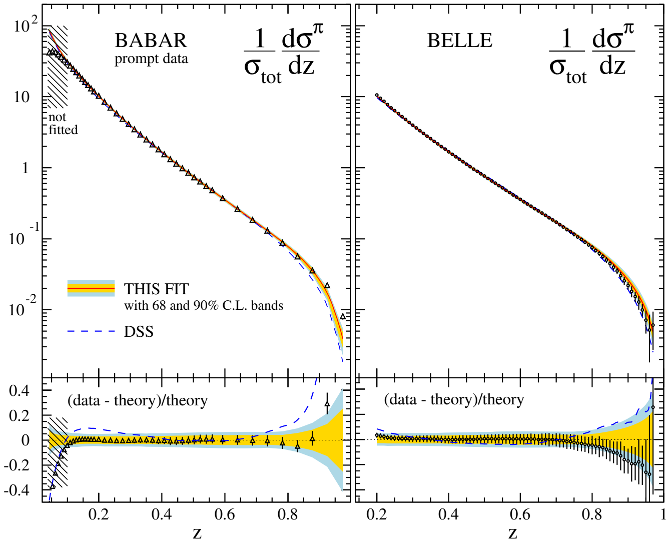
– *BaBar collaboration - Phys Rev D 88, 032011 (2013)* –

Extraction of fragmentation functions

➡ global fit



➡ good agreement with data *–Phys Rev D91 014035 (2015) –*



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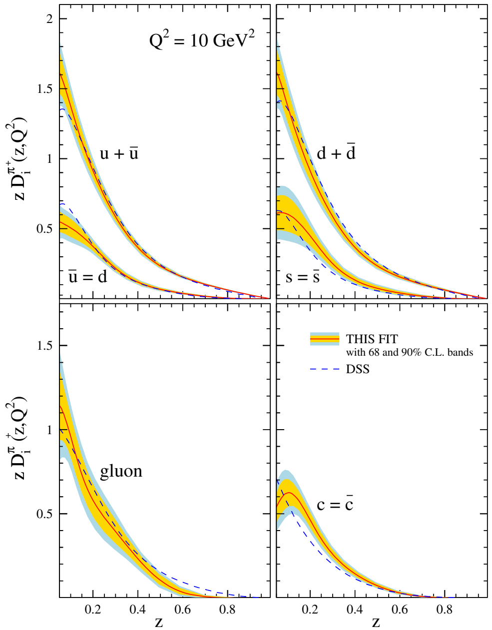

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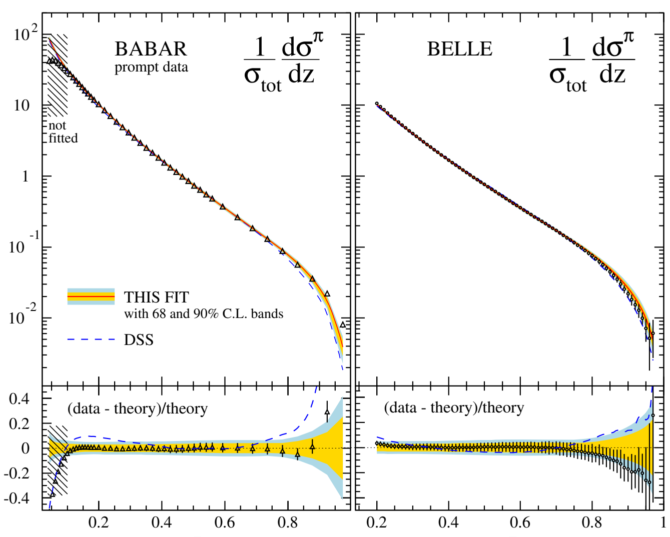
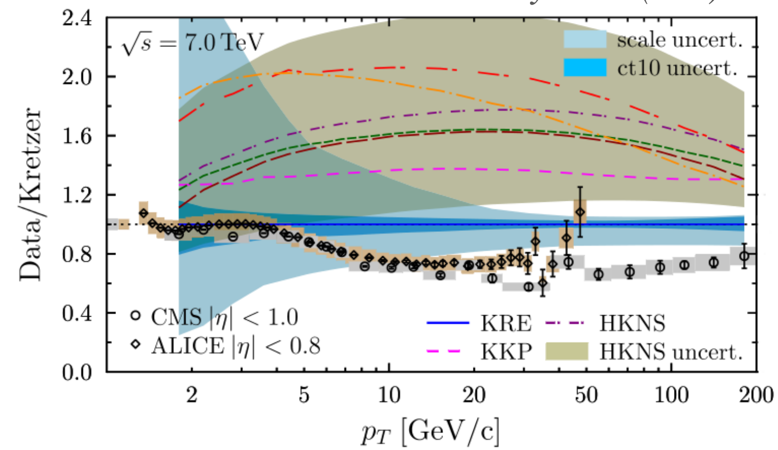
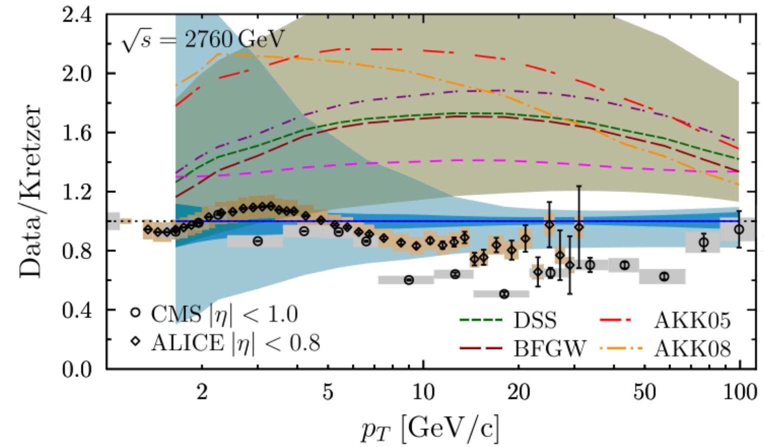


Surprises come with new data

– Nucl Phys B 883 (2014) 615 –





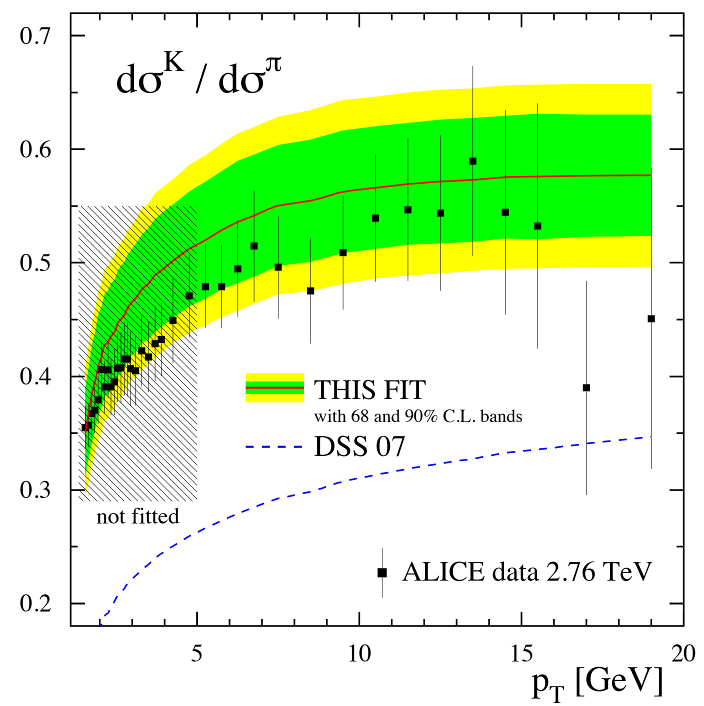
➡ predictions from all available FF sets are not compatible with CMS and ALICE inclusive charged hadron spectra

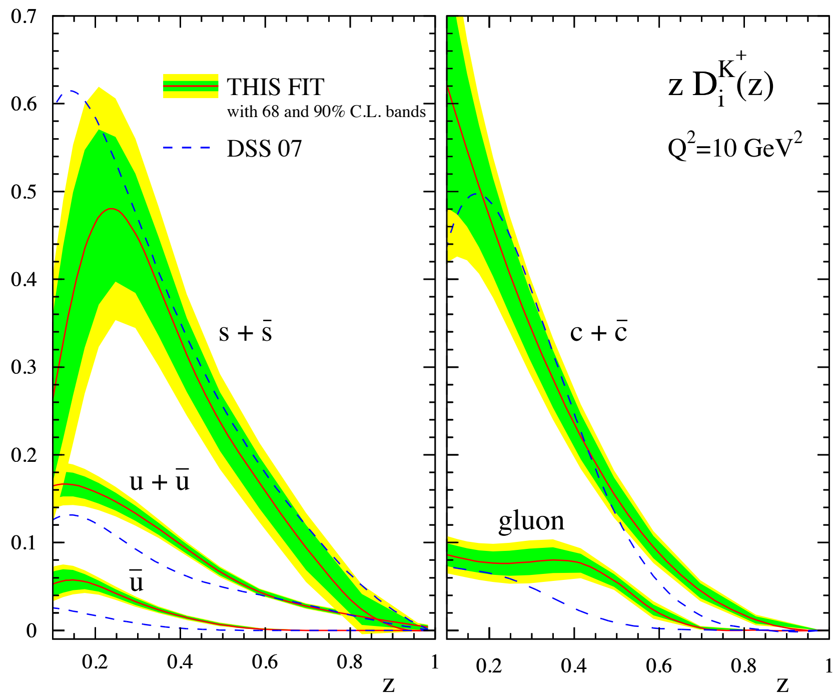
➡ reason might be the gluon-to-hadron FFs

New global fits including the ALICE data

- the main constraints on FFs come from e^+e^- data
  - gluon-to-hadron fragmentation functions largely unconstrained
- gluon FFs constraints from pp data
  - data from RHIC at small values of $p_T < 5$ GeV
- inclusion of new data from LHC is mandatory
  - $d\sigma^K/d\sigma^\pi$ from Alice

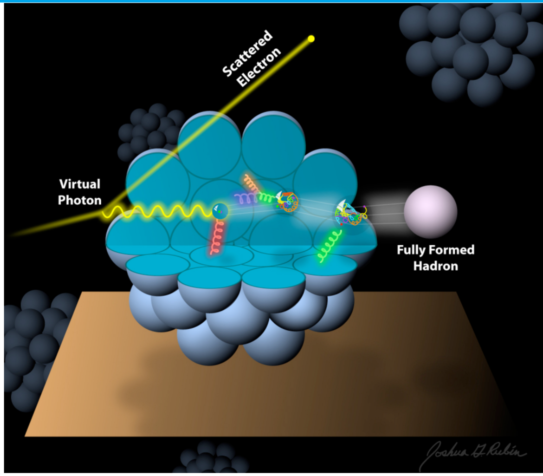
– de Florian et al, 2017 –





- substantial differences between new and old fits
  - reduced gluon-to-pion fragmentation functions
  - larger gluon-to-kaon fragmentation functions

The Lund string model

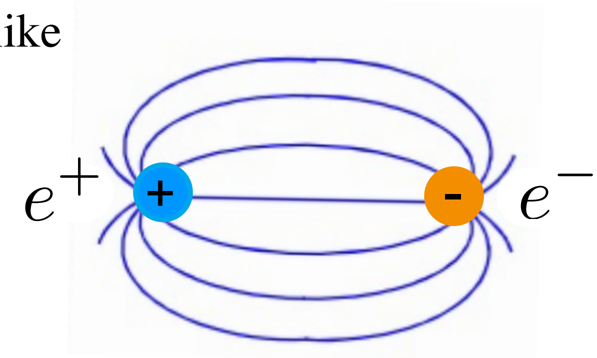


- The fragmentation process has yet to be understood from first principles
- Commonly used phenomenological models of hadronisaion:
  - **String model**
  - Cluster model
  - Independent model
  - …
- All models have a probabilistic nature → probabilistic rules are given for the production of new flavours, and for the sharing of energy and momentum between the products
- String fragmentation model was proposed by X. Artru and G. Mennessier as early as 1974
- Later was developed by **Lund** group
- And still is widely in use in Monte Carlo generators
  - **PYTHIA**
  - Lepto
  - …
- … is the basic part of many computer simulations which are necessary to obtain accurate predictions for production of hadrons

The basic picture

- **Asymptotic freedom**: at short distances the force between the quark-antiquark pair becomes increasingly QED-like

QED:



- At long distances, gluon self-interaction makes field lines attract each other
  - gluon interactions described by flux tubes – strings

QCD:

- Approximately constant energy density in the string

$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm}$$

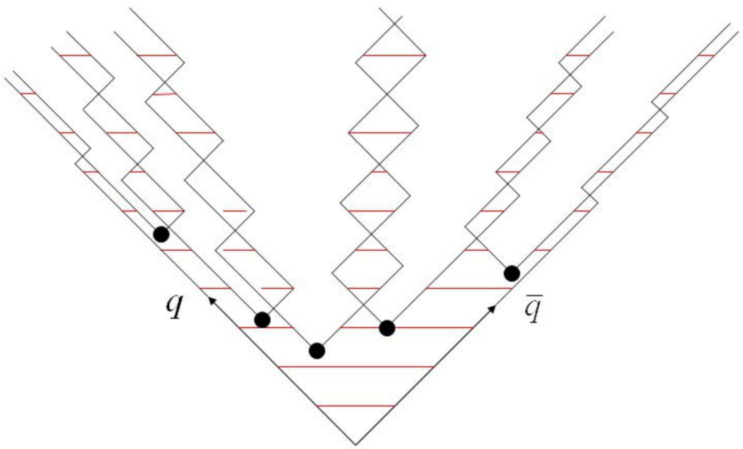
- **Confinement**: linear potential at long distances → needs an infinite energy to drag the quarks apart

$$V(r) \approx \kappa r$$

String fragmentation

Stretch enough and the strings break apart!

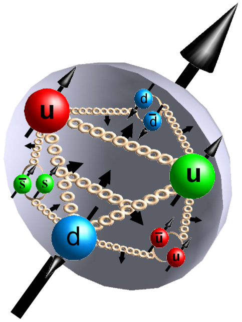
- String break by tunnelling: $\mathcal{P} \propto \exp(\frac{-\pi m_T^2}{\kappa}) = \exp(\frac{-\pi p_T^2}{\kappa}) \exp(\frac{-\pi m^2}{\kappa})$
  - common Gaussian p_T spectrum
  - suppression of heavy-quark production → $u : d : s : c \approx 1 : 1 : 0.3 : 10^{-11}$
  - diquark ~ antiquark ⇒ simple model for baryon production
- Motion of quark and antiquark pairs with adjacent pairs forming hadrons



- generate quark-antiquark pair
- Gaussian transverse momentum
- select the hadron state (L=0, S=0 or 1)
- determine the longitudinal momentum

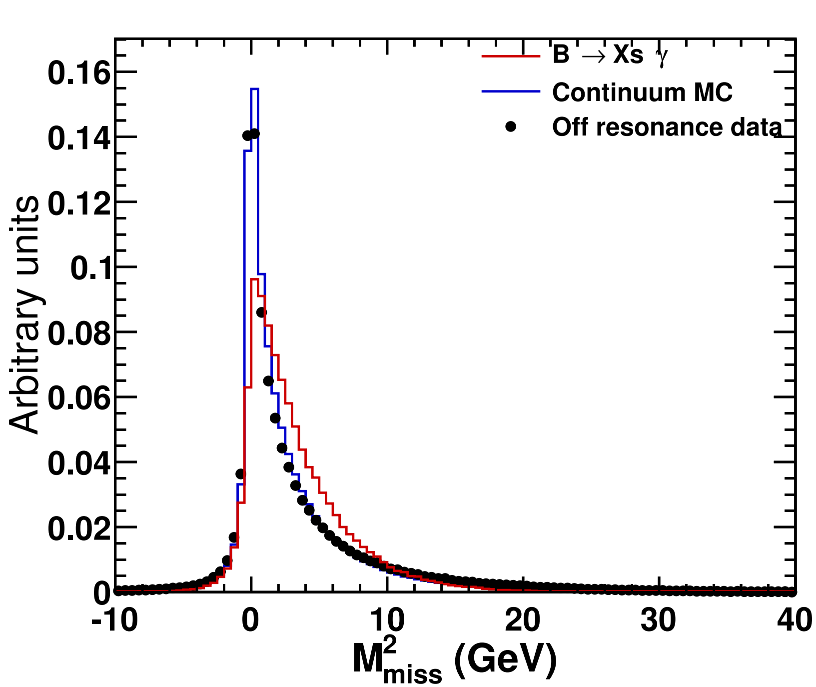
Continuum spectrum

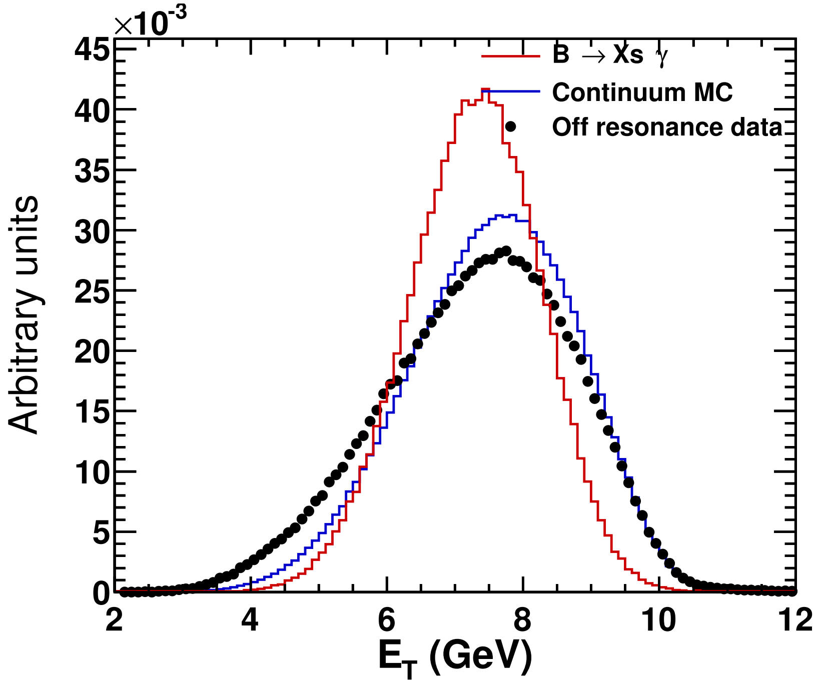
Understanding the hadronization and the continuum spectrum



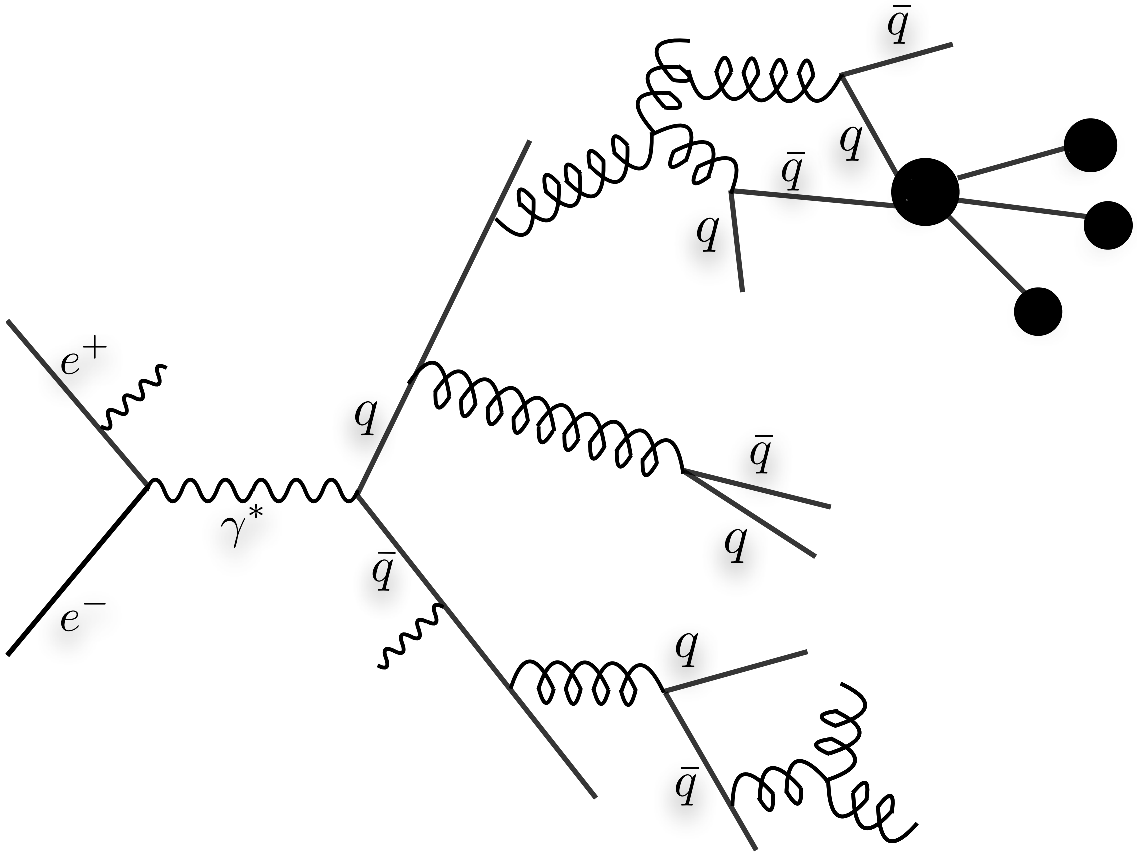
- contribute to all processes with hadrons in the final state
- **particularly important for studying the spin structure of nucleons**
- a tool to study the QCD vacuum structure
- background in NP searches

– Belle collaboration – PRL 114, 151601 (2015) –





Belle → Belle II: Monte Carlo generators



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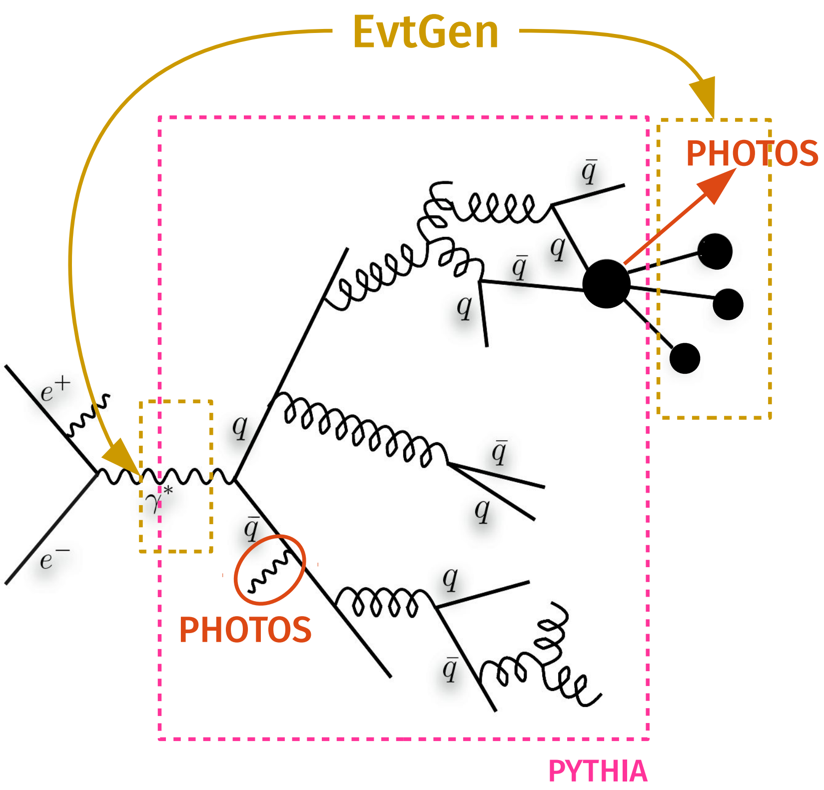

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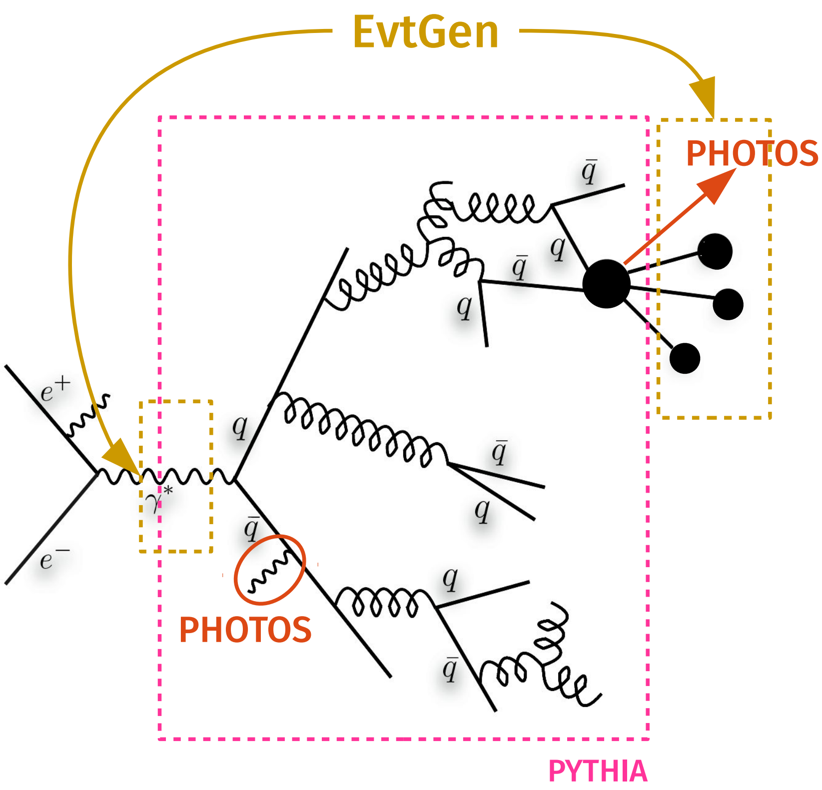

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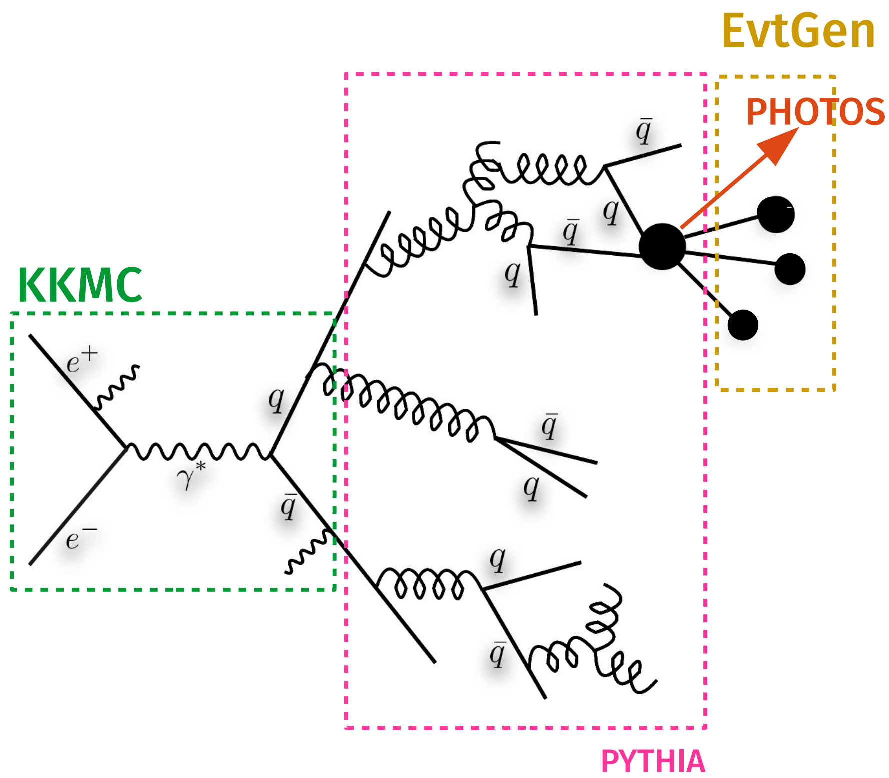
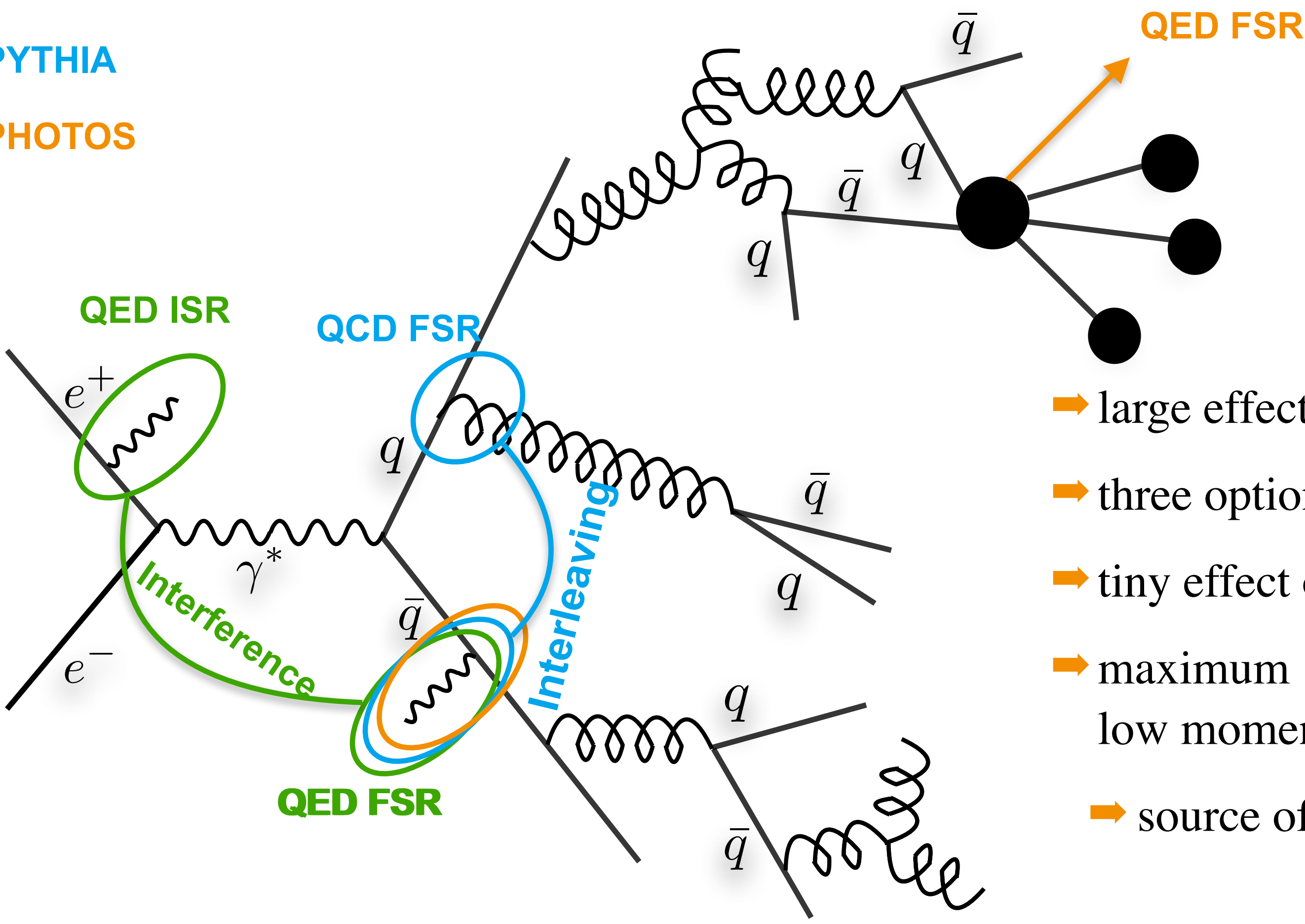


Belle II Monte Carlo generators

KKMC

PYTHIA

PHOTOS



- large effect of ISR
- three options to generate the FSR
- tiny effect of ISR/FSR interference
- maximum 10-20% effect of FSR at low momenta
  - source of systematic uncertainty

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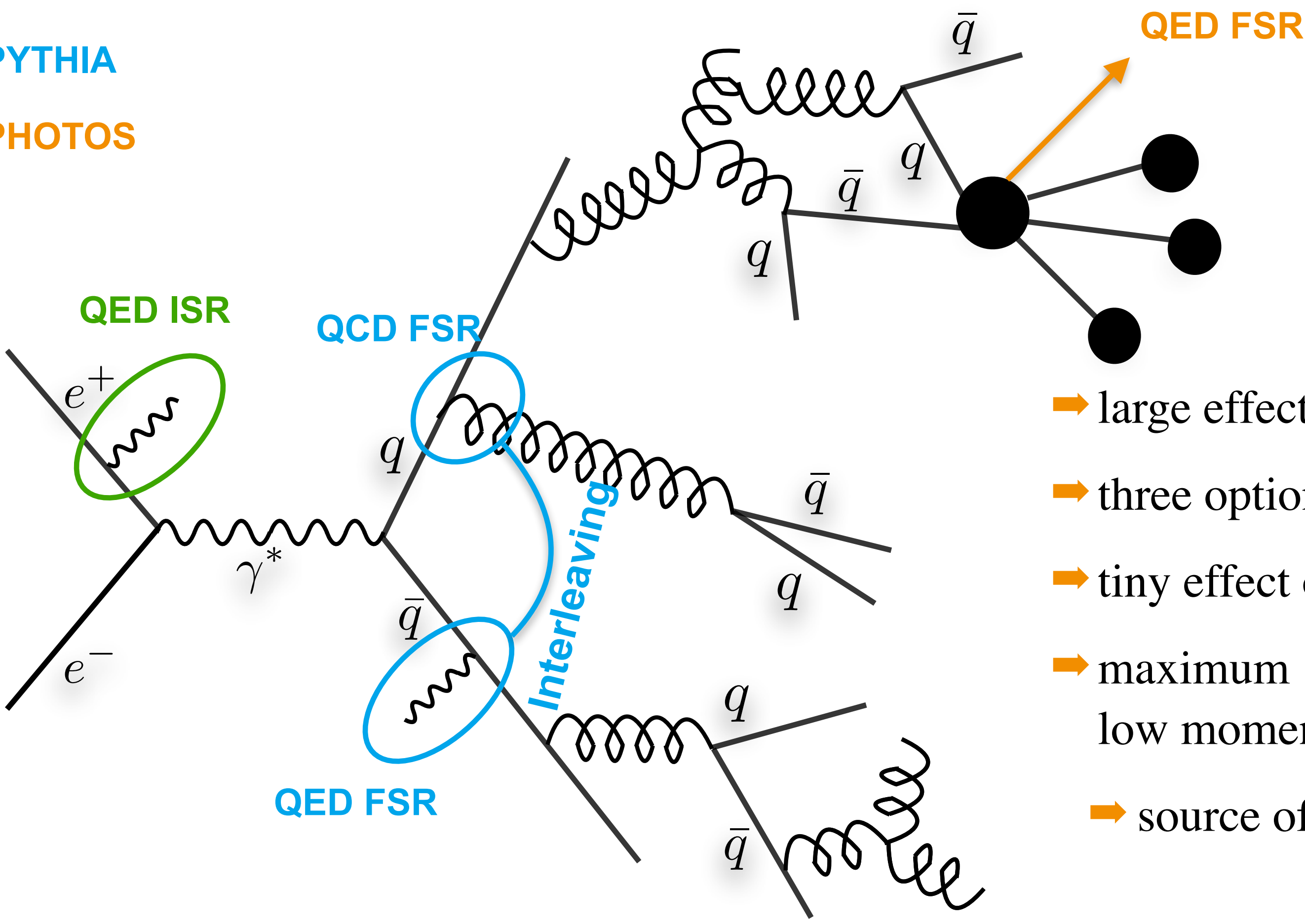

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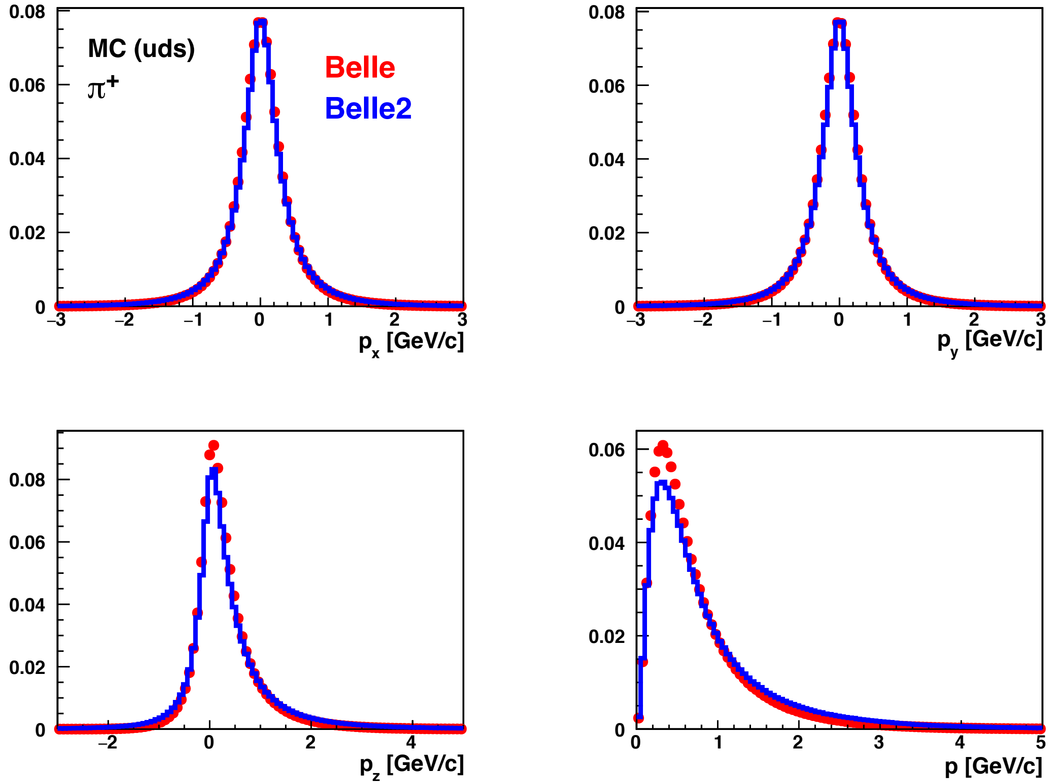
Belle MC % Belle2 MC

Pythia 8 is a clean new start, to provide a successor to Pythia 6.

➡ in general PYTHIA 8 is different from PYTHIA 6

➡ not possible to "port" a PYTHIA 6 tune to PYTHIA 8



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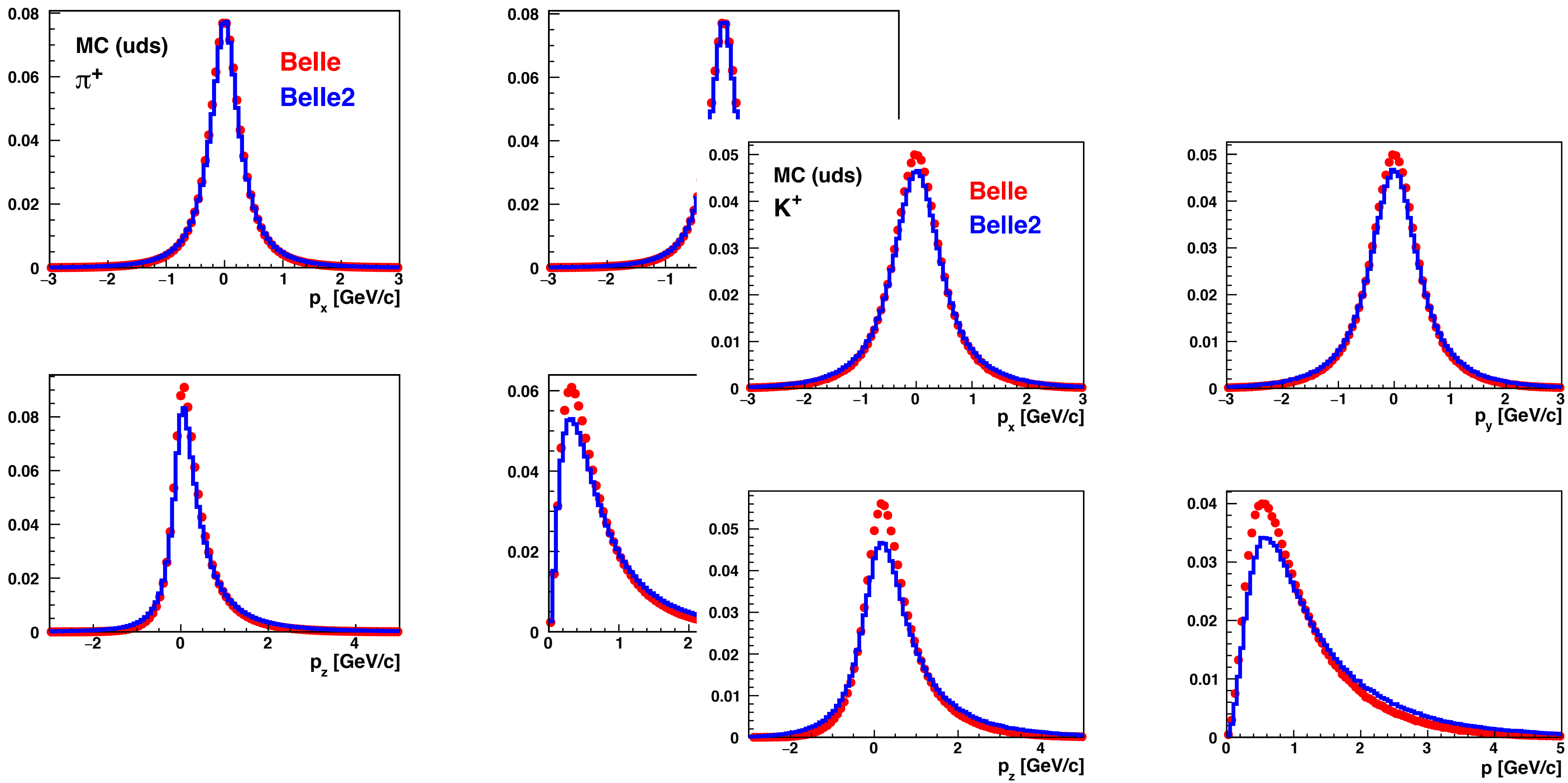
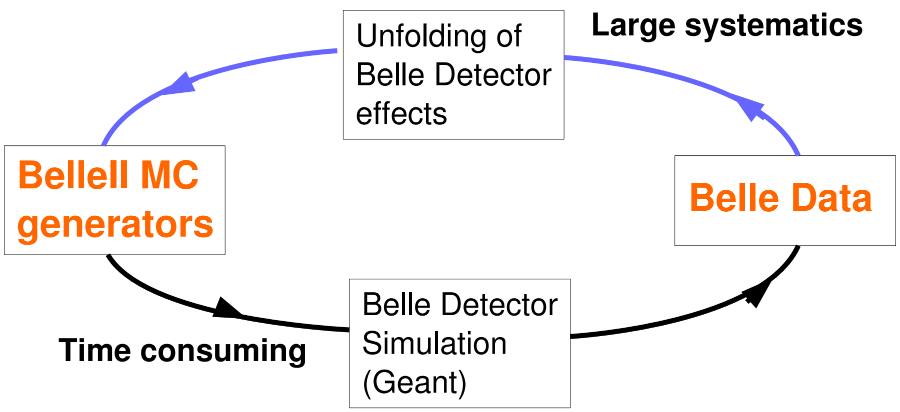


Towards PYTHIA8 tuning



use Belle data

- ➡ off-resonance data: $q\bar{q}$ events (q=u, d, s, c)

use Belle II MC generators

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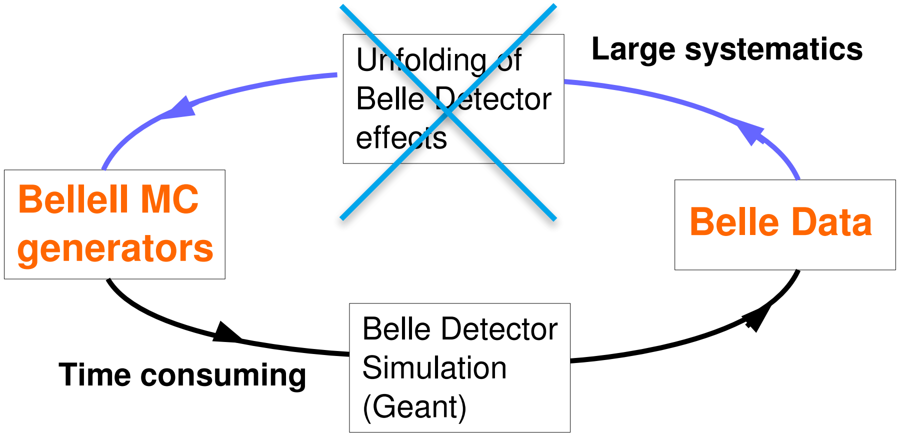

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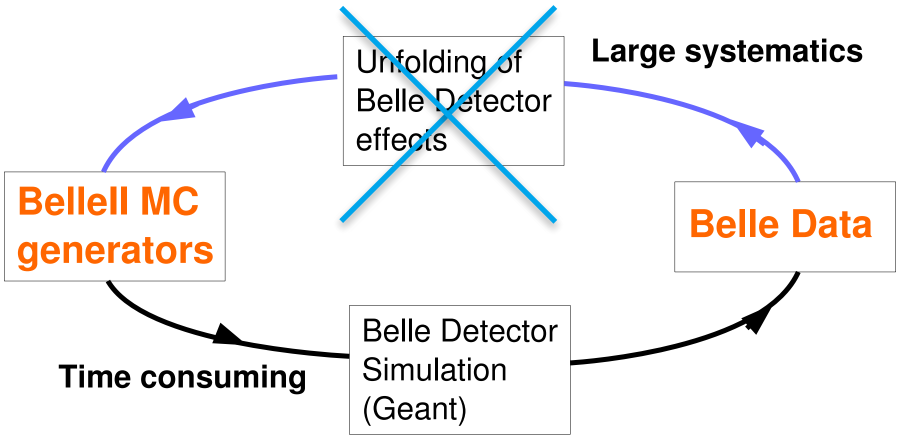


use Belle data

- ➡ off-resonance data: $q\bar{q}$ events (q=u, d, s, c)

use Belle II MC generators

- ➡ a tuning tool for Monte Carlo event generators
  - ➡ automated tuning approach
  - ➡ tune itself is very fast
- ➡ professor supplies the parameter grid
- ➡ generate Monte Carlo for a given set of parameter values
- ➡ calculate observables
- ➡ build interpolations
  - ➡ parametrise the MC in parameter space with a polynomial
- ➡ tune polynomial to data
  - ➡ determination of minimum in parameters space

Parameter sensitivity

PYTHIA8 fragmentation → ~100 parameters → can't tune all

$$res_i = \frac{r_i - R\,\hat{p}_i}{\sqrt{R\,\hat{p}_i \left(\frac{1-R}{R+M}\right)(1-\hat{p}_i)}} \quad \text{with} \quad \hat{p}_i = \frac{r_i + m_i}{R + M}$$

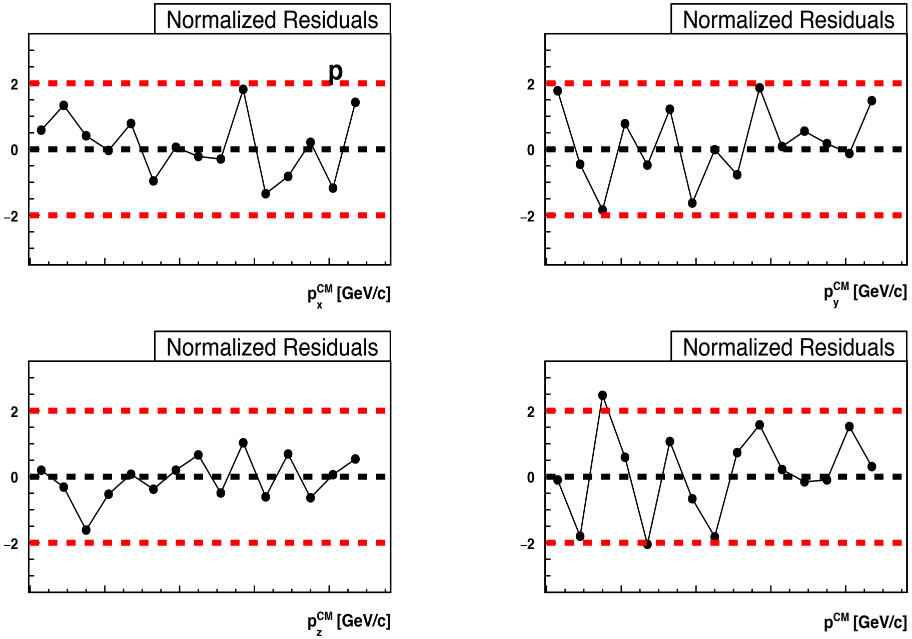
r_i → number of events in i[th] bin in the reference sample

R → total number of events in the reference sample

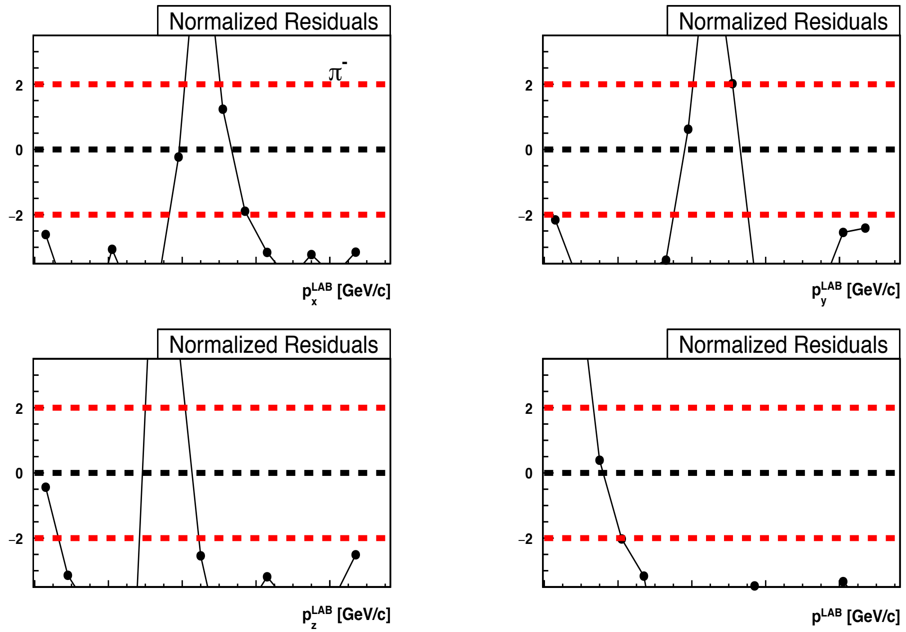
m_i → number of events in i[th] bin in the modified sample

M → total number of events in the modified sample

insensitive



sensitive



The parameter list

- Lund symmetric fragmentation functions

$$f(z) = \frac{1}{z} \; (1-z)^{\mathrm{StringZ:aLund}} \; e^{-\mathrm{StringZ:bLund} \; \mathrm{m_T^2/z}}$$

  - parameters modifying **s-quark, diquark and c-quark fragmentation**

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particles

π^+, π^-, π^0, $\pi^+ + \pi^-$

K^+, K^-, $K^+ + K^-$

η, η', γ

Λ, $\overline{p}$

D^0, D_0^*

observables

z, p_T, M_{2h}

multiplicities

thrust, R_2

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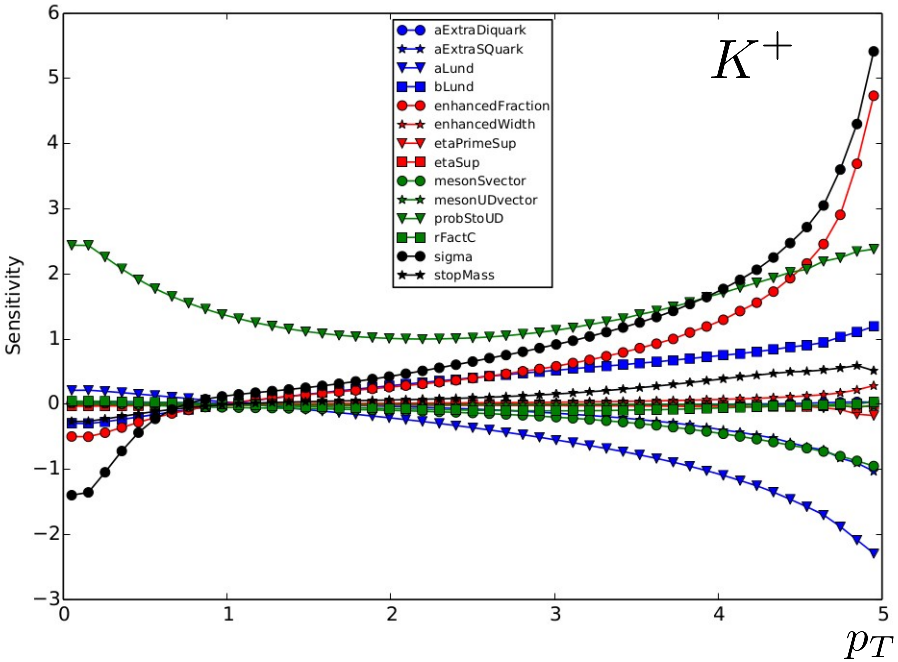

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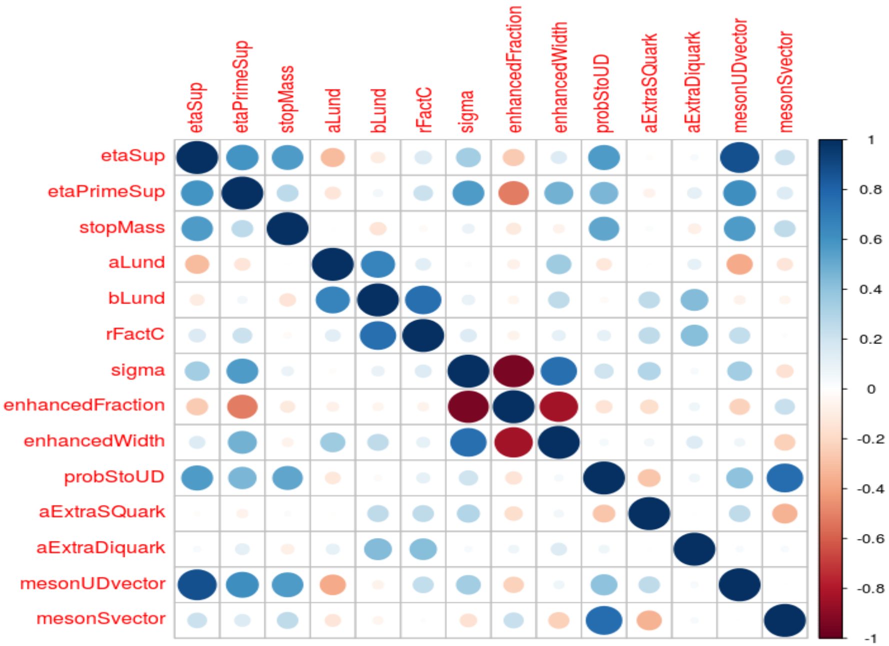
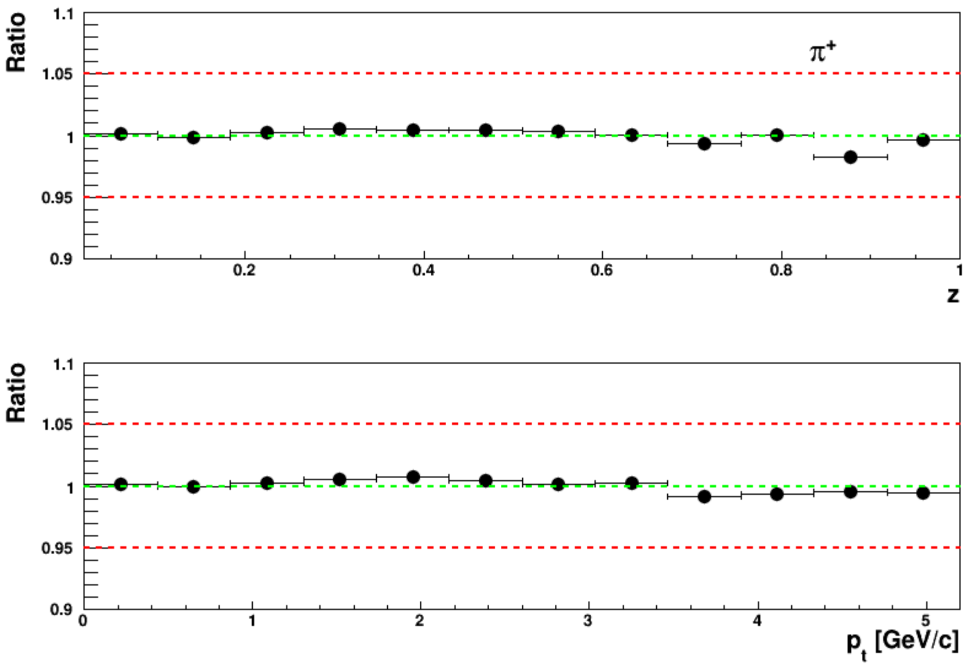


Testing the tuning procedure

- Simultaneous tuning of all 14 parameters
  - requires 1362 Monte Carlo samples → ~ 40 TB
- Testing the procedure on Monte Carlo "true" kinematics and "true" PID



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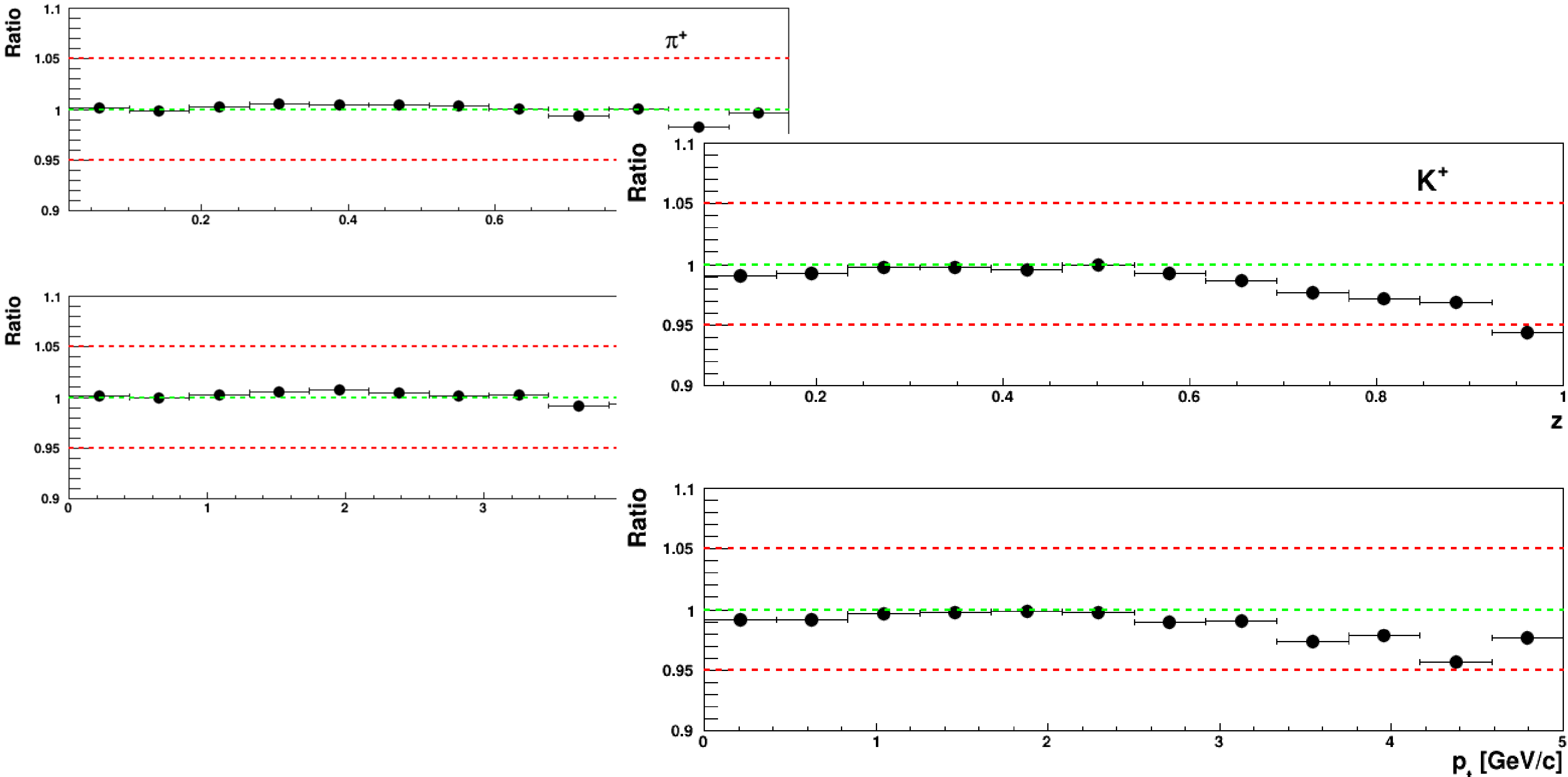

Belle II perspectives: fragmentation functions

Rich program to study the fragmentation process

- ➡ release the integration over the transverse-momentum of hadrons
- ➡ extend to different quark or hadron polarisations
- ➡ consider di-hadron production

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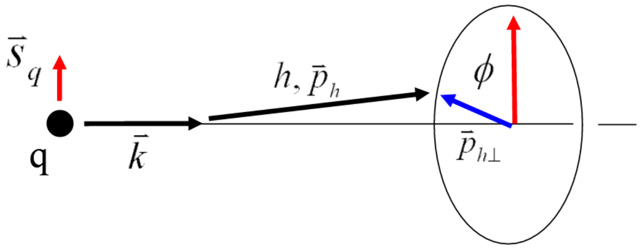

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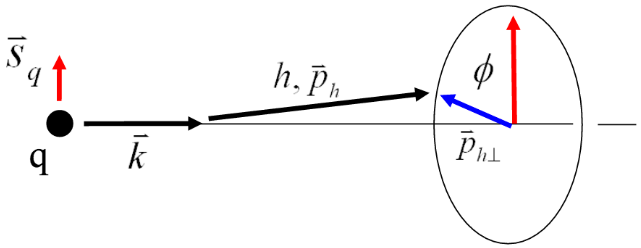

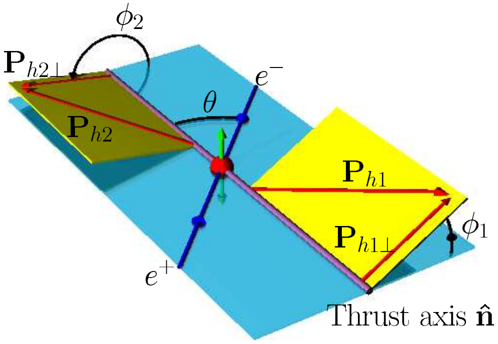

$$\sigma \propto 1 + \frac{\sin^2\theta}{1+\cos^2\theta} \cos(\phi_1 + \phi_2) \frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1(z_1)\bar{D}_1(z_2)}$$

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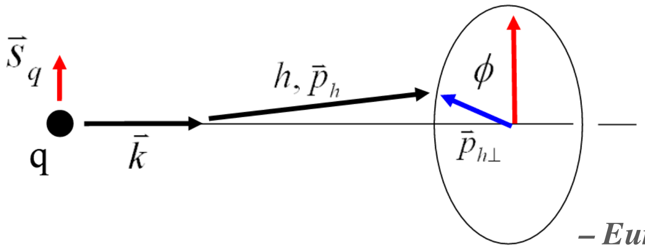
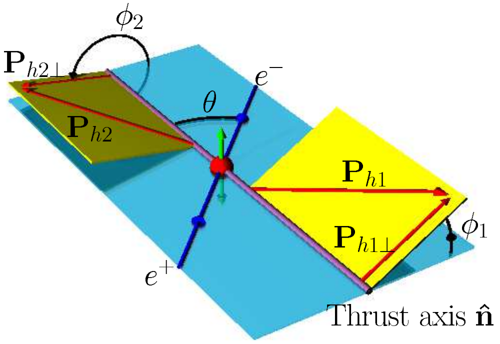
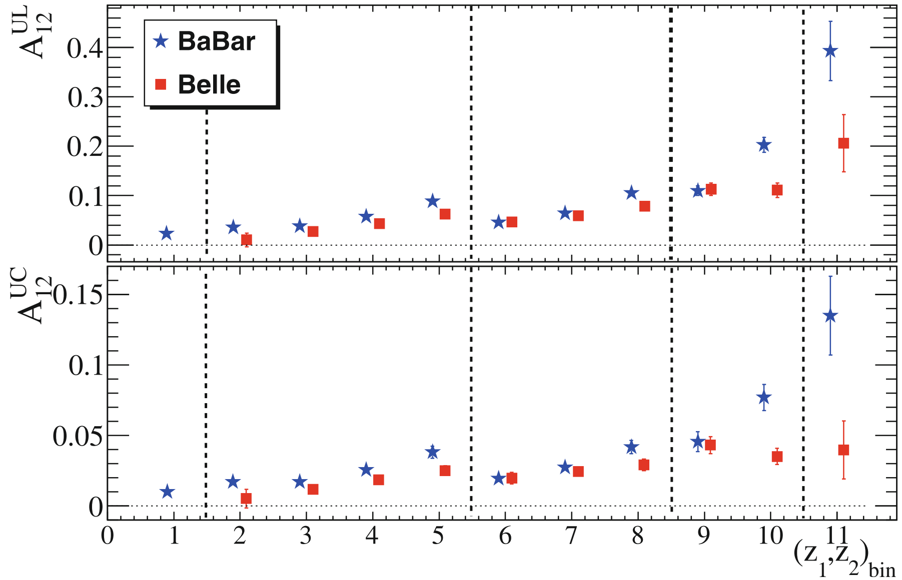




– Eur. Phys. J. A (2016) 52: 152 –



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tension between Belle and BaBar results

- ➡ thrust axis corrections
- ➡ background corrections
- ➡ z<0.9 for BaBar, z<1 for Belle

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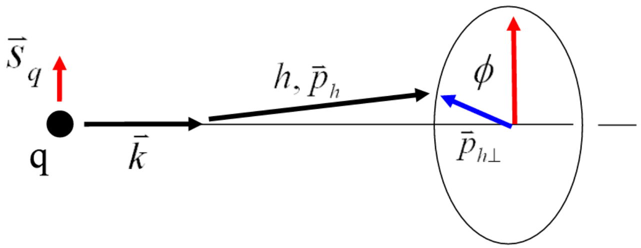

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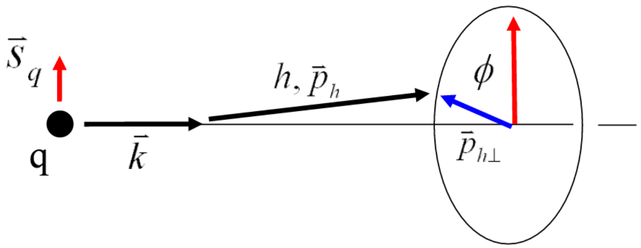
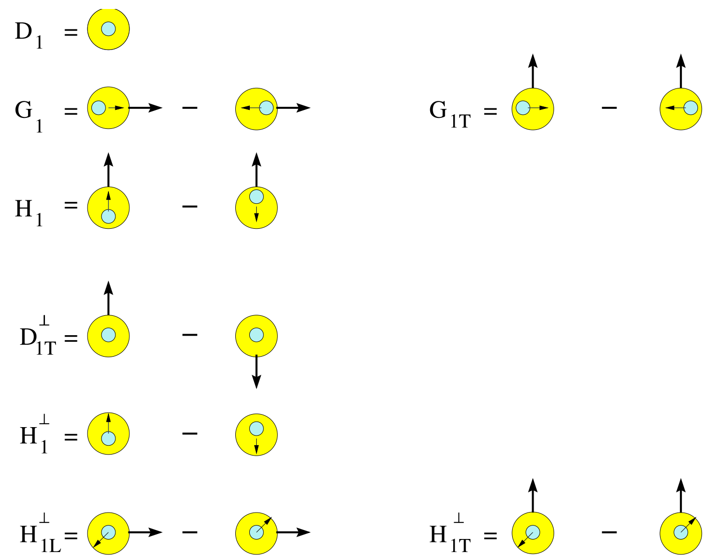


2. fragmentation into one spin-1/2 hadron



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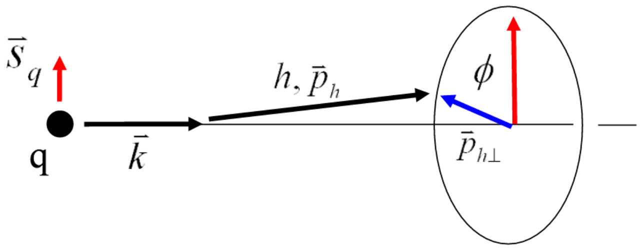

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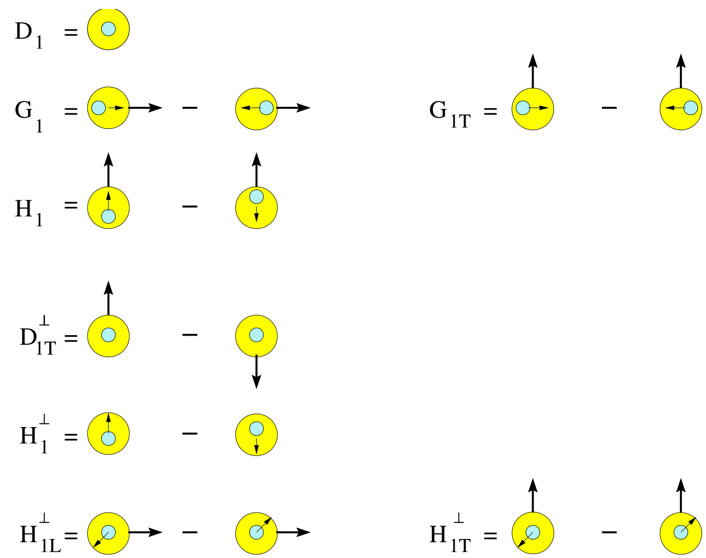
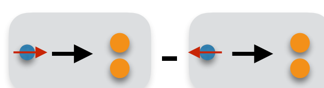
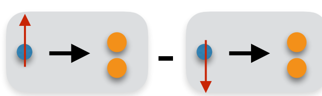


3. fragmentation into two hadrons

$D_1^{(2h)} =$ 

$G_1^{\perp\,(2h)} =$ 

$H_1^{\perp\,(2h)},\ H_1^{\sphericalangle} =$ 

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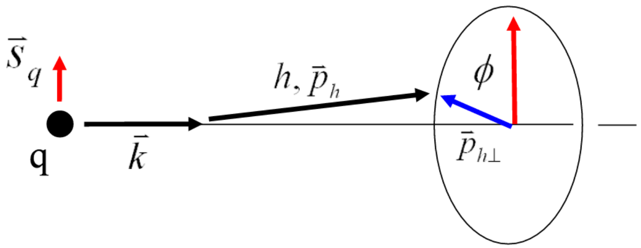

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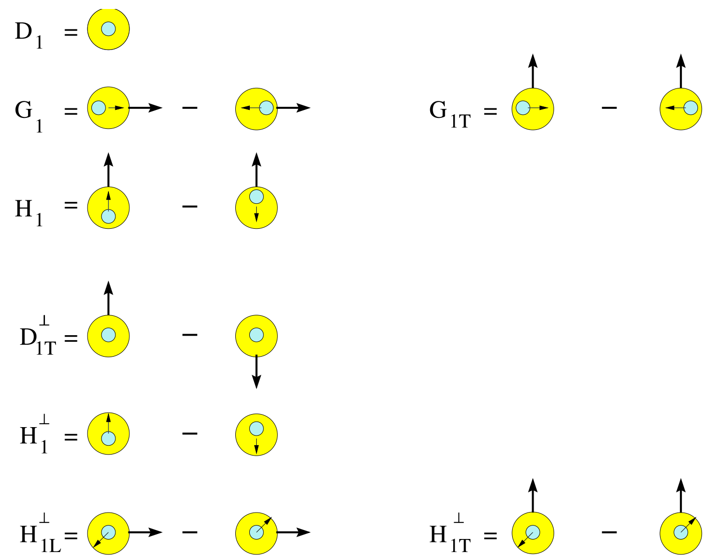

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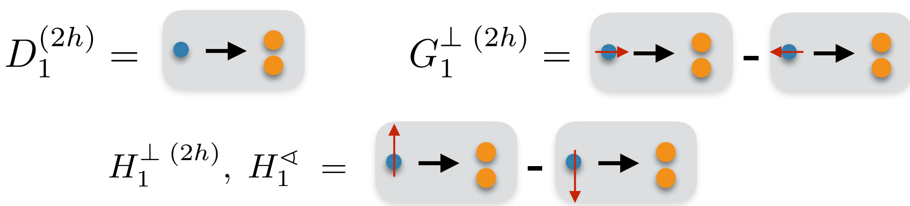


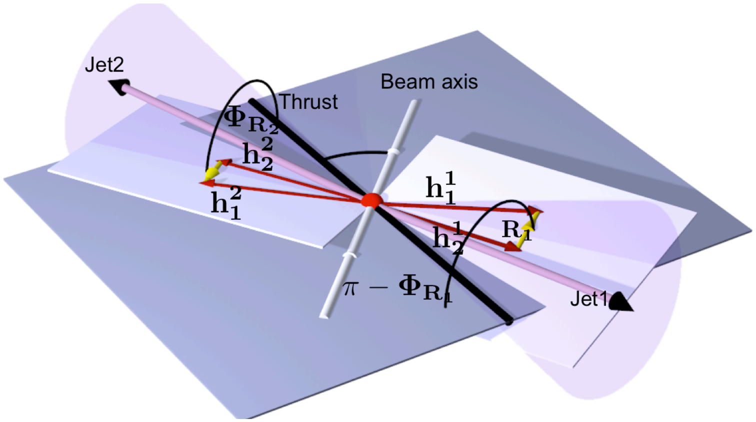
Next generation high precision measurements from Belle II

- ➡ systematic uncertainty under control
  - ➡ better vertex reconstruction
  - ➡ more precise hadron identification
- ➡ an immense amount of data
  - ➡ provide multi-dimensional results (small bin sizes)
  - ➡ better constraints on FFs

Belle II perspectives: QCD vacuum structure

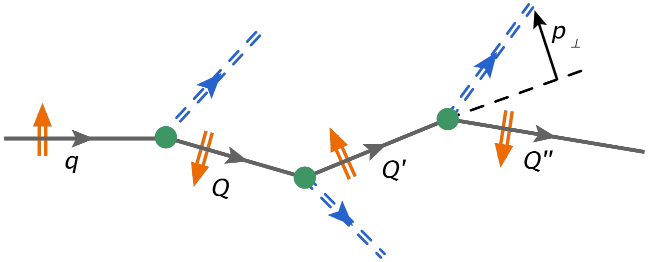
Hadronisation depends on the QCD-vacuum structure!

$$e^+ + e^- \to \gamma^* \to q\bar{q} \to (h_1 h_2) + (\bar{h}_1 \bar{h}_2) + X$$



Quark fragmentation in:

> perturbative QCD vacuum



➡ spin-dynamics of hadronisation

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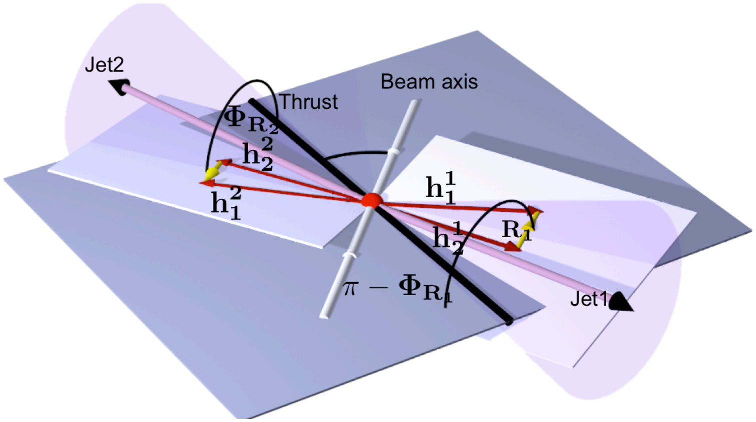

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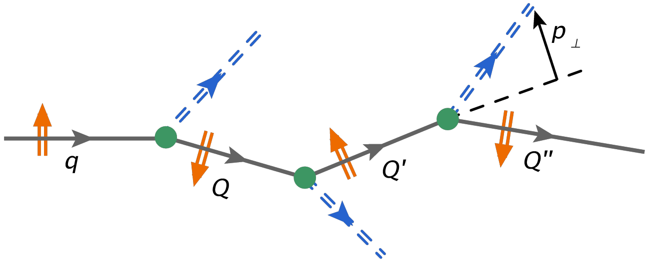
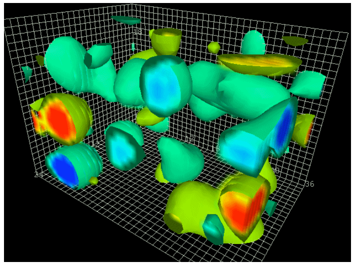


➡ spin-dynamics of hadronisation

> θ-vacuum

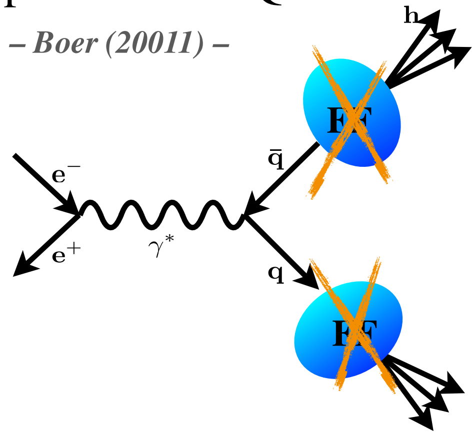
– Kang, Kharzeev (2011) –



➡ local CP violation

> non-perturbative QCD vacuum

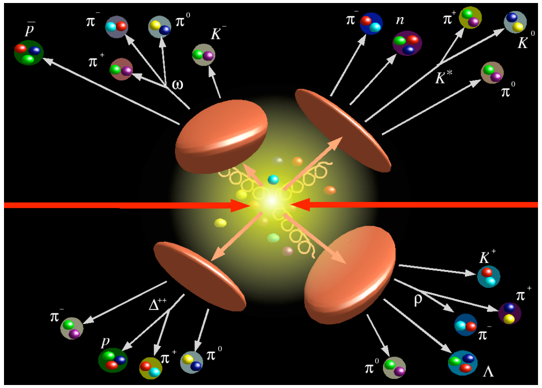
– Boer (20011) –



➡ factorisation breaking

Outlook

- Long way ahead before the fragmentation functions will be as precise as the PDFs
- The spin-dependent and transverse momentum unintegrated fragmentation functions even less constraint
- Belle II will be a major player in the near future



  - The framework for generating the continuum spectrum is ready and validated
  - The strategy for tuning of PYTHIA8 has been settled
  - Tuning using the Belle off-resonance data is in progress
  - As soon as the Belle II data is available, tune using the Belle II data
    - systematics dominated: both from experimental and phenomenological part

Backups

KEKB → SuperKEKB

$$L = \frac{\gamma_{\pm}}{2 e r_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\,\xi_{y\pm}}{\beta_{y\pm}}\frac{R_L}{R_{\xi_y}}$$

Lorentz factor

classical electron radius

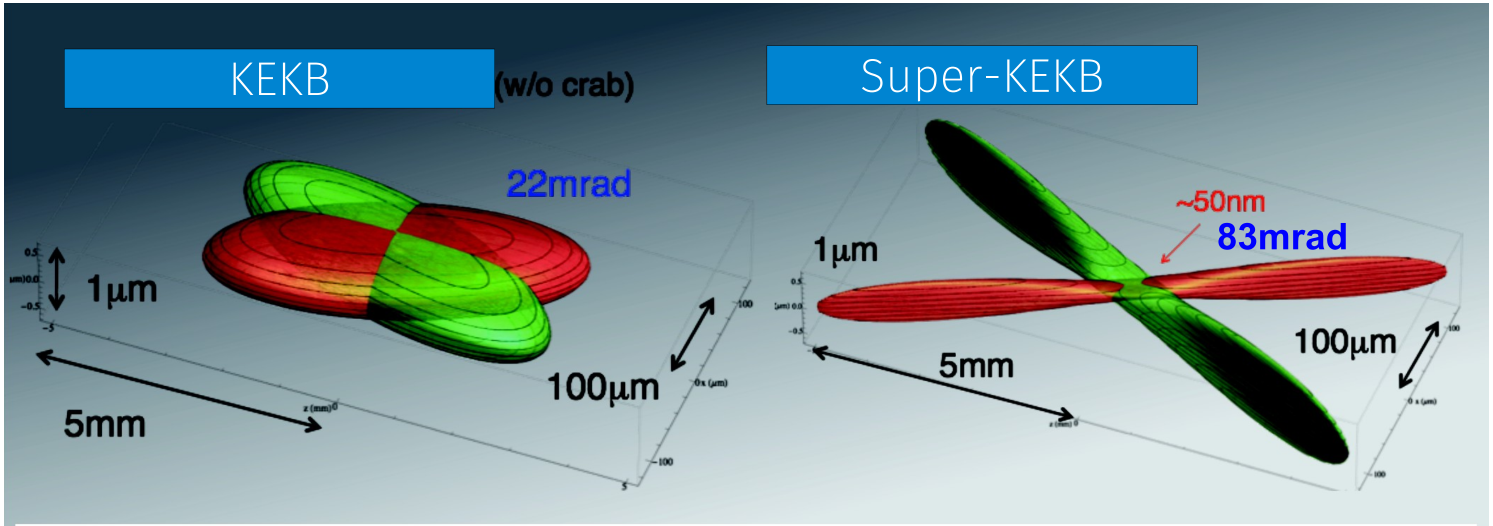
beam size ratio at IP 1-2% (flat beam)

beam current

vertical beta function at IP

beam-beam parameter

geometrical reduction factors (crossing angle, hourglass effect)

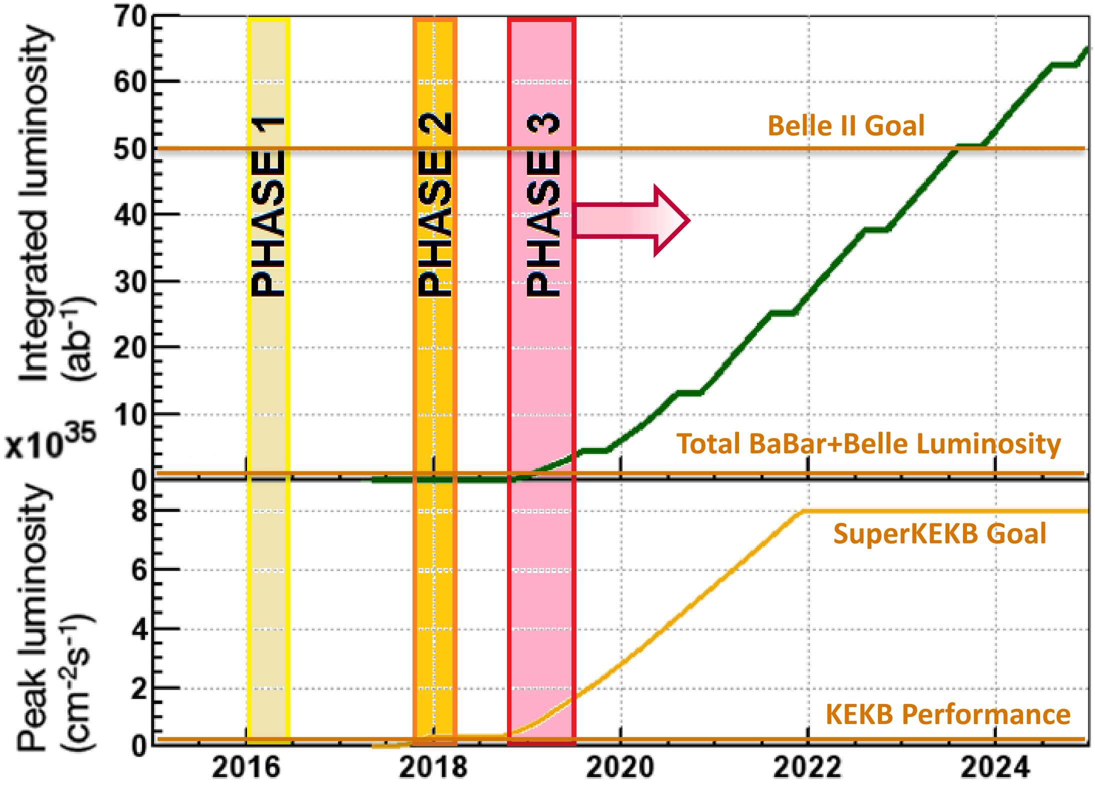


	E (GeV) LER/HER	β*$_y$ (mm) LER/HER	β*$_x$ (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm^{-2}s^{-1})
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

factor 20   factor 2-3   factor 40

Belle II Schedule

- Phase 1 (2016, complete):
  - Accelerator commissioning
  - No detector
- Phase 2 (start of 2018):
  - Partial detector
  - Background studies
  - First physics
- Phase 3 (end of 2018):
  - Full detector
  - Belle II run

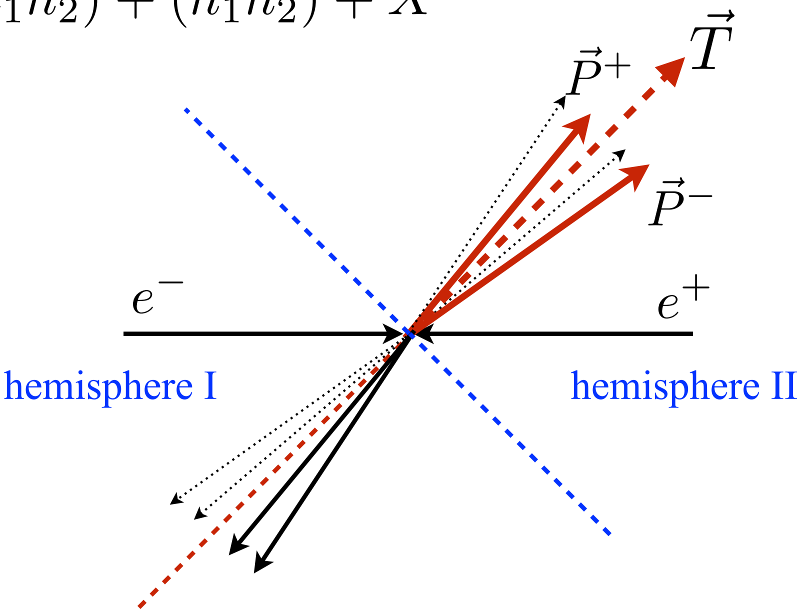


Methodology

$$e^+ + e^- \to \gamma^* \to q\bar{q} \to (h_1 h_2) + (\bar{h}_1 \bar{h}_2) + X$$

- "left" pairs:
  - ➡ $\Omega < 0$
- "right" pairs:
  - ➡ $\Omega > 0$

$$\Omega = \frac{(\vec{P}^+ \times \vec{P}^-) \cdot \vec{T}}{|\vec{P}^+||\vec{P}^-|}$$



The experimental observables for disentangling the hadronization mechanisms :

- jet handedness

$$H = \frac{N_R(\Omega > 0) - N_L(\Omega < 0)}{N_R(\Omega > 0) + N_L(\Omega < 0)}$$

jet handedness correlation

$$C = \frac{\langle \Omega_1 \Omega_2 \rangle - \langle \Omega_1 \rangle \langle \Omega_2 \rangle}{\sqrt{\langle \Omega_1^2 \rangle - \langle \Omega_1 \rangle^2}\sqrt{\langle \Omega_2^2 \rangle - \langle \Omega_2 \rangle^2}}$$

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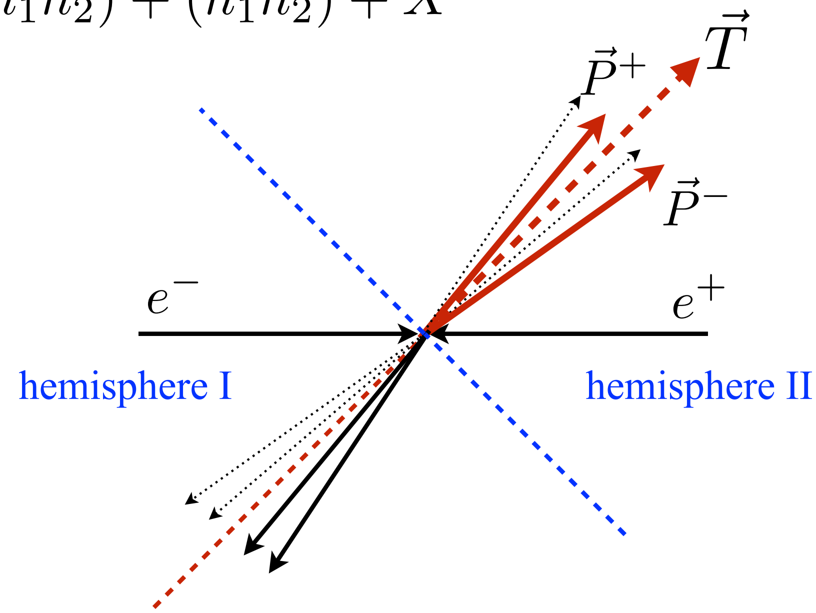

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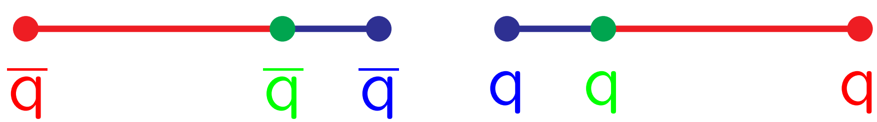
Baryon production

Meson production ≈ same colour everywhere.
Fluctuations with other colour ⟶ no net force.

i.e. $r + g = \bar{b}$
Baryon production as if diquark
when only one break
inside “wrong-colour” region:



Popcorn when several breaks: