A proposal for absolute luminosity measurement at 1 %

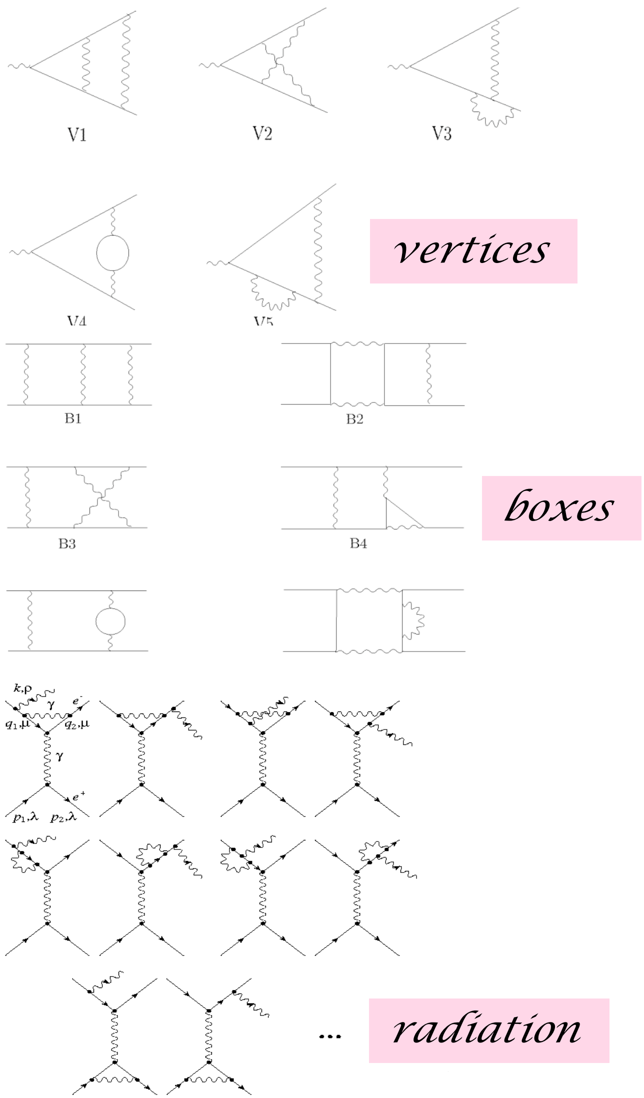
Mieczyslaw Witold Krasny, CNRS, IN2P3
University Paris 6 et 7, LPNHE

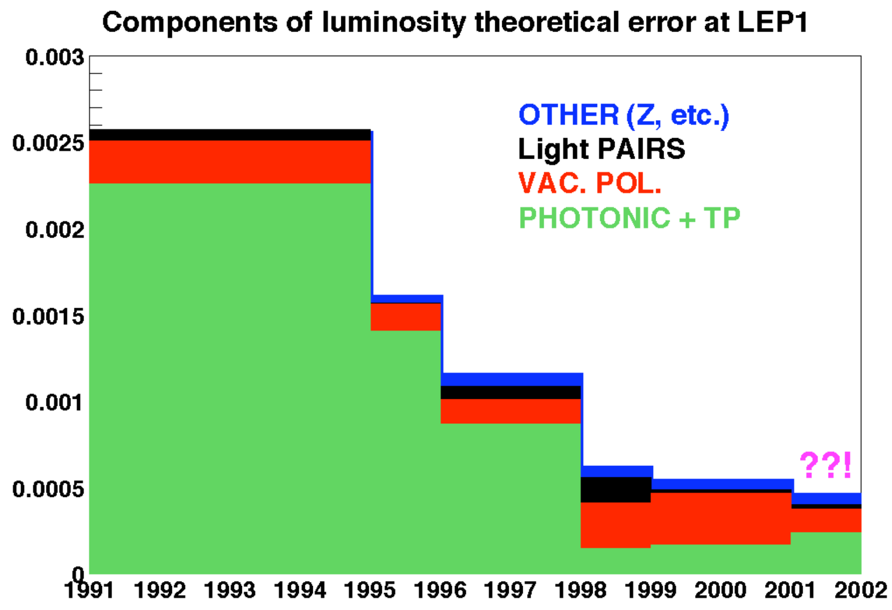
Based on:

M.W.K., J.Chwastowski,K.Slowikowski:
Nucl.Instrum.Meth.A584:42-52,2008; e-Print: arXiv:1006.3858 [physics.ins-det]; e-Print: arXiv:1111.5851 [hep-ex]
submitted to NIMA.

CERN, 29 February 2012

Lessons from LEP





LEP case:

initially 5% was considered good enough, later 2% …but it was possible to achieve 0.1% and in retrospect this proved vital for establishing the electroweak standard model as a non-abelian gauge theory

Lessons from HERA

Point-like protons at HERA-indirect tagging

DESY and H1 radiative corrections working group (1990-1994), Z.Phys.C66:529-542,1995

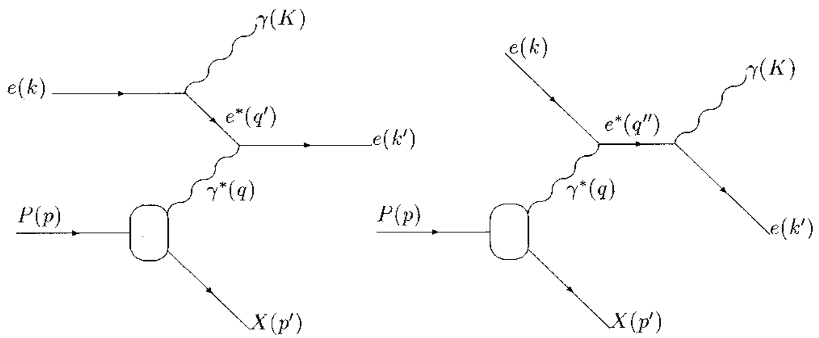


Fig. 1. The diagrams for the radiative ($ep \to e\gamma + X$) scattering

In the limit $q \to 0$ ($q << m_p$) purely point-like elastic EM process (X=proton)

Two experimental methods to control the four-momentum transfers

- The *bremsstrahlung process* corresponding to the poles in both the virtual electron and the virtual photon propagators.
- The *QED Compton process* corresponding to the pole in the virtual photon propagator and to a large virtual electron mass.

HERA case:

Vital experience in tagging point-like protons by measuring large angle electron/photon in the central detector (directly applied in the presented method…)

Why precision wanted?

Present paradigms

Michelangelo Mangano, CERN Lumi Days January 2011

$$\int dx_1\, dx_2 \sum_{i,j} f_i(x_1)\, f_j(x_2)\, \boxed{\hat{\sigma}_{(ij\to Z)}} (\boxed{M_Z, g_{EW}}, \ldots) = \frac{\boxed{N_{events}(Z)}}{\text{Luminosity}}$$

known to 2%, most accurately known elementary cross section at the LHC

known to sub-‰ level

$$\sigma(f_i\, f_j) \sim 2\% \oplus \sigma(\text{lum})$$

The real precision cannot be estimated naively like this, because of the convolution integral, external constraints on the range of PDFs, etc. See later for concrete examples

This is the process that defines, as of today, the ultimate target of the absolute luminosity measurements:

± 2%

…within the reach of the VdM scan method … why bother?

Why precision wanted?

precision observables

Four principal reasons to push the precision frontier as much as possible:

• ***Measurement of the cross sections ratios at different CM-energies***
(EW physics, Primakoff processes, Higgs searches, etc…)

• ***Measurement of the cross section ratios with different beam species***
(use ions to modify the medium effects in hard EW and QCD processes)

•***Relative normalization of the cross sections measured in different phase-space regions*** *(e.g. ATLAS/CMS versus LHCb in the measurement of $\sin^2\theta_W$)*

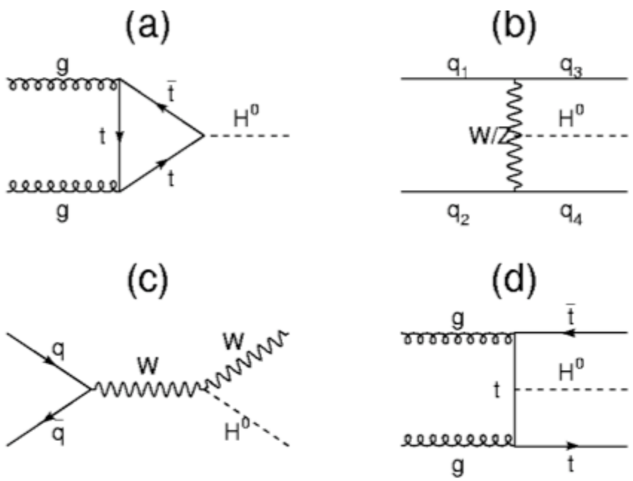
•***Relative normalization of cross sections measured at the LHC and Tevatron***
(precision unfolding of the flavour and sea/valence structure of the proton)

M.W. Krasny, W. Placzek, A. Siodmok, F. Fayette, S. Jadach:
Eur.Phys.J.C69:379-397,2010, Acta Phys.Polon.B42:2133,2011, Eur.Phys.J.C63:33-56,2009,
Eur.Phys.J.C51:607-617,2007, Eur.Phys.J.C44:333-350,2005

An example:

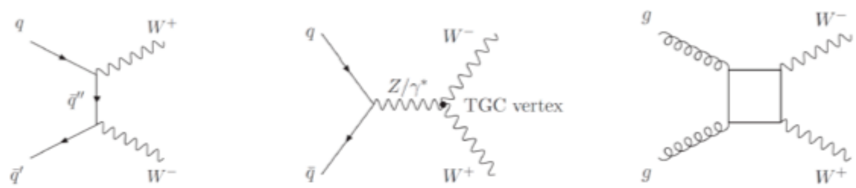
How to filter out the Higgs production processes against the Standard Model background? (M.W.K - Acta Phys.Polon.B42:2133,2011)

---> exploiting the difference in the production mechanism of the signal and the background events ---->



Higgs: Mostly gluonic process

(90 % gg and 10 % qq)



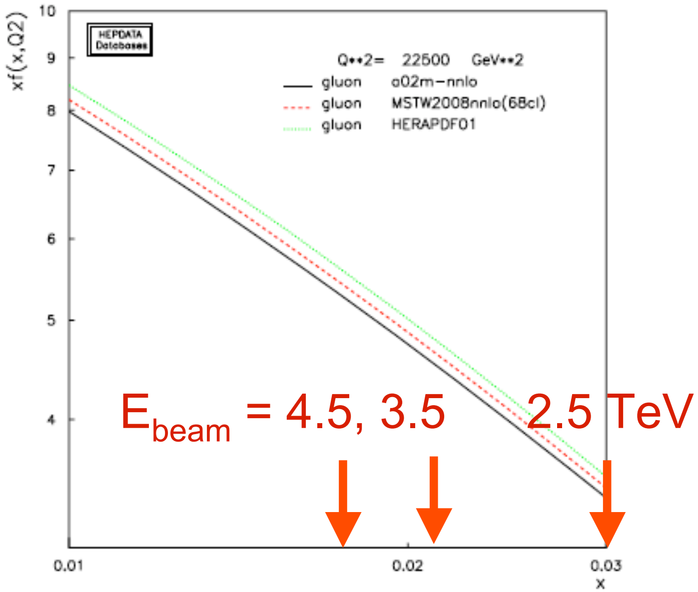
Background(0jet): Mostly quarkonic process

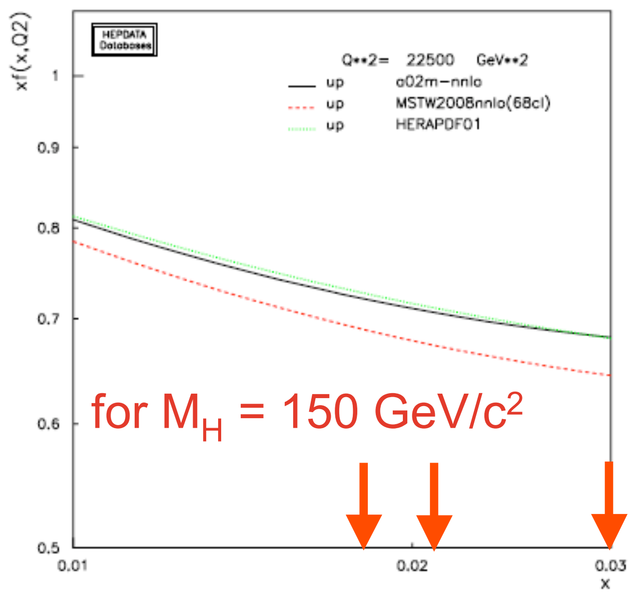
(97 % qq and 3 % gg)

production of e.g. O(140 GeV/c^2) Higgs bosons in the central rapidity region -

$$x_g = M_H/2E_{beam}$$

… runs at different beam energy correspond, to different x of partons producing Higgs. The difference in the momentum distribution of quarks and gluons allows to filter out experimentally the gluonic processes (Higgs) against the quarkonic processes (background) provided that the ratio of cross sections is measured to better than 1%…





Nota bene: The ratios of fluxes have ~ 10 smaller errors than the absolute gg and qq fluxes

Main limitations of the present methods

• ***Absolute cross sections measured in dedicated runs (VdM, large β^* runs) and subsequently "transported" to the requisite data taking period***

•***Sensitivity to the beam optics and beam-beam effects (energy and beam-species dependence)***

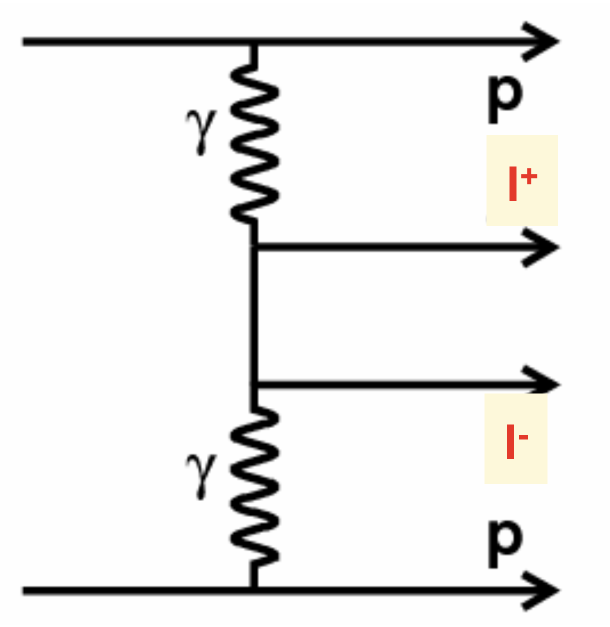
• ***Limitations in the experimental tools to precisely control the monitoring of the instantaneous (relative) luminosity (μ - dependence, long time stability)***

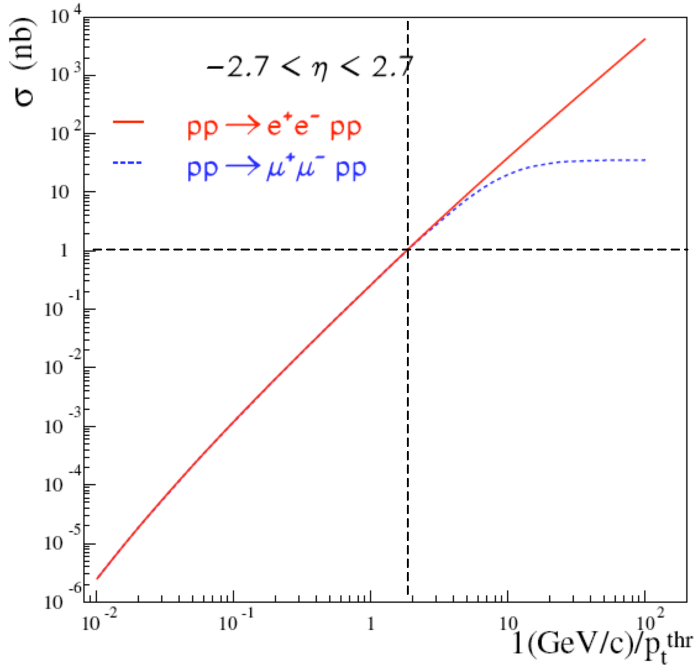
•***Need a concurrent sampling of luminosity events and user selected events (as much as possible independent of the beam particle species and energy)***

•***Need to base the relative luminosity measurement on robust observables which can be controlled at 0.1% level by the off-line procedures (exploiting the excellent performance of the current LHC detectors)***

Lepton Pair production at the LHC

promises





O(1) events/sec for L=10^{33} $s^{-1}cm^{-2}$ and p_t^{thr} >0.5 GeV/c cut
(the transverse momentum of each of the two leptons > 0.5 GeV/c)

Lepton Pair production at the LHC

promises

Beam energy dependence of the lepton-pair production cross section is driven by the proton point-like contribution and can be controlled to a high precision

The rise of the cross section for coherent production of lepton pairs in pA and AA collisions counterbalances the drop in the corresponding luminosities - the rate of luminosity events stays fairly constant:

$$Rate_{ll}(L_{pp}=10^{33}) \sim Rate_{ll}(L_{pPb}=10^{29}) \sim Rate_{ll}(L_{PbPb}=5x10^{24})$$

… for the same kinematical cuts

Earlier work - LHC context

[13] V. M. Budnev, I. F. Ginzburg, G. V. Meledin and V. G. Serbo,
The possibility of applying the process pp → ppe^+e^- for calibration of cross-sections in colliding pp beams. Phys. Lett. B39, 521(1972).

[14] V. Telnov, On Possibility of Luminosity Measurement in ATLAS Using the Process pp → pp + e^+e^-. ATLAS note PHYS-94-044 (1994), unpublished.

[15] K. Piotrzkowski, Proposal for Luminosity Measurement at LHC. ATLAS note PHYS-96-077 (1996), unpublished. D. Bocian, Luminosity Measurement of pp Collisions with the Two-Photon Process, PhD thesis (2005), unpublished.

[16] ATLAS Collaboration, Detector and Physics Performance. Technical Design Report. CERN/LHCC/99-14 TDR 14, (1999).

[17] A. Courau, Luminosity Monitoring of Experiments at e^+e^-, ep, $\bar{p}p$ Super Colliders. Phys. Lett. B151, 469 (1985).

[18] A. G. Shamov and V. I. Telnov, Precision Luminosity Measurement at LHC Using Two-Photon Production of $\mu^+\mu^-$ pairs. Nucl. Instr. Meth. A494, 51 (2002).

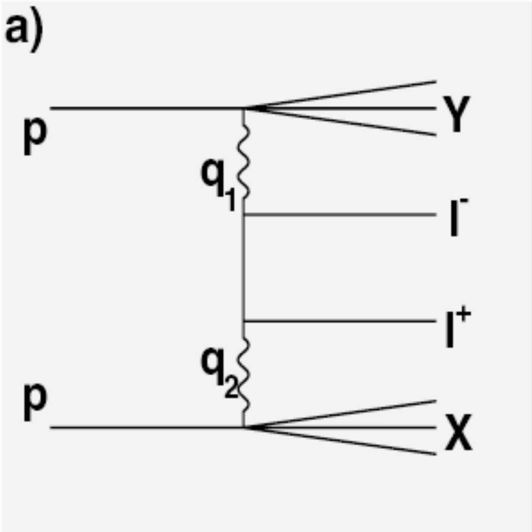
+ already impresive experience of the LHCb collaboration

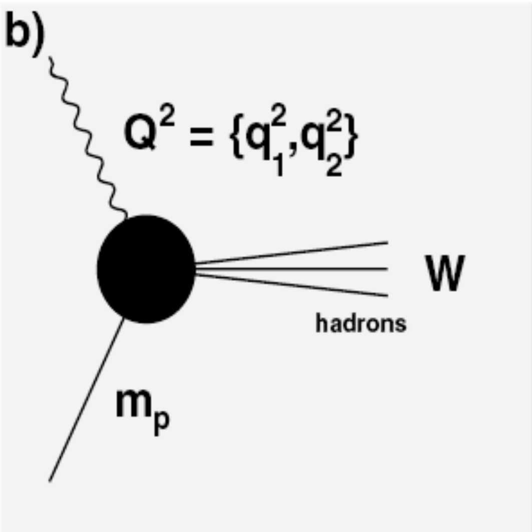
Lepton Pair production at the LHC

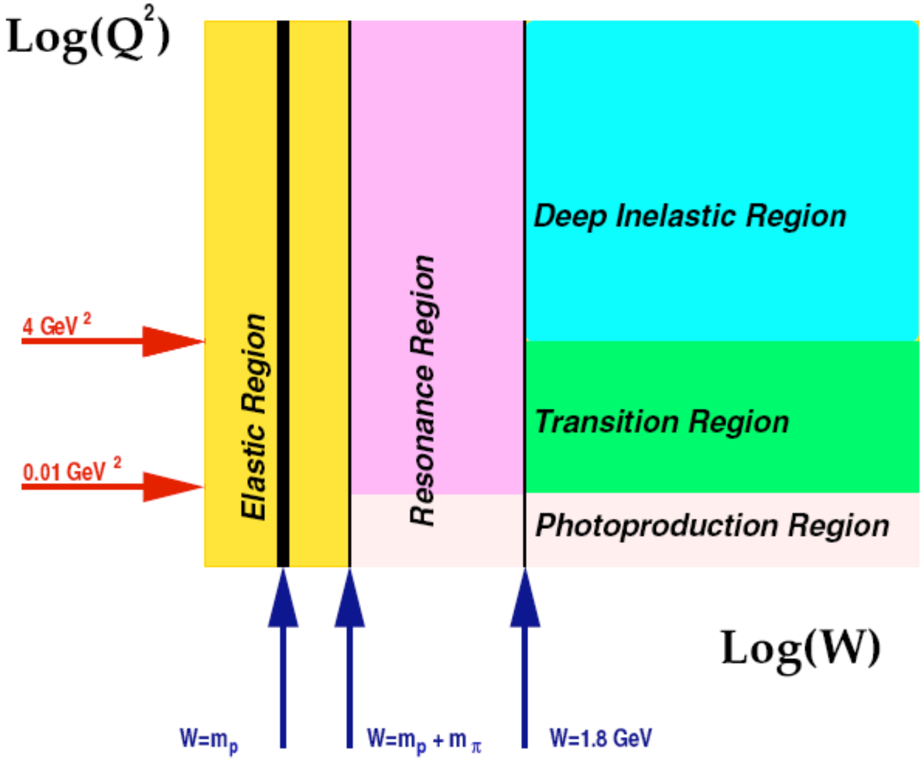
Theoretical problems

1. *collisions resolving the dipole structure of the proton*
2. *inelastic excitations of the proton*
3. *re-scattering corrections*
4. *radiative corrections*
5. *“Coulomb corrections” for ions*

- inelastic excitations of the proton



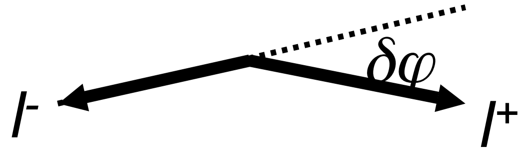




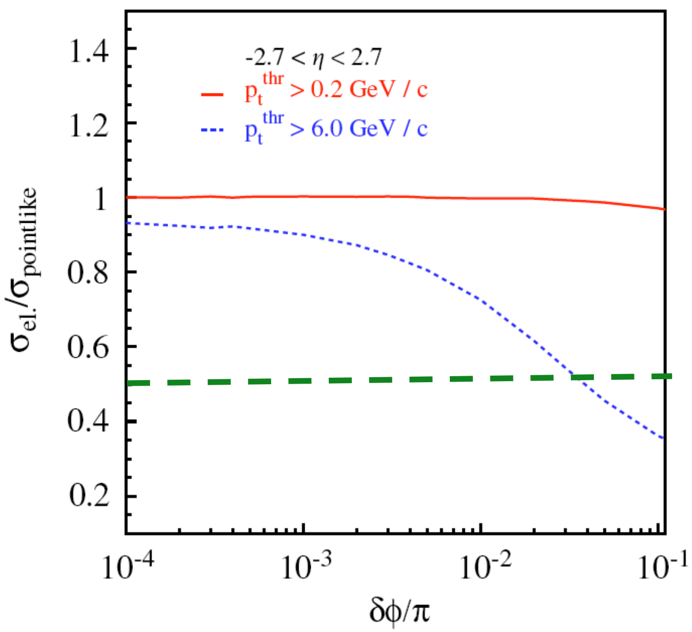
… to achieve <1% control of the cross sections the contribution of inelastic processes must be kept below 10% level and the contribution of processes resolving the dipole structure of the proton below 50%

- dominance of collisions of point-like protons

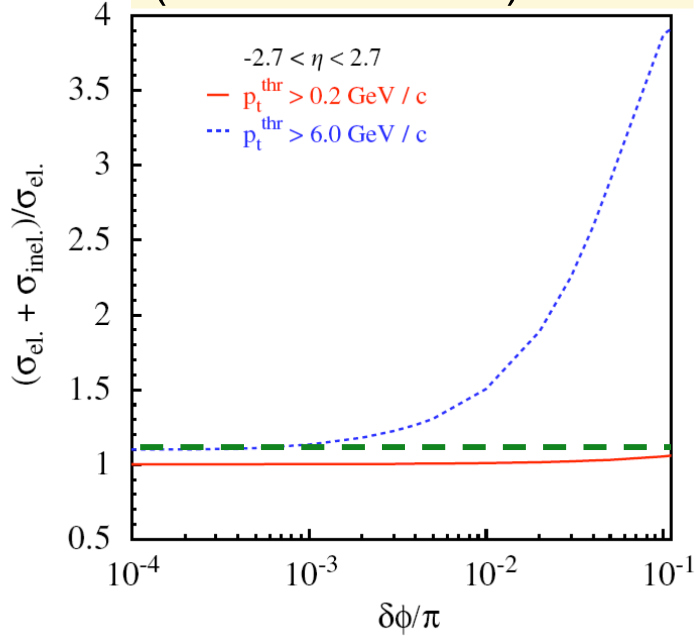
$$\delta\phi = \pi - min(2\pi - |\phi_1 - \phi_2|, |\phi_1 - \phi_2|)$$



elastic/point-like



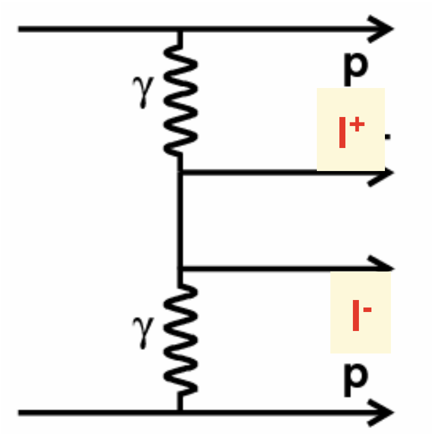
(elastic+inelastic)/elastc

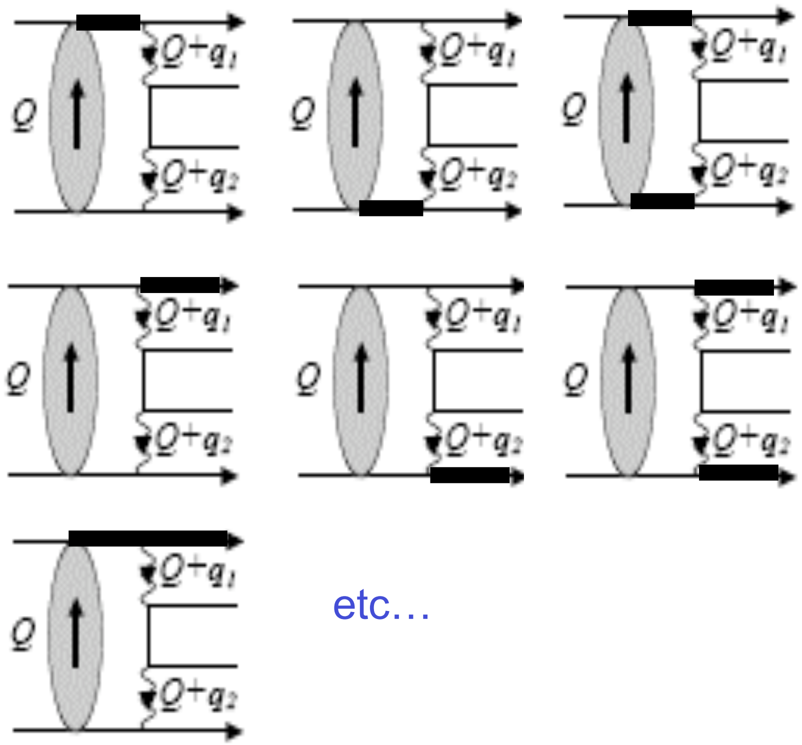


Note:

Unrealistic precision required for $p_t^{thr} = 6\ \ MeV/c$ to reduce the contribution of inelastic processes to the requisite 10 % level. Precision measurement using muon pairs possible only for the LHCb detector (note 1/cosθ term in the resolution)

- re-scattering corrections





etc…

… to achieve <1% control of the cross sections either the p_t^{thr} must be low:

p_t^{thr} < O(1) GeV /c

…or the transverse momentum of the lepton pair must be reconstructed with a precision/resolution:

δ (p_t^{pair}) < O(100) MeV /c

Unrealistic for (p_t^{thr} = 6 GeV/c), easy for (p_t^{thr} < 0.6 GeV/c)

V.A. Khoze[a], A.D. Martin[a], R. Orava[b] and M.G. Ryskin[a,c]

Eur.Phys.J.C19:313-322,2001

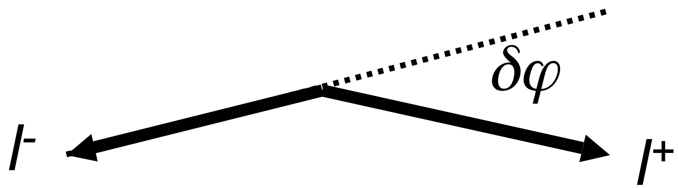
Lepton Pair production at the LHC

Overcoming theoretical problems

kinematical domain to assure the requisite theoretical control of the rates:

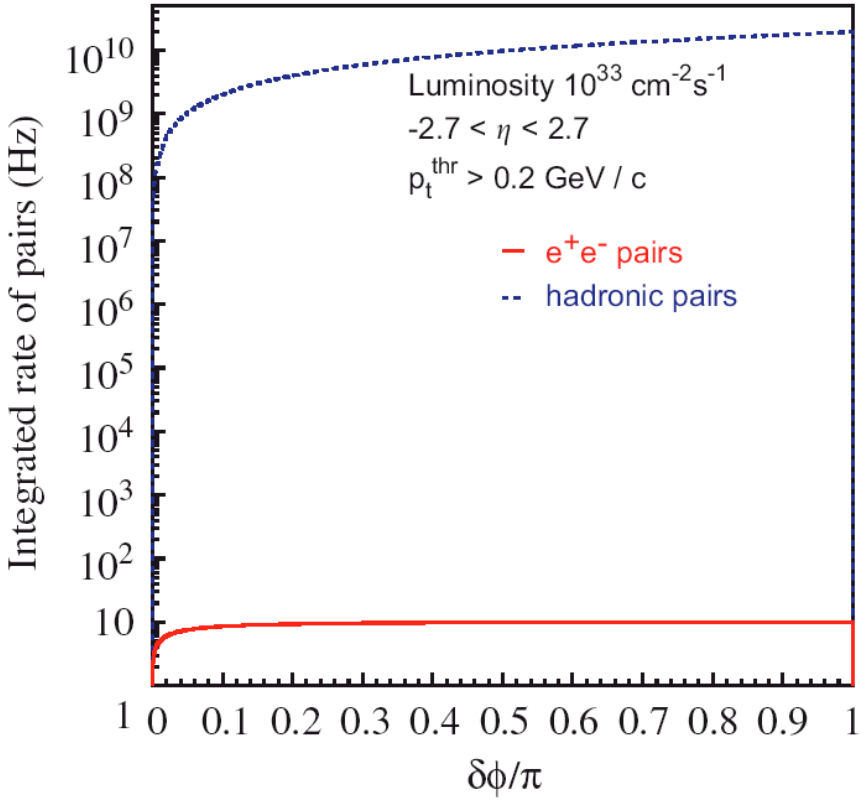
$p_t^{thr} < 400$ MeV/c, $\delta\varphi/\pi < 0.01$

$$\delta\phi = \pi - min(2\pi - |\phi_1 - \phi_2|, |\phi_1 - \phi_2|)$$



Lepton Pair production at the LHC

Experimental problems - trigger

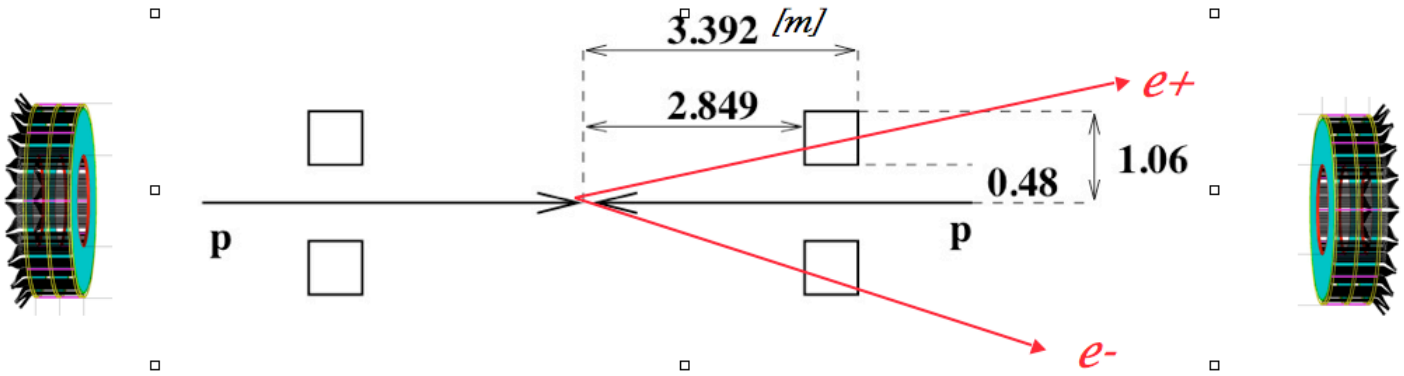


The overall rejection power of hadronic pairs of 10^9 is required…

Moreover, a rejection factor of at least 10^6 must be achieved by the LVL1 trigger, if the Luminosity events were to be collected within the host detector data acquisition chain (O(1 kHz) accept rate at LVL1)

Lepton Pair production at the LHC

Experimental problems - place



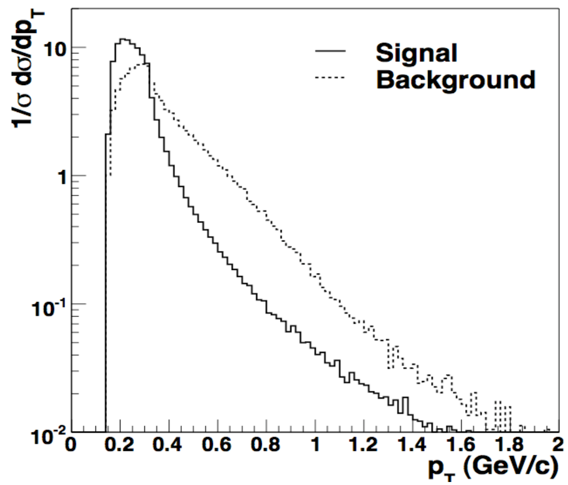
The "empty space" left over by not constructing the ATLAS TRT C-wheels turns out to be an optimal place for the luminosity detector because of:

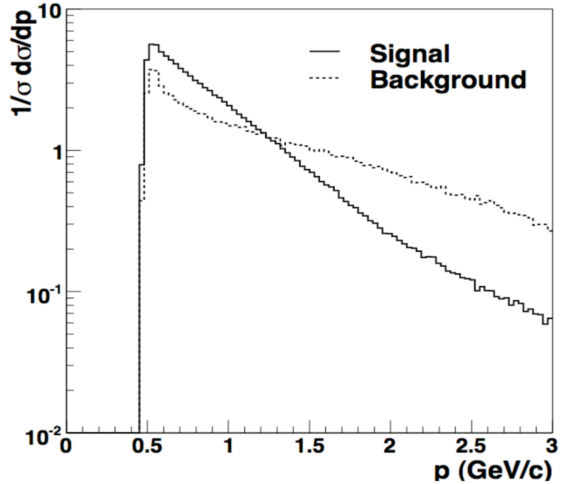
(the largest possible Lorenz boost within the acceptance region of the ATLAS silicon tracker and the LAr electromagnetic calorimeter and comfortable* 1/cosθ term *)

…note large dead material budget and related radiation and MS problems

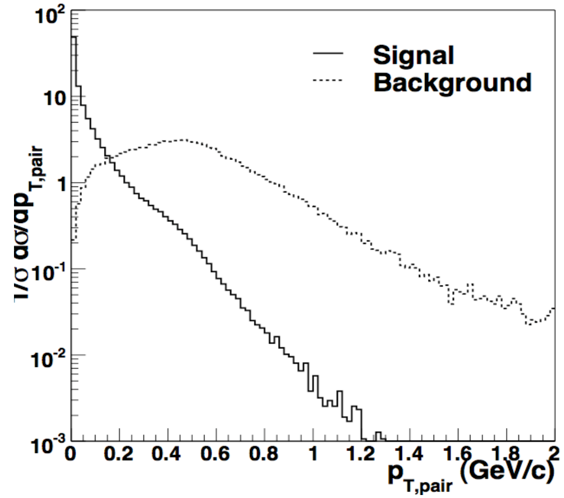
Particle pairs in the luminosity detector

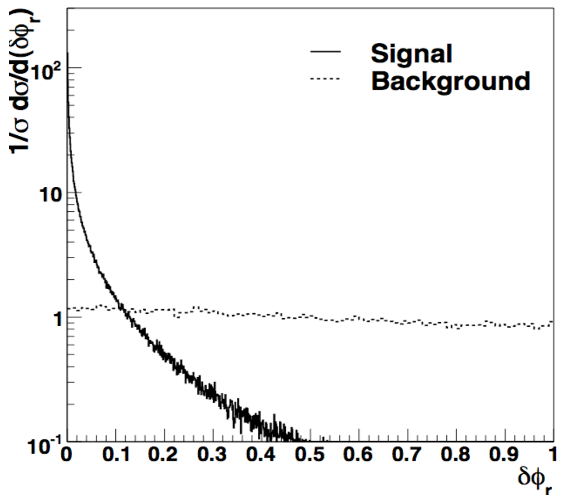
Signal and background





Inclusive distributions





"pair" distributions

Overcoming the experimental problems
The underlying concepts

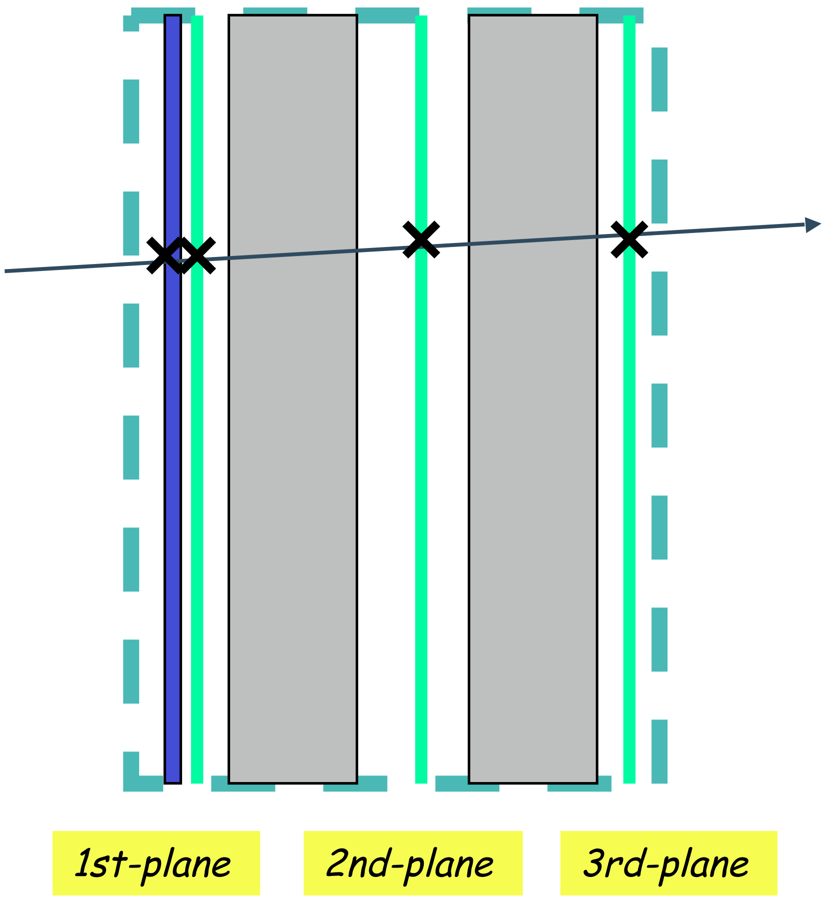
1. *The luminosity detector plays two-fold role: it delivers to the CTP of the host detector the LVL1 trigger bits for the "luminosity measurement" bunch crossings and counts locally its "in-time" track segments.*

2. *The LVL1 algorithms are based on the luminosity detector hit patterns.*

3. *Only "silent bunch crossings" are used in the luminosity determination (extension to the μ > 1 periods will be discussed later).*

4. *The host detector data are used in the LVL2/EF selection chain and in the offline reconstruction of lepton pair production events.*

The luminosity detector model



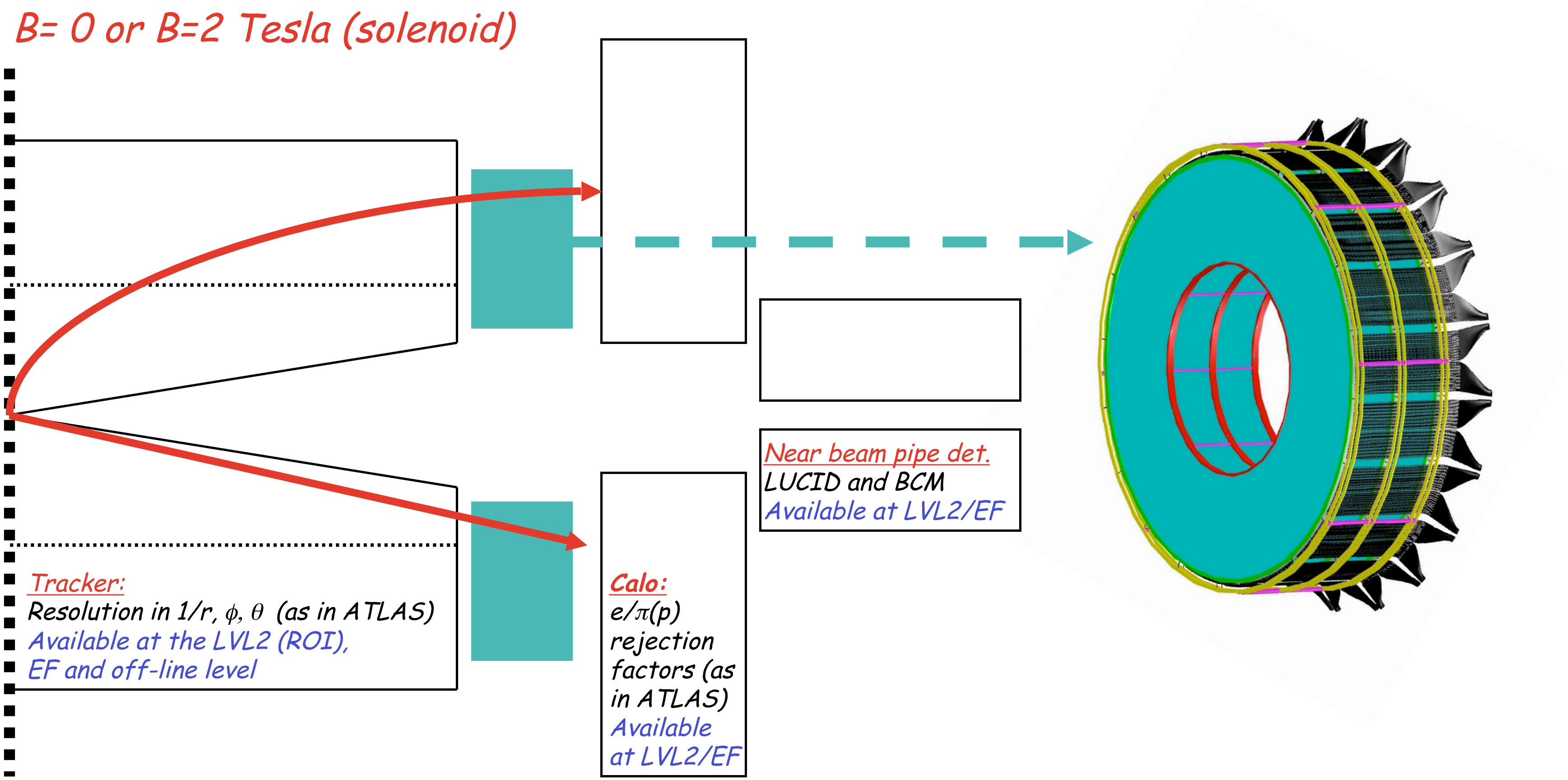
LVL1

ϕ-hit plane: fine ϕ resolution: 3142 sectors, "poor" time resolution (bunch crossing association)

t-hit plane: "poor" ϕ resolution: 36 sectors, fine O (1 ns) timing resolution

Extensions of the base-line detector and optimisation aspects discussed in arXiv:1006.3858 [physics.ins-det]

The proof of principle



Event selection scheme

B=0 Tesla case

LVL1
-fast hit based algorithms

LVL2
-link of the two LVL1 track segments to the E>1 GeV electromagnetic clusters and to the SCT tracks
-acoplanarity recalculated
- no particles traversing LUCID

EF
-No other vertex constrained tracks in the central tracker [-2.5-+2.5]
-No particles traversing the BCM
-sharpening rejection of hadronic clusters

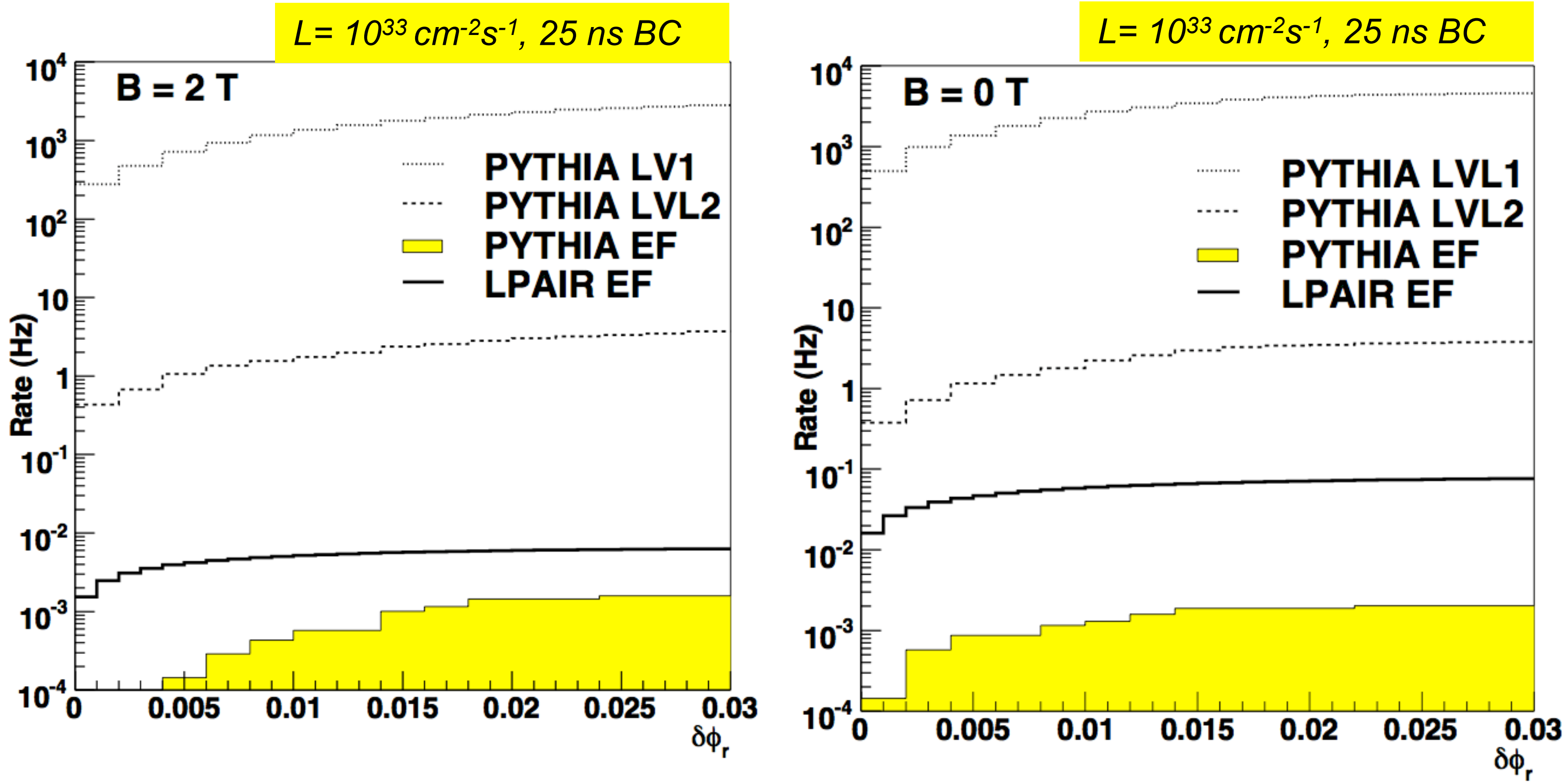
B=2 Tesla case

LVL1
- fast hit based algorithms

LVL2
-link of the two LVL1 track segments to the electromagnetic clusters and to the SCT tracks
-acoplanarity recalculated
- no particles traversing LUCID

EF
-No other vertex constrained tracks in the central tracker [-2.5-+2.5]
-No particles traversing the BCM
-sharpening rejection of hadronic clusters
-$pt_{pair} < 60$ MeV/c

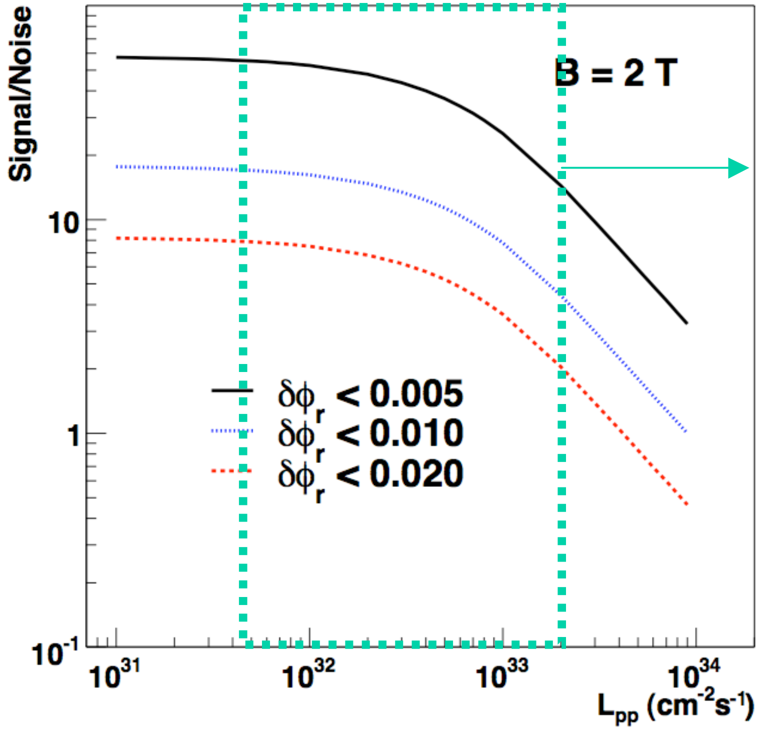
Event selection performance

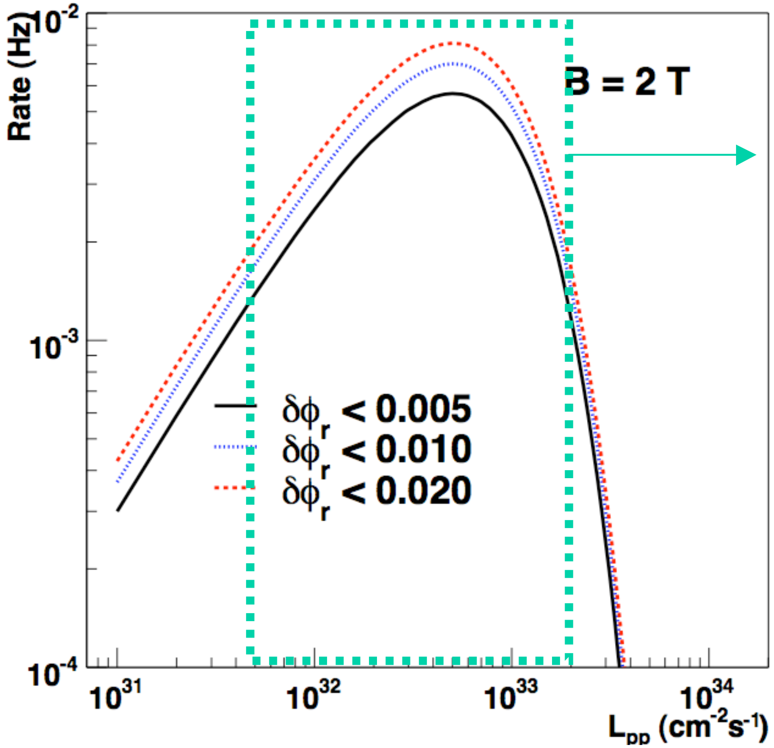


Sampling time to achieve 1 % statistical precision:
-30 hours for the B=0 T configuration
-20 days for the B=2 T configuration (photon radiation!)

Performance and limitations

The method works for luminosities of: $L < 2 \times 10^{33}$ $cm^{-2}s^{-1}$



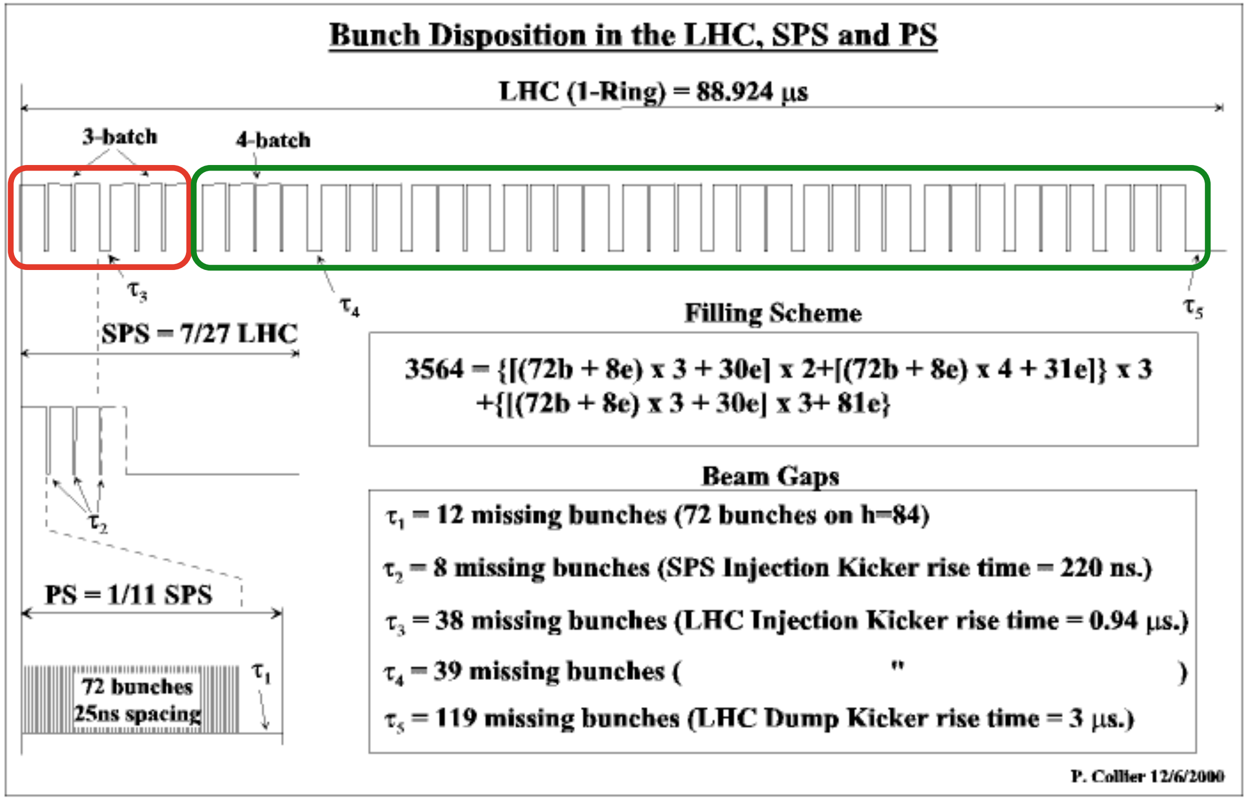


Two methods of extending the method to $\mu >> 1$:

-an extension of the luminosity detector functionality (timing, LVL1 z_v)
-extrapolation to large μ using a strong interaction process (require a precision measurement of relative luminosity in large and small μ bunch-crossings)

Extension of the method to large μ

measurement



extrapolation

Luminosity loss:

(3+3)/39 = 0.15

Negligible

Measure absolute luminosity for the first two "3-batch" bunch crossings for which the proton number is set to assure $\mu \sim 1$ and extrapolate to all remaining bunch crossings (the proposed running scenario is, in the long term, indispensable for the precision physics and considered by S.Myers as feasible)

Extension of the method to large μ

Alternative (conservative solution):

- *Absolute luminosity in dedicated 1-2 days-long $\mu \sim 1$ runs (B=0 solenoid field).*

- *Subsequent extrapolation to the nominal B-field configuration runs (using reconstructed $Z \rightarrow e^+e^-$) and to an arbitrary μ*

Both methods require a robust and precise measurement of the instantaneous BC luminosities over the full μ-range and in fine, O(1 min) time intervals

Measurement of instantaneous luminosity

The underlying concepts

•Measure the rate of the luminosity detector LVL1 “in time” track segments (in-time track segments are those originated from the beam crossing fiducial volume - determination on the basis of the local track curvature and the LVL1 timing of the track segment)

•Counting done locally at the luminosity detector level

•Use phi-segmentation of the detector for covering the full μ-range

•Precise off-line corrections on the bases of matching the luminosity detector LVL1 trigger signals with tracks reconstructed in the silicon tracker of the host detector

Systematic uncertainties

L= 10^{33} $cm^{-2}s^{-1}$, 25 ns BC

$$L_{int} = \sum_{t_i} \frac{N_s(t_i) \cdot (1 - \beta(t_i))}{P^{silent}(t_i) \cdot Acc(t_i) \cdot \epsilon(t_i) \cdot \sigma_{e+e-}}$$

$\beta(t_i)$ - background subtraction error < 0.4 % (model independent extrapolation)

σ_{e+e-} - theory error < 0.3 % for the selected sample (rad. corr. to be calculated))

$Acc(t_i)$ - all studied contributions below 0.8 % (for details see arXiv:1111.5851 [hep-ex)

$P^{silent}(t_i)$ - can be avoided altogether within a dedicated measurement procedure

$\epsilon(t_i)$ - will be determined with a negligible error using the photon conversions

all the correction factors can be controlled directly off-line in the model independent way using parasitically recorded minimum bias events ("lumi particles" traverse the host detector tracker volume!)

Conclusions and Outlook

- ***The method is anything but easy …but promising to achieve better than 1 % precision of the luminosity measurement***

- ***We may need a cross check of VdM method (CERN neutrino flux story in the 70-ties)***

- ***Easy extension to different collision schemes (energy, pp,pA, AA)***

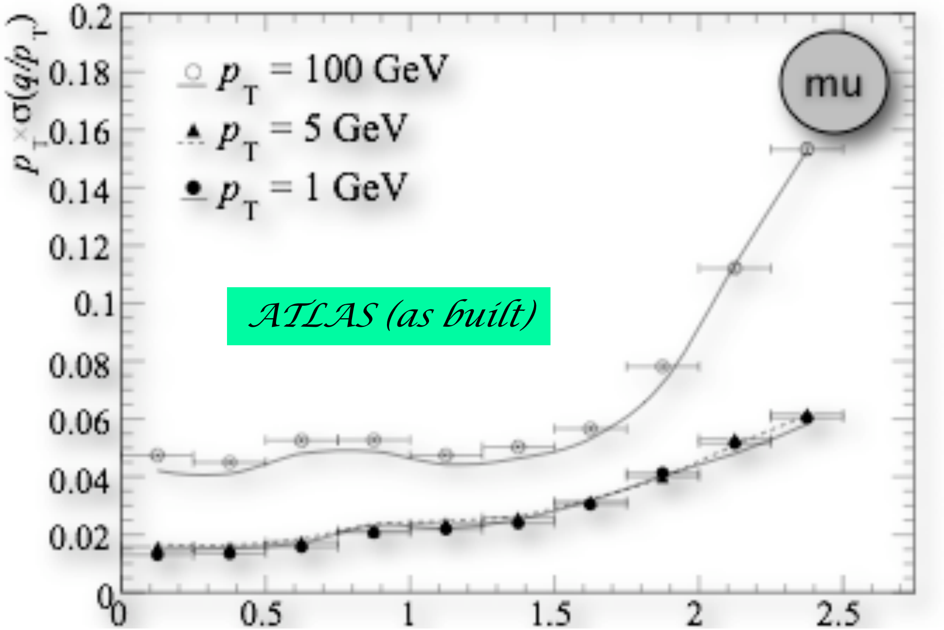
- ***It provides a robust instantaneous lumi monitoring based on the "in-time" LVL1 track segments***

- ***Easy use (luminosity blocks no longer needed)***

- ***This work is only a starting point for more advanced studies which must be based on the concrete hardware design***

- ***A prerequisite is the recognition that the precision goal is worth an effort and the proposed method has a large potential to achieve it***

Achievable $P_{t,pair}$ pair resolution



6 Gev/c cut:

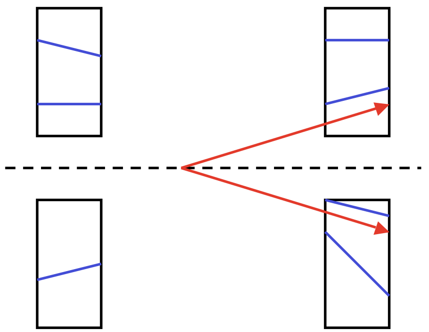
$\sigma(p_{t,pair}) \sim 140MeV/c$

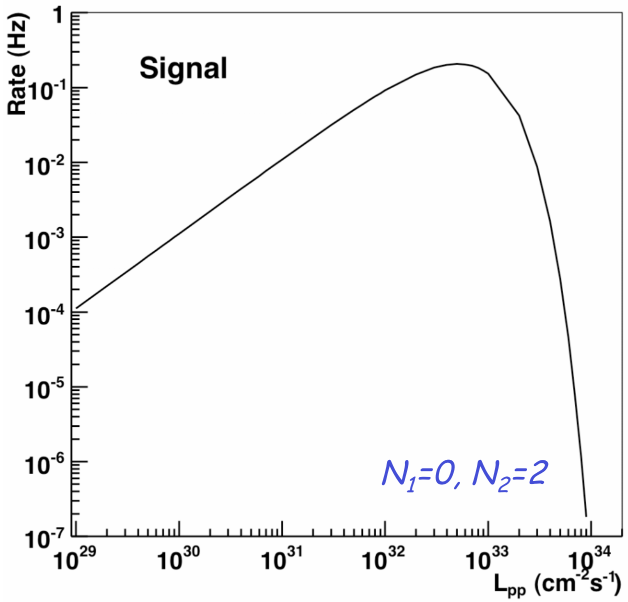
0.4 Gev/c cut

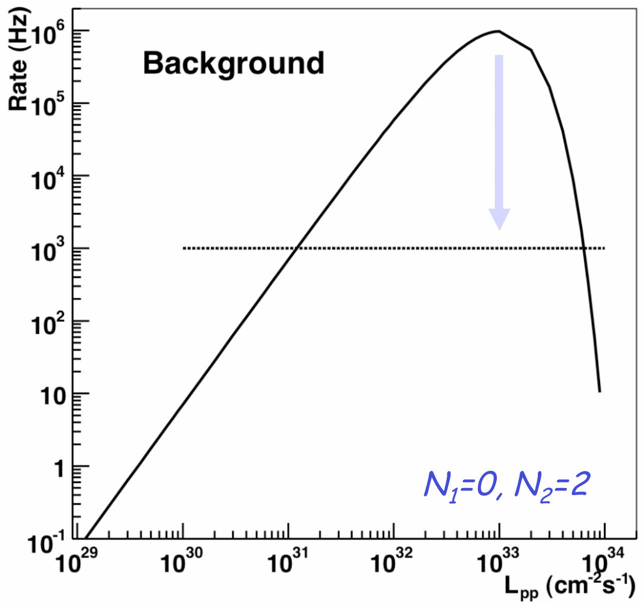
$\sigma(p_{t,pair}) \sim 20MeV/c$

The strategy - cont.

"N_1+N_2" topology of the time-stamp-validated track segments in "silent" bunch crossings





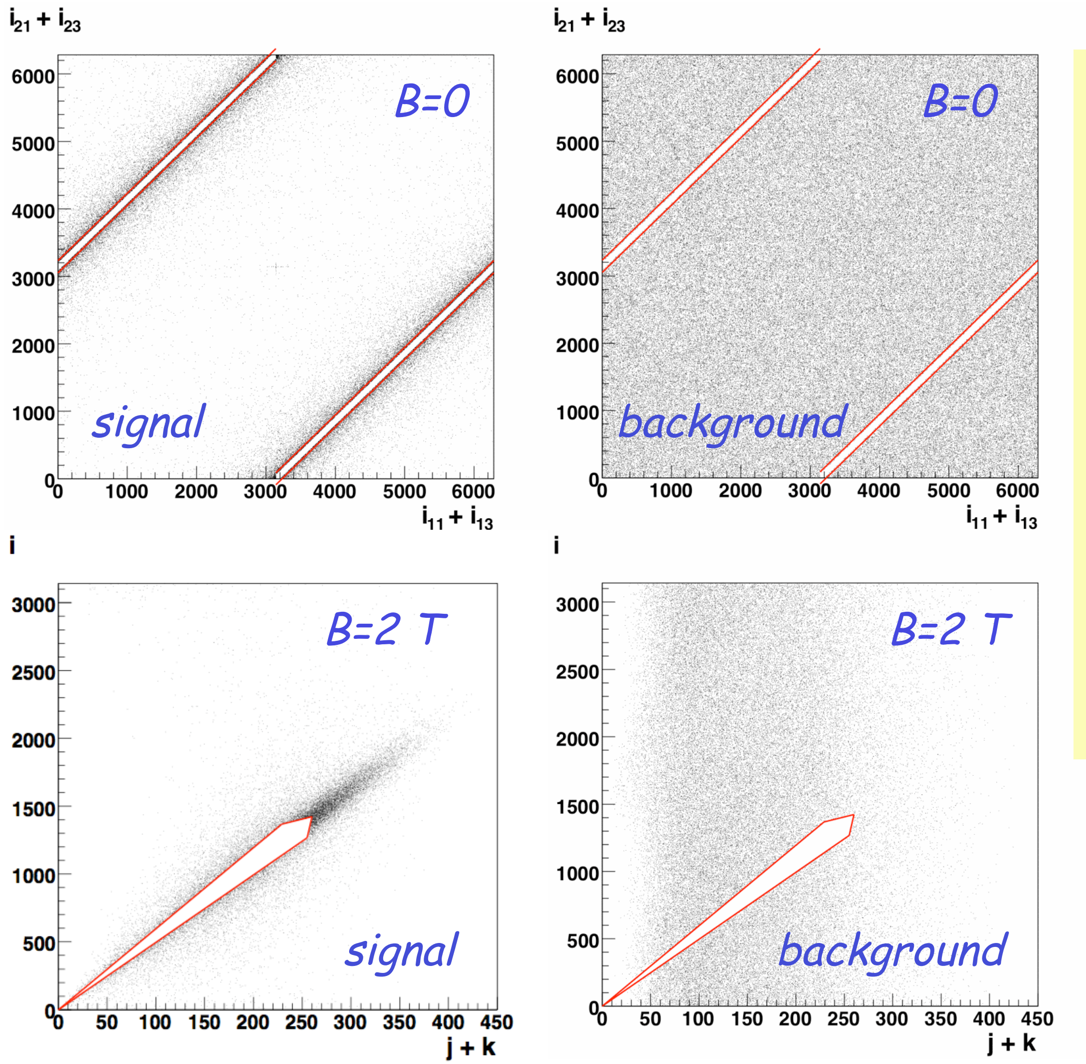


Another specificity of our method:

The requisite LVL1 Trigger rejection of hadronic pairs (to the level of 2-3 kHz) achieved by applying a topological cut using the time-stamp validated hits. Cuts optimized for p> 1 GeV/c, highly coplanar opposite charge particle track segments

LVL1 trigger algorithm

Example: 3124 ϕ-strips, three ϕ-hit planes; $N_1=3$, $N_2=1$, $N_{LVL1} < 2$ Hz



1. Select events with small multiplicities in the first t-hit planes $N_{left(right)} < N_1$ and $N_{right(left)} < N_2$

2. Search for the time-stamp validated track segments on the basis of hit triplets in the three ϕ–hit planes.

3. Select pairs of rigid ($\delta\phi_{13} < 10^o$) opposite curvatures track segments

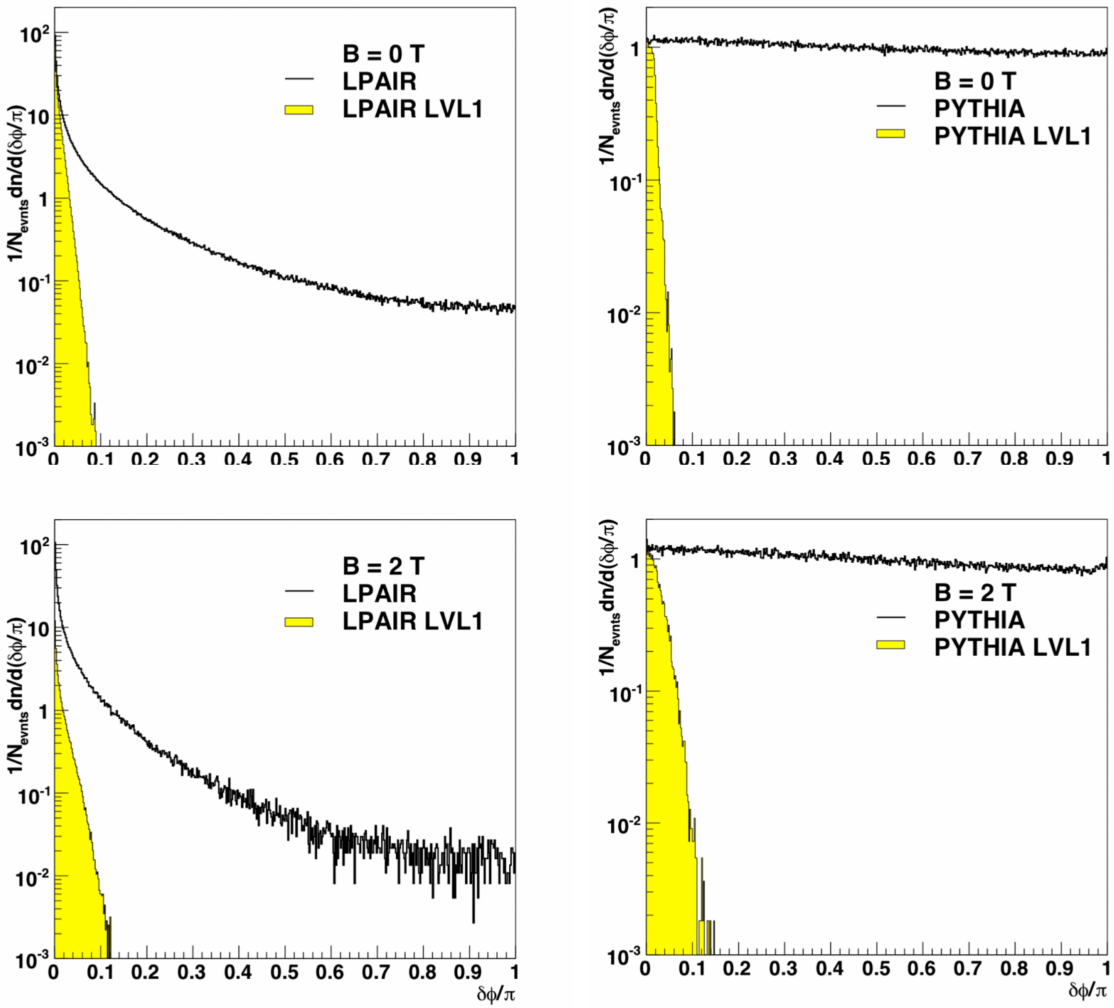
4. Compare the strip-hit combination to the look-up table (i11, i13, i21, i23)

5. If a given hit configuration is accepted on the right(left) side verify that there are no time-stamp validated segments on left(right) side

i_{mn} - particle m crosses strip i of the n-plane

$i = i_{11}-i_{21}$, $j=i_{13}-i_{11}$, $k= j=i_{23}-i_{21}1$

LVL1 trigger acceptance



<u>The "worst" case study</u>

All dead material (0.9 Xo) put in the vicinity of the collision vertex - maximal multiple-scattering and bremsstrahlung effects

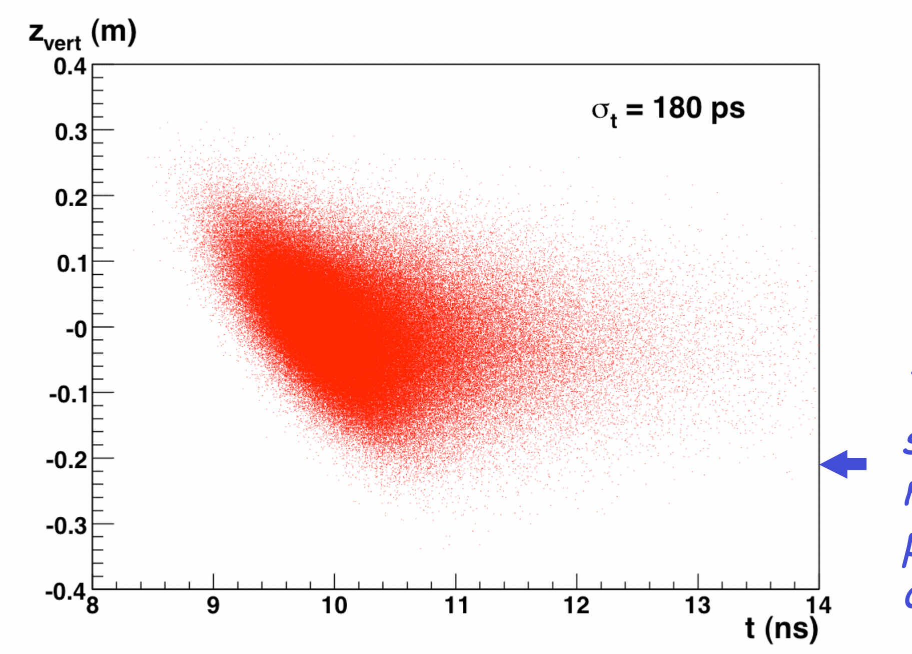
No attempt to correct for the time and the z-position of the collision (detector precise-timing capacities switched off!) (7.5 cm bunch size RMS)

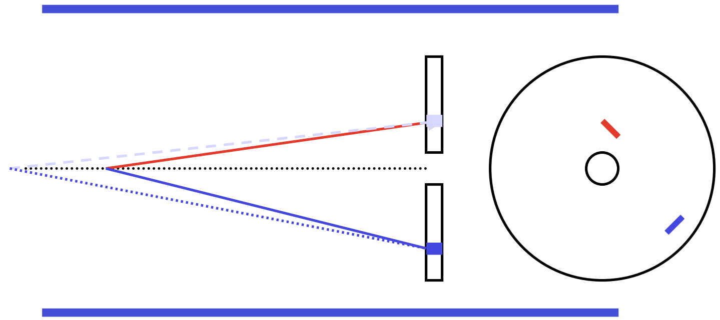
Host detector allows only for less than 2 kHz LVL1 accept rate for luminosity events

LVL1 trigger backtracking of coplanar lepton pairs - optimization of the ϕ- resolution

Effects affecting the LVL1 trigger back-tracking precision:

- ***ϕ- resolution, time-stamp resolution***
- *z-vertex and t-vertex smearing due to longitudinal emittance of the beam*
- *multiple scattering and bremsstrahlung in the dead material,*
- *"noise" track segments*





Time stamps of the lepton track segments reflect the lepton momentum (helix-length), position of the vertex, and time of collision